Core-to-Core Program

Improvement of the Sensitivity with Radiative Decay Counter for the MEG II experiment

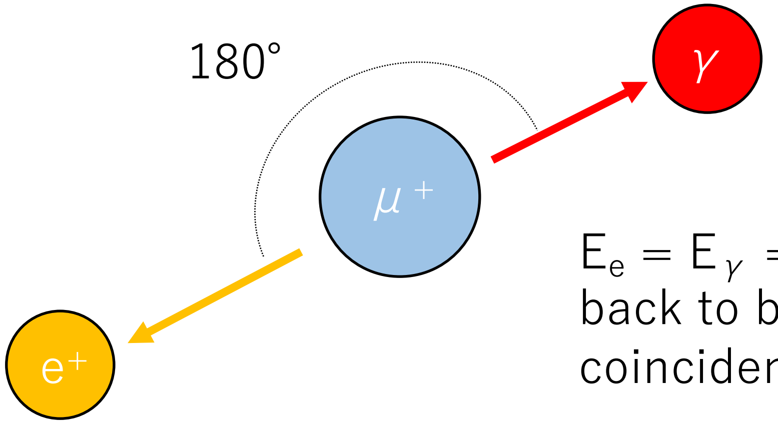
Rina Onda

On behalf of MEG II collaboration

The University of Tokyo

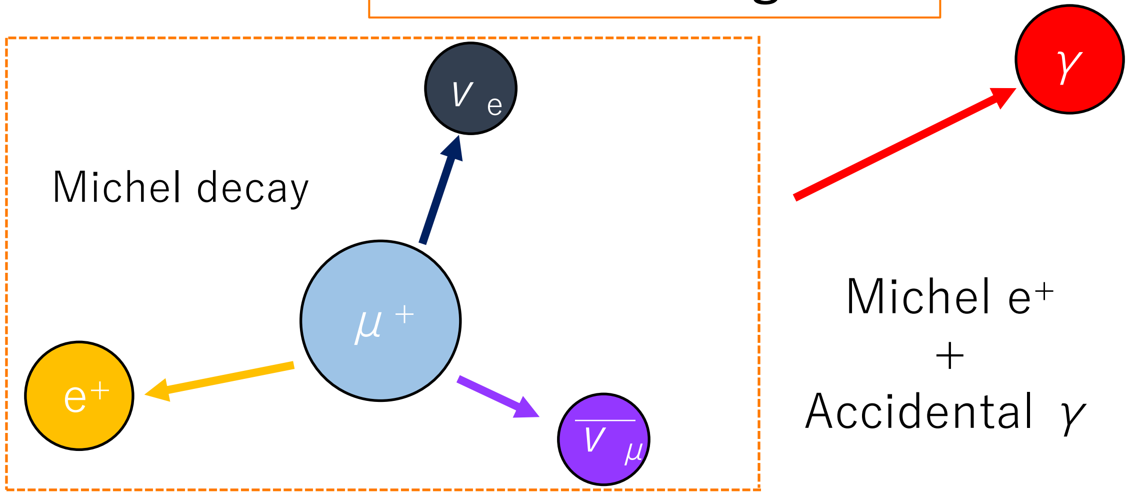
Signal & BG in MEG II

$\mu \rightarrow e\gamma$ signal



$E_e = E_\gamma = 52.8$ [MeV]
back to back
coincident in time

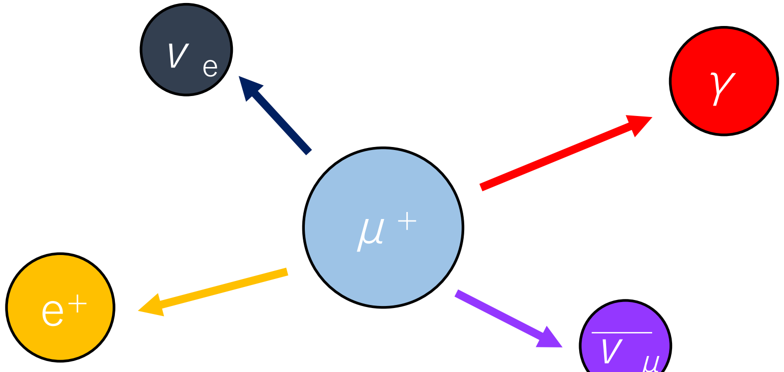
Dominant Background



Michel e^+
+
Accidental γ

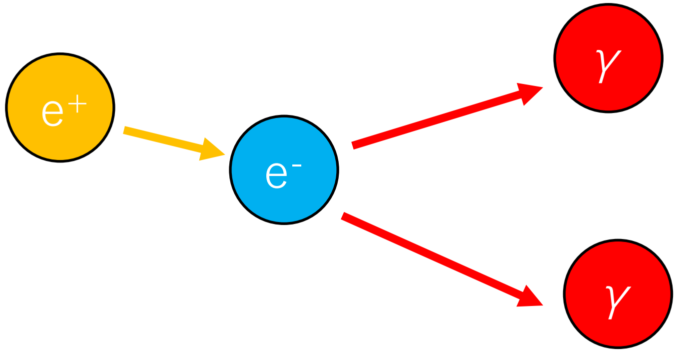
Sources of Accidental γ

Radiative Muon Decay(RMD)

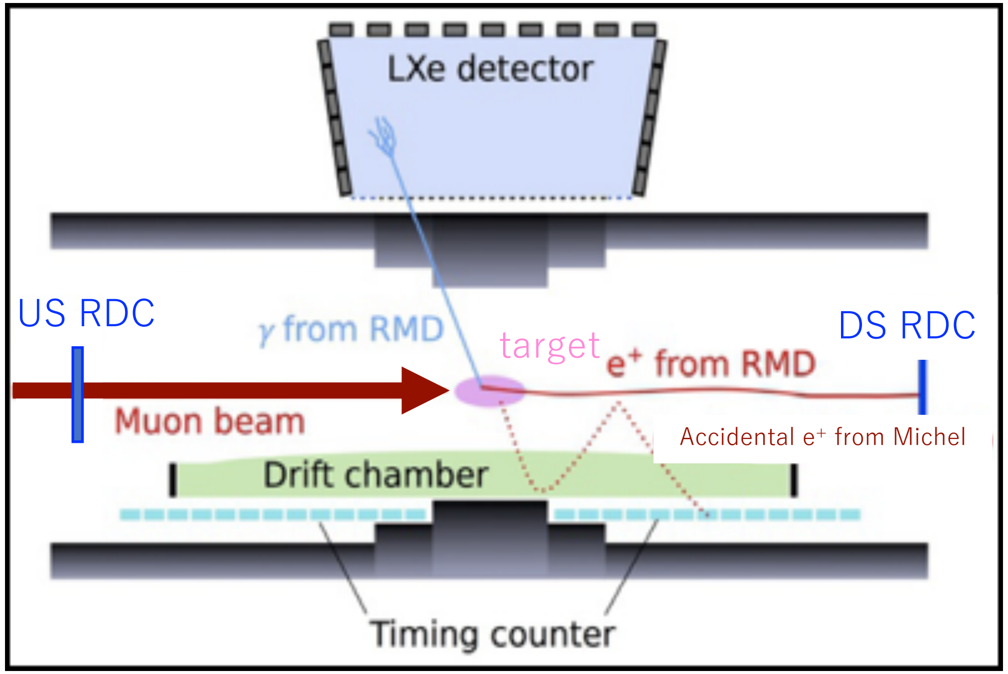


2 : 1
(E_γ > 48 MeV)

Annihilation In Flight(AIF)



Radiative Decay Counter (RDC)



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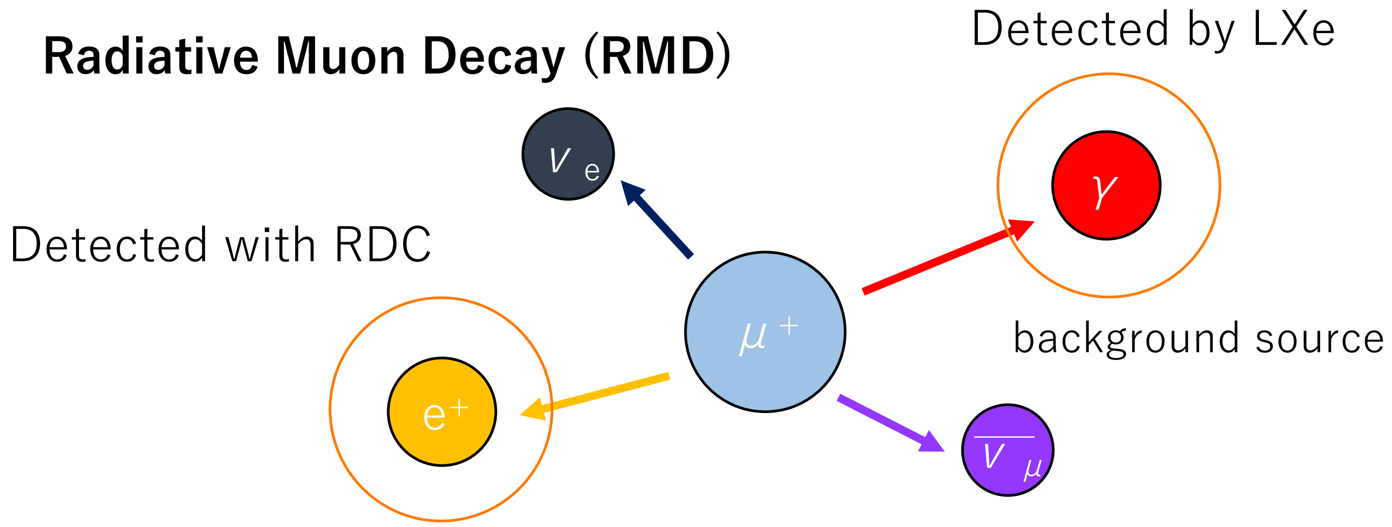
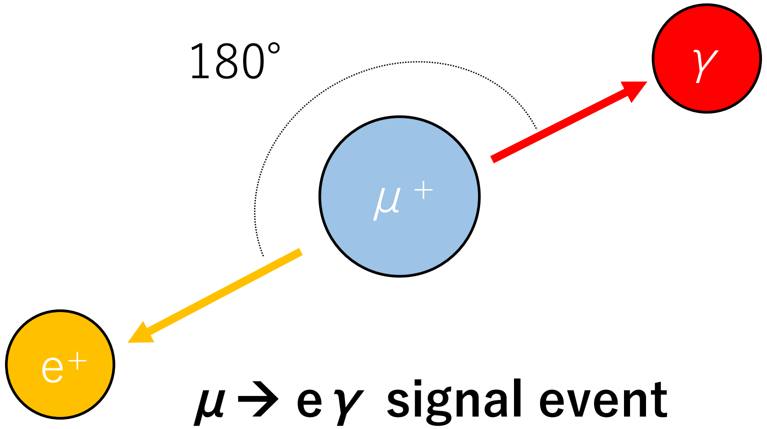


- Newly installed in MEG II
- Identify RMD events, which is a source of accidental γ background, by detecting low energy e^+ deriving from RMD.
  → time coincidence with γ detected by LXe
- RDC can be installed in upstream and downstream sides.
  - Upstream: detection of timing, under construction (15aSF-1)
  - Downstream: detection of timing and energy, already installed

Physics Analysis



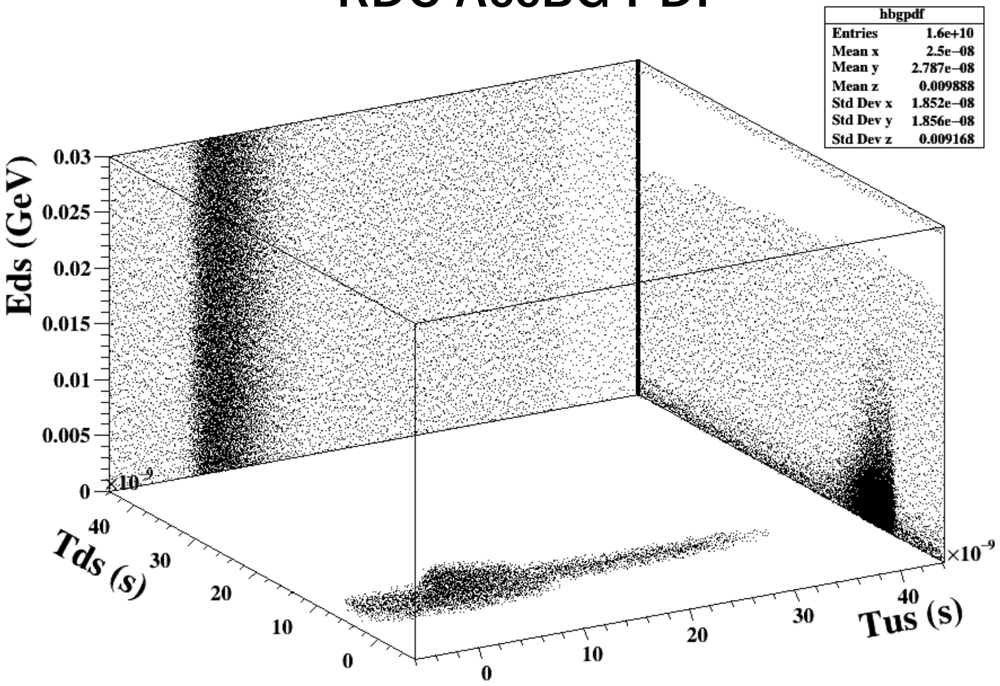
$\mu \rightarrow e\gamma$ signal event

- $\mu \rightarrow e\gamma$ signal event can be characterized by
  - $E_e = E_\gamma = 52.8$ MeV
  - back to back ($\theta_{e\gamma}$)
  - coincident in time ($T_{e\gamma}$)
- MEG physics analysis is based on the Maximum Likelihood Analysis.
- The number of signal event (N_{sig}) is estimated.
- Likelihood function contains three probability density functions (PDFs)
  - Signal
  - Radiative muon decay (RMD)
  - Accidental background (AccBG)
- RDC observables, T_{us}, T_{ds} and E_{ds} are added to the analysis by defining RDC PDFs.

Expected Improvement of the Sensitivity by RDC

The sensitivity calculation for MEG II update was done under the following configuration.

RDC AccBG PDF



- Format was 3D histogram
  - x-axis : T_{us} (timing detected by US RDC)
  - y-axis : T_{ds} (timing detected by DS RDC)
  - z-axis : E_{ds} (energy detected by DS RDC)

- RMD:AIF event ratio was fixed to 65:35 for AccBG PDF.
- Assumed detector performance

	Upstream detector	Downstream detector
Energy threshold	25 keV	30 keV
Detection efficiency	90%	100%
Energy resolution	–	8% @ 1 MeV
Time resolution	500 psec	100 psec
RMD fraction	52%	48%
Accidental probability	15%	9%
RMD acceptance	88%	88%

15% improvement by DS RDC and 10% further improvement by US RDC was expected.

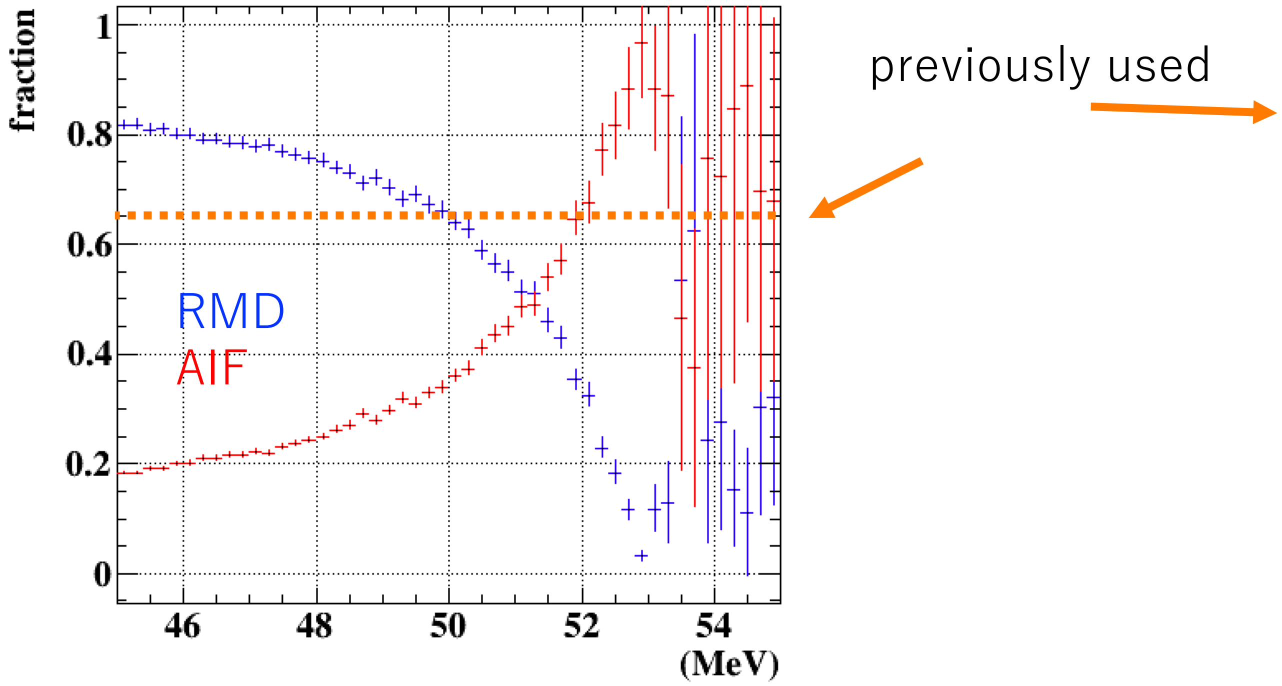
Modification of RDC PDF

The goal of this study is to update the RDC PDFs and evaluate the sensitivity taking **E_γ dependence of RDC parameters for AccBG PDF** into account:

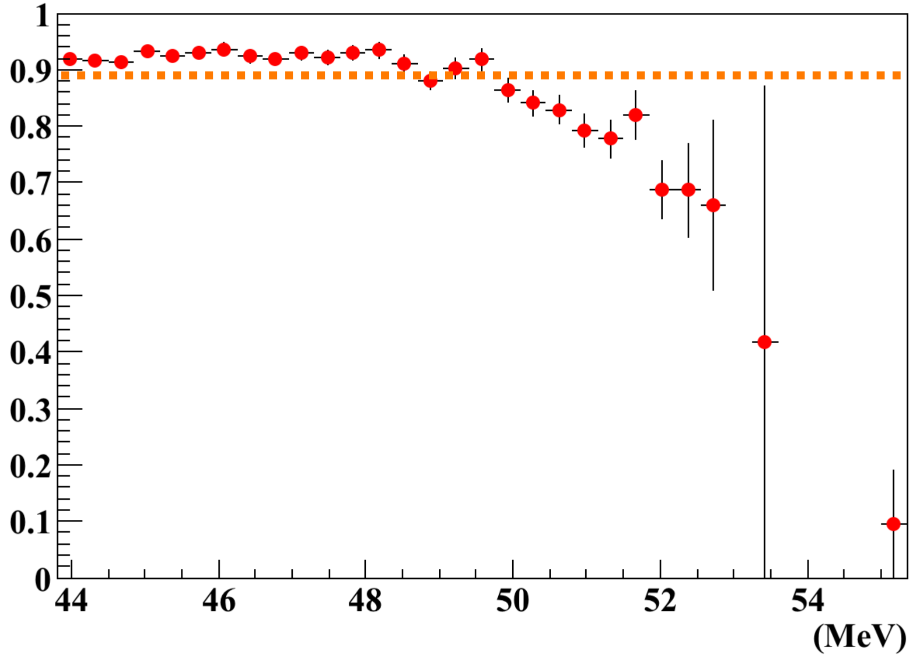
- Fraction of RMD in AccBG gets smaller near 52.8 MeV.
- E_{ds} should depend on E_γ.
- Detection efficiency can depend on E_{ds}.

E_γ Dependence of RDC Parameters

RMD/AIF Trigger Fraction (MC truth, no pileup)



RDC Detection Efficiency of RMD e^+

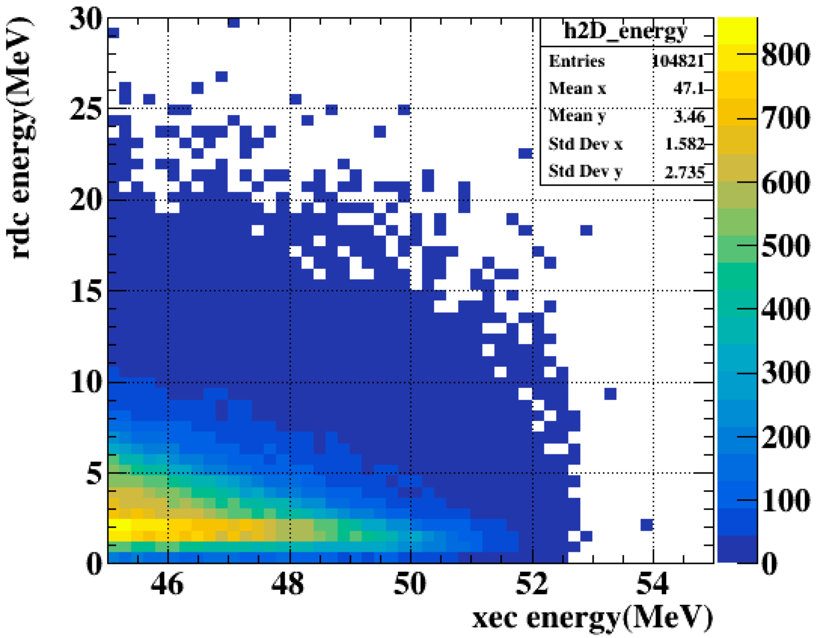


- There is E_γ dependence of RMD/AIF event fraction.
  - Average value 0.65 (E_γ > 48 MeV) was previously used.
  - AIF events are dominant in the higher energy region.
- There is E_γ dependence of RMD detection efficiency.
  - Fixed value, 0.88, was used for E_γ > 48 MeV.
  - The efficiency gets worse as E_γ becomes higher because E_{ds} becomes lower accordingly.

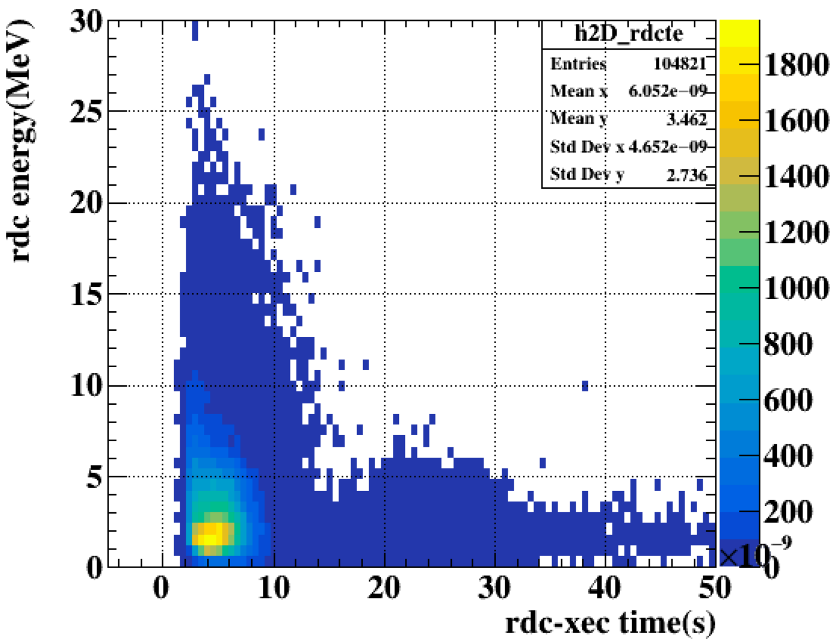
Worse identification performance in the signal region than assumed previously.

E_γ Dependence of RDC Parameters

Correlation b/w E_γ and E_{ds}



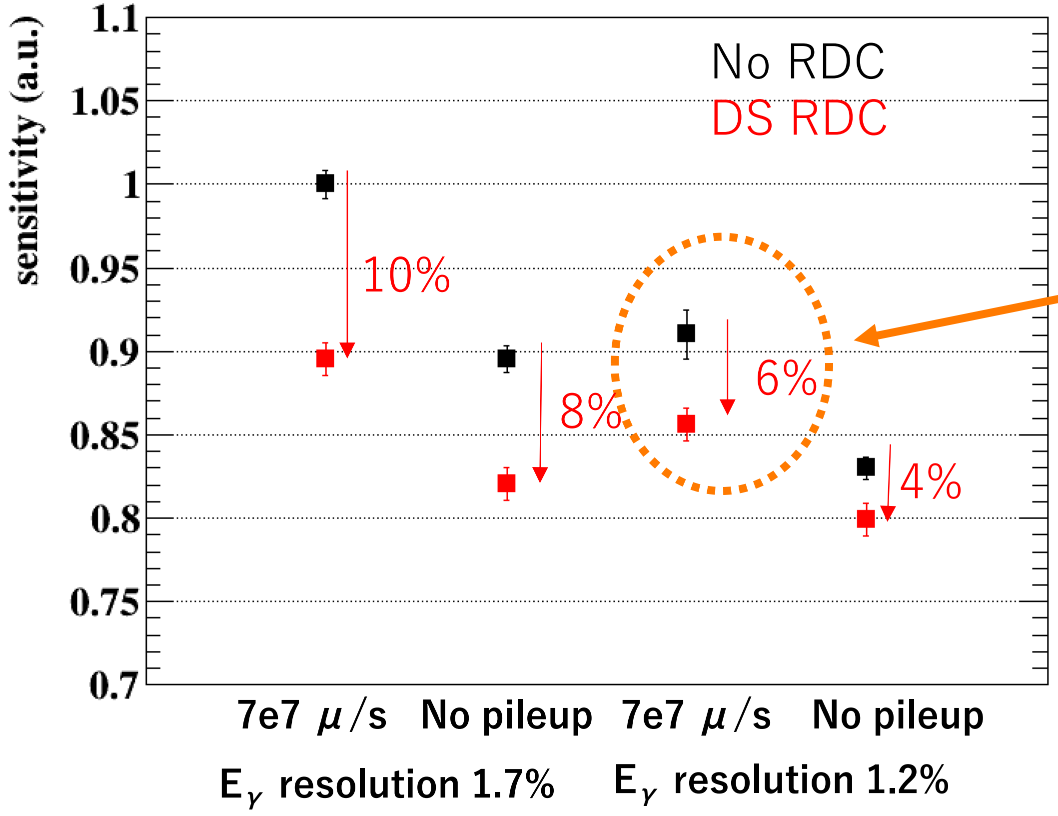
Correlation b/w T_{ds} and E_{ds}



E_γ dependence of T_{ds} and E_{ds} distributions was also not considered in the previous PDF.

- Anti-correlation b/w E_{ds} and E_γ
- The timing tail component in low E_{ds}
  ← Some low energy e^+s come back to DS after flying to US once.

Effect of E_γ Dependence on Sensitivity



- The sensitivity was calculated taking the E_γ dependence into account.
- Assuming 7×10^7 μ/s, E_γ resolution 1.2%, a benefit from DS RDC is ~6%.
  ← It was 15% in proposal.
- However, the measured E_γ resolution is 1.7%. In this case, DS RDC contribution becomes larger (~10%).
  → The effect of worse E_γ resolution is recovered by RDC.
- Without pileup events RMD events in the high E_γ region reduces.
  ← DS RDC contribution will be smaller at low beam rate.

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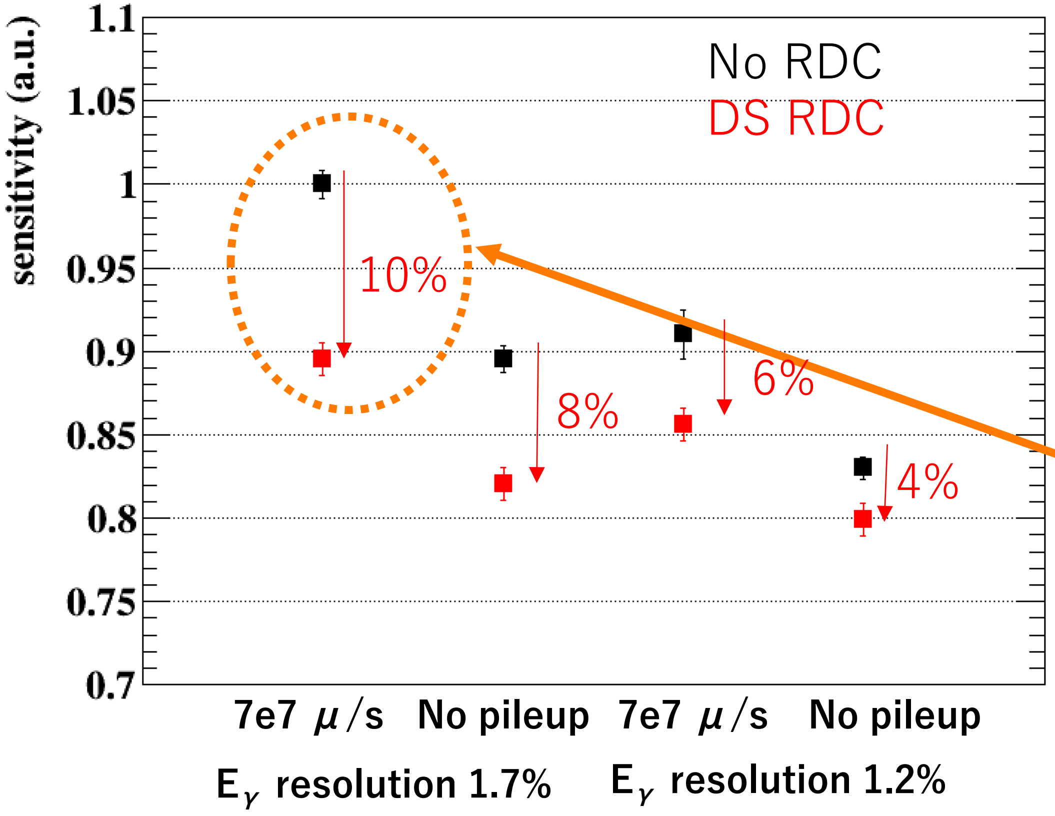

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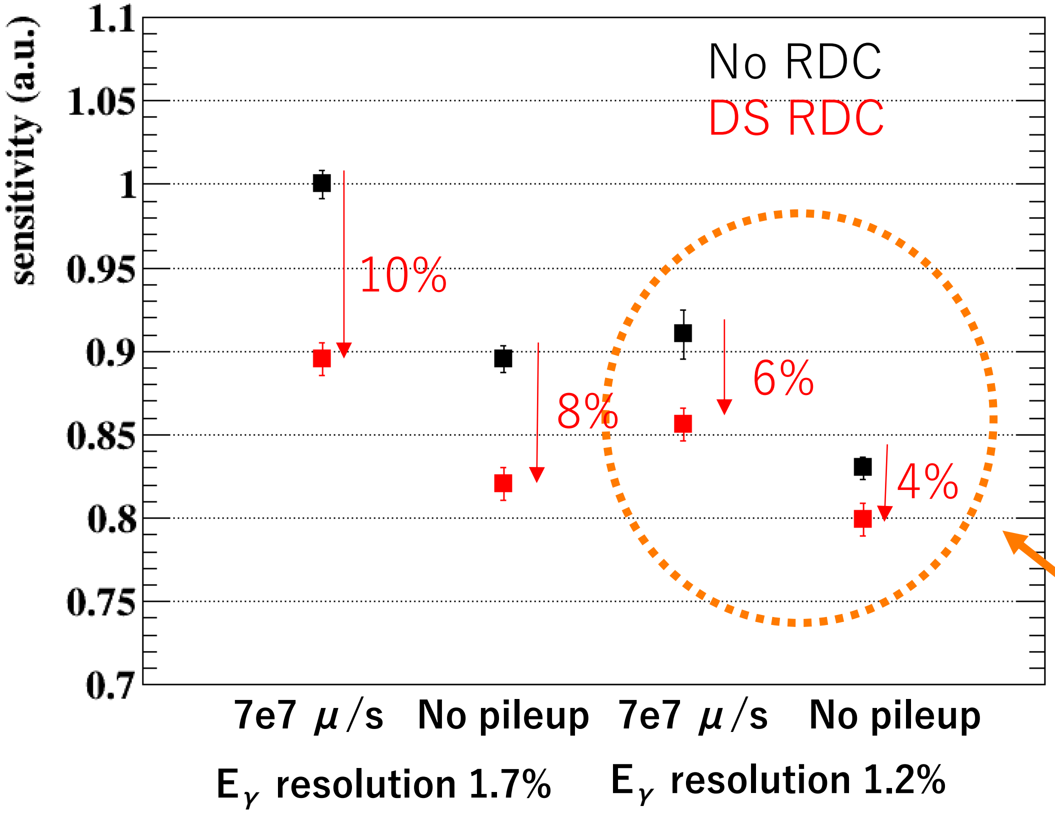

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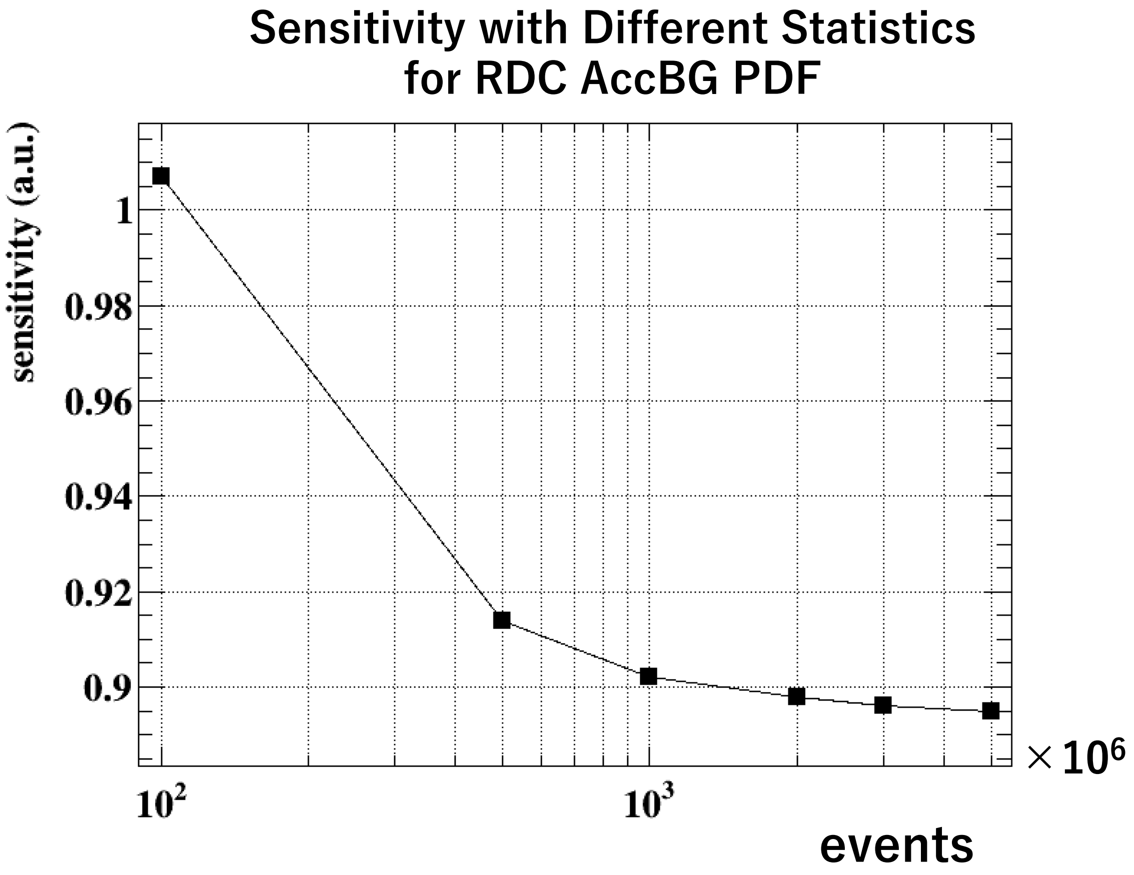
How to make RDC AccBG PDF under Statistical Limitation

Required Statistics for RDC AccBG PDF



- Statistical limitation can be a problem for RDC AccBG PDF.
  ← not for Signal/RMD PDF because they need only Michel energy distribution, which can be obtained from timing sideband data in 1 dimension.
- The sensitivity was calculated assuming the different amounts of events for RDC AccBG PDF to estimate the required statistics.
- The sensitivity can be biased if the number of events is small.
  ← The PDFs are distorted due to low statistics.
- Expected DAQ time @ 10Hz, 1% event selection efficiency:
  5×10^9 events ~ 600000 days
- DAQ time is not reasonable.
  → Must be reduced to ~120 days (1×10^6 events).

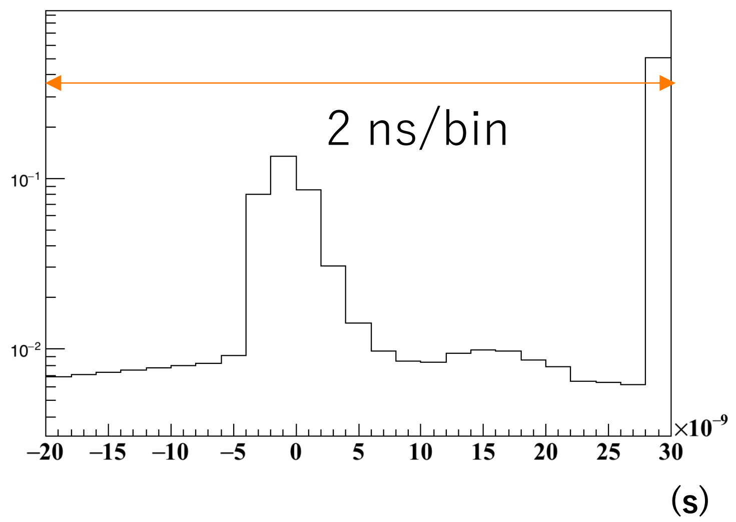
Reduction of Required Statistics

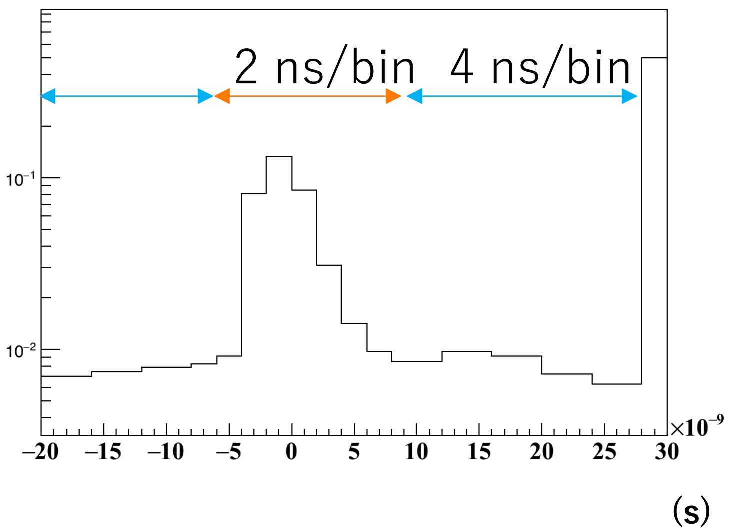
- Required DAQ time was found to be too long.
- The problem can come from **a sparsity of 4D histograms**.
- There are several solutions:
  1. Optimization of bin width
  2. Dimension reduction
  3. Extraction of distributions in reduced dimension

Optimization of Bin Width

- Originally, bin widths were set to be narrow enough not to affect the sensitivity.
- The importance of the bins is different depending on their positions:
  - The timing coincident region is more important than the side band.
  - The low energy region is more important than the high energy region.
- **Variable bins can maintain the information in the important region and increase entries in the sparse region.**

T_{ds} distribution

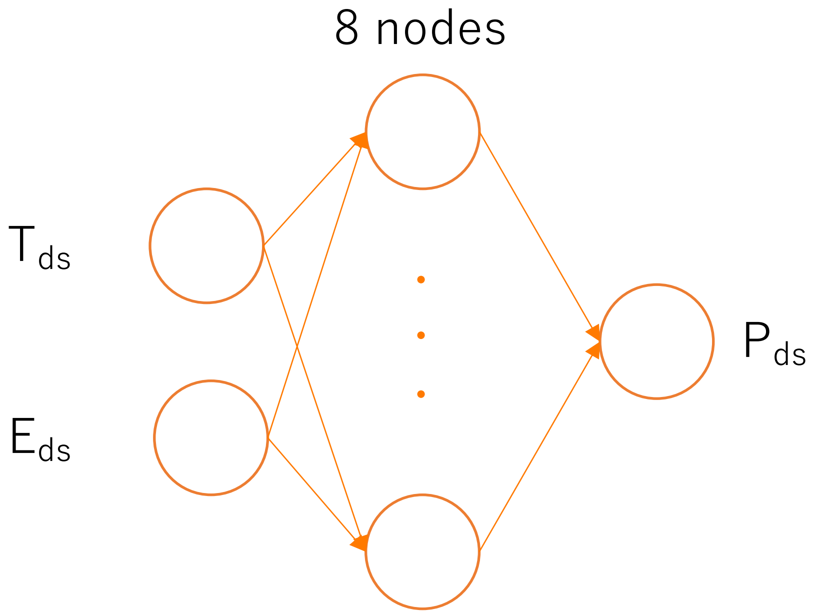




Dimension Reduction with Neural Network

- The other idea is to reduce dimension:

  $(E_\gamma, T_{us}, T_{ds}, E_{ds}) \rightarrow (E_\gamma, T_{us}, P_{ds})$
- **T_{ds} and E_{ds} can be compressed into a combined parameter P_{ds} with Neural Network.**
- Configuration
  - inputs : T_{ds}, E_{ds}
  - 8 nodes in one hidden layer
  - output : probability that e^+ is generated from RMD
- Dataset
  - MC RMD (E_γ > 40 MeV) : 378,607 events
  - MC Michel : 923,498 events



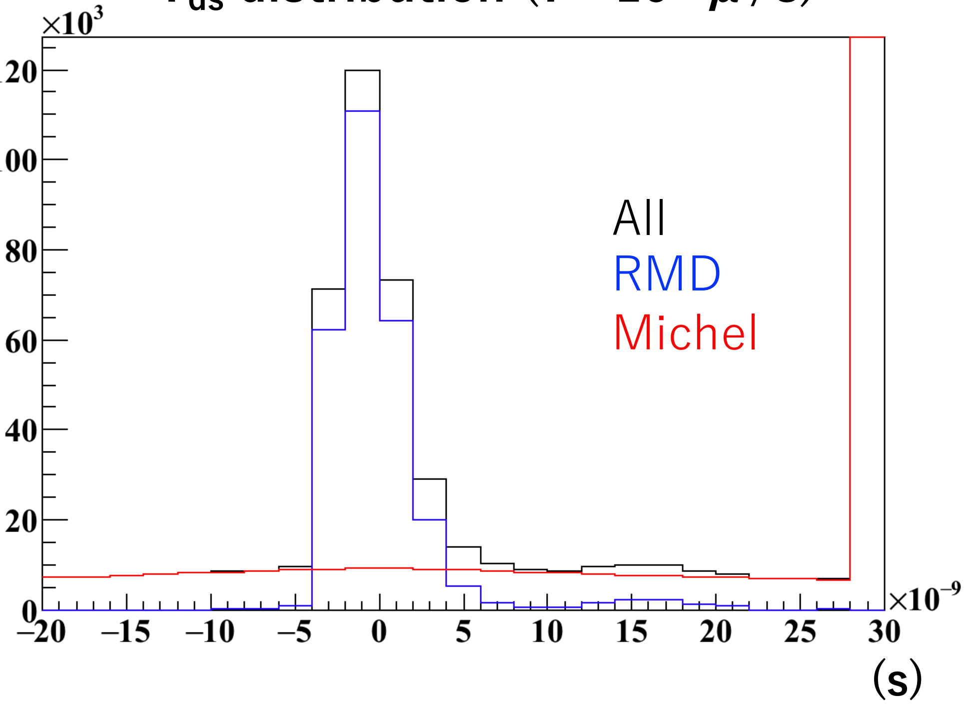
Extraction of Distributions in Reduced Dimension

- Filling events to 4D histograms directly can waste statistics:
  - E_γ dependence of the timing/energy distribution of RMD e^+ might not be so important.
  - The energy distribution of Michel e^+ does not depend on E_γ and timing.
- **Extraction of those distributions in reduced dimension can increase the effective statistics**.
- PDF can be generated by adding the distributions weighted by RMD fraction detected by RDC.

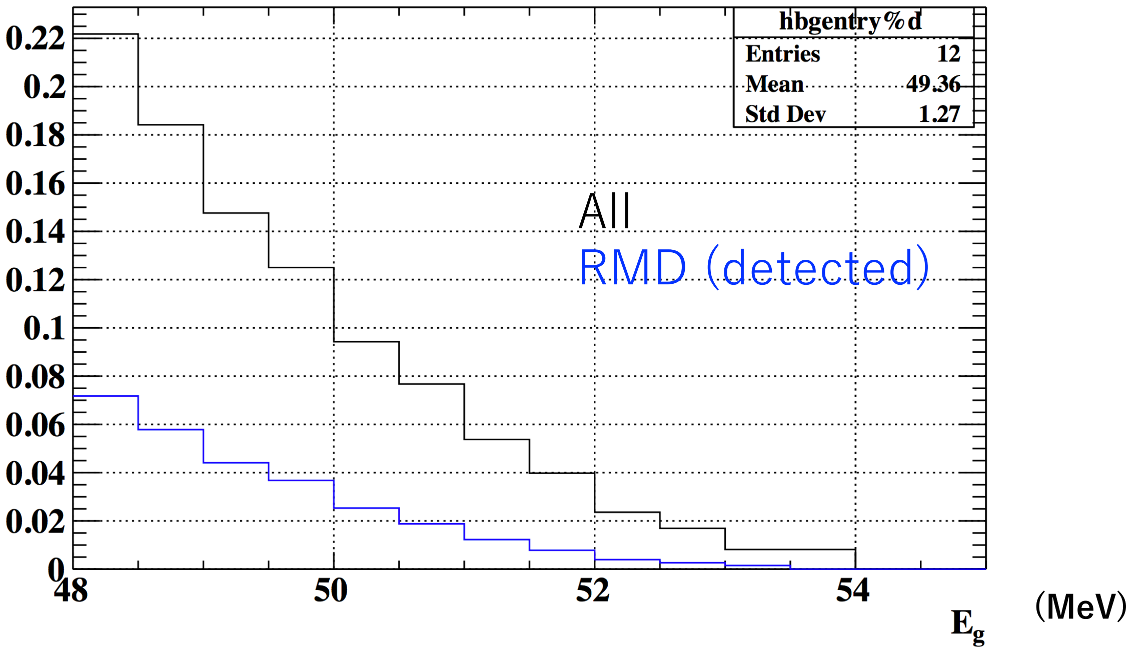
Extraction of RMD Fraction Detected by RDC

- RMD fraction detected by RDC is calculated by the entries in the RMD timing peak.
- The RMD peak can be extracted by subtracting the Michel timing distribution, which can be calculate by Michel e^+ hit rate.

T_{ds} distribution (7×10^7 μ/s)

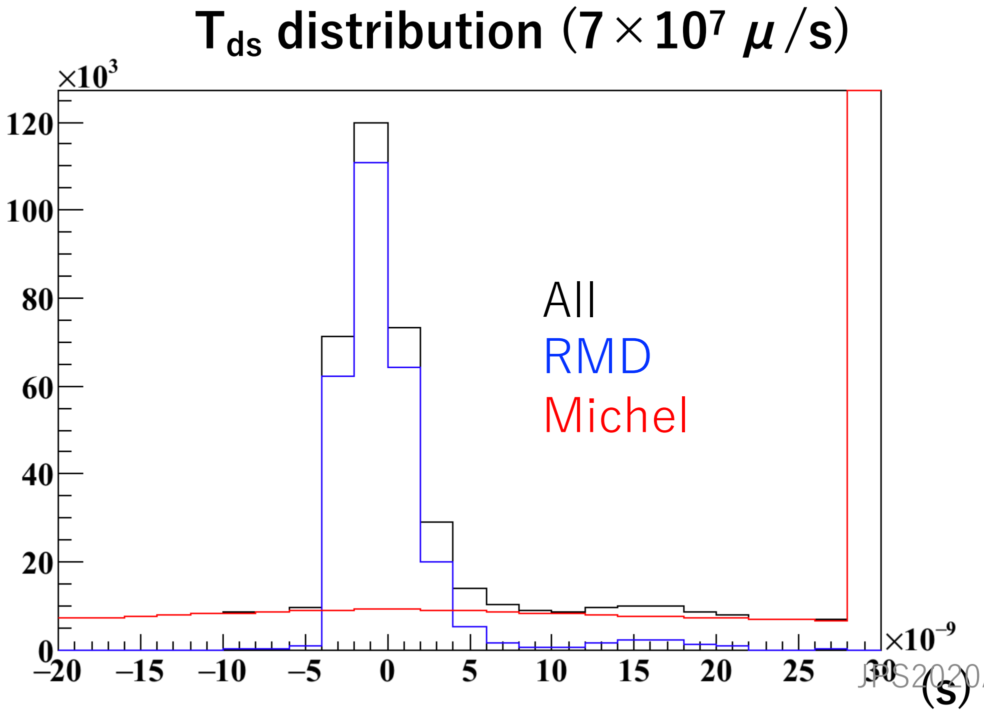


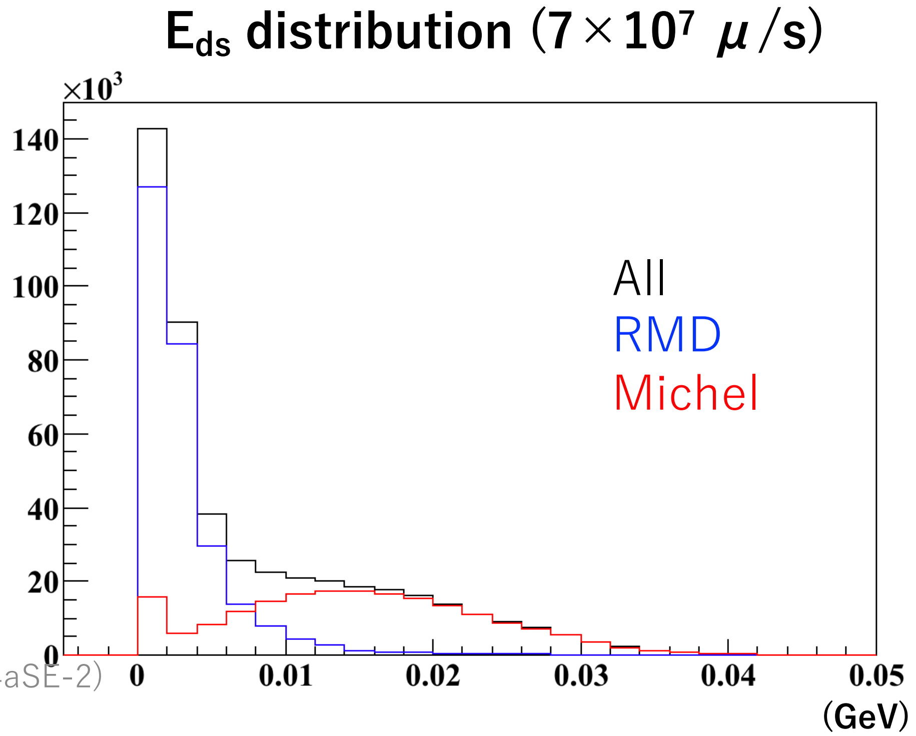
E_γ distribution



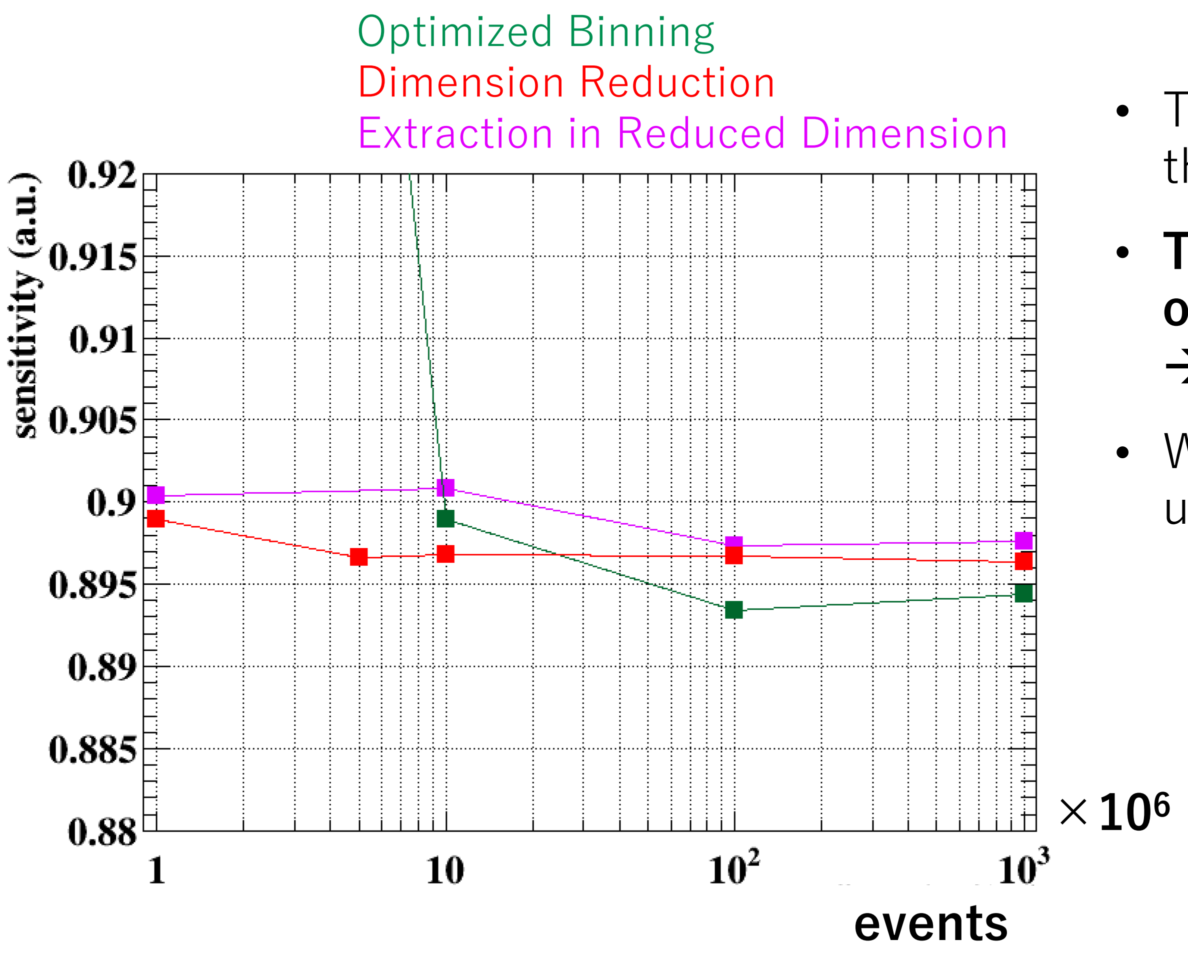
Extraction of RMD Distribution

- The RMD timing distribution can be extracted by subtracting the Michel timing distribution.
- The RMD energy distribution is extracted by subtracting Michel energy distribution, which can be taken in timing sideband.





Sensitivity after Statistics Reduction



- The sensitivity was calculated with PDFs after applying the methods.
- **The required statistics was successfully reduced to the objective statistics** except for optimized binning.
  → can be taken in 120 days.
- Which method should be used depends on the systematic uncertainty of each PDF.

Summary

- The effect of RDC is re-evaluated considering E_γ dependence:
  The sensitivity can be **improved by ~10% thanks to DS RDC**.
- Statistics to create RDC PDF was found to be very high.
- Three solutions were discussed to decrease the required statistics:
  - Optimization of bin width
  - Dimension reduction
  - Extraction of distributions in reduced dimension
- They successfully reduced the required statistics.
  ← Can be taken within ~120 days.

Prospect

- The uncertainty of sensitivity coming from RDC PDF must be investigated.

  → It will be decided which PDF generation method should be used:

    - Dimension reduction
    - Extraction of distributions in reduced dimension.

- The effect of non-linearity of DS RDC energy must be checked w/ data.

    ➢ Non-linearity distorts E_{ds} distribution.

Backup Slides

Physics Analysis

- MEG physics analysis is based on the Maximum Likelihood Analysis.
- The number of signal event (N_{sig}) is estimated.
- Likelihood function contains three probability density functions (PDFs)
  - Signal
  - Radiative muon decay (RMD)
  - Accidental background (AccBG)

The statistical term

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

$$\boxed{\frac{e^{-N}}{N_{\mathrm{obs}}!} e^{-\frac{\left(N_{\mathrm{RMD}}-\langle N_{\mathrm{RMD}}\rangle\right)^2}{2\sigma_{\mathrm{RMD}}^2}} e^{-\frac{\left(N_{\mathrm{BG}}-\langle N_{\mathrm{BG}}\rangle\right)^2}{2\sigma_{\mathrm{BG}}^2}}} \times$$

PDF of signal/RMD/AccBG

$$\prod_{i=1}^{N_{\mathrm{obs}}} \left(\underline{N_{\mathrm{sig}}} S\left(\vec{x_i}\right) + \underline{N_{\mathrm{RMD}}} R\left(\vec{x_i}\right) + \underline{N_{\mathrm{BG}}} B\left(\vec{x_i}\right)\right)$$

The number of signal/RMD/AccBG events

Likelihood Function w/ RDC

w/o RDC

$$\mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right) = \frac{e^{-N}}{N_{\mathrm{obs}}!} e^{-\frac{\left(N_{\mathrm{RMD}}-\langle N_{\mathrm{RMD}}\rangle\right)^2}{2\sigma_{\mathrm{RMD}}^2}} e^{-\frac{\left(N_{\mathrm{BG}}-\langle N_{\mathrm{BG}}\rangle\right)^2}{2\sigma_{\mathrm{BG}}^2}} \times \prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S\left(\vec{x_i}\right) + N_{\mathrm{RMD}} R\left(\vec{x_i}\right) + N_{\mathrm{BG}} B\left(\vec{x_i}\right)\right)$$

w/ RDC

$$\mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right) = \frac{e^{-N}}{N_{\mathrm{obs}}!} e^{-\frac{\left(N_{\mathrm{RMD}}-\langle N_{\mathrm{RMD}}\rangle\right)^2}{2\sigma_{\mathrm{RMD}}^2}} e^{-\frac{\left(N_{\mathrm{BG}}-\langle N_{\mathrm{BG}}\rangle\right)^2}{2\sigma_{\mathrm{BG}}^2}} \times \prod_{i=1}^{N_{\mathrm{obs}}} \left(N_{\mathrm{sig}} S\left(\vec{x_i}\right) \boxed{S_{\mathrm{RDC}}\left(\vec{y_i}\right)} + N_{\mathrm{RMD}} R\left(\vec{x_i}\right) \boxed{R_{\mathrm{RDC}}\left(\vec{y_i}\right)} + N_{\mathrm{BG}} B\left(\vec{x_i}\right) \boxed{B_{\mathrm{RDC}}\left(\vec{y_i}\right)}\right)$$

RDCPDF of signal/RMD/AccBG

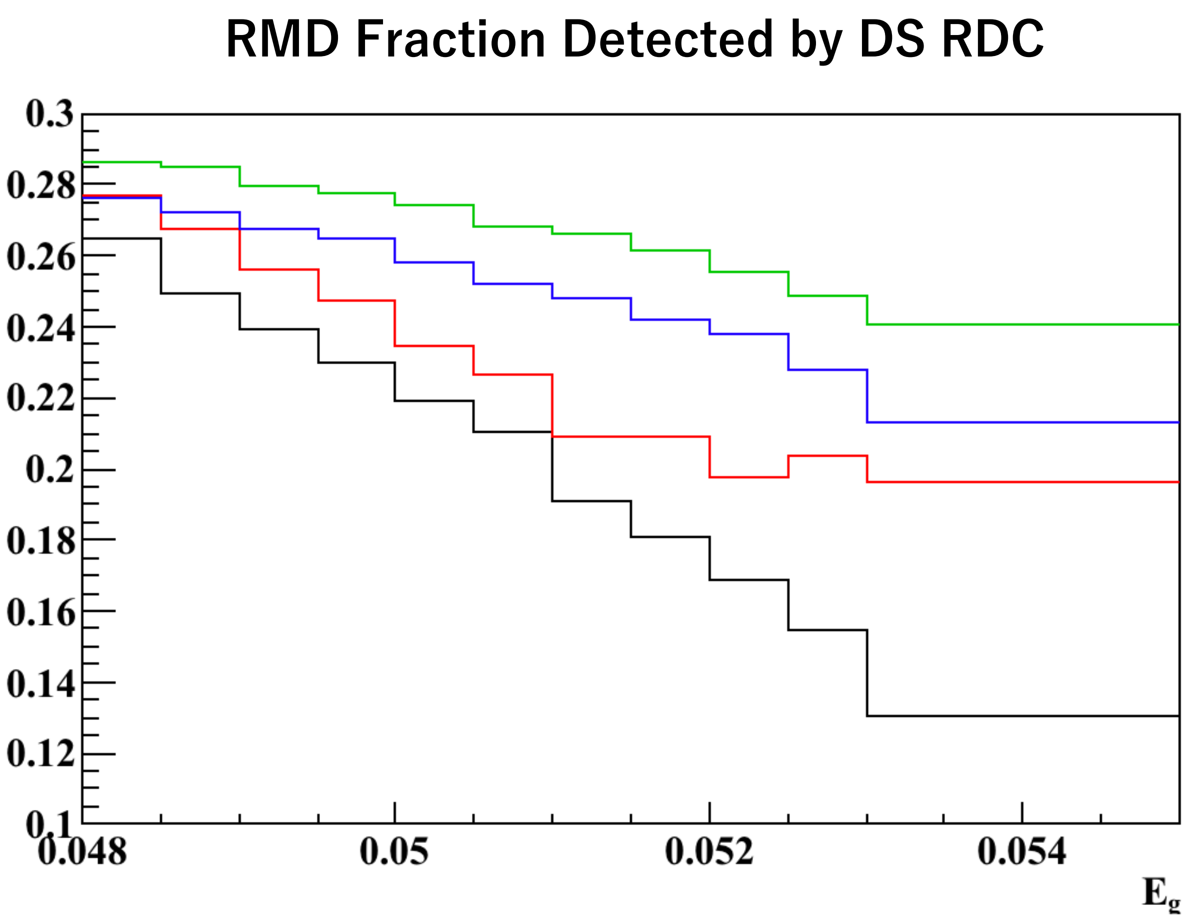
PDFs of RDC observables can be added to the likelihood function

- S_{RDC} : Signal
- R_{RDC} : RMD
- B_{RDC} : Accidental BG

RDC observables, y_i

- T_{US} : detected time by US RDC
- T_{DS} : detected time by DS RDC
- E_{DS} : detected energy by DS RDC

RDC Fraction



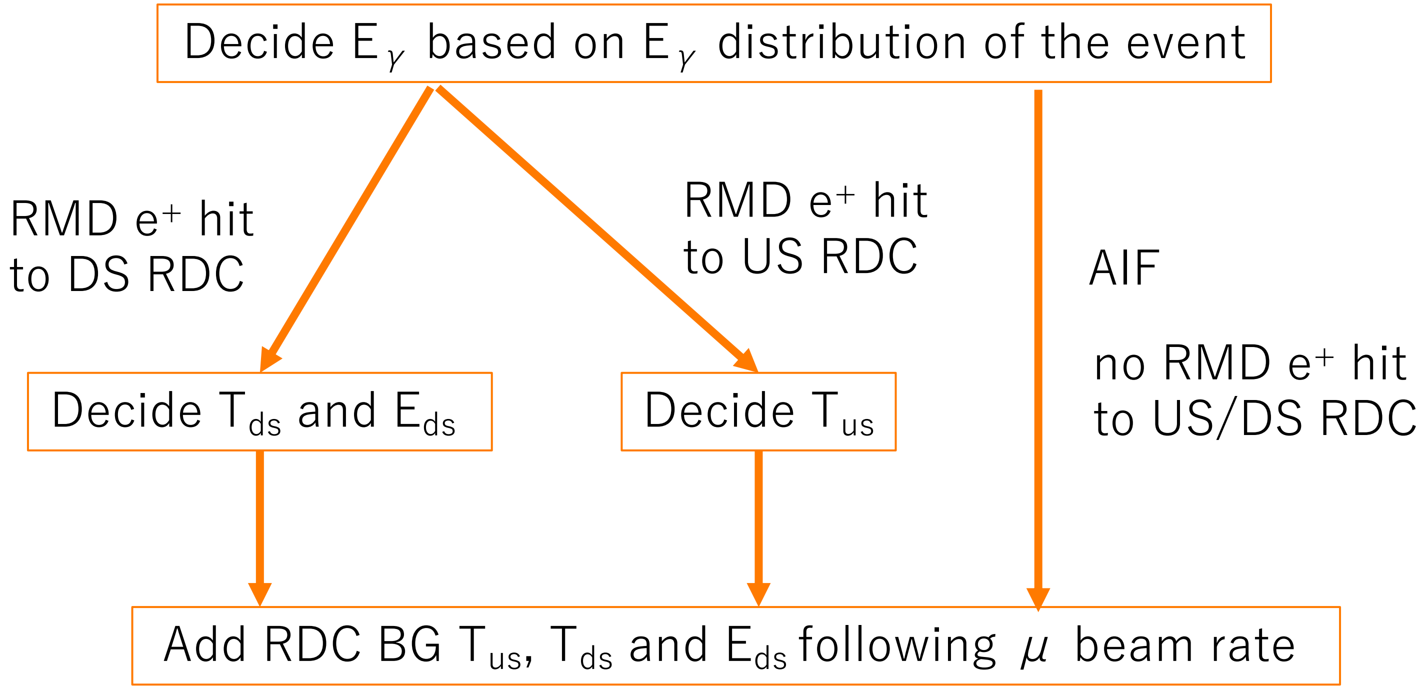
7e7 μ/s, E_γ resolution 1.9%
8e6 μ/s, E_γ resolution 1.9%
7e7 μ/s, E_γ resolution 1.2%
8e6 μ/s, E_γ resolution 1.2%

PDF Generation from Data

PDF can be generated by

- E_γ distribution
- RMD fraction detected by RDC
- RMD timing/energy distribution
- Michel timing/energy distribution

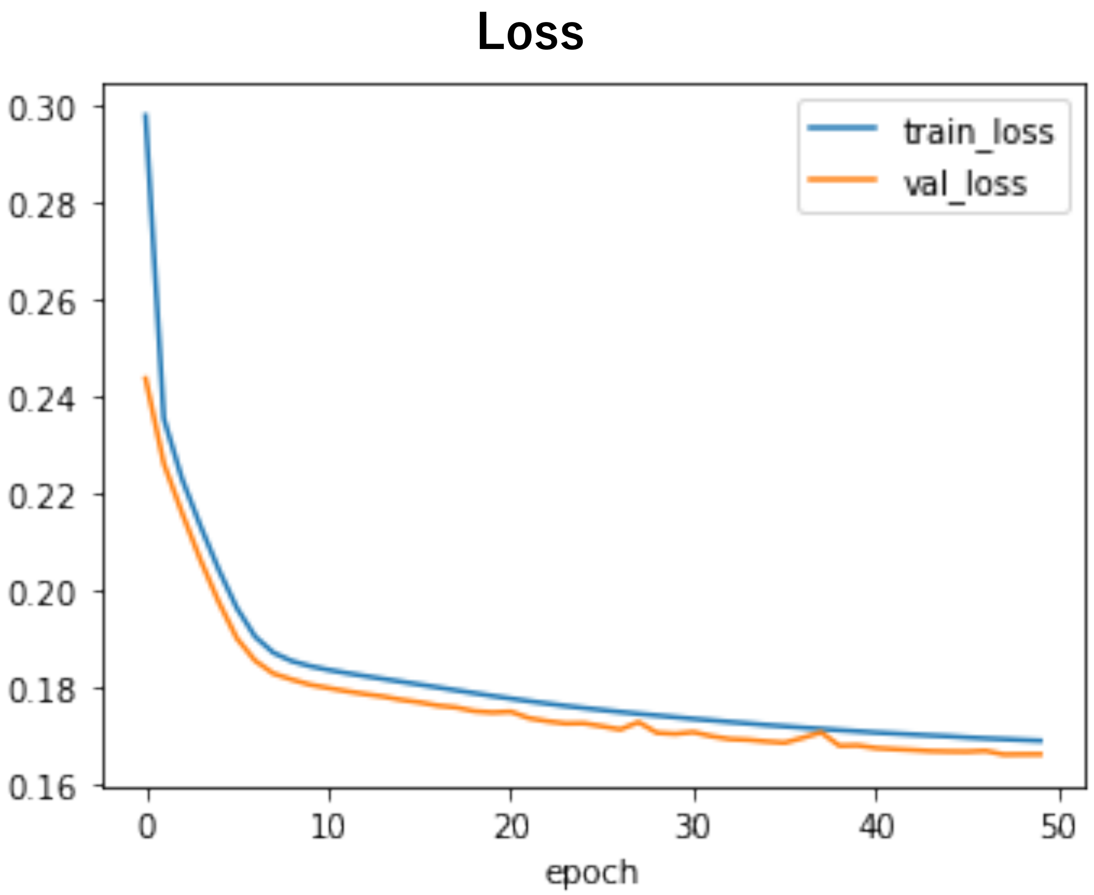
extracted from data.



Neural Network Training

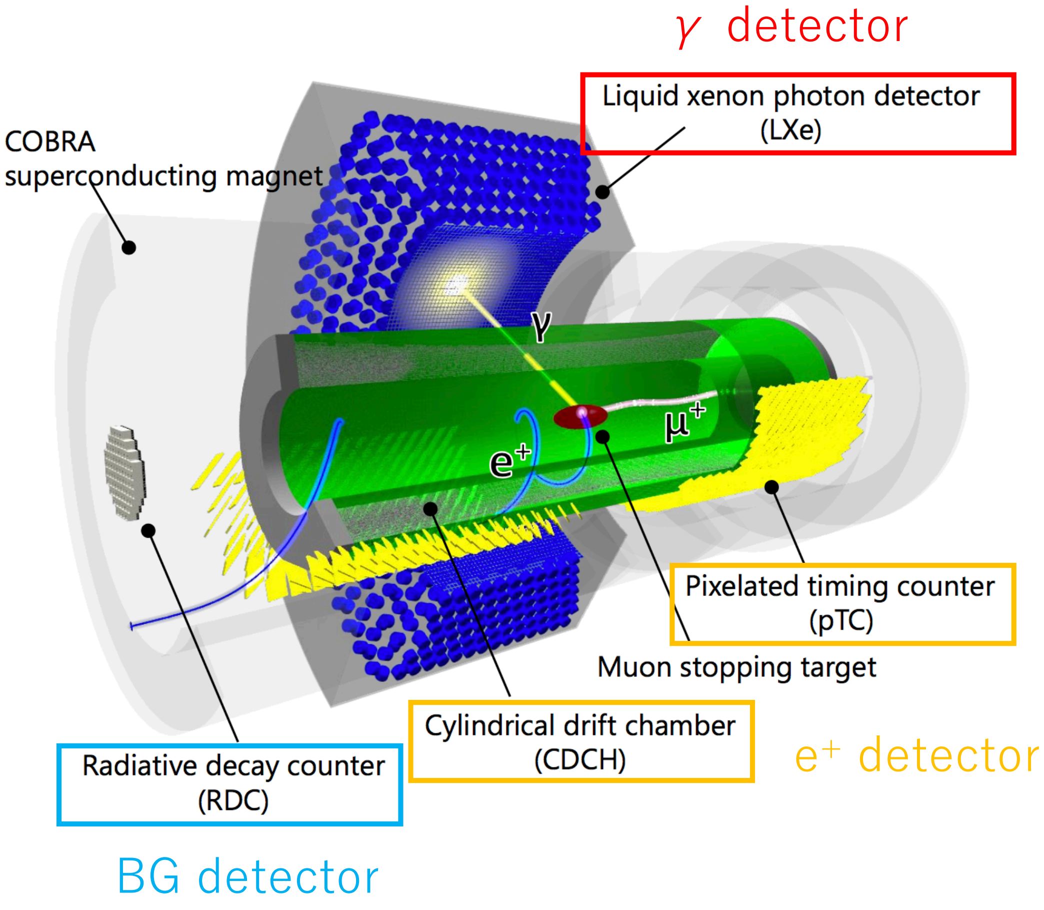
Training configuration

- activation: ELU
- optimizer: NAG (lr=5e-3)
- loss: binary cross entropy



The model converged successfully without over-fitting.

MEG II Experiment



Upgraded from MEG

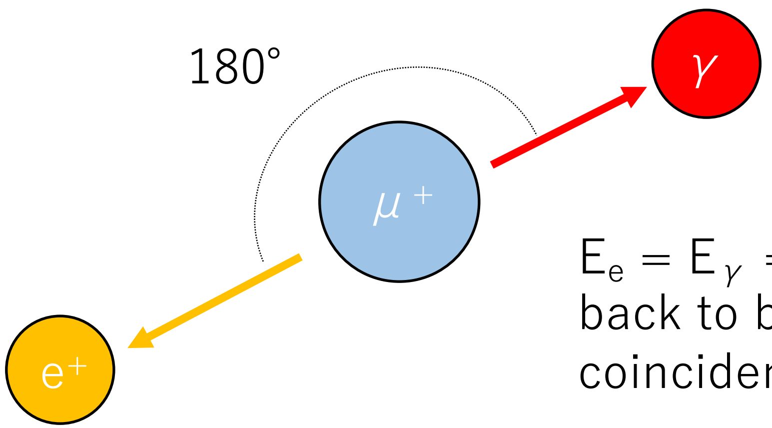
- μ^+ beam stopping rate
  $3\times10^7\ \mu^+$ stops/s $\rightarrow 7\times10^7\ \mu^+$ stops/s
- Improved efficiency and resolution of each detector
- Installed a new detector for BG detection

Expected sensitivity :

$5.3\times10^{-13} \rightarrow 6\times10^{-14}$

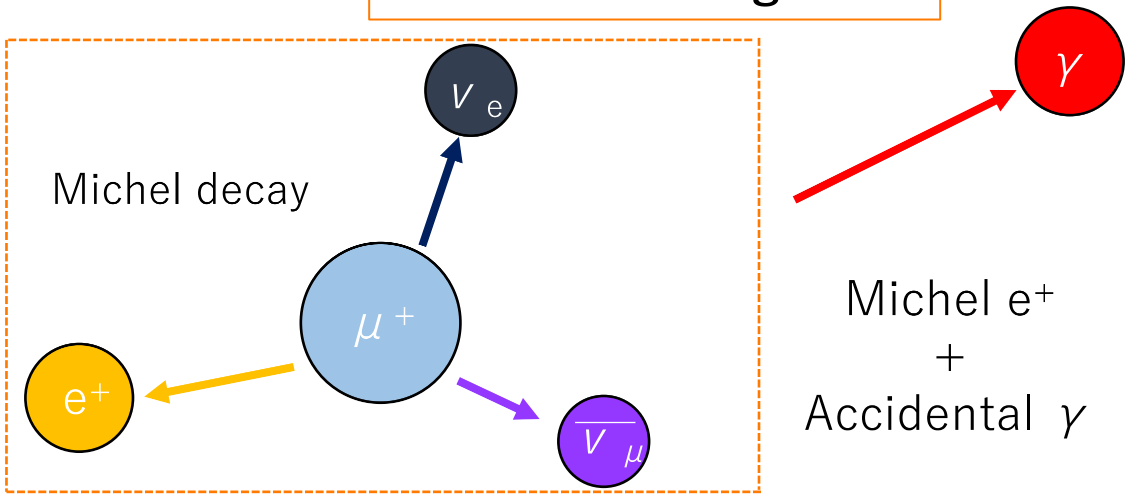
Signal & BG in MEG II

$\mu \rightarrow e\gamma$ signal



$E_e = E_\gamma = 52.8$ [MeV]
back to back
coincident in time

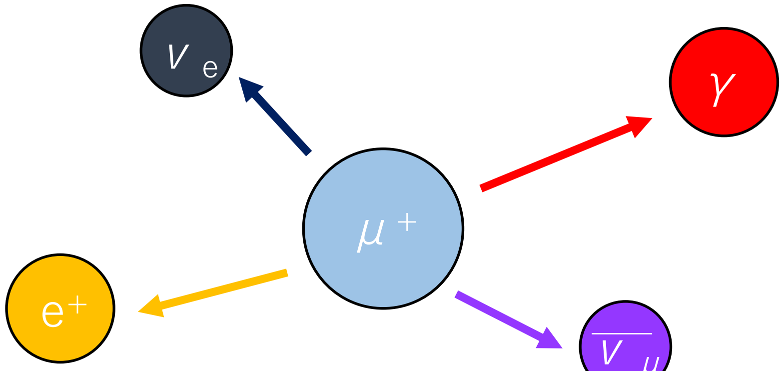
Dominant Background



Michel e^+
+
Accidental γ

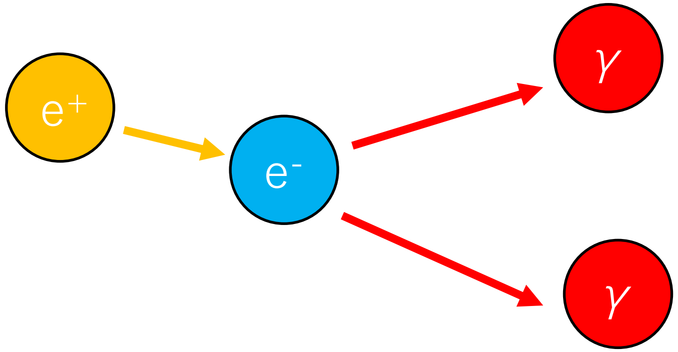
Sources of Accidental γ

Radiative Muon Decay(RMD)



2 : 1
(E_γ > 48 MeV)

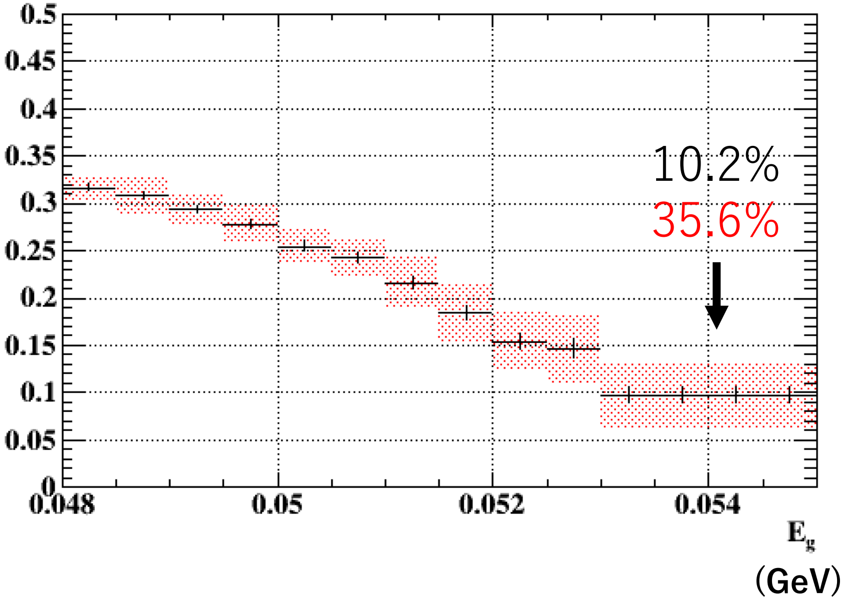
Annihilation In Flight(AIF)



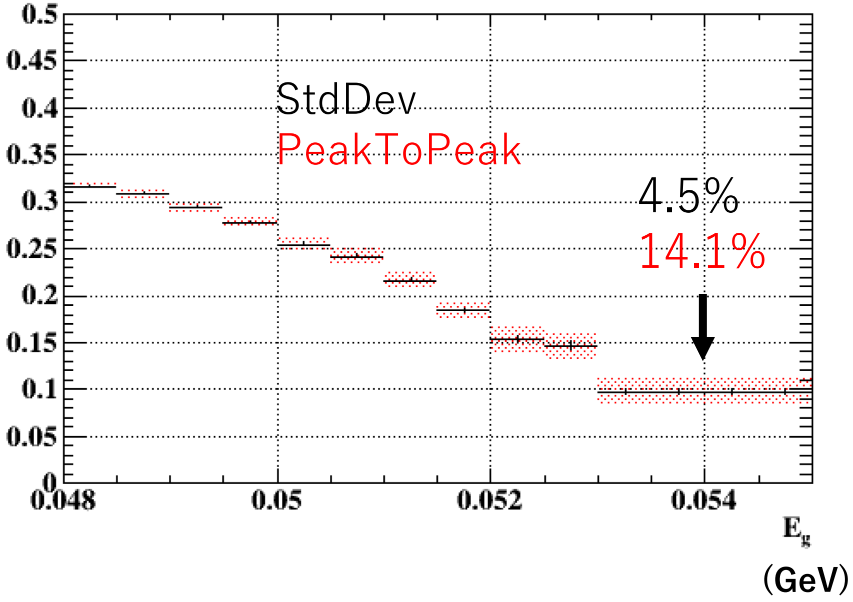
Uncertainty from RDC PDF

Uncertainty of RMD Fraction Detected by RDC

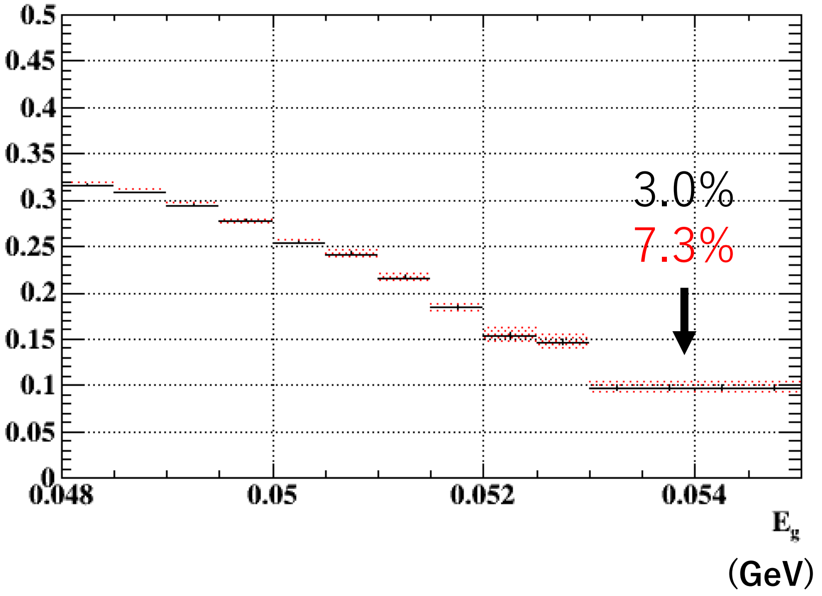
1×10^{6} events



5×10^{8} events



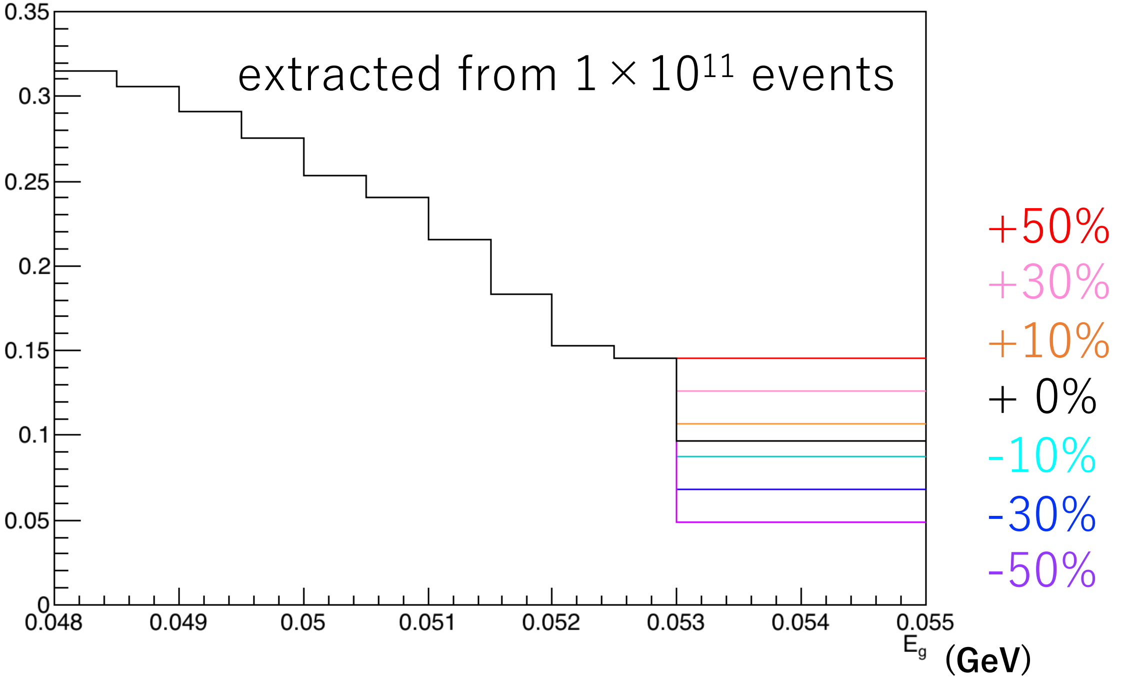
1×10^{7} events



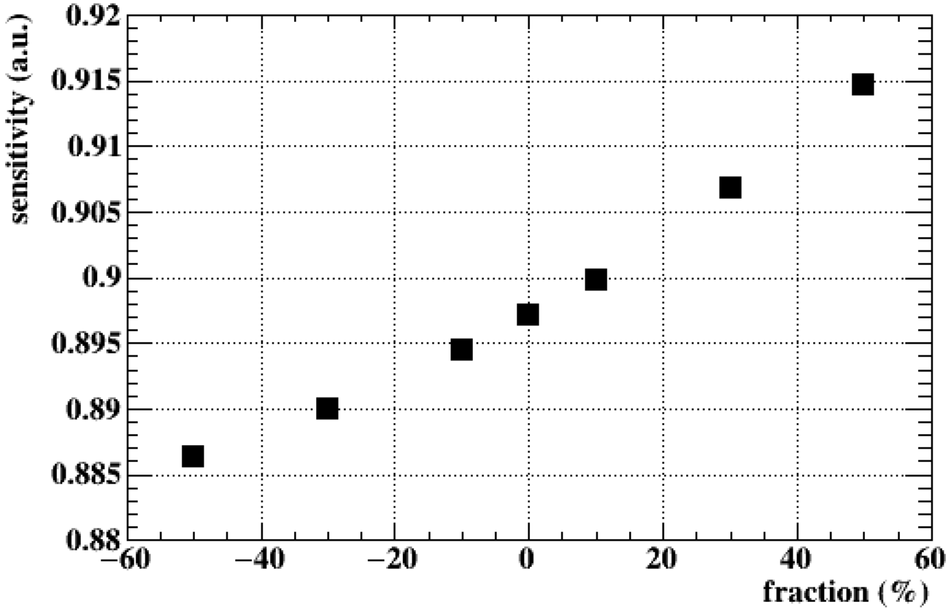
- Uncertainty of sensitivity coming from RDC PDF must be investigated.
- The uncertainty of RMD fraction detected by RDC can be dominant.
  - RDC fractions were extracted with different datasets.
  - Their mean and uncertainty are shown.
  - Large uncertainty was observed.

Effect of High E_γ Bin

RMD Fraction Detected by RDC

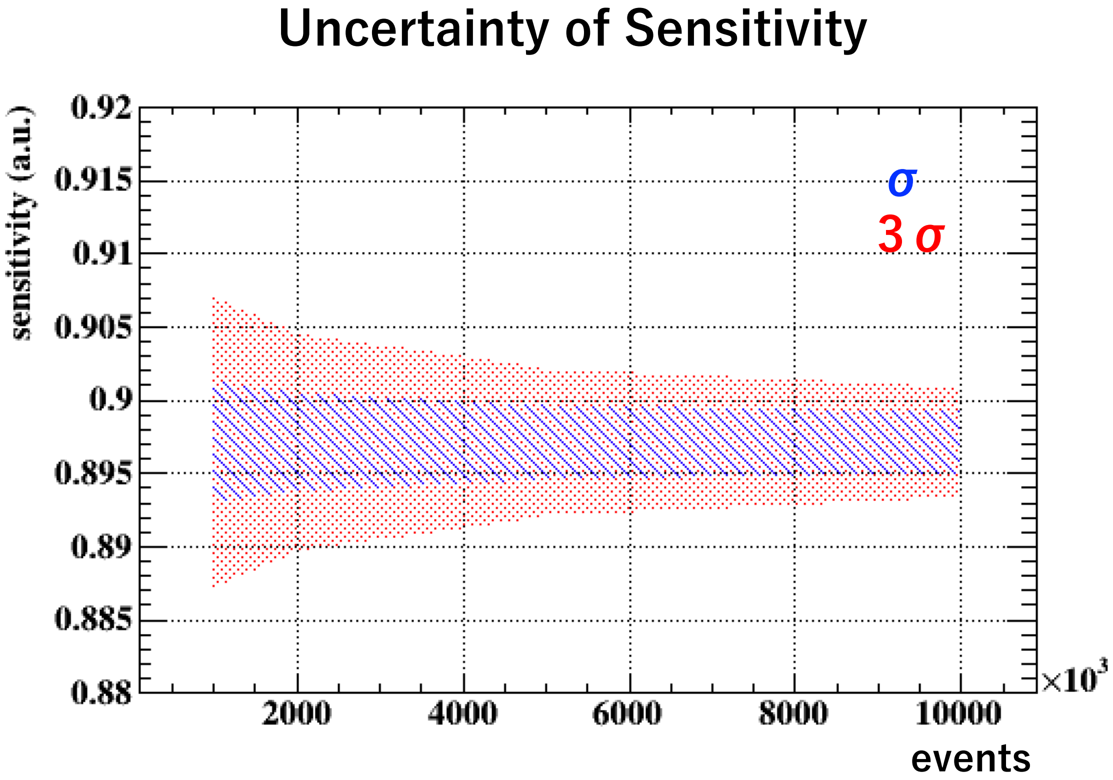


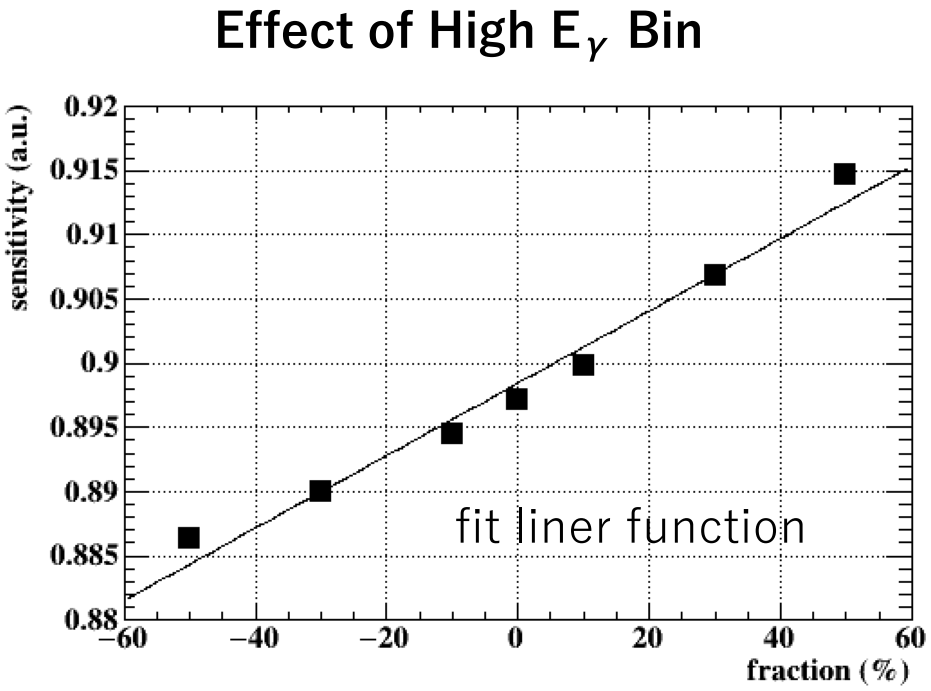
Sensitivity with Different Fraction



- The effect of the uncertainty of RDC fraction was studied.
  - RDC fraction was extracted with the same way from a higher statistics PDF.
  - The fraction of the final bin was changed manually to evaluate its effect.
- The sensitivity changed accordingly.
  → The uncertainty of the final bin affects the sensitivity.

Uncertainty of RMD Fraction Detected by RDC





- The effect on the sensitivity was estimated.
  - Only the uncertainty of the final bin was taken into account.
  - The relation between the sensitivity and the error was supposed to be linear (see the right plot).
- The uncertainty is 0.3% with ~1×10^6 entries.

Improvement of the Uncertainty of RDC Fraction

- The uncertainty of RDC fraction can affect the sensitivity.
- Two possible ways to improve the uncertainty:

1. **Increase of statistics**
    - The limitation comes from selection efficiency.
    - Original: 10Hz * 3600 sec * 24 h * 120 days ~ 1×10^8 events per year
    - After selection: ~1×10^6 events
    - Improvement of selection scheme can increase statistics for RDC PDF.
2. **Extraction based on MC**
    - Fitting RDC fraction can reduce the uncertainty in the low statistics region.
    - Consistency with data and effects of fitting errors must be evaluated.

Summary & Prospect

- The effect of RDC is re-evaluated considering E_γ dependence:

  The sensitivity can be **improved by ~10%/4% thanks to DS/US RDC**.
- Statistics to create RDC PDF was found to be very high.
- Three solutions were discussed to decrease the required statistics:
  - Optimization of bin width
  - Dimension reduction
  - PDF Generation from Data
- The required statistics is still high.
- The limitation mainly comes from statistics for RDC fraction.

Summary & Prospect

- Possible ways to improve the uncertainty of RDC fraction:
  - Increase of statistics
    → investigation of optimal selection scheme after taking physics data
  - Extraction based on MC
    → on-going
- The effect of non-linearity of LYSO must be checked w/ data.

Recalculation of the Sensitivity with RDC

06/08/2020

Reminder

Physics Analysis

- MEG physics analysis is based on the Maximum Likelihood Analysis.
- The number of signal event (N_{sig}) is estimated.
- Likelihood function contains three probability density functions (PDFs):
  - Signal
  - Radiative muon decay (RMD)
  - Accidental background (AccBG)
- RDC observables, T_{us}, T_{ds} and E_{ds} are added to the analysis by defining RDC PDFs.