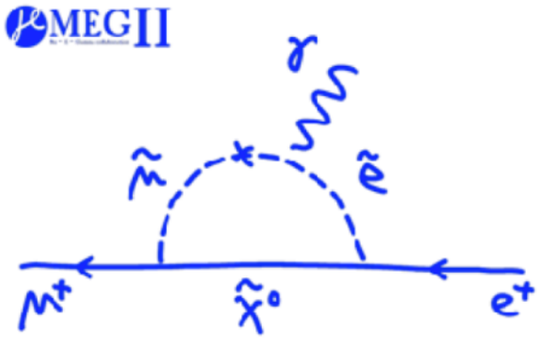
東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo



MEG II実験
run2022データを用いたレプトンフレーバーを破る
ミュー粒子崩壊 μ → eγ の探索 に向けて

Sei Ban (ICEPP), for the MEG II collaboration
17th Sep. 2024, JPS 2024年次大会 @北海道大学

Outline

Introduction : cLFV and MEG II experiment

Reconstruction of 2021+2022 data

Physics analysis of 2021+2022 data

Prospects

Summary

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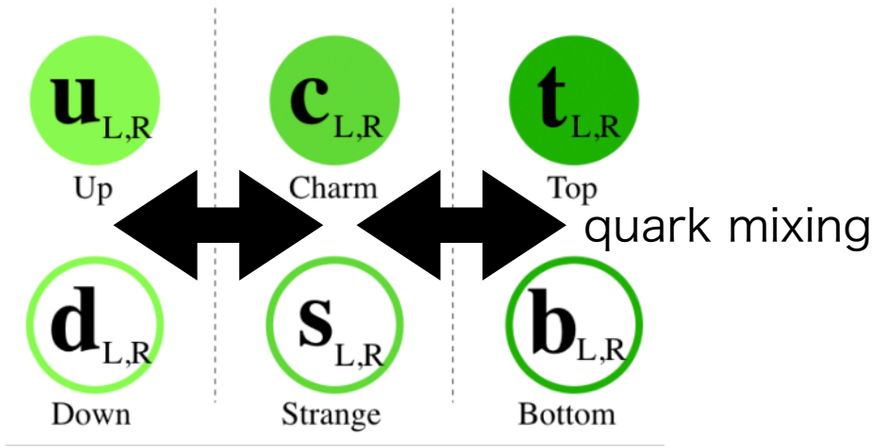
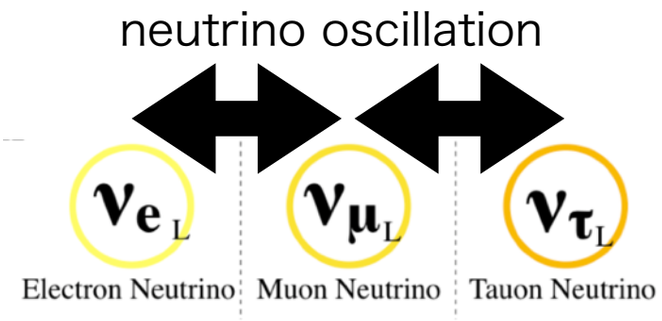
Charged Lepton Flavor Violation

- In quark and neutrino (neutral lepton) sector, the flavor violates in SM





- Some theories BSM predict flavor violation in the charged lepton sector
  - In the Standard Model (+ν osci.), it is practically prohibited : $Br(\mu \to e\gamma) = 10^{-54}$
  - In BSM, $Br(\mu \to e\gamma) \sim O(10^{-14})$ is predicted (not observed yet)

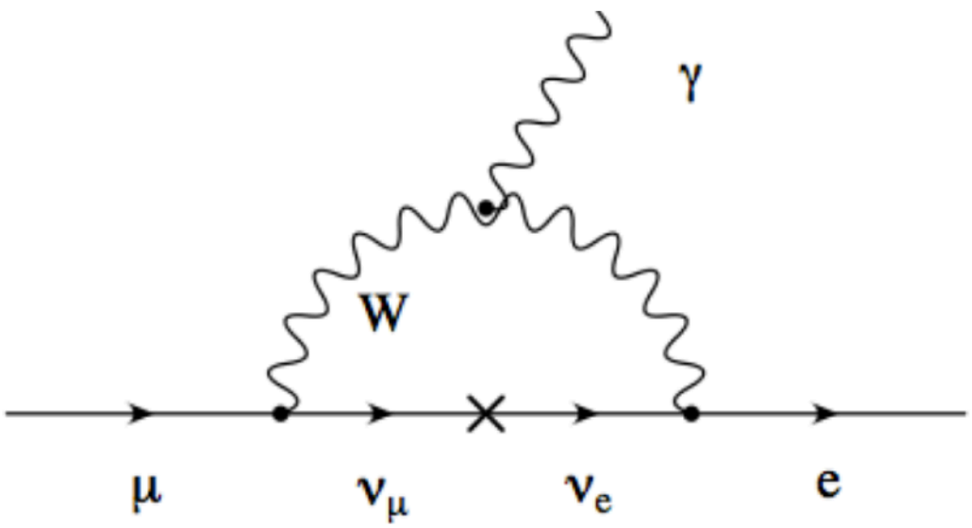
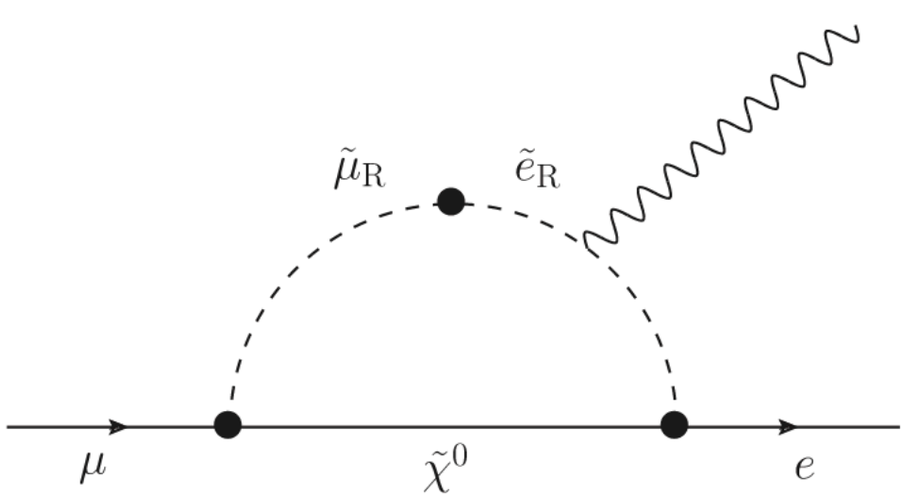


Diagram in the SM + neutrino oscillation

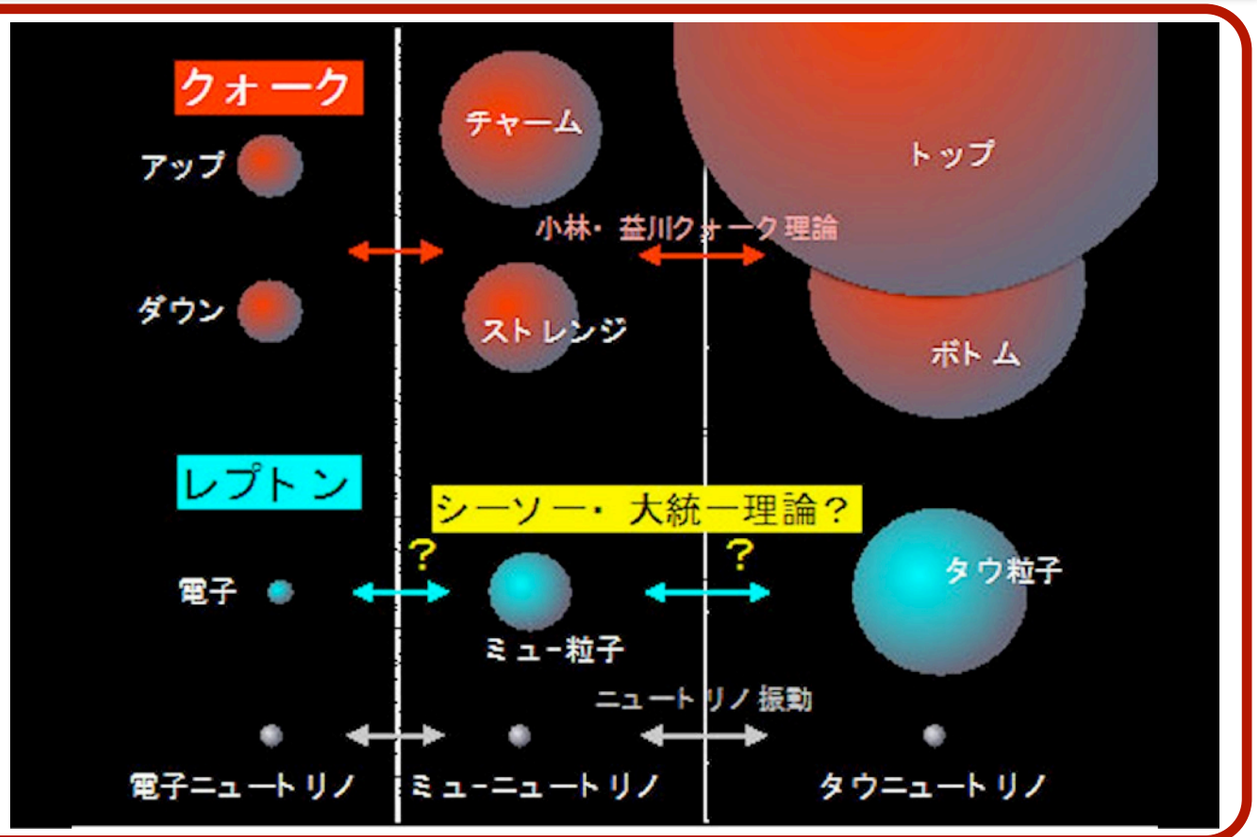


Possible diagram in SUSY-GUT senario

Charged Lepton Flavor Violation

- **Strong evidence of new physics once it observes**

- Grand Unified Theory predicts cLFV
  - SUSY-GUT, SUSY-seesaw
  - Typical prediction :
    - Br(μ→eγ) ~ O(10^{-14})
      - Can be observed realistically



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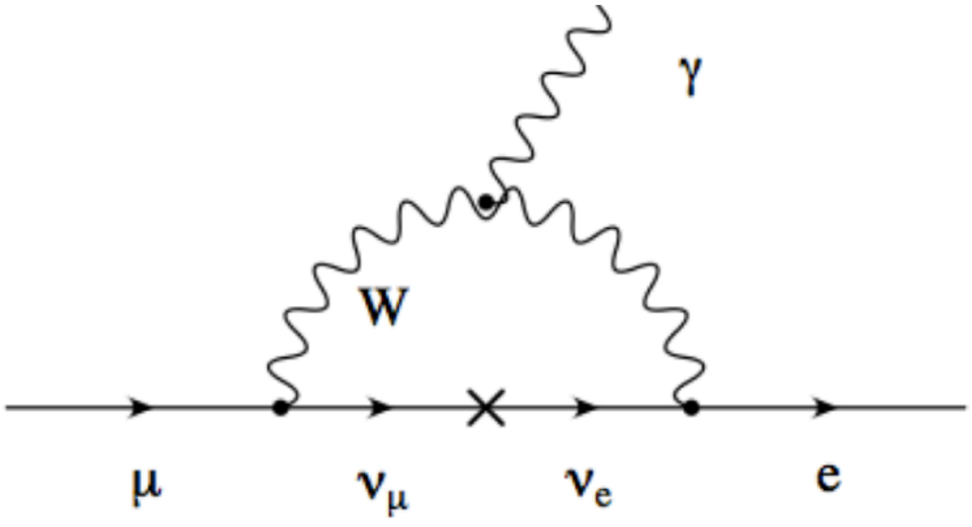
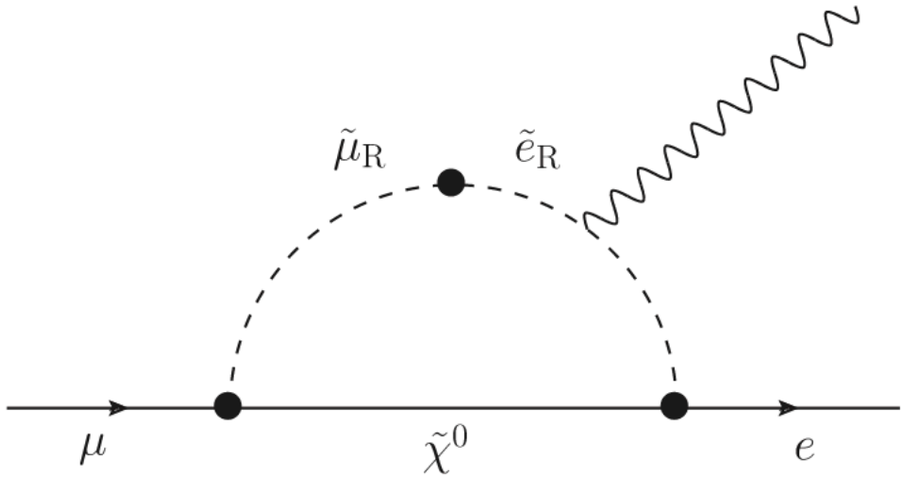


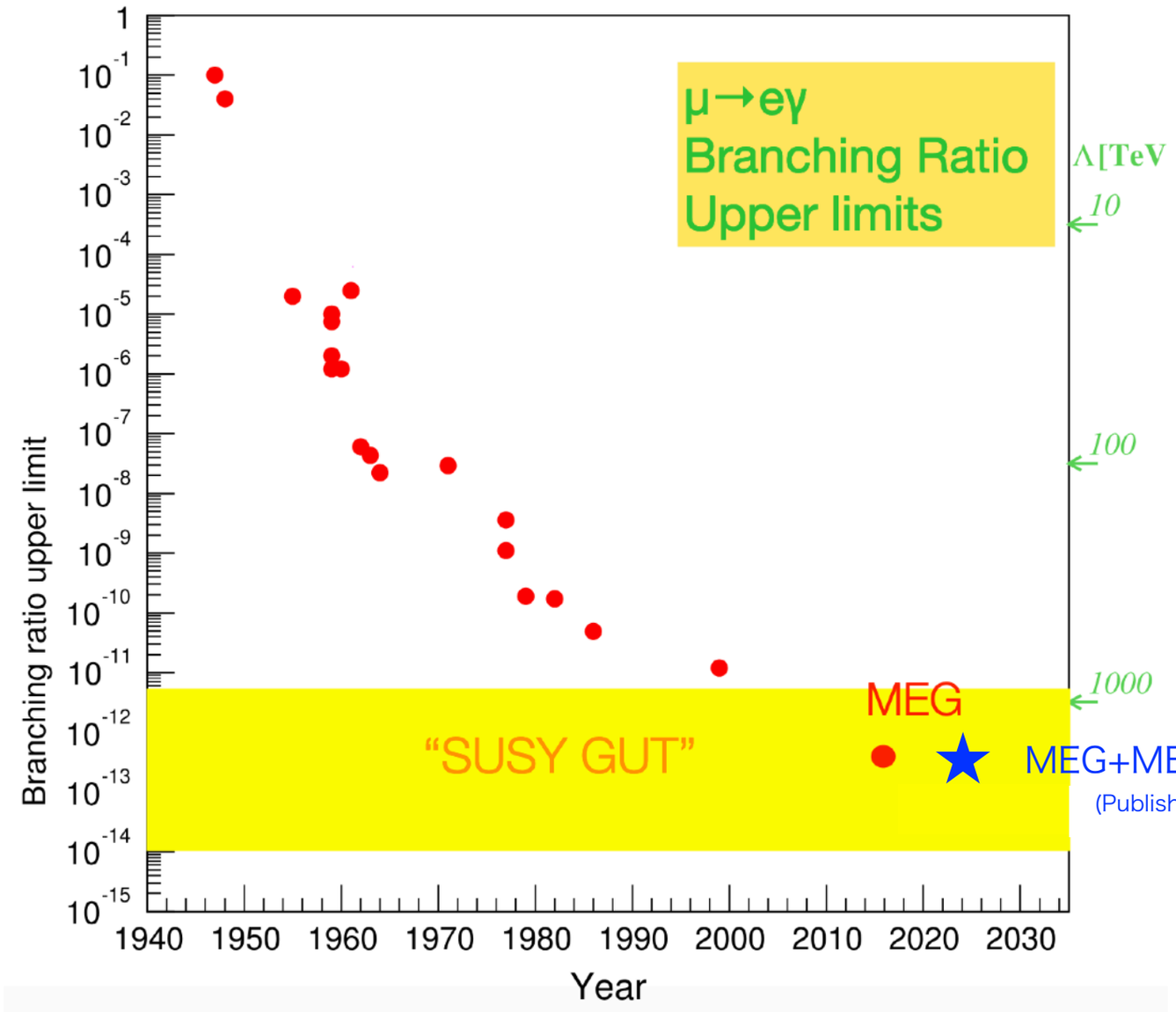
Diagram in the SM + neutrino oscillation

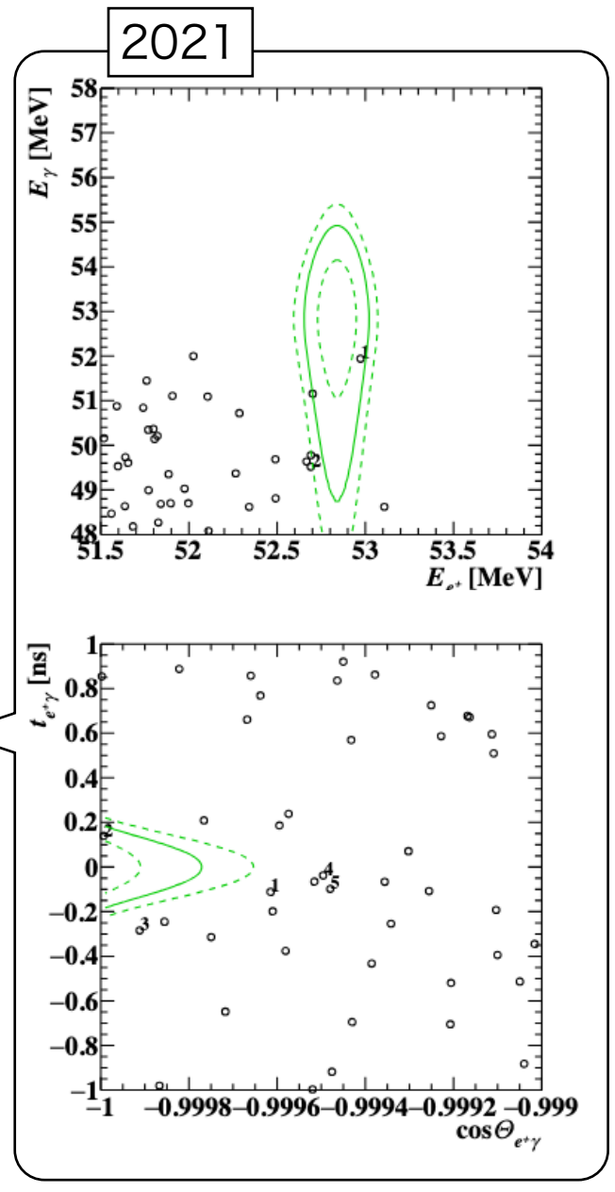


Possible diagram in SUSY-GUT senario

Current status of cLFV (and other experiments)

- Most strict limit for cLFV : Br(μ→eγ) < 3.1×10^{-13} (90% C.L.) by MEG II (+MEG)

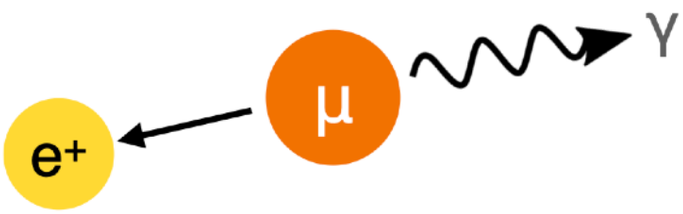




- Other channels to search for cLFV
  - $\mu^+\to e^+e^-e^+$: Mu3e
  - $\mu^-N\to e^-N$: COMET, DeeMe, Mu2e
- Still under development/preparation for physics run

MEG II experiment : signal and background

- Signal : Gamma-ray and positron with 52.8 MeV (=$m_\mu/2$)

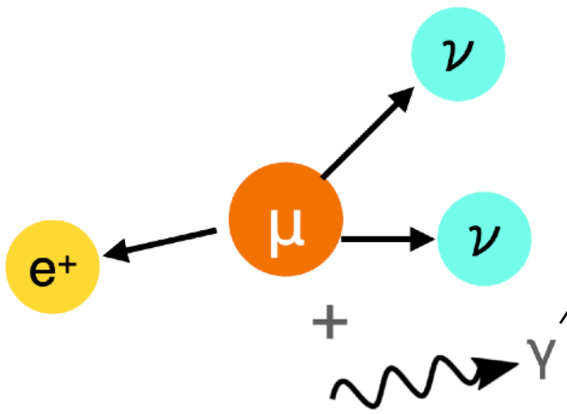


back-to-back

on-timing

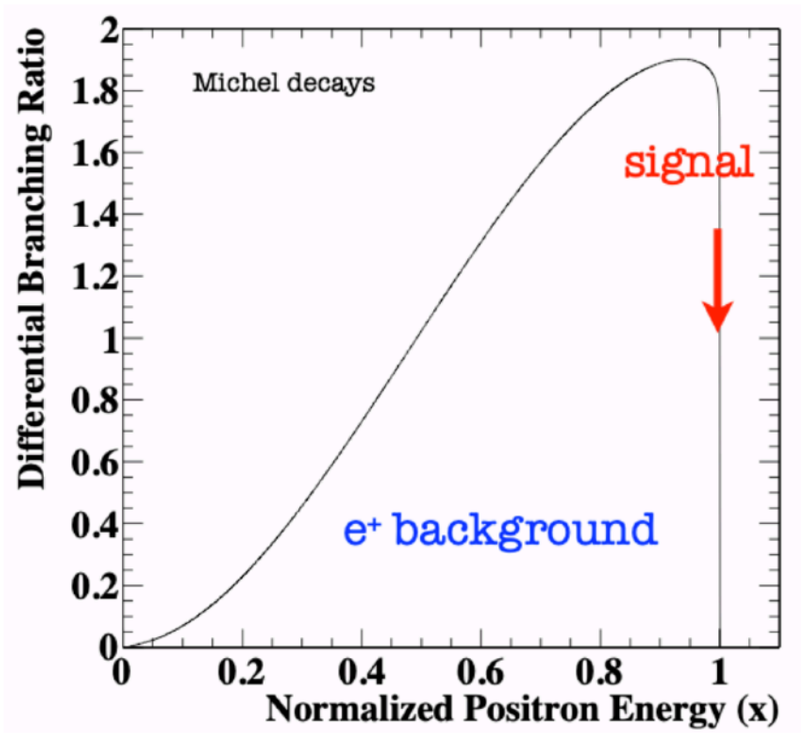
$$N_{sig} \propto R_\mu \times T \times \mathrm{Efficiency}$$

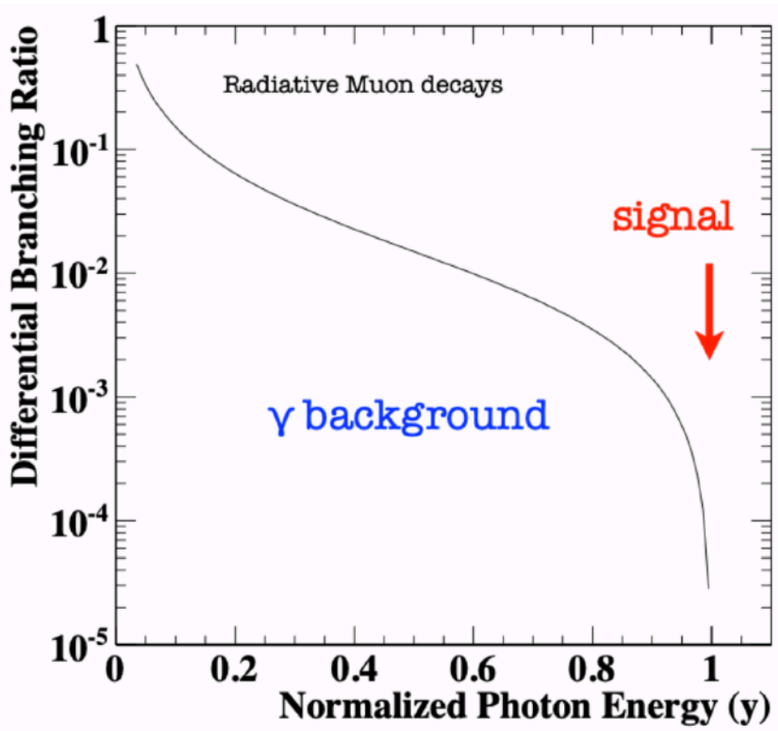
- Dominant background : Accidental coincidence of Michel positron and gamma



Gamma originated from
- Annihilation in flight
- Radiative muon decay

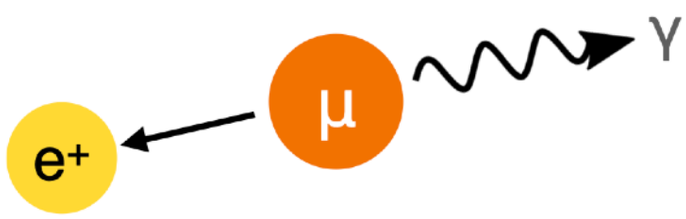
$$N_{acc} \propto \underbrace{R_\mu^2}_{\text{beam rate}} \times \underbrace{T}_{\text{time}} \times \underbrace{\Delta E_\gamma^2 \times \Delta E_e \times \Delta \Theta_{e\gamma}^2 \times \Delta T_{e\gamma}}_{\text{Resolutions}}$$





MEG II experiment : signal and background

- Signal : Gamma-ray and positron with 52.8 MeV (=$m_\mu/2$)



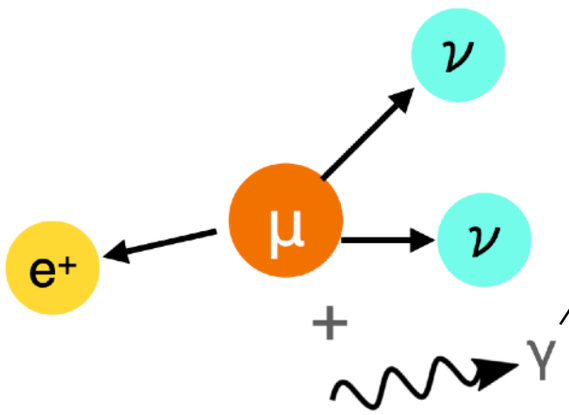
back-to-back

on-timing

$$N_{sig} \propto R_\mu \times T \times \text{Efficiency}$$

High intensity continuous beam is preferred

- Dominant backgrou positron and gamma



Gamma originated from
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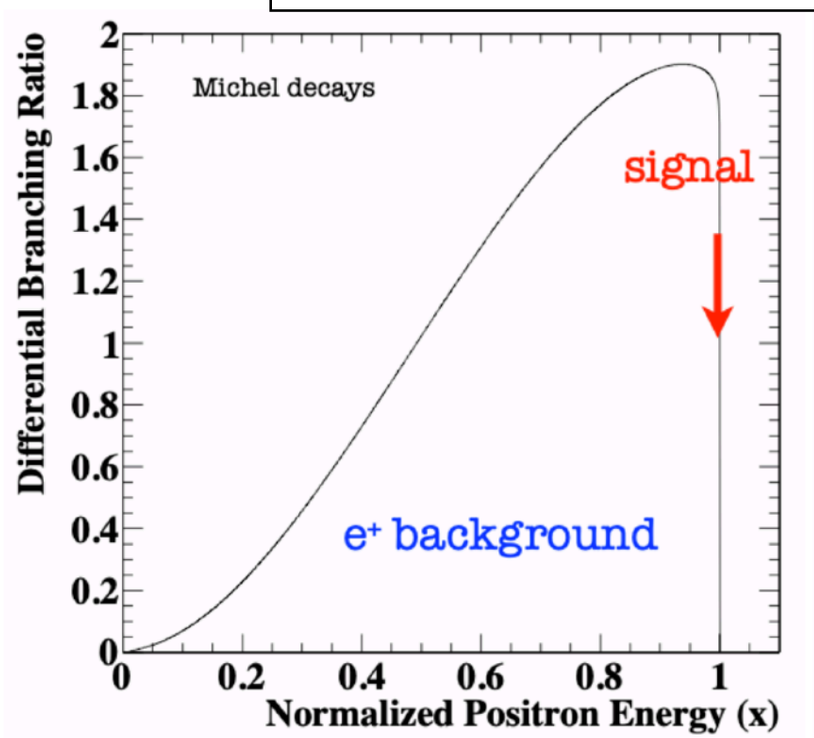
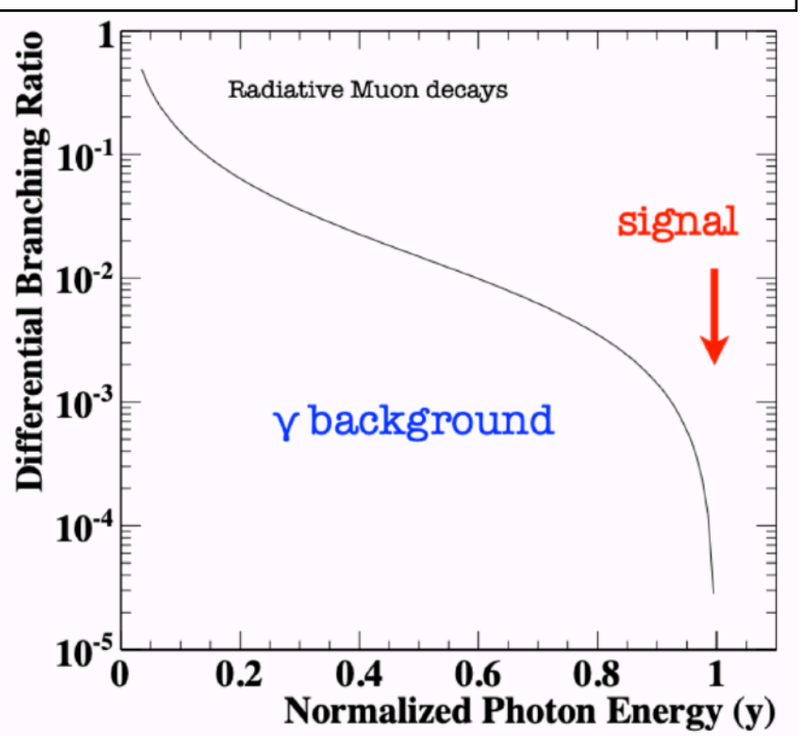
- Radiative muon decay

$$N_{acc} \propto R_\mu^2 \times T \times \Delta E_\gamma^2 \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta T_{e\gamma}$$

beam rate, time, Resolutions

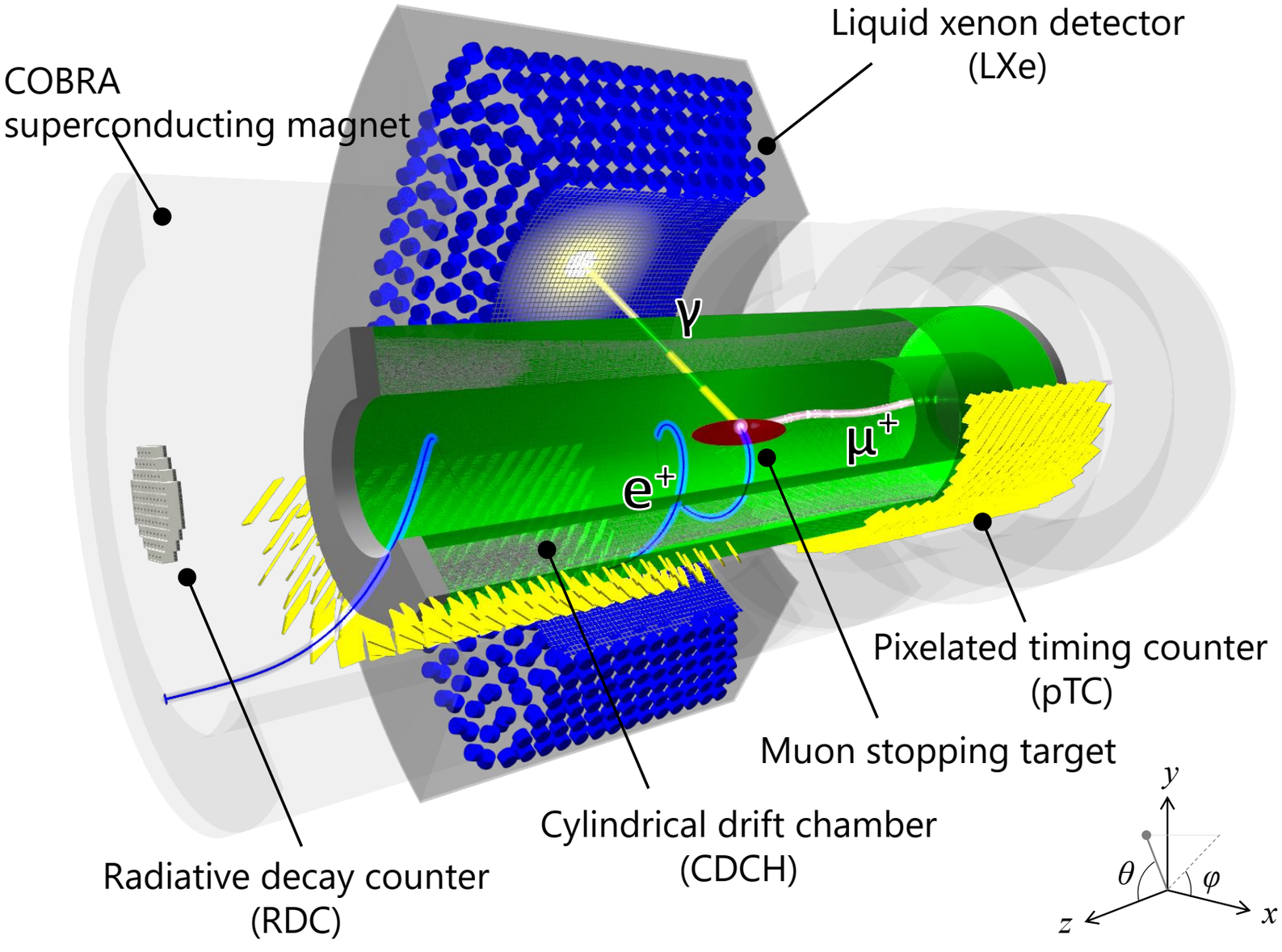
Detector with good resolutions is key to reduce BGs

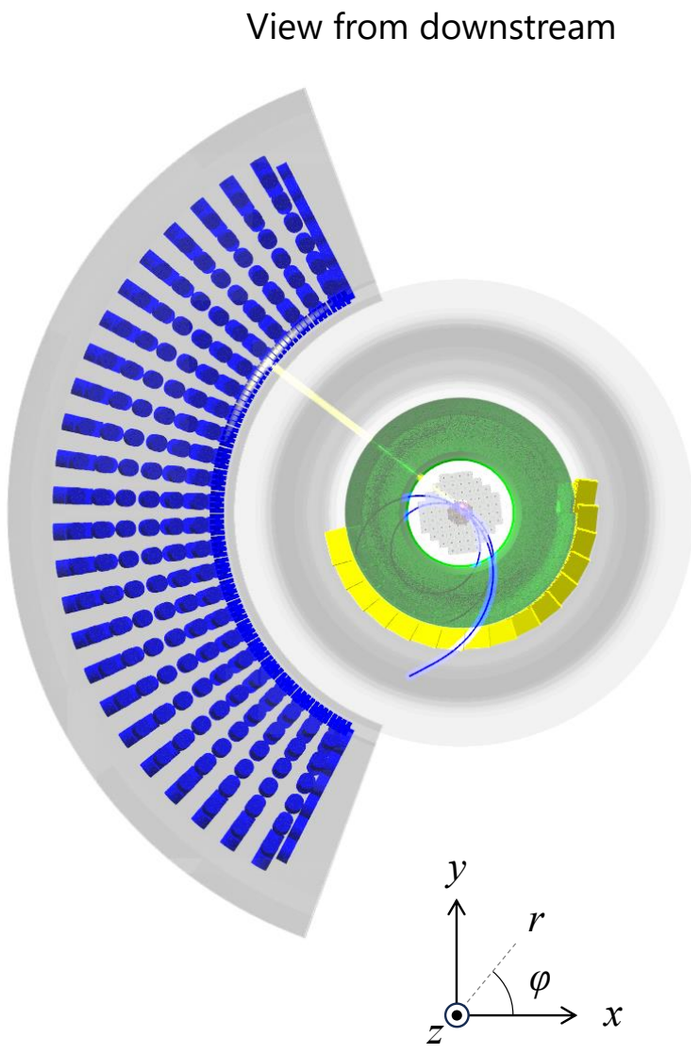




MEG II experiment

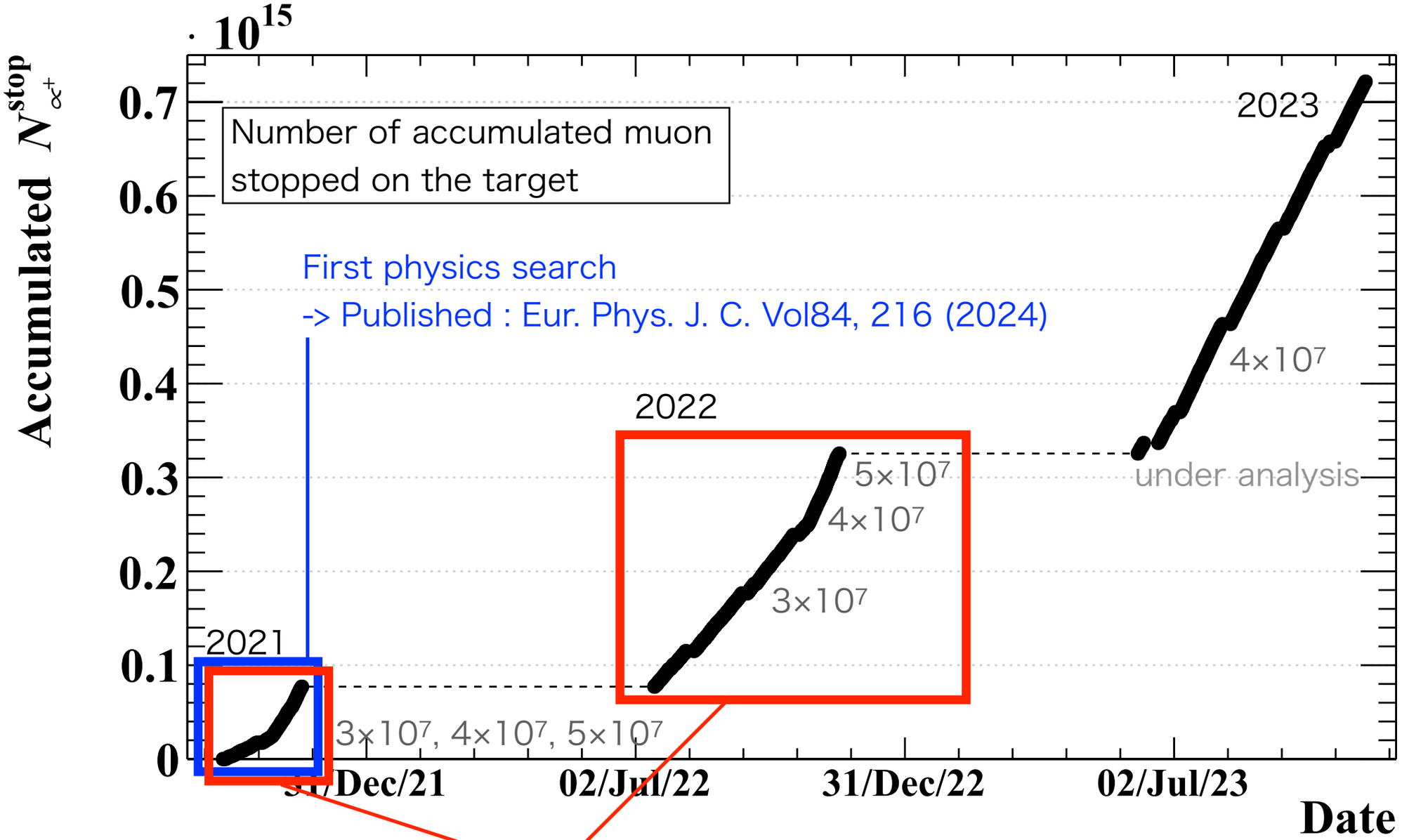
- MEG II experiment aims to search for charged lepton flavor violation : $\mu^+ \rightarrow e^+\gamma$
  - with higher sensitivity by one order of magnitude compared to the MEG
  - Using high intensity continuous muon beam at Paul Scherrer Institut (PSI)
  - Target sensitivity of Br($\mu^+ \rightarrow e^+\gamma$) : 6×10^{-14}





Timeline of the MEG II experiment

- Physics run started since 2021
  - First result was reported in 2023 (published in 2024)
- Data acquiring was continued in 2022, 2023, and is planned in 2024



Main topic of this presentation

- Updated analysis for 2021 and newly analyzed for 2022 data

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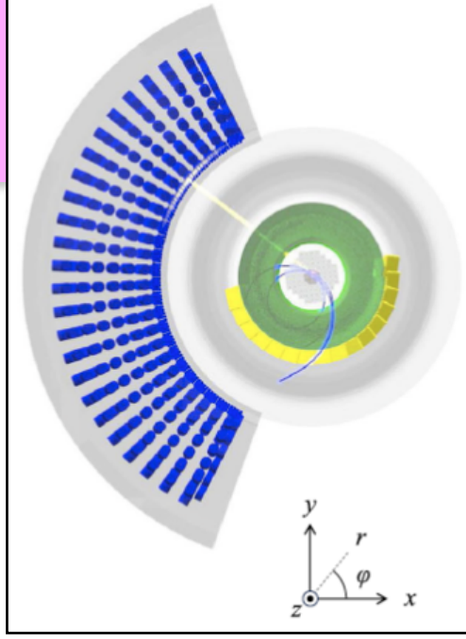
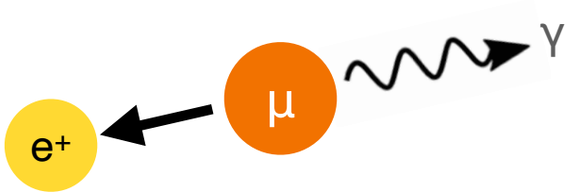
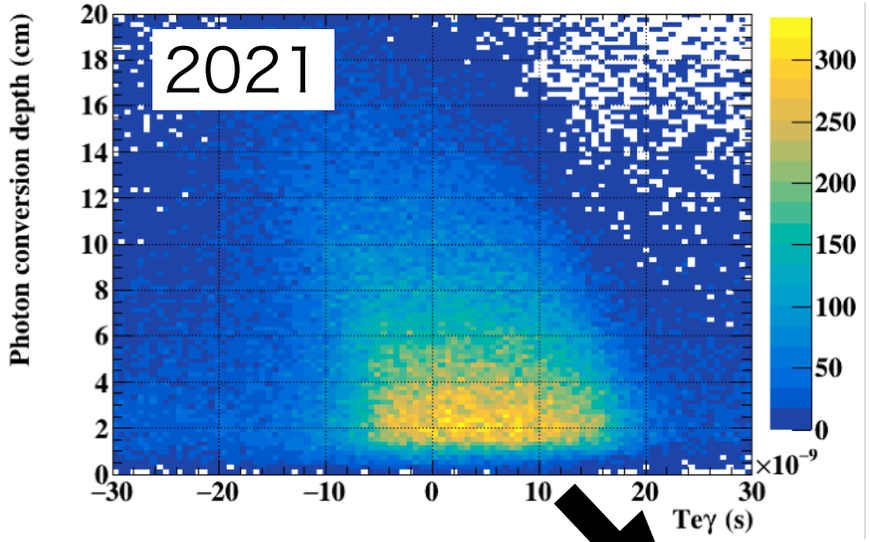
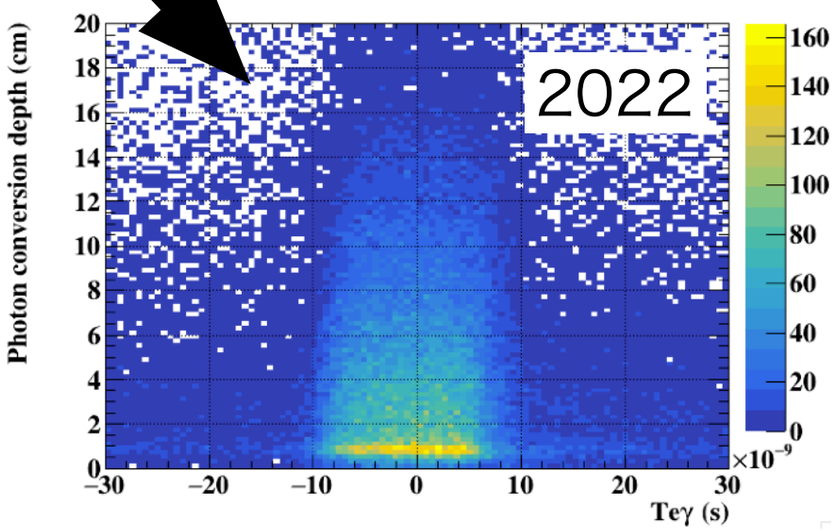
Trigger efficiency improvement

- Trigger logic for MEG event
  - E_γ > Threshold (~ 40-45 MeV)
  - $|T_{e\gamma}|$ < Time window (~ 12.5 ns)
  - Direction matching : eγ hit position correlation
- In 2022 run, time walk effect on gamma-ray side was improved by using PMT instead of MPPCs for timing trigger

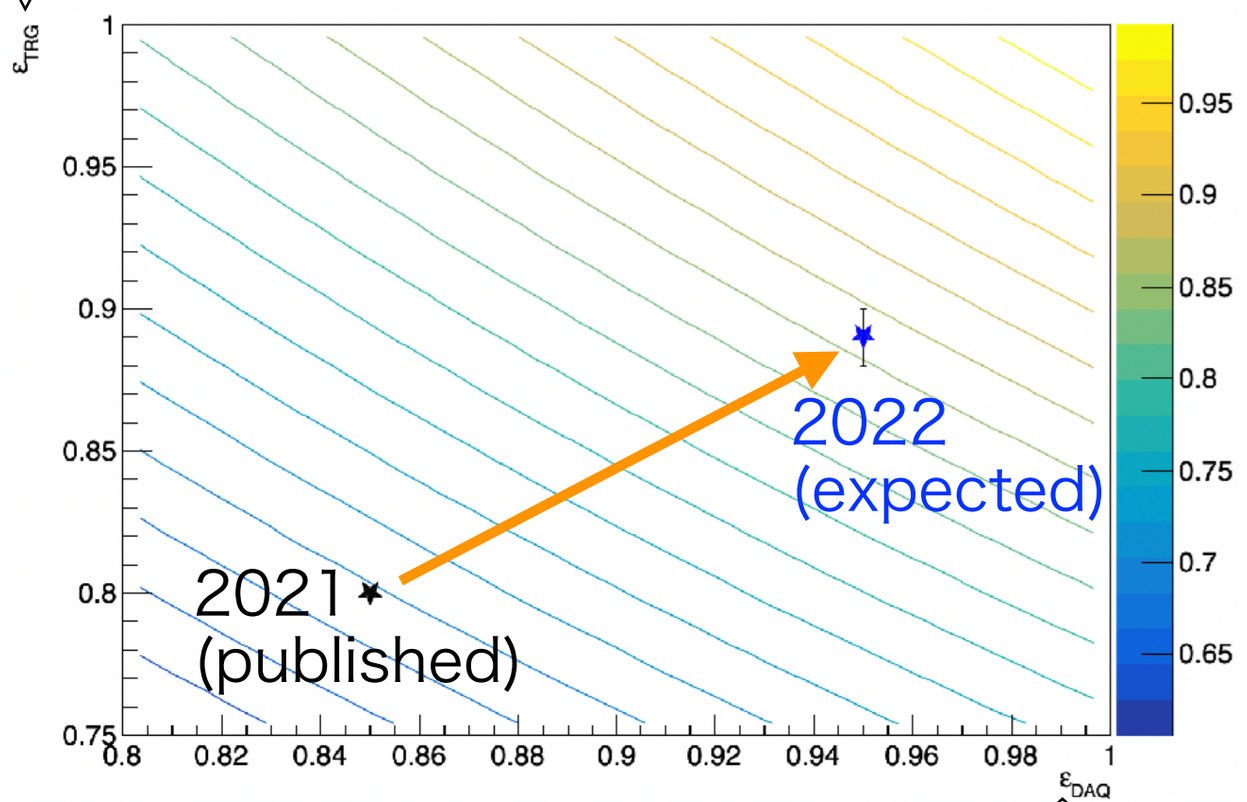








$$\epsilon_{TRG} = \epsilon_{E_\gamma}^{TRG} \times \epsilon_{T_{e\gamma}}^{TRG} \times \epsilon_{DM}$$



$$\epsilon_{DAQ} = N_{recorded}/N_{triggerd}$$

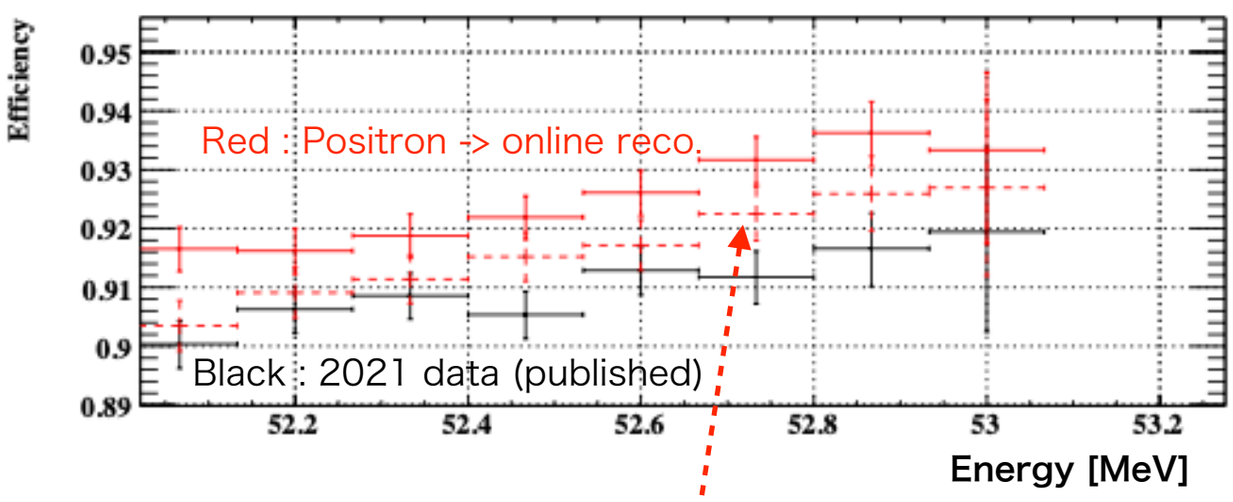
Trigger efficiency improvement

- Direction matching efficiency is re-evaluated

$$\epsilon_{DM} = \epsilon_{table} \times \epsilon_{e^+hit} \times \epsilon_{\gamma hit}$$

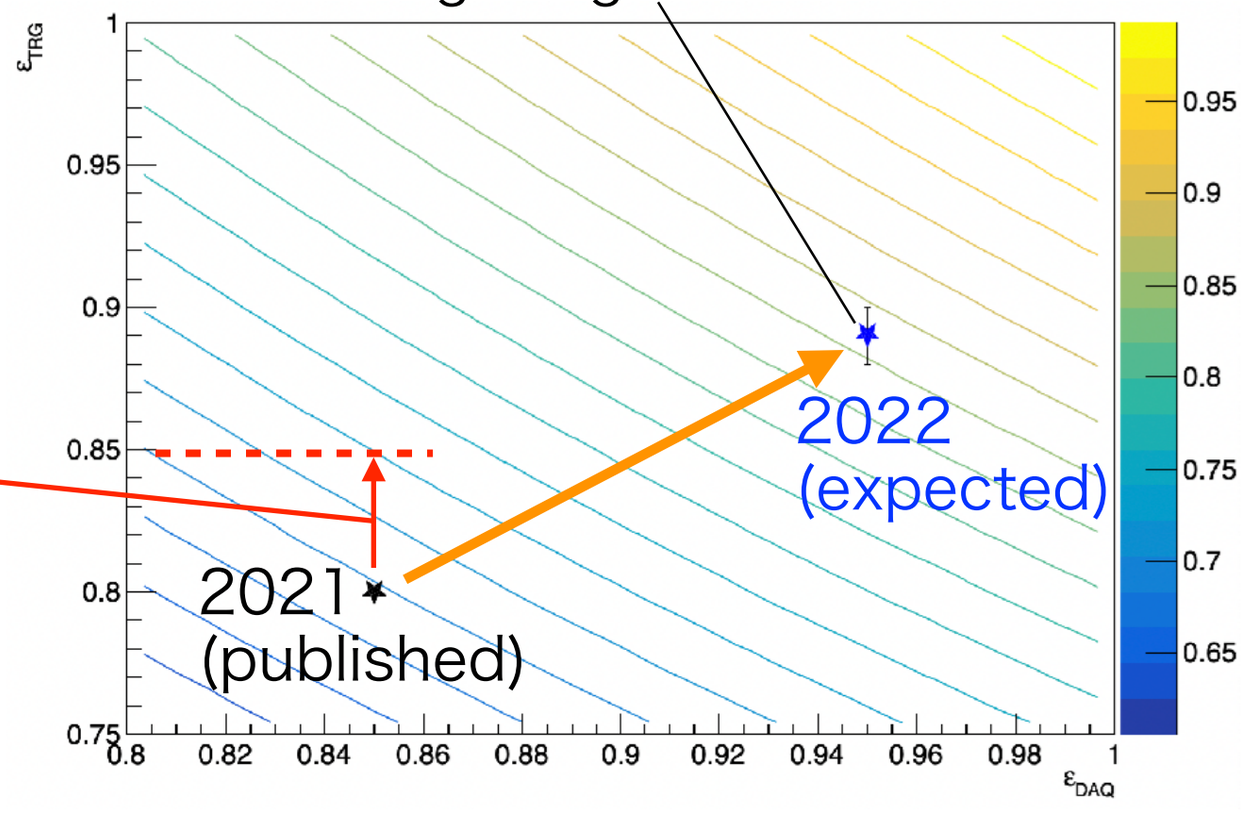
Re-evaluate using calibration data (17.6MeV gamma)
- instead of muon beam data

Re-evaluate e+ hit using online reconstruction
- instead of offline reconstruction



Dashed red :
- Positron -> online reco.
- Gamma -> using 17.6 MeV gamma

Evaluation of 2022 trigger efficiency
-> waiting for gamma reconstruction

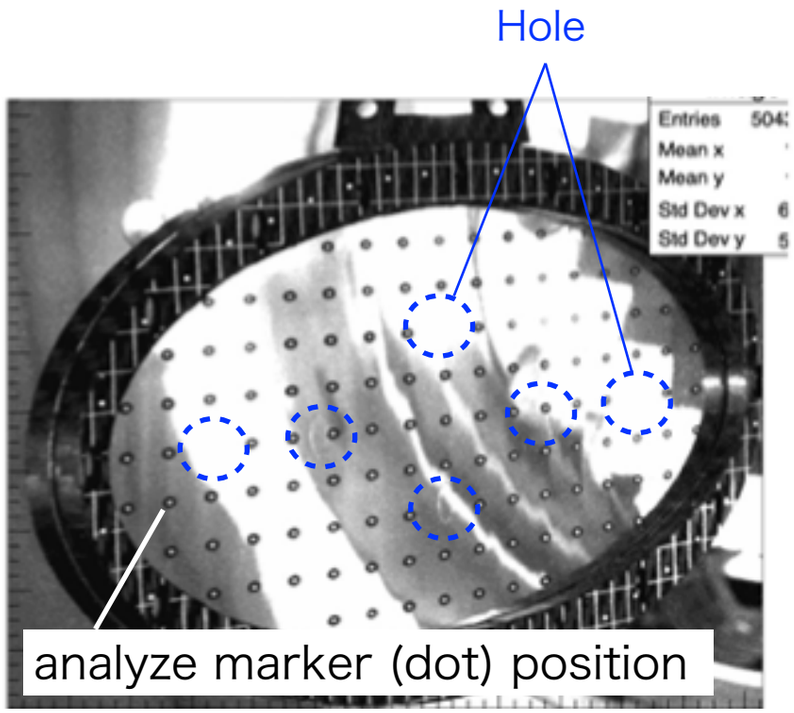


- In addition, further inefficiency in positron reconstruction is considered

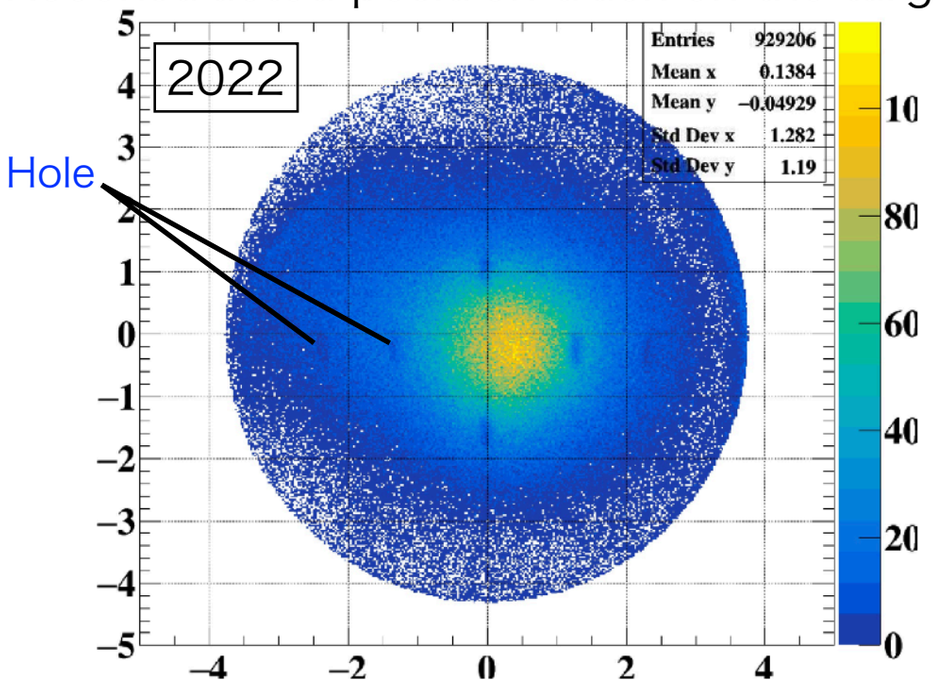
Target analysis

- Muon stopping target : 174±20μm thickness polyvinyltoluene (scinti. material)
- In MEG experiment, the largest uncertainty came from target deformation
- In MEG II experiment, it is monitored by Camera

- Marker analysis
  - monitored the target position/rotation and deformation
  - -> implemented into event reconstruction
- Hole analysis
  - Hole reconstruction by positron tracks
  - Reduced target position uncertainty : ±100 μm (2021) -> ±35 μm (2022) (xy)



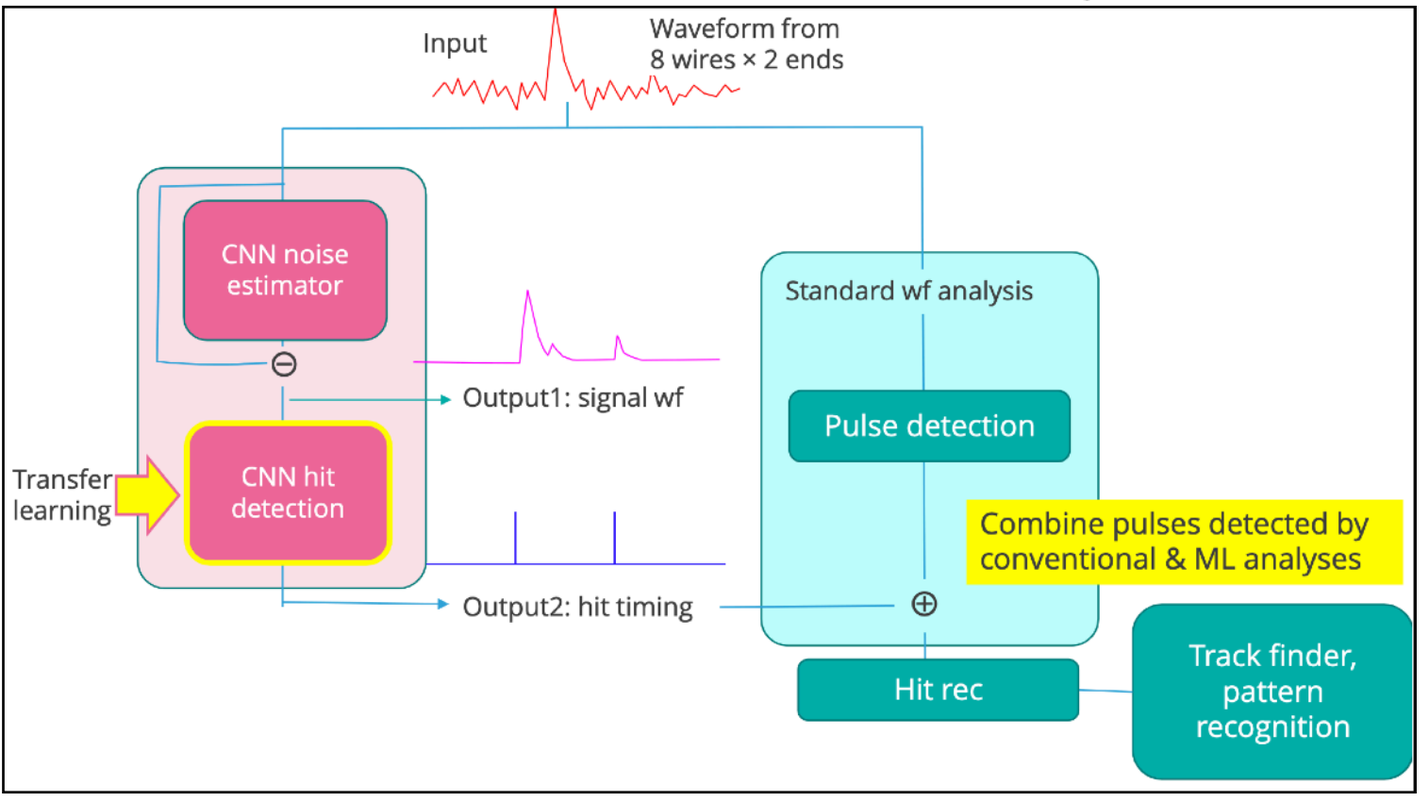
Reconstructed positron track on the target

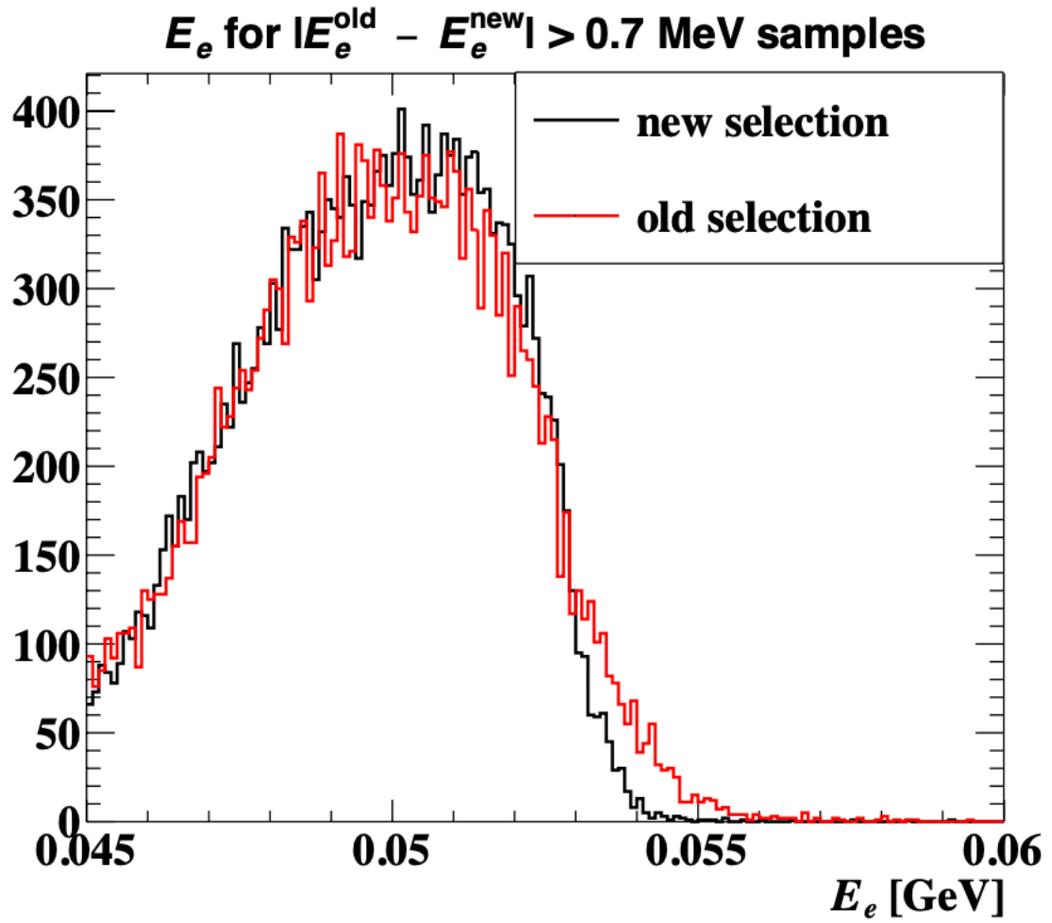


Positron reconstruction

- Hit selection : Standard waveform analysis + Machine-learning technique
  - Adopted in 2021 analysis (in the previous publication)
  - Parameters optimization for 2022 analysis : **done**
- Then tracks are reconstructed
  - Improved algorithm to select “ghost track” (better quality track)
  - Sharper Michel positron edge is obtained with new track selection
    - Note : events with differently judged ghost track and $\Delta E_{e(\text{new-old})}$>700 keV

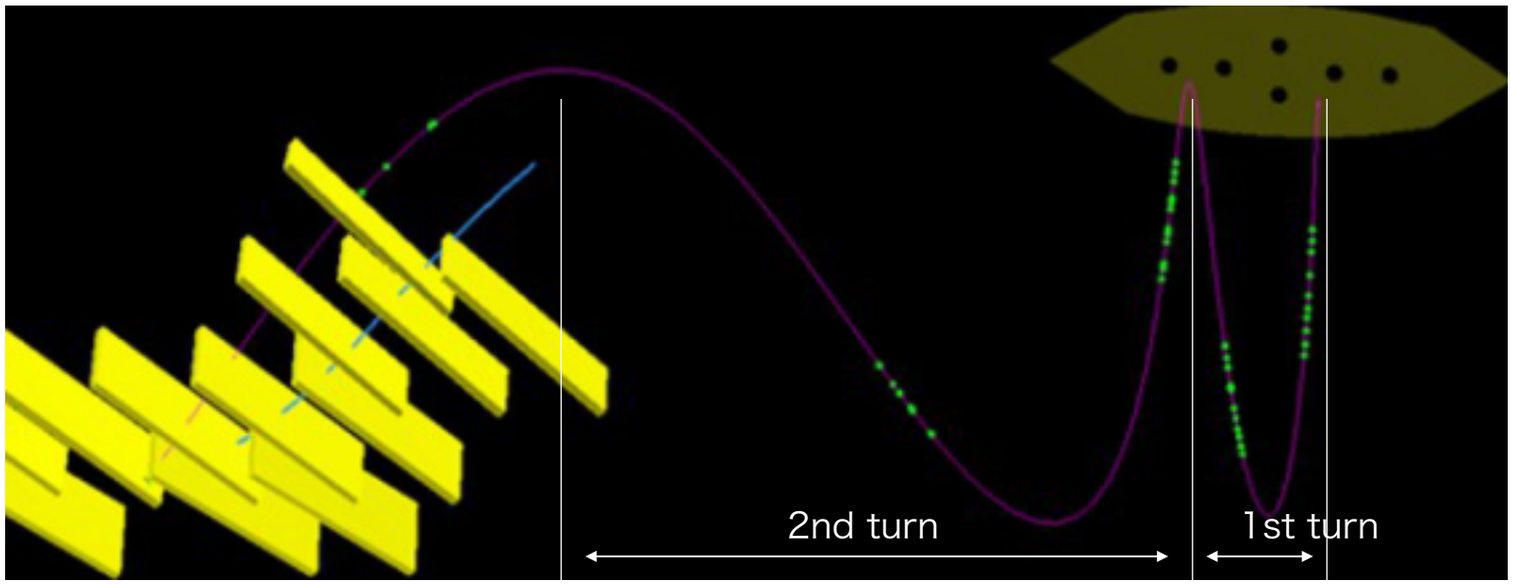
Schematic of hit selection (standard WF analysis + ML)





Double turn analysis in positron tracking

- Double turn track is used for evaluation of the resolutions of e^+ kinematics
  - combining with MC study

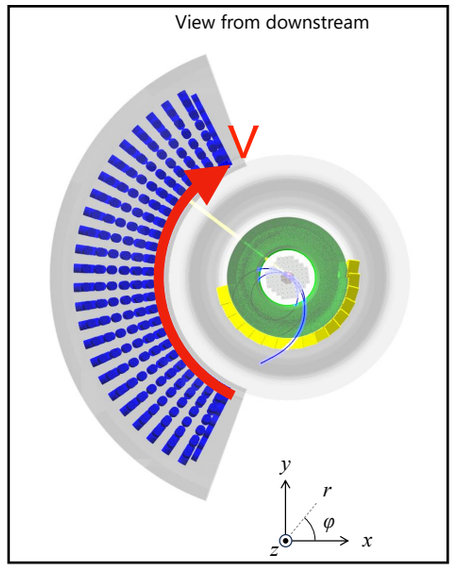


Resolution table with various beam rate

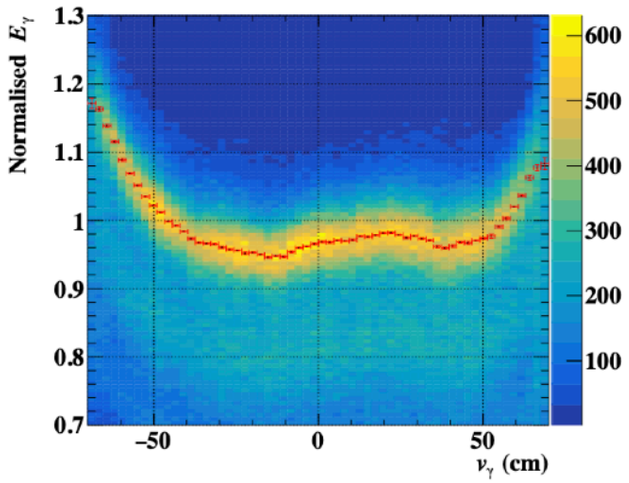
	Variable	3×10^7	2×10^7	3×10^7	4×10^7	5×10^7
2021	y [mm]	0.65	0.64	0.60	0.67	0.67
	z [mm]	1.83	1.76	1.80	1.89	1.97
	ϕ ($\phi = 0$) [mrad]	5.22	4.83	5.28	5.12	5.43
	θ [mrad]	6.56	6.17	6.27	6.23	6.30
	p [keV]	82.30	76.11	81.26	87.83	90.08
2022	y [mm]	-	-	0.61	0.67	0.67
	z [mm]	-	-	1.76	1.89	1.93
	ϕ ($\phi = 0$) [mrad]	-	-	5.22	5.34	5.43
	θ [mrad]	-	-	6.20	6.16	6.5
	p [keV]	-	-	78.60	87.60	87.35

Energy reconstruction of gamma-ray

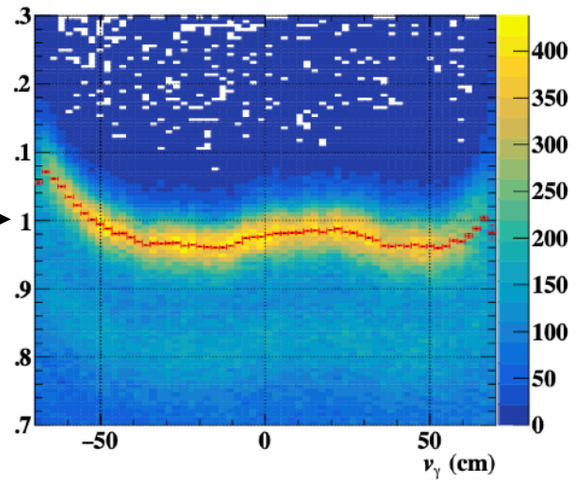
- Sensor calibrations are updated for 2021 data, and done for 2022 data
- In 2022 data, temporal evolution of non-uniformity is observed
  - Because the purity changed over the run time
  - Time-varying non-uniformity correction is implemented



Non-uniformity on Jul. 2022



Non-uniformity on Oct.. 2022

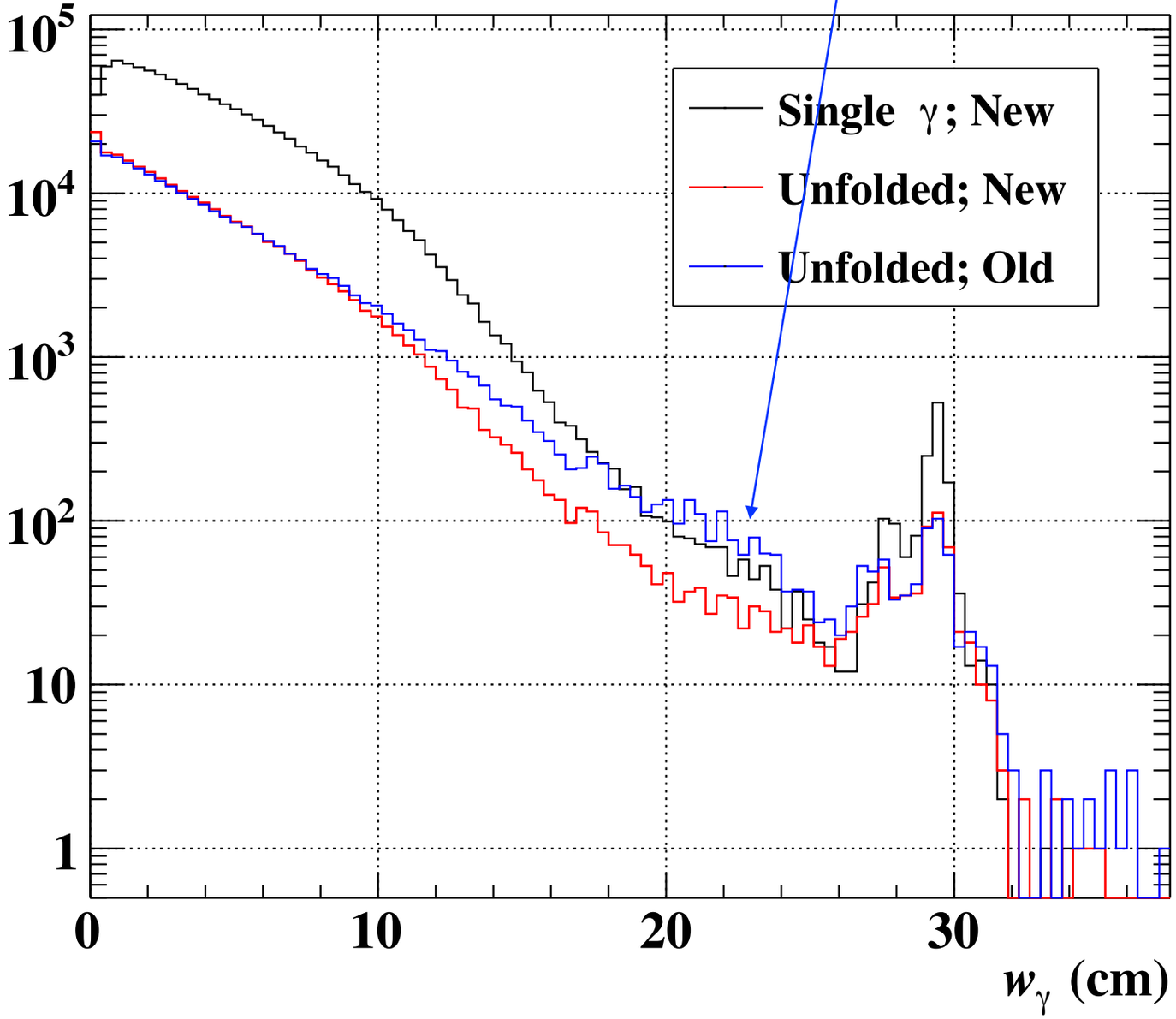


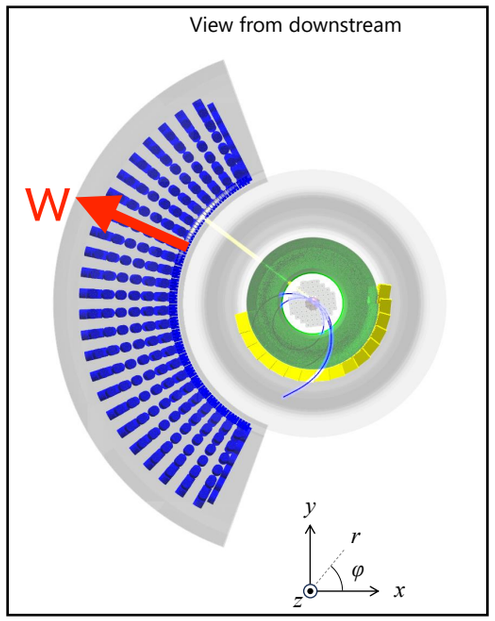
Energy resolution history for 17.6 MeV gamma-ray (Left: 2021, Right: 2022)

→ Good stability for long term operation is achieved (by calibration)

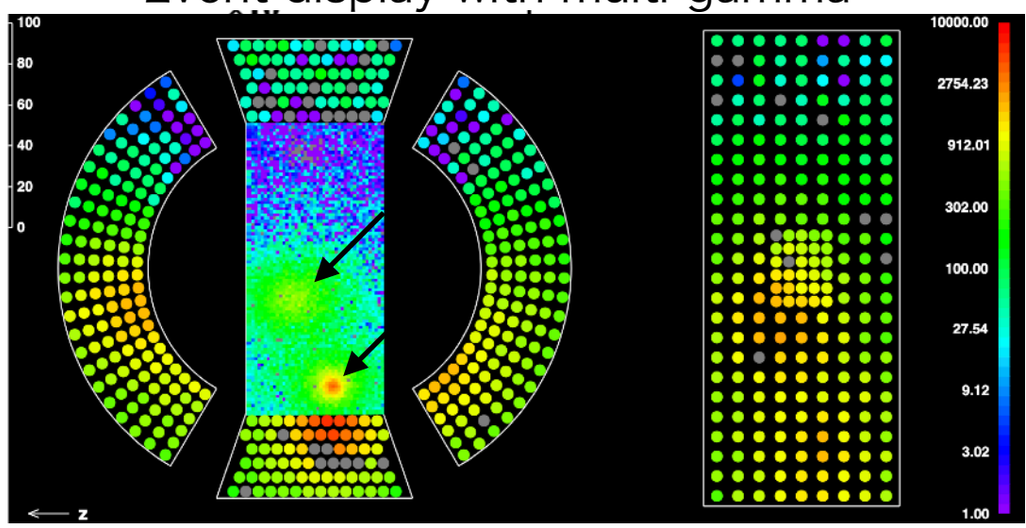
Reconstruction of gamma-ray : w distribution

- Improvement of position reconstruction algorithm (along w-direction)
- (not perfect but) consistent behavior in the w distribution
  - b/w single gamma event and pileup gamma event
  - w distribution with pileup before algorithm update shows larger distribution for higher w-position



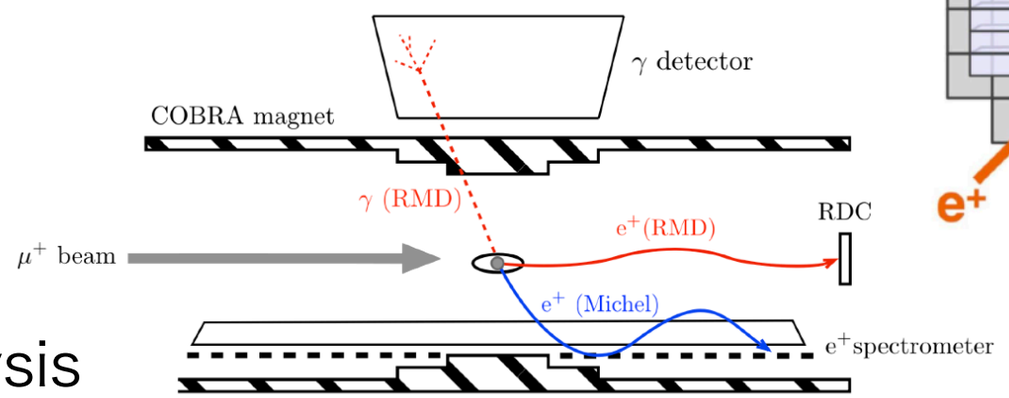


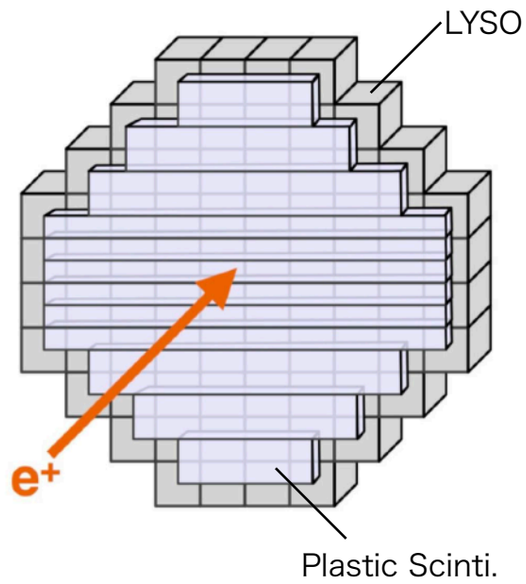
Event display with multi-gamma



Radiative Decay Counter

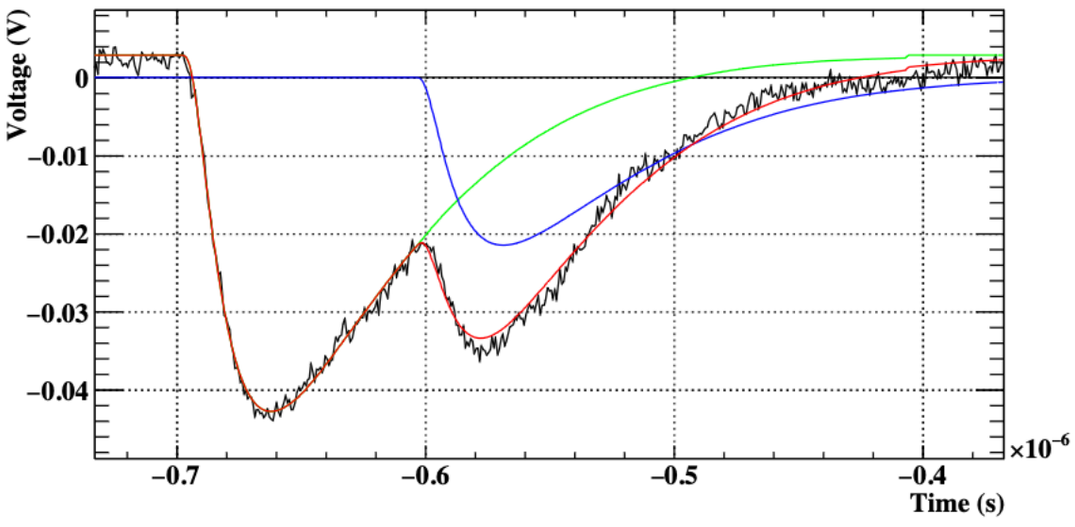
- Radiative decay counter to detect low momentum positron
  - accompanied with high energy gamma-ray in RMD
  - RDC information is one of an input for likelihood analysis

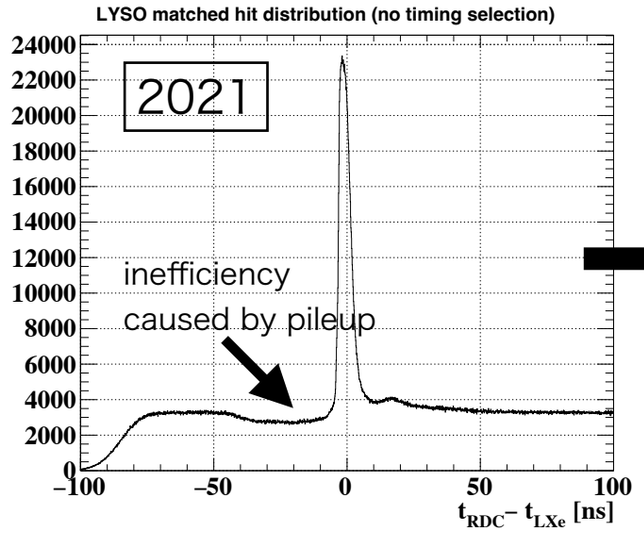


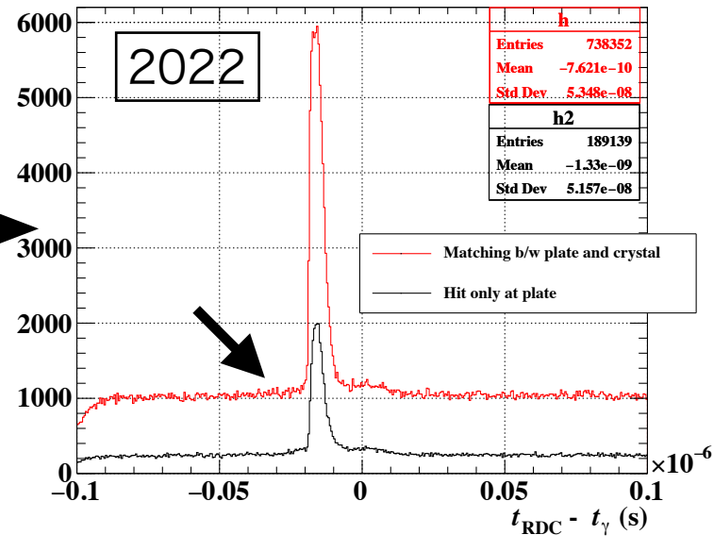


- Improvement of waveform analysis
  - Reduce noise, pileup analysis with template waveform fitting
  - Inefficiency observed in 2021 analysis is disappeared thanks to the template fitting method
    - Tagged-RMD fraction improved : 22.0(8)% → 25.3(8)% (2021, 4e+7 data)

Template waveform fitting (green, blue : template)



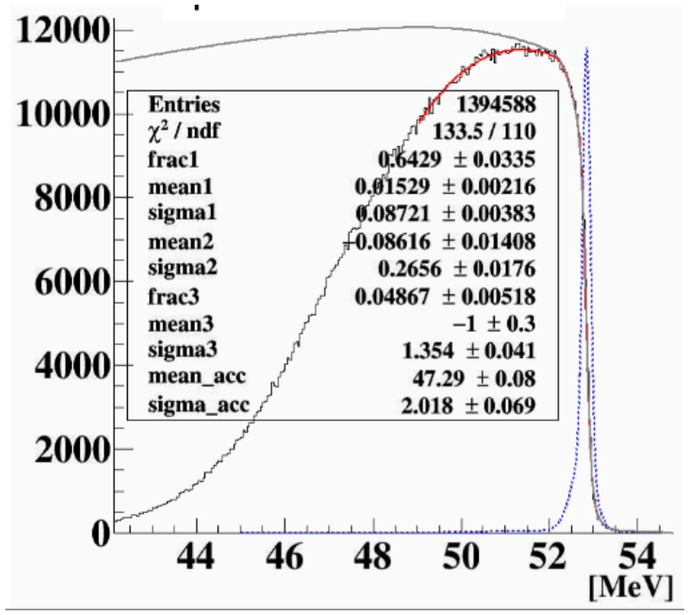




Summary of reconstruction and performance

- Reconstruction status
  - Positron : Completed
  - Gamma : to be finalized soon (energy)
  - RDC : Completed

- Detector performances summary
  - Performance for positron reconstruction is improved
  - Performance for gamma reconstruction will be evaluated soon after final reconstruction



	P_e	θ_e	E_γ	$Position_\gamma$	$T_{e\gamma}$	ε_e	ε_γ
MEG	380 keV/c	9.4 mrad	2.4%/1.7%	5 mm	122 ps	30%	63%
2021 (published)	89 keV/c	7.2 mrad	2.0%/1.8%	2.5 mm	78 ps	67%	62%
2022 (3e+7)	79 keV/c	6.2 mrad	yet	2.5 mm	yet	67%	62%

Outline

Introduction : cLFV and MEG II experiment

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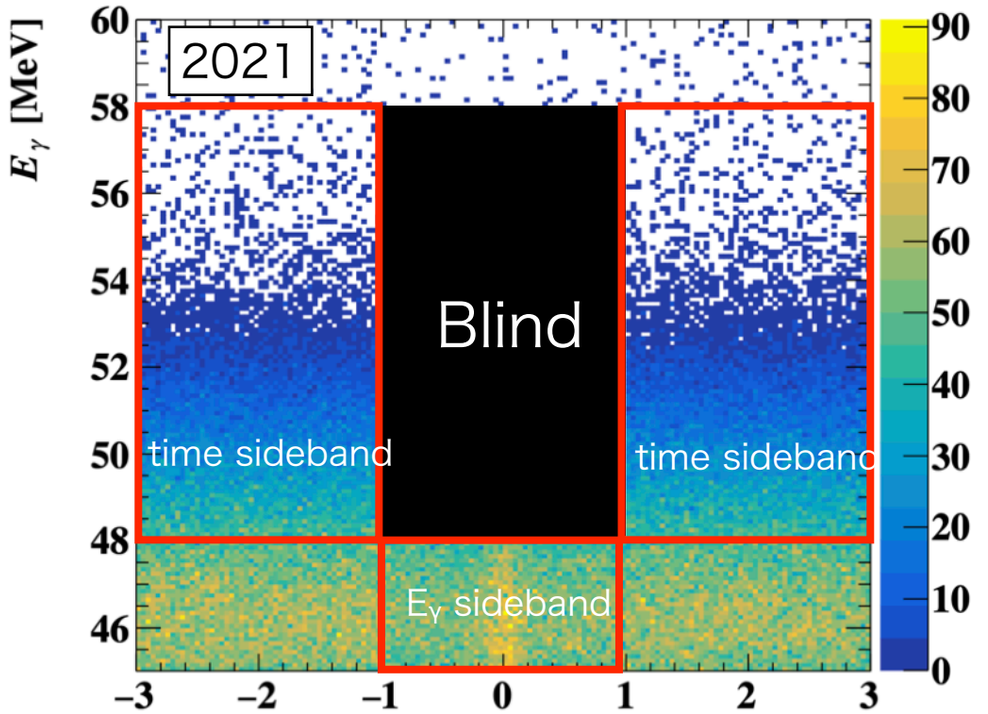
Summary

Likelihood analysis to search for $\mu^+ \to e^+\gamma$

- Blind analysis
  - E_γ : [48, 58] MeV, $t_{e\gamma}$: [-1, 1] ns

- Likelihood analysis
  - Per event Probability Distribution Function (Per event PDF) is adopted
  - PDFs are extracted from the sideband

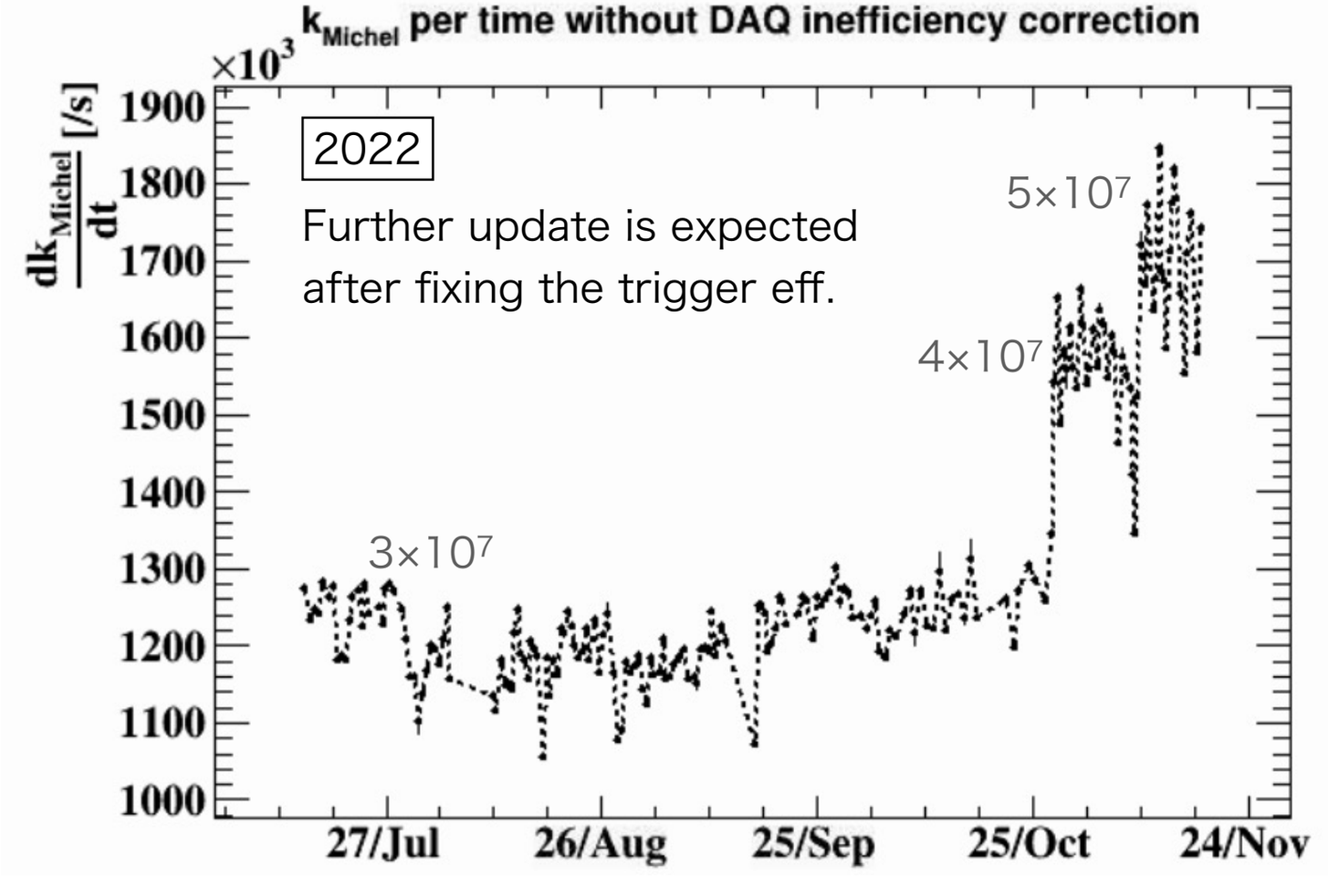


$$
\begin{aligned}
& L(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{Acc}}, X_{\mathrm{TGT}}) \\
:= \quad & \exp\left(-\frac{(X_{\mathrm{TGT}})^2}{2\sigma_{\mathrm{TGT}}^2}\right) && \text{: Target alignment term} \\
& \times \exp\left(-\frac{(N_{\mathrm{RMD}} - \langle N_{\mathrm{RMD}}\rangle)^2}{2\sigma_{\mathrm{RMD}}^2}\right) \times \exp\left(-\frac{(N_{\mathrm{Acc}} - \langle N_{\mathrm{Acc}}\rangle)^2}{2\sigma_{\mathrm{Acc}}^2}\right) && \text{: Constraint for \#BG by sideband} \\
& \times \frac{e^{-(N_{\mathrm{sig}}+N_{\mathrm{RMD}}+N_{\mathrm{Acc}})}}{N_{\mathrm{obs}}!} \prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S(\vec{x_i}|X_{\mathrm{TGT}}, \vec{q_i}) + N_{\mathrm{RMD}} R(\vec{x_i}|\vec{q_i})) + N_{\mathrm{Acc}} A(\vec{x_i}|\vec{q_i})\right) \\
& && \text{: Ordinal extended likelihood}
\end{aligned}
$$

Normalization

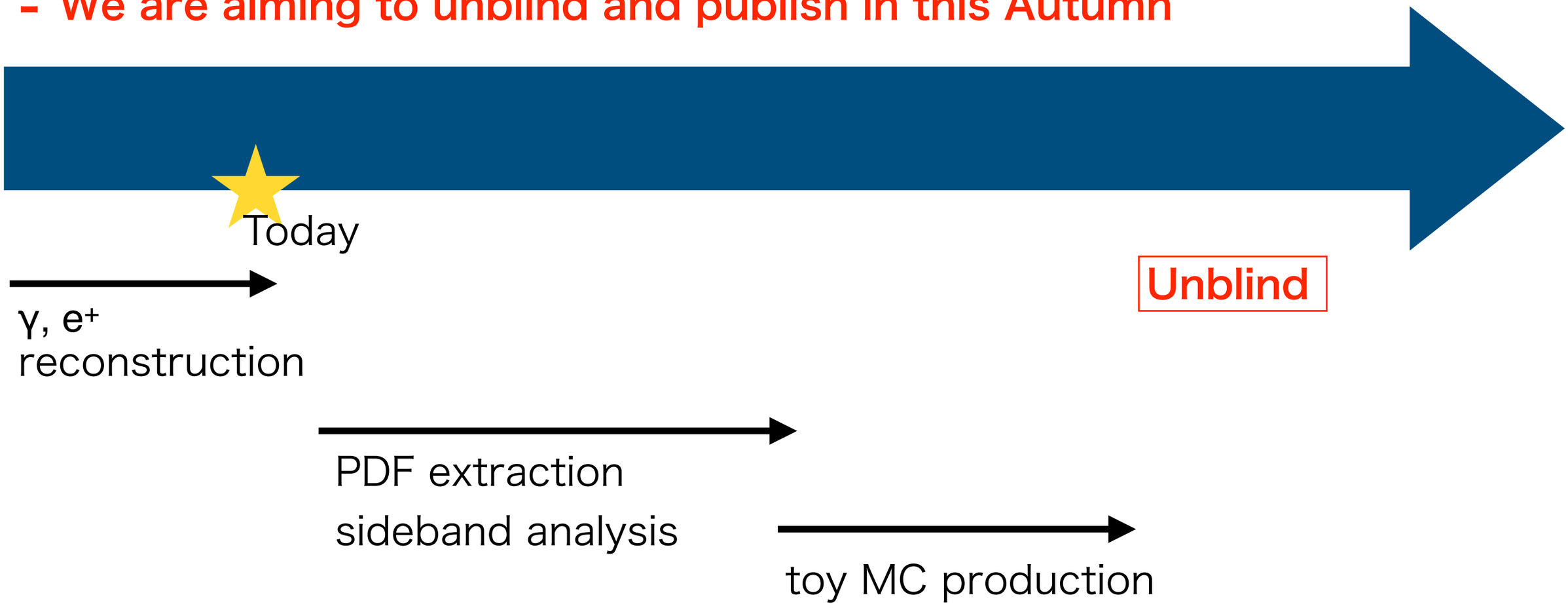
- Number of effectively measured muon decay is estimated using Michel positron
  - $k_{2022} = 1.01\times10^{13}$
  - **~3.8 times larger statistics** than 2021
  - Not finalized yet : will be updated after gamma reconstruction ($\varepsilon^{\mathrm{TRG}}$ fix)
- Cross-check by RMD normalization will be done after final reconstruction

$$k_{\mathrm{Michel}} = \frac{N^{e\nu\bar{\nu}}}{\mathcal{B}^{e\nu\bar{\nu}}} \frac{\epsilon^{e\gamma}_{\mathrm{trg}}}{\epsilon^{e\nu\bar{\nu}}_{\mathrm{trg}}} \frac{\epsilon^{e\gamma}_{e}}{\epsilon^{e\nu\bar{\nu}}_{e}} \frac{P^{e\nu\bar{\nu}}}{P^{e\gamma}} \epsilon_{\gamma} A^{e\gamma}_{\gamma} \epsilon^{e\gamma}_{\mathrm{sel}}$$



Analysis prospects

- Reconstruction of positron : completed
- Reconstruction of gamma : almost final stage
- Extraction of the PDFs and sideband analysis are starting
- Toy experiments production by MC will follow
  - to evaluate sensitivity
- **We are aiming to unblind and publish in this Autumn**



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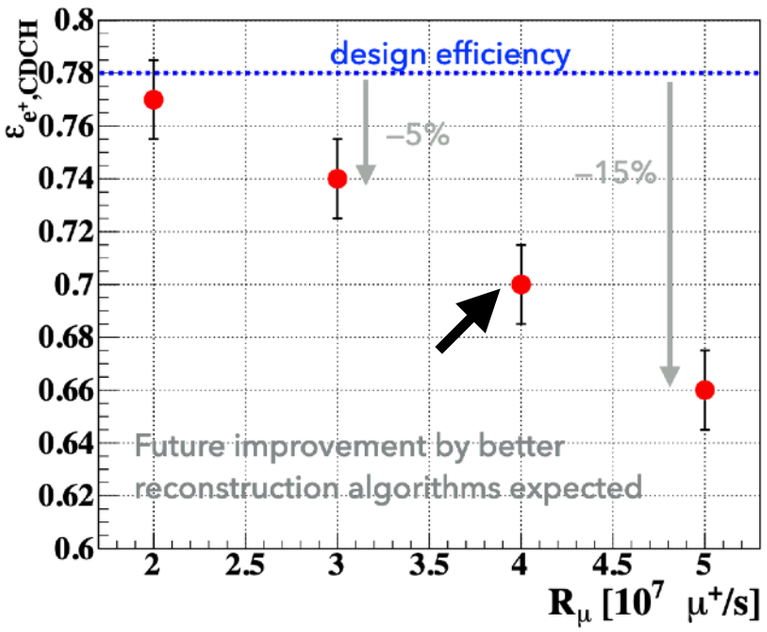
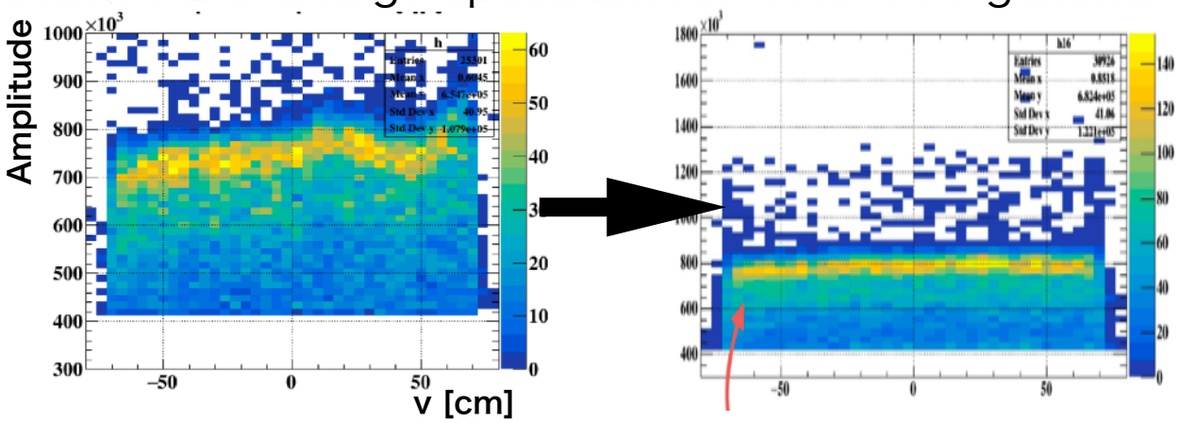
Outlook and improvement of 2023 data

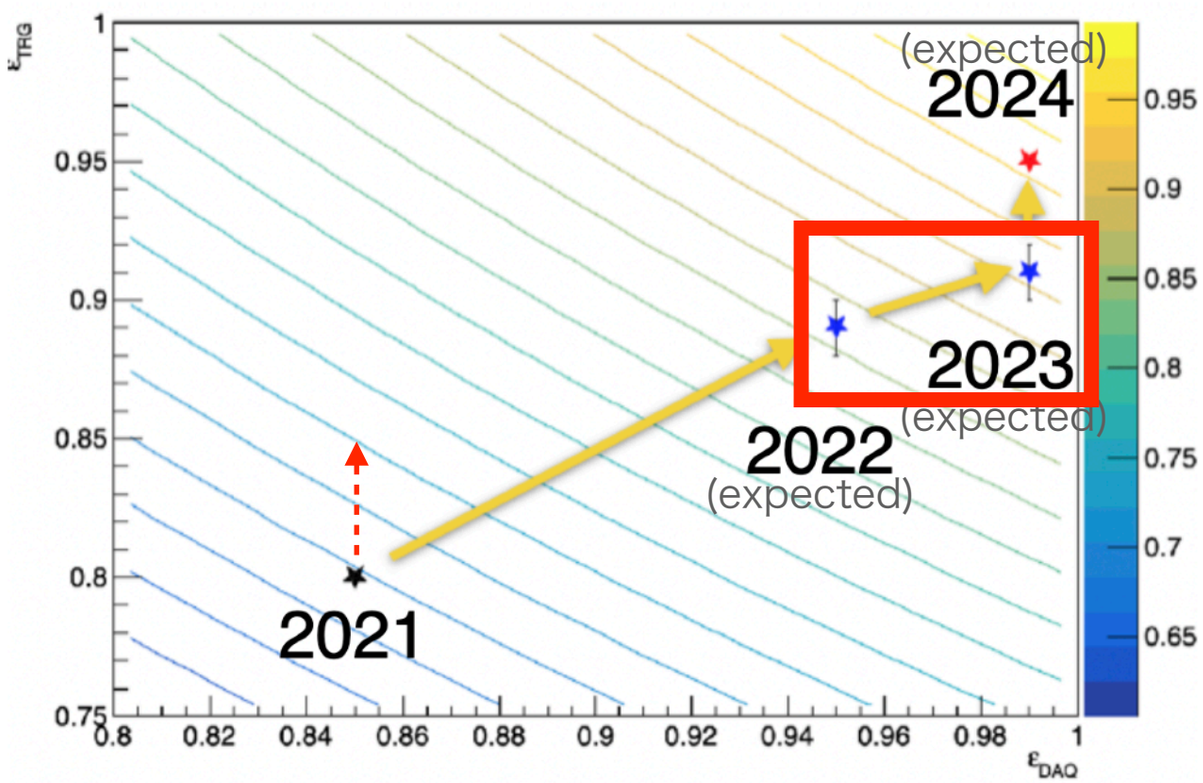
- In 2023 run, online E_γ uniformity was improved
  - Could set higher E_γ trigger threshold, thus was available
- Positron reconstruction efficiency decrease with higher beam rate is known
  - **4e+7 beam rate** is current best choice in terms of sensitivity
- With higher intensity and longer run time, **achieved ~1.6 times statistics**
- Analysis is ongoing



Positron reconstruction efficiency as a function of beam rate

Online ADC charge spectrum for 17.6 MeV gamma

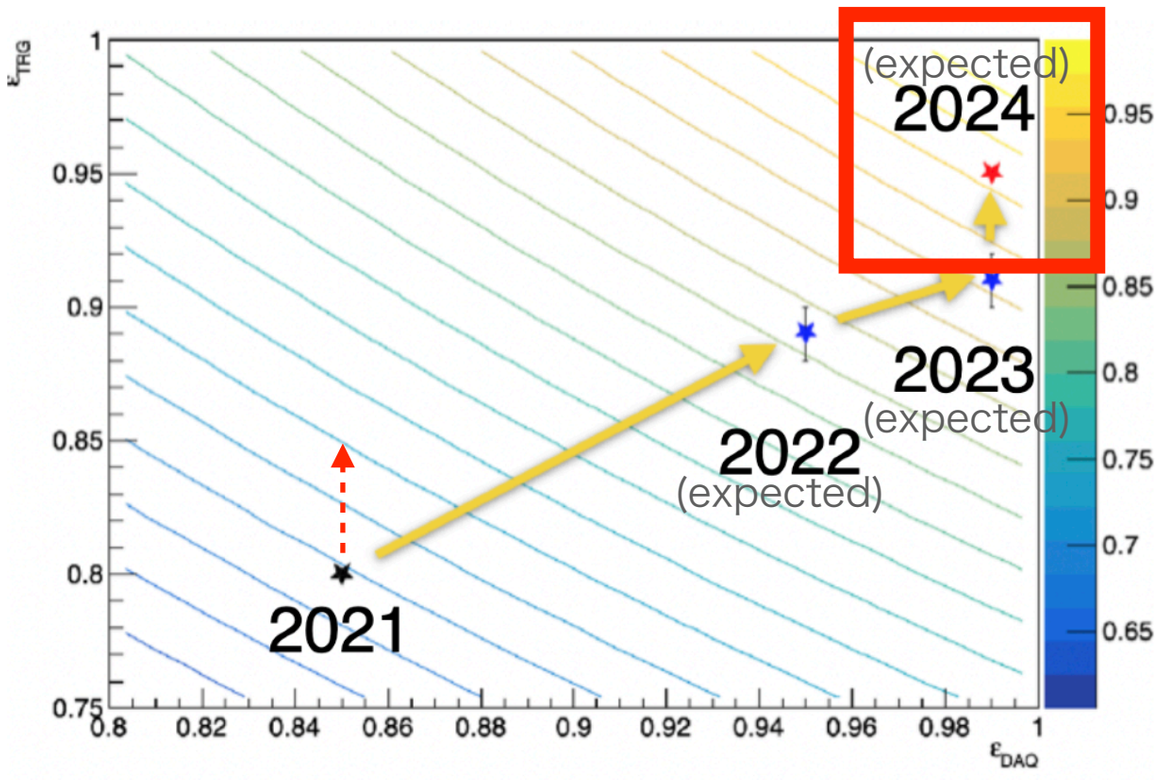




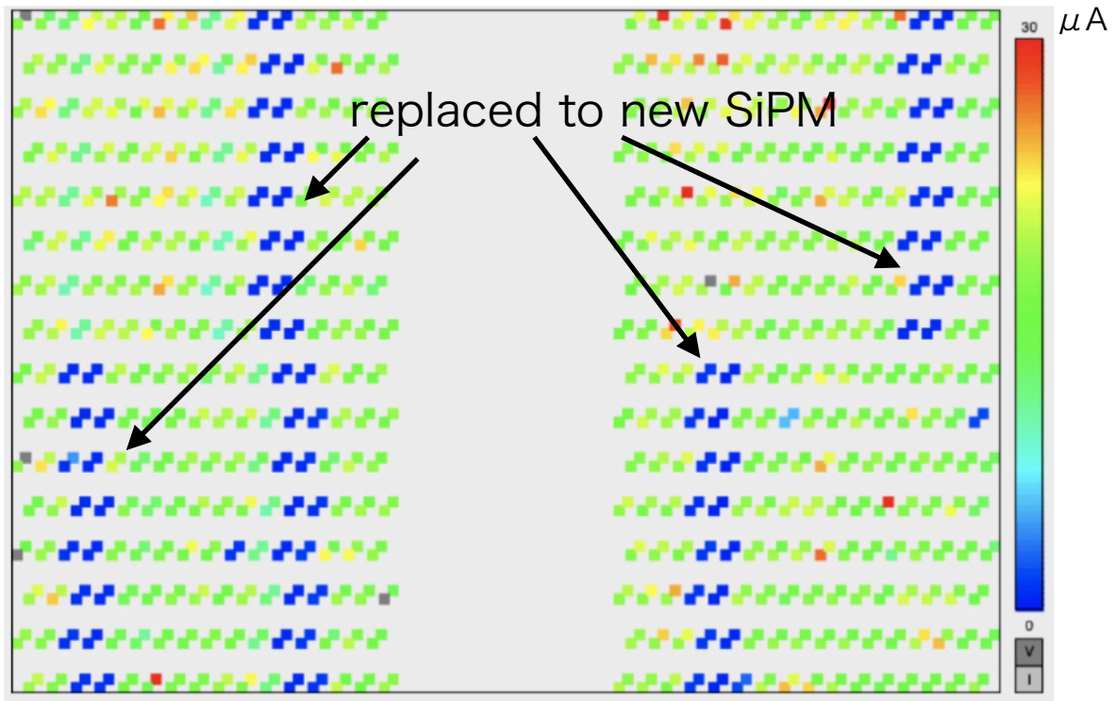
Status of 2024 run

- In 2024, beam time is assigned from June to December
- Improvements for 2024 run :
  - Direction matching table optimization in the trigger section to improve trigger efficiency
  - Refreshment (replacement) of SiPMs in the TC was done

- Currently, physics run is suspended by a failure of LHe supply by cryo-plant
  - will be resumed in October



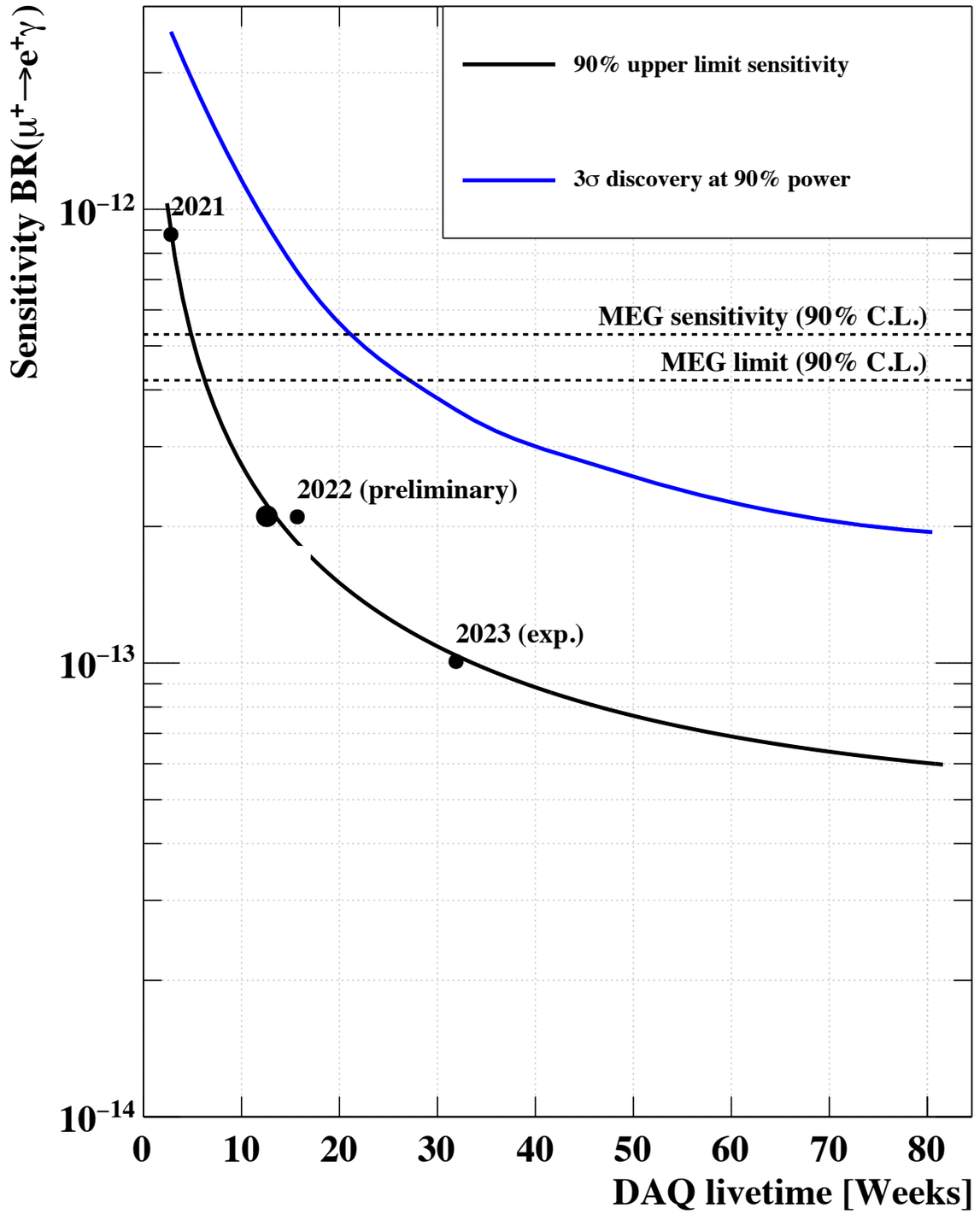
Current map of SiPMs (TC)



Prospect of sensitivity

- $Br(\mu \to e\gamma) = N_{sig} / k$
- Sensitivity is calculated as 90% C.L. upper limit with BG only hypothesis
- Median 90% C.L. upper limit for N_{sig} : 2.7
- → **Sensitivity(2021+2022) : 2.1×10^{-13}**
  - Preliminary estimation
  - will be updated by final gamma reco.
  - **First MEG II (only) exposure beyond MEG sensitivity**

- MEG II experiment will continue by 2026
  - PSI πE5 beam line update in 2027-28
- In 2025-26, beam time will be shared with Mu3e experiment?
- -> aim to reach $(5\text{-}6) \times 10^{-14}$



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Introduction : cLFV and MEG II experiment

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Physics analysis of 2021+2022 data

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Summary

- MEG II experiment searches for $\mu \to e\gamma$ decay
- Physics run started since 2021 and will continue by the end of 2026

- Analysis status for 2022 data (and update for 2021 data)
  - Reconstructions are almost on the final stage
    - Target, Positron, RDC : done
    - Gamma : will be finalized soon
  - Aim to publish new result in this Autumn
  - Sensitivity (2021+2022) : $\mathrm{Br}(\mu \to e\gamma) = 2.1 \times 10^{-13}$
    - Will be updated (improved) by gamma reconstruction

- Analysis of 2023 data is on-going
  - Lager statistics than 2022
- Physics run in 2024 will resume in October

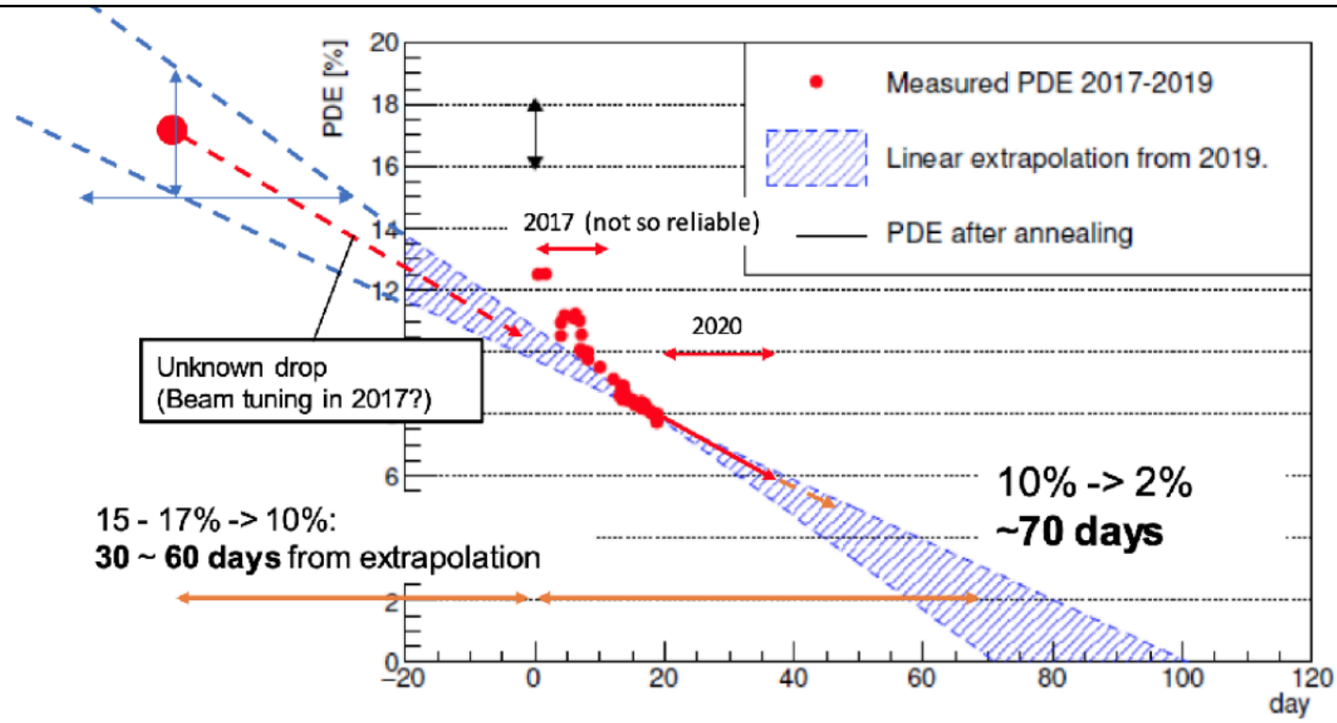
Back up

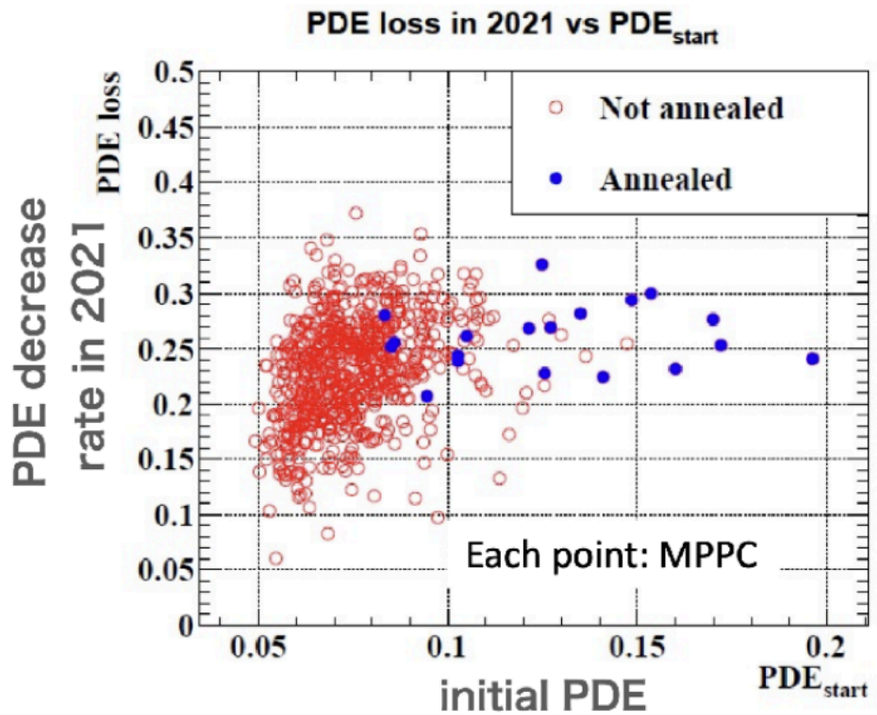
PDE decrease

Slide from T. Iwamoto (15aA562-4)

γ detector (LXe) Issue

- MPPC PDE decrease
  - observed in 2017 under muon beam
  - The cause to be investigated
  - Based on 2021 operation, PDE will change from 16% to 2% in ~100 days MEG II intensity
  - Annealing recovers PDE fully
- Strategy for run 2022
  - LXe MPPC can sustain ~ 120 days with 5×10^7 μ/s
    - Beam intensity optimization necessary
  - Annealing for all MPPCs during accelerator winter shutdown period

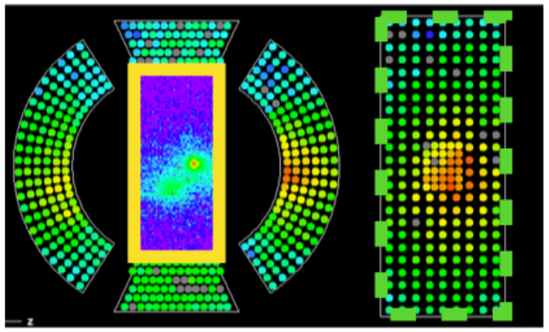




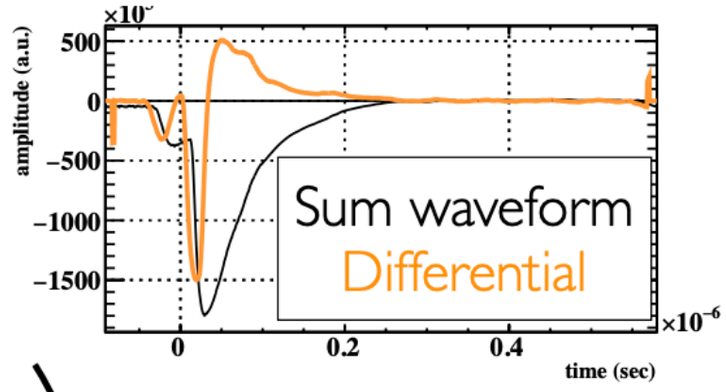
Pileup rejection update in the liquid xenon detector

- Pileup search and unfolding
  - Using information of spacial clustering and #pulses in sum waveform
  - Then unfold the sum waveform by template waveform fit
  - Simultaneous fit between PMT and MPPC sum waveform is performed

Peaks in light distribution

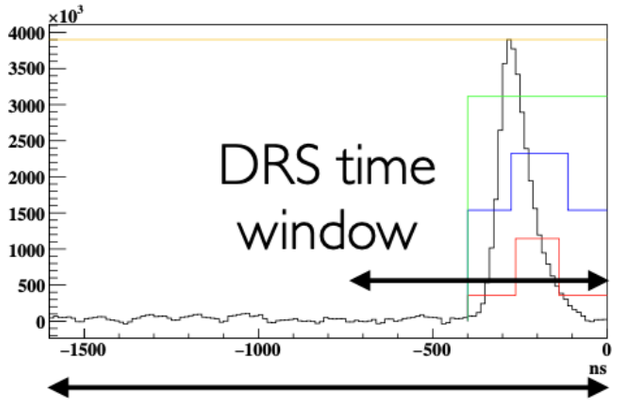


PMT differential waveform



newly implemented

FADC waveform for trigger



Inputs to template fit

Template waveform fit