2021年物理ランにおけるMEG II実験 液体キセノンガンマ線検出器の性能評価

日本物理学会
2022年 秋季大会
(岡山理科大学)
7aA442-1

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The University of Tokyo

ICEPP The University of Tokyo

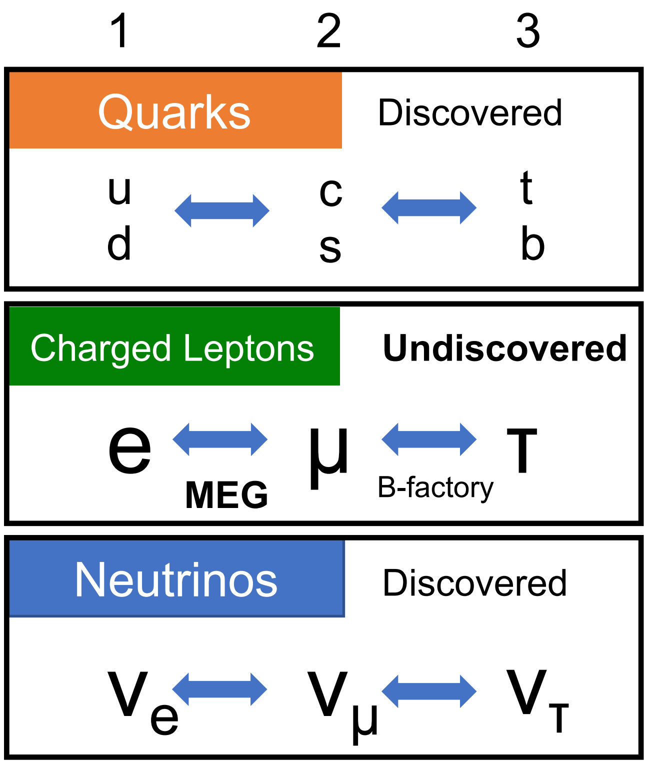
THE UNIVERSITY OF TOKYO

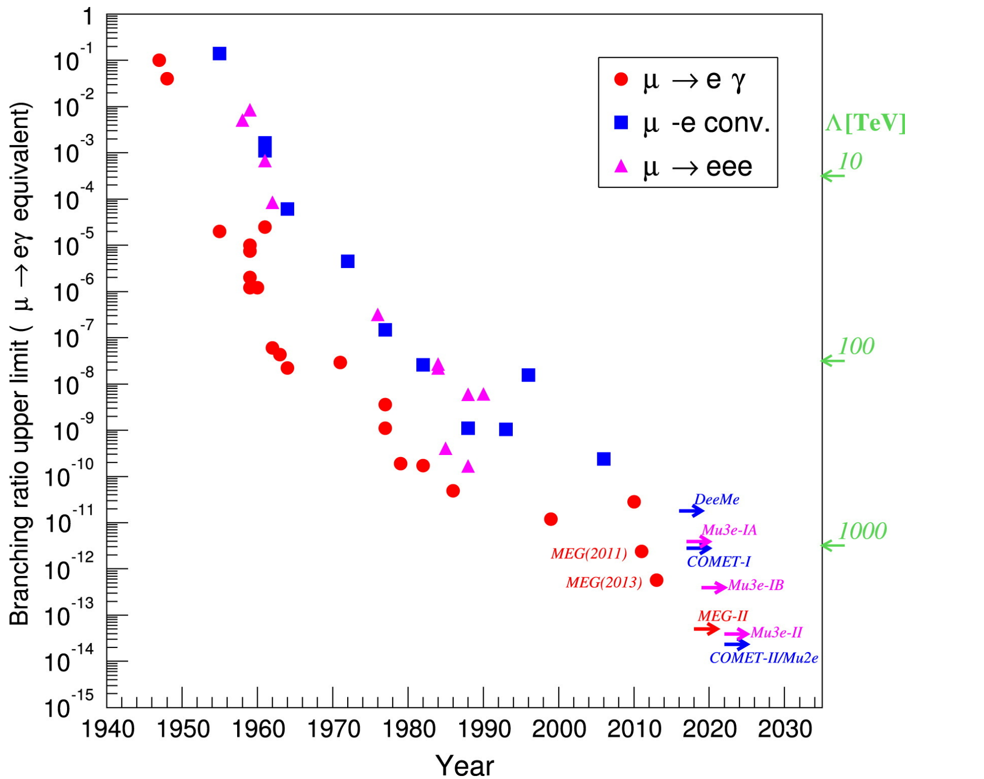
Core-to-Core Program

Outline

- Introduction
  - MEG II experiment
  - Liquid Xenon gamma-ray detector
  - Charge exchange measurement
- Performance
  - Energy resolution
  - Timing resolution
  - Efficiency
- Summary & Prospects

Charged Lepton Flavor Violation (cLFV)

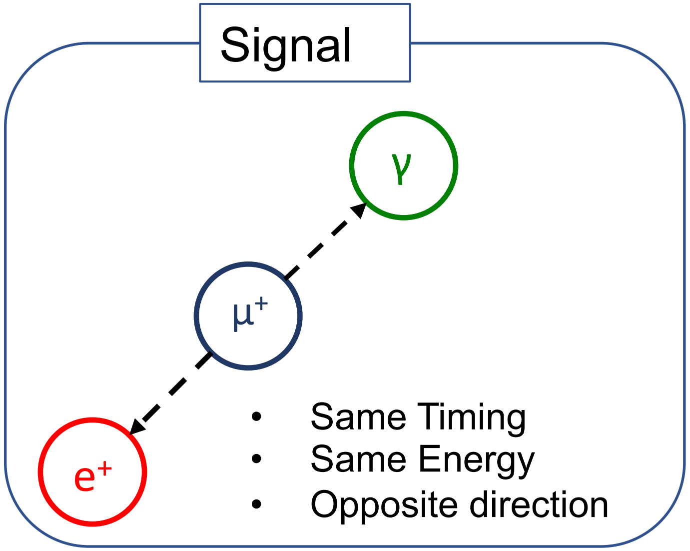


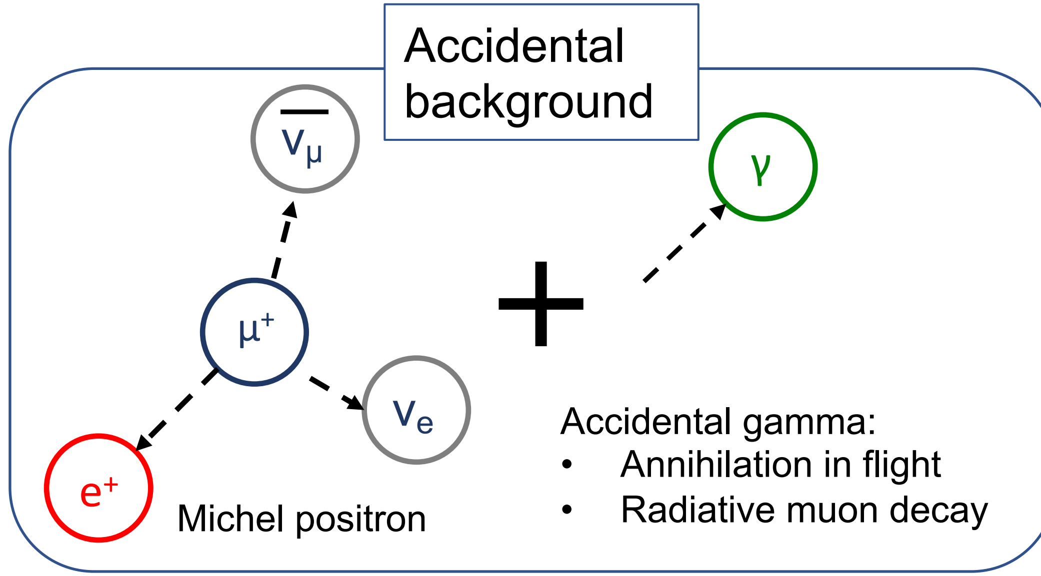


"An Experimental Review of Charged Lepton Flavor Violation in Muon Channel ", W. Ootani

- Flavor mixing is not observed only for charged leptons.
- cLFV is strongly suppressed in SM + ν oscillation ($Br(\mu \to e\gamma) \sim 10^{-54}$).
- Large enhancement is predicted by new physics.
- High energy scale beyond LHC is indirectly accessible.

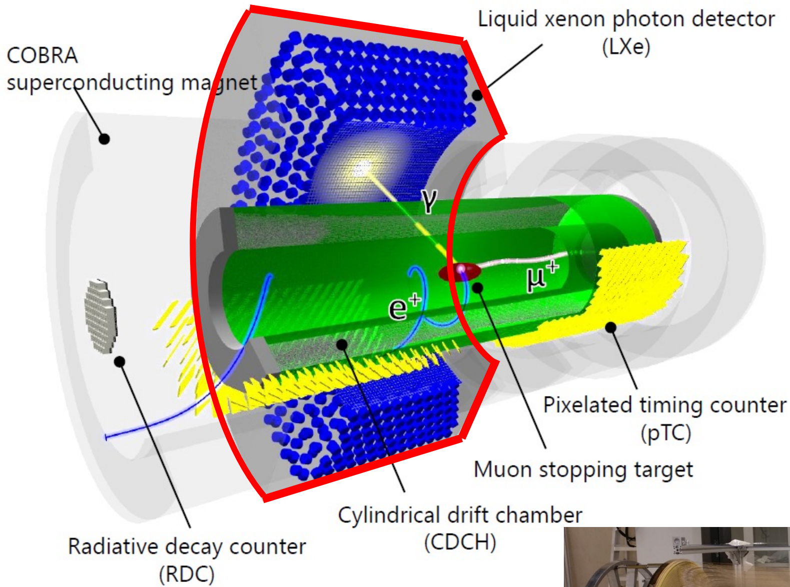
μ→eγ Search

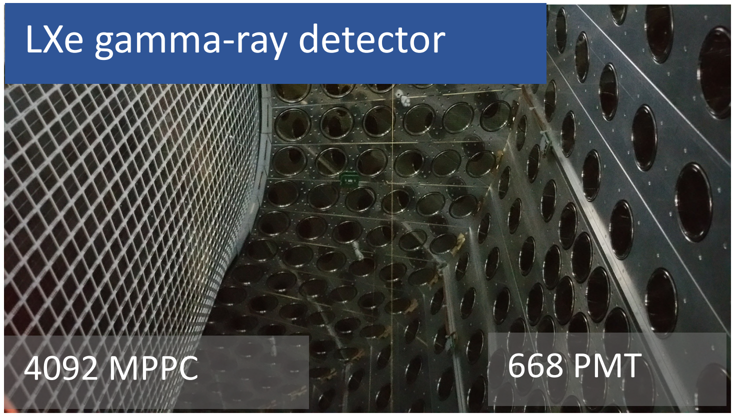


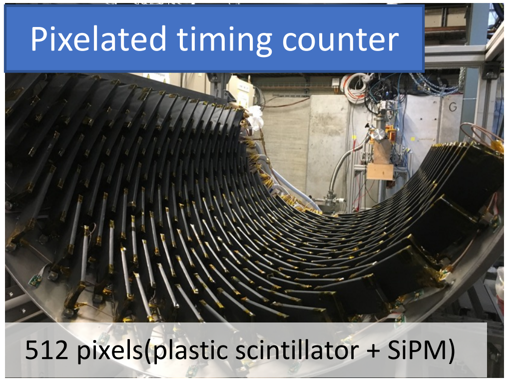


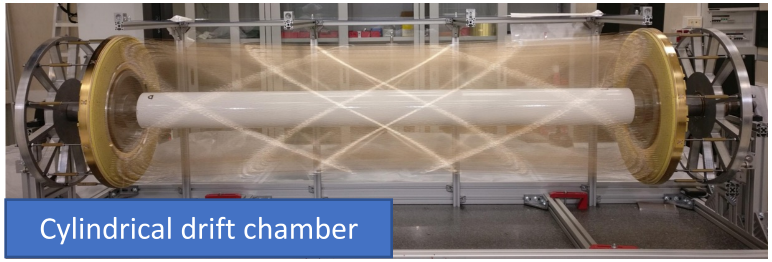
- $\mu^+ \to e^+\gamma$ decay: two-body decay
  - Signal: Coincidence & back-to-back & 52.8 MeV e^+ and γ
  - Main background: accidental
    - Positron from Michel decay + accidental gamma-ray.
  - Key: Precise measurement of e^+ and γ to discriminate signal and BG.
- Current limit: Br($\mu^+ \to e^+\gamma$) < 4.2×10^{-13}(90% C.L., MEG)

MEG II experiment





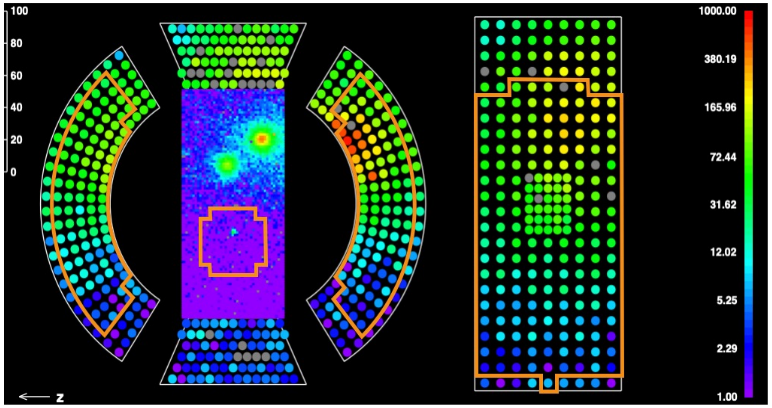




- MEG II started searching for $\mu^+ \to e^+\gamma$ decay in 2021.
  - Goal: Br(μ→eγ) ~ 6×10^{-14} in 3 years (2021:pilot run + 2022-2024).
  - Continuous high intensity muon beam ($\geq 3\times10^7 \mu/s$) @PSI, Switzerland
  - Detector upgrade (Resolution improvement for each detector)

Liquid Xenon detector upgrade

Performance	MEG	MEG II (design)	MEG II (measured)
Position resolution[mm]	5 – 6	2.5	2.5
Energy resolution[%]	2.4 / 1.7	1.0 / 1.1	**2.0 / 1.7**
Time resolution[ps]	62	50 - 70	**61**
Efficiency[%]	65	69	**64**



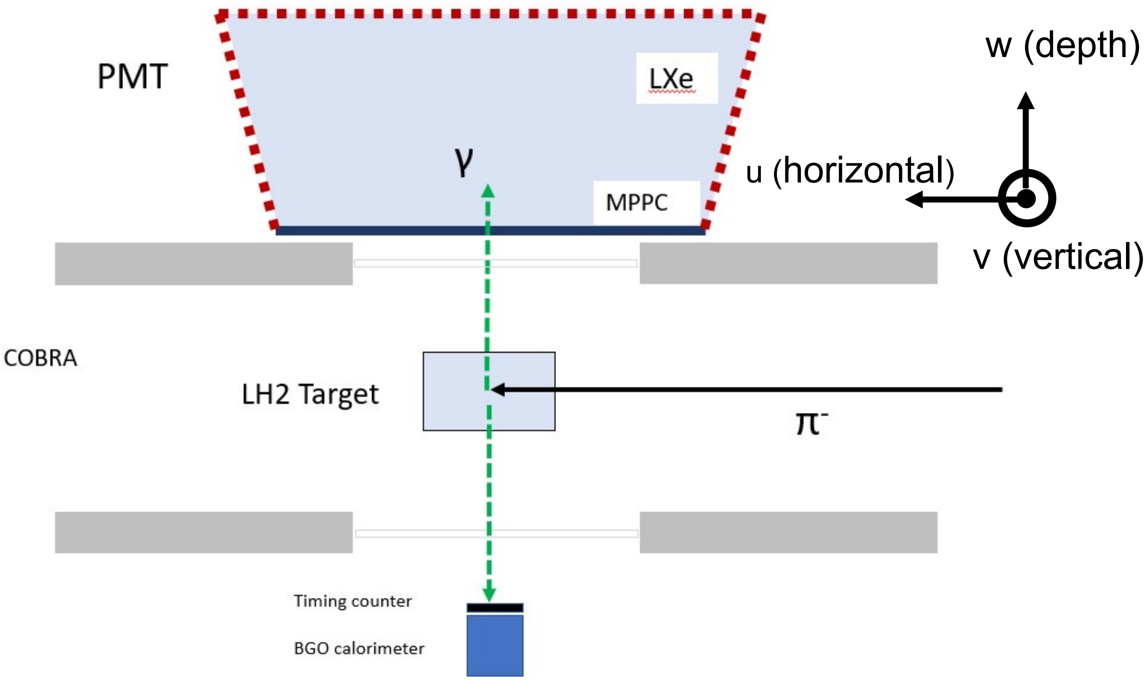
Orange: 2020 readout

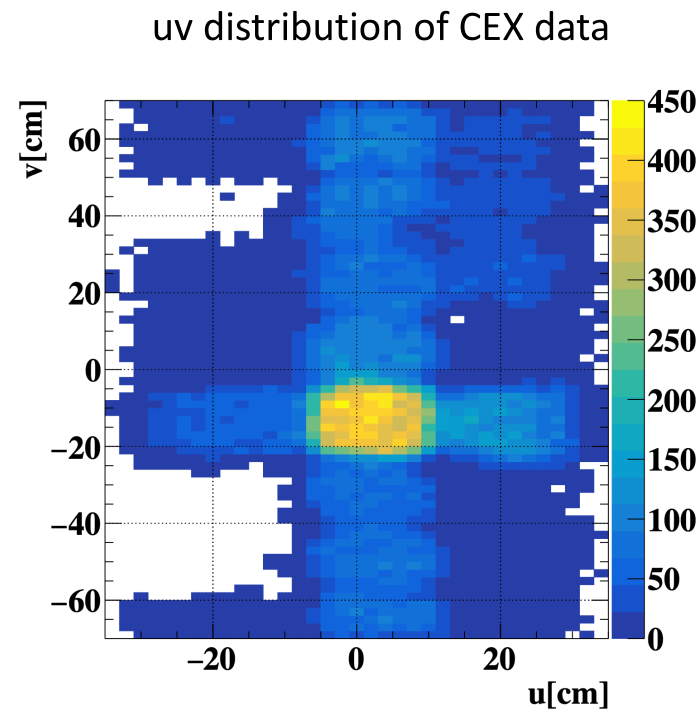
- The entrance face is covered with 4092 VUV-sensitive Multi-Pixel Photon Counters (MPPC).
  - Uniform light collection efficiency → Improve energy & position resolution.
  - Reduced material budget → Higher detection efficiency
- In this talk, measured performances in RUN 2021 will be presented.
  - Energy & time resolution, and detection efficiency with full-scale detector.
  - The number of readout was limited to ~1000 up to 2020.

MEG talks

- 7aA442-[1-4]
  - S. Kobayashi: Performances of the LXe detector in 2021
  - A. Oya: Combined analysis in 2021
  - S. Ban: 2022 RUN
  - A. Matsushita: Calibration of the LXe detector in 2022
- 6pA421-[1-2] : M. Takahashi, K. Yamamoto
  - RPC for MEG II
- 8aA421-2: Y. Uchiyama
  - Machine Learning for positron reconstruction
- 7pA442-[1-2] : R. Yokota, F. Ikeda
  - Future cLFV search

Charge Exchange(CEX) Measurement

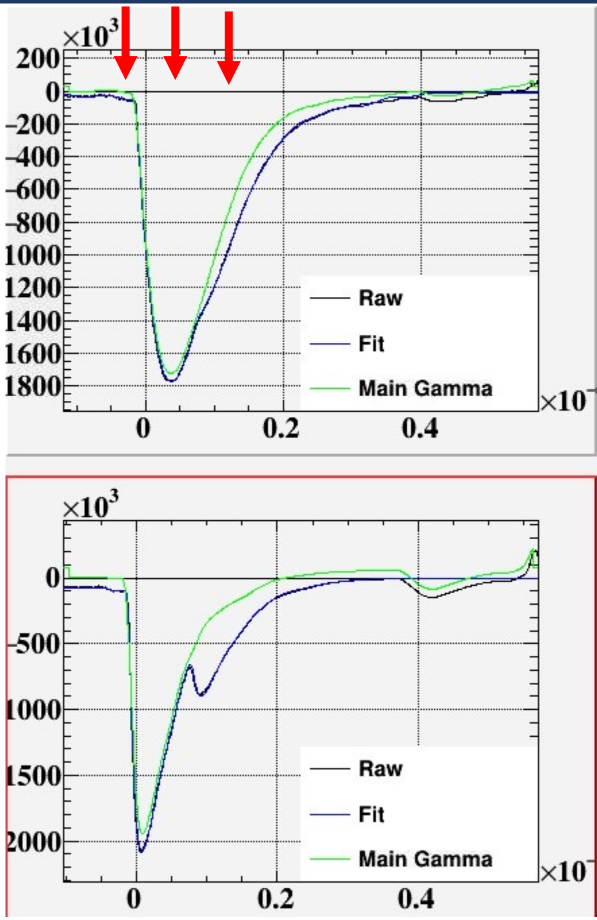


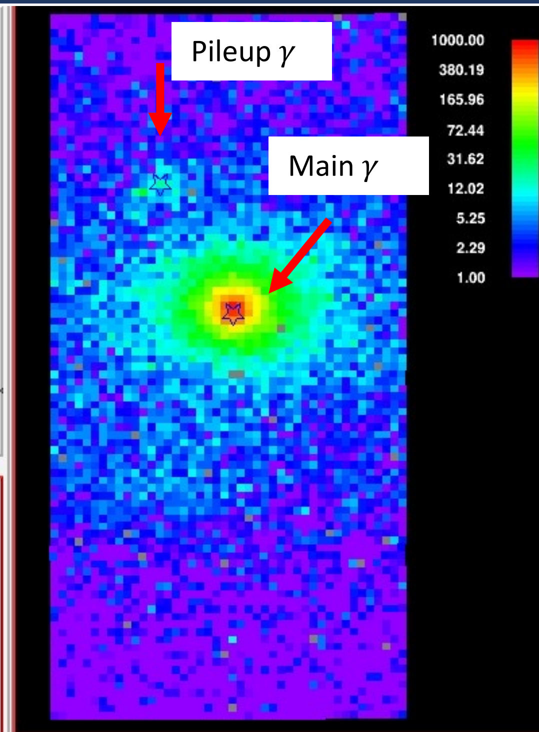


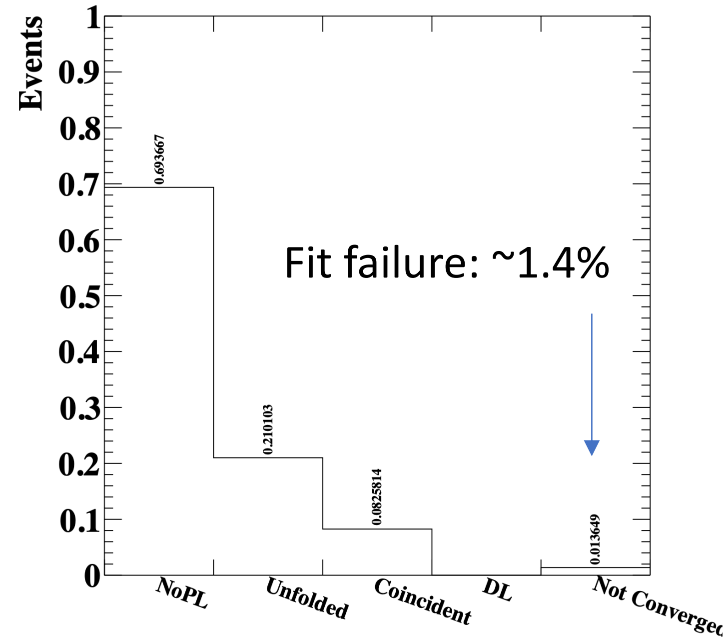
- Correlated gamma-rays from $\pi^- p \rightarrow \pi^0 n, \pi^0 \rightarrow \gamma\gamma$.
- Tag one gamma-ray and measured the other with the LXe detector.
  - Energy measurement with BGO crystal + PMT
  - Timing measurement with plastic scintillator + MPPC (pre-shower counter)
- Back-to-back gamma-ray pair : 55 MeV and 83 MeV.
- The full scan over the detector was not completed due to LH2 target failure.

Development of pileup analysis

Yamamoto & Kobayashi

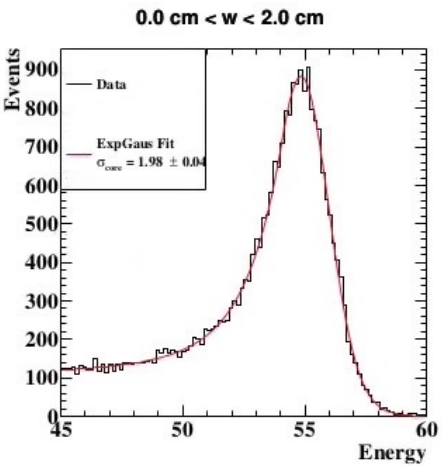


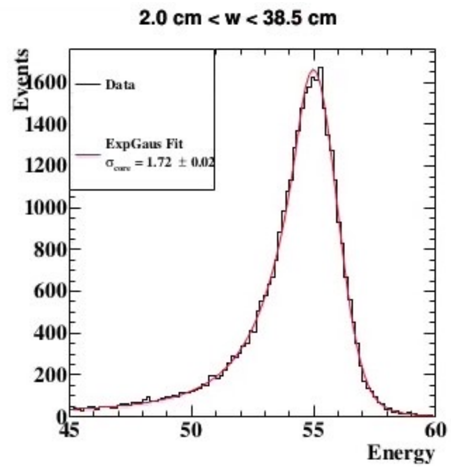




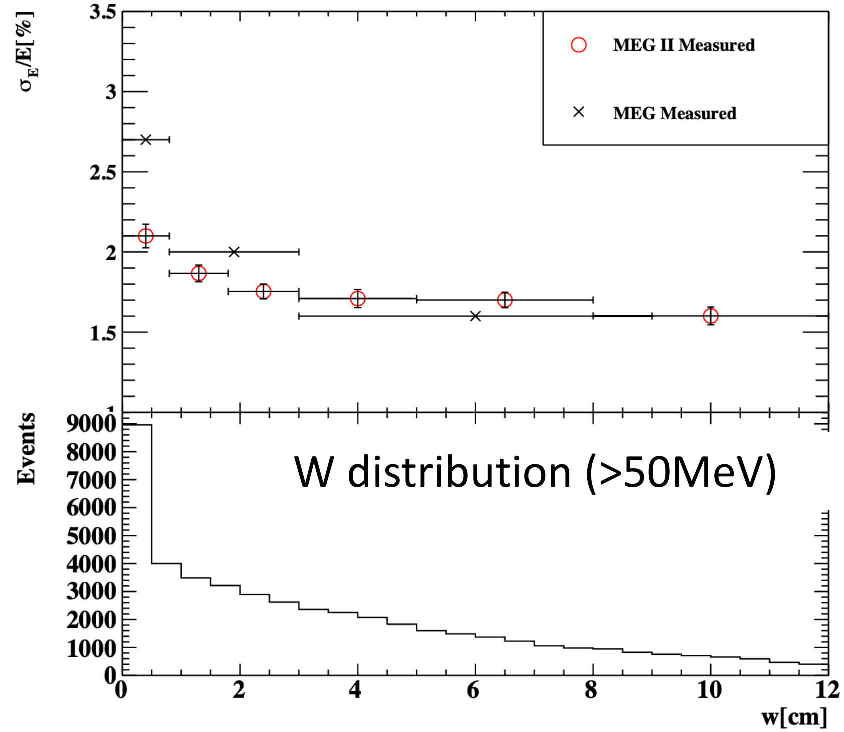
- Pileup analysis for the data was developed.
  - It was tested only with MC simulation.
  - Peak search of light distribution + template fit of waveform.
- Ratio of fit failure in CEX measurement is limited to 1.4%

Energy Resolution of central region





Resolution vs conversion depth



$$\sigma_E = \sqrt{\sigma_{core}^2 - \sigma_{true}^2}$$

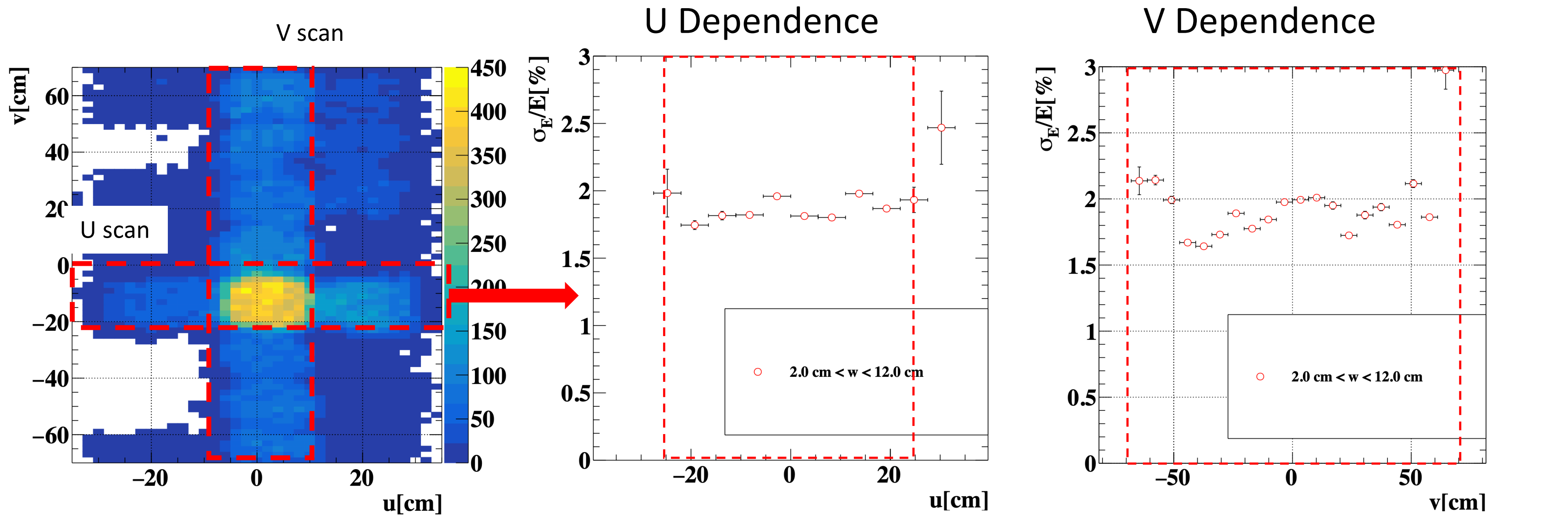
Resolution

Spread of true energy deposit: 0.4%

- Spectrum is fitted with an Exponential + Gaussian function.
- **Energy resolution: 2.0% (w < 2 cm) / 1.7% (w > 2 cm):**
  - consistent with previous measurements.
- Improved for gamma-ray hit in shallow region (w < 2 cm) from MEG.
- Significantly worse than MC (1.0%) as in MEG.

Uniformity of energy resolution

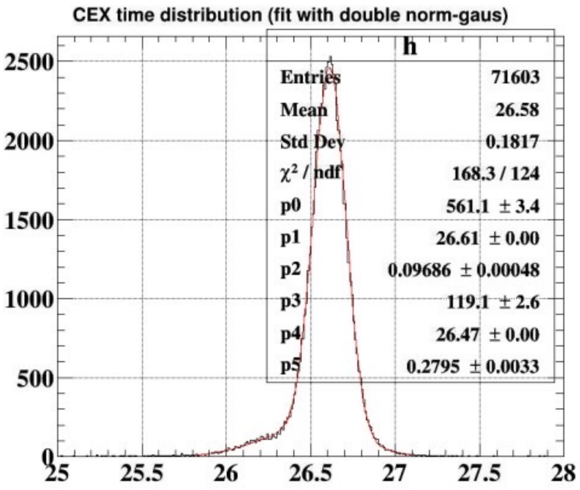
Preliminary



- Resolution is relatively uniform in u within acceptance.
- Energy resolution is < 2.0% for almost all v, but non-uniformity is observed.
  - Resolution is 1.7-1.8% for the area with a large statistics.
  - Further calibration and correction would provide better uniformity.

Time Resolution

Oya & Matsushita

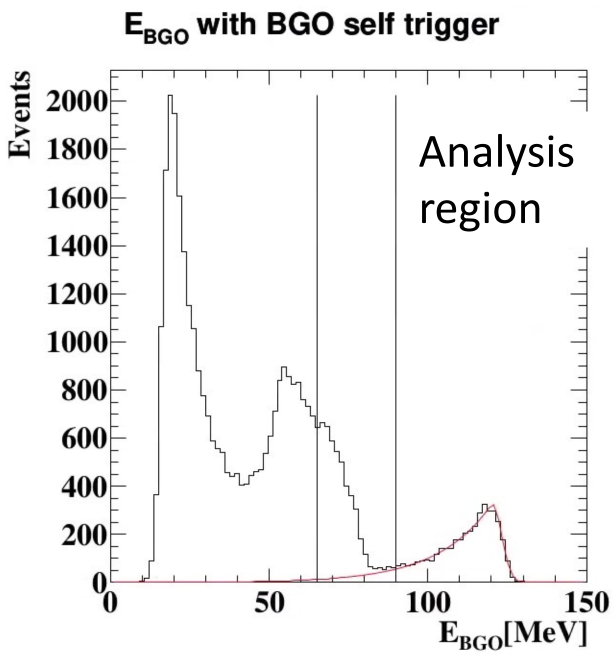


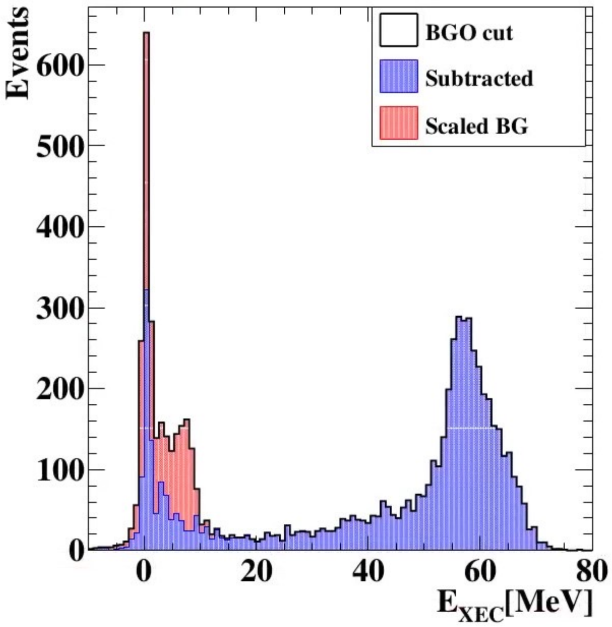
$$\sigma_{\Delta t} = \sigma_{LXe} \oplus \sigma_{pre-shower} \oplus \sigma_{vertex}$$

$\sigma_{\Delta t}$	**Spread of time difference**	**96.9±0.4 ps**
σ_{vertex}	Contribution from vertex size	70.0±5.7 ps
$\sigma_{pre-shower}$	Resolution of pre-shower counter	28.4±0.2 ps
σ_{LXe}	Resolution of LXe detector	60.7±6.0 ps

- Time resolution can be measured with the time difference between the LXe detector and pre-shower counter.
- The time resolution is 61 ps: better than previous JPS (85 ps).
  - Comparable resolution to MEG: 62 ps.
  - Waveform analysis configuration was revised.
- Tail component comes from non-uniform time response.

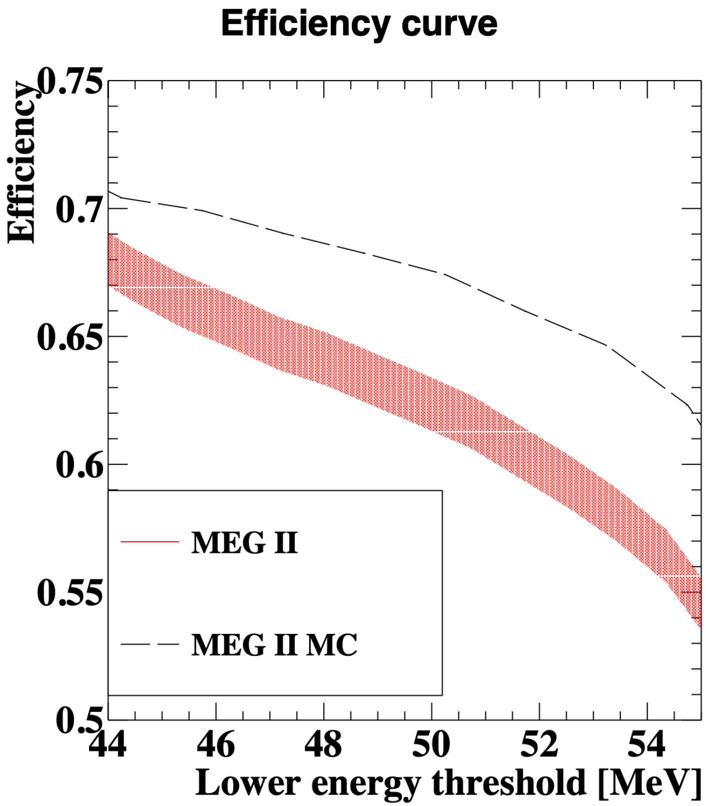
Detection Efficiency





- Principle:
  - Trigger events based on energy of BGO crystal
  - Select events of E_{BGO} ~ 83 MeV.
  - Eliminate background from radiative capture.
    - $\pi^- p \to \gamma n$, E_γ~129 MeV & E_n ~ 9 MeV
  - Calculate a fraction of events with E_{LXe} larger than a given lower bound.
- Material budget before LXe volume deteriorates the efficiency.

Detection Efficiency



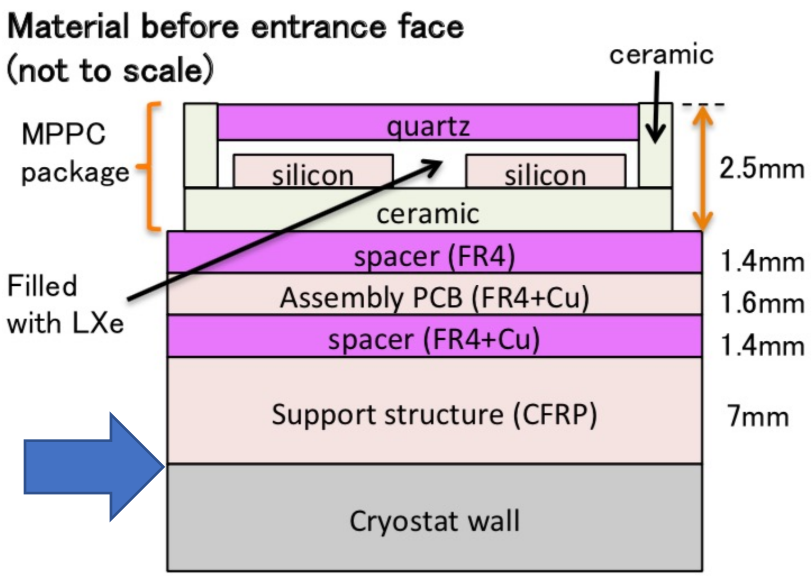
$$\epsilon_{\gamma} = \epsilon_{\gamma,MC} \times \epsilon_{CEX,Data} / \epsilon_{CEX,MC}$$

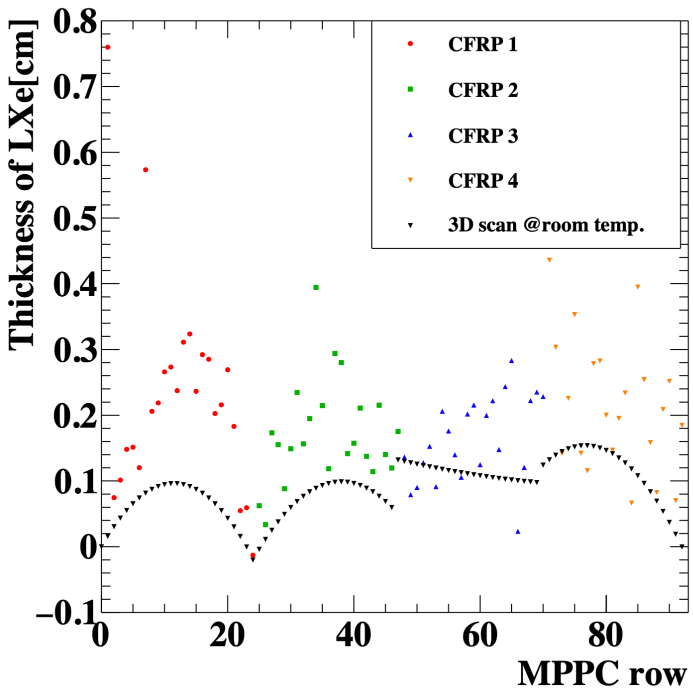
64 % 69 % 62 % 68 %

Material	Radiation length [X_0]
Magnet	0.197
MPPC	0.019
Support structure	0.091
Liquid xenon (1.5 mm)	**0.054**

- Efficiency for signal γ is estimated as 64$\pm$1% (E_{γ} > 48 MeV).
  - Dominant uncertainty is estimation of radiative capture BG.
- Source of inefficiency with respect to MC:
  - Low-energy tail (5%) + LXe in the entrance face (3%).
- MEG detection efficiency: 65% (w/o analysis efficiency)

LXe Volume before MPPC





- LXe is filling the gap in the MPPC support structure.
  - Gap between CFRP and the cryostat wall.
- Thickness of LXe volume is estimated by “reusing” MPPC alignment measurement.
  - MPPC alignment with a well-aligned low-energy gamma-ray.
  - Rate of gamma-ray events is sensitive to LXe thickness.
- 1.5 mm LXe on average → 2.7% inefficiency.

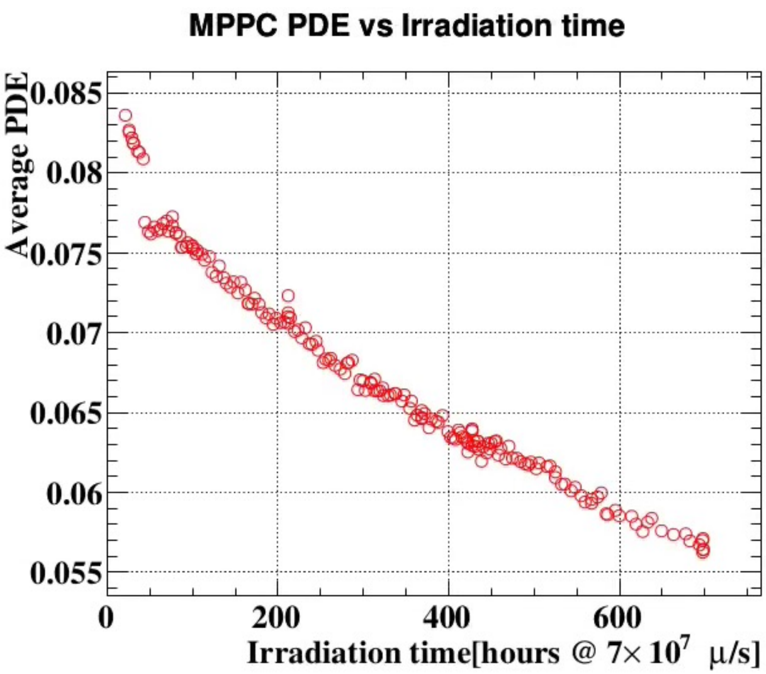
Summary

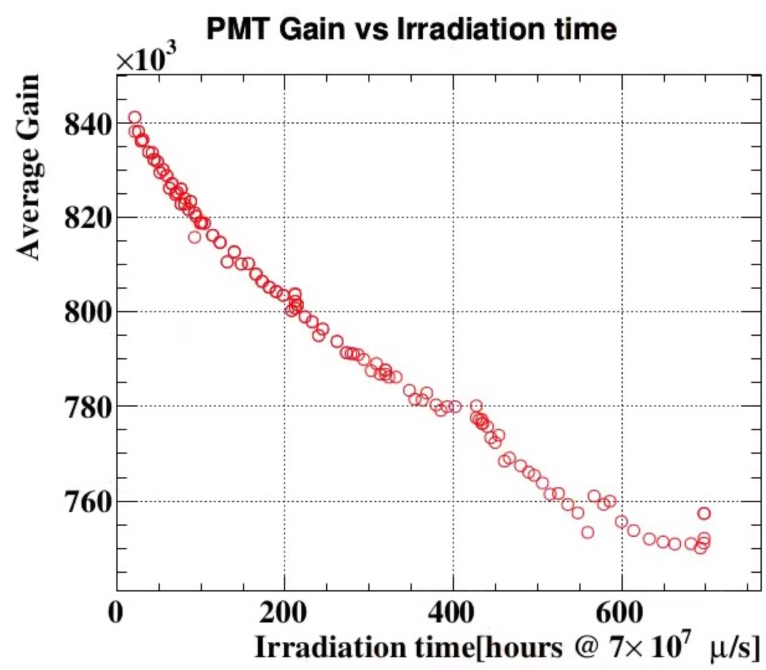
Performance	MEG	MEG II (design)	MEG II (measured)	Comments
Position resolution[mm]	5 – 6	2.5	2.5	Measured in 2018
Energy resolution[%]	2.4 / 1.7	1.0 / 1.1	2.0 / 1.7	CEX 2021
Time resolution[ps]	62	50 - 70	61	CEX 2021
Efficiency[%]	65	69	64	CEX 2021 w/o analysis efficiency

- MEG II started physics run to search for $\mu^+ \to e^+\gamma$ in 2021.
- $\pi^0 \to \gamma\gamma$ decay was used to evaluate resolutions and detection efficiency.
- Energy resolution for shallow gamma-ray hit is improved from MEG.
  - Discrepancy between MC and data remains.
  - The result implies that the bottleneck of the energy resolution is not the readout.
  - Non-uniformity of the resolution in v implies limits the overall resolution.
- Efficiency and time resolution were comparable to MEG.
- The sensitivity improvement from the detector upgrade is ~35 % in total.
  - 25% from position resolution, 10% from energy resolution.

Backup

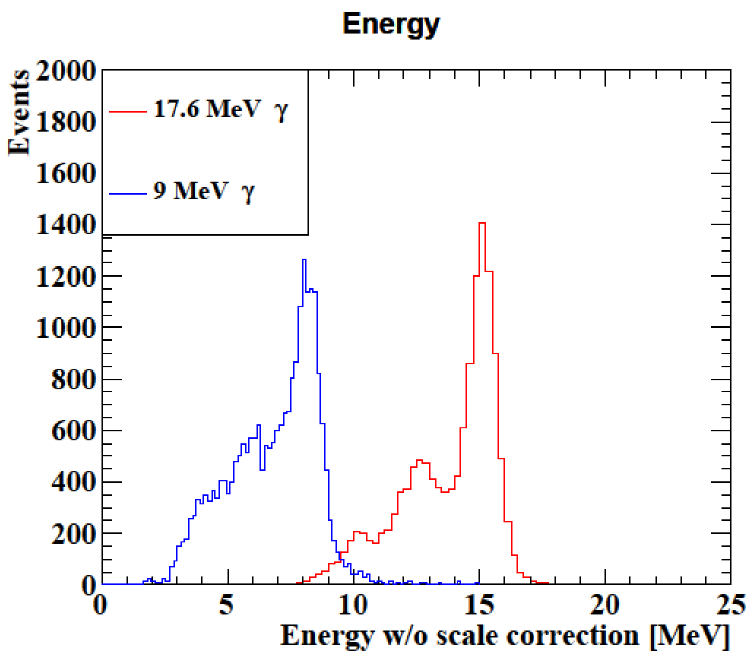
2021 RUN – Sensor Calibration -

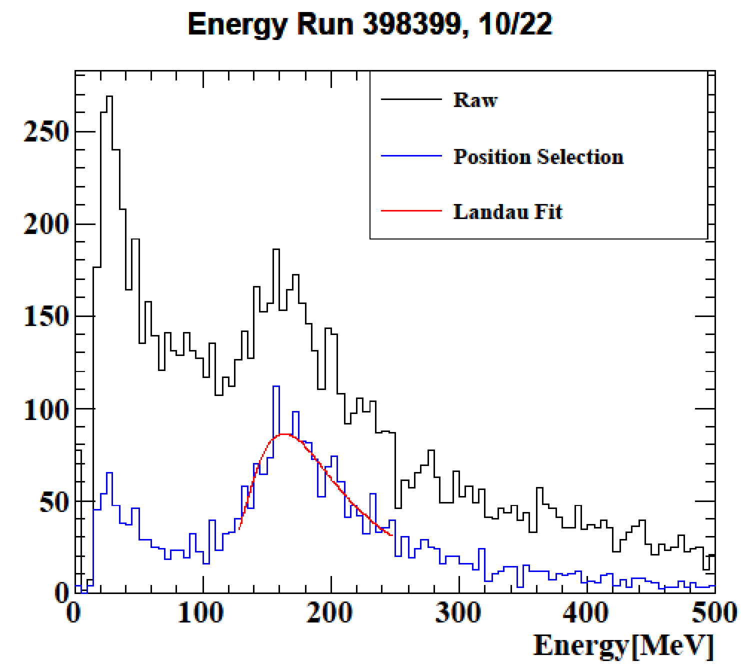




- Photosensor performance was frequently monitored with intrinsic calibration sources (LED and Am source).
- Radiation damage during 2021 run:
  - PMT gain: 840k -> 750k (11% decrease)
  - MPPC PDE: 8.4% -> 5.6%

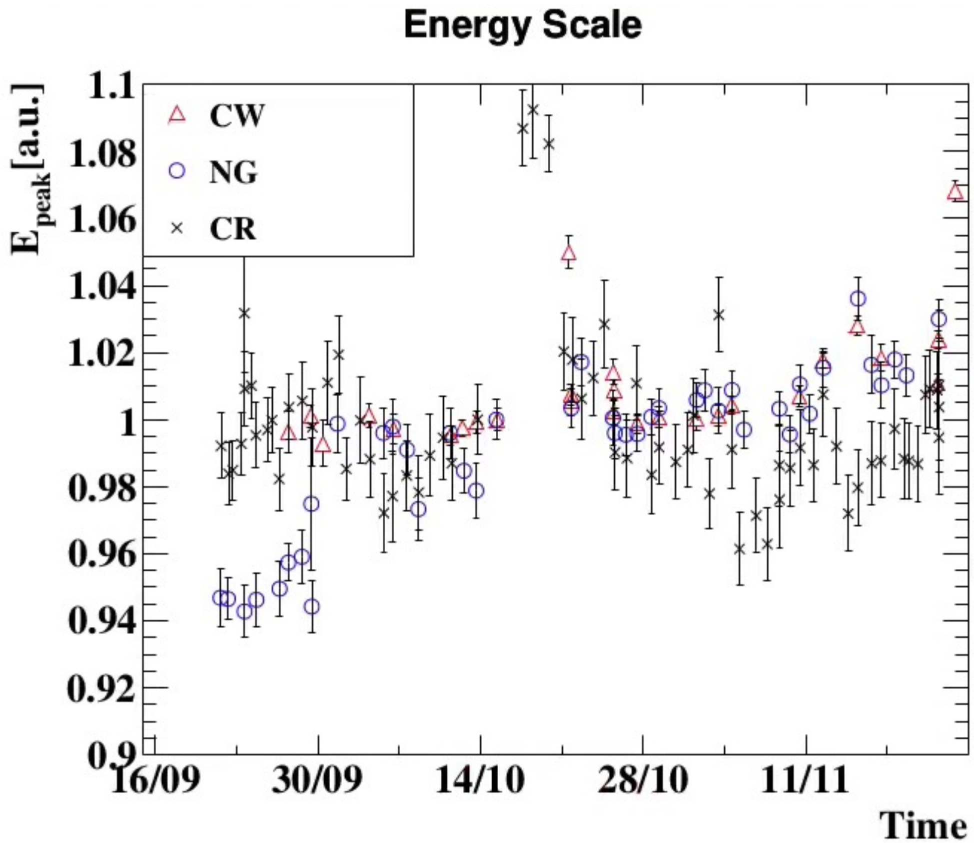
2021 RUN – Detector Response -





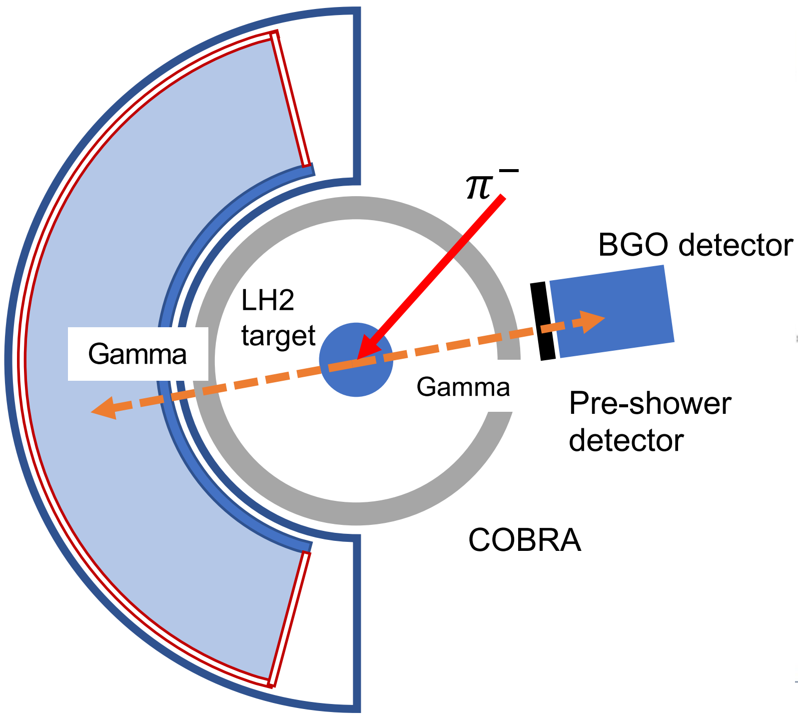
- The detector response during the beam time was monitored with
  - 9 MeV gamma-ray from thermalized neutron capture.
  - 17.6 MeV gamma-ray from
  - ~170 MeV Cosmic-ray energy peak.

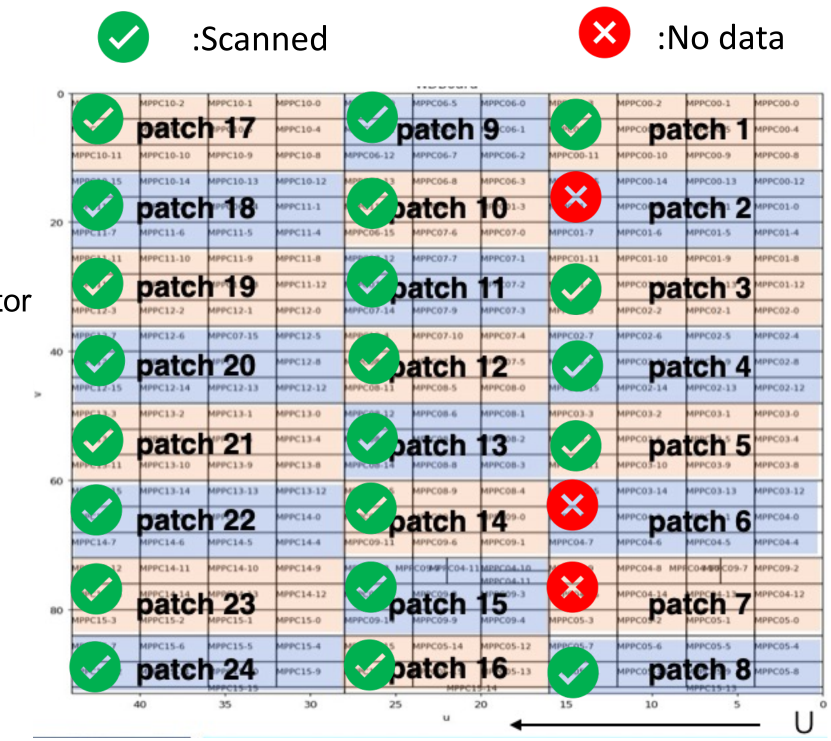
2021 RUN – Energy Scale -



- The energy scale must be measured with a better precision than the energy resolution (1.8%).

RUN2021: Charge Exchange(CEX) Measurement





- Uniformity of the energy scale and energy resolution was measured with CEX setup.
- 21 out of 24 patches are scanned by moving the BGO detector.
- The full scan over the entire detector was not completed due to the short livetime of the LH2 target.
- The analysis of the energy resolution and efficiencies are in progress.

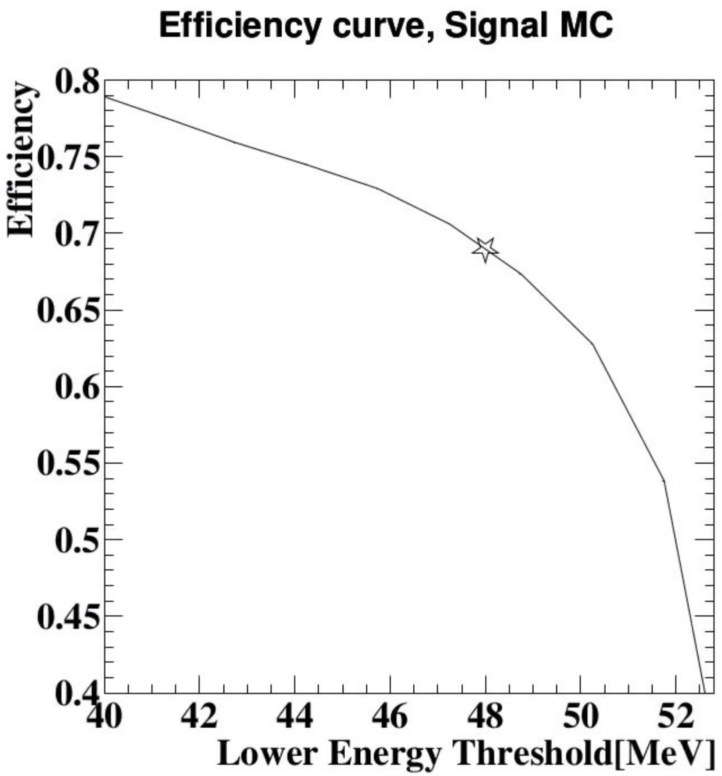
Material Budget of LH2 target

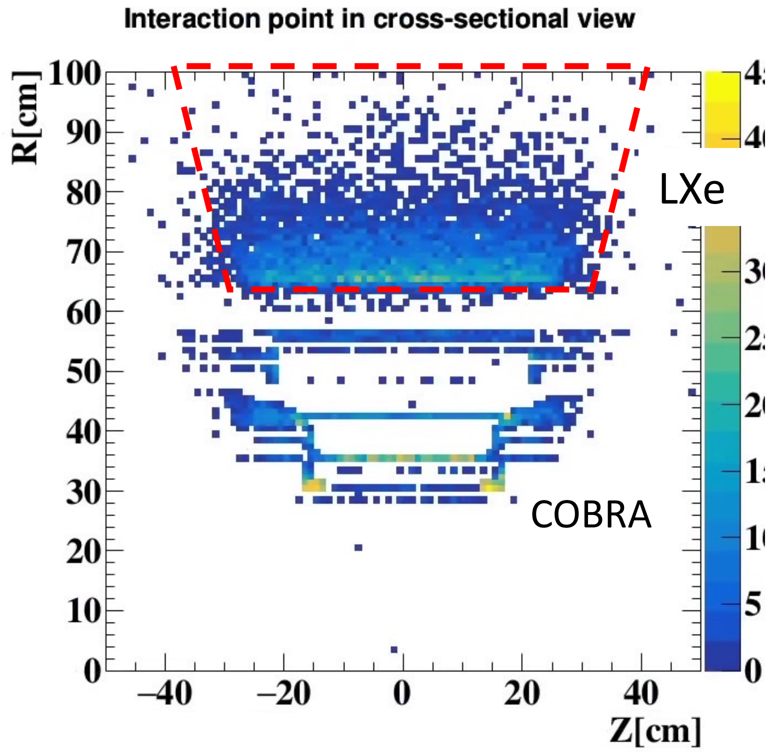
Target	Cell	Tube	transmission probability
MEG (old)	Stainless, 0.5 mm	Stainless, 1 mm	98.6% * 97.3% = 95.9%
MEG II (new)	Stainless, 0.5 mm	Stainless, 3 mm	98.6% * 92.0% = **90.7%**
Current gem4	Al, 1 mm	Stainless, 0.5 mm	99.4% * 98.6% = **98.0%**

Based on the info. by Angela.

- Material budget of LH2 target can explain the discrepancy of efficiency curve.
  - **7.5%** between MC and MEG II target.
- This doesn’t affect the efficiency of signal gamma.
  - Only CEX measurement is affected.

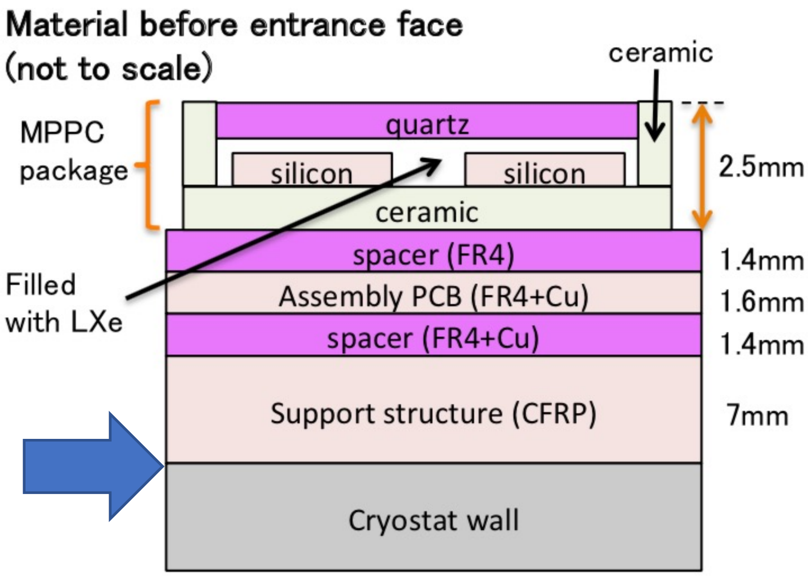
Efficiency for signal gamma

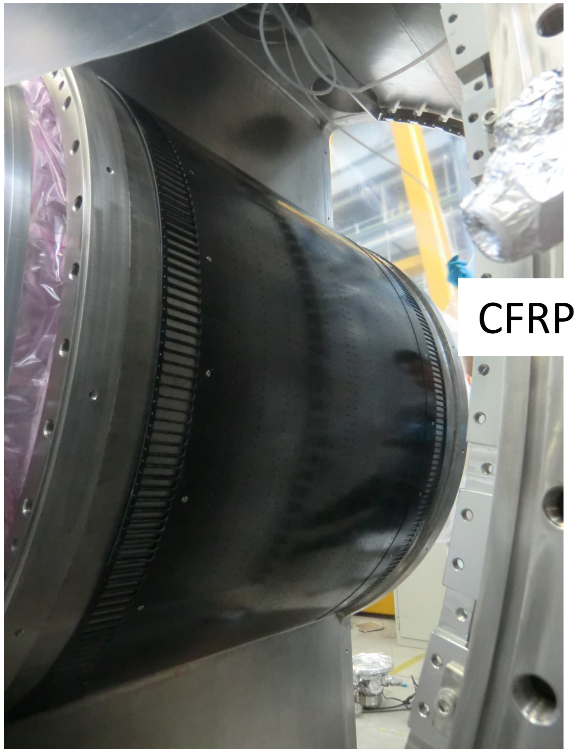




- Efficiency for nominal acceptance: 69% in MC
  - 48 MeV, |u| < 25 cm, |v| < 69.3 cm
  - Same value as the design paper.
- Efficiency in data: 69% * 98%(LXe) * 94 $\pm$ 1% (energy response + unknown) = 64 $\pm$ 1%.
  - The final efficiency value depends on the definition of the acceptance.

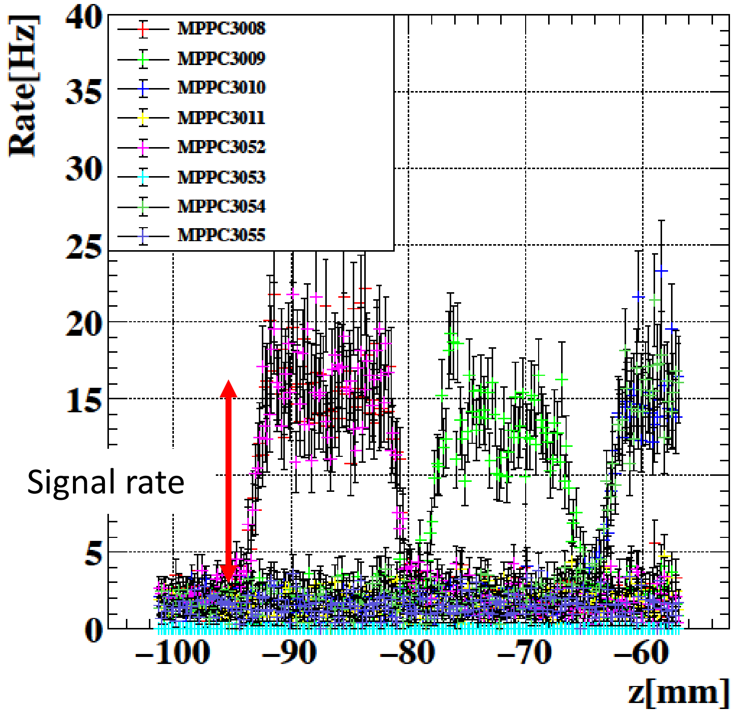
LXe Volume before MPPC

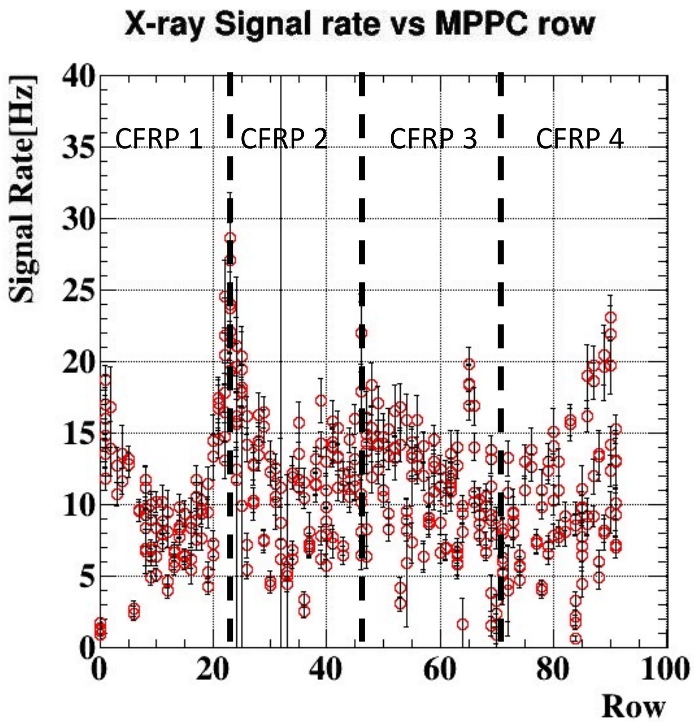




- LXe is filling the gap in the MPPC support structure.
  - Gap between CFRP and the cryostat wall.
  - The curvature of CFRP is not completely the same as the cryostat wall.
  - Thickness is estimated with low-energy gamma-ray.

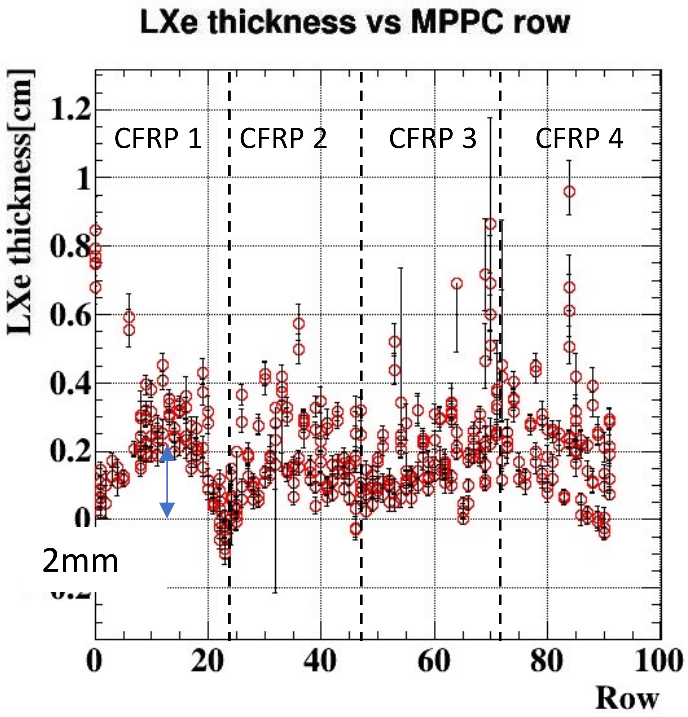
LXe Volume before MPPC

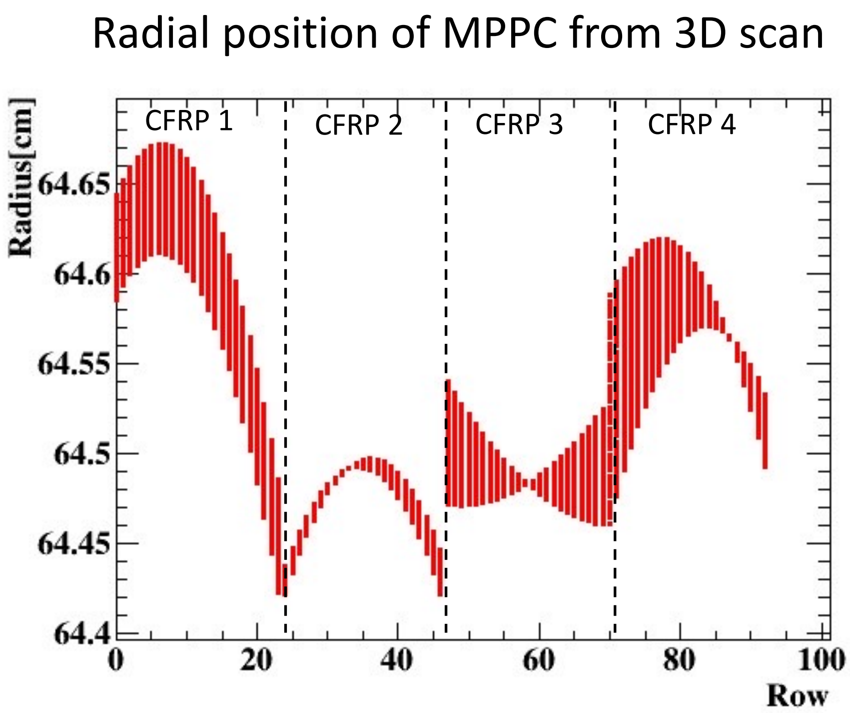




- We “reused” MPPC alignment measurement in 2018:
  - Scan 124 keV gamma-ray beam over the entrance face.
  - Low-energy → sensitive to LXe thickness.
- Signal rate has a large position dependence derived from thickness of LXe volume.

LXe Volume before MPPC





- Position dependence of signal rate is translated to LXe thickness.
  - Normalized at the edge of CFRP.
- LXe thickness is ~2 mm at the middle of CFRP.
  - The average thickness is 1 mm (0.036 X_0) ~ 1.8 % inefficiency
- The measured radius by 3D laser scanner at room temperature has a similar trend.
  - Direct comparison is difficult because of thermal contraction.