# MEG II 実験2021年データを用いた $\mu \to e\gamma$ 崩壊探索の状況

## - 陽電子再構成のまとめ及び感度・系統誤差の評価 -

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2023年日本物理学会春季大会

Core-to-Core Program

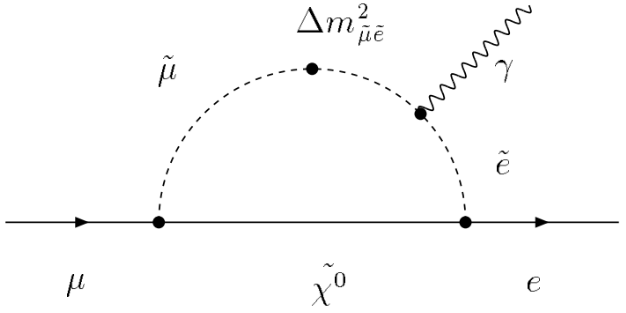
# Outline

- Introduction
- Analysis
- Summary and prospect

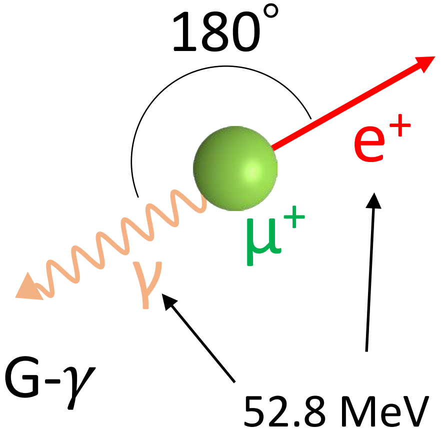
# Motivation and principle of $\mu \to e\gamma$ search

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

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




- 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-$\gamma$
    - $N_{BG} \propto R_\mu^2 \cdot T \cdot \delta E_e \cdot \delta E_\gamma^2 \cdot \delta\Theta^2 \cdot \delta T$
      → Use of DC beam @PSI
      → High resolution measurement
  - Second BG: Radiative decay with small energy $\bar{\nu}\nu$
    - $\times$ 0.1 compared to the # of accidental




| Notation | |
|---|---|
| $R_\mu$ | $\mu$ rate |
| $T$ | Experiment time |
| $\epsilon$ | Efficiency |
| $\delta E, \delta T, \delta\Theta$ | Resolution |

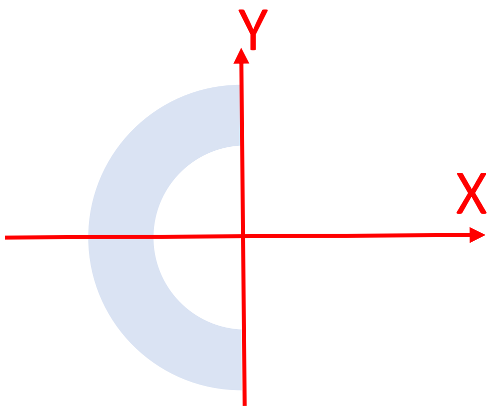
| Kinematics | Signal | BG |
|---|---|---|
| $e\gamma$ time difference | Same time | No correlation |
| $e\gamma$ direction | Opposite | No correlation |
| $E_e$ | 52.8 MeV | < 52.8 MeV |
| $E_\gamma$ | 52.8 MeV | < 52.8 MeV |

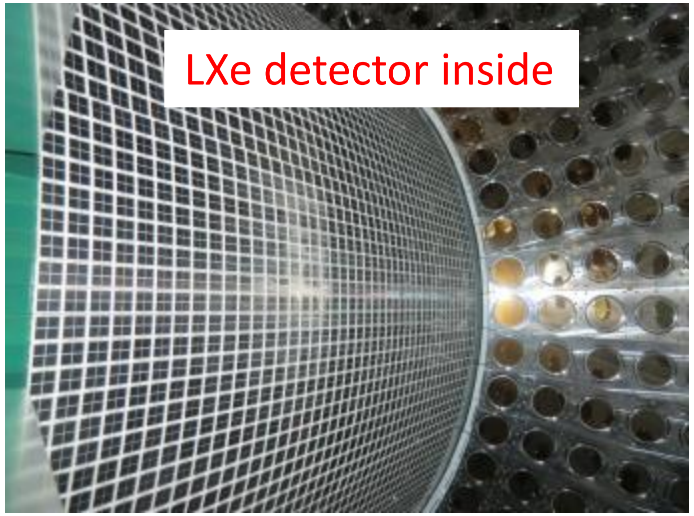
# MEG II apparatus

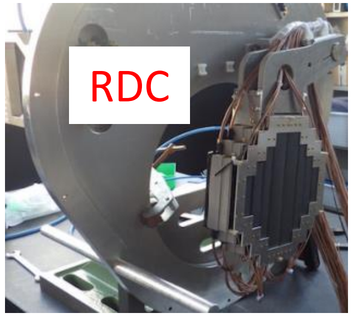
- Muon stopped on target
- Positron detection with magnet + DCH + pTC
- Gamma detection with LXe detector
  - BG-$\gamma$ tagging with RDC detector

## Coordinate definition

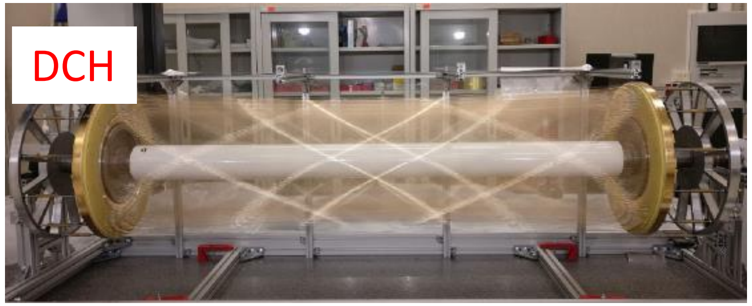
- X-axis in opposite of LXe
- Z-axis in downstream
- $\theta, \phi$: polar coordinate



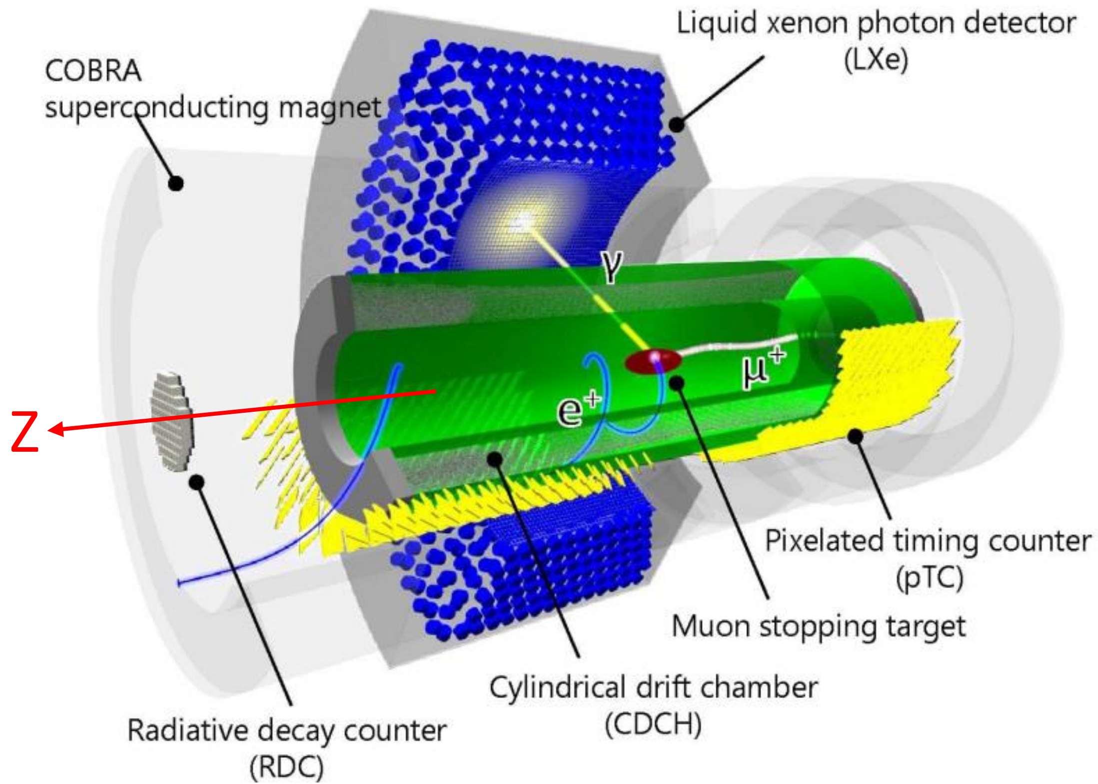







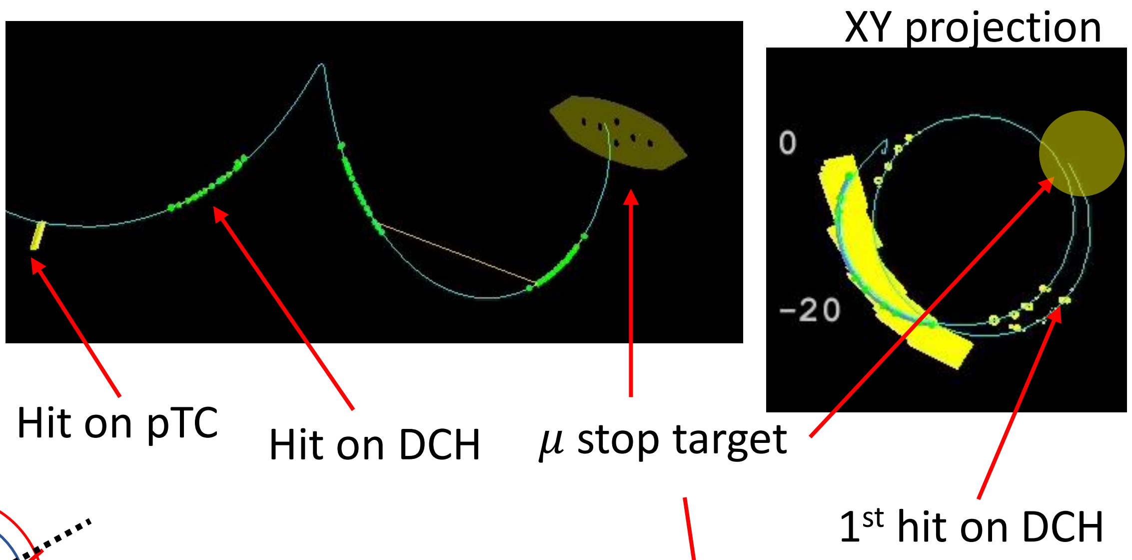




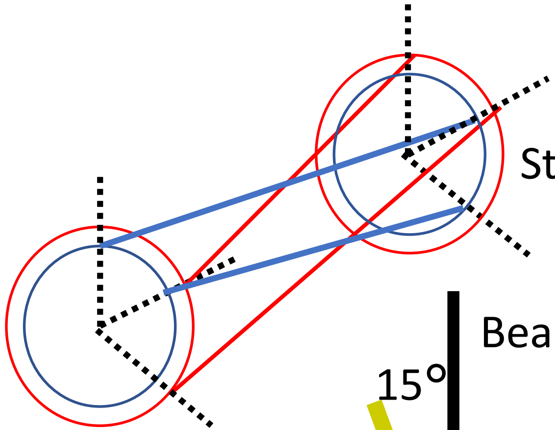
# MEG II apparatus for vertex & track



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

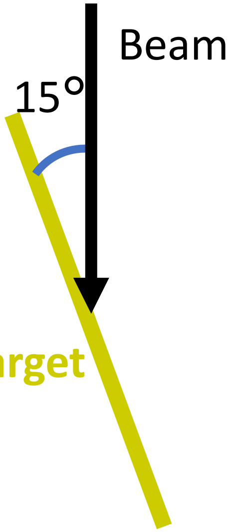


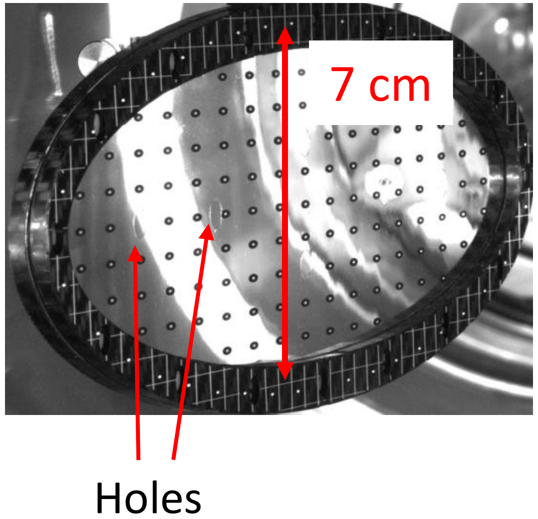

- Drift chamber
  - Stereo geometry wire chamber
  - $r_{inner} = 17$ cm, $r_{outer} = 27$ cm

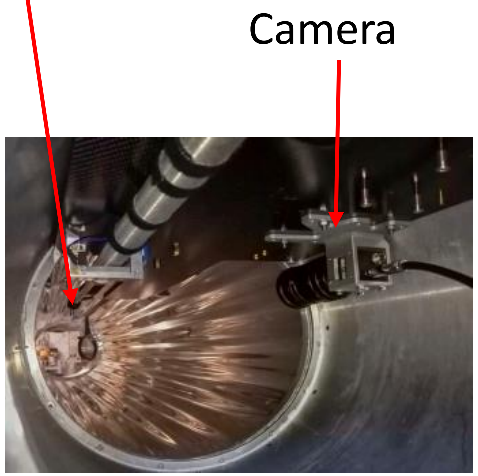



- $\mu$ stop target
  - $15^{\circ}$ slanted w.r.t beam
  - $r \sim 3.5$ cm projected on XY plane
  - 6 holes
  - Camera
  - Dot markers

  } For alignment

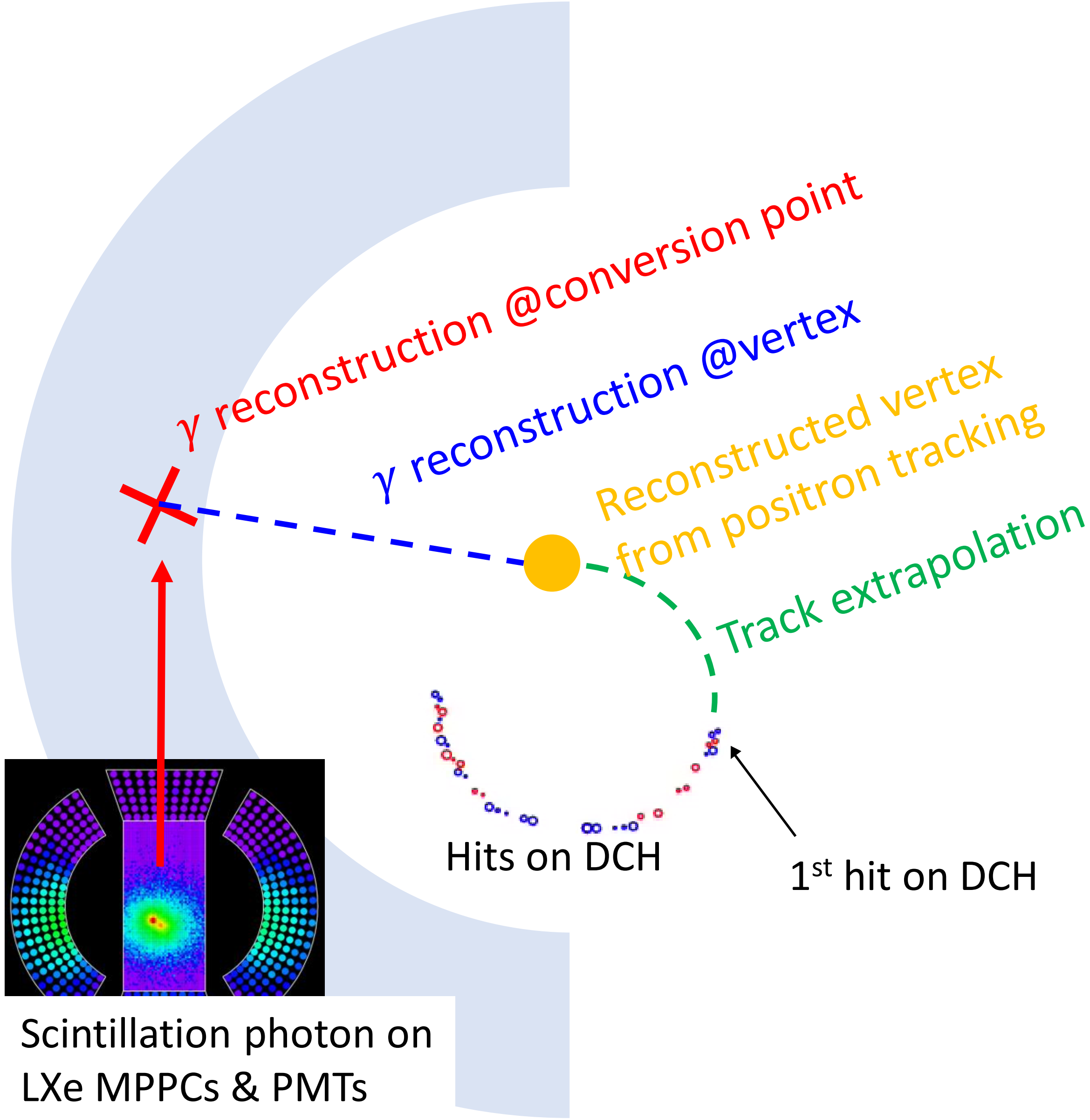



https://doi.org/10.1063/5.0034842

# Reconstruction



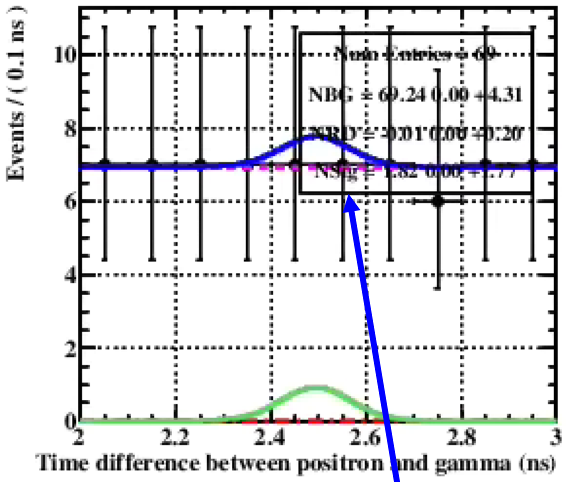

- Positron reconstruction
  - Decay position and angle by track extrapolation to target
  - Time measured at pTC & TOF correction with track
  - Energy from track curvature & B-field
- Gamma reconstruction **@conversion point**
  - Conversion position by light distribution
  - Time by combining measurements at photo sensors
  - Energy by total number of scintillation photons
- Full reconstruction of kinematics **@vertex**
  - Gamma angle by combining with vertex reconstructed by positron spectrometer
  - Gamma time @vertex reconstructed with TOF correction

# Observables in analysis

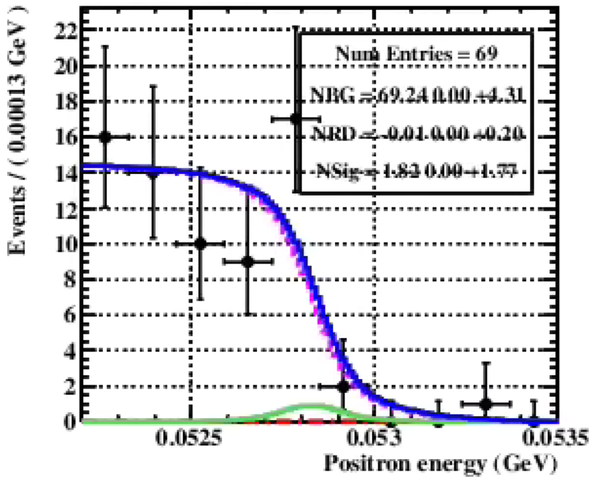
- List of observables
  - $t_{e\gamma} \coloneqq t_\gamma - t_e$
  - $\phi_{e\gamma} \coloneqq \pi + \phi_e - \phi_\gamma$
  - $\theta_{e\gamma} \coloneqq \pi - \theta_e - \theta_\gamma$
  - $E_\gamma$
  - $E_e$
  - RDC hit

Opening angle decomposed into $\theta, \phi$

$t_{e\gamma}$



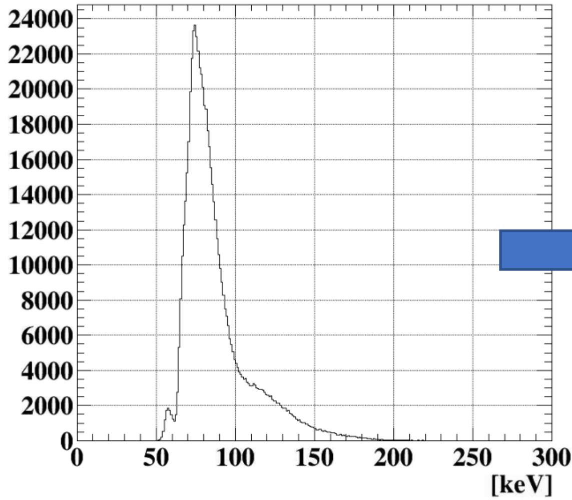

$E_e$




Signal peak in the flat BG distribution (if $N_{sig}$ > 0)

- Conditional observables
  - Track fitting uncertainty
  - $\phi$ emission angle
    (Parameter correlation depends on $\phi$)
  - Conversion depth in LXe

Tracking momentum uncertainty




With smaller uncertainty, signal peak in $E_e$ distribution becomes sharp

# Statistical method of $\mu \to e\gamma$ search



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

Additional external constraints

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

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

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: $Br = \frac{N_{sig}}{k} = N_{sig} \times \text{SES}$

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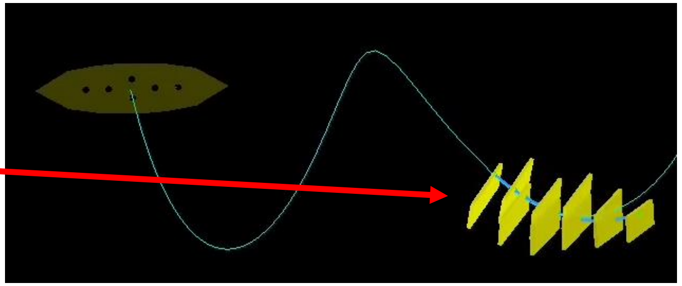
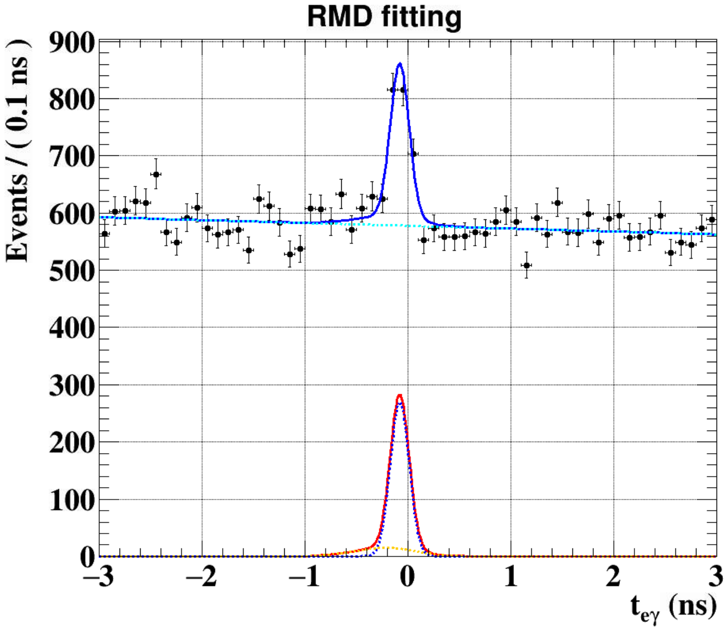
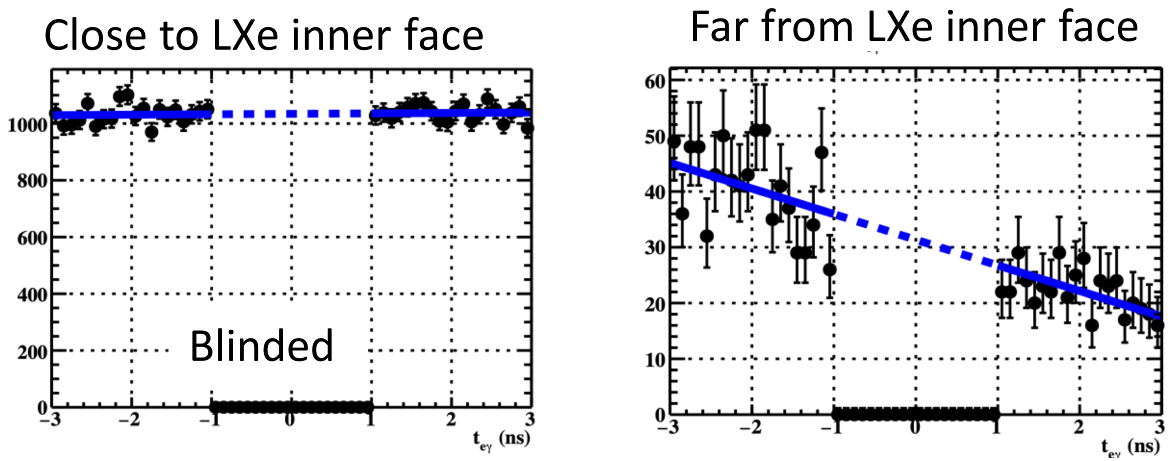
# Time PDF

- Signal time resolution evaluated with RMD
  - $\sigma_t = 66 \oplus \frac{112}{\sqrt{n_{TC}}}$ ps
    - Depends on # hits on pTC
  - Average $\sigma_{t\gamma}$: 83 ps






- Background distribution
  - Non-flatness due to $t_\gamma$ time-walk in trigger logic
  - Included in PDF evaluation




In 2021, trigger $t_\gamma$ used only sensors on inner face

- Uncertainty
  - 7 ps uncertainty on peak center position
  - 5 ps uncertainty on resolution
  
  → O(0.1 %) impact to $\mu \to e\gamma$ sensitivity

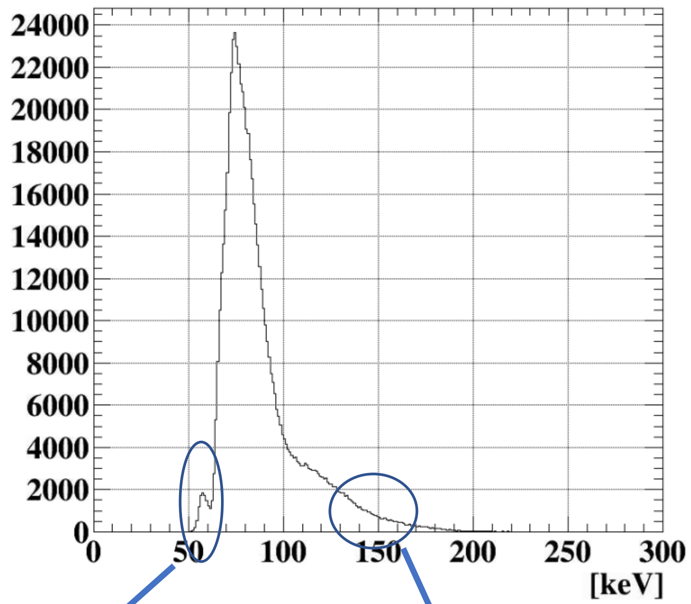
# Positron momentum PDF

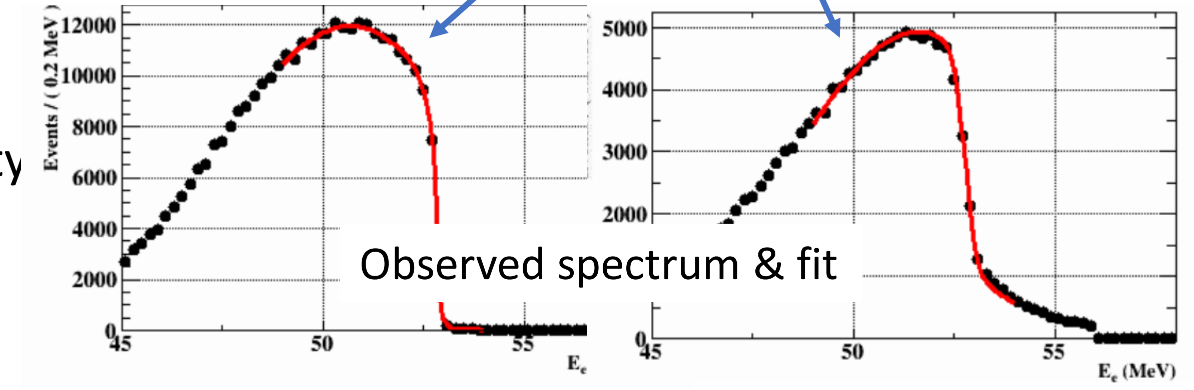
- PDF evaluation from background (Michel) fitting
  - Can calibrate energy scale and resolution
  - Fit function: $\left(\mathrm{Theory} \times \mathrm{Eff}(E_e)\right) \otimes \mathrm{Resolution\ of}\ E_e$
    - $\mathrm{Eff}(E_e)$: $E_e$ dependence of efficiency (Modeled with erf)
  - Tracks categorized on $E_e$ uncertainty in track fitting
    - Clear change in resolution and $\mathrm{Eff}(E_e)$

- Uncertainty
  - Energy scale: 10 – 20 keV
  - Resolution: up to $\sim$10 %
    - Fit resolution well agrees with tracking uncertainty

→ O(0.1 %) impact to $\mu \to e\gamma$ sensitivity

Tracking momentum uncertainty



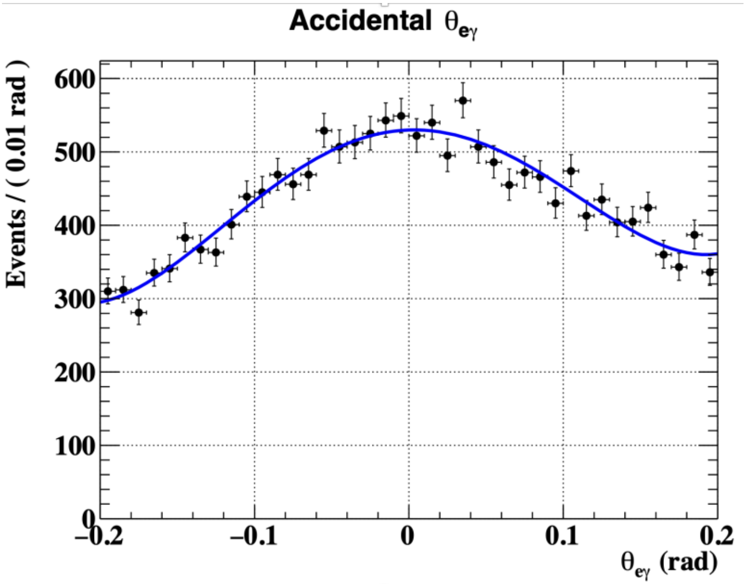




Observed spectrum & fit

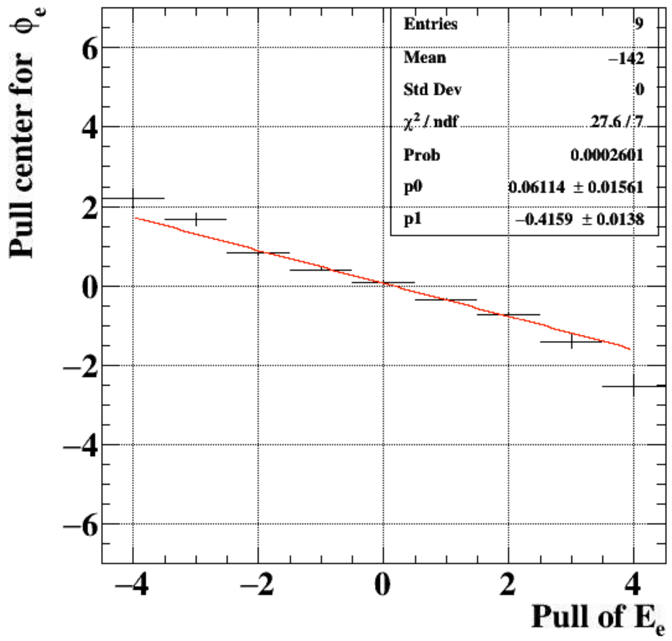
# Angle PDF

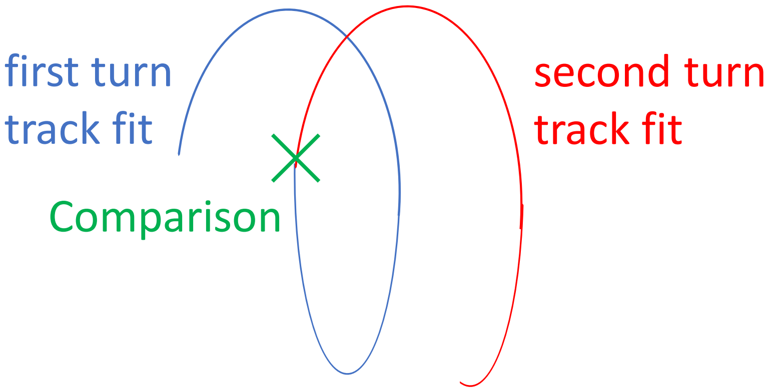
- Accidental background
  - Non-flat distribution
    - Trigger requires direction match between positron & gamma
  - Directly taken from sideband

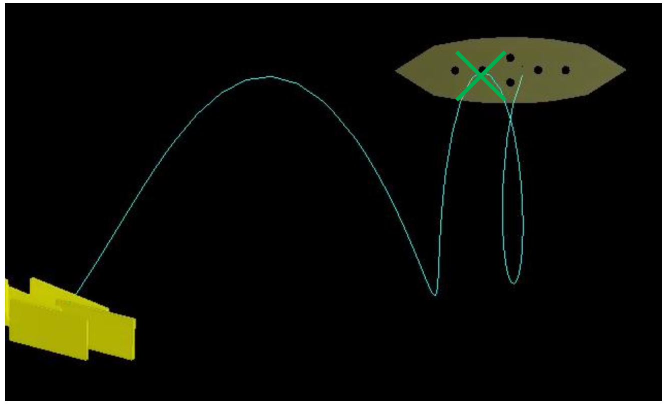
- Signal
  - Correlation is known b/w $\delta E_e, \delta\theta_e$ & $\delta\phi_e$
  - Correlation parameter estimation in progress
    - By double turn analysis combined with studies on MC samples




Signal $\phi_e$ error vs $E_e$ error (MC)

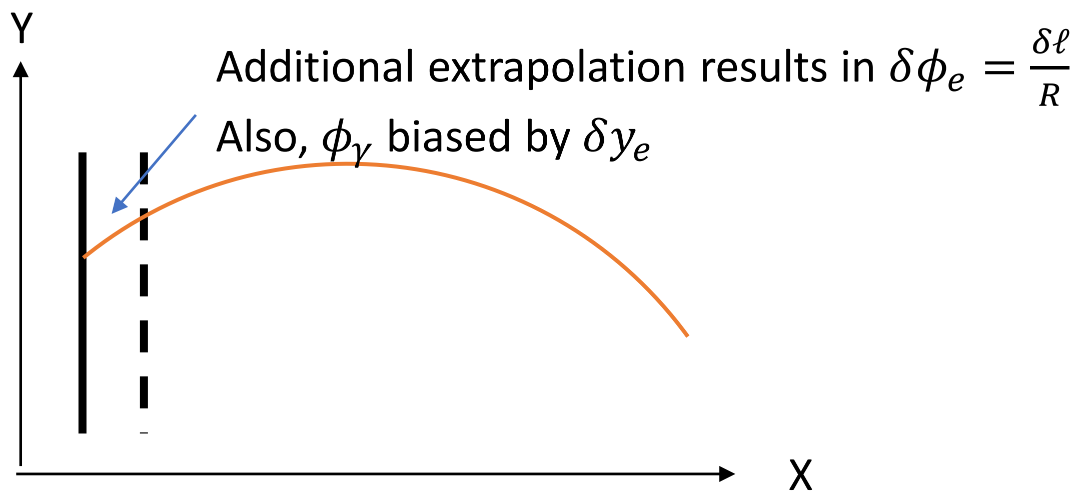


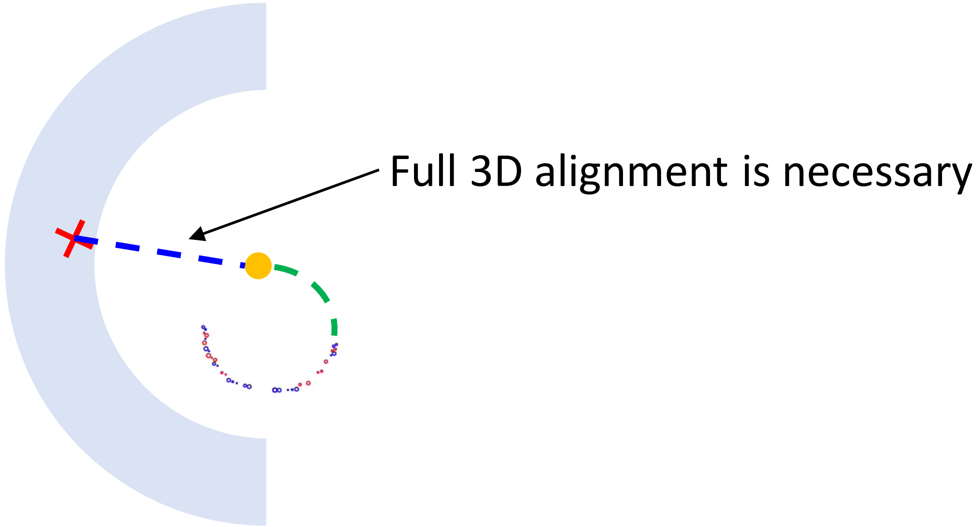



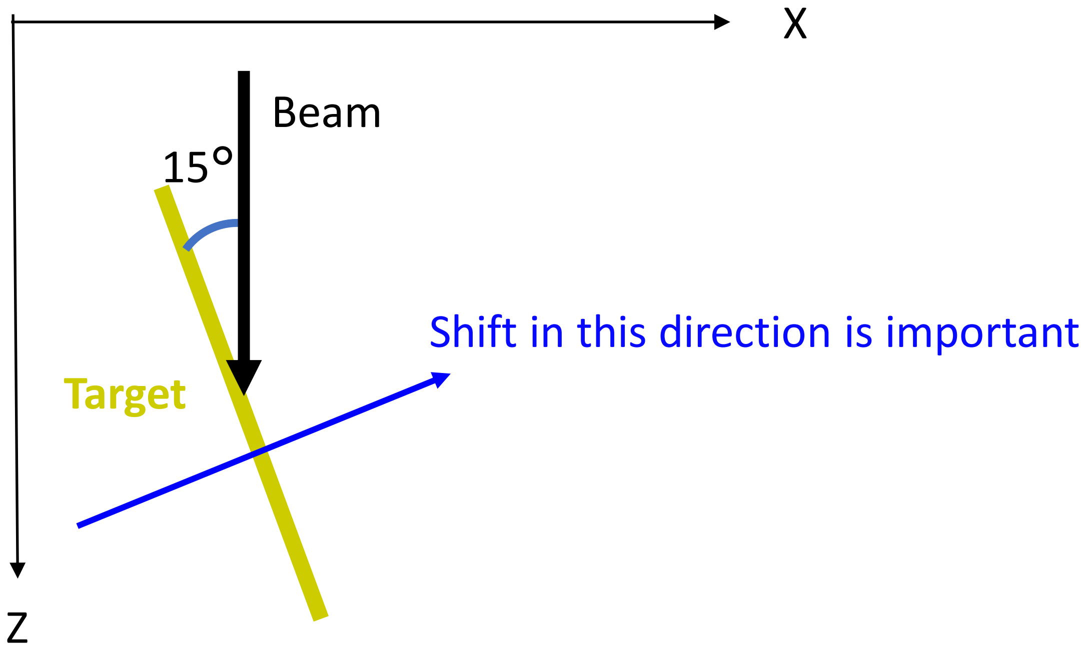



# Alignment (angle PDF uncertainty)

- Mis-alignment shifts signal PDF
  - No physical calibration source
  - Precise alignment is a must
  - Largest systematics source in MEG I
- Important parameters
  1. DCH – LXe relative alignment in 3D
  2. DCH – target alignment in X coordinate

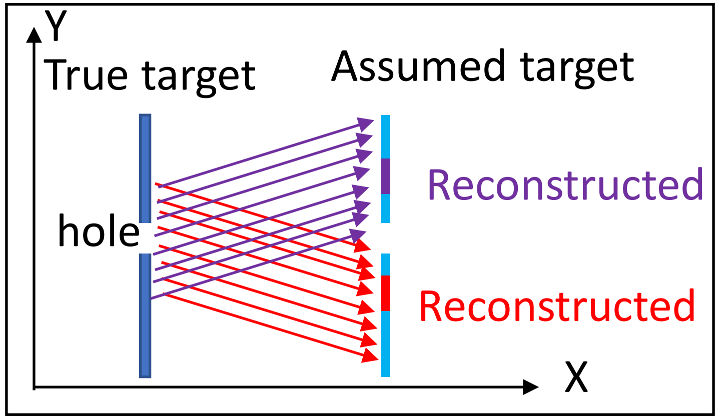


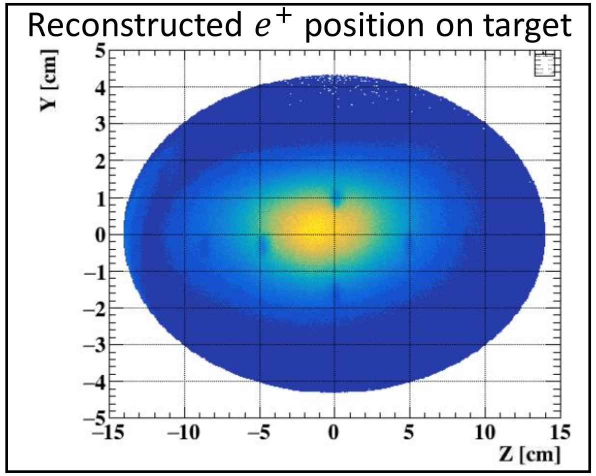



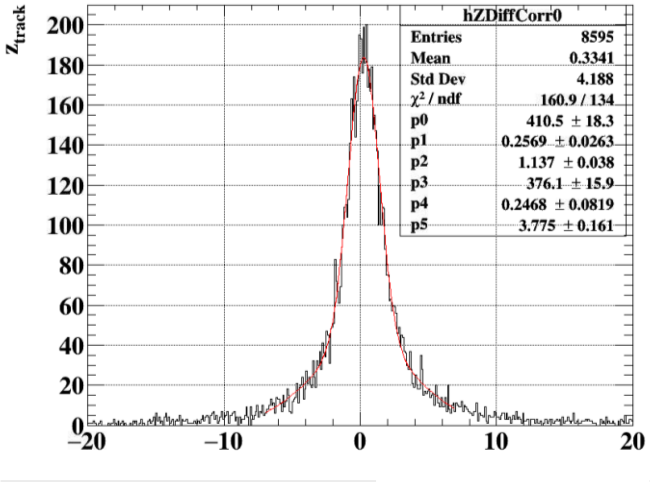
# Alignment (angle PDF uncertainty)

- DCH – target alignment in X
  - From hole analysis
  - 200 μm consistency between holes
  - 500 μm difference from optical method
    - Position change not included yet
      → Most suspected cause. Camera data needs to be combined to improve




- DCH – LXe relative alignment
  - Relies mainly on optical method
  - Z alignment cross-checked with cosmic tracks
    → Disagreement of 2.5 mm
  - Possible causes
    1. Mistake in LXe optical survey
    2. Tracking bias only for cosmic linear tracks




$z_{track} - z_{XEC}$

Mis-alignment systematics is still large
(Can potentially be largest systematic source)

# Sensitivity estimate

| | 2021 performance |
|---|---|
| $\theta_e, \phi_e$ | 7.7/5.6 mrad (Double turn analysis) |
| $y_e, z_e$ | 0.8/2 mm (Double turn analysis) |
| $E_e$ | 90 keV for core (Michel fit) |
| $E_\gamma$ | 2% (CEX resolution analysis) |
| $u, v, w_\gamma$ | 2.5 mm for w < 2 cm (Collimated gamma ray data) |
| $t_{e\gamma}$ | $\frac{112}{\sqrt{n_{TC}}} \oplus$ 66 ps (RMD samples) |
| RDC | Installed since middle of 2021 run |

- Median 90 % C.L. sensitivity: $\mathbf{8.2 \times 10^{-13}}$
  - Study with temporary PDFs for those not fully ready
    - Background distribution is not perfect
  - Systematic uncertainty is not fully evaluated yet

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# Summary

- Presented PDF evaluation with focuses on positron side
  - Time & positron momentum PDFs are ready with negligible systematics
  - Angle PDF evaluation in progress
  - Disagreement found in alignment

- $\mathbf{8.2 \times 10^{-13}}$ branching ratio sensitivity with **2021 pilot run** dataset
  - Approaching the MEG I full data (2009 – 2013) sensitivity
    - Though limited 2021 beamtime for physics DAQ (effectively 4 weeks)
    - Thanks to improved resolution and efficiency
  - Still systematics not included yet

| | Normalization | Br sensitivity |
|---|---|---|
| 2021 | $2.68 \times 10^{12}$ | $8.2 \times 10^{-13}$ |
| MEG I full data | $1.71 \times 10^{13}$ | $5.3 \times 10^{-13}$ |

# Prospect

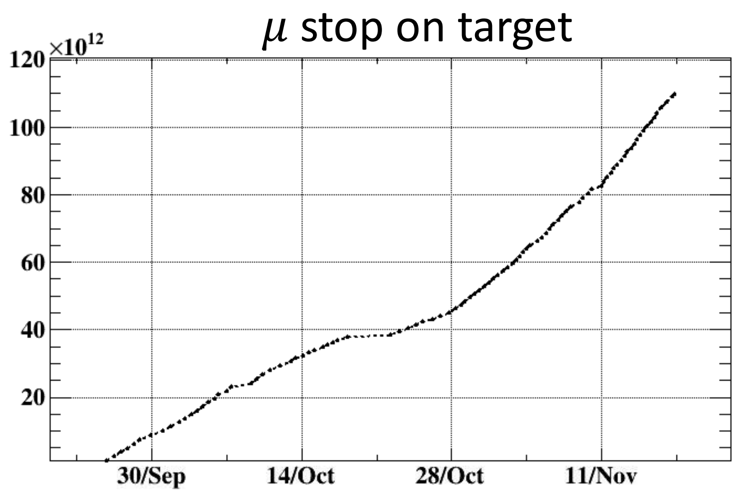
- 2021 analysis
  - Final estimation of PDF
  - Further investigation on highly uncertain parameters
    - Alignment
    - $E_\gamma$ energy scale (previous talk)
  - Final evaluation of systematic uncertainty
  - 2021 result will be presented in Sep (If everything on schedule)
    - Unblinding in May – Jun

- Further data taking
  - Physics data taking continued 2022 → Discussed in the next presentation
  - 2023 also planned, with further improved data-taking scheme
    - With experience in 2022 run

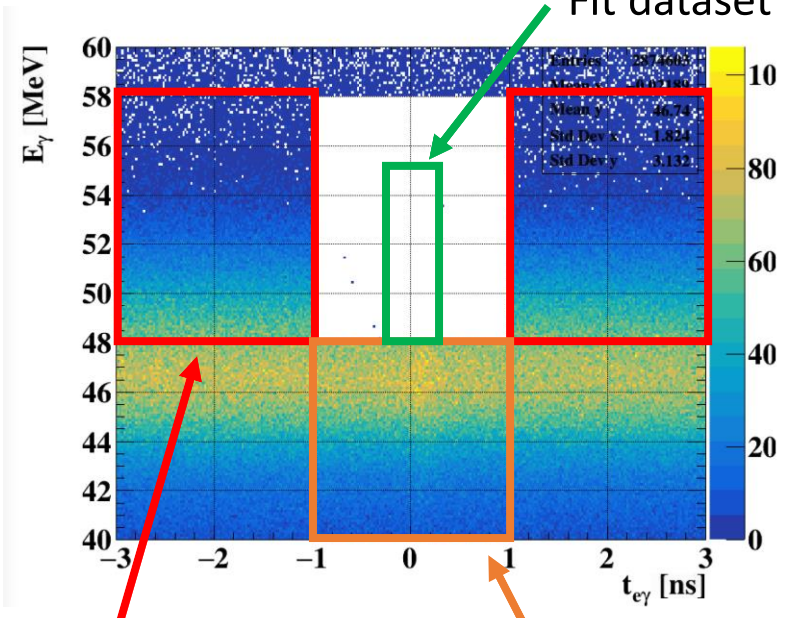
# Backup

# 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

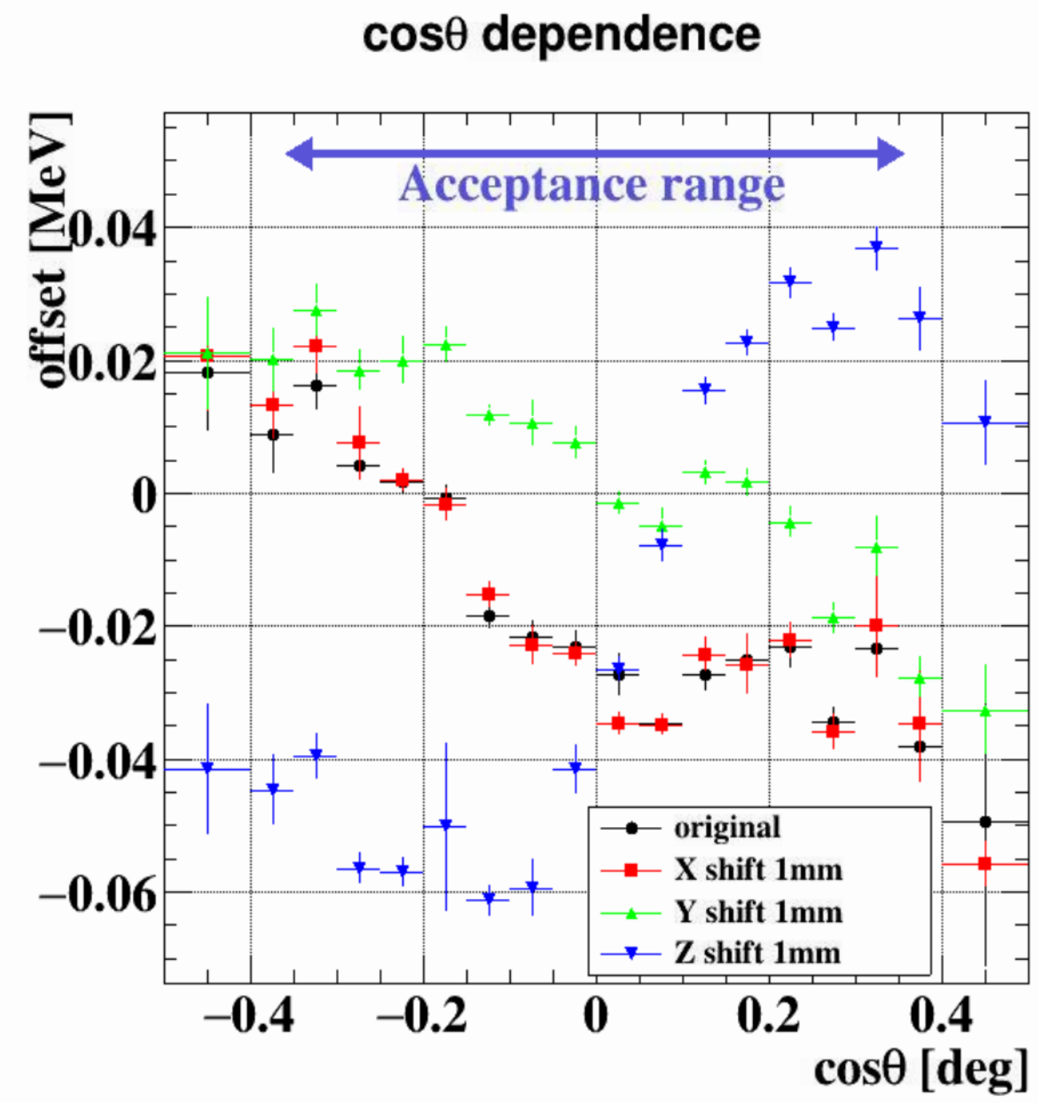


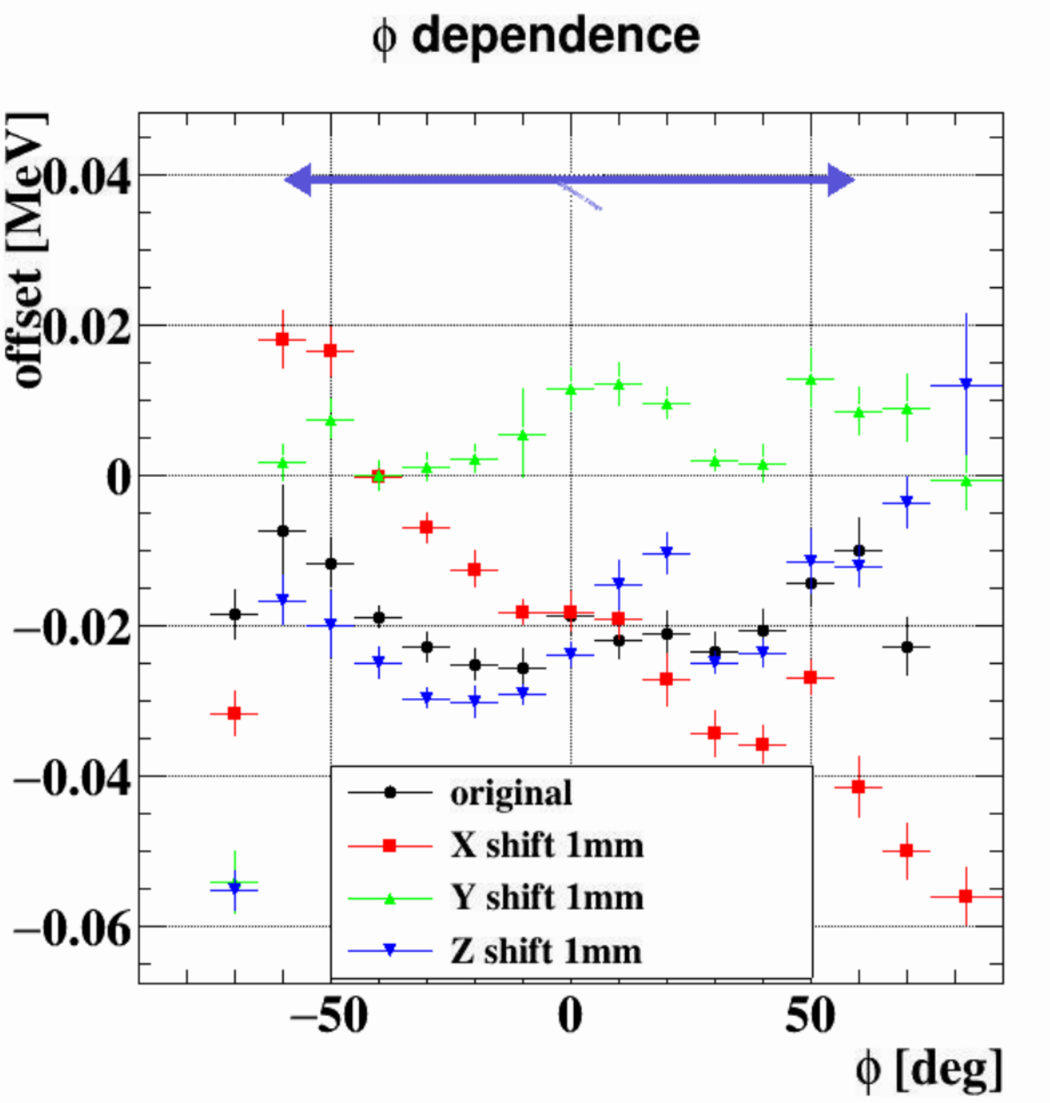
# Performance comparison

| | Currently achieved performance in MEG II | Performance in MEG |
|---|---|---|
| $\theta_e, \phi_e$ | 7.7/5.6 mrad (Double turn analysis) | 9.4/8.7 mrad |
| $y_e, z_e$ | 0.8/2 mm (Double turn analysis) | 1.2/2.4 mm |
| $E_e$ | 90 keV for core (Michel fit) | 306 keV |
| $E_\gamma$ | 2% (CEX resolution analysis) | 2.4% (w<2 cm), 1.7% (w>2cm) |
| $u, v, w_\gamma$ | 2.5 mm for w < 2 cm (Collimated gamma ray data) | 5 mm |
| $t_{e\gamma}$ | $\frac{112}{\sqrt{n_{TC}}} \oplus$ 66 ps (RMD samples) | 122 ps |
| RDC | Installed since middle of 2021 run | Not installed |

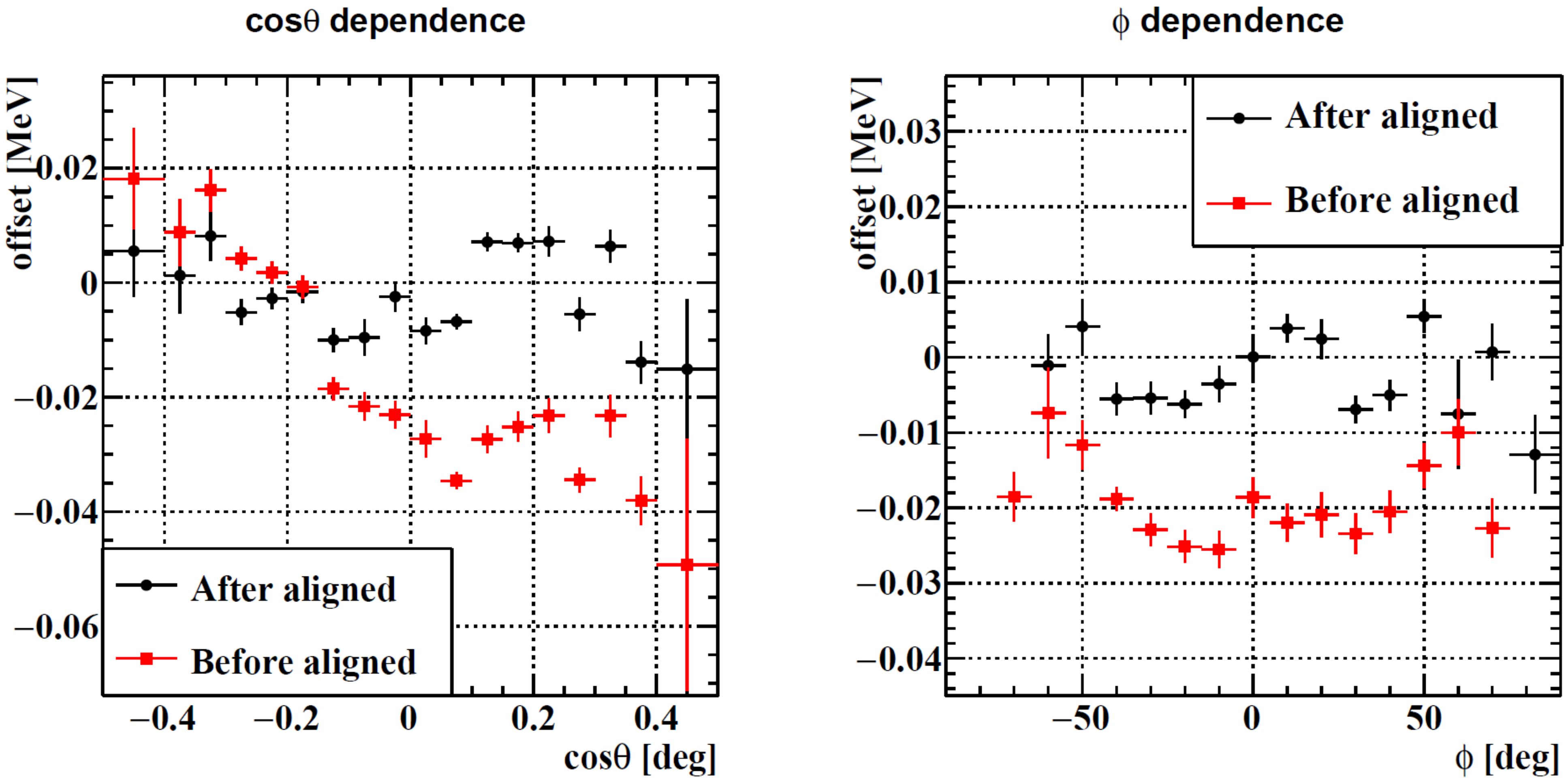
# Alignment w.r.t B-field





# Alignment result (B-Field)




0.1 mm in X
0.7 mm in Y
0.3 mm in Z

# Full 3D comparison of target holes

- Z misalignment is not present
- Y misalignment in agreement with B-field observation

| Survey (2021) + CT scan | Track 2021 | Difference |
|---|---|---|
| 1.30243, -0.319128, -4.69109 | 1.285(6), -0.304(4), - 4.774(7) | 0.017, -0.015, 0.08 |
| -1.32782, -0.314651, 4.97927 | -1.40(1), -0.302(6), 5.025(14) | 0.072, -0.013, -0.046 |
| 2.3601, -0.313624, -8.53115 | 2.339(14), -0.287(9), -8.638(15) | 0.021, -0.027, 0.11 |
| -0.0312347, 0.97017, 0.138845 | -0.087(6), 1.000(3), 0.139(8) | 0.056, -0.030, 0.00 |
| -0.0414534, -1.62367, 0.14167 | -0.096(13), -1.614(7), 0.116(17) | 0.054, -0.01, -0.026 |
| -2.33435, -0.297131, 8.84869 | Not enough statistics | |