Liquid Xenon Calorimeter for MEG

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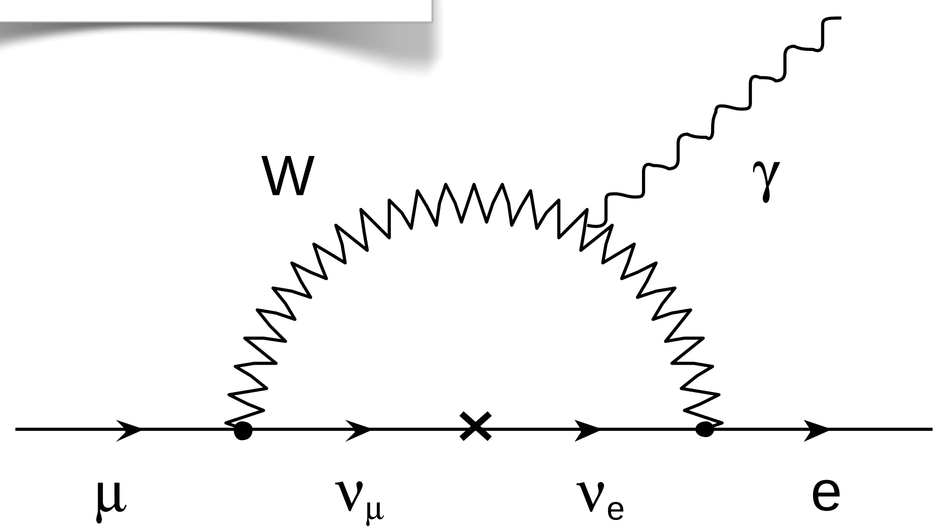
$\mu \to e\gamma$ physics motivation

Standard model



Branching ratio of $\mu \to e\gamma$ ($<10^{-40}$) is very small

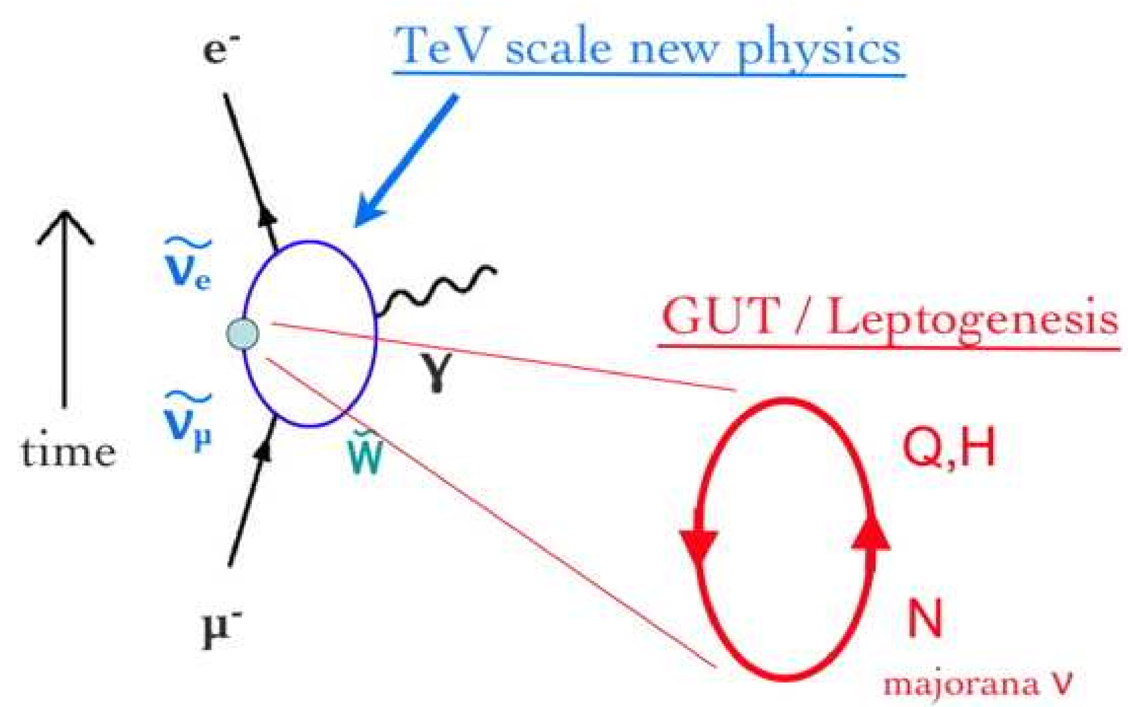
Current limit : Br < **5.7×10^{-13}** (90% C.L.)
MEG, 2013, arXiv:1303.0754
submitted to Phys. Rev. Lett.

Discovery of $\mu \to e\gamma$ is a clear evidence of new physics

New physics

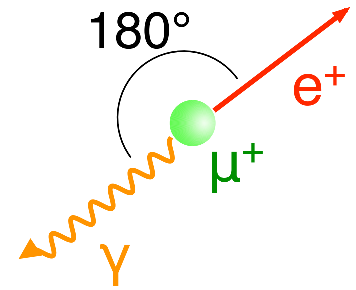
Many new theories beyond the standard model predicts large branching ratios

Br ~ 10^{-14}-10^{-11}



T.Mori hep-ex/0605116

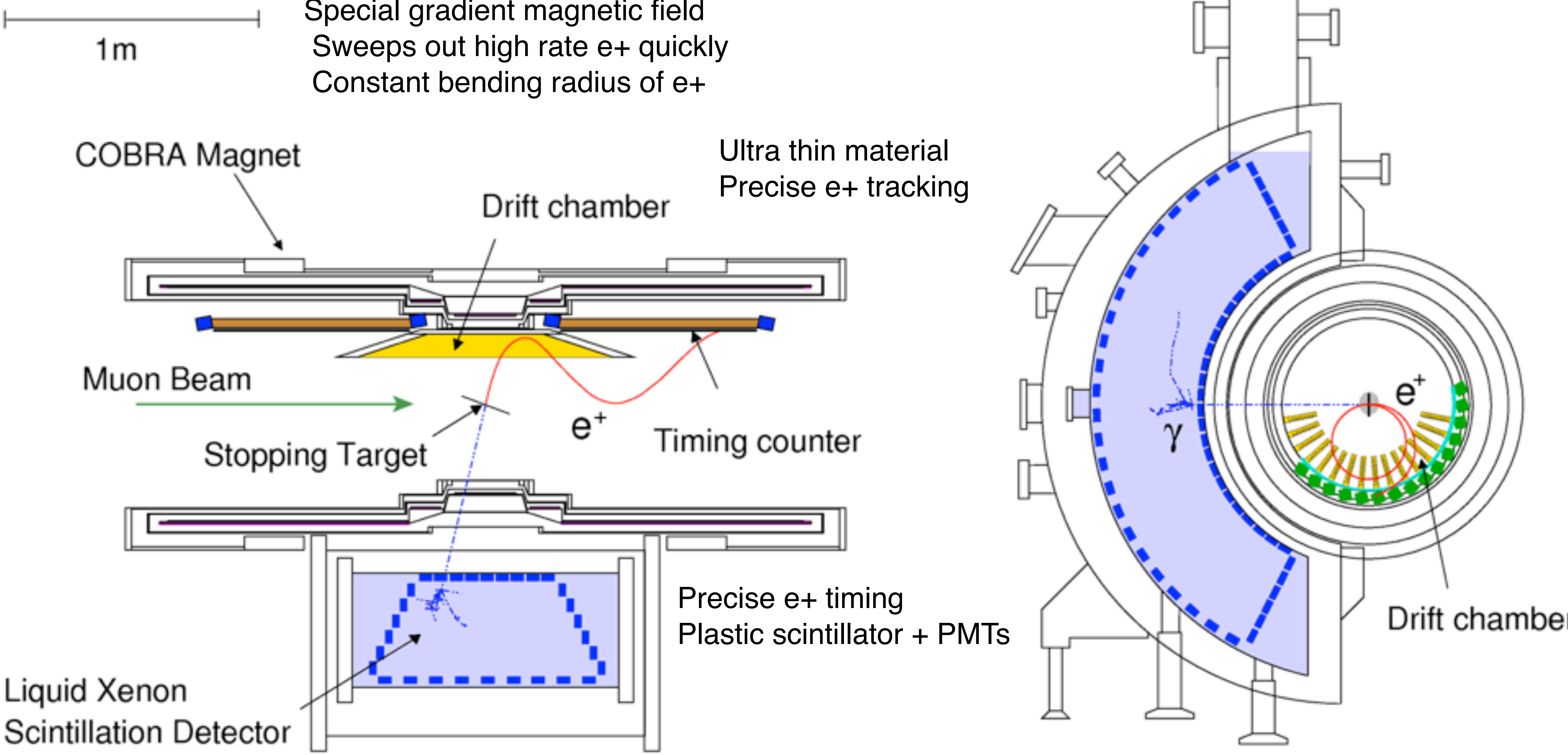
MEG detector



Signal
52.8 MeV e+ and γ

Special gradient magnetic field
Sweeps out high rate e+ quickly
Constant bending radius of e+

Ultra thin material
Precise e+ tracking



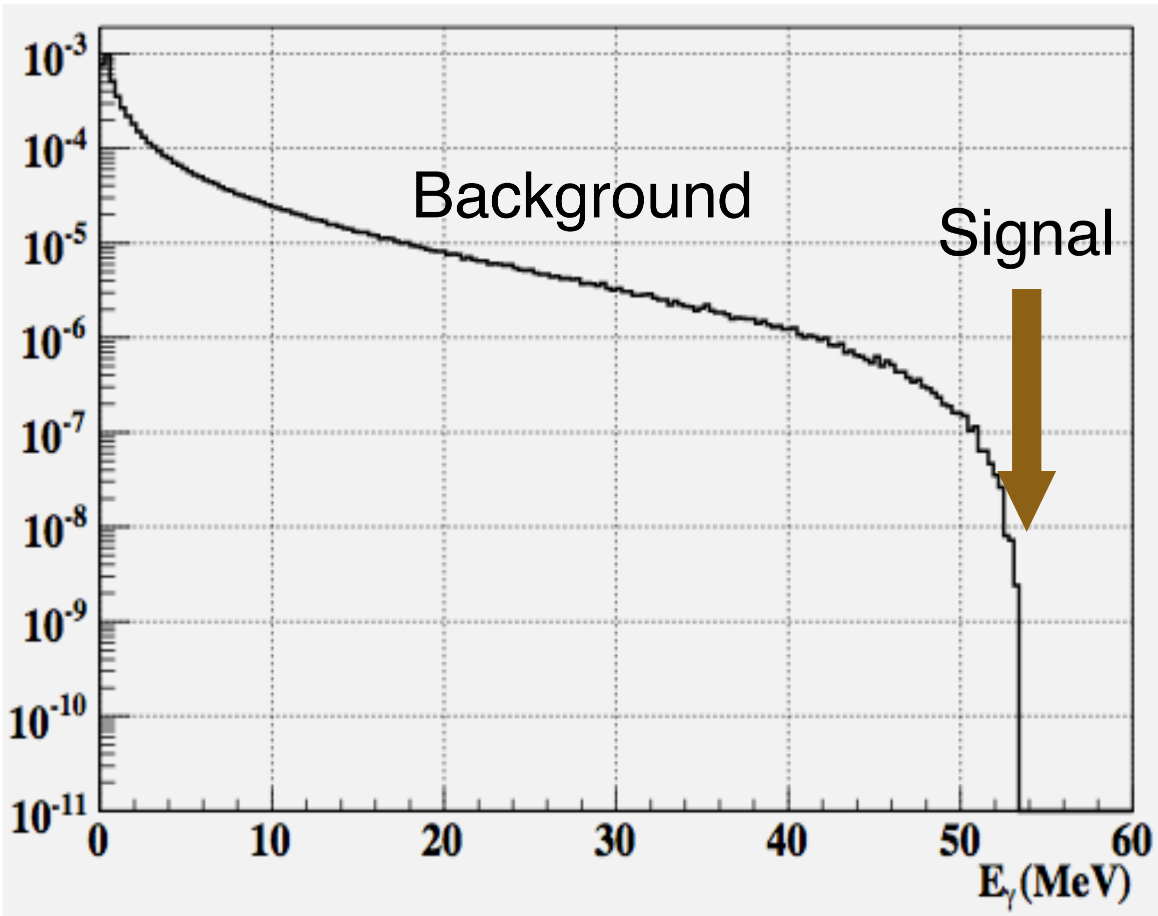
Precise e+ timing
Plastic scintillator + PMTs

2.7 ton of liquid xenon
Homogeneous detector
Good time, position, energy resolution

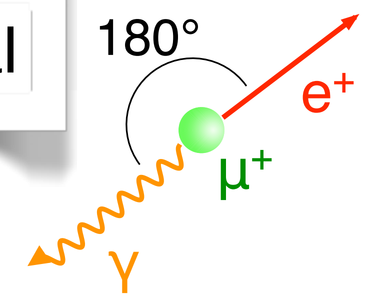
Waveform digitizer for all detectors (pileup ID)

Requirements of LXe gamma detector

γ background



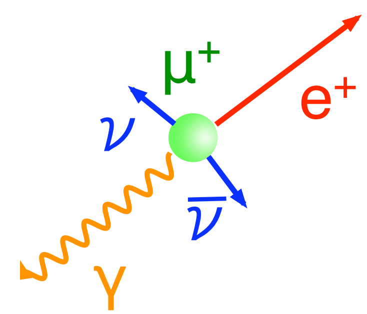
Signal



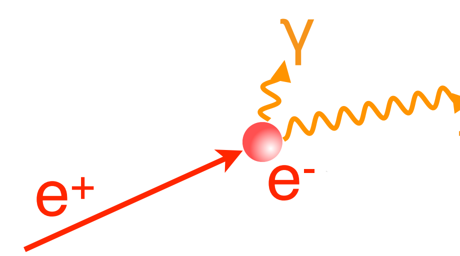
52.8 MeV
monochromatic

Background

Radiative μ decay



e+ annihilation in flight



$$N_{\mathrm{acc}} \propto R^2 \cdot \delta E_{\mathrm{e}} \cdot \delta E_{\gamma}^2 \cdot \delta\theta_{\mathrm{e}\gamma}^2 \cdot \delta t_{\mathrm{e}\gamma}$$

Energy resolution

Position resolution

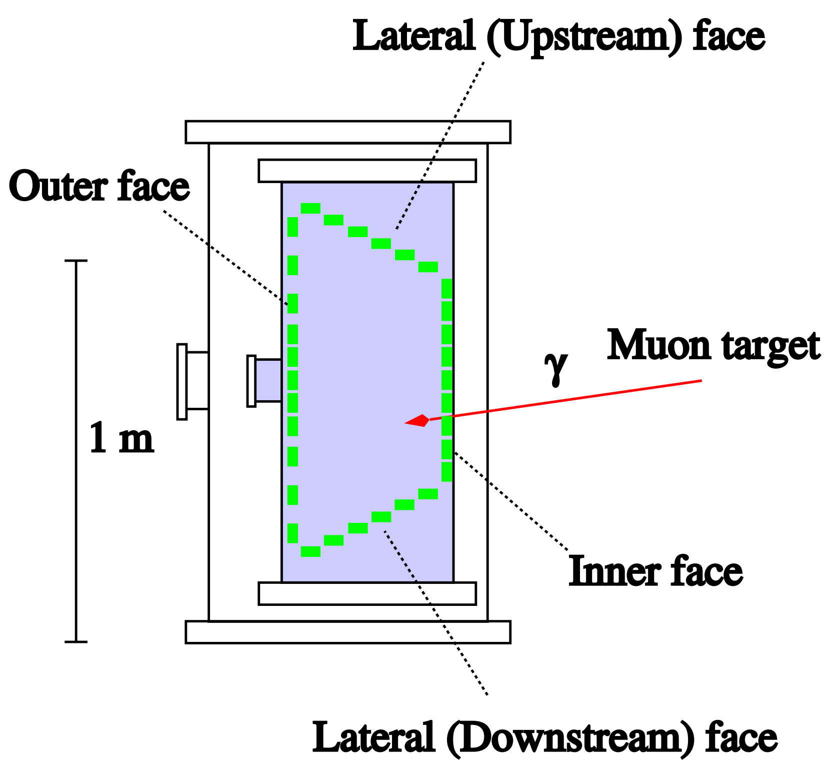
Time resolution

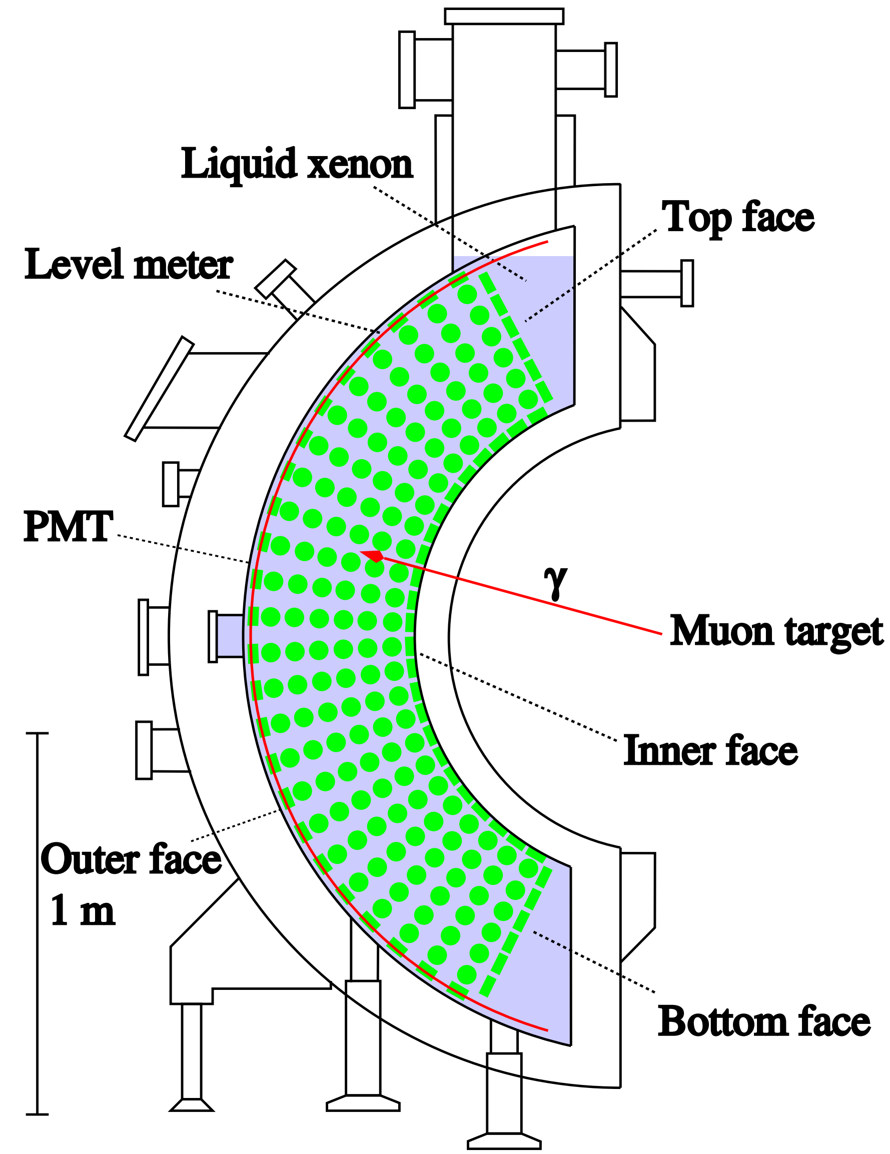
Good resolutions of LXe detector is important to reduce background

Inorganic scintillators and LXe

	NaI(Tl)	CsI(Tl)	BaF2	BGO	LSO(Ce)	PWO	LaBr3(Ce)	GSO	LFS-3	LXe
Density (g/cm3)	3.67	4.51	4.89	7.13	7.40	8.3	5.29	6.71	7.35	**2.98**
Radiation Length (cm)	2.59	1.86	2.03	1.12	1.14	0.89	1.88	1.38	1.15	**2.8**
Hygroscopicity	Yes	Slight	No	No	No	No	Yes	No	No	**-**
Luminescence (nm) at peak	410	550	300 220	480	402	425 420	356	430	425	**175**
Decay Time	245	1220	650 0.9	300	40	30 10	20	30-60	25-33	**45**
Light Yield (%)	100	165	36 4.1	21	85	0.3 0.1	221	20	80-85	**80**

2.7 t (900l) LXe calorimeter



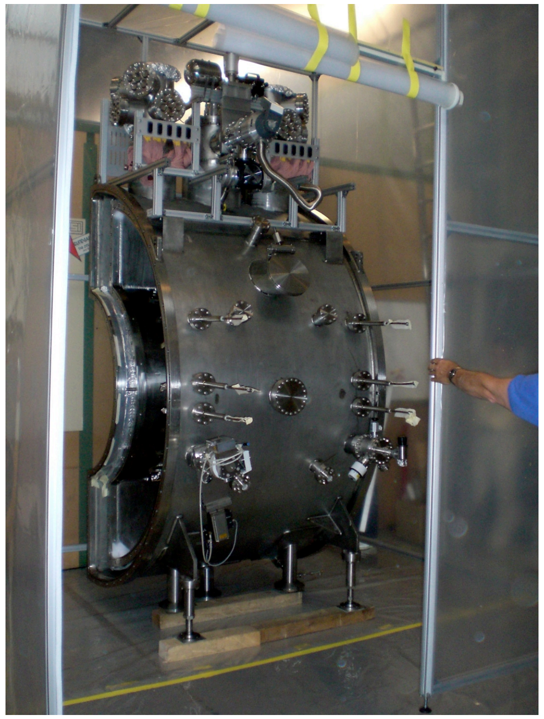


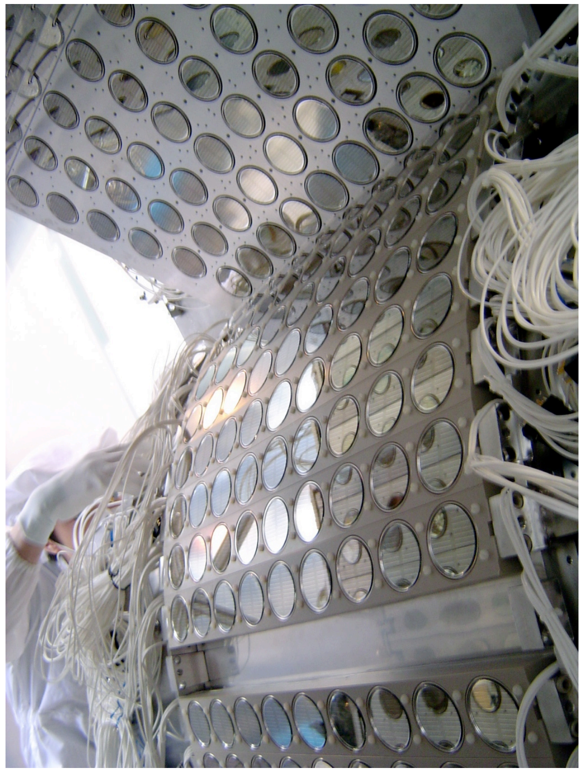
- Merits
  - High light output(80% of NaI)
  - Fast timing response(45ns)
  - Heavy(3g/cm3)
- Challenges
  - Low temperature(160K)
    - 200W pulse tube cryocooler
  - Short scintillation wavelength (175nm)

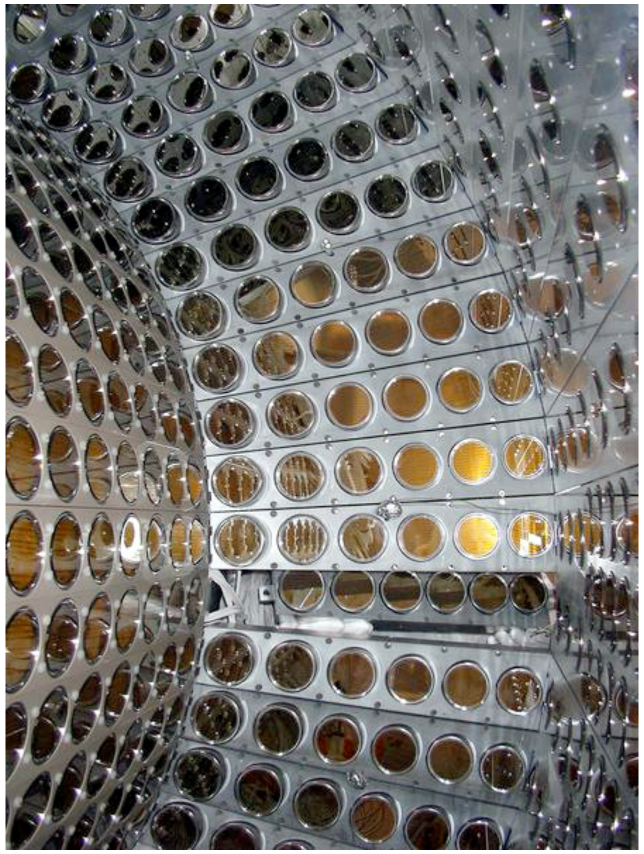
- 846 2" PMTs (Hamamatsu)
  - Sensitive to 175nm VUV
  - Submerged in Liquid
- Purification system
  - Gas phase (metal heated getter)
  - Liquid phase (Molecular sieves)

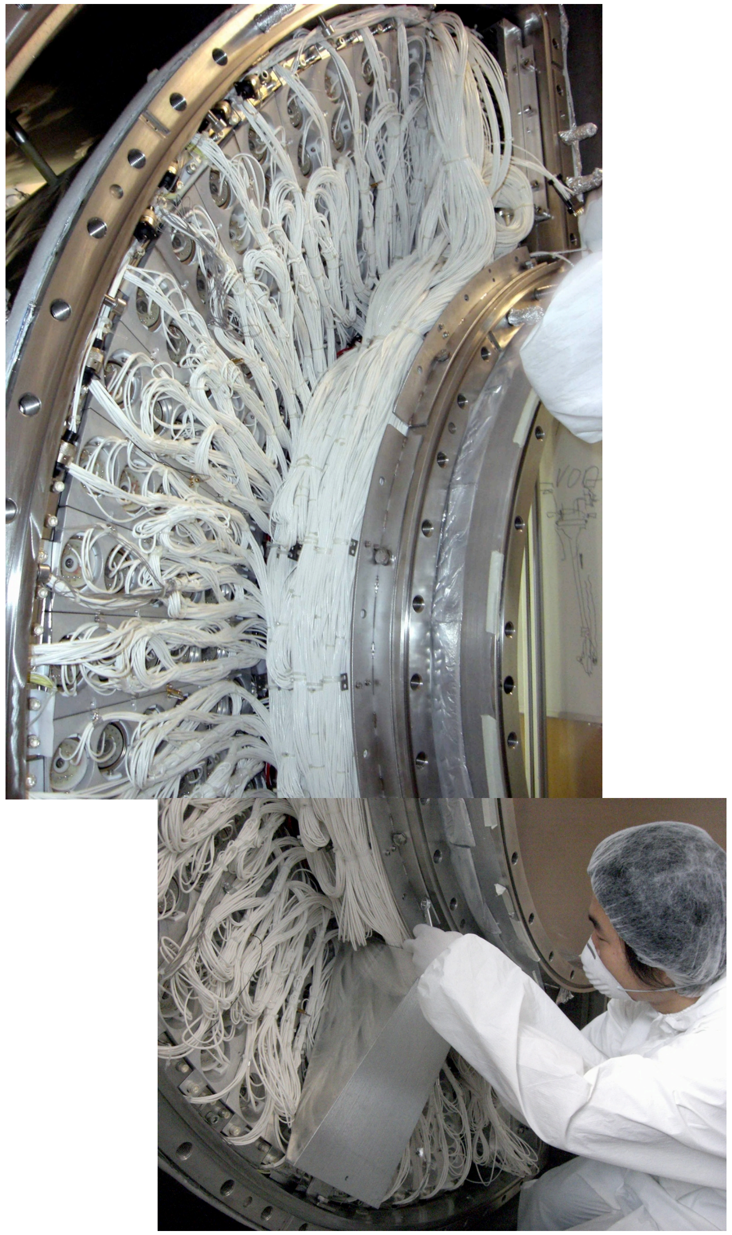
Construction

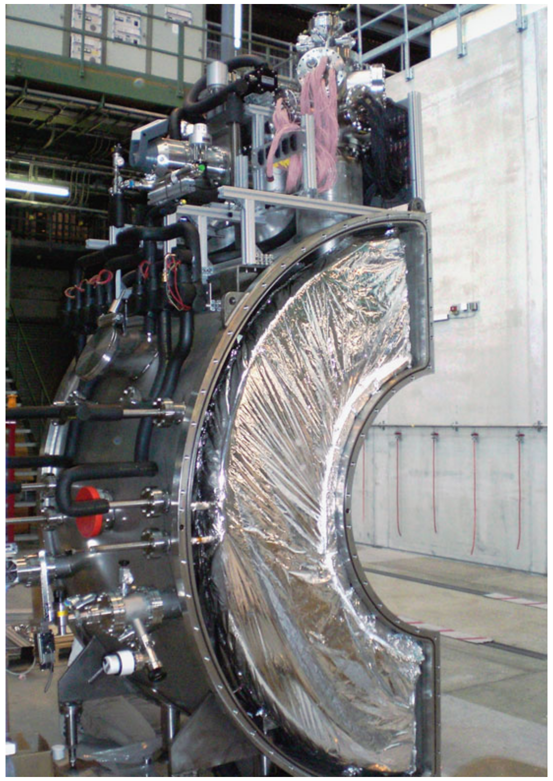
In 2007











Calibration and monitoring

PMT

LED
Alpha source (5.5 MeV)

Energy

AmBe (4.4MeV)
Neutron capture (9MeV)
Li(p,γ)Be (17.6 MeV)
π0→γγ (55, 83 MeV)
Cosmic ray (160 MeV)

Time

B(p,γ) (4.4+11.7 MeV)
π0→e⁺eγ (55-83 MeV)
Muon radiative decay

Process		Energy (MeV)	Frequency
Charge exchange	$\pi^- p \to \pi^0 n$	54.9, 82.9	yearly
	$\pi^0 \to \gamma\gamma$		
Charge exchange	$\pi^- p \to n\gamma$	129.0	yearly
Radiative μ^+ decay	$\mu^+ \to \mathrm{e}^+\gamma\nu\nu$	52.83 endpoint	weekly
Proton accelerator	$^7\mathrm{Li}(p, \gamma_{17.6(14.8)})^8\mathrm{Be}$	14.8, 17.6	weekly
	$^{11}\mathrm{B}(p, \gamma_{4.4}\gamma_{11.6})^{12}\mathrm{C}$	4.4, 11.6	weekly
Nuclear reaction	$^{58}\mathrm{Ni}(n, \gamma_{9.0})^{59}\mathrm{Ni}$	9.0	daily
AmBe source	$^9\mathrm{Be}(\alpha_{^{241}\mathrm{Am}}, n)^{12}\mathrm{C}_*$	4.4	daily
	$^{12}\mathrm{C}_* \to {}^{12}\mathrm{C}\gamma_{4.4}$		

Calibration and monitoring

PMT

LED
Alpha source (5.5 MeV)

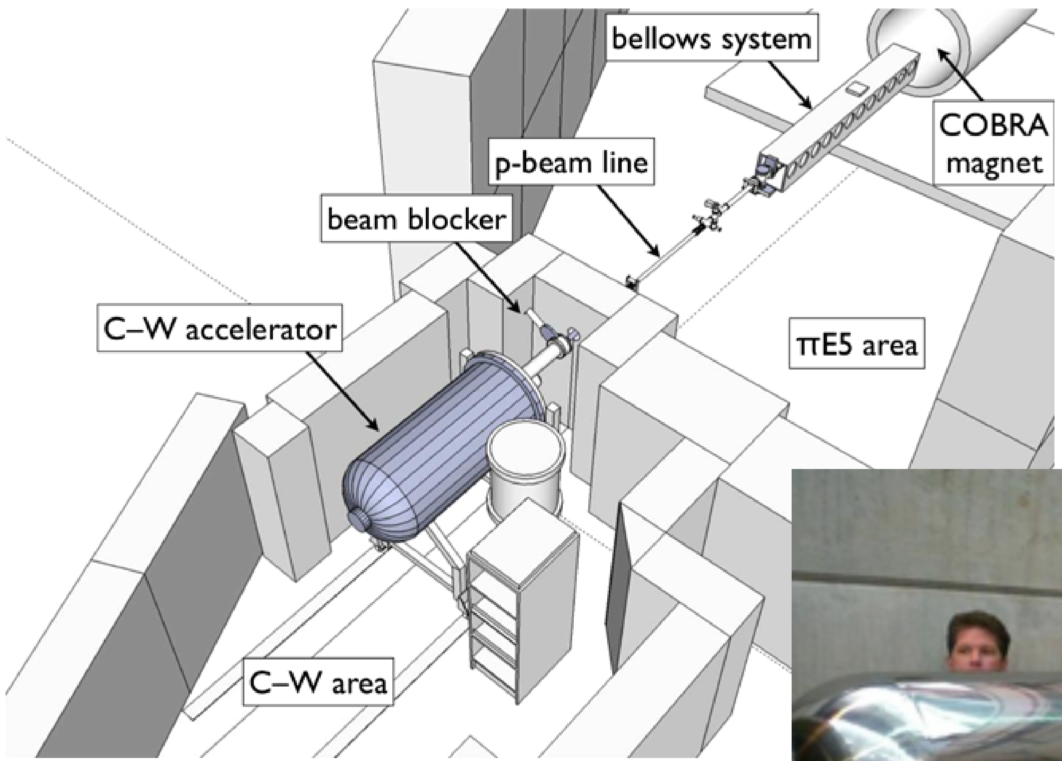
Energy

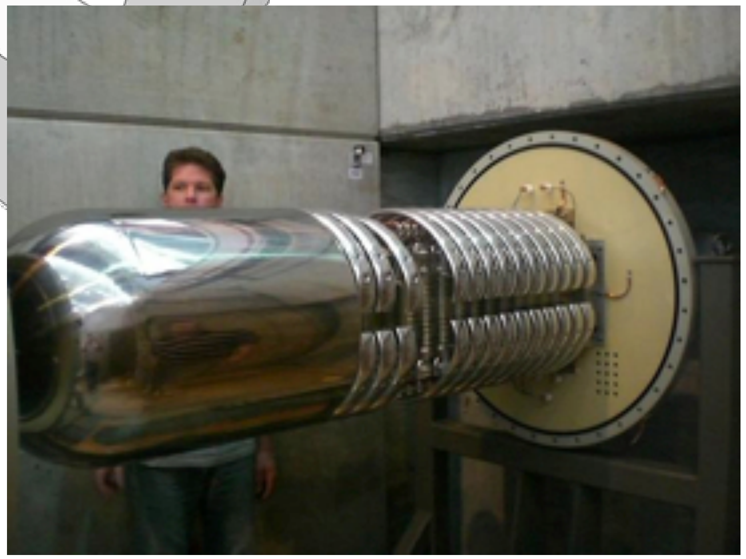
AmBe (4.4MeV)
Neutron capture (9MeV)
Li(p,γ)Be (17.6 MeV)
π0→γγ (55, 83 MeV)
Cosmic ray (160 MeV)

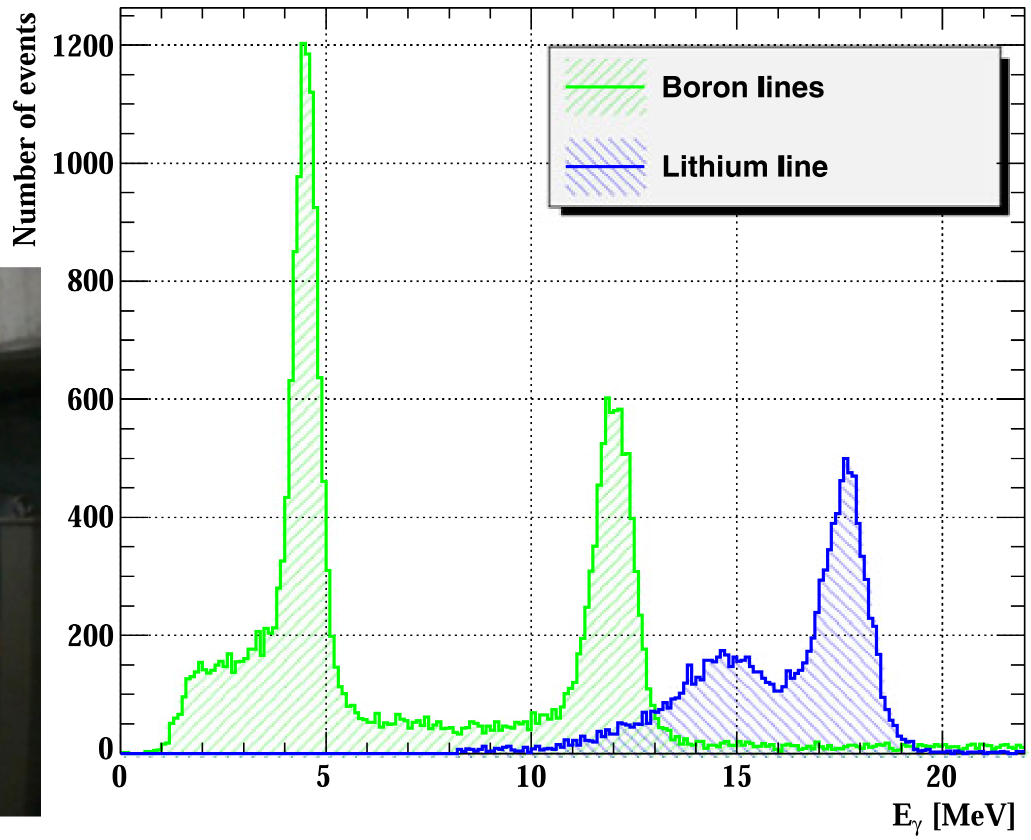
Time

B(p,γ) (4.4+11.7 MeV)
π0→e⁺eγ (55-83 MeV)
Muon radiative decay

Weekly energy and time calibration



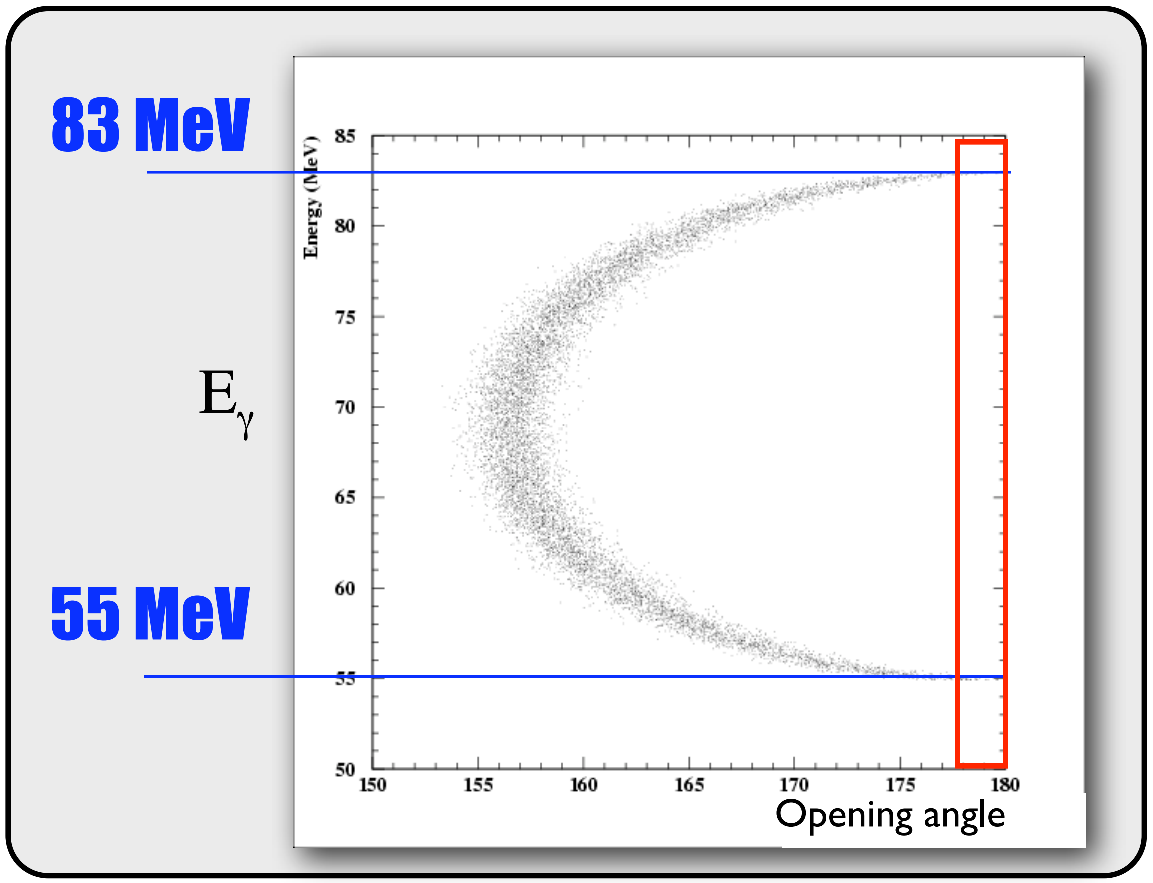




MEG Cockcraft-Walton(C.W.) proton accelerator

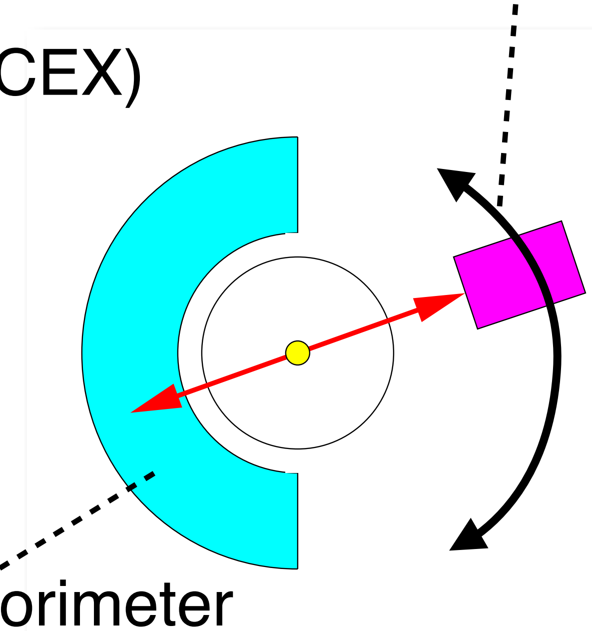
Calibration and monitoring

PMT	Energy	Time
LED Alpha source (5.5 MeV)	AmBe (4.4MeV) Neutron capture (9MeV) Li(p,γ)Be (17.6 MeV) π0→γγ (55, 83 MeV) Cosmic ray (160 MeV)	B(p,γ) (4.4+11.7 MeV) π0→e⁺eγ (55-83 MeV) Muon radiative decay



Once (or twice) per year
Absolute energy calibration
PMT time calibration
Energy and time resolution

Pion **C**harge **EX**change (CEX)



$\pi^- + p \rightarrow \pi^0 + n$

$\pi^0 \rightarrow \gamma\gamma$ (55MeV, 83MeV)

LH_2 target

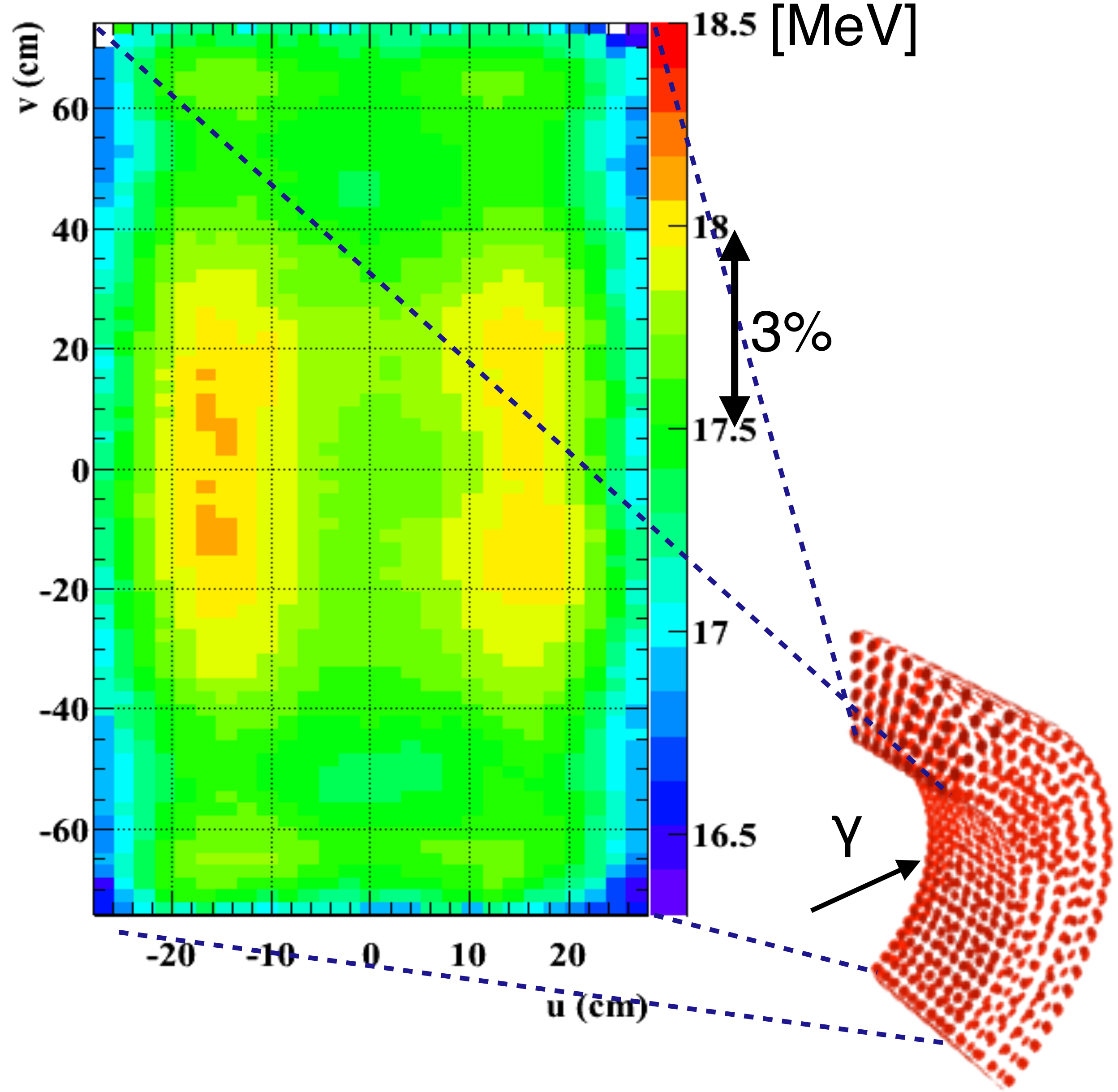
Energy Scale Uniformity

- Non-uniformity due to
  - Geometry
  - Reconstruction algorithm
- Correction using
  - 17.6 MeV CW gamma for position
  - 55 MeV CEX gamma for depth (energy dependent)
- Checked using background gamma spectrum during physics run

After correction : ~0.2 % uniform

17.6 MeV CW data

uniformity before correction

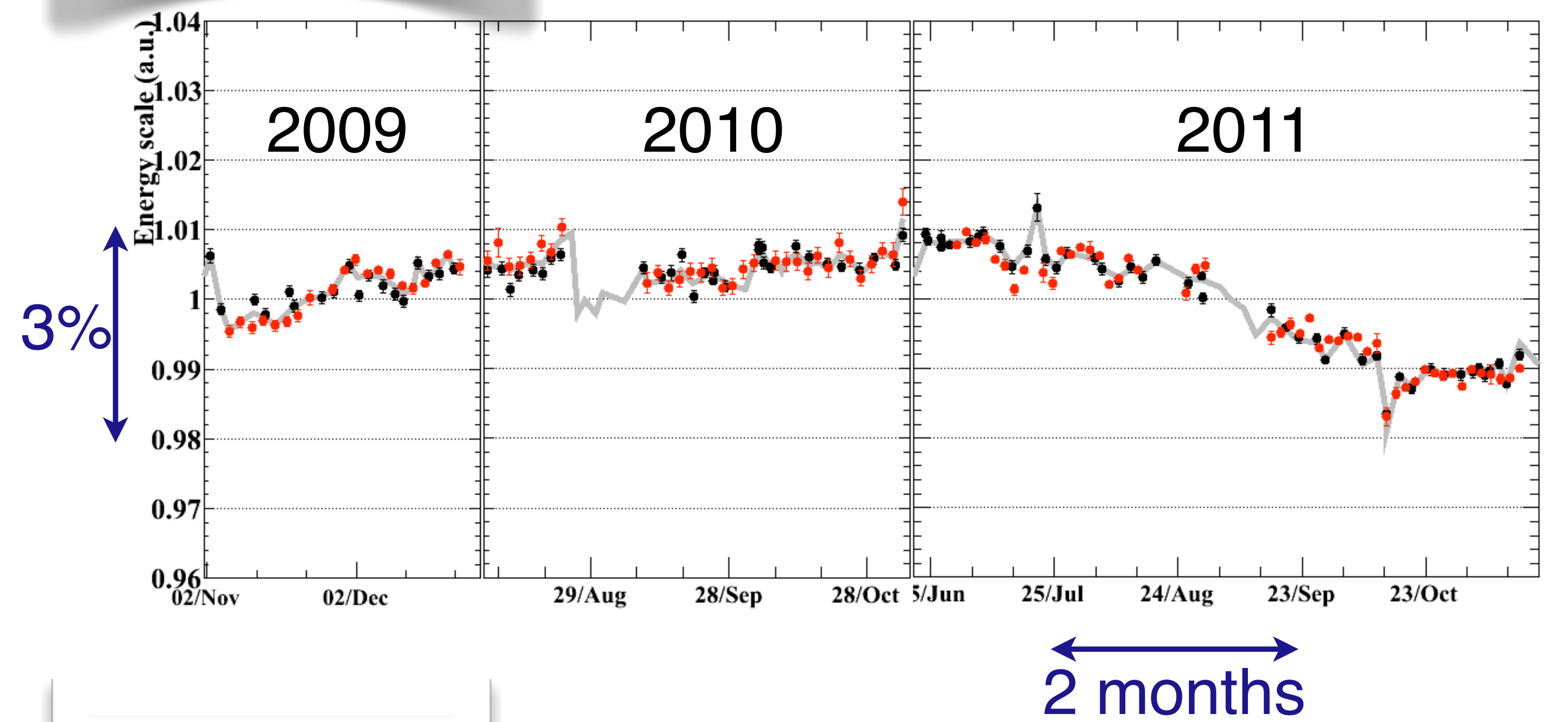


Energy Scale Stability

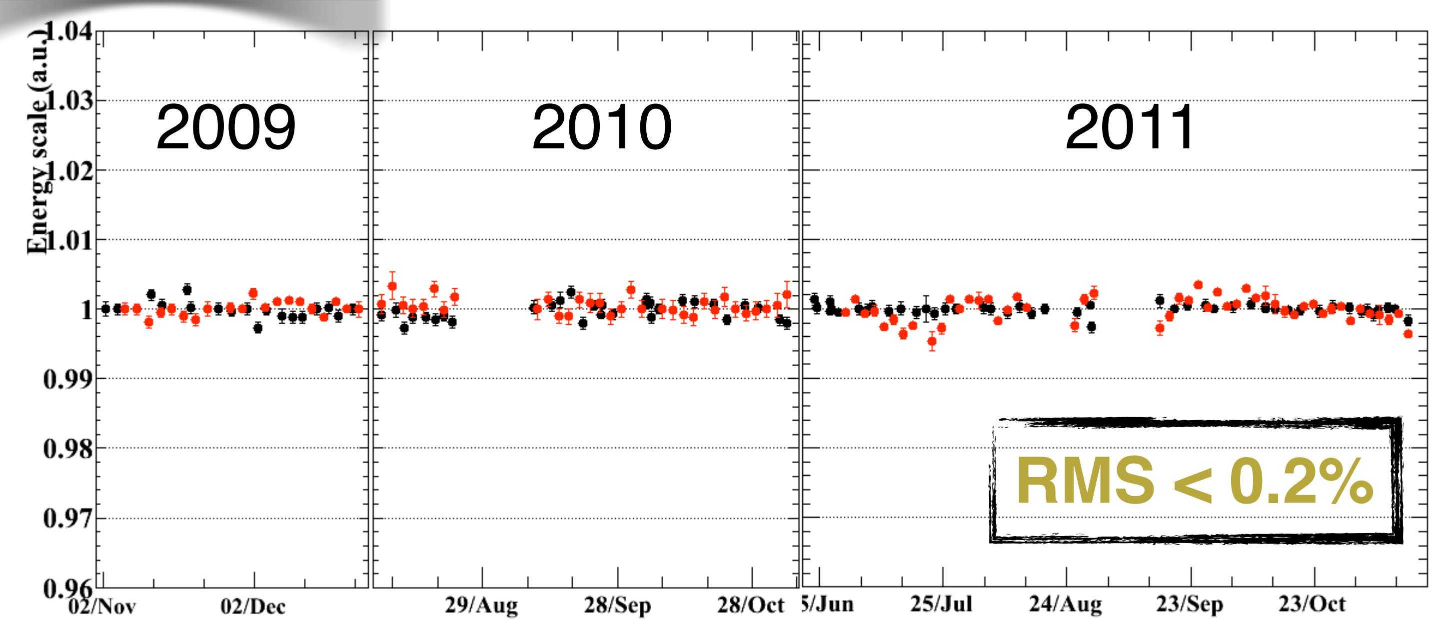
- Absolute scale calibration
  - 55 MeV CEX gamma
- Time variation corrected using
  - 17.6 MeV CW gamma
  - 9 MeV Ni-n gamma
  - 4.4 MeV AmBe gamma
  - Cosmic ray peak
- Checked using background gamma spectrum during physics run

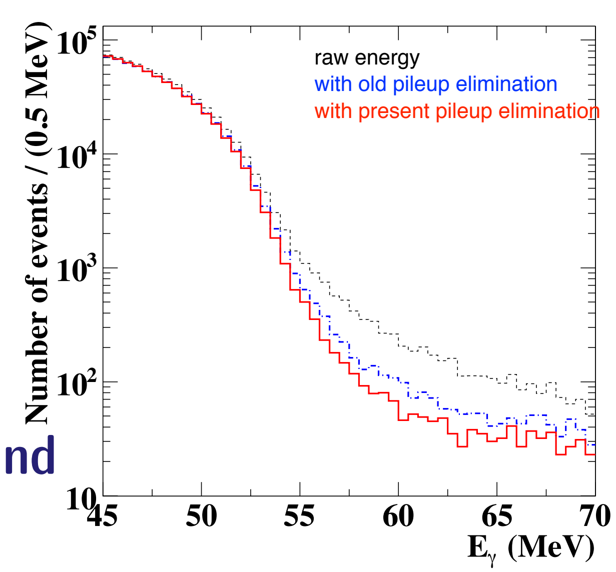
● CW data (used for correction)
● BG data (not used for correction)

Before correction



After correction



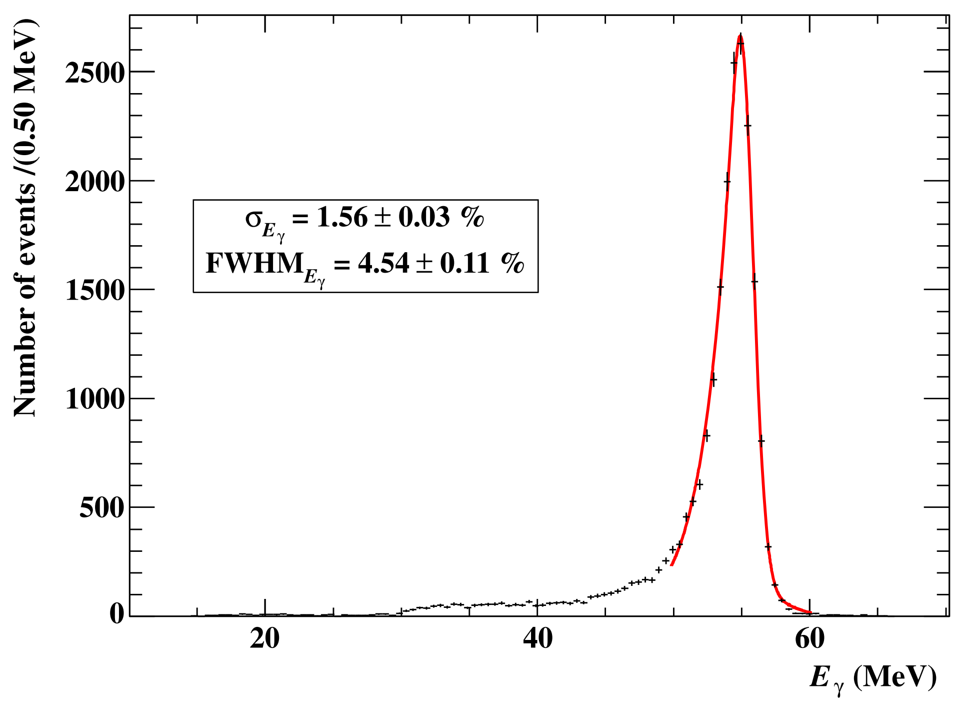


Background spectrum

Energy resolution

Measured using 55 MeV CEX gamma rays

Typical 55 MeV CEX spectrum

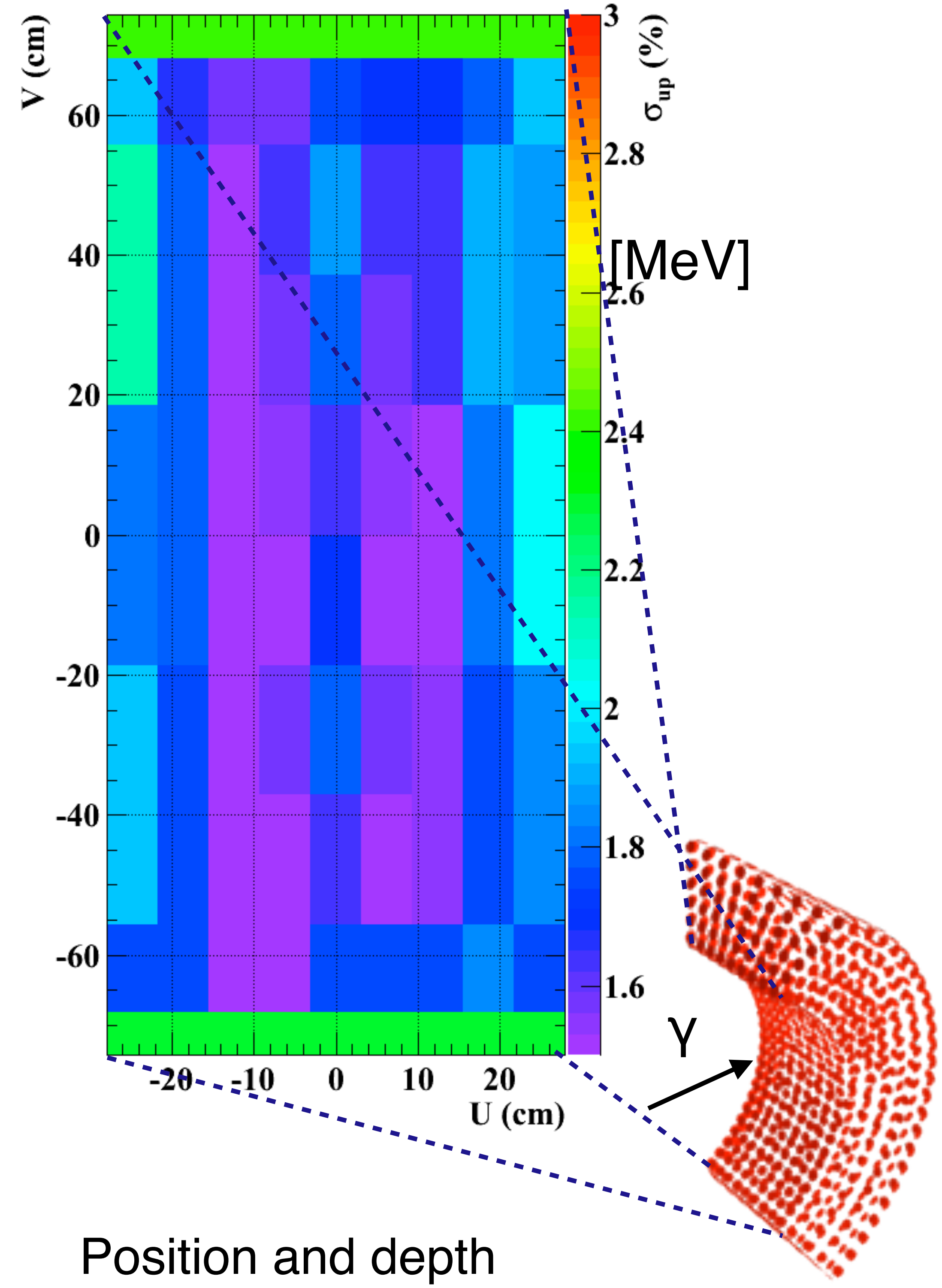


Lower tail due to

- Energy deposit in material before entering LXe (Magnet, cryostat, PMT holder etc.)
- Energy escape from LXe

Average resolutions
1.7% (depth>2cm), 2.4% (depth<2cm)

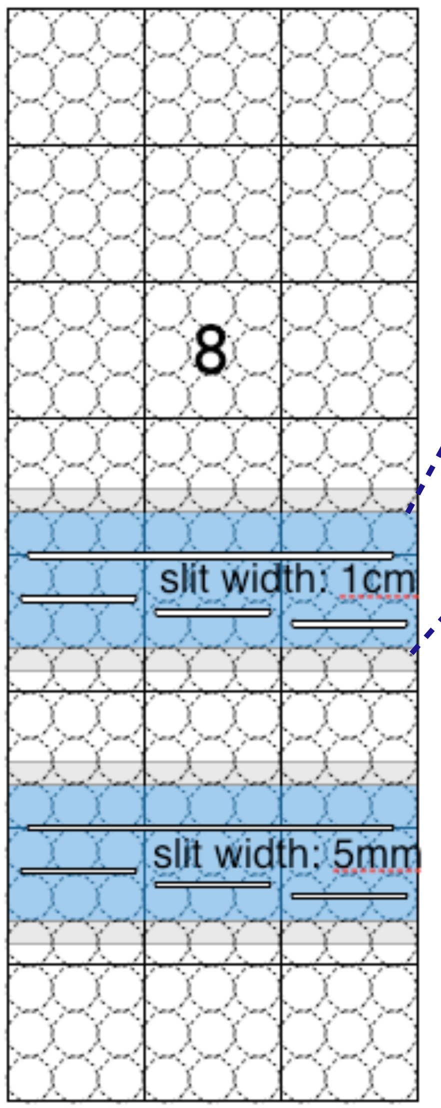
Resolution map

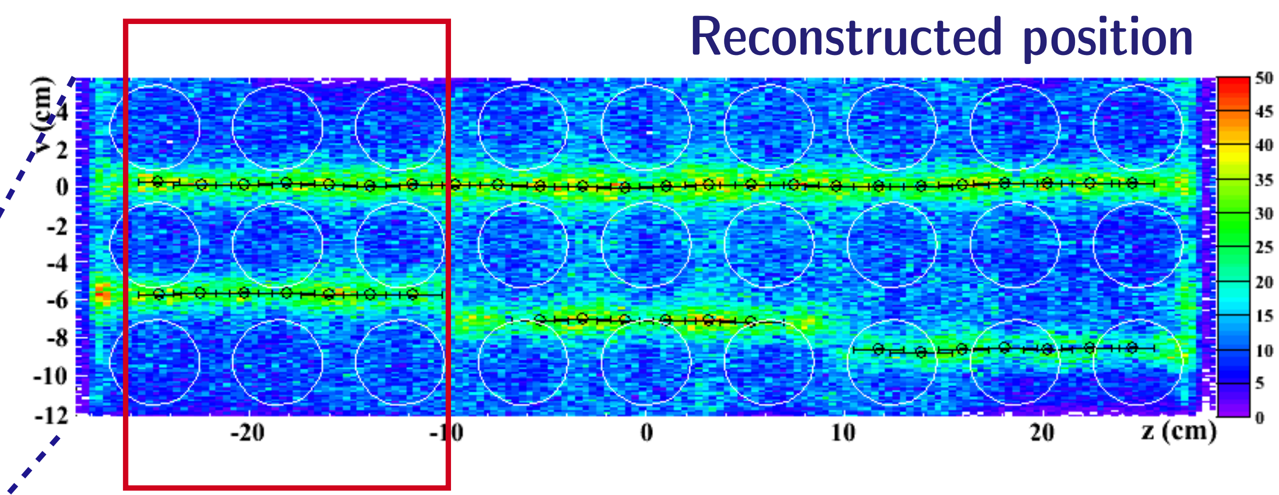


Position and depth dependences are measured

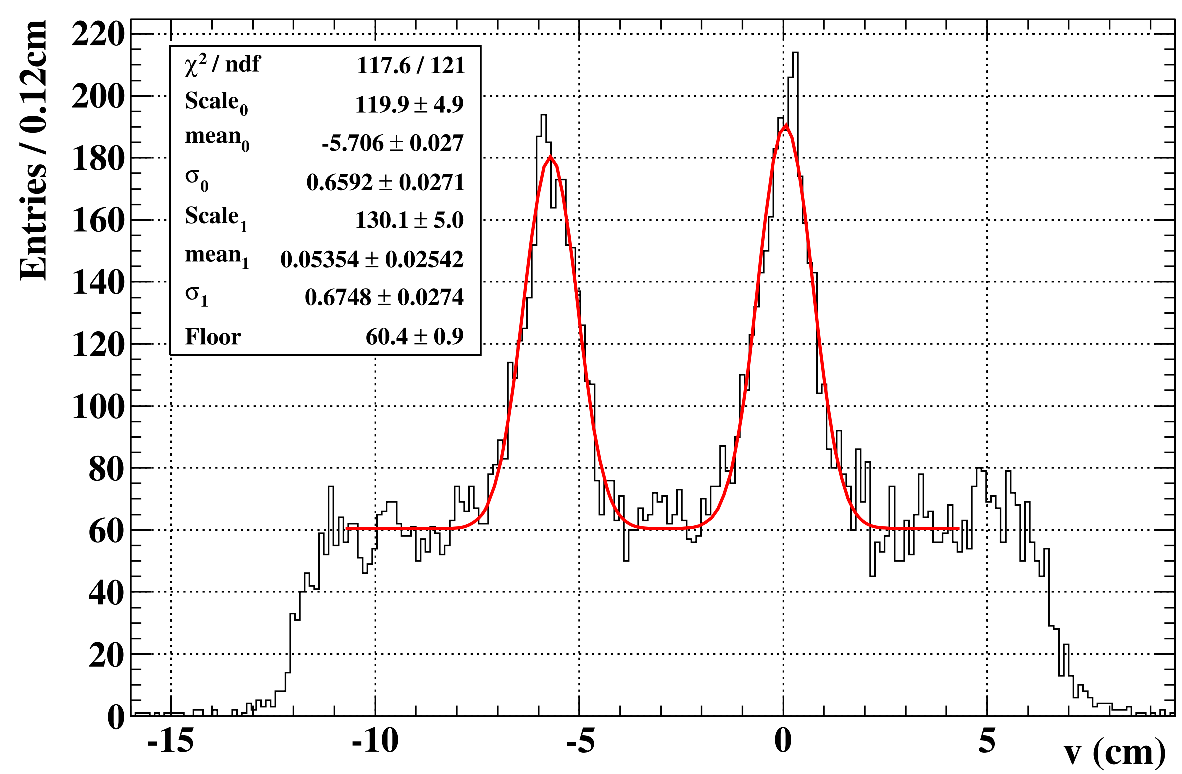
Position resolution

Measured using lead collimators with CEX data





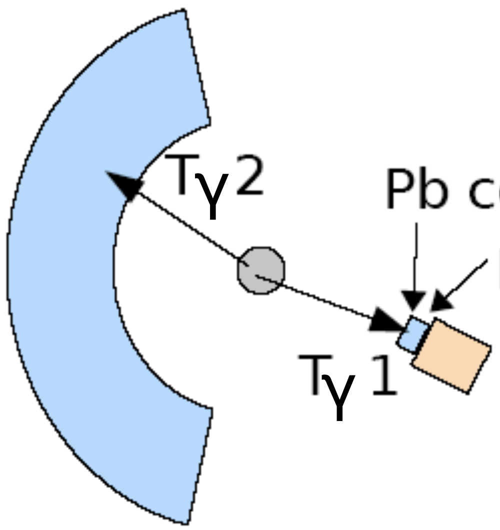
Projection



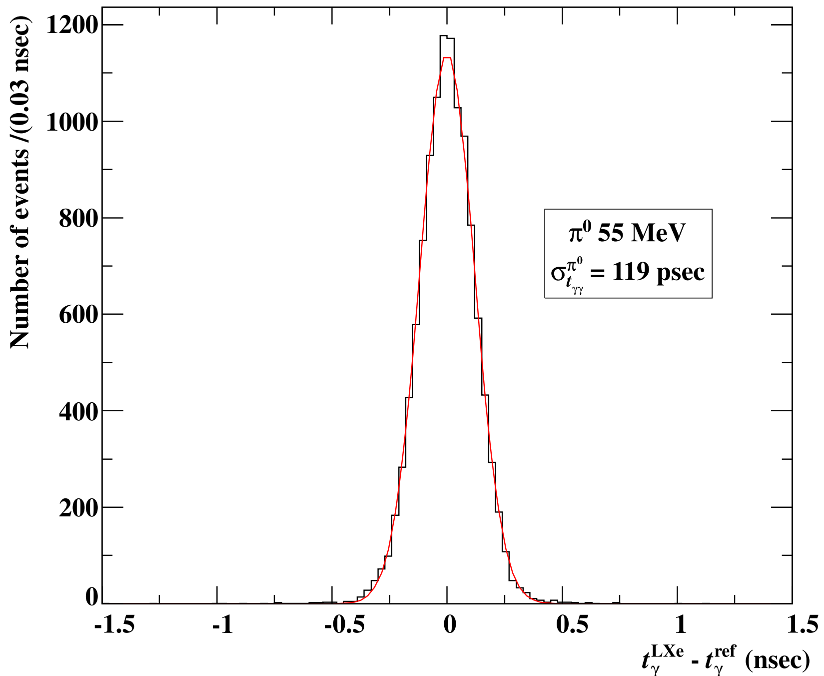
Position resolution : 5 mm

Width is compared with MC

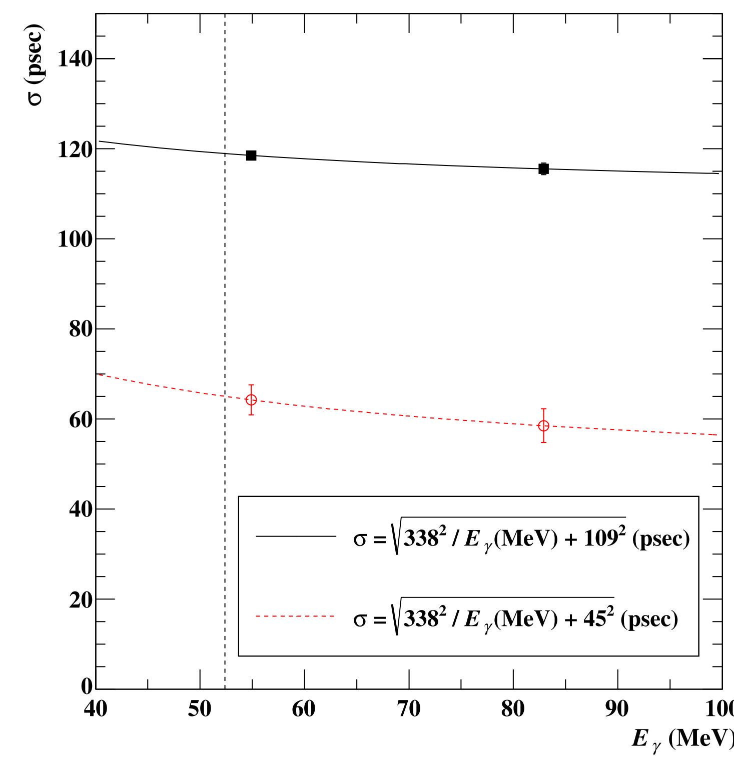
Timing resolution



Time difference between LXe calorimeter and a reference counter in CEX data



Energy dependence



Time resolution : 67 ps

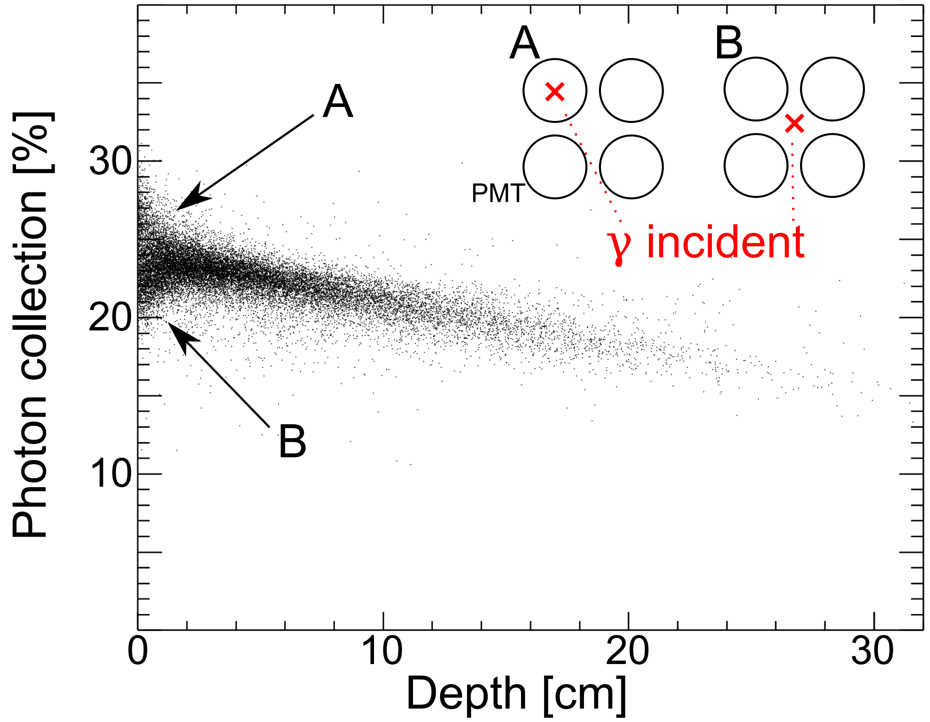
= 119ps - beam spread(58ps) - resolution of reference counter(81ps)

Breakdown

Intrinsic	36 ps
ToF (depth)	20 ps
Electronics	24 ps
Position resolution and shower fluctuation	46 ps

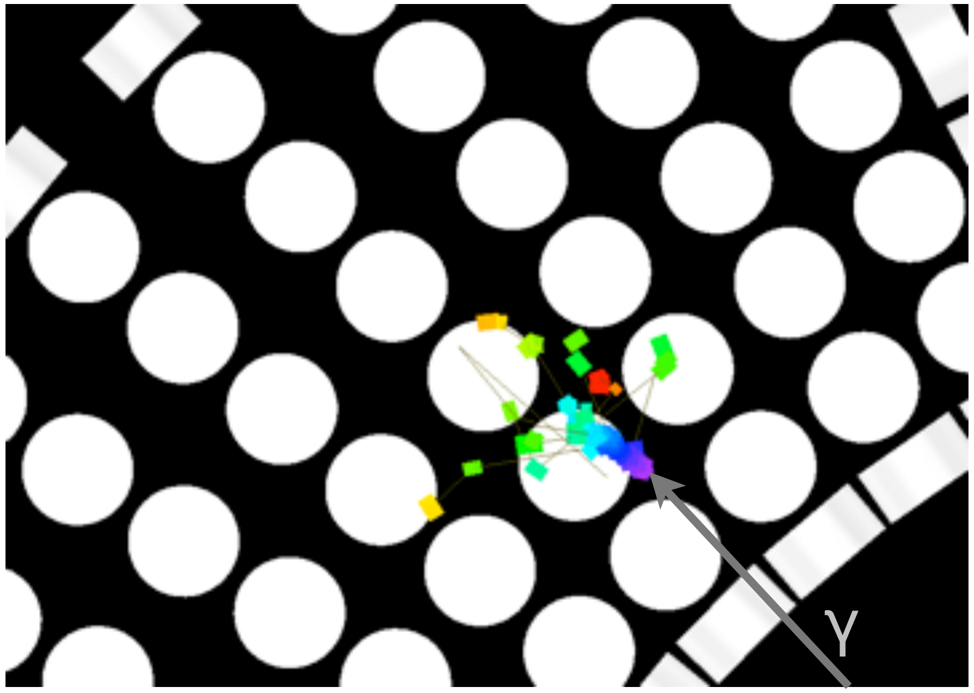
What is limiting the resolutions ?

- Photo-electron statistics is not the main component. (N_{phe} ~ 100,000)
- Non uniformity of photon collection efficiency
- Fluctuation of shower shape
- Other possibilities
  - Angular dependence of PMT response ?
  - Insufficient knowledge of LXe properties ?



Typical energy deposit in LXe

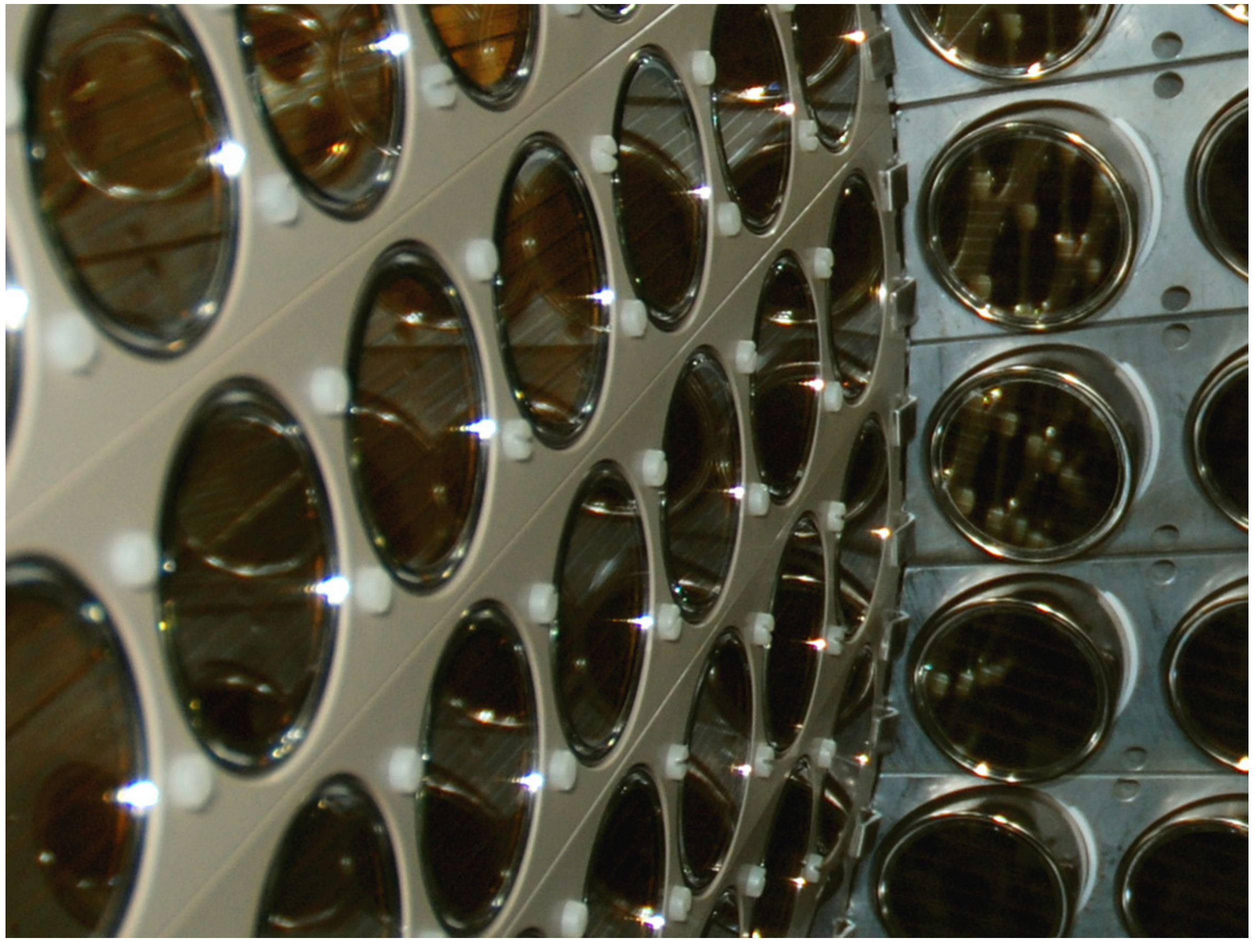
(color represents time of deposits)

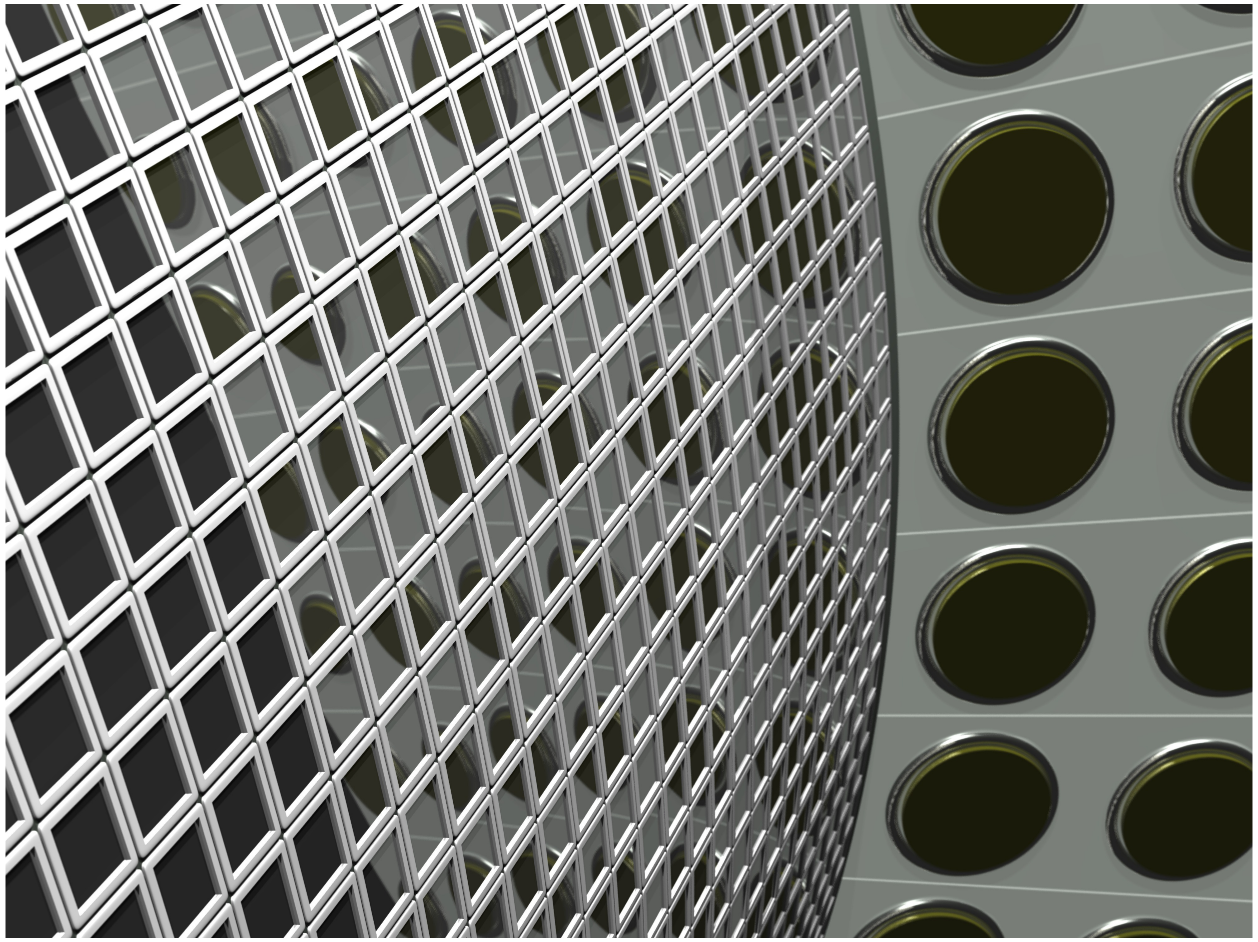


Upgrade

New detector concept

Replacing PMTs in entrance face with SiPMs





Present detector

2 inch PMT

Upgraded detector (CG)

12×12 mm² SiPM (Hamamatsu MPPC)

Higher granularity
More uniform collection efficiency
Less material before LXe

→

Better position and energy resolutions
Higher efficiency (9% improvement, MC)

(Gamma rays enter from the left side of the picture)

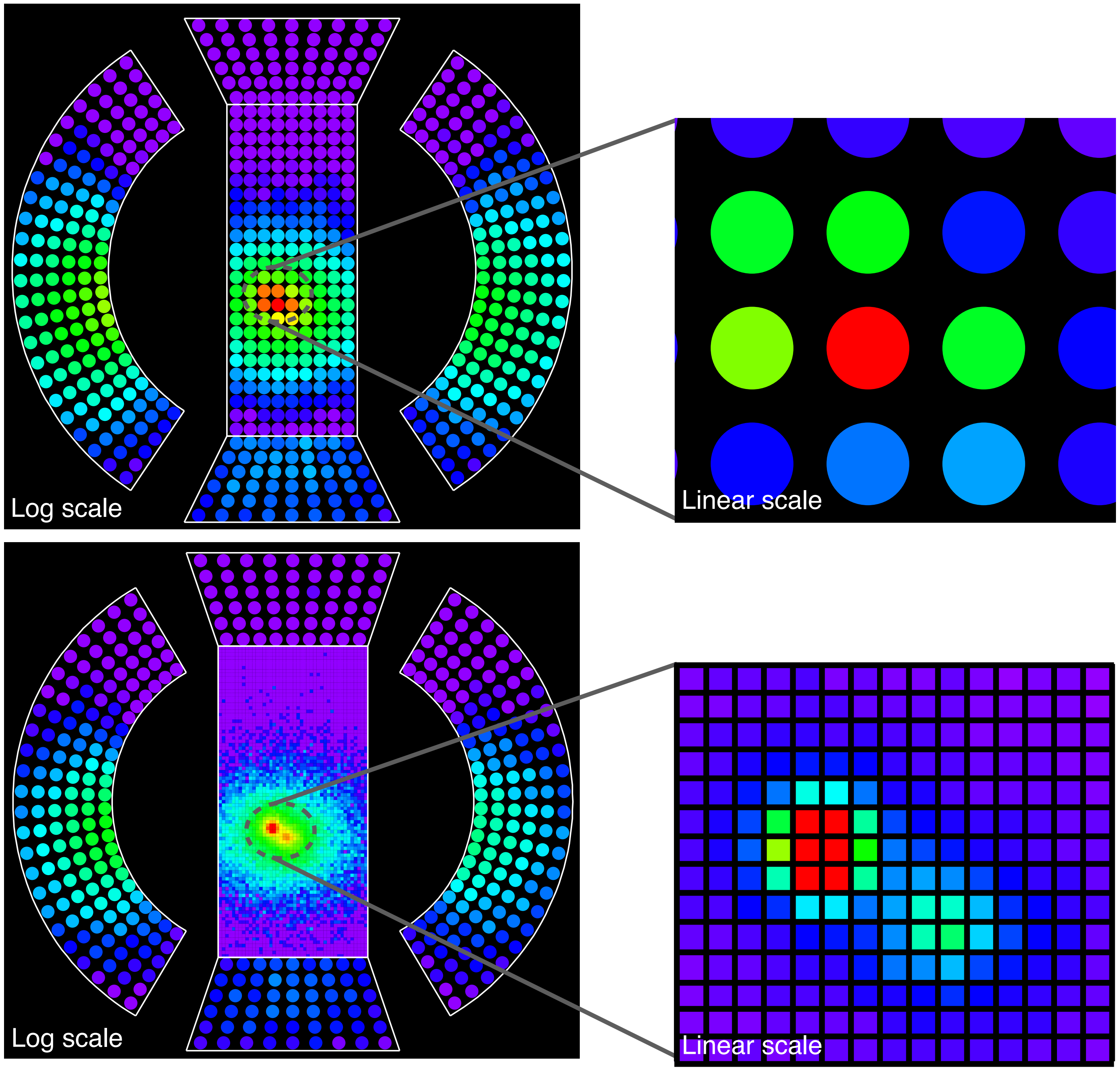
Imaging Calorimeter

Event display of the same MC event

Two gamma rays pileup

Present

Upgraded



216 PMT

in entrance face

×16 more "pixels"

~4000 SiPMs

in entrance face

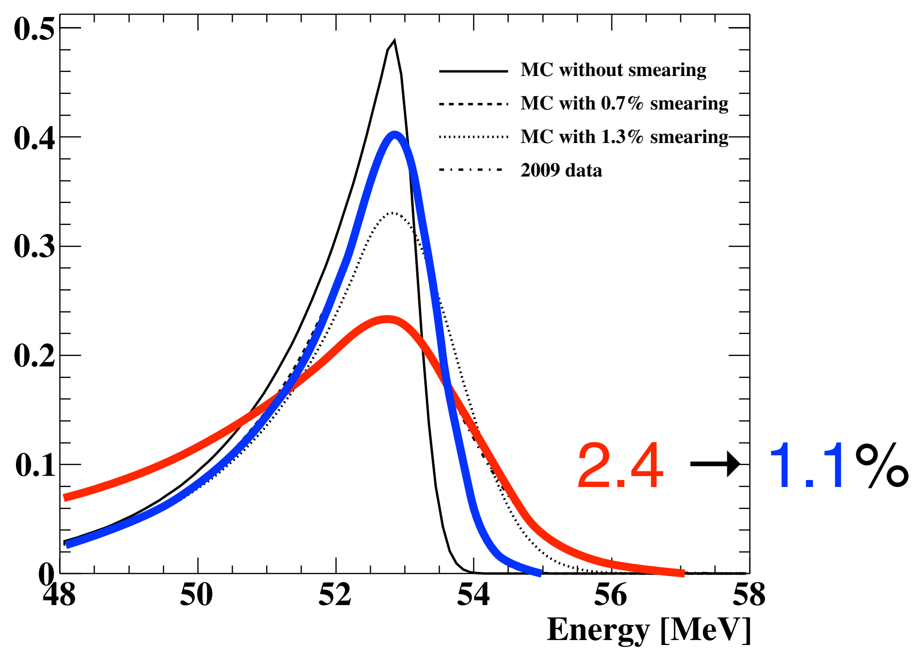
Color code : N_{phe} / area

Expected performance

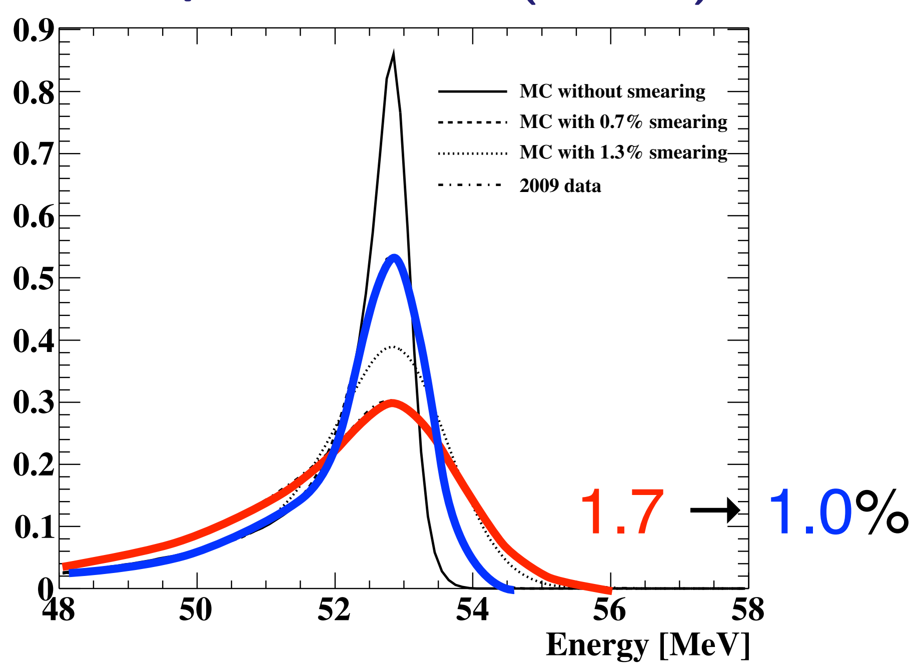
Energy response

Present detector
Upgraded detector

shallow conversion (<2cm)

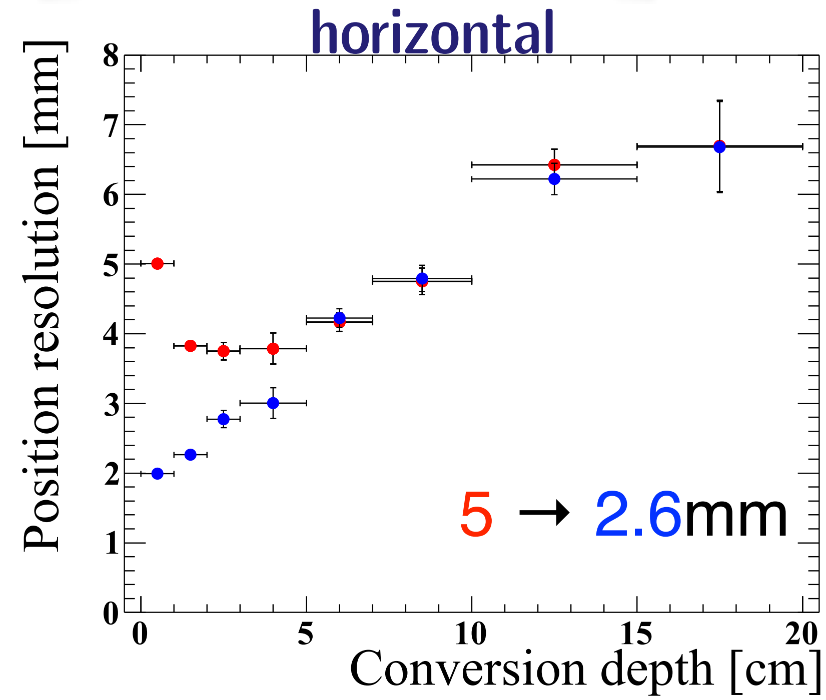


deep conversion (>2cm)

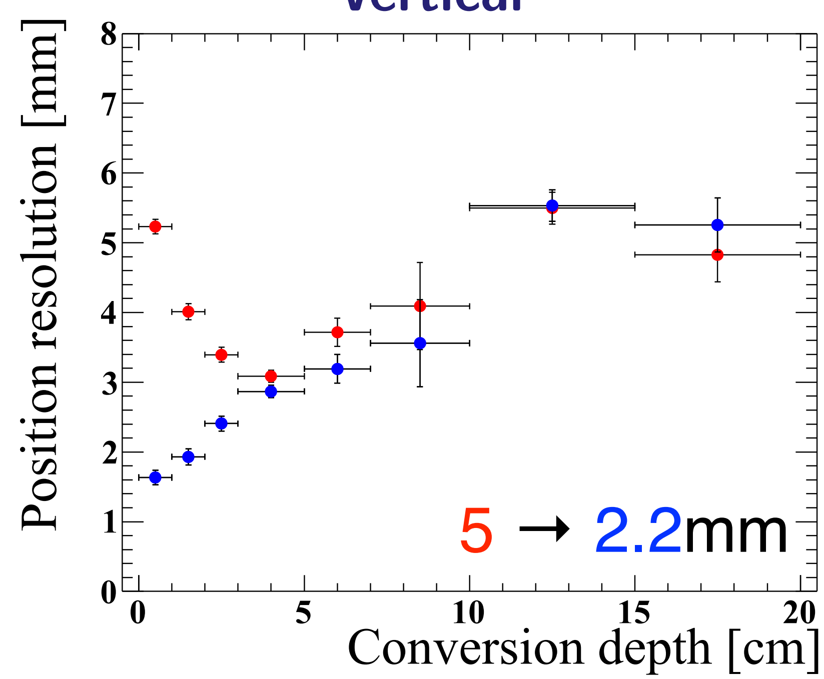


Position resolution

horizontal



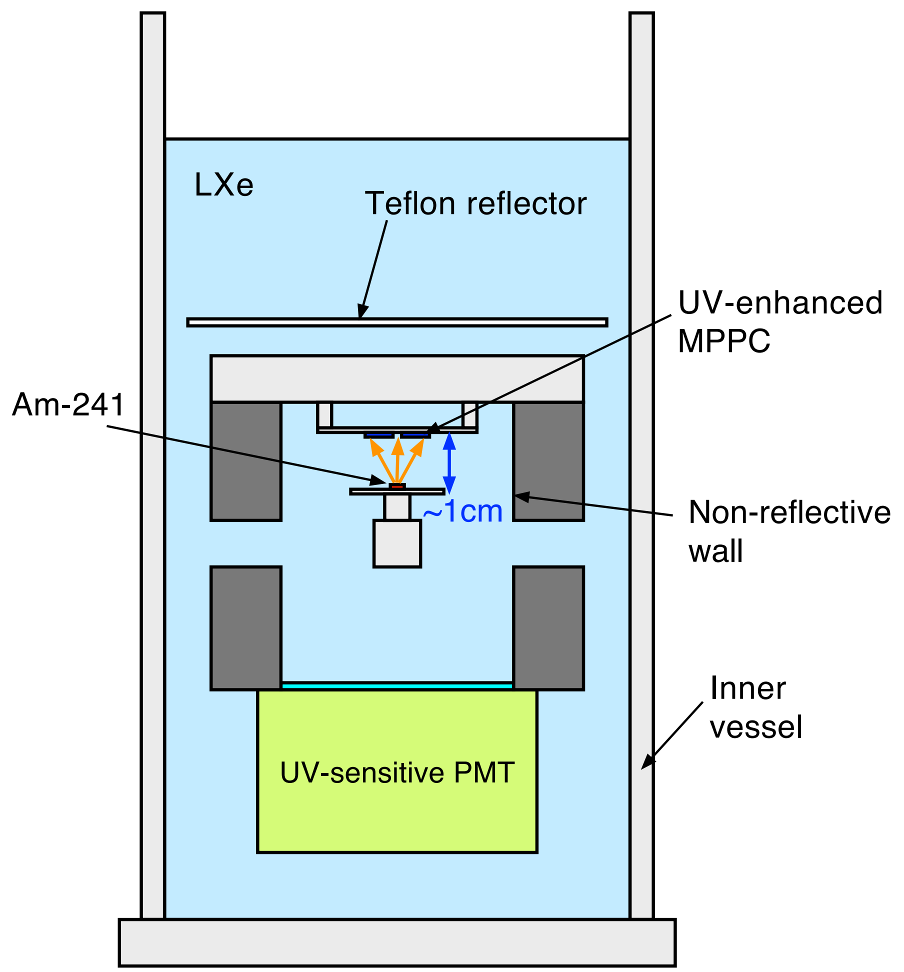
vertical



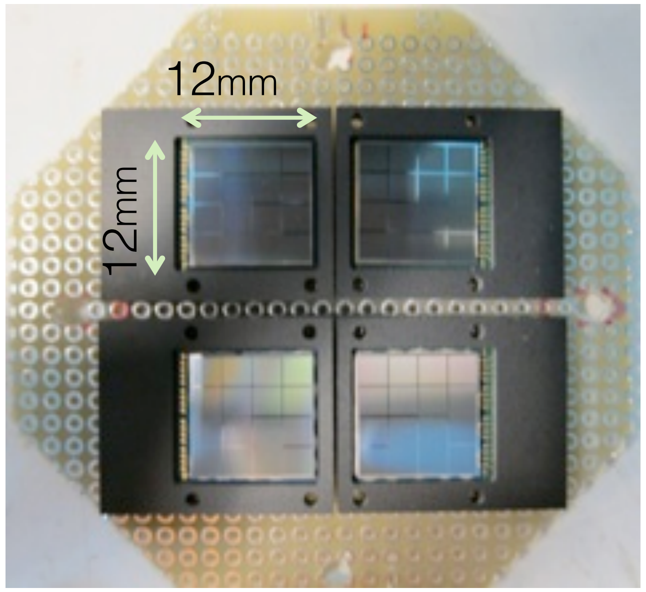
Development of new SiPM for LXe

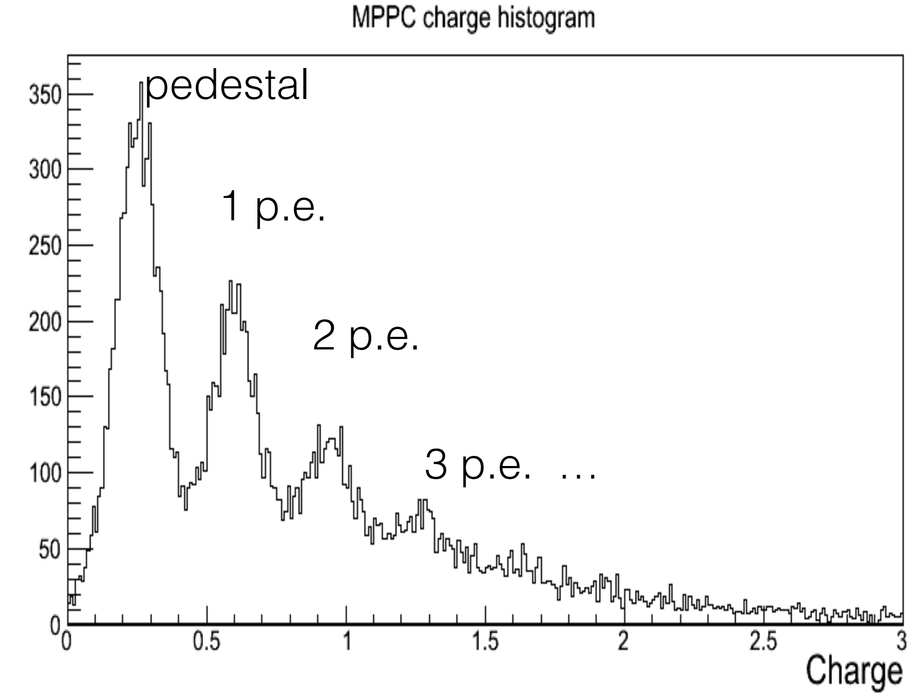
No commercially SiPMs sensitive to LXe light is available.

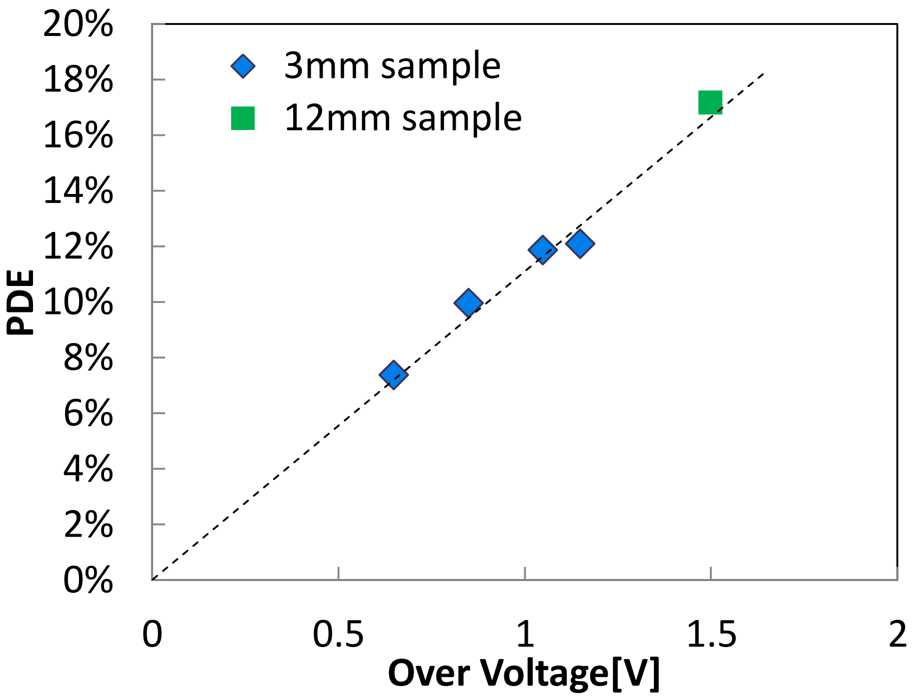
We are developing a new type of MPPC sensitive to LXe VUV light



Prototype







- Successfully operated in LXe
- Single photon counting is possible
- **17%** of PDE for LXe light is obtained

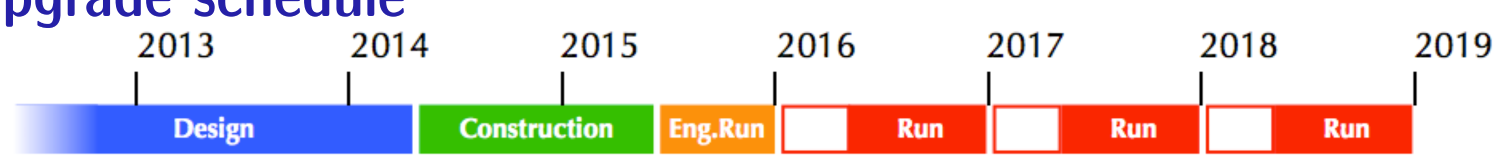
Summary

- The world largest LXe scintillation detector for MEG was developed
- Stable operation for >5 years
- Sophisticated calibration by many methods
- Performance measured

Energy Resolution	1.7%
Position Resolution	5 mm
Relative time Resolution	67 ps
Efficiency	63%

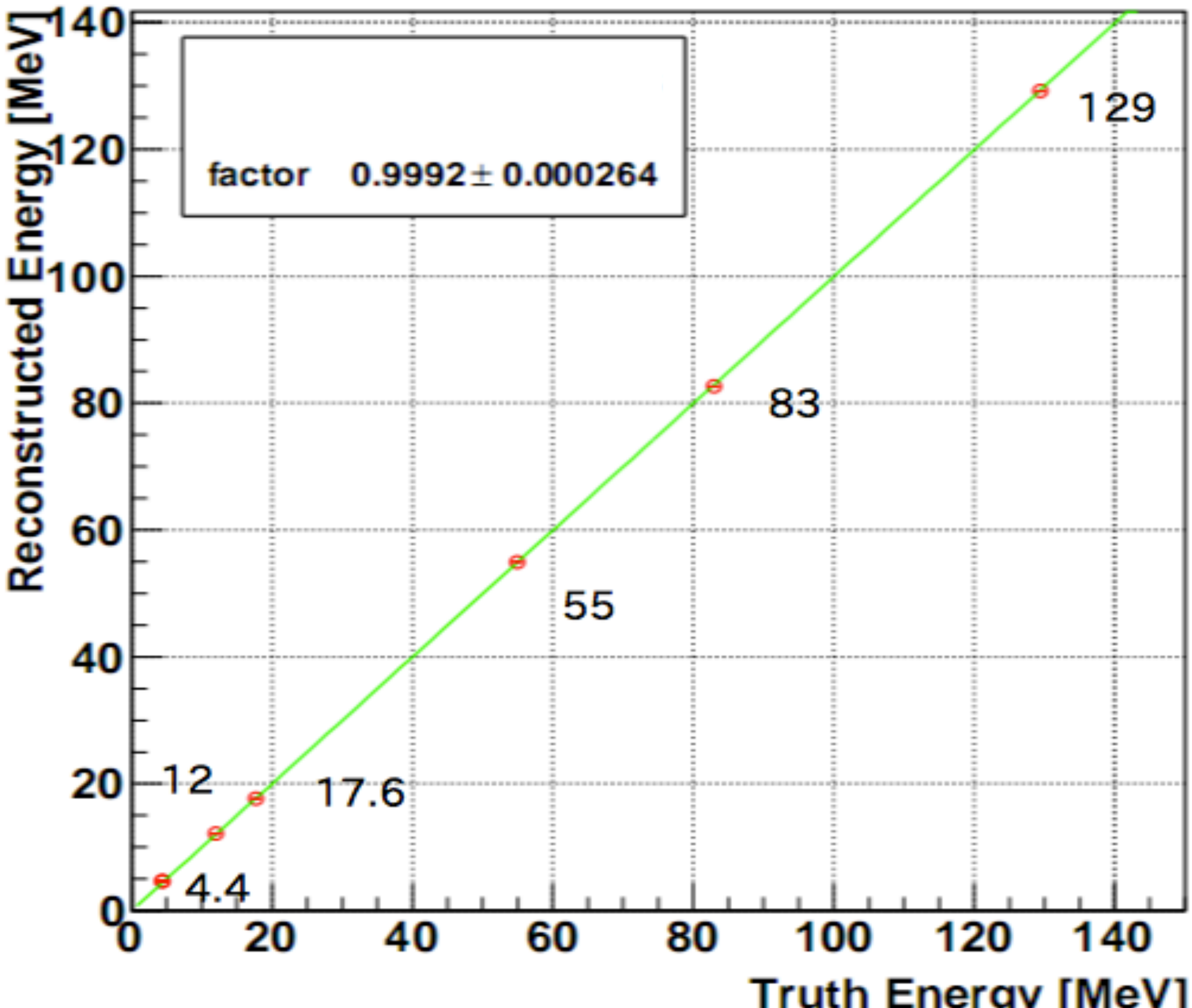
- Upgrade using a new type of SiPM sensitive to LXe light
  - R&D in progress

Upgrade schedule



Back up

Linearity



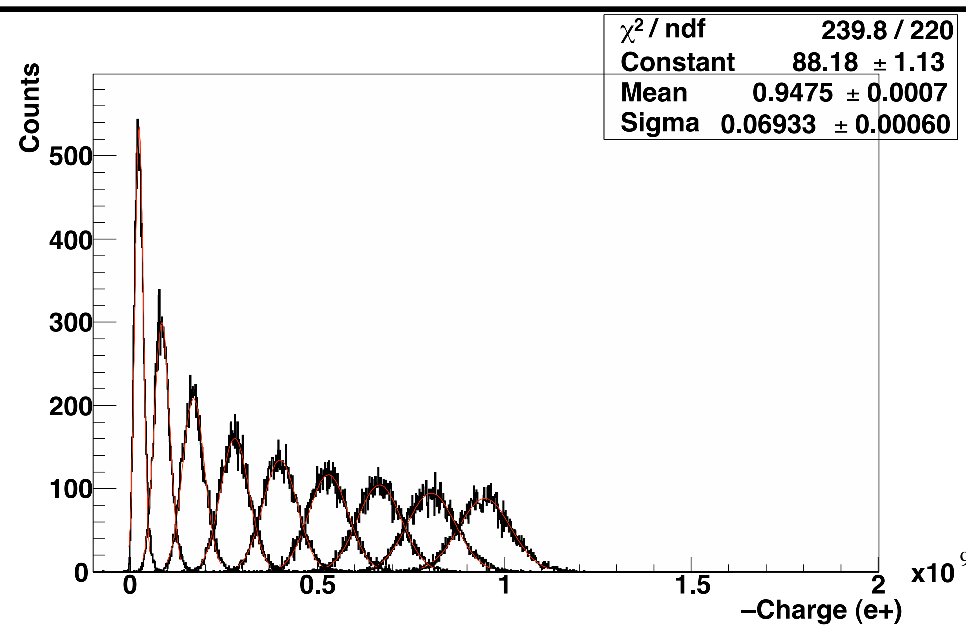
factor 0.9992 ± 0.000264
129
83
55
12
17.6
4.4
Reconstructed Energy [MeV]
Truth Energy [MeV]
0
20
40
60
80
100
120
140

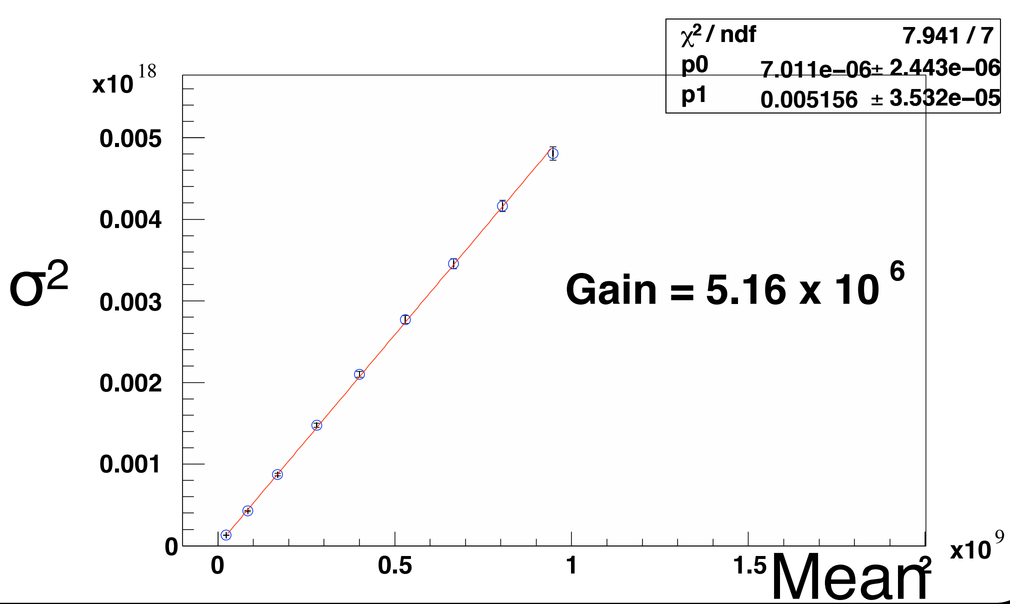
Calibration

PMT	Energy	Time
LED Alpha source (5.5 MeV)	AmBe (4.4MeV) Neutron capture (9MeV) Li(p,γ)Be (17.6 MeV) $\pi^0 \to \gamma\gamma$ (55, 83 MeV) Cosmic ray (160 MeV)	B(p,γ) (4.4+11.7 MeV) $\pi^0 \to e^+e\gamma$ (55-83 MeV) Muon radiative decay

Gain Estimation

36 LEDs are installed





Calibration

PMT

LED
Alpha source (5.5 MeV)

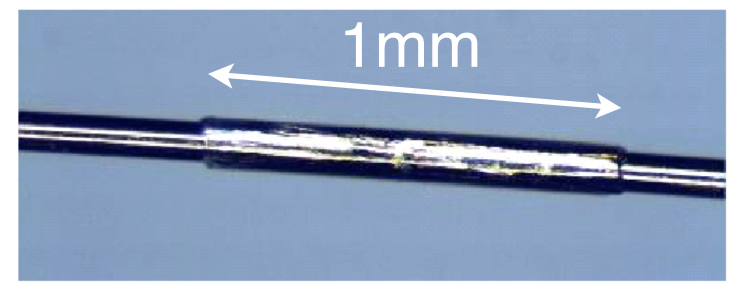
Q.E. Estimation

Energy

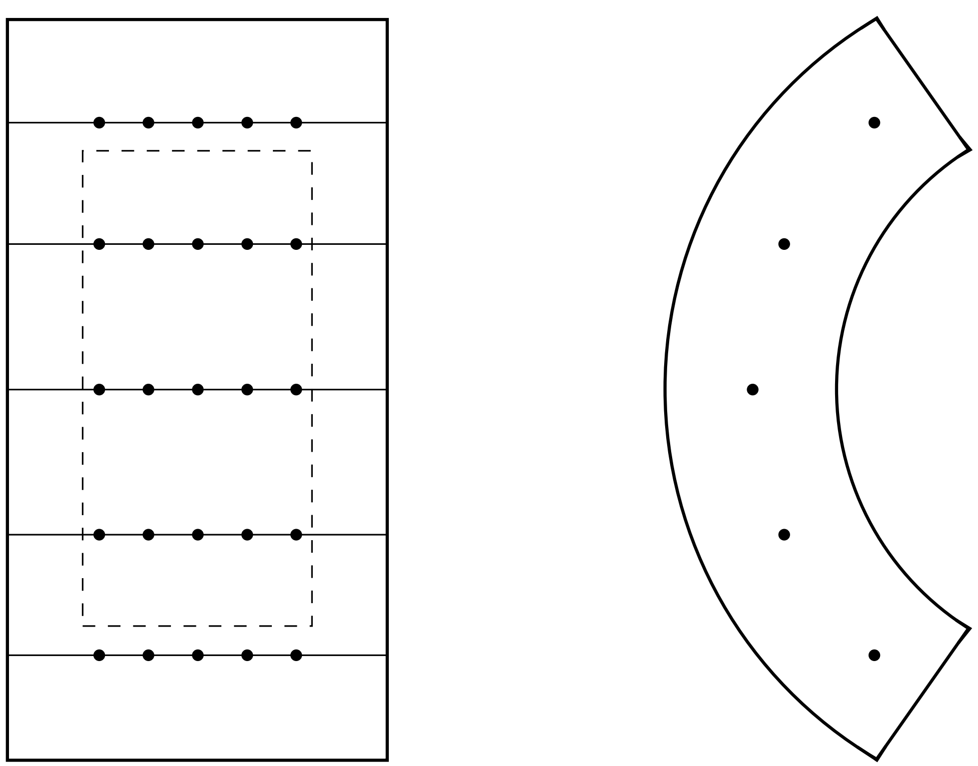
AmBe (4.4MeV)
Neutron capture (9MeV)
Li(p,γ)Be (17.6 MeV)
$\pi 0 \rightarrow \gamma\gamma$ (55, 83 MeV)
Cosmic ray (160 MeV)

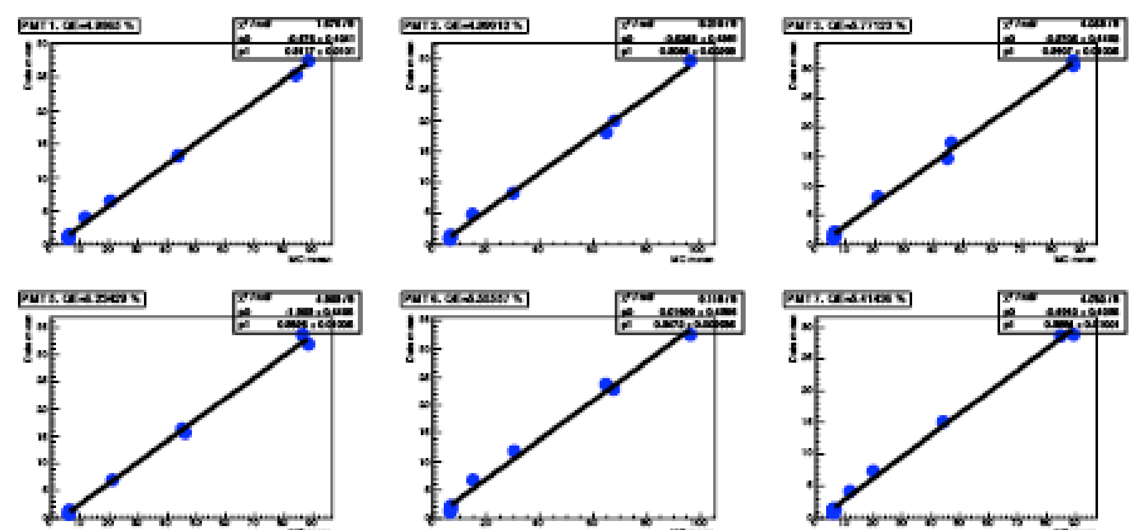
Time

B(p,γ) (4.4+11.7 MeV)
$\pi 0 \rightarrow e^{+}e\gamma$ (55-83 MeV)
Muon radiative decay



25 alpha sources on wire (100 µm ϕ)





Estimation of Q.E. from Q_{data}/Q_{MC}

Upgraded Detector