日本物理学会　第80回年次大会

MEG II 実験陽電子タイミングカウンター 2023–2024年データのキャリブレーションと時間分解能評価

Calibration and time resolution evaluation of 2023–2024 dataset for Pixelated Timing Counter in the MEG II experiment

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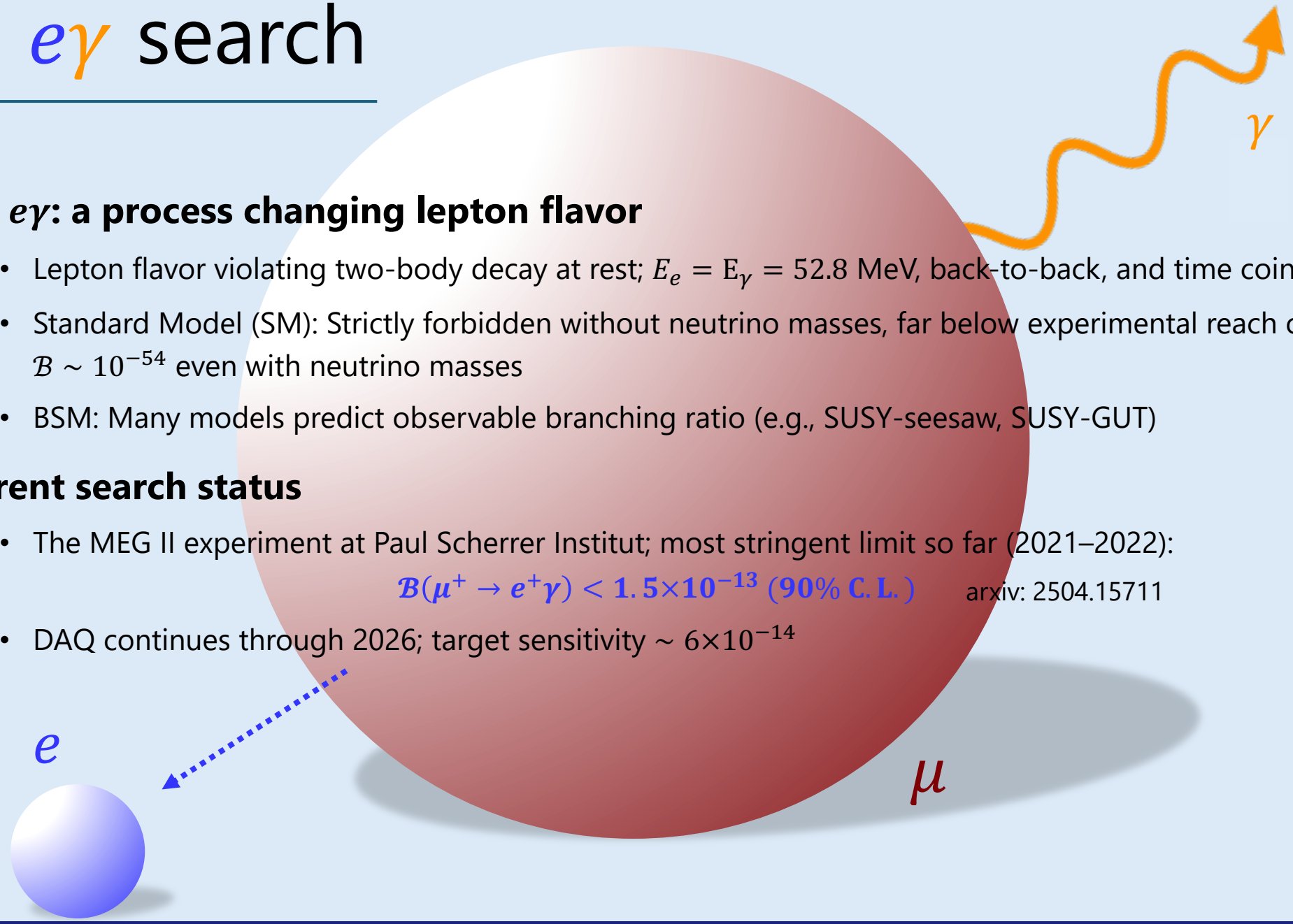
（東大理）

Core-to-Core Program

$\mu \to e\gamma$ search



$\mu \to e\gamma$: a process changing lepton flavor

- Lepton flavor violating two-body decay at rest; $E_e = \mathrm{E}_\gamma = 52.8$ MeV, back-to-back, and time coincident
- Standard Model (SM): Strictly forbidden without neutrino masses, far below experimental reach of $\mathcal{B} \sim 10^{-54}$ even with neutrino masses
- BSM: Many models predict observable branching ratio (e.g., SUSY-seesaw, SUSY-GUT)

Current search status

- The MEG II experiment at Paul Scherrer Institut; most stringent limit so far (2021–2022):

$$\mathcal{B}(\mu^+ \to e^+\gamma) < 1.5\times10^{-13}\ (90\%\ \mathrm{C.L.})$$ arxiv: 2504.15711

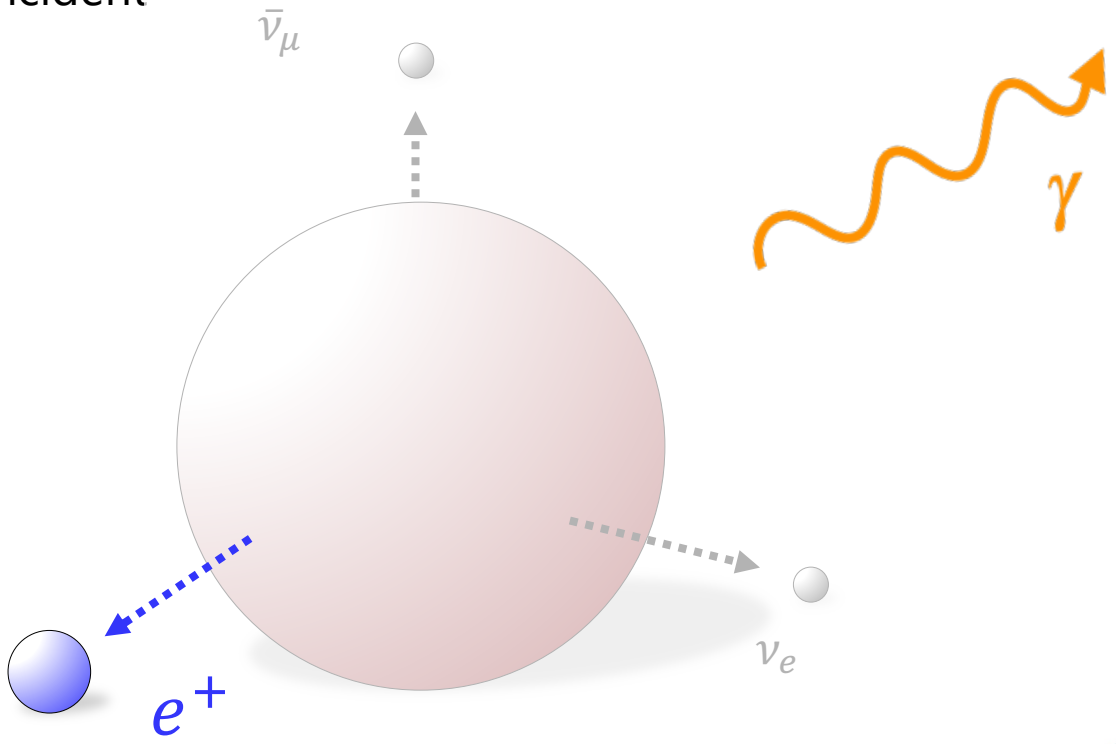
- DAQ continues through 2026; target sensitivity $\sim 6\times10^{-14}$

Main Background

$E_{e^+}, E_\gamma \sim 52.8$ MeV, near back-to-back, near time coincident

- e^+ source: Michel decay $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$
- γ source:
  - Annihilation $e^+ e^- \to \gamma\gamma$
  - Radiative muon decay (RMD) $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e \gamma$

$\to R_{\mathrm{BG}} \propto R_\mu \cdot \delta E_{e^+} \cdot (\delta E_\gamma)^2 \cdot \delta \Theta_{e^+\gamma} \cdot \delta t_{e^+\gamma}$

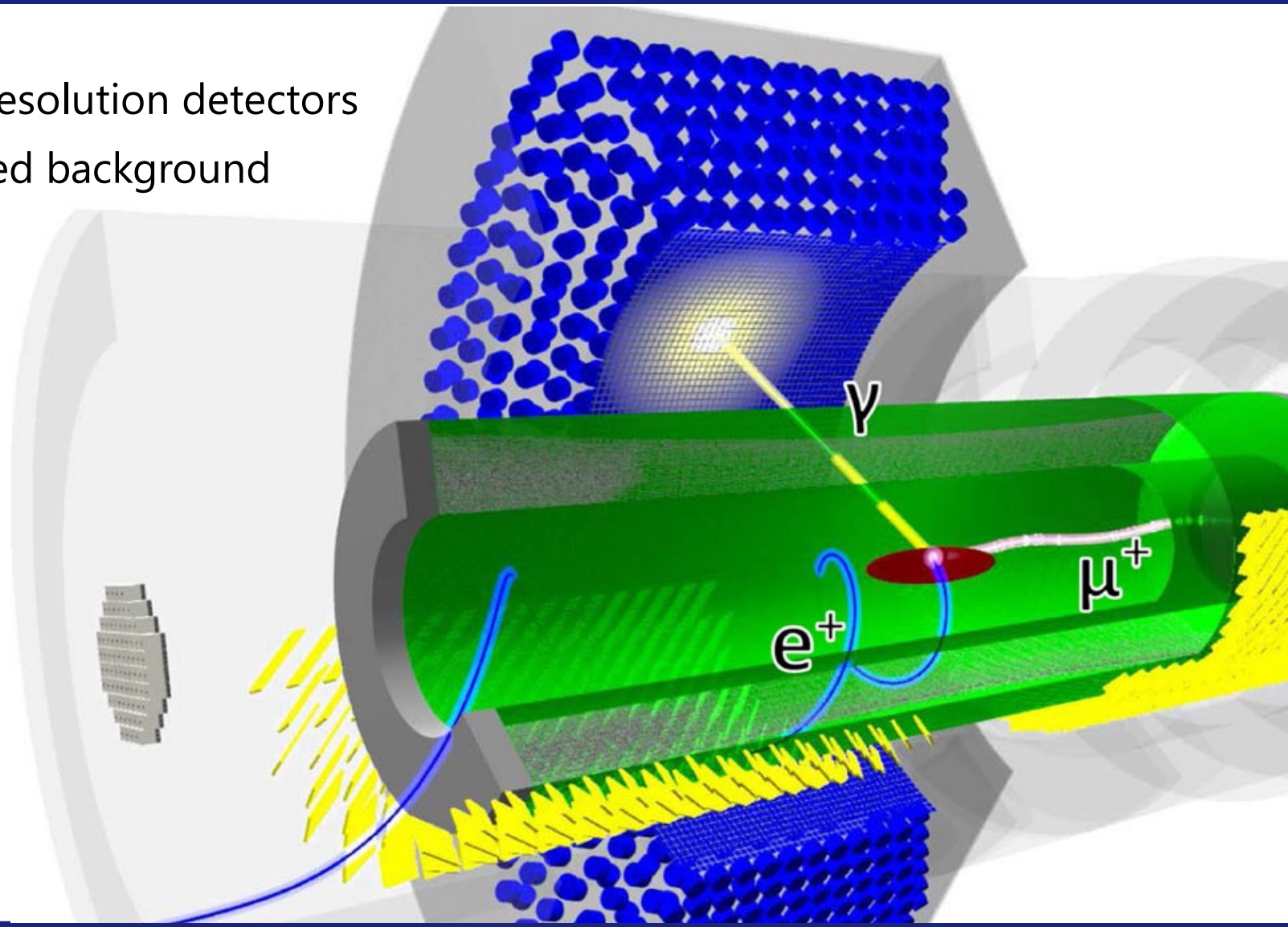


MEG II

High-rate DC muon beam × High-resolution detectors

Deliver large statistics with controlled background

—Maximizing sensitivity



MEG II

High-rate DC muon beam × High-resolution detectors

Deliver large statistics with controlled background

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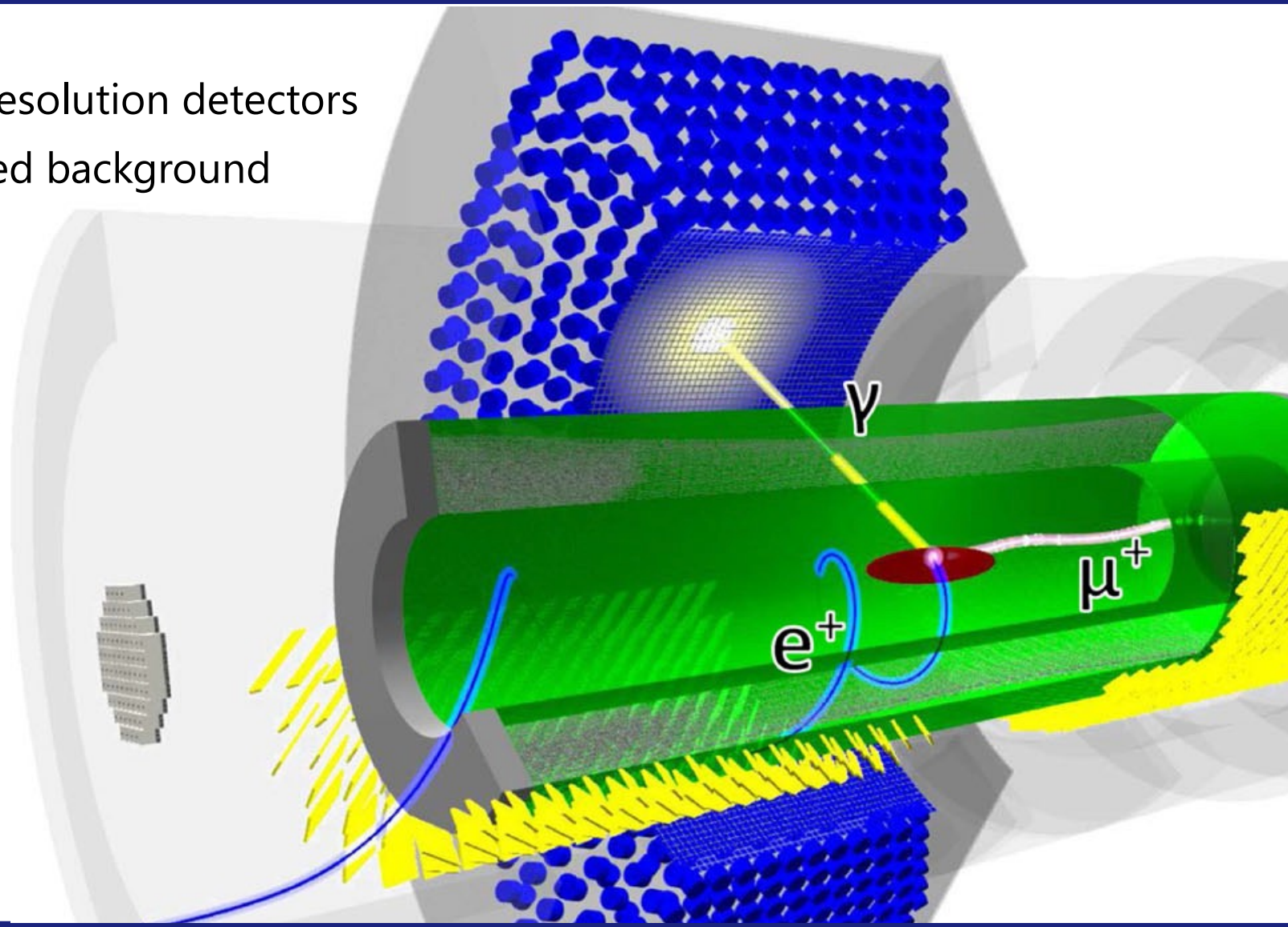
What is MEG II? Comprehensive summary was presented by Kensuke (16aEK108-13)

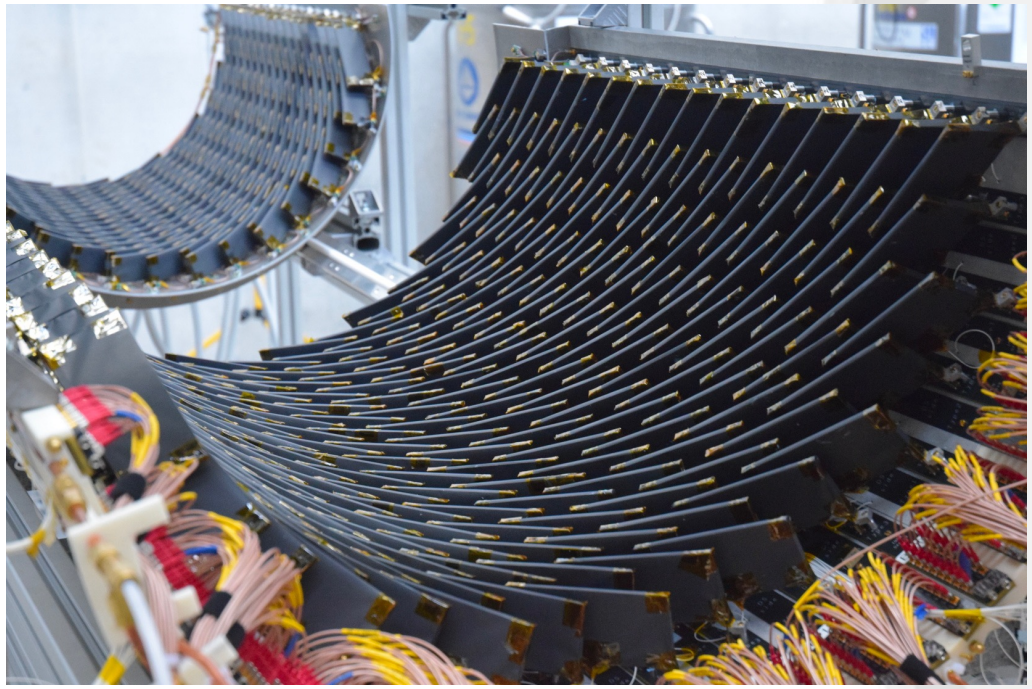
Want to know more about detectors and analysis? Check talk by Atsushi, Sei, and Ryusei (16pEK104-7, 17aEK104-{6,7})

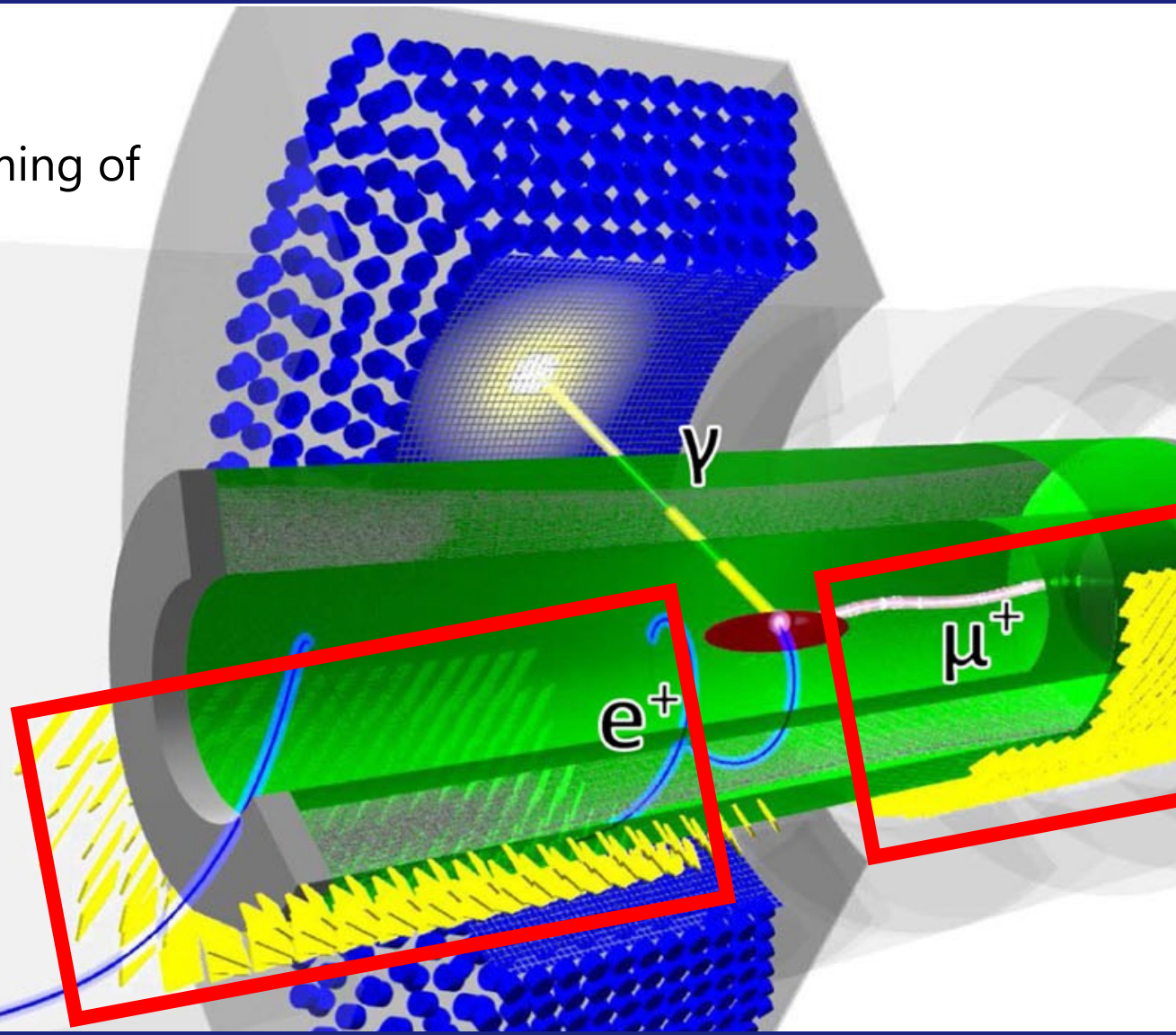
After 2026? Okay, let's talk about the future! Coming right after this talk by Rei (18pEK104-2)



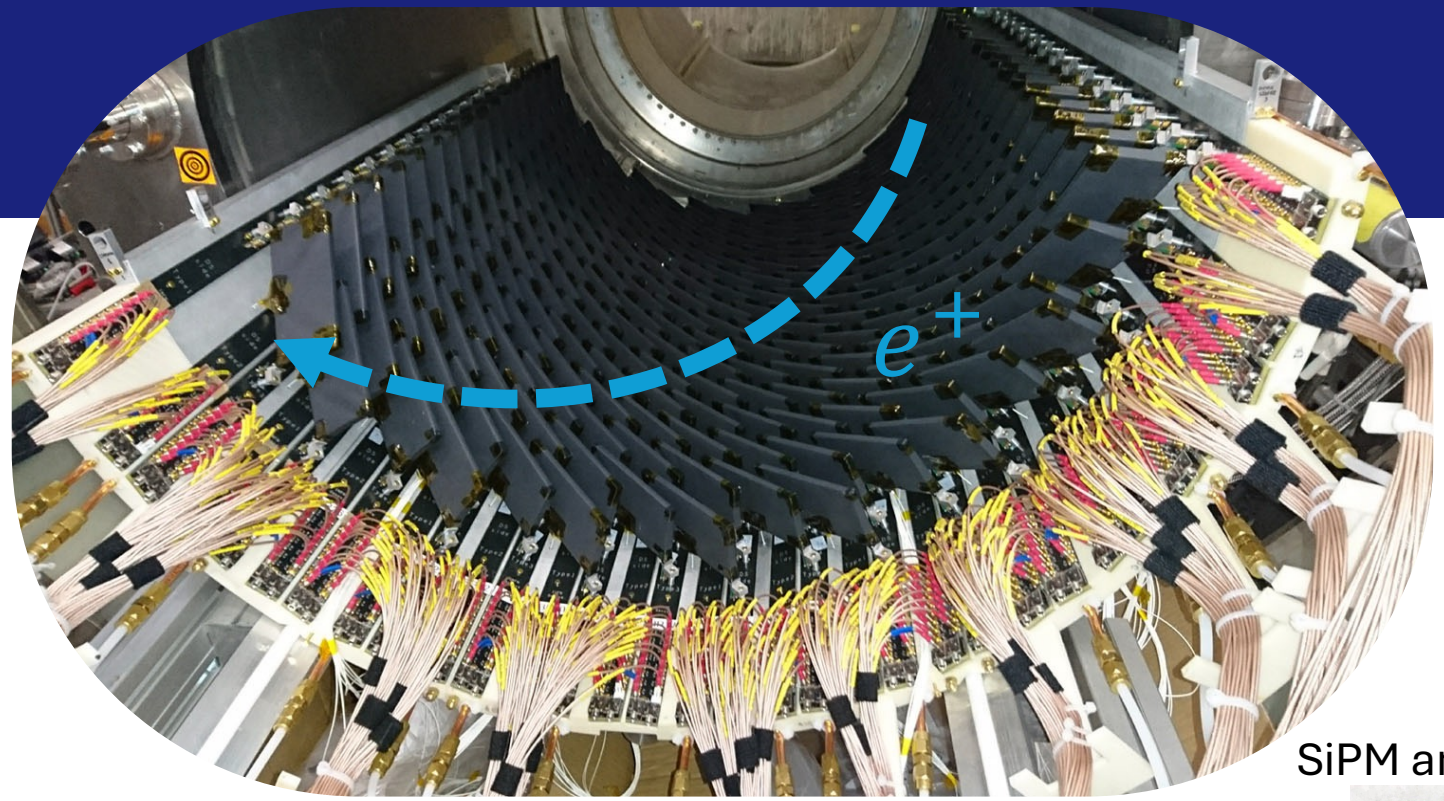
MEG II

Pixelated Timing Counter (pTC) measures the timing of positrons in average ~40 ps



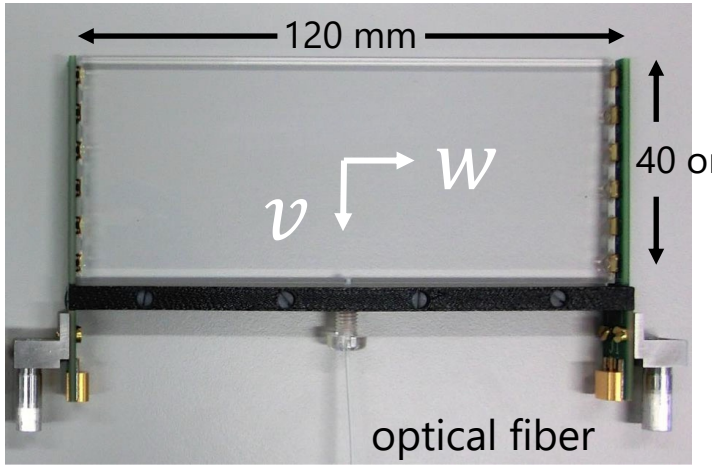


pTC Features

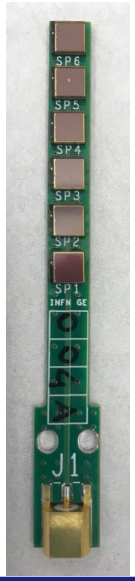


- 512 tiles of fast plastic scintillator,
  256 for up/downstream each
  * high-resolution by multiple hits
    improves as $\propto 1/\sqrt{N_{\mathrm{hit}}}$
- Readout at both ends by series-connected arrays of six SiPMs
  * Not sensitive to v position in the pixel
- Laser fiber embedded at the center per tile enables inter-pixel synchronization and performance monitoring

※ 80 counters replaced (2023→2024) to mitigate irradiation damage accumilated in past years



SiPM array



pTC Time Calibration

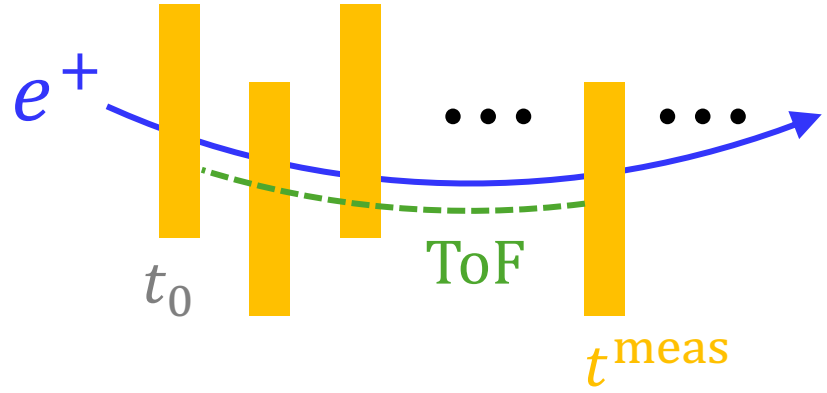
"Timing alignment" —two complementary method

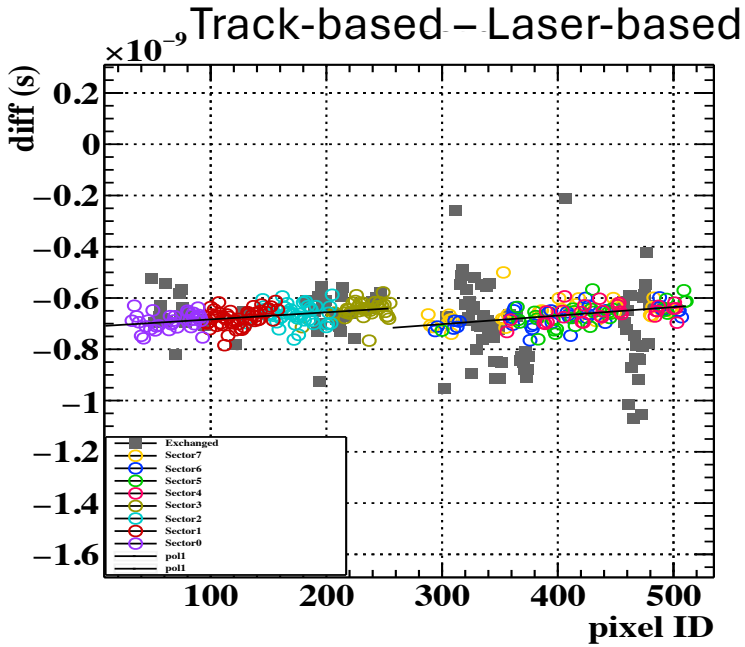
- Track-based:

$$\chi^2 = \sum^{\text{events}} \sum^{\text{hits}} \left(\frac{t^{\text{meas}} - (t_0 + \text{ToF} + \text{offset})}{\sigma} \right)^2$$

Calibrate offset to minimize χ^2

- Laser-based
  - Removes position-dependent biases in the track-based method
  - Defines upstream-downstream relative offset
  - Check & split calibration period



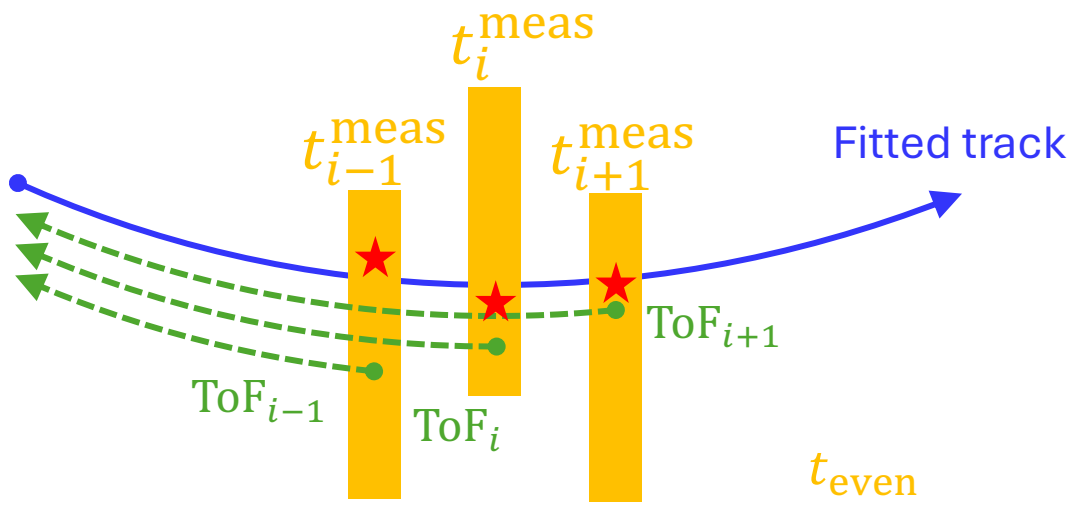


pTC Time Reconstruction & Resolution Evaluation

Time reconstruction

- ToF_i from track fit
- pTC reconstructed time:

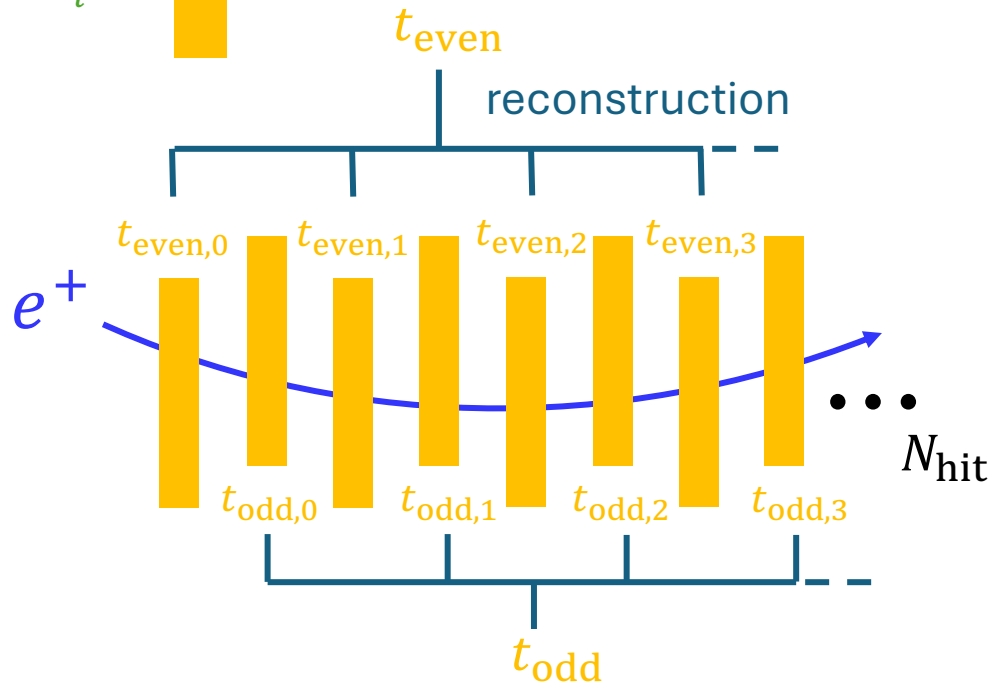
$$t_{\mathrm{pTC}} = \mathrm{avg}(t_i^{\mathrm{meas}} - \mathrm{ToF}_i)$$



Resolution evaluation: Even-Odd method

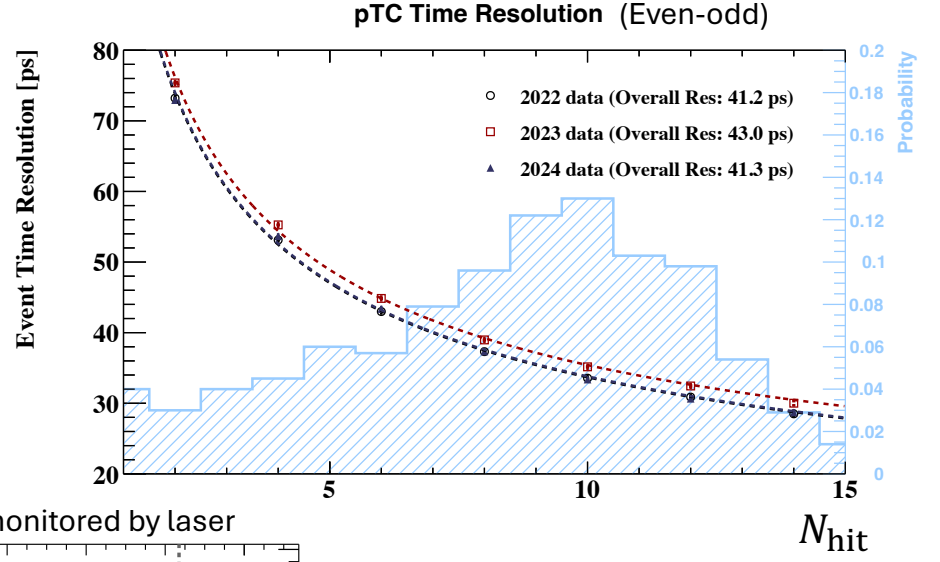
- Select tracks with even number of hits (N_{hit})
- Split hits into even/odd indices
- Reconstruct t_{even}, t_{odd} independently
- Compare and evaluate time resolution according to N_{hit}

$$\sigma(t_{\mathrm{pTC}}) \approx \sigma(t_{\mathrm{even}} - t_{\mathrm{odd}})/2$$

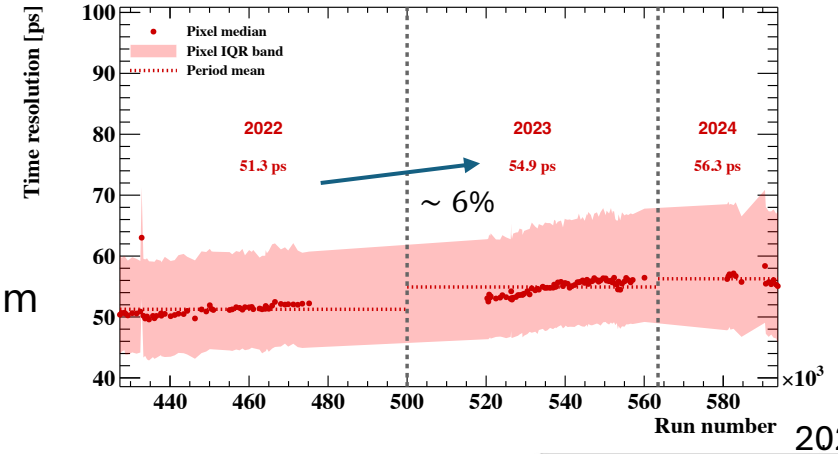


pTC Time Resolution

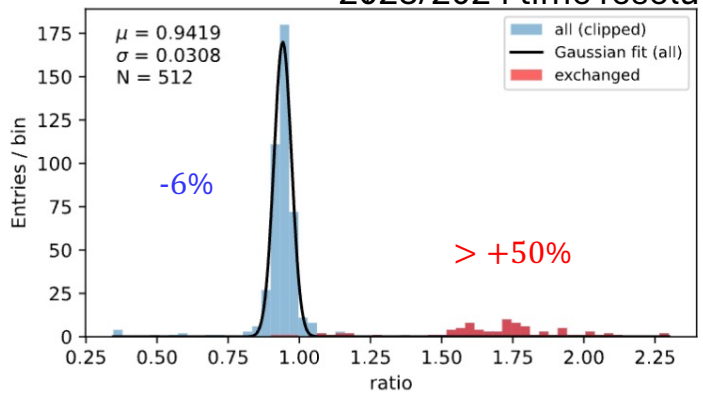
- Weighted by the signal N_{hit} distribution from MC to gain overall time resolution
  - 2023: 43 ps
  - 2024: 41 ps
- 2023 shows ~ 4% degradation from 2022 —most likely due to irradiation damage
  - Laser monitor which shows pure contribution from each pixel has degradation of ~ 6% in ave.
- 2024 recovered to 2022 level
  - Thanks to partial renewal of 80 pixels
  - Unchanged pixels degraded by ~ 6 % due to long run period + suboptimal cooling
  - Newly installed pixels shows more than 50% resolution improvement



Time resolution monitored by laser



2023/2024 time resolution ratio

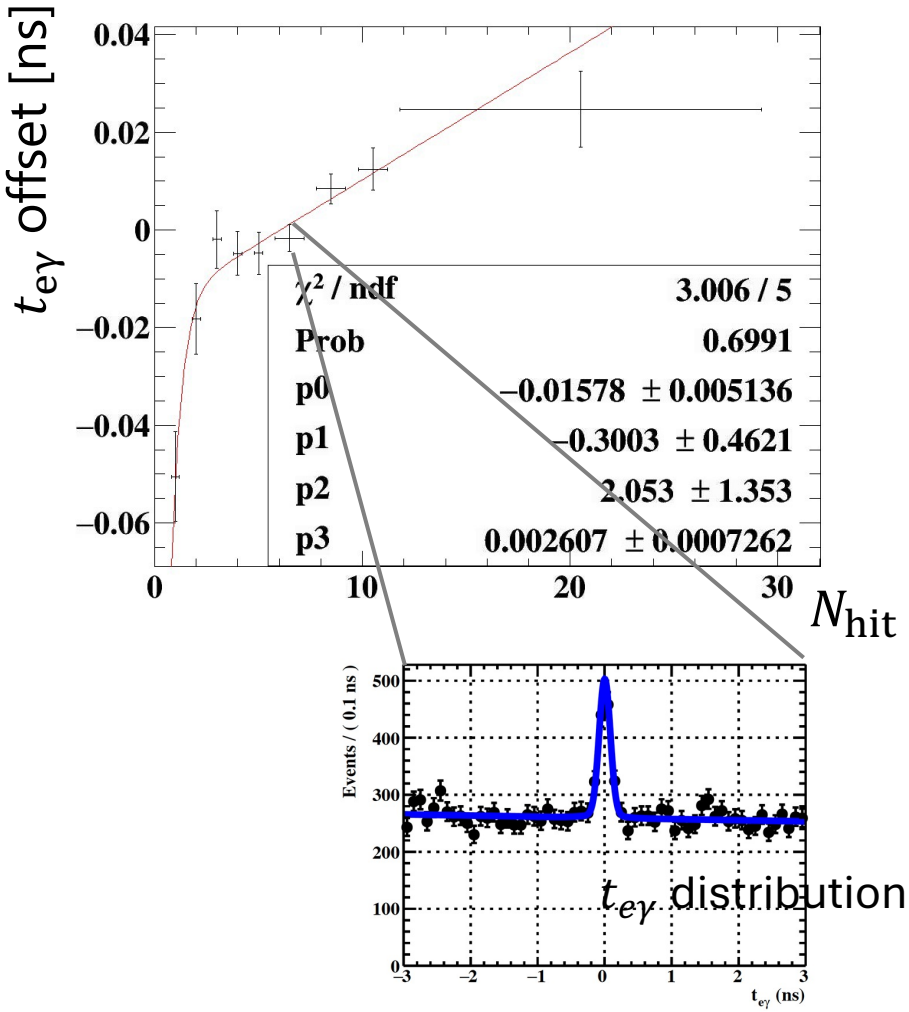


Time Bias Investigation

RMD time offset

- Radiative muon decay (RMD): $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e \gamma$
- Using RMD events to calibrate time offset for $t_{e\gamma} = t_{e^+} - t_\gamma$
- Observed an $\mathcal{O}(10\,\mathrm{ps})$ bias correlated N_{hit} in 2021–2022 dataset
- Prior analyses used an ad-hoc N_{hit} correction

Time bias correlated to N_{hit}



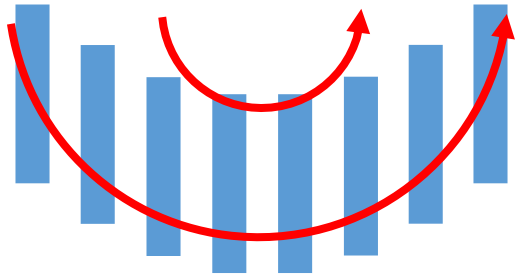
$t_{e\gamma}$ distribution from RMD

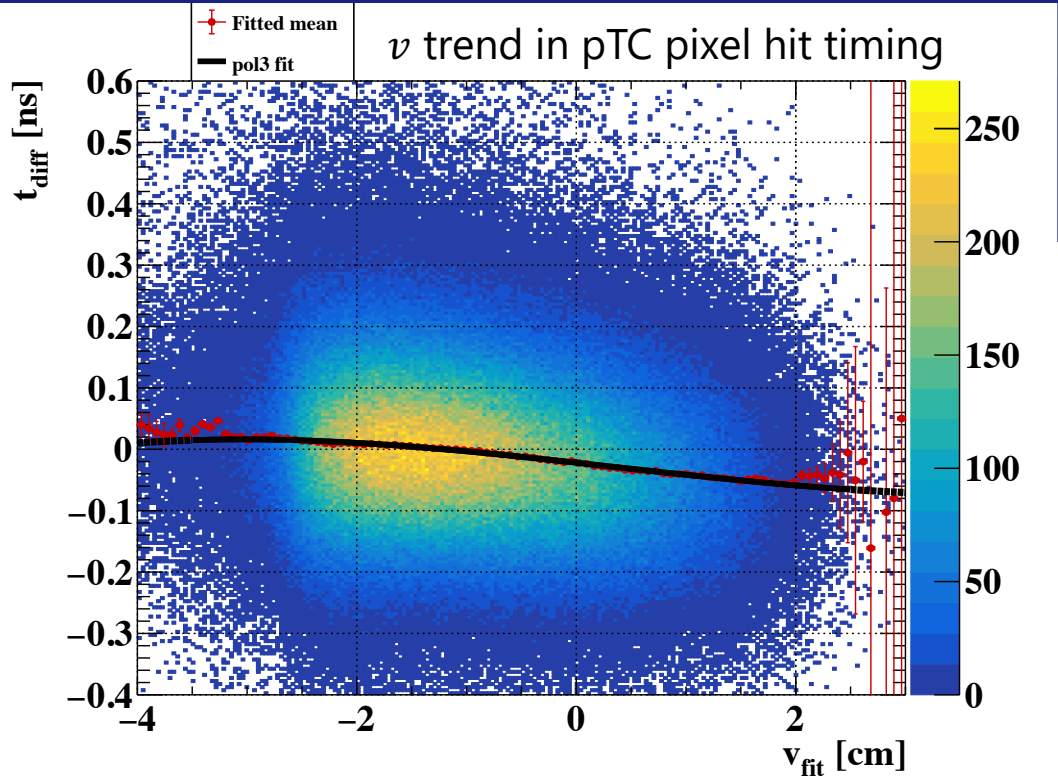
Time Bias Investigation

v position dependence

- The per-hit coordinate v_{fit} from track fits reveals a residual bias in $t_{\mathrm{diff}} = t^{\mathrm{meas}} - t_{\mathrm{pTC}}$ of $\mathcal{O}(10\ \mathrm{ps})$
- The bias exists in t_{pTC} as well
  → A few iteration with updated t_{pTC} to extract pure v dependency
- Validation with RMD is ongoing

Time Bias Investigation





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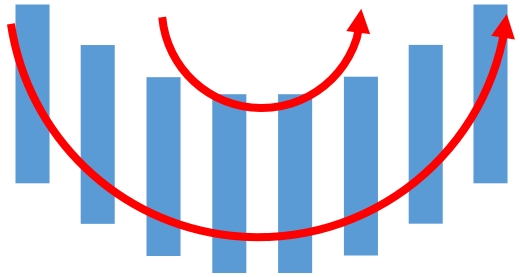
Time Bias Investigation

Low N_{hit} ~ Low v



High N_{hit} ~ High v

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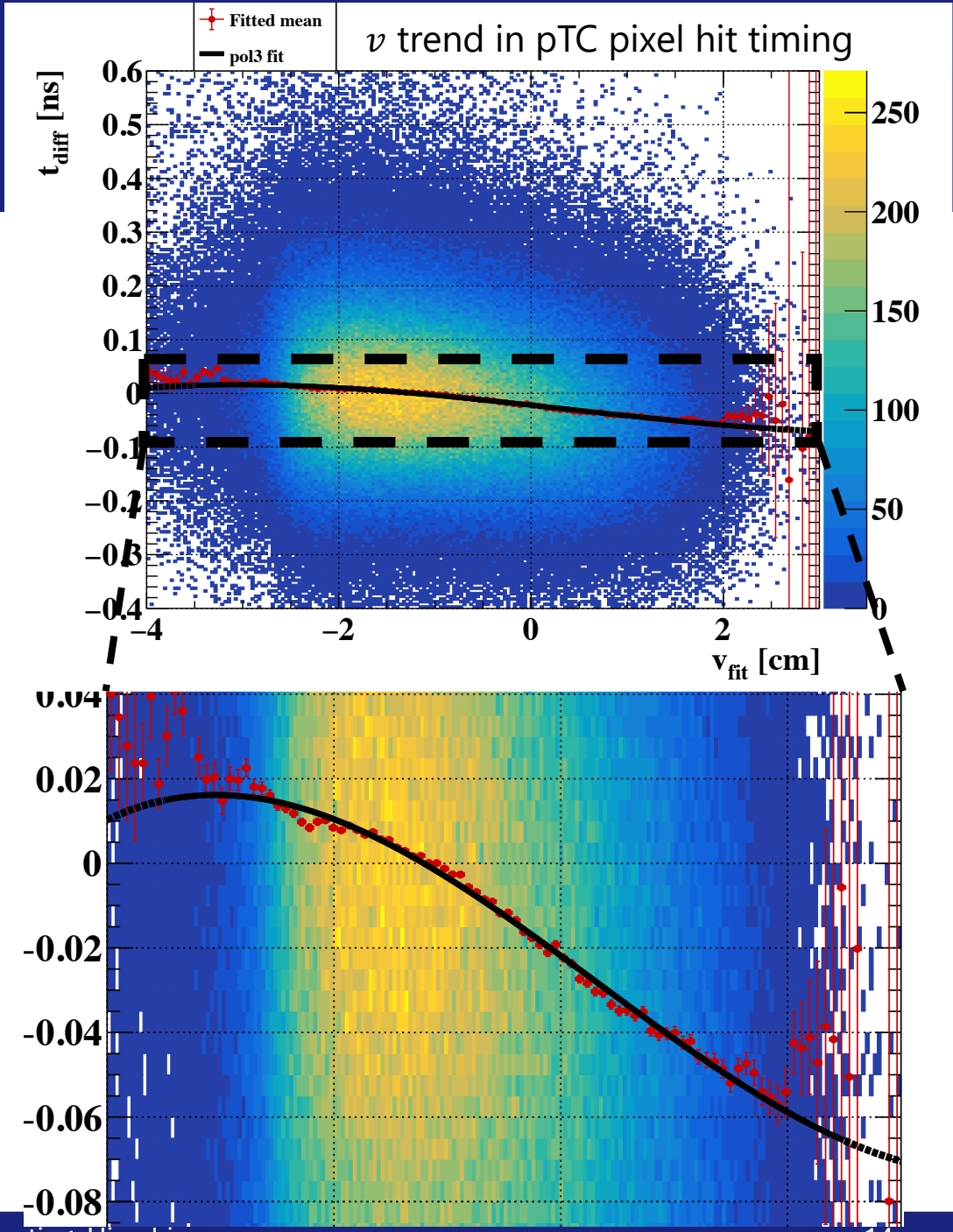

Summary

- The MEG II experiment searches for $\mu \to e\gamma$;
  started in 2021 and will continue DAQ until 2026
- Calibration of pTC for 2023 and 2024 datasets have completed:
  time resolution of 43 ps and 41 ps.
- Time bias by v position of the hits in pTC is as large as $\mathcal{O}(10\ \mathrm{ps})$,
  which likely to explain the time offset bias in $t_{\mathrm{e\gamma}}$