THE NEUTRAL PION RADIATIVE WIDTH MEASUREMENT: RESULTS FROM PRIMEX (Jefferson Lab)

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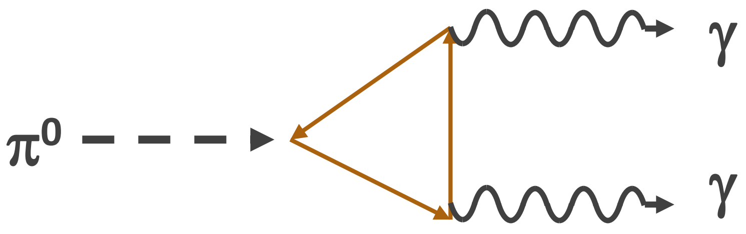
On behalf of the PrimEx collaboration

Outline

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

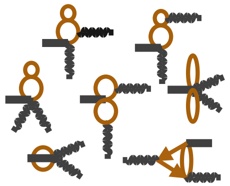
QCD predictions for $\Gamma(\pi^0\to\gamma\gamma)$



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

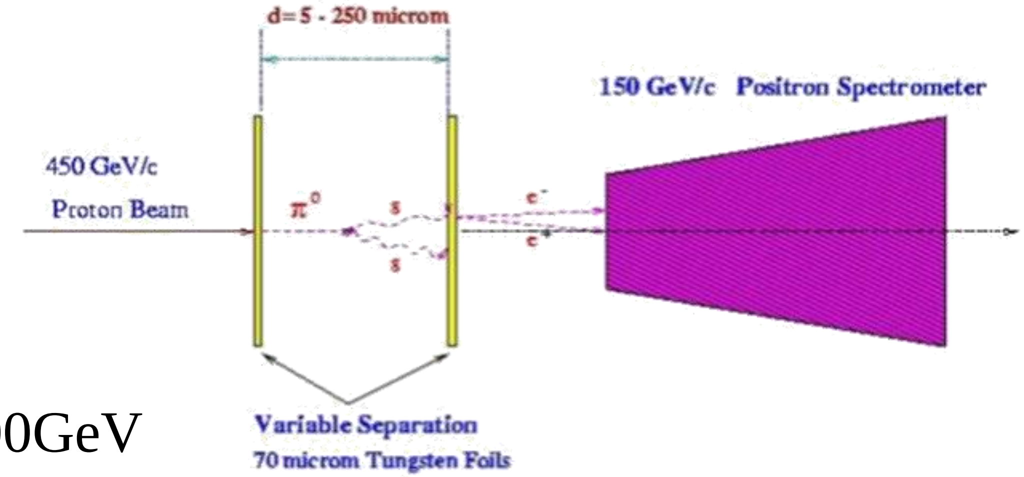
$$\Gamma(\pi^0\to\gamma\gamma)=\frac{\alpha^2 N_C^2 m_{\pi^0}^3}{576\pi^3 F_{\pi^0}^2}=7.725\ \pm 0.044\ eV$$

- 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

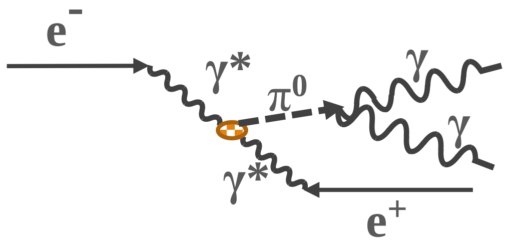
- Direct decay length measurement



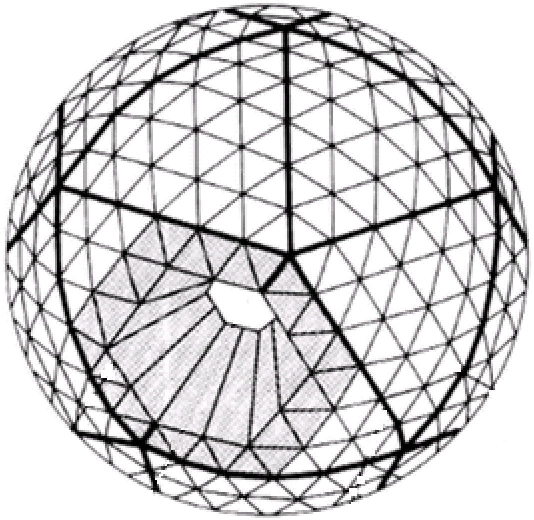
- Decay length is only ~20μm at 100GeV
- Limited by unknown π^0 momentum spectrum
- No need to know production mechanism and cross section
- Measurements:
  - CERN (1984) $\Gamma(\pi^0 \to \gamma\gamma) = 7.25\text{eV} \pm 3.1\%$

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$: 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) $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.75\text{eV} \pm 6.4\%$

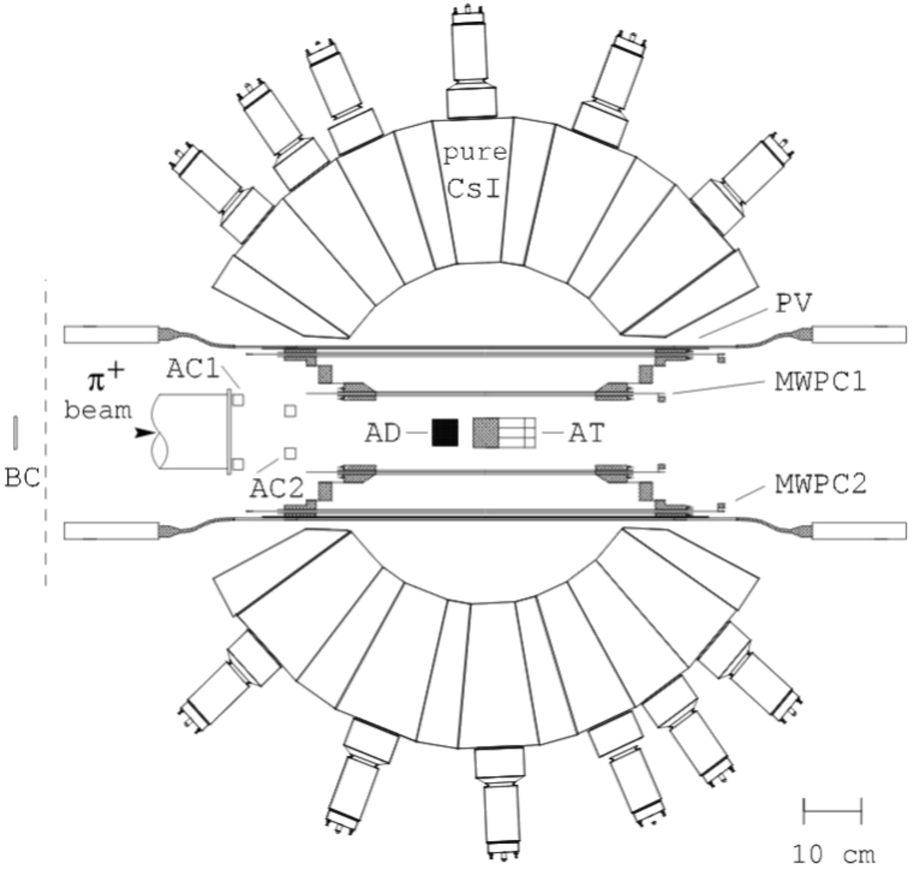


$\Gamma(\pi^0 \rightarrow \gamma\gamma)$: experimental methods and measurements: π^+ radiative decay measurement

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

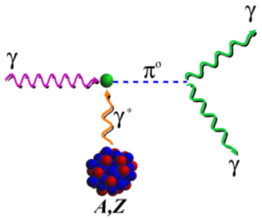
$$\Gamma(\pi^0 \rightarrow \gamma\gamma^*) = \frac{\alpha^2 \pi m_{\pi^0}}{2} |F_V(0)|^2$$

- Measurements:
  - PIBETA (2009) $\Gamma(\pi^0 \rightarrow \boldsymbol{\gamma\gamma}) = 7.65\text{eV} \pm 13\%$

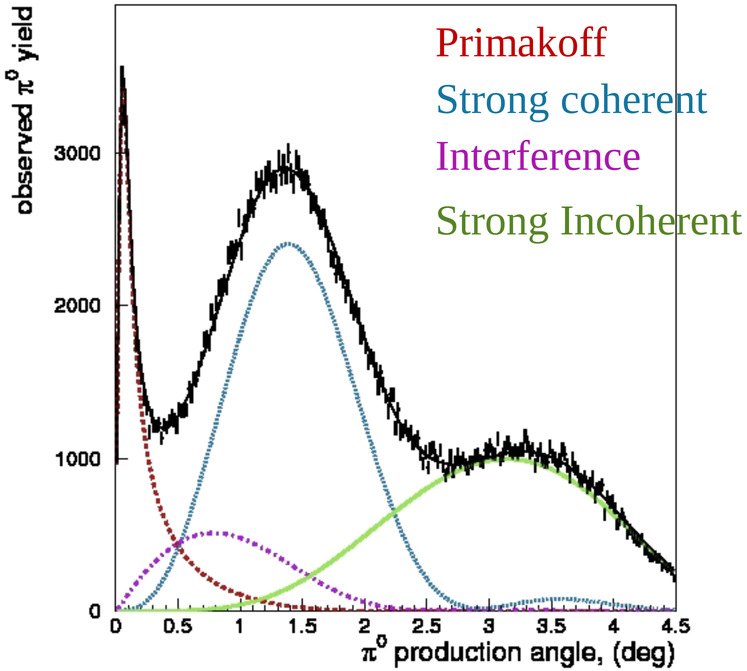


$\Gamma(\pi^0 \to \gamma\gamma)$: Primakoff method

- π^0 photoproduction in nucleus coulomb field

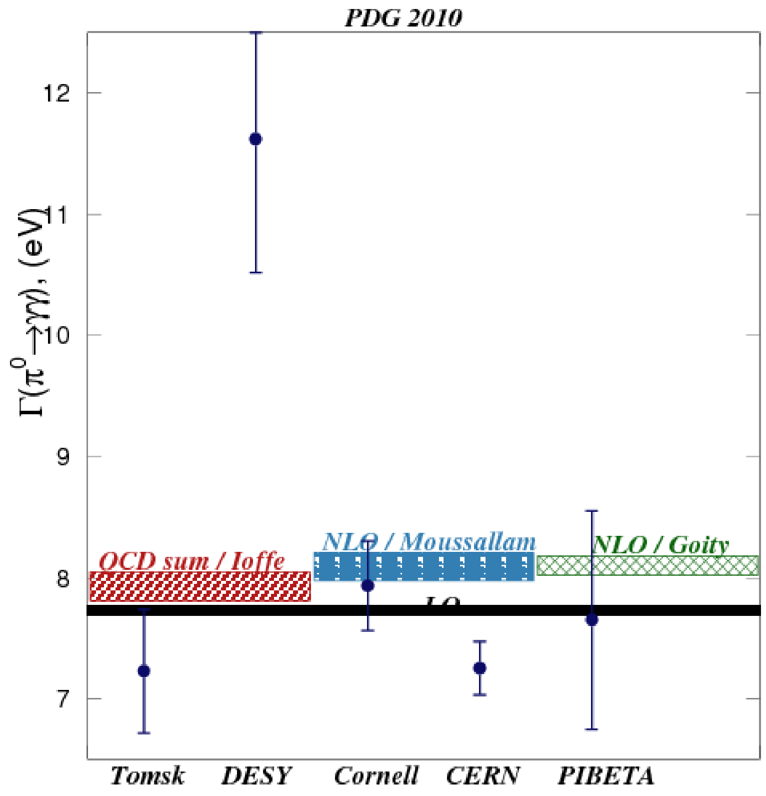


- Coulomb part of photoproduction cross section needs to be extracted: $\left(\frac{d\sigma}{d\Omega}\right)_{Pr} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\pi^3} \frac{\beta^3 E^4}{Q^4} |F_{em}(Q)|^2 \sin^2\theta_\pi$
- Challenge: separate Coulomb and Strong photoproduction
- Most recent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

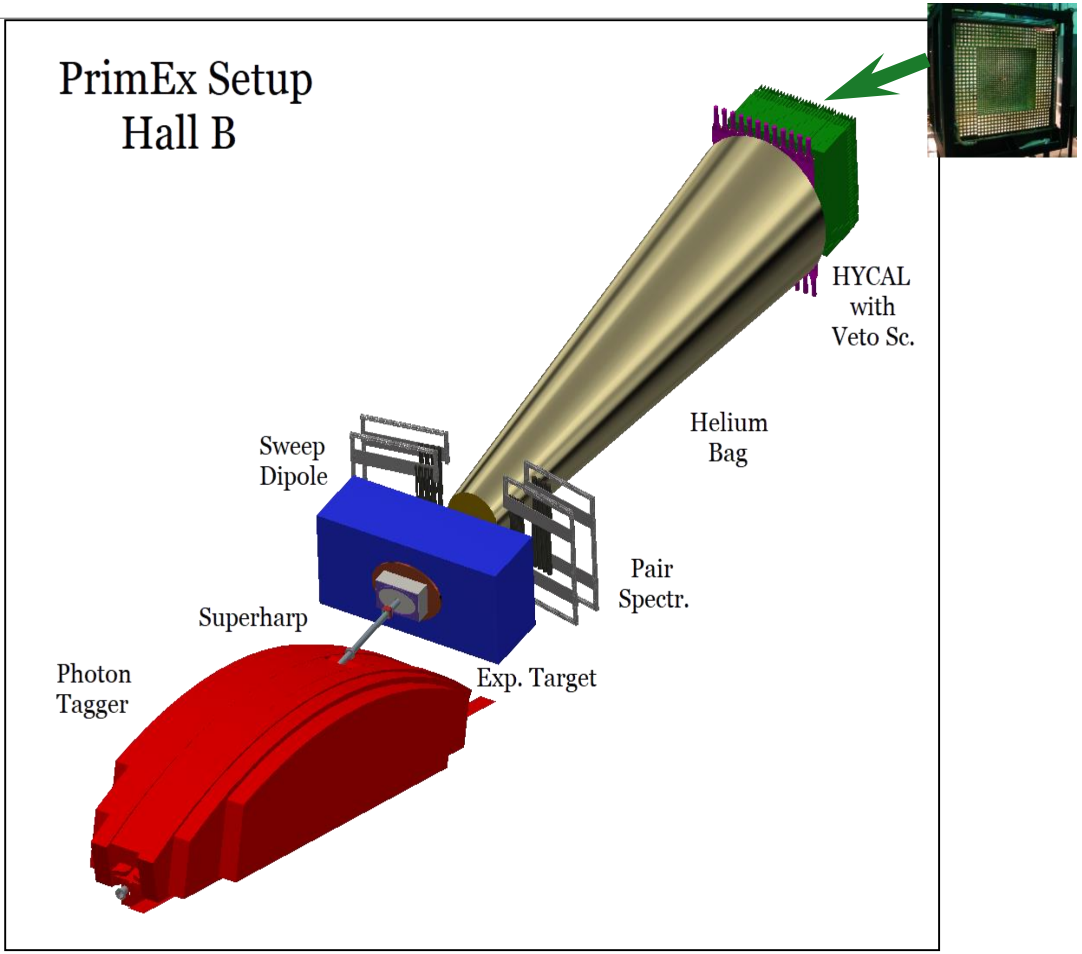


PrimEx Milestones

- **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**
- **2020: Combined PrimEx-I and -II result published** (*Science* 05/2020: Vol. 368, Issue 6490, pp. 506-509)

PrimEx Setup

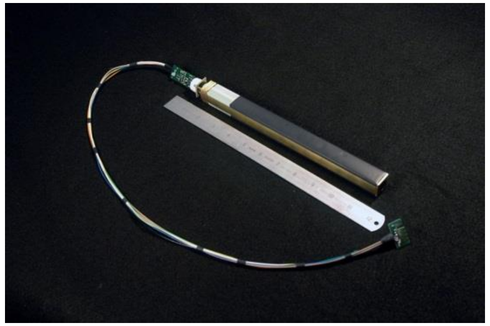
- Tagging facility:
  - Precise photon beam flux control
  - High resolution beam energy and time
- Hybrid EM calorimeter:
  - Excellent energy, spatial and time resolution
  - Large geometrical acceptance
- Pair spectrometer for additional flux monitoring
- Ability to control apparatus systematics by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



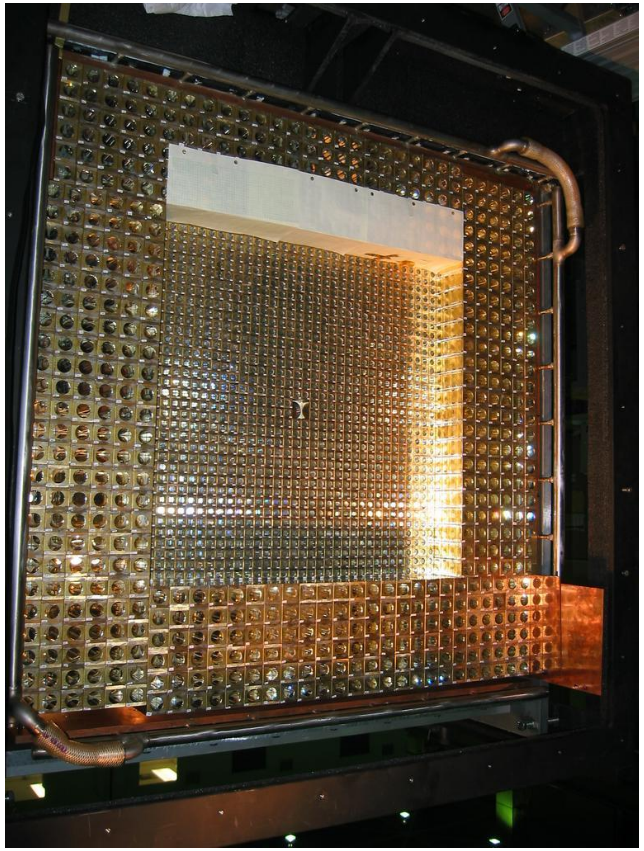
PrimEx Electromagnetic Calorimeter

- Combination of $PbWO_4$ and Pb-glass detectors (118x118 cm^2) :
  - $PbWO_4$ crystals in the center
    34x34 matrix of 2.05x2.05x18 cm^3 $PbWO_4$ blocks
    with 2x2 hole for beam
  - Lead glass out part saves on budget
    576 lead-glass blocks of 3.82x3.82x45.0 cm^3
  - 7.0…7.3m distance from target
- Hybrid EM calorimeter:
  - Excellent energy, spatial and time resolution:
    $\sigma_E / E \sim 2.6\% / \sqrt{E}$; $\sigma_x / E \sim 2.6\ mm / \sqrt{E}$
  - Large geometrical acceptance

Single $PbWO_4$ detector



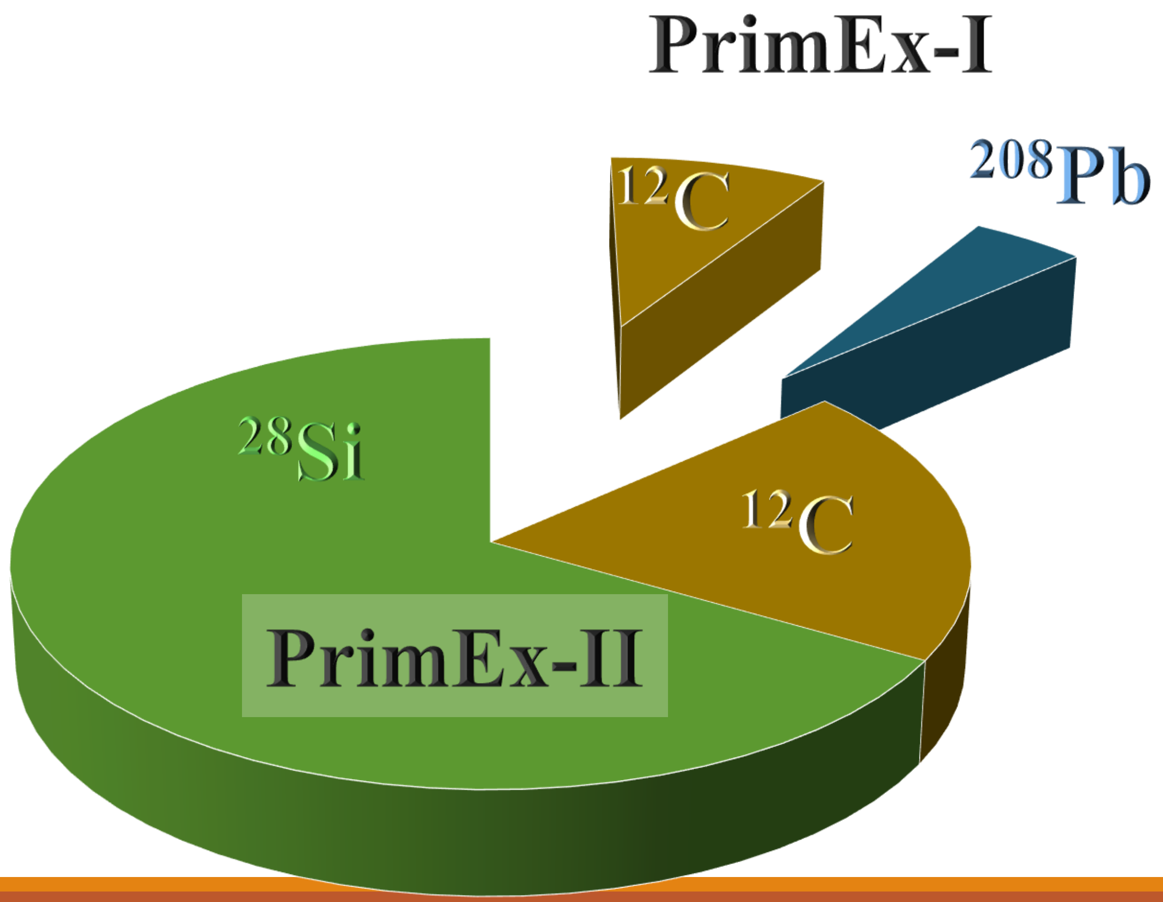
Front view, before Light Monitoring System



PrimEx upgrade for the 2^{nd} run

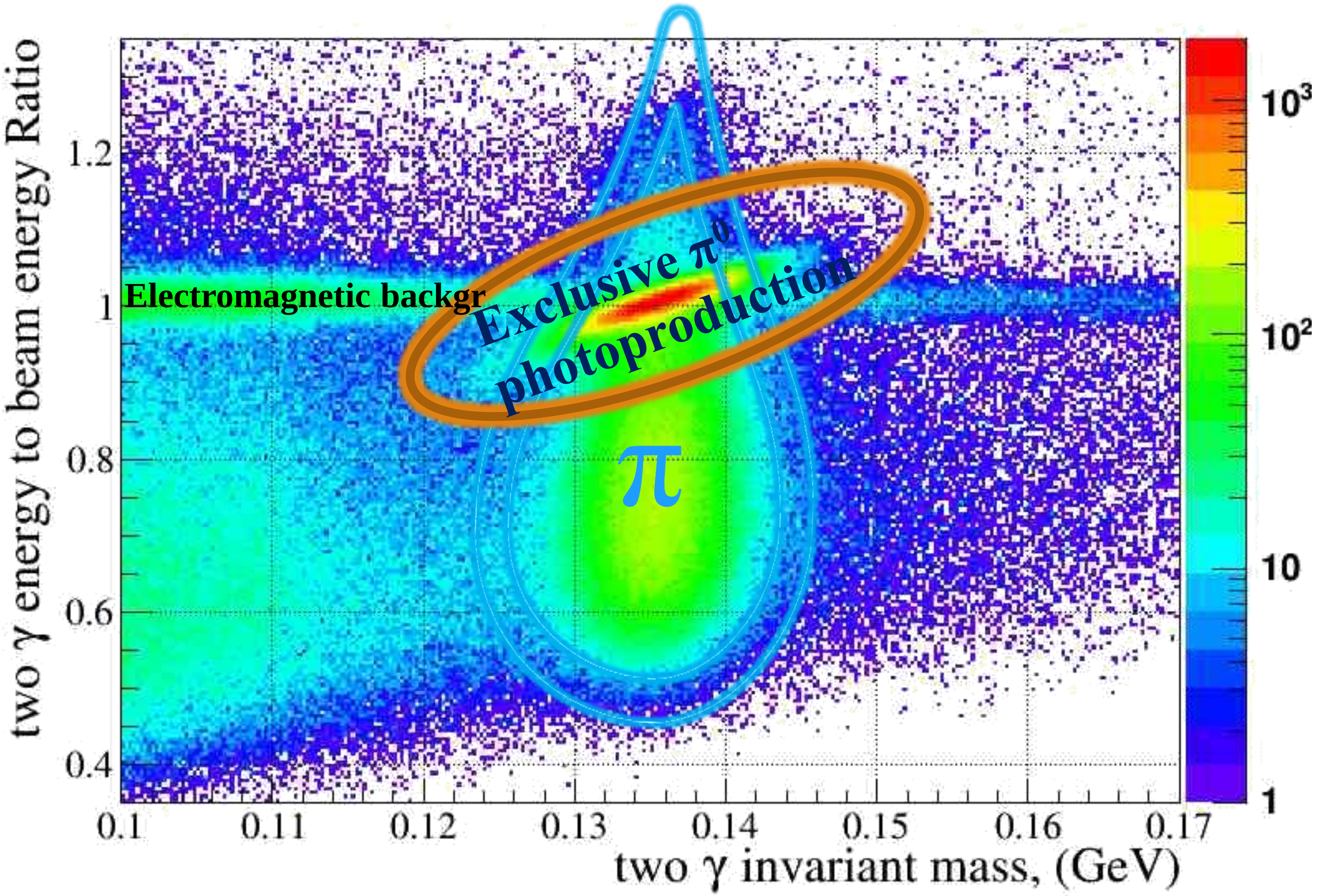
- **PrimEx-II used 8% r.l. Carbon and new 10% r.l. Silicon targets:**
  - PrimEx-II successfully collected twice more statistics on Carbon compare to PrimEx-I and about 5 times more statistics on Silicon compare to PrimEx-I Carbon
  - Higher Z target (but not too high Z: still good control of the strong production part)
- **Tagger energy range has been increased by factor of ~1.5**
- **Central part of HyCal was upgraded with individual TDC modules:**
  - out of time clusters were rejected
  - HyCal time resolution improved from 1.7ns to 0.9ns
- **Upgraded DAQ electronics**
- **Trigger from HyCal signal w/o tagger coincidence**
  - Better accidentals study
- **New calorimeter reconstruction algorithm has been implemented**
- **HyCal moved closer to the target: 7.0m vs 7.3m**
  - larger acceptance for the incoherent production region allows separating it better

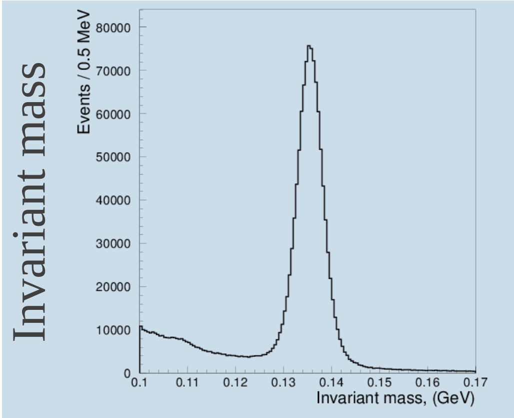
PrimEx I and II data chart

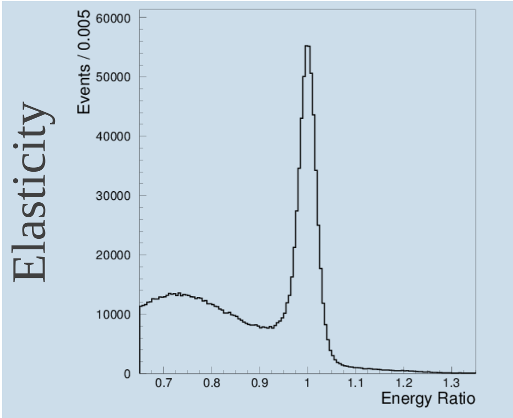


PrimEx run	Target	Thickness [% r.l.]	Beam flux [$\times 10^{12}$]	Beam energy [GeV]
I	^{12}C	5	1.4	4.9…5.5
I	^{208}Pb	5	0.72	4.9…5.5
II	^{12}C	8	2.0	4.4…5.3
II	^{28}Si	10	5.3	4.4…5.3

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

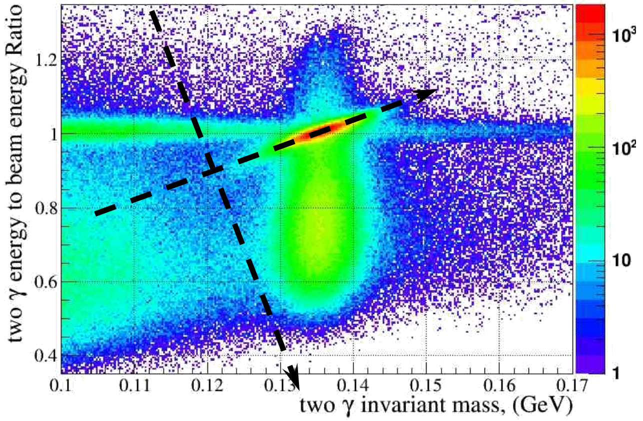




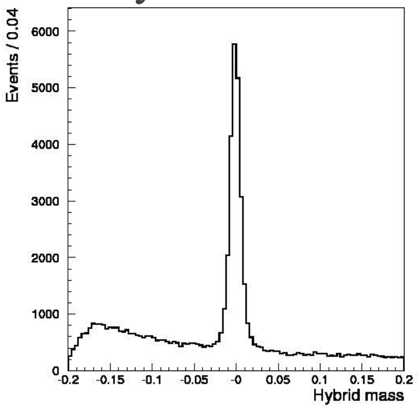


Elastic π^0 yield extraction

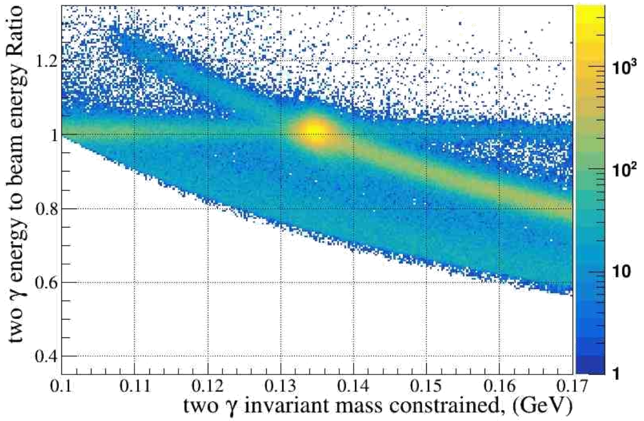
- **Hybrid mass analysis:** analyze rotated axes projection



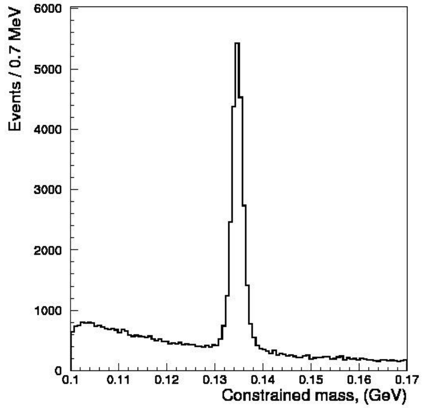
"Hybrid" mass



- **Constraint mass analysis:** correct energies reported by the calorimeter so they give exactly the beam energy



"Energy constraint" mass

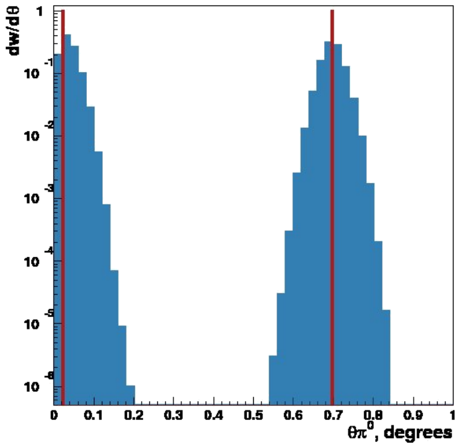


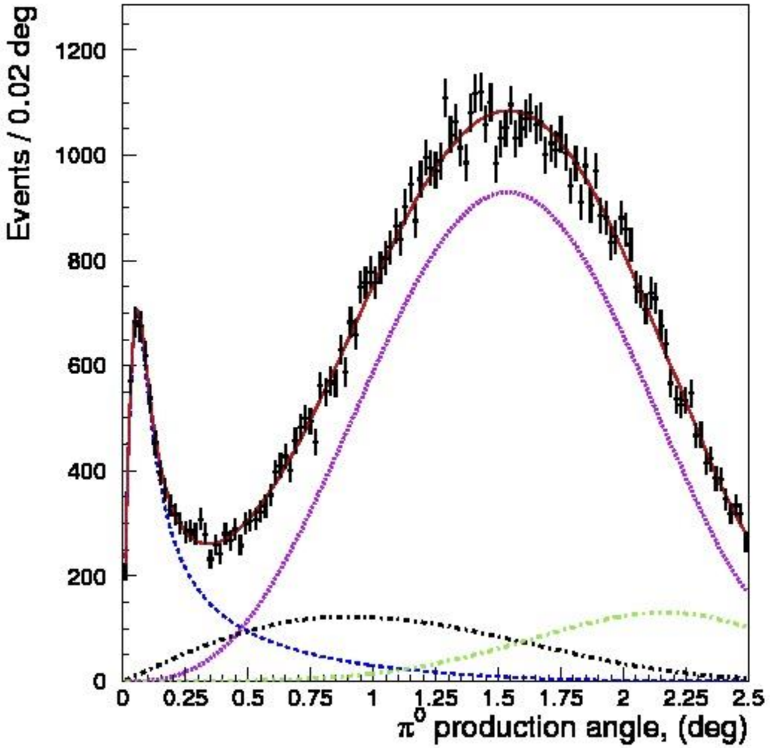
Fit to extract $\Gamma(\pi^0\rightarrow\gamma\gamma)$

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

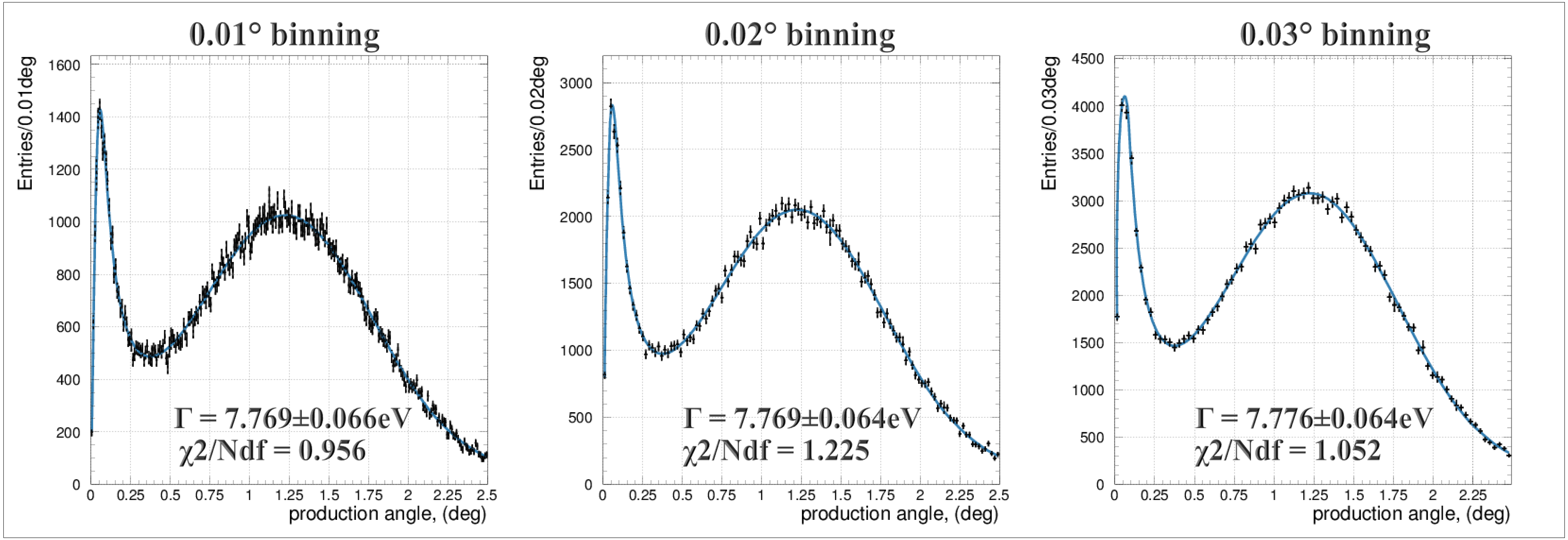
$\otimes$

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

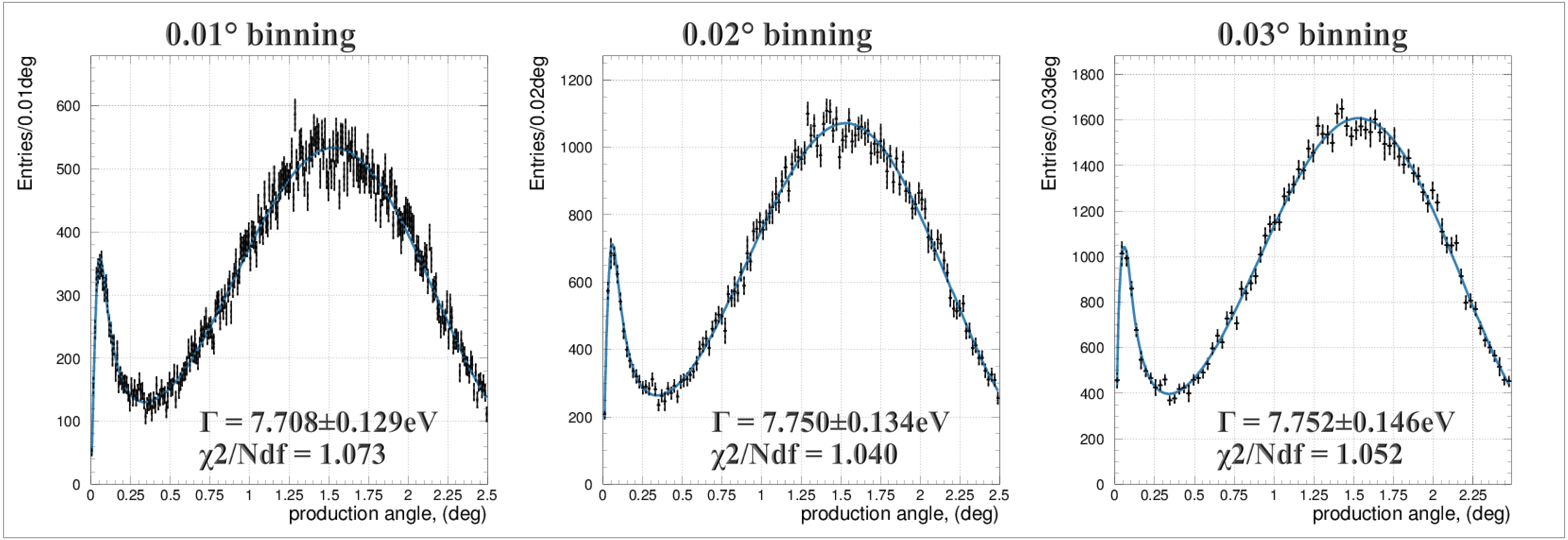




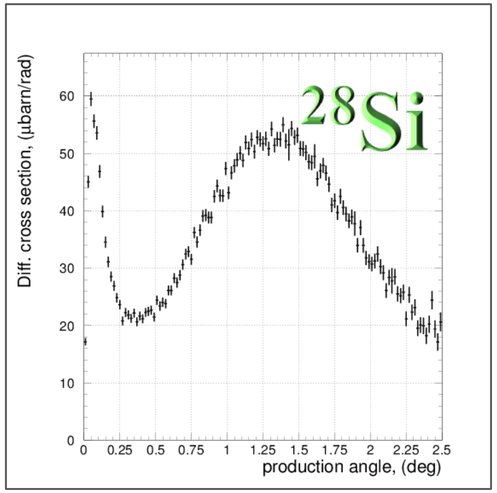
PrimEx-II π^0 yield fit, Silicon target

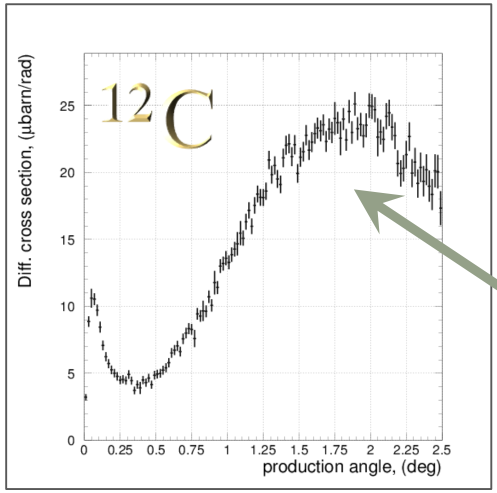


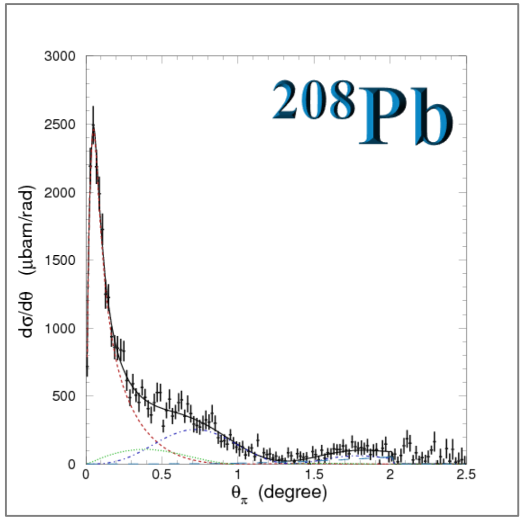
PrimEx-II π^0 yield fit, Carbon target

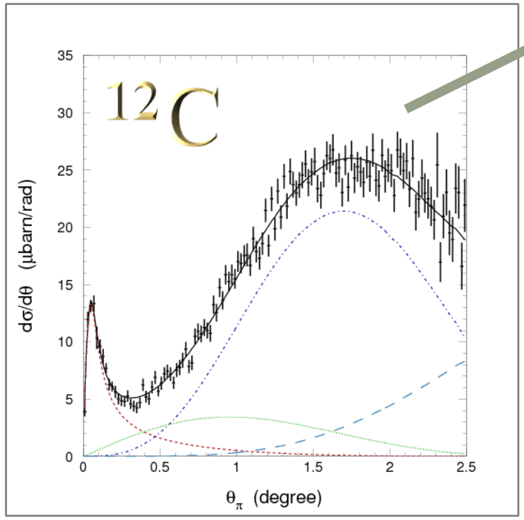


Differential cross section vs production angle









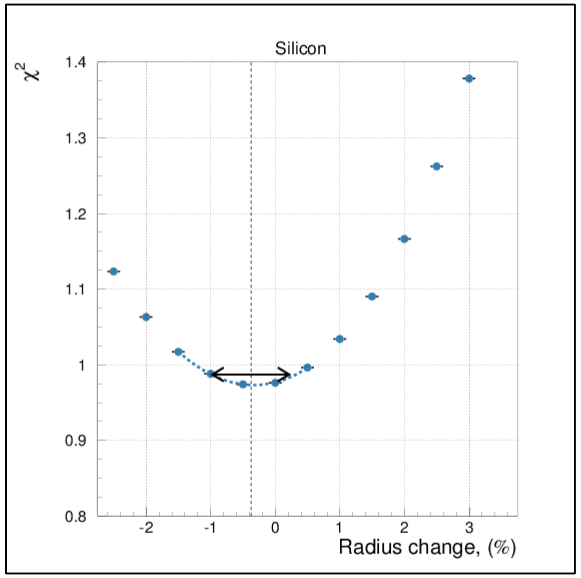
PrimEx-II: 4.45GeV…5.3GeV photon beam energy

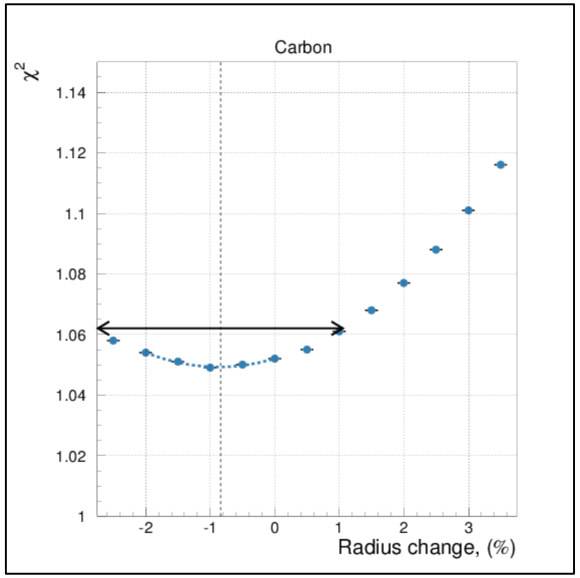
Error bars decrease due to higher statistics

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

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

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





Change the radius to minimize χ^2:

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

Statistical uncertainty of this procedure is going directly to the systematics:

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

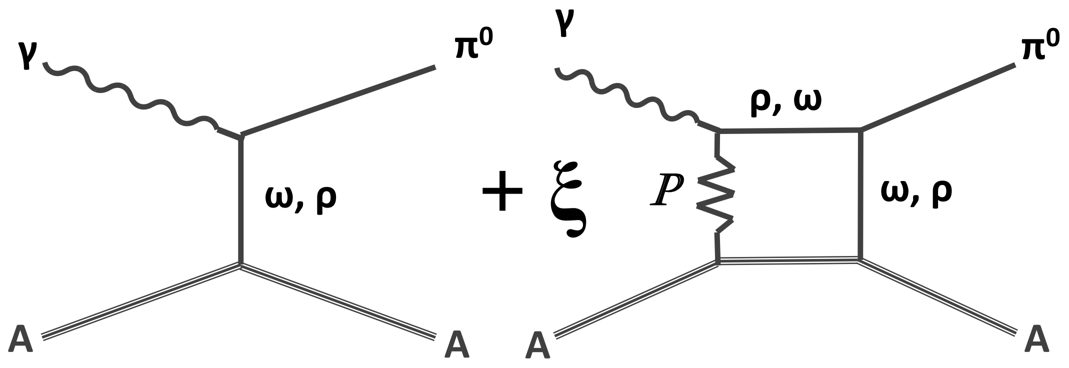
“Second step” contribution (“shadowing” effect)

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 nucleon (ω contribution is additionally suppressed by opposite sign of amplitudes on protons and neutrons). This gives an additional term for the strong amplitude mostly originating from the 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:

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



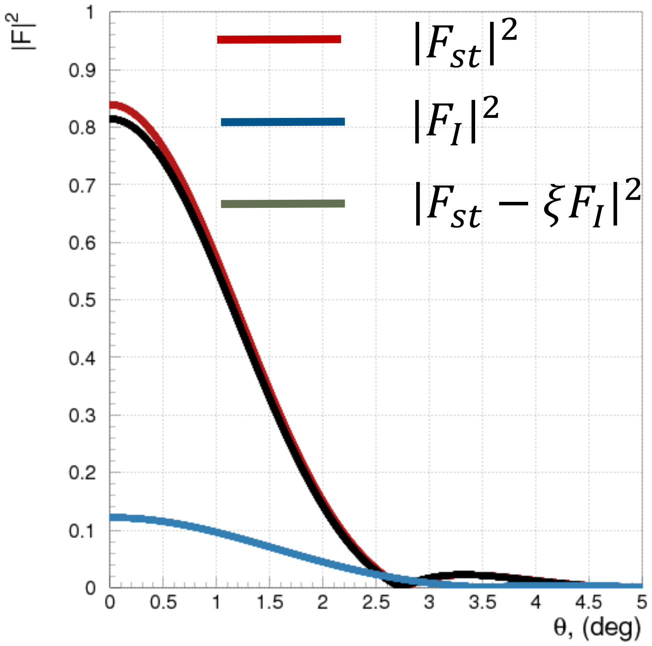
and is within range between 0 (no shadowing) and 1 (VDM)
$\xi = 0.25$ value has been used in analysis*

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

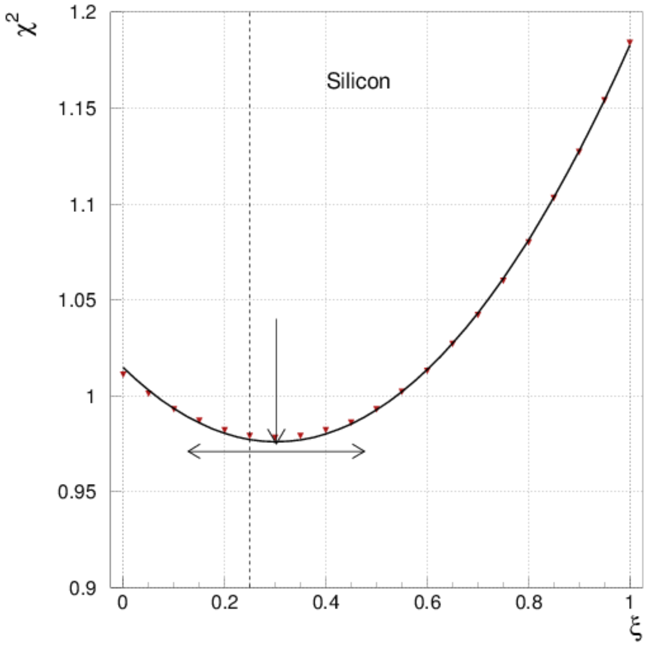
$\Gamma(\pi^0 \to \gamma\gamma)$ systematic uncertainty item: Shadowing parameter ξ

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

Strong FF and shadowing



Data fit χ2 vs shadowing parameter



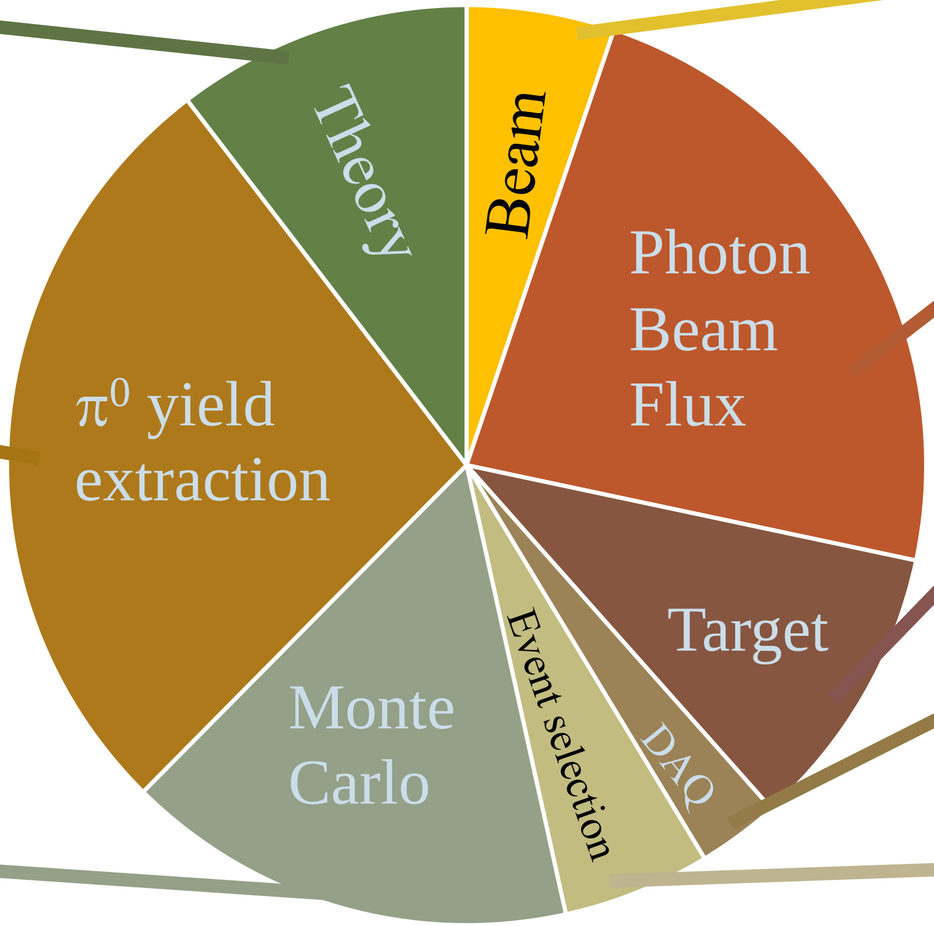
* *W. Meyer et al., Phys. Rev. Lett. 28, 1344 (1972);*
A. M. Boyarski et al., Phys. Rev. Lett. 23, 1343 (1969)

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/dθ binning 0.01°, 0.02°, 0.03°	0.12%
Extraction from MC test	0.2%
Total	0.93%

Target absorption	0.24%
π^0 angular resolution	0.23%
π^0 two gamma decay branching	0.034%
Calorimeter geometry	0.05%
Calorimeter energy response	0.45%
Limited statistics	0.02%
Total	0.58%



Energy	0.14%
Position	0.05%
Slope	0.09%
Width	0.08%
Total	0.18%

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	0.05%
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%**

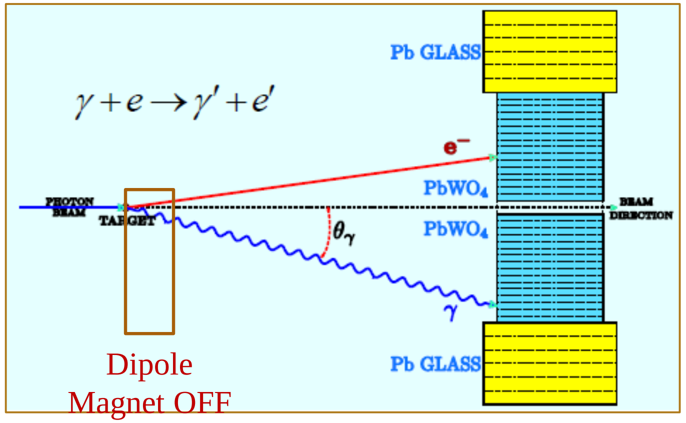
(partly) correlated items

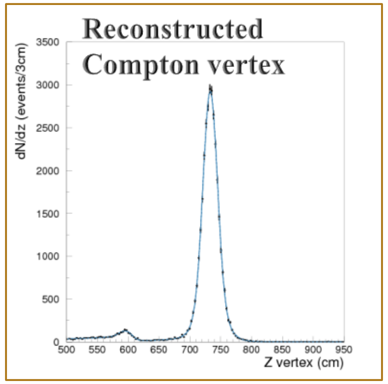
Better beam quality

Statistically driven systematics (improved statistics)

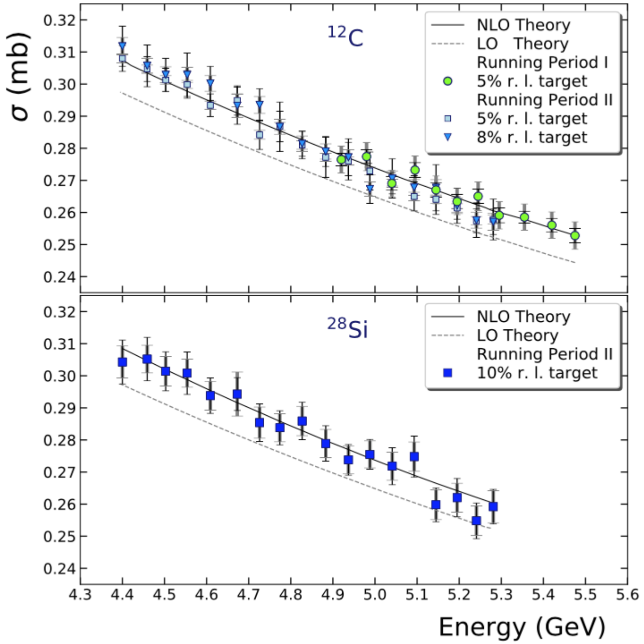
Verification with Compton cross section

Compton event

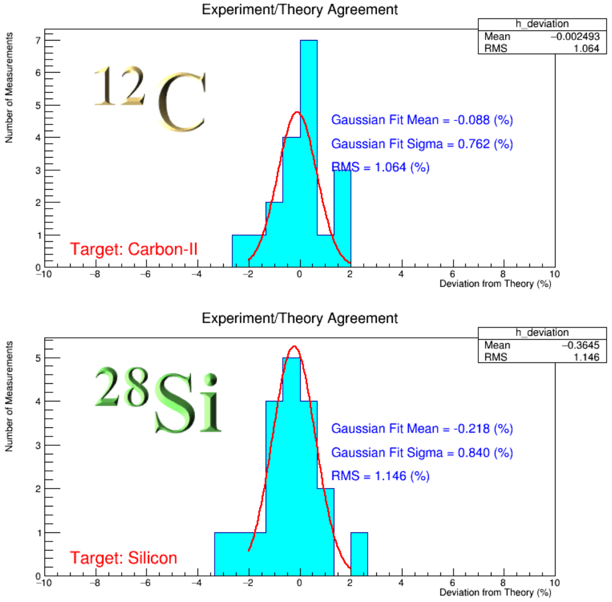




Compton cross section deviation from theory prediction vs photon beam energy

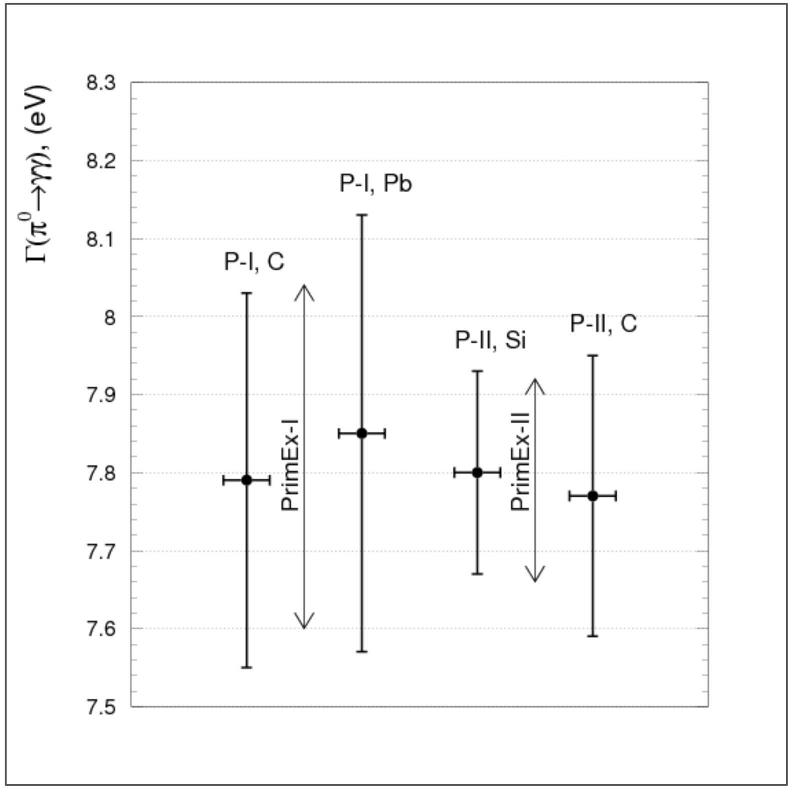


Projected points



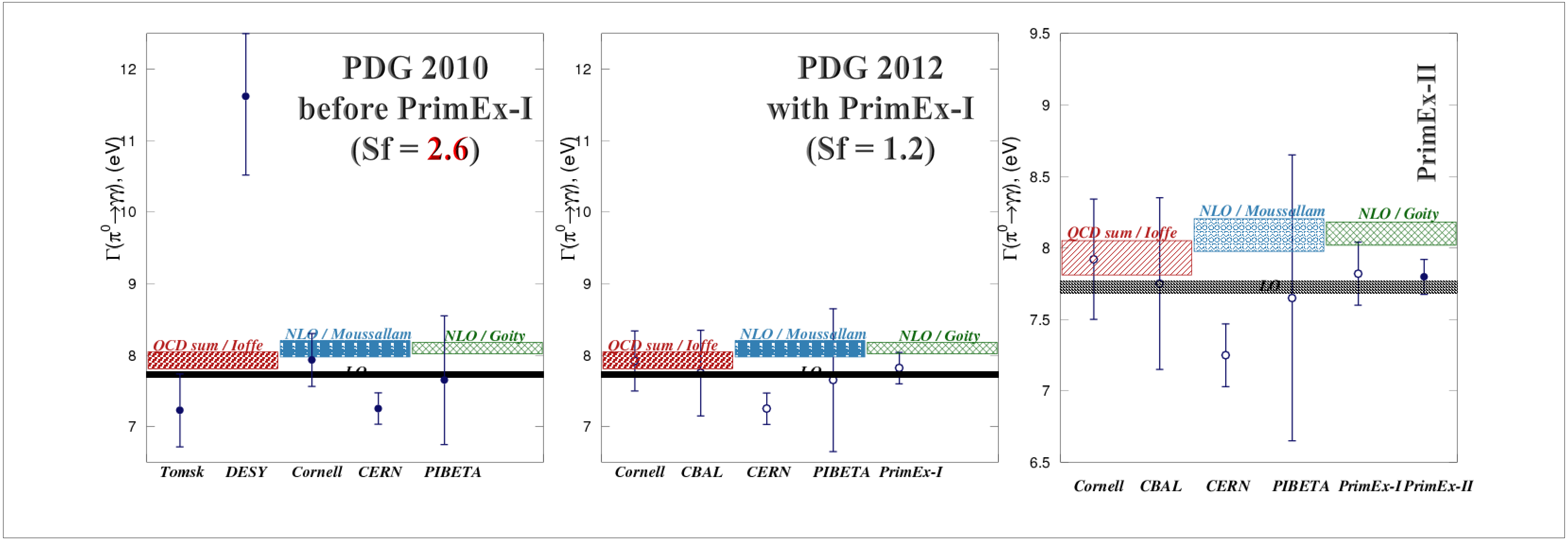
The extracted cross sections are in agreement with the theory prediction at the level of systematic uncertainty of 1.5%

PrimEx I vs PrimEx II result



Run	Target	$\Gamma(\pi^0 \rightarrow \gamma\gamma)$, 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

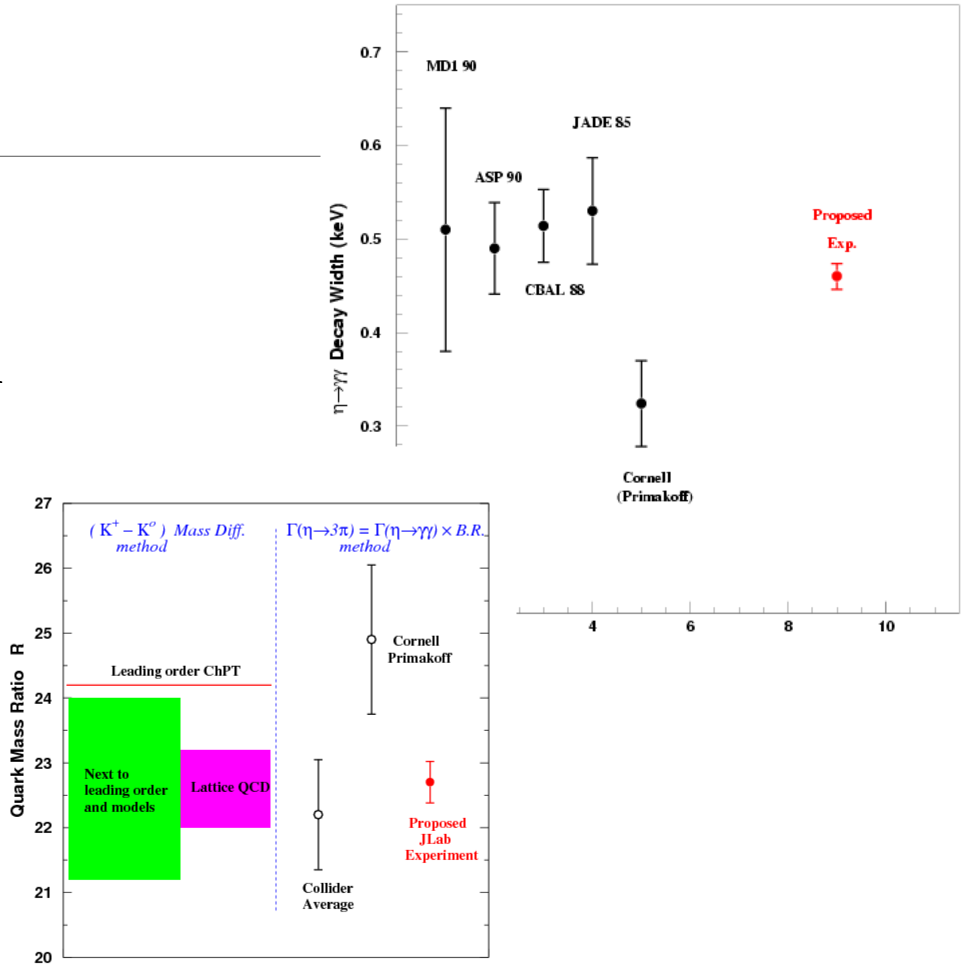
PrimEx result changed PDG landscape on $\Gamma(\pi^0\to\gamma\gamma)$ part



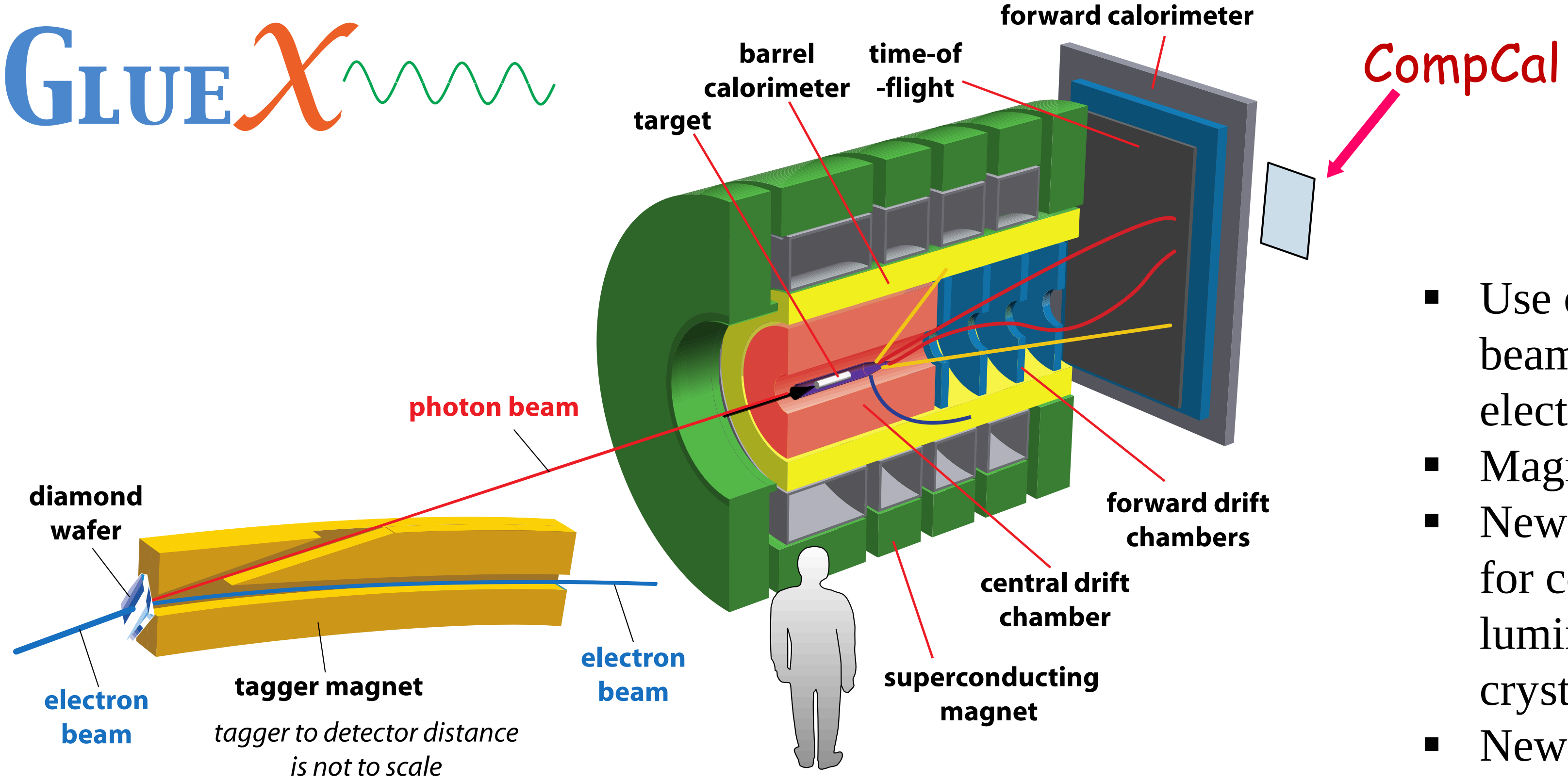
Γ(η→γγ) Experiment @ 12 GeV

1. New Primakoff Γ(η→γγ) measurement with a precision of 3.2%: potentially resolve discrepancy between collider and Primakoff measurements
2. Improve η-η' mixing angle
3. Determine light quark mass ratio in the most model independent way

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \qquad \text{where } \hat{m} = \frac{1}{2}(m_u + m_d)$$



Measurement of Γ(η→γγ) in Hall D at 12 GeV with the GlueX detector setup

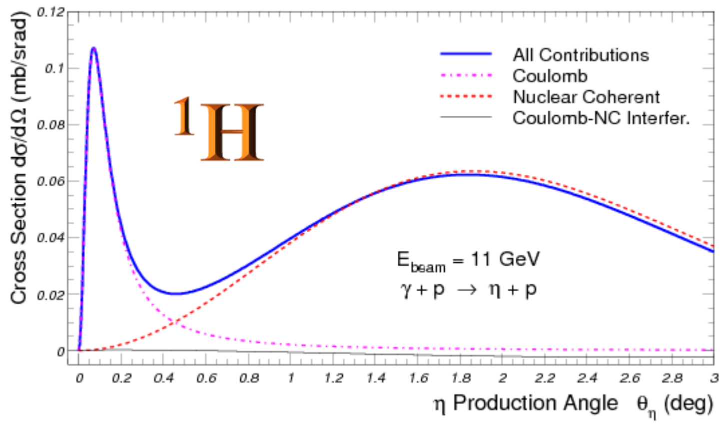


- Use of hall-D tagged photon beam and forward electromagnetic calorimeter
- Magnetic field off
- New Compton calorimeter for continuous control of luminosity (12x12 PWO crystal calorimeter)
- New cryogenic liquid helium target

Target choice for the Γ(η→γγ) Primakoff Experiment

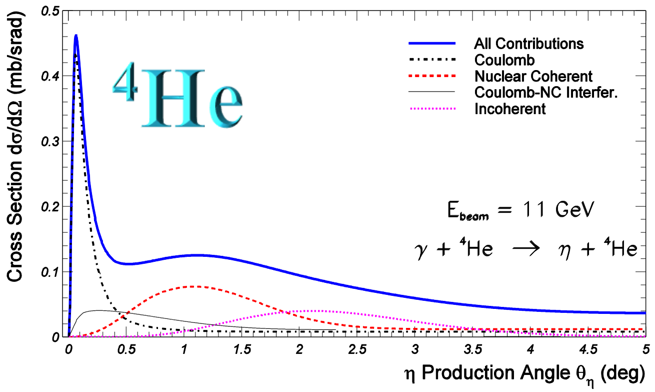
Precision Primakoff measurement requires low A targets to control contributions from nuclear processes. High A targets may have higher systematics related to the in-medium interactions

Hydrogen target:
- inelastic hadronic contribution and FSI suppressed
- Good separation between Primakoff and strong production



Helium target:
- Higher Primakoff cross section
- Compact nucleus
- New theoretical developments for FSI

  (*S. Gevorgyan et al., Phys. Rev. C 80, 2009*)



LH and LHe targets
- have well know form factors
- Require target walls subtraction

$\Gamma(\eta\to\gamma\gamma)$ Beam Time, Statistics, and Projected Uncertainties

- Targets: 3.46% r.l. LH_2, 3.99% r.l. LHe4
- Photon flux: ~7×10^6 γ/s ($E\gamma$ > 10 GeV)
- About half of statistics has been collected during 2019 run (we are analyzing the data); the second half is planned to be collected during summer 2021

Beam time request (~1% stat. error)

LH2 target run	40 days
LHe4 target run	30 days
Empty target run	6 days
Tagger efficiency, TAC runs	4 days
Setup calibration and checkout	8 days
Total	88 days

$\Gamma(\eta\to\gamma\gamma)$ estimated uncertainties

Uncertainty item	Contribution [%]
Photon flux	1.0
Target	0.5
Yield extraction	2.6
Acceptance	0.5
Beam energy	0.2
Detection efficiency	0.5
Branching ratio (PDG)	0.5
Total Systematic	3.0
Statistical error	1.0
Total error	3.2

Summary

- *The PrimEx collaboration performed two new generation Primakoff experiments:*

PrimEx-I physics result:

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

PrimEx-II physics result:

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

PrimEx combined result (Science 05/2020: V.368, p.506) :

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

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- *The next generation Primakoff radiative width measurement experiment is currently in progress in Jefferson Lab: the part of statistics (about half) has been collected last year; and the remaining part is planned to be collected during summer 2021 run.*