実測のガンマ線検出器性能に基づいた MEG II実験物理探索感度

MEG II physics sensitivity based on measured gamma-ray detector performances

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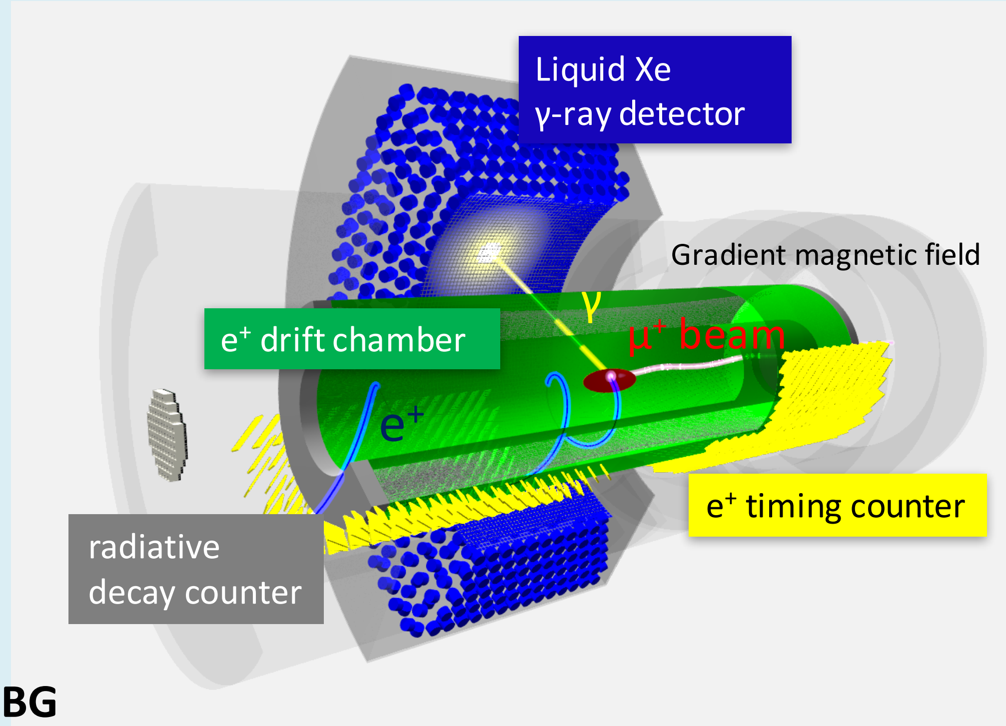
MEG II experiment

Upgrade of MEG experiment

- Searches for a charge lepton flacor violation, $\mu \rightarrow e\gamma$.
- Aiming to improve the branching ratio sensitivity by one order of magnitude.
- Dominant BG : accidental BG



- **More statistics**
  - x2.3 muon beam rate
  - x2 positron efficiency
- **Better separation of signal event from BG**
  - x2 for all detector resolutions
  - New detector for background tagging will be introduced

Engineering run from 2021

- Followed by the physics data taking.

Reference :
"The design of the MEG II experiment", Eur. Phys. J. C (2018) 78:38

MEG II sensitivity at design

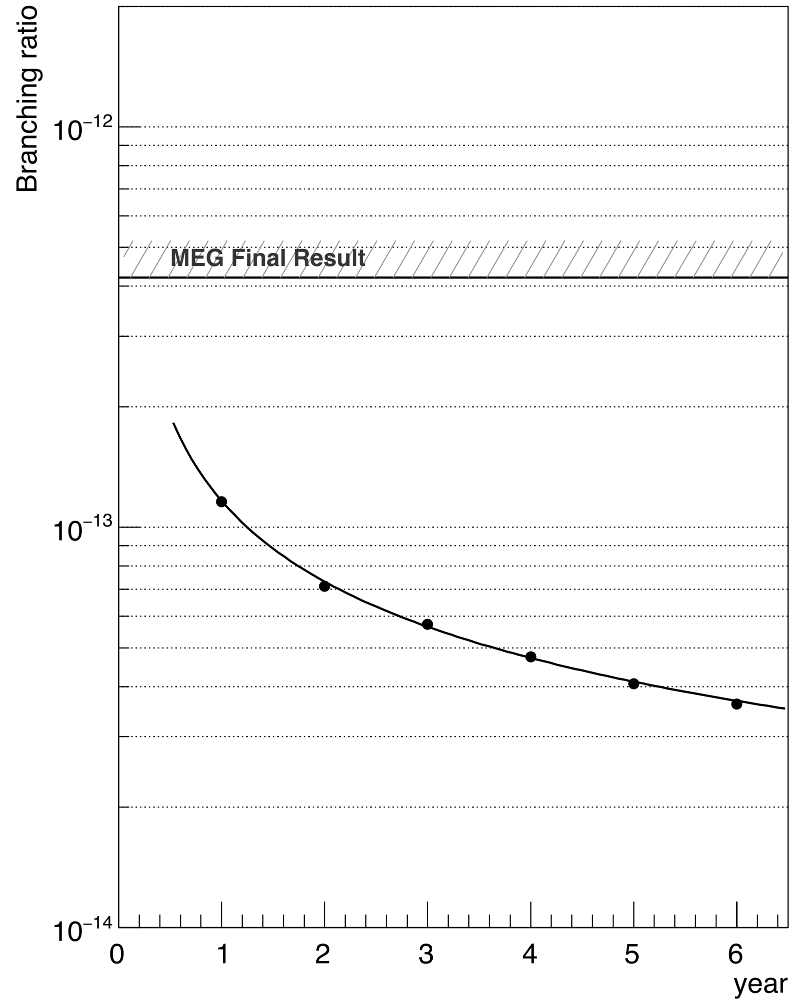
- Expected branching ratio sensitivity of MEG II is being updated.

- Performance of each detector is a key in the search of $\mu \rightarrow e\gamma$.
  - Radiative decay counter: prev. talk
  - LXe γ-ray detector: **this talk**
  - Positron spectrometer: next talk

- By the 3 years MEG II DAQ, $Br(\mu \rightarrow e\gamma) = 5.6 \times 10^{-14}\ (90\%\ C.L.)$ was expected assuming the LXe detector performances in design.
  - after the update of RDC analysis in previous talk.

MEG II sensitivity vs. DAQ year

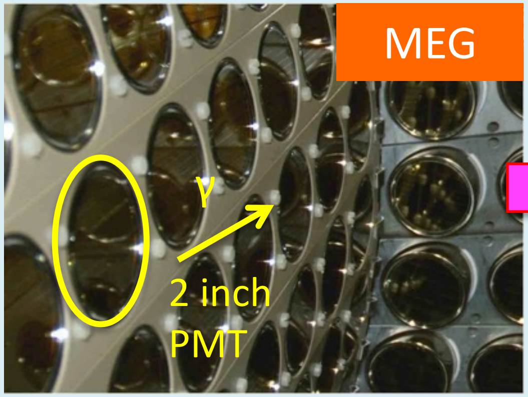
with LXe detector performance in design

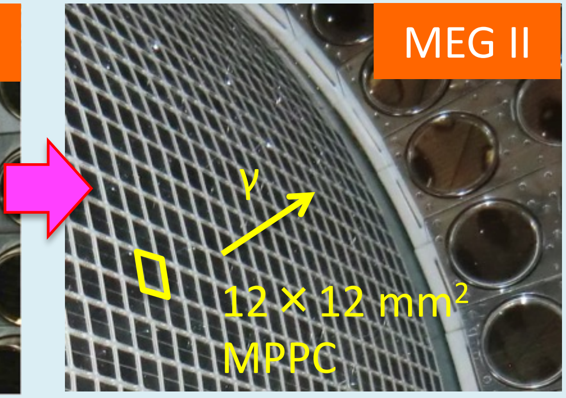


LXe detector in MEG II

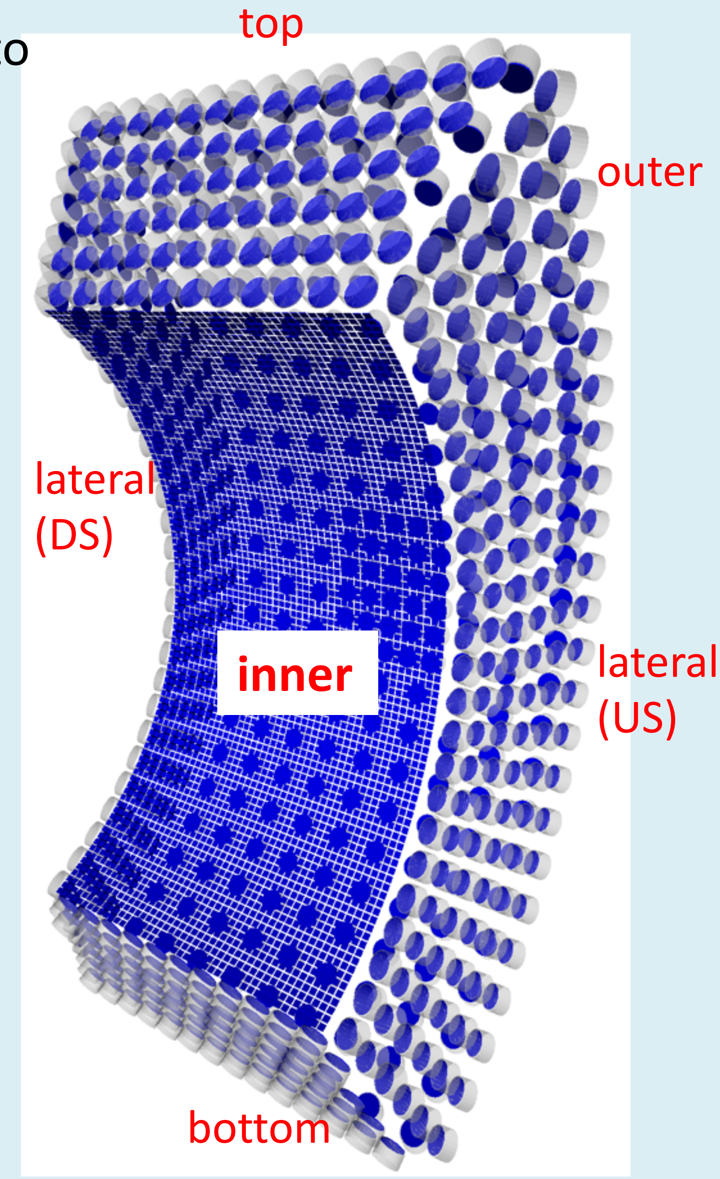
- LXe γ-ray detector has been upgraded for MEG II to significantly improve the performance.

Replace 216 PMTs on the entrance face with 4092 newly developed VUV-MPPCs





216 2-inch PMTs **4092 12 × 12 mm² MPPCs**



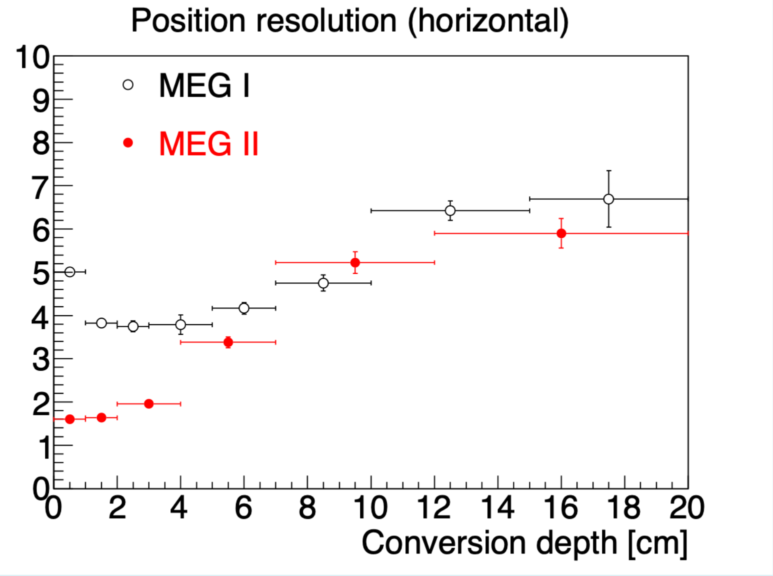
- Better readout granularity
  → better hit position resolution.
- Better readout uniformity
  → better energy resolution
- Reduced material budget of entrance face
  → better detection efficiency

LXe detector in MEG II (cont'd)

- Thanks to the high granularity and uniformity realized by the MPPCs, better position and energy resolution are expected.
  - Especially for shallow events (depth < 2cm, ~40% of events.)

	MEG (measured)	MEG II (design)
position resolution $(u/v/w)$(mm)	5/5/6	2.6/2.2/5
energy resolution (%)($w < 2$ cm$/w > 2$ cm)	2.4/1.8	1.1/1.0
timing resolution (ps)	62	76
efficiency (%)	63	69

- A series of pilot runs were performed in 2017-2019 to evaluate the performance.



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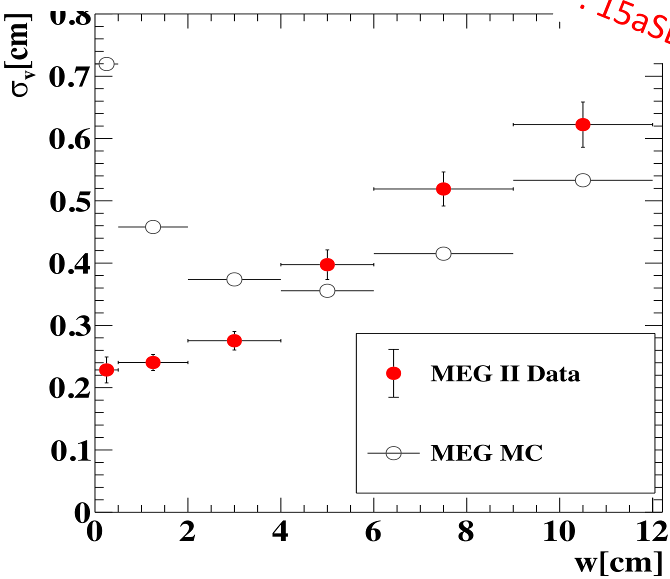
Resolution improvement for shallow events

- Thanks to the better granularity and the uniformity by the MPPCs, position and energy resolution for shallow events are improved from MEG.

Position resolution vs depth

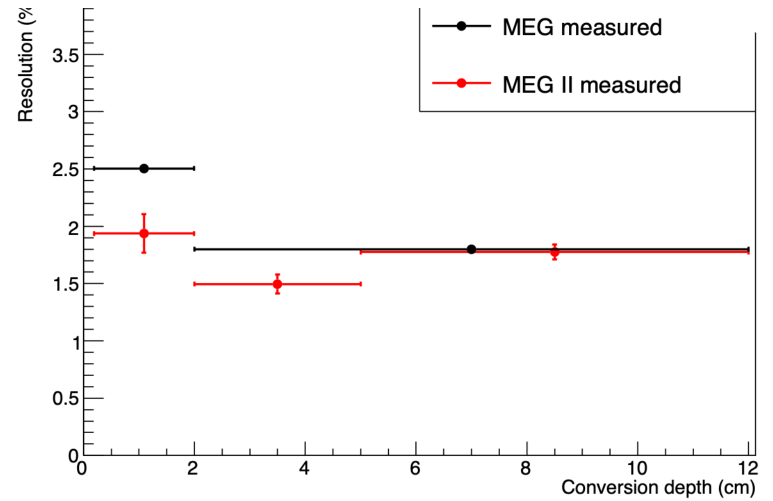
talk at this JPS : 15aSE-9



measured from a reconstructed position distribution by a collimator placed in front of the detector

Energy resolution (for 53MeV γ) vs depth

Ref: 15aK210-1, 15aK210-2 in 74th JPS

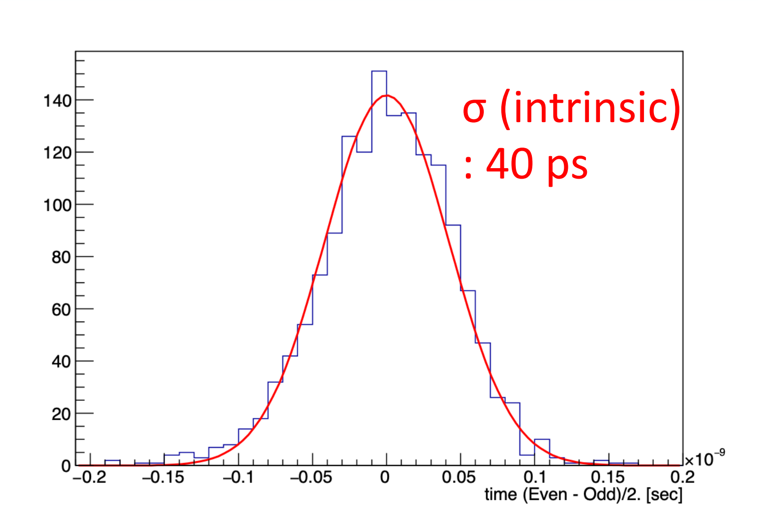


estimated by fitting the γ-ray spectrum from muon beam (radiative muon decay & annihilation of Michel positron)

Timing resolution improvement

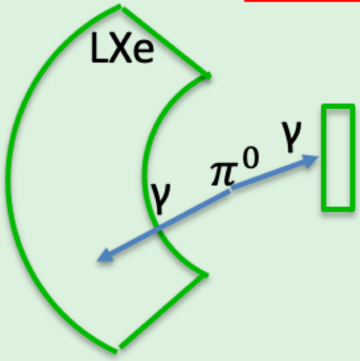
Ref:
25aK206-1 in 73th JPS

- Though the timing resolution have not been directly measured, a dominant term (called "intrinsic resolution") is measured.
- Thanks to the optimized parameter for the reconstruction, the intrinsic resolution is improved from 56 ps to 40 ps.
  - threshold optimization for the timing extraction from the waveforms.



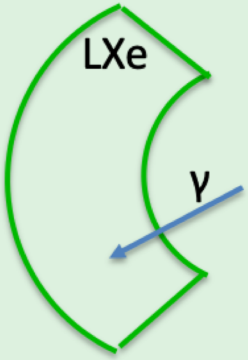
- The timing resolution is expected to be 55 ps.

Absolute resolution



- Use coincident 2γ & reference counter.
- $\sigma(T_\gamma) =$ $\sigma(T_\gamma - T_{ref}) \ominus \sigma(T_{ref})$

Intrinsic resolution



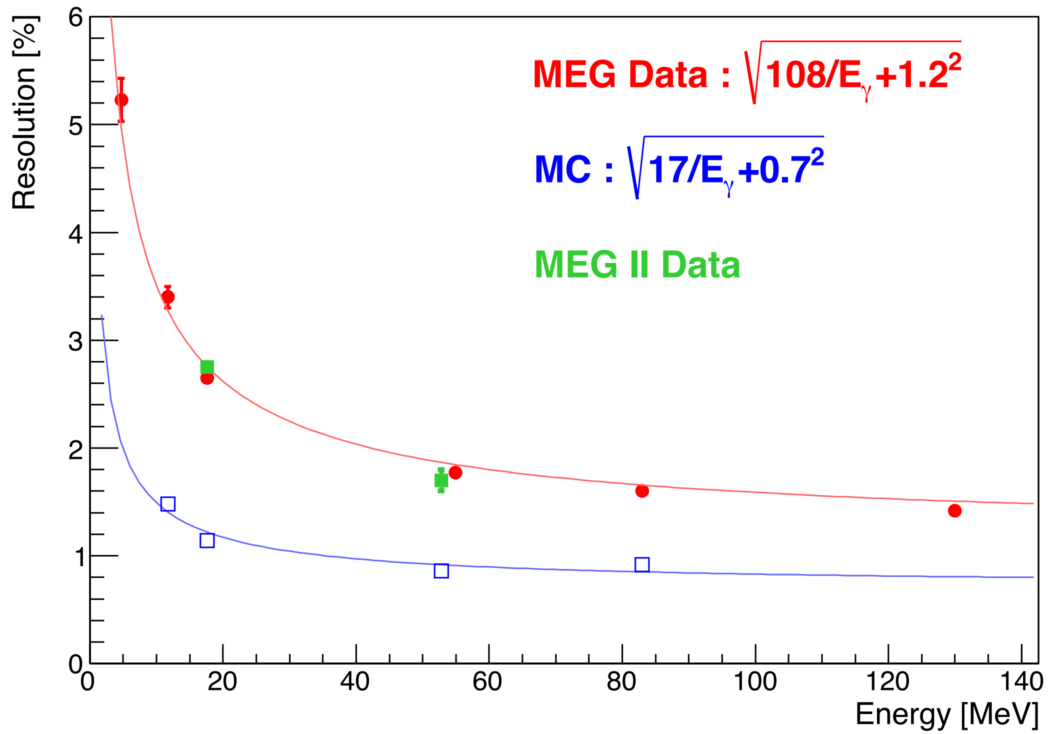
- Reconstruct γ timing from even/odd ch separately.
- $\sigma(T_\gamma) =$ $\sigma(T_{EVEN} - T_{odd})/2$

unknown term in γ energy resolution

- Measured energy resolutions are worse than expectation from the simulation.
- The discrepancy called "unknown term" between data and MC was also known in the MEG LXe detector.
- The size of unknown term is the same between MEG and MEG II.
- Should be caused by the same reason, but not identified yet.
  - common issue on our detector?
  - some intrinsic property of LXe?
- The unknown term was expected to be halved in the design.
  → Measured energy resolution is worse than the design.

Energy resolution of LXe detector vs. γ-ray energy

for the deep events not affected by the non-uniformity in MEG



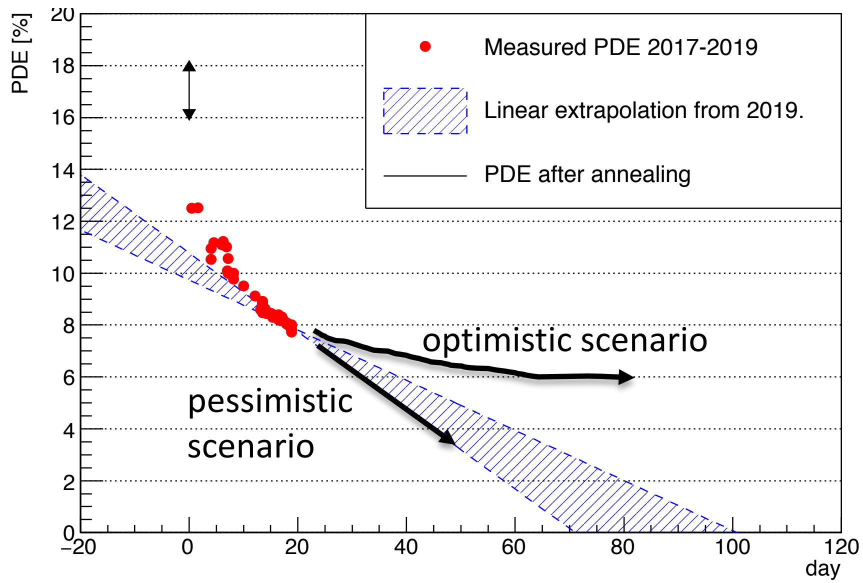
MPPC PDE degradation

Ref:
16pG22-11, 16pG22-12,
17aG22-7 in 75th JPS

- A degradation of VUV PDE while using MEG II muon beam was observed.
  - Since it is correlated with a beam usage, this should be due to some radiation damage.
- This was unexpected since the radiation level is sufficiently small.
  - O(1e-2) γ-ray dose, O(10e6) neutron/cm^2 fluence.
- The cause of the degradation is under investigation. (talk at this JPS: 15pSF-5)
  - Maybe related to a special detection mechanism of VUV photon in our MPPC.
- The degradation can be almost fully recovered by annealing MPPCs.

- The degradation speed is too fast to be ignored.
  - Optimistic case
    PDE degradation saturated at some point (e.g. 6%)
  - Pessimistic case:
    PDE gets zero after 70 days MEG II data taking.

VUV PDE of MPPC
vs. accumulated MEG II beam time



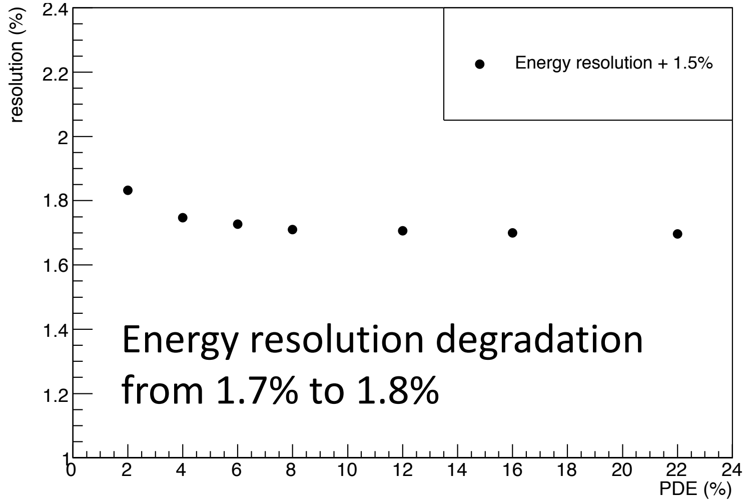
γ-ray resolution vs. MPPC PDE

Ref:
16pG22-11 in 75th JPS

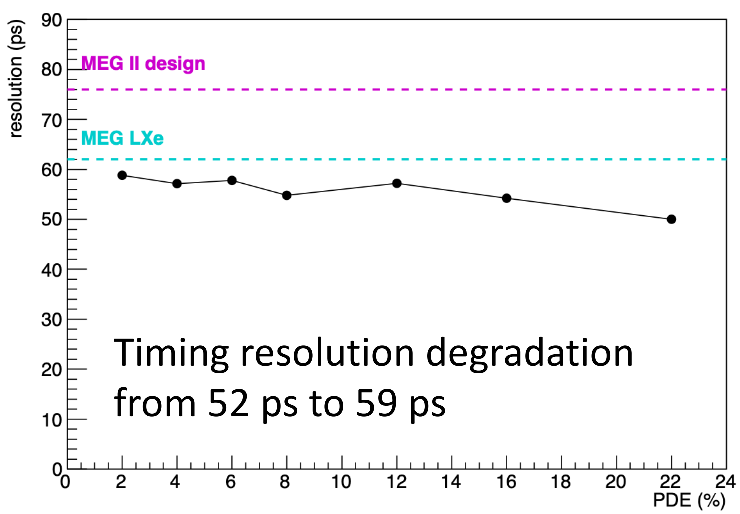
- The γ-ray resolutions can get worse than the above measurement (at PDE 7-8%) when the MPPC PDE gets lower.
  - Larger statistical fluctuation & Worse signal to noise ratio.
- In principle, the resolution degradation should be limited because
  - the statistical fluctuation of the MPPCs is not a dominant contribution in the resolution.
  - the signal to noise ratio can be recovered by utilizing an amplifier since the dominant noise comes from waveform digitizer after amplification.

Simulated energy resolution vs PDE

including measured unknown term

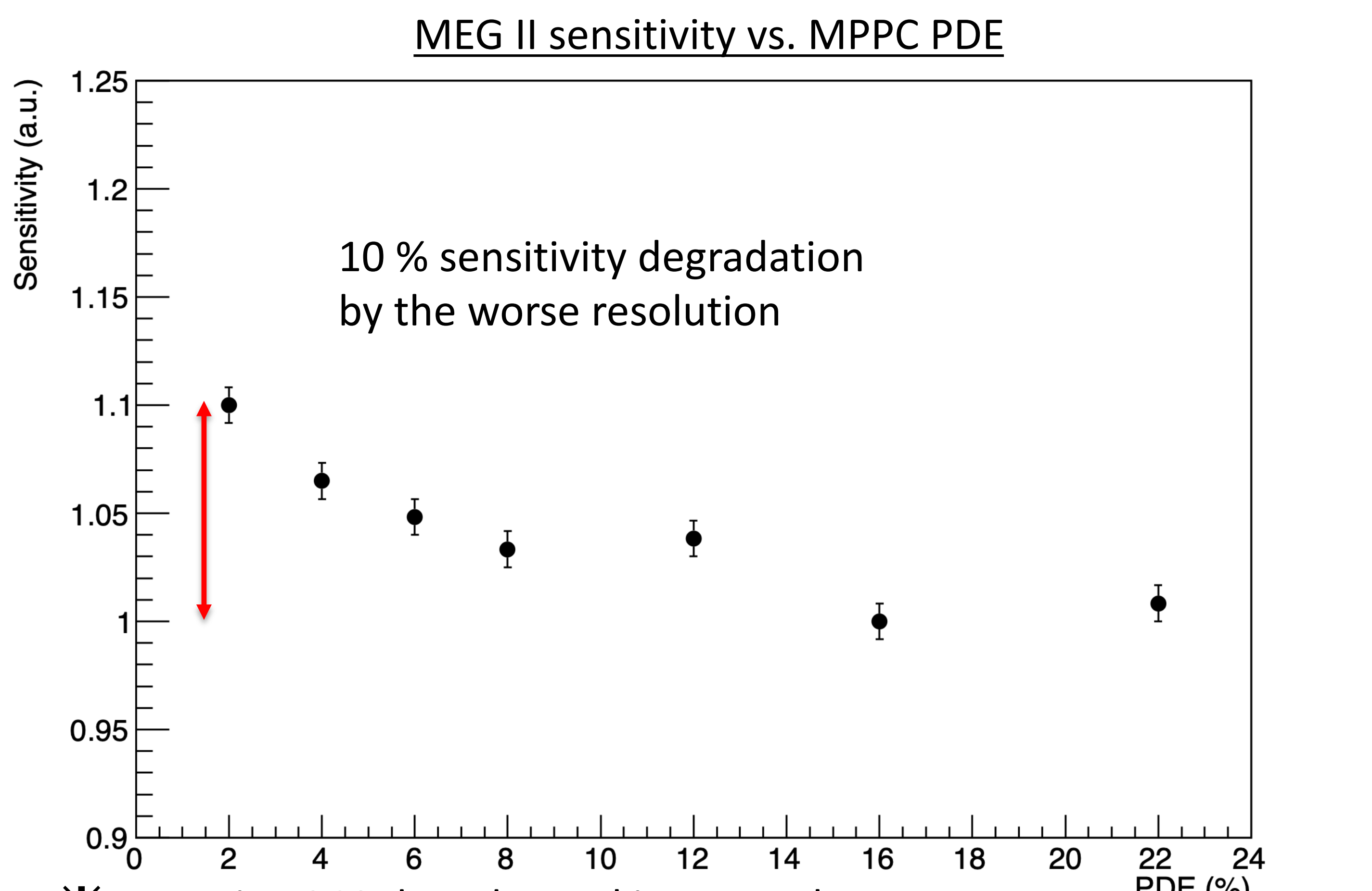


Simulated timing resolution vs PDE



γ-ray resolution vs. MPPC PDE (cont'd)

- The degradation of the MEG II sensitivity by that of the γ-ray resolution from that of the MPPC PDE is limited.



※ assuming 360 days data-taking at each PDE

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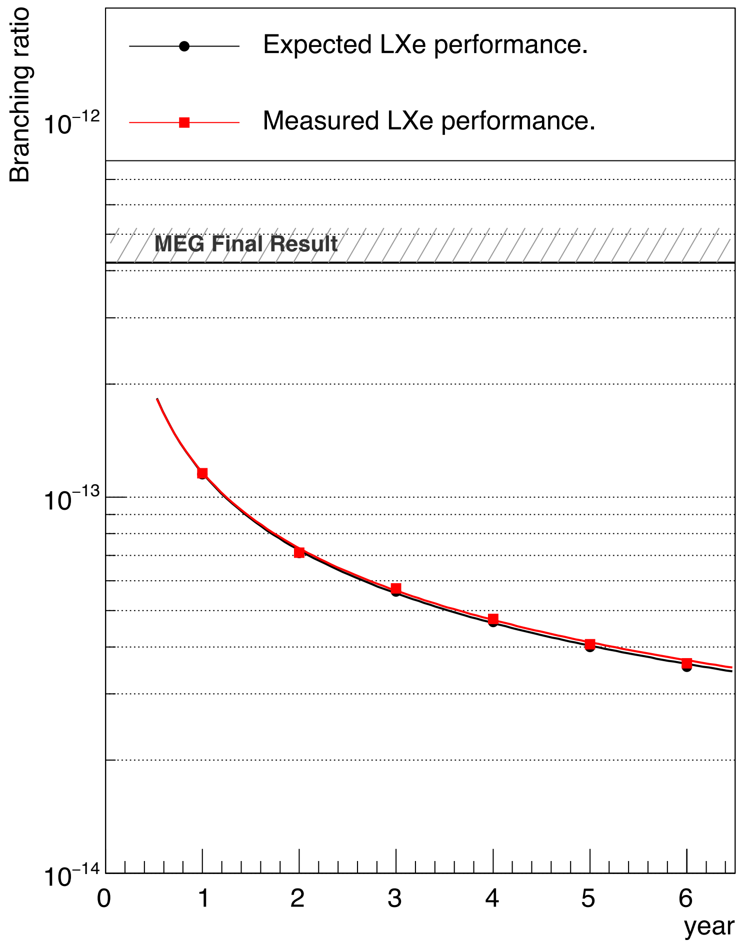
MEG II sensitivity -optimistic scenario-

- If the PDE degradation is saturated at 6%, little effect on the sensitivity from the PDE degradation.

- Expected MEG II sensitivity with measured LXe detector performance in the pilot runs.
  - By the 3 years MEG II DAQ, $Br(\mu \rightarrow e\gamma) = 5.6 \times 10^{-14}$ $(90\%\ C.L.)$
  - A degradation by worse energy resolution and an improvement by better timing resolution are compensating.
  - Part of the degradation from the worse energy resolution is also compensated by the RDC (prev. talk).

MEG II sensitivity vs. DAQ year

with measured LXe detector performance



MEG II sensitivity -pessimistic scenario-

The data-taking plan of MEG II has to be modified.

- PDE gets below 2% after 60 days MEG II beam usage.
- We can anneal all the MPPCs
  during the annual accelerator shutdown period (Jan-May).
- Original MEG II plan (120 days beam time/year x 3 years) is not possible.

- If we simply carry out 60 days DAQ at MEG II beam intensity for each year,
  by the 3 years MEG II DAQ,
  - $Br(\mu \to e\gamma) = 9.7 \times 10^{-14}$ (90% $C.L.$)

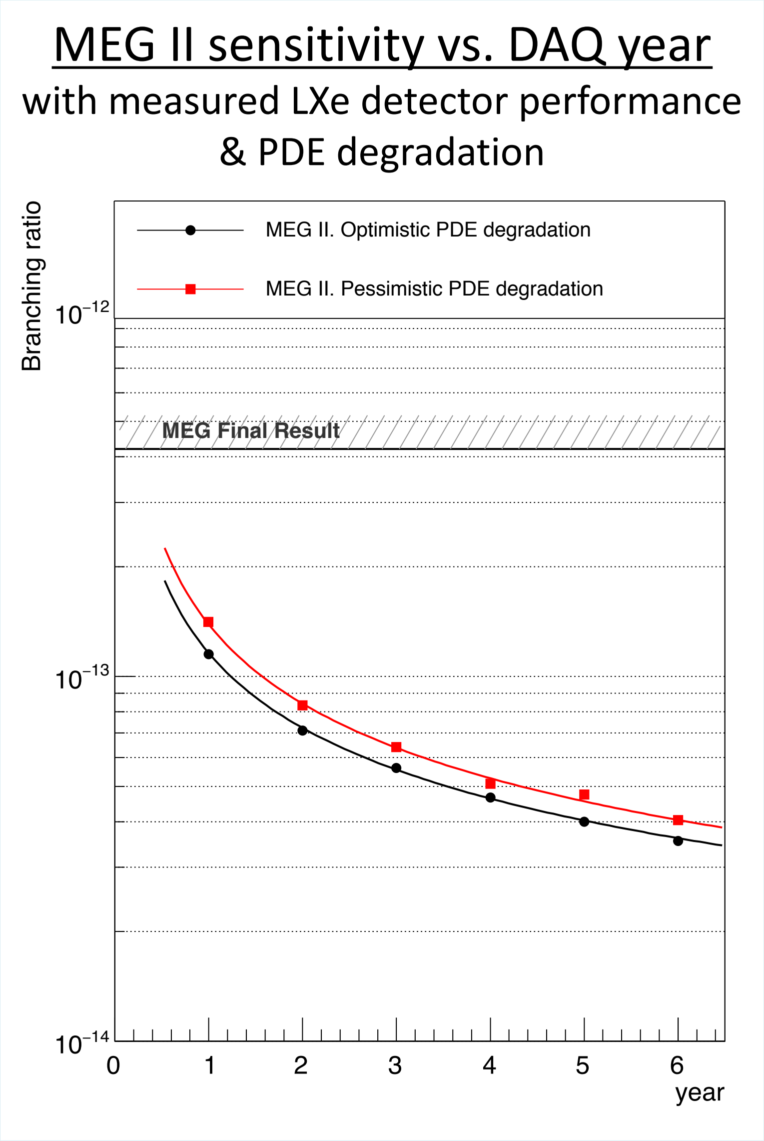
- The degradation can be suppressed by reducing the beam rate so that we can keep our detector operating for the 120 days beam time.
  - $Br(\mu \to e\gamma) = 6.4 \times 10^{-14}$ (90% $C.L.$)
  - Thanks to the better significance ($N_{SIG}/\sqrt{N_{BG}}$)
    and the better pileup environments.

Conclusion

- The MEG II sensitivity achievable with the real LXe detector performance is discussed.
  - Measured γ-ray resolution in the pilot run.
  - MPPC PDE degradation by beam usage.

- Reducing the beam rate will be useful if the PDE cannot be kept at the MEG II intensity beam.

- By the 3 years MEG II DAQ, $Br(\mu \to e\gamma) = 5.6\text{–}6.4 \times 10^{-14}\ (90\%\ C.L.)$ is expected.
- The uncertainty comes from that of the PDE degradation speed in the future.

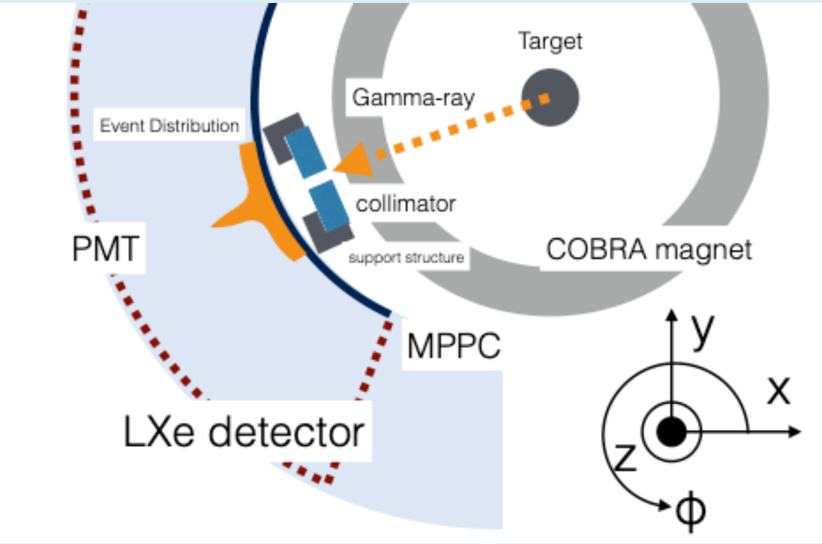


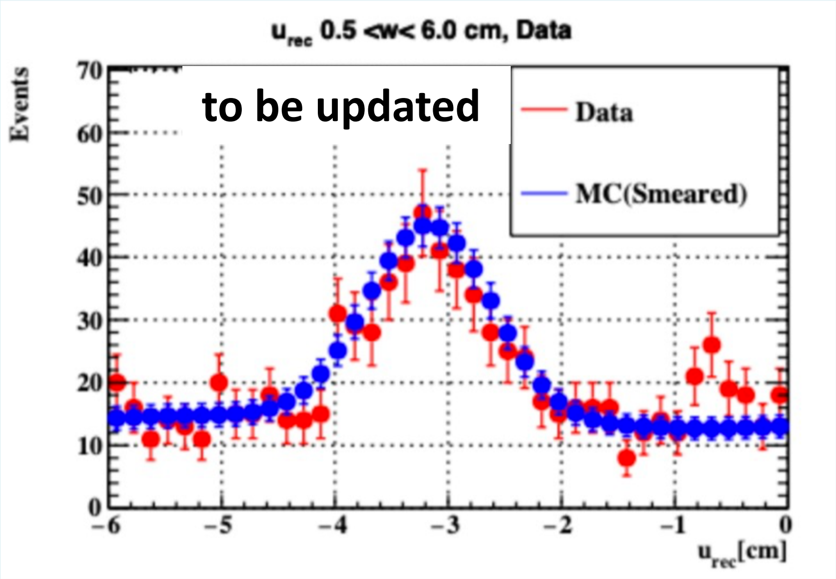
BACKUP

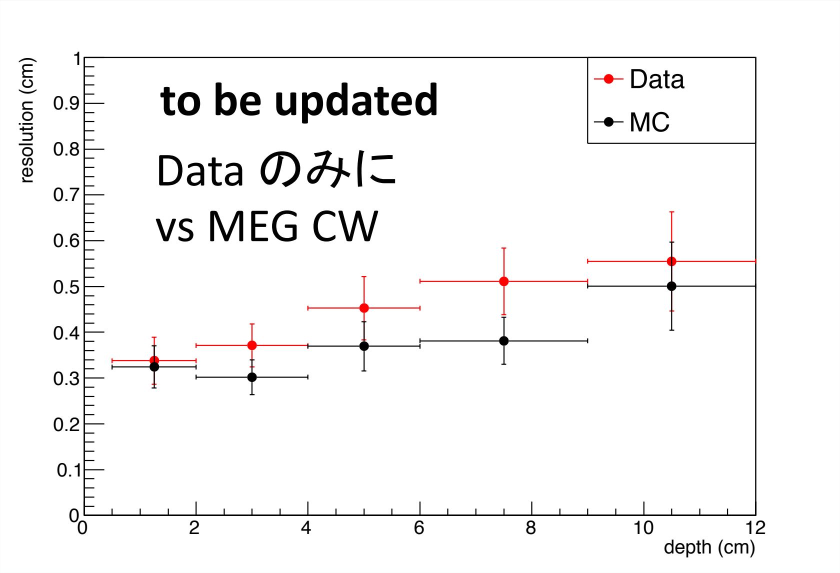
γ-ray position resolution

talk at this JPS
: 15aSE-9

- The hit position resolution was measured.
- A lead collimator was placed in front of the detector.
- The resolution is estimated from the peak width of the reconstructed position distribution.
- **Resolution improvement for the shallow events confirmed.**





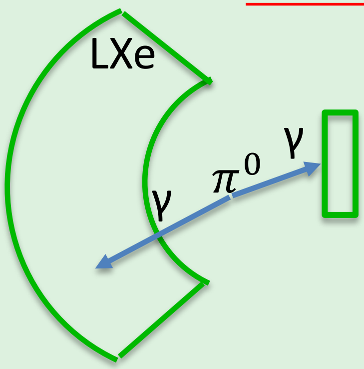


γ-ray timing resolution

Ref:
25aK206-1 in 73th JPS

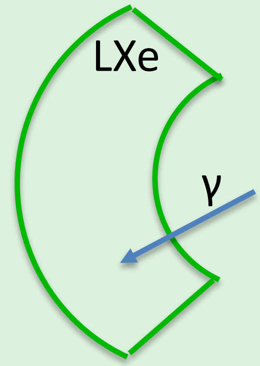
- The "intrinsic" timing resolution is estimated by an even-odd analysis.
  - Signal-like energy γ-rays from radiative muon decays are used.

Absolute resolution



- Use coincident 2γ & reference counter.
- $\sigma(T_\gamma) = \sigma(T_\gamma - T_{ref}) \ominus \sigma(T_{ref})$

Intrinsic resolution



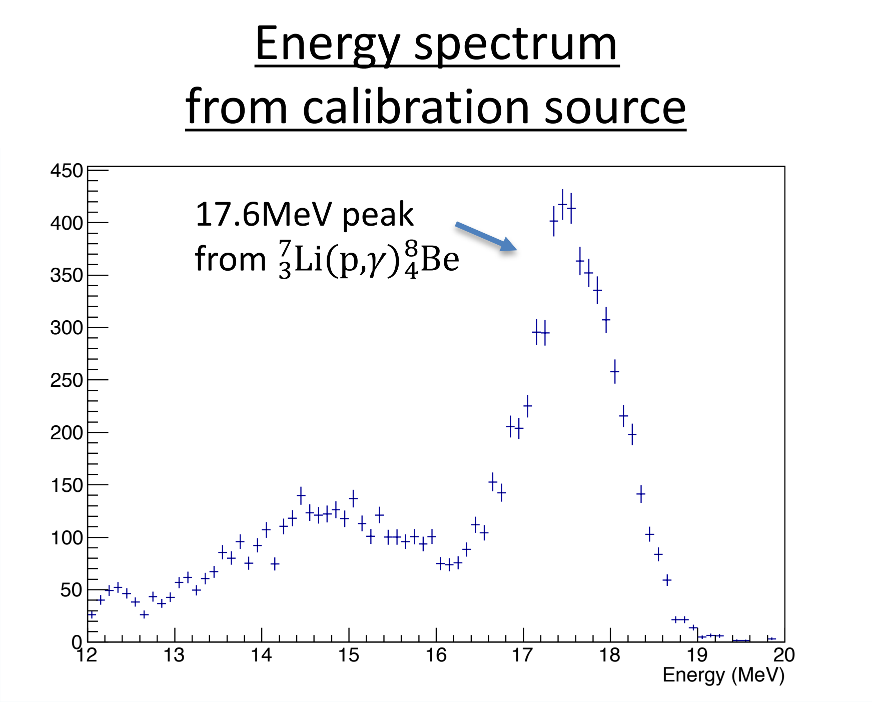
- Reconstruct γ timing from even/odd ch separately.
- $\sigma(T_\gamma) = \sigma(T_{EVEN} - T_{odd})/2$

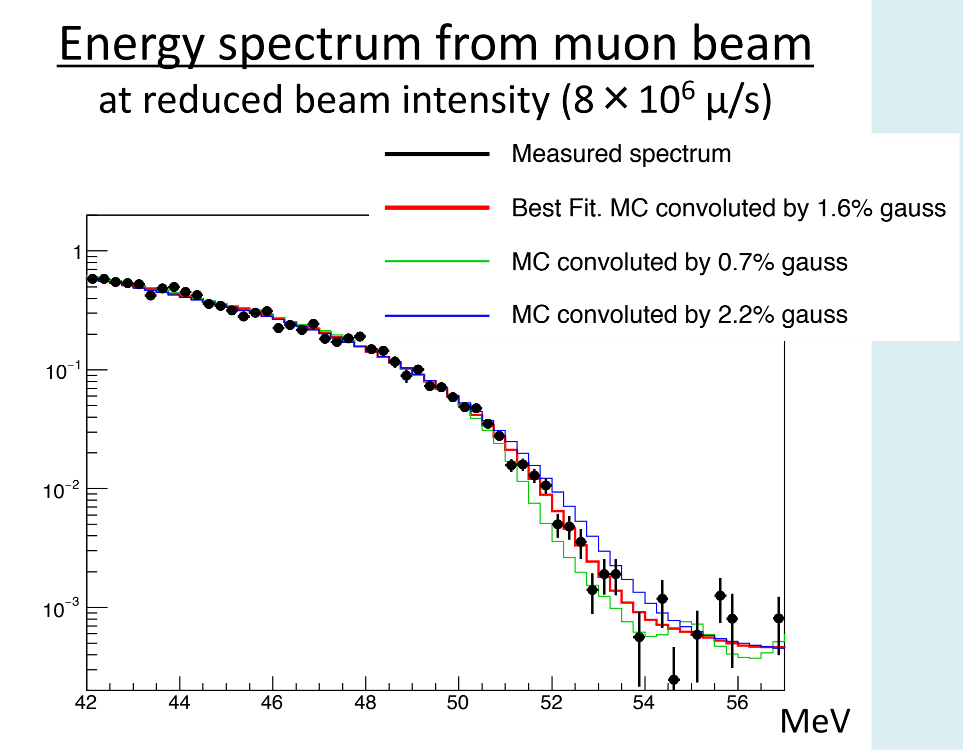
- **The intrinsic resolution is measured to be 40 ps.**
  - consistent with 43 ps expected from the simulation.
- The "intrinsic" resolution is a part of the "absolute" resolution which is directly related to the $\mu \to e\gamma$ search.
  - TOF uncertainty from the hit position resolution, coherent noise etc..
- **The absolute resolution is estimated to be 55 ps** from the simulation.
  - This is better than 76 ps assumed in design, mainly due to a threshold optimization used for the timing extraction from the waveforms.

γ-ray energy resolution

Ref:
15aK210-1, 15aK210-2
in 74th JPS

- The γ-ray energy resolution is estimated.
- **3.1(1) % for 17.6MeV γ-ray** by using monochromatic γ from ${}^7_3\mathrm{Li}(\mathrm{p},\gamma){}^8_4\mathrm{Be}$.
- **1.7(1) % for 52.8MeV (signal-like) γ-ray** by fitting the measured γ-ray spectrum from the muon beam.
  - coming from radiative muon decay and annihilation of Michel positron in flight.





Data-taking time

The data-taking plan of MEG II has to be modified.

- In the worse case, PDE gets below 2% after 60 days MEG II beam usage.
- We can anneal all the MPPCs
  during the annual accelerator shutdown period (Jan-May).
- Original MEG II plan (120 days beam time/year x 3 years) is not possible.

Three alternative annual DAQ plans are compared.

- **Plan A: 60 days DAQ at MEG II beam intensity.**
- **Plan B: 120days DAQ at halved beam intensity.**
  - Pros: Better significance ($N_{SIG}/\sqrt{N_{BG}}$)
    and better pileup environment than plan A.
- **Plan C: 67 days DAQ at MEG II beam intensity + an annealing in the middle.**
  - it will take 60 days to anneal all the MPPC
    (current best estimate, may include uncertainty).
  - Pros: Larger muon statistics, and higher PDE than plan B.

Sensitivity of alternative DAQ plans

- Plan B has a best sensitivity in these alternative plans.