Radioactive Background and Muon Flux at One-ton Prototype

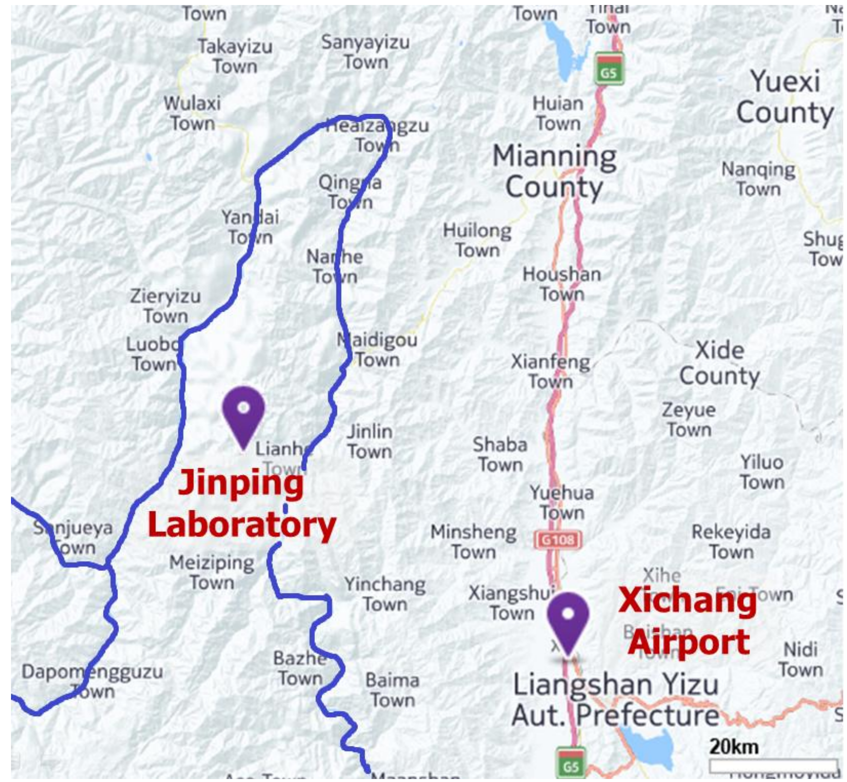
Jinjing Li
(for Jinping Neutrino Experiment Research Group)
MAIL: lijj16@mails.tsinghua.edu.cn
Department of Engineering Physics, Tsinghua University

2018-06-20

■ Outline

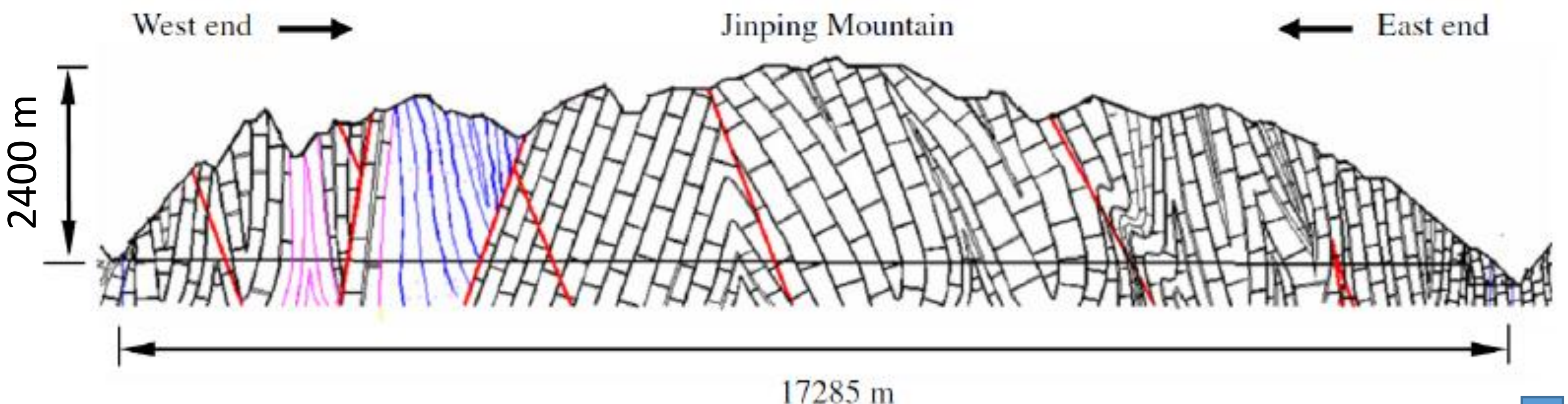
- Jinping Underground Lab
- 1-ton Prototype Experiment
  - Introduction
  - Motivation
  - Event Selection of Bi-214
  - Radon leakage study
  - Radioactive Background Level Estimation
  - Muon Flux
- Conclusion

■ Location of Jinping Underground Laboratory

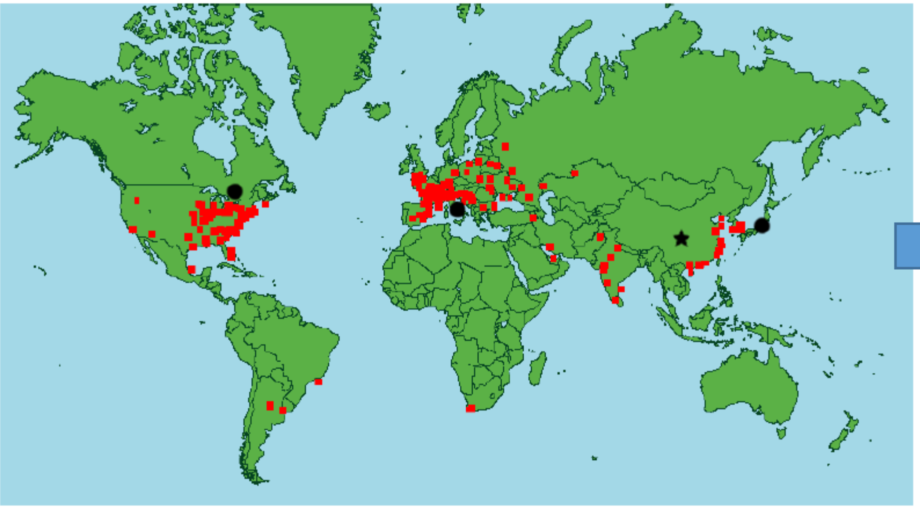


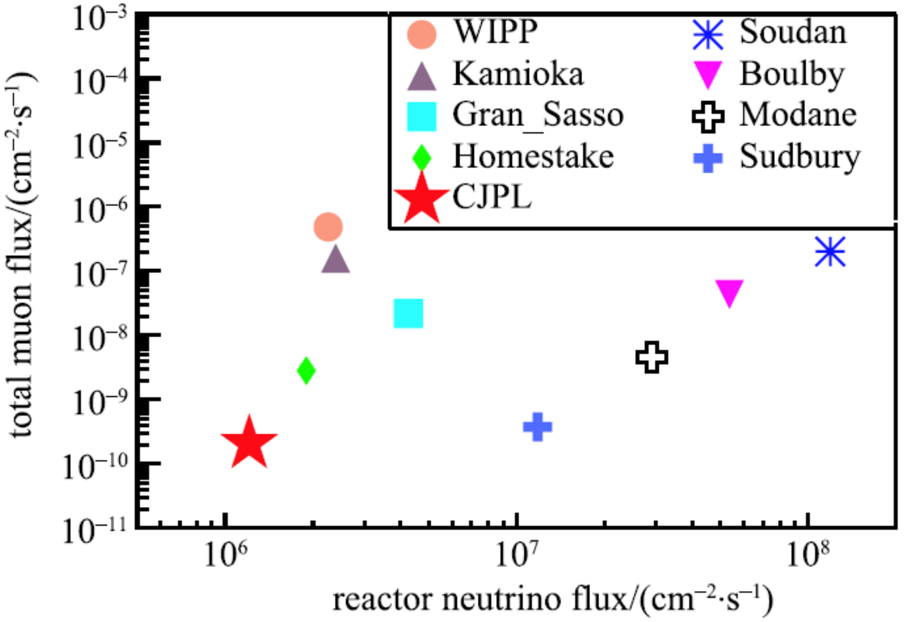
Southwestern region of China (Sichuan Province)
Direct flight from Beijing to Xichang + 2 hour drive

Low muon flux and reactor neutrino background



2400 m overburden, C10, C11 background suppressed

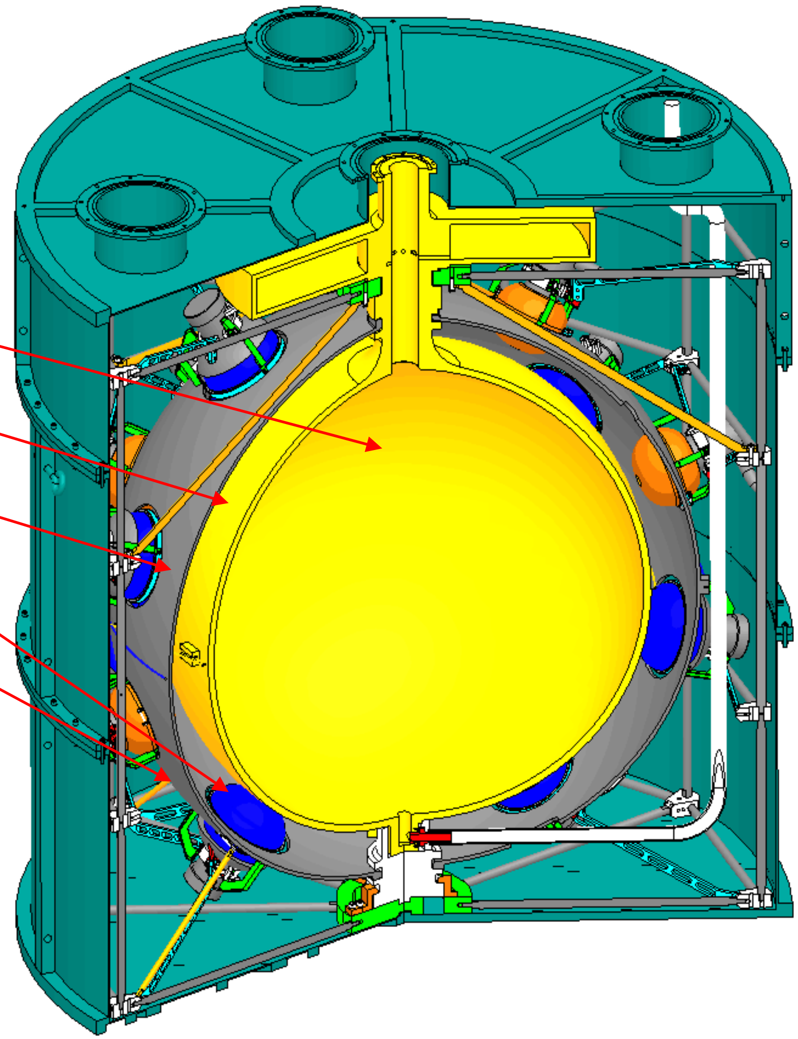




950 km to closest reactor

■ 1-ton Prototype Detector

1 ton liquid scintillator
Transparent acrylic vessel
Water
30 8" PMTs
Black non-reflective shielding
Lead shielding
Coverage: 12%
FADC 10 bit 1GS/s

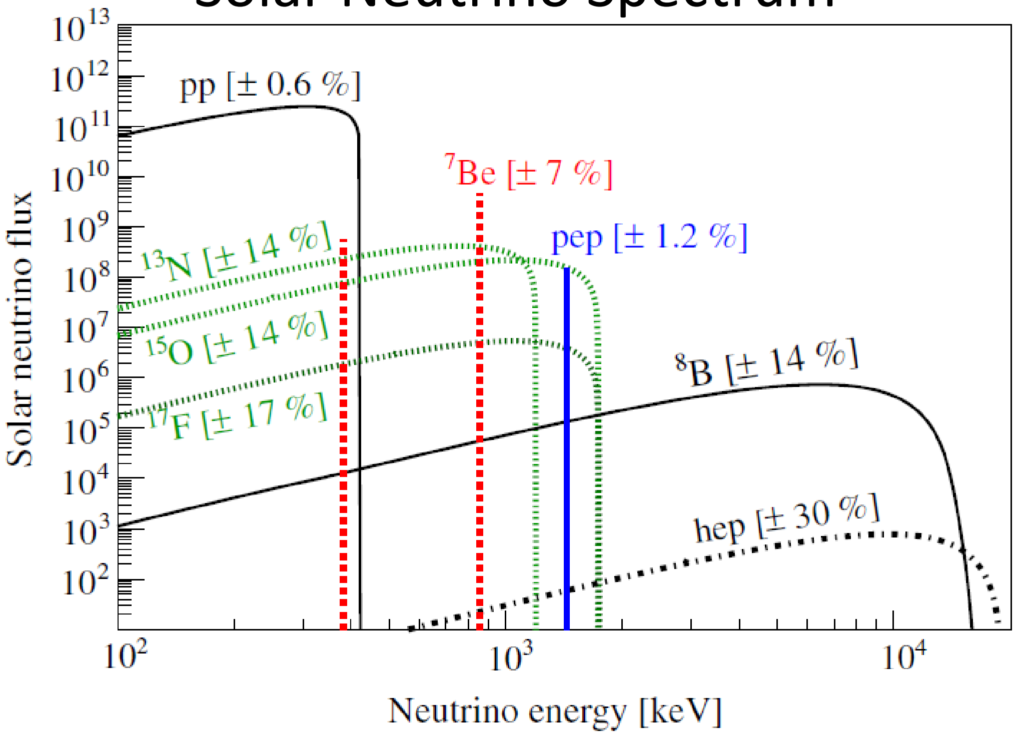


Since May 10, 2017, Started with pure water. Now taking data with a type of liquid scintillator (LAB+0.07g/L PPO+13mg/L bis-MSB) from July 31, 2017.

■ Motivation

- The precise detection of different species of solar neutrinos demands low level of the low energy bkg.

Solar Neutrino Spectrum

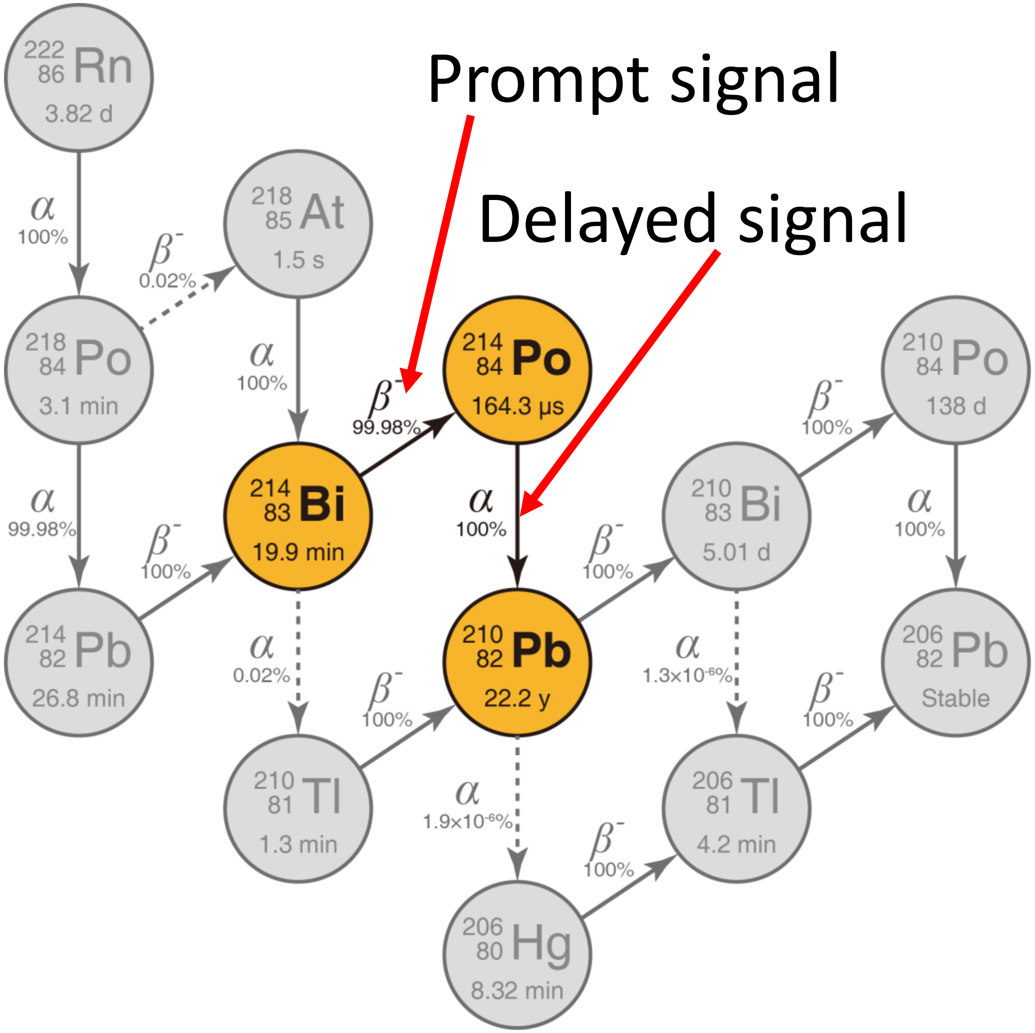


Requirement (Borexino)

Components	^{238}U (g/g)	^{232}Th (g/g)
Stainless steel tank wall	$1\cdot10^{-8}$	$1\cdot10^{-8}$
Water buffer	$1\cdot10^{-10}$	$1\cdot10^{-10}$
Water CTF shield	$1\cdot10^{-13}$	$2\cdot10^{-13}$
Stainless Steel Sphere	$2\cdot10^{-10}$	$1\cdot10^{-10}$
PMTs	$3\cdot10^{-8}$	$1\cdot10^{-8}$
PC buffer	$1\cdot10^{-15}$	$1\cdot10^{-15}$
Nylon film for inner vessel	$5\cdot10^{-12}$	$2\cdot10^{-11}$
Scintillator	$1\cdot10^{-16}$	$1\cdot10^{-16}$
N_2 for scintillator sparging		

Astroparticle Physics 18 (2002) 1–25

■ Bi-214 Signal Signature



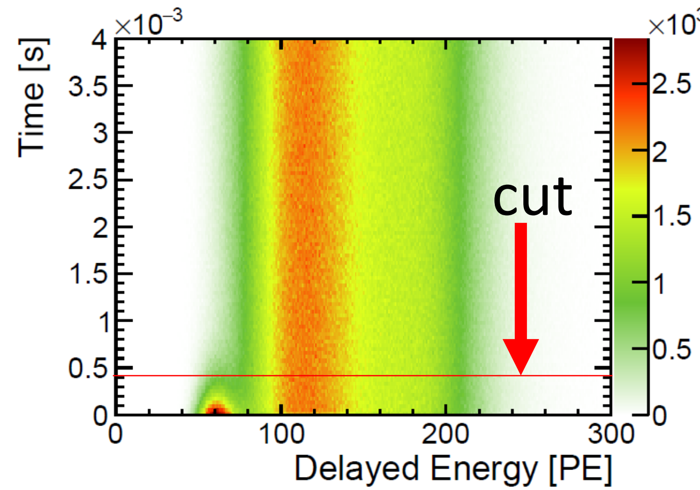
Vertex:

$$\vec{R} = \frac{3}{2} \times \frac{\sum_{i=0}^{29} \mathrm{PE}[i] \times \vec{r}_i}{\sum_{i=0}^{29} \mathrm{PE}[i]}$$

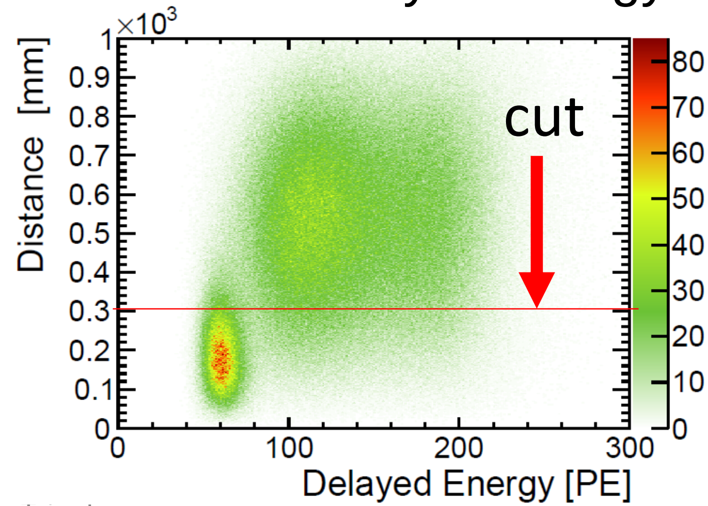
■ Event Selection

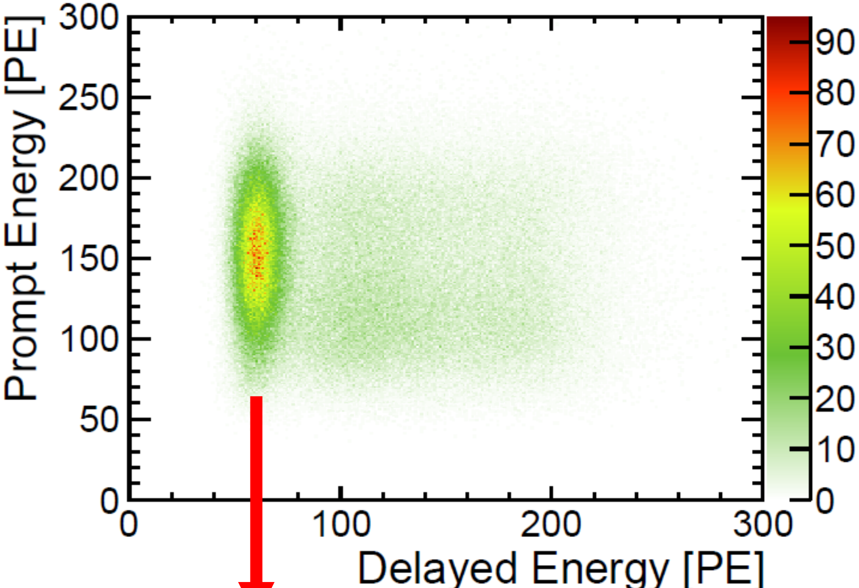
- Dataset: First month
- Prompt signal $-\beta$
- Delayed signal $-\alpha$ (visible energy $\sim$ 1 MeV)

Coincidence time vs delayed energy



Distance vs delayed energy

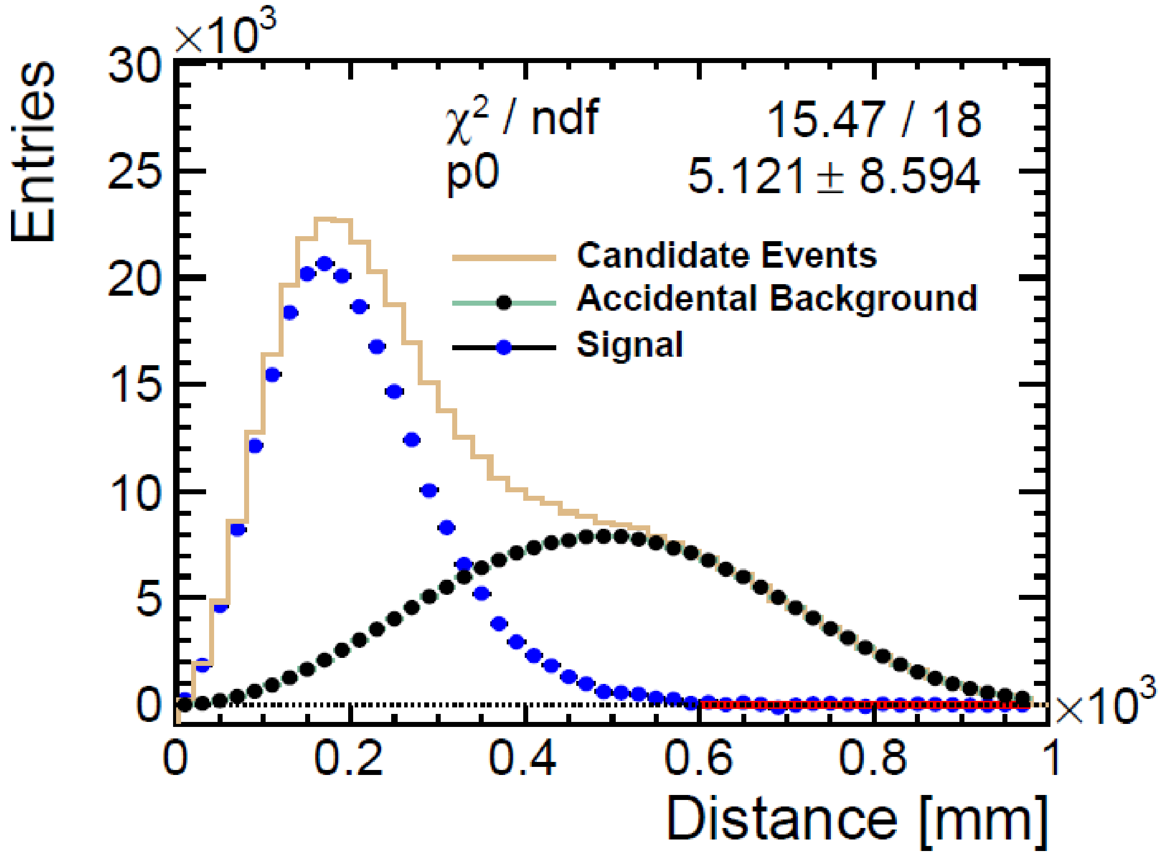




1 MeV $\sim$ 60 PE

■ Signal and Accidental Background

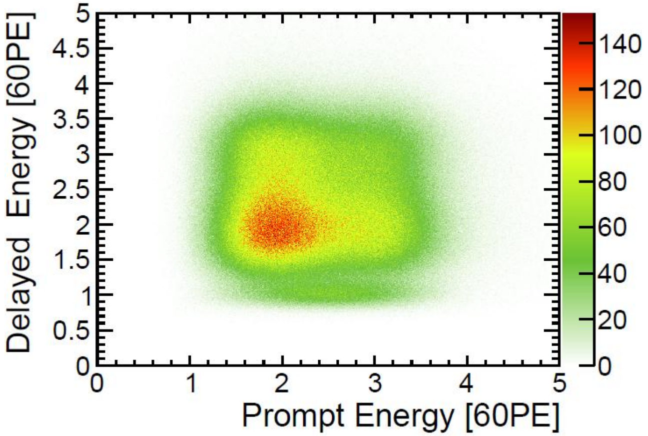
- Distance between prompt and delayed signal
- Dataset: First month



Jingyi Yu, Zhe Wang, and Shaomin Chen. arxiV:1301.5085[physics.ins-det]

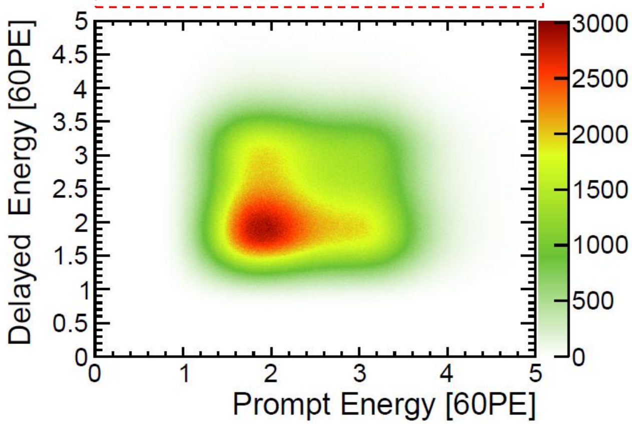
■ Signal and Accidental Background

- Dataset: First month
- Prompt energy versus Delayed energy

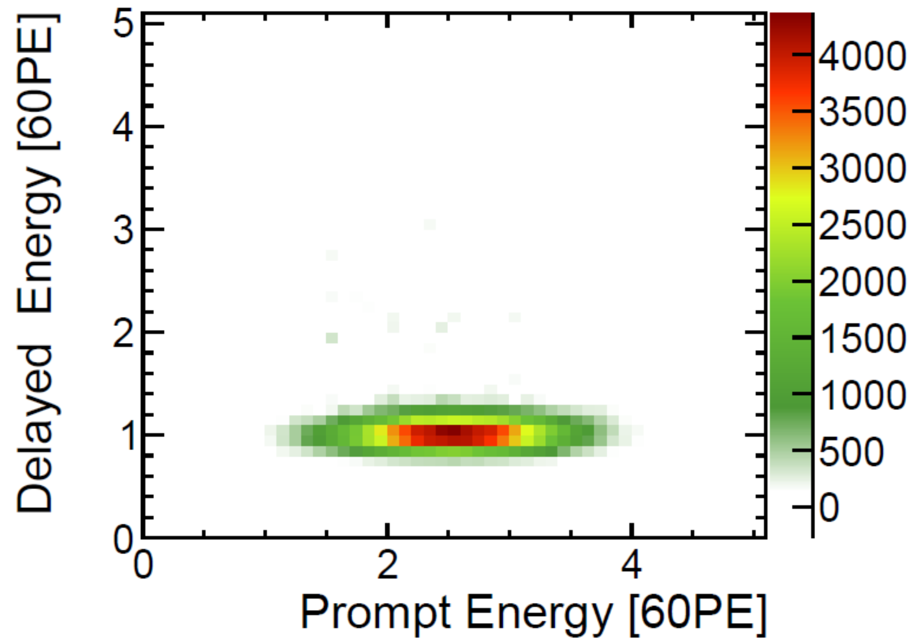


Candidate Events

Subtracts



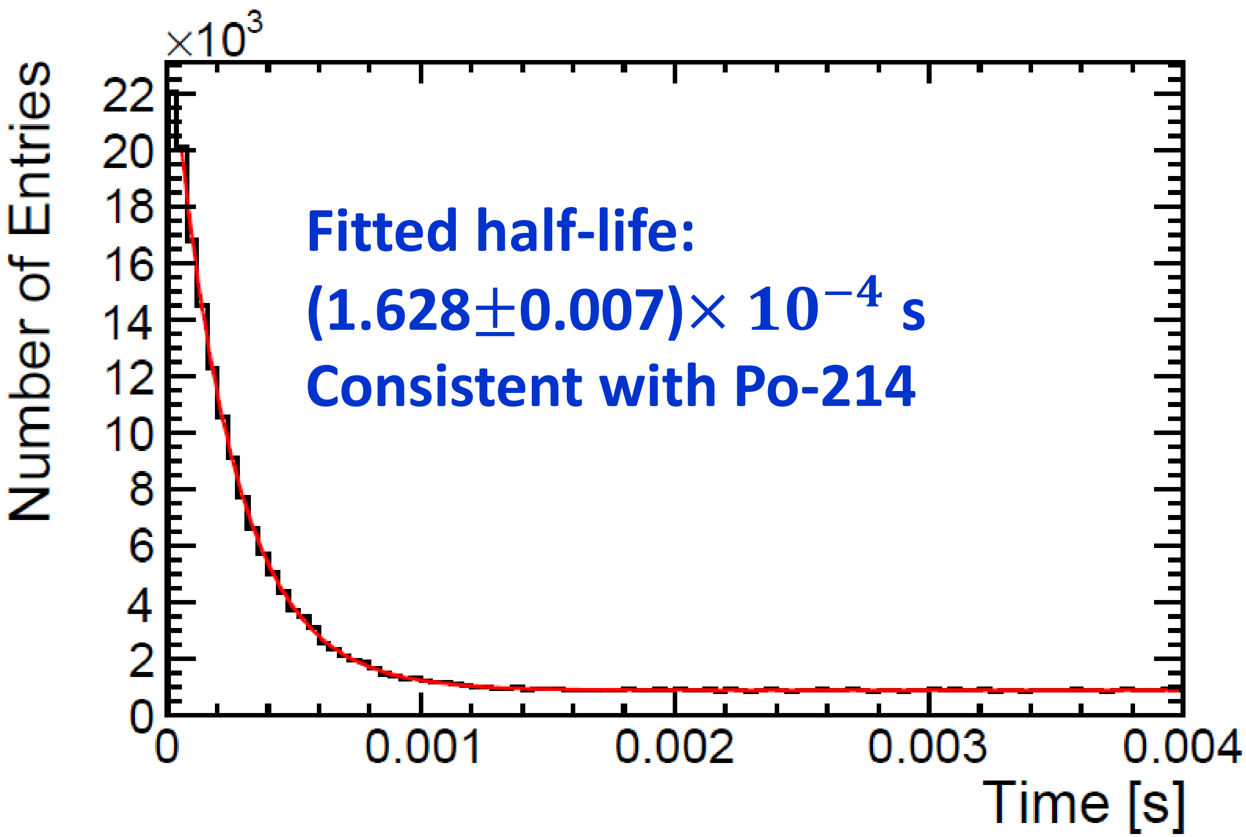
Accidental Background



Signal

■ Half-Life of Po-214

- Time difference between prompt and delayed signals
- Function to fit: $f(x) = A0 + A1\exp(-x/\tau)$
- Dataset: First month

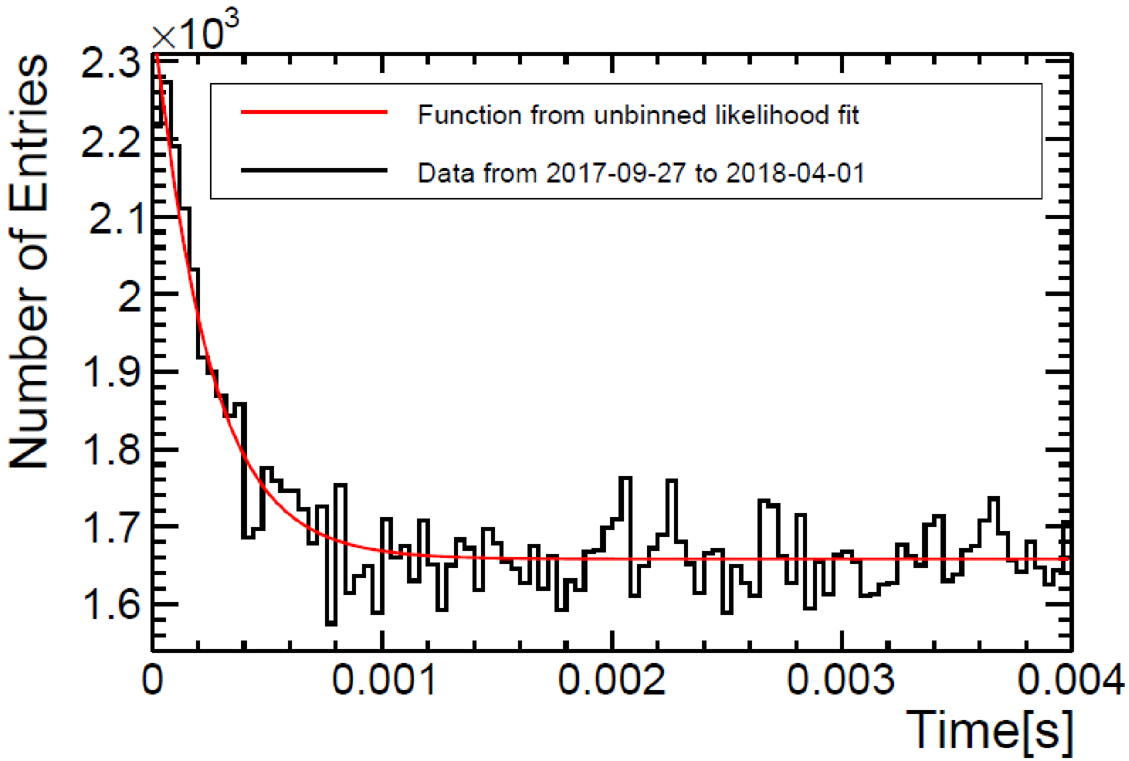


^{214}Po	
Reference	Half-life (μs)
Von Dardel, 1950	163.7 ± 0.2
Ballini, 1953	158.0 ± 2.0
Ovilvie, 1960	159.5 ± 3.0
Dobrowolski and Young, 1961	164.3 ± 1.8
Erlik et al., 1971	165.5 ± 3.0
Zhou et al., 1993	160.0 ± 12.0
Nuclear Data Sheet: Wu, 2009	164.3 ± 2.0[c]
Table de Radionucléides: Christé and Bé (2007)	162.3 ± 1.2[d]

■ Bi-214 Decay Chain Signal

- Dataset: about two months after liquid scintillator deploying
- Unbinned likelihood fit:

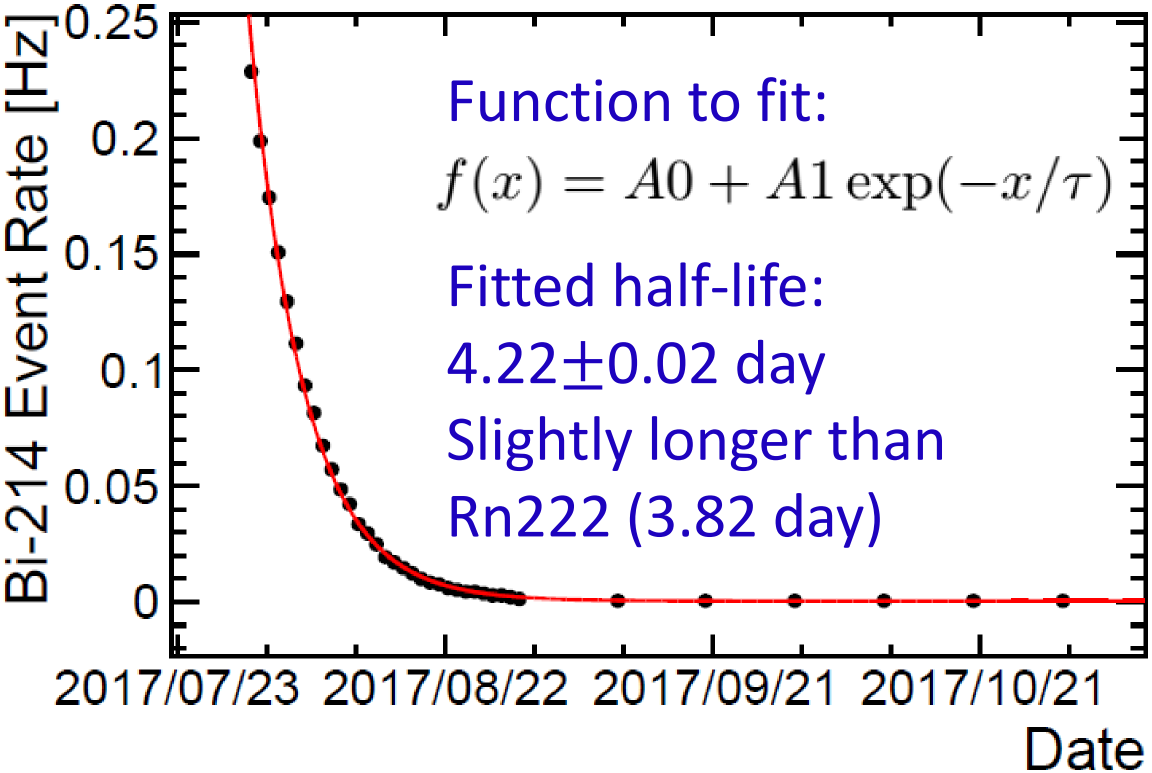
$$-\ln L(\nu_s) = (\nu_s + \nu_b) - \sum_{i=1}^{N} \ln\left(\frac{\nu_s}{\tau}\exp(-t_i/\tau) + \nu_b \times 250\right)$$

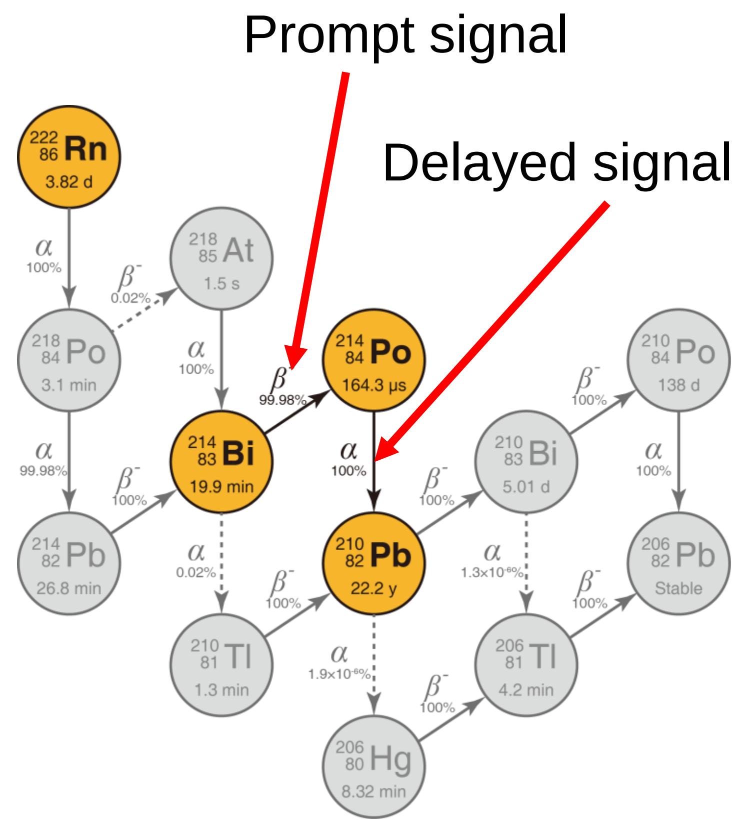


Bi-214 signal number = 4279.7±153.6

■ The Source of Bi-214

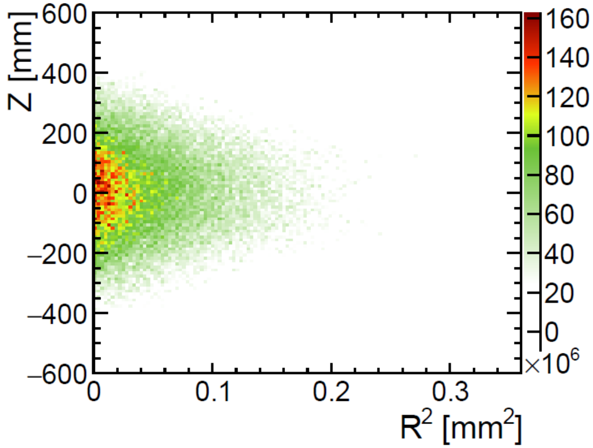
- Observed Bi-214 is consistent with that from Rn-222 decay



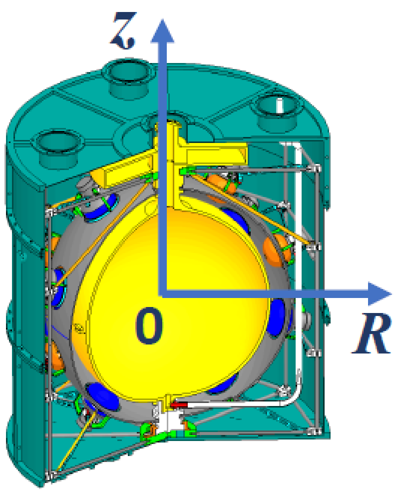


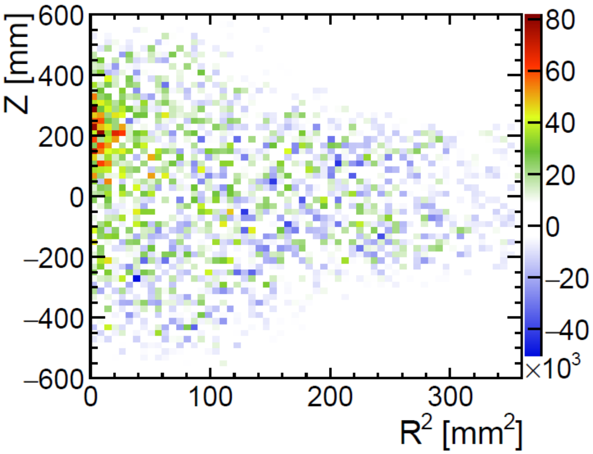
■ Radon Leakage Study

- Observed uniform vertex distribution in First month is dominant by original radon background in liquid scintillator
- Vertex distribution concentrated in top part of detector in later data is consistent with expected leakage from the hole in the top



Dataset: first month from liquid scintillator deploying



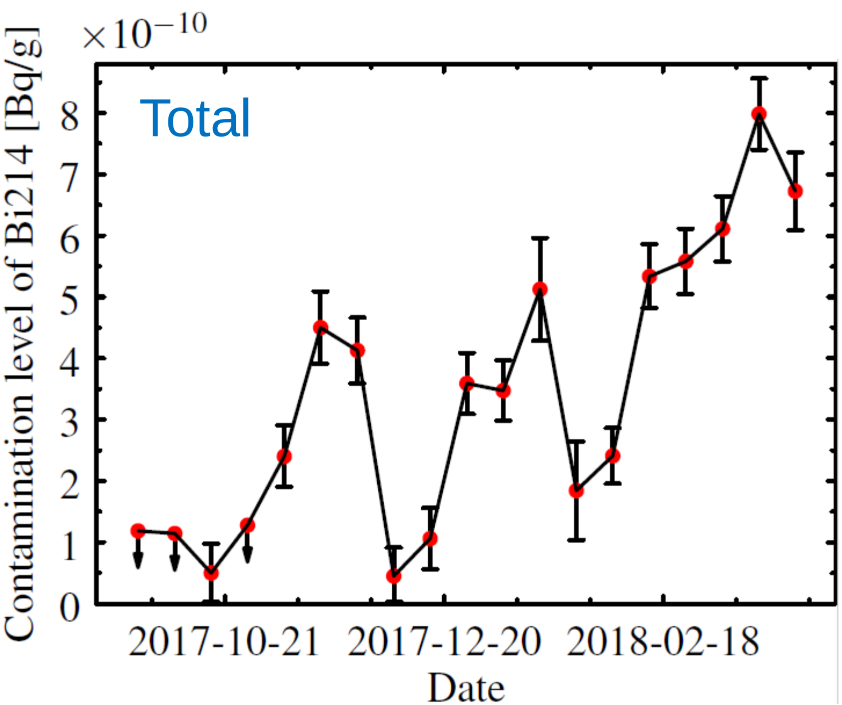


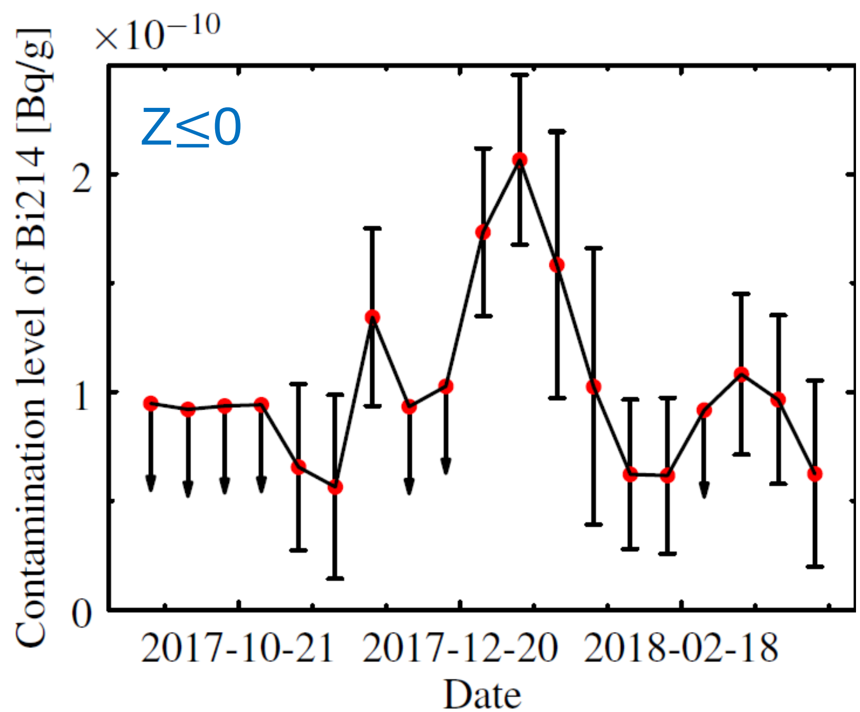
Dataset: 57 days after liquid scintillator deploying

Air leak from top filling and instrument pipes

■ Radon Leakage Study

- Dataset: two months after liquid scintillator deploying
- Selection efficiency is not considered in fig
- Observed contamination level rising is consistent with the expected leakage of Radon
- While the contamination level in the bottom is relatively stable





■ Radioactive Background Level Estimation

- Based on data two months after liquid scintillator deploying
- Live time : t ≈1.44× 10^7 s
- Selection efficiency : η ≈12.5%

$$R_{\text{Bi-214}} = \frac{\nu_{\text{sig}}}{m \times t \times \eta}$$
$$\approx (2.5 \pm 0.1) \times 10^{-9}\ \text{Bq/g}$$

Assuming secular equilibrium is valid

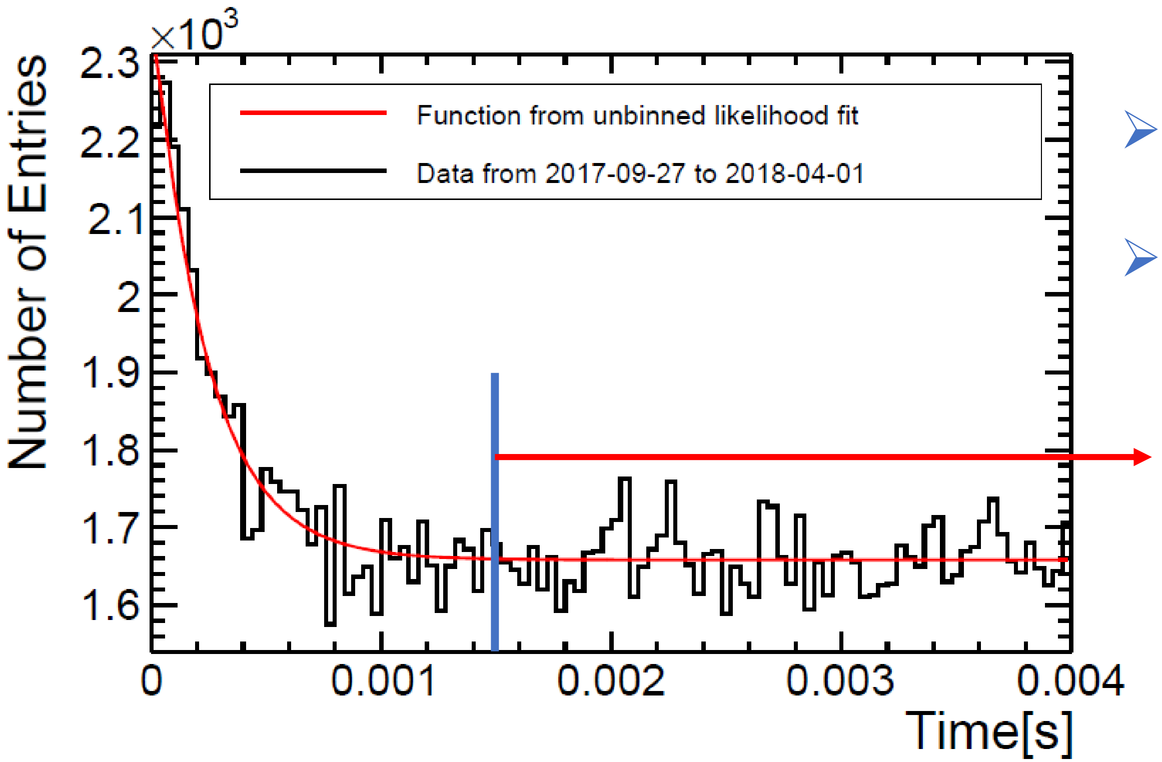
$$R_{\text{U-238}} = (2.5 \pm 0.1) \times 10^{-9}\ \text{Bq/g}$$
$$\approx (2.0 \pm 0.1) \times 10^{-13}\ \text{g/g}$$

Restrict the Bi-214 in bottom of detector by Z≤0:

$$R_{\text{U-238}} = (7.9 \pm 1.2) \times 10^{-10}\ \text{Bq/g}$$
$$\approx (6.4 \pm 1.0) \times 10^{-14}\ \text{g/g}$$

■ Radioactive Background Level Estimation

- Radioactive level of Bi-214 can be decreased by a factor of 180/4279.7≈0.042
- That is 8.4×10^{-15} g/g (assuming current bkg. level)
- Purification efficiency can be measured



- Close to the required level claimed by Borexino
- Cheap and Operate easily

Upper limit is 180 (90%C.L.)

■ Estimation of Upper Limit of Bi-212(Th-232) Radioactive Level

- Th-232 decay chain $\text{Bi-212} \rightarrow \text{Po-212}(T_{1/2} = 300\text{ns}) \rightarrow \text{Pb-208}$
- Live time : t ≈1.3× 10^7 s
- Selection efficiency : η ≈(1.51±0.04)%
- Upper limit (90%C.L.) of number of Bi-212 : 8.6

Upper limit of Bi-212:

$$R_{\text{Bi-212}} \approx 4.54 \times 10^{-11}\ \text{Bq/g}$$

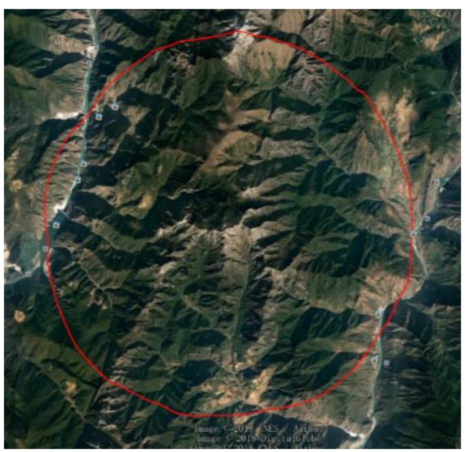
Assuming secular equilibrium is valid:

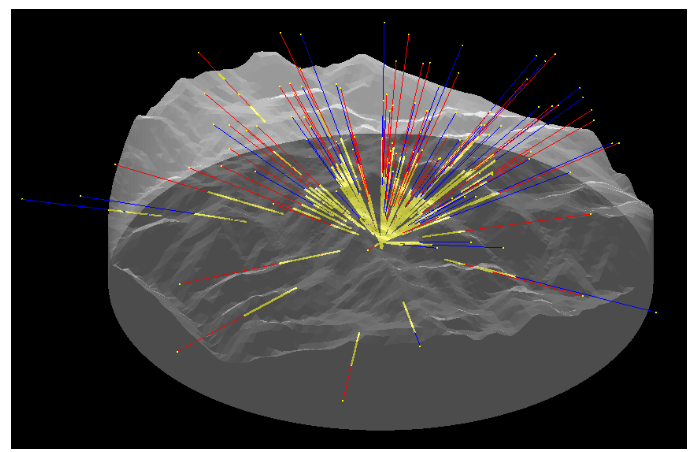
Upper limit of Th-232:

$$\begin{aligned} R_{\text{Th-232}} &\approx 4.54 \times 10^{-11}\ \text{Bq/g} \\ &\approx 1.12 \times 10^{-14}\ \text{g/g} \end{aligned}$$

■ Muon Spectrum Simulation

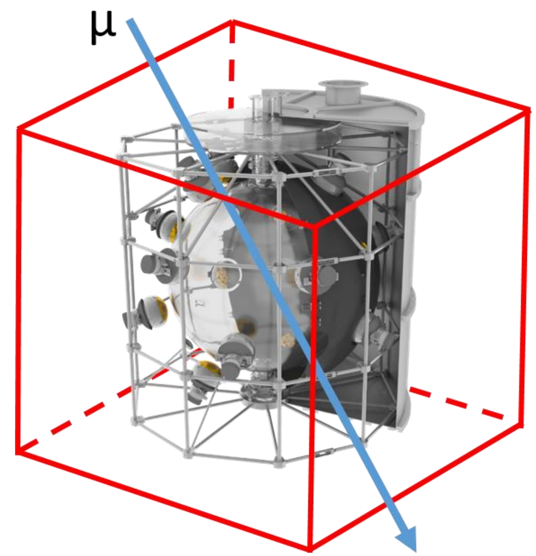
- Simulate muon penetrating in the mountain rock by Geant4.
- The muon generator in the atmosphere depends on the modified Gaisser formula.



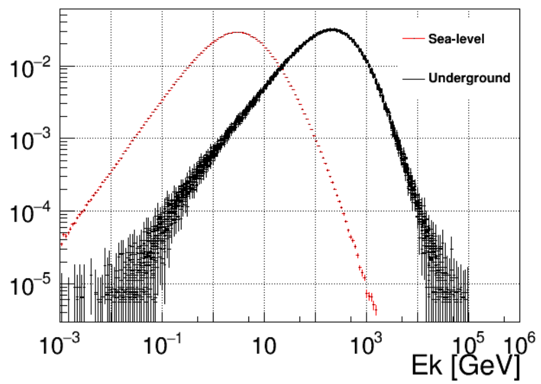


Detection Efficiency Simulation

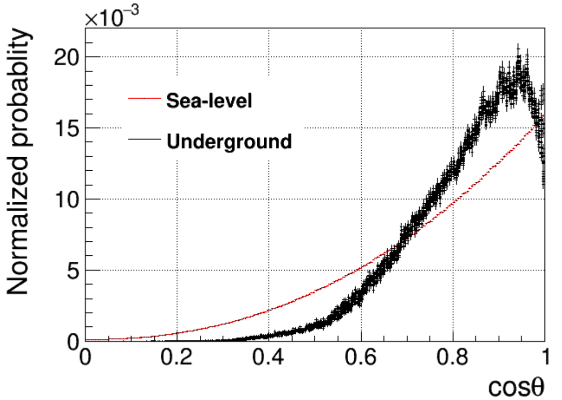
- Generate muons on the 5 surfaces of the box (side length = 3m) covering the detector.
- The muon energy and angular distribution is given by the simulation result on the previous page.
- The detection efficiency is defined as the ratio of triggered events to the total events



$$\epsilon \equiv \frac{R_{\text{trig}}}{R_{\mu}} = \frac{N_{\text{trig}}}{N_{\text{total}}}$$



Muon kinetic energy distribution (simulation result)



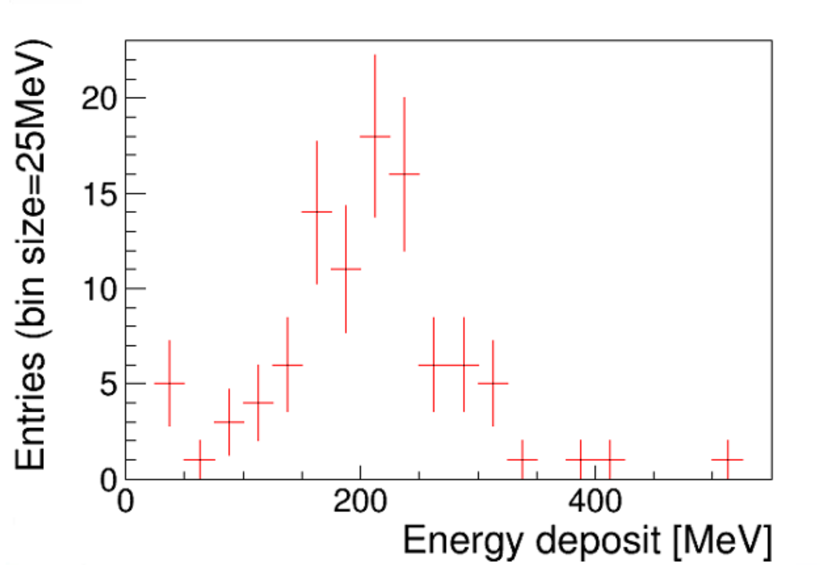
Muon zenith distribution (simulation result)

■ Muon Flux

The muon flux is calculated by

$$f = R_{\rm trig} \cdot \frac{N_{\rm top}}{\epsilon S_{\rm top} N_{\rm total}}$$

- where Rtrig is muon rate from the data, other values are efficiency factors from simulation.
- Live time: 1.832×10^7 s = 212 days
- 99 muon candidates.
- The preliminary muon flux is at 10^{-10} $cm^{-2}s^{-1}$ level



Energy deposit of muon event candidates

■ Conclusion

- The half-lifes of Po-214 we measured agree well with expected values and confirmed Rn-222 related.
- The leakage of Radon is investigated by the cascade decay of Bi-214.
- Muon simulation is performed in Jinping. Muon flux : 10^{-10} $cm^{-2}s^{-1}$ level.
- Estimation of radioactive level of U-238 gives a value $\sim 6.4 \times 10^{-14}$ g/g. And the upper limit of Th-232 contamination is estimated at 10^{-14} g/g level.
- Limit of detection for U-238: 10^{-15} g/g – a low background facility.

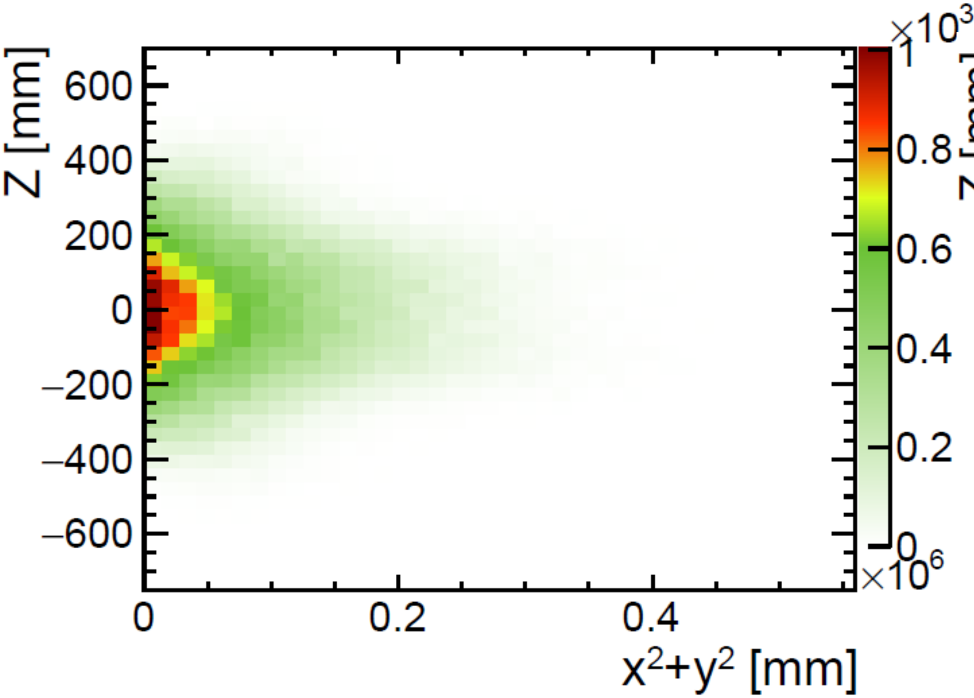
Purification efficiency can be measured and equipment upgrade (purification, air tight) in plan.

Thank You

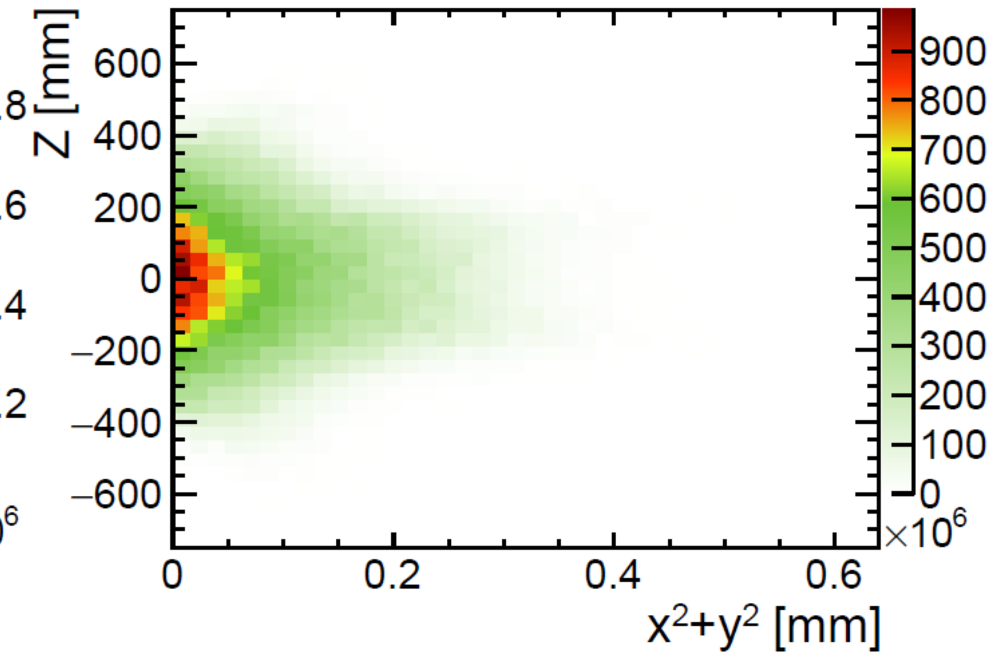
Backup

■ Radon in LS study

- Monte Carlo dataset



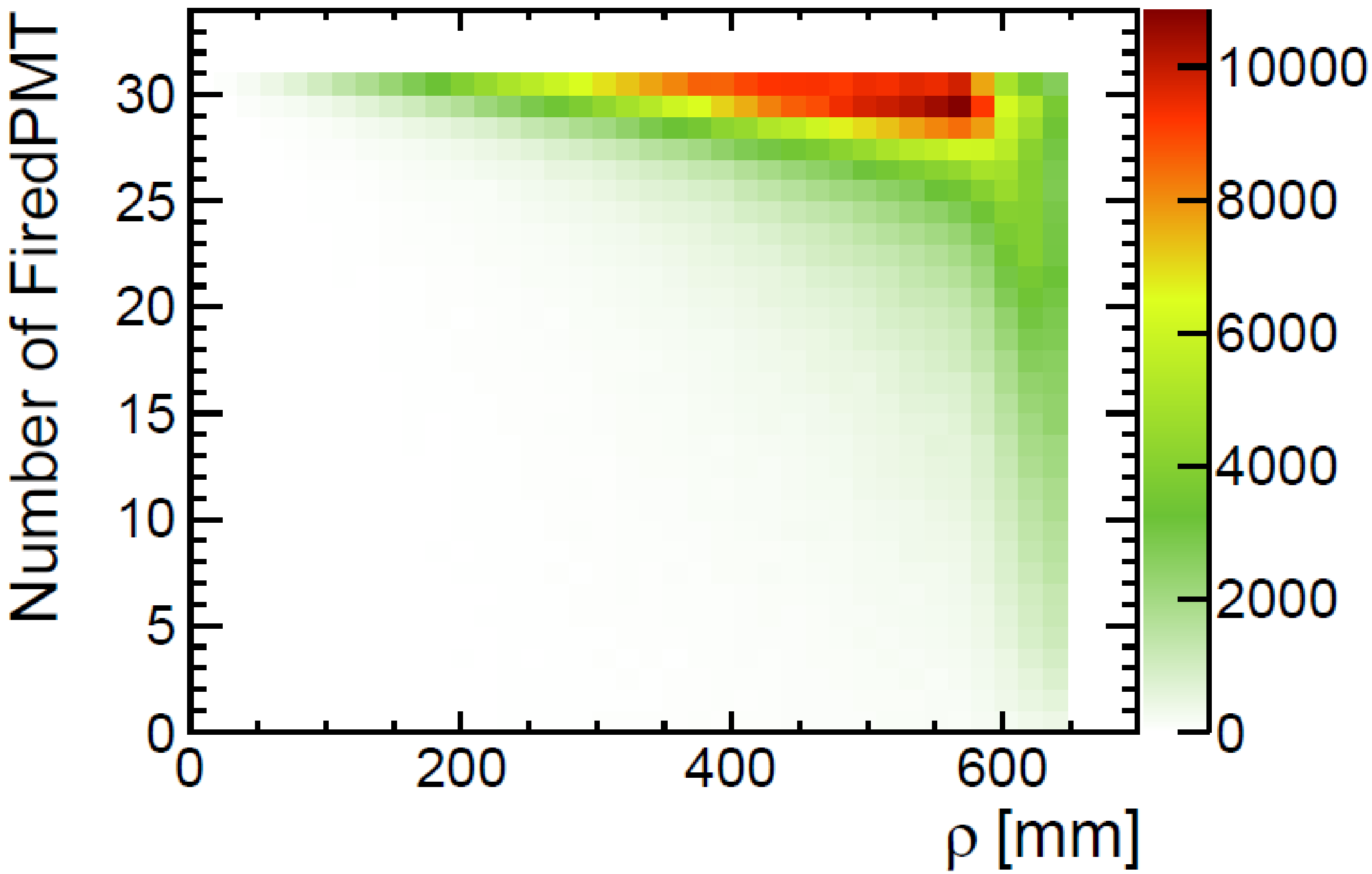
Prompt signal



Delayed signal

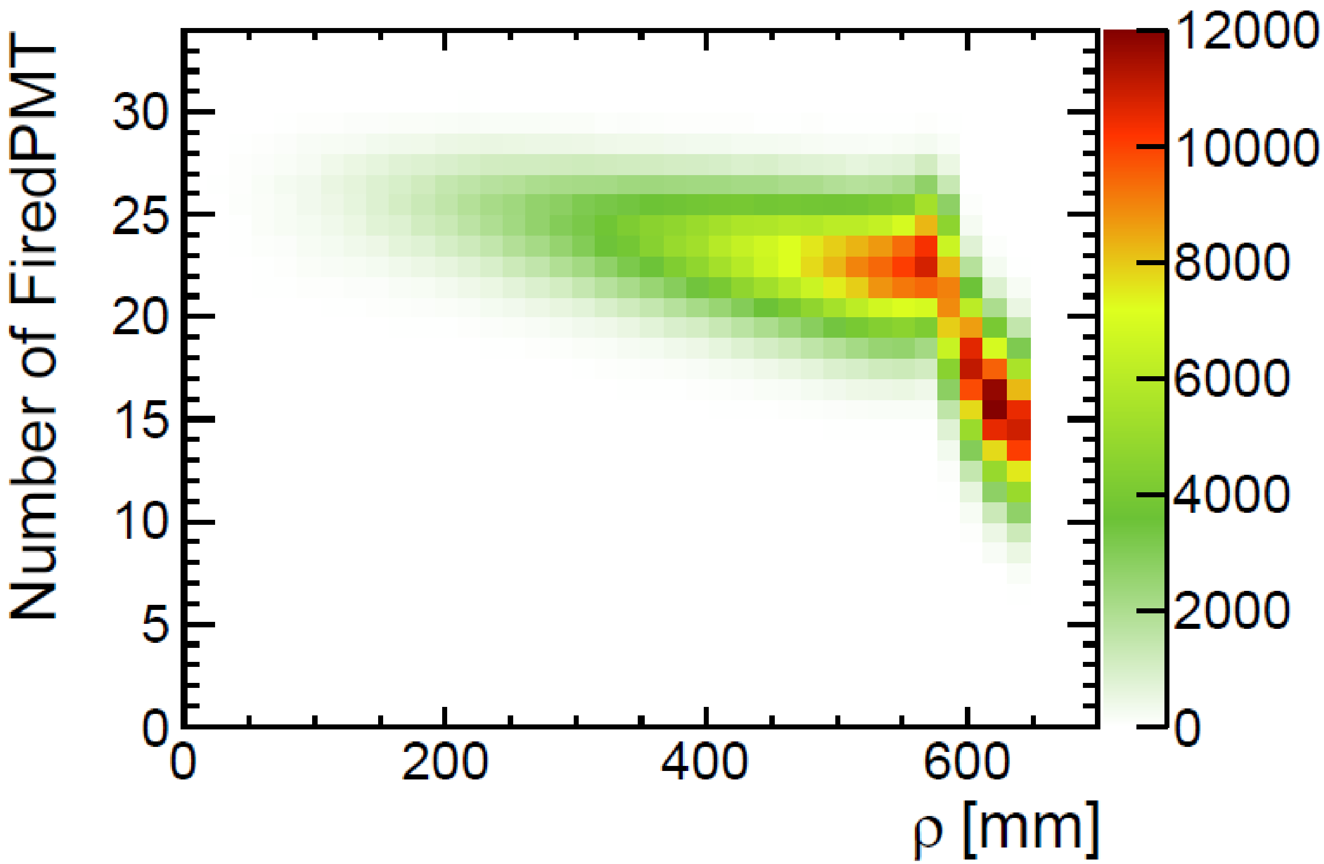
■ Monte Carlo Simulation of Bi-214 Signal

- Beta Particle



■ Monte Carlo Simulation of Bi-214 Signal

- Alpha Particle



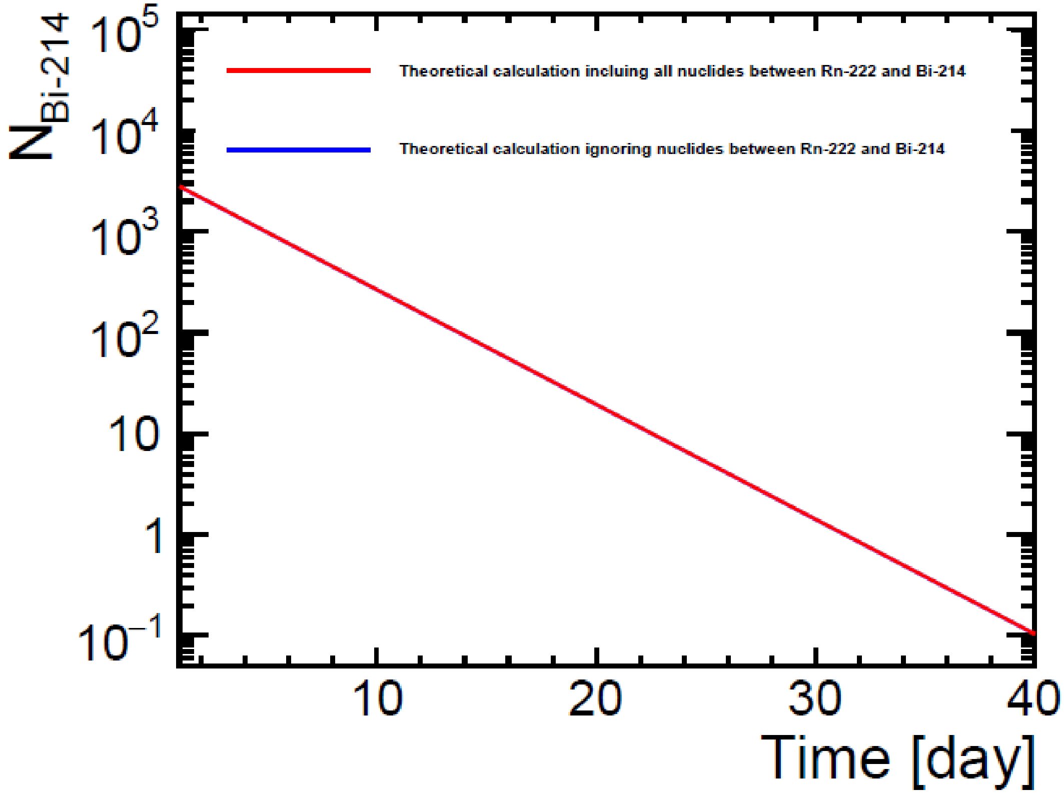
■ Exact Formula of Number of Bi-214

dominant

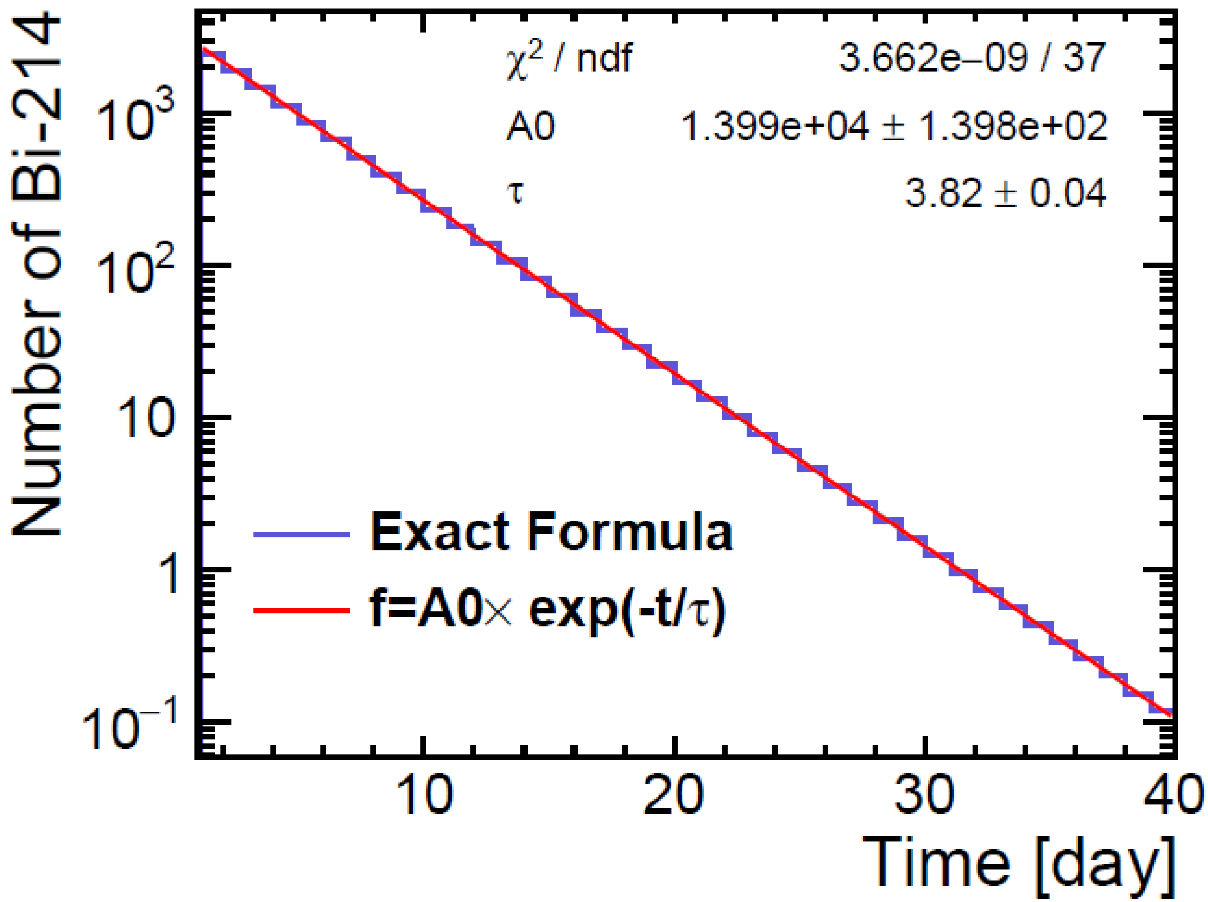
$$
\begin{aligned}
N_{\text{Bi-214}} = N_{\text{Rn-222}}(0) \times \lambda_{\text{Rn-222}}\lambda_{\text{Po-218}}\lambda_{\text{Pb-214}} \times \{ \\
& \boxed{\exp(-\lambda_{\text{Rn-222}}t)} / \left[(\lambda_{\text{Po-218}} - \lambda_{\text{Rn-222}})(\lambda_{\text{Pb-214}} - \lambda_{\text{Rn-222}})(\lambda_{\text{Bi-214}} - \lambda_{\text{Rn-222}})\right] \\
& + \exp(-\lambda_{\text{Po-218}}t) / \left[(\lambda_{\text{Rn-222}} - \lambda_{\text{Po-218}})(\lambda_{\text{Pb-214}} - \lambda_{\text{Po-218}})(\lambda_{\text{Bi-214}} - \lambda_{\text{Po-218}})\right] \\
& + \exp(-\lambda_{\text{Pb-214}}t) / \left[(\lambda_{\text{Rn-222}} - \lambda_{\text{Pb-214}})(\lambda_{\text{Po-218}} - \lambda_{\text{Pb-214}})(\lambda_{\text{Bi-214}} - \lambda_{\text{Pb-214}})\right] \\
& - \exp(-\lambda_{\text{Bi-214}}t) \times (1 / \left[(\lambda_{\text{Po-218}} - \lambda_{\text{Rn-222}})(\lambda_{\text{Pb-214}} - \lambda_{\text{Rn-222}})(\lambda_{\text{Bi-214}} - \lambda_{\text{Rn-222}})\right] \\
& + 1 / \left[(\lambda_{\text{Rn-222}} - \lambda_{\text{Po-218}})(\lambda_{\text{Pb-214}} - \lambda_{\text{Po-218}})(\lambda_{\text{Bi-214}} - \lambda_{\text{Po-218}})\right] \\
& + 1 / \left[(\lambda_{\text{Rn-222}} - \lambda_{\text{Pb-214}})(\lambda_{\text{Po-218}} - \lambda_{\text{Pb-214}})(\lambda_{\text{Bi-214}} - \lambda_{\text{Pb-214}})\right])\}
\end{aligned}
$$

■ Does the (short-life) intermediate nuclides matter

- Po-218, Pb-214 are(red) and aren't (blue) considered

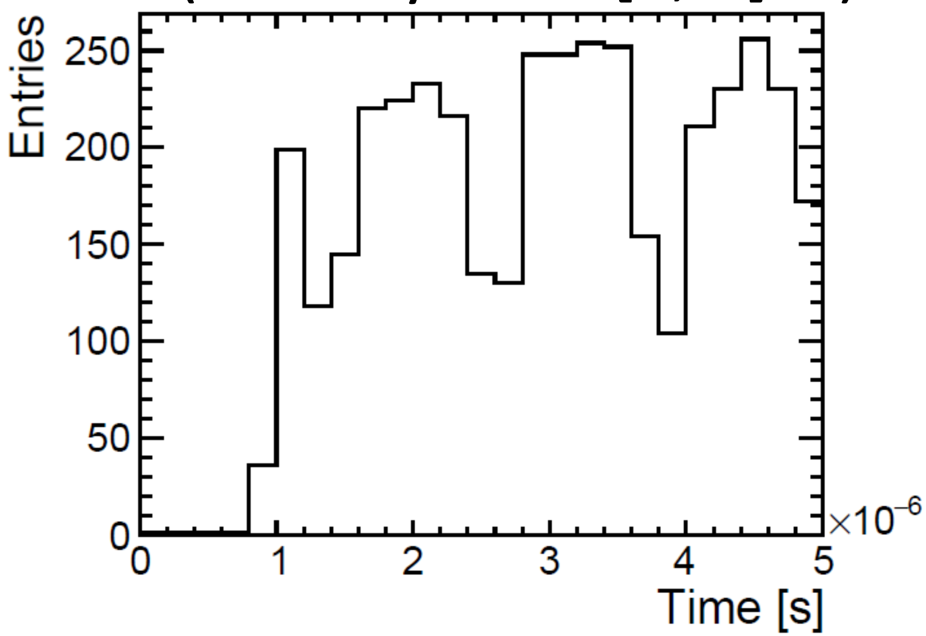


■ **Can the single expo be good enough to describe Rn-222 decay**

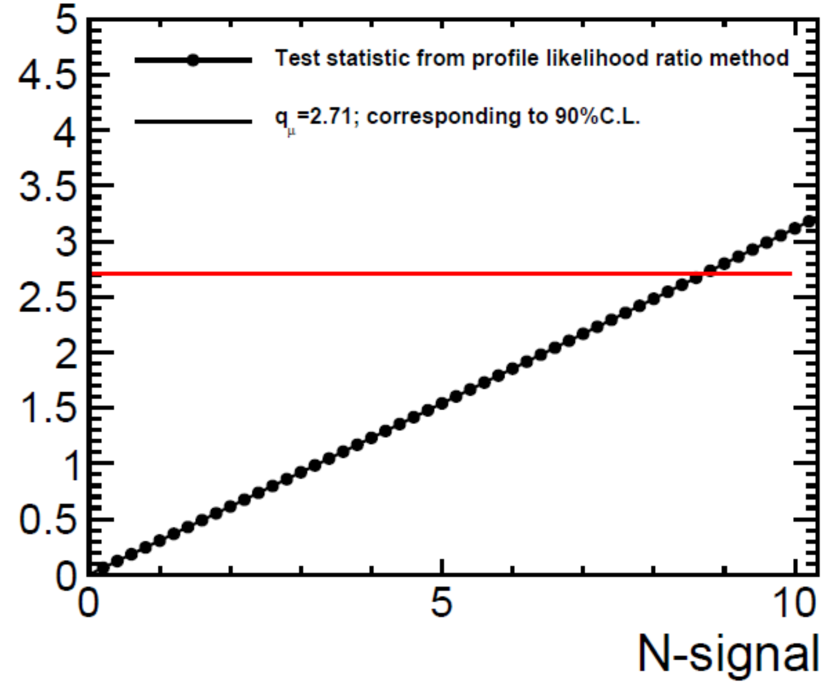


■ How to give the upper limit of Bi-212

Data (actually used [1, 5]us)



Profile likelihood ratio method



■ Detector simulation

Generate Ntotal muons on the 5 surfaces of the box, Ntop of them are on the top surface. The relationship between flux and muon rate is

$$R_\mu = f \cdot \frac{N_{\text{total}}}{N_{\text{top}}} \cdot S_{\text{top}}$$

Where f is the muon flux, Stop is the area of top surface.

The trigger rate is proportional to the muon rate,

$$R_{\text{trig}} = \epsilon \cdot R_\mu = \epsilon \cdot f \cdot \frac{N_{\text{total}}}{N_{\text{top}}} \cdot S_{\text{top}}$$

epsilon is the defined as the detection efficiency, which can be estimated by the ratio of triggered events and total events,

Therefore the measured flux is

$$\epsilon \equiv \frac{R_{\text{trig}}}{R_\mu} = \frac{N_{\text{trig}}}{N_{\text{total}}}$$

Rtrig is obtained from the data, other values are form MC.

$$f = R_{\text{trig}} \cdot \frac{N_{\text{top}}}{\epsilon S_{\text{top}} N_{\text{total}}} = R_{\text{trig}} \cdot \frac{N_{\text{top}}}{S_{\text{top}} N_{\text{trig}}}$$