

# Muon Spallation Products in KamLAND

14th Geant4 Users Workshop

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# KamLAND Collaboration

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(The KamLAND Collaboration)



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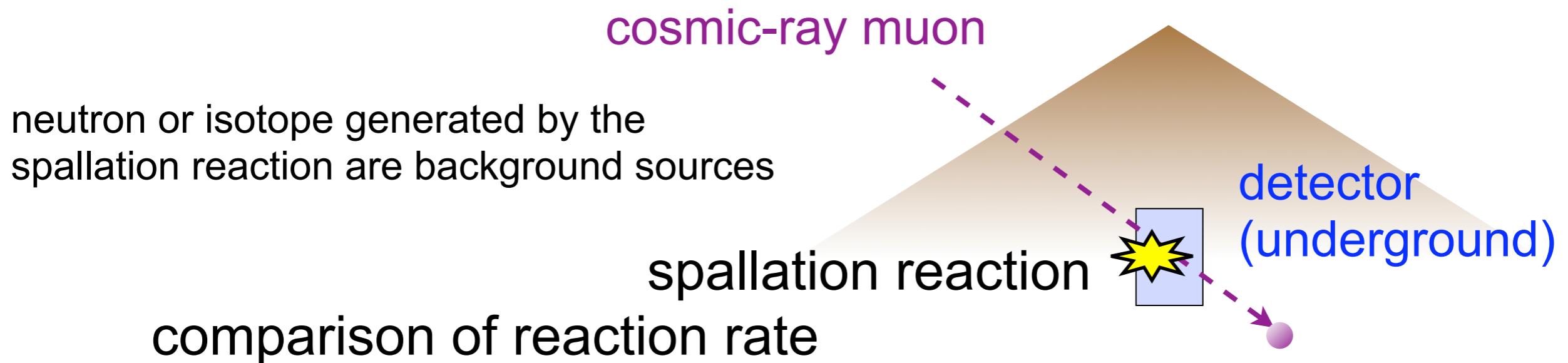
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# Motivation

Understanding of the nature of cosmogenic backgrounds is important for rate event detection in neutrino detectors, double-beta-decay experiment, and dark matter searches



solar neutrino ( ${}^8\text{B}$ )

~ 3 events / day / kton

$0\nu\beta\beta$  ( ${}^{136}\text{Xe}$  loaded LS)  
 $\langle m_\nu \rangle = 0.15 \text{ eV}$

~ 1.5 events / day / kton

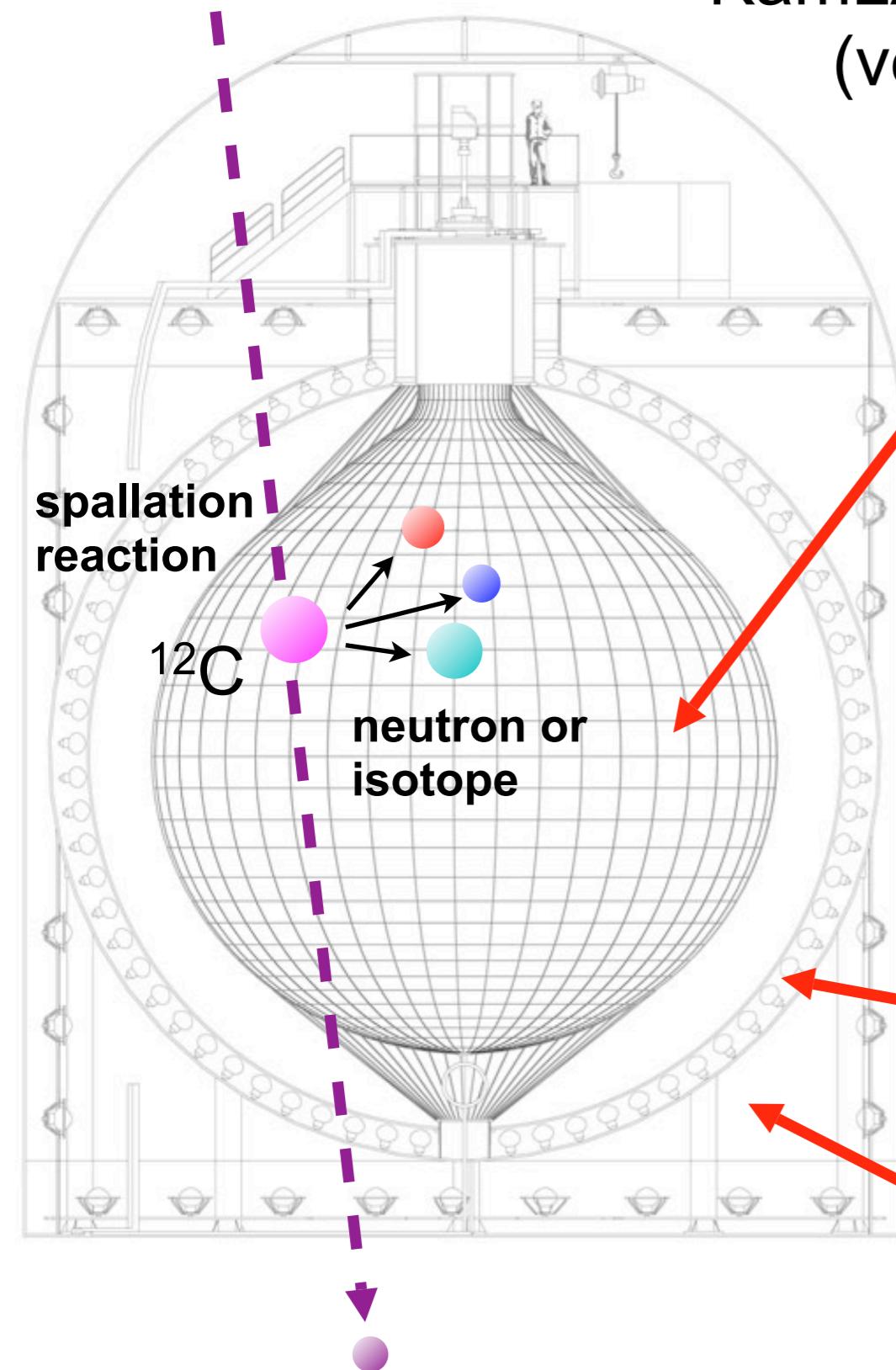
muon spallation (neutron)  
@ 1,000 m depth

~ 3000 events / day / kton

spallation neutron or isotope can be background sources

# KamLAND Detector

cosmic-ray muon

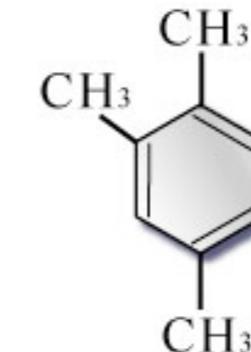
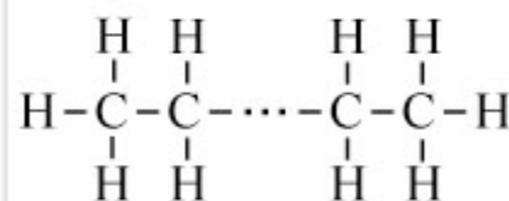


KamLAND is located under the peak of Ikenoyama  
(vertical rock overburden is  $\sim 2700$  m.w.e.)

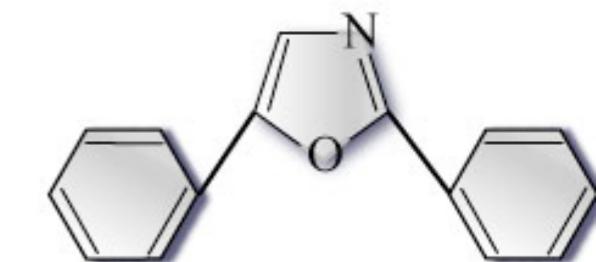
1,000 ton liquid scintillator

Pseudocumene (20%)

Dodecane (80%)



PPO (1.5 g/l)



Dodecane ( $\text{C}_{12}\text{H}_{26}$ ) : 80%

Pseudocumene : 20%  
(1,2,4-Trimethyl Benzene)

PPO : 1.5 g / l  
(2,5-Diphenyloxazole)

PMT (1325 17 inch + 554 20 inch)

detection of scintillation light

water cherenkov outer detector

tag the cosmic-ray muon

# Rock Overburden for Muon

3D Monte Carlo codes dedicated to muon simulations

## MUSIC (MUon SImulation Code)

reference : P. Antonioli et al., Astropart. Phys. 7, 357 (1997)

typical rock density       $2.65 \sim 2.75 \text{ g/cm}^3$

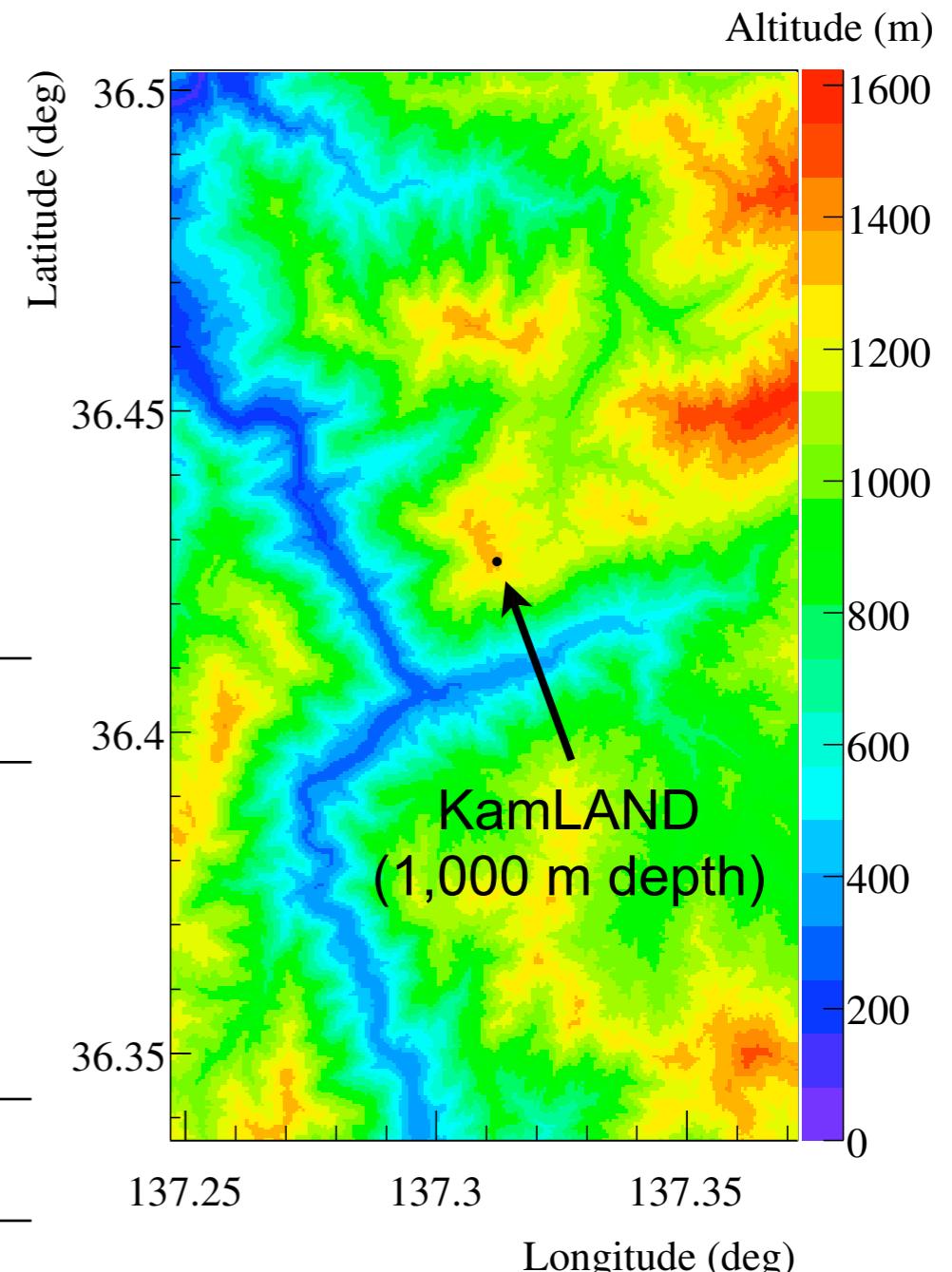
mountain profile (Geographical Survey Institute of Japan)

### muon flux and energy @ KamLAND

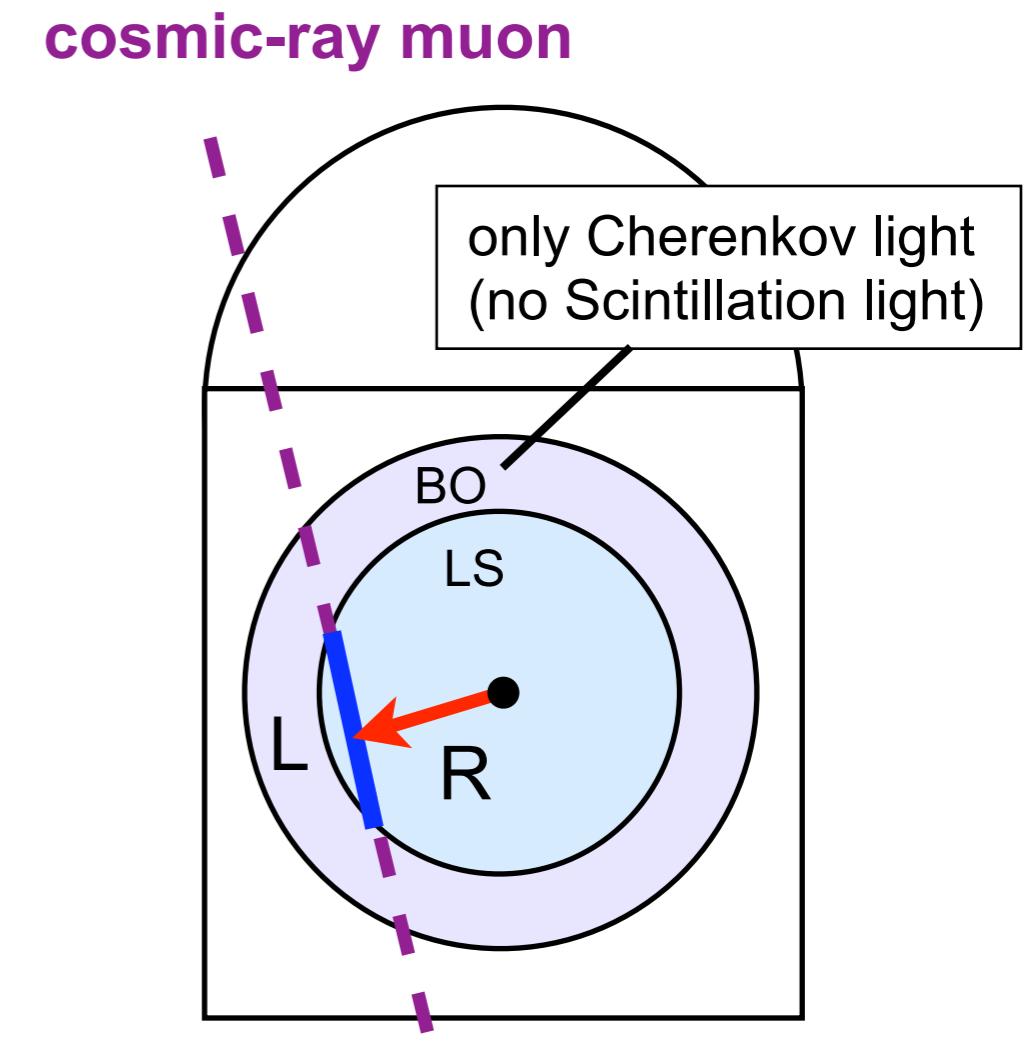
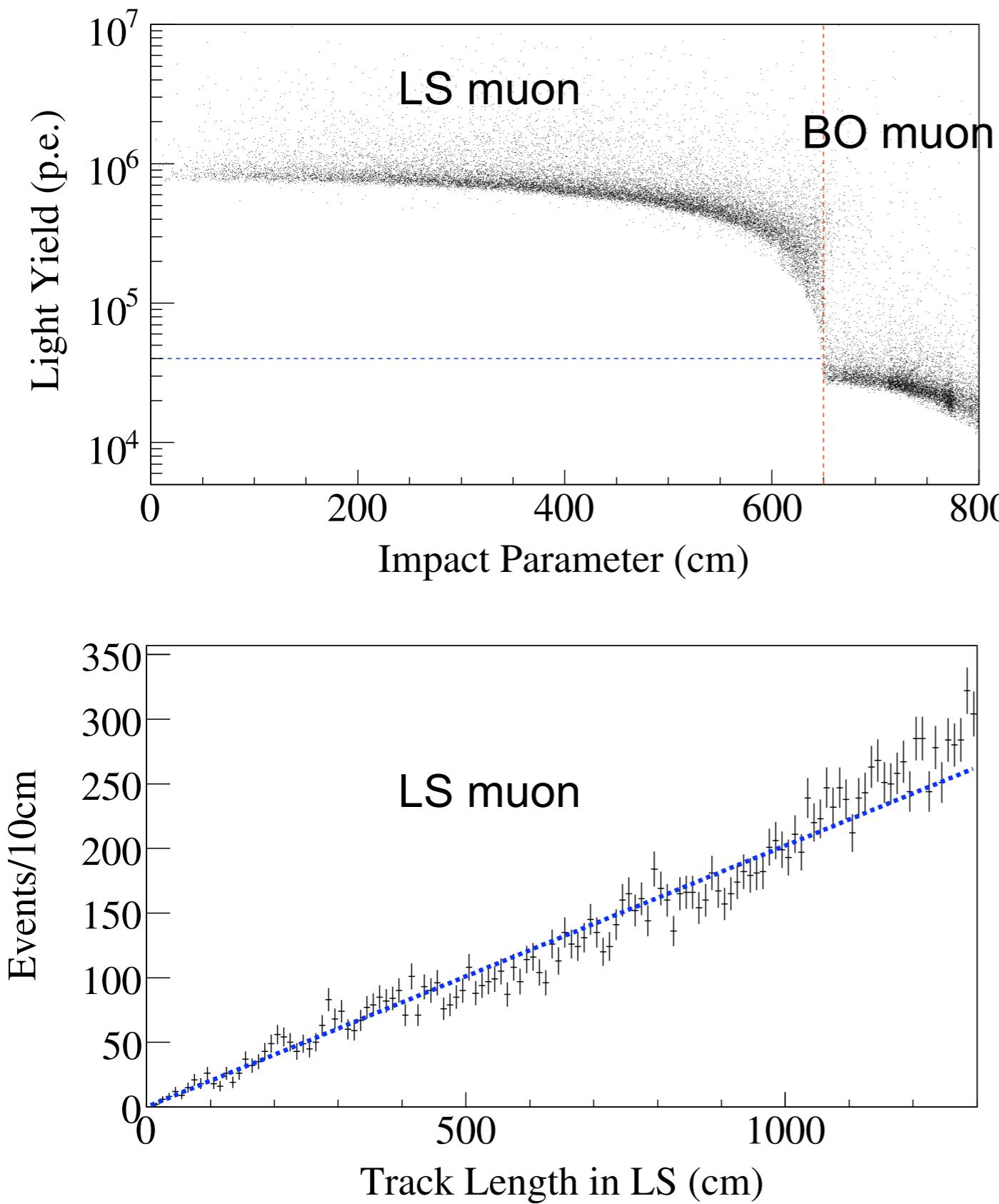
	$J_\mu (\text{m}^{-2} \text{ h}^{-1})$	$E_\mu (\text{GeV})$
Inishi Rock	$5.66 \sim 6.71$	$262 \sim 268$
Standard Rock	$4.95 \sim 5.83$	$256 \sim 262$
Generic Skarn	$4.90 \sim 5.82$	$254 \sim 260$
Measurement	$5.37 \pm 0.41$	—

### Rock Overburden Effect

	flux (measurement)	mean energy
surface	$(1.90 \pm 0.12) \times 10^{-2} \text{ cm}^{-2} \text{ s}^{-1}$	$\sim 7 \text{ GeV}$
KamLAND (2,700 m.w.e)	$(1.49 \pm 0.11) \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$	$\sim 260 \text{ GeV}$ (MUSIC)



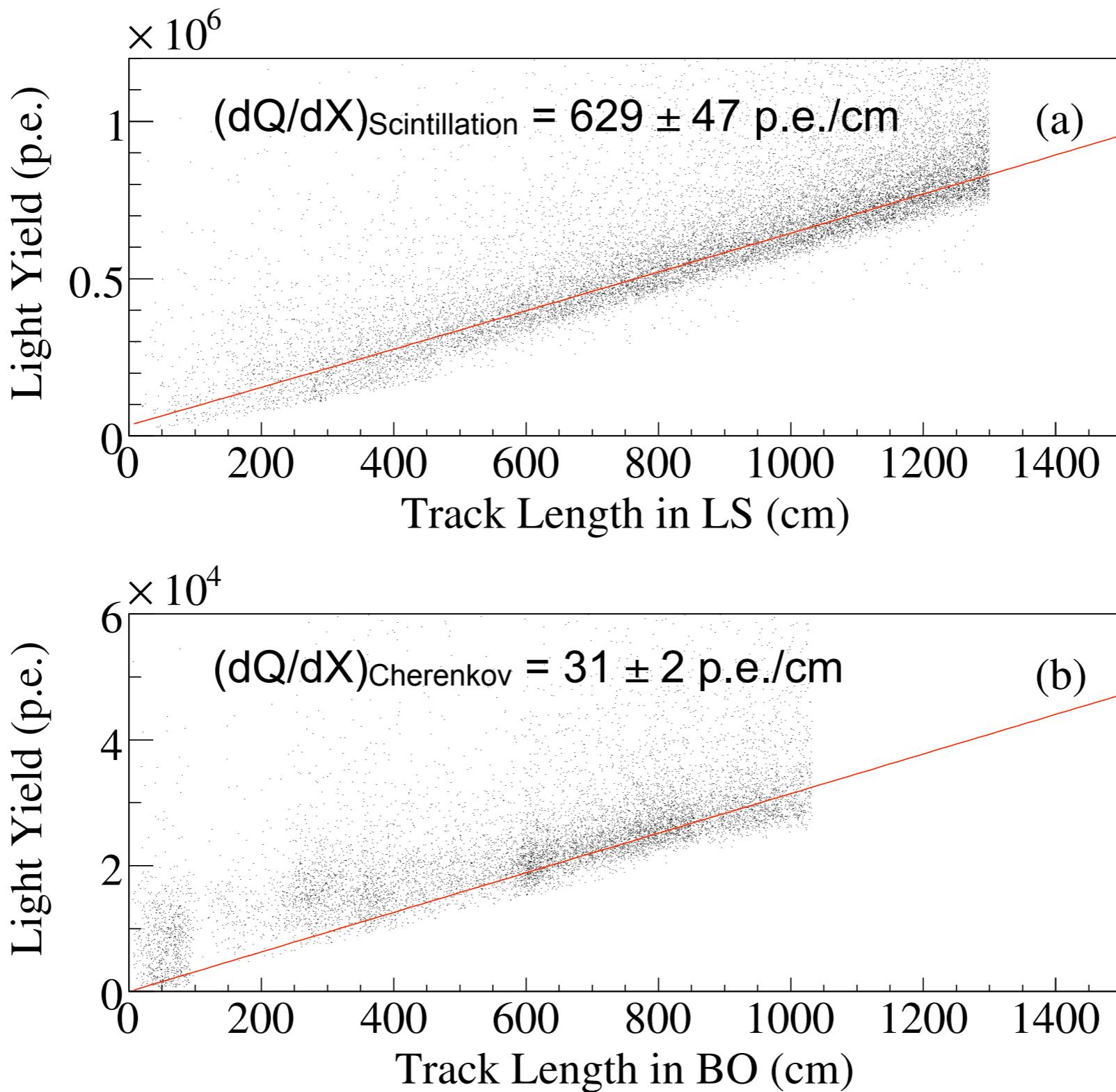
# Cosmic-ray Muon Detection (1)



R : impact parameter  
L : track length in LS

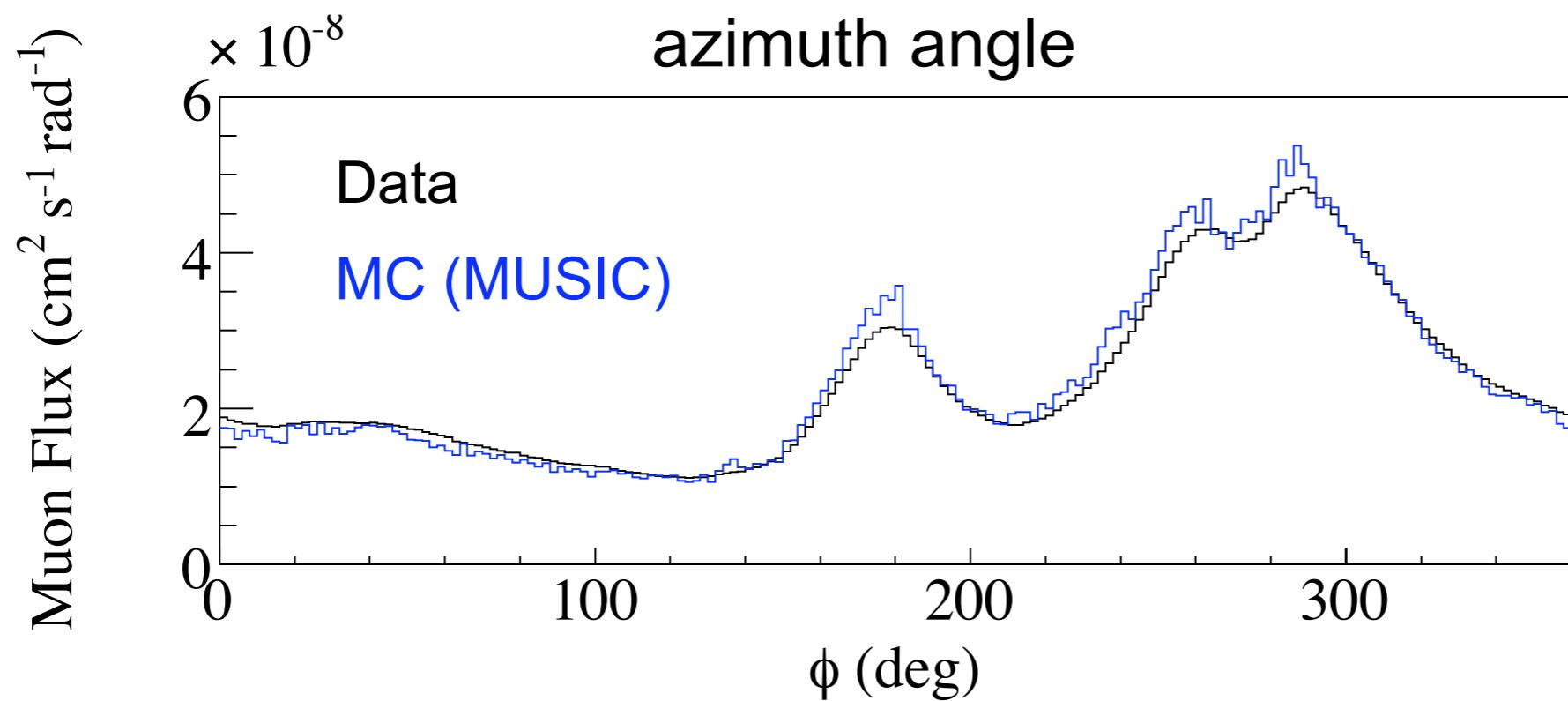
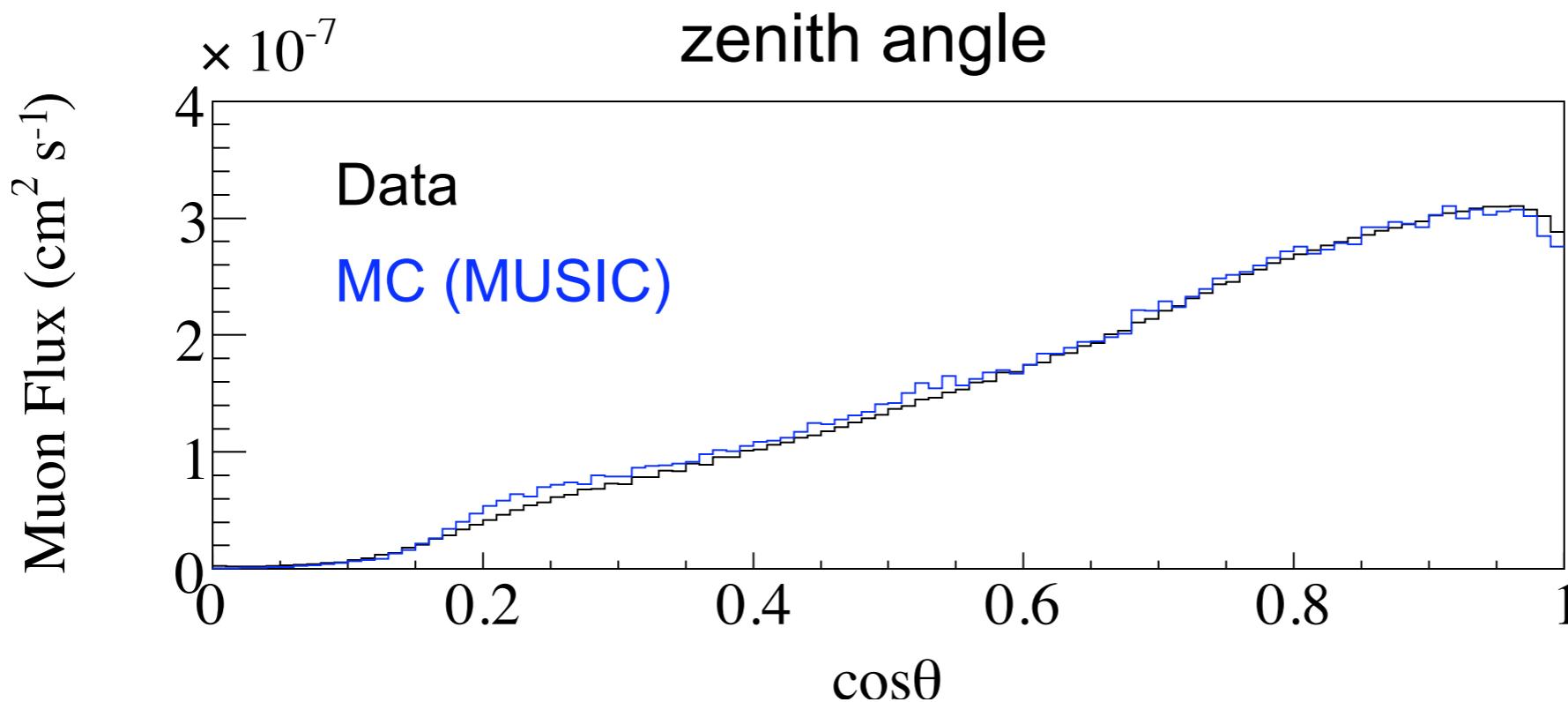
measured average  $L = 878$  cm  
calculated average  $L = 874 \pm 13$  cm

# Cosmic-ray Muon Detection (2)



Scintillation/Cherenkov ratio  $\sim 20$

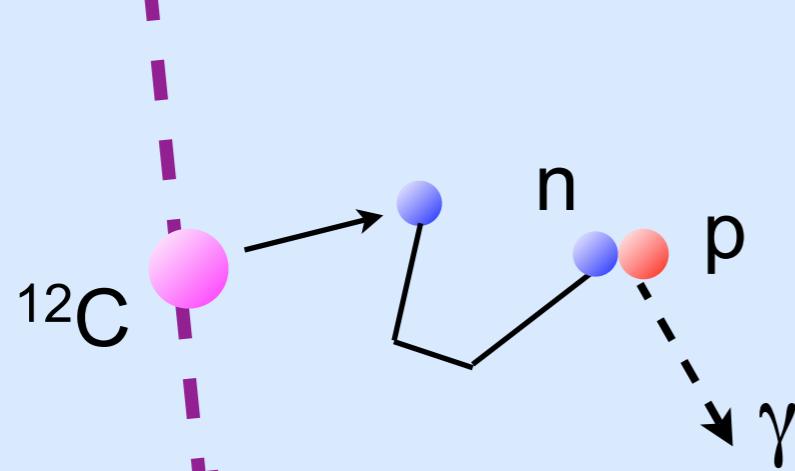
# Cosmic-ray Muon Detection (3)



# Neutron Detection

neutron capture reaction

cosmic-ray muon



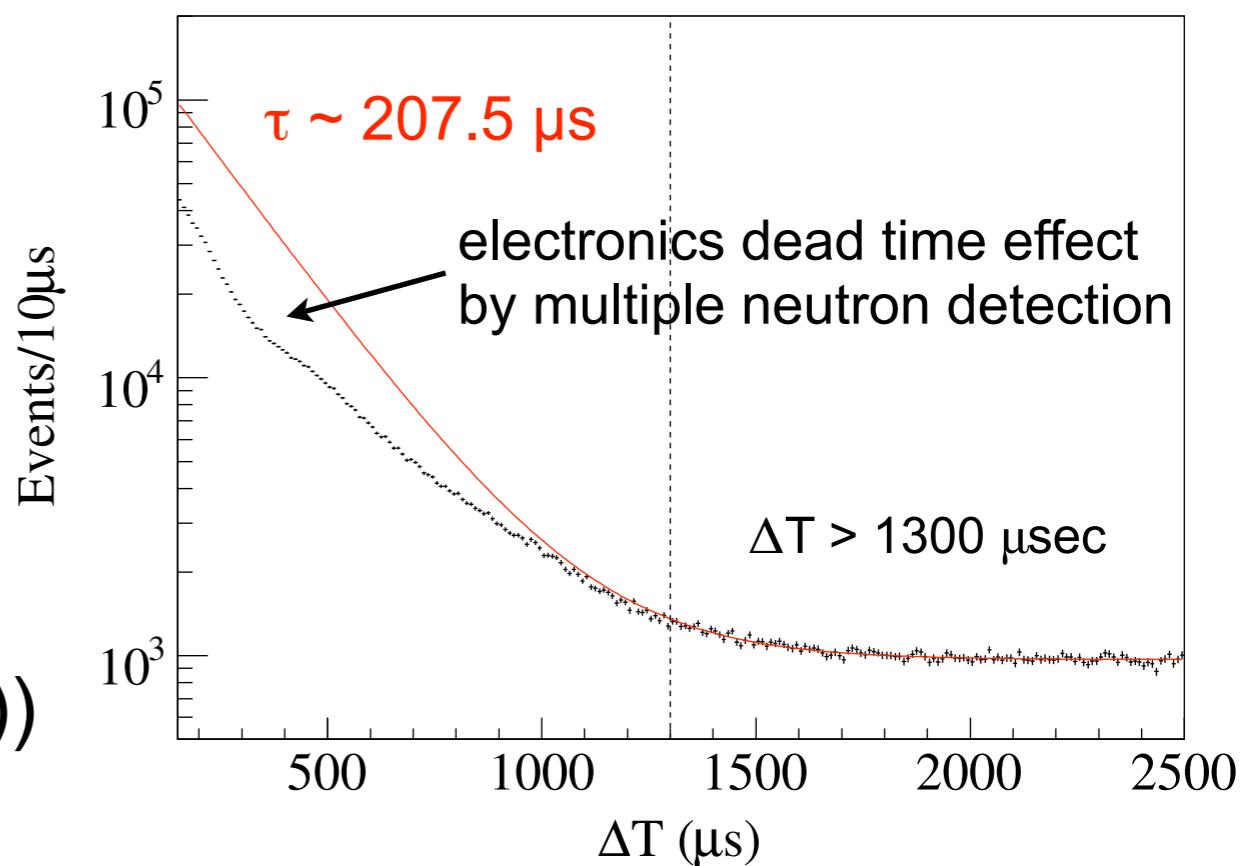
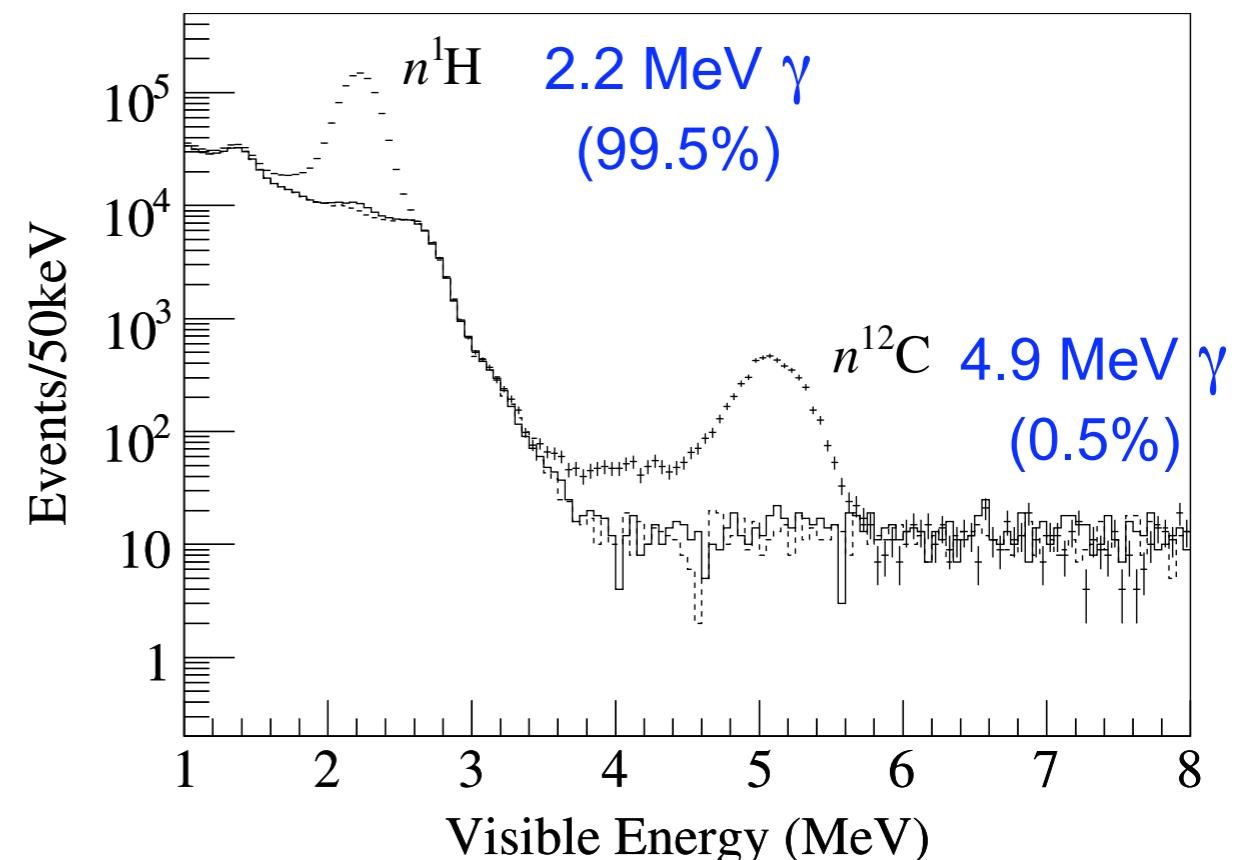
mean capture time  
 $= 207.5 \pm 2.8 \mu\text{s}$

$\Delta T$  distribution fit by  
“exponential + constant”



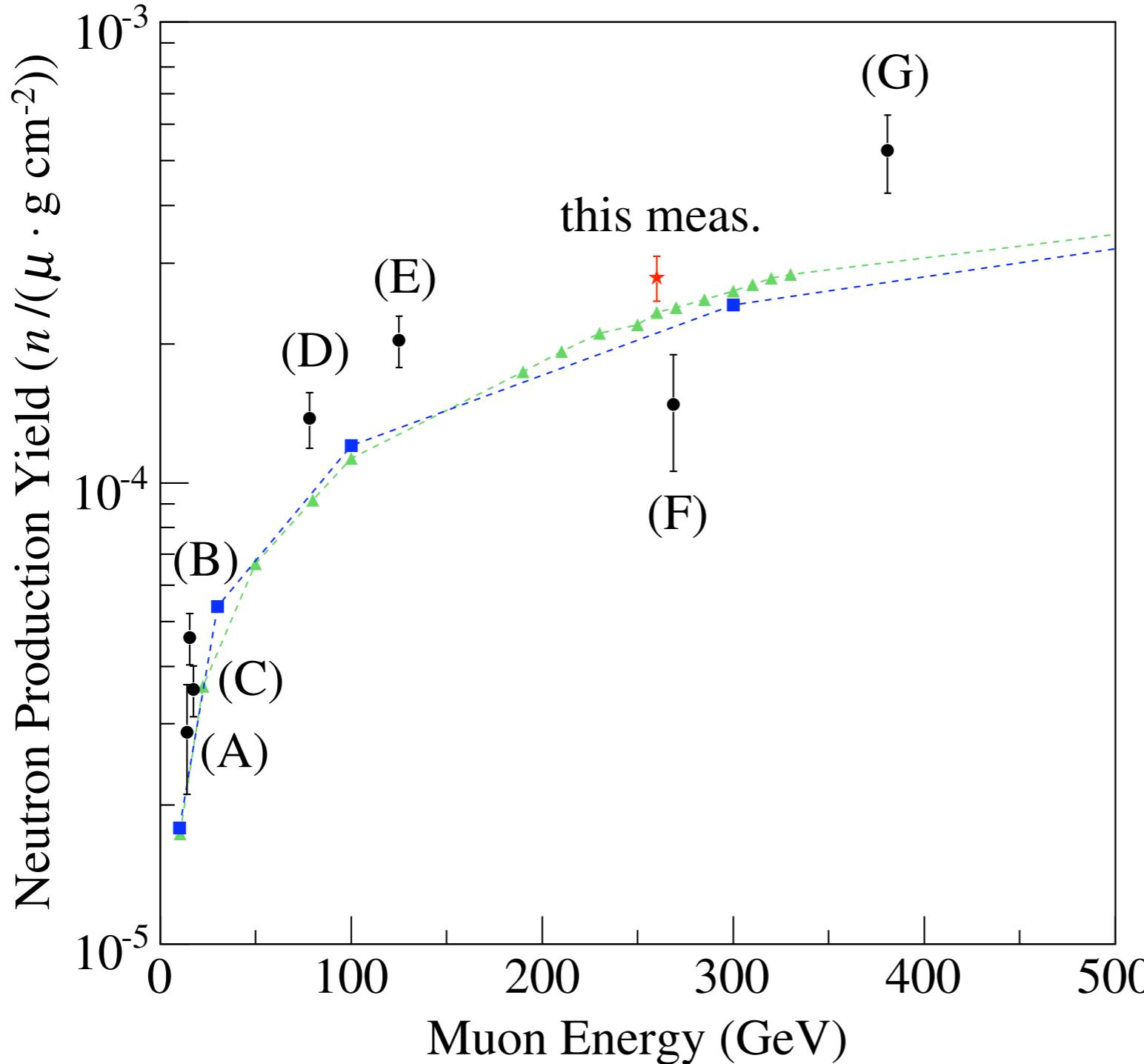
neutron production yield

$$Y_n = (2.8 \pm 0.3) \times 10^{-4} n / (\mu \cdot (\text{g/cm}^2))$$



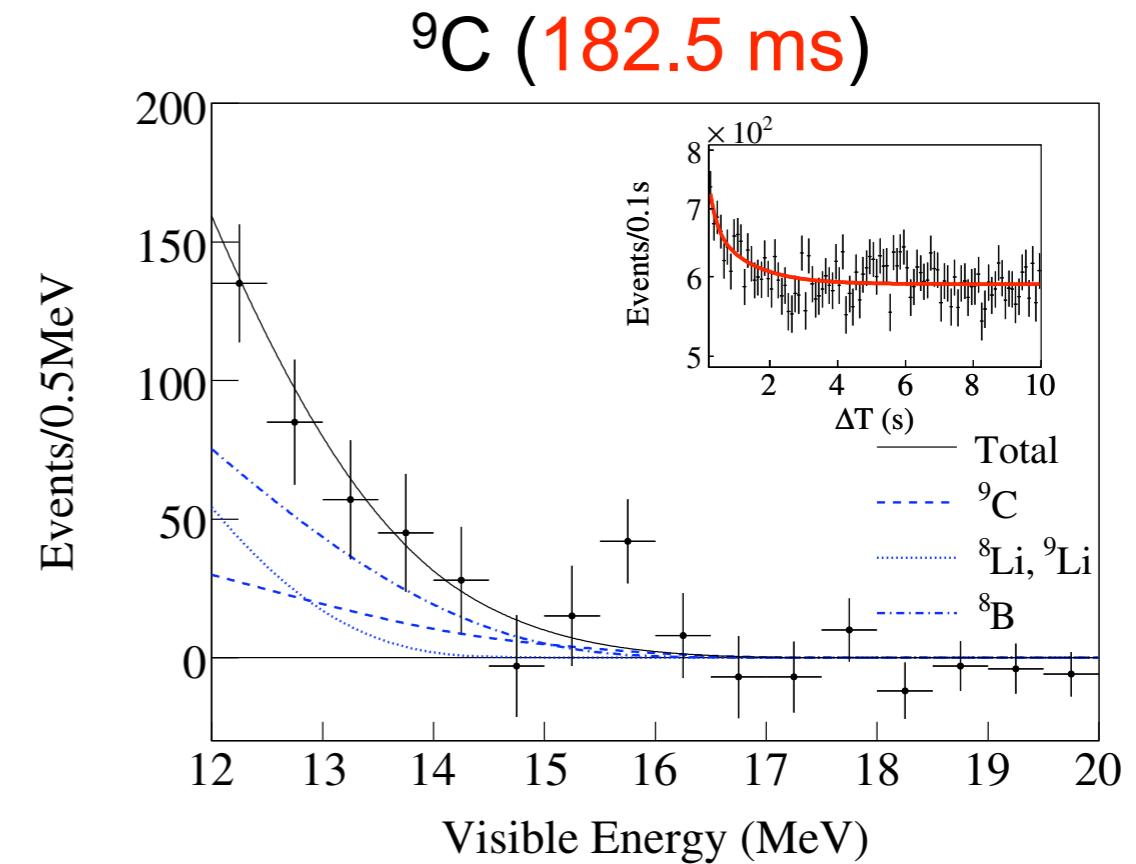
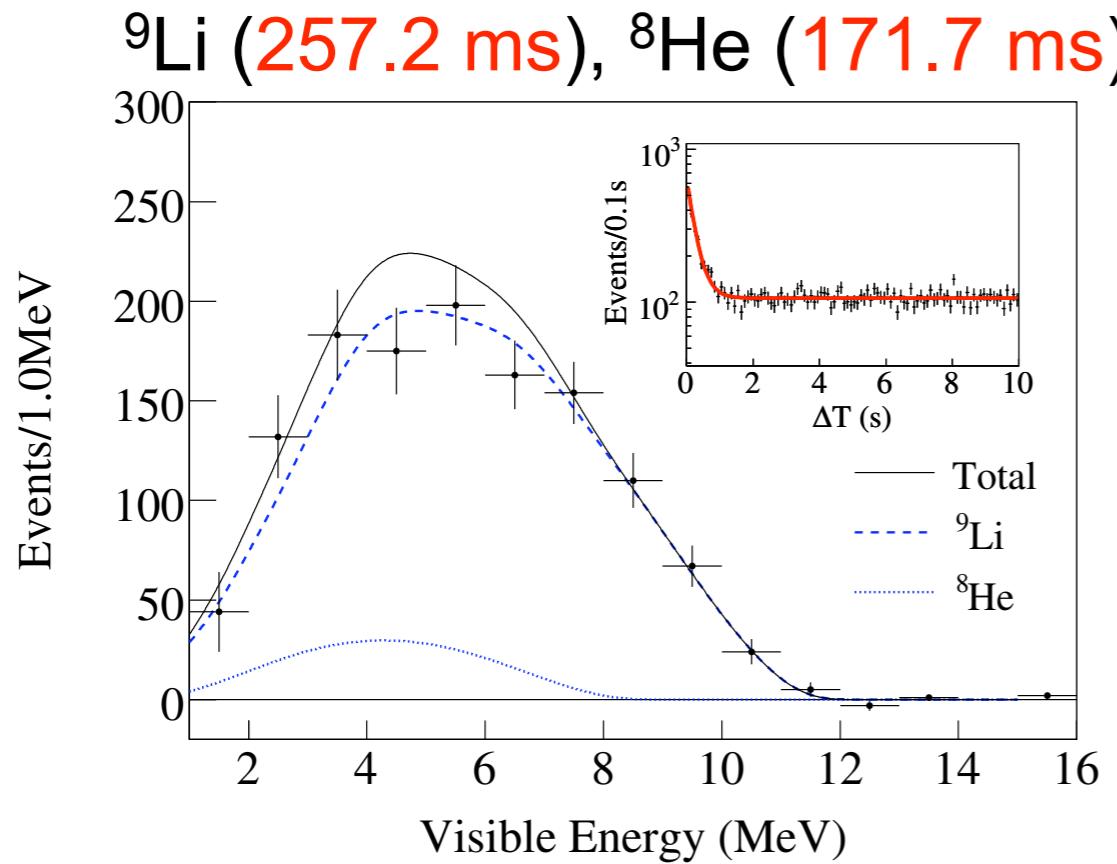
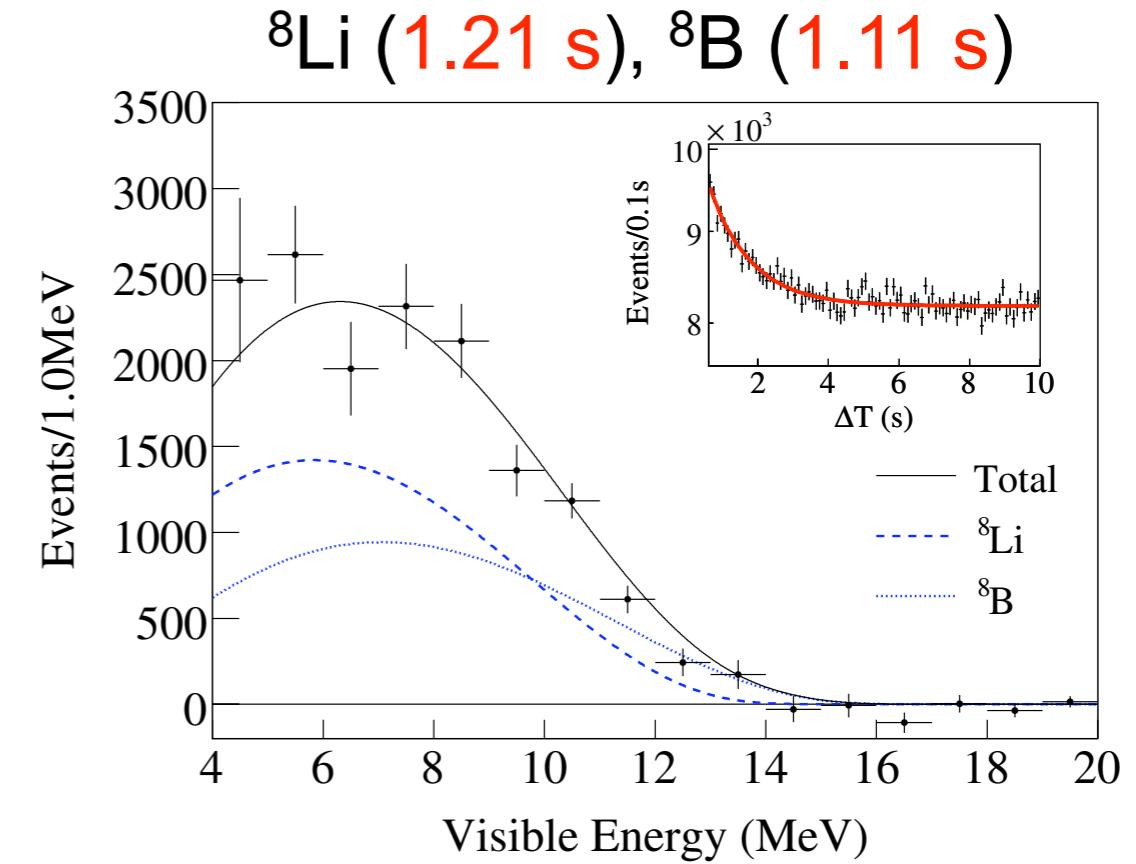
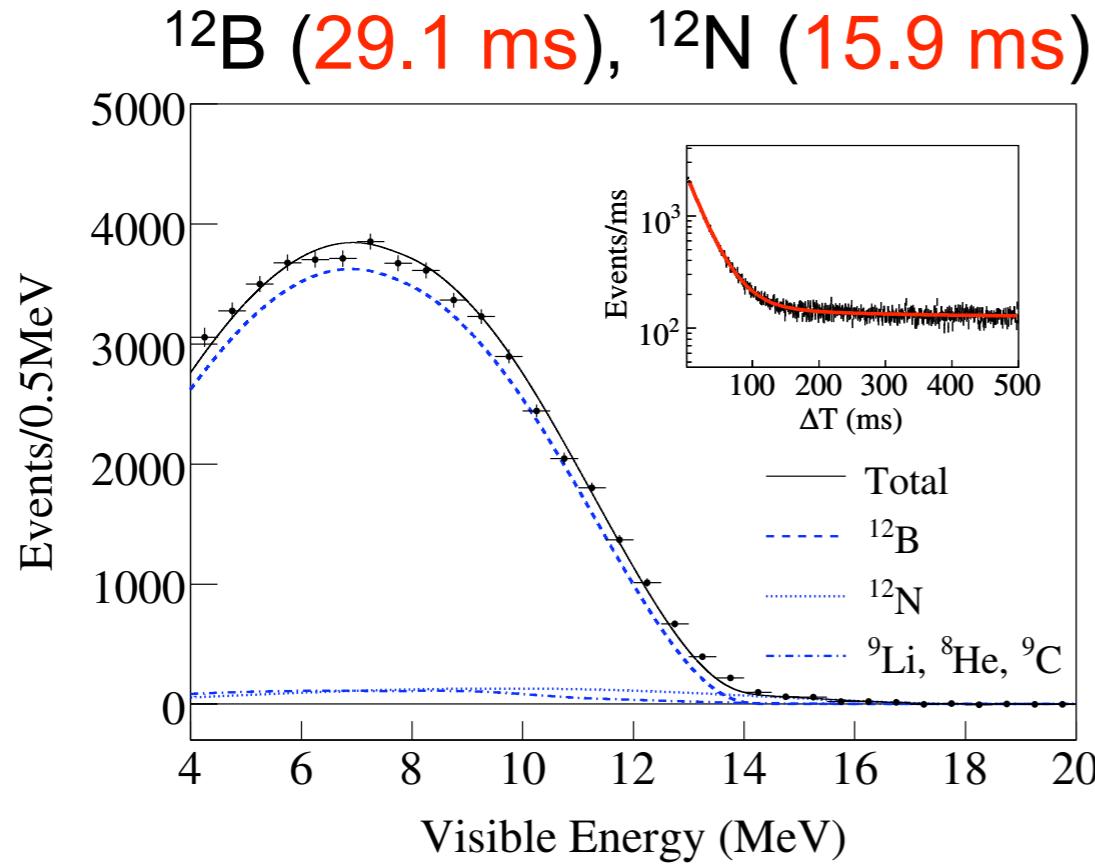
# Neutron Yield

neutron yield v.s. muon energy

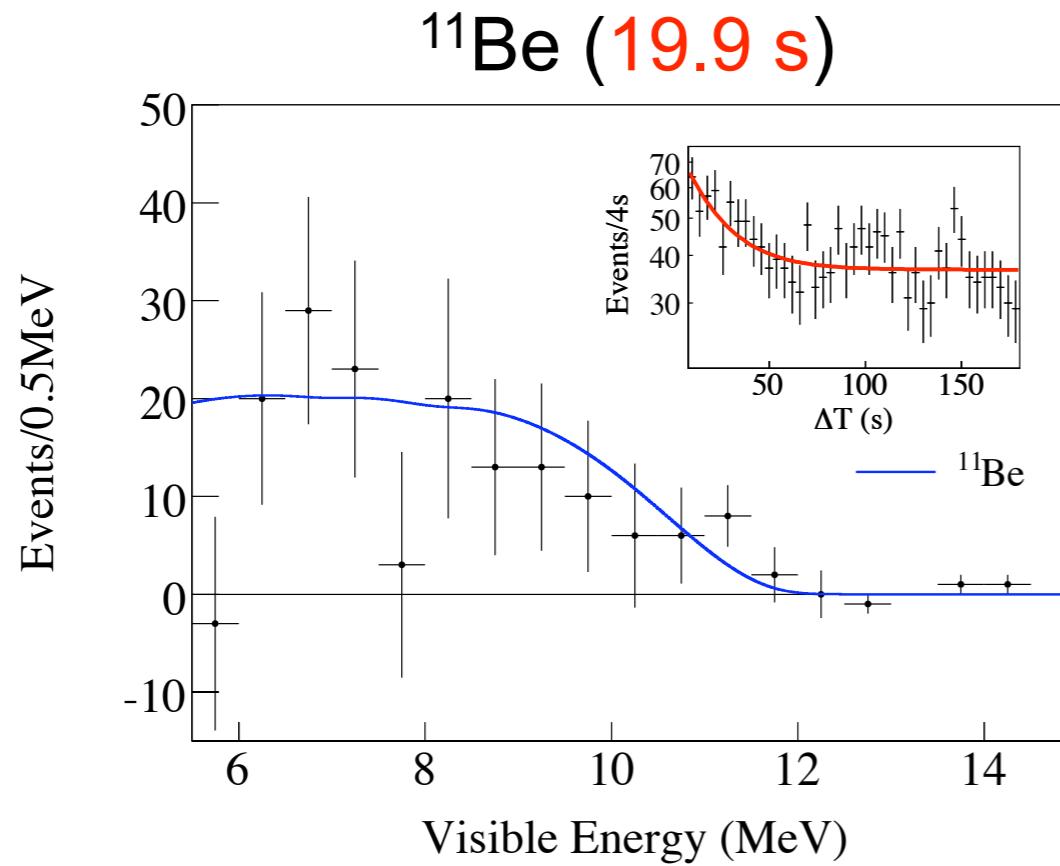
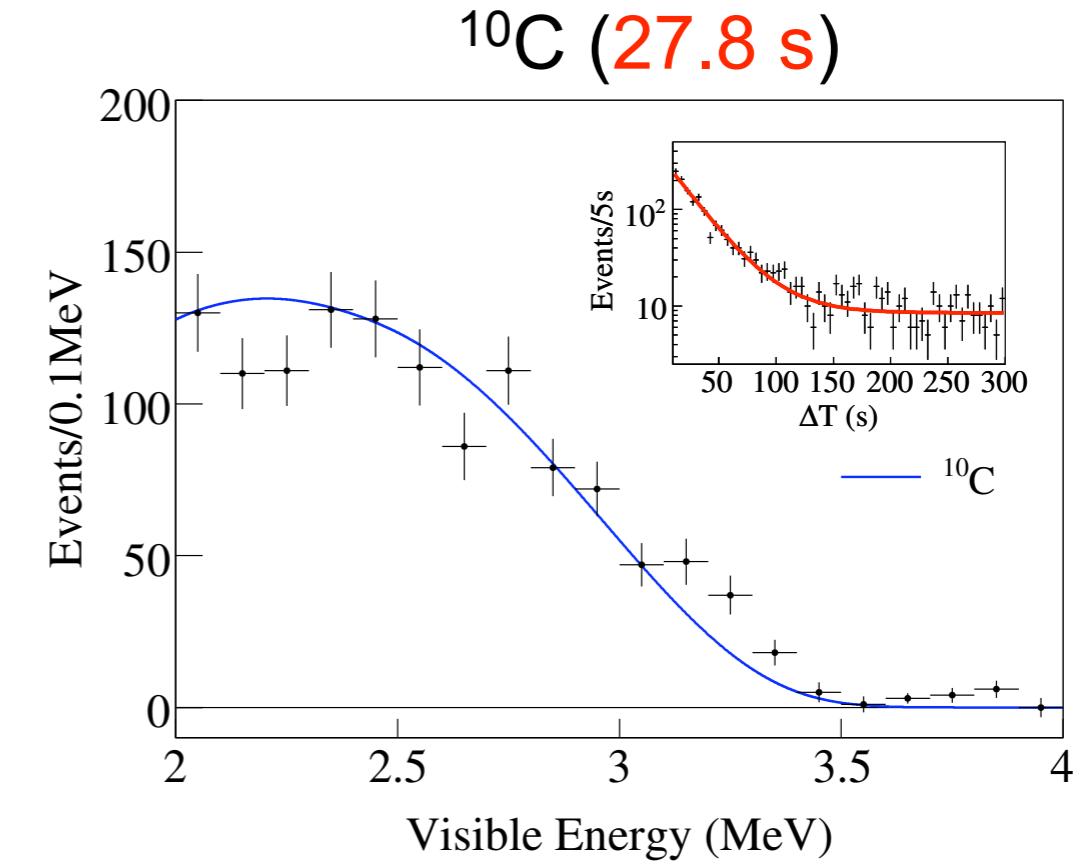
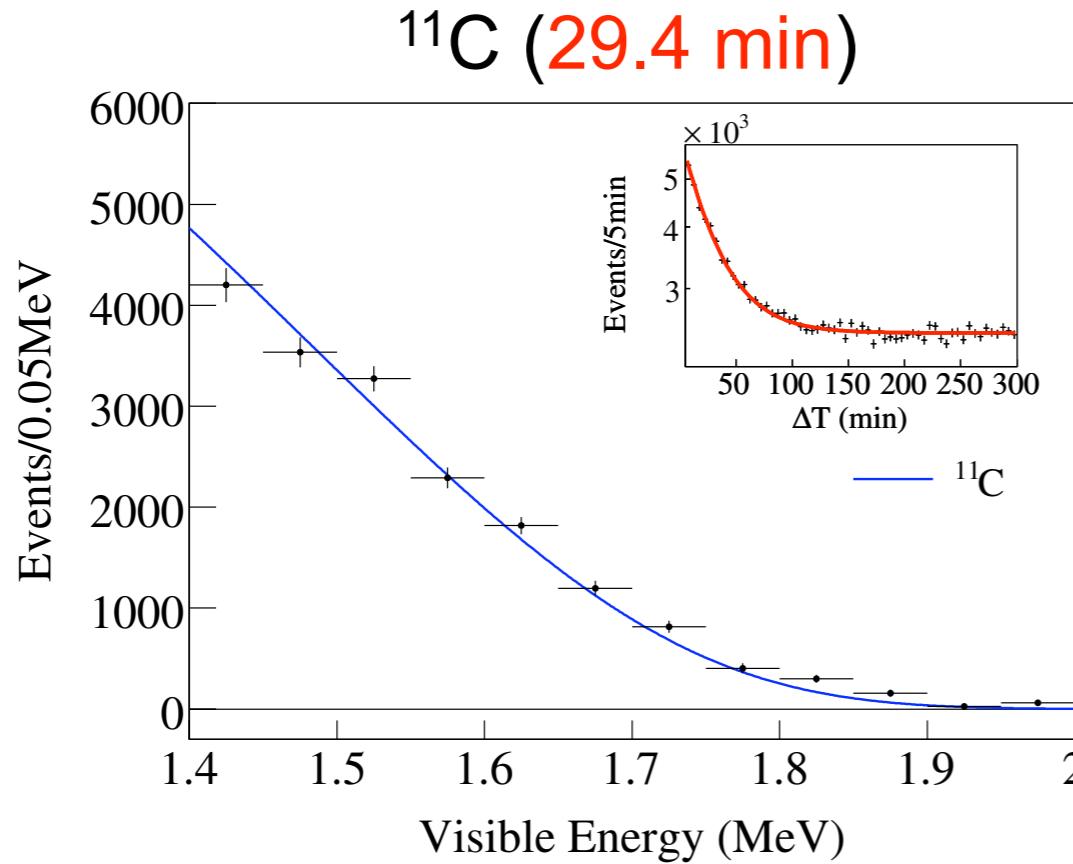


MC gives lower production yield than that of Data

# Isotope Detection (1)



# Isotope Detection (2)



yield estimation based on  
the energy and  $\Delta T$  fitting

main background for rare event search

reactor, geo neutrino

$^8\text{He}, ^9\text{Li}$

$^8\text{B}$  solar neutrino

$^{11}\text{Be}, ^8\text{Li}, ^8\text{B}$

pep/CNO solar neutrino

$^{11}\text{C}$

$0\nu\beta\beta$  ( $^{136}\text{Xe}$ )

$^{10}\text{C}$

# Muon Beam Experiment

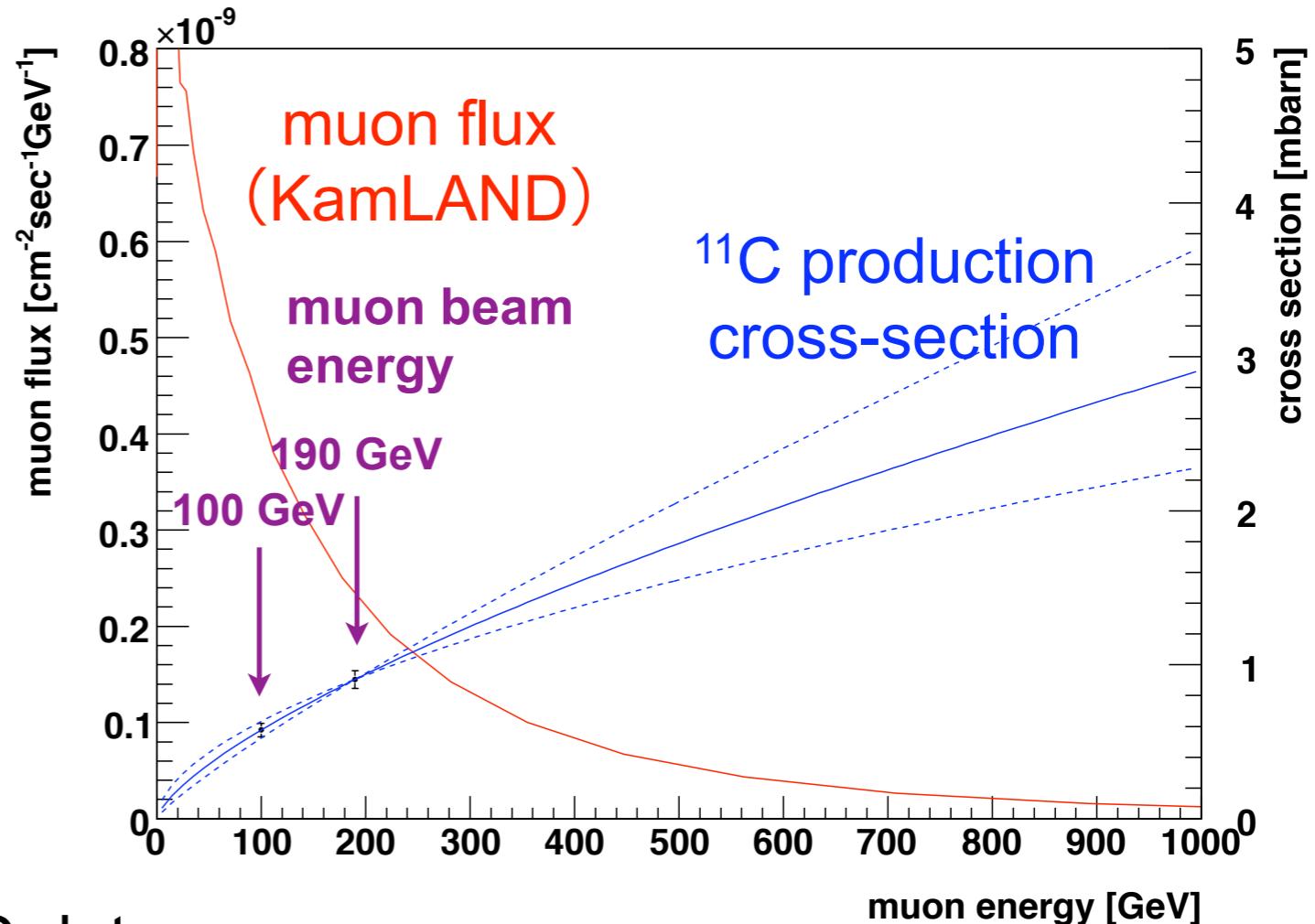
Super Proton Synchrotron (SPS)  
muon beam experiment @ CERN

T. Hagner et al., Astropart. Phys. 14, 33 (2000)

isotope yield estimation ( $^{12}\text{C}$  target)

$$R_{isotope} = N_{^{12}\text{C}} \sigma_0 \int_0^\infty \left( \frac{E_\mu}{1 \text{ GeV}} \right)^\alpha \frac{dN_\mu}{dE_\mu} dE_\mu$$

$E_\mu^\alpha \rightarrow$  assuming power-low



Comparison with KamLAND data

Hagner et al.

$(4.2 \pm 0.7) \times 10^{-5} / (\mu \cdot (\text{g/cm}^2))$

KamLAND

$(8.7 \pm 1.5) \times 10^{-5} / (\mu \cdot (\text{g/cm}^2))$

$^{11}\text{C}$  yield

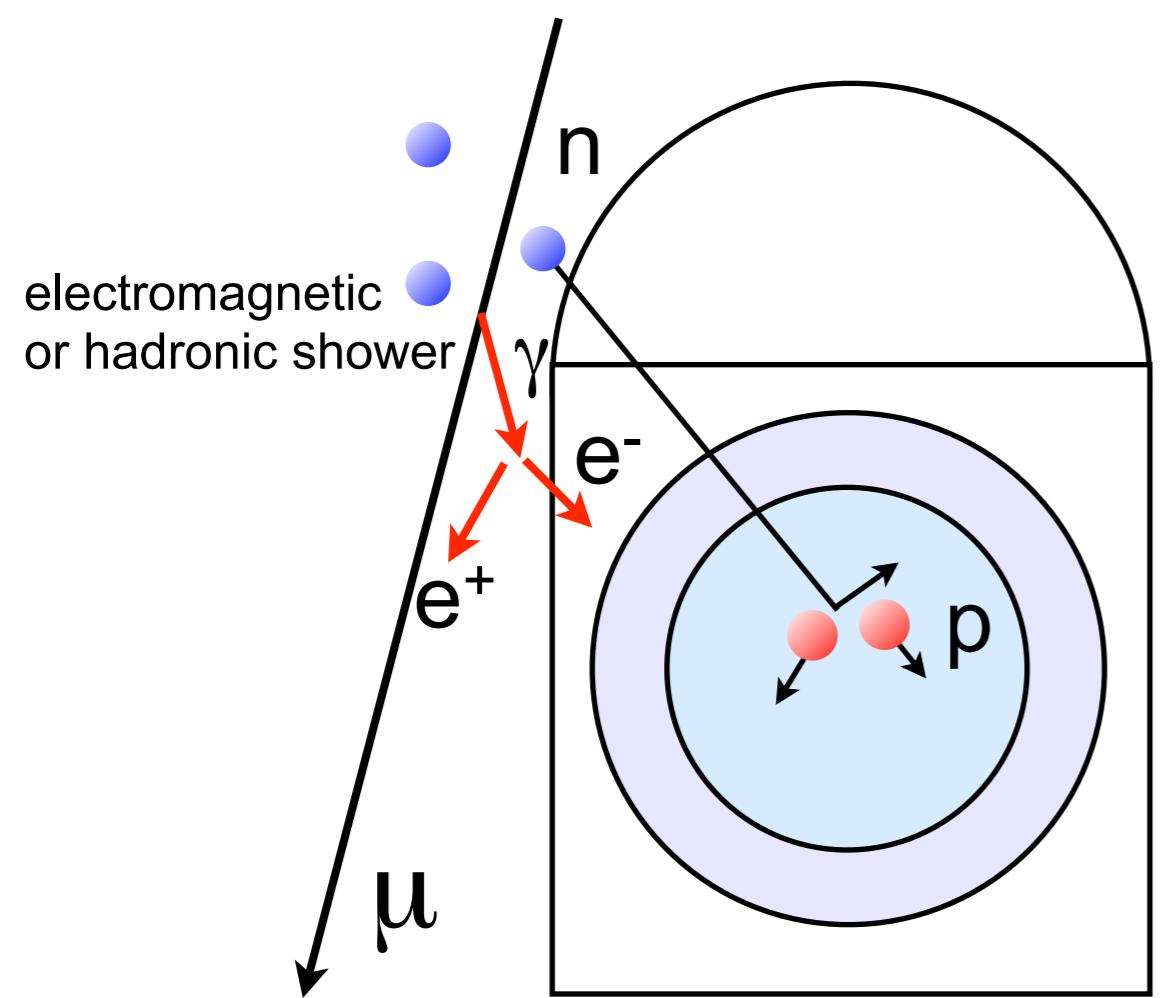
$^{11}\text{C}$  yield in KamLAND data is factor  $\sim 2$  higher than  
the estimation based on the muon beam experiment  
( $E_\mu^\alpha$  extrapolation may not be appropriate)

# Isotope Production Rate

	Life time	Q value	muon beam experiment	MC	KamLAND experiment	
	Life time	Q value	Hagner et al. ( $10^{-7}/\mu \text{ g cm}^{-2}$ )	FLUKA calc. ( $10^{-7}/\mu \text{ g cm}^{-2}$ )	Measurement ( $10^{-7}/\mu \text{ g cm}^{-2}$ )	Fraction of showering $\mu$
$^{12}\text{B}$	29.1 msec	13.4 MeV ( $\beta^-$ )	-	$27.8 \pm 1.9$	$42.9 \pm 3.3$	$68 \pm 2\%$
$^{12}\text{N}$	15.9 msec	17.3 MeV ( $\beta^+$ )	-	$0.77 \pm 0.08$	$1.8 \pm 0.4$	$77 \pm 14\%$
$^8\text{Li}$	1.21 sec	16.0 MeV ( $\beta^-$ - $\alpha$ )	$1.9 \pm 0.8$	$21.1 \pm 1.4$	$12.2 \pm 2.6$	$65 \pm 17\%$
$^8\text{B}$	1.11 sec	18.0 MeV ( $\beta^+$ - $\alpha$ )	$3.3 \pm 1.0$	$5.77 \pm 0.42$	$8.4 \pm 2.4$	$78 \pm 23\%$
$^9\text{C}$	182.5 msec	16.5 MeV ( $\beta^+$ )	$2.3 \pm 0.9$	$1.35 \pm 0.12$	$3.0 \pm 1.2$	$91 \pm 32\%$
$^8\text{He}$	171.7 msec	10.7 MeV ( $\beta^-$ - $\gamma$ n)	$1.0 \pm 0.3$	$0.32 \pm 0.05$	$0.7 \pm 0.4$	$76 \pm 45\%$
$^9\text{Li}$	257.2 msec	13.6 MeV ( $\beta^-$ - $\gamma$ n)		$3.16 \pm 0.25$	$2.2 \pm 0.2$	$77 \pm 6\%$
$^{11}\text{C}$	29.4 min	1.98 MeV ( $\beta^+$ )	$421 \pm 68$	$416 \pm 27$	$866 \pm 153$	$62 \pm 10\%$
$^{10}\text{C}$	27.8 sec	3.65 MeV ( $\beta^+$ - $\gamma$ )	$54 \pm 12$	$19.1 \pm 1.3$	$16.5 \pm 1.9$	$76 \pm 6\%$
$^{11}\text{Be}$	19.9 sec	11.5 MeV ( $\beta^-$ )	$< 1.1$	$0.84 \pm 0.09$	$1.1 \pm 0.2$	$74 \pm 12\%$
$^6\text{He}$	1.16 sec	3.51 MeV ( $\beta^-$ )	$7.5 \pm 1.5$	$12.08 \pm 0.83$	-	-
$^7\text{Be}$	76.9 day	0.478 MeV (EC $\gamma$ )	$107 \pm 21$	$105.3 \pm 6.9$	-	-

# Neutron Detection from External

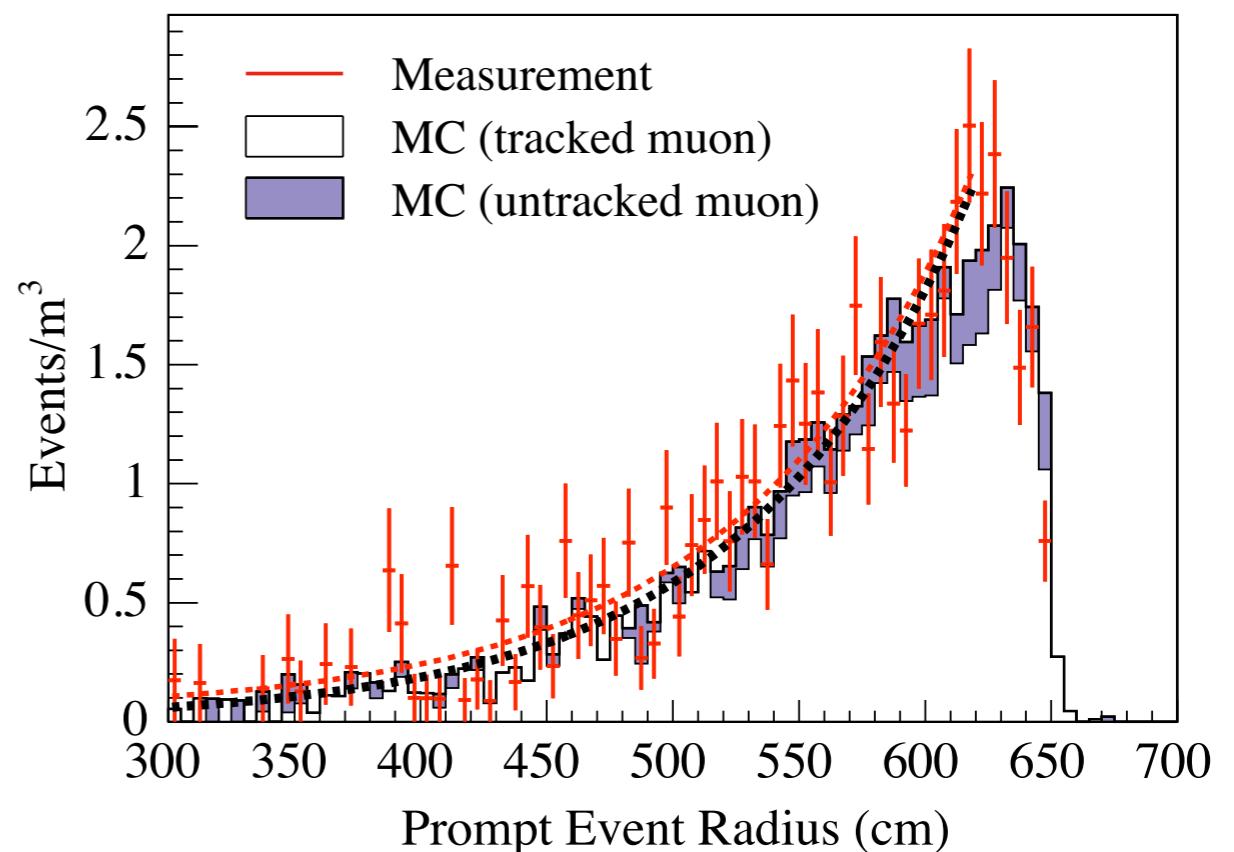
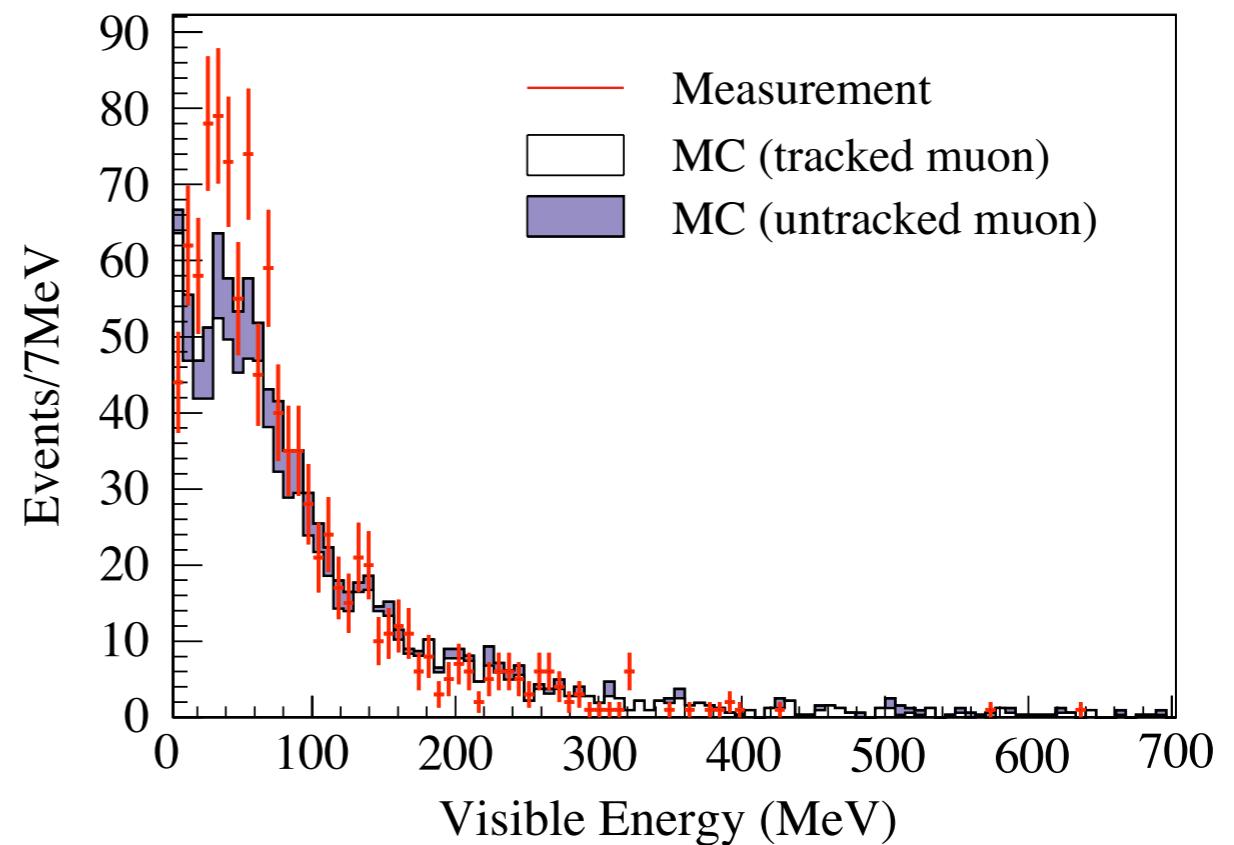
muon tagged by the outer detector



attenuation length of neutron

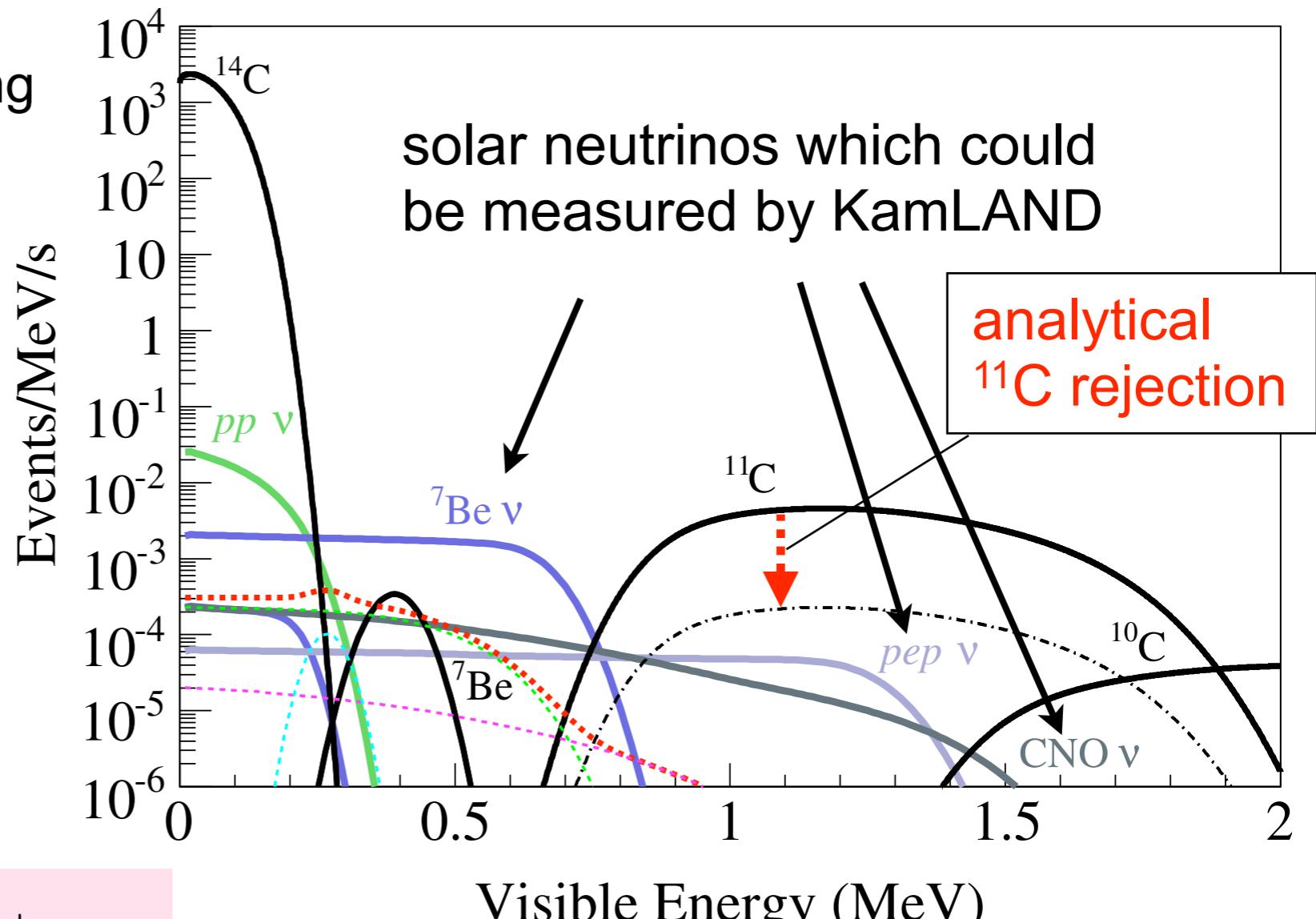
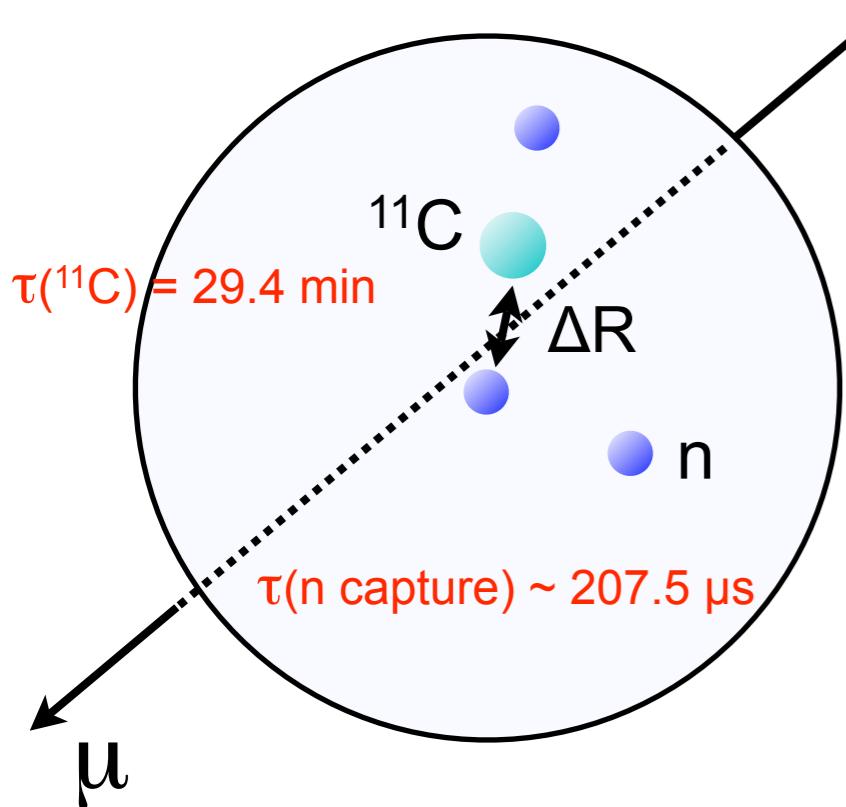
Data	$70 \pm 2 \text{ g/cm}^2$
MC (Geant4) v 9.1	$69 \pm 2 \text{ g/cm}^2$

consistent within uncertainty



# Future Prospects

$^{11}\text{C}$  rejection by neutron tagging



$$\text{X} = \gamma, n, p, \pi^-, \pi^+, e, \mu$$

$$(\text{n emission probability}) = 96.3 \pm 2.0\%$$

consistent with theoretical estimation 95.6%

C. Galbiati et al., Phys. Rev. C71 055805 (2005)



# Summary

- We evaluated the production rate of spallation neutron and isotope using the KamLAND liquid scintillator.
- MC (Geant4, FLUKA) gives lower neutron production yield than that of Data.
- Some isotope production yields are found to be inconsistent with expectations based on a power law dependence with respect to muon energy.
- The results will be useful for the background estimation in the future rate event detection experiment.

# Defined Physics Model

