MEG II 実験2021年データを用いた $\mu \to e\gamma$ 探索結果

大矢 淳史, 他MEG IIコラボレーション

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MEG II 実験2021年データを用いた
$\mu \rightarrow e\gamma$ 探索~~結果~~

今日の講演には間に合いませんでした。

Some important details are omitted from this presentation.
Also see cited presentations in the past JPS for details.

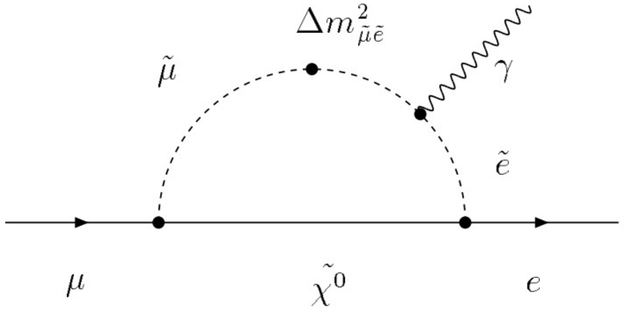
Outline

- Introduction
- Updates since last JPS
- Analysis
- Summary and prospect

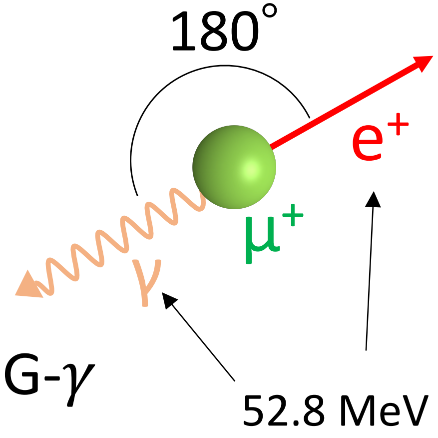
Motivation and principle of $\mu \rightarrow e\gamma$ search

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

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



- Search strategy
  - Signal identified by kinematics
    - Statistics: $N_{sig} \propto R_\mu \cdot T \cdot Br(\mu \rightarrow e\gamma) \cdot \epsilon$
  - 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
  - Second BG: Radiative decay with small energy $\bar{\nu}\nu$
    - $\times 0.1$ compared to the # of accidental



Notation	
R_μ	μ rate
T	Experiment time
$\boldsymbol{\epsilon}$	Efficiency
$\delta E, \delta T, \delta\Theta$	Resolution

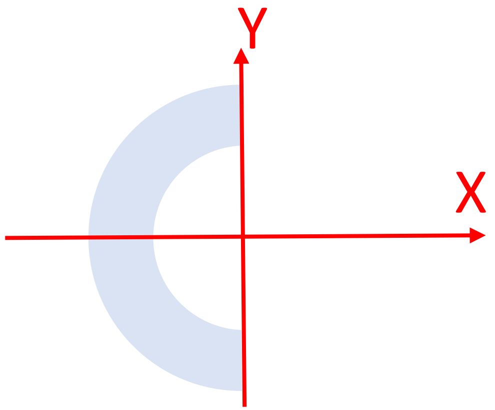
Kinematics	Signal	BG
$e\gamma$ time difference	Same time	No correlation
$e\gamma$ direction	Opposite	No correlation
E_e	52.8 MeV	< 52.8 MeV
E_γ	52.8 MeV	< 52.8 MeV

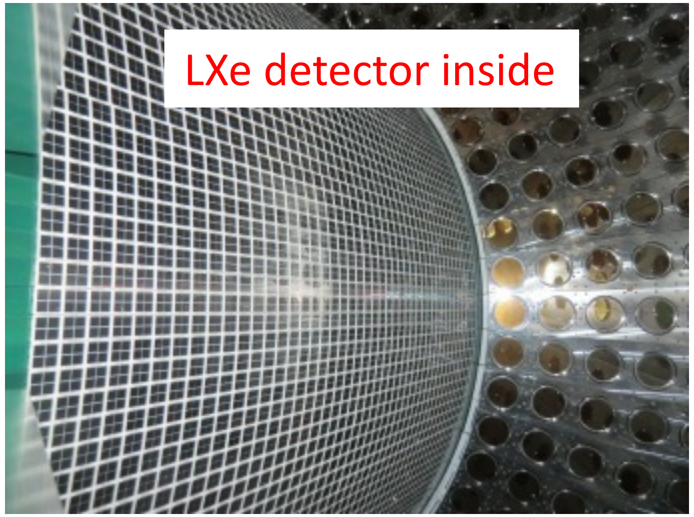
MEG II apparatus

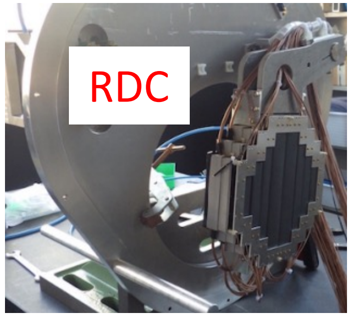
- Muon stopped on target
- Positron detection with magnet + DCH + pTC
- Gamma detection with LXe detector
  - BG-γ tagging with RDC detector

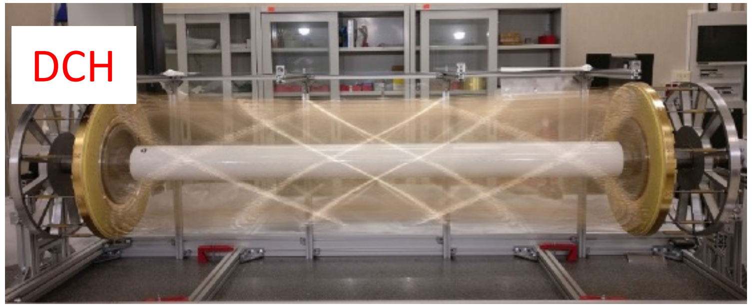
Coordinate definition

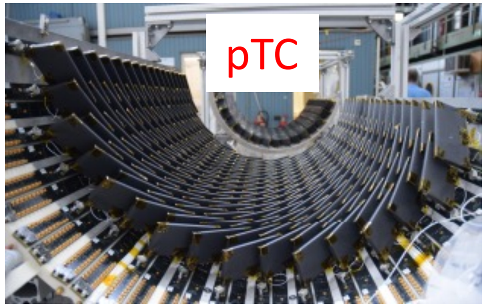
- X-axis in opposite of LXe
- Z-axis in downstream
- θ, ϕ: polar coordinate

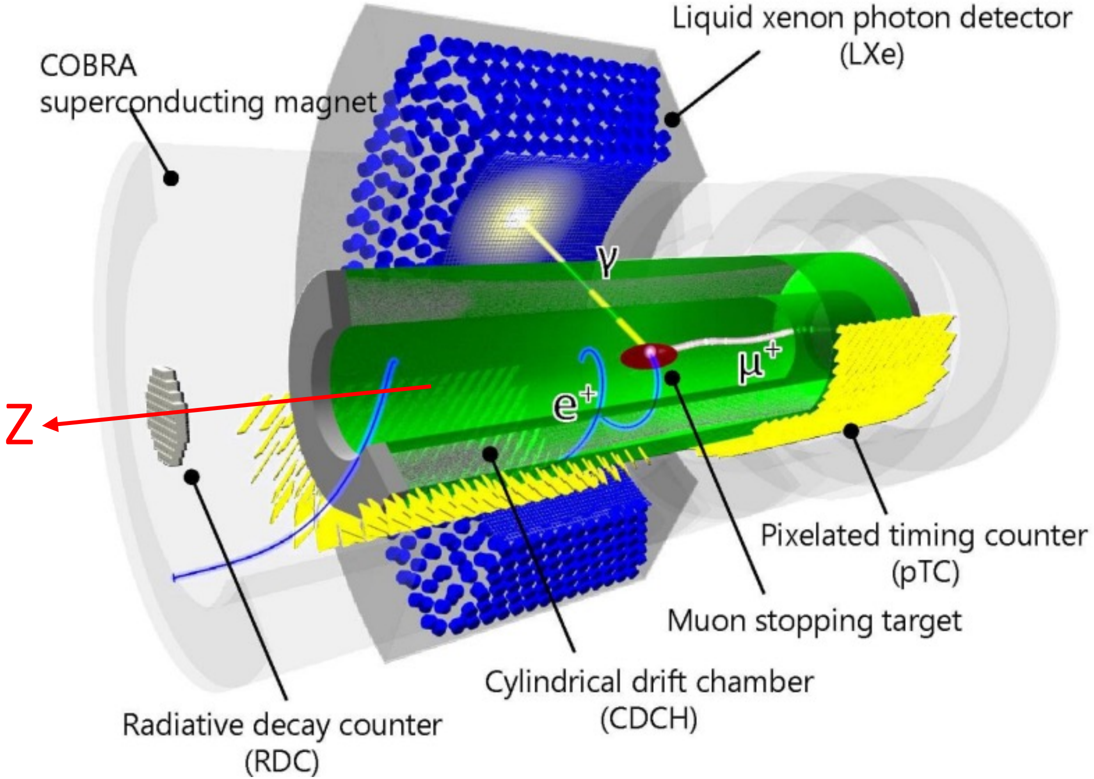










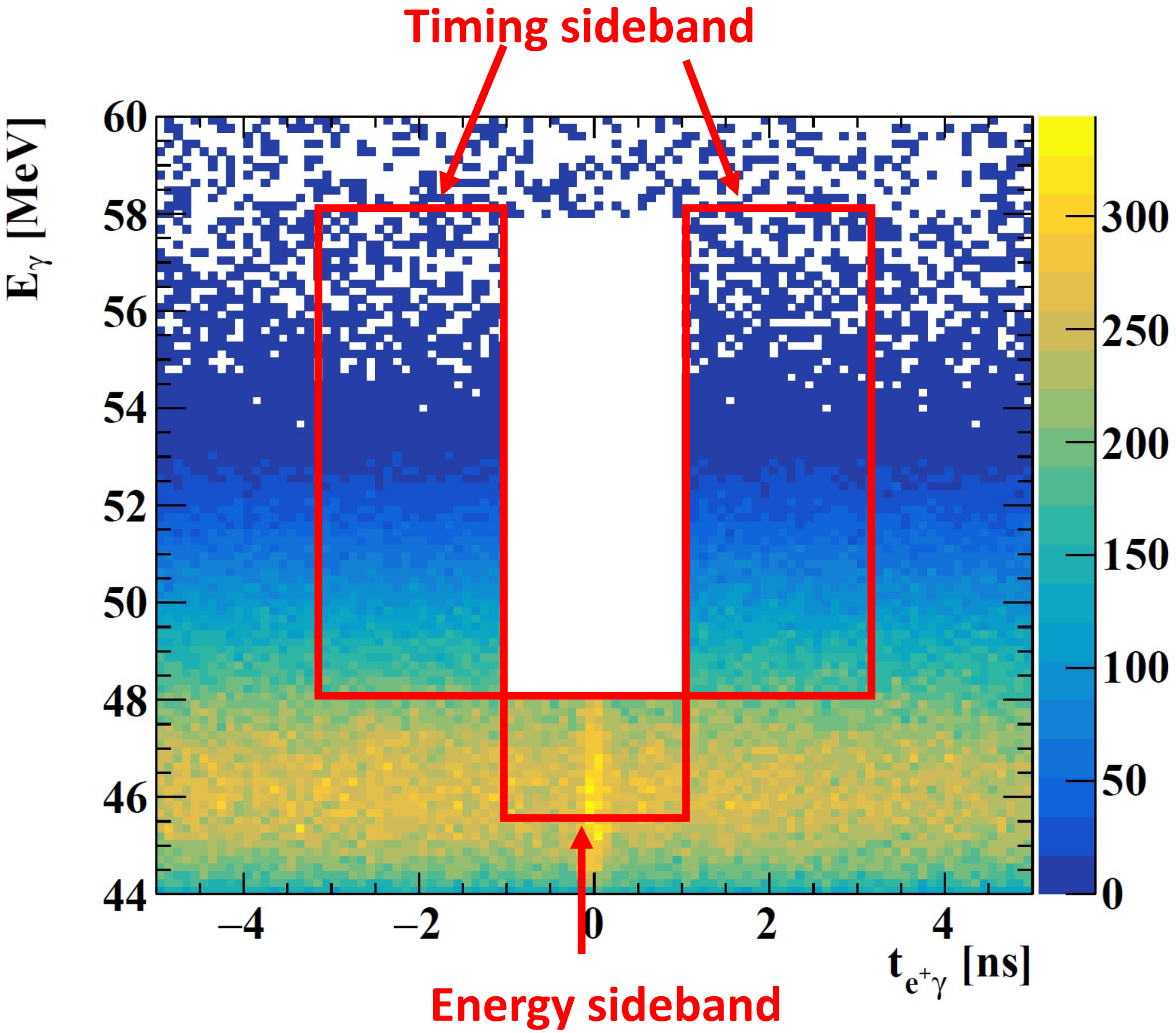


Data samples

- 7 weeks of DAQ in 2021

- Blinded box
  - Time coincidence within 1 ns
  - 48 MeV $< E_\gamma <$ 58 MeV

- Backgrounds in data
  - Accidental coincidence (Major)
    - Study in the timing sideband region
  - Radiative decay (Very few events)
    - Study in the energy sideband region (Peak in the right plot)



Outline

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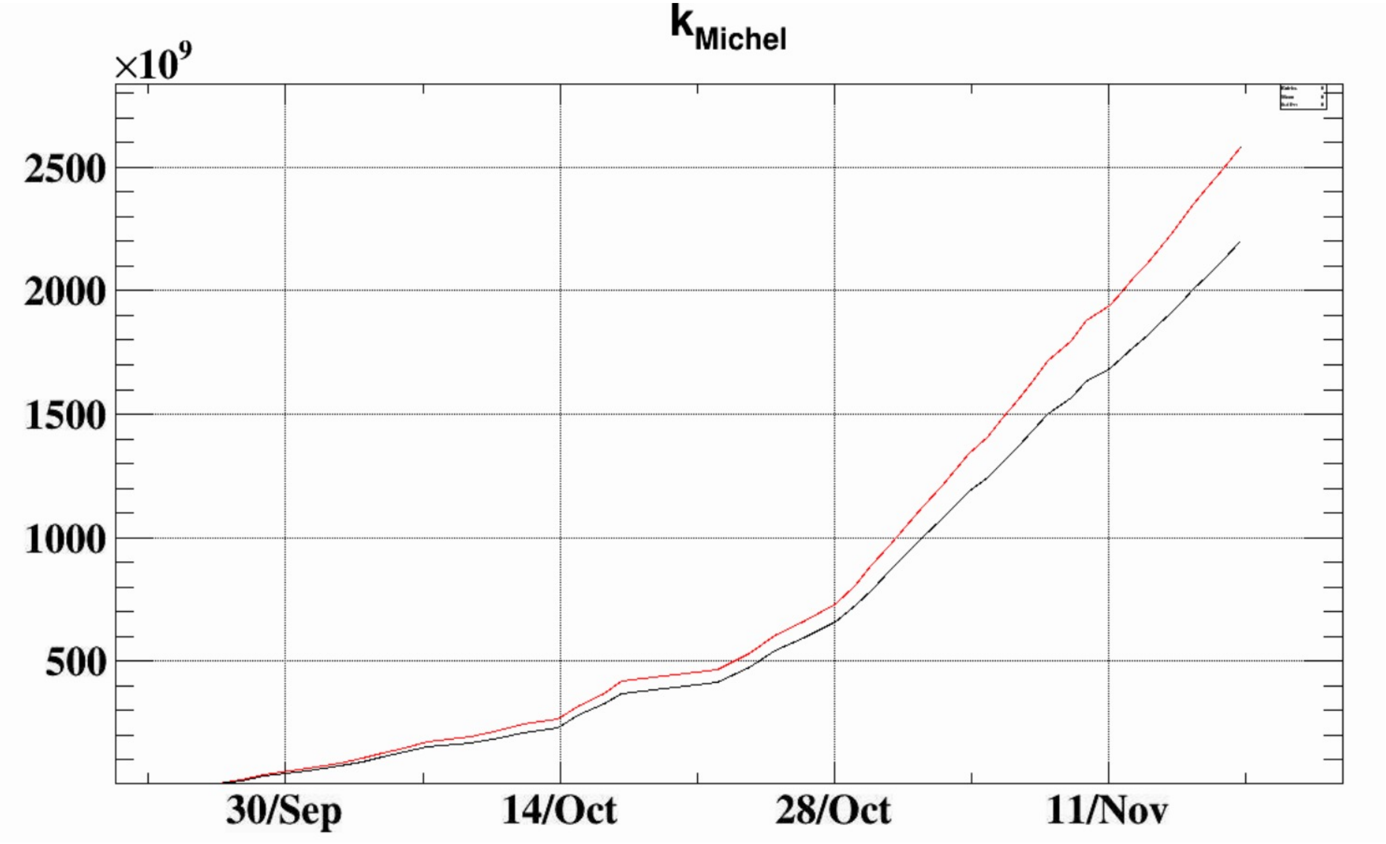
Update since last meeting

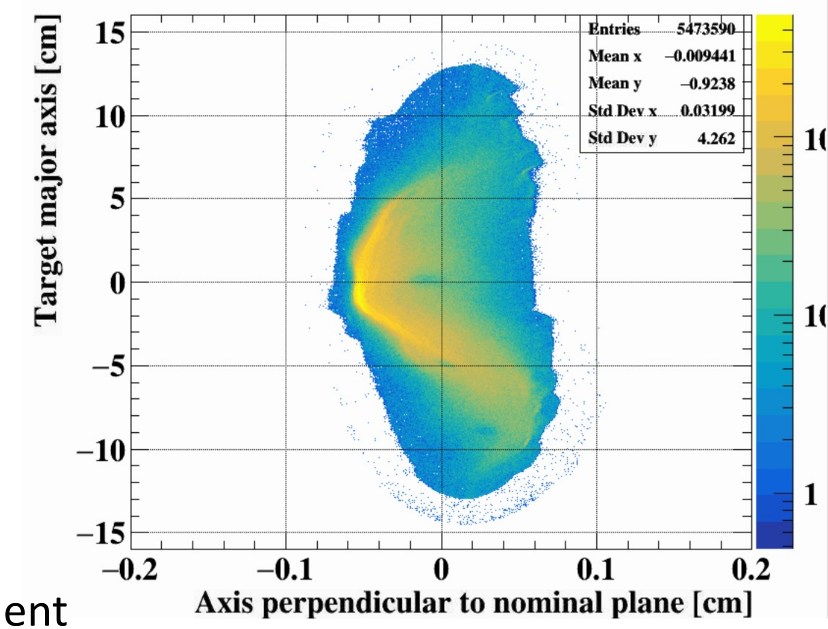
1. Improved efficiency in positron track reconstruction
    - Introduced machine learning method in hit reconstruction
        - Details presented in 8aA421-2 (2022 autumn)
    - **Improved tracking efficiency by 15 – 20%**



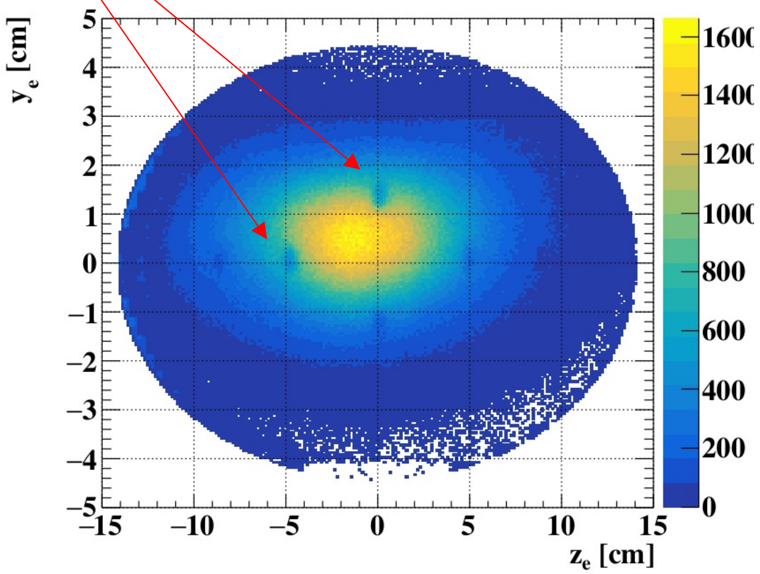
Update since last meeting

2. Finalized alignment

- Target deformation is considered in tracking
  - Bowing of up to 1 mm
- Updated target hole alignment
  - Method discussed in
    - 23pT1-2 (2023 spring)
    - 7aA442-2 (2022 autumn)
- Updated cosmic ray tracking
  - Used to align XEC to CDCH in z direction
- **Concluded alignment uncertainty**
  - **~ 100 μm in target alignment**
  - **~ 1 mm in LXe vs CDCH alignment**



Holes used for alignment



Update since last meeting

3. Finalized analysis towards unblinding
    - Finalized evaluation of systematic uncertainties
        - Gamma energy scale uncertainty (previous talk)
        - Alignment uncertainty
    - Checked analysis reliability
        - Fitting to sideband **(today's talk)**
        - Fitting to full detector simulation

Outline

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- Analysis

- Summary and prospect

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

- Likelihood analysis to estimate N_{sig}

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

Additional external constraints

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

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

  - Confidence interval
    - Feldman-Cousins method, profile likelihood ratio used for ordering: $\lambda(N_{sig}) = \dfrac{L(\text{best fit with fixed } N_{sig})}{L(\text{full best fit})}$
      https://doi.org/10.1103/PhysRevD.57.3873
  - Observables in fitting
    - $\phi_{e\gamma} \coloneqq \pi + \phi_e - \phi_\gamma,\ \theta_{e\gamma} \coloneqq \pi - \theta_e - \theta_\gamma,\ E_\gamma, E_e, t_{e\gamma} \coloneqq t_\gamma - t_e$, RDC hit
  - PDF details
    - 7aA442-2 (2022 autumn), 23pT1-2 (2023 spring), 18pRA34-7

Normalization

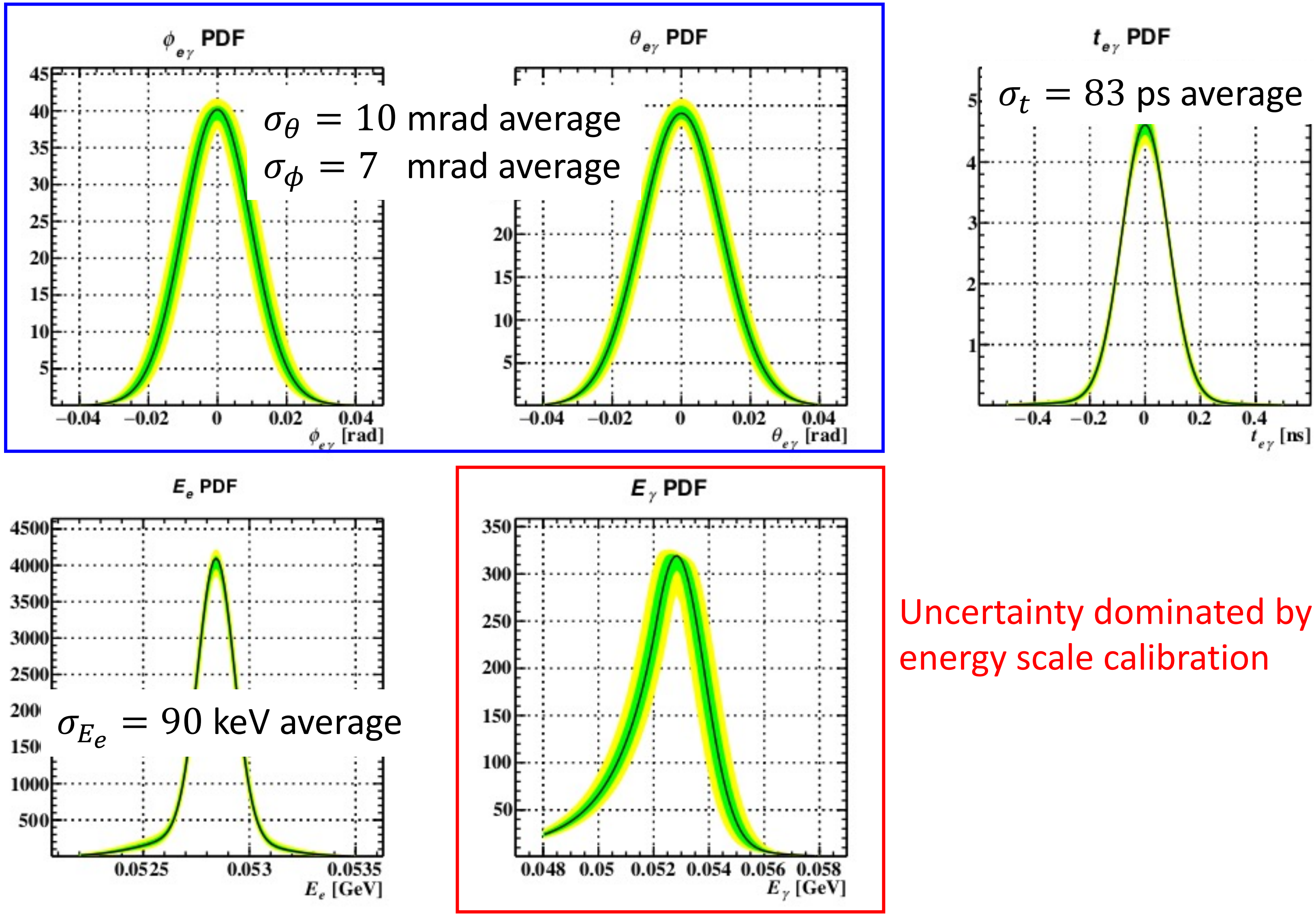
- Normalization: To convert N_{sig} estimation of likelihood into branching ratio
  - $Br = N_{sig}/\boldsymbol{N_{\mu}}$
    - $\boldsymbol{N_{\mu}}$: The number of effectively measured muon decays
  - Two independent approaches discussed in 7aA442-2 (2022 autumn)

- Updated value including positron reconstruction improvement
  - Positron counting method
    - $(2.55 \pm 0.13)\times 10^{12}$
  - RMD event counting in energy sideband
    - $(3.1 \pm 0.3)\times 10^{12}$
  - Combined result: $(2.64 \pm 0.12)\times 10^{12}$

Systematic uncertainties

- Signal PDF uncertainty
    - Shown in the right
    - Large contribution from
        - Alignment (angle PDF)
        - E_γ calibration
- Normalization
    - 5% uncertainty

Uncertainty dominated by detector alignment



$\sigma_\theta = 10$ mrad average

$\sigma_\phi = 7$ mrad average

$\sigma_t = 83$ ps average

$\sigma_{E_e} = 90$ keV average

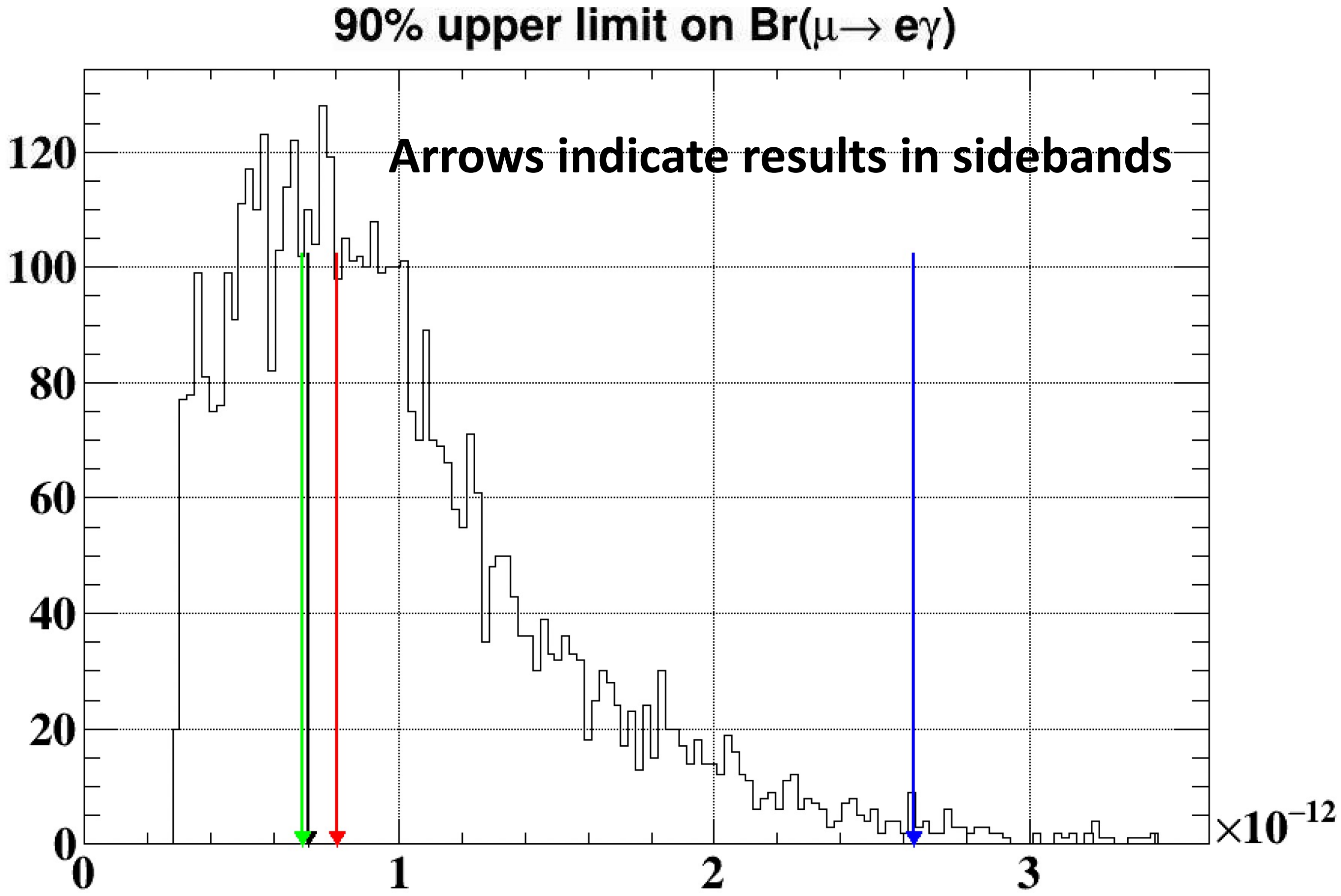
Uncertainty dominated by energy scale calibration

Sensitivity & fitting to BG-only data

- Sensitivity
  - Definition: Median of upper limit in zero signal toy experiments
  - $Br(\mu \rightarrow e\gamma) < 8.4\times10^{-13}$ w/o systematics
  - $Br(\mu \rightarrow e\gamma) < 8.8\times10^{-13}$ w/ systematics

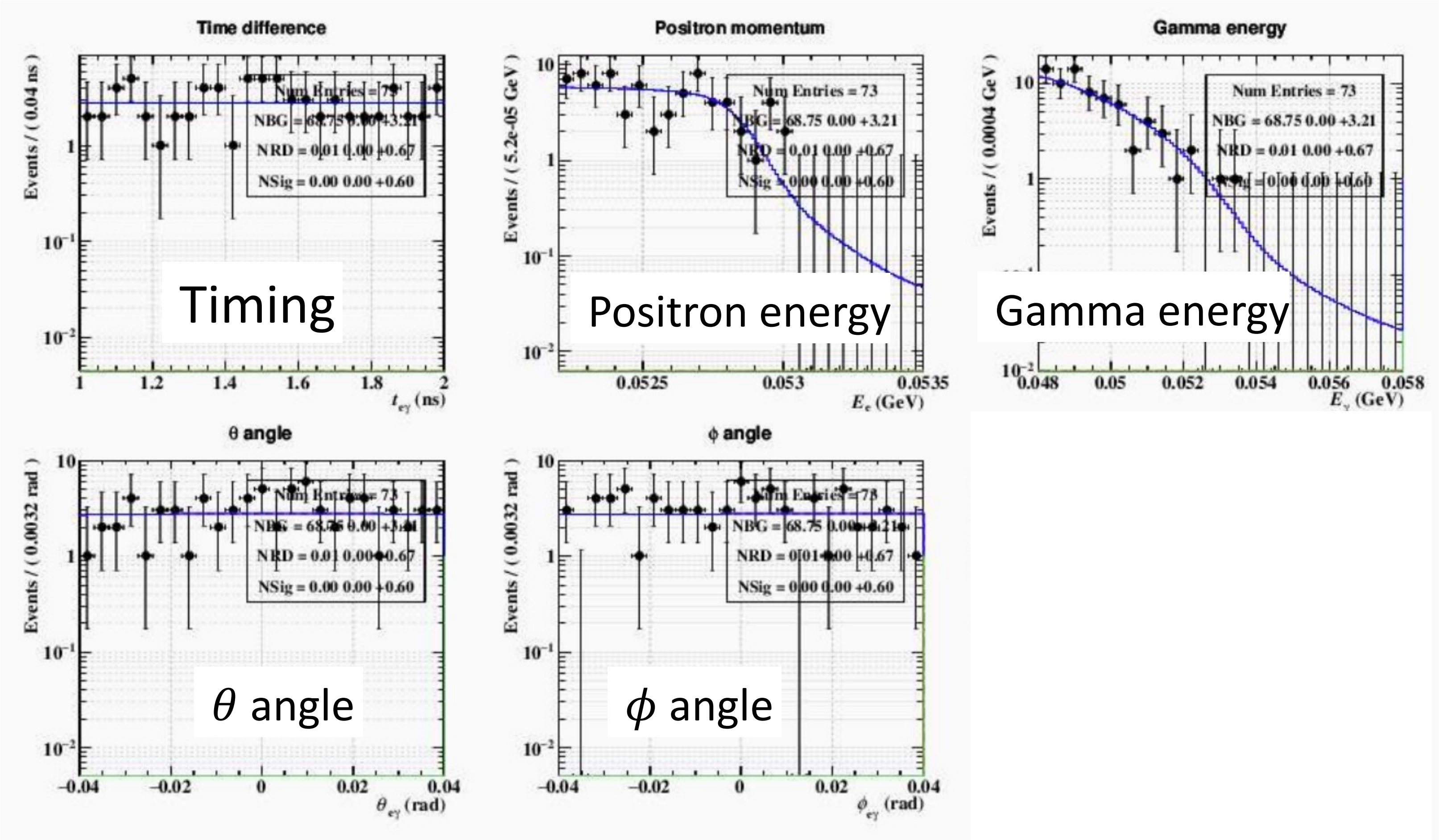
- Result will be reported soon
  - “PSI special seminar” in Oct/20

- Today’s talk: Sideband analysis
  - Analysis for timing sideband data
  - Four sidebands are analyzed
    - $-3 < t_{e\gamma} < -2$ ns
    - $-2 < t_{e\gamma} < -1$ ns
    - $1 < t_{e\gamma} < 2$ ns
    - $2 < t_{e\gamma} < 3$ ns



Fitting to sideband: Example1

- Fit to sideband as a cross-check before unblinding
  - Only accidental events identical to those in blinded region → Checks about BG PDF
  - Below: sideband 1 ns – 2 ns



Fitting in another sideband

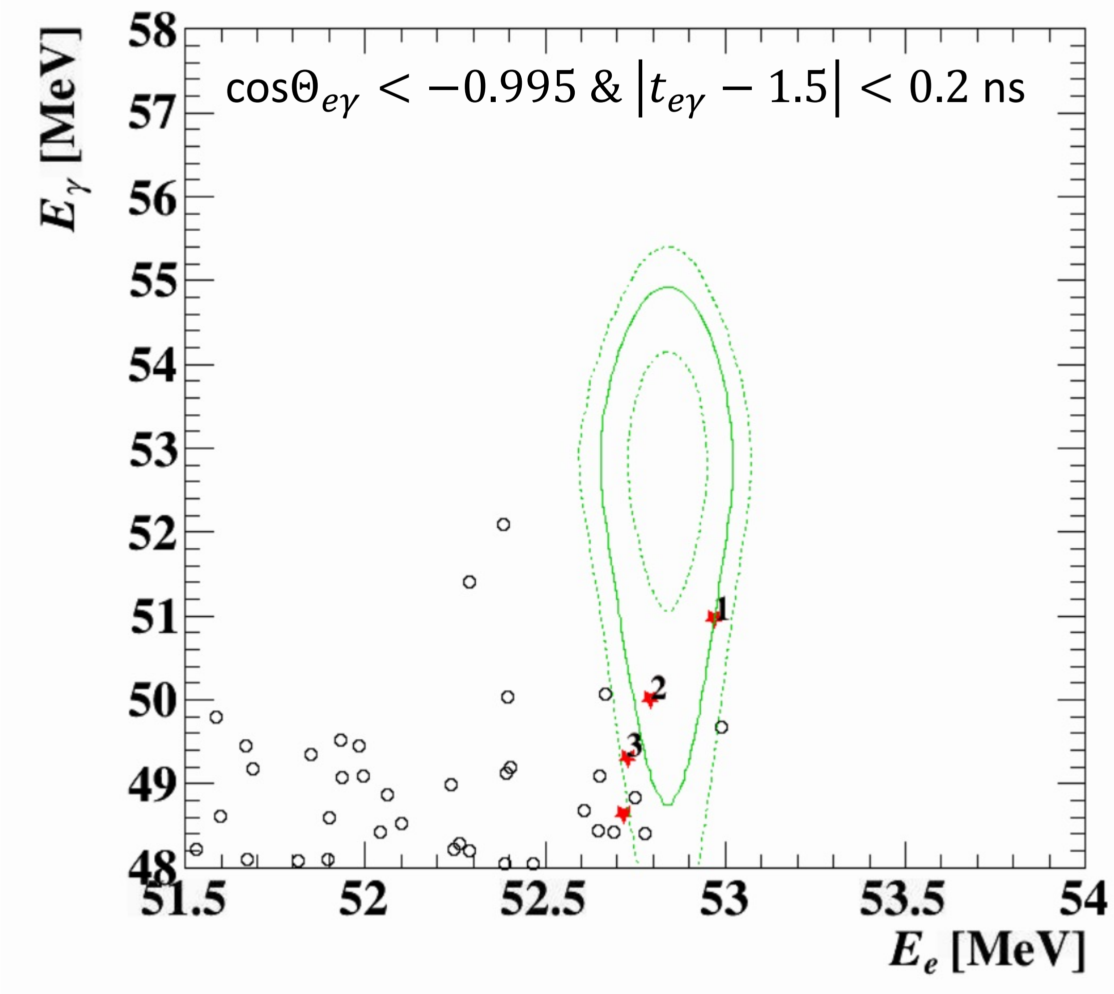
- Consistent with Br = 0
- Confidence interval
  - $\mathrm{Br} < 6.9 \times 10^{-13}$

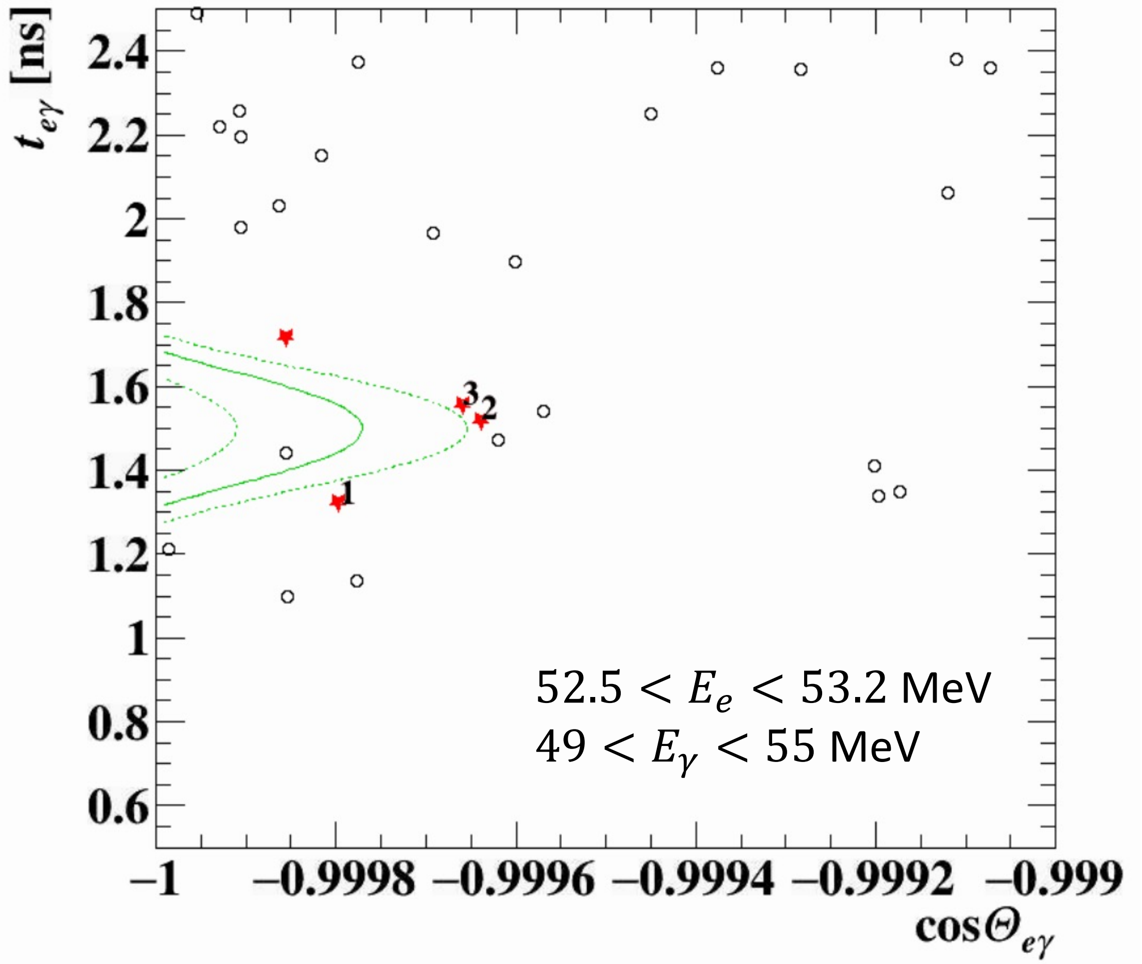
Event distribution in sideband: Example1

- Event distribution
  - Signal likelihood ranked by PDF ratio: $S(x)/B(x)$

✶ **High rank 5 events**

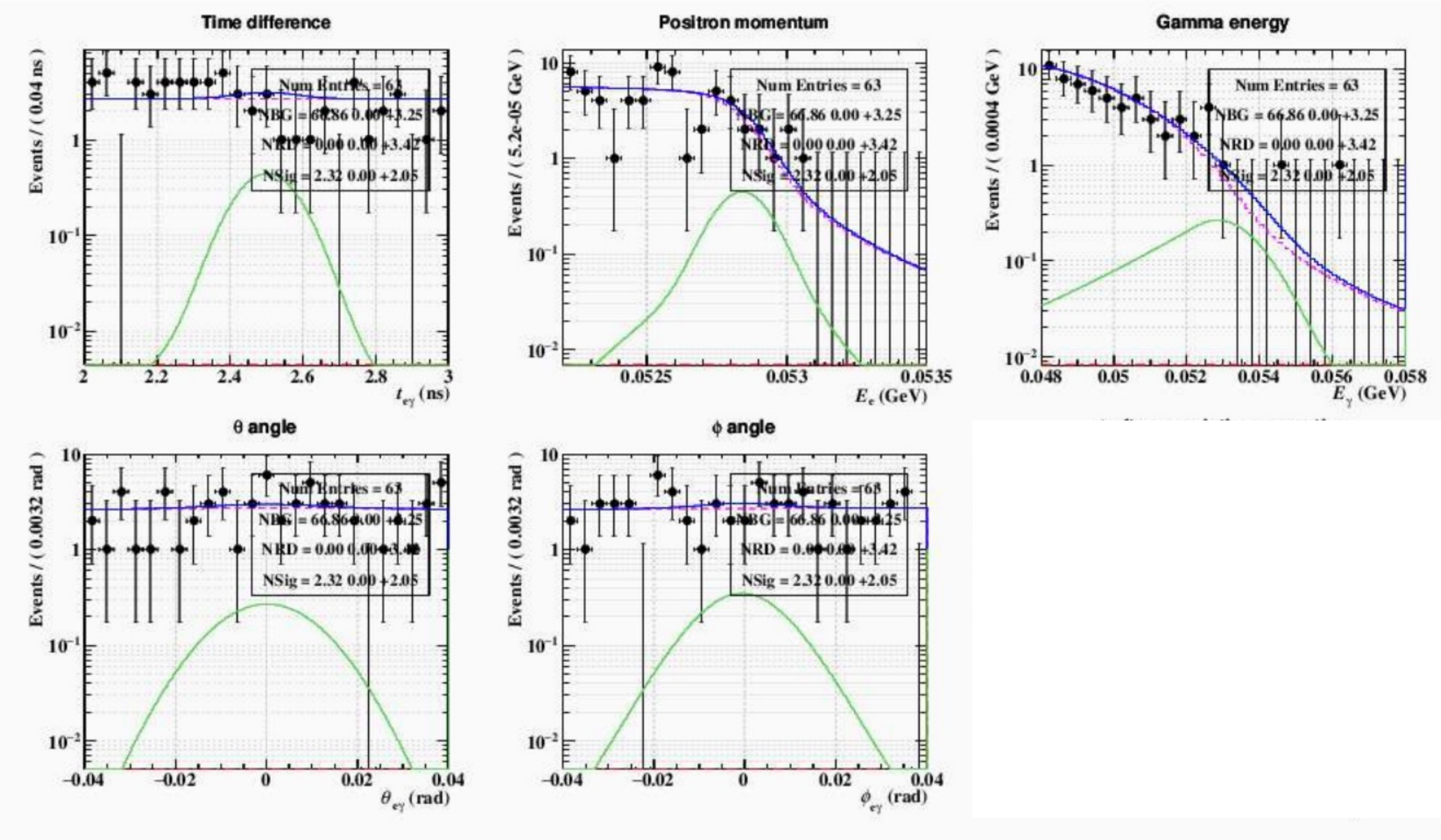
(Some of them dropped by cuts)





Fitting to sideband: Example2

- Fit to sideband as a cross-check before unblinding
  - Only accidental events identical to those in blinded region → Checks about BG PDF
  - Below: sideband 2 ns – 3 ns



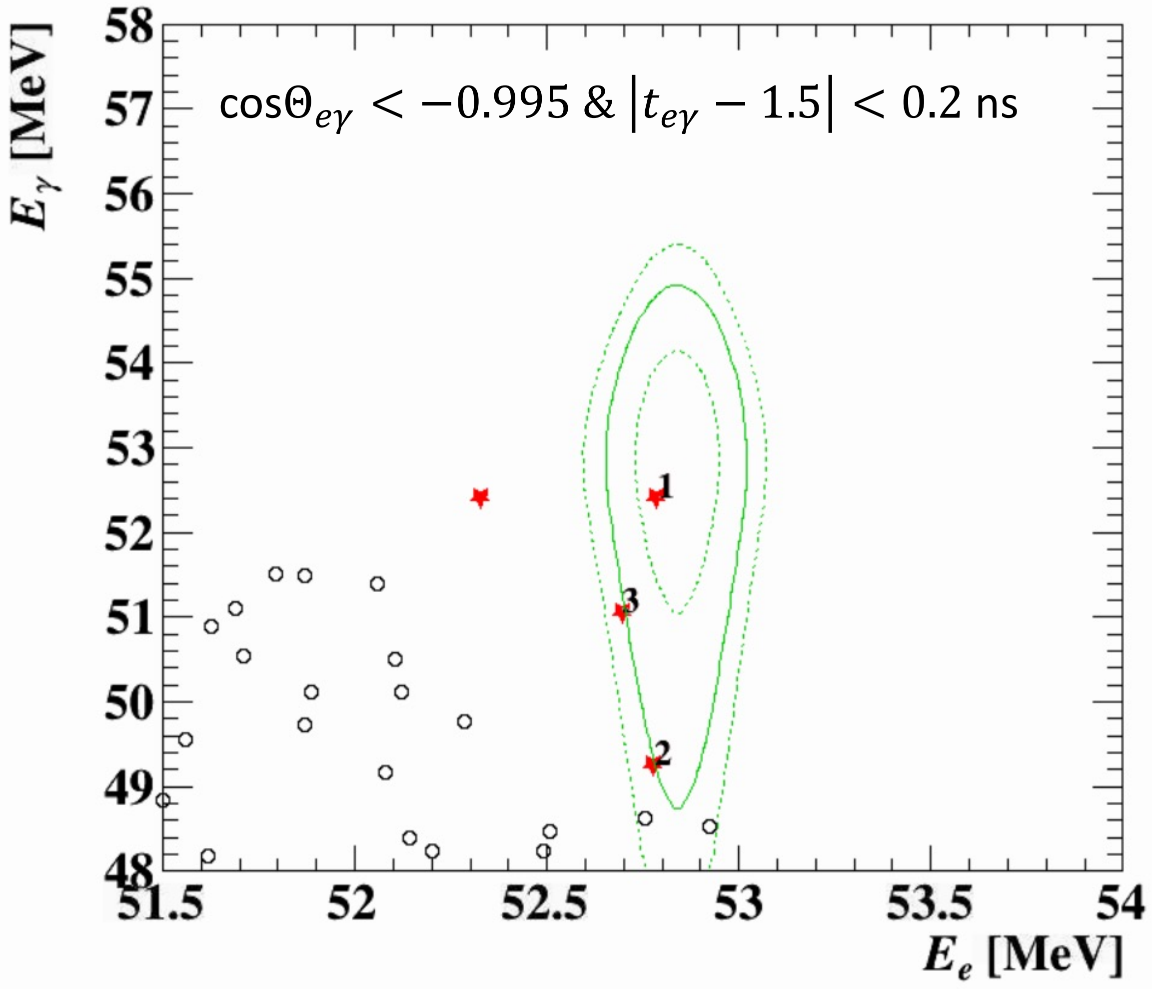
Fitting in another sideband

- Observed 3 signal-like events
- But within statistical fluctuation
  - 5% probability expected

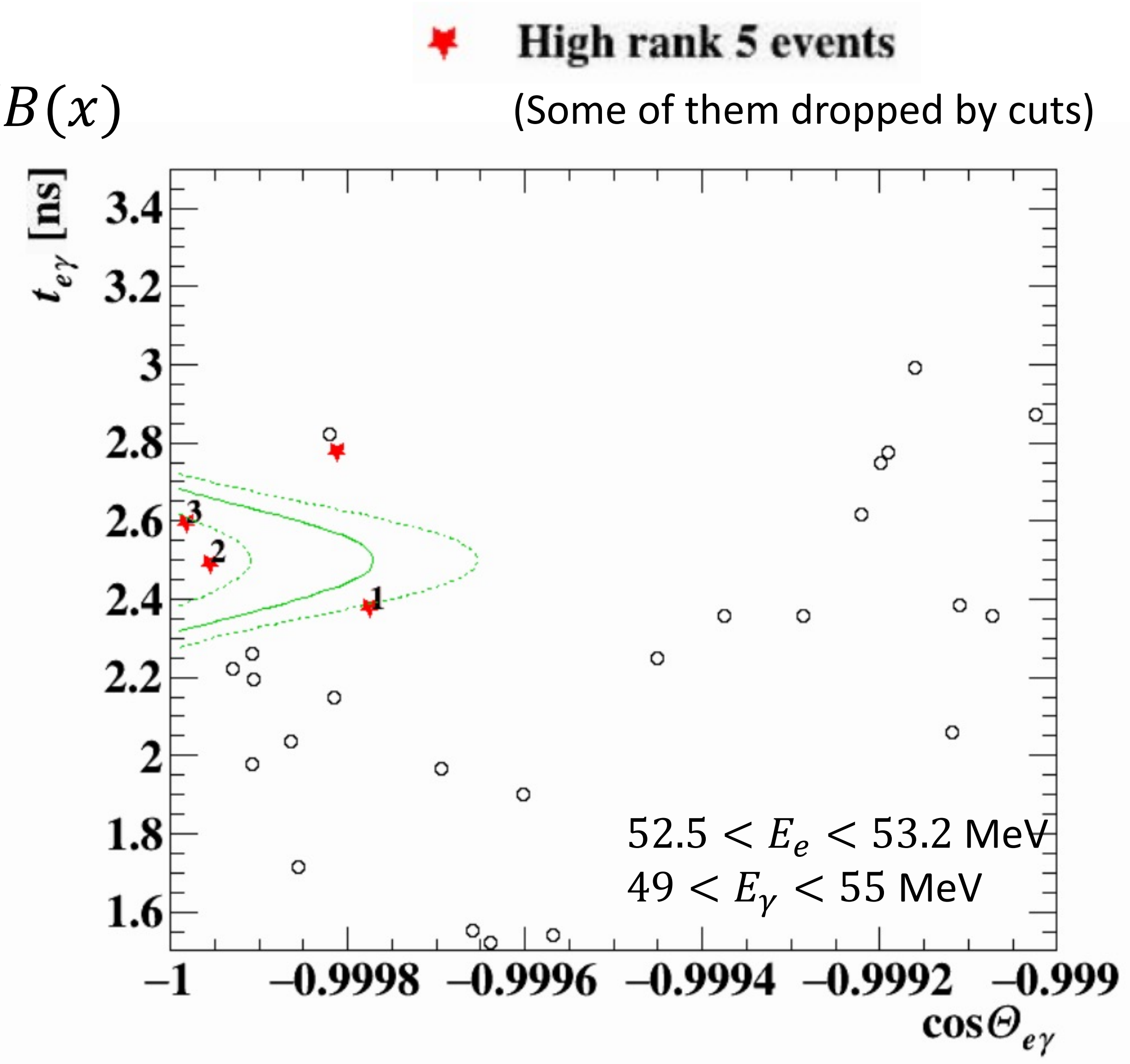
- Confidence interval (90% C.L.)
  - $1.6\times10^{-13} < \text{Br} < 2.6\times10^{-12}$

Event distribution in sideband: Example2

- Event distribution
  - Signal likelihood ranked by PDF ratio: $S(x)/B(x)$



$\cos\Theta_{e\gamma} < -0.995$ & $|t_{e\gamma} - 1.5| < 0.2$ ns



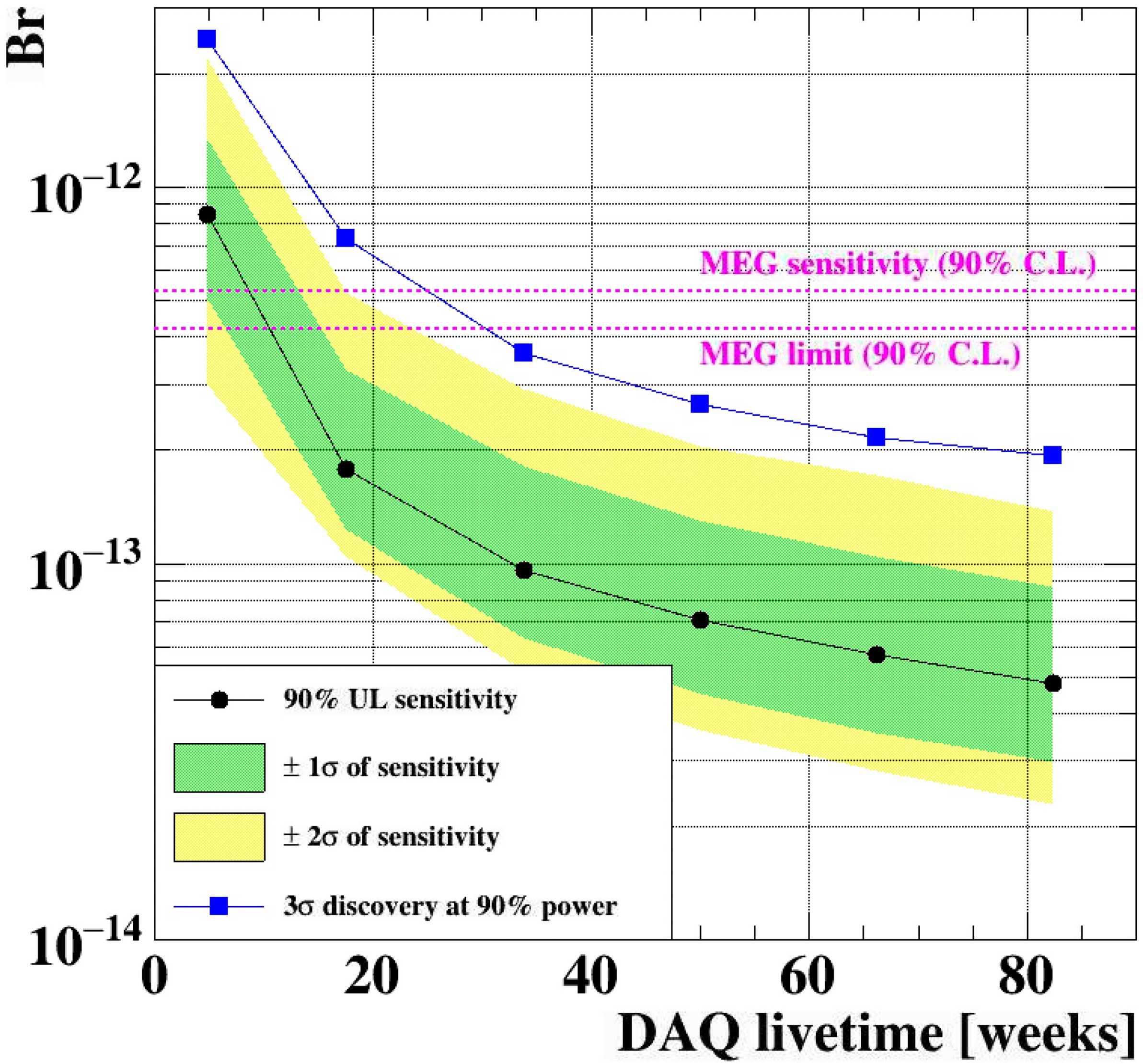
(Some of them dropped by cuts)

$52.5 < E_e < 53.2$ MeV
$49 < E_\gamma < 55$ MeV

Summary and prospect

- 2021 analysis
  - Sensitivity to Br($\mu \rightarrow e\gamma$): 8.8×10^{-13}
  - Will be published soon
  - "PSI special seminar" in Oct/20
- 2022 analysis
  - Calibration works in progress
- 2023 DAQ and onwards
  - 2023 data taking with good condition so far

Projected sensitivity based on 2021 performance



Backup

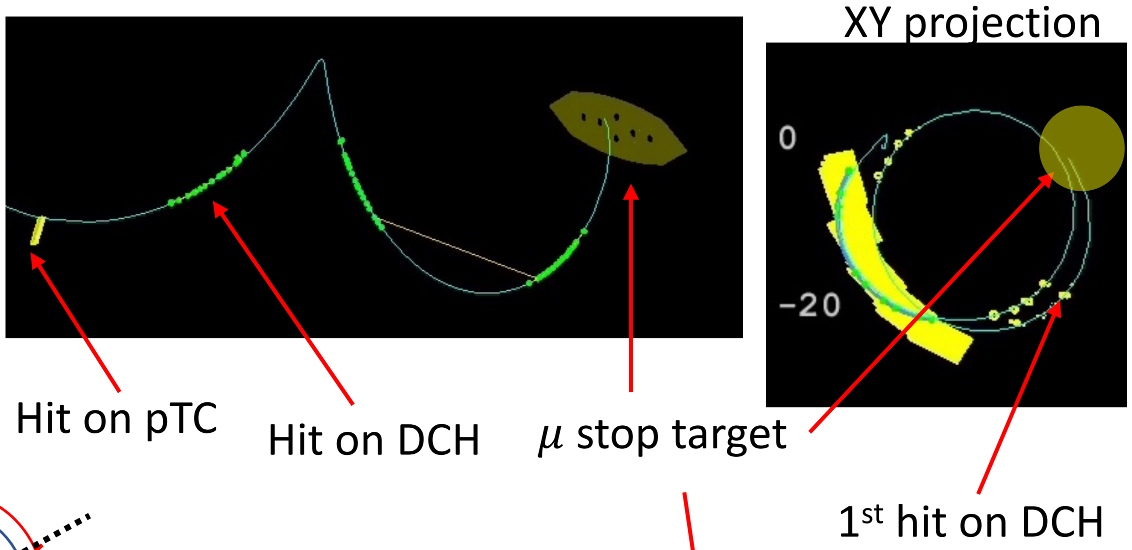
Performance comparison

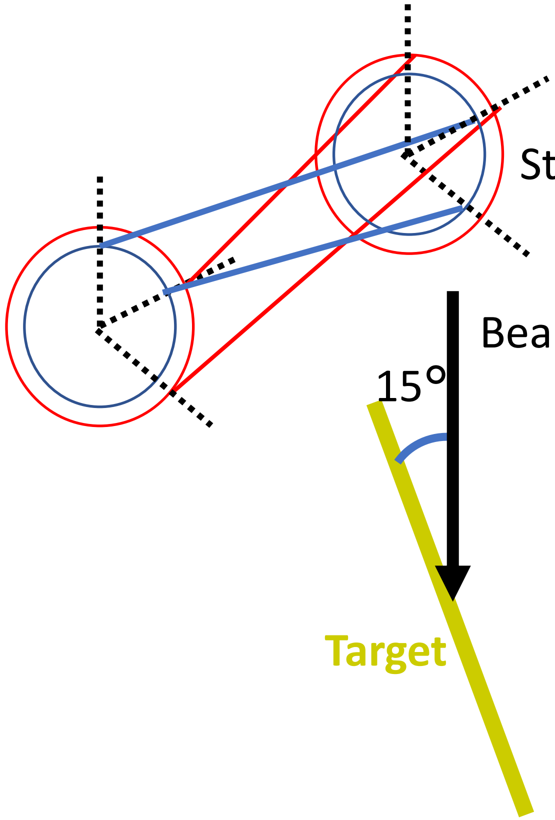
	Currently achieved performance in MEG II	**Performance in MEG**
θ_e, ϕ_e	7.7/5.6 mrad (Double turn analysis)	9.4/8.7 mrad
y_e, z_e	0.8/2 mm (Double turn analysis)	1.2/2.4 mm
E_e	90 keV for core (Michel fit)	306 keV
E_γ	2% (CEX resolution analysis)	2.4% (w<2 cm), 1.7% (w>2cm)
u, v, w_γ	2.5 mm for w < 2 cm (Collimated gamma ray data)	5 mm
$t_{e\gamma}$	$\frac{112}{\sqrt{n_{TC}}} \oplus$ 72 ps (RMD samples)	122 ps
RDC	Installed since middle of 2021 run	Not installed

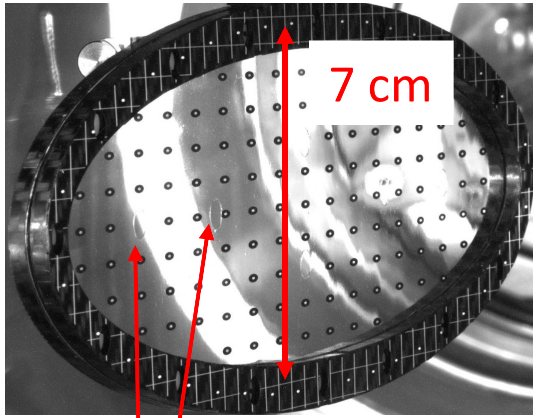
MEG II apparatus for vertex & track

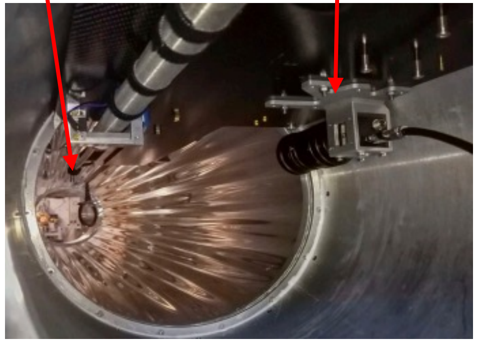
- Positron trajectory in B-field
  1. Emitted from target
  2. Make hits on drift chamber (DCH)
  3. 1.5 or 2.5 turns from target to timing counter (pTC)
- Drift chamber
  - Stereo geometry wire chamber
  - $r_{inner} = 17$ cm, $r_{outer} = 27$ cm
- μ stop target
  - 15° slanted w.r.t beam
  - $r \sim 3.5$ cm projected on XY plane
  - 6 holes
  - Camera
  - Dot markers

For alignment



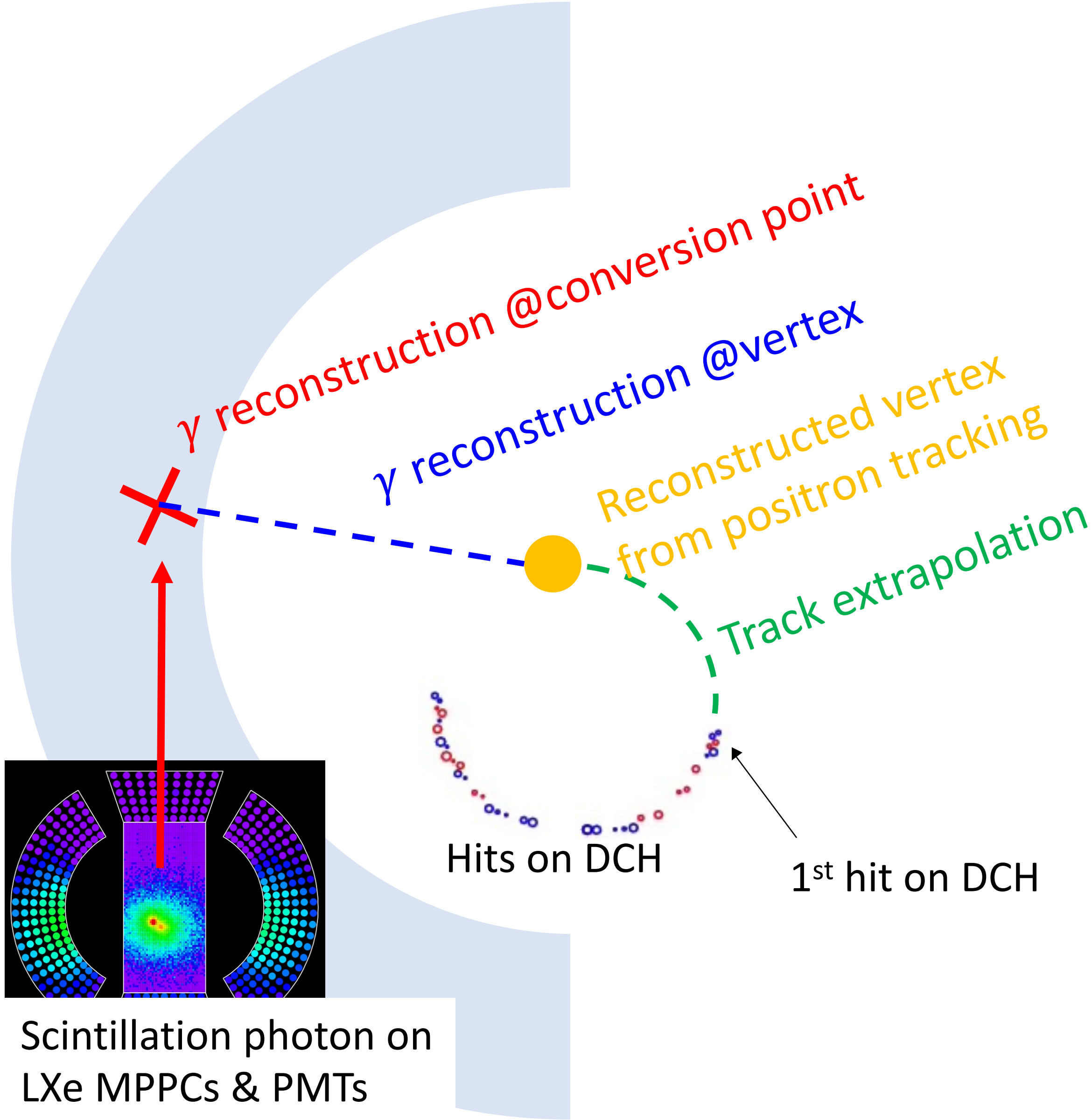






https://doi.org/10.1063/5.0034842

Reconstruction



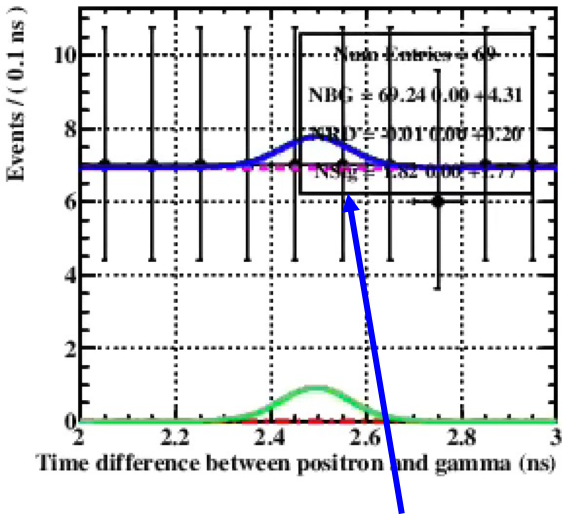
- Positron reconstruction
  - Decay position and angle by track extrapolation to target
  - Time measured at pTC & TOF correction with track
  - Energy from track curvature & B-field
- Gamma reconstruction **@conversion point**
  - Conversion position by light distribution
  - Time by combining measurements 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

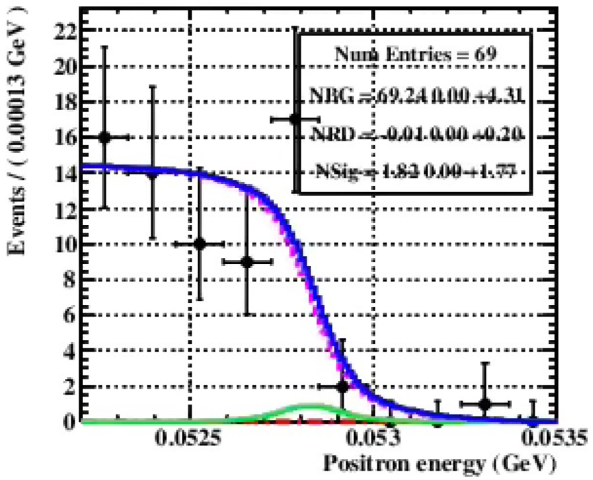
- List of observables
  - $t_{e\gamma} := t_\gamma - t_e$
  - $\phi_{e\gamma} := \pi + \phi_e - \phi_\gamma$
  - $\theta_{e\gamma} := \pi - \theta_e - \theta_\gamma$
  - E_γ
  - E_e
  - RDC hit

Opening angle decomposed into θ, ϕ

$t_{e\gamma}$



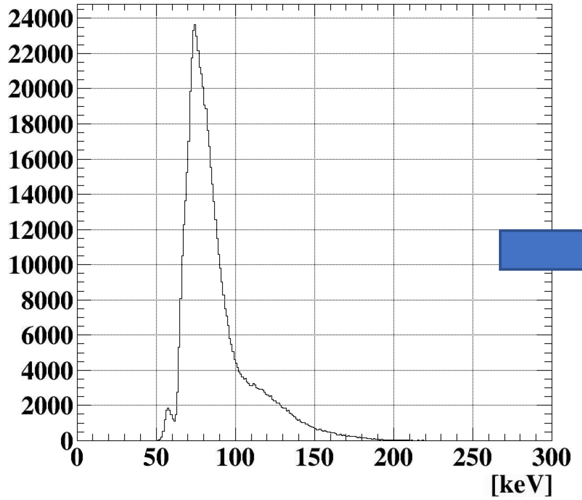
E_e



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

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

Tracking momentum uncertainty



With smaller uncertainty, signal peak in E_e distribution becomes sharp

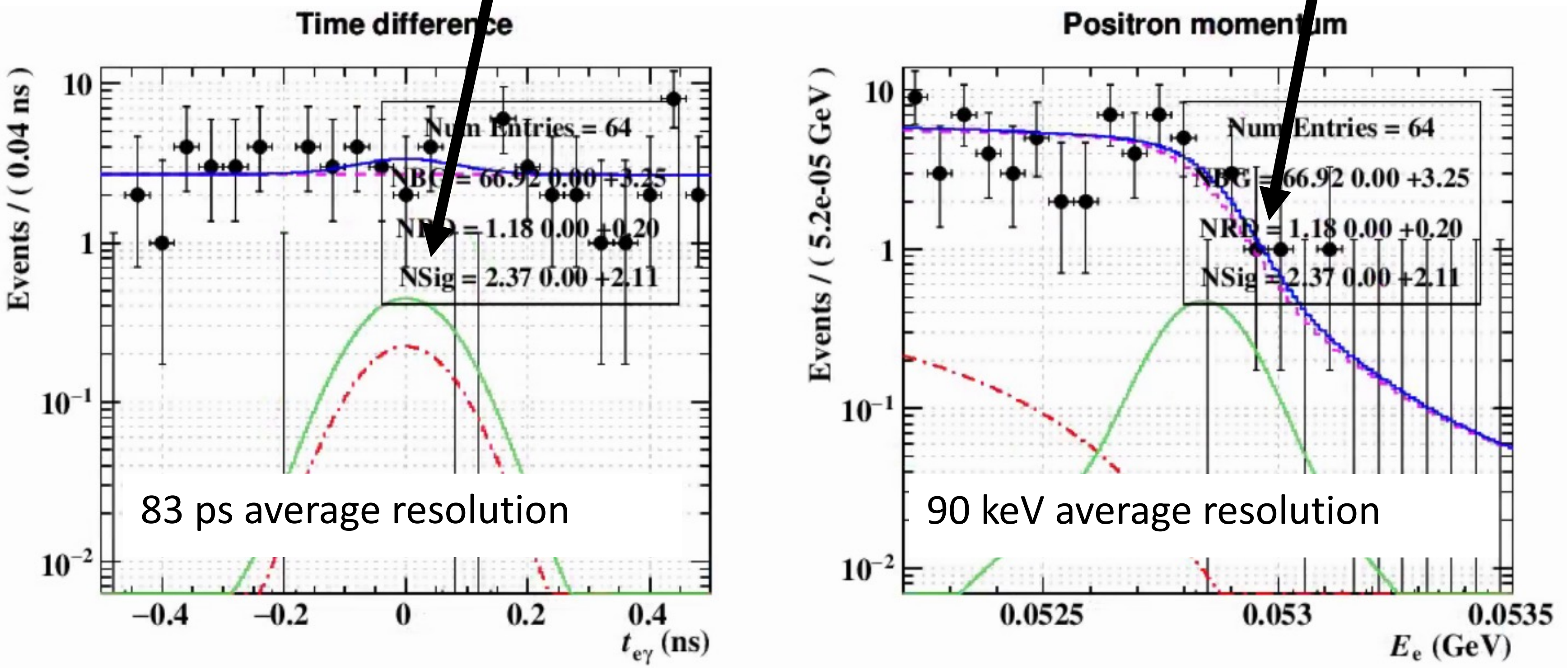
Overview of PDFs

- List of observables
  - $\phi_{e\gamma} := \pi + \phi_e - \phi_\gamma$
  - $\theta_{e\gamma} := \pi - \theta_e - \theta_\gamma$
  - E_γ → Discussed in previous talk
  - $\boldsymbol{E_e}$
  - $\boldsymbol{t_{e\gamma} := t_\gamma - t_e}$
  - RDC hit

Signal PDF
BG PDF
RMD PDF
Full PDF

RMD events in energy sideband used for resolution evaluation

Kinematic endpoint smeared by resolution
→ Resolution evaluated by spectrum fitting



83 ps average resolution

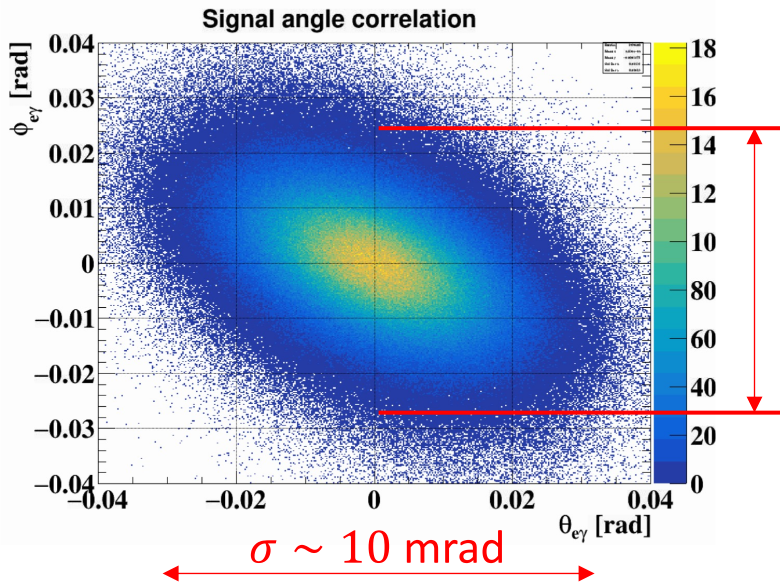
90 keV average resolution

Also see
1.23pT1-2 (2023 spring)
2.7aA442-2 (2022 autumn)

Overview of PDFs

- List of observables
  - $\boldsymbol{\phi_{e\gamma} := \pi + \phi_e - \phi_\gamma}$
  - $\boldsymbol{\theta_{e\gamma} := \pi - \theta_e - \theta_\gamma}$
  - E_γ → Discussed in previous talk
  - E_e
  - $t_{e\gamma} := t_\gamma - t_e$
  - RDC hit

Opening angle decomposed into θ, ϕ



$\sigma \sim 10$ mrad

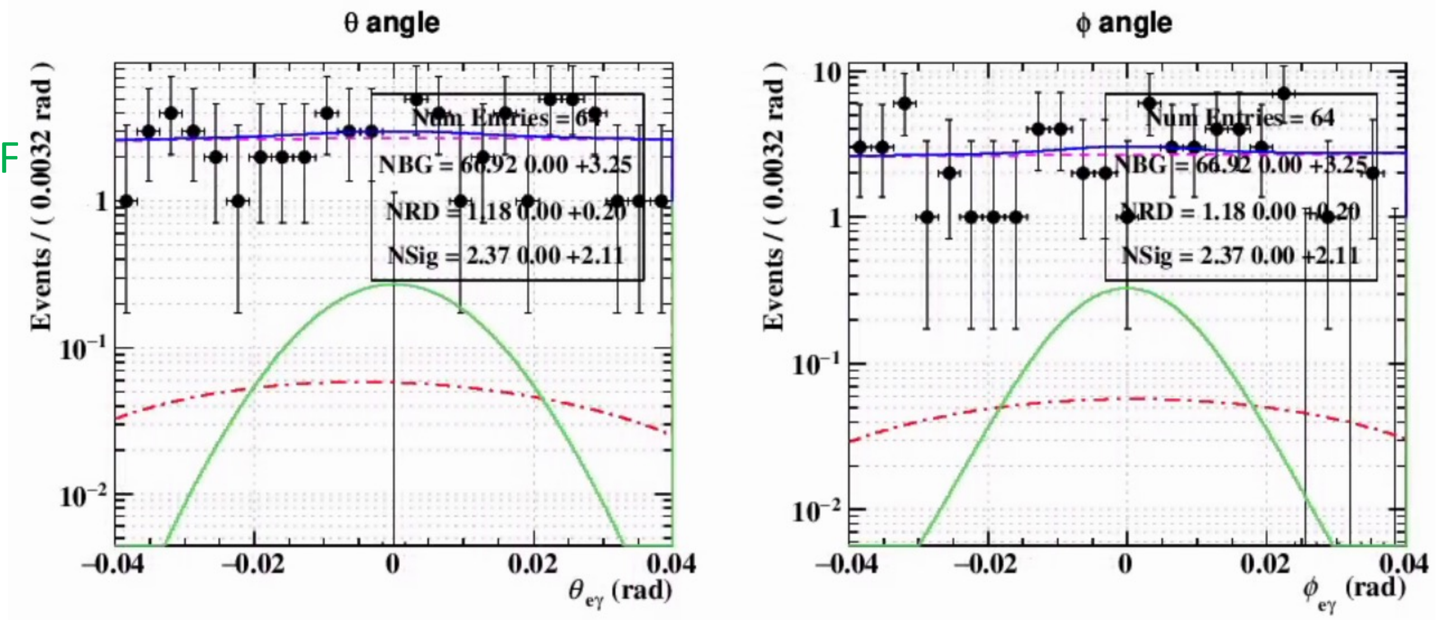
$\sigma_{inner} \sim 7$ mrad after correlation correction

Signal PDF

BG PDF

RMD PDF

Full PDF



Positron resolution by two-turn analysis
Detail in
1.23pT1-2 (2023 spring)
2.7aA442-2 (2022 autumn)

Gamma resolution by DAQ w/ collimator
Detail in 15aSE-9 (2020 autumn)

Normalization

- Normalization with two independent methods

Michel positron counting method

- Use of pre-scaled positron only trigger
- Automatically include
  - Positron efficiency
  - Beam intensity
- Need precise knowledge of
  - Selection efficiency
  - Trigger efficiency
  - Gamma efficiency

5 % uncertainty

- $(2.55 \pm 0.13) \times 10^{12}$

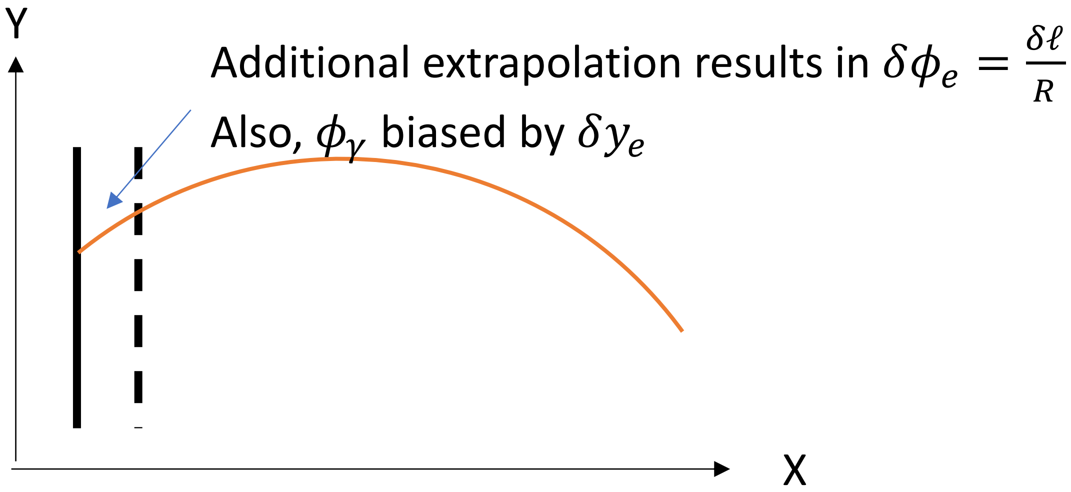
RMD counting method

- Use of RMD in energy sideband region
- Automatically include both
  - Positron efficiency
  - Gamma efficiency
- Need to correct
  - Efficiency vs energy dependence
  - Impact of detector resolution
- $(3.1 \pm 0.3) \times 10^{12}$
  - Large uncertainty in gamma-ray response convolution

→ Combined result: $(2.64 \pm 0.12) \times 10^{12}$

Alignment (angle PDF uncertainty)

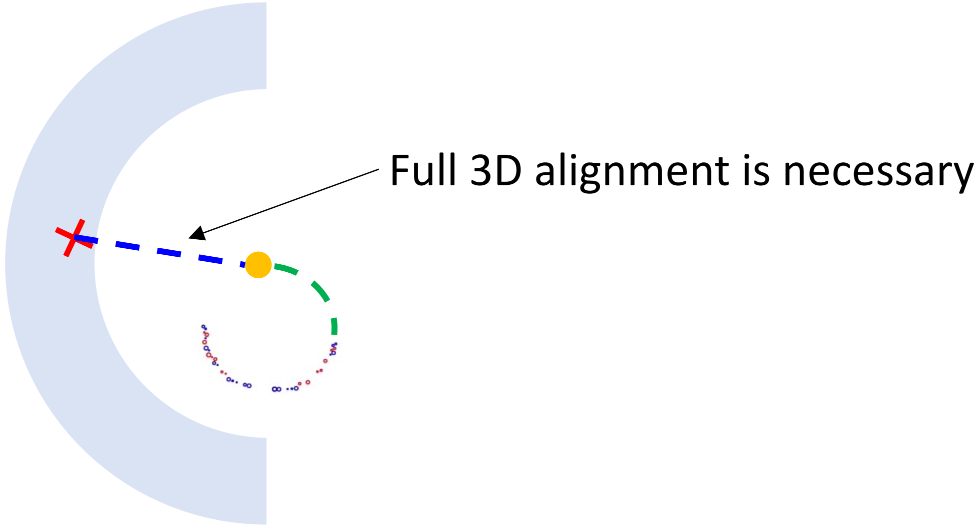
- Mis-alignment shifts signal PDF
    - No physical calibration source
    - Precise alignment is a must
    - Largest systematics source in MEG I



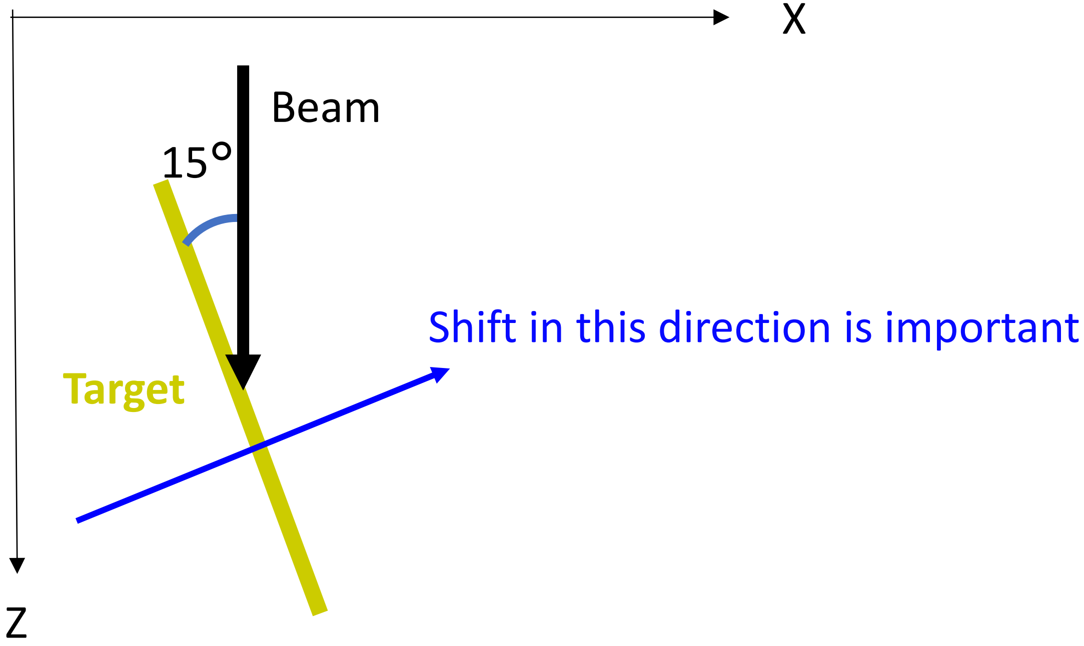
Additional extrapolation results in $\delta\phi_e = \frac{\delta\ell}{R}$

Also, ϕ_γ biased by δy_e

- Important parameters
    1. DCH – LXe relative alignment in 3D
    2. DCH – target alignment in X coordinate



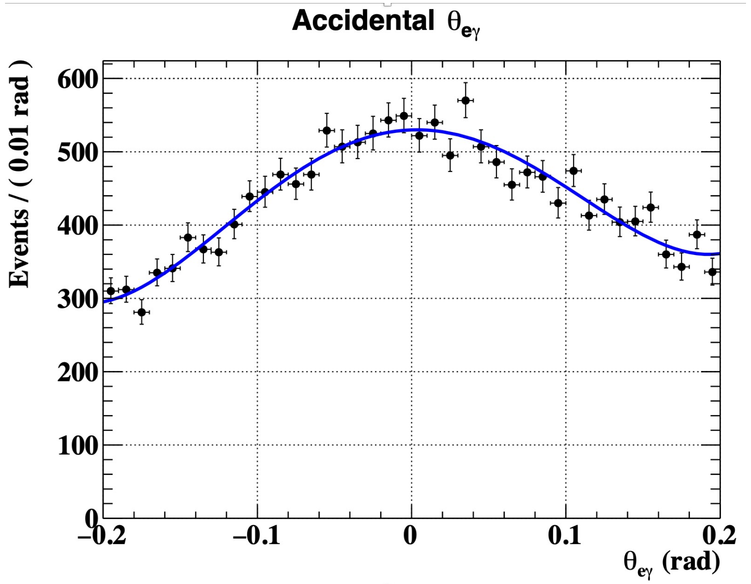
Full 3D alignment is necessary



Shift in this direction is important

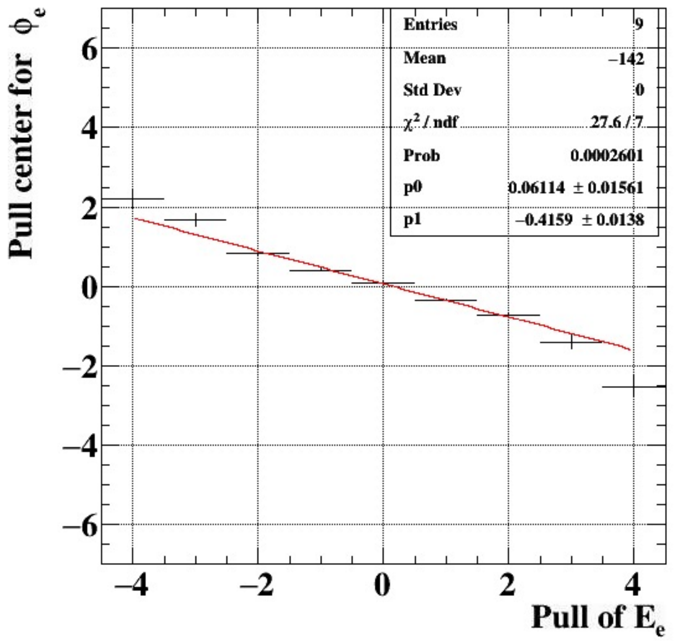
Angle PDF

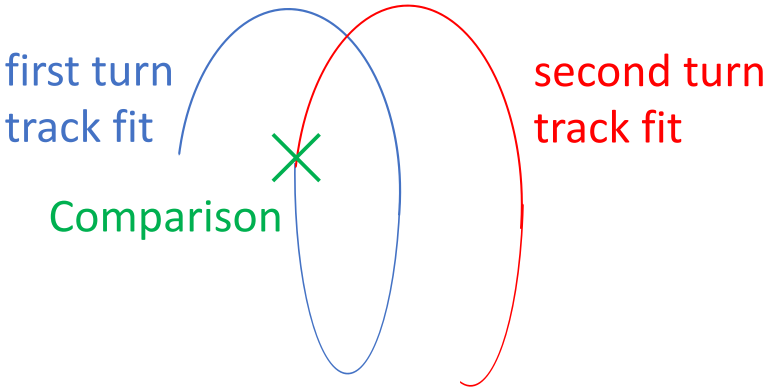
- Accidental background
  - Non-flat distribution
    - Trigger requires direction match between positron & gamma
  - Directly taken from sideband

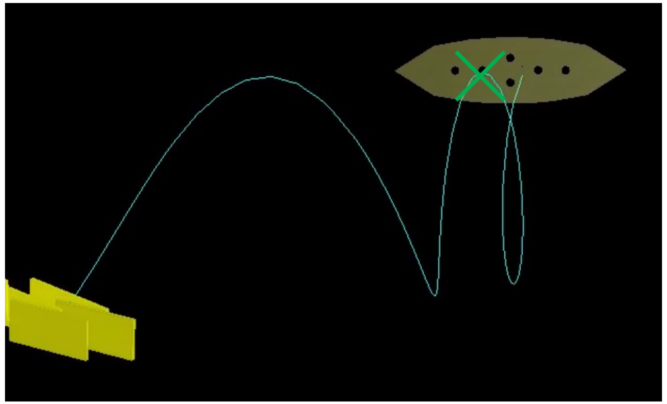


- Signal
  - Correlation is known b/w $\delta E_e, \delta\theta_e$ & $\delta\phi_e$
  - Correlation parameter estimation in progress
    - By double turn analysis combined with studies on MC samples

Signal ϕ_e error vs E_e error (MC)







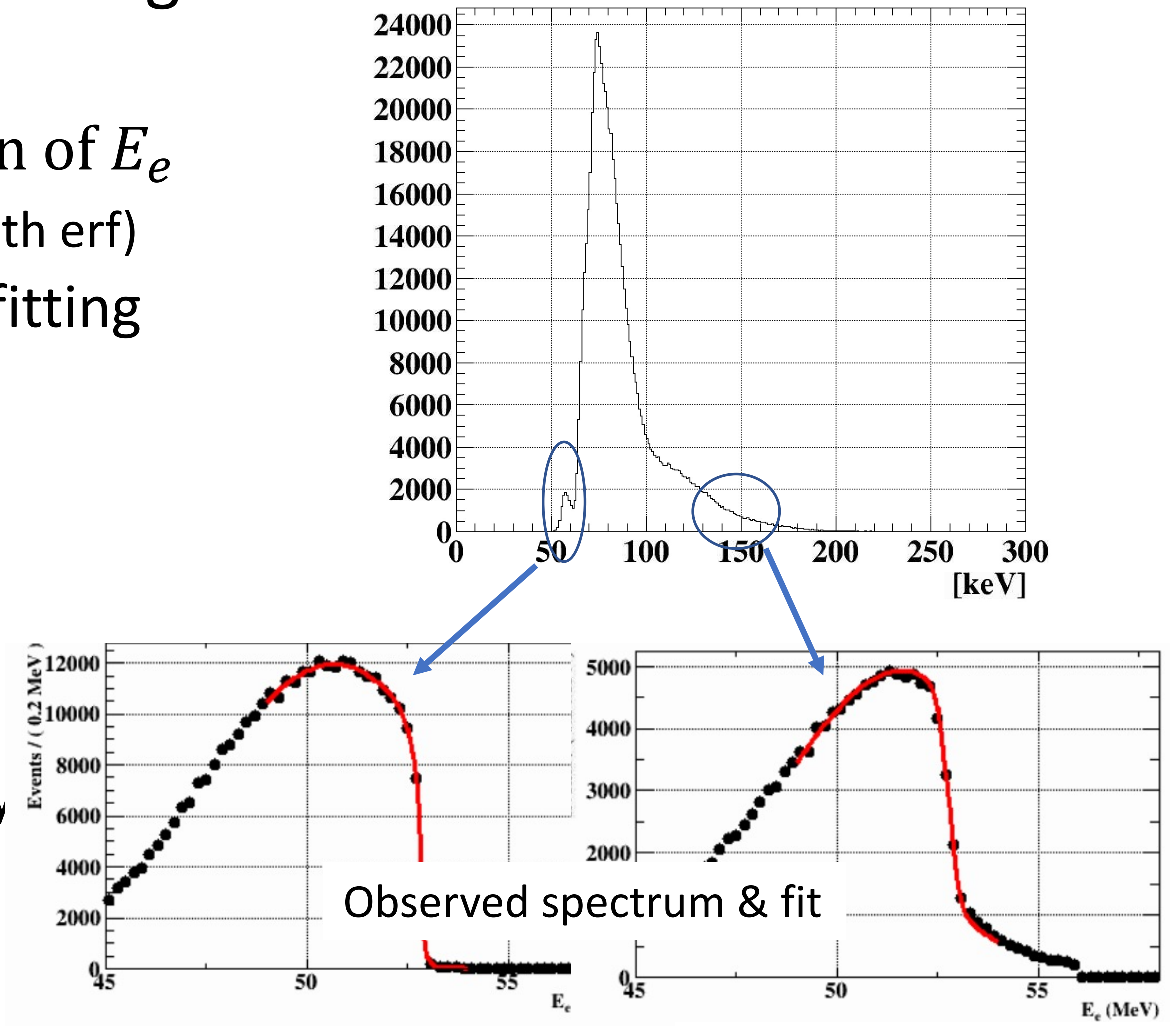
Positron momentum PDF

- 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