Photon energy reconstruction with MEG II liquid xenon calorimeter

Kensuke Yamamoto (The University of Tokyo)
on behalf of the MEG II collaboration

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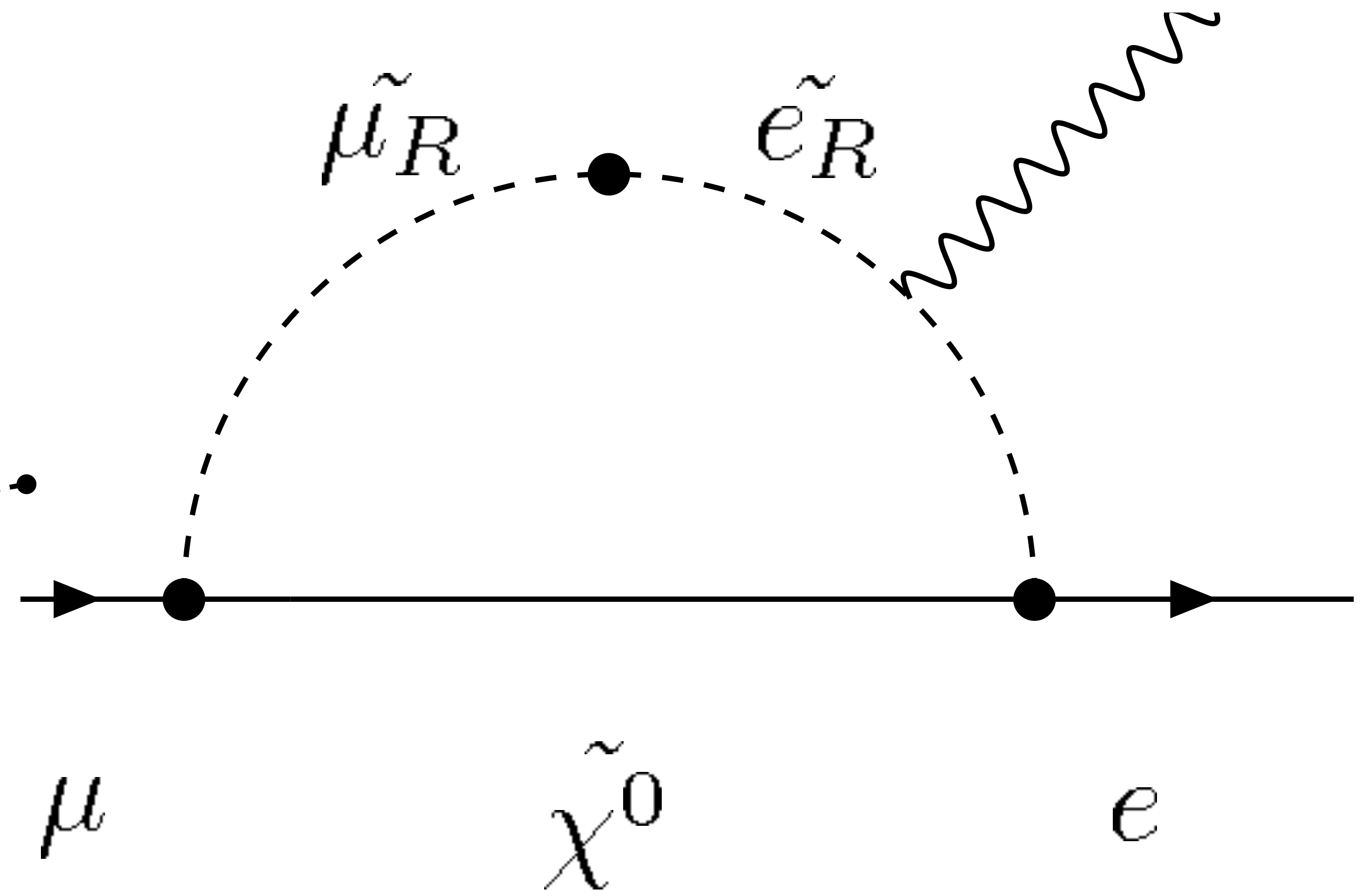
20-24 May 2024

Introduction to $\mu \to e\gamma$

- $\mu \to e\gamma$ search by MEG II experiment
  - LFV, forbidden in SM
  - Predicted in BSM, e.g. SUSY
  - MEG II target sensitivity $\sim 6 \times 10^{-14}$

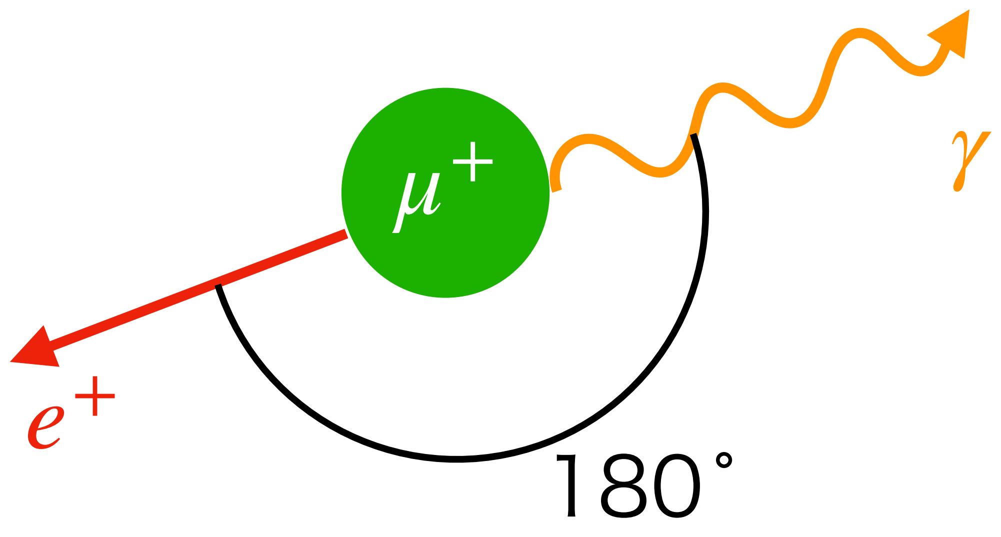


SUSY-GUT $SU(5)$

$BR(\mu \to e\gamma) \sim 10^{-14} - 10^{-11}$

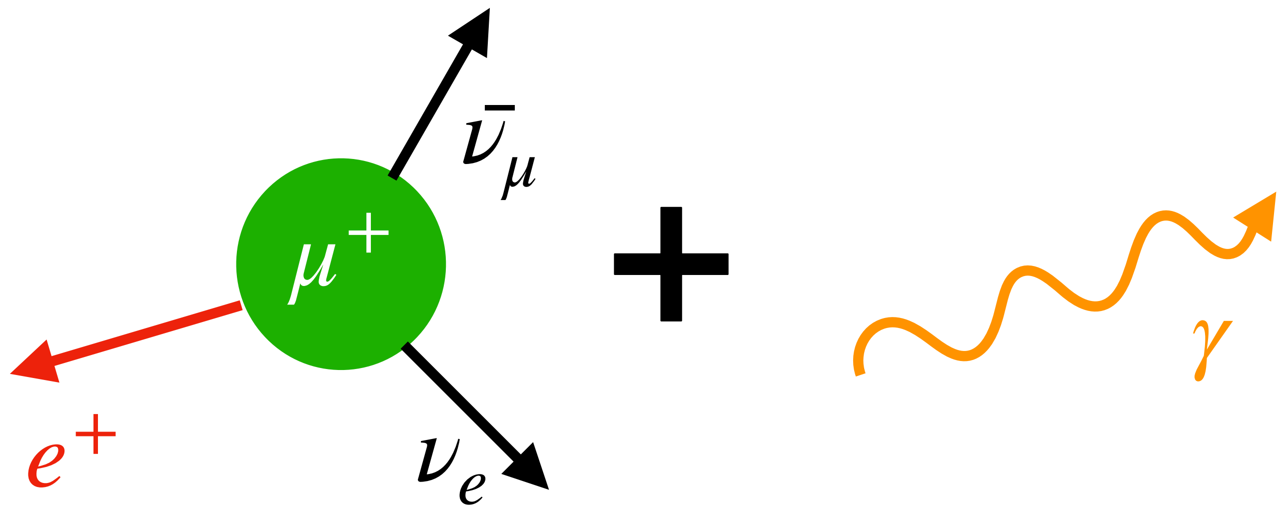
- Signal & background characteristics

Signal

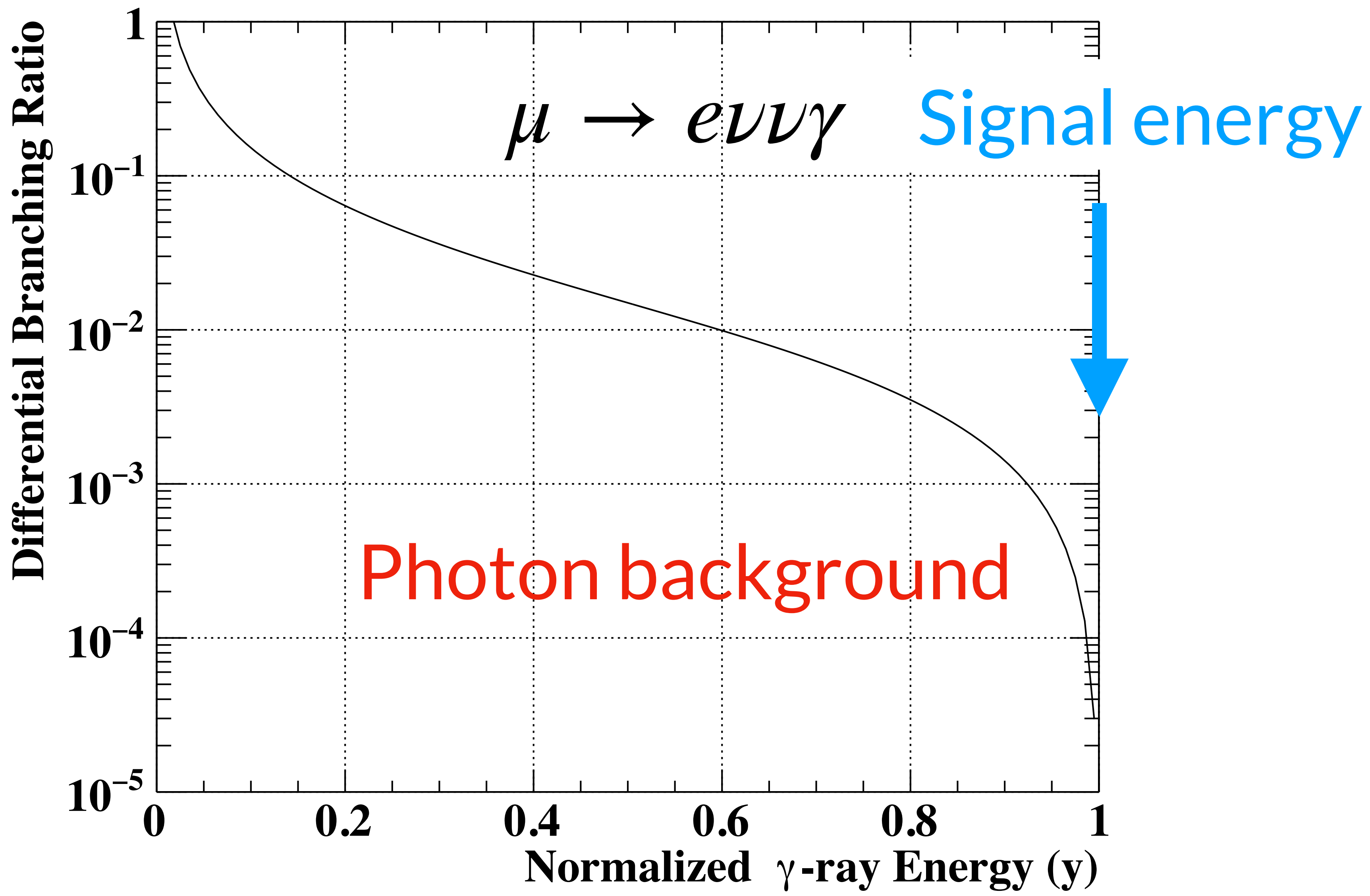


Monochromatic energy of 52.8 MeV (=$m_\mu/2$)

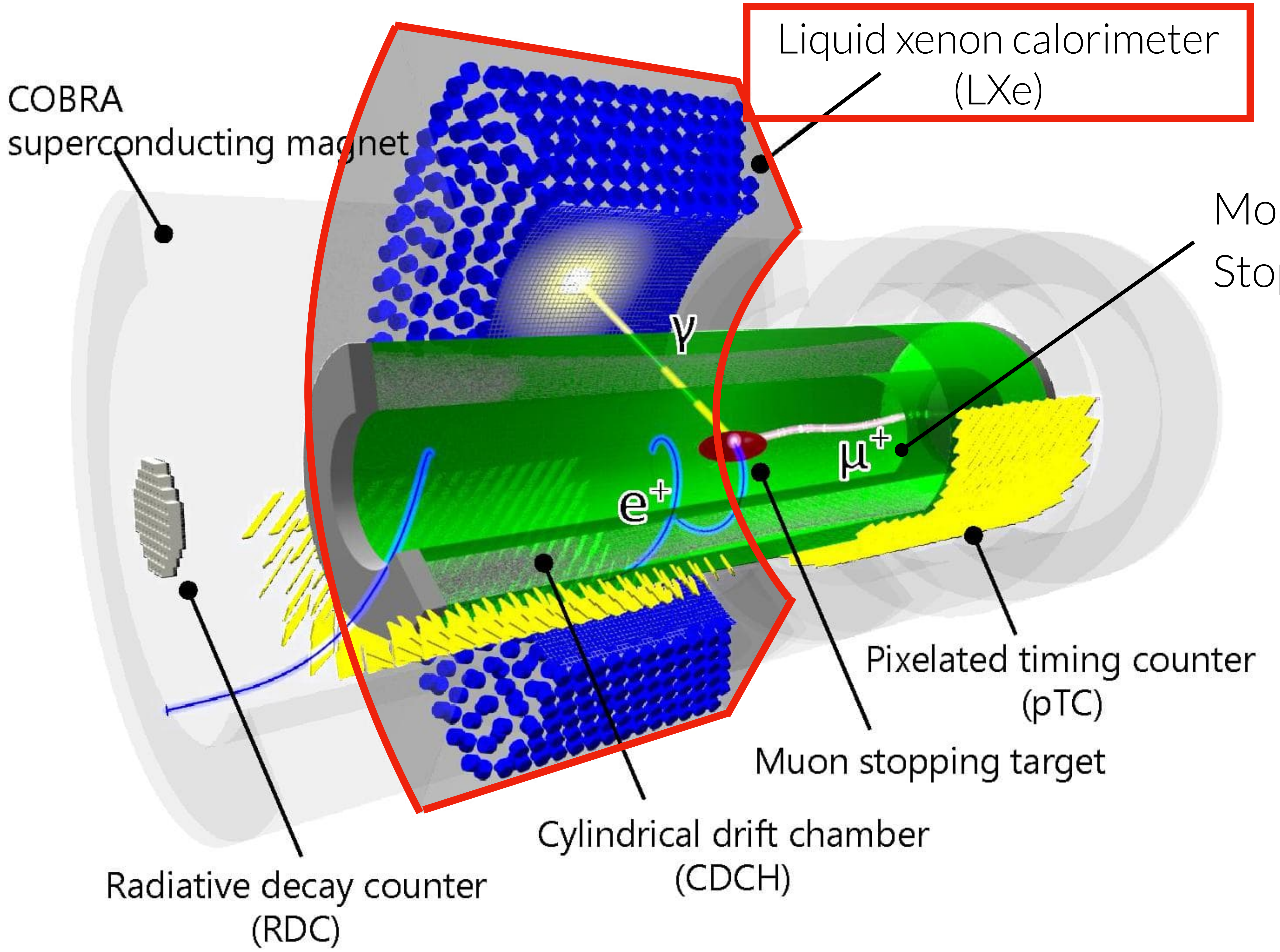
Background



$N_{BG} \propto \sigma^2_{E_\gamma}$



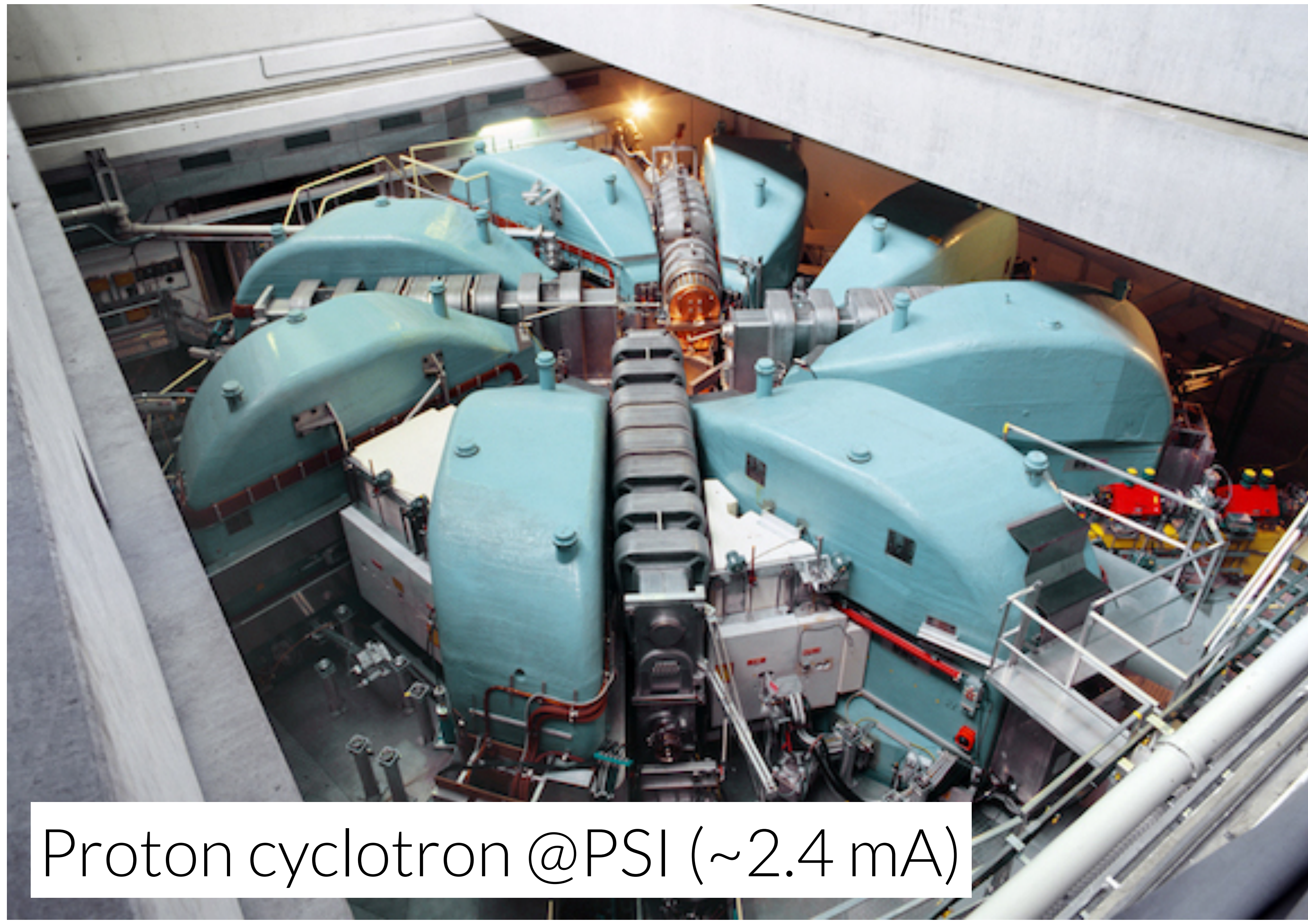
MEG II apparatus



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

Most intense DC μ^+ beam at Paul Scherrer Institut

Stopping rate $R_\mu = 3 - 5 \times 10^7\ \mu/\mathrm{s}$


Proton cyclotron @PSI (~2.4 mA)

Liquid xenon (LXe) calorimeter

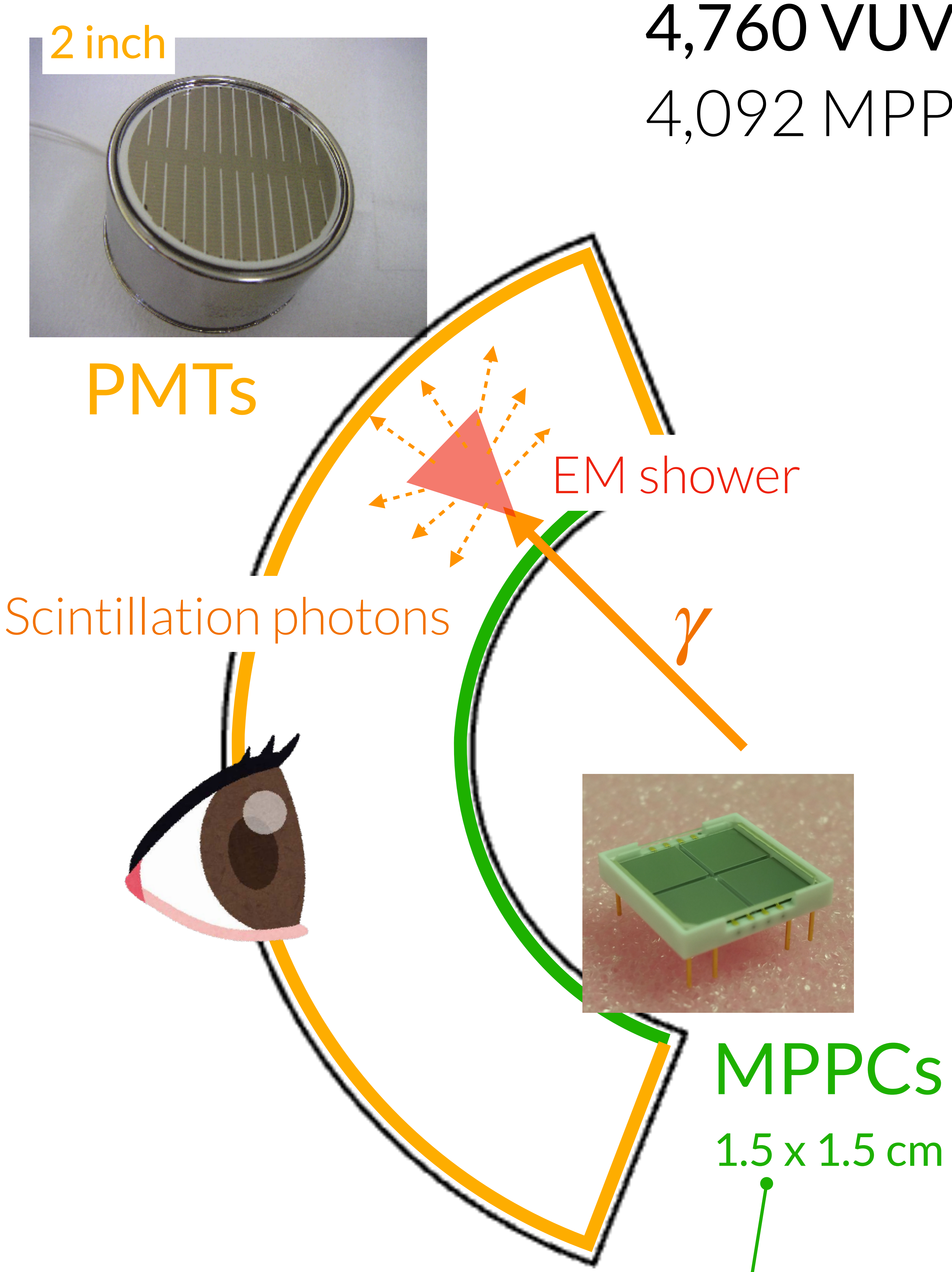
4,760 VUV-sensitive photosensors

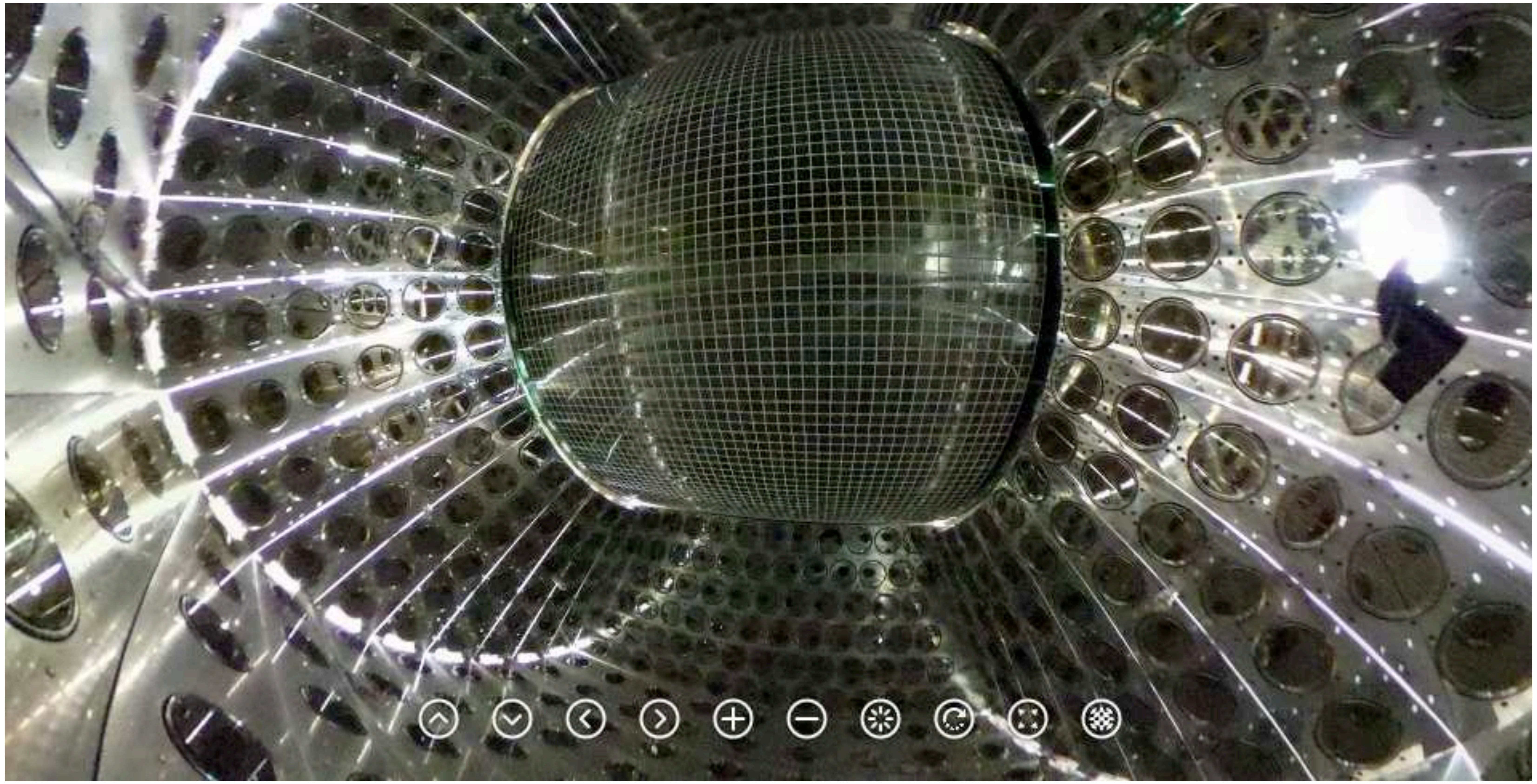
4,092 MPPCs + 668 PMTs

×

900 L liquid xenon

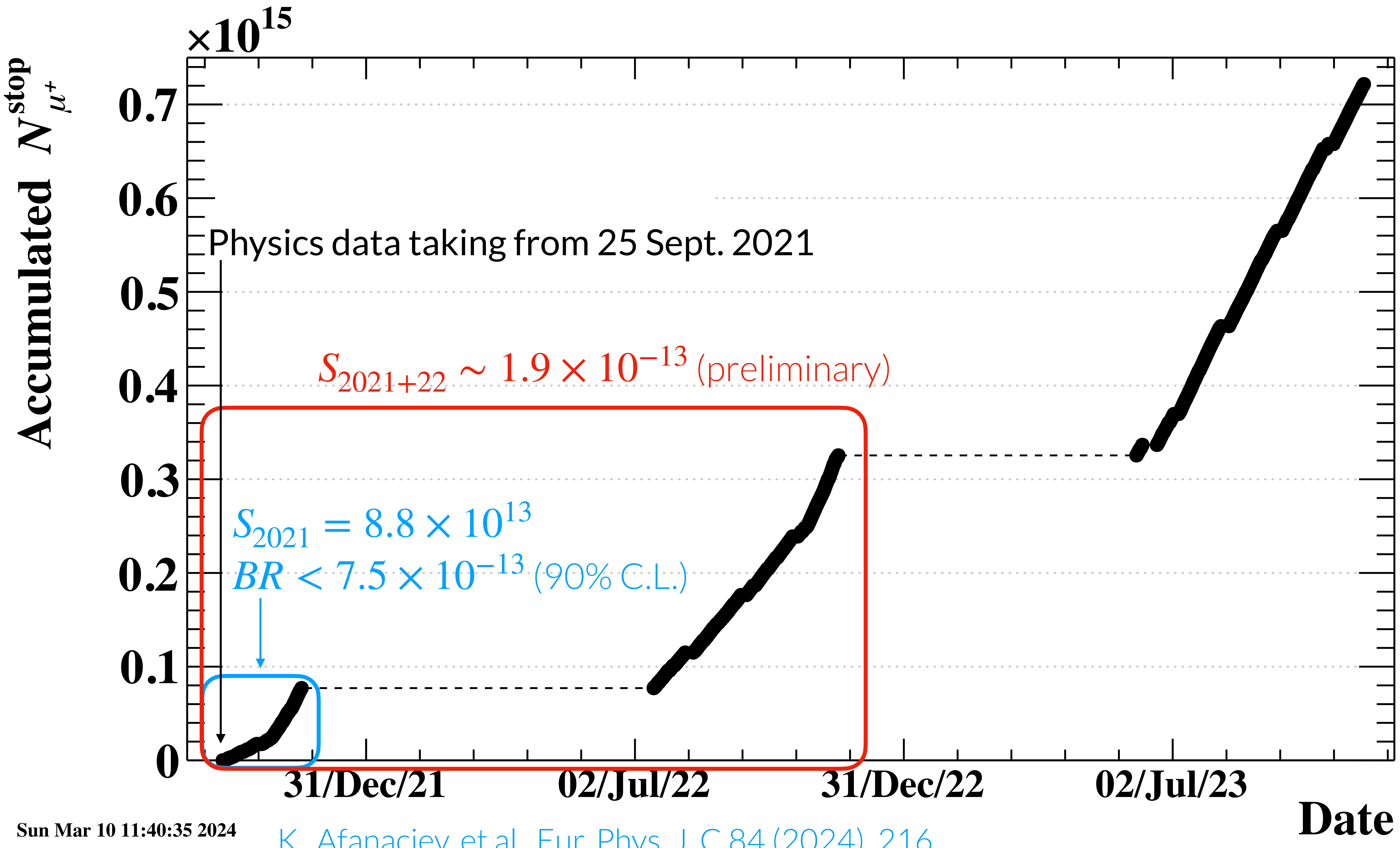
- High stopping power (X_0 = 2.8 cm)
- High light yield (46,000 photons/MeV)
- Fast response (45 ns decay time)





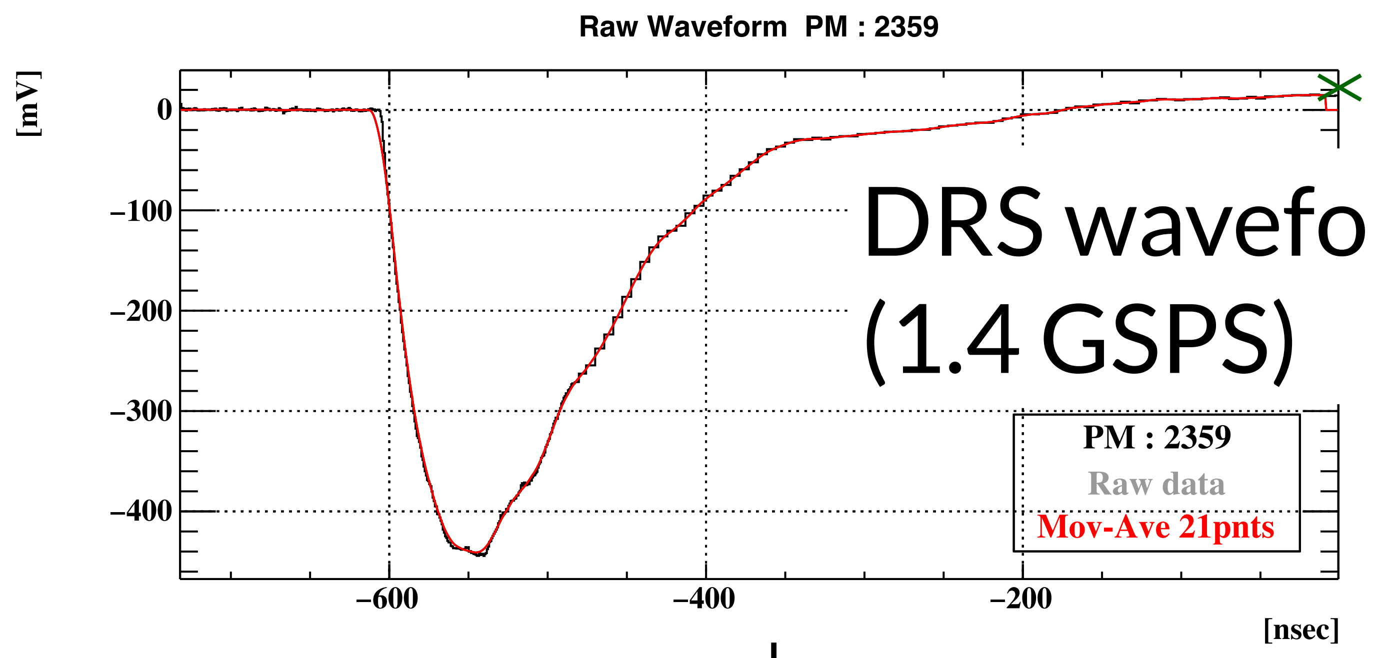
K. Ieki, et al., Nucl. Instru. Meth. A 925 (2019), 148-155

MEG II DAQ and analysis status so far



K. Afanaciev, et al., Eur. Phys. J. C 84 (2024), 216

Energy reconstruction flowchart in LXe calorimeter



DRS waveform (1.4 GSPS)

↓ Waveform analysis

Charge

↓ Conversion

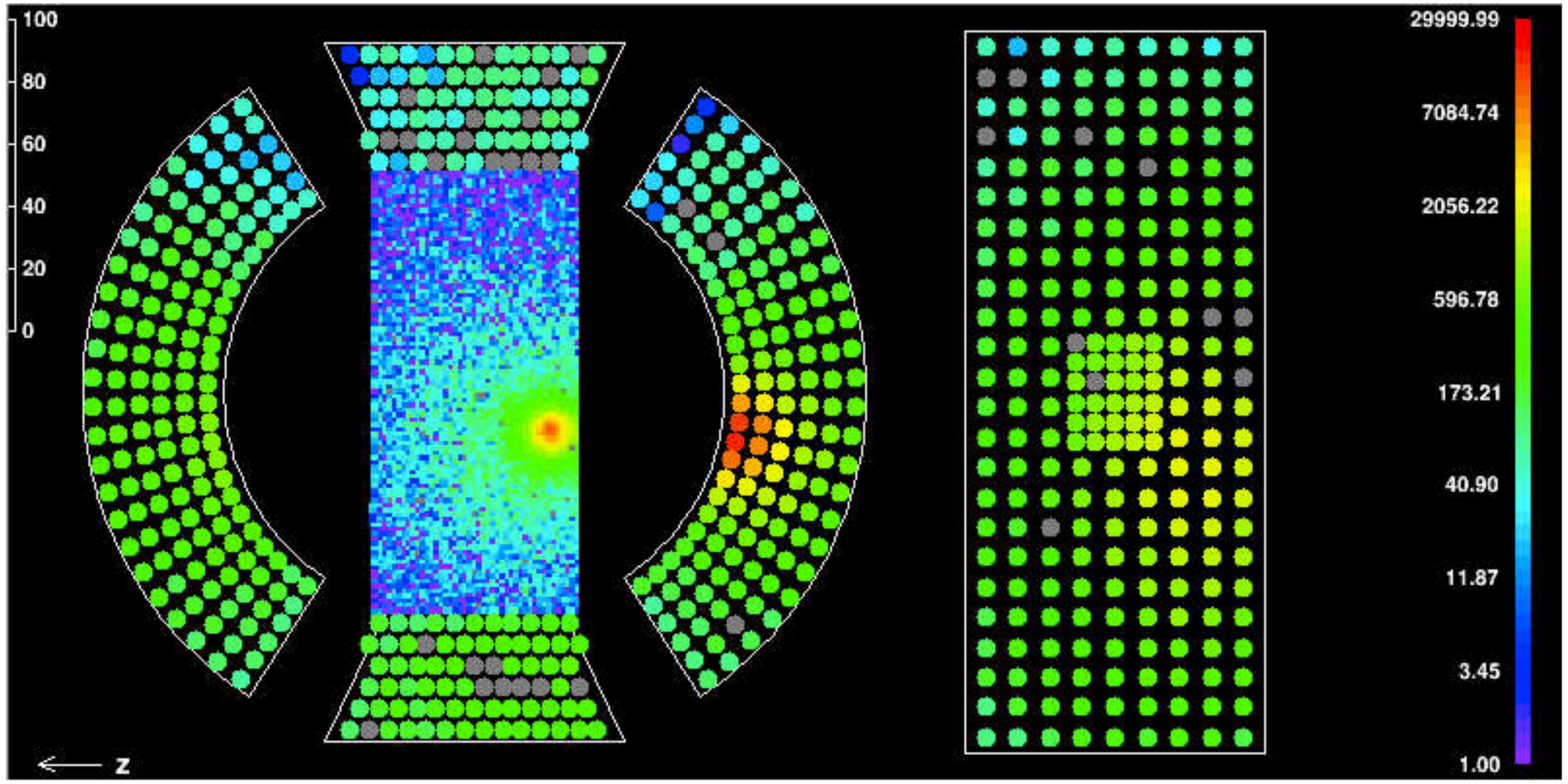
Number of impinging scintillation photons N_{pho}

Position $\vec{x}_\gamma$

Multi-γ elimination

Energy E_γ

Distribution of number of impinging scintillation photons



Concept: Summing up all impinging scintillation photons & converting it

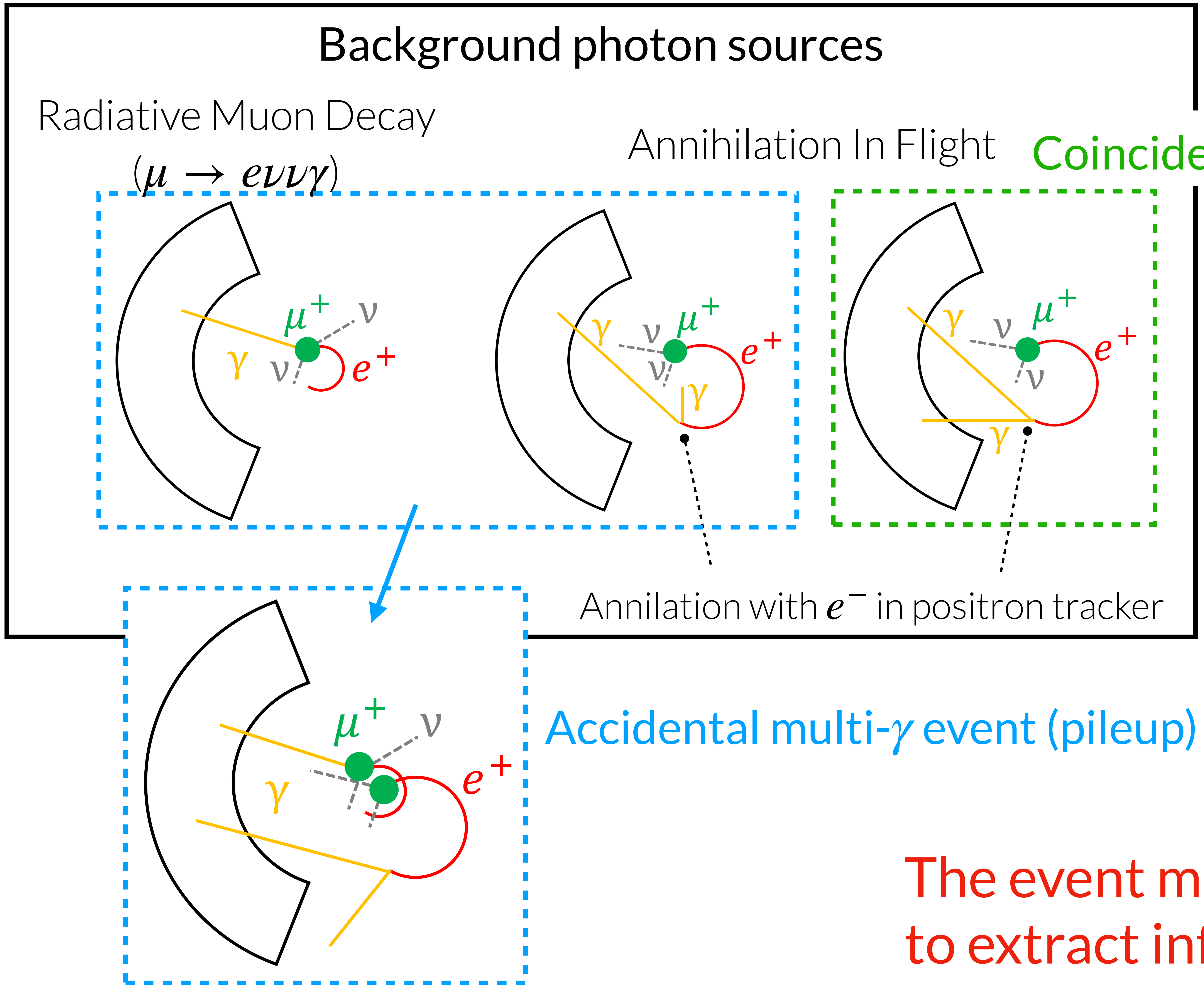
$$E_\gamma = N_{\text{sum}} \times S \times T(t) \times U(\vec{x}_\gamma)$$

*Single γ-ray assumed

N_{sum}: $\sum (N_{\text{pho}} \times \text{weight})$

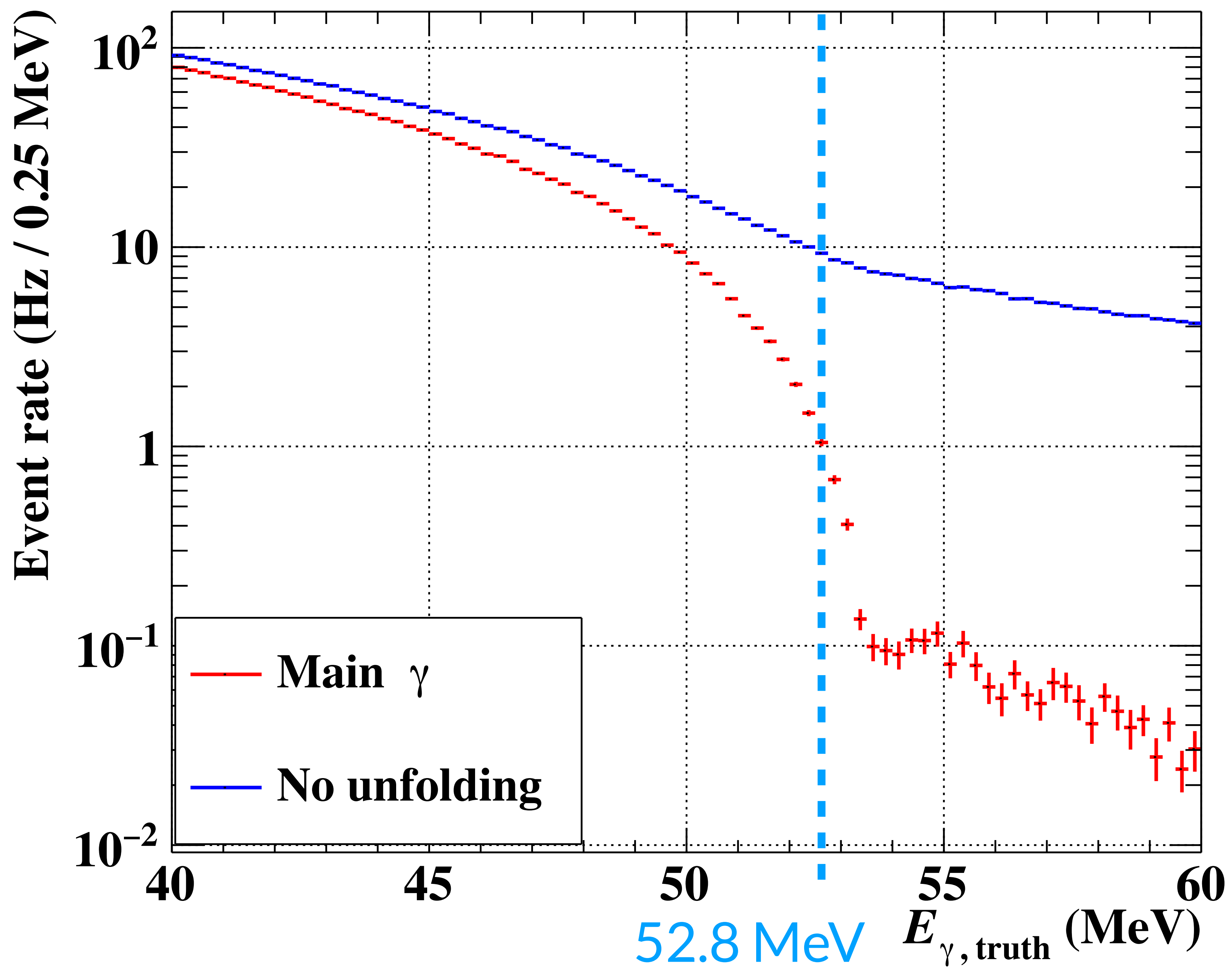
$S \times T(t) \times U(\vec{x}_\gamma)$: Conversion factor + Correction table

Necessarity of multi-photon elimination



Coincident multi-γ event

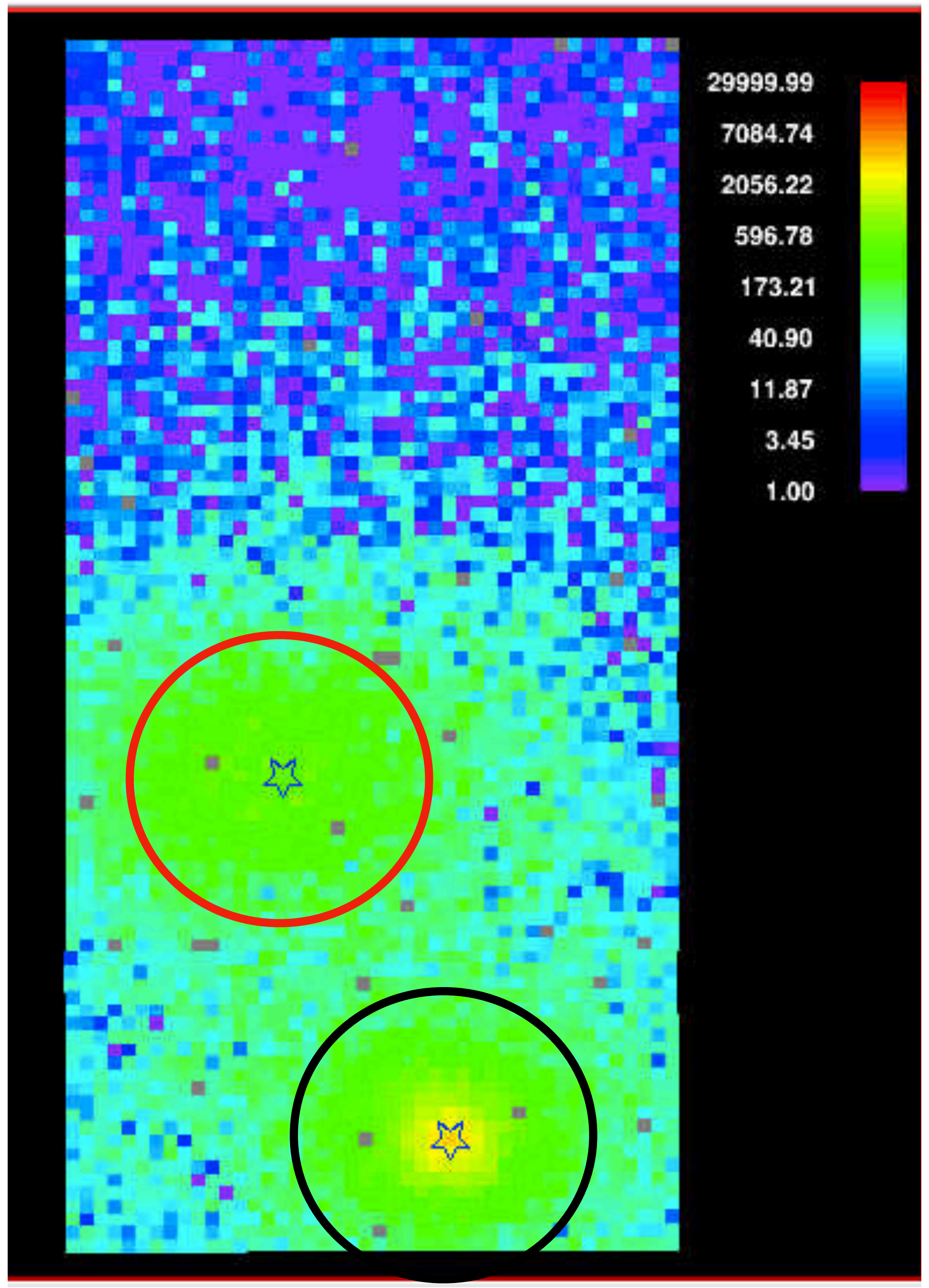
Deposited energy in LXe in MC



The event must be unfolded
to extract information of each individual photon

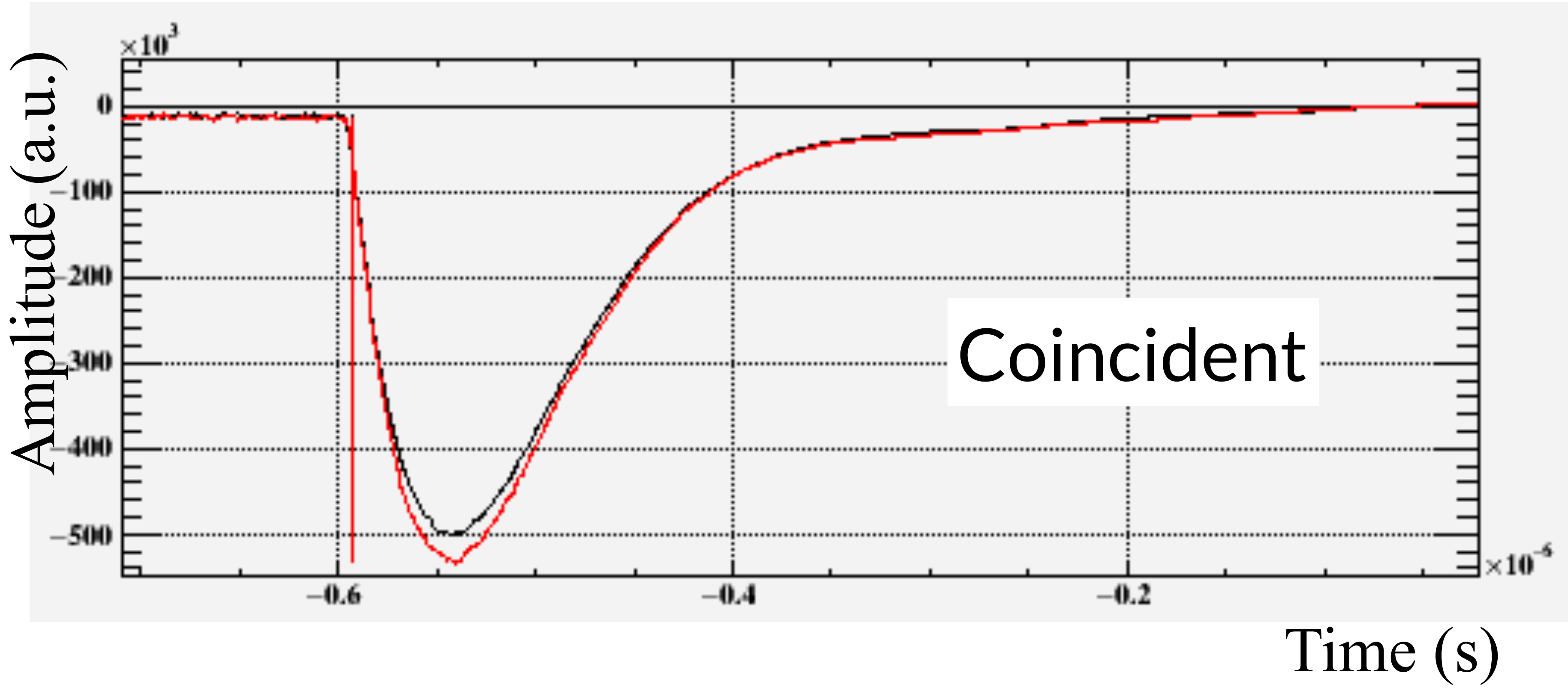
Multi-photon elimination algorithms

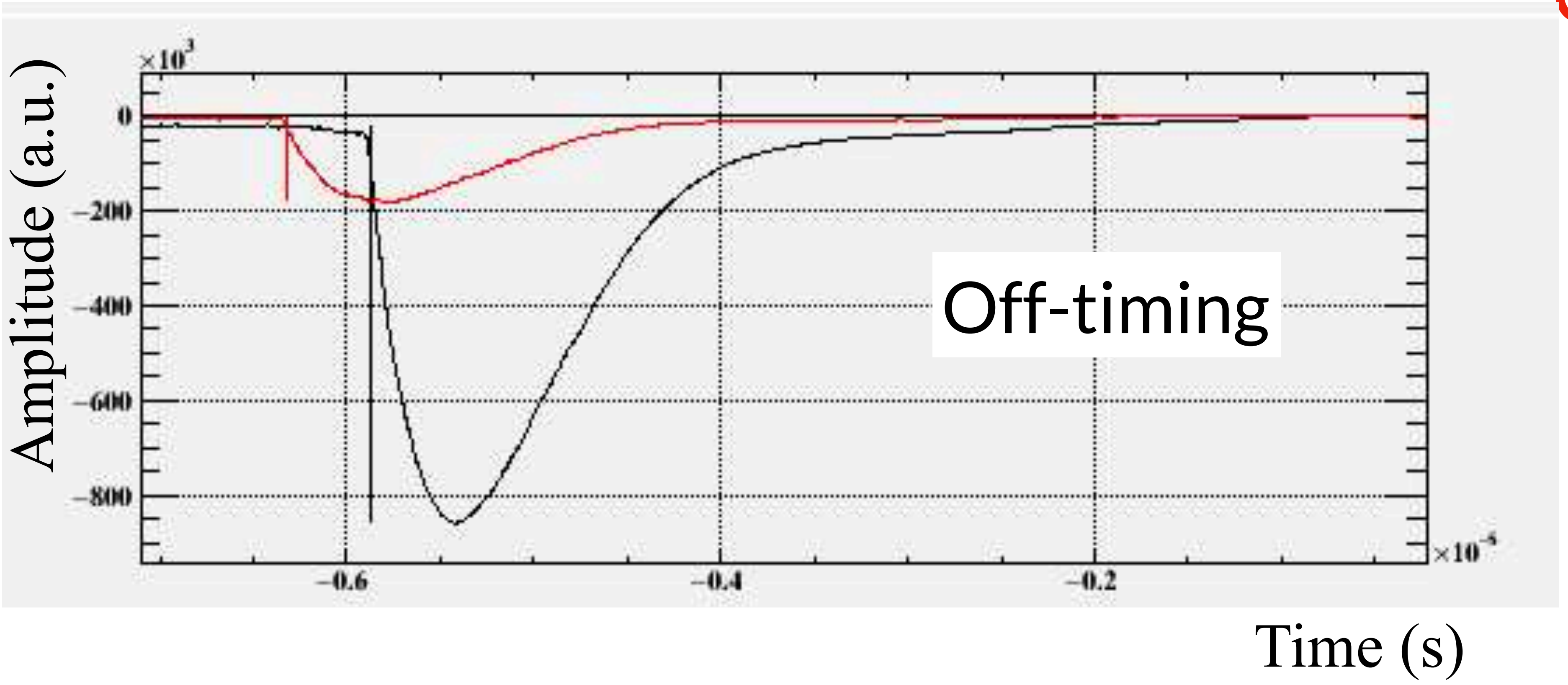
Peak search in spatial distribution

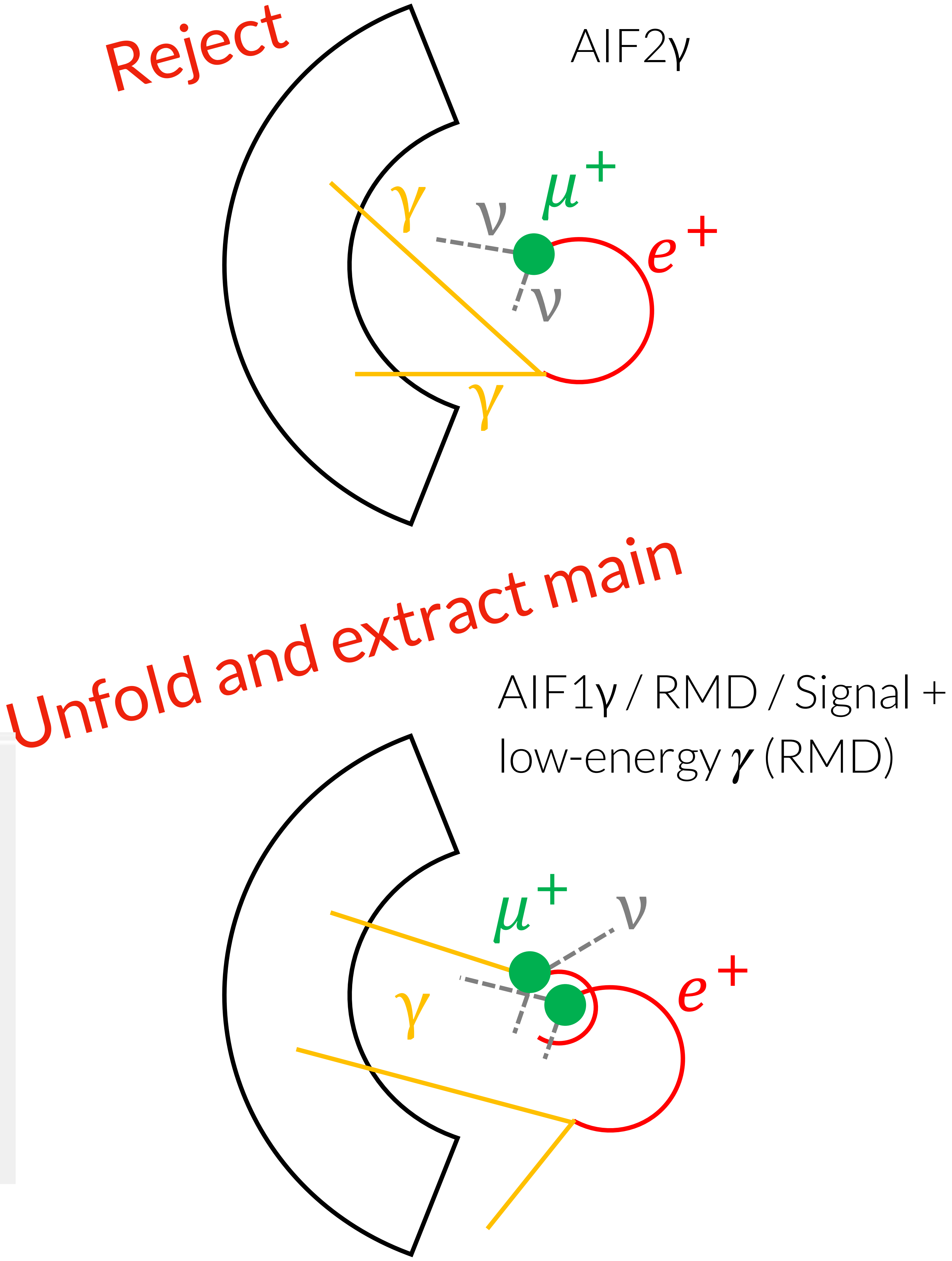


N_{pho} in entrance face (MPPCs)

Peak search in temporal distribution

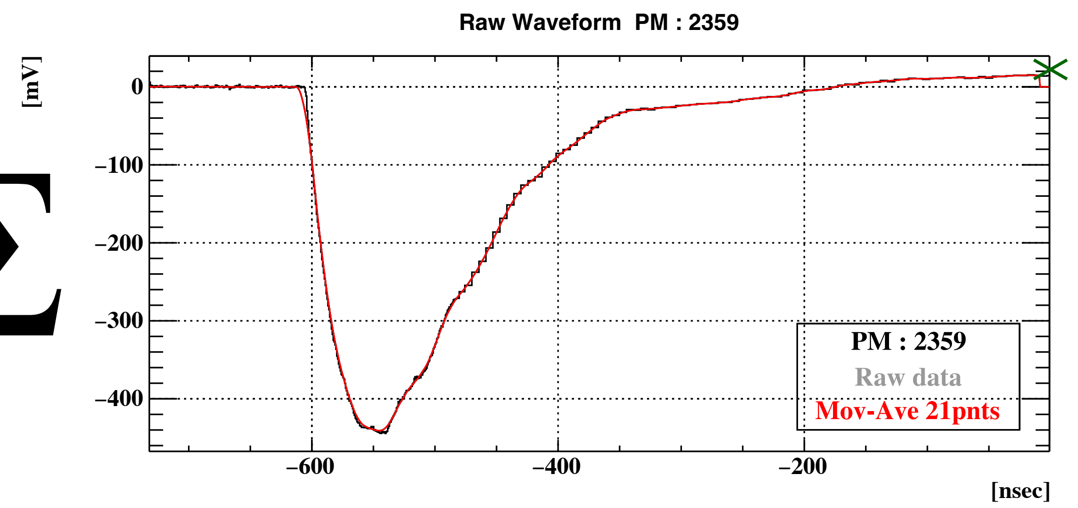






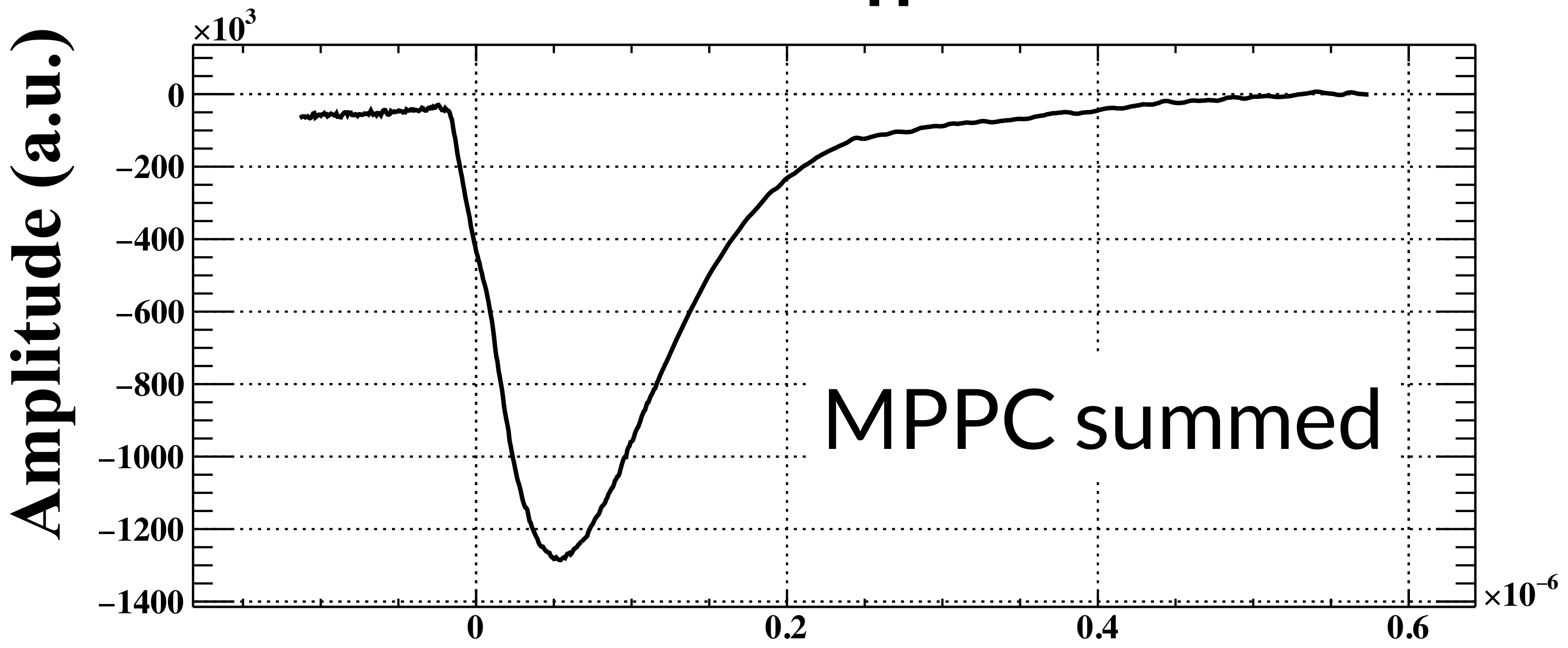
Pileup analysis: Summed waveform analysis

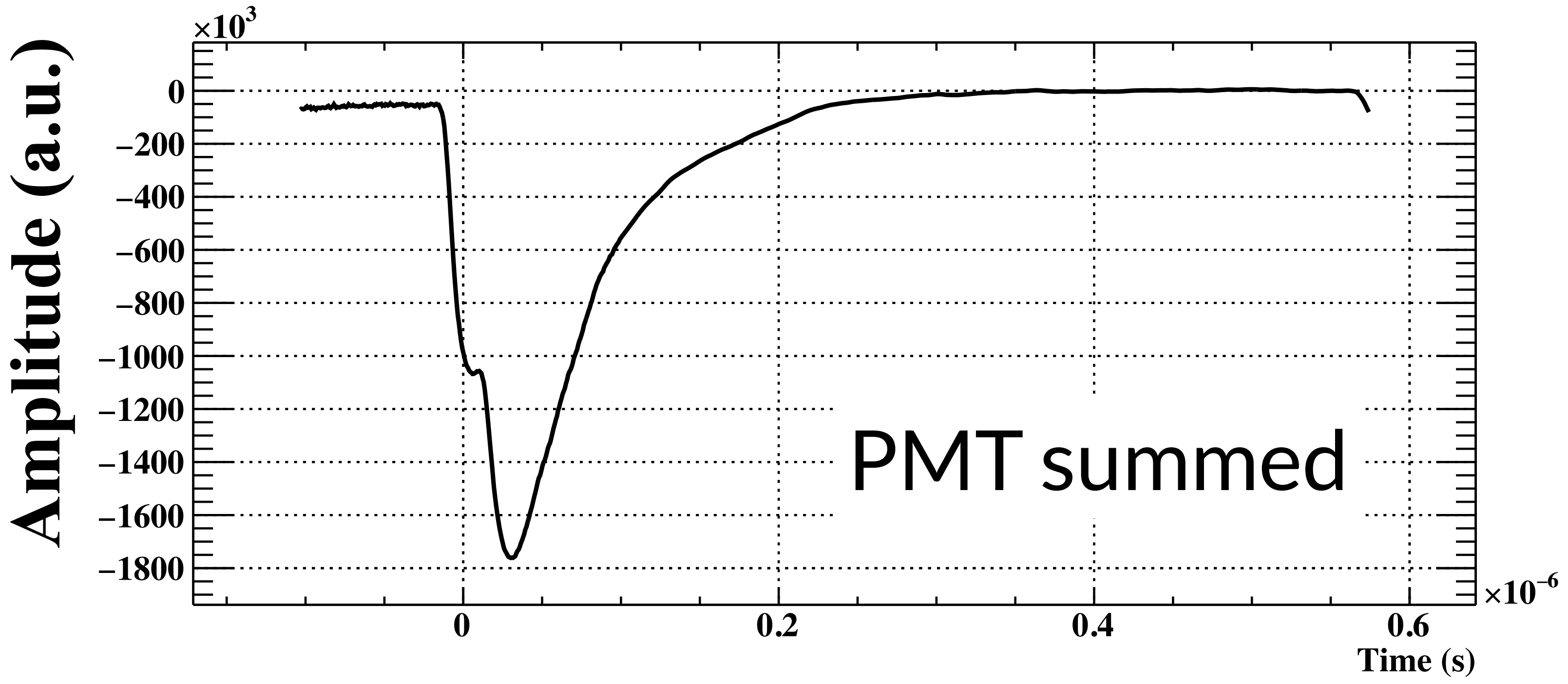
- Concept: **Pulse unfolding with summed waveform template fit**

Σ


× weight

||



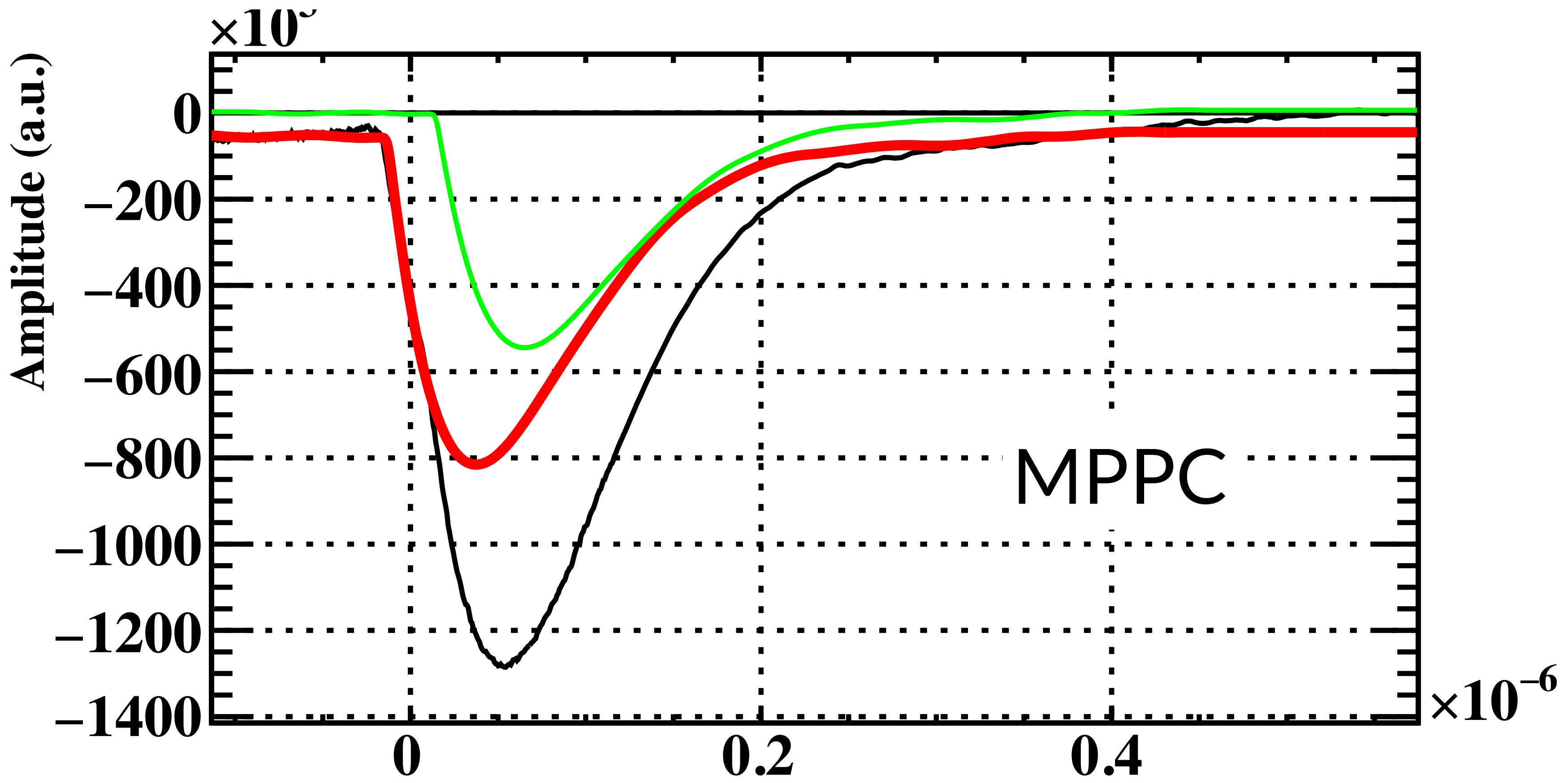


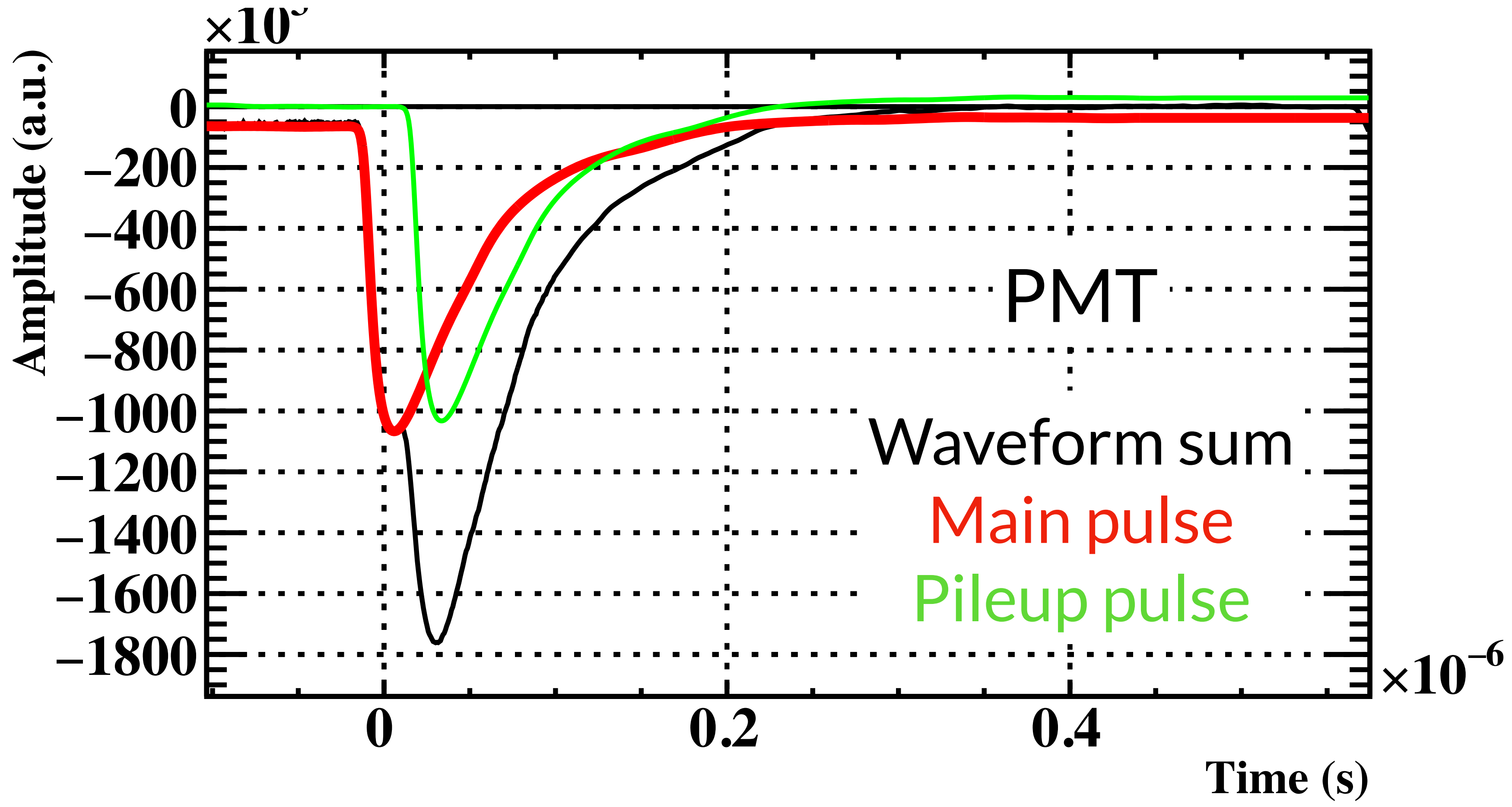
Detect seed pulses
(= Calculate initial fit parameters)

- Number of pulses
- Amplitude
- Time
- Baseline

→

Minimise χ^2

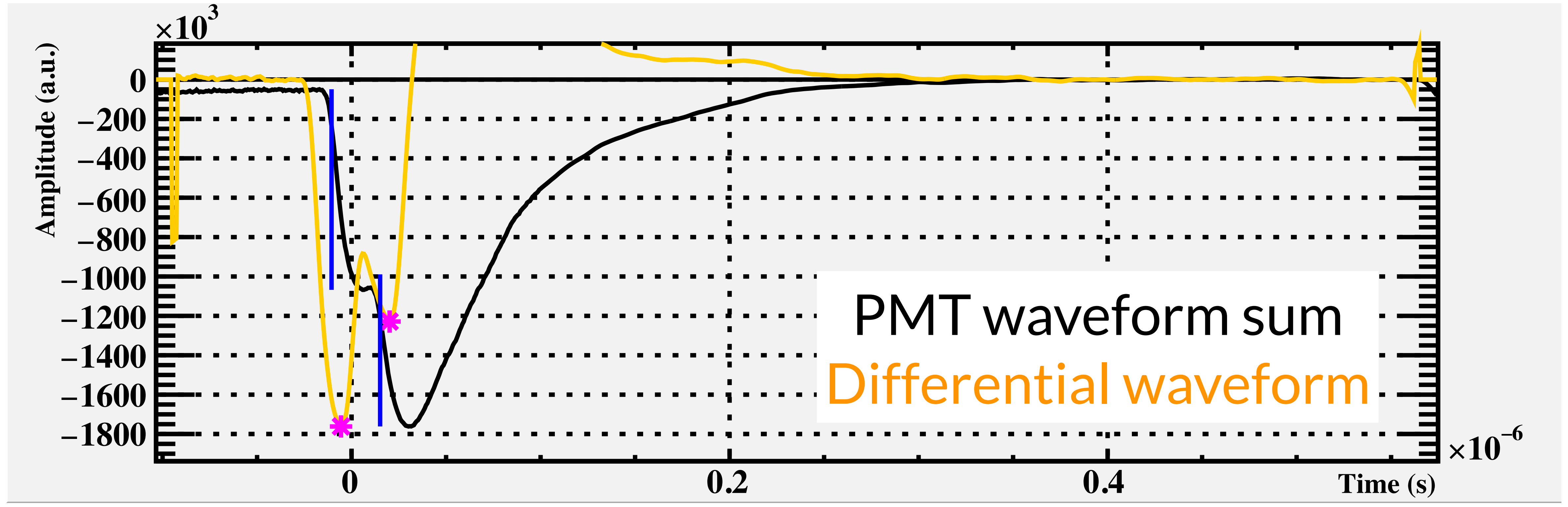




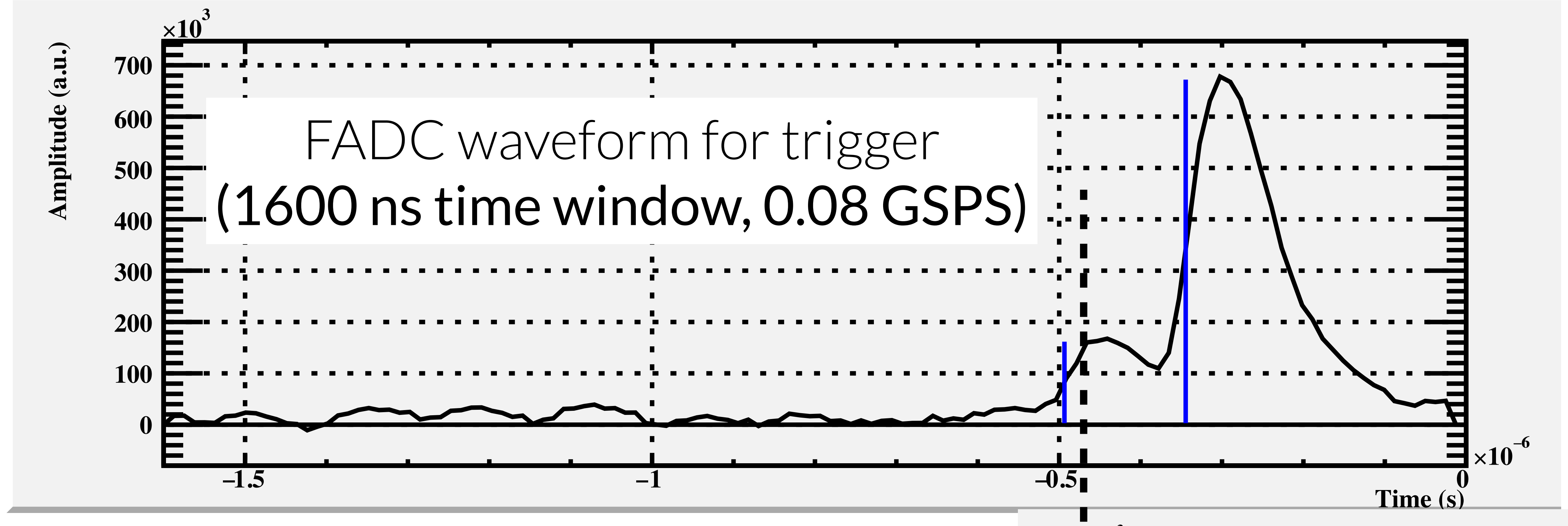
Only main pulse reconstructed

Seed pulse detection in multi-photon events

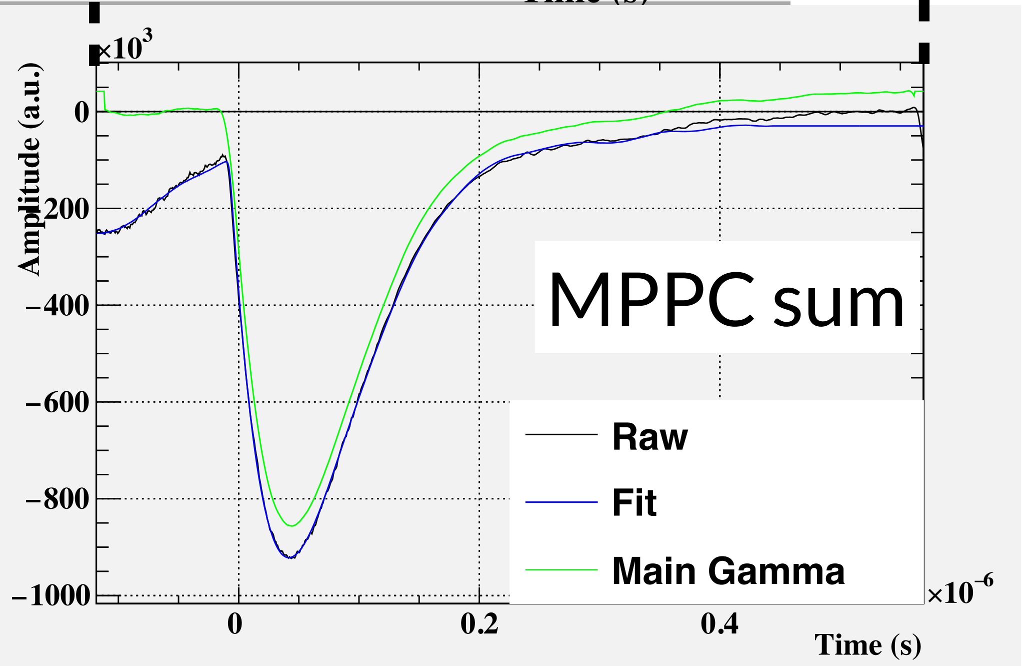
Differential waveform sensitive to multiple peaks

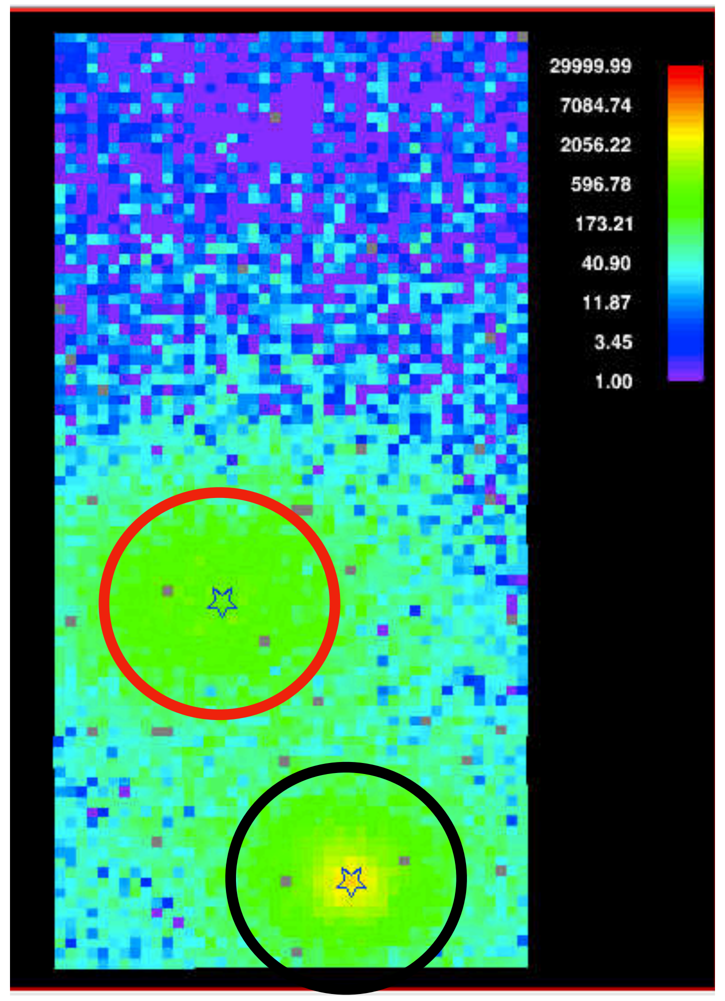


FADC waveform with wider time window detecting pulse before DRS one

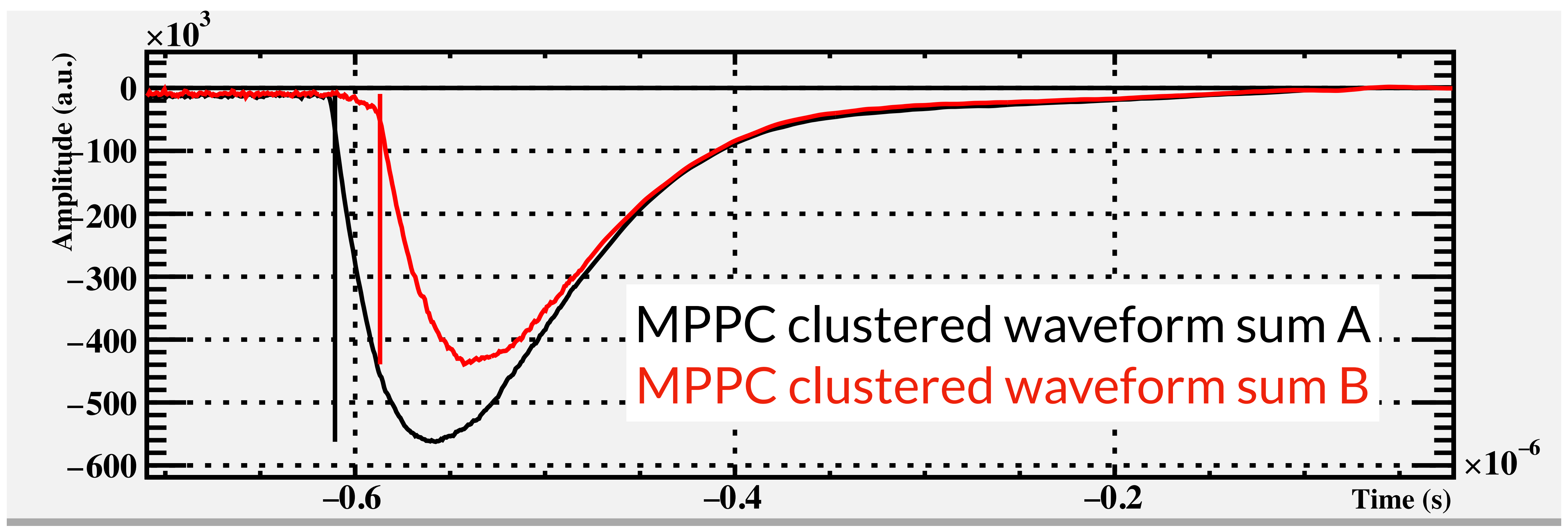


DRS waveform
(~700 ns time window, 1.4 GSPS)





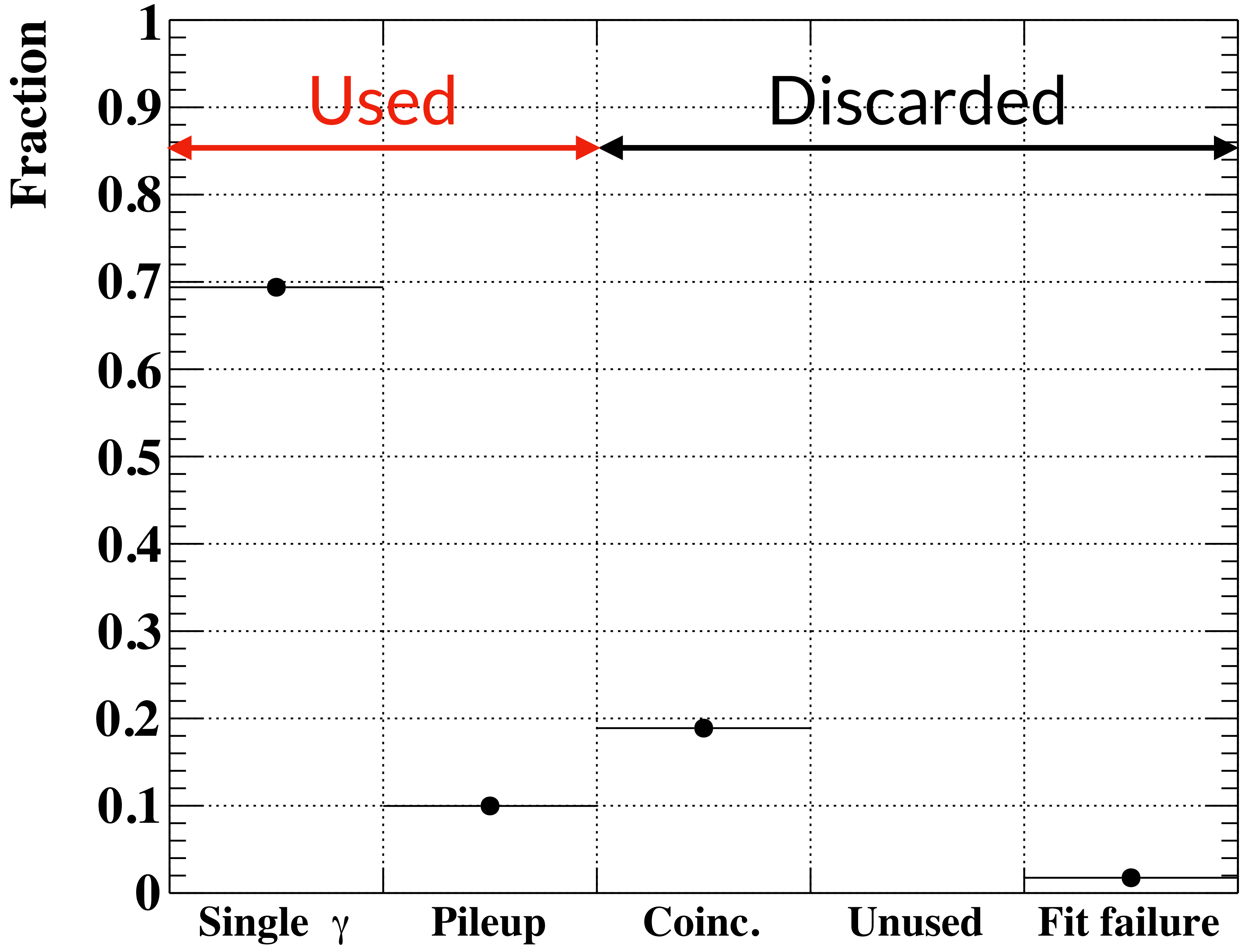
Clustering based on spatial distribution

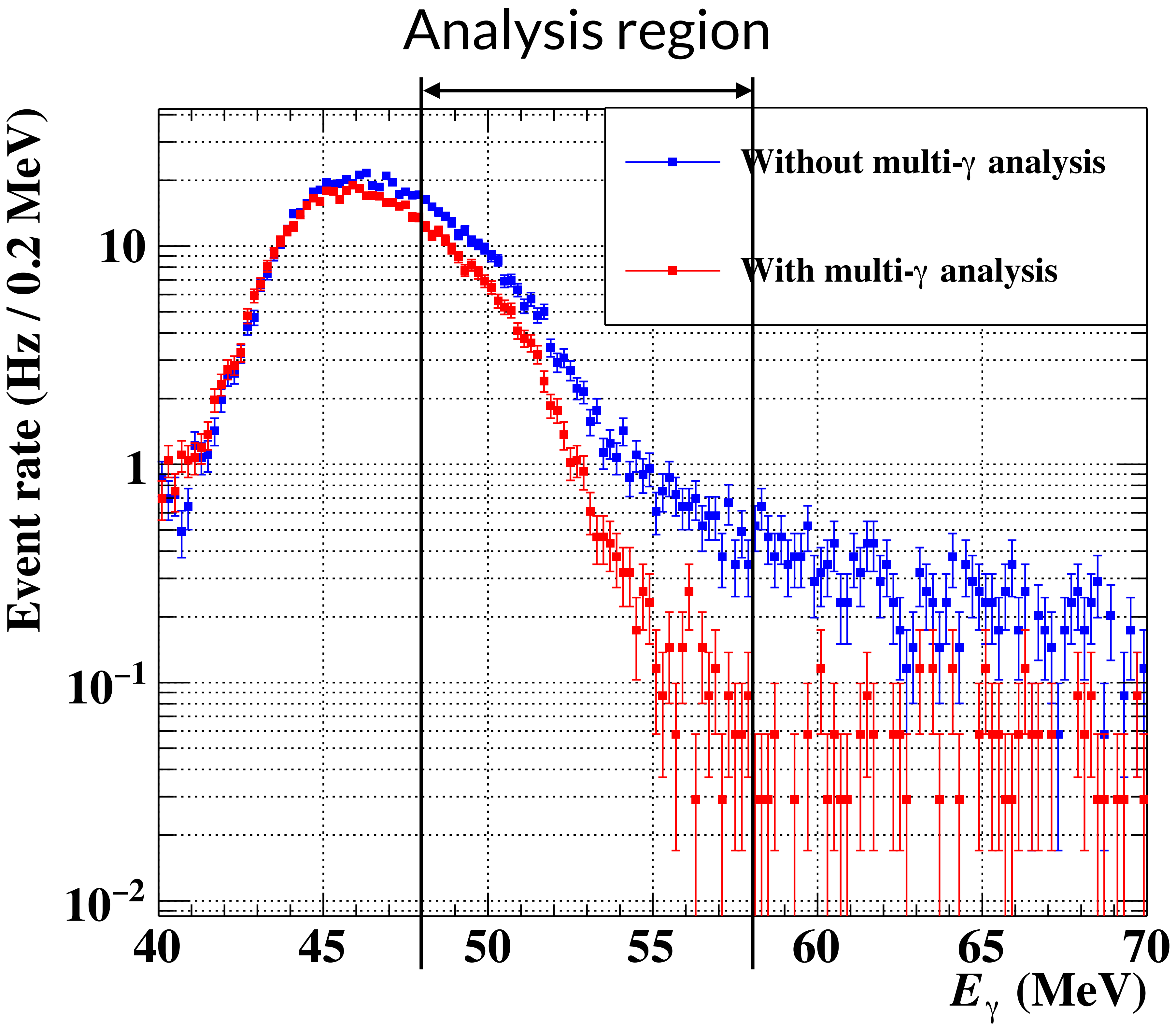


Robust waveform template fit requires precise seed pulse detection

Preliminary multi-photon analysis performance

- Number of background photons in analysis region reduced by 34%
- Signal efficiency: 95% due to detection of fake peak in spatial distribution
  - Based on signal γ MC sample



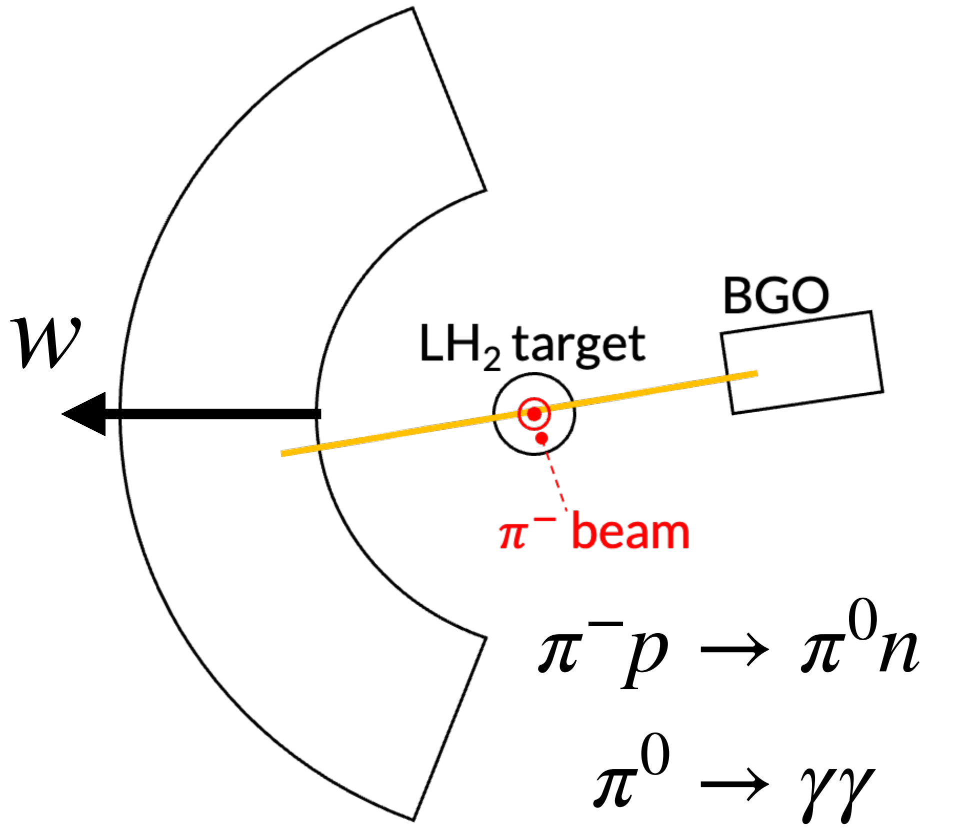


Energy scale calibration datasets

$$E_\gamma = S \times U(\vec{x}_\gamma) \times T(t) \times N_{\mathrm{sum}}$$

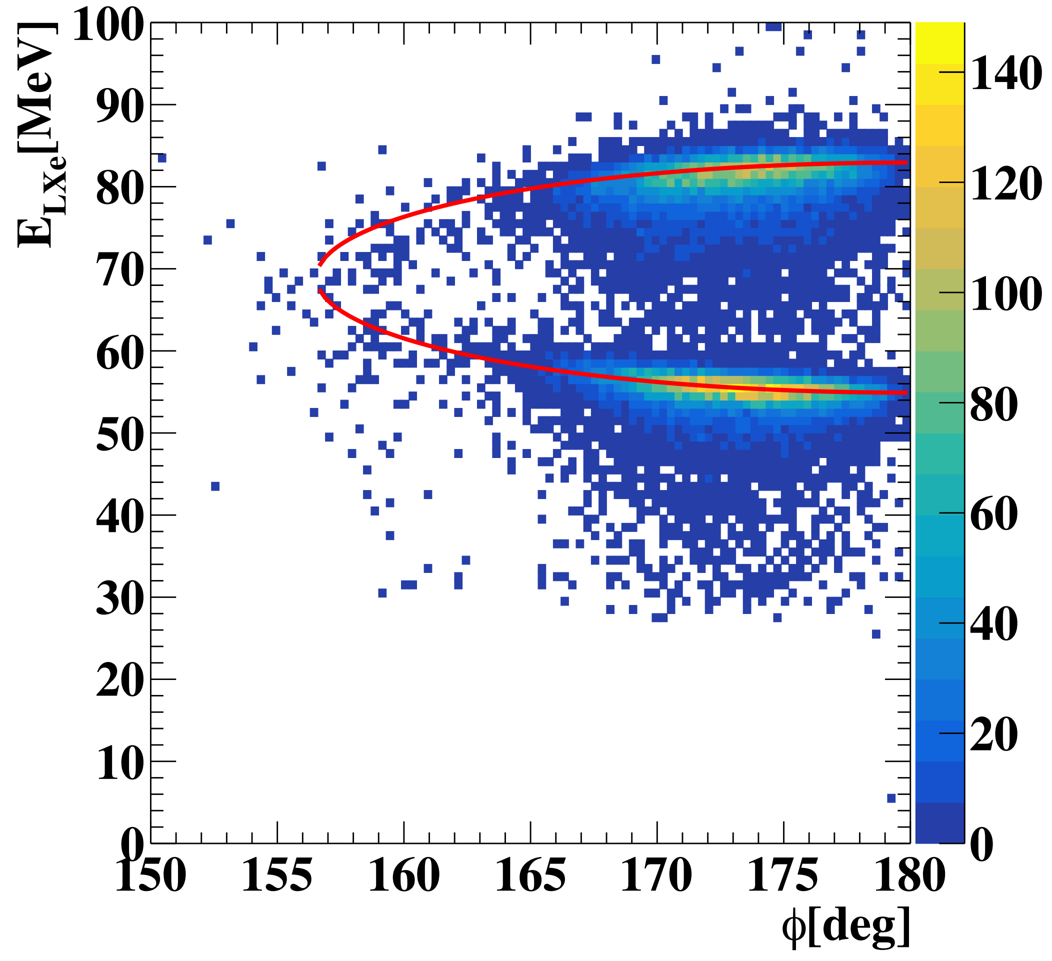
Summed N_{pho} for **single γ-ray** reconstructed through multi-γ elimination

55 MeV γ from $\pi^0 \rightarrow \gamma\gamma$

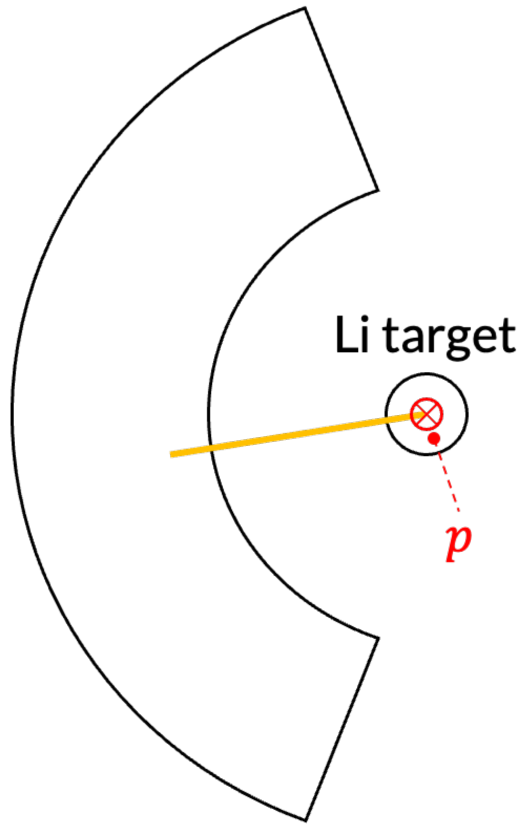


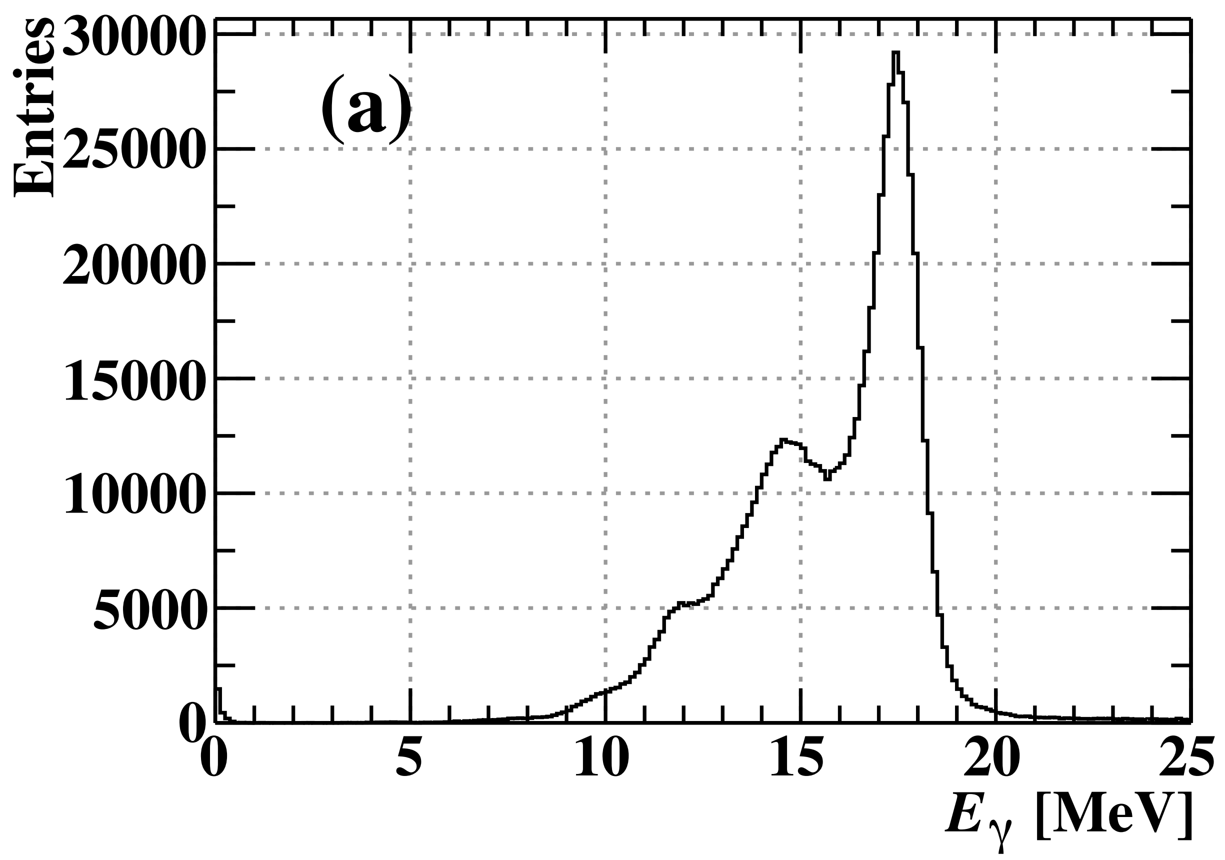
$\pi^- p \rightarrow \pi^0 n$

$\pi^0 \rightarrow \gamma\gamma$

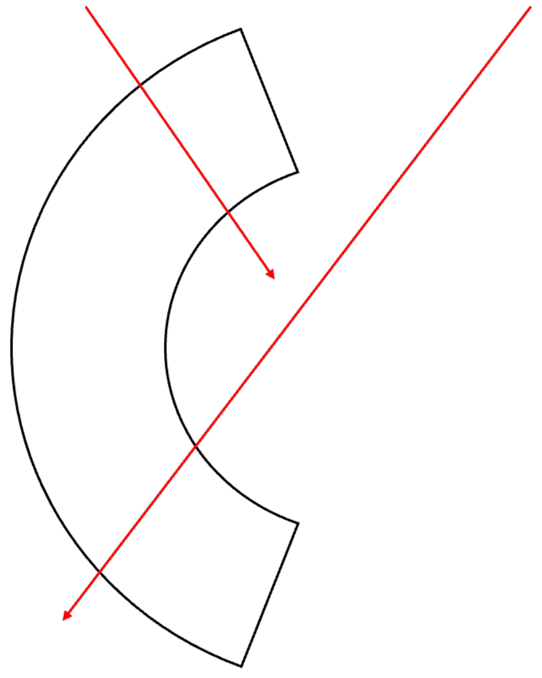


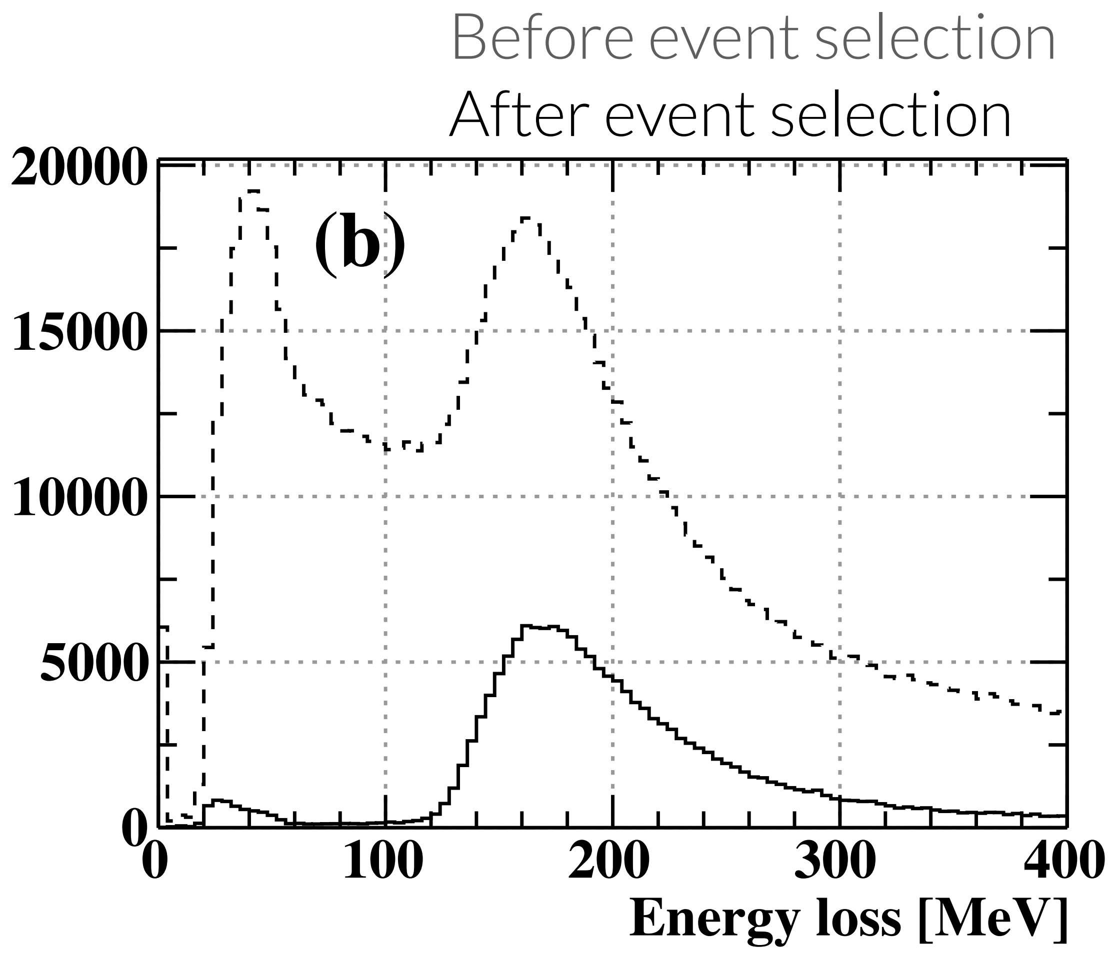
17.6 MeV γ from ${}^7\mathrm{Li}(p,\gamma){}^8\mathrm{Be}$





Cosmic-ray μ



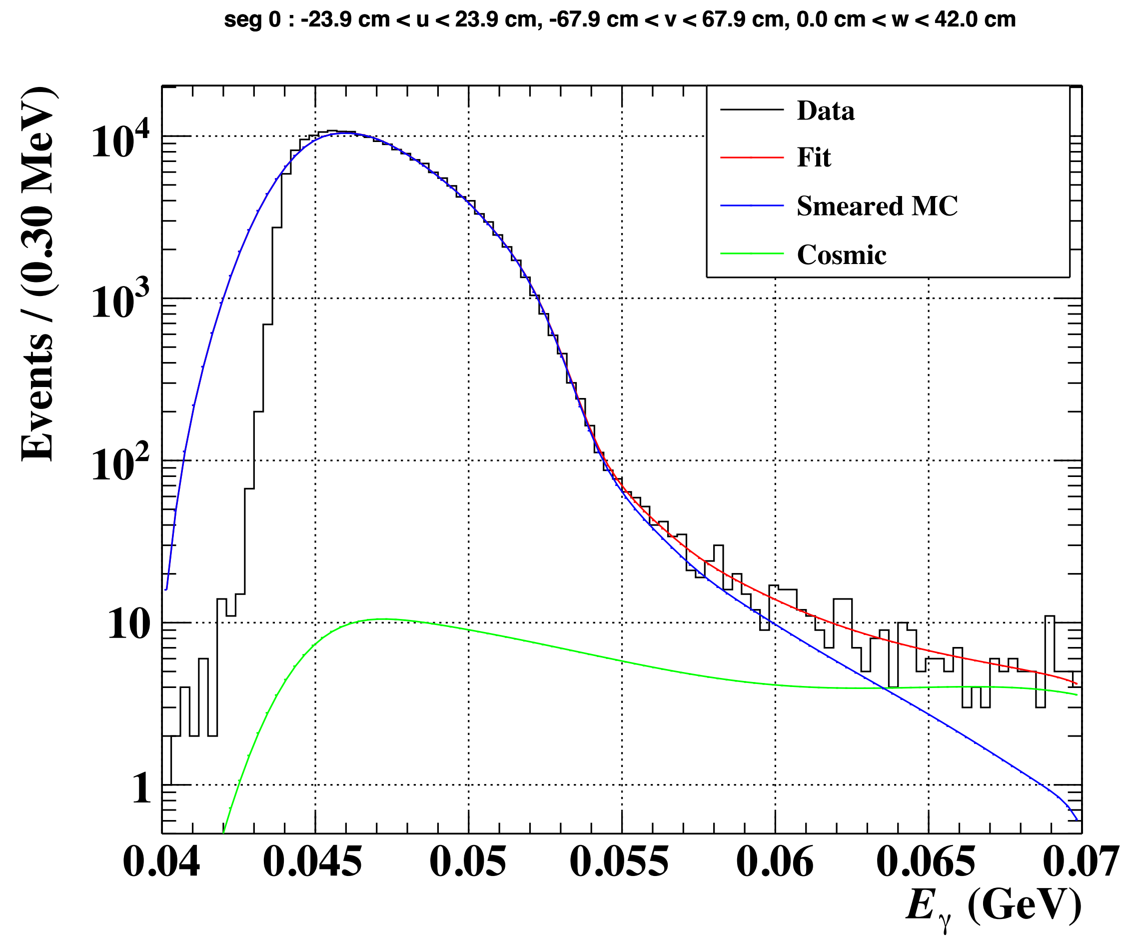


BG spectrum fit

Compare data with dedicated MC

Major fitting parameters

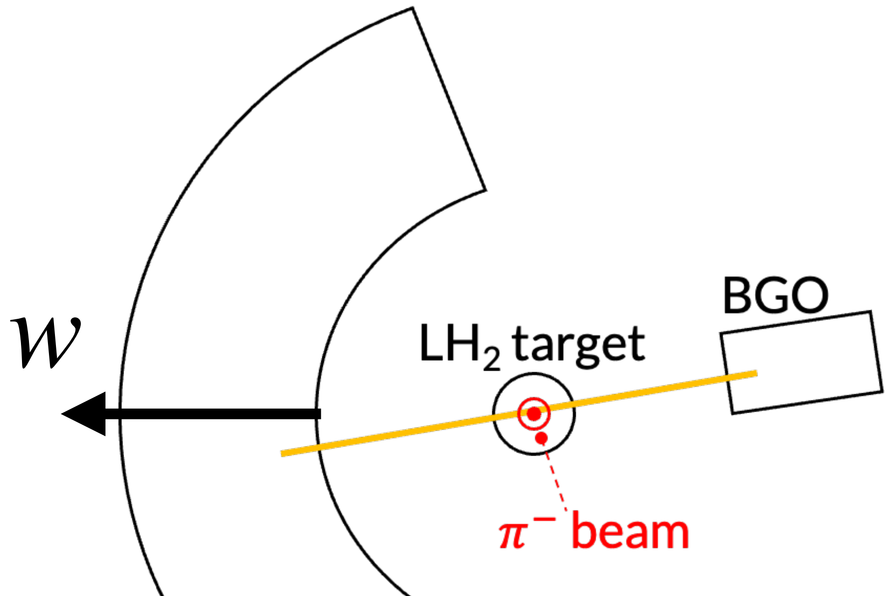
- Energy scale
- Resolution
- Trigger threshold



Energy scale factor & uniformity calibration

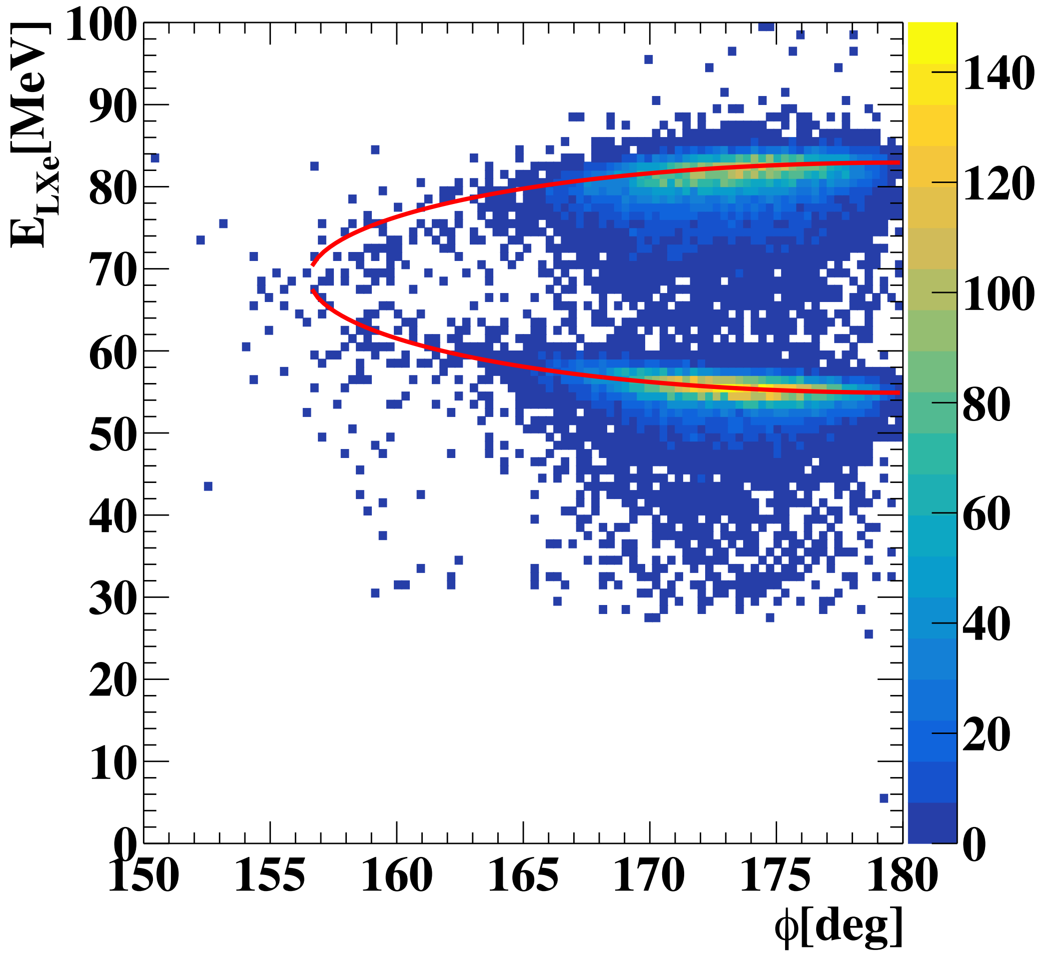
$$E_\gamma = \underline{S} \times \underline{U(\vec{x}_\gamma)} \times T(t) \times N_{\mathrm{sum}}$$

55 MeV γ from $\pi^0 \to \gamma\gamma$

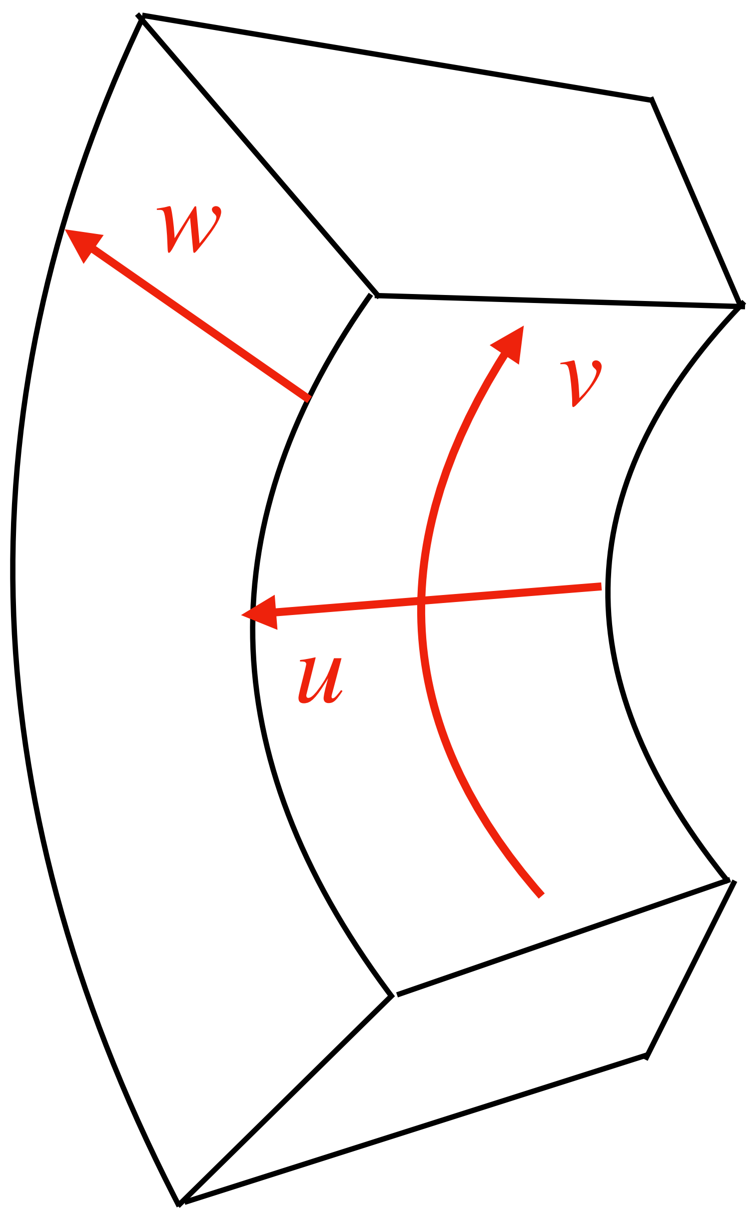


$\pi^- p \to \pi^0 n$

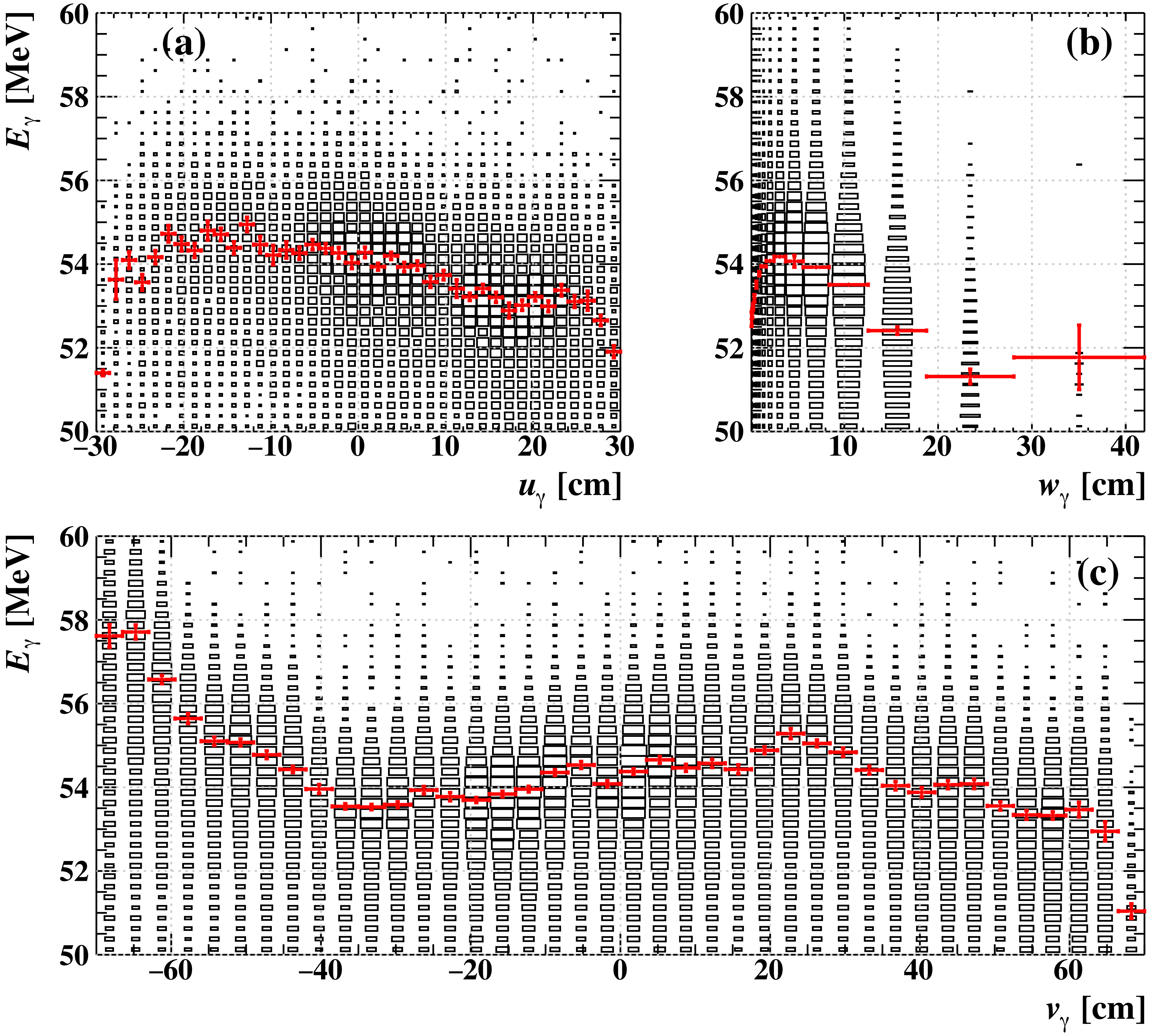
$\pi^0 \to \gamma\gamma$



Close to signal γ energy (52.8 MeV)



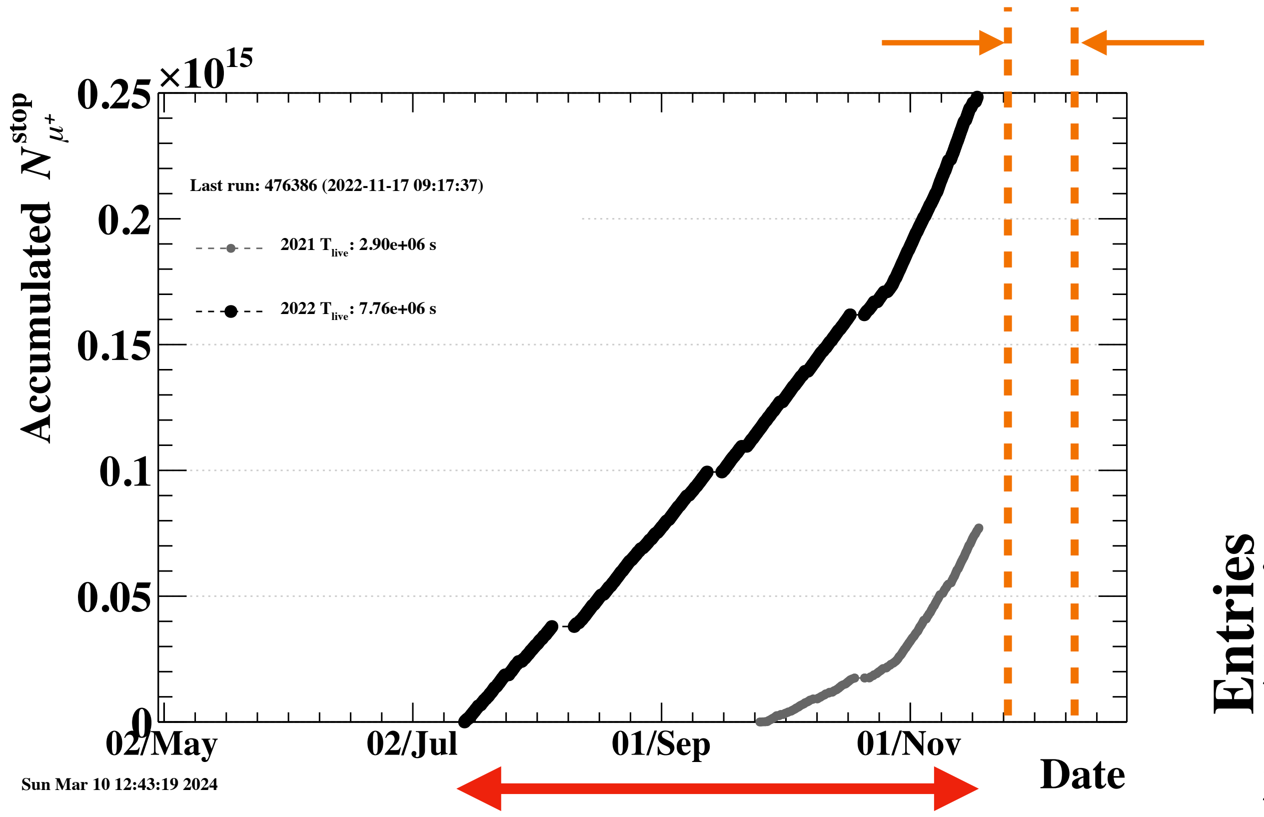
Non-uniform response to 55 MeV photon



Energy scale history calibration datasets

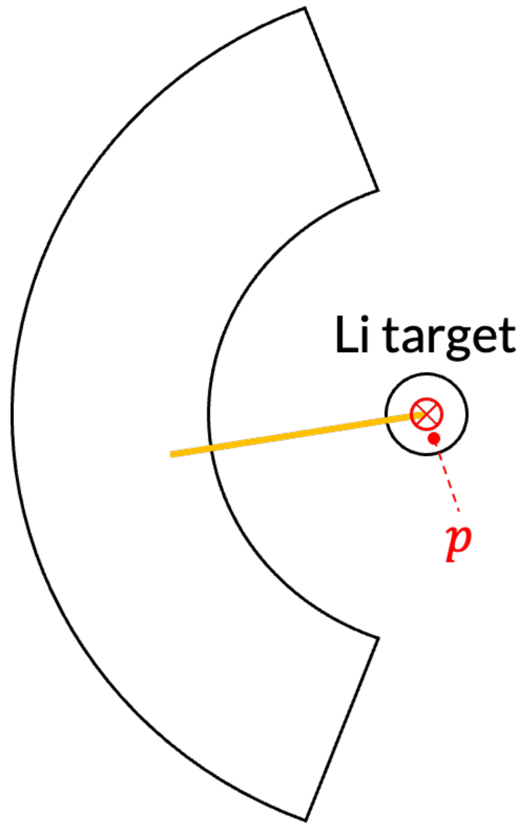
$$E_\gamma = S \times U(\vec{x}_\gamma) \times T(t) \times N_{\mathrm{sum}}$$

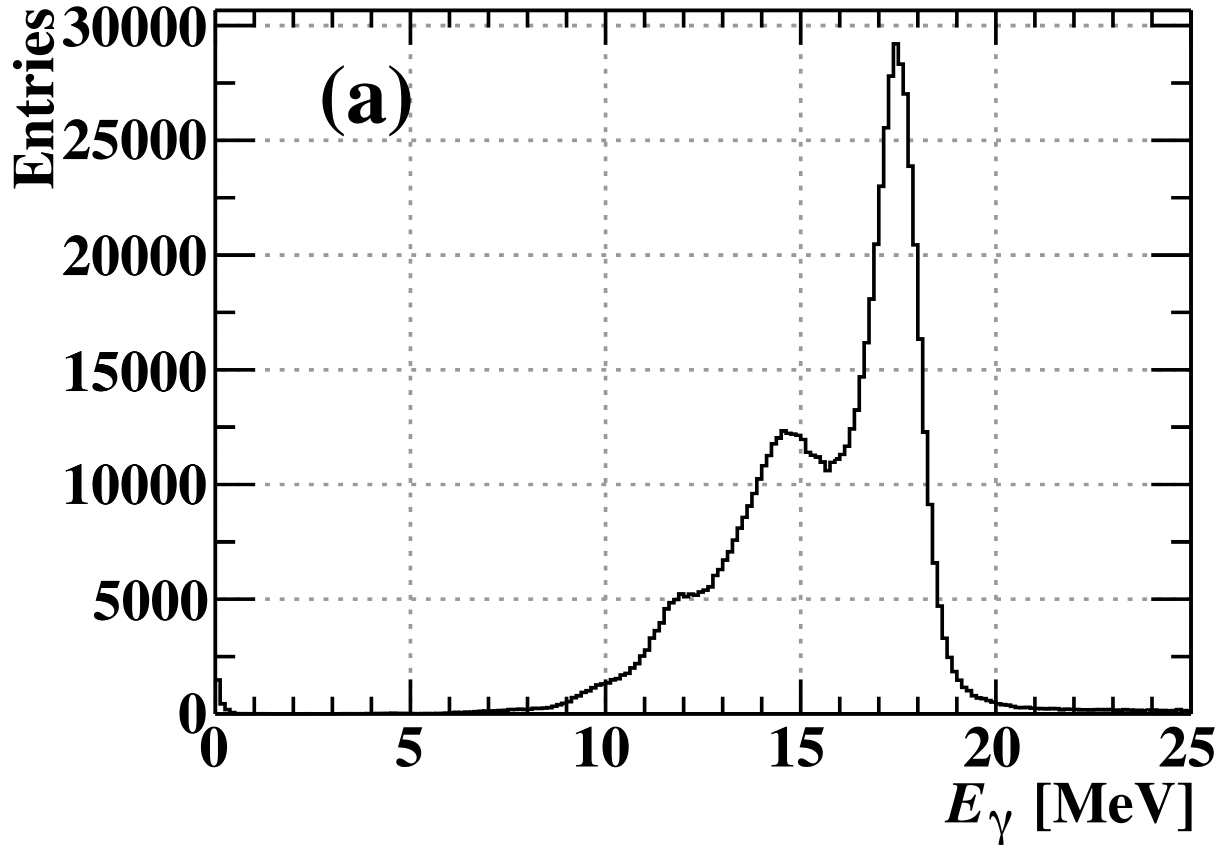
$\pi^0 \to \gamma\gamma$ DAQ



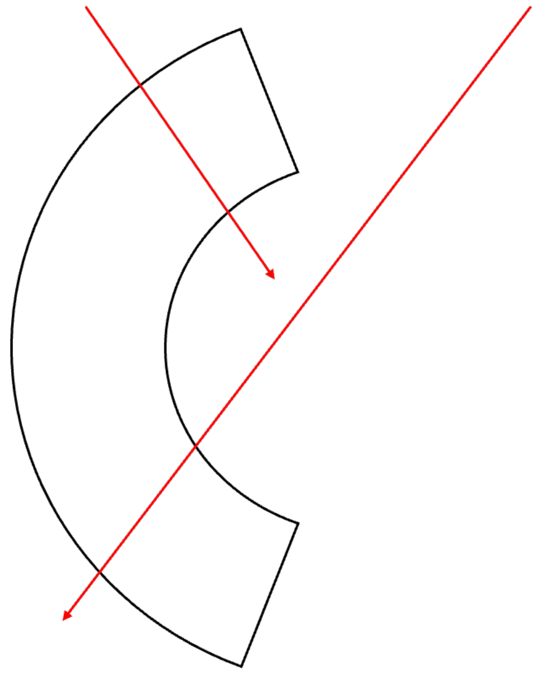
Physics data acquision

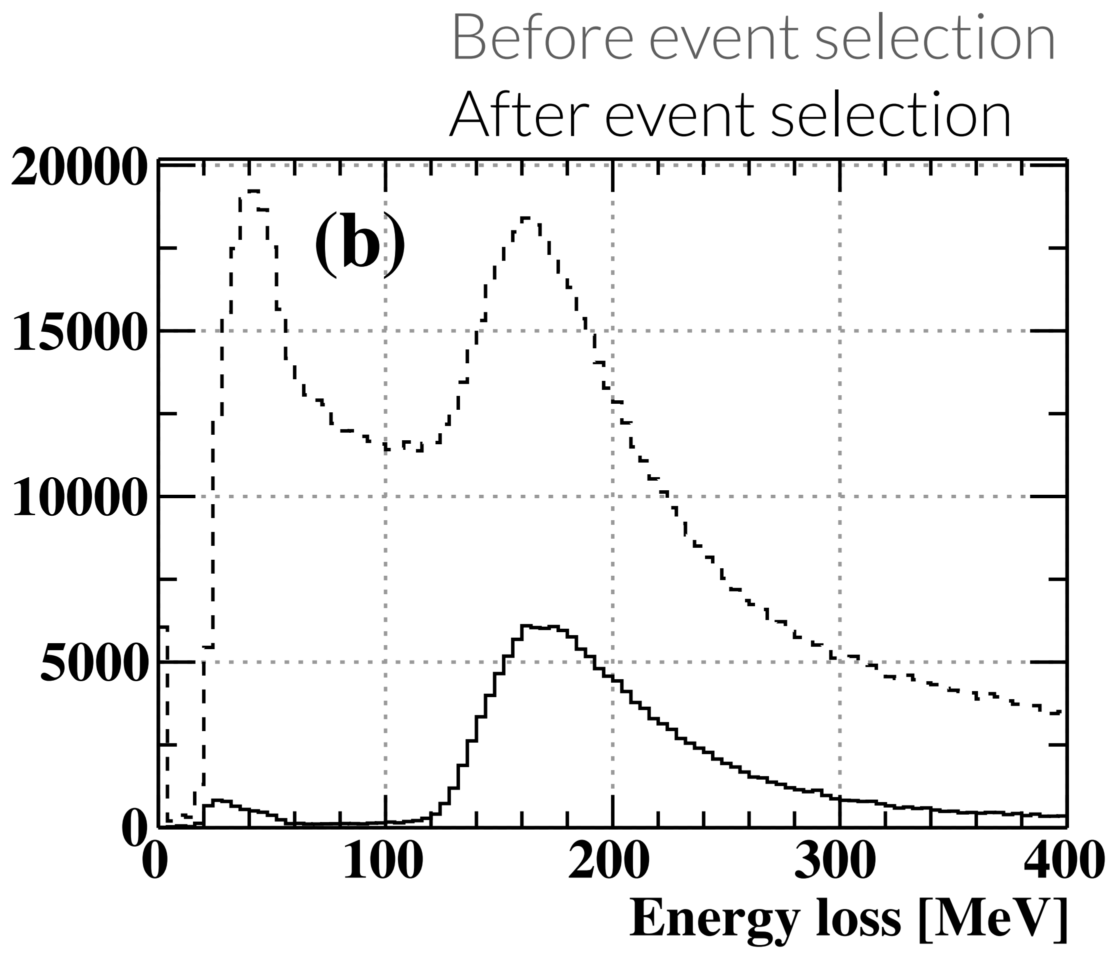
17.6 MeV γ from $^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$





Cosmic-ray μ



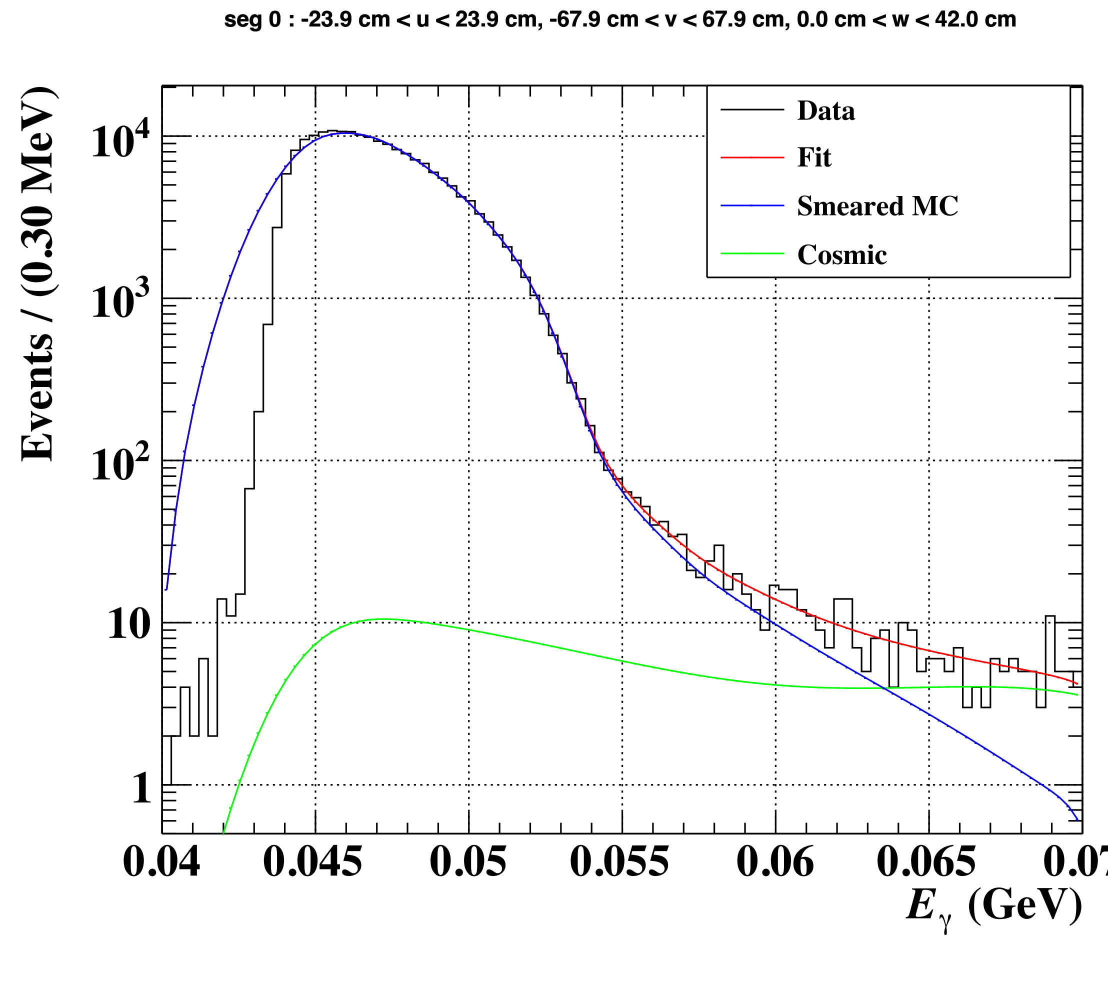


BG spectrum fit

Compare data with dedicated MC

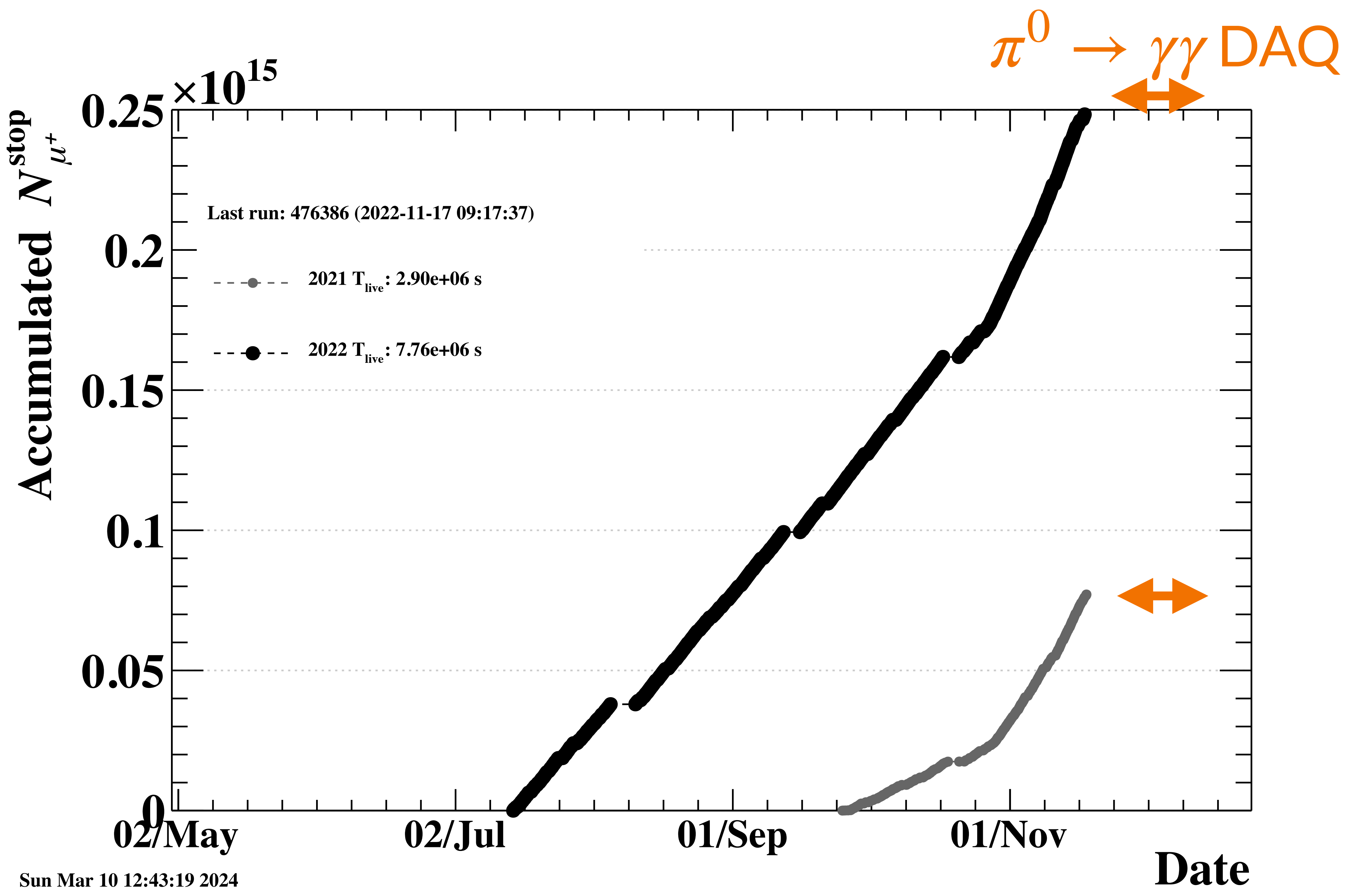
Major fitting parameters

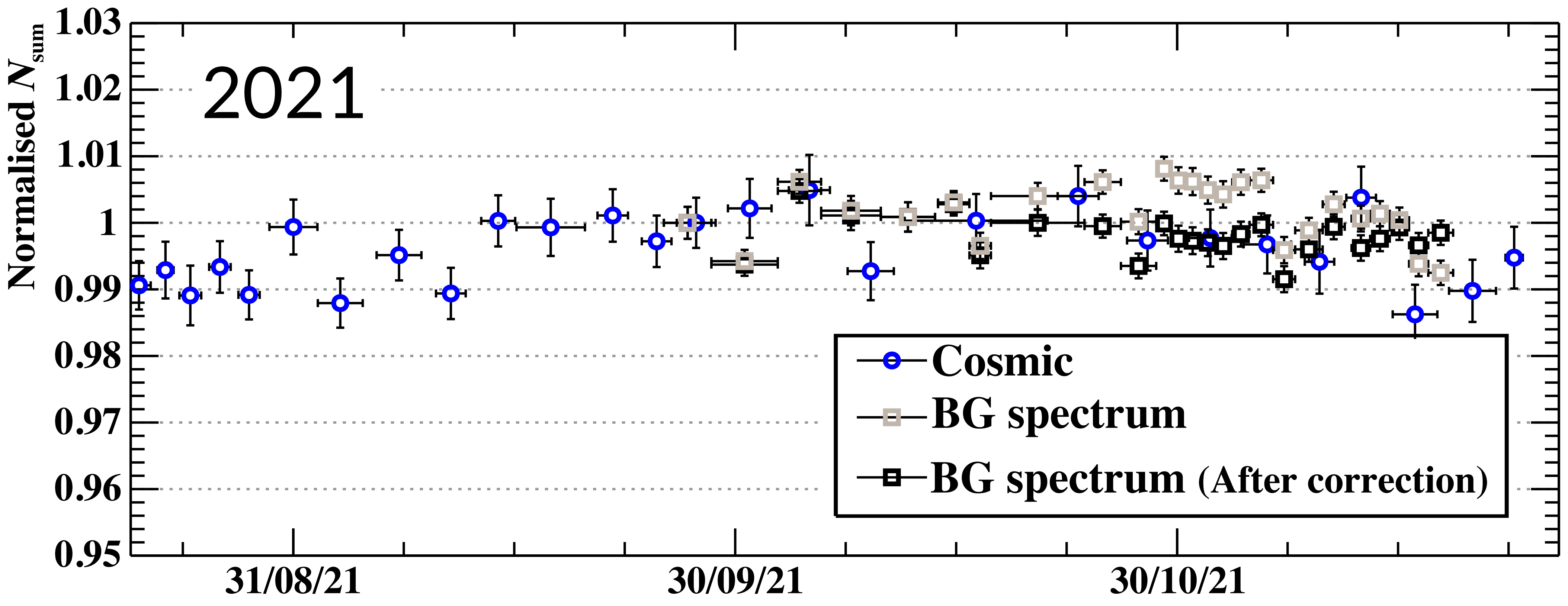
- Energy scale
- Resolution
- Trigger threshold

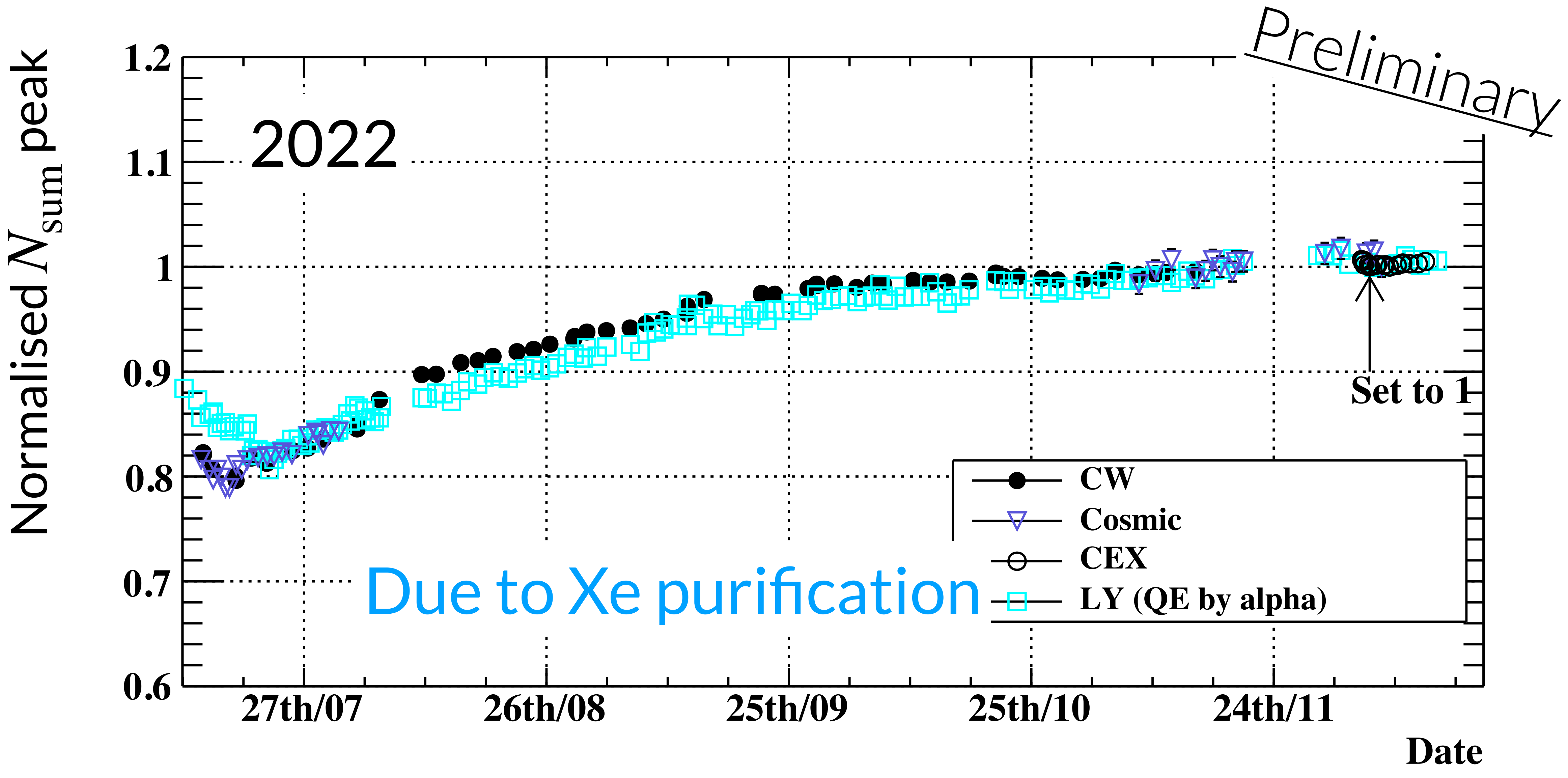


Energy scale history calibration

$$E_\gamma = S \times U(\vec{x}_\gamma) \times T(t) \times N_{\mathrm{sum}}$$







Uncertainty of energy scale suppressed to 0.4% in 2021

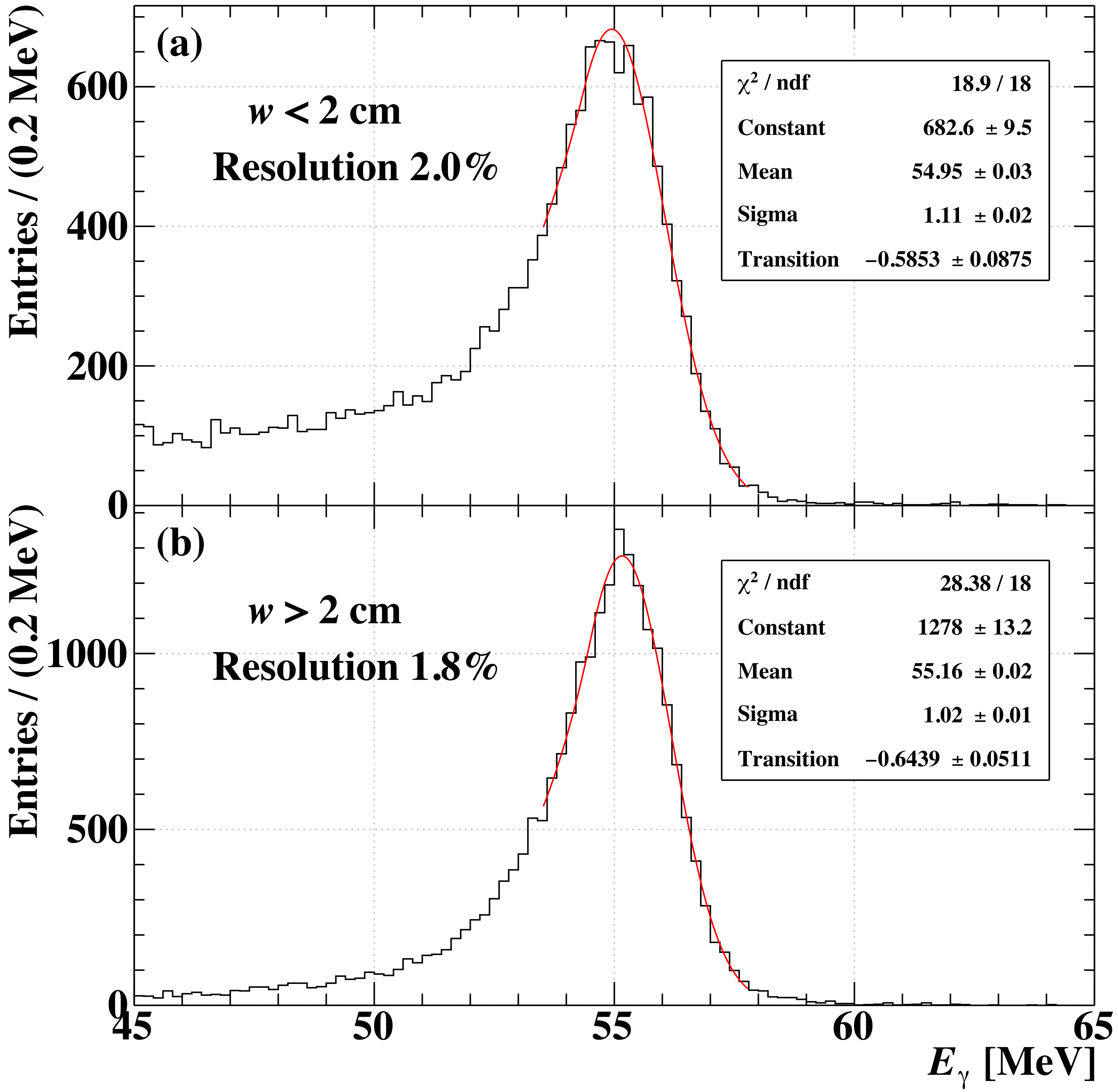
Energy resolution

- Energy resolution evaluated with 55 MeV photon
  - 2.0%/1.8% for w < 2 cm/w > 2 cm
    - EM shower leaks from entrance face
  - Fitting function: Exponential + Gaussian

$$f(x) = \begin{cases} A\exp\left(-\frac{(x-\mu)^2}{\sigma^2}\right) & (\text{if } x > \mu + \tau) \\ A\exp\left(-\frac{\tau(\tau/2 - x + \mu)}{\sigma^2}\right) & (\text{if } x \leq \mu + \tau) \end{cases}$$

- Calibration for the 2022 data ongoing

Energy response to 55 MeV photon in 2021



Conclusion & prospects

- MEG II liquid xenon calorimeter reconstructs photon energy precisely to distinguish signal and background
- Multi-photon elimination needed to reconstruct a single photon
- **Preliminary multi-γ analysis performance: Photon background reduction of 34%**
- **Energy resolution of 1.8% (2.0%) achieved for w_γ > 2 cm (< 2 cm) in 2021 dataset**
- Prospects for 2022 photon data reconstruction
  - Careful calibration to be done for calorimeter energy scale
  - Multi-γ analysis performance to be evaluated

Backup

Photosensor calibration

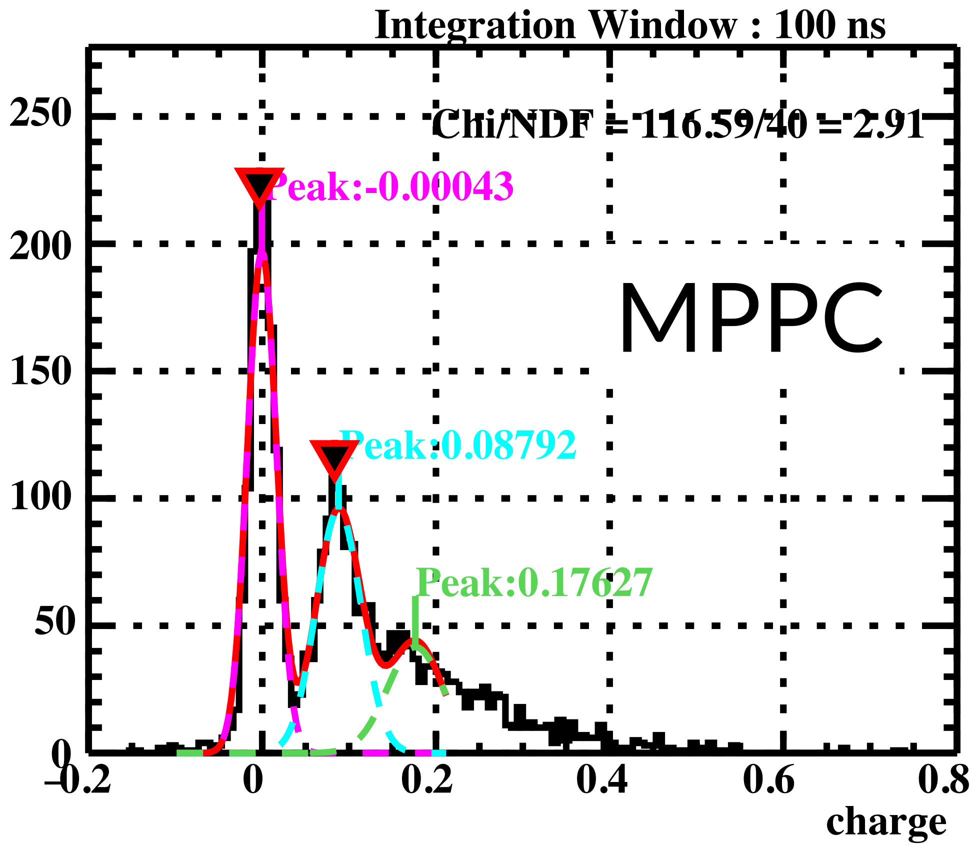
Charge Q_i

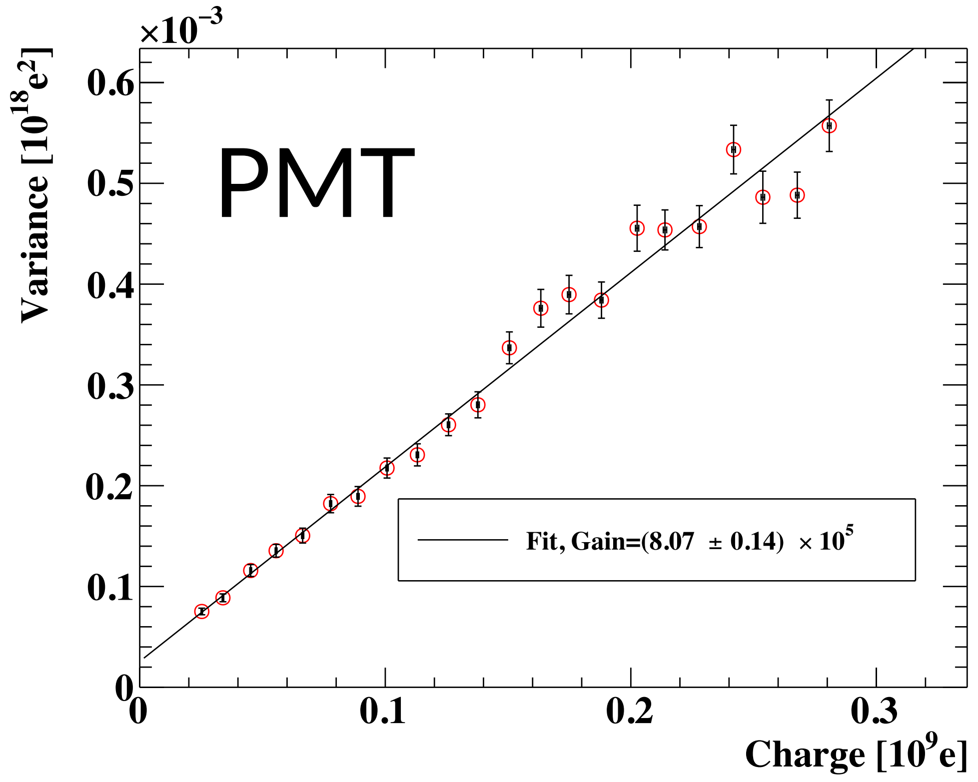
↓ **Gain**

Number of detected photoelectrons $N_{\mathrm{phe},i}$

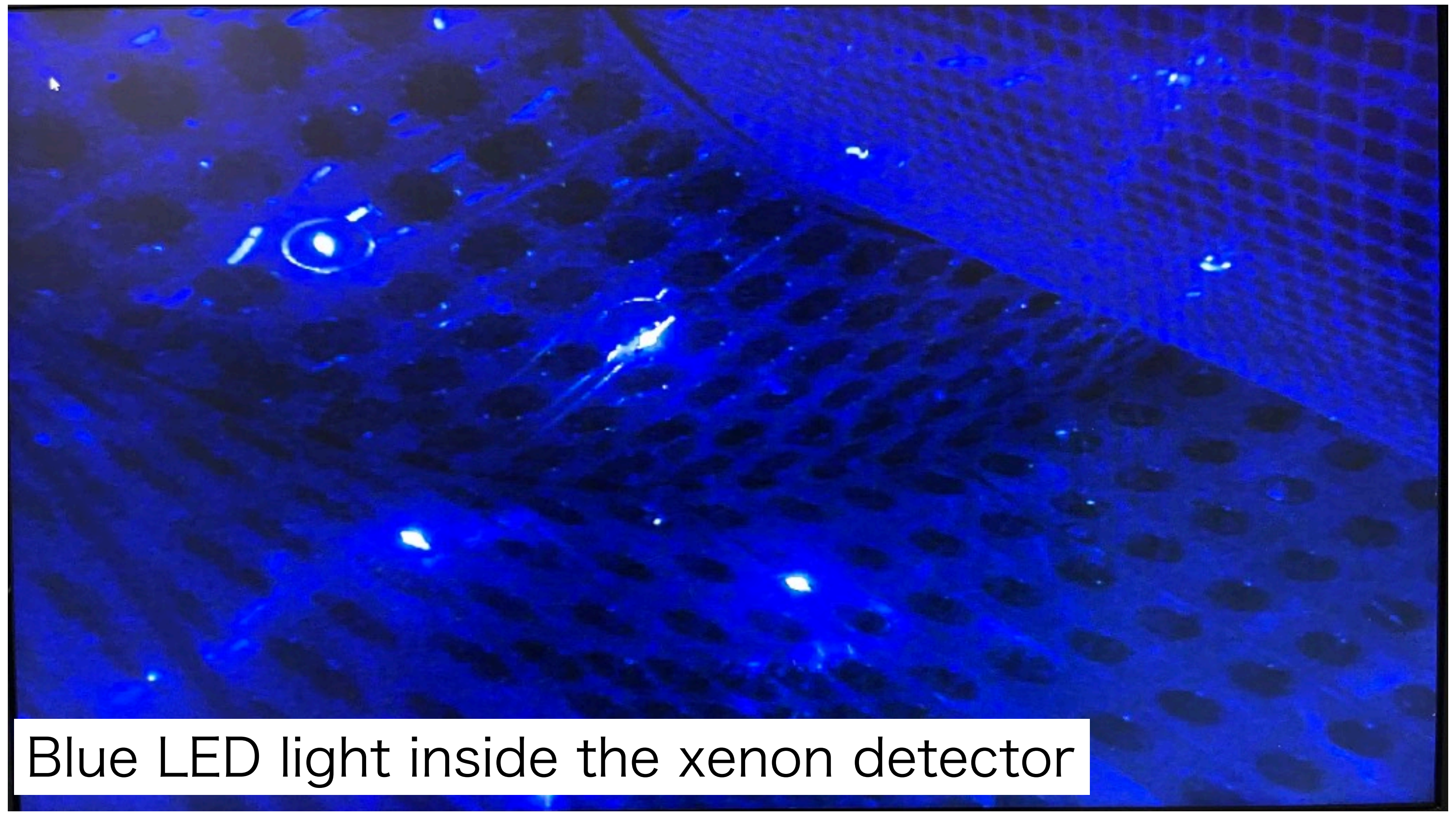
↓ **Photon detection efficiency for MPPC**
Quantum efficiency for PMT

Number of impinging scintillation photons $N_{\mathrm{pho},i}$



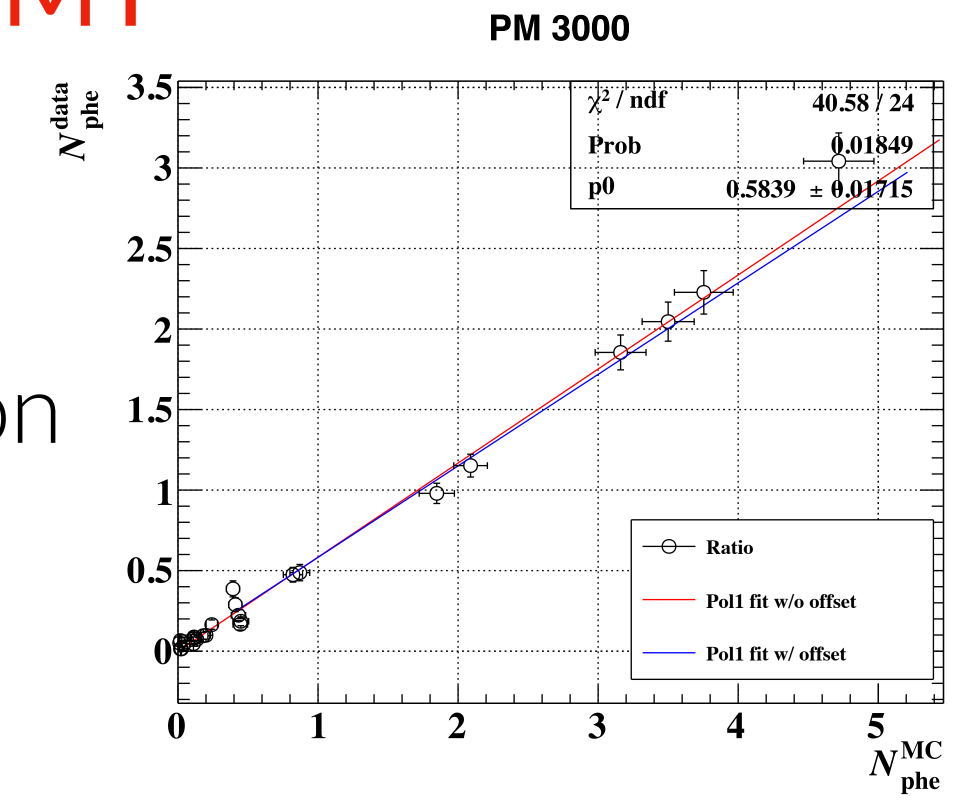


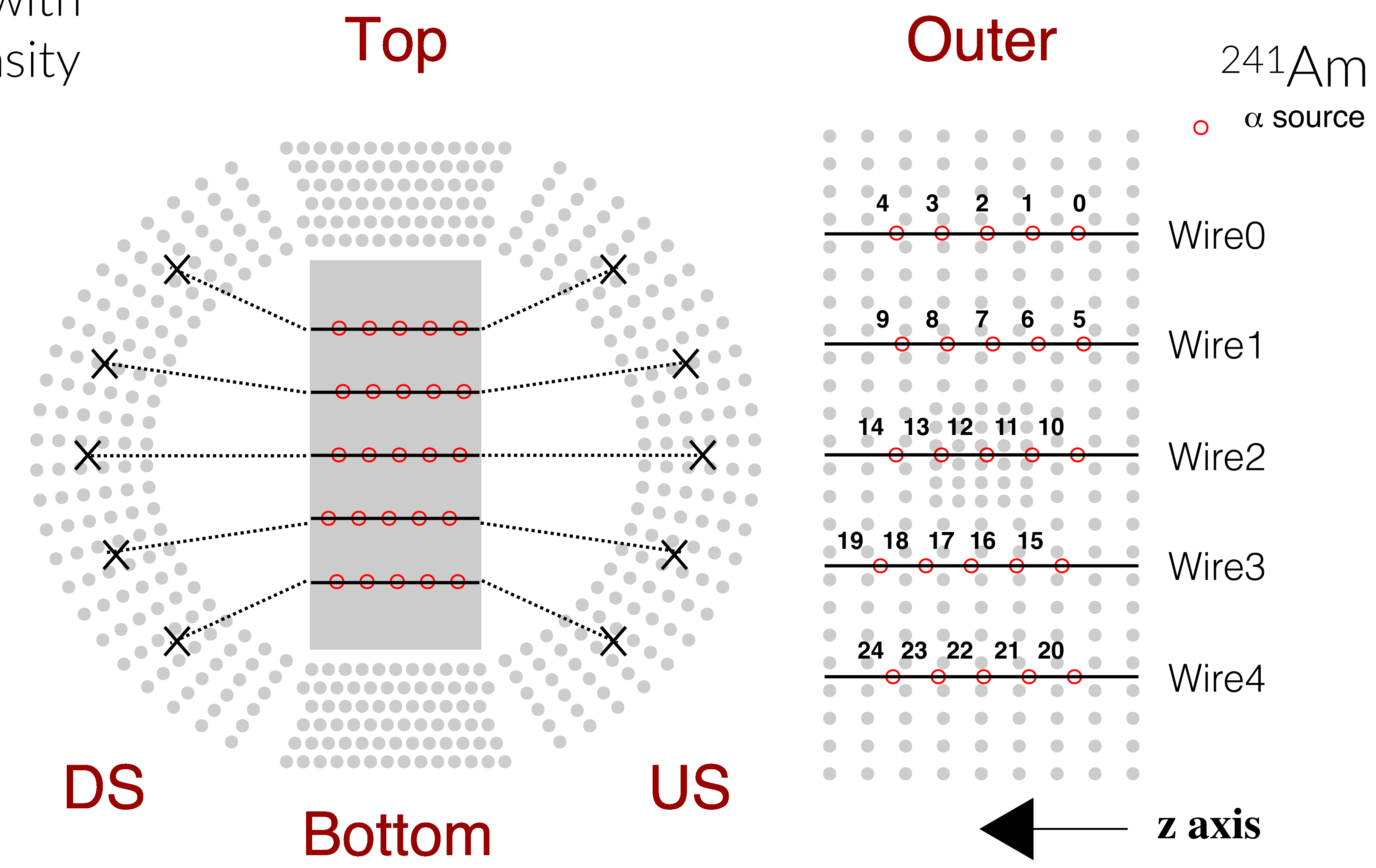
Charge calculated with different LED intensity
→ Slope: Gain



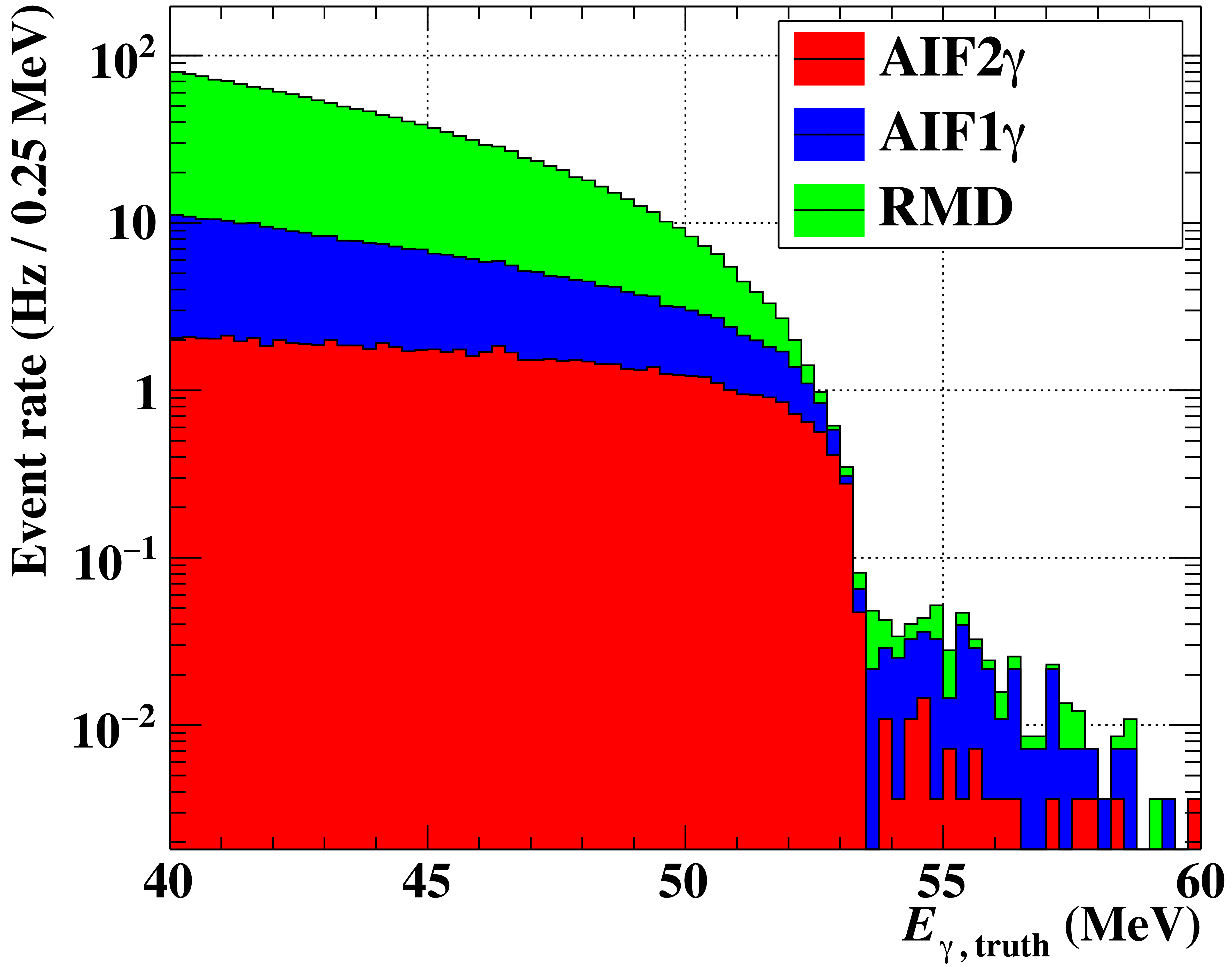
Blue LED light inside the xenon detector

N_{phe} comparison between data and MC

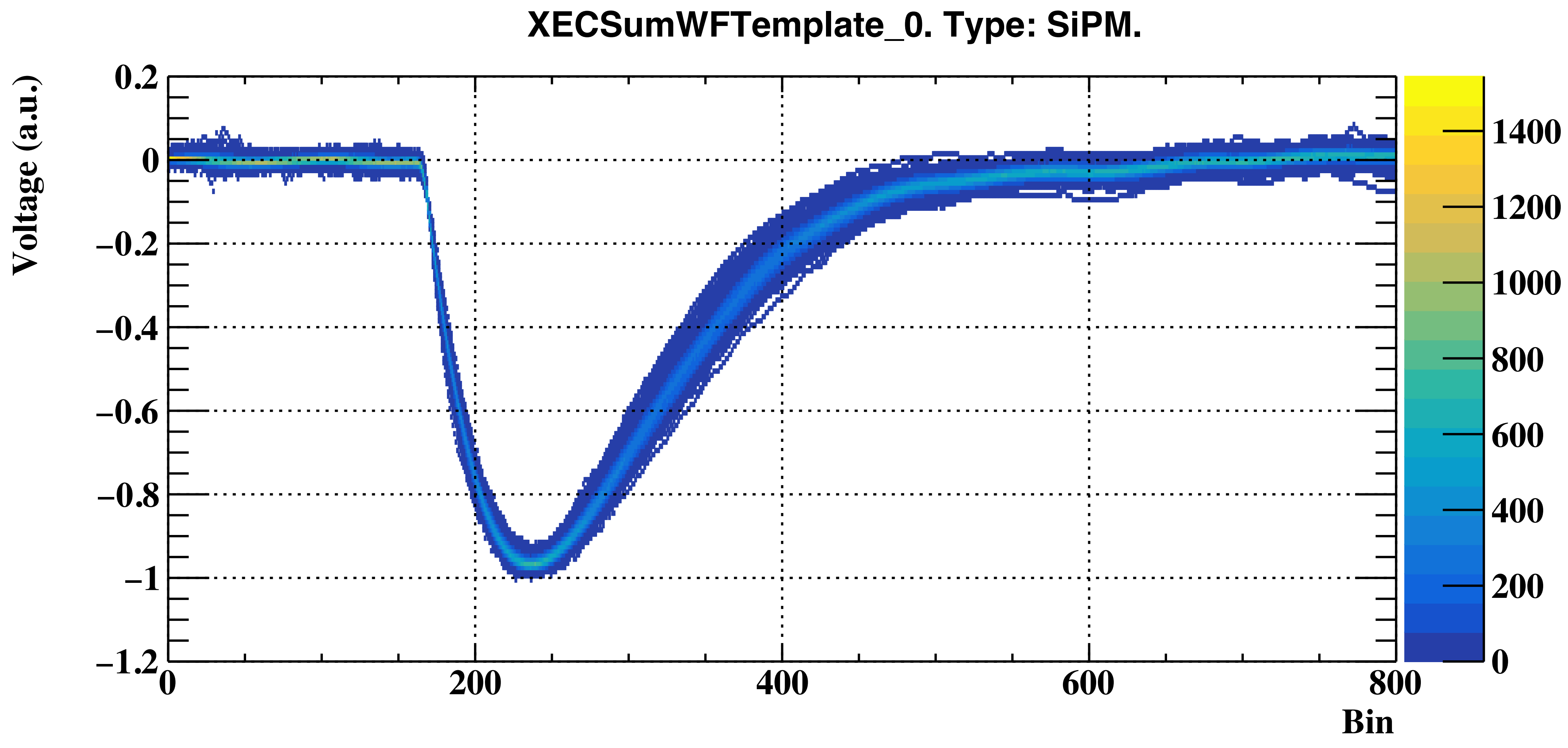


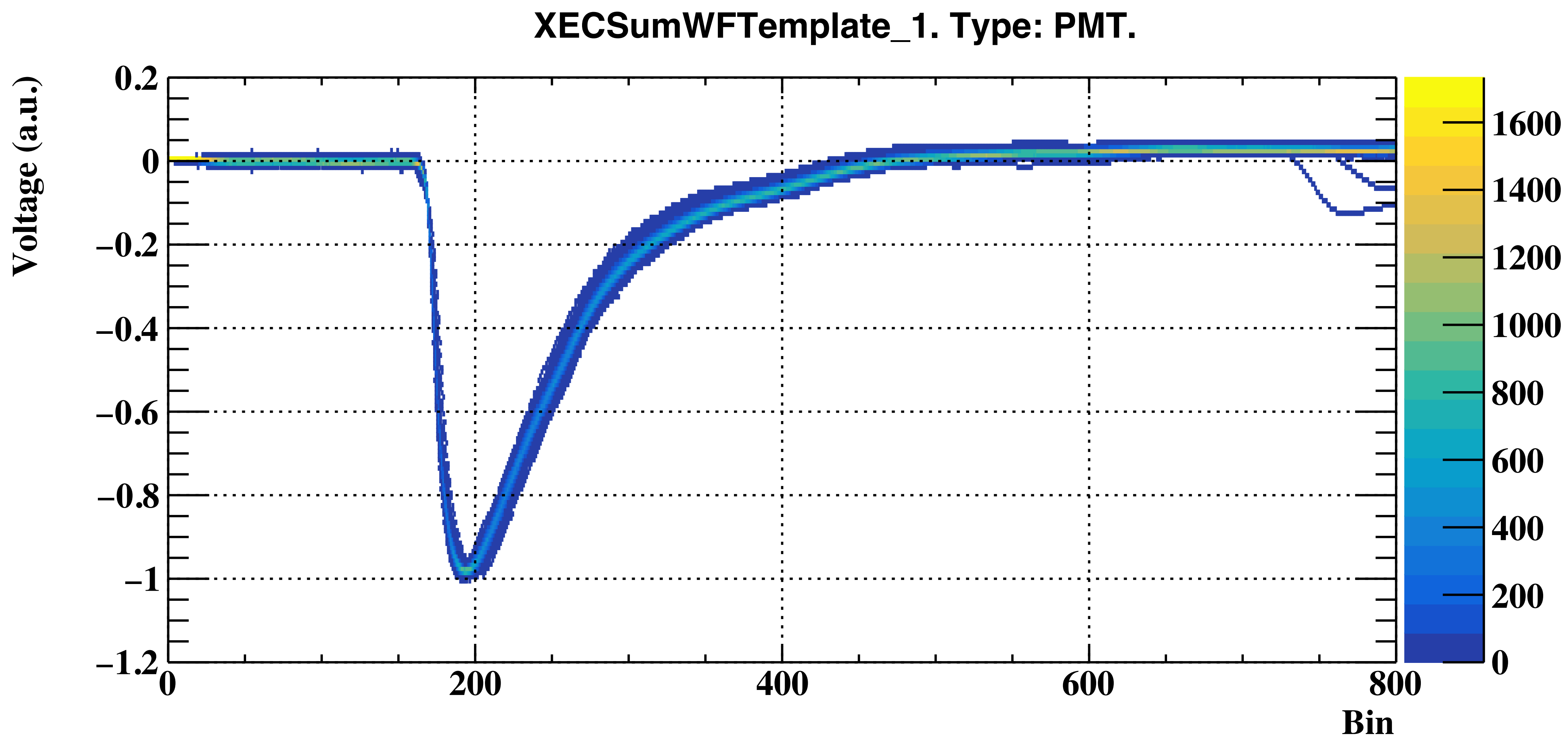


Background photon characteristics



Template summed waveform





$$\chi^2 = \sum_{i}^{\text{fit range}} \sum_{\text{MPPC,PMT}} \frac{\left(V_{\text{meas},i} - V_{\text{fit},i}\right)^2}{\sigma_i^2}$$