# MEG II 実験 2021・2022年データを用いた最高感度での$\mu \to e\gamma$探索

- イントロダクション
- 分岐比推定手法
- 本解析の暫定的な探索感度

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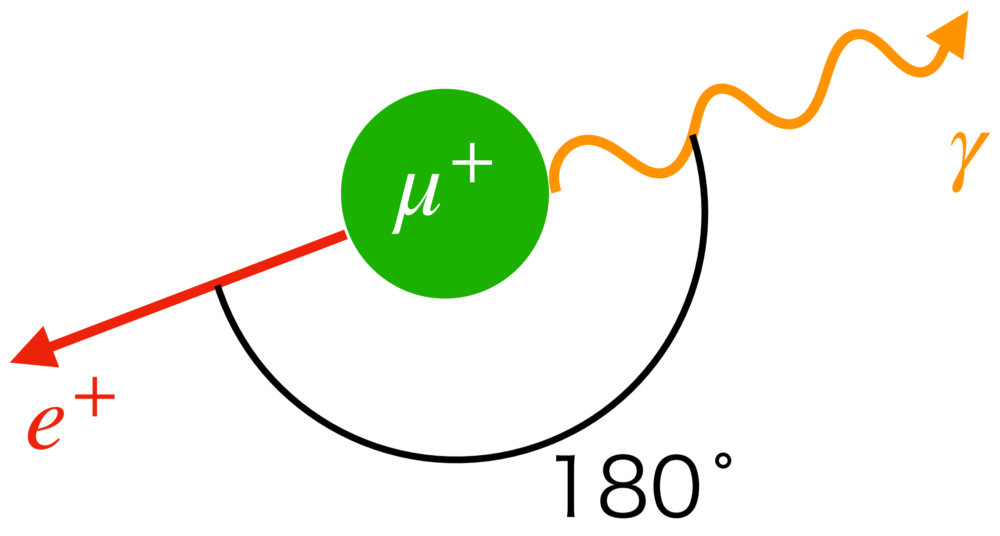
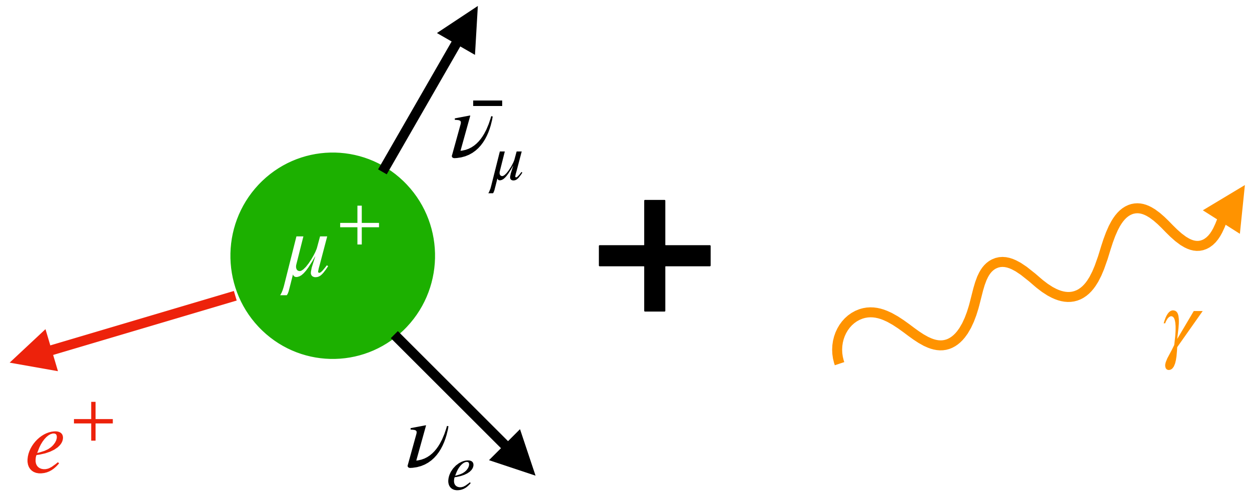
日本物理学会2025年春季大会

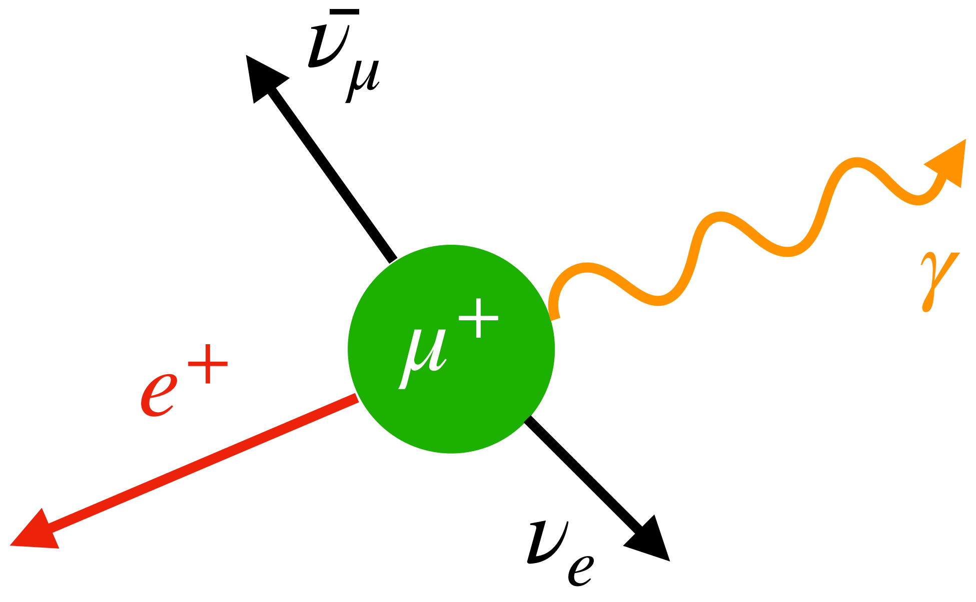
2025年3月18日(火)-21日(金)

18aT1-7

# $\mu \to e\gamma$ signature and background



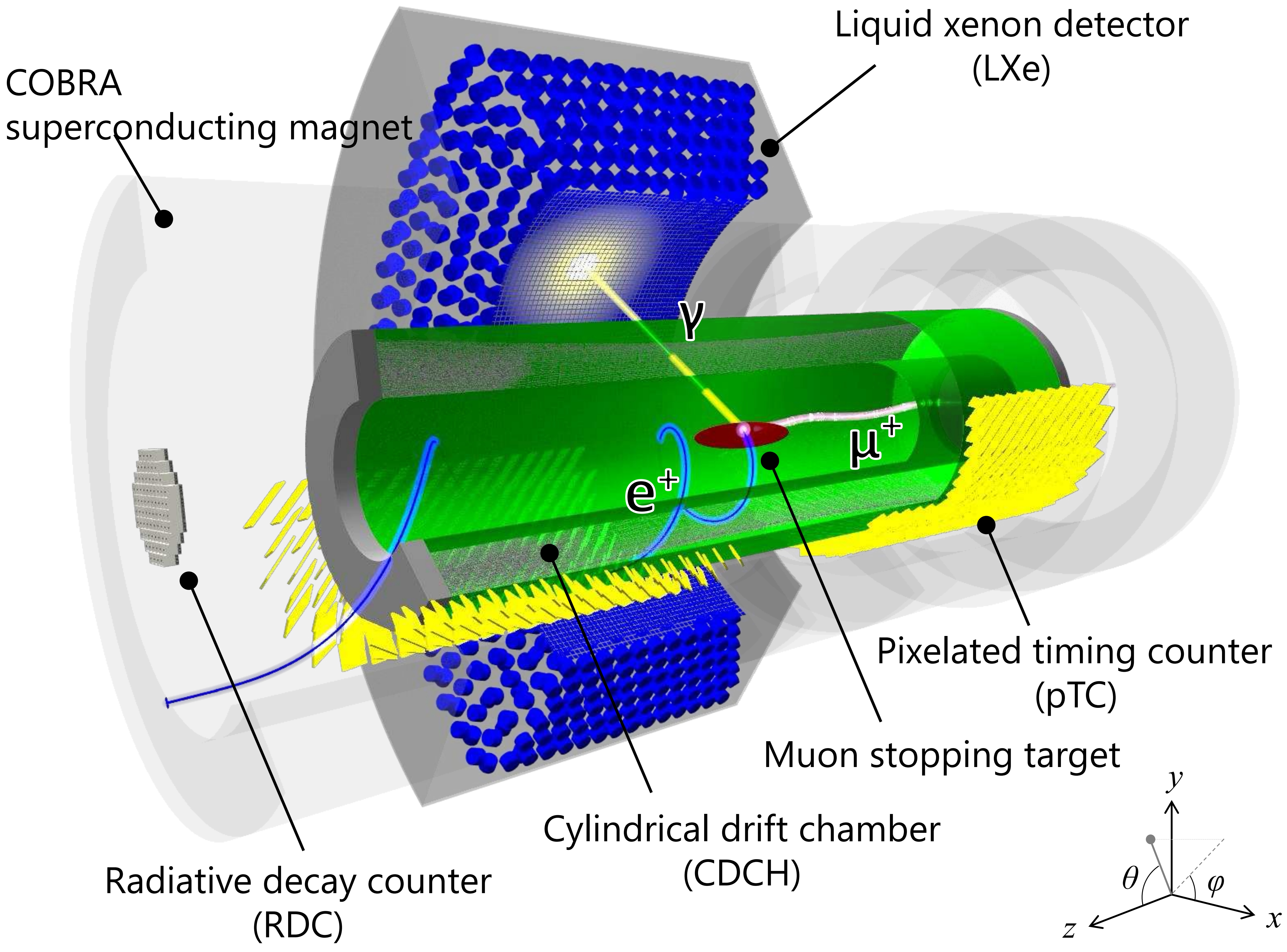



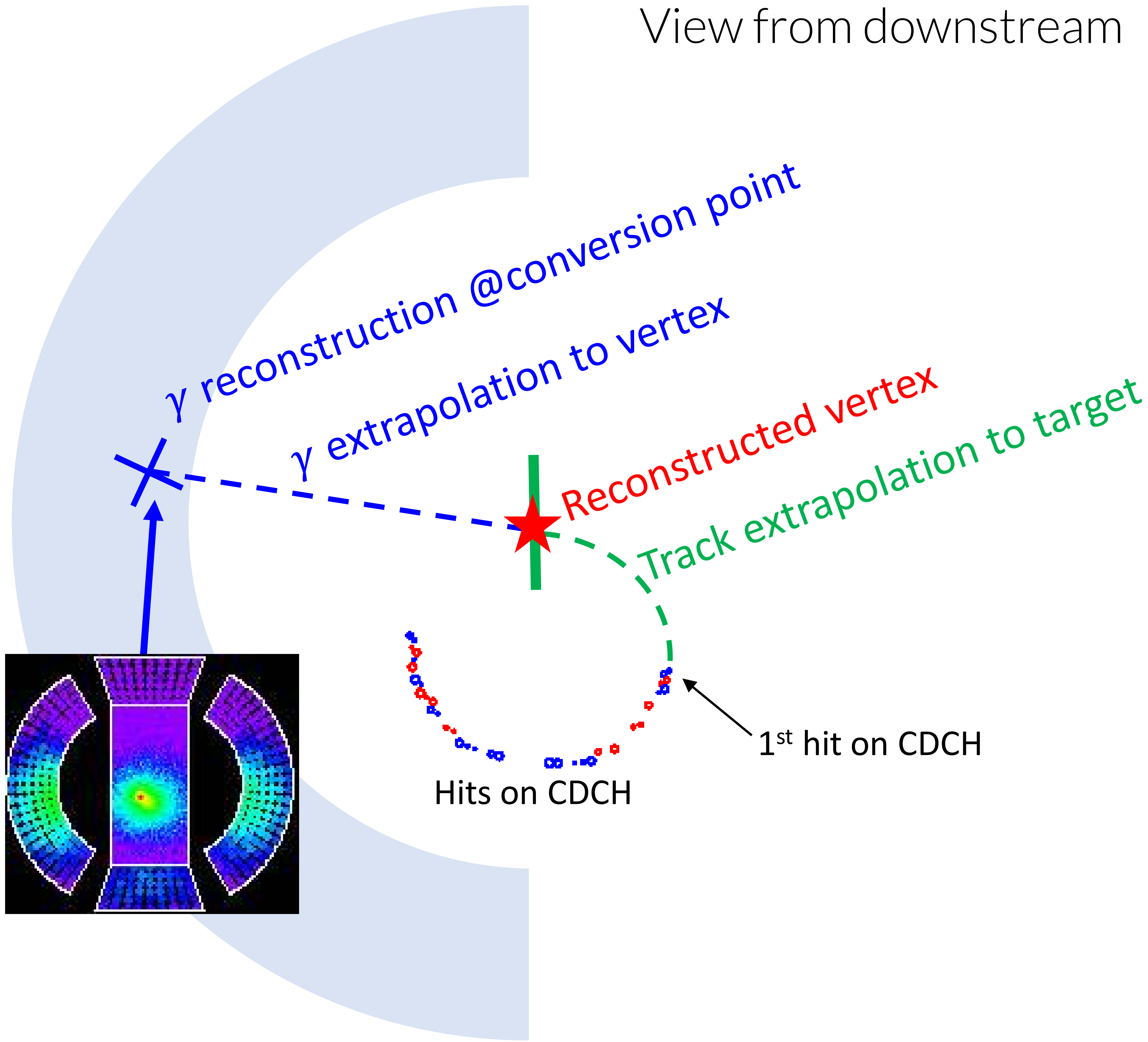




| | Signal | Accidental background $\gg$ | RMD background |
|---|---|---|---|
| $E_\gamma$ | 52.8 MeV | <52.8 MeV | <52.8 MeV |
| $E_e$ | 52.8 MeV | <52.8 MeV | <52.8 MeV |
| $t_{e\gamma} = t_\gamma - t_e$ | 0 s | Flat | 0 s |
| Opening angle | 180° | <180° | <180° |

**Precise kinematics measurement required to distinguish signal from backgrounds**

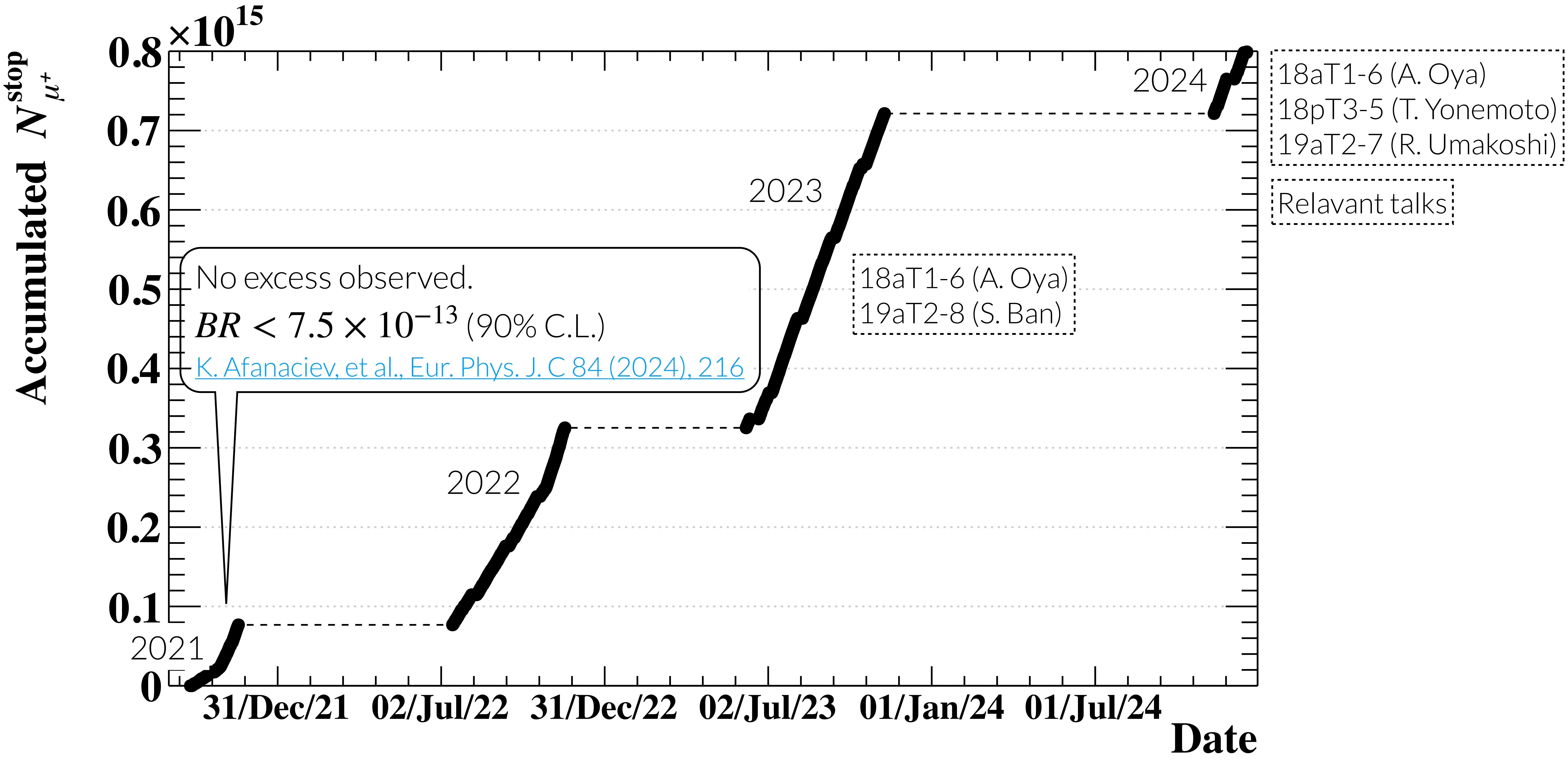
# MEG II detector & event reconstruction



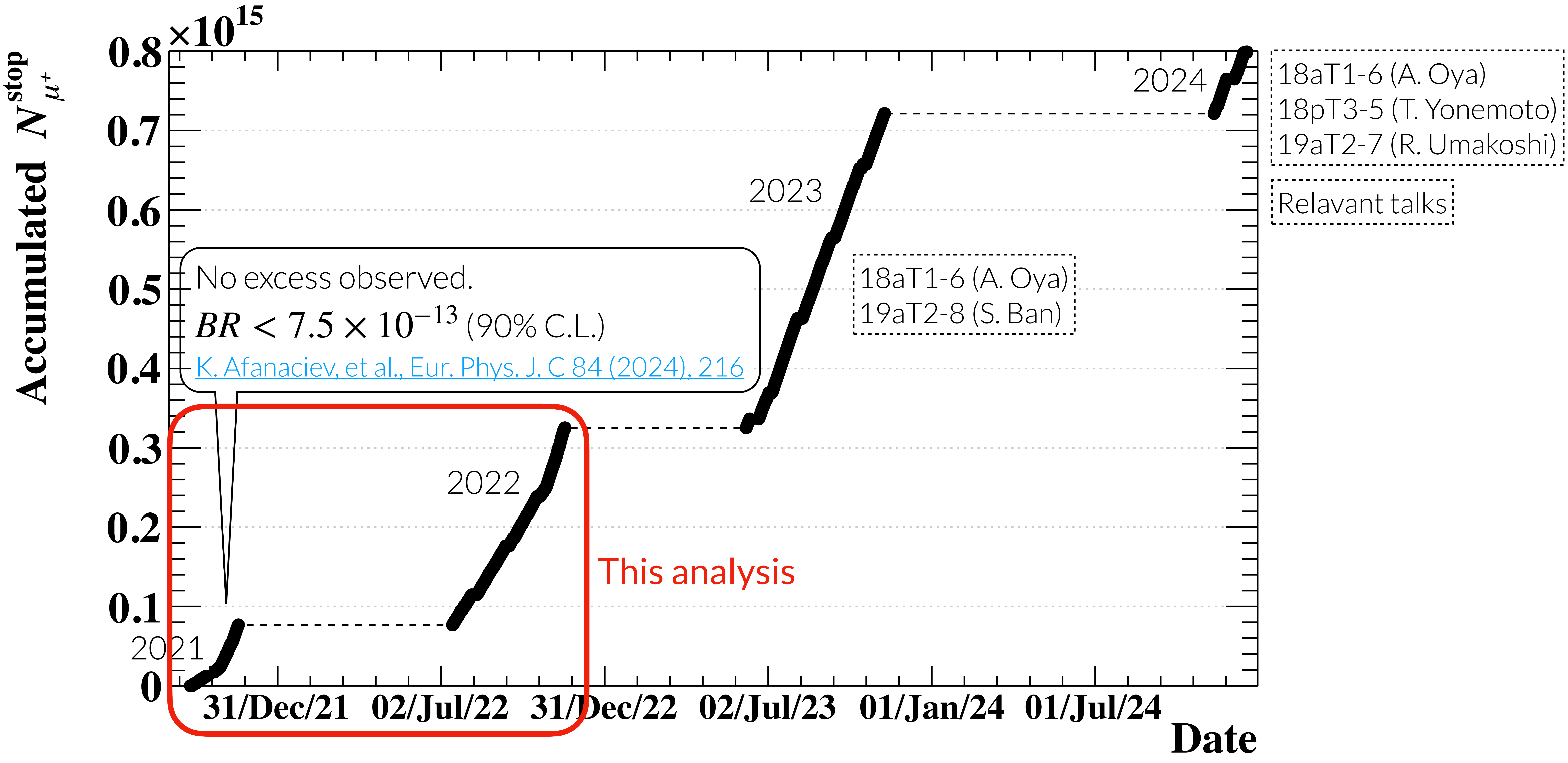




K. Afanaciev, et al., Eur. Phys. J. C 84 (2024), 190

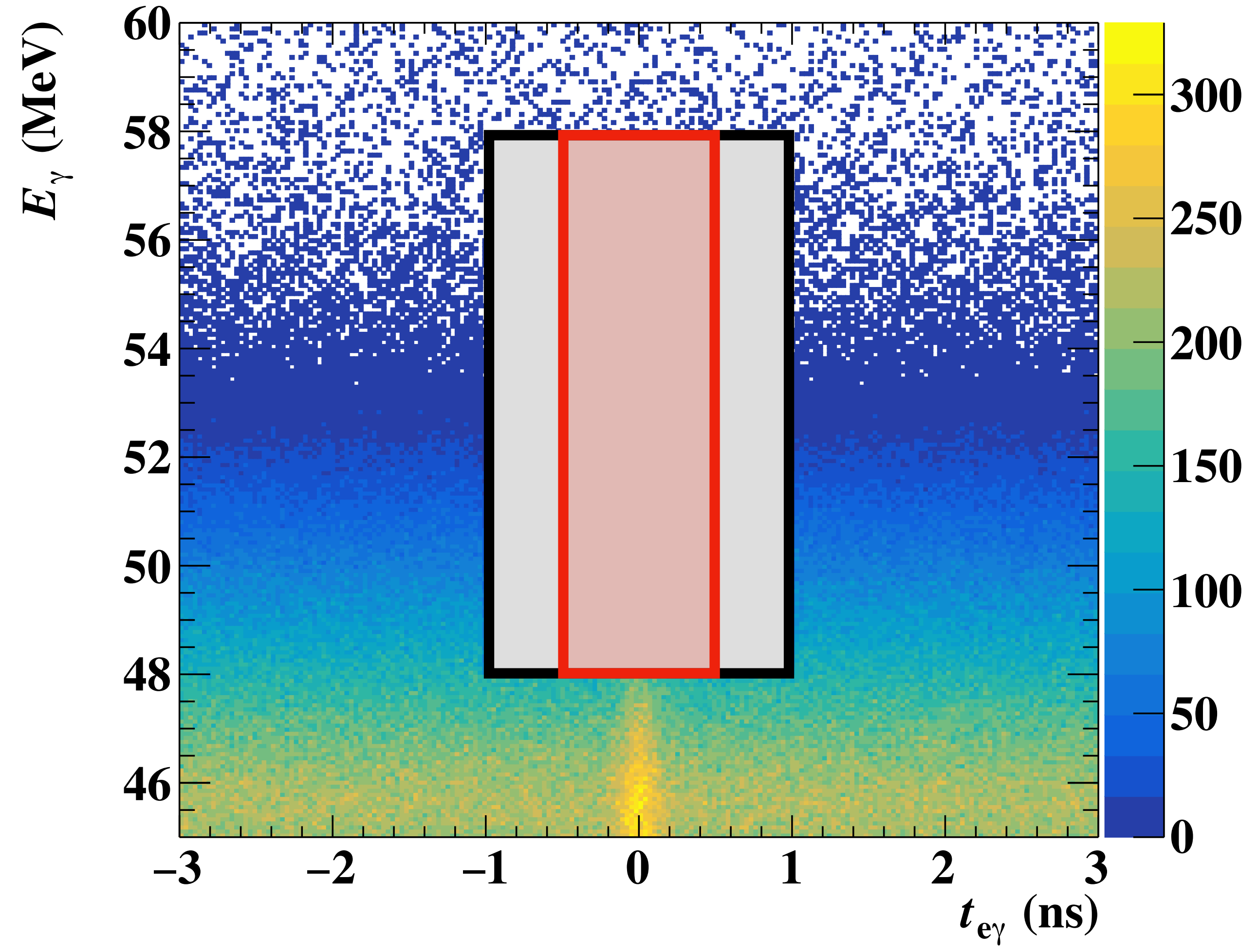
# Data collection



# Data collection



# Analysis strategy




Analysis window

- 48 MeV < $E_\gamma$ < 58 MeV
- 52.2 MeV < $E_e$ < 53.5 MeV
- $|t_{e\gamma}|$ < 0.5 ns
- $|\theta_{e\gamma}|$ < 40 mrad
- $|\phi_{e\gamma}|$ < 40 mrad

- Blind analysis
  - To prevent any biases in the analysis
  - Blind box fully covers analysis window
- $BR(\mu \to e\gamma)$ converted from $N_{\mathrm{sig}}$ by number of effectively measured muons $k$
  - Extended maximum likelihood analysis estimates the number of signal events $N_{\mathrm{sig}}$

$$BR(\mu \to e\gamma) = \frac{N_{\mathrm{sig}}}{k} \qquad k \sim N_\mu^{\mathrm{stop}} \times \Omega \times \epsilon_\gamma \times \epsilon_e$$

- Confidence interval calculated by the Feldman-Cousins approach with profile-likelihood ordering
  G. Feldman, R. Cousins, Phys. Rev. D 57 (1998), 3873
  - $N_{\mathrm{sig}}$ 90% C.L. upper (lower) limit normalised to $BR$ 90% C.L. upper (lower) limit

# Number of effectively measured muons $k$

- Count Michel positrons above 50 MeV and correct it

$$k = \frac{N^{e\nu\bar{\nu}}}{BR(\mu \to e\nu\bar{\nu})} \times \epsilon_{\gamma} \times \epsilon_{\rm sel} \times \text{Corrections} = \mathbf{(1.33 \pm 0.07) \times 10^{13}}$$

Corrections: Response difference between $\mu \to e\gamma$ and $\mu \to e\nu\bar{\nu}$

| | **Last publication with the 2021 data** | **2021** | **2022** |
|---|---|---|---|
| Trigger efficiency for μ→eγ | (80 ± 1) % | (88 ± 2) % | (91 ± 1) % |
| Trigger efficiency for μ→eνν | (91 ± 1) % | (91 ± 1) % | (99 ± 1) % |
| **k** | **(2.64 ± 0.12) x 10$^{12}$** | **(2.76 ± 0.14) x 10$^{12}$** | **(10.5 ± 0.5) x 10$^{12}$** |

Last publication → 2021 (μ→eγ): Reconstruction updates, Estimation method update

2021 → 2022 (μ→eγ): Trigger logic improvement

2021 → 2022 (μ→eνν): Trigger logic improvement

# Likelihood function to estimate $N_{\mathrm{sig}}$

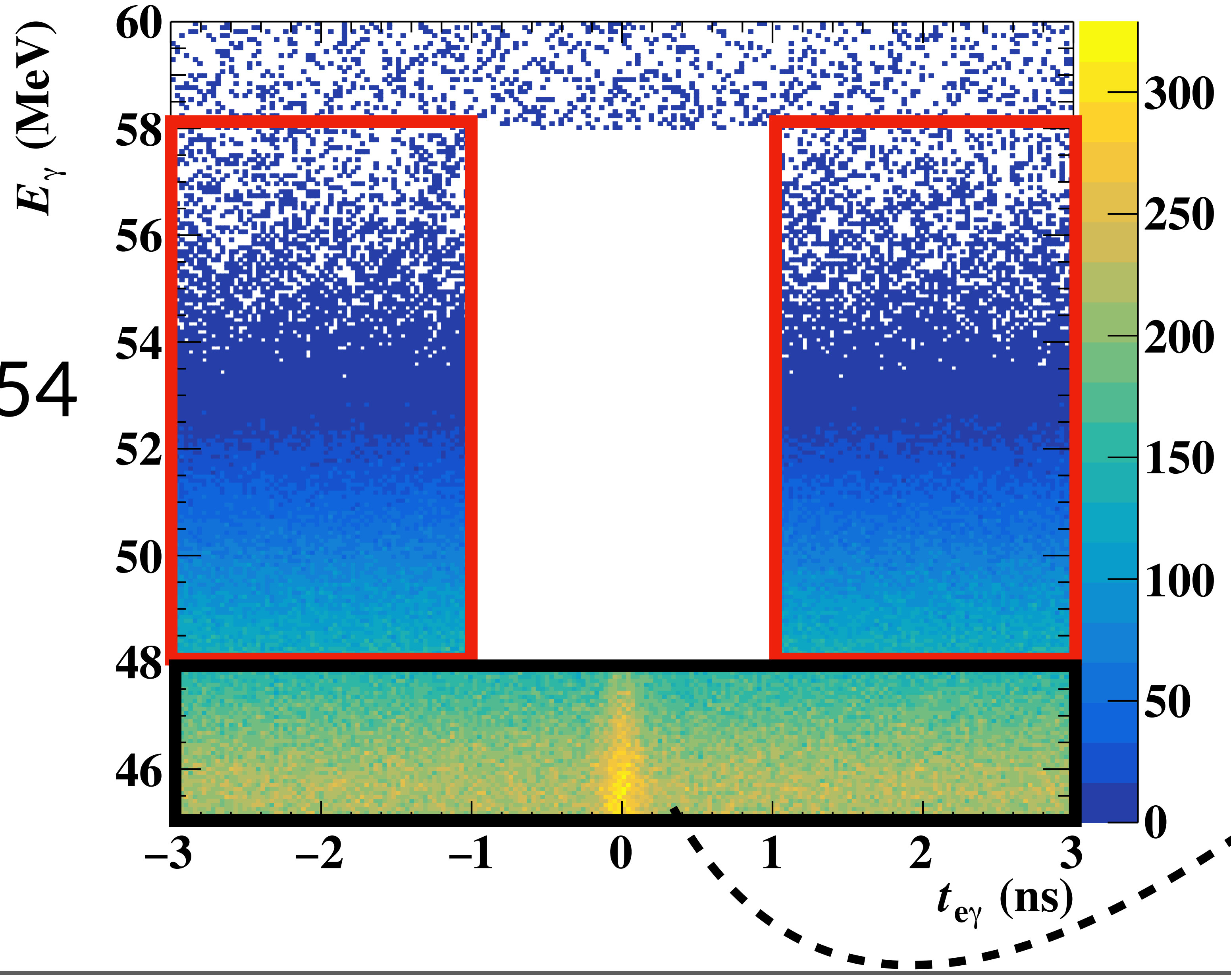
- Extended maximum likelihood analysis estimates
  - Number of signal events $N_{\mathrm{sig}}$
  - Number of accidental and RMD background events, $N_{\mathrm{ACC}}$ and $N_{\mathrm{RMD}}$ (Nuisance parameters)

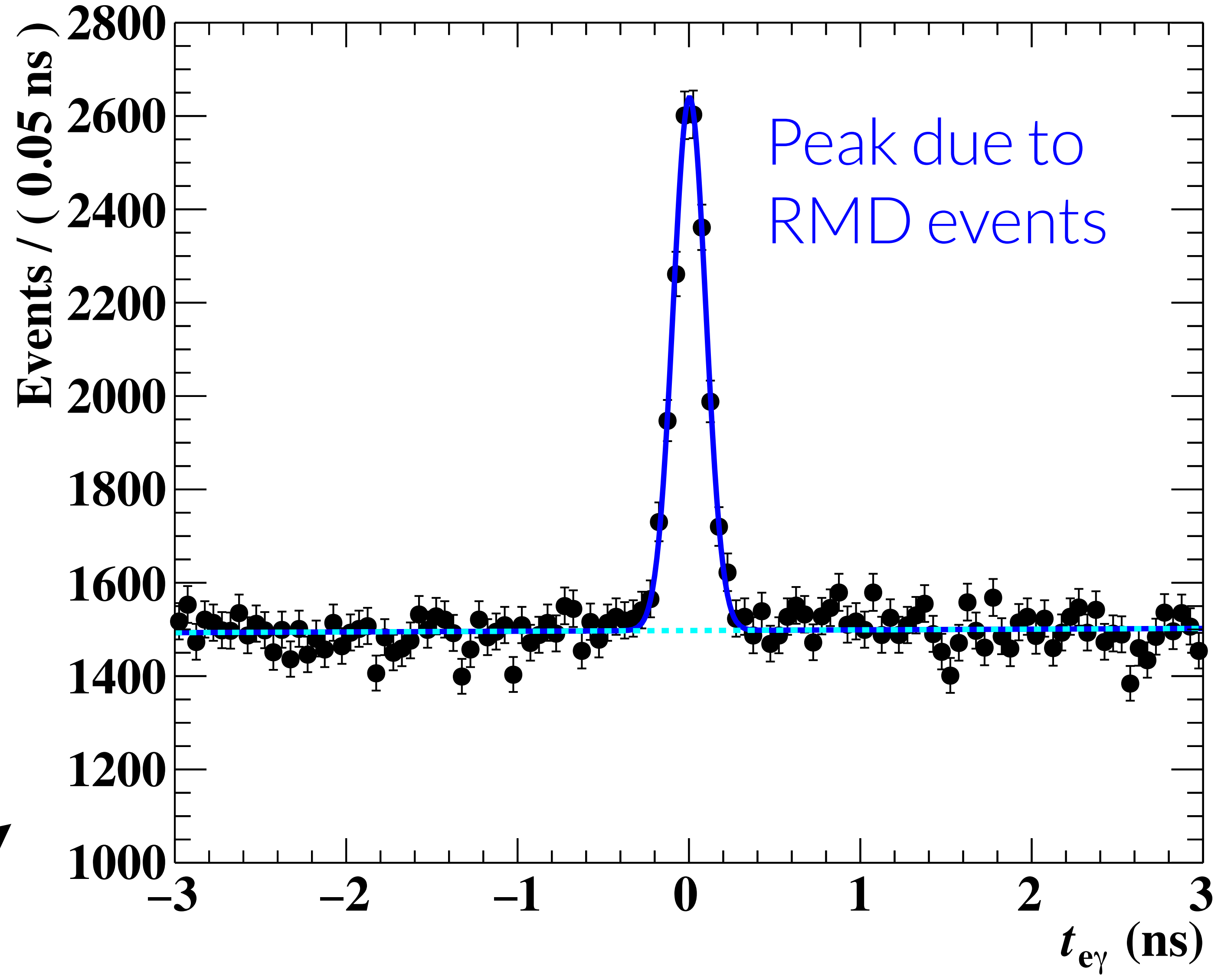
$$\mathscr{L}(N_{\mathrm{sig}}, N_{\mathrm{ACC}}, N_{\mathrm{RMD}}) = \underbrace{C(N_{\mathrm{ACC}}, N_{\mathrm{RMD}})} \times \frac{e^{-N}}{N_{\mathrm{obs}}!} \prod_{i=1}^{N_{\mathrm{obs}}} \left[ N_{\mathrm{sig}} \cdot S(\vec{x}_i) + N_{\mathrm{ACC}} \cdot A(\vec{x}_i) + N_{\mathrm{RMD}} \cdot R(\vec{x}_i) \right]$$

Constraints based on side-bands

Event-by-event probability density functions (PDFs)

Count events in $t_{e\gamma}$ side-bands
→ $N_{\mathrm{ACC}}$ = 364 ± 9.54



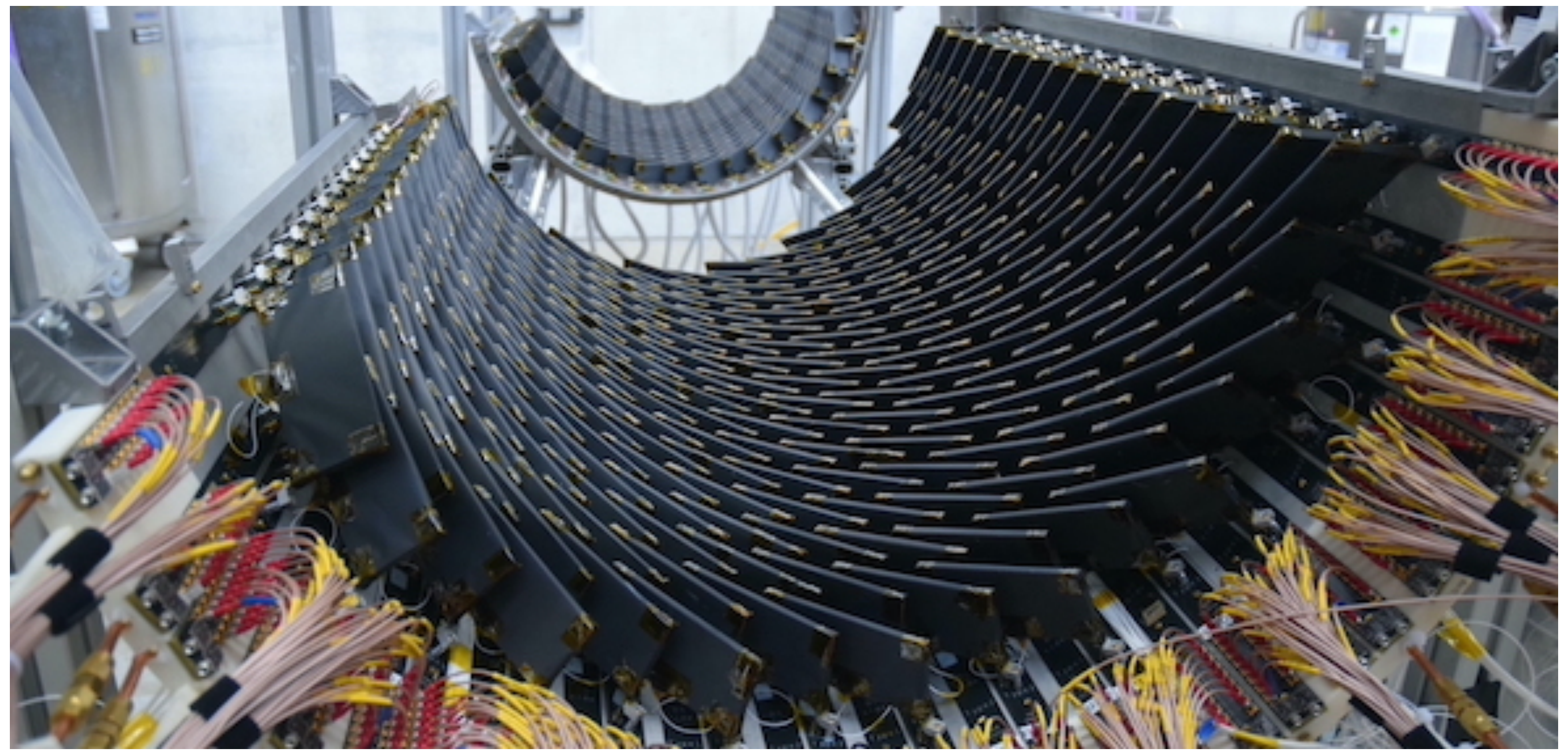

Count on-peak events in $E_\gamma$ side-band and extrapolate it
→ $N_{\mathrm{RMD}}$ = 10.1 ± 1.7

# $t_{e\gamma}\,( = t_\gamma - t_e)$ PDFs

- Signal PDF built based on
  - $t_{e\gamma}$ peak originating from RMD events
  - # pTC hits (depending on $E_e$)

$$\sigma_{\rm const} \oplus \frac{\sigma_{\rm single}}{\sqrt{n_{\rm pTC}}}$$

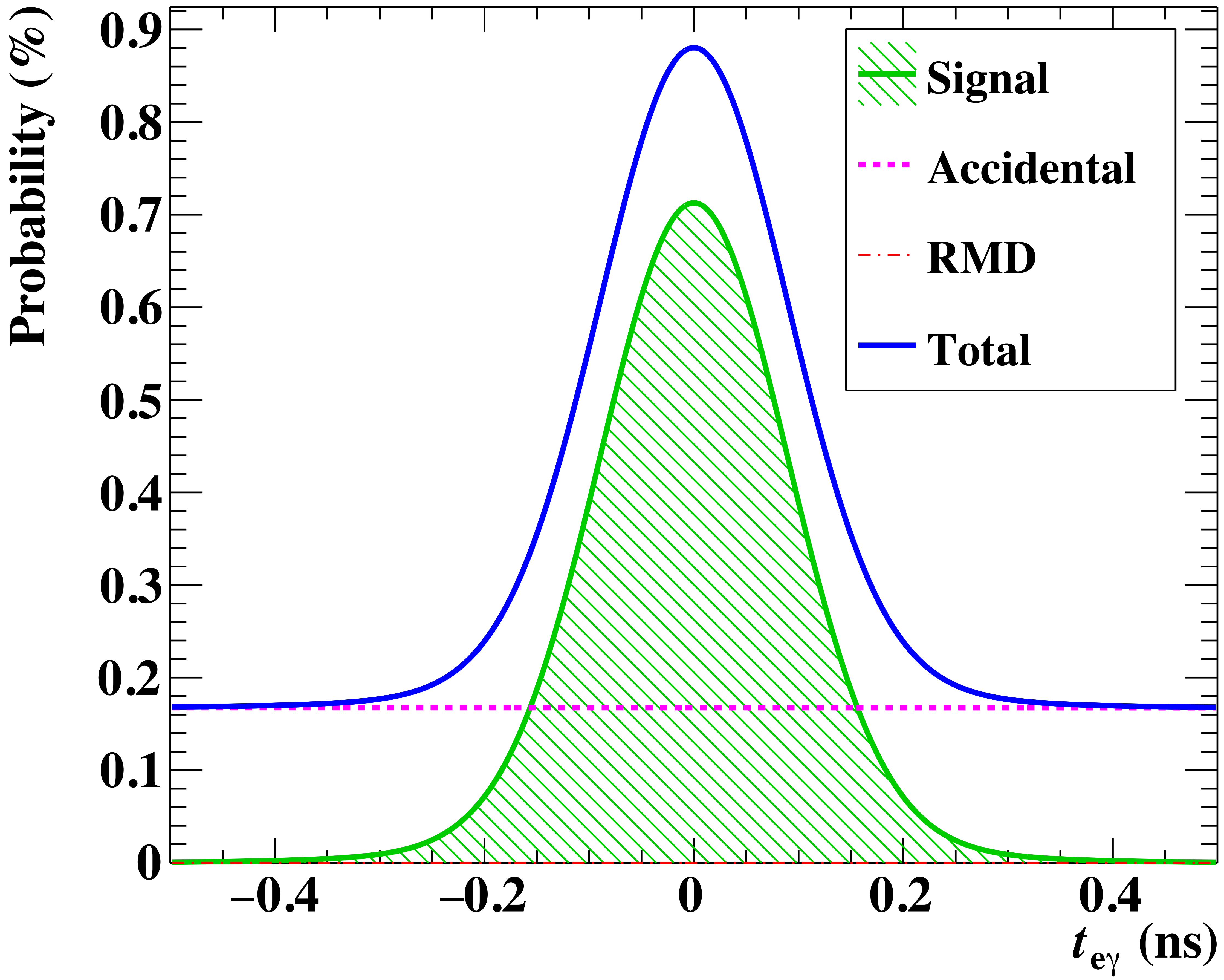
- $\sigma_{\rm const}$: Dominated by $t_\gamma$ resolution (65 ps)
- $\sigma_{\rm single}$: pTC single counter resolution (110 ps)



- Accidental BG PDF modelled as a flat distribution

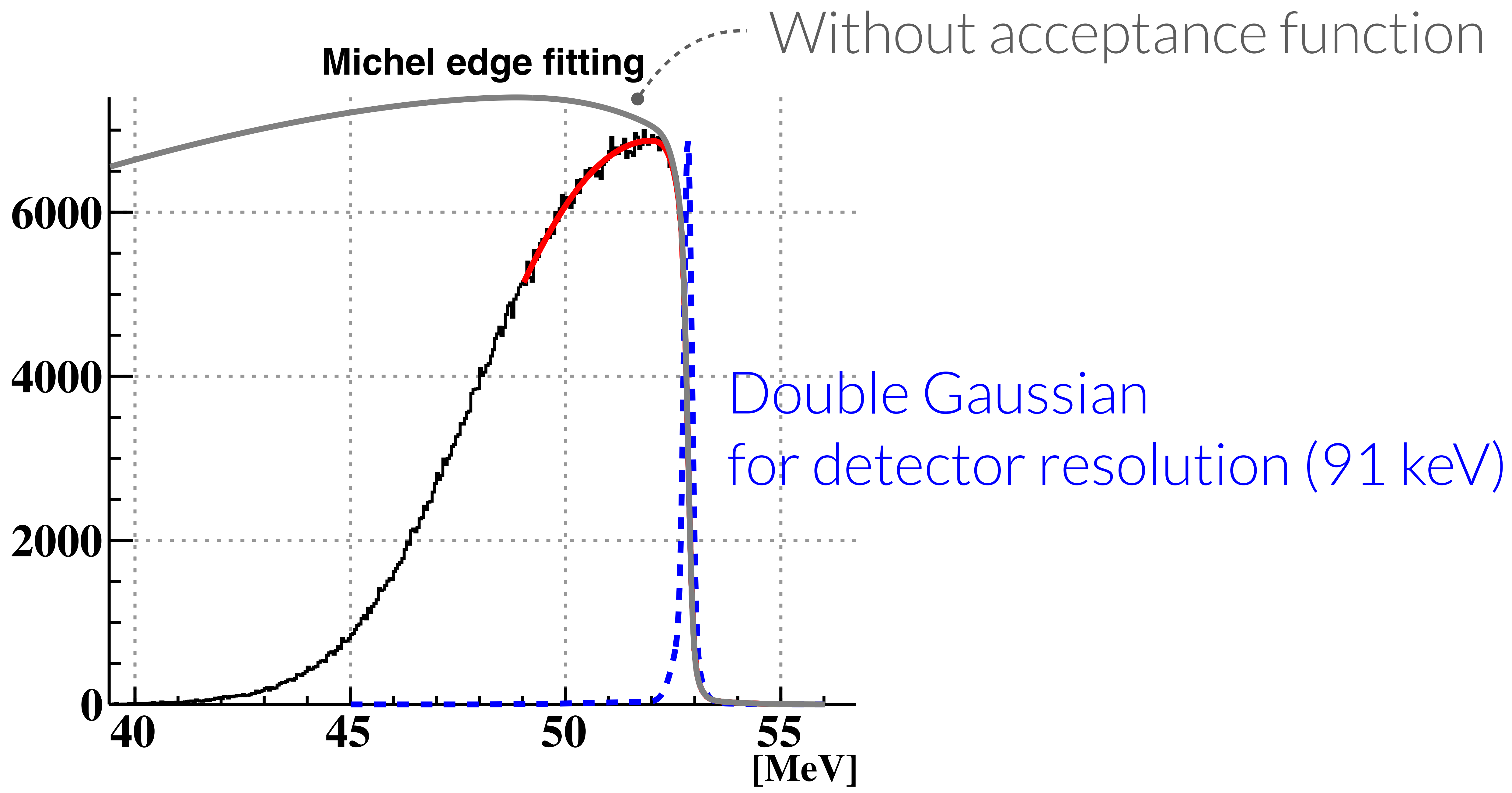
Toy sample with $N_{\rm sig}$ = 2,500 and $N_{\rm ACC}$ = 2,500

Averaged projected $t_{e\gamma}$ PDF



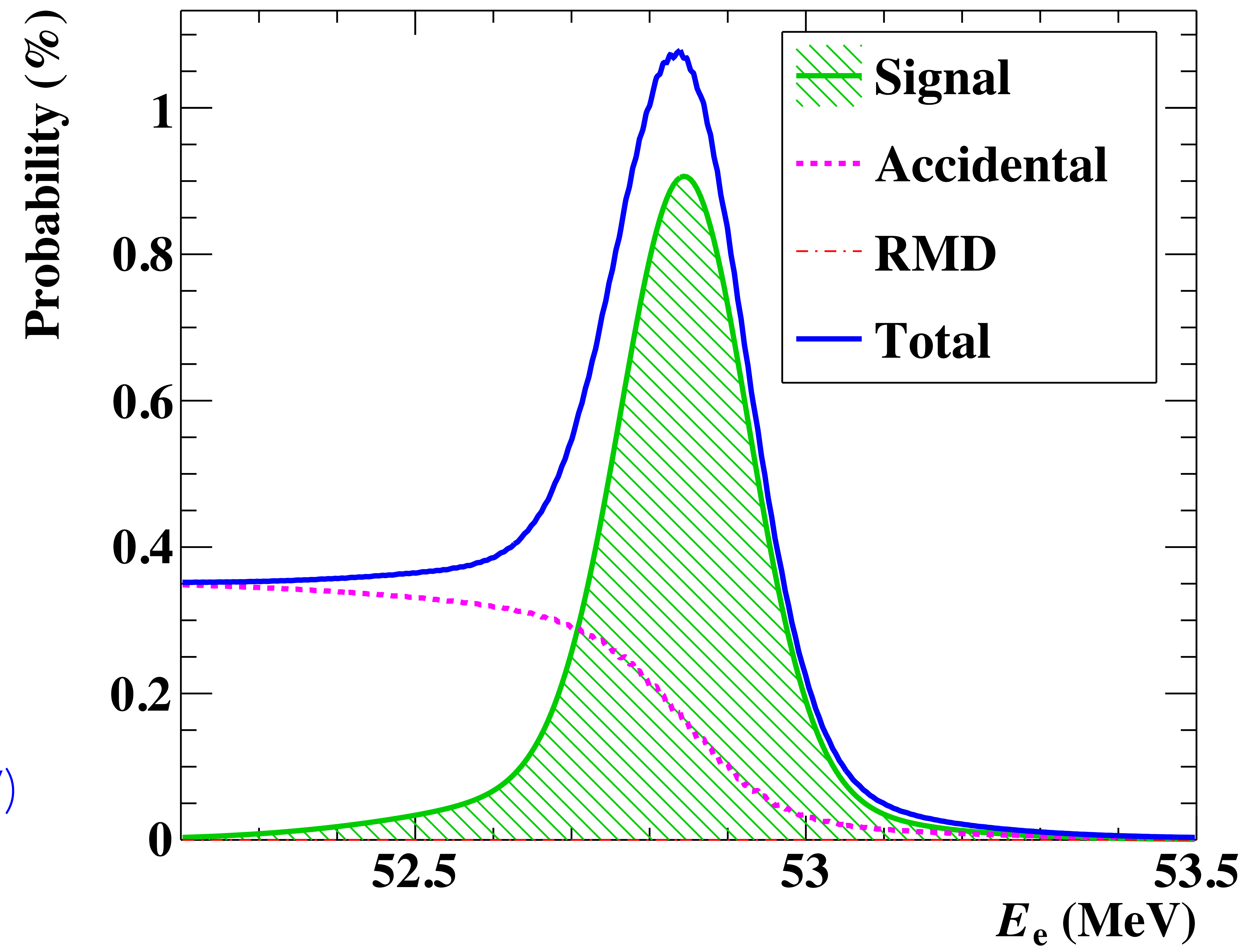
# $E_e$ PDFs

- Positron momentum spectrum fitted with the function accounting for
  - Theoretical function
  - Acceptance
  - Resolution → Signal PDF




Toy sample with $N_{\mathrm{sig}}$ = 2,500 and $N_{\mathrm{ACC}}$ = 2,500

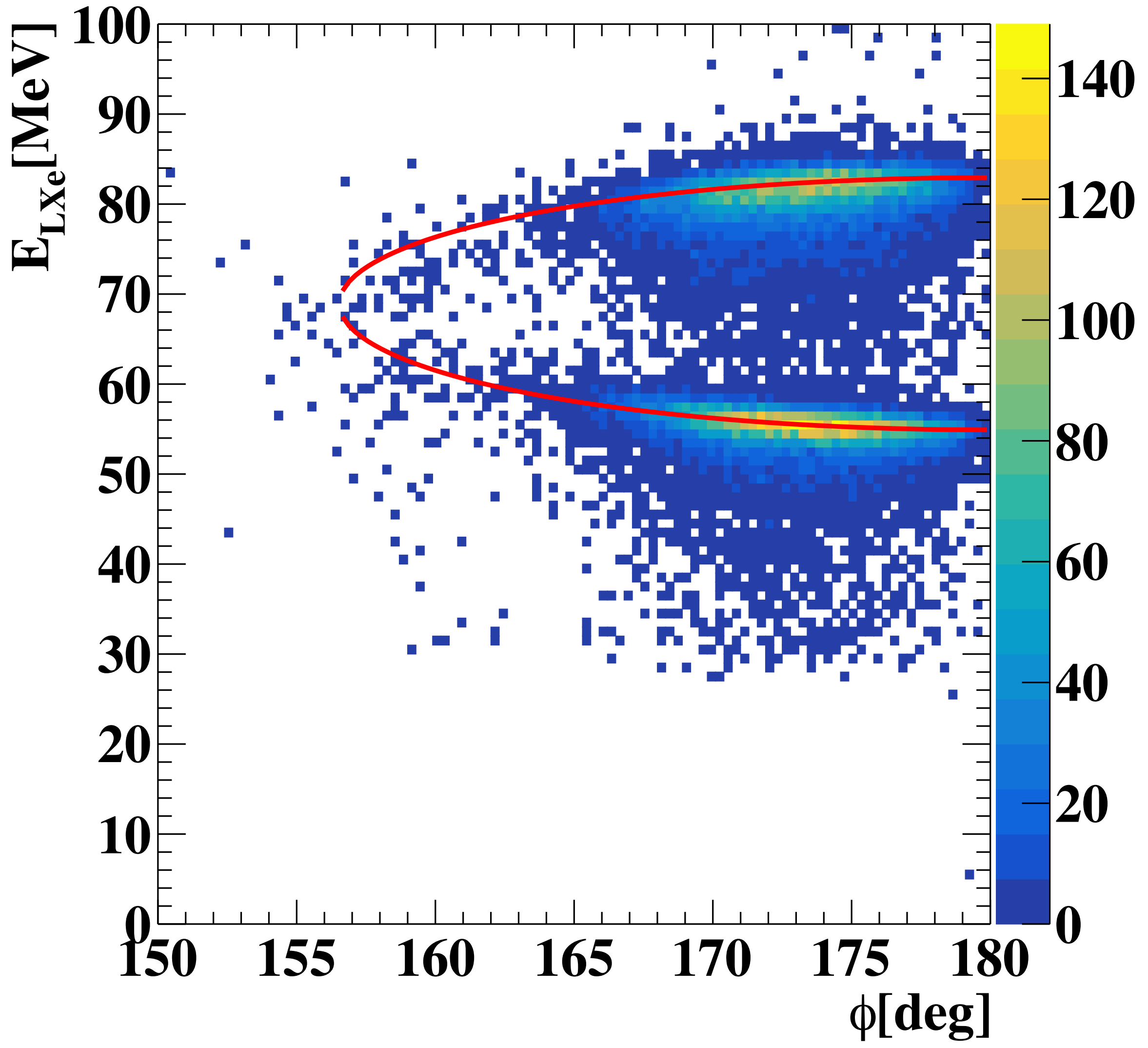
Averaged projected $E_e$ PDF



# $E_\gamma$ PDFs

- Signal PDF built based on response to 55 MeV $\gamma$
  - Dedicated run conducted after physics run

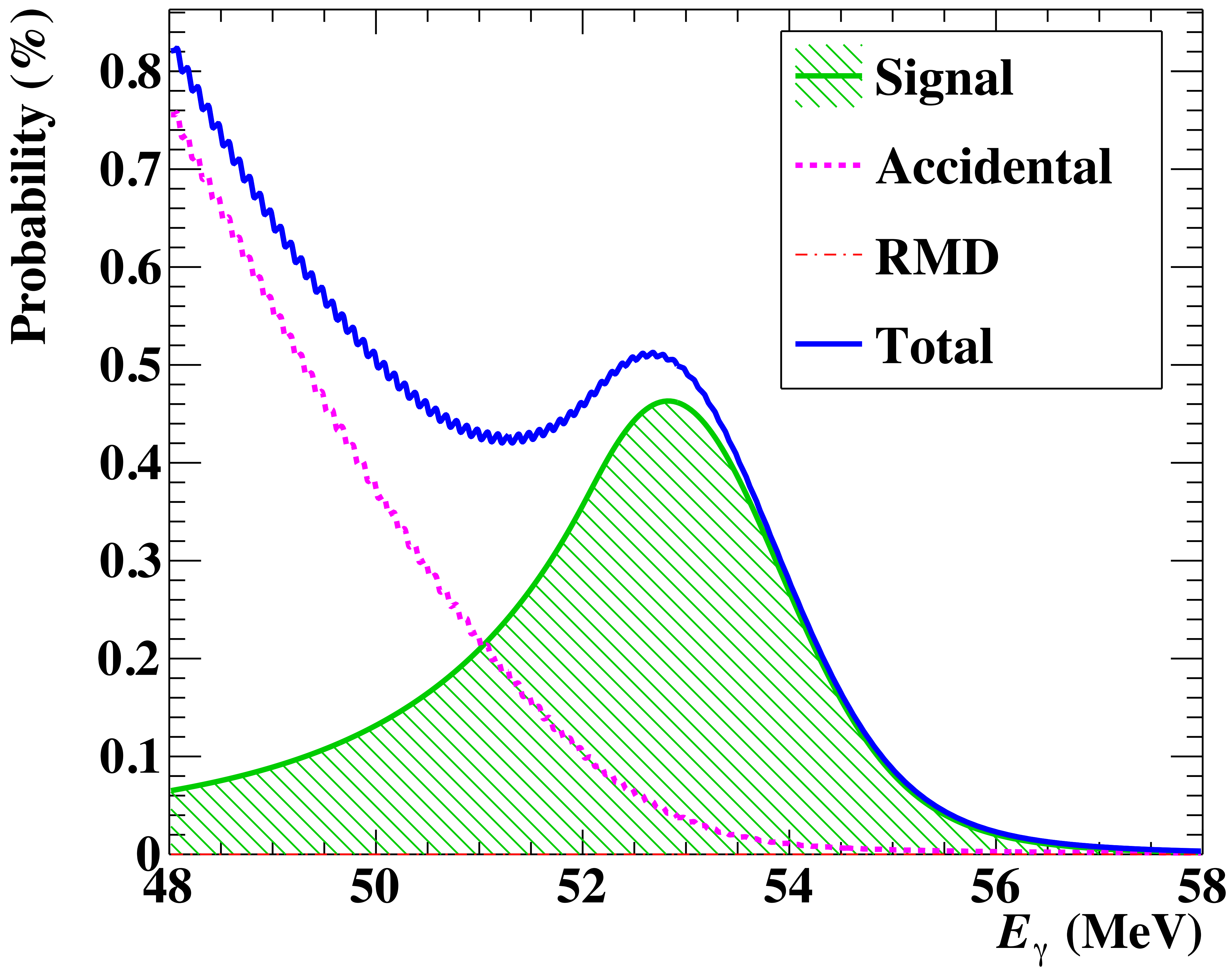
$$\pi^- p \to \pi^0 n$$
$$\hookrightarrow \pi^0 \to \gamma\gamma$$




- Accidental BG PDF based on spectrum in $t_{e\gamma}$ side-bands

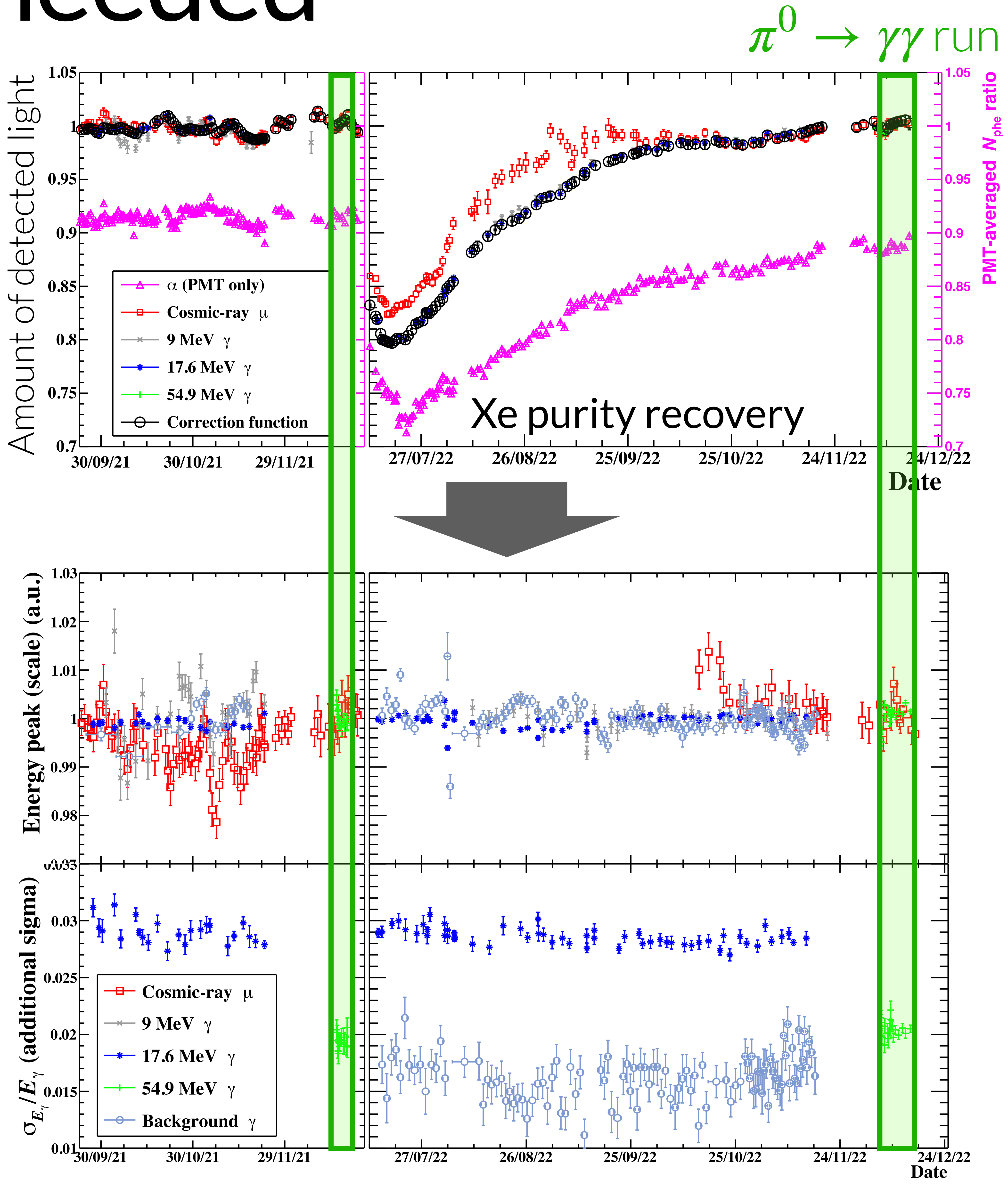
Toy sample with $N_{\rm sig}$ = 2,500 and $N_{\rm ACC}$ = 2,500

Averaged projected $E_\gamma$ PDF

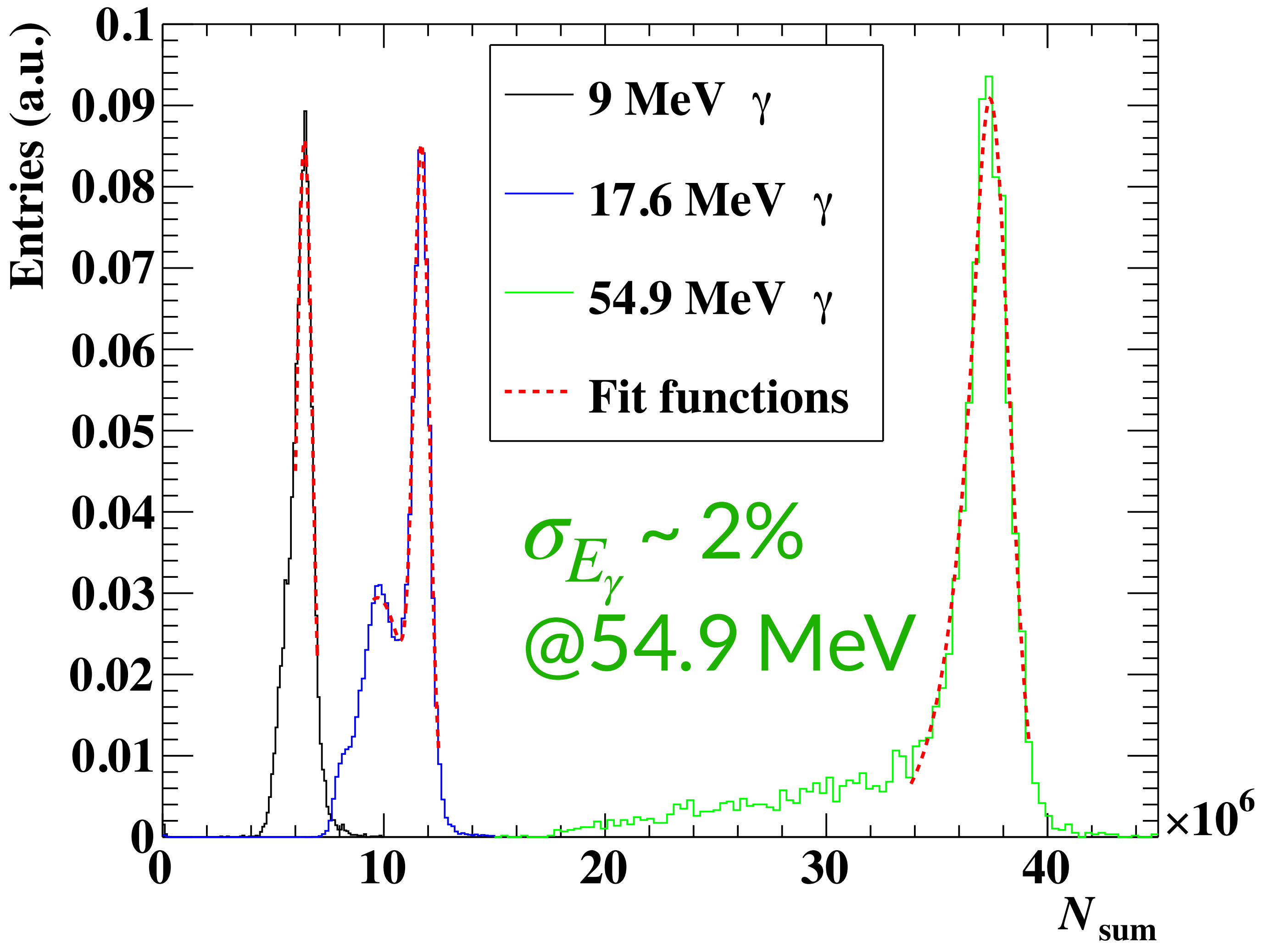


# Careful detector calibration needed

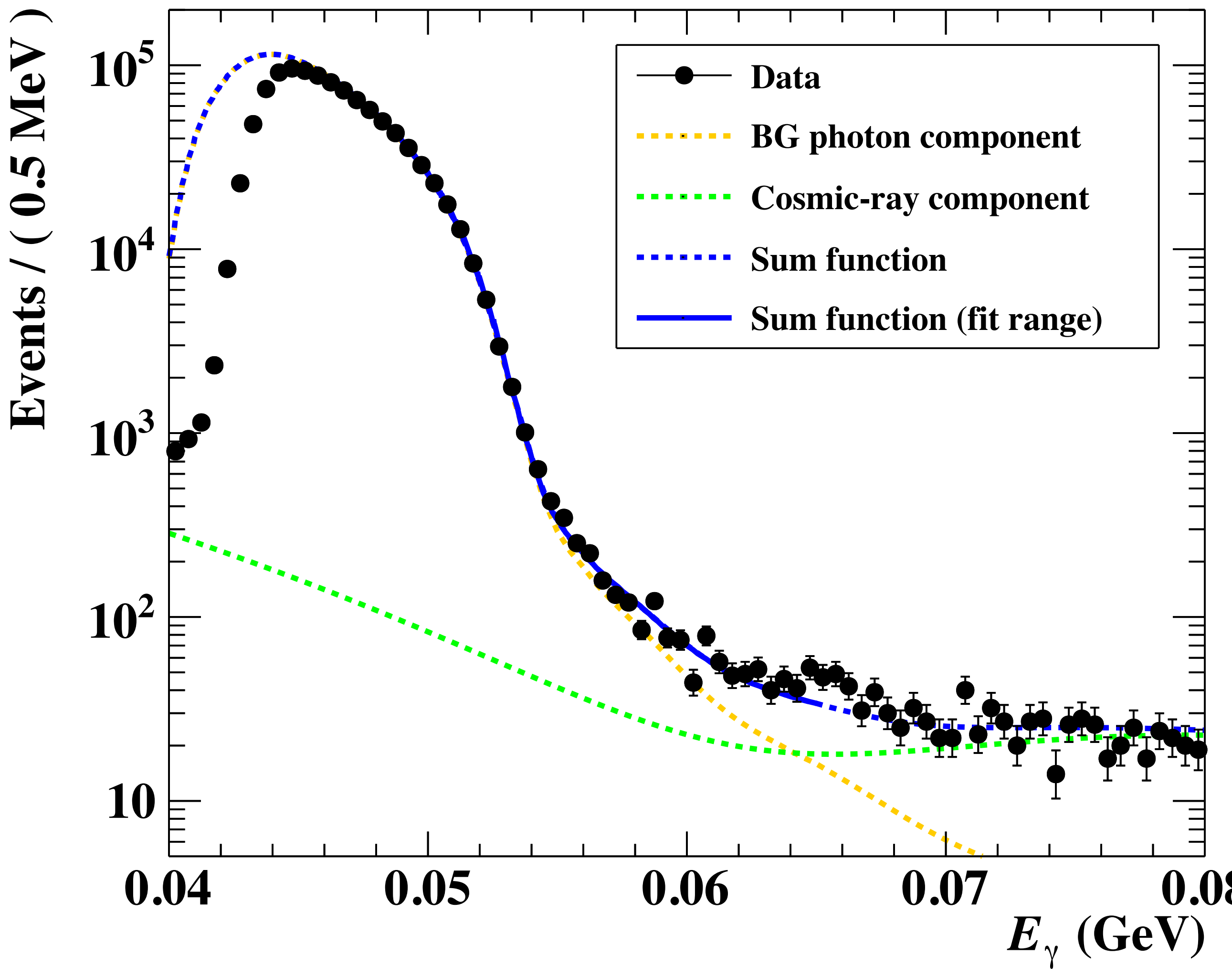
- Signal response examined with $\pi^0 \rightarrow \gamma\gamma$
- **Must correct temporal variations** of
  - Energy scale
  - Position dependence of the energy scale
  - Resolution




Response to monochromatic $\gamma$



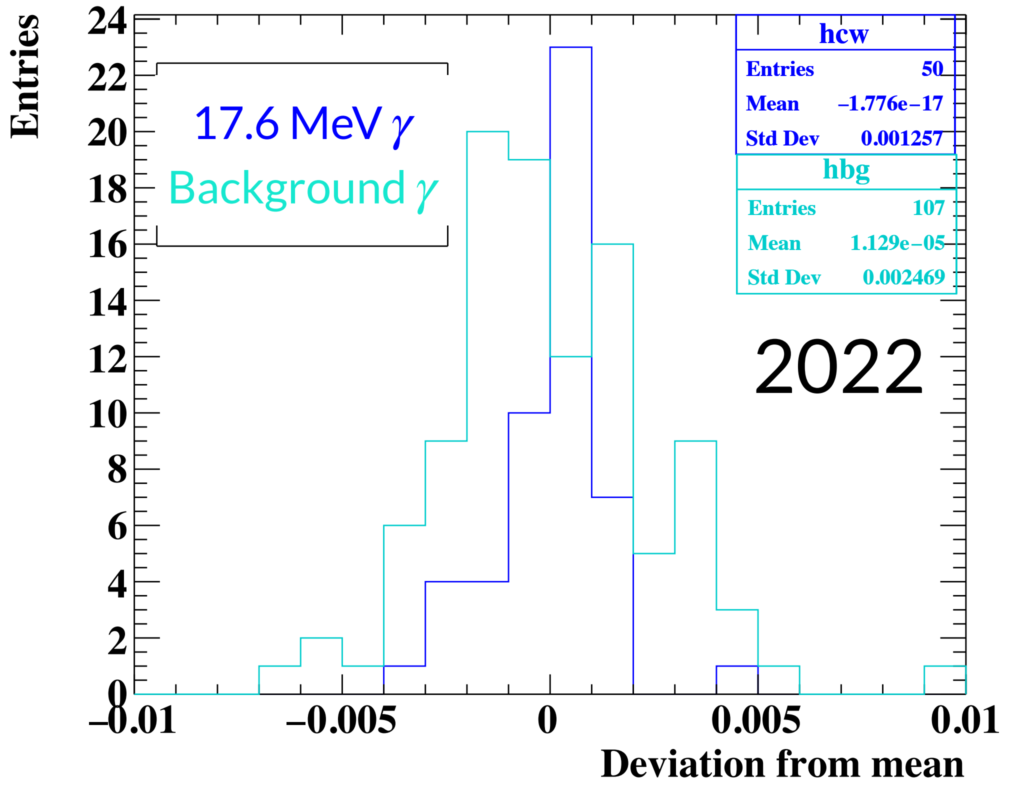

Response to background $\gamma$



# Uncertainty on the energy scale

- Temporal variation dominates the uncertainty of 0.18%
  - 0.3% in the last publication with the 2021 data

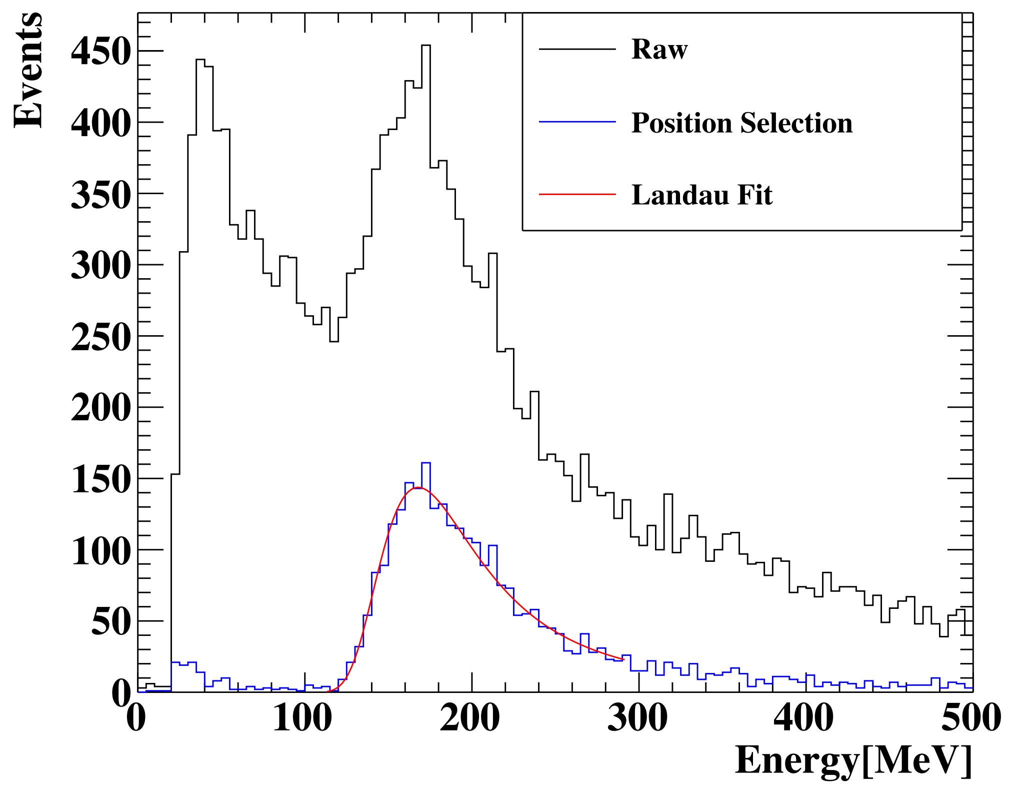
## Temporal variation during the physics run



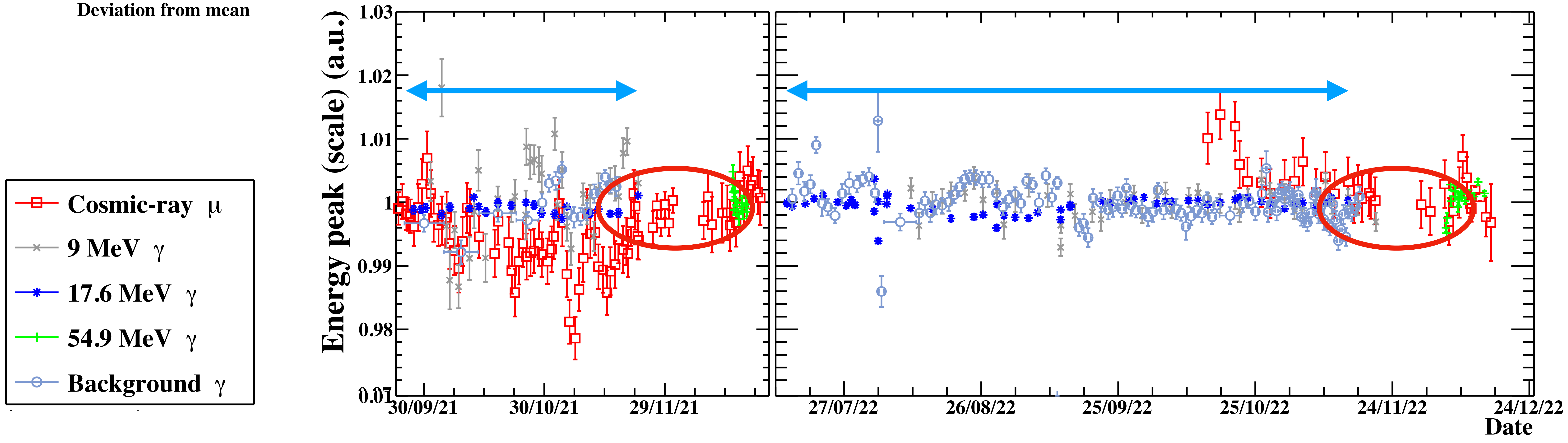

| | |
|---|---|
| 2021 | 0.14% |
| 2022 | 0.11% |

## Connection between the physics & $\pi^0$ run

| | |
|---|---|
| 2021 | 0.11% |
| 2022 | 0.14% |




Statistical uncertainty on Landau peak extraction for cosmic-ray muons



# Angle PDFs

$$\theta_{e\gamma} = (\pi - \theta_e) - \theta_\gamma$$
$$\phi_{e\gamma} = (\pi + \phi_e) - \phi_\gamma$$

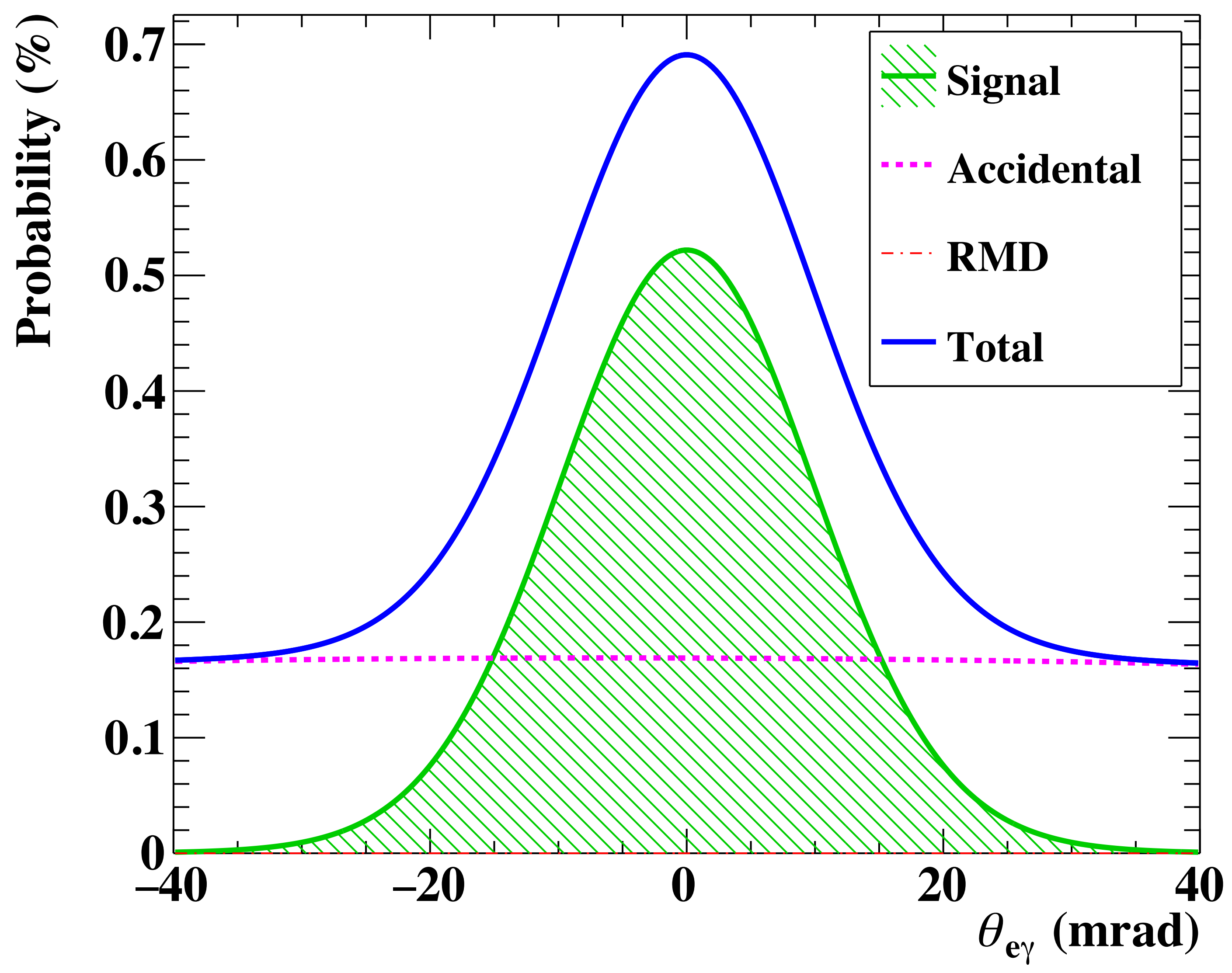
- Signal PDFs parametrised by the combination of
  - **Positron angle & vertexing resolutions**

| $\sigma_{y_{e+}}$ (mm) | $\sigma_{z_{e+}}$ (mm) | $\sigma_{\phi_{e+}}$ (mrad) | $\sigma_{\theta_{e+}}$ (mrad) |
|---|---|---|---|
| 0.74 | 2.0 | 4.1 | 7.2 |

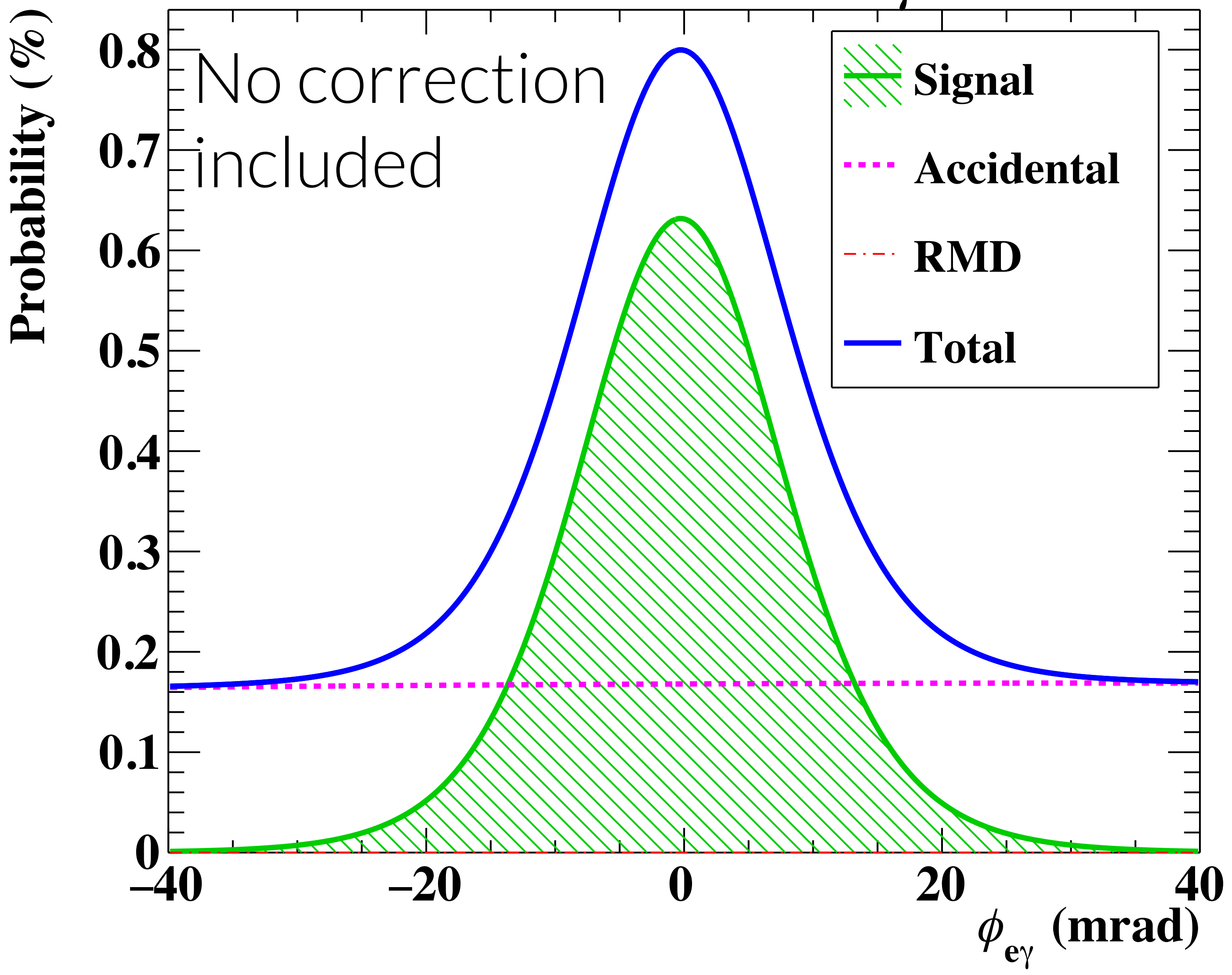
  - **Photon position resolution**
    - 2.5-4 mm depending on conversion depth
- $\theta_{e\gamma}$ vs $\phi_{e\gamma}$ correction taken into account
- The largest systematics: **Detector alignment**
  - Profiling approach adopted
- Accidental PDFs extracted from $t_{e\gamma}$ side-bands

Toy sample with $N_{\text{sig}}$ = 2,500 and $N_{\text{ACC}}$ = 2,500

Averaged projected $\theta_{e\gamma}$ PDF




Averaged projected $\phi_{e\gamma}$ PDF



# Sensitivity & fitting to $t_{e\gamma}$ side-bands

- Thousands of toy samples with a null-signal hypothesis

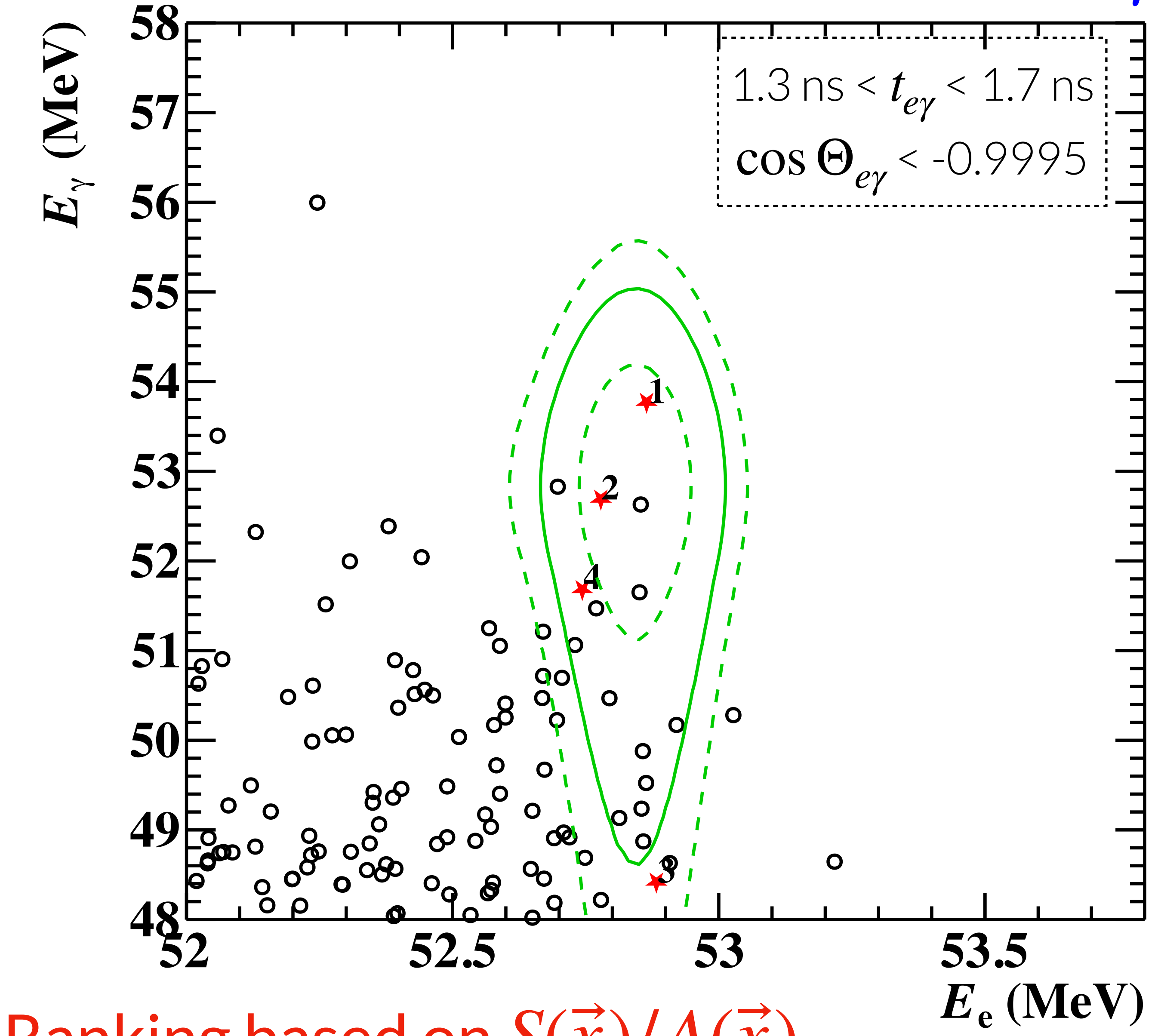
➡ **Median 90% C.L. upper limit on $BR$ is defined as sensitivity**

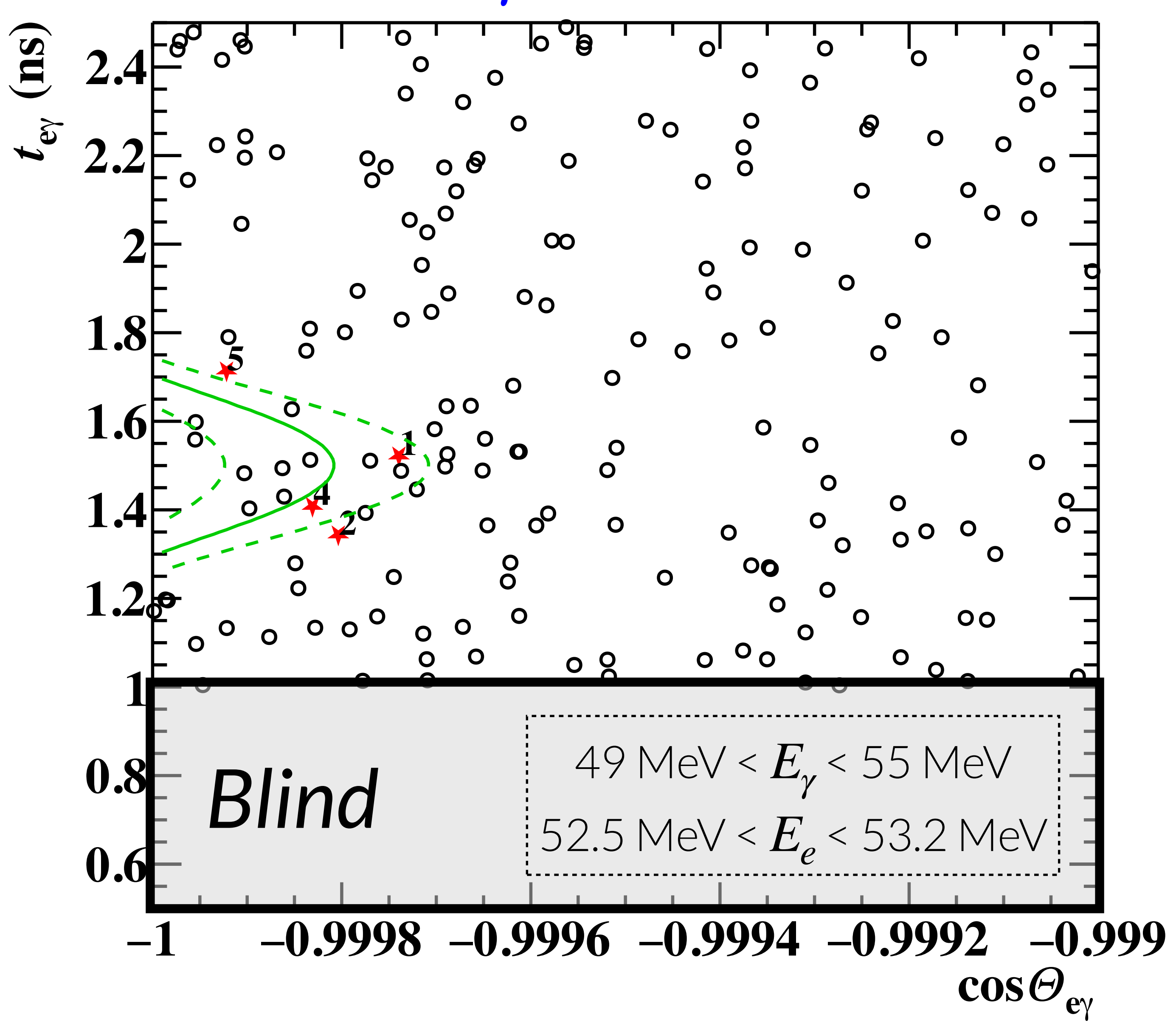
$S_{90} = 2.2 \times 10^{-13}$ (preliminary)

- MEG final: $5.3 \times 10^{-13}$
- MEG II 2021: $8.8 \times 10^{-13}$

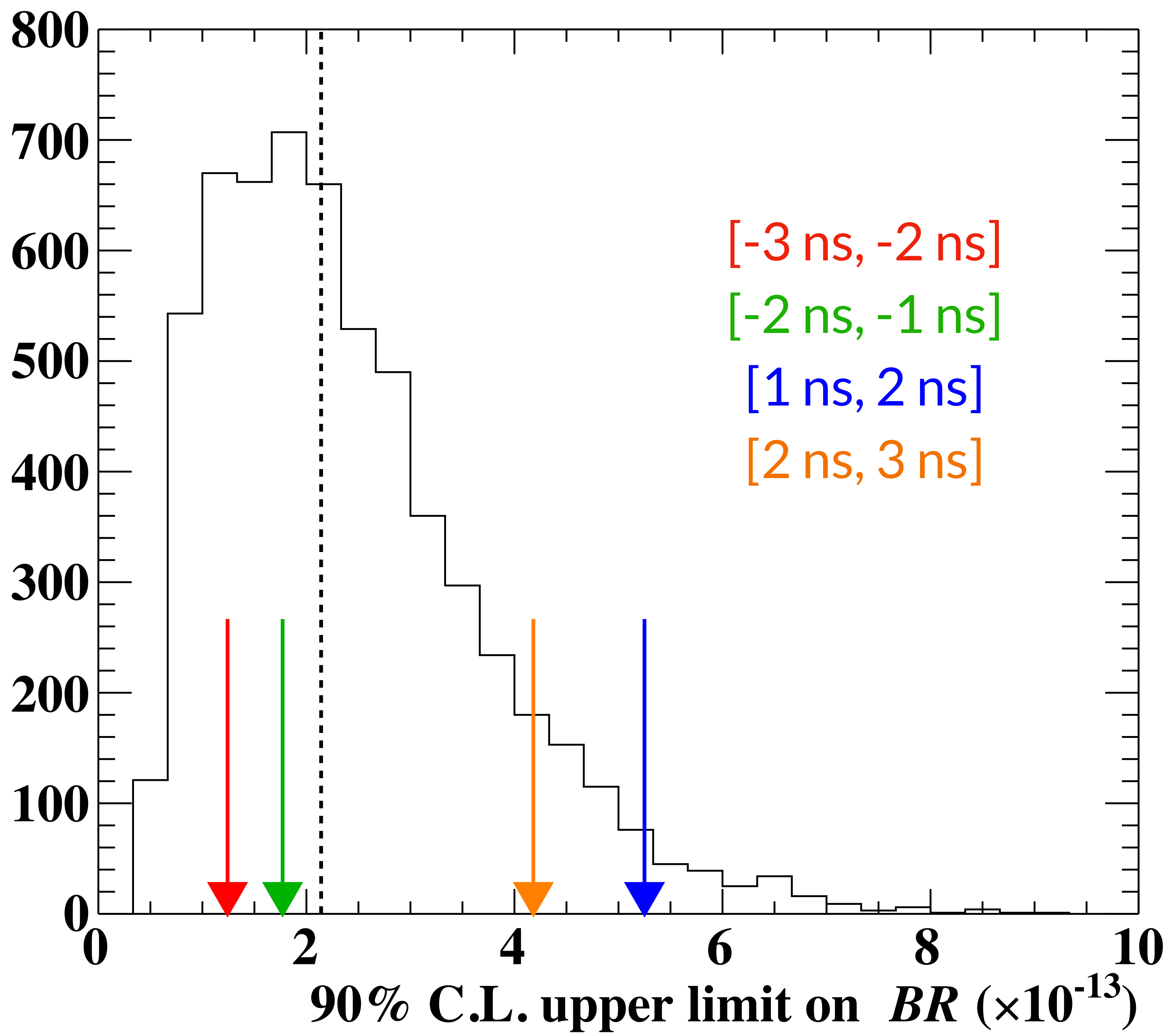
- Fit to $t_{e\gamma}$ side-bands

Event distribution in a $t_{e\gamma}$ side-band (1 ns < $t_{e\gamma}$ < 2 ns)



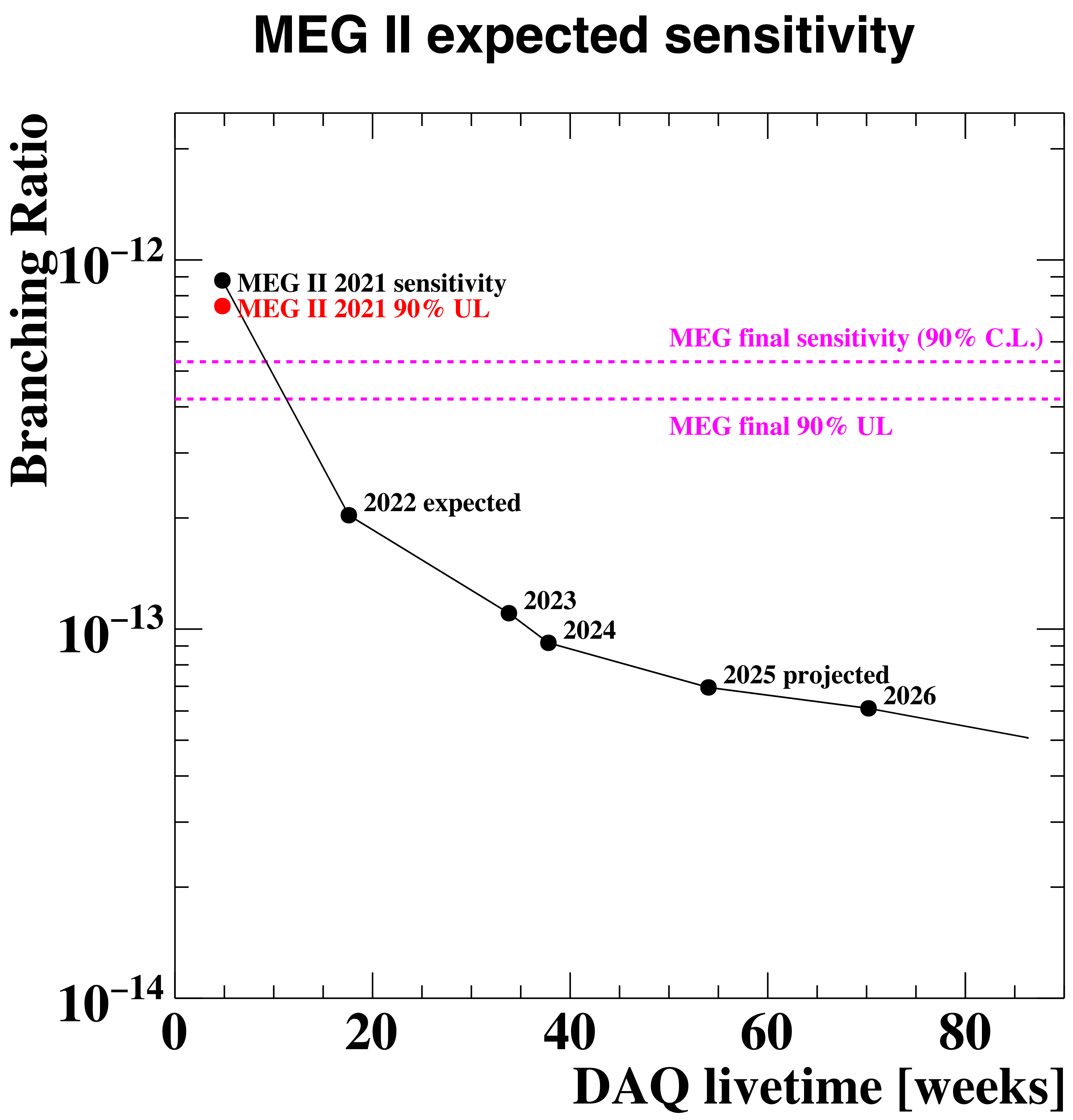




Ranking based on $S(\vec{x})/A(\vec{x})$



# Conclusion & prospects

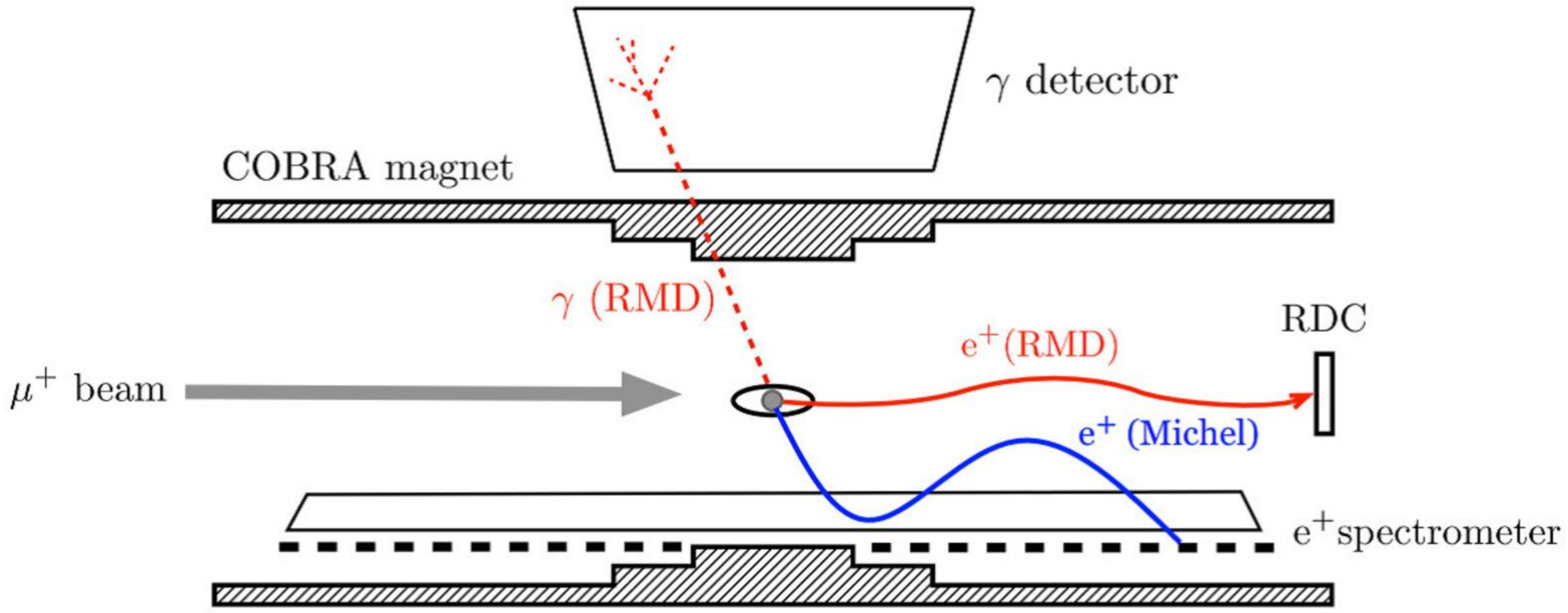
- Search for $\mu \to e\gamma$ with the MEG II 2021 and 2022 data
  - With a preliminary sensitivity of $2.2 \times 10^{-13}$
  - To be published soon!
- Analysis ongoing for the 2023 and later data
  - Positron tracking (A. Oya, 18aT1-6)
  - LXe detector calibration (S. Ban, 19aT2-8)
- Higher statistics by data-taking in 2025 and 2026
- Stay tuned!



# Backup

# RDC PDFs

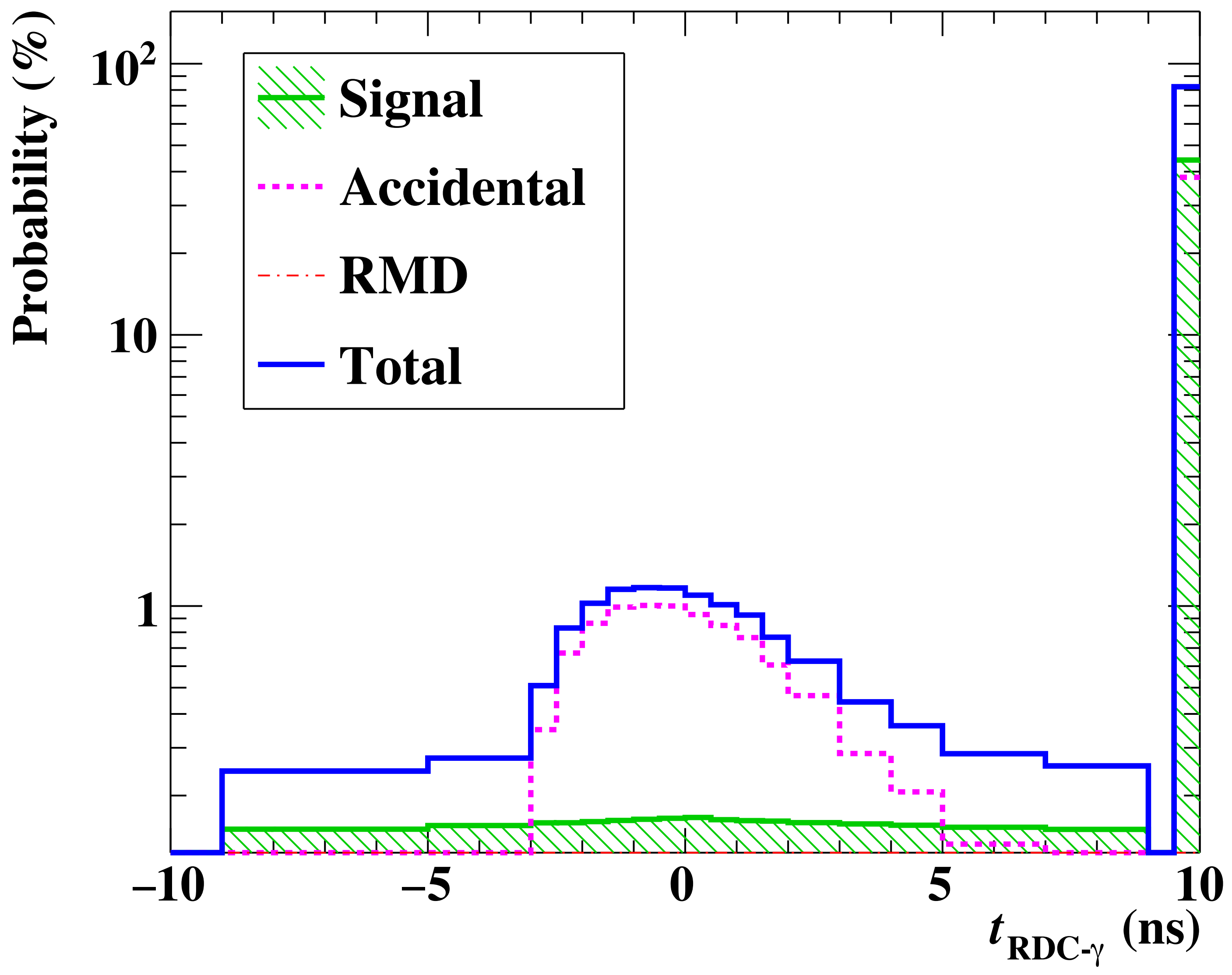
- Radiative Decay Counter identifies RMD-originating >48 MeV $\gamma$ by tagging low-energy $e$
- Improve separation power between signal and accidental background events




- PDFs extracted from time side-bands
  - Off-peak events can be used to build signal PDFs
  - On-peak events for background PDFs

Toy sample with $N_{\mathrm{sig}}$ = 2,500 and $N_{\mathrm{ACC}}$ = 2,500

Averaged projected $t_{\mathrm{RDC}-\gamma}$ PDF




Averaged projected $E_{\mathrm{RDC}}$ PDF