MEG II実験2021年物理データの解析
- 陽電子測定の評価と物理解析の現状 -

大矢 淳史, 他MEG IIコラボレーション

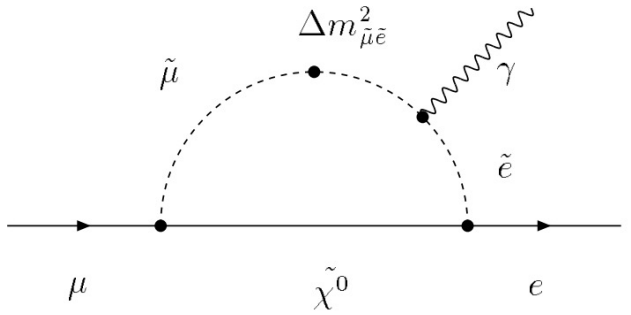
日本物理学会2022年秋季大会

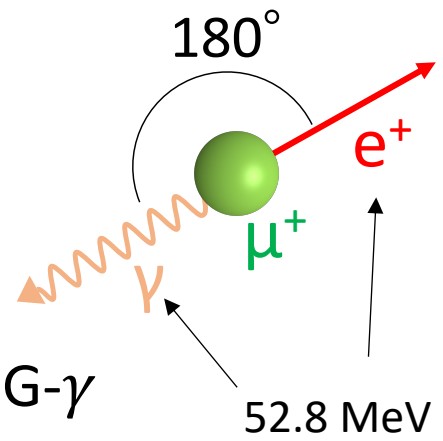
Motivation and principle of $\mu \to e\gamma$ search

- $\mu \to e\gamma$ search at MEG II
  - CLFV decay, forbidden in SM
  - Target sensitivity: Br($\mu \to e\gamma$) ~ $\mathbf{6\times10^{-14}}$
    → Can probe O(10 TeV) physics

- Search strategy
  - Signal identified by kinematics
    - Statistics: $N_{sig} \propto R_\mu \cdot T \cdot Br(\mu \to e\gamma) \cdot \epsilon$
  - Main BG: Accidental coincidence of BG-e & BG-γ
    - $N_{BG} \propto R_\mu^2 \cdot T \cdot \delta E_e \cdot \delta E_\gamma^2 \cdot \delta\theta^2 \cdot \delta T$
      → Use of DC beam @PSI
      → High resolution measurement

New physics example:
$\mu \to e\gamma$ from slepton mixing



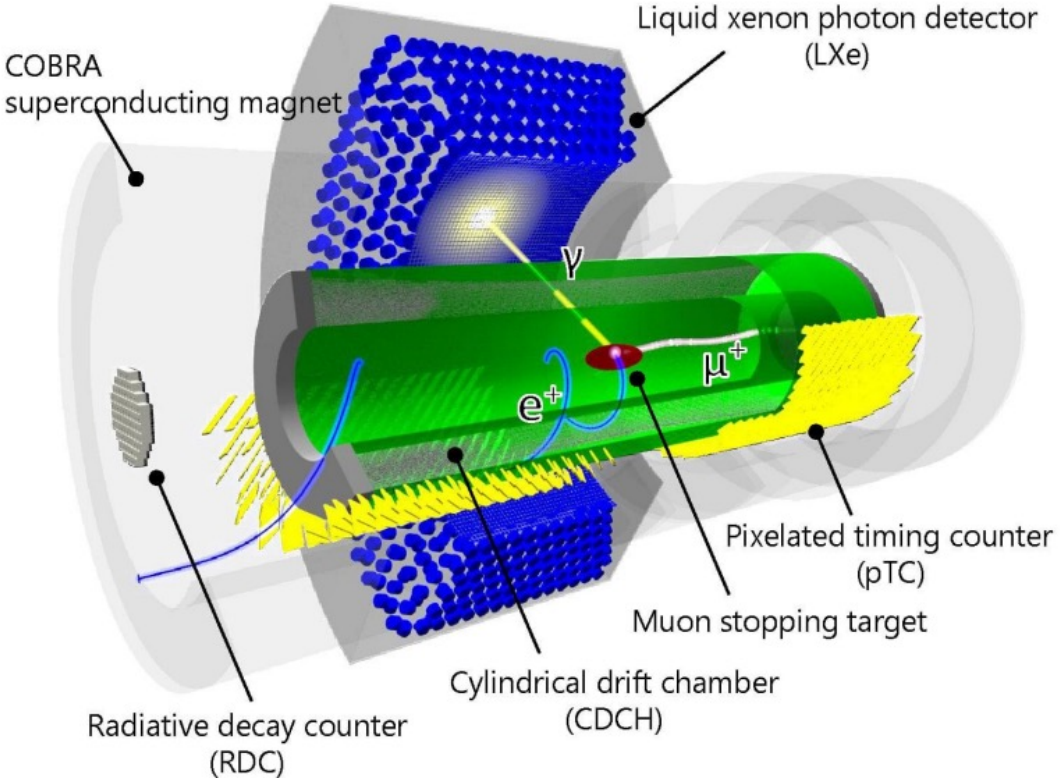


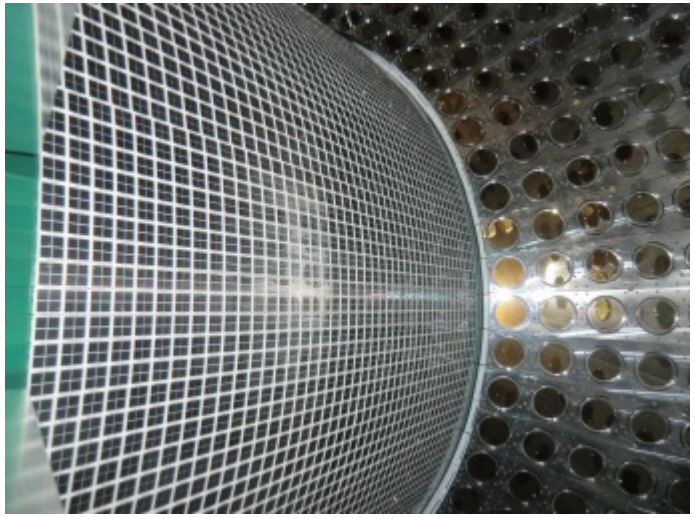
Notation	
R_μ	μ rate
T	Experiment time
ϵ	Efficiency
$\delta E, \delta T, \delta\theta$	Resolution

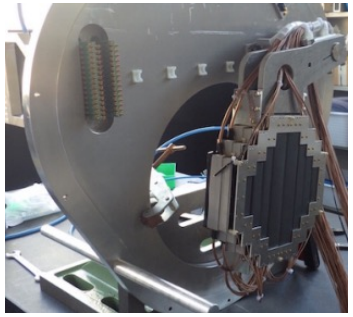
Kinematics	Signal	BG
$e\gamma$ time difference	Same time	No correlation
$e\gamma$ direction	Opposite	No correlation
E_e	52.8 MeV	< 52.8 MeV
E_γ	52.8 MeV	< 52.8 MeV

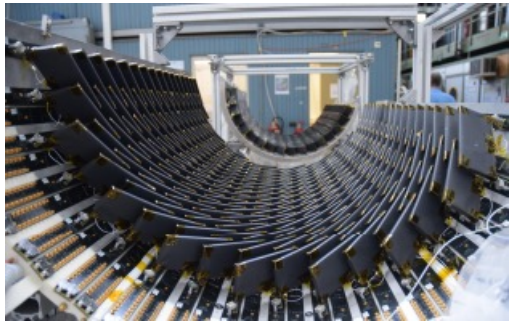
MEG II apparatus

- Apparatus
  - Muon stopped on target
  - Positron detection with magnet + DCH + pTC
  - Gamma detection with LXe detector
  - BG-γ tagging with RDC detector



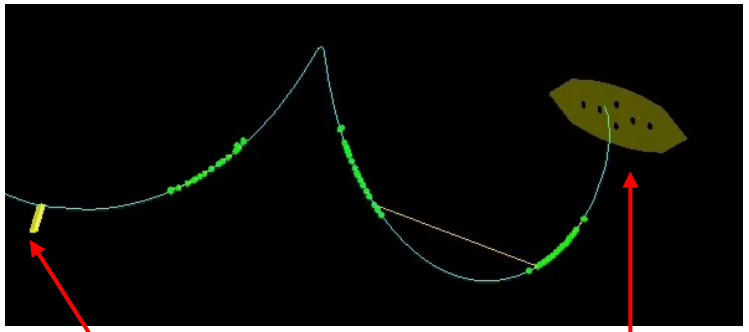


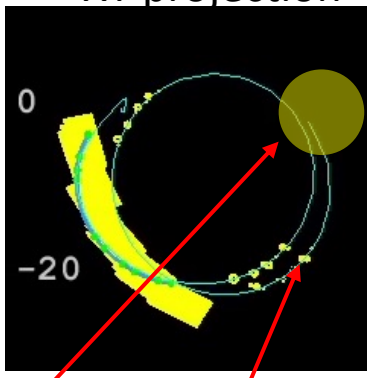




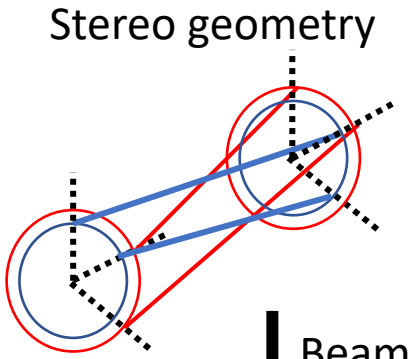
MEG II apparatus (vertexing & tracking)

- Positron trajectory
  1. Emitted from target
  2. Make hits on drift chamber (DCH)
  3. 1.5 or 2.5 turns from target to timing counter (pTC)



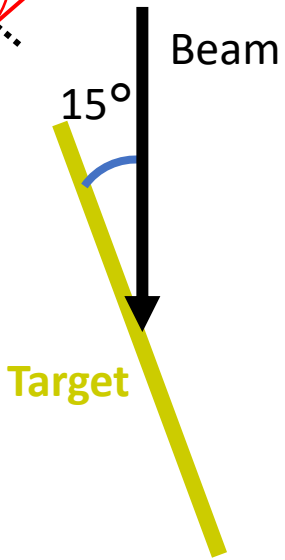


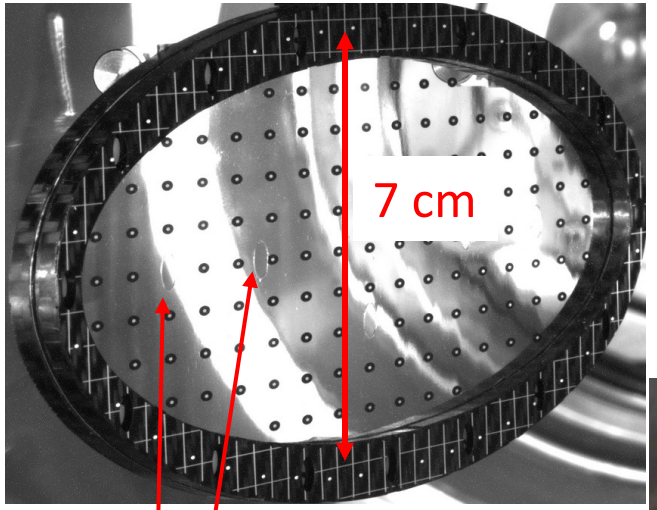
- Drift chamber
  - Stereo geometry wire chamber
  - $r_{inner} = 17$ cm, $r_{outer} = 27$ cm

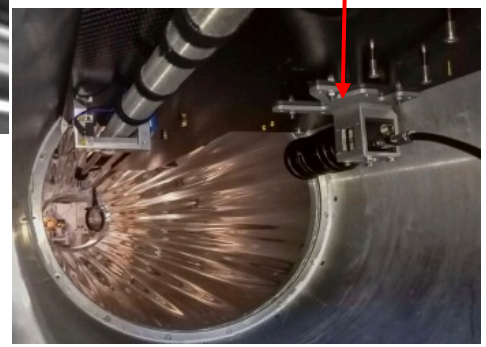


- μ stop target
  - 15° slanted w.r.t beam
  - $r \sim 3.5$ cm projected on XY plane
  - 6 holes
  - Camera
  - Dot markers

  } For alignment







https://doi.org/10.1063/5.0034842

Event reconstruction

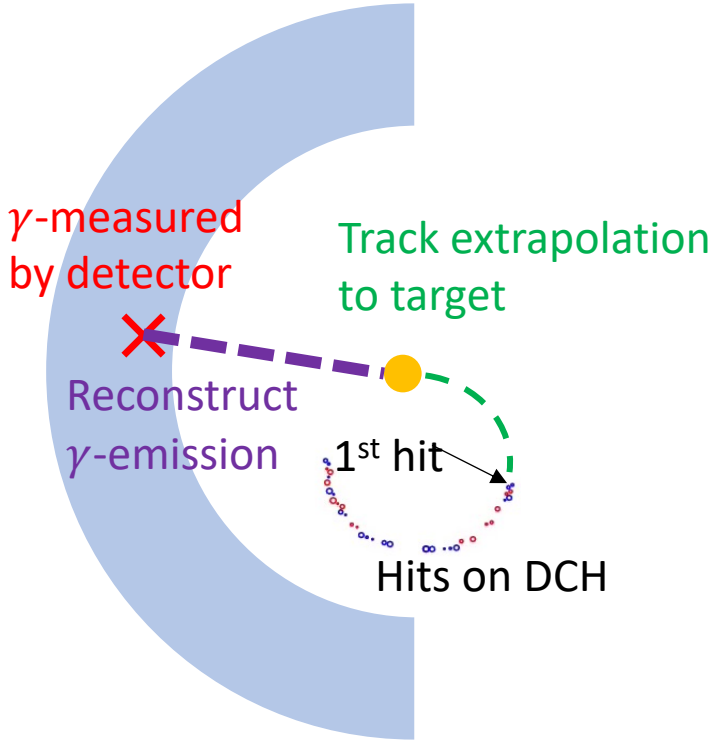
- Positron reconstruction
  - Decay position and angle by track extrapolation to target
  - t_e measured at pTC & TOF corrected (use decay point)
  - E_e from track curvature

  → **Evaluation of tracking & vertexing performance**

- Combination of positron and gamma
  - LXe detector measures variables at reaction point
  - Full γ-reconstruction rely on decay position from track
    - t_γ at vertex reconstructed with TOF correction
    - Gamma angle at vertex by connecting vertex and reaction point

  → **Need precise target alignment**

  → **Evaluation of combined resolution**



Outline

- Introduction

- Positron reconstruction and combined analysis
  - Tracking & vertexing performance evaluation
  - Combined time reconstruction
  - Alignment

- Sensitivity estimate
  - Overview of dataset
  - Likelihood analysis
  - Normalization

- Summary and prospect

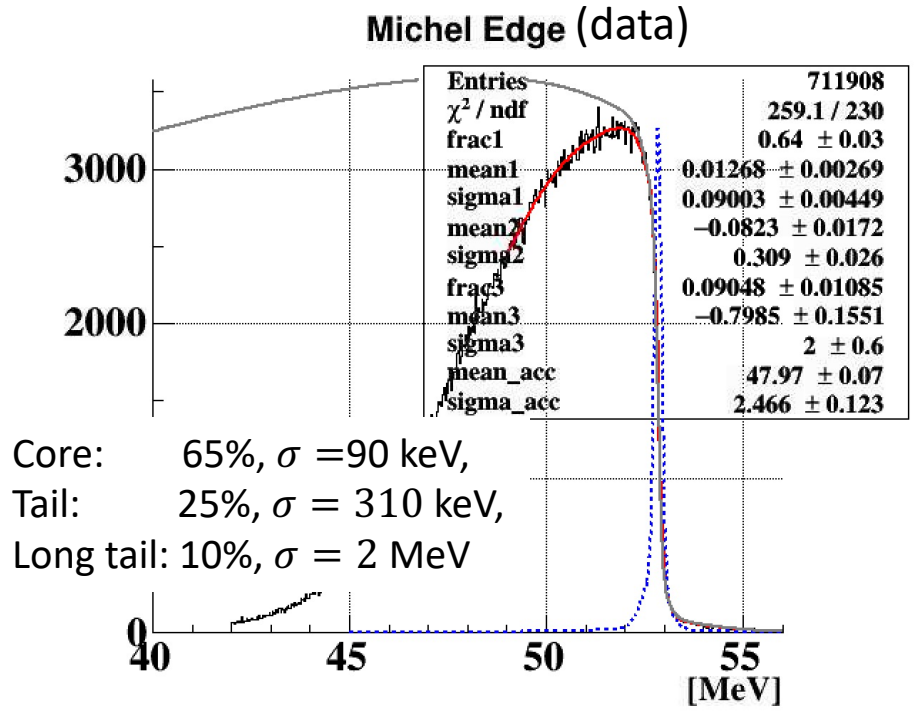
Tracking performance (1/2)

- Michel edge fitting
  - Fit function: $\mathrm{Eff}(E_e) \otimes$ Resolution of E_e
    - $\mathrm{Eff}(E_e)$: E_e dependence of efficiency (erf modeling)
    - Resolution: Modeled with triple gaussian

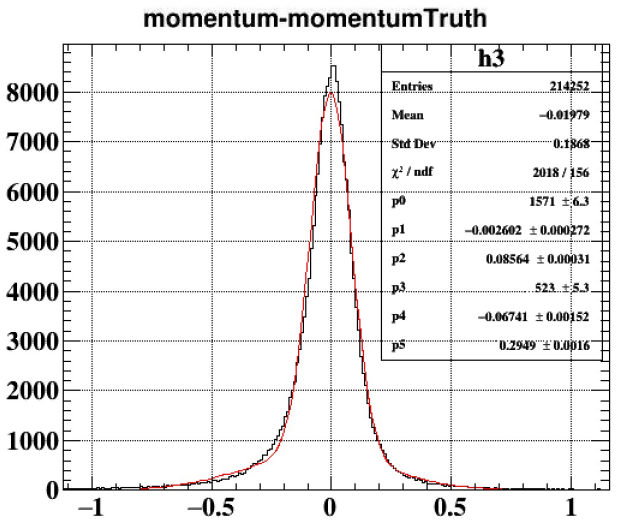
✓Good data-MC agreement achieved (a few %)

	Core	Core frac	Tail	Tail frac	Method
Data	90 keV	70%	310 keV	30%	Michel fit
MC	86 keV	75%	295 keV	25%	MC truth

- Improvement from MEG
  - MEG resolution was 306 keV
  - ×3 improvement achieved



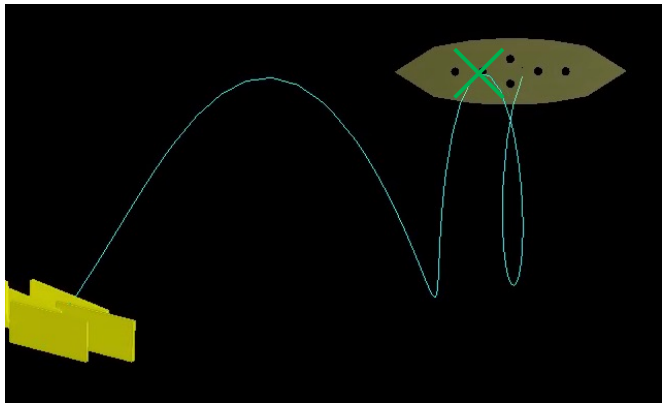
Core: 65%, σ =90 keV,
Tail: 25%, σ = 310 keV,
Long tail: 10%, σ = 2 MeV



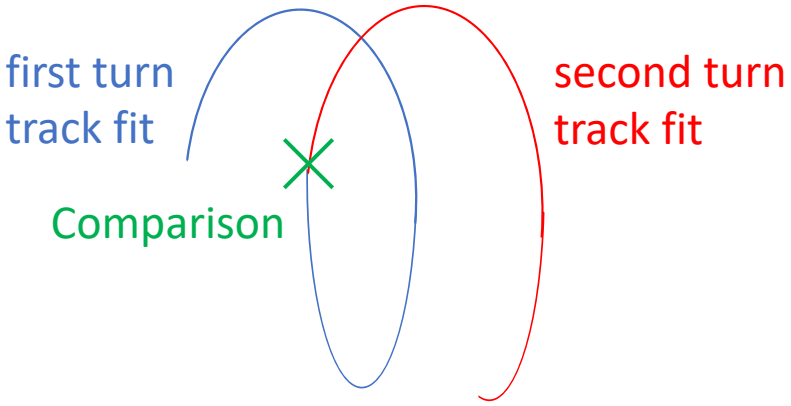
MC study:
MC reco − MCtruth

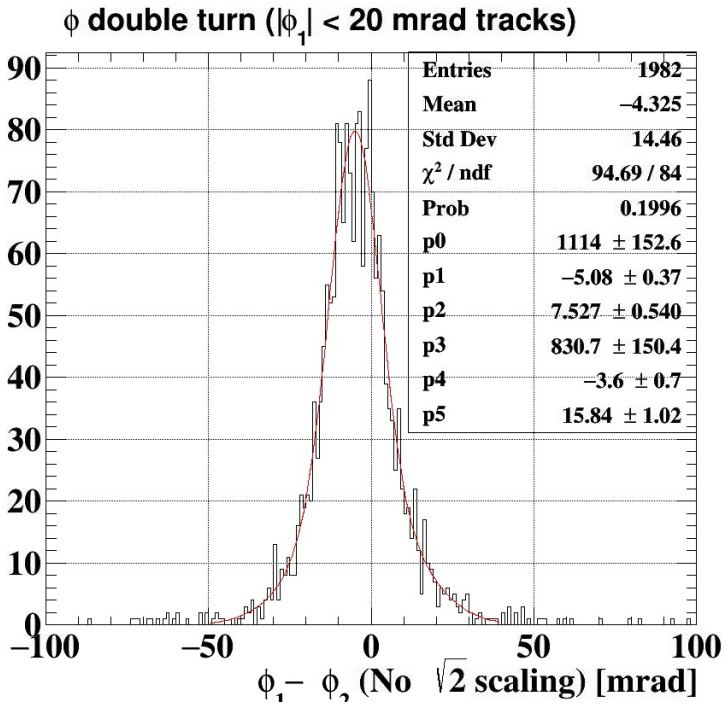
Tracking performance (2/2)

- Double turn analysis
  - Divide 2-turn tracks into different 1-turn tracks and compare
  - $\sigma_\phi, \sigma_\theta, \sigma_y, \sigma_z$ evaluation, σ_P cross-check
  - Systematics found and under investigation
    - Offset in difference b/w 1st turn and 2nd turn
    - B-field mis-calibration?
    - Wire mis-alignment?



	Currently achieved	MEG I
σ_ϕ	5.6 mrad	8.7 mrad
σ_θ	7.7 mrad	9.4 mrad
σ_y	0.8 mm	1.2 mm
σ_z	2 mm	2.4 mm

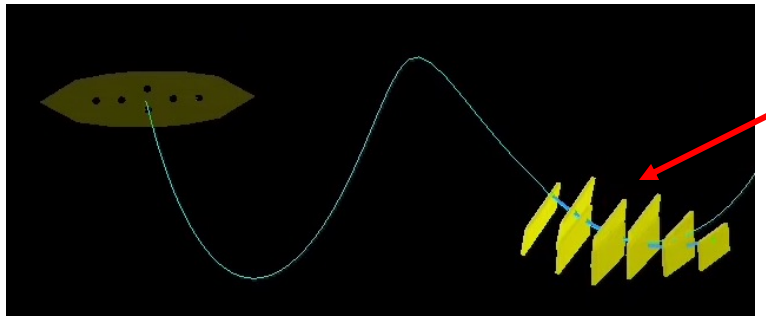




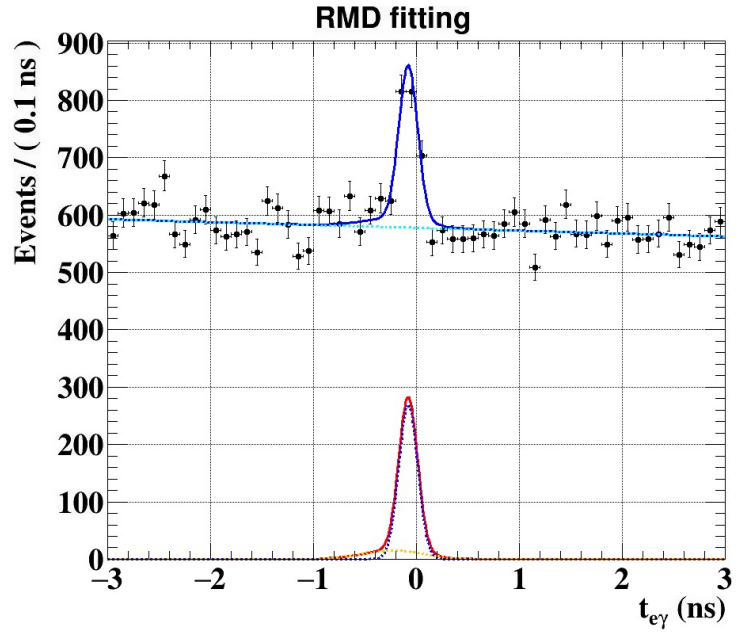
Combined time resolution

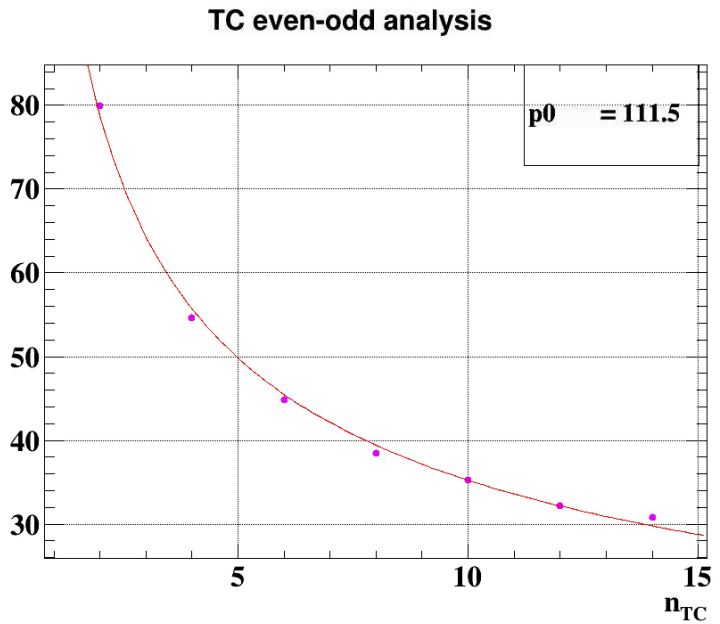
- Combined σ_t in RMD
  - Applied kinematical selections to have good S/B in fit
  - Result: $\sigma_t = 91 \pm 9$ ps

- Time resolution from each detector
  - ✓Even-odd analysis of pTC gives $\frac{112\ \text{ps}}{\sqrt{n_{TC}}}$ resolution
  - ✓CEX gives 61 ± 6 ps resolution for t_γ (previous talk)
  - $\sigma_t \ominus \frac{112\ \text{ps}}{\sqrt{n_{TC}}} = 75 \pm 10$ ps



Multiple hits are made on pTC.
n_{TC} is # of pTC counter used in timing.

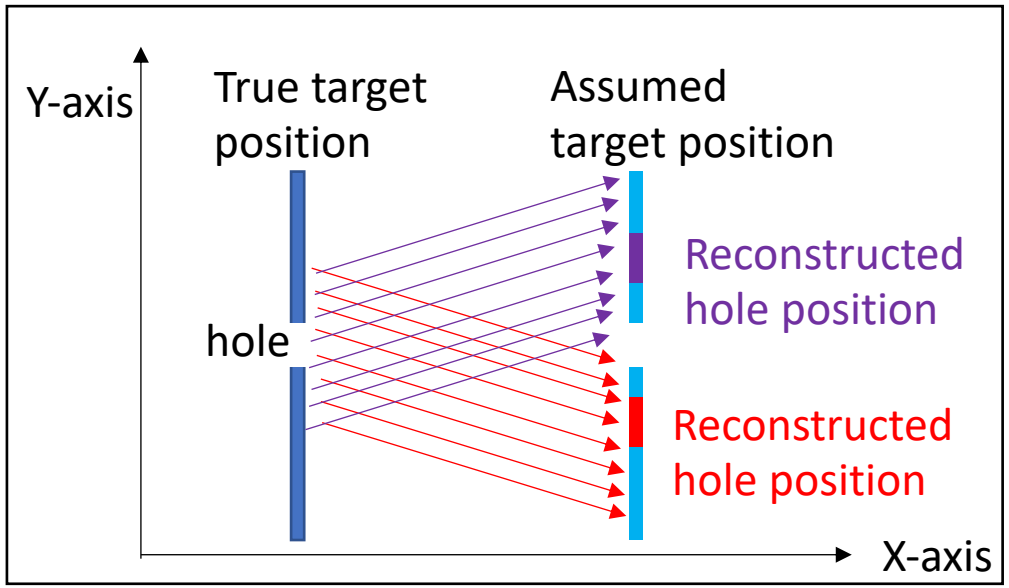


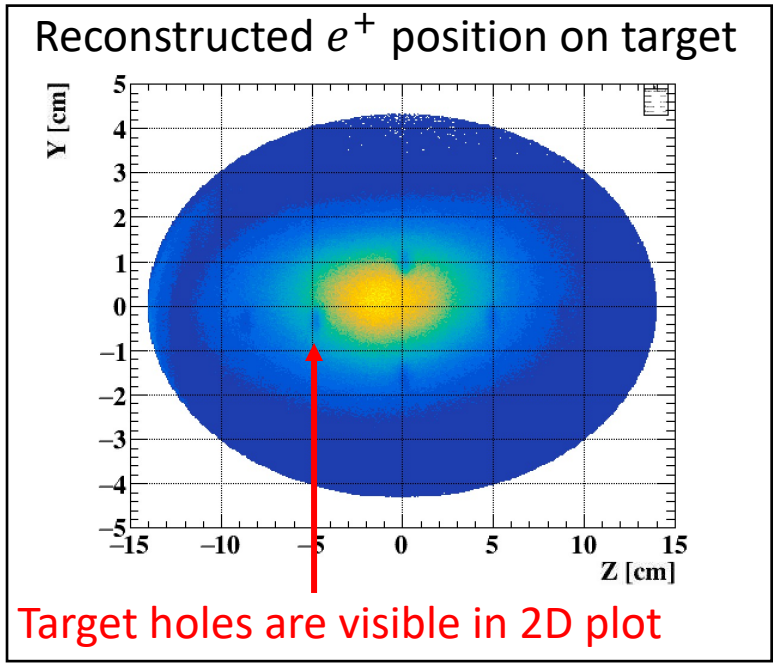


Detector alignment

✓DCH-target alignment with target hole analysis

- Hole position vs track direction analysis
- Up to 200 – 300 μm difference between track and optical method (CT-scan)





Track – CT difference for different holes

Difference of x,y,z (cm)
(-0.011, -0.008, 0.05)
(-0.01, -0.005, 0.05)
(0.003, -0.027, 0.003)
(-0.003, -0.022, 0.016)
(0.032, -0.029, -0.014)

➡ Global offset roughly (0.01, -0.017, 0.02)

- **To do**
  - Global alignment between DCH and LXe detector with cosmic ray
  - Time variation of target position with camera data (up to 300 μm is already found)

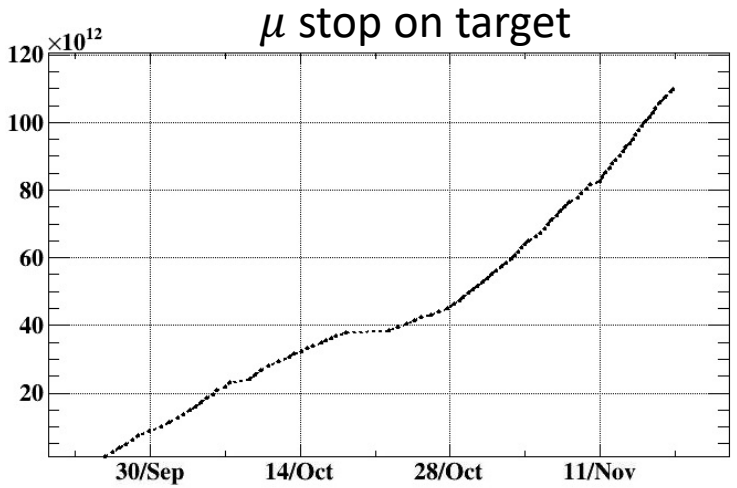
Outline

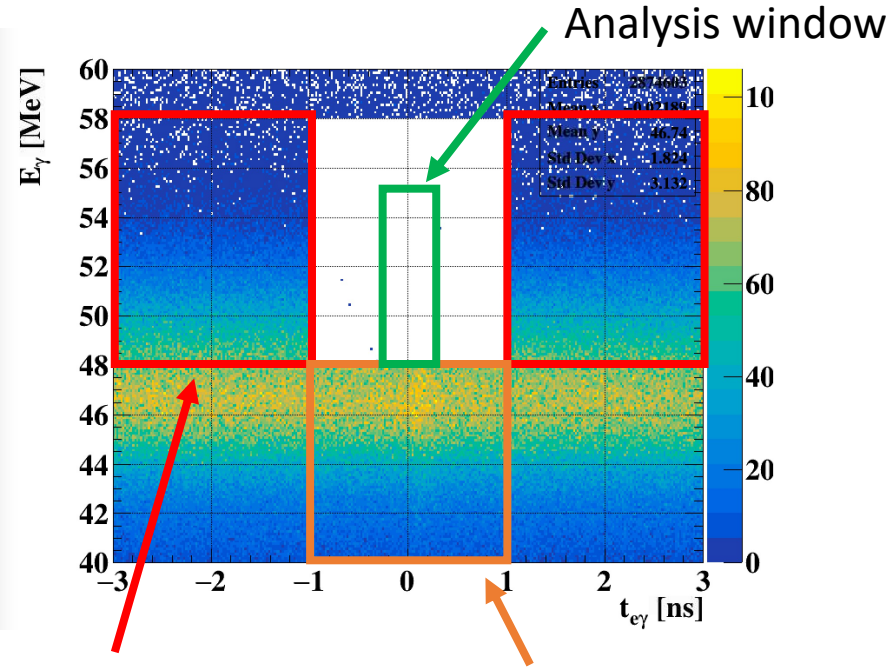
- Introduction
- Positron reconstruction and combined analysis
  - Tracking & vertexing performance evaluation
  - Combined time reconstruction
  - Alignment
- Sensitivity estimate
  - Overview of dataset
  - Likelihood analysis
  - Normalization
- Summary and prospect

2021 dataset

- DAQ in 2021 pilot run
  - Not a full-year physics run
    - Needed to define data taking scheme
    - Finally achieved fully efficient DAQ in Oct
  - Beam rate change during the run
  - Also took required set of calibration data

- Situation with 2021 data analysis
  - Enough quality for physics analysis
  - Analysis in progress
    - Blinded done with $t_{e\gamma}, E_\gamma$
    - Detector performance evaluation
    - BG studies with sidebands





Analysis overview

- Likelihood analysis to estimate N_{sig}
  - Extended un-binned fit on energy, angle, time and RDC

$$L(N_{sig}, N_{Acc}, N_{RMD}) = \exp\left(-\frac{(N_{RMD}-\mu_{RMD})^2}{2\sigma_{RMD}^2}\right) \times \exp\left(-\frac{(N_{Acc}-\mu_{Acc})^2}{2\sigma_{Acc}^2}\right)$$

Constraints to BG from sidebands
(Addition to usual extend fit)

$$\times \frac{e^{-(N_{sig}+N_{Acc}+N_{RMD})}}{N_{obs}!} \times \prod_{dataset}\left(N_{sig}\cdot S(x) + N_{acc}\cdot A(x) + N_{RMD}\cdot R(x)\right)$$

Same as usual extend fit formalism

PDFs of $E_e, E_\gamma, t_{e\gamma}$ etc.

  - Confidence interval
    - Feldman-Cousins method, profile likelihood ratio used for ordering: $\lambda(N_{sig}) = \frac{L(\text{best fit with fixed } N_{sig})}{L(\text{full best fit})}$
      https://doi.org/10.1103/PhysRevD.57.3873

- Branching ratio
  - Branching ratio given by dividing with normalization: $Br = \frac{N_{sig}}{k} = N_{sig} \times \text{SES}$

PDF parameters for sensitivity estimation

	Currently achieved performance in MEG II	Performance in MEG
θ_e, ϕ_e	7.7/5.6 mrad: From double turn analysis	9.4/8.7
y_e, z_e	0.8/2 mm: From double turn analysis	1.2/2.4
E_e	Double gaussian (90 keV + 310 keV): From Michel fit	306
E_γ	2%: From CEX resolution analysis	2.4% (w<2 cm), 1.7% (w>2cm)
u, v, w_γ	2.5 mm for w < 2 cm: From collimated gamma ray data	5 mm
$t_{e\gamma}$	85 ps for core (83%), 280 ps for tail (17%): From RMD time	122 ps
RDC	Not yet included in sensitivity calculation	Not installed

- Notes
  - Core $t_{e\gamma}$: $\frac{112}{\sqrt{n_{TC}}} \oplus 70$ in reality, but per-event error is not ready in sensitivity calculation
  - E_γ: In edge region, 2021 calibration data lacks statistics and expected to be worse than 2%
  - u, v, w_γ: Dependent on w_γ

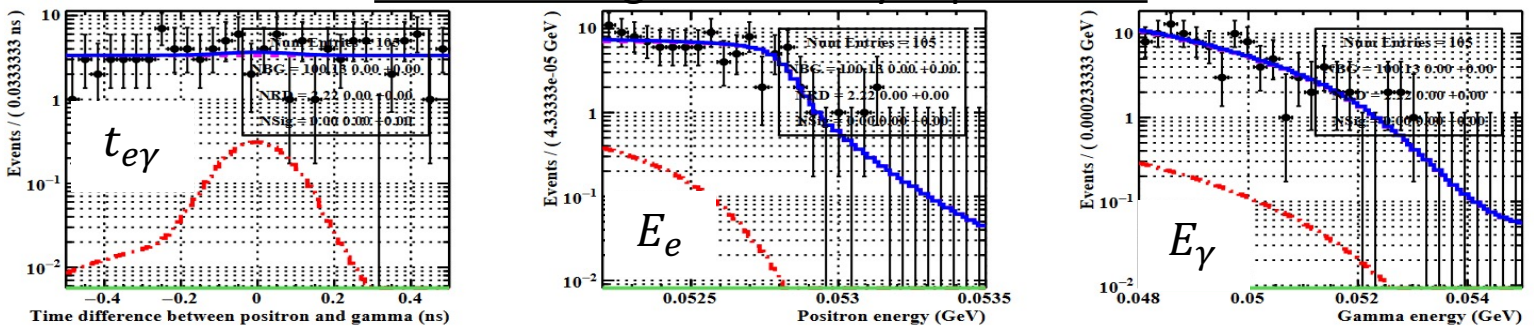
Sensitivity to N_{sig}

- Analysis with preliminary selections
  - Analysis window
  - No gamma selections (cosmic veto, pileup etc.)
  - Preliminary positron tracking quality cuts

Analysis window
- $\theta_{e\gamma}$ < 40mrad
- $\phi_{e\gamma}$ < 40mrad
- $t_{e\gamma}$ < 500 ps
- 52.2 MeV< E_e <53.5 MeV
- 48 MeV< E_γ <55 MeV

- Expected 90% C.L sensitivity on $N_{sig} = 2.3$ for 2021
  - Expected with N_{BG} estimated from $t_{e\gamma}$ sideband data
  - 2.3 is almost BG-free like value
  - Sensitivity: Median of upper limit in toy experiments

Fit to one of generated toy experiments



Michel normalization

- Method with **positron efficiency & beam rate automatically included**
  - Use of events on positron-only trigger (applied with pre-scaling)
  - Calculation

$$k_{Michel} = \frac{N_{\mathrm{Michel}}}{Br(\mu \to e\nu\nu)} \cdot \frac{P_{\mathrm{MEG}}}{P_{\mathrm{Michel}}} \cdot \frac{\epsilon_{\mathrm{MEGTRG}}}{\epsilon_{\mathrm{MicTRG}}} \cdot \frac{\epsilon_{53\,\mathrm{MeV}}}{\epsilon_{\mathrm{Michel}}} \cdot \epsilon_{\gamma} \cdot \epsilon_{\mathrm{sel}}$$

: Evaluation of $\epsilon_{\mathrm{MEGTRG}}$, ϵ_{γ}, ϵ_{sel} still in progress

Reconstructed # / branch

Trigger pre-scale correction

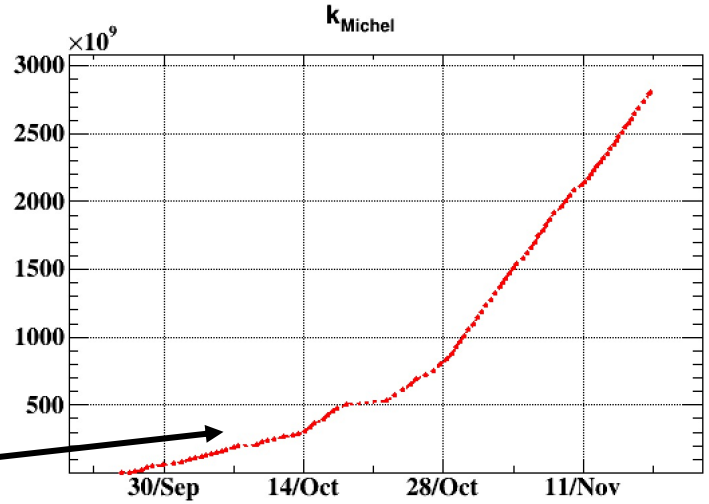
Trigger efficiency correction

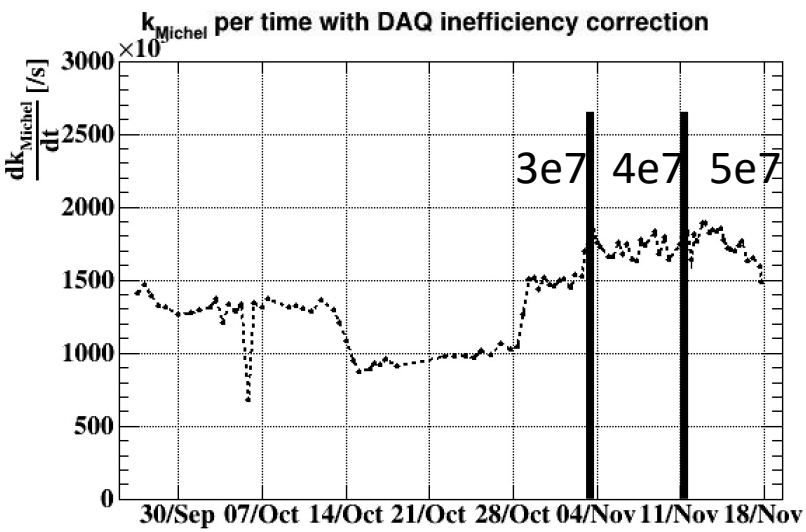
Gamma efficiency and selection efficiency

Correction of positron efficiency dependence on E_e

- Result
  - $k_{Michel} = 2.8\times10^{12}$
  - May have up to 20 % systematics
    - Selection efficiency

DAQ was not fully-efficient in the first period





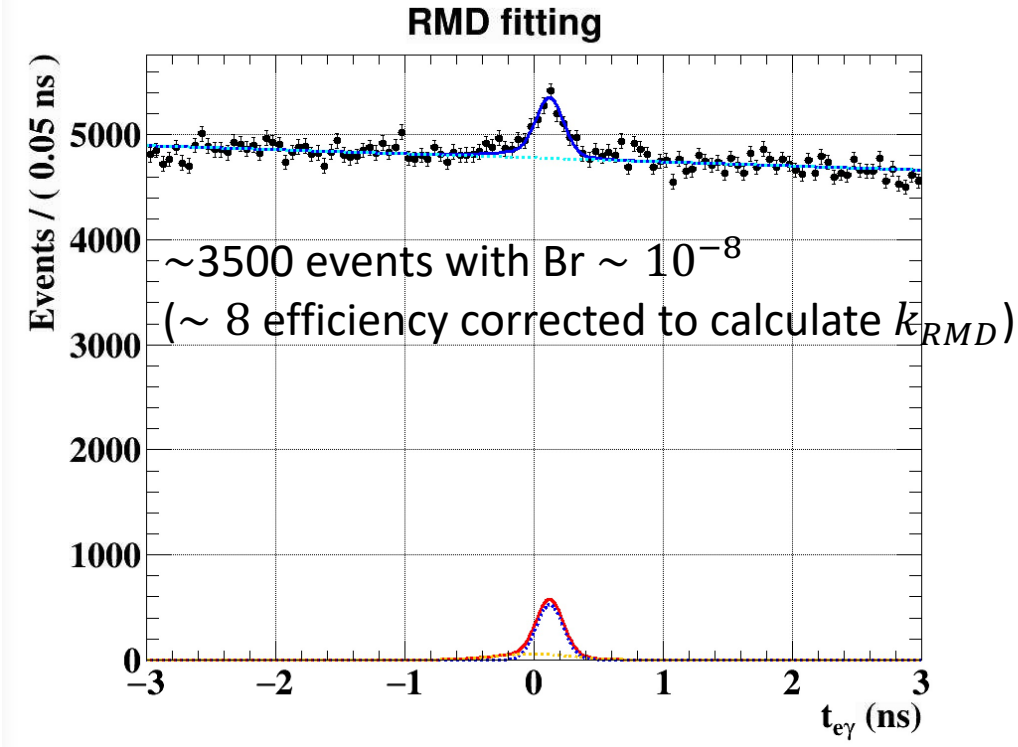
RMD normalization

- Method with **gamma efficiency also automatically included**
  - Larger correction than Michel normalization
  - Use of energy sideband data: $45 < E_e < 52.8$ & $45 < E_\gamma < 48$ region
  - Calculation

$$k_{RMD} = \frac{N_{RMD}}{Br(RMD)} \cdot \frac{\epsilon_e^{SIG}}{\epsilon_e^{RMD}} \cdot \frac{\epsilon_\gamma^{SIG}}{\epsilon_\gamma^{RMD}} \cdot \frac{\epsilon_{TRG}^{SIG}}{\epsilon_{TRG}^{RMD}} \cdot \frac{\epsilon_{sel}^{sig}}{\epsilon_{sel}^{RMD}}$$

Efficiency corrections:
~ 8 (preliminary) correction for
$45 < E_e < 52.8$ & $45 < E_\gamma < 48$

Evaluated with extended fit to time peak



- Result
  - $k_{RMD} = 2.75 \times 10^{12}$
  - May have > 20% systematics
    - Can be improved with detailed investigation with different kinematical cuts

Summary and prospect

- Presented positron tracking performance

	Currently achieved performance
$\theta_e, \phi_e, y_e, z_e$	7.7mrad/5.6 mrad/0.8 mm/2mm : Evaluated from double turn analysis
E_e	Double gaussian (90 keV + 310 keV): From Michel fit

- $\mathbf{8.2\times10^{-13}}$ branching ratio sensitivity with 2021 **pilot run** dataset
  - Approaching the MEG I full data (2009 – 2013) sensitivity
  - Though **beam time was not fully exploited** for physics data taking (effectively 4 weeks)

	Normalization	N_{sig} sensitivity	Br sensitivity
2021	2.8×10^{12}	2.3	8.2×10^{-13}
MEG I full data	1.71×10^{13}	9.1	5.3×10^{-13}

- Prospect
  - Physics data taking started this July → Detail in the next presentation
  - Analysis for 2021 in progress