Radiative Decay Counter for active background identification in MEG II experiment

R. Iwai

The University of Tokyo

Technology and Instrumentation in Particle Physics (TIPP)
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Outline

I. Introduction

II. Radiative Decay Counter

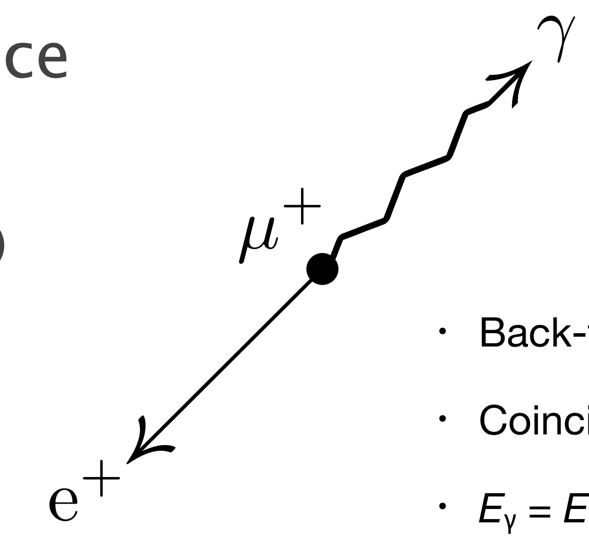
III. Commissioning

IV. Upstream detector option

V. Summary and outlook

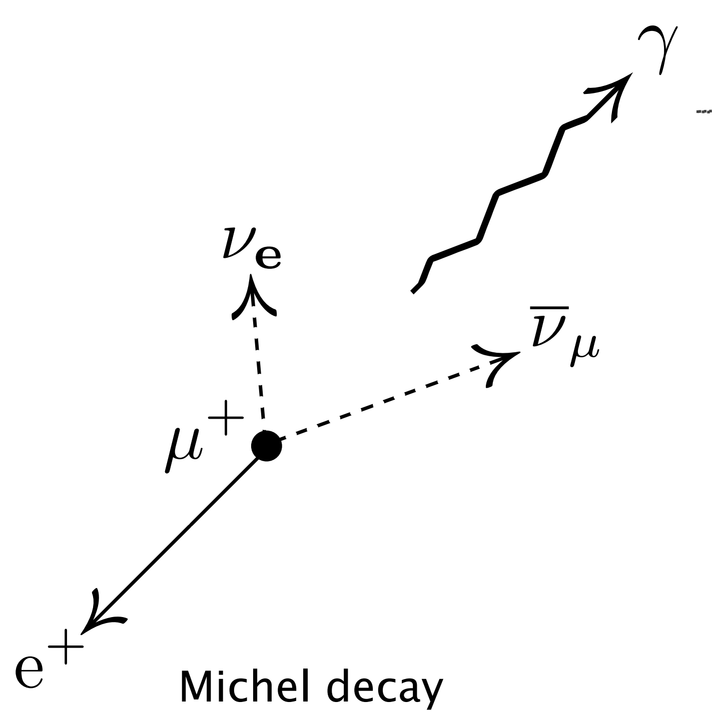
MEG II experiment

- Lepton flavor violating decay $\mu^+ \to e^+\gamma$ will be an evidence of BSM if discovered
  - Best upper limit : $\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ (90% C.L.) (MEG, 2016)
  - Upgrade experiment aiming at sensitivity $\mathcal{O}(10^{-14})$ (MEG II, 2018-)



- Back-to-back
- Coincident in time
- $E_\gamma = E_{e+} = 52.8$ MeV

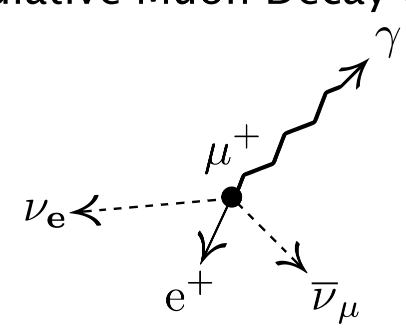
- Dominant BG : Accidental coincidence of energetic e+ & γ



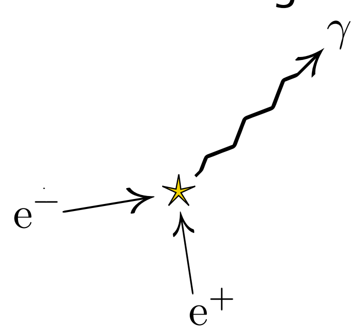
Michel decay

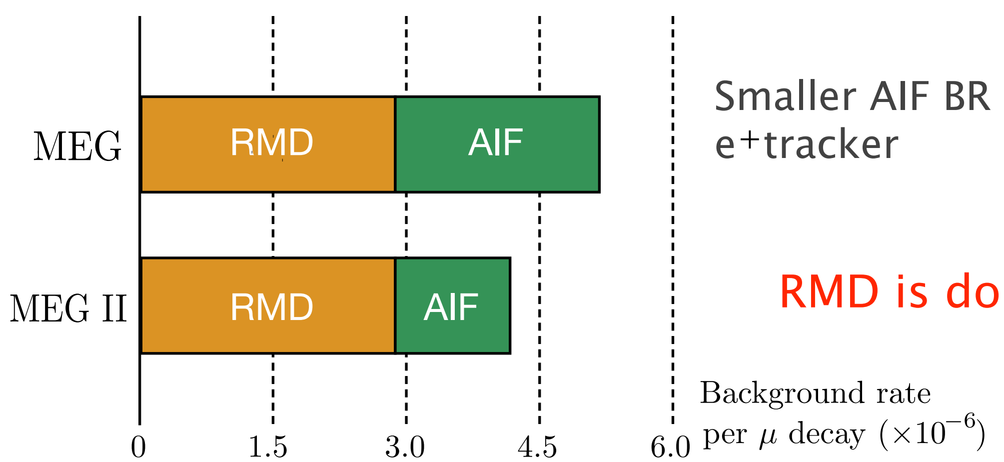
Source of BG γ

Radiative Muon Decay (RMD)



Annihilation In Flight (AIF)





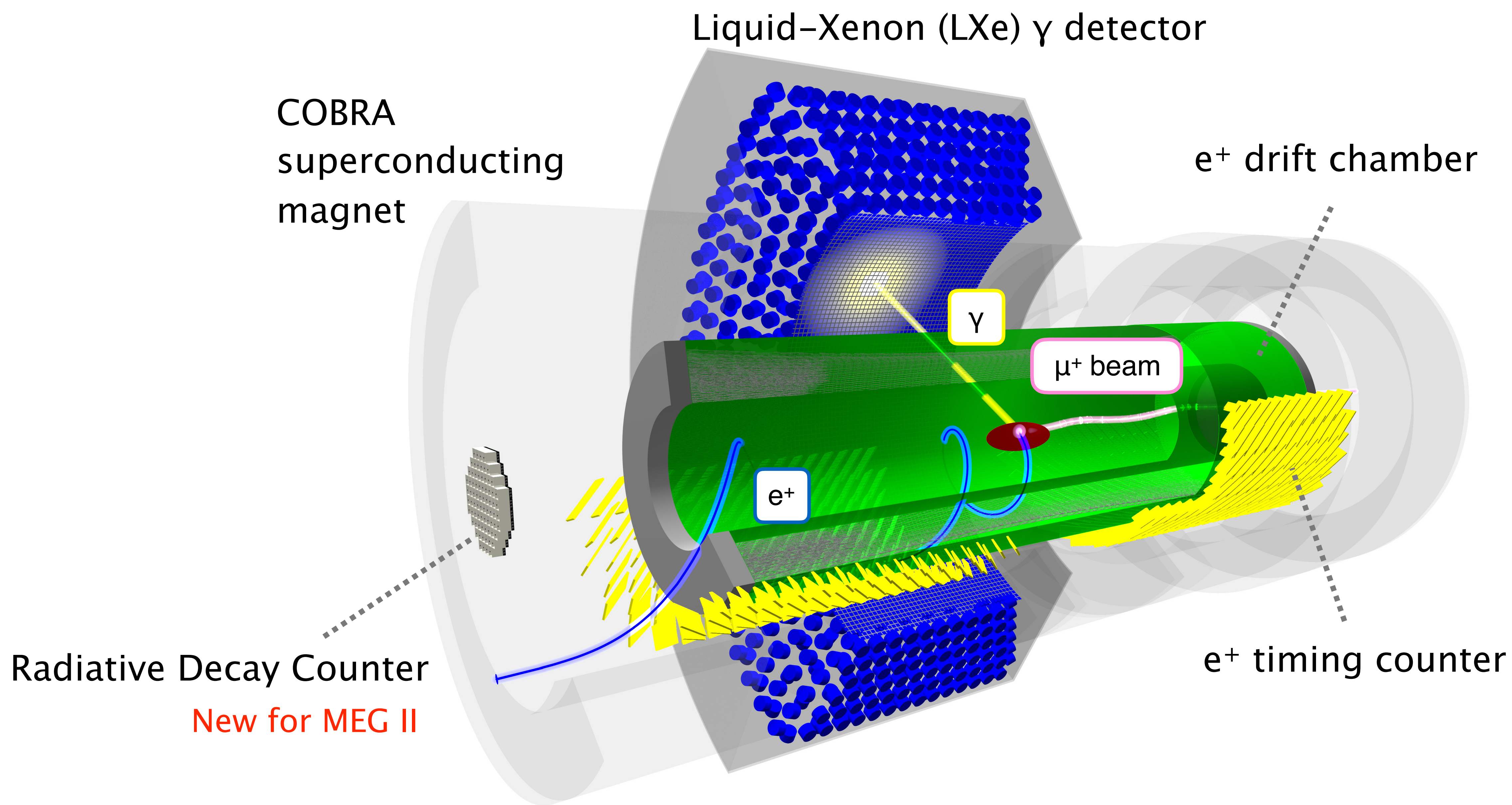
Smaller AIF BR thanks to low mass e+tracker

⇩

RMD is dominant in MEG II

MEG II detector

- High intensity DC μ^+ beam : 3×10^7 μ^+/s (MEG) → 7×10^7 μ^+/s (MEG II)
- Keys of detector upgrade : Suppress accidental background
  - Improved energy, timing, angular resolutions (~×2) of e^+ & γ detectors
  - Low mass μ^+ stopping target & e^+ detecter
  - New detector for tagging BG γ from RMD



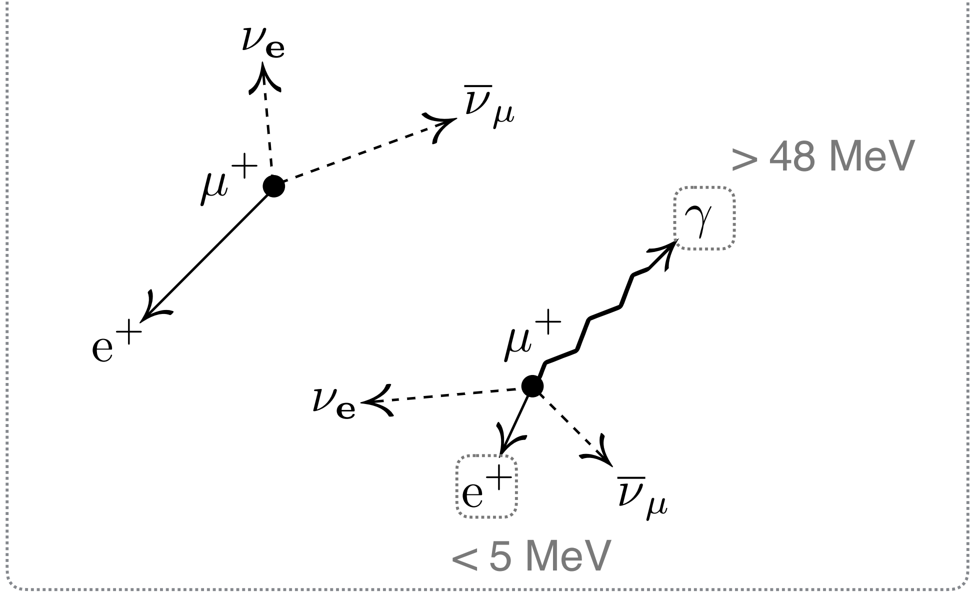
Radiative Decay Counter (RDC)

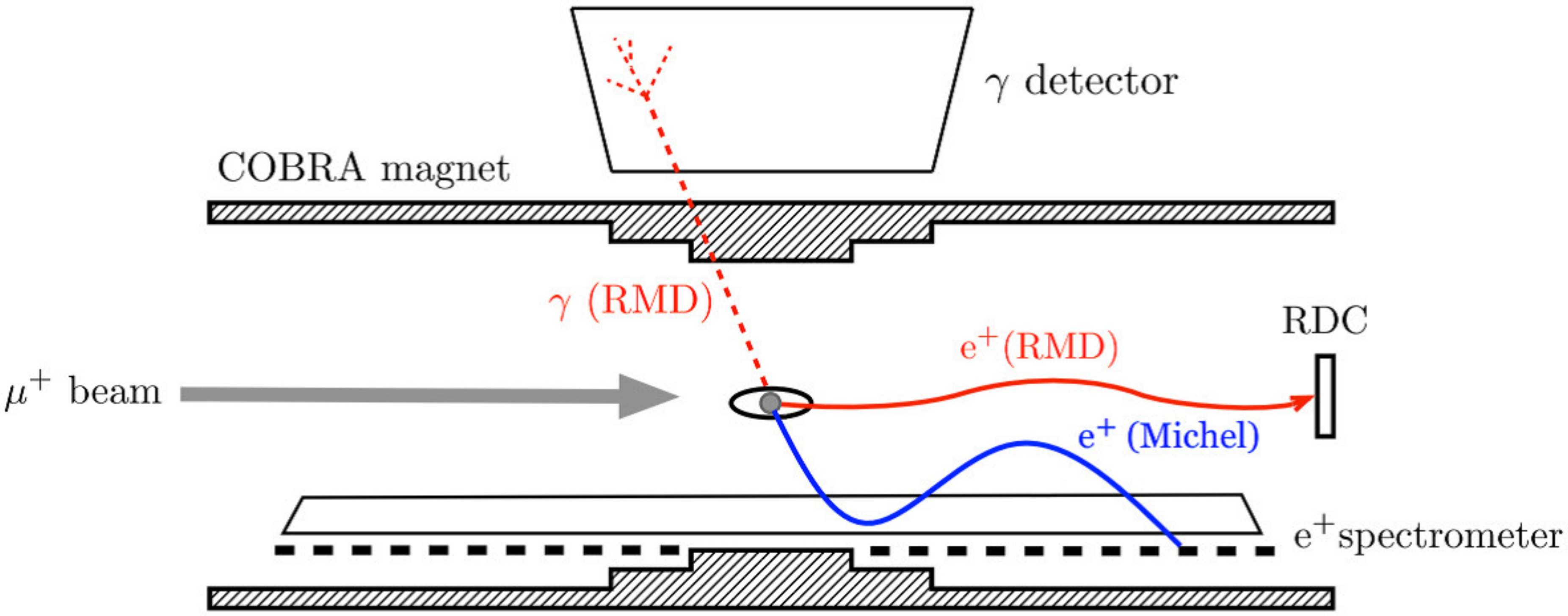
- RDC identifies BG γ from RMD
  - By detecting time coincident low momentum e^+
  - MEG II sensitivity improvement with RDC:

    $5.0 \times 10^{-14} \rightarrow 4.3 \times 10^{-14}$ (−16%)
- Requirements for detector :
  - Compact detector to install inside magnet bore
  - Able to distinguish high hit rate of Michel e^+ (~MHz)

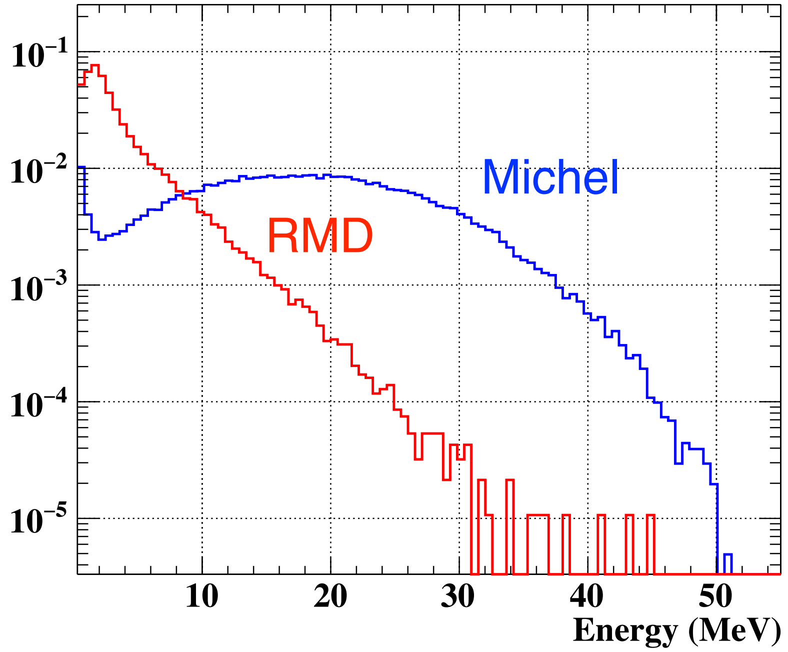
    └ Finely segmented, distinguish by E_{e+}

Dominant BG (Michel + RMD)





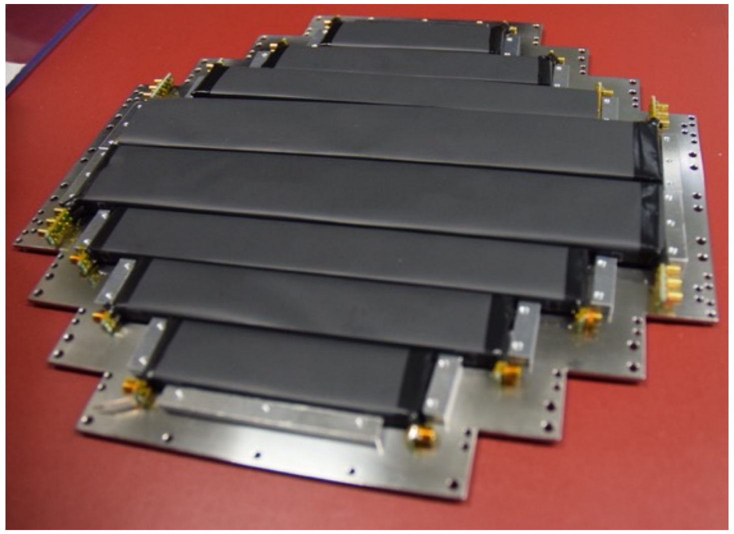
Energy deposit in RDC



Detector design

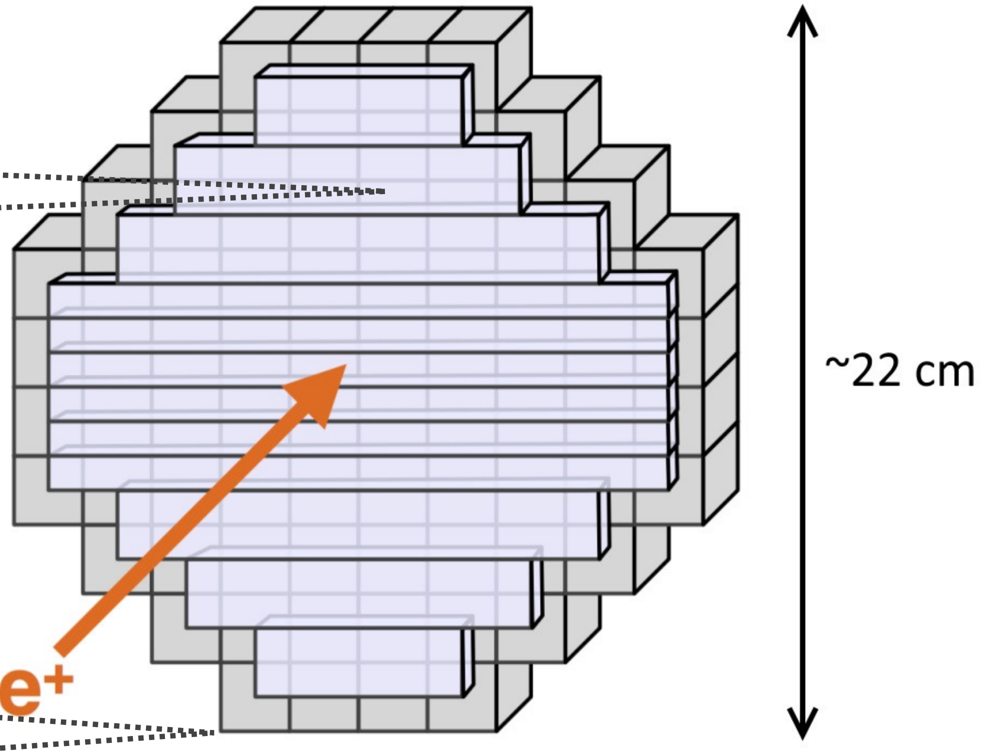
Plastic scintillator

- Measure e+ timing
- Fast rise & decay time
- 12 scintillator bars (l = 7–19 cm, w = 1–2 cm)
- Multi-SiPMs readout at two ends



LYSO (Lutetium Yttrium Orthosilicate) crystal

- Measure e+ energy
- Fast decay time, large light output
- 76 LYSO crystals ($2 \times 2 \times 2$ cm^3)
- Single SiPM readout



Plastic scintillator part

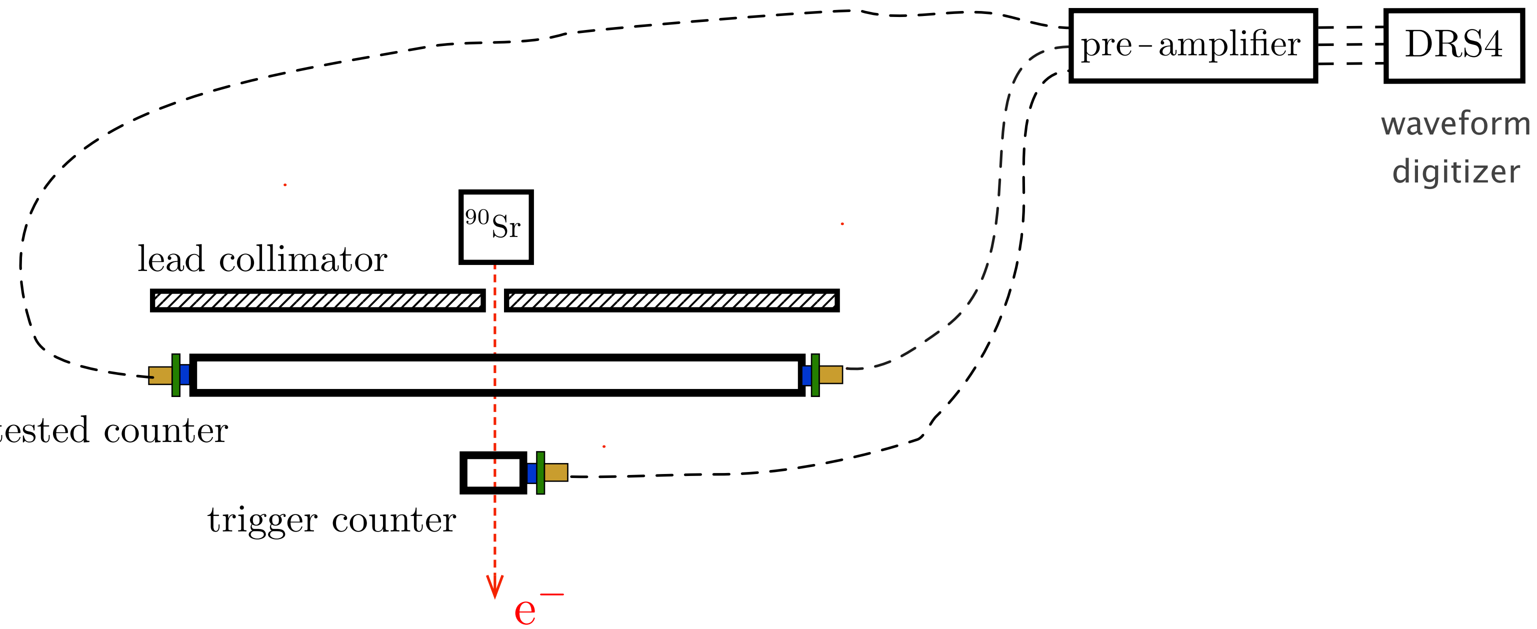
✦ Counter design

Plastic scintillator : Saint-Gobain BC418

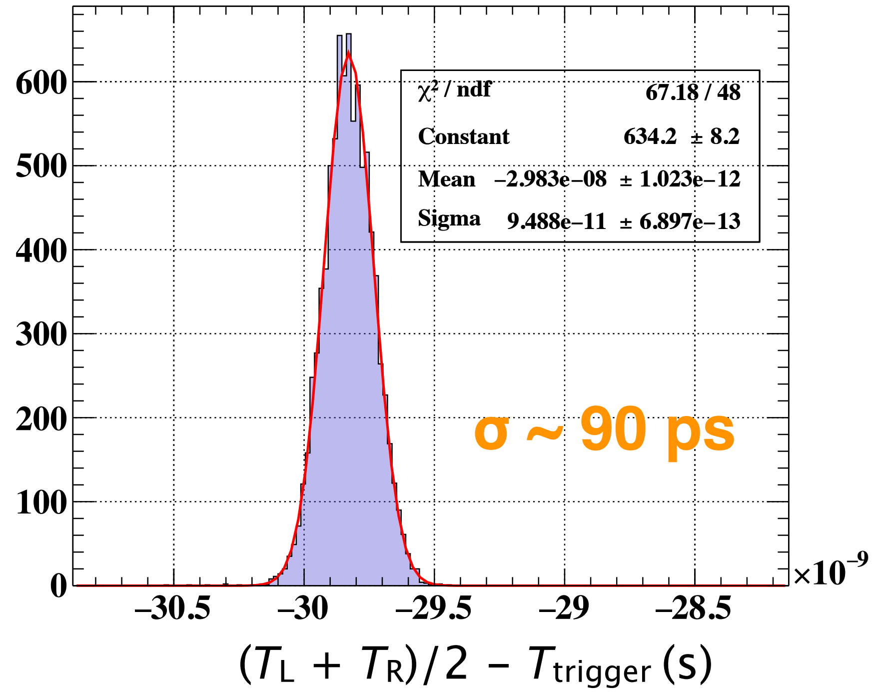
SiPM : Hamamatsu S13360-50PE

- Surface mount type
- Active area : 3×3 mm^2
- Pixel pitch : 50 μm
- 2-3 SiPMs connected in series
  - └ For reducing $N_{channel}$, shorter waveform

✦ Performance check with β-ray source



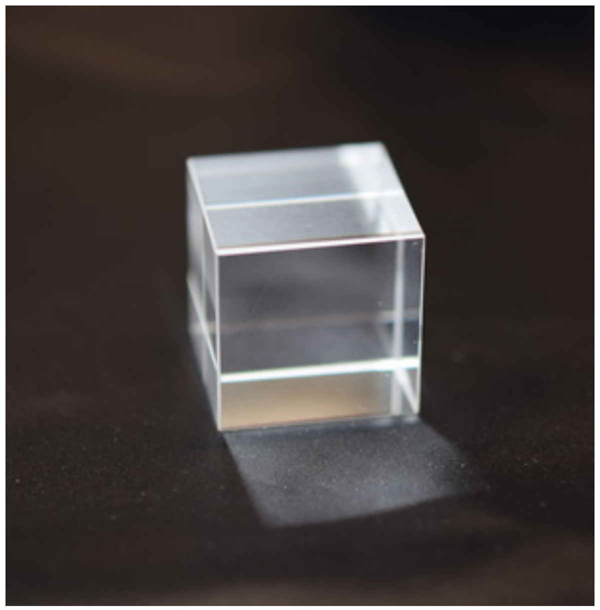
Measured timing

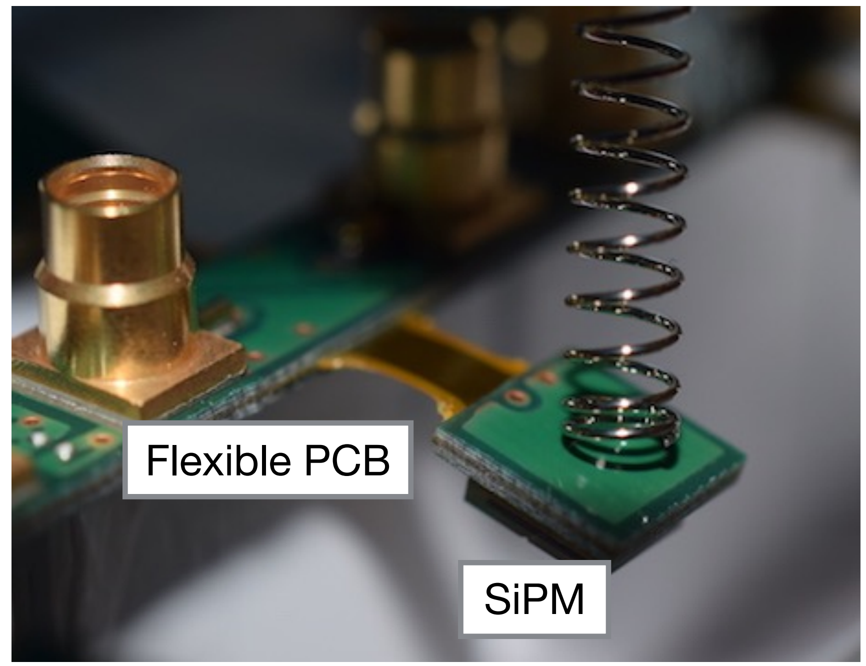


LYSO crystal part

✦ Readout scheme

LYSO crystal
(Shanghai Institute of Ceramics)

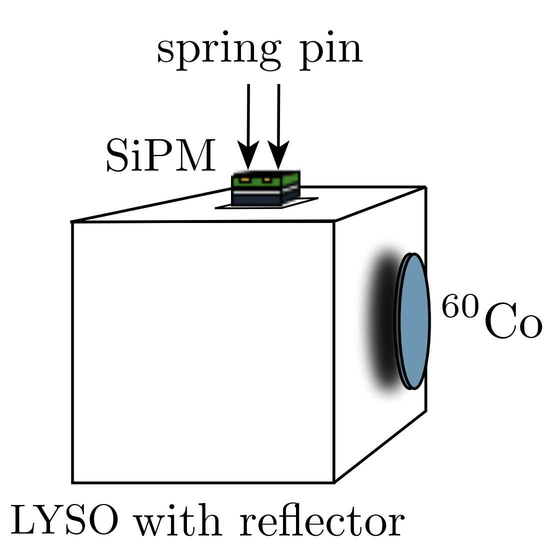




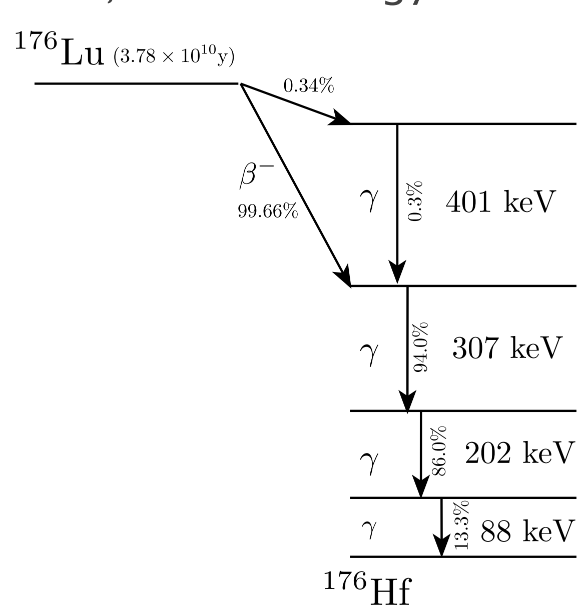
SiPM : Hamamatsu S12572-025

- Active area : 3×3 mm^2
- Pixel pitch : 25 μm
- Pressed on back of each crystal (for easy maintenance)
- Crystal & SiPM are coupled with optical grease

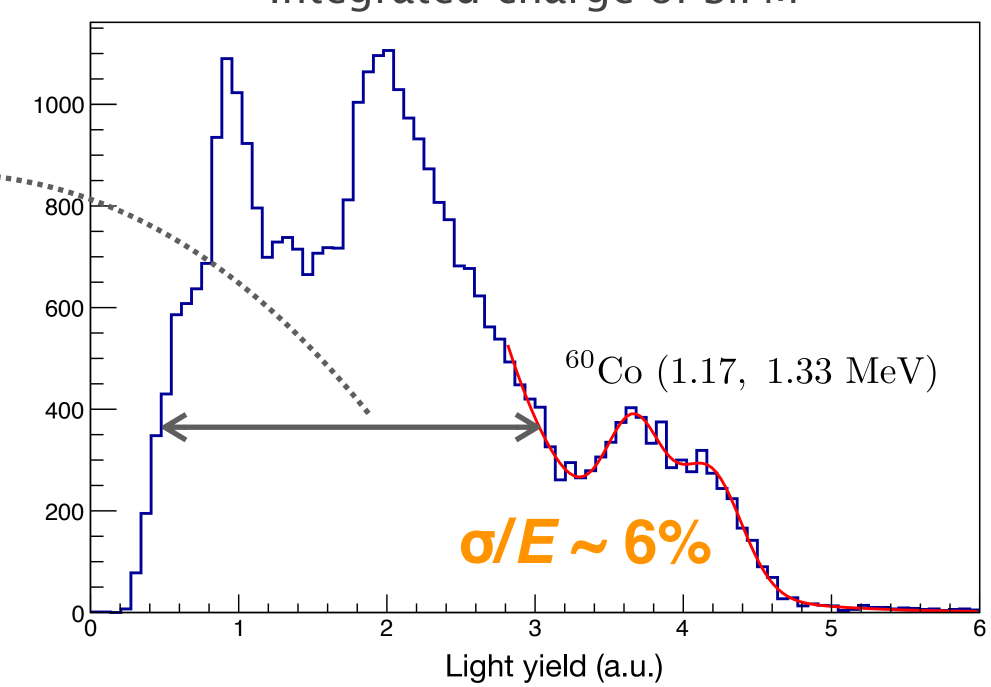
✦ Performance check with γ-ray source



Intrinsic radioactivity of Lu
(2kHz, use for energy calibration)



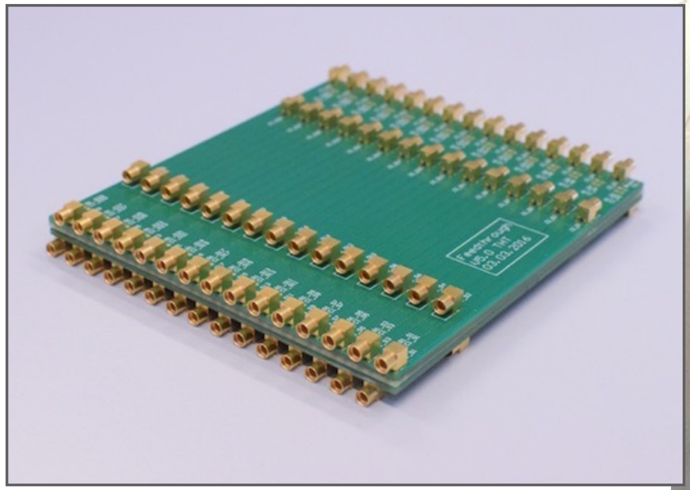
Integrated charge of SiPM



Installation

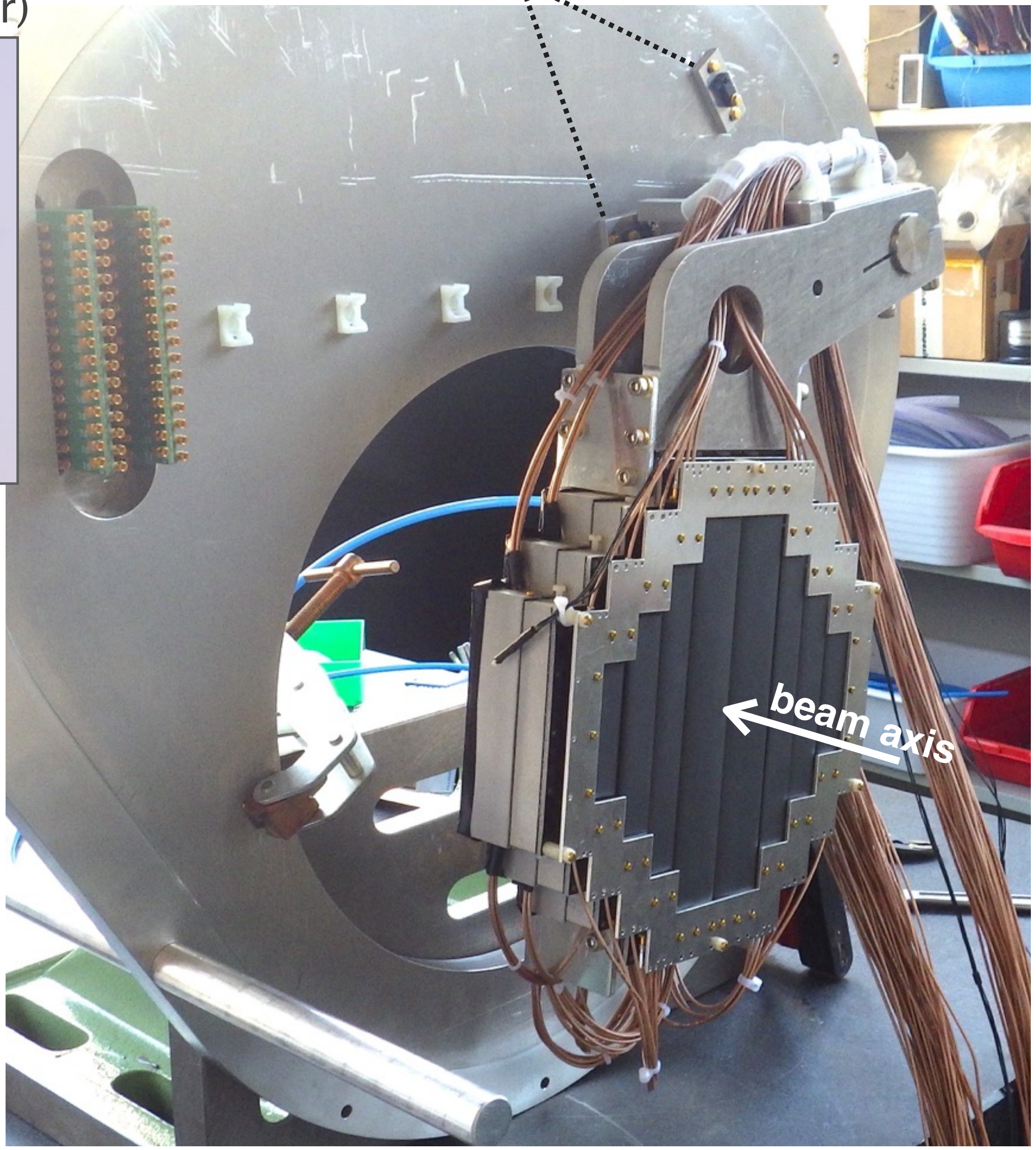
- RDC detector is inserted in spectrometer magnet bore with moving arm
  - With 2 water pistons behind the stage

PCB type feedthrough (He → Air)

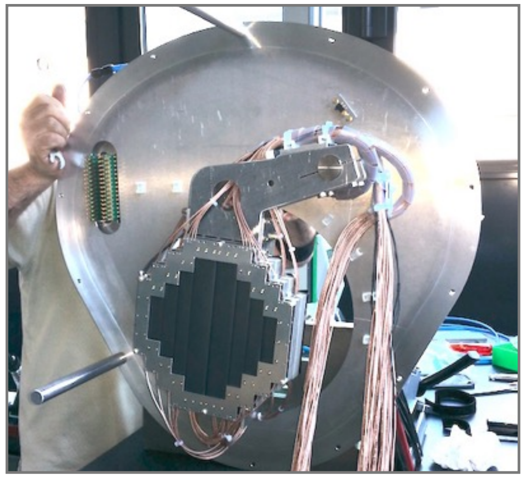


Signal transmitted to MEG II waveform digitizer (WaveDREAM)

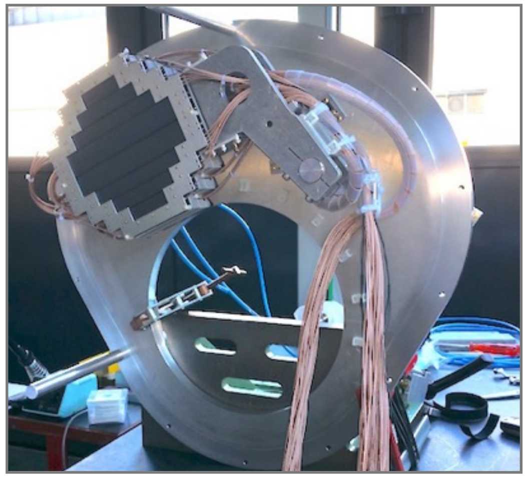
End switch



Measuring position

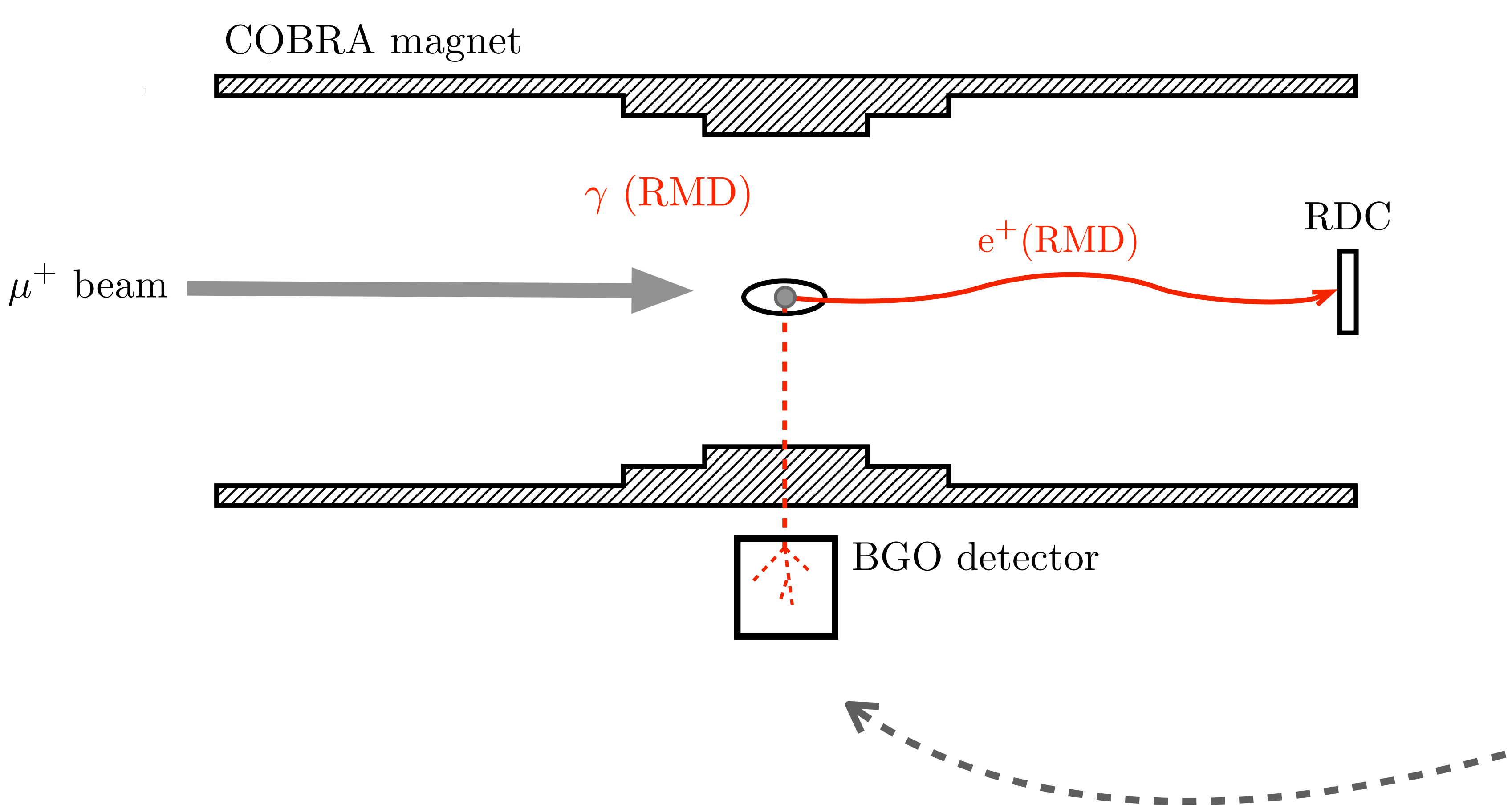


Parking position
(during calibration target for LXe is inserted)

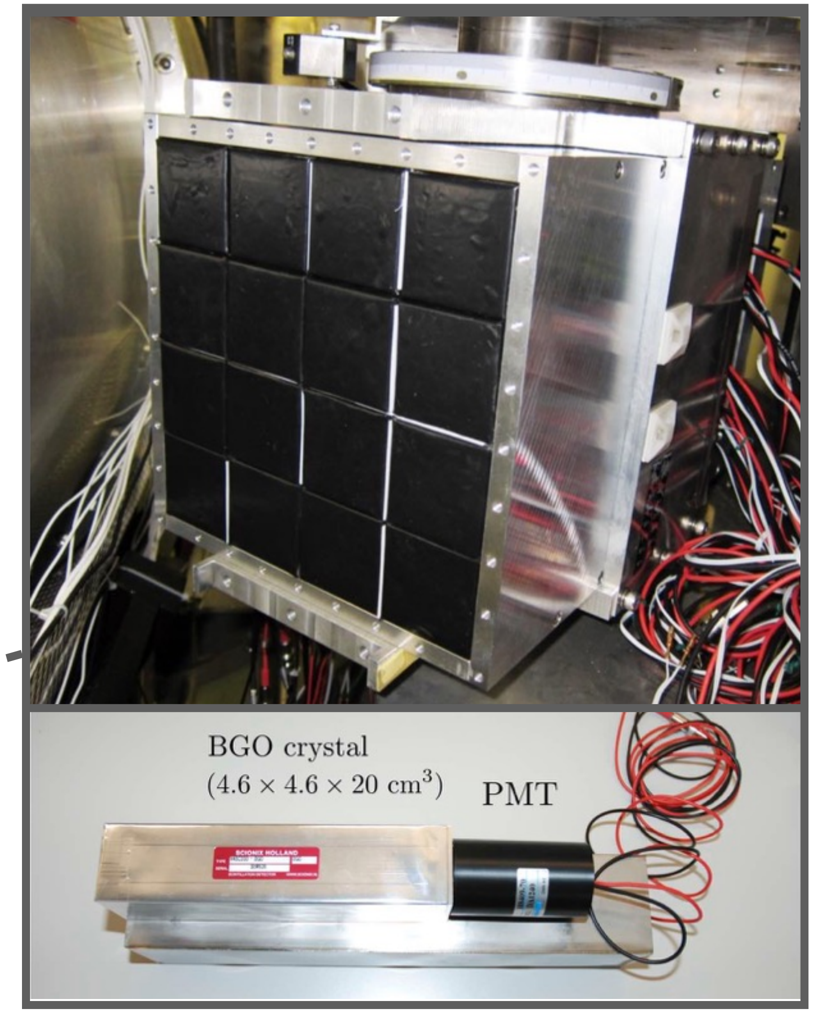


Commissioning

- First commissioning of RDC detector in 2016
- Demonstrated BG identification capability with high intensity μ^+ beam (10^8 μ^+/s)
- Tested trigger & DAQ (WaveDREAM)



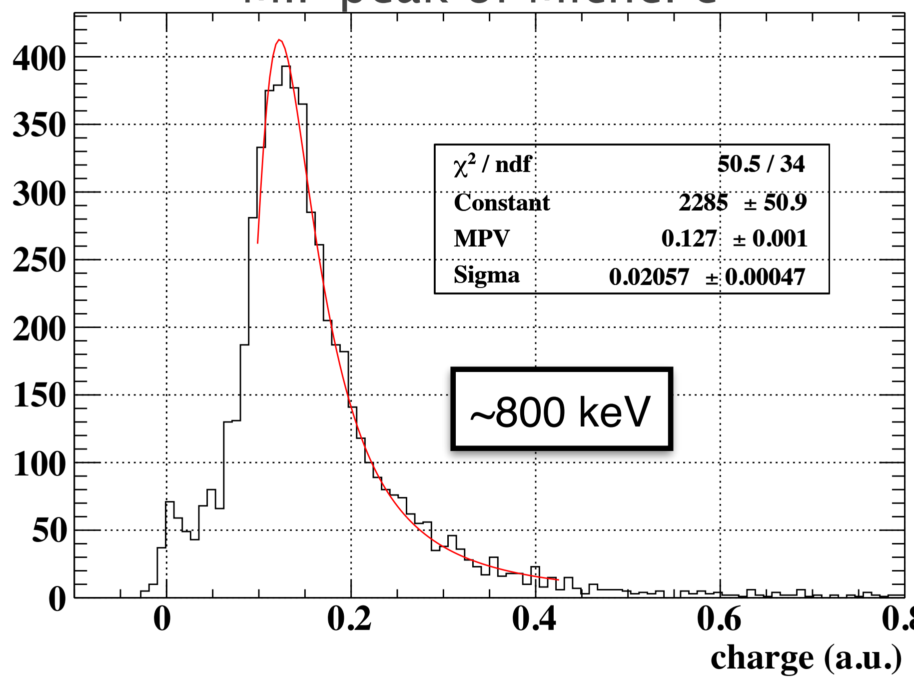
16 BGO crystals + PMTs
(substitution for LXe detector)



Calibration

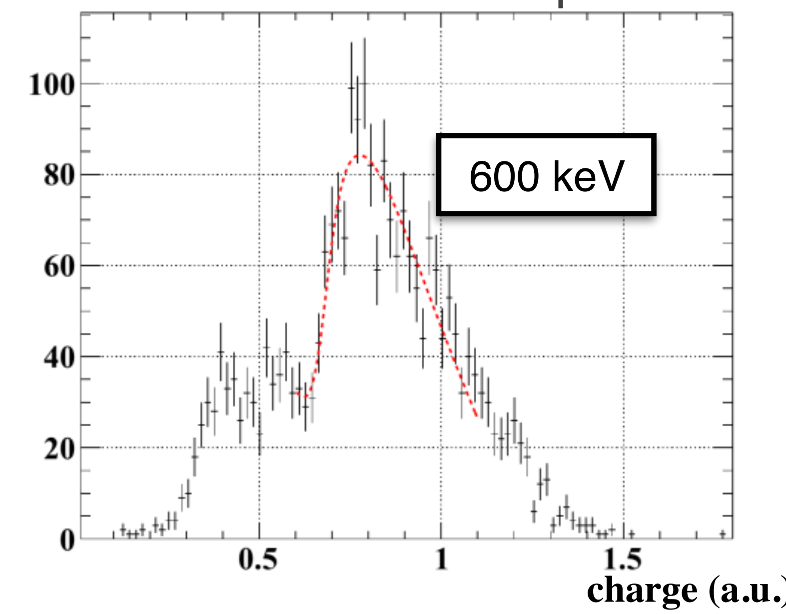
Plastic scintillator

MIP peak of Michel e+



LYSO crystal

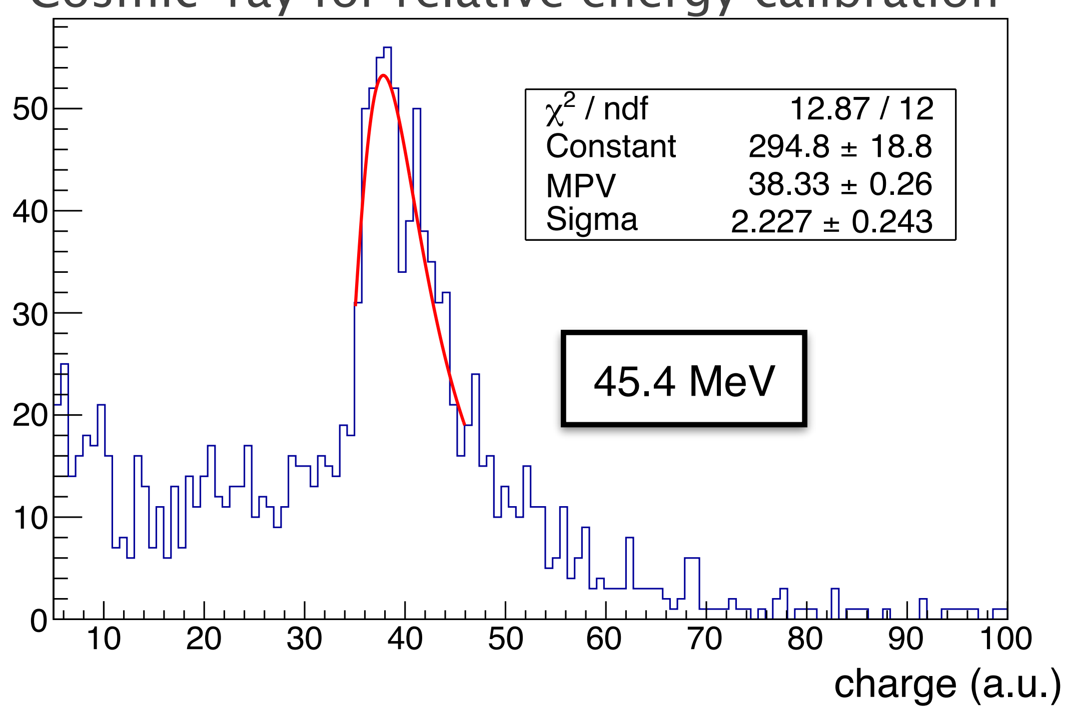
Intrinsic radiation peak



Fitting function : (γ peaks + β decay spectrum) ⊗ Gaussian smearing ($\sigma = E_{res}$)

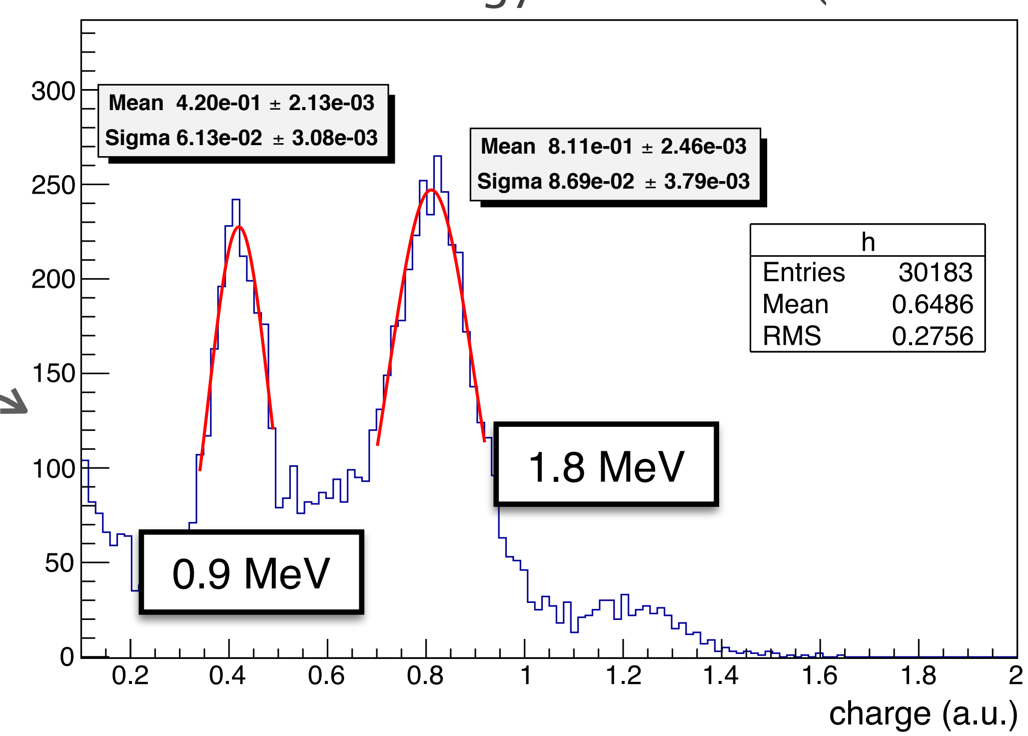
BGO crystal

Cosmic-ray for relative energy calibration



Slightly inconsistent

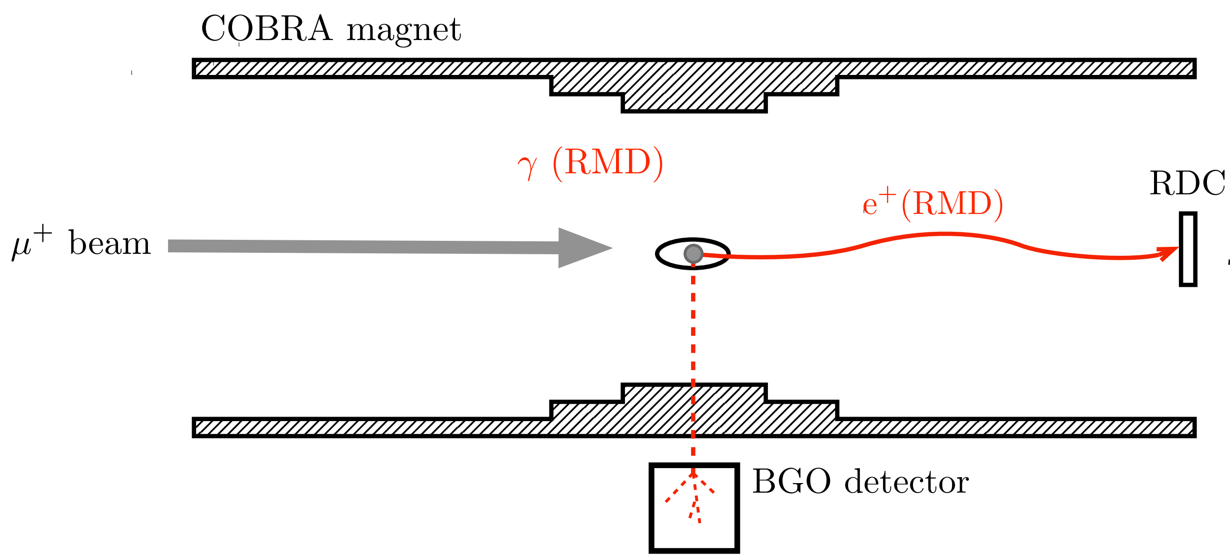
^{88}Y for absolute energy calibration (1 channel)

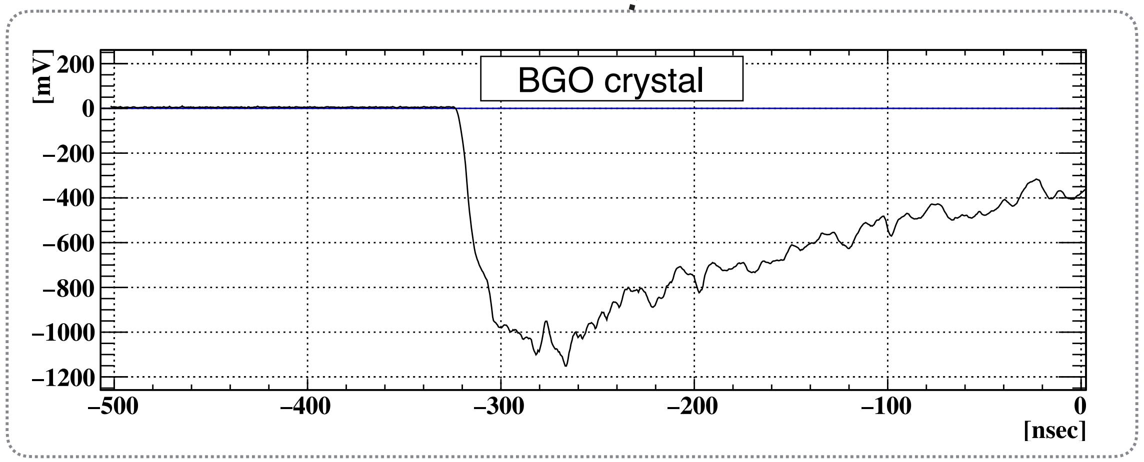


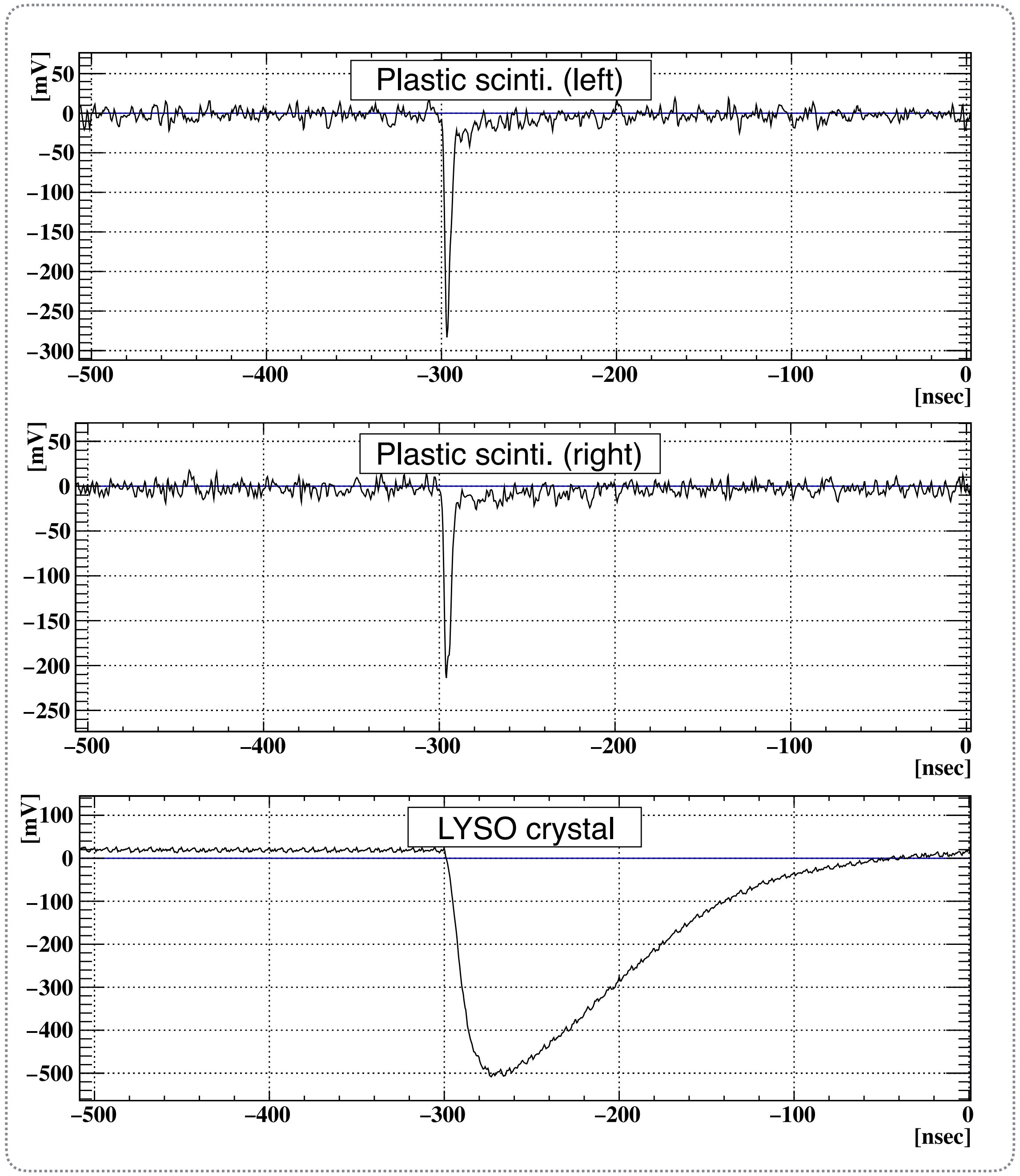
Data taking

- Conditions of data taking :
  - Trigger : Any hit of BGO crystals
  - Energy threshold : ~35 MeV
  - DAQ rates : ~5 Hz

- Example waveforms of RMD candidate



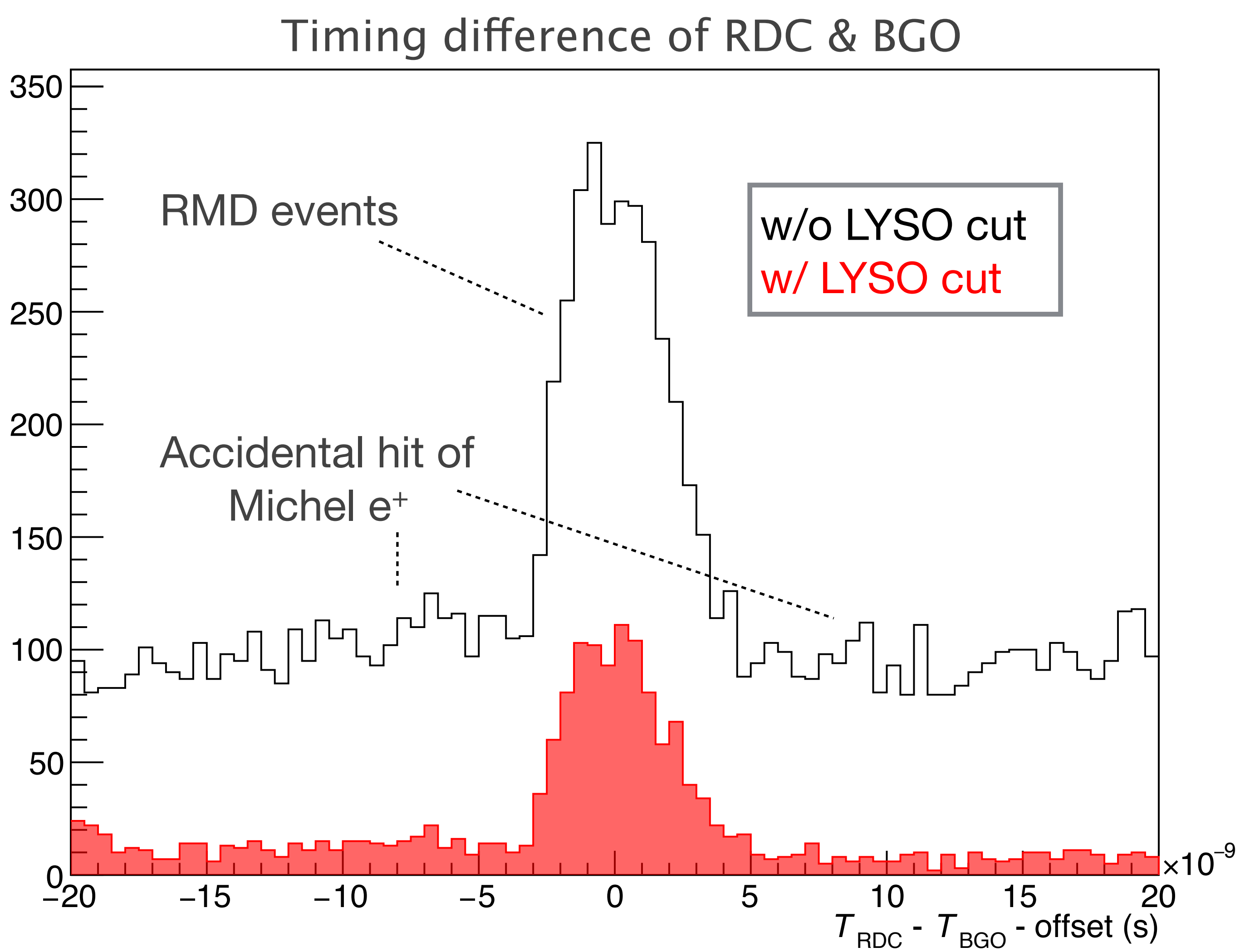


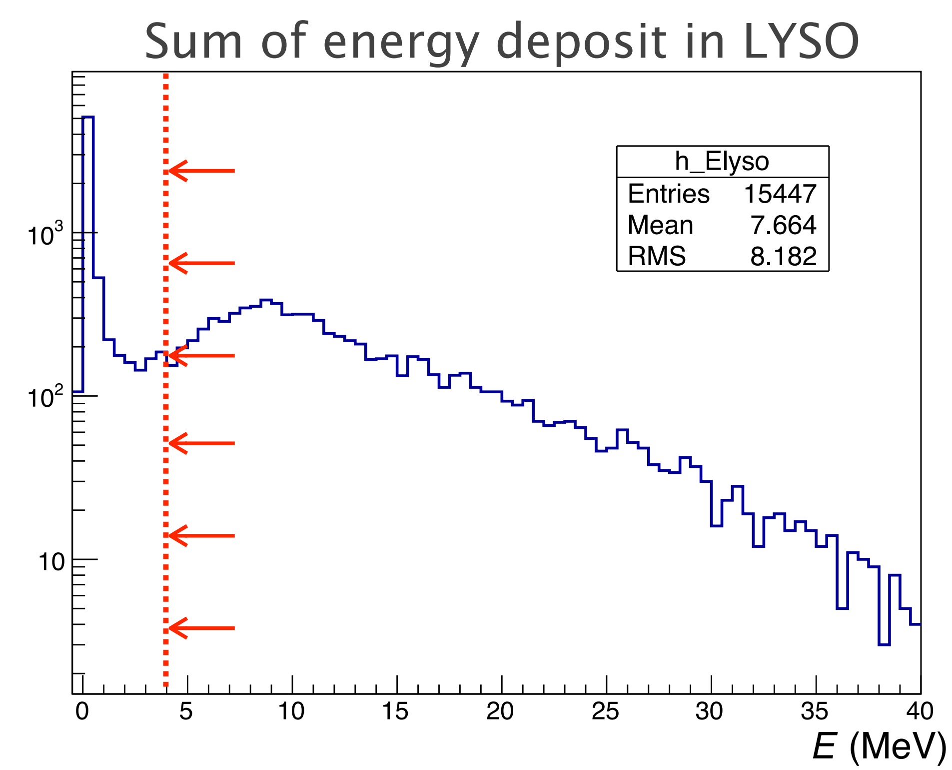


Analysis

- Analysis to reject events triggered by cosmic-ray
  - ① Require largest hit in central BGO crystals
  - ② Reject too large energy deposit (> 55 MeV)
  - ⇨ Rejected 98% of triggered events

- Observed clear timing peak of RMD events





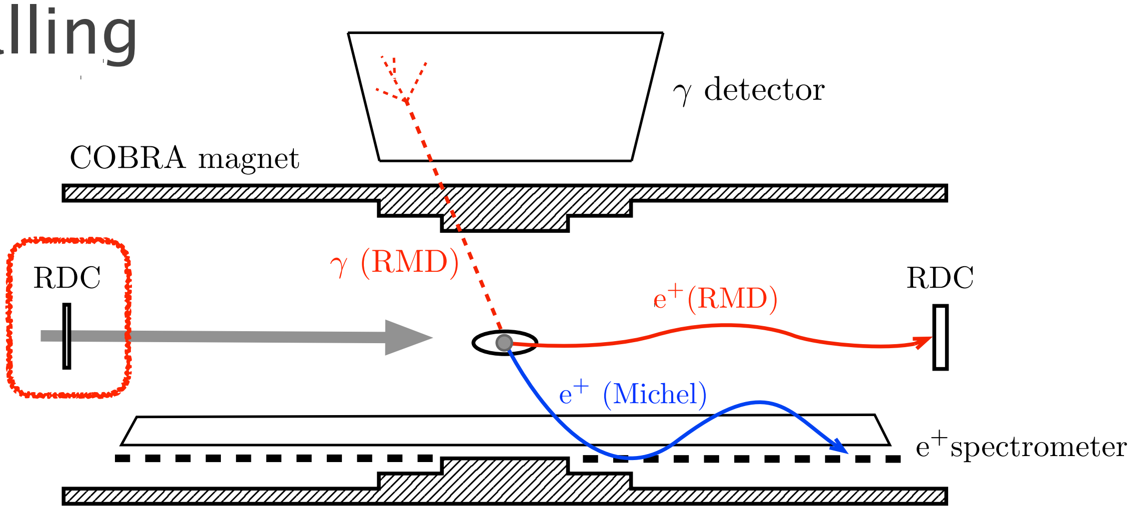
- Reduced pileup Michel e+ by 1/10 after cutting E_{e+} > 4 MeV

* RMD events with large E_{e+} were also rejected due to low E_γ threshold

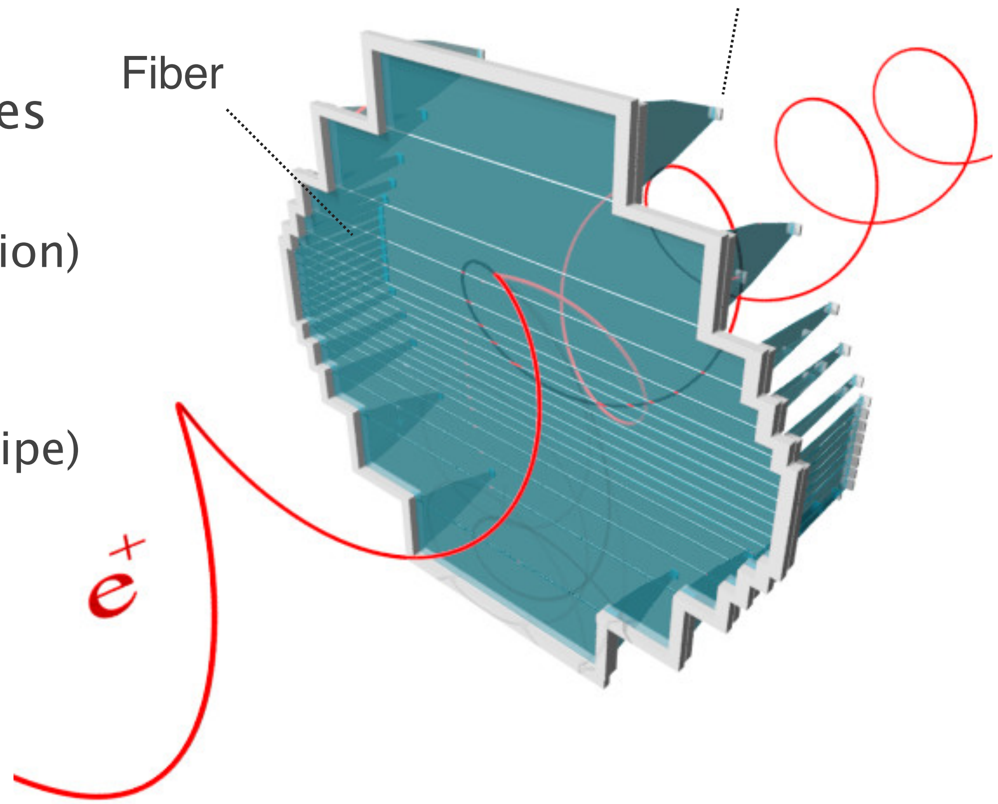
- Next plan : Measure detection efficiency with LXe detector for precisely known E_γ

Upstream detector option

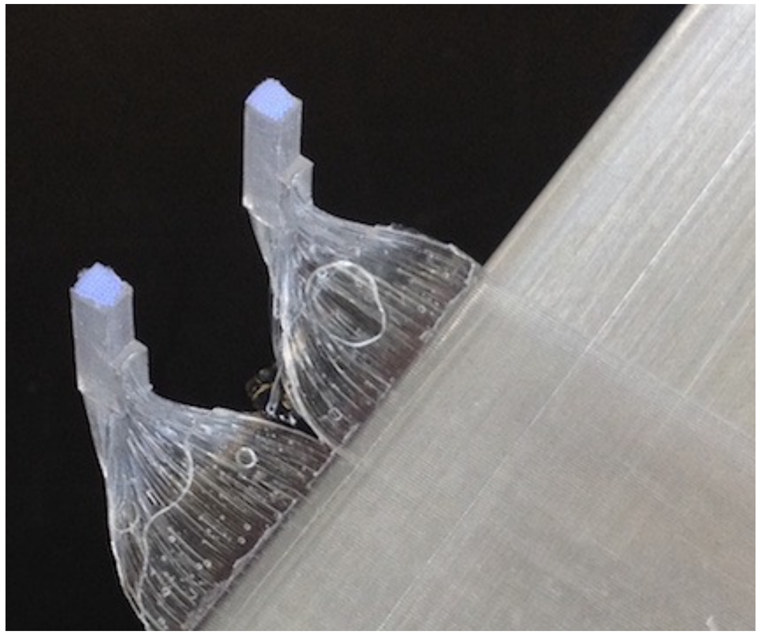
- Aiming further background reduction by installing RDC upstream the μ^+ stopping target
  - Developing detector operational in μ^+ beam
    └ low material, high hit rate, radiation hard…



- Provisional design : Use thin multi-clad scintillating fiber
  - 250μm thick square shaped fiber
  - Grouped into few-ten bundles to reduce N_{channel} (small width at high hit rate region)
  - Readout at right angles (due to limited space in beam-pipe)

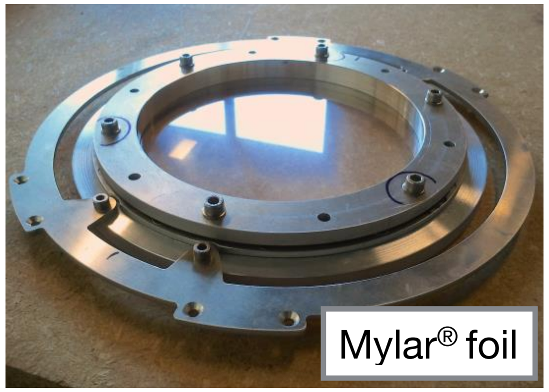


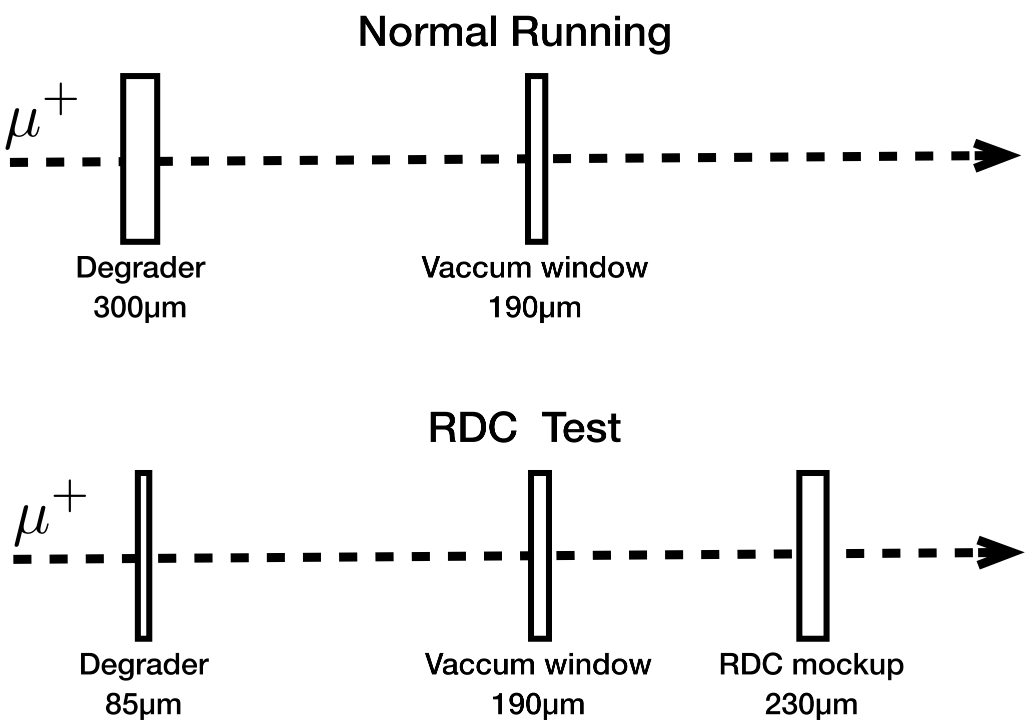
Fiber bundle prototype with Saint-Gobain BCF-12 (8×8 fibers each)



Upstream detector option

- Small influence on beam transportation
  - Beam spot size increased ~7.5% with mockup
    - └ Small influence is expected in physics analysis





  - Change of μ stopping rate −0.5% (according to simulation result)

- Sensitivity improvement with 2 RDC detectors :
  - $5.0 \times 10^{-14} \rightarrow 3.9\sim4.1 \times 10^{-14}$ (22−28%)

* Depends on capability of pileup μ^+ rejection

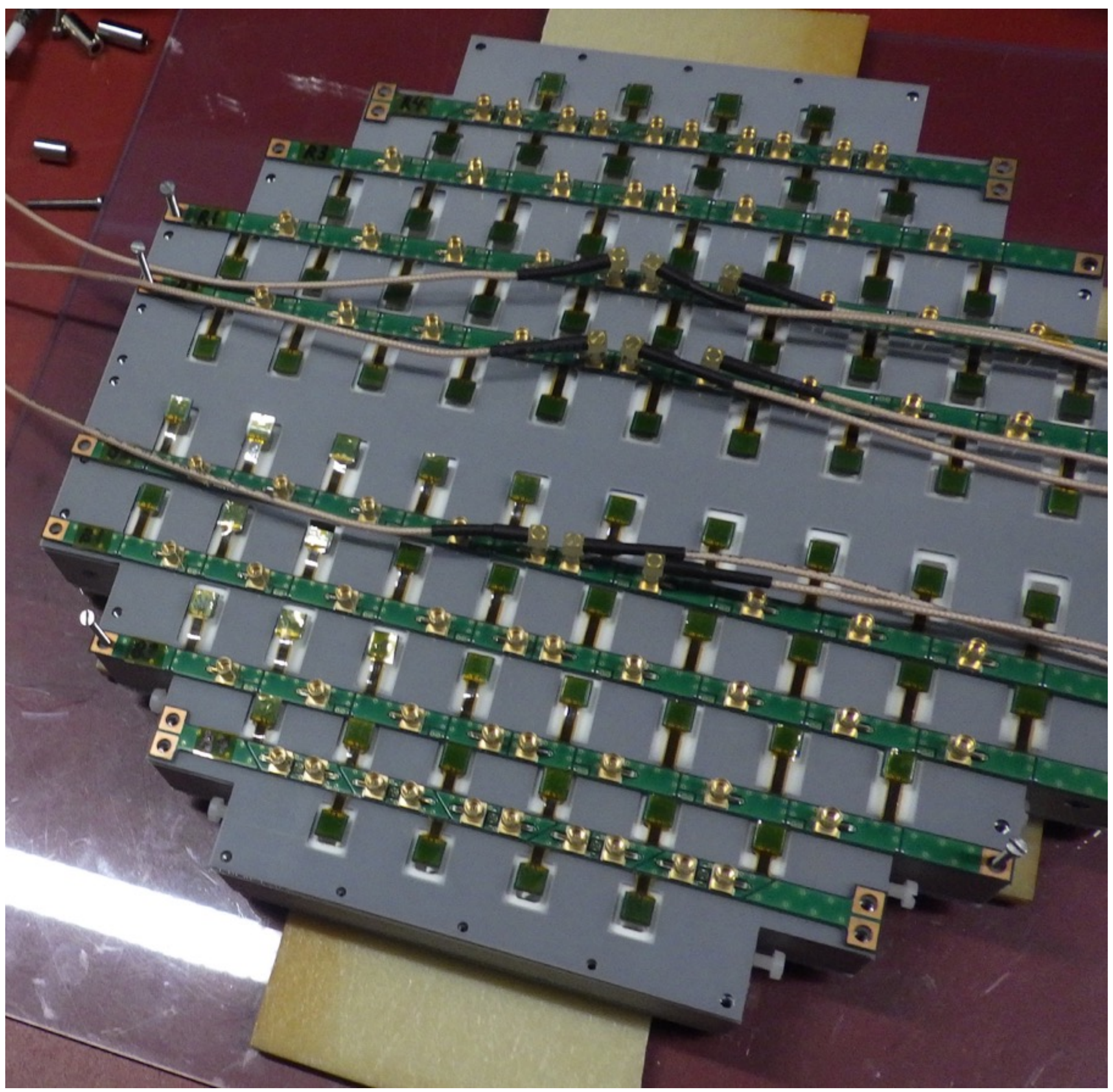
- Next plan : Irradiation test of scintillating fiber at Proton Irradiation Facility at Paul Scherrer Institut
  - μ^+ hit rate : 500 kHz, total dose : $\mathcal{O}(10^5)$ Gy (central fiber) for 3 years physics run
  - R&D for alternative plan : Radiation hard thin synthetic diamond detector

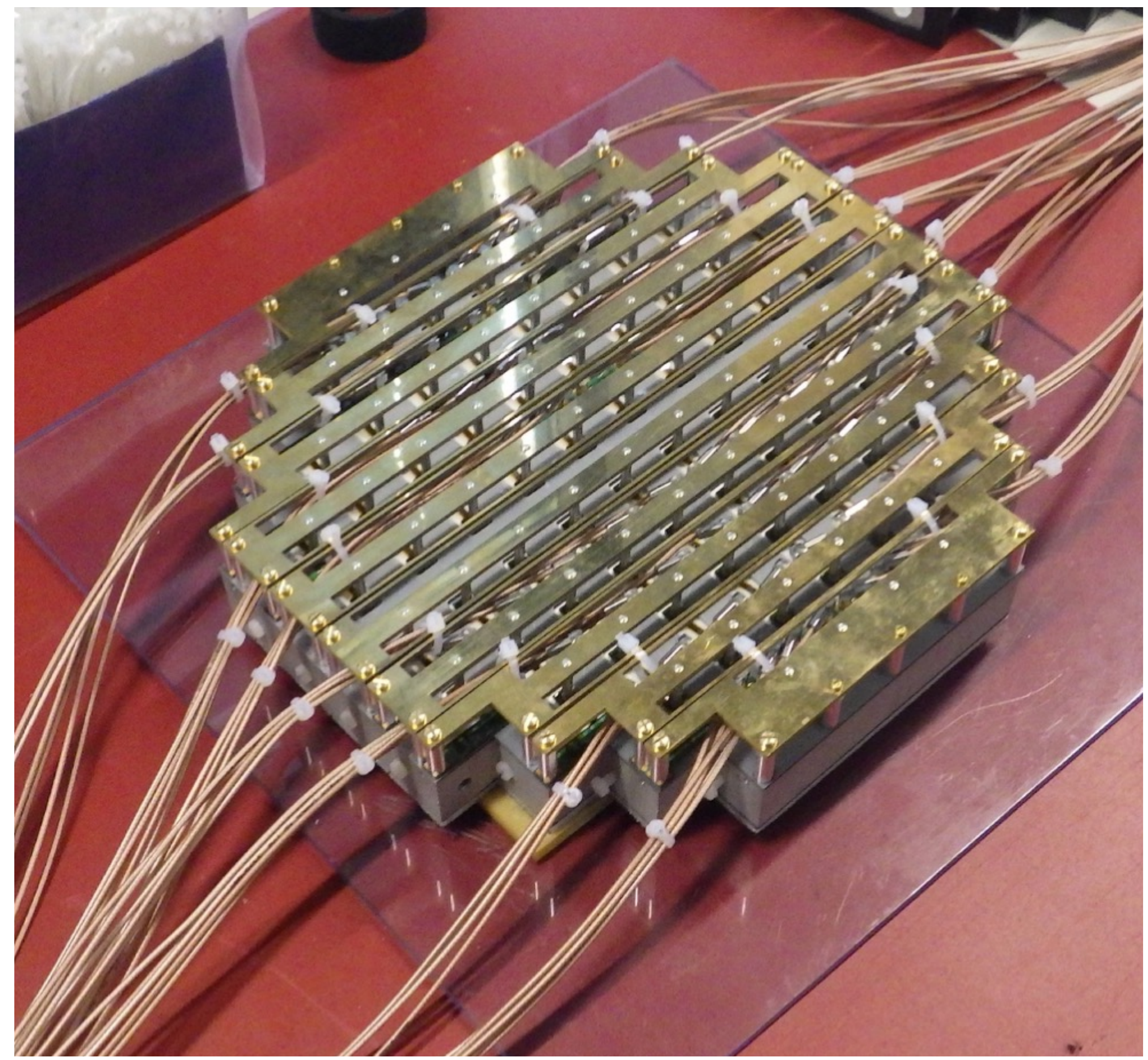
Summary and outlook

- In MEG II, RDC will be newly installed for active background identification. Sensitivity will be improved by 16%
- RDC identifies dominant background γ by detecting time coincident low momentum e^+
- Construction & commissioning was successfully completed in 2016. Capability of background identification was demonstrated.
- Performance of RDC will be precisely checked with LXe detector in this year
- R&D for upstream detector installed in high intensity μ^+ beam is ongoing (sensitivity improvement with 2 RDC : 22–28%)

Backup

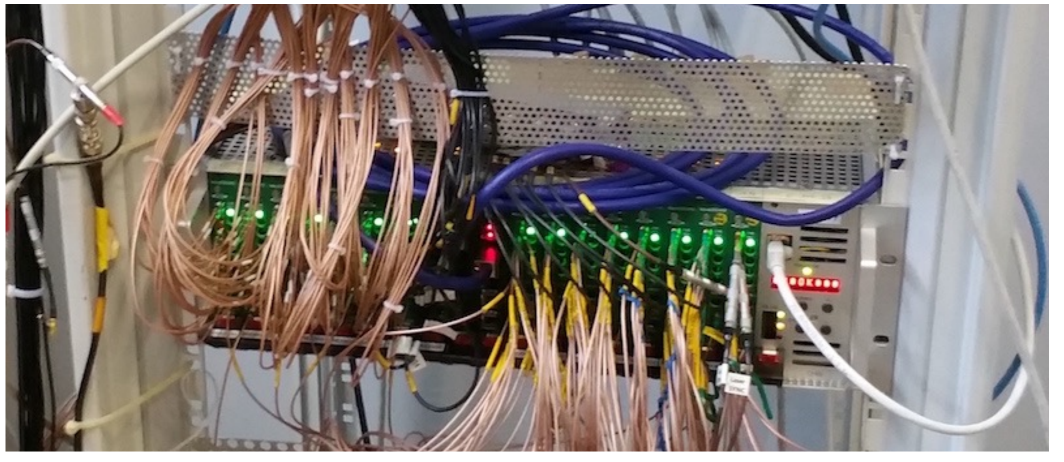
LYSO SiPM support





DAQ electronics

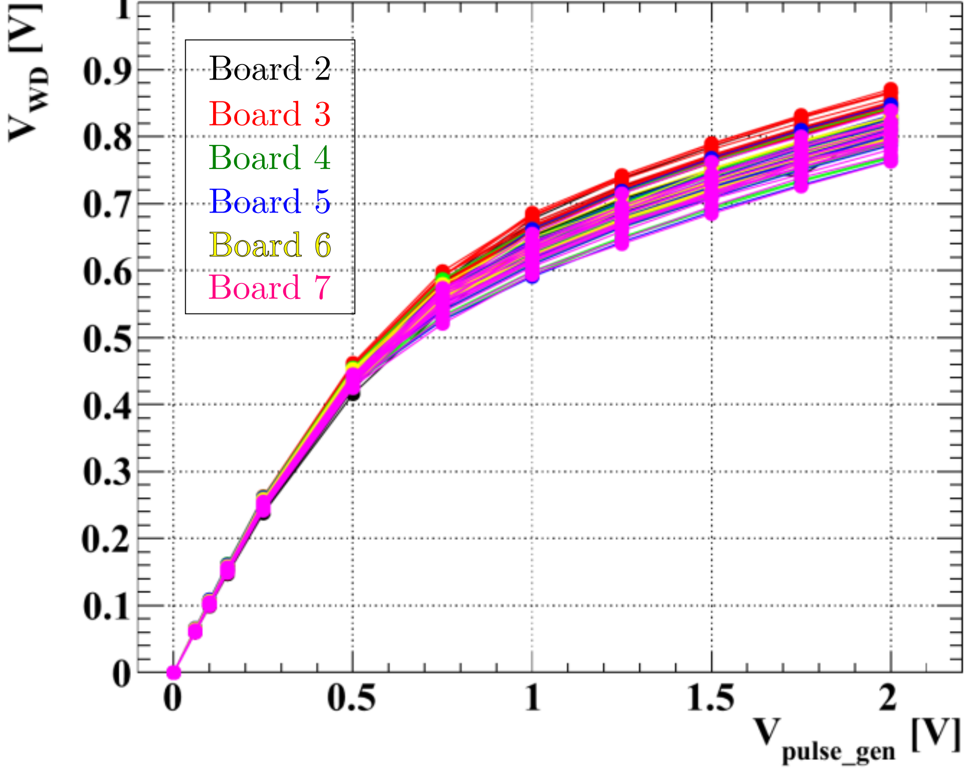
- WaveDREAM boards (developed in PSI)



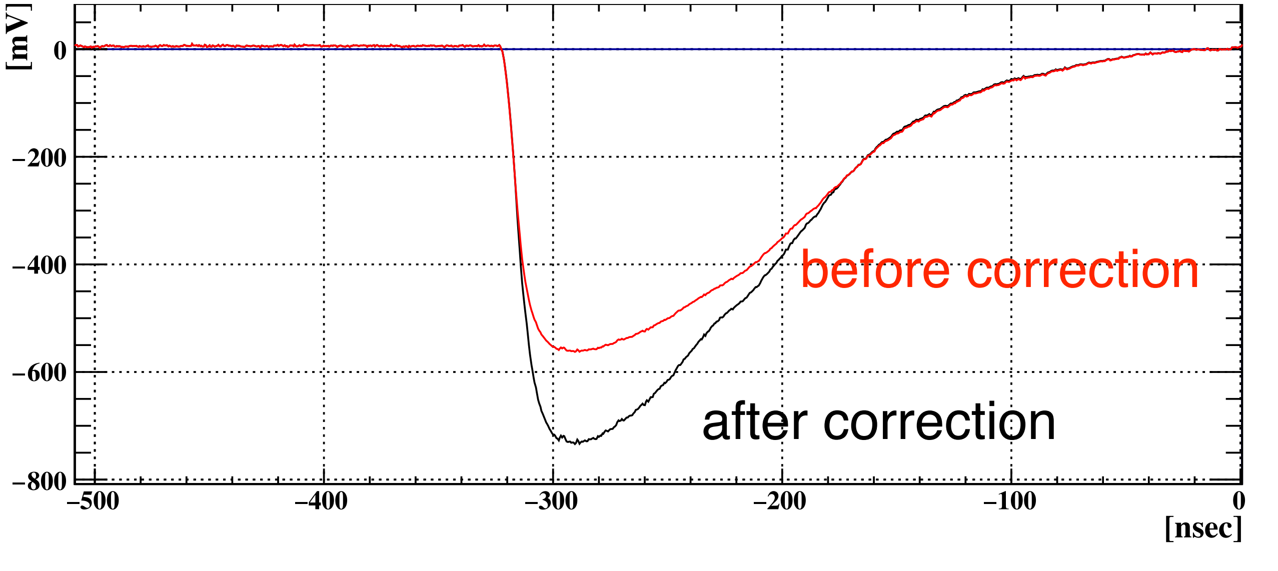
- Combined following devises
  - Pre-amplifier (gain : 1-100)
  - Waveform shaper
  - Waveform digitizer (based on DRS4)
  - HV supply for SiPM

- Non-linearity of WaveDREAM readout amplitude was found
  - All BGO + LYSO channels were scanned by using pulse generator
  - This problem will be fixed

Input amplitude vs readout amplitude

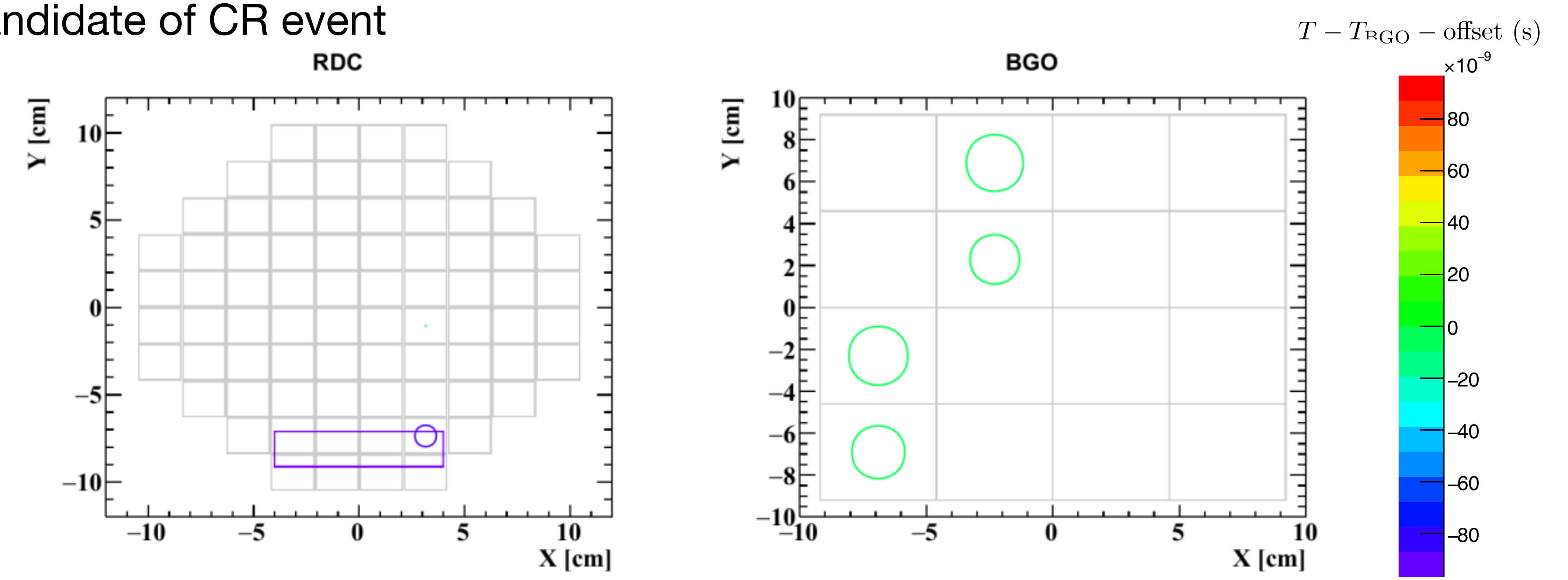


Waveforms were corrected response functions

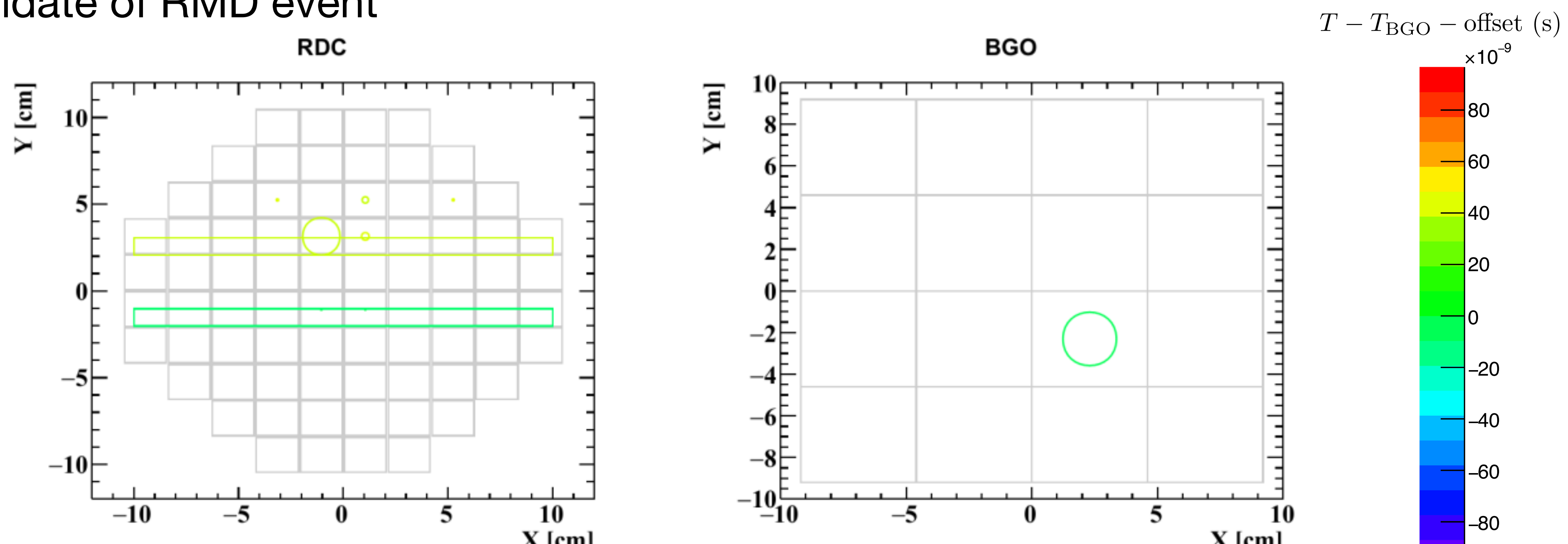


Event display

- Marker size : energy, Marker color : timing
  - Candidate of CR event

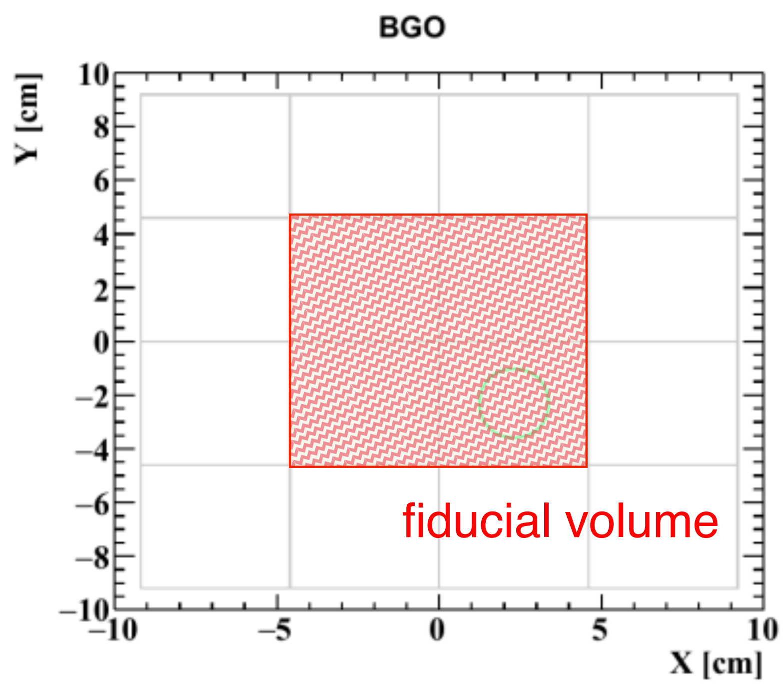


  - Candidate of RMD event

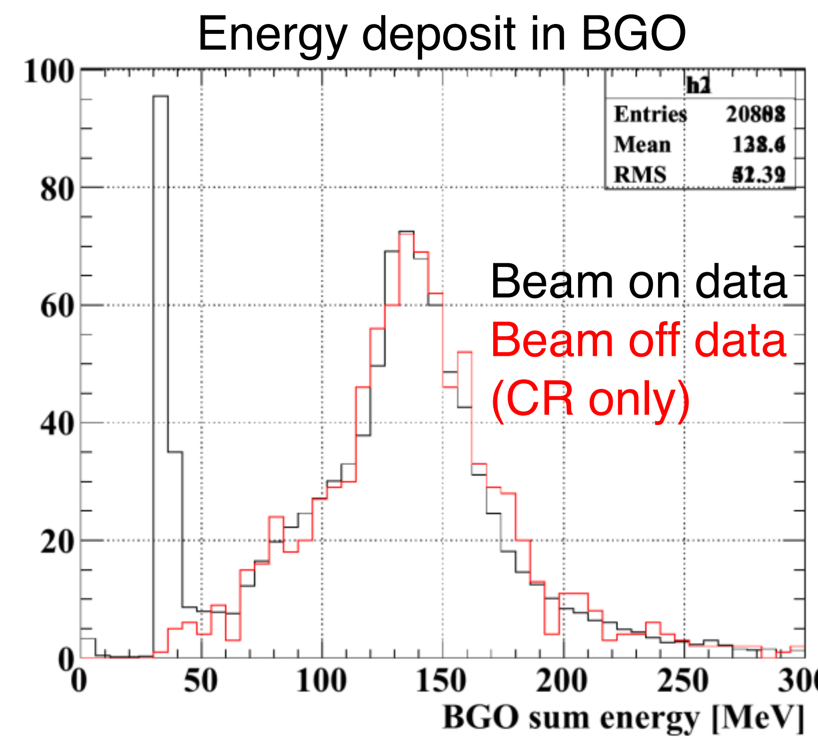


Event selection

- 2 event cuts for good RMD events selection with BGO

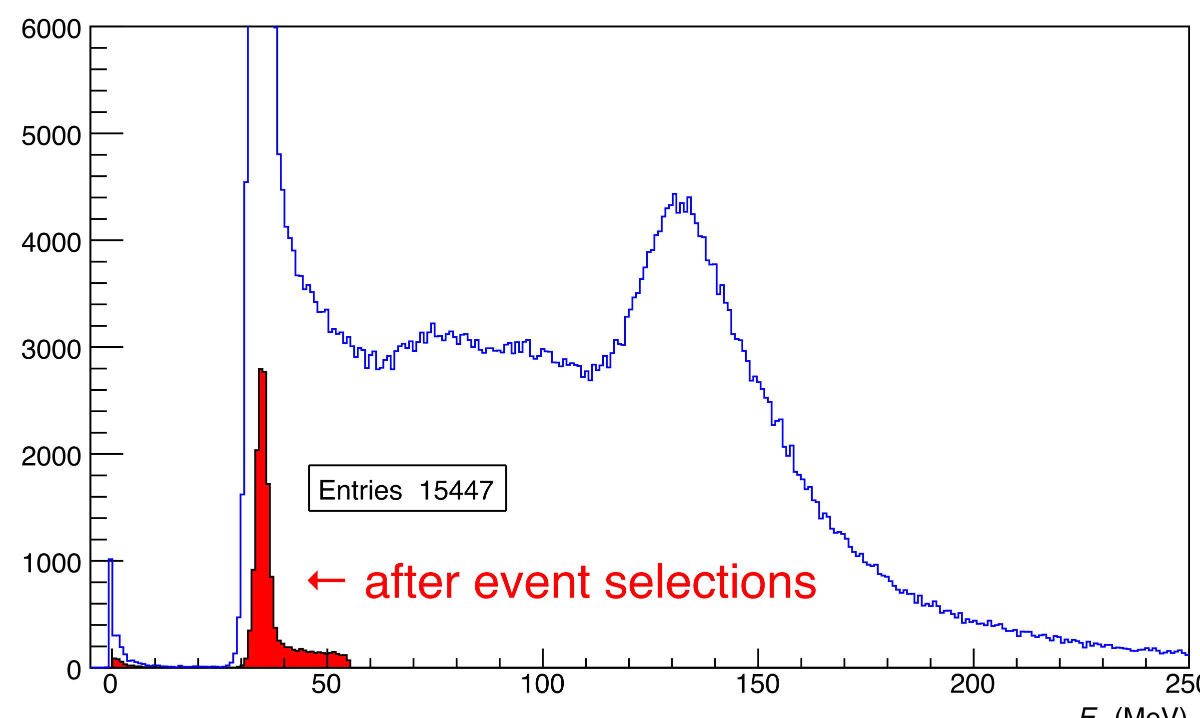


1. Require the largest hit in fiducial volume



2. Cut with energy sum (below 55 MeV)

- 98% of cosmic-ray events were rejected

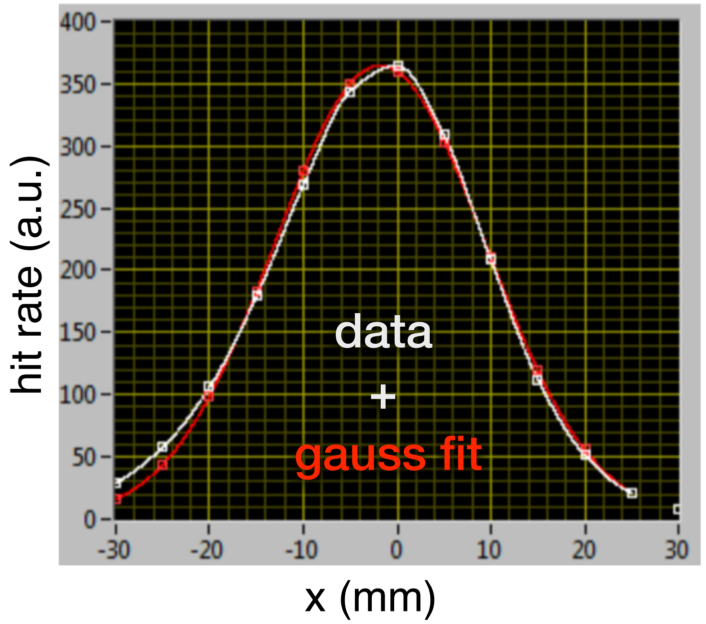


Influence on μ beam

- Comparison of beam spot size at target position

Dummy RDC (230 μm MYRALR foil)

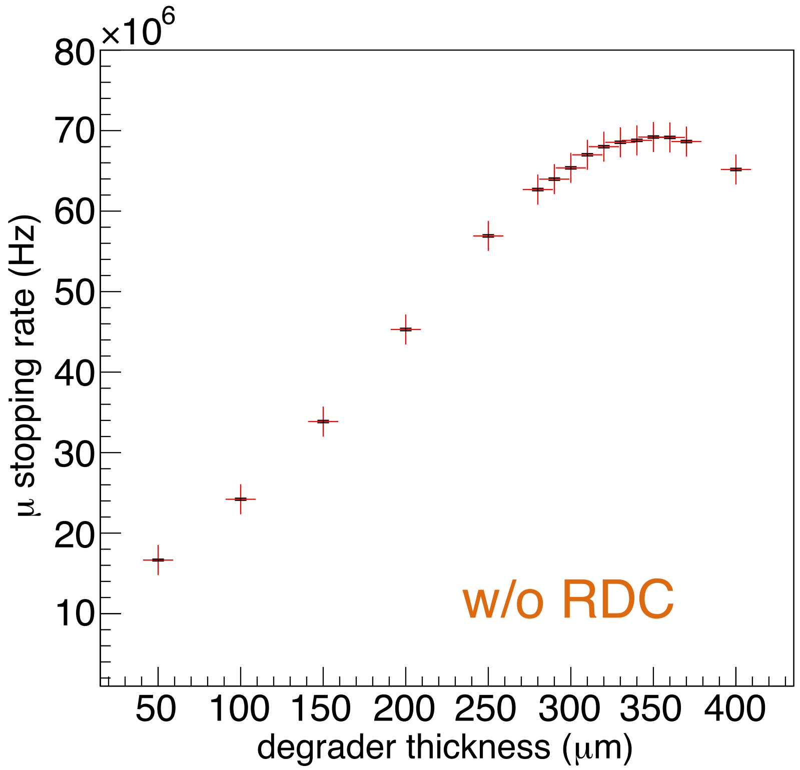
Scan hit rate for x-y with APD

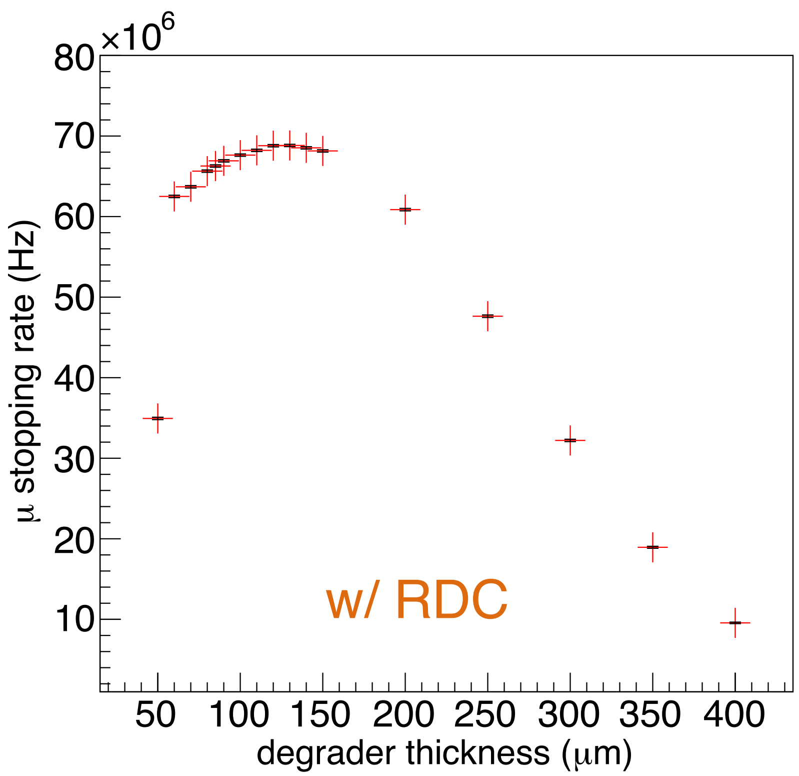


- $\sigma_x \times \sigma_y$ increased by ~16%

	σ_x(mm)	σ_y(mm)
normal run	10.7 ± 0.2	10.4 ± 0.2
dummy test	11.5 ± 0.2	11.2 ± 0.2

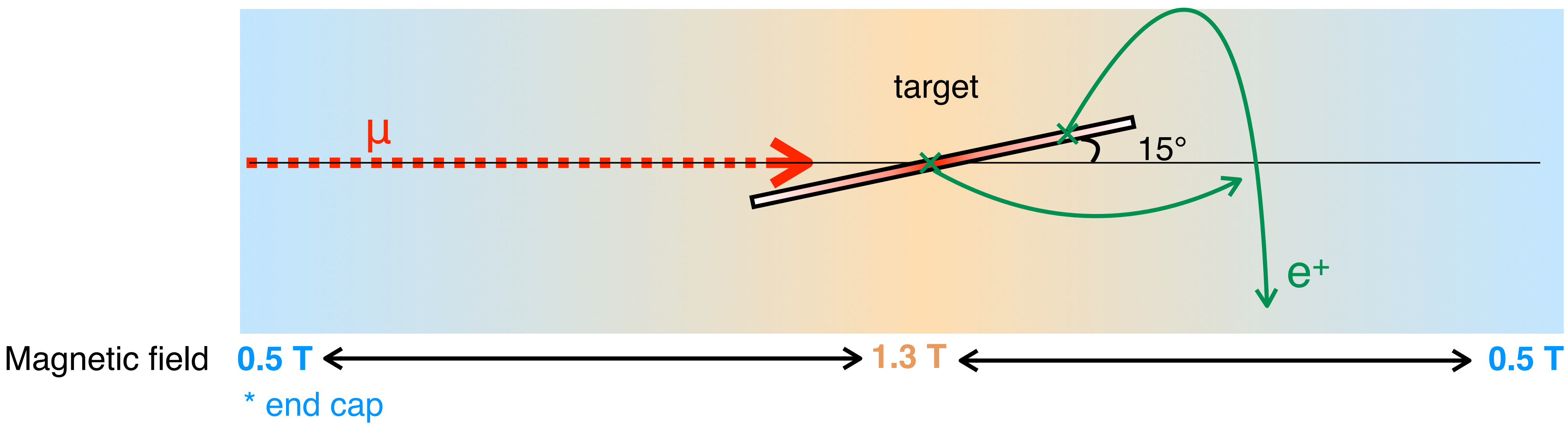
- Comparison of μ stopping rate (Geant4)
  - Investigated optimal degrader thickness (min. step = 10 μm)
  - Stopping rate loss ~0.54%





Effect of larger beam spot

- μ stopping distribution is stretched along beam axis due to slanted angle of the target
  - Influence on e^+ tracking could be enhanced



- Studied influence on e^+ tracking performance with Geant4

  ① **Efficiency loss for signal e^+ : 0.8% w/ RDC**

  ② **Drift chamber hit rate : increased 0.8% w/RDC**

  ③ **Reconstructed momentum resolution : degraded 1.3% w/RDC**

- Conclusion : Influence on μ beam is small

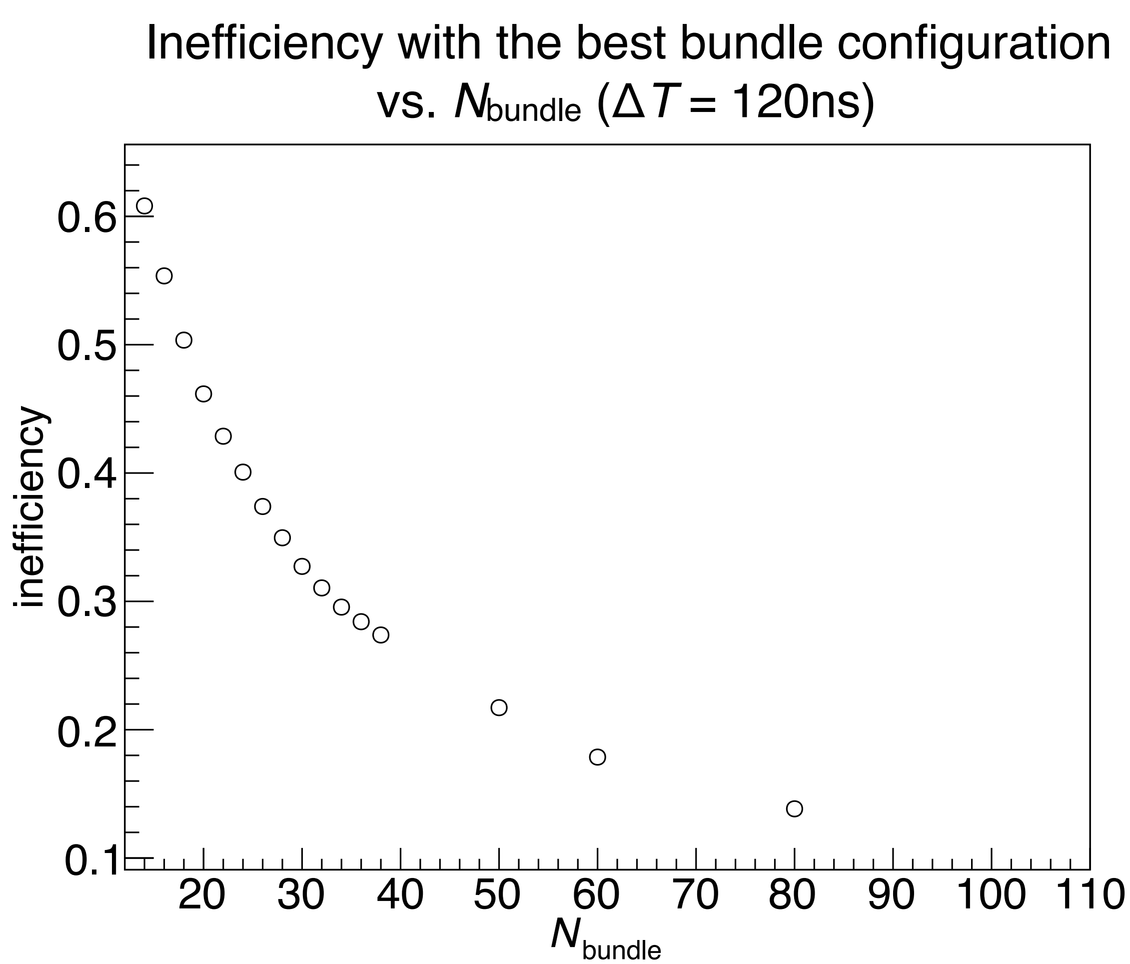
Prospects to reduce pileup

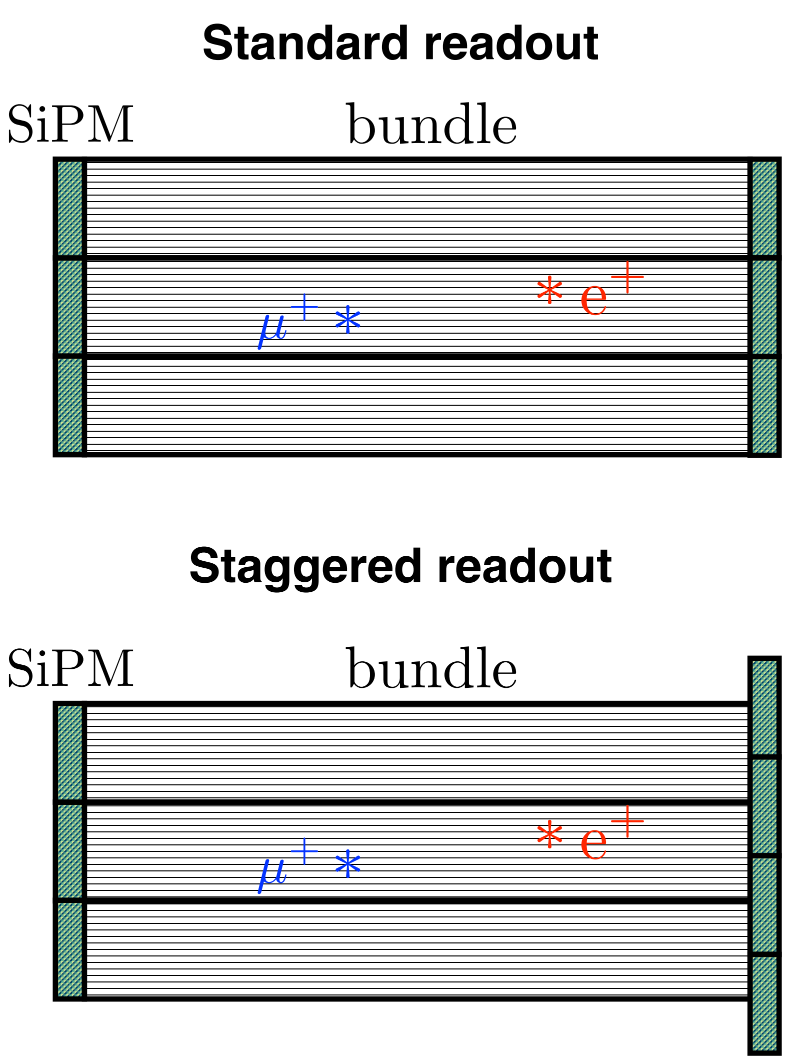
① Increase N_{bundle} (currently limited by available space for readout)

② Use staggered readout

③ Make PDF of the after pulse and use it in likelihood analysis

(characterization of the after pulse should be studied)



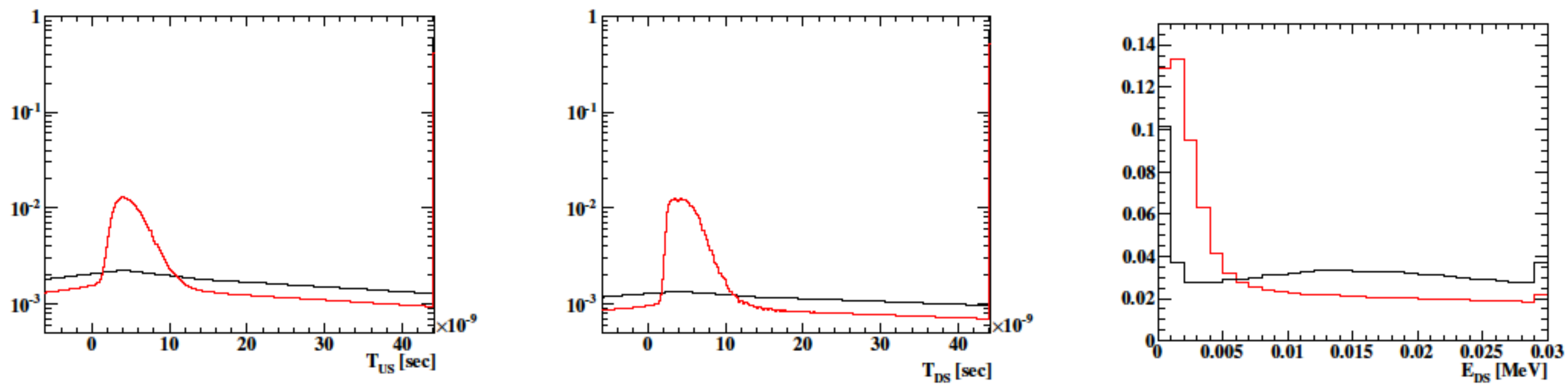


RDC data in physics analysis

- MEG II uses Maximum likelihood analysis to decide number of signals

$$\boxed{\mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right)}$$

- RDC makes PDF of 3 observables (t_{ds}, E_{ds}, t_{us}) and implement in likelihood function



(a) T_{us} (b) T_{ds} (c) E_{ds}

Figure 27: Projection of RDC PDF. The red and black line shows the accidental background and the signal PDF, respectively.