ジルコニウム96を用いたニュートリノを放出しない二重ベータ崩壊事象の探索XXIV
～ニュートリノを放出する二重ベータ崩壊事象の観測実験の準備状況～

日本物理学会　第80回年次大会
（広島大学東広島キャンパス）

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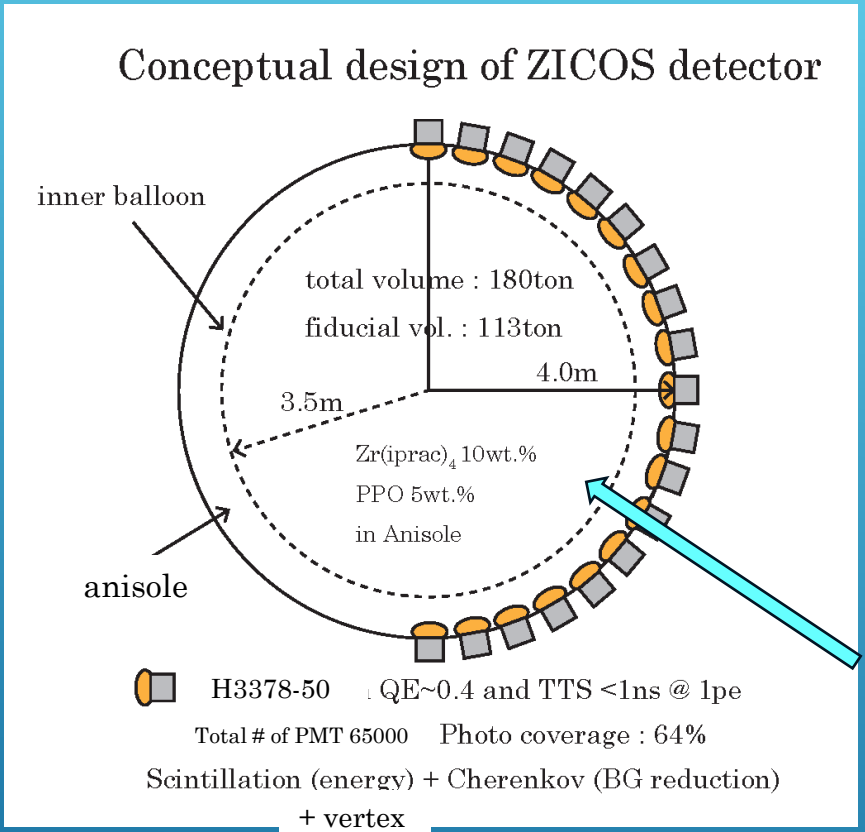
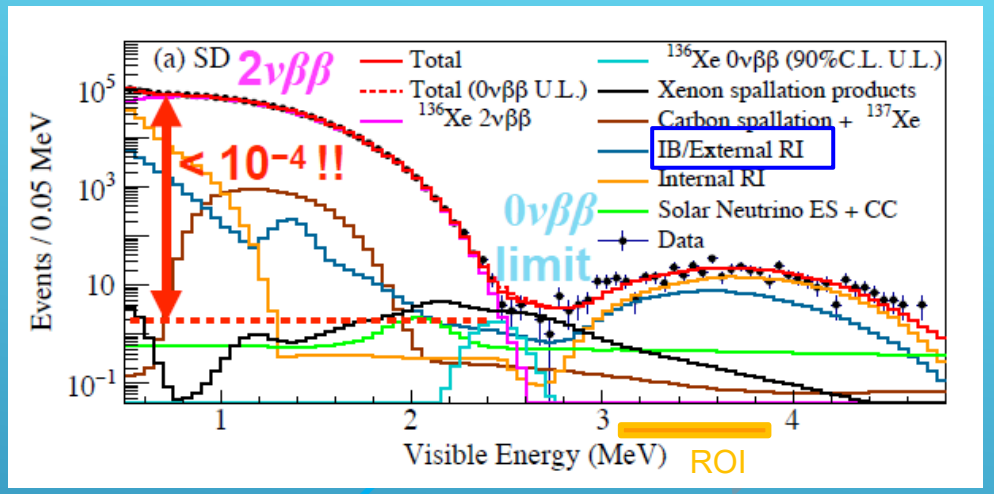
ZICOS experiment for ^{96}Zr 0νββ observation





I.Shimizu, Plenary talk at Neutrino2024 conference.

Liquid scintillator loaded ^{96}Zr

NEMO3 : $T^{0\nu}_{1/2} > 9.1 \times 10^{21}$ yrs

^{96}Zr : 45 kg (nat.) → 865 kg(50 % enrich)→1/20 BG

$T^{0\nu}_{1/2} > 4 \times 10^{25}$ yrs → 2×10^{26}yrs → ~1 $\times 10^{27}$yrs

Setup for 2ν-ZICOS detector

- 20 2” Ultra Low BG PMT Hamamatsu R10789.
- 16 cm diameter round bottom flask using ultra-pure Quartz.
- 0.73L of ZICOS LS loaded 73g of $Zr(iPrac)_4$ including ^{96}Zr 0.27g.

2ν+ZICOS detector

- 20 2” Ultra Low BG PMT Hamamatsu R10789.
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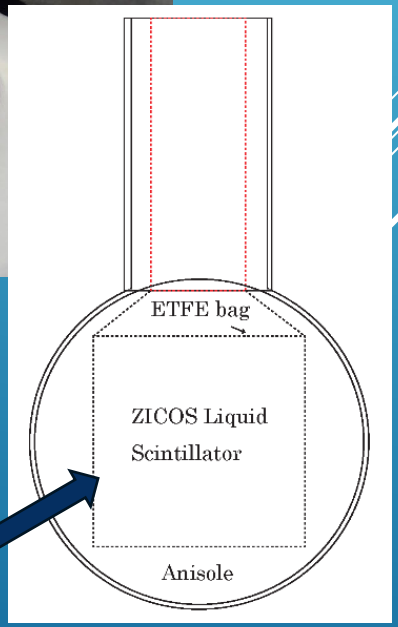
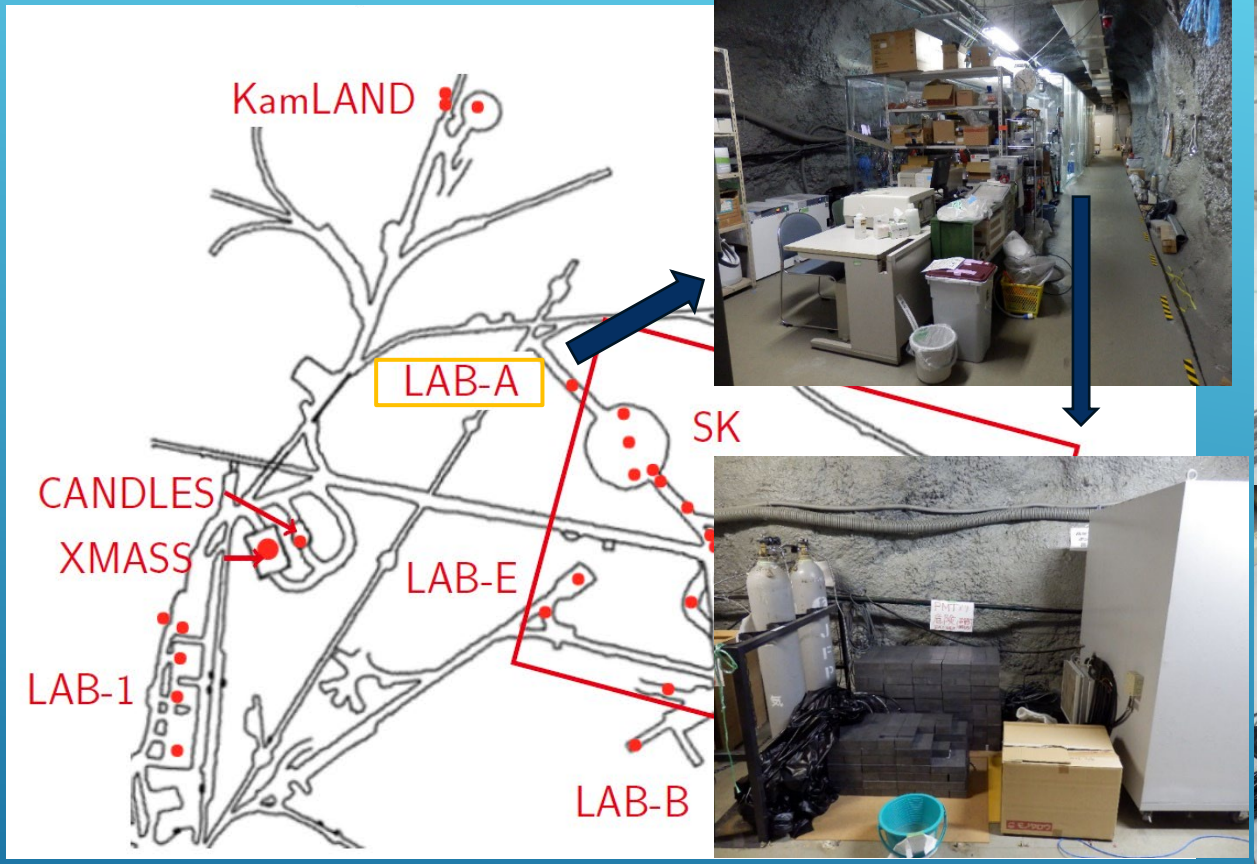
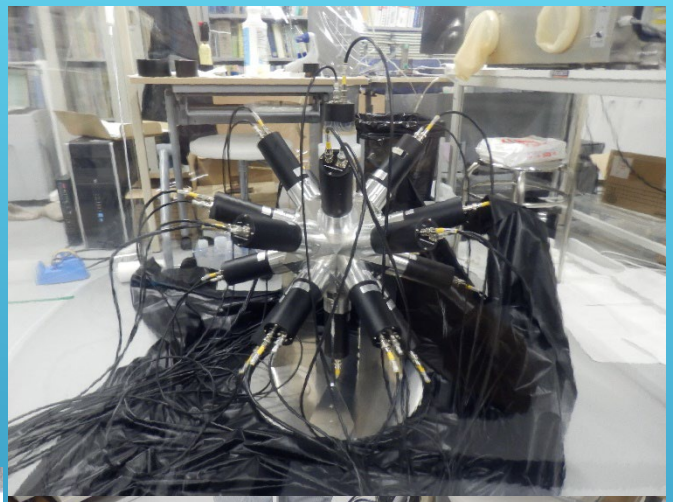
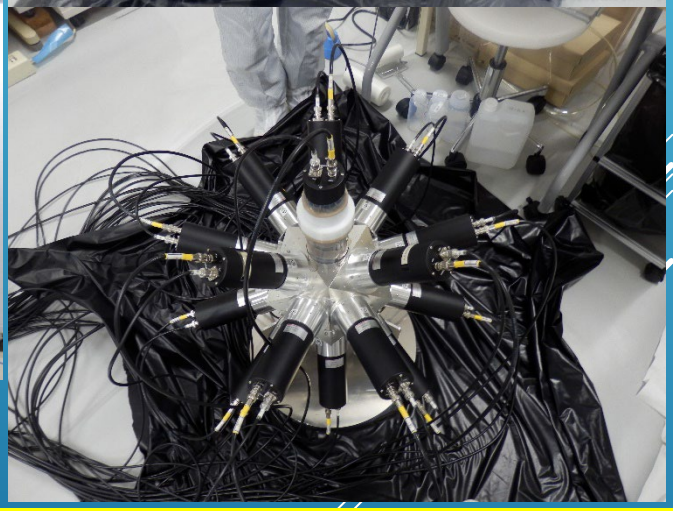


9cm cubic ETFE bag for reducing external BG events

2ν-ZICOS for measurement of 2νββ half-life



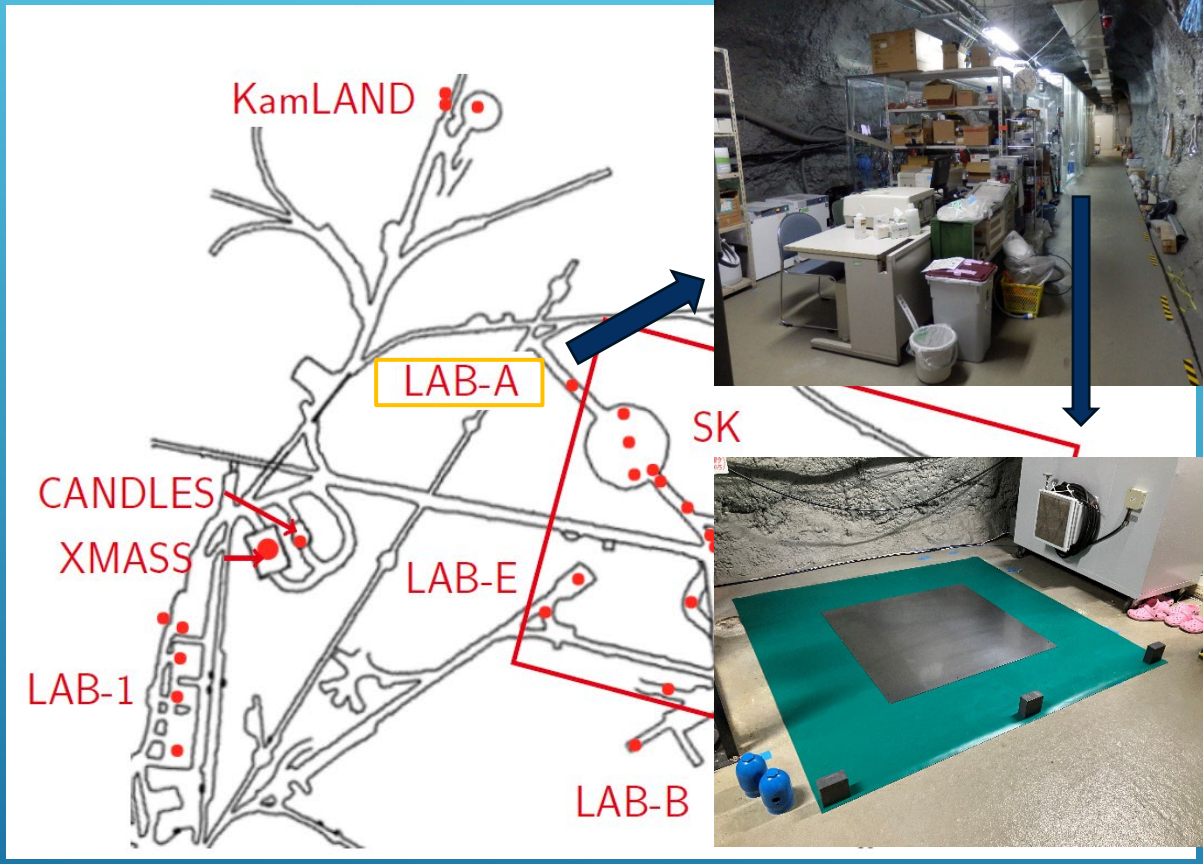


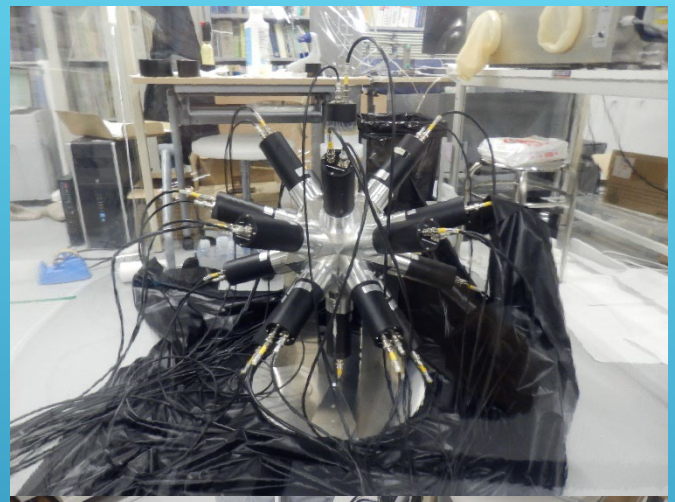


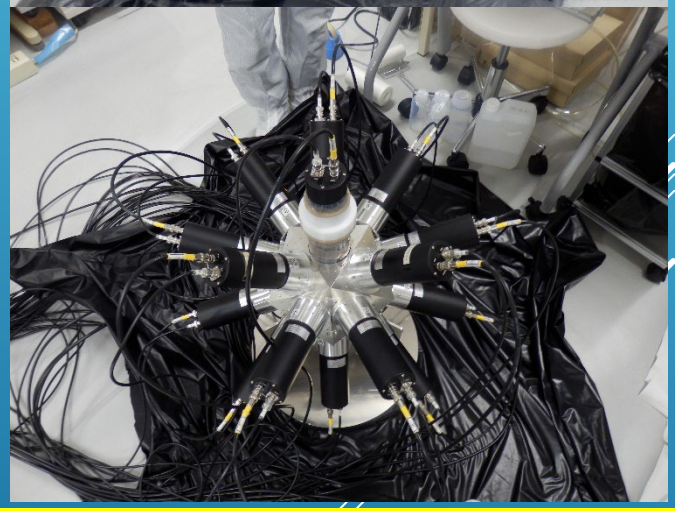
In Kamioka mine LAB-A : Behind of LINAC control room

Now we are testing on the ground.

2ν-ZICOS for measurement of 2νββ half-life







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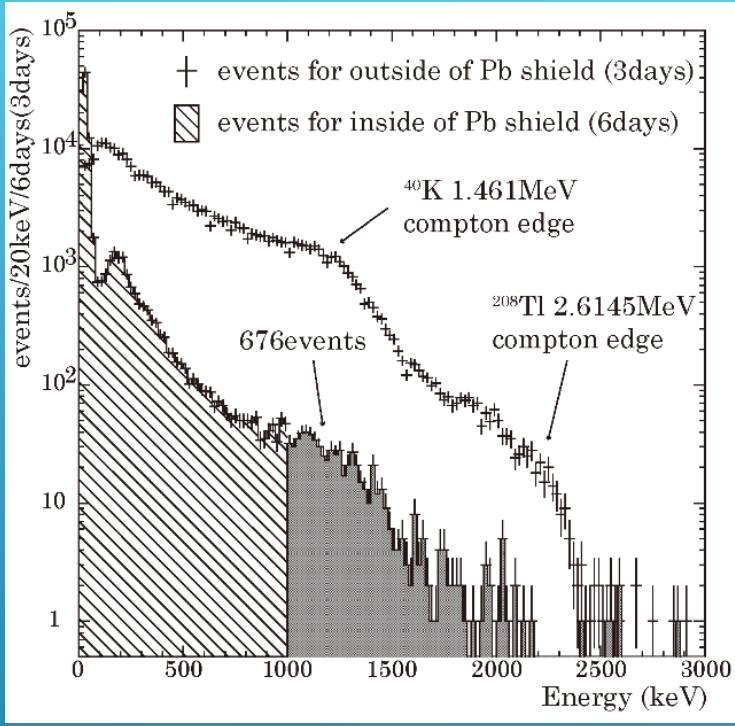
Are we ready to start 2ν-ZICOS in the mine?

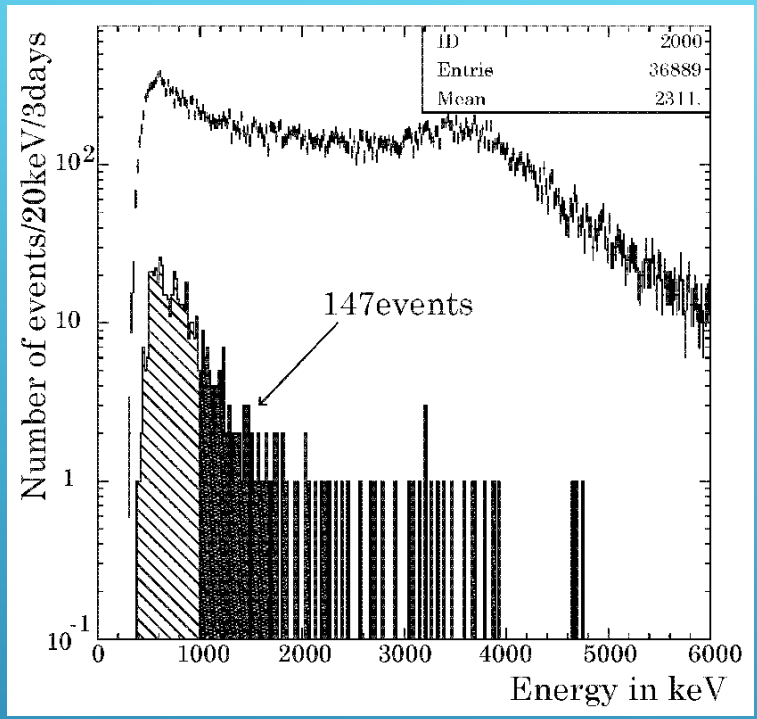
To show the detector performance of 2ν-ZICOS experiment, we measured following things.

1. Using calibration source, is observed energy spectrum consistent with simulation?
2. Does energy scale have a linearity?
3. Are all PMT gains adjusted for reconstructed vertex position and averaged angle?
4. Are reconstructed vertex and averaged angle consistent with the simulation?
5. Is background events low enough?
6. Is background spectrum understood?

Comparison between H3378-50 and R10789



H3378-50

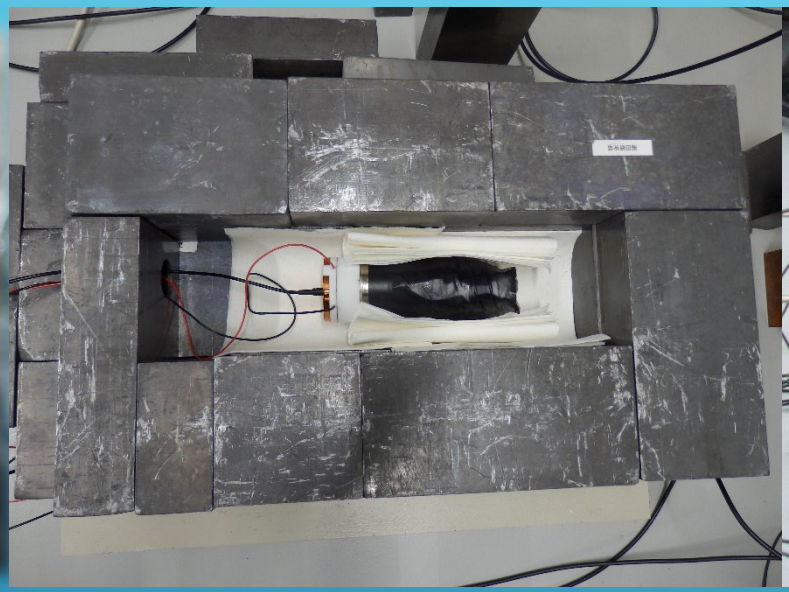


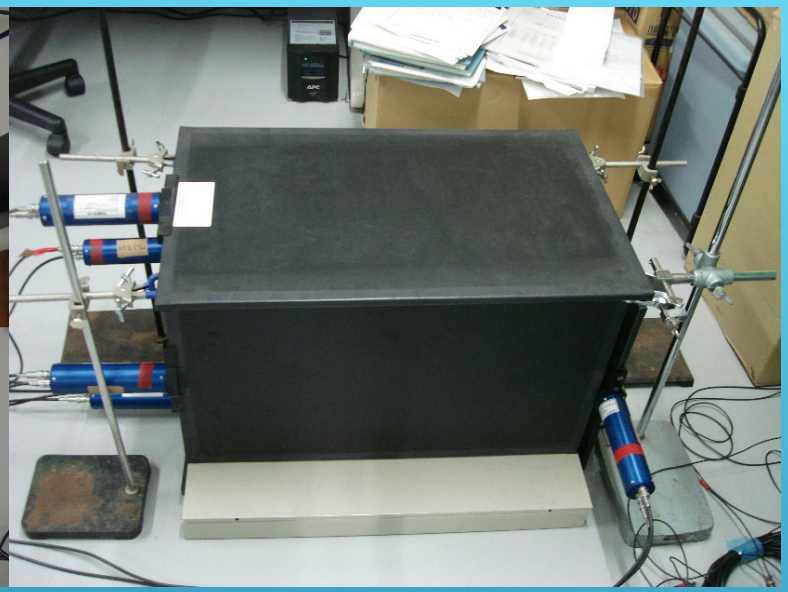
R10789

- No. of BG events above 1MeV decreased about 1/3
- Most of those events come from PMT origin.

We must use PMT R10789 for 2n-ZICOS

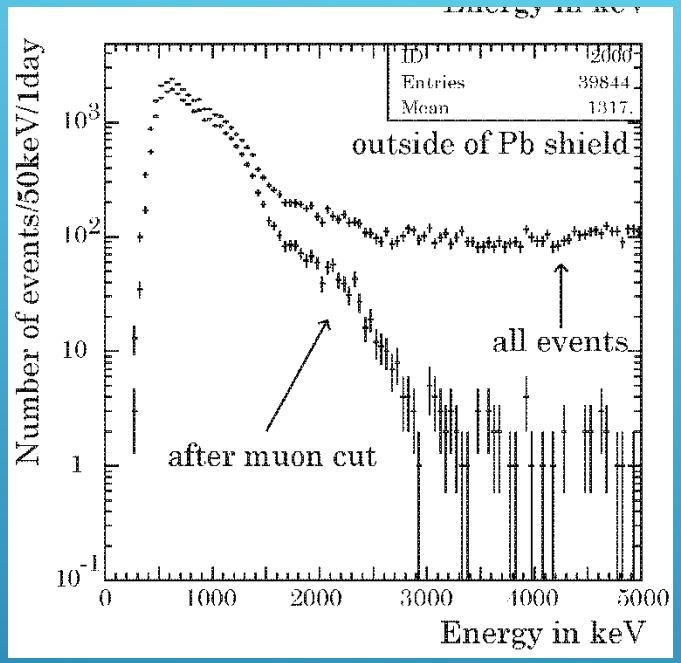
BG measurement using 20mL quartz vial

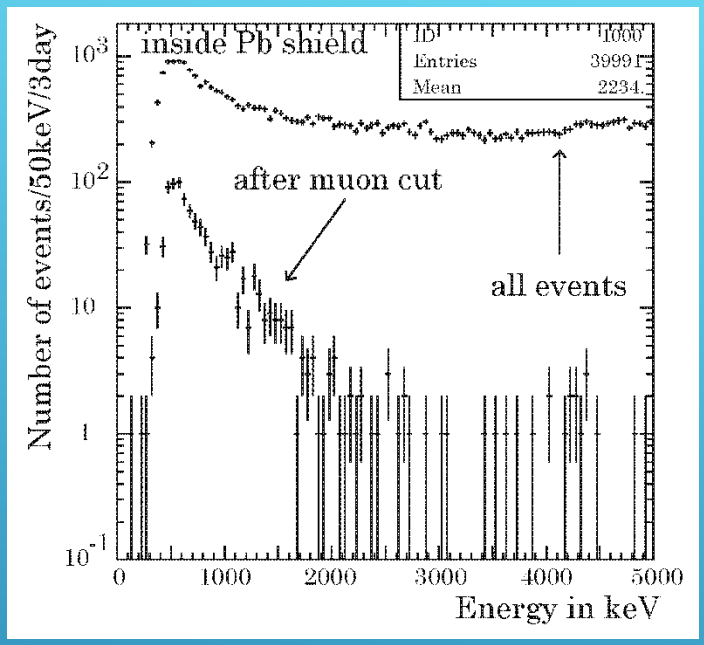




- Difficult to measure BG events for 2ν-ZICOS detector inside of Pb shield due to limit of number of Pb block.
- 17.5mL ZICOS LS filled in 20mL quartz vial.
- The vial contacted with XMASS PMT R10789 covered by Myra film.
- 10cm thickness of Pb radiation shield was prepared.
- In order to veto cosmic muons, plastic scintillators were located around Pb shield.

Energy spectra using Quartz vial detector



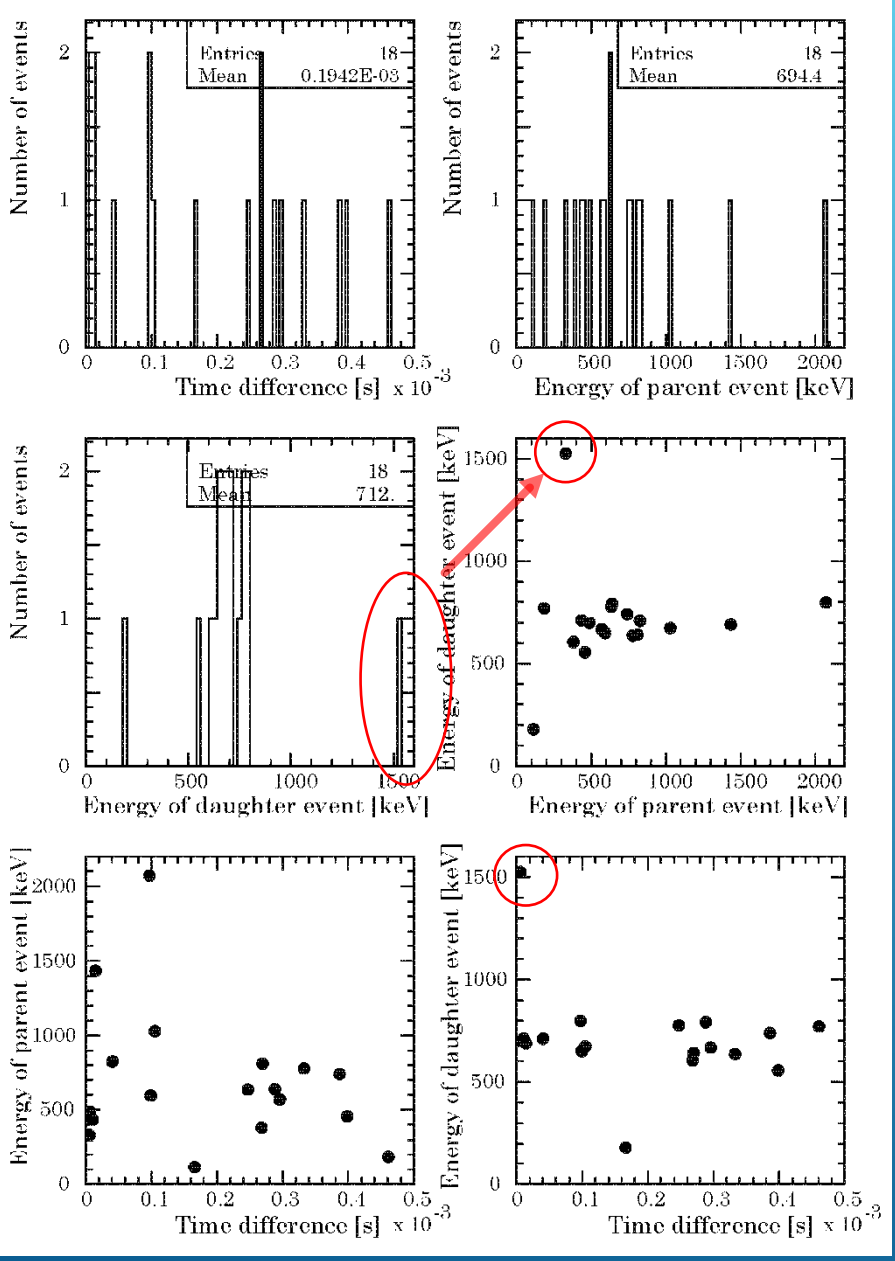


Outside of shield

Inside of shield

- Compton scattering gammas from natural ^{40}K and ^{208}Tl decay were observed for outside of Pb shield.
- Some background events were found inside of Pb shield.
- Assuming these events from U/Th in LS, we should search for ^{214}Bi -^{214}Po candidates (τ=1.643 × 10^{-4}sec)

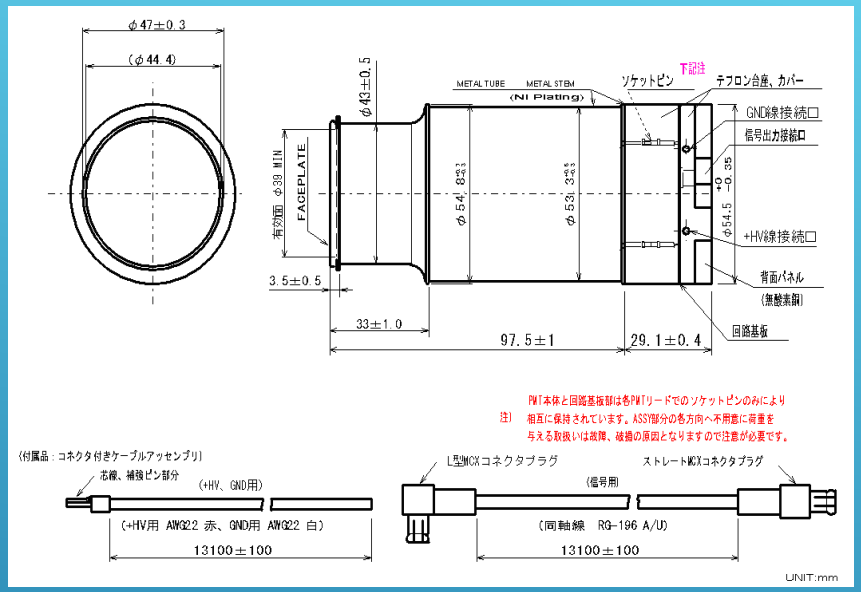
Search for ^{214}Bi-^{214}Po candidates

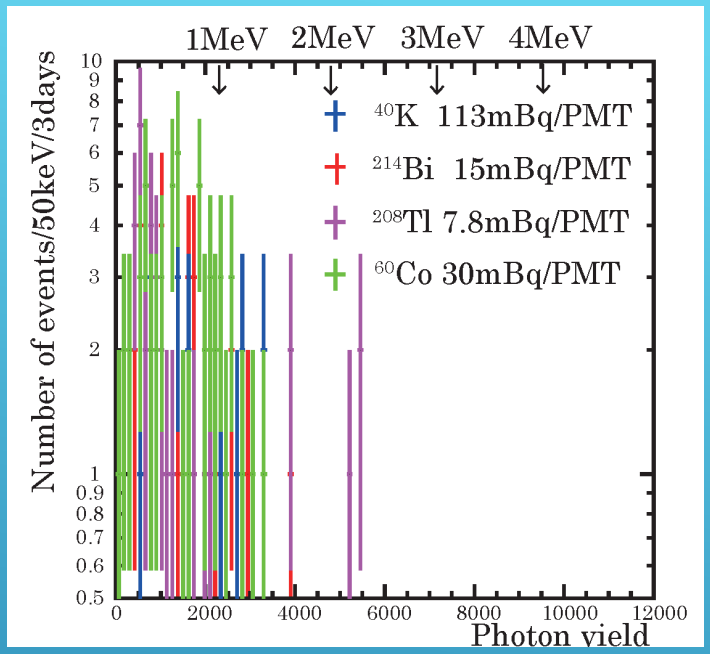


- 18events have time difference < 5×10^{-4} s except parent muon
- Parent events have wider energy distribution than daughter events
- Daughter events have narrow distribution (like α quenching)

17events looks ^{214}Bi-^{214}Po candidates. But they don't contribute residual events.

BG events from PMT R10789





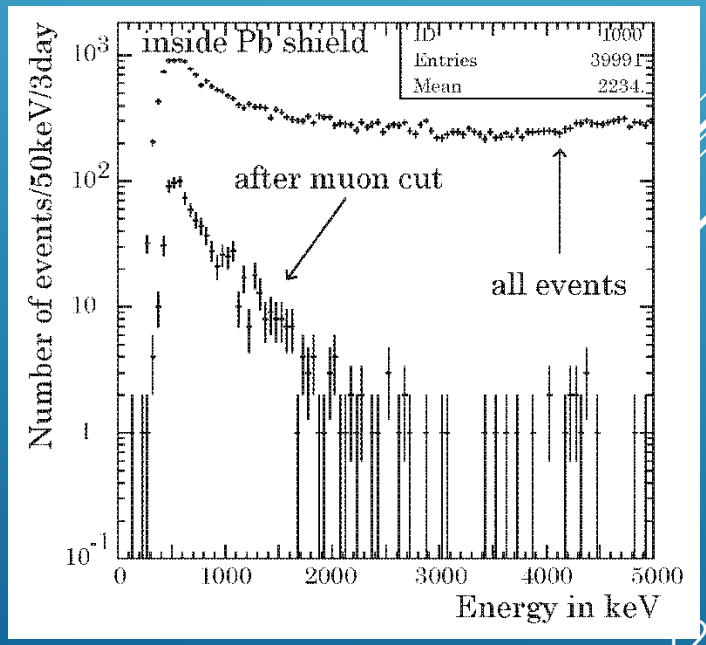
Ref: NIMA 922(2019)171-176

1.2 ± 0.3 mBq/PMT of ^{226}Ra

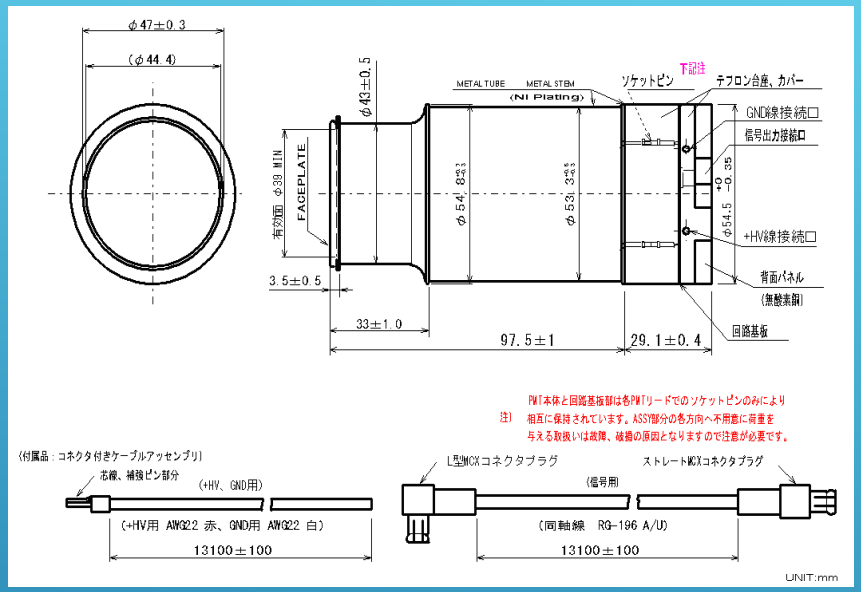
< 0.78 mBq/PMT of ^{228}Ra

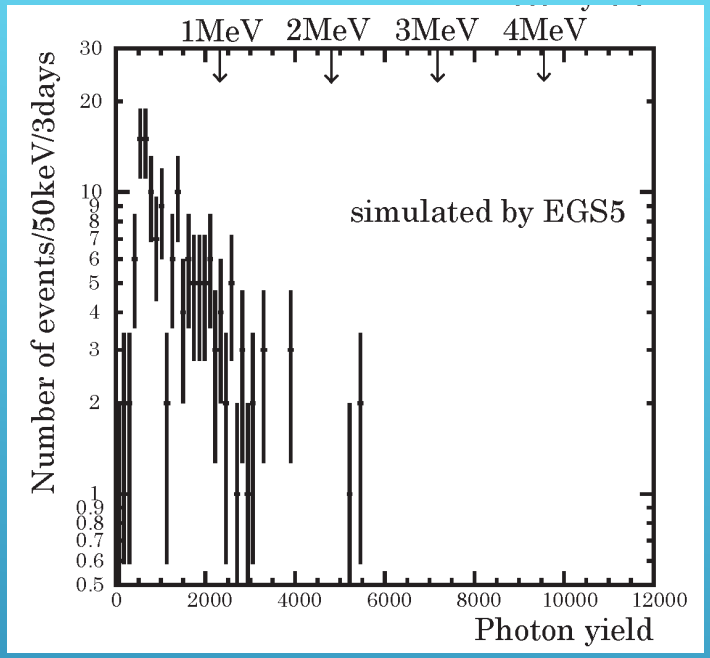
9.1 ± 2.2 mBq/PMT of ^{40}K

2.8 ± 0.2 mBq/PMT of ^{60}Co.



BG events from PMT R10789





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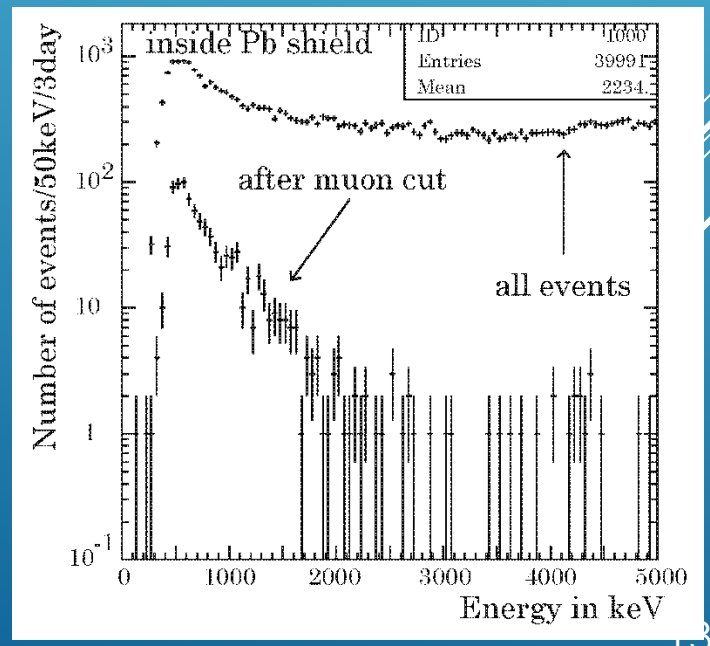


Need ~40 times larger BG events to explain the residual events.

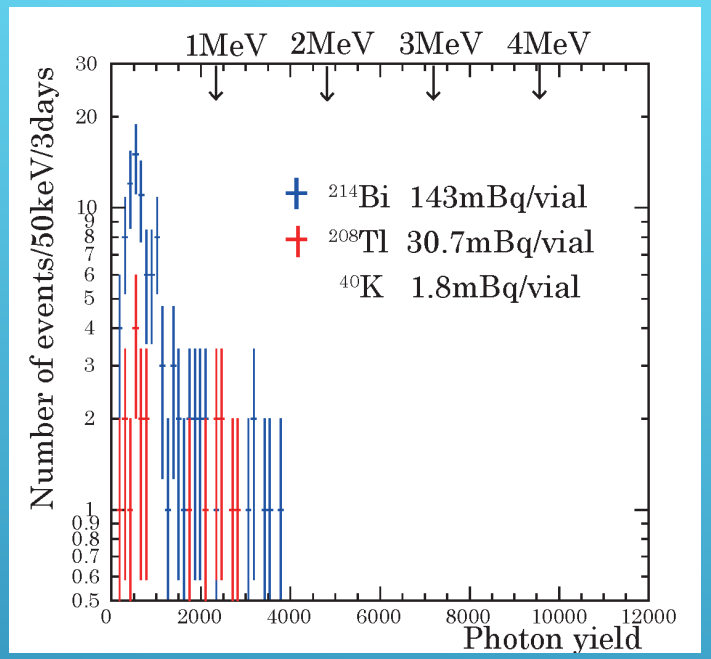
BG events from Quartz

表　分析結果

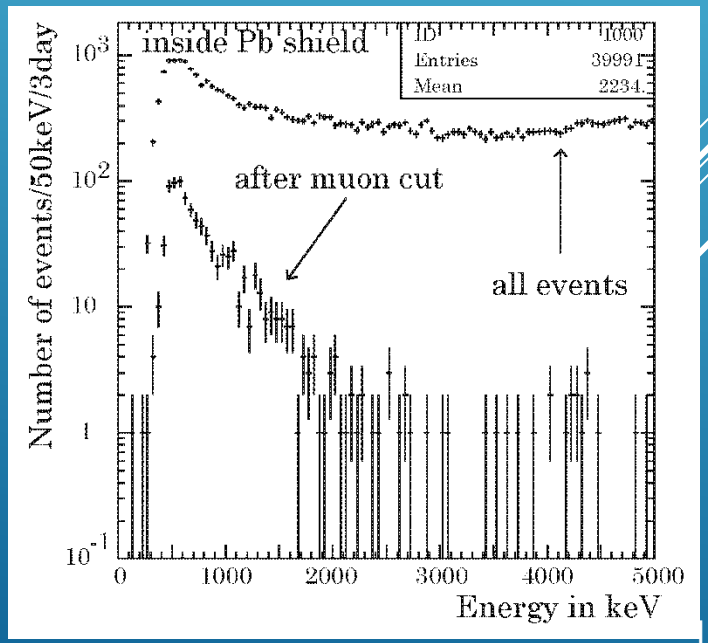
単位：ng/g

試料名	K	Th	U
RQ200	330	42	64
GE214	180	15	29
定量下限	5	1	1

Measured by Toshiba analysis using IPC mass spectrometer



14.3mBq/vial of ^{214}Bi
3.07mBq/vial of ^{208}Tl
0.18mBq/vial of ^{40}K



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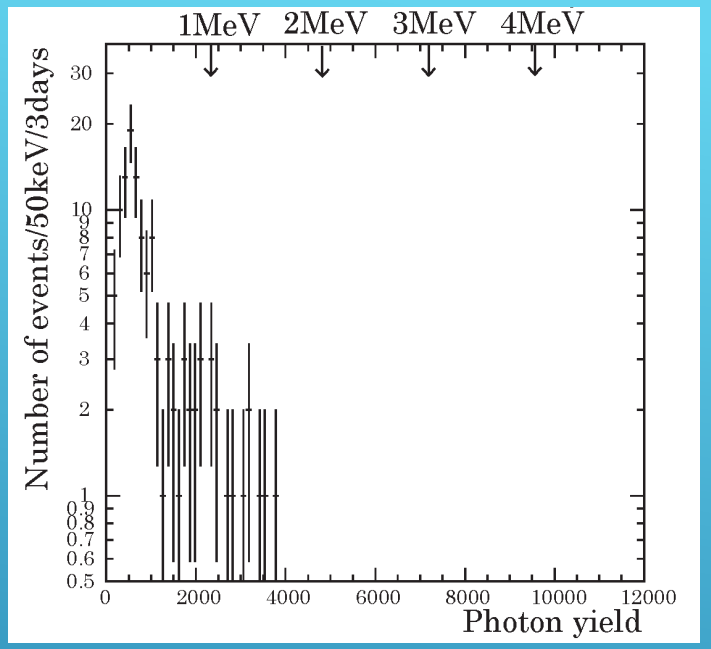

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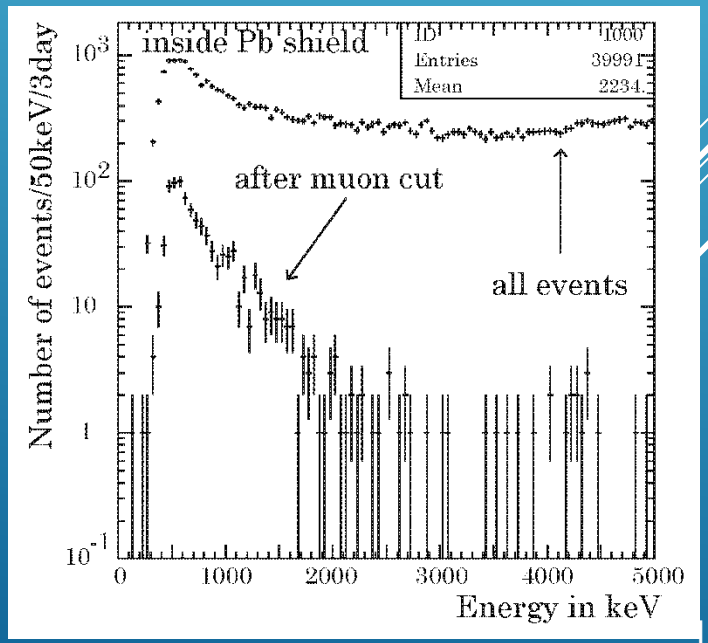
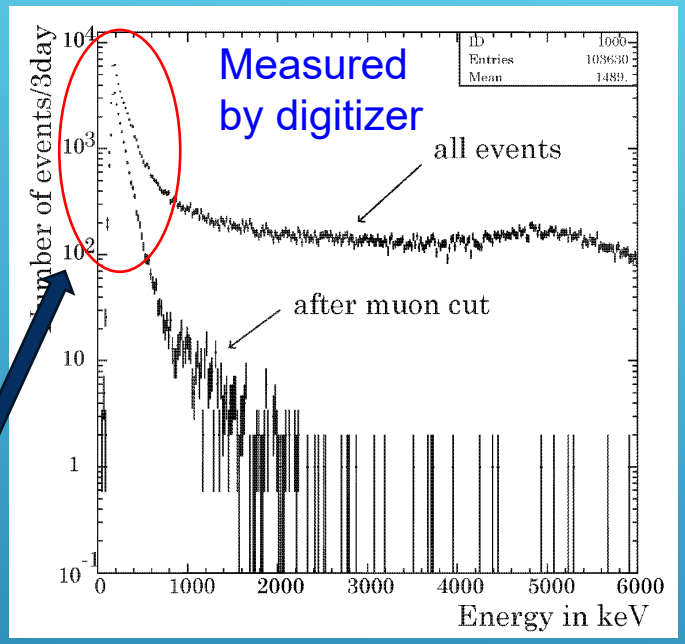
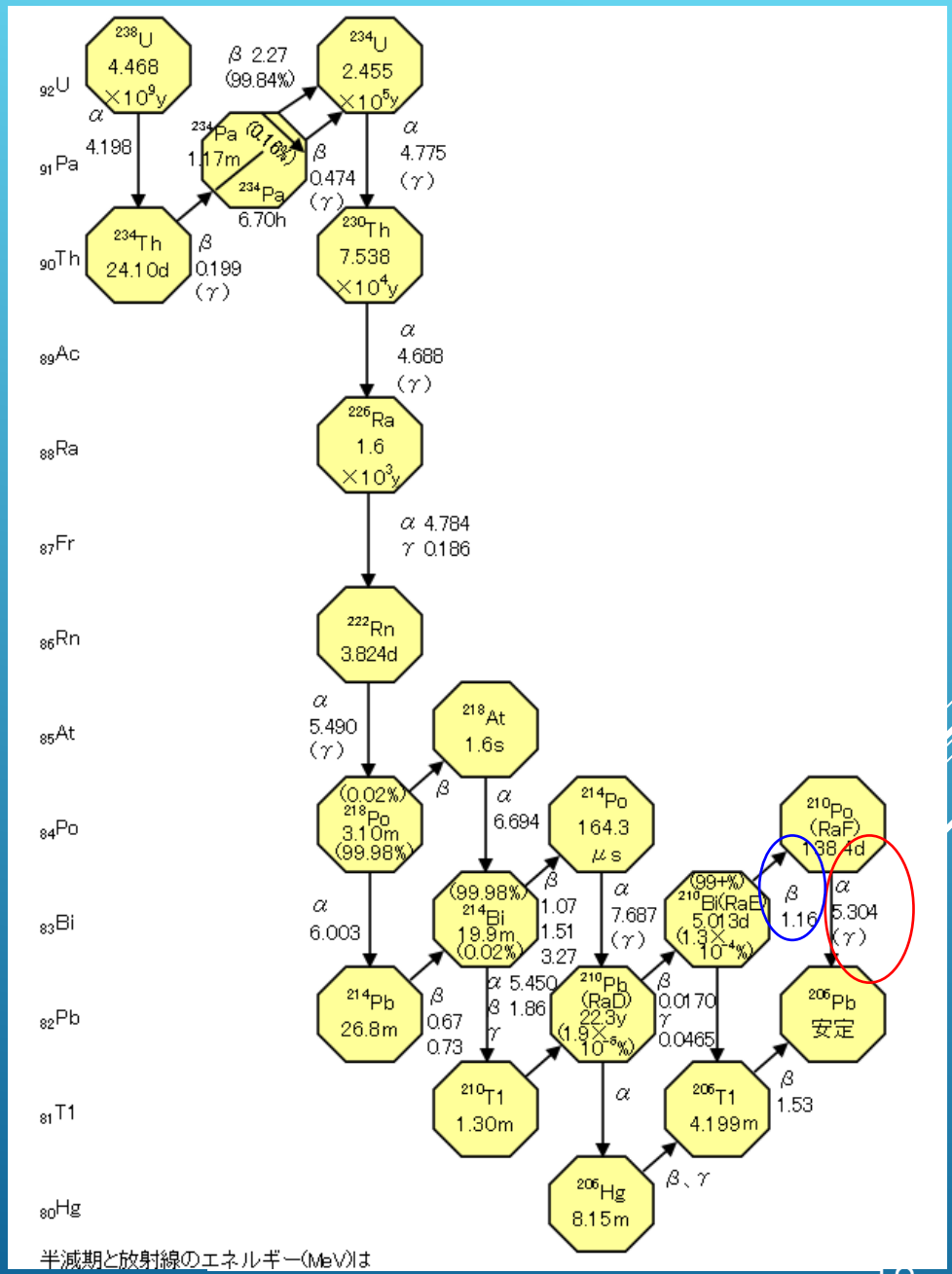


Even more 50 times larger BG events could not explain the residual events.

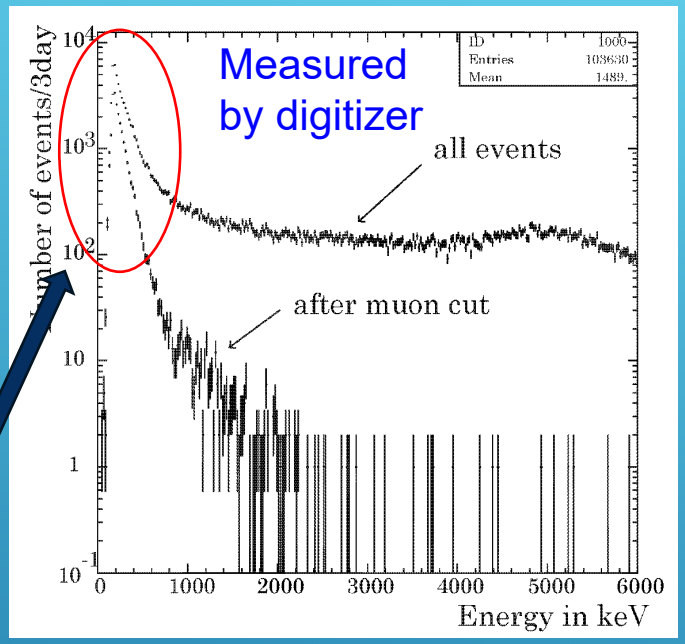
BG events from surface of Quartz

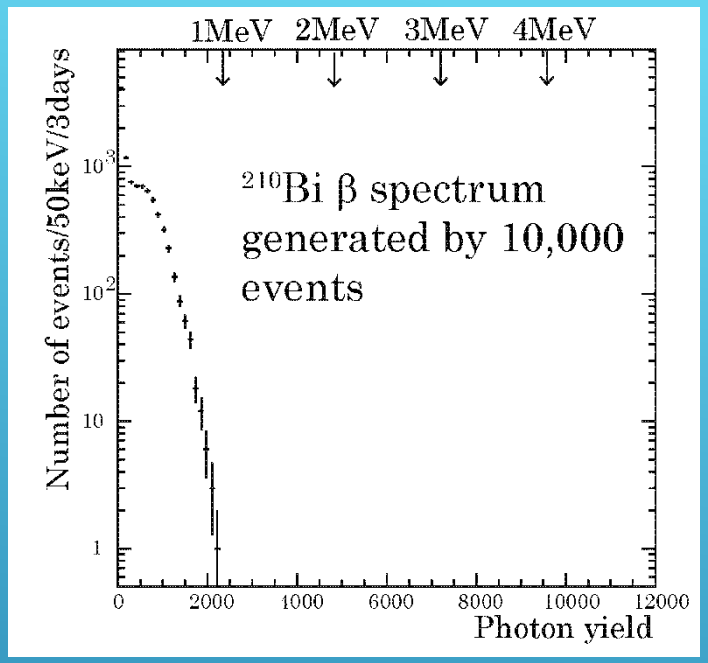


α from ^{210}Po? if so, β from ^{210}Bi should be observed by same order of events.



BG events from surface of Quartz





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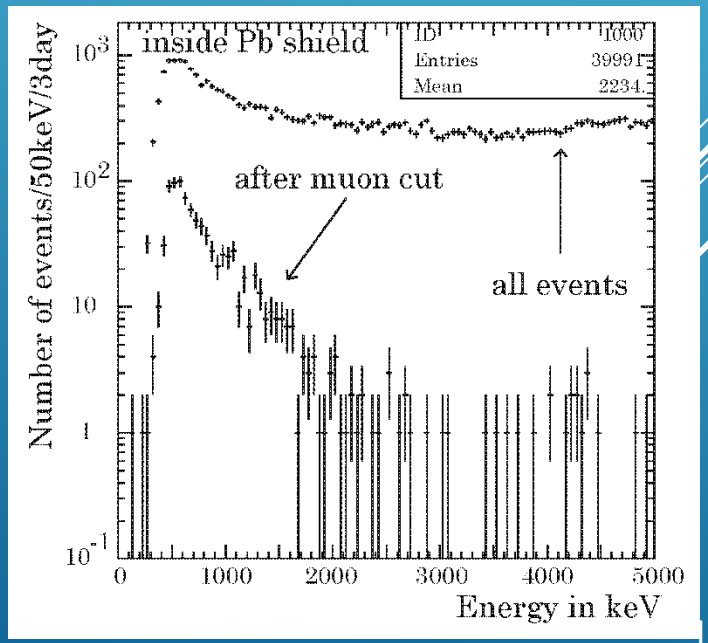
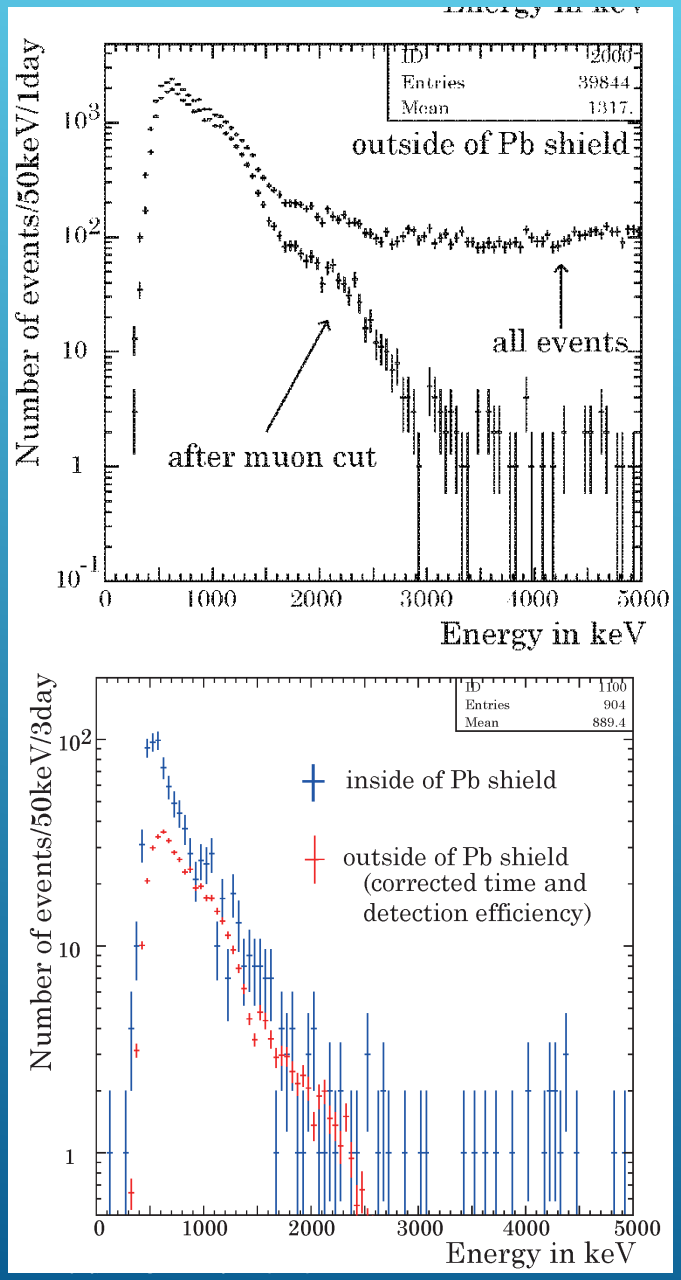


Observed rate correspond to 2mBq/cm^2, but XMASS estimated as 1μBq/cm^2.

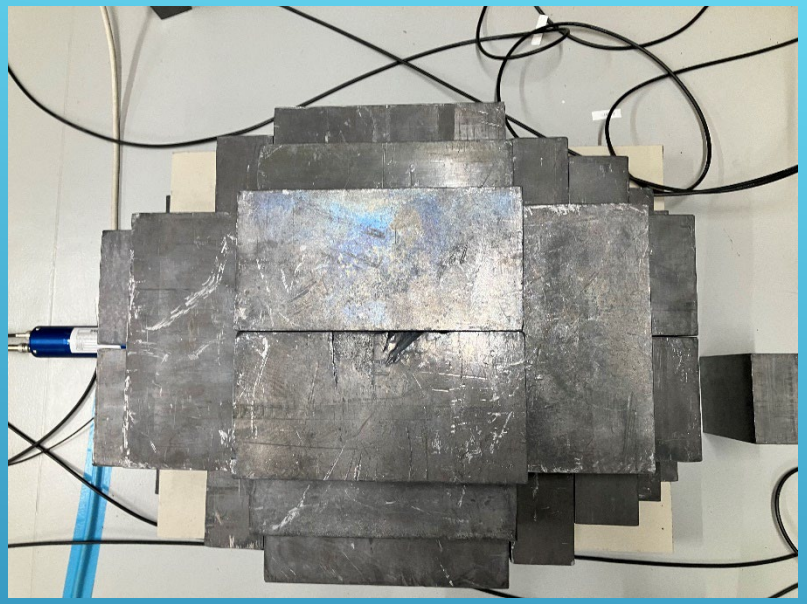
Comparing distributions using natural gamma

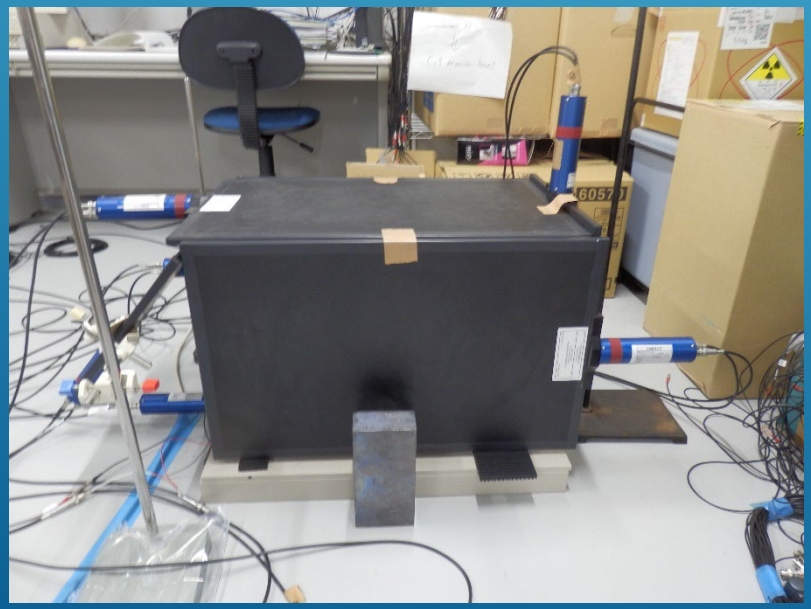


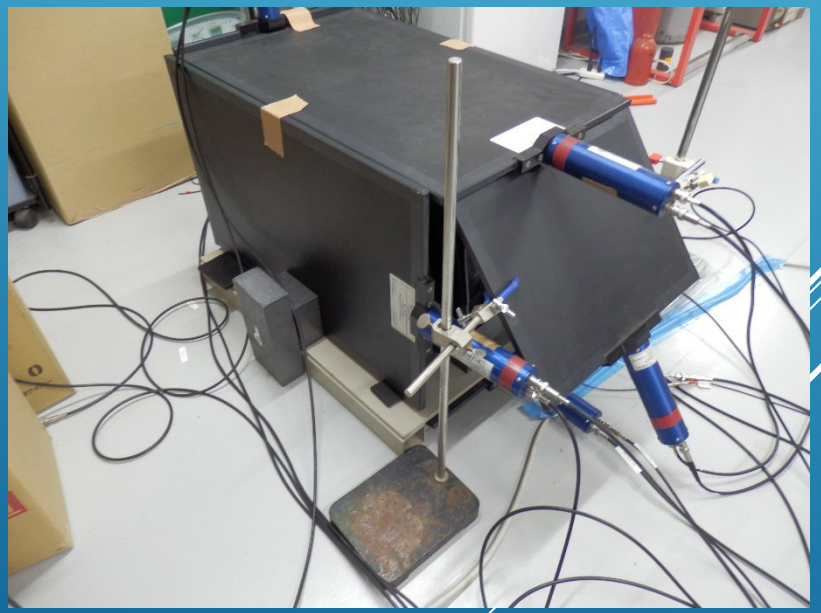
Almost the energy spectrum of residual events is consistent with environmental gammas observed at outside of shield.

No obvious BG event exists except those above, we are still investigating the source of residual events.
(At least, it is not internal BG.)

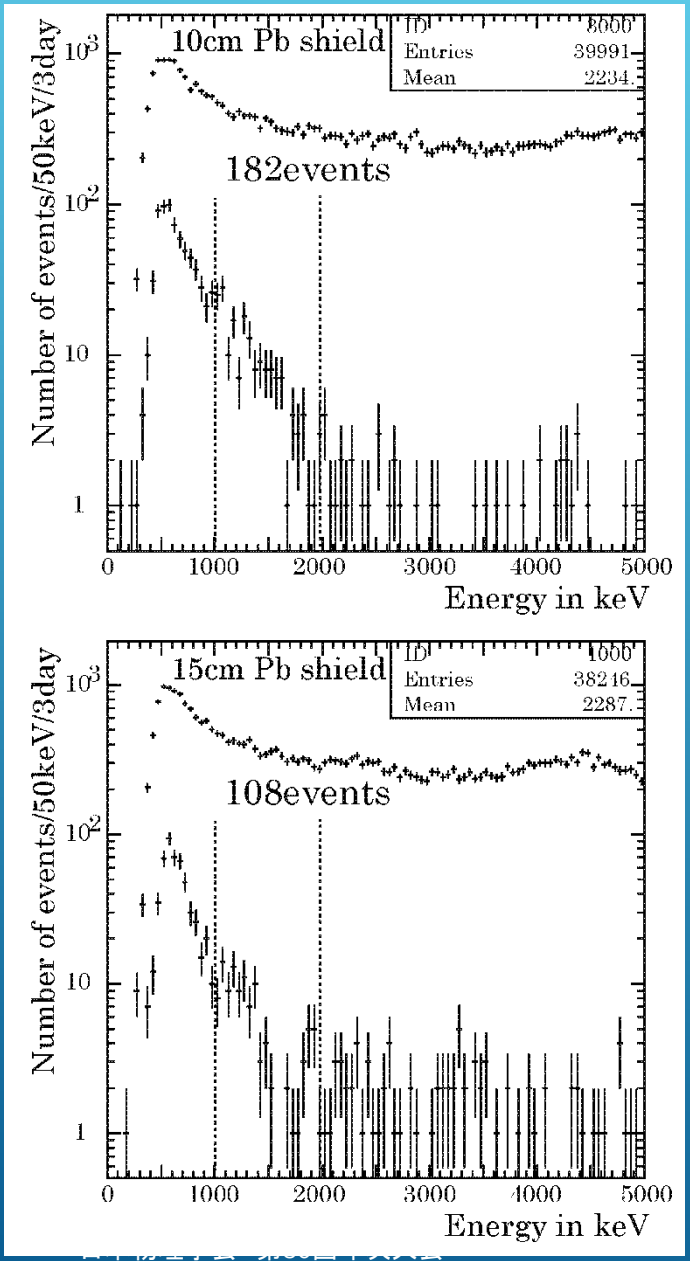
BG measurement inside 15cm Pb shield







Background events in case of 15cm Pb shield



Compare number of events between – 2 MeV

- 10cm shield 182events/3days
- 15cmshield 108events/3days

results： reduced about 40% events due to attenuation of Pb

Most of residual events might be caused by external gamma ray.

Are we ready to start 2ν-ZICOS in the mine?

To show the detector performance of 2ν-ZICOS experiment, we measured following things.

1. Using calibration source, is observed energy spectrum consistent with simulation?
2. Does energy scale have a linearity?
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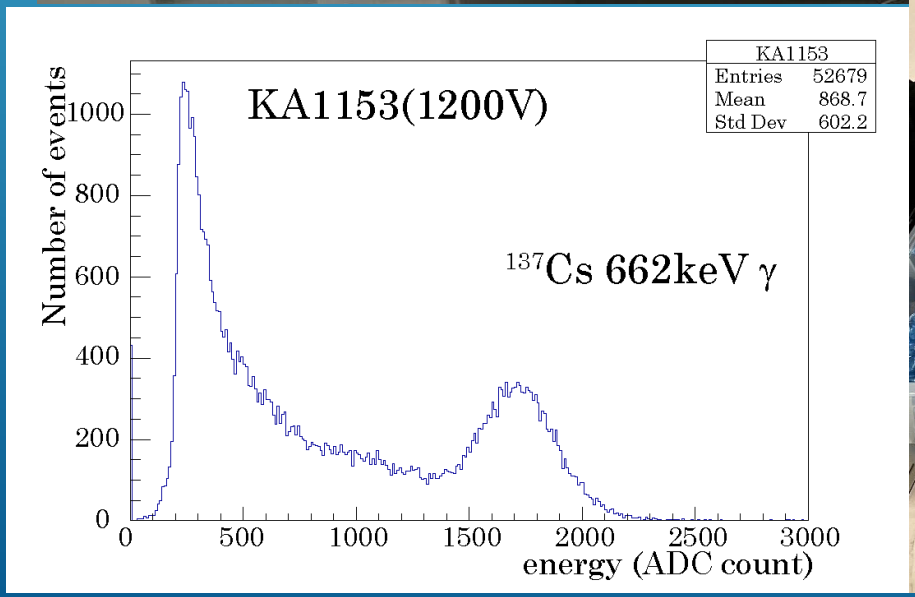
Gain adjustment for R10789 using GSO



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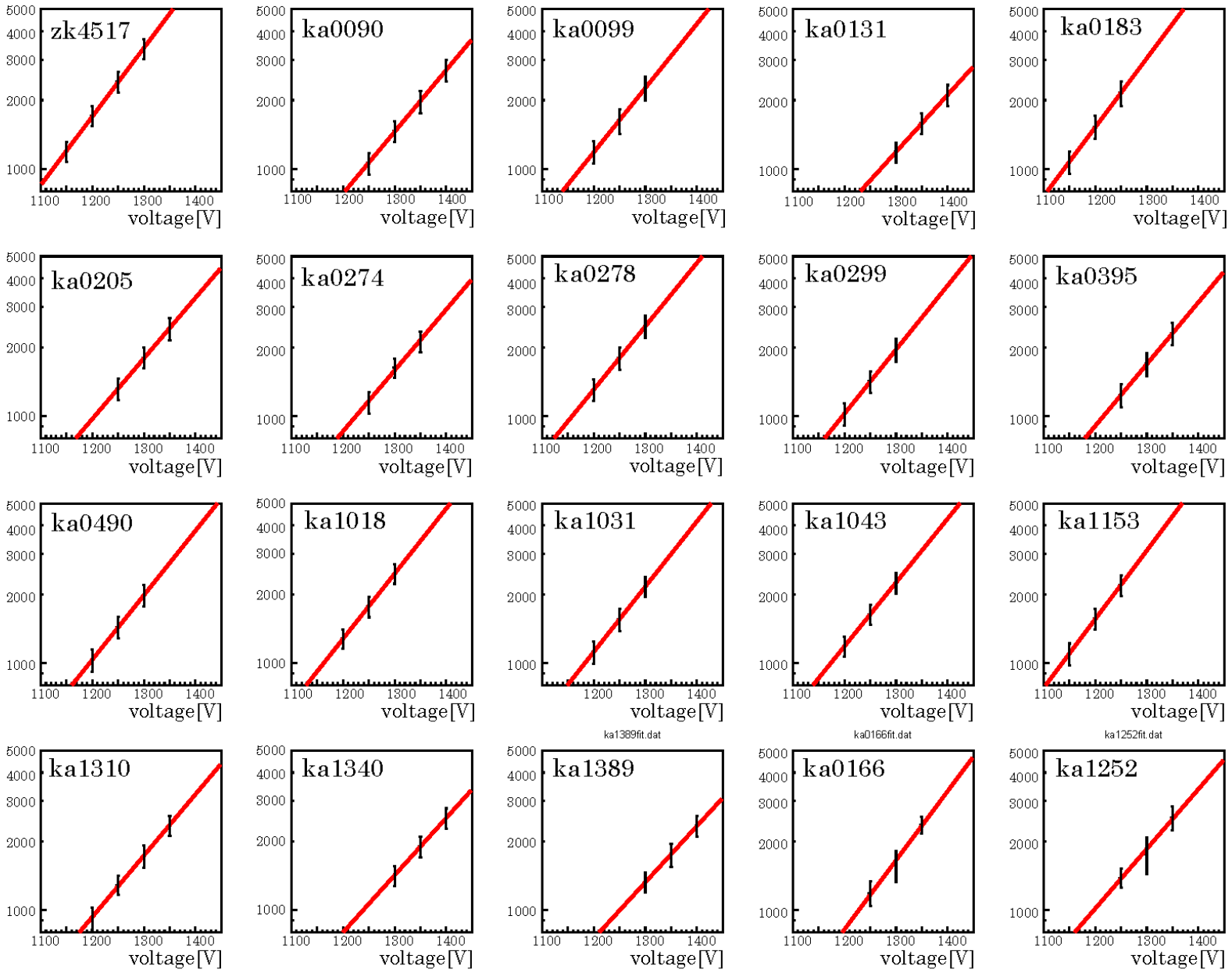
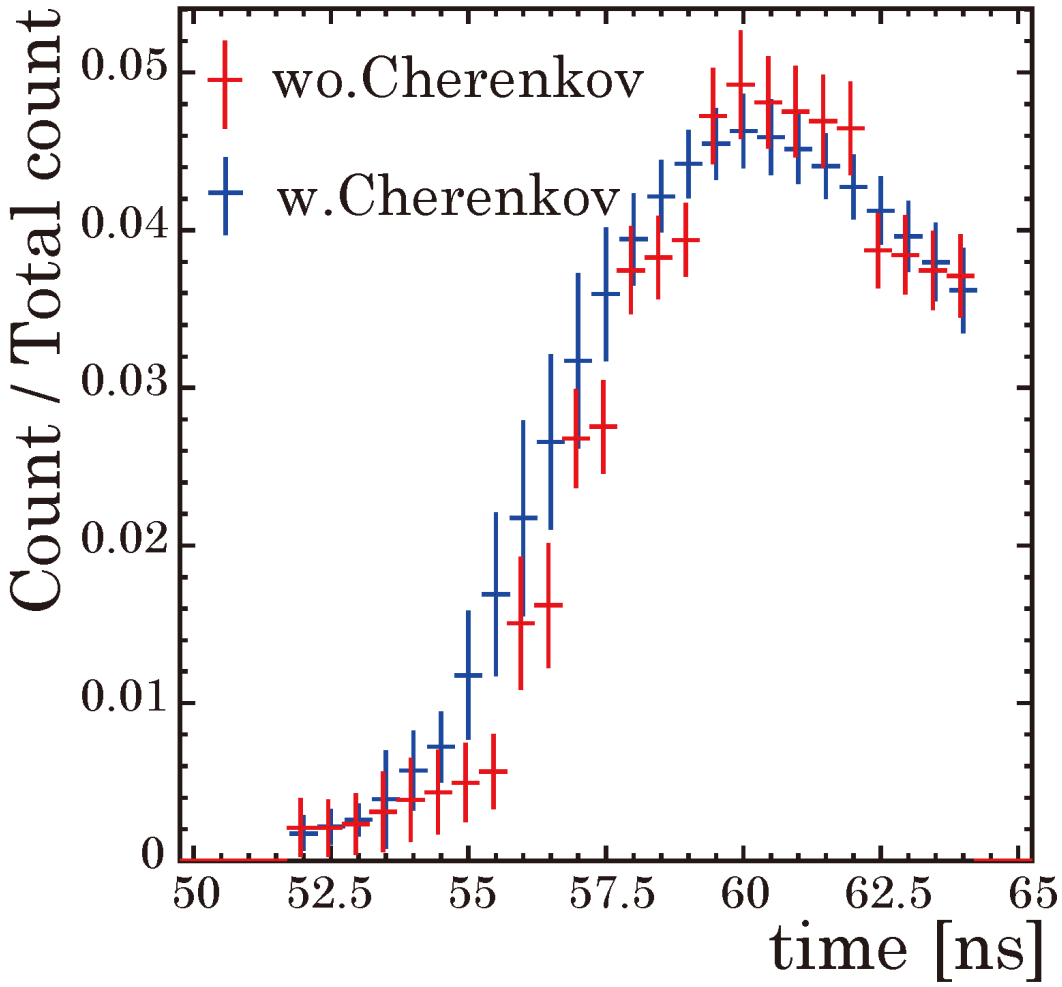


Averaged angle for PMT R10789



Although R10789 has a slower rise time than H3378-50, R10789 observes Cherenkov light clearly.

Averaged angle may be available for PMT R10789.

HV system with A1932AP and SY5527LC

- R10789 uses for positive high voltage supply.
- We have negative high voltage supply for H3378-50.
- XMASS used CAEN A1932AP board for OD PMT.
- We used CAEN SY5527LC for main frame.

Just Fit! But SY5527LC was broken due to loss backup battery (we have same trouble last year)

Summary

- We have decided to use PMT Hamamatsu R10789.
- Observed 17 events as ^{214}Bi-^{214}Po candidate, which is consistent with result of ^{226}Ra 2.72 ± 1.33 mBq/kg measured by Ge detector in Kamioka mine.
- BG events from U/Th/K in both PMT R10789 and Quartz vial are quite few.
- Surface event rate is inconsistent with XMASS estimation.
- Residual events seem to not be internal BG events. In fact, 30～40% of residual events are caused by external gamma.
- Most of things to do before starting 2ν-ZICOS experiment seem to be done, so we have moved all equipment to Kamioka in August.
- HV board A1932AP will be installed by SY5527LC, but…
- 神岡施設安全委員会で審議（宿題があるが、ほぼ承認？）
- The observation will start at this Autumn. Stay tuned!

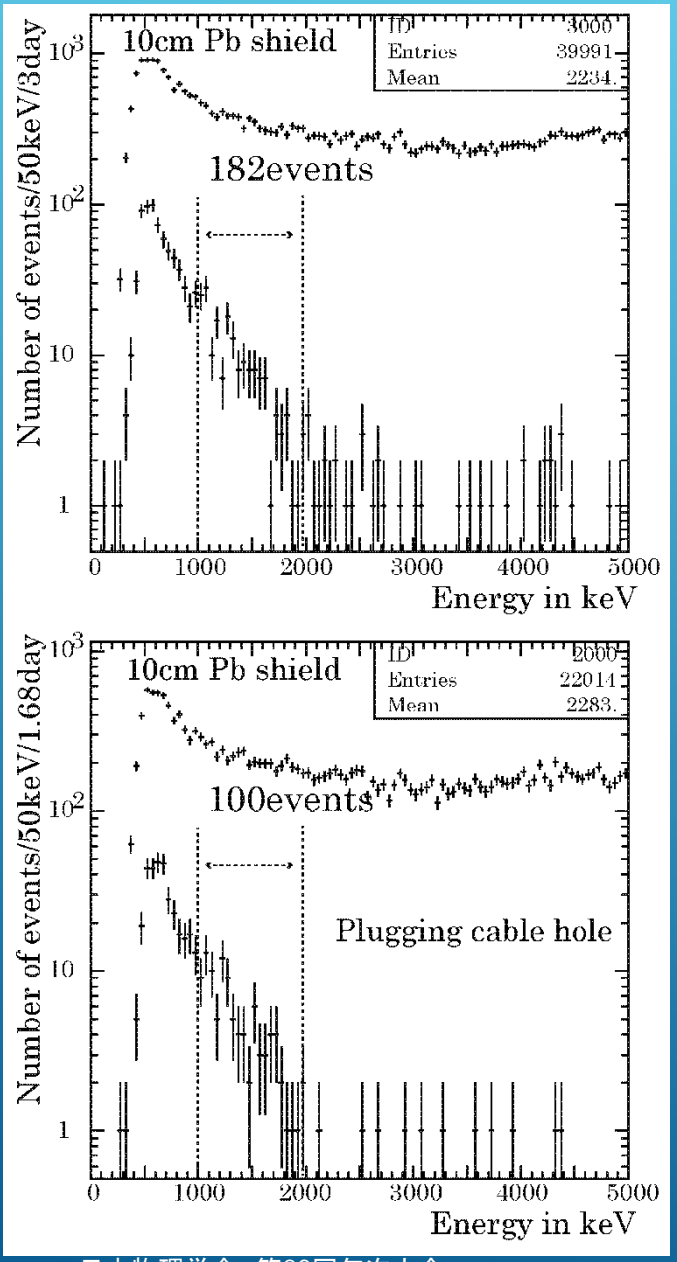
backup

Why 2ν-ZICOS should do in Kamioka mine?

There is huge backgrounds for the observation of $2\nu\beta\beta$ events on the surface of earth due to cosmic muons.

- Cosmic muon rate is ~2Hz on the surface of earth.
- Most significant spallation product is ^{11}C which decays in beta plus and emits total energy ~2MeV.
- Maximum 270 events per day will be observed on ground.
- The half-life of ^{11}C is 1200sec and the detector should have no live-time if veto for all muons.
- In the mine, the cosmic muon rate will be 2×10^{-5}Hz, so dead-time is about 2.4% even if veto for all muons.
- Expected event rate due to ^{11}C, which is caused by neutron produced by muon spallation, is ~20 events per year using measured neutron flux. (same expected number was obtained by KamLAND data. Ref:Phys.RevC.107.054612)

Cable holeを鉛ブロックで塞いでBG観測



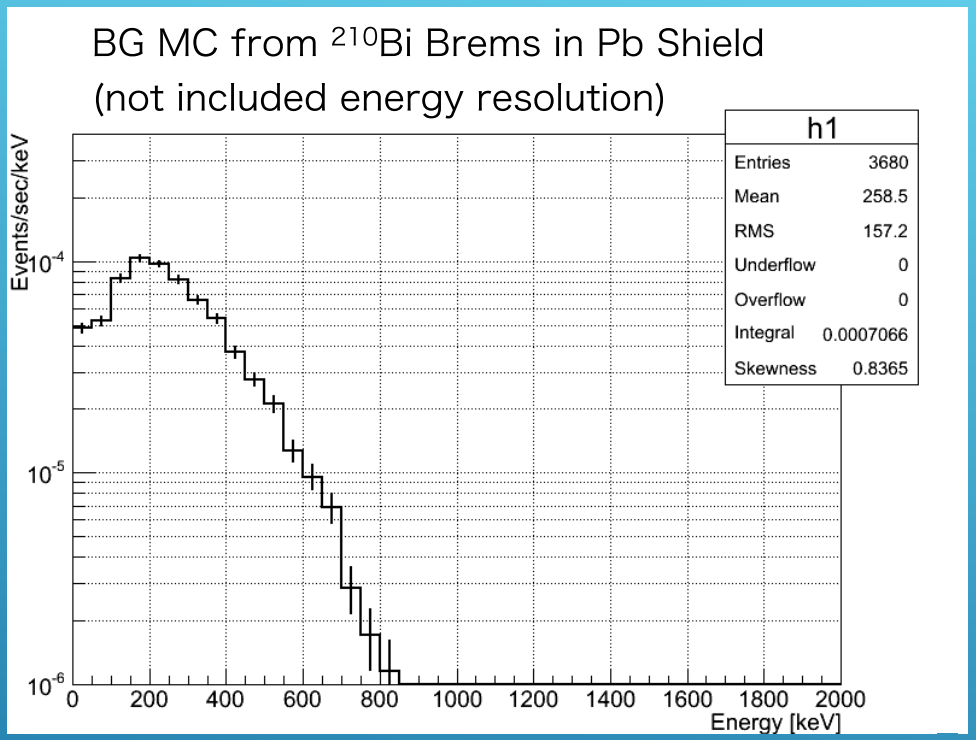
1MeV-2MeV間の事象数を比較

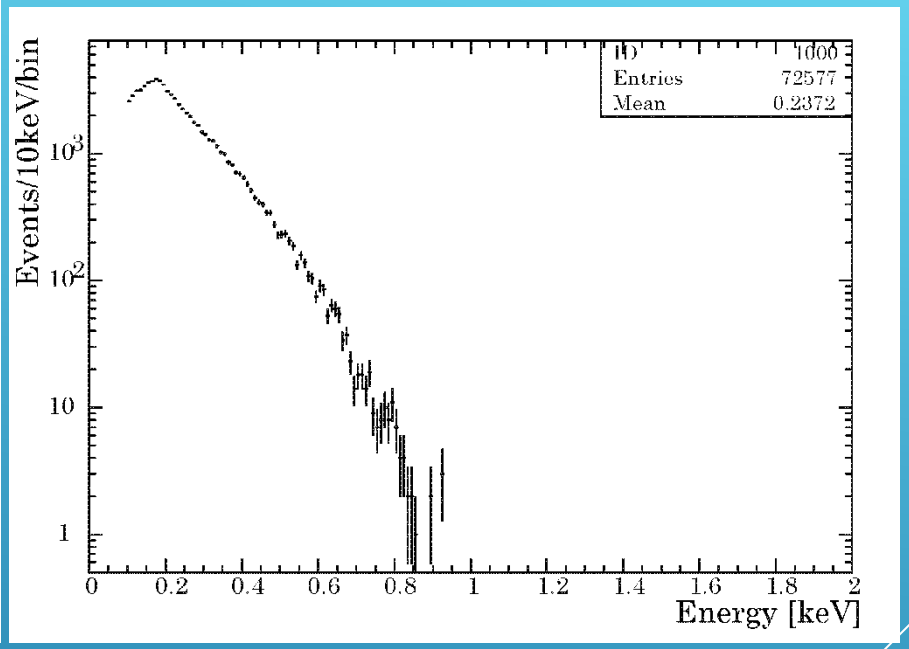
・穴を塞ぐ前　182事象/3日間

・穴を塞いだ後　100事象/1.68日間
＝　179事象/3日間

結論：　穴の効果は見られなかった

鉛ブロック内の^{210}Pbのベータ線からの制動放射

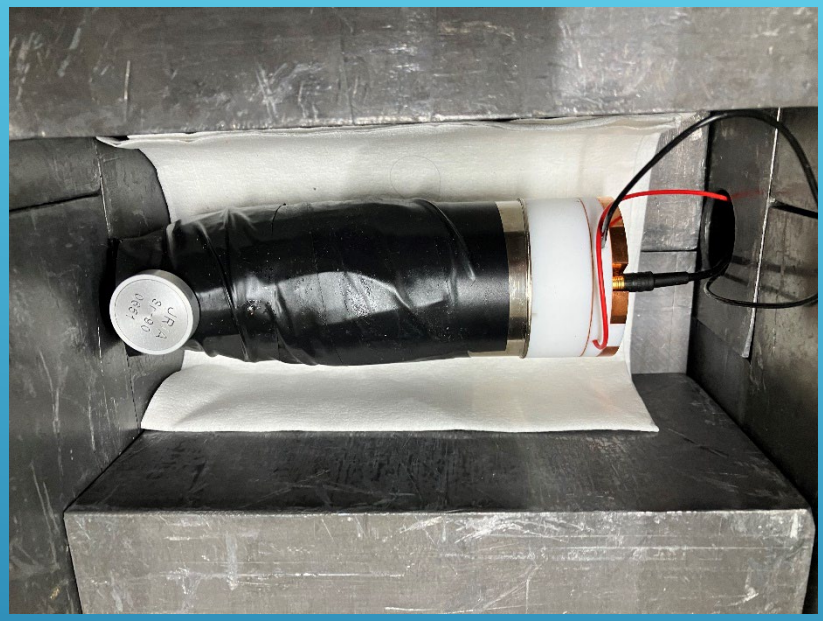


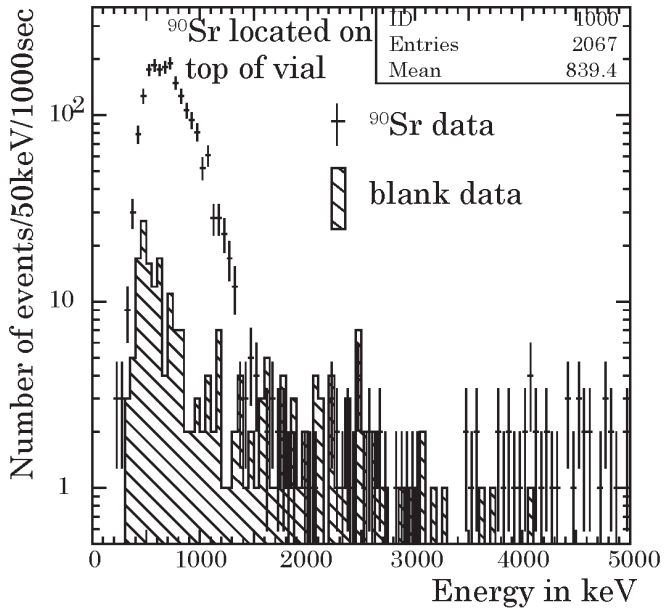


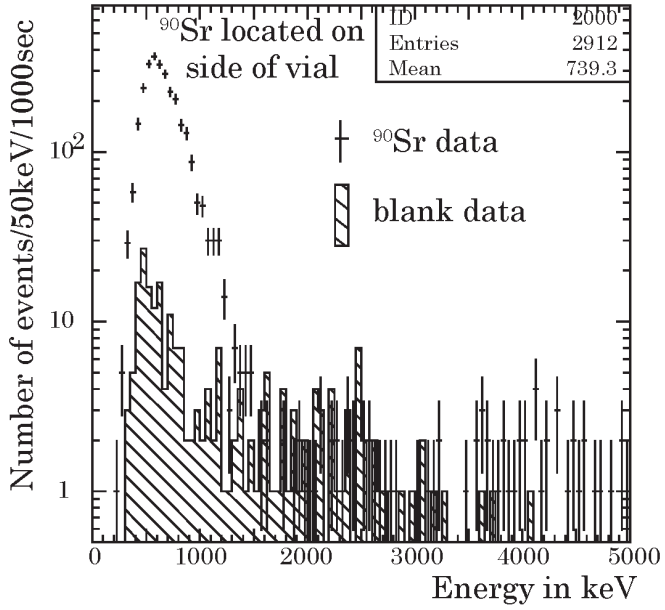
市村さんが振った鉛シールド内の^{210}Biのベータ事象からの制動放射事象のエネルギー分布と、EGS5で同様に振った事象のエネルギー分布

よく似ているが、EGS5の方が少しエネルギーが低い

鉛ブロックからの^{210}Biのベータ線が見える可能性



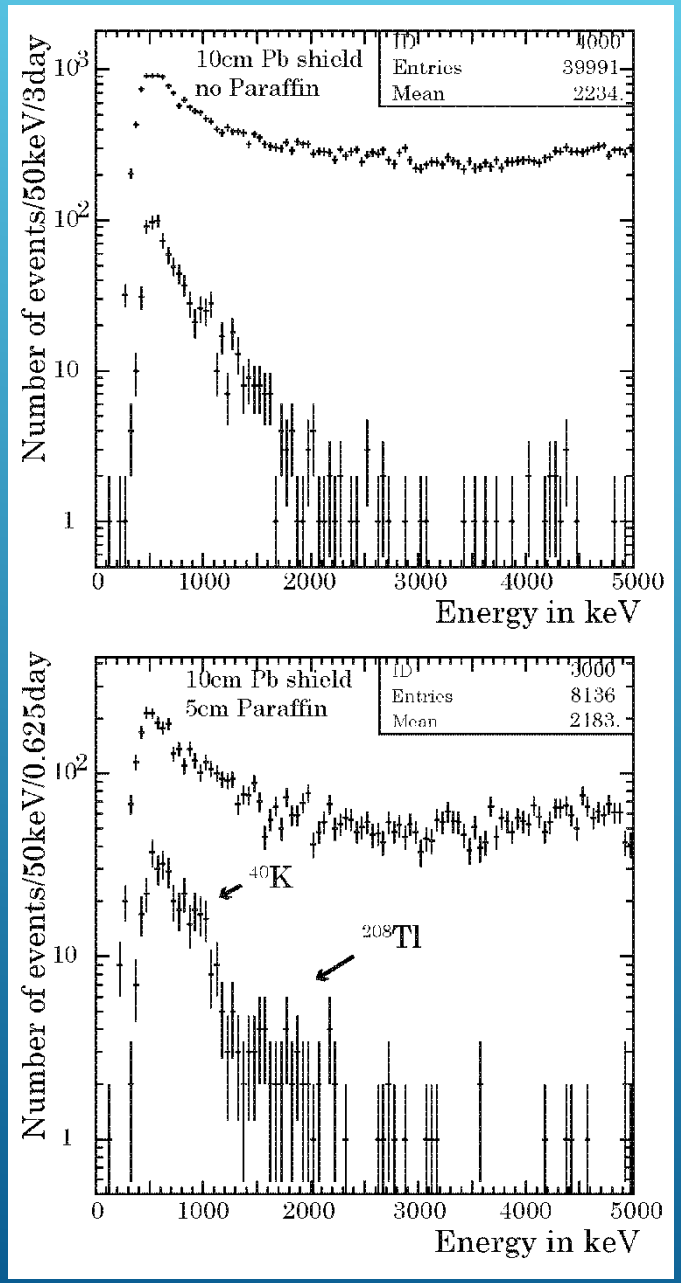


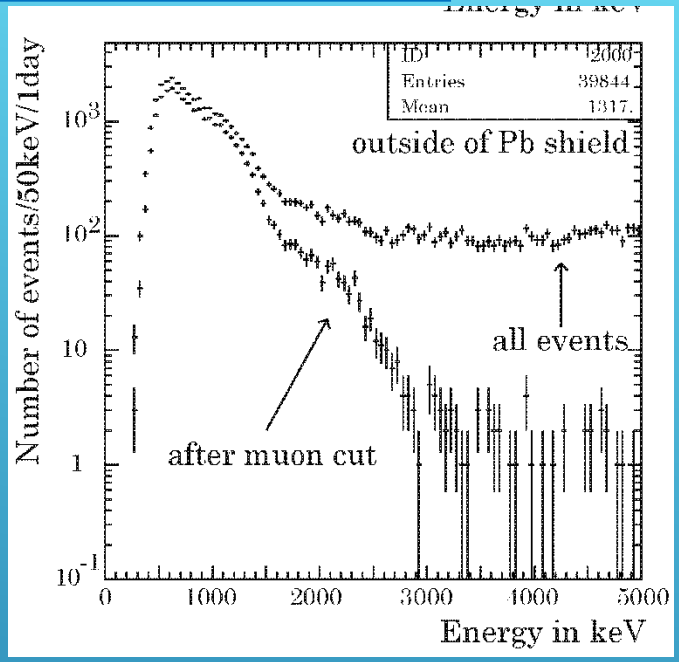


^{90}Srのベータ線（Emax=2.28MeV)が見える。

鉛ブロックからの^{210}Biのベータが見える可能性がある

パラフィンブロックで囲んでBG測定





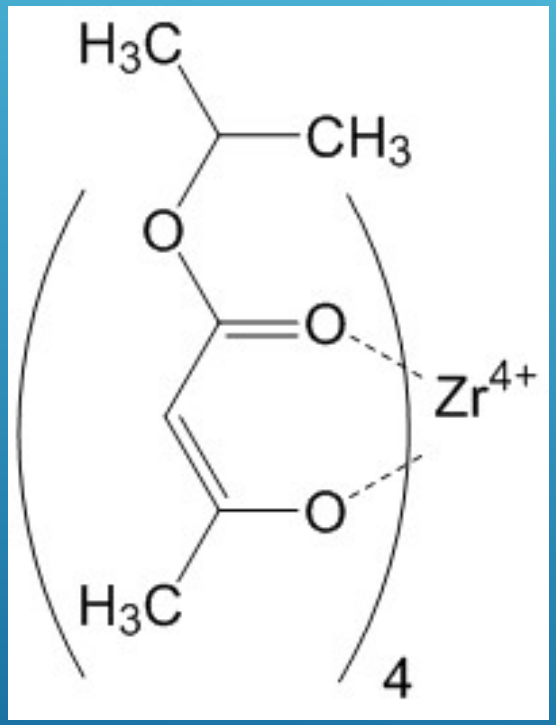
パラフィンで囲んだ場合の600keVの事象数が0.625時間で約30に対し、鉛だけの場合は72時間で約100なので、内部事象なら20事象存在するはずだが、予測される数しか観測されていない。

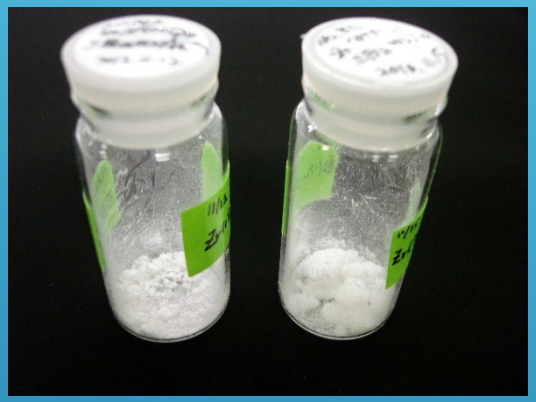
低エネルギー側は鉛からのベータか？

Zirconium β-keto ester complex

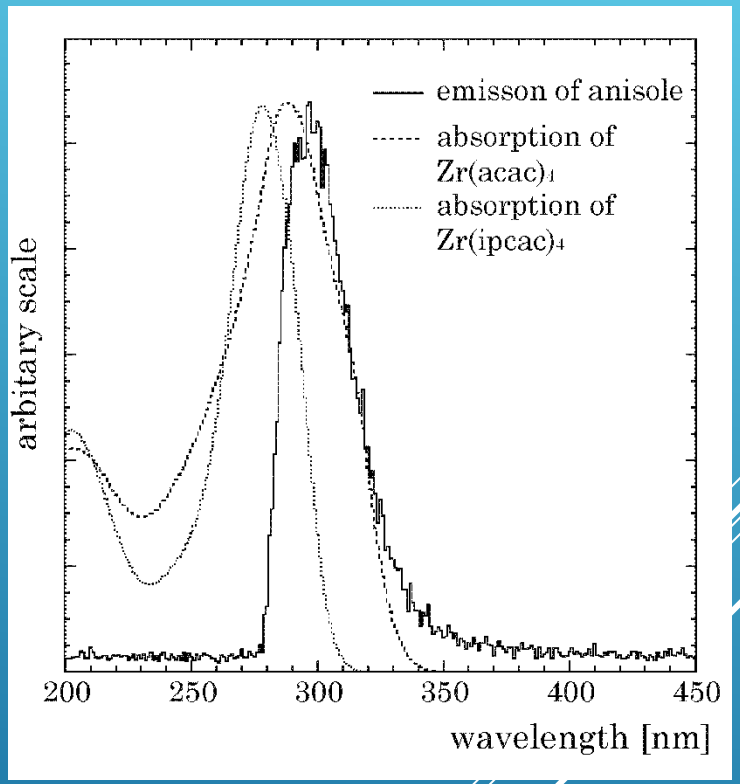
$Zr(CH_3COCHCOOCH(CH_3)_2)_4$ = $Zr(iPrac)_4$ mw : 663.87

Tetrakis(isopropyl acetoacetate) Zirconium





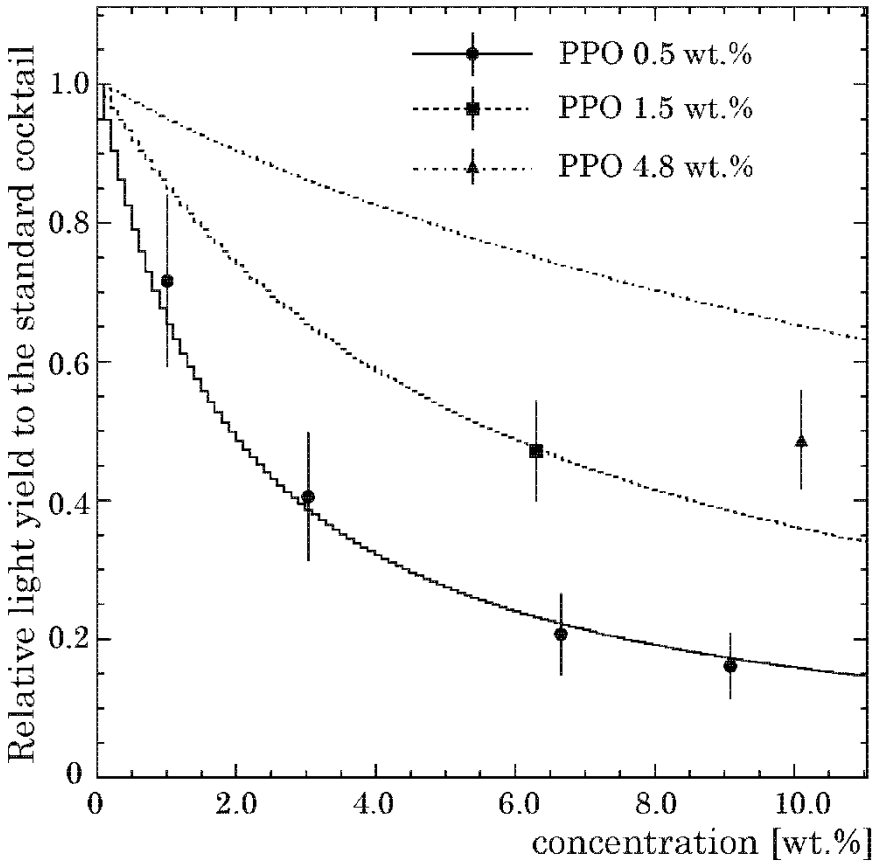
Synthesized by Prof. T.Gunji (Tokyo University of Science)

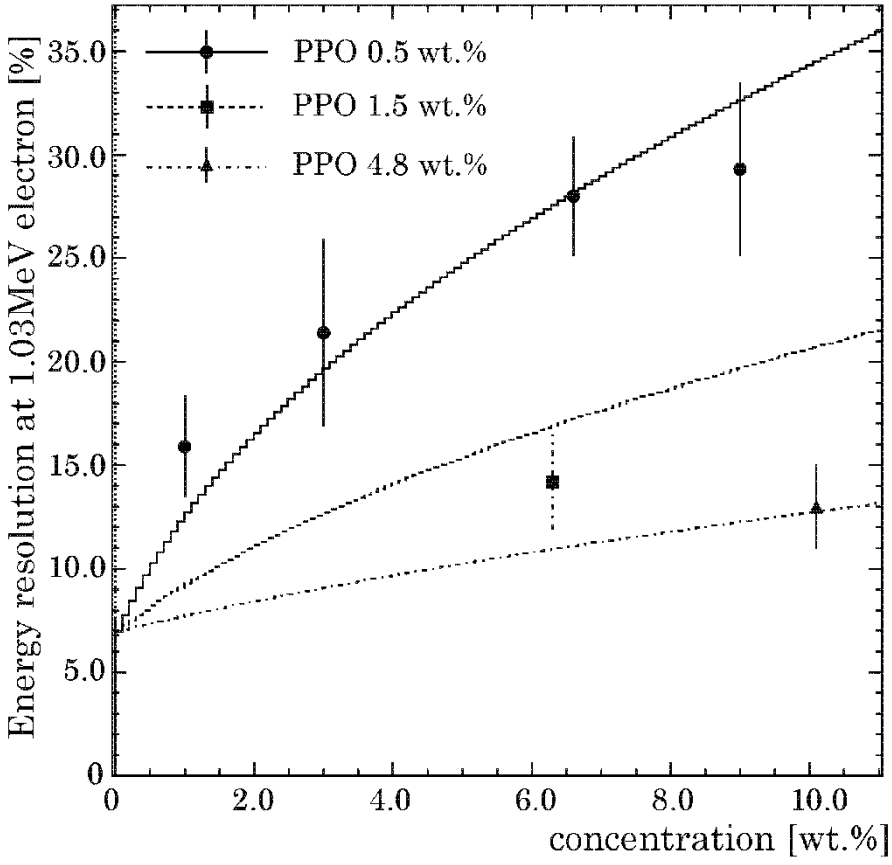


No commercial product

Shorter wavelength for absorbance

Improve of light yield and resolution



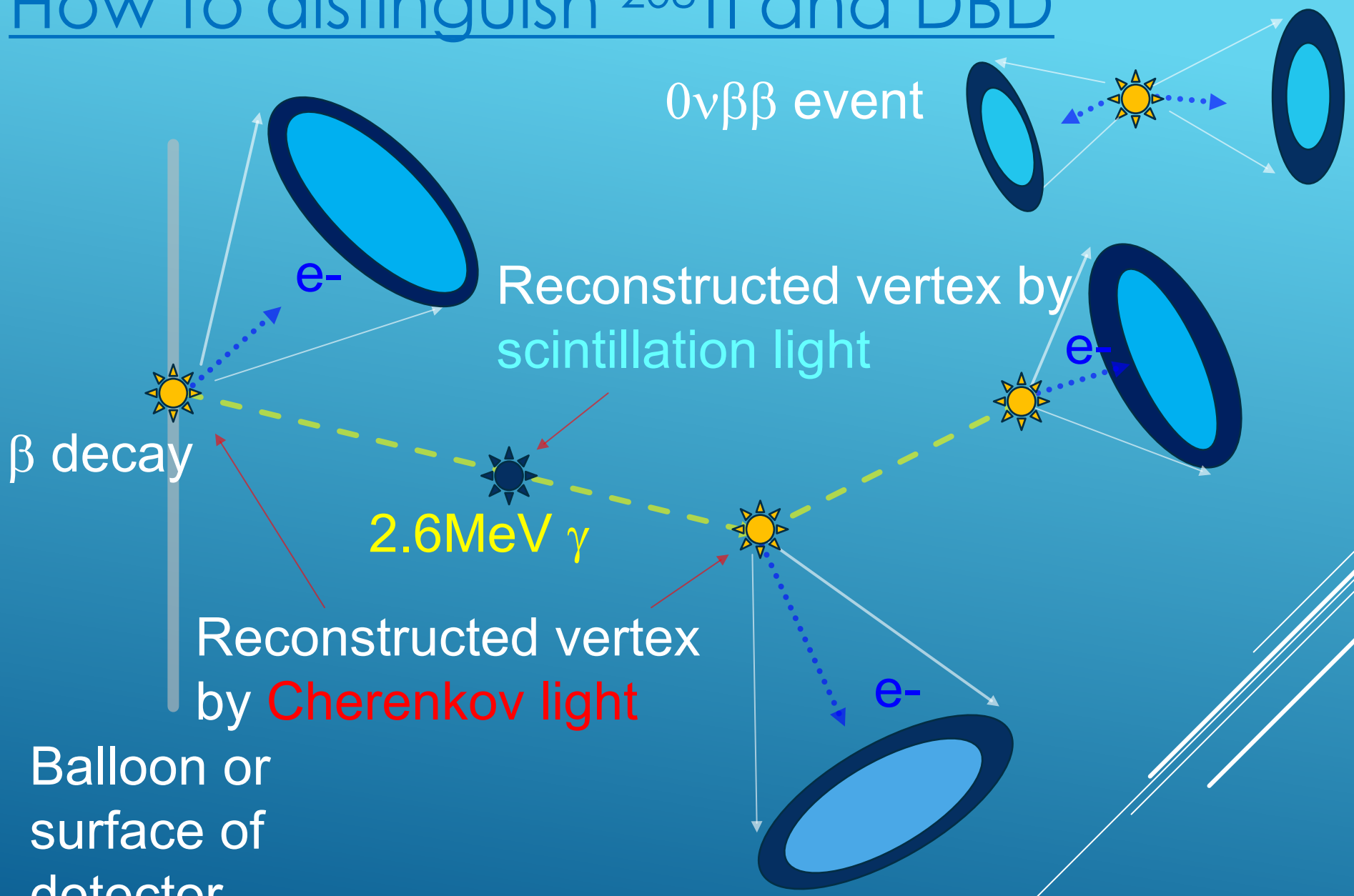


$Zr(iPrac)_4$ absorbs the scintillation photon and makes the energy resolution worth, however PPO could improve them.

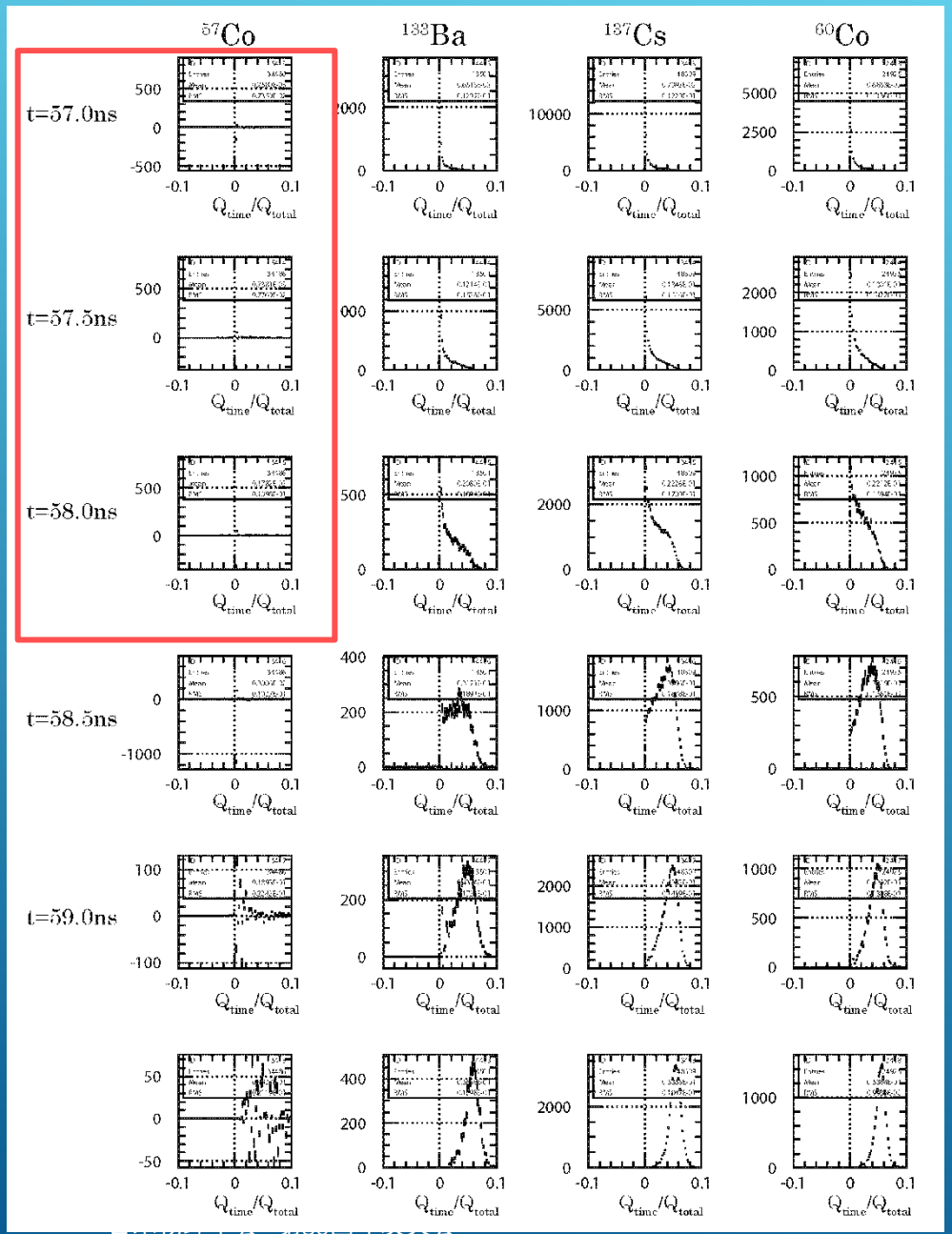
$$\frac{13.0 \pm 2.0\%}{\sqrt{40\%/9\% * 0.72 * 3.35\text{MeV}/1.03\text{MeV}}}$$

$= 4.1 \pm 0.6\%$ at 3.35MeV

How to distinguish ^{208}Tl and DBD



ZICOS LSを用いたガンマ線事象の立ち上がり

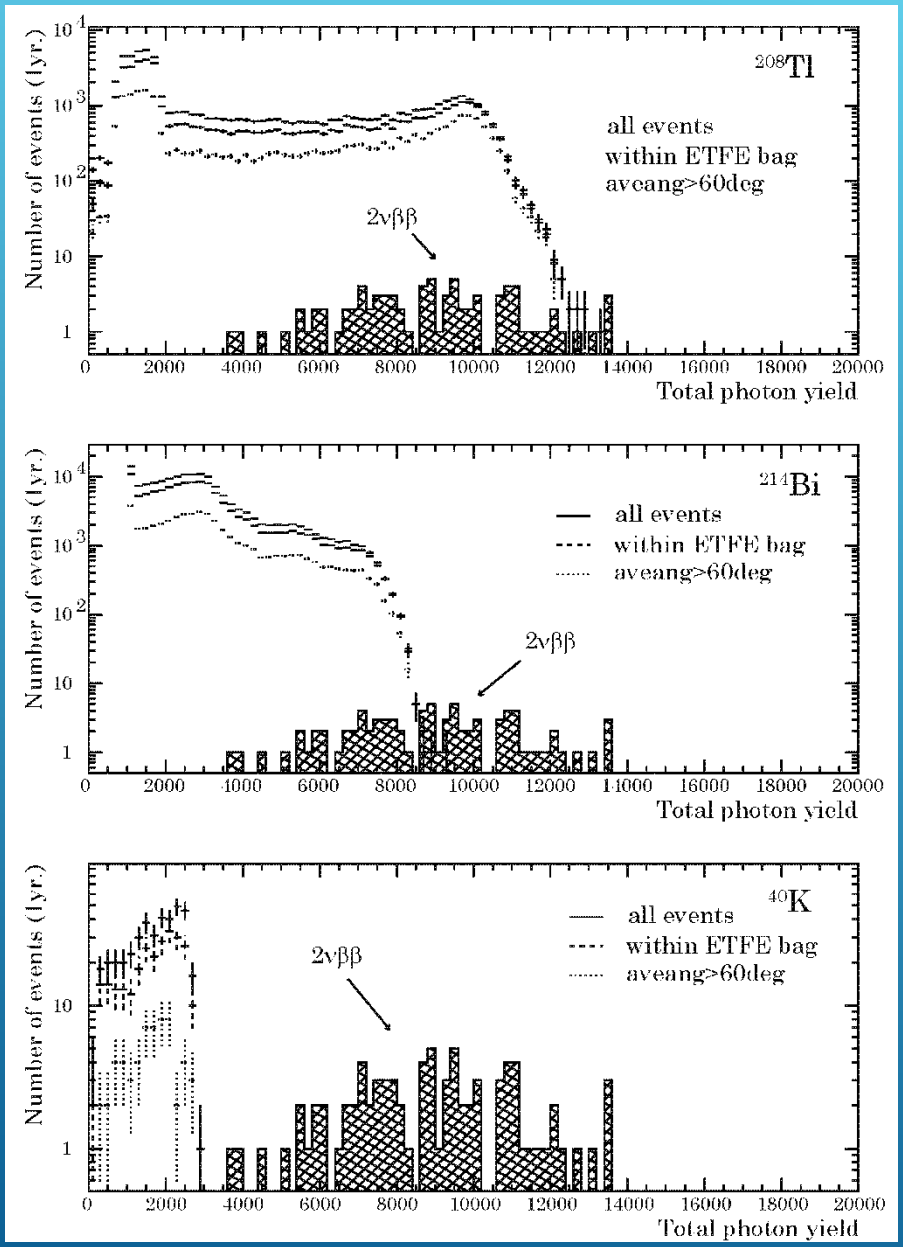


- t=57ns~58nsの時間帯で立ち上がり方に違いが見える
- エネルギーが大きいほど立ち上がり方も大きい
- t>58.5nsの波形はエネルギーによらず一定

t=57ns~58nsの波形はチェレンコフ光が優勢と考えられる。

^{57}Coの波形をシンチレーション光のテンプレートとして作成

BG simulation in worst case

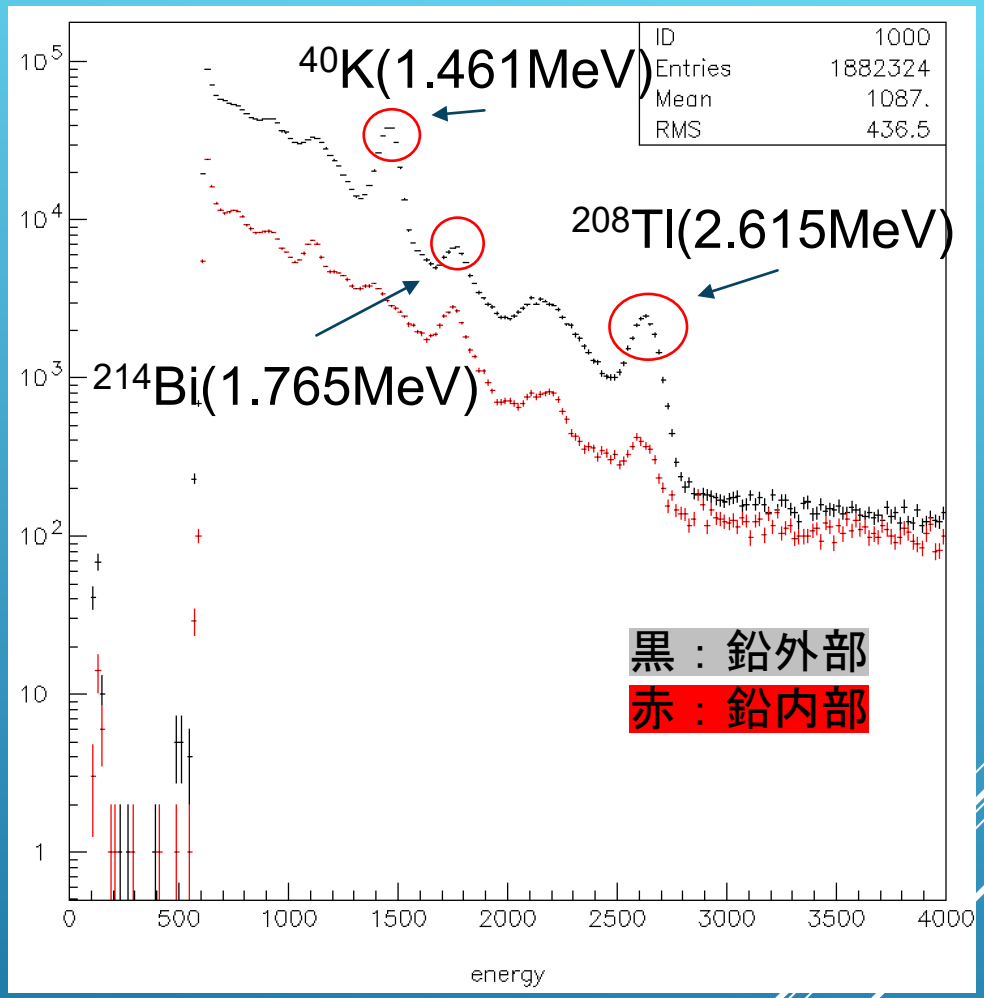


Assuming BGs from flask

- ^{40}K affects only part of 2νββ observation.
- ^{214}Bi is significant BG, but small fraction of 2νββ events should be observed.
- ^{208}Tl is most serious BG for 2νββ. A few events might be observed.

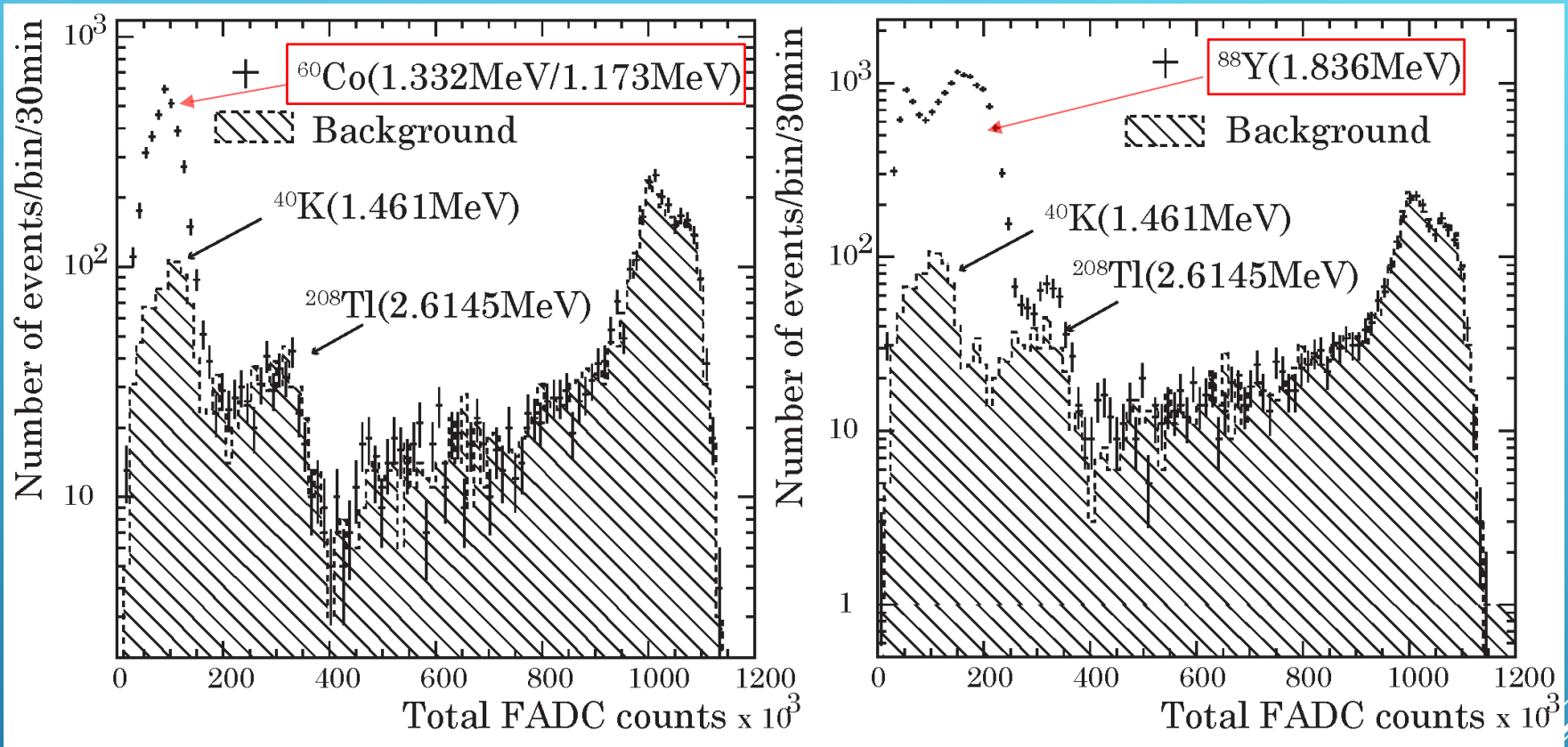
Need actual measurement for ^{96}Zr 2νββ

10cm mini Pb shield and CsI detector



Due to limit of number of Pb block, we will use 15cmm thickness

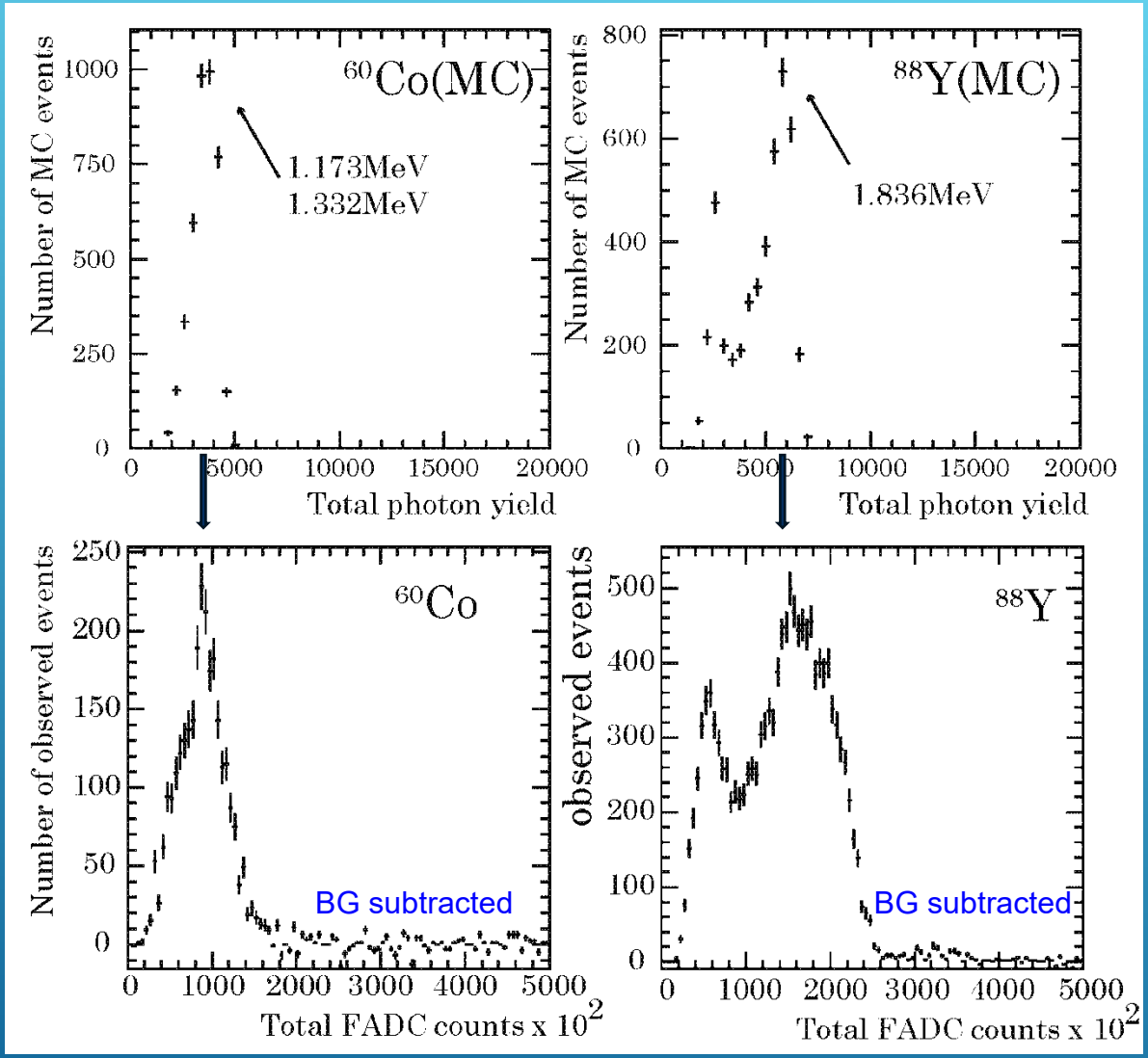
Energy spectra for 2ν-ZICOS detector



- Energy spectra for BG and calibration source
- Compton edges of both BG ^{40}K / ^{208}Tl gamma and calibration source were observed.

Energy scale looks good.

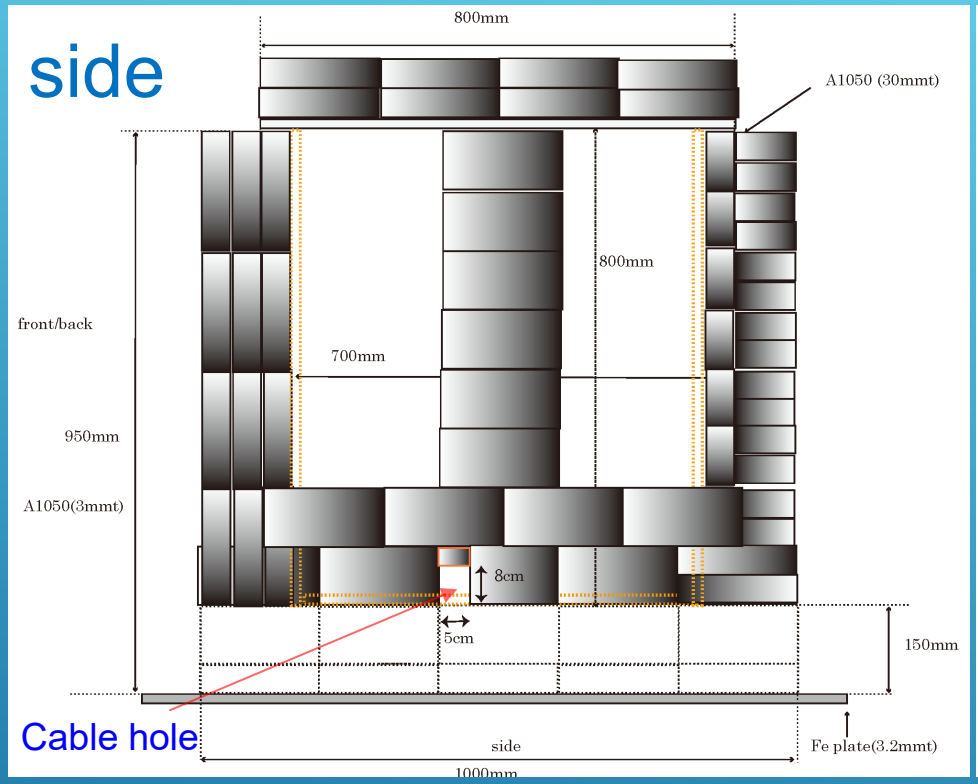
Energy calibration for 2ν-ZICOS detector

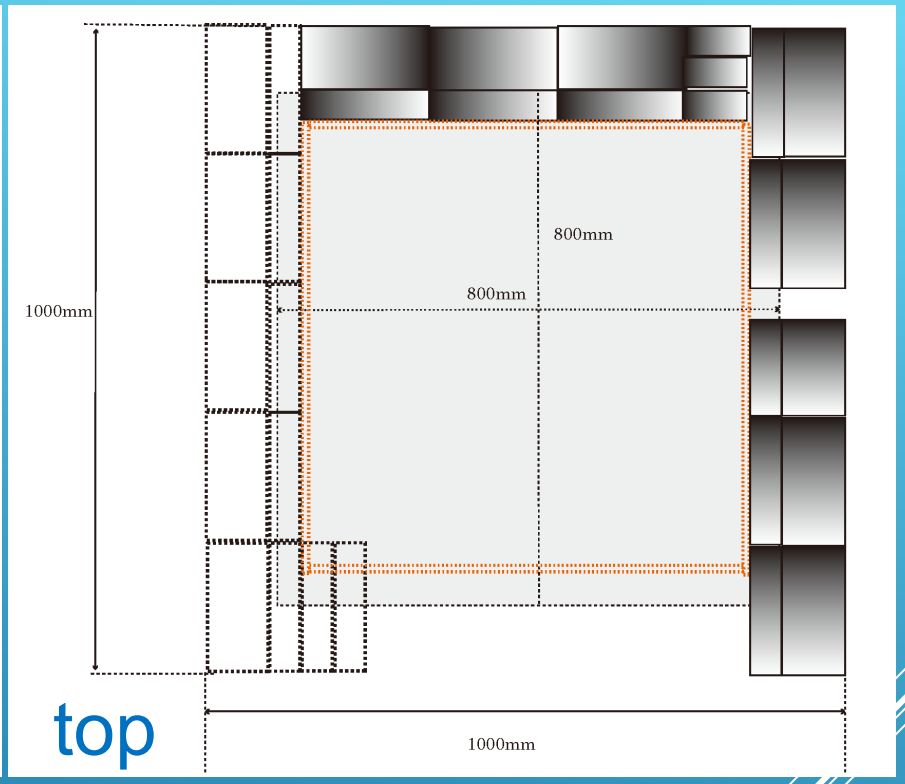


- Found clear Compton edge of gamma sources.
- Trigger simulation was also applied for MC data.
- Energy resolution was worth than simulation which does not consider the fluctuation of light intensity for PMT.

Energy spectrum seems to be reproduced by simulation.

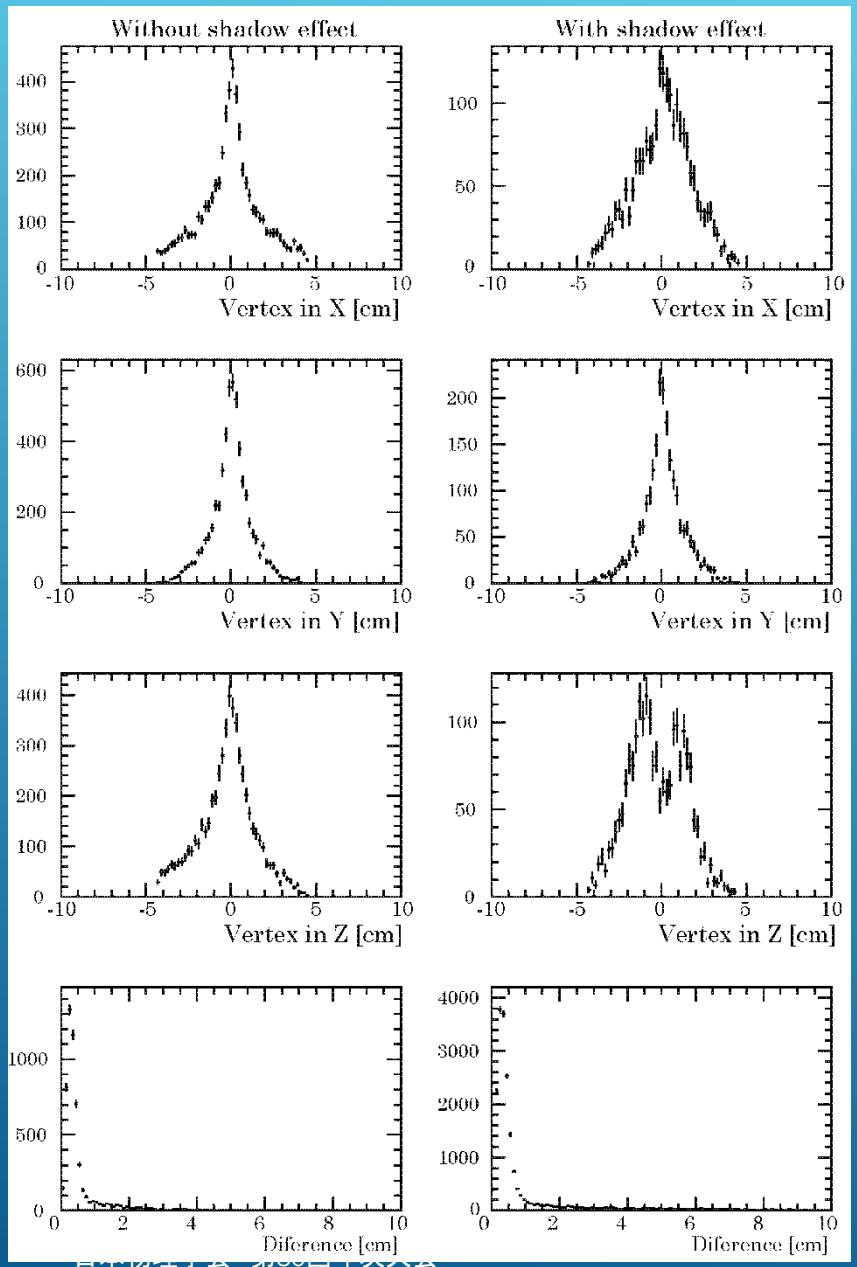
Pb shield for 2ν-ZICOS experiment

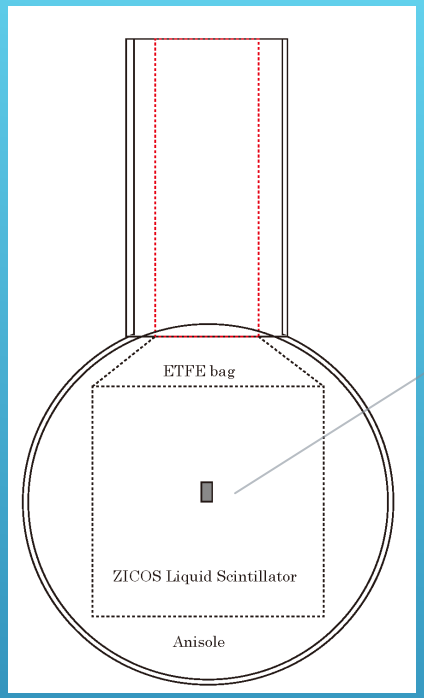


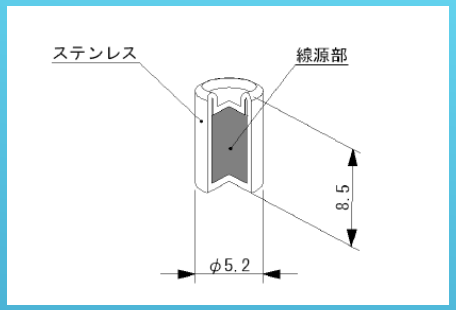


- 15cm thickness of Pb shield will be constructed at present.
- A1050 aluminum box for both structure of Pb shield and N_2 gas filling for safety issue.
- Aluminum bar structure will be constructed for outer shield.

Calibration of vertex reconstruction



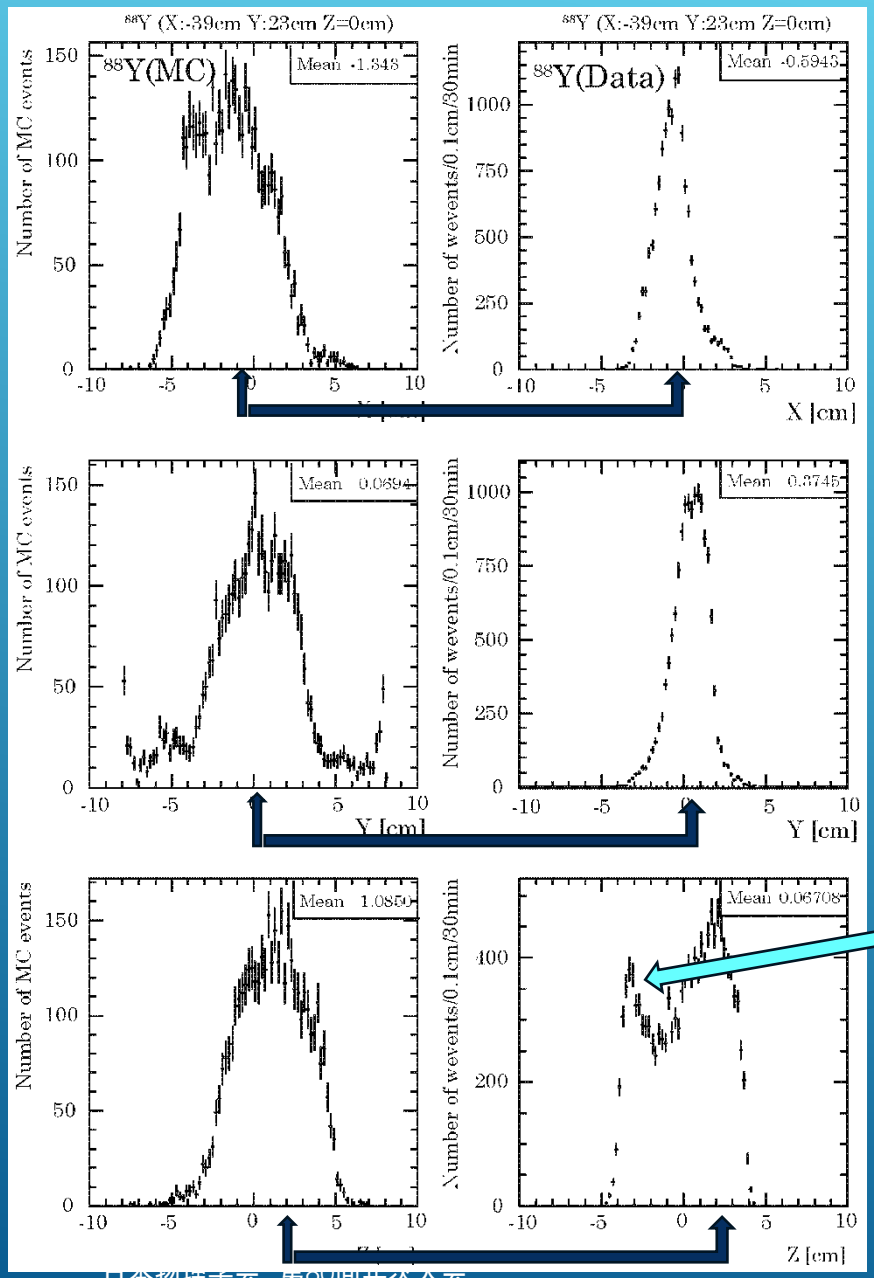


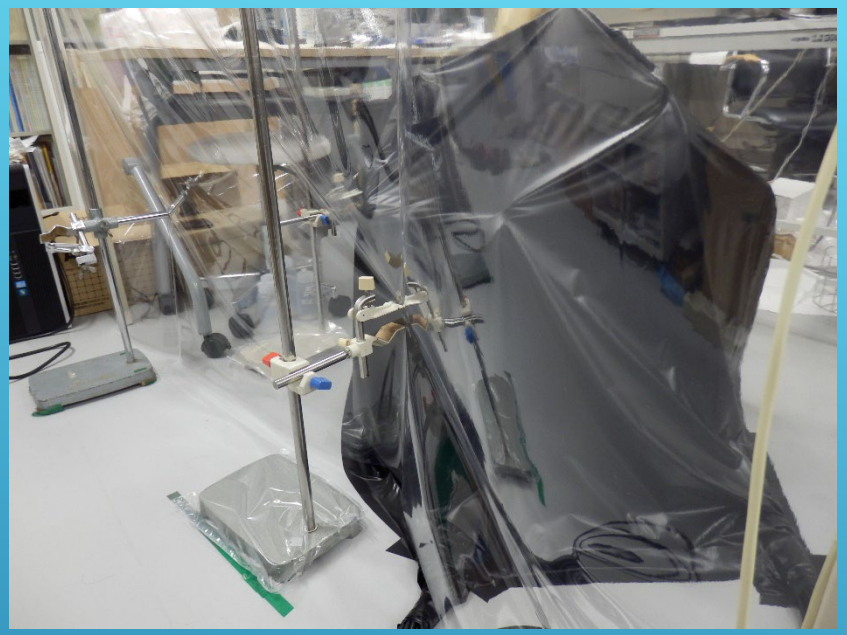


日本アイソトープ協会　標準ガンマ線　516タイプ
100kBq！

Larger pulse signal from ^{137}Cs type 516 source will be used for calibration of vertex reconstruction.

Vertex reconstruction using calibration data

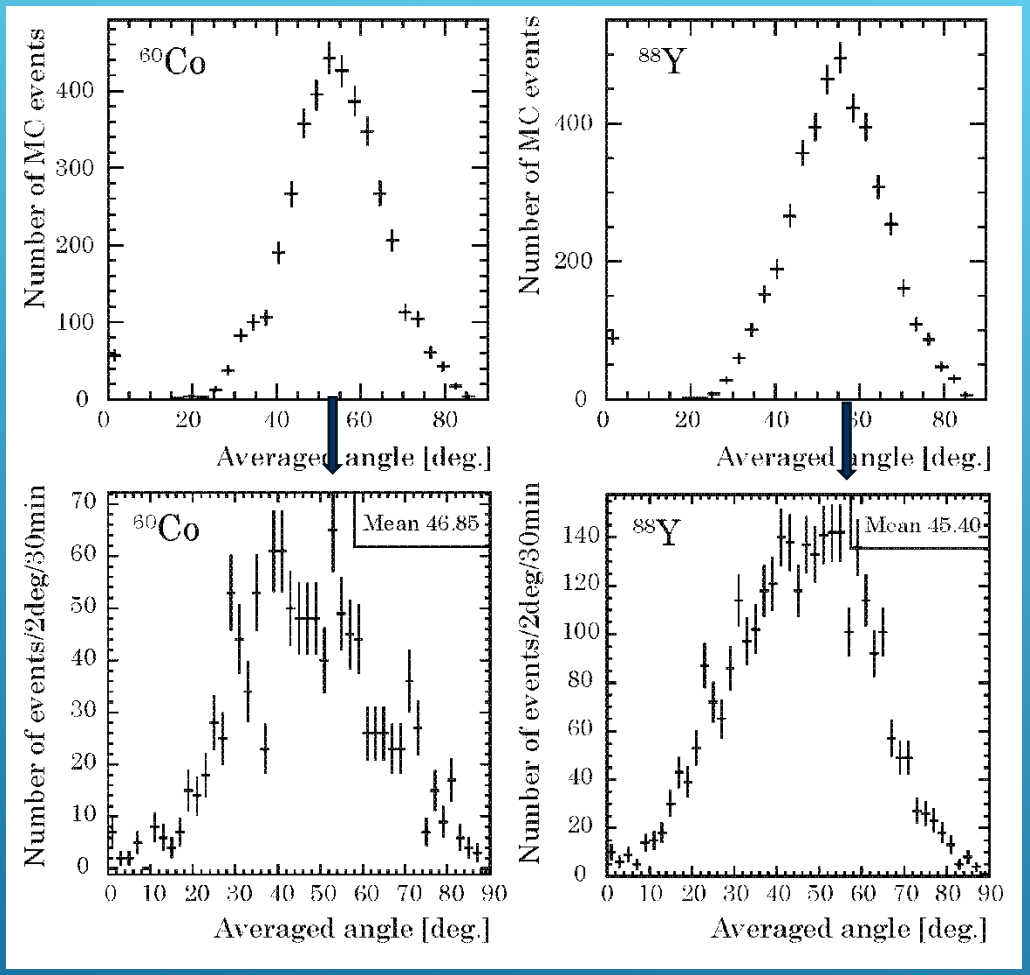


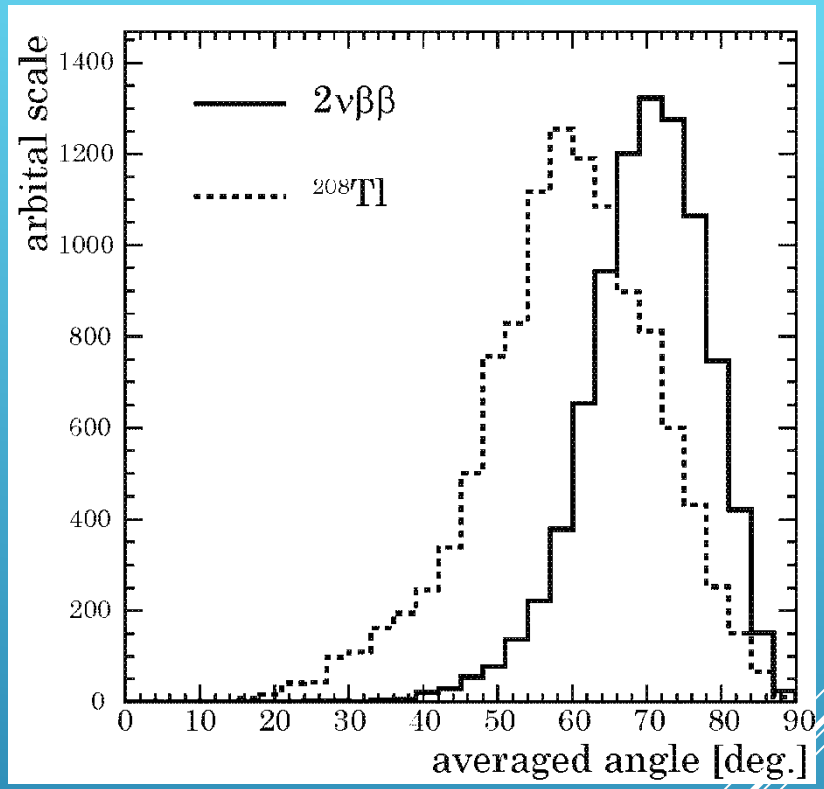


- Simulation vertices roughly reproduce the data.
- Extra cluster was found at Z<-3cm for data.

Need precise tuning or adjustment of PMT gain.

Averaged angle using calibration data





The peak position were seen at 58 and 70 degree for 2νββ and ^{208}Tl β decay, respectively.

Averaged angle of simulation seems to roughly reproduce the calibration data (Selection of PMT which receives Cherenkov light might be OK), but vertex still does not reproduce well.