Cosmic Muon Spallation and Production of Radioactive Isotopes in KamLAND

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Lindley Winslow

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Production of radioactive isotopes through cosmic muon spallation in KamLAND

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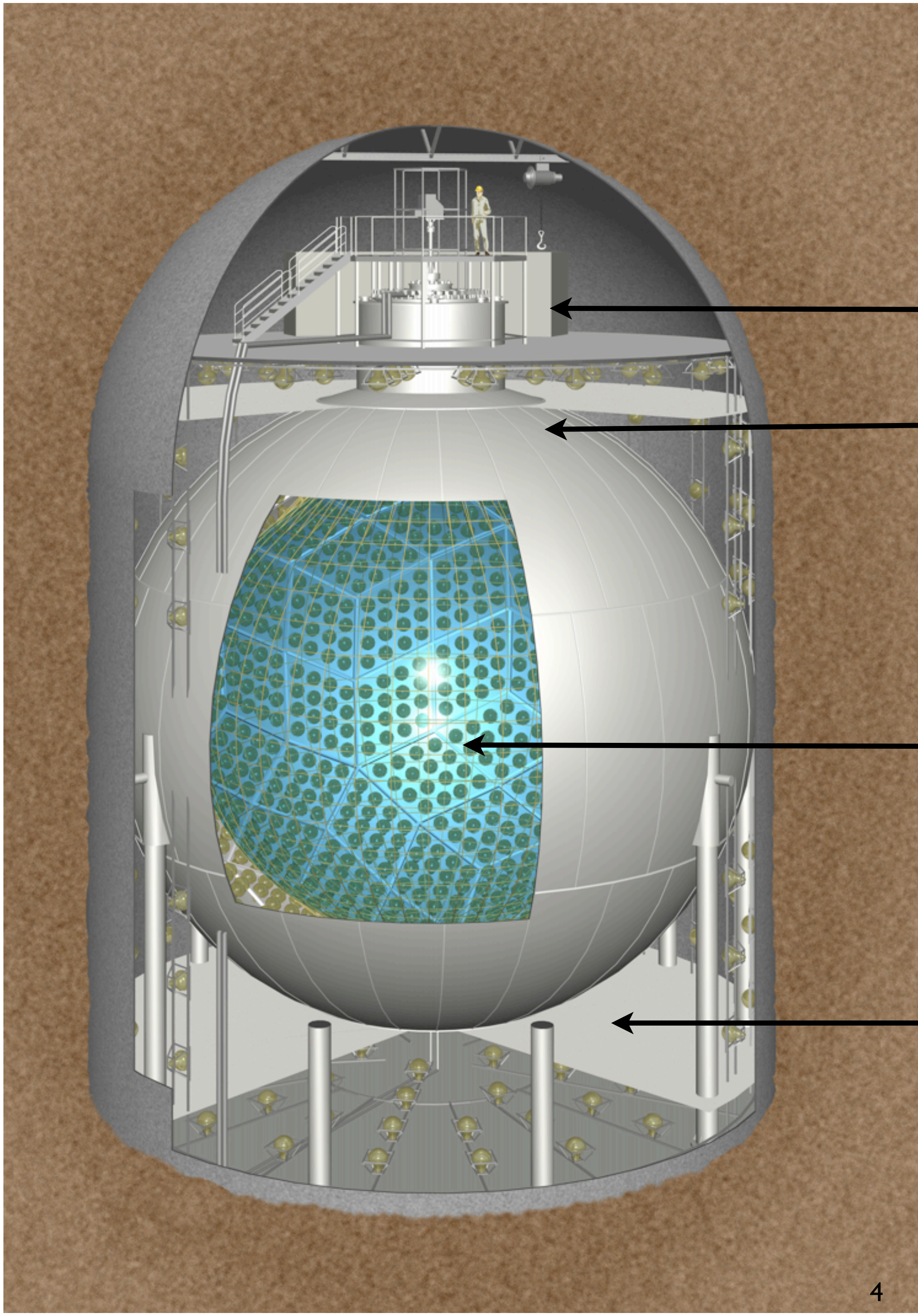
Muons, Neutrons and so much more.....

Isotope	Half-Life	Endpoint	Decay Type
^{12}N	0.011 s	17.4 MeV	e^+
^{13}B	0.017 s	13.4 MeV	e^-
^{12}B	0.0202 s	13.4 MeV	e^-
^{11}Li	0.09 s	16.0 MeV	e^-
^{8}He	0.12 s	10.6 MeV	e^- with n
^{9}C	0.13 s	16.0 MeV	e^+ with p or α
^{9}Li	0.18 s	13.6 MeV	e^- with n
^{8}B	0.77 s	17.97 MeV	e^+ with α
^{6}He	0.81 s	3.5 MeV	e^-
^{8}Li	0.84 s	16.0 MeV	e^- with α
^{16}N	7.1 s	10.4 MeV	e^-
^{11}Be	13.8 s	11.5 MeV	e^- with α
^{10}C	19.3 s	1.9 MeV	e^+
^{14}O	71 s	5.15 MeV	e^+
^{15}O	122 s	2.76 MeV	e^+
^{11}C	20.38 min	0.96 MeV	e^+
^{13}N	9.97 min	2.22 MeV	e^+
^{7}Be	53 days	0.862 MeV	electron capture
^{10}Be	1.5×10^6 years	0.556 MeV	e^-

KamLAND: The Detector

A Kilo-Tonne Liquid Scintillator!



Electronics Hut

Stainless Steel Sphere

- 8.5m radius
- 1325 17'' PMTs
- 554 20'' PMTs

Nylon Balloon

- 6.5m radius
- Separates BO and LS.

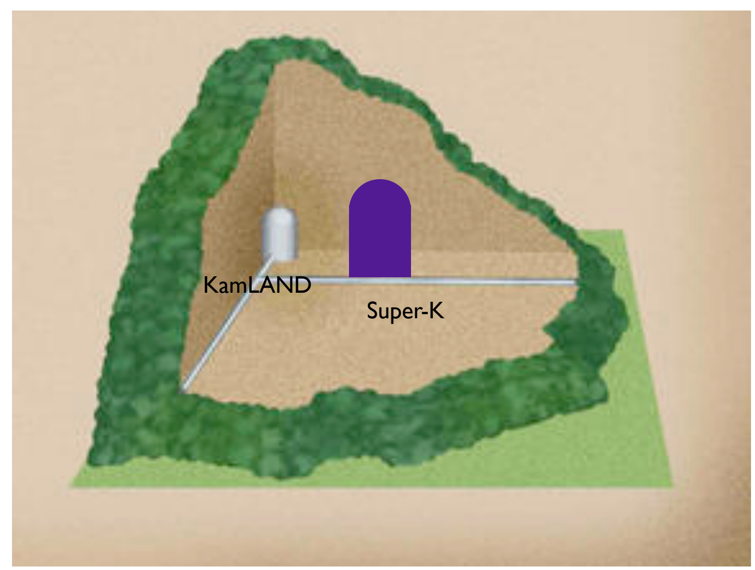
Water Cerenkov Veto

- 225 20'' PMTs

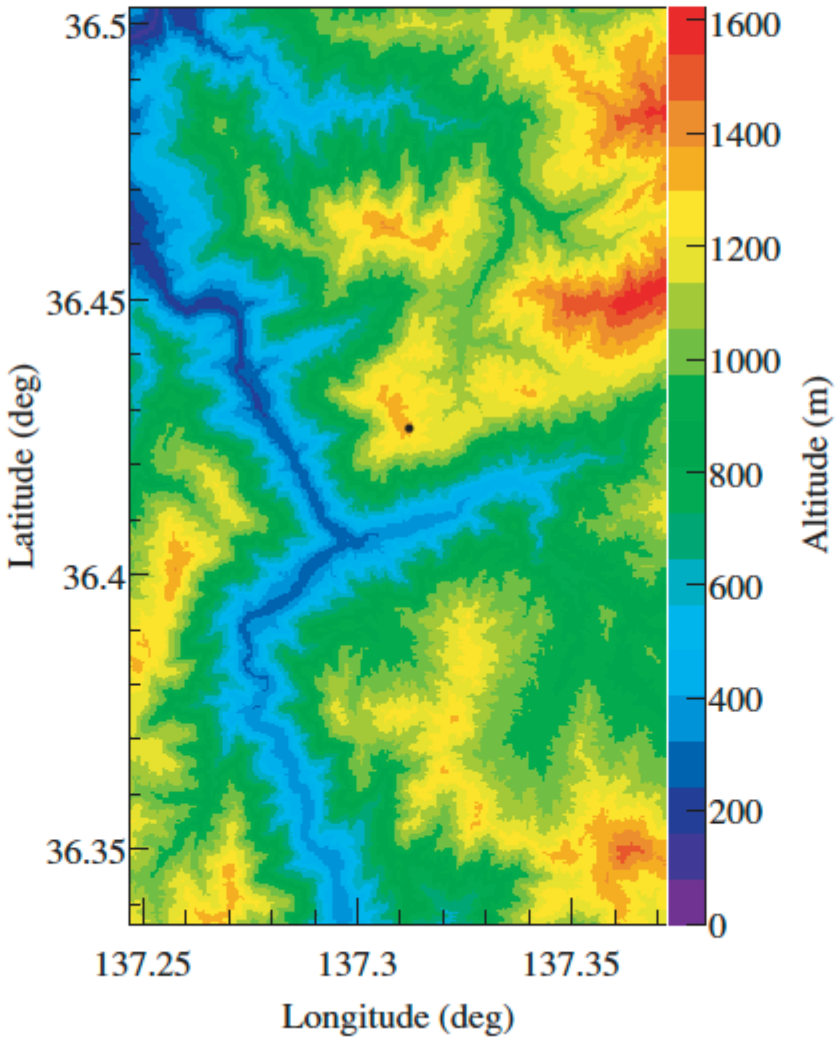
KamLAND LS is 80% mineral oil, 20% psuedo-cumene, and 1.36 g/L PPO.

Where is KamLAND?

- The Kamioka mine is centrally located on the main island of Japan.
- This is the same mine as you find Super-K.



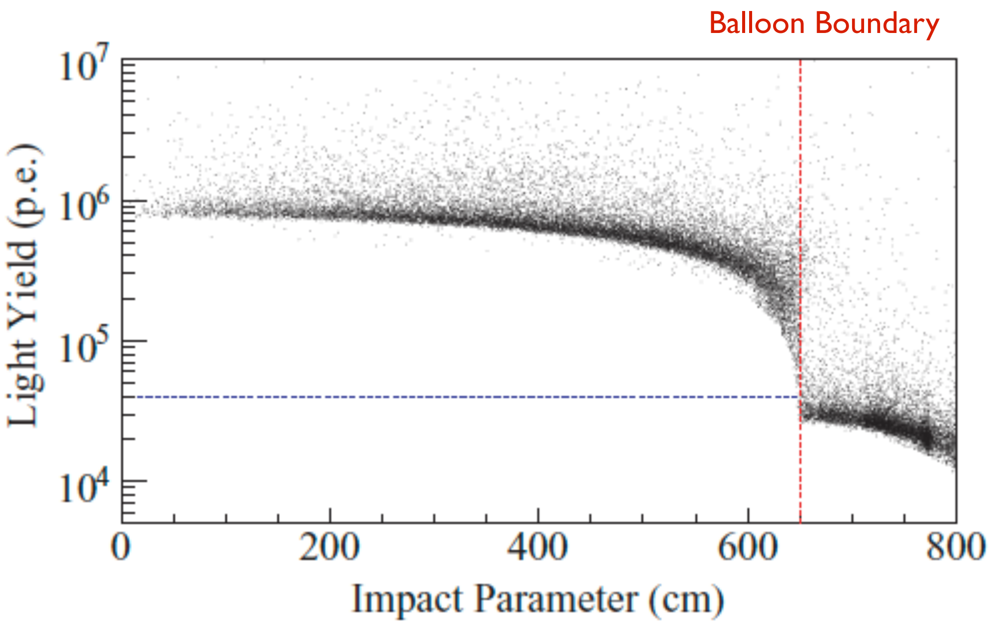
Getting Oriented:

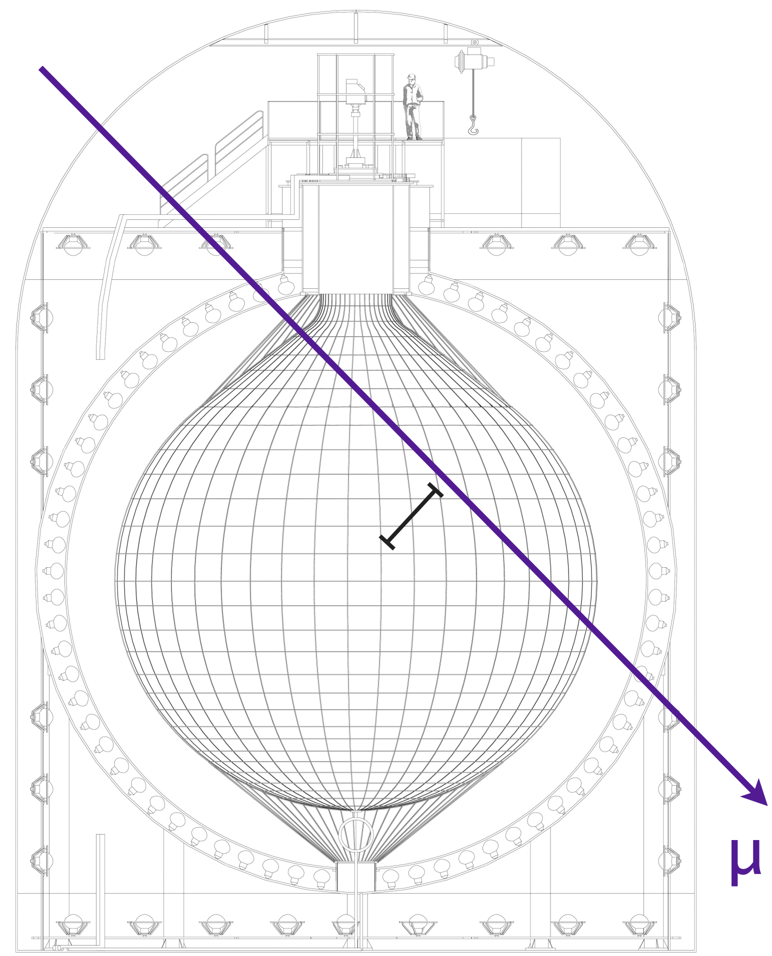


pictures from j. raaf

Mt. Ikenoyama rises 1000m above KamLAND. The smallest overburden is approximately 900m due to a near by valley.

Muons in KamLAND:





There are two distinct populations of muons those who pass through the liquid scintillator and those that just pass through the buffer oil.

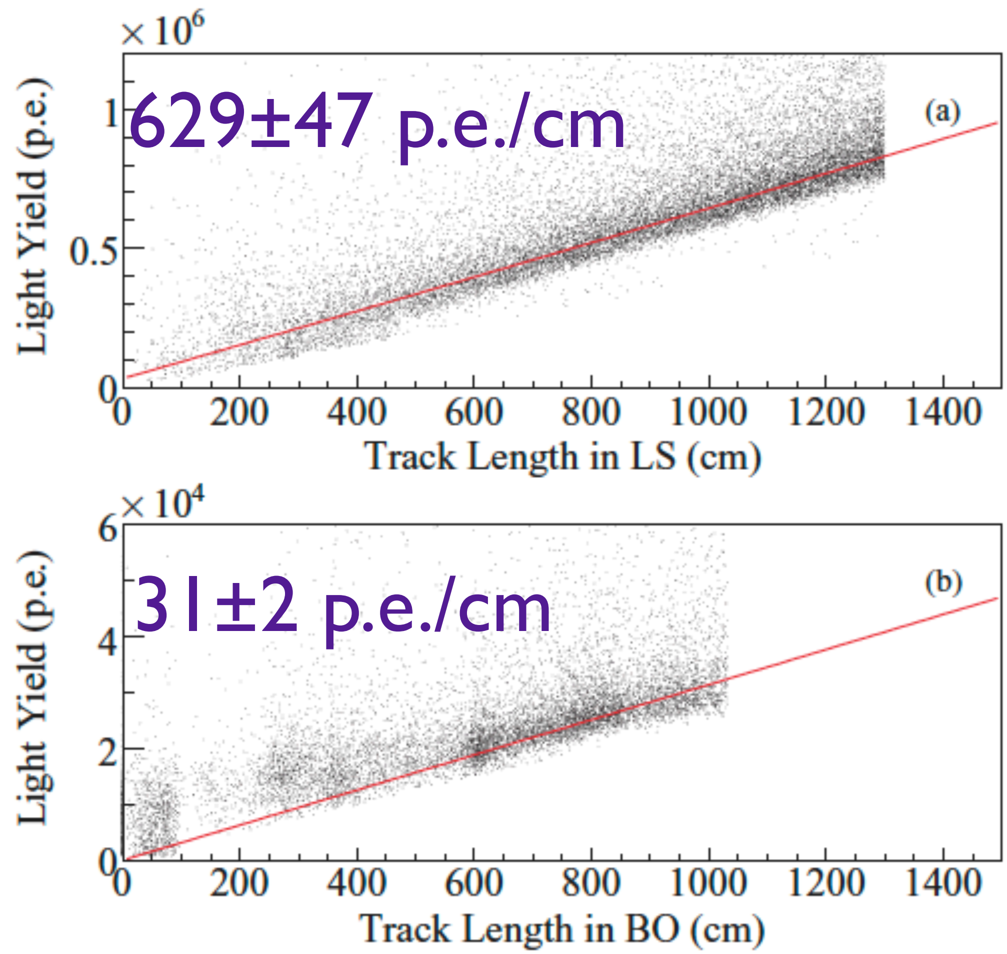
Muons in KamLAND:

The light yield per unit length is found by fitting the reconstructed track length vs. light yield to a line.

You may notice a population of events producing more light per unit track length.

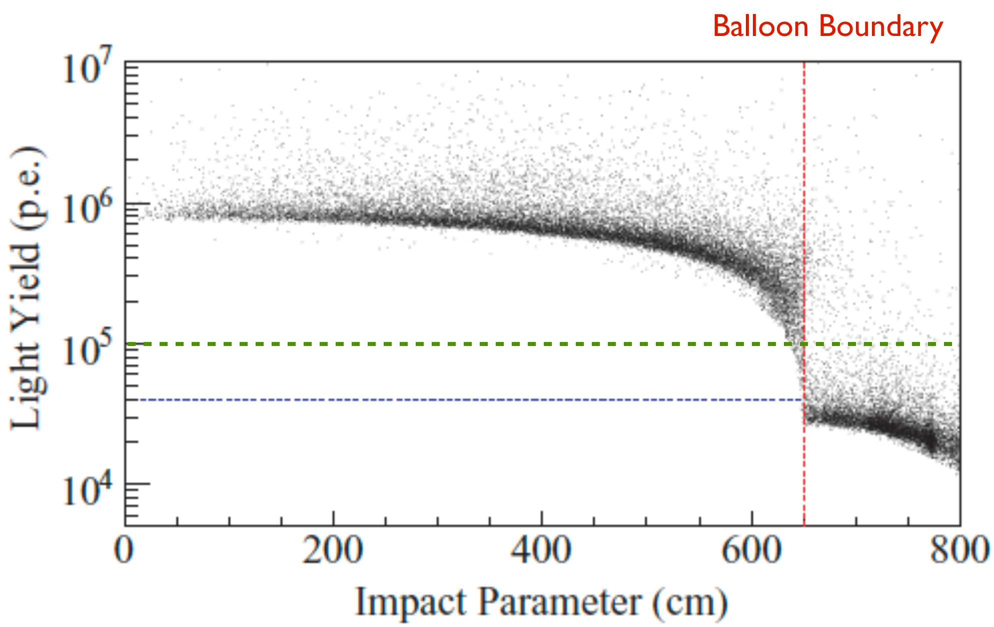
We define this excess light by:

$$\Delta\mathcal{L} = \mathcal{L}_{\rm ID} - L_{\rm BO}\left\langle\frac{d\mathcal{L}_{\check{C}}}{dX}\right\rangle - L_{\rm LS}\left\langle\frac{d\mathcal{L}_{S}}{dX}\right\rangle$$



These are our showering muons which we will hear more about.....

Determining the Muon Rate:



The upper limit on the muon rate comes from requiring a Light Yield $> 1\times10^5$.

The lower limit on the muon rate comes from requiring:
Impact Parameter < 650 cm
Light Yield $> 4\times10^4$.

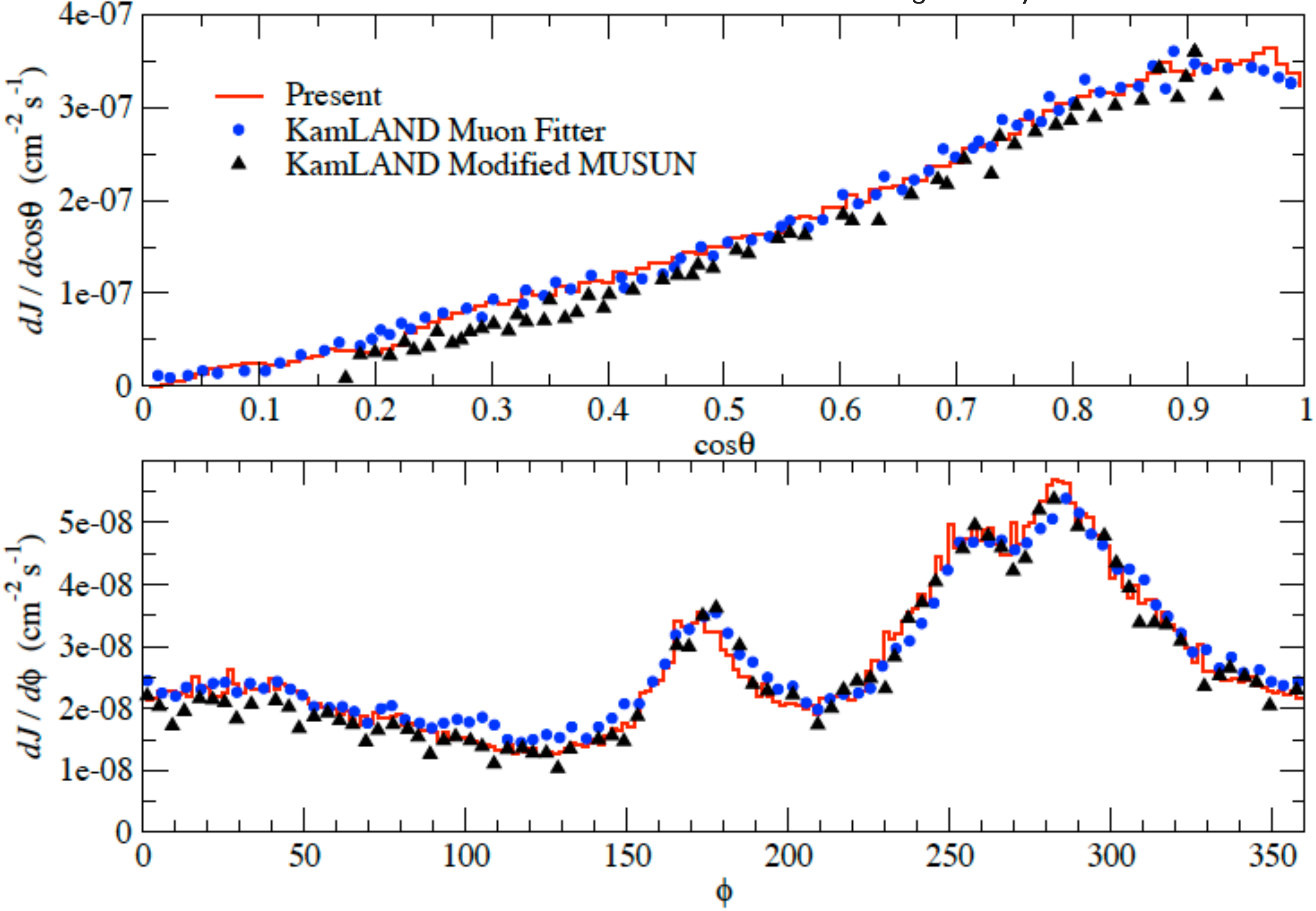
Averaging together these results:

$R_\mu = 0.198\pm0.014$ Hz

A < 5% correction for muon bundles was included, but the uncertainty is dominated by the two methods for determining the rate.

Interpreting the Muon Rate with MUSIC:

Tang et al. Phys. Rev. D 74:053007



The angular distributions are well reproduced by simulation.

Interpreting the Muon Rate with MUSIC:

The corresponding integrated muon intensity is

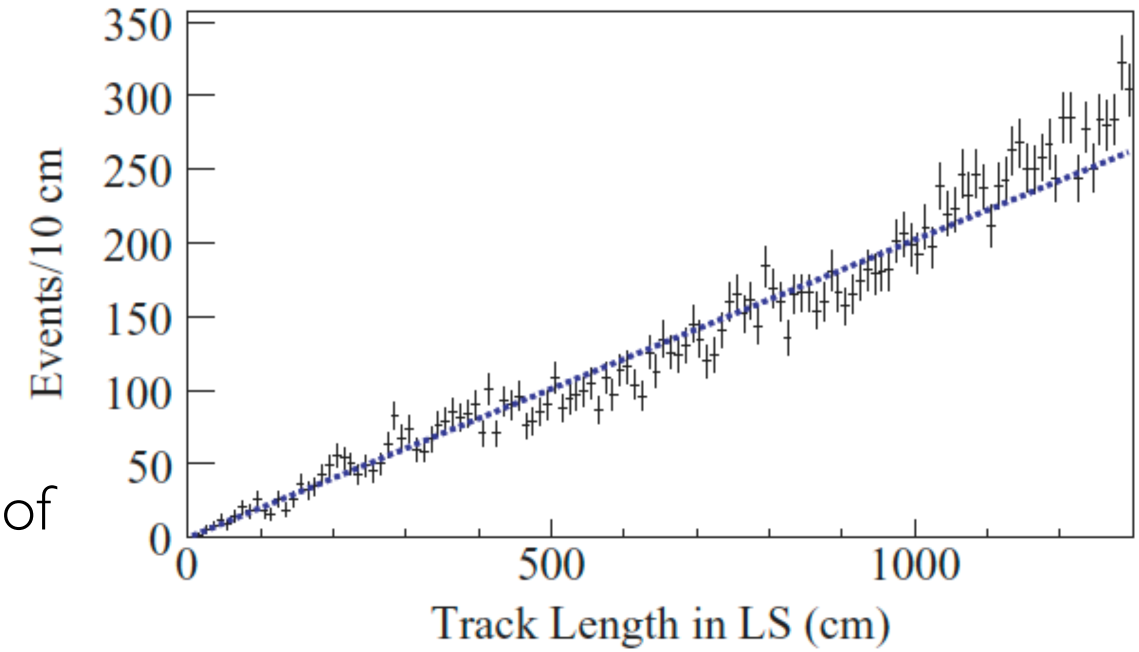
$J_\mu = 5.37 \pm 0.41\ m^2\ h^{-1}$

and average track length

Measured L_μ = 878 cm
Calculated L_μ = 874±13 cm

The issue is then not an issue of the muon angular distribution, but the rate. This means the mountain profile is not of an issue as the uncertainty in the rock type and density.

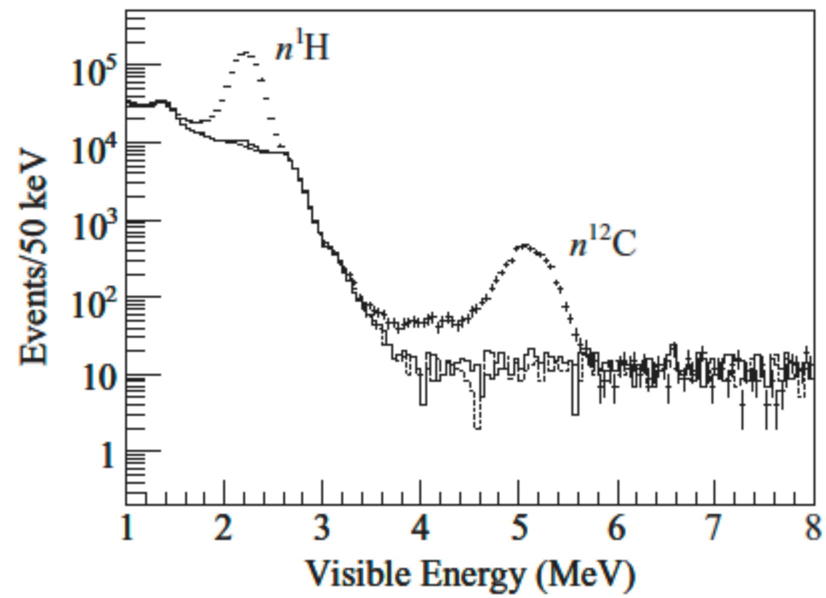
E_μ = 260±8 GeV



Ikenoyama rock model	J_μ ($m^2\ h^{-1}$)	$\overline{E}_\mu$ (GeV)
Inishi rock	5.66–6.71	262–268
Standard rock	4.95–5.83	256–262
Generic skarn	4.90–5.82	254–260
This measurement	5.37 ± 0.41	–

Neutrons in KamLAND:

We look for the characteristic 2.2 MeV gamma from neutron capture on hydrogen. The 4.9 MeV capture on carbon following a muon event is also visible.



The probability to capture on any other components of the scintillator is < 0.02%.

Element	Stoichiometry	Number of targets (per kiloton)
Hydrogen	1.97	8.47×10^{31}
Carbon	$\equiv 1$	4.30×10^{31}
Nitrogen	1×10^{-4} to 6×10^{-4}	5×10^{27} to 3×10^{28}
Oxygen	1×10^{-4}	5×10^{27}

Neutrons in KamLAND:

We look for neutron capture events on hydrogen, 1.8MeV < Evis < 2.6 MeV, following muons. The number of neutrons is obtained from a binned maximum likelihood fit to the time since all preceding muons.

$$r(t) = \frac{N_n}{\tau_n} e^{-(t-t_\mu)/\tau_n} + r_B$$

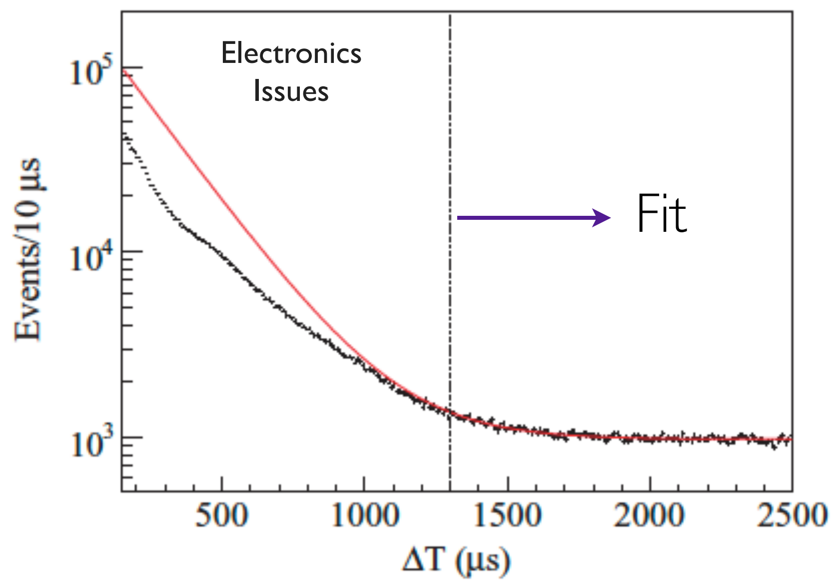
where the neutron capture time is

$$\tau_n = 207.5 \pm 2.8\ \mu s$$

and the total number requires correction for the efficiency

$$\mathcal{N}_n = \frac{N_n}{\epsilon_n}$$

4.7±0.4×10^6 neutrons



Effect	Value
Neutron-eliminating reactions, e.g., (n, p)	$(96.3 \pm 3.7)\%$
Neutron captures on ^{1}H	$(99.5 \pm 0.1)\%$
LS-BO boundary	$(93.3 \pm 2.0)\%$
Electronics dead time effects	>98%
Combined efficiency	$(89.4 \pm 3.8)\%$

Comparing to Other Measurements....

To compare this measurement to those at other location we need to convert the number of neutrons to:

$$Y_n = \frac{\mathcal{N}_n}{R_\mu T_L \rho L_\mu}$$

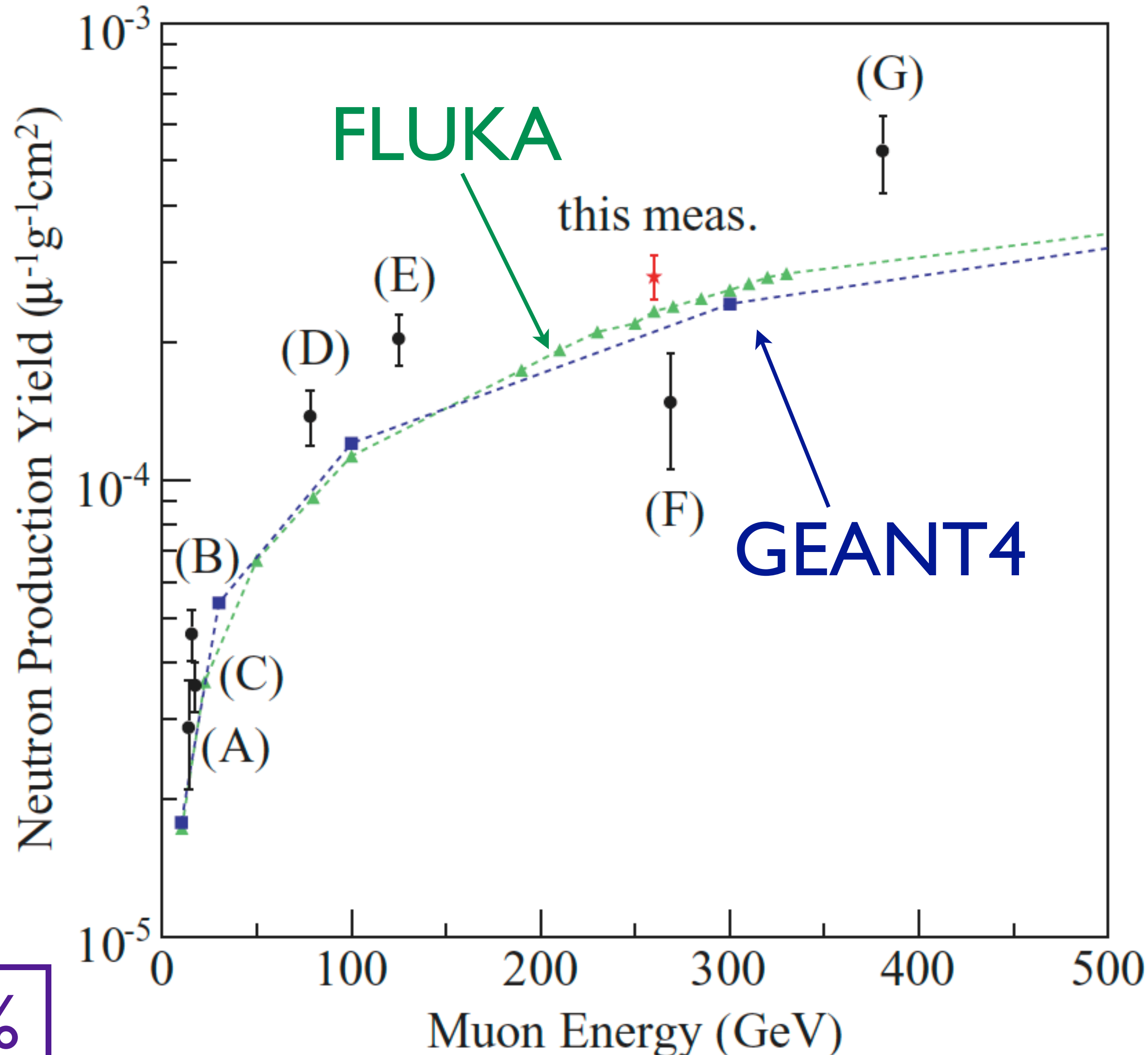
where

R_μ = 0.198±0.014 Hz
T_L = 1.24×10^8 s
ρ = 0.780±0.001 g/cm^3
L_μ = 874±13 cm

2.8±0.3×10^{-4} μ^{-1}g^{-1}cm^2

Showering Muons:

$\Delta\mathcal{L} > 10^6$ p.e. **64±5%**

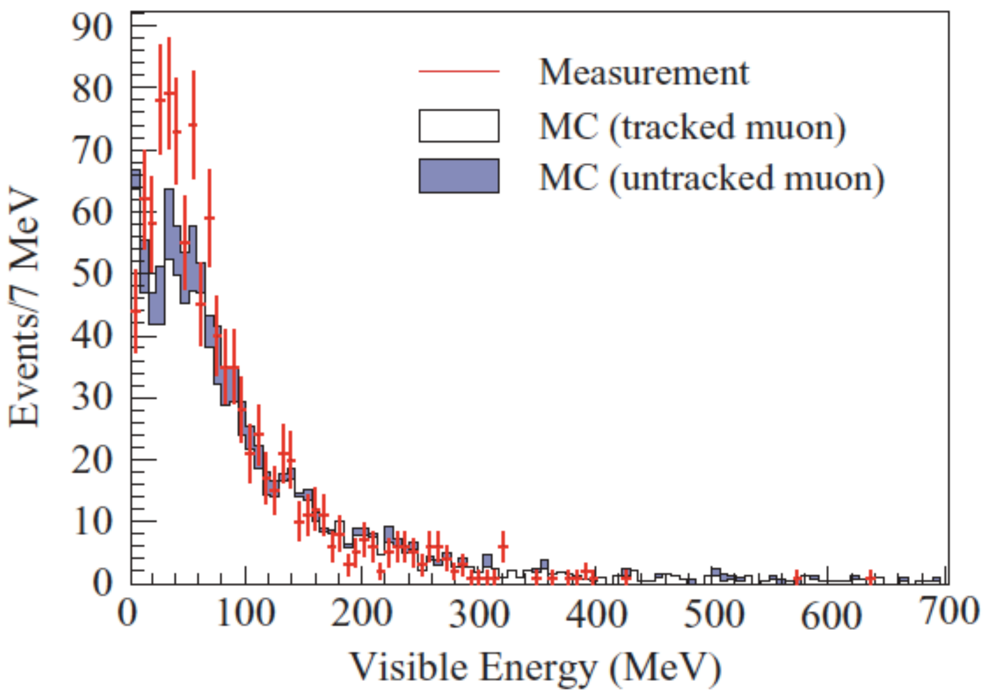


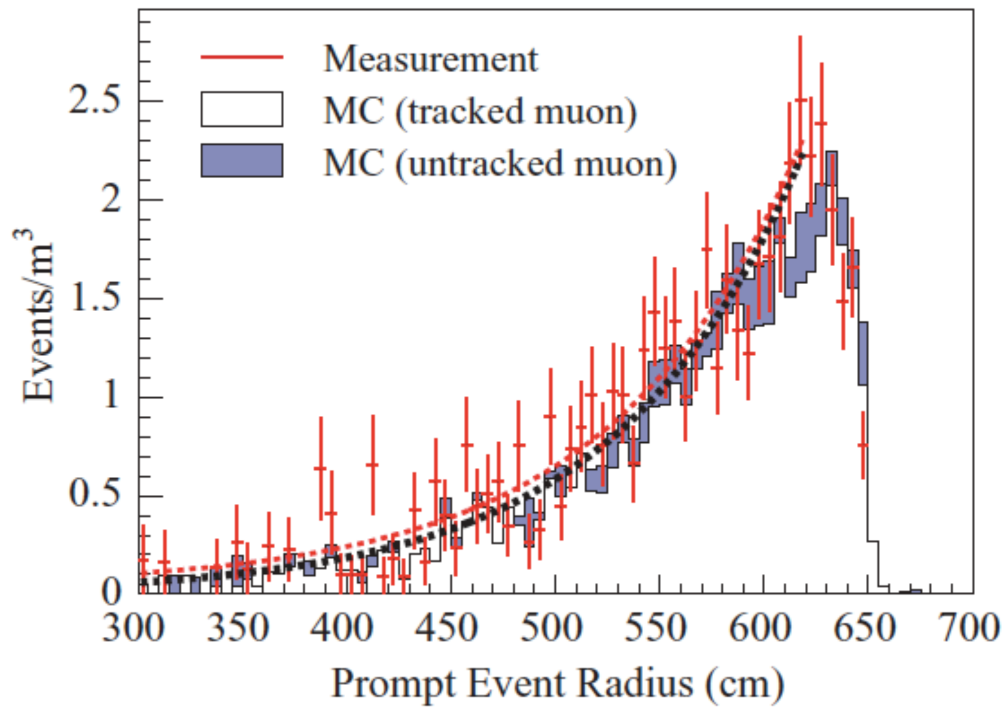
Fast Neutrons i.e. those coming from the rock surrounding KamLAND.

Geant4 and Neutrons in KamLAND:

Geant 4 version 9.1 with physics lists QGS_BIC and G4EMEXTRAPHYSICS were used to simulate both a generic block of KamLAND scintillator and the more complicated tracking of muon induced neutrons produced in the material surrounding KamLAND.

Neutrons Produced in Surrounding Material:





Measured Measured 70±2 g/cm^2
Simulated Attenuation 69±2 g/cm^2

Some we just do not have sensitivity too due to endpoint, lifetime, or scintillator composition...

Isotope	Half-Life	Endpoint	Decay Type
^{12}N	0.011 s	17.4 MeV	e^+
~~^{13}B~~	~~0.017 s~~	~~13.4 MeV~~	~~e^-~~
^{12}B	0.0202 s	13.4 MeV	e^-
~~^{11}Li~~	~~0.09 s~~	~~16.0 MeV~~	~~e^-~~
^{8}He	0.12 s	10.6 MeV	e^- with n
^{9}C	0.13 s	16.0 MeV	e^+ with p or α
^{9}Li	0.18 s	13.6 MeV	e^- with n
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~~^{6}He~~	~~0.81 s~~	~~3.5 MeV~~	~~e^-~~
^{8}Li	0.84 s	16.0 MeV	e^- with α
~~^{16}N~~	~~7.1 s~~	~~10.4 MeV~~	~~e^-~~
^{11}Be	13.8 s	11.5 MeV	e^- with α
^{10}C	19.3 s	1.9 MeV	e^+
~~^{14}O~~	~~71 s~~	~~5.15 MeV~~	~~e^+~~
~~^{15}O~~	~~122 s~~	~~2.76 MeV~~	~~e^+~~
^{11}C	20.38 min	0.96 MeV	e^+
~~^{13}N~~	~~9.97 min~~	~~2.22 MeV~~	~~e^+~~
~~^{7}Be~~	~~53 days~~	~~0.862 MeV~~	~~electron capture~~
~~^{10}Be~~	~~1.5×10^6 years~~	~~0.556 MeV~~	~~e^-~~

Now Spallation Isotopes i.e. everything you can make off of carbon.

The Shortest Lived Isotopes: ^{12}B and ^{12}N

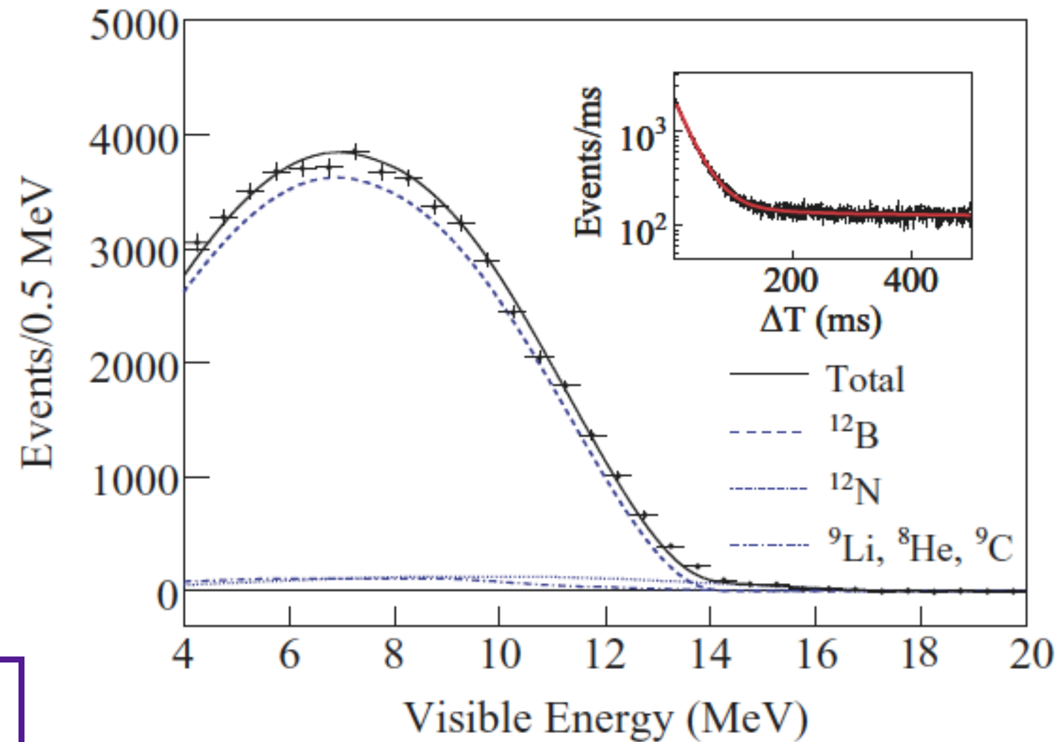
Like for the neutrons, a binned maximum likelihood to the time since previous muon is used.

^{12}N is fit using an energy window above the endpoint of ^{12}B, 14 MeV < E < 20 MeV.

$$Y(^{12}N)=1.8\pm0.4\times10^{-7}\ \mu^{-1}g^{-1}cm^{2}$$

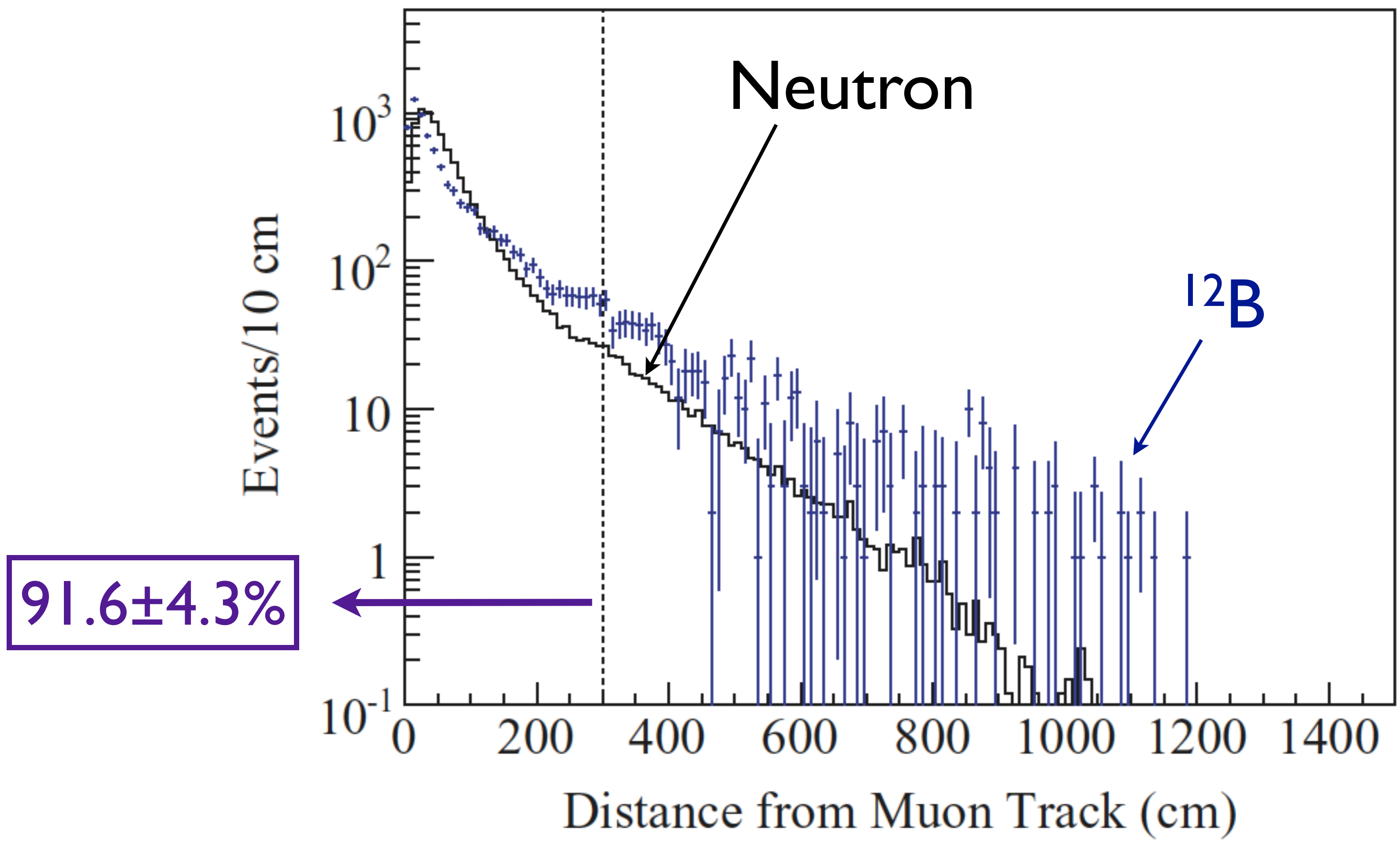
^{12}B is fit using an energy window, 4 MeV < E < 20 MeV with background components of ^{12}N and a longer component due to ^{9}Li, ^{8}He and ^{9}C

$$Y(^{12}B)=42.9\pm3.34\times10^{-7}\ \mu^{-1}g^{-1}cm^{2}$$



Distribution from Non-Showering Muon Track:

The production of ^{12}B is sufficient enough to study the distribution relative to the primary muon track. This will be key in the coming analyses

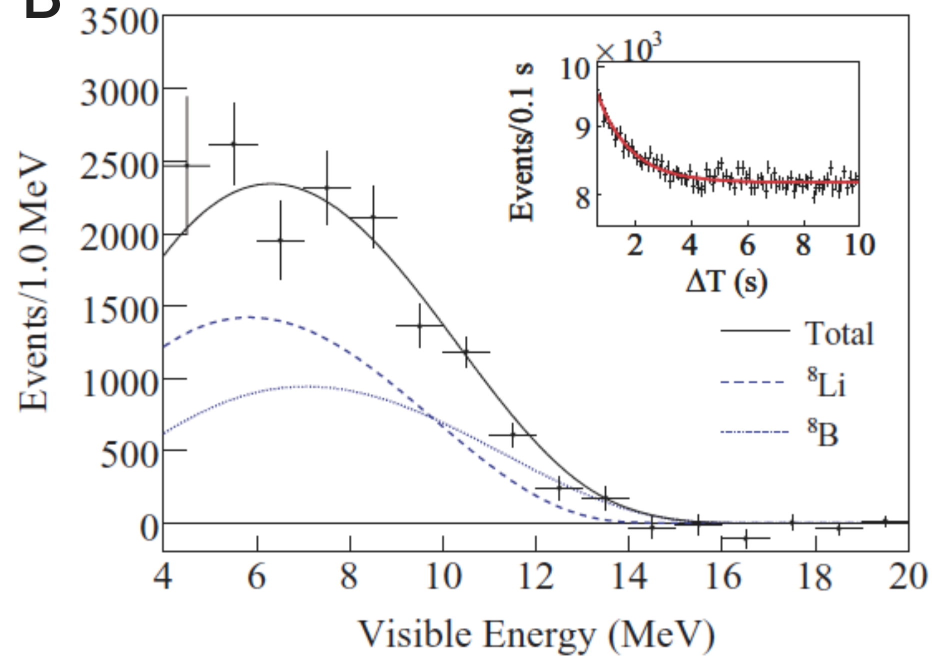


Additional corrections based on isotope come from the FLUKA simulation described later.

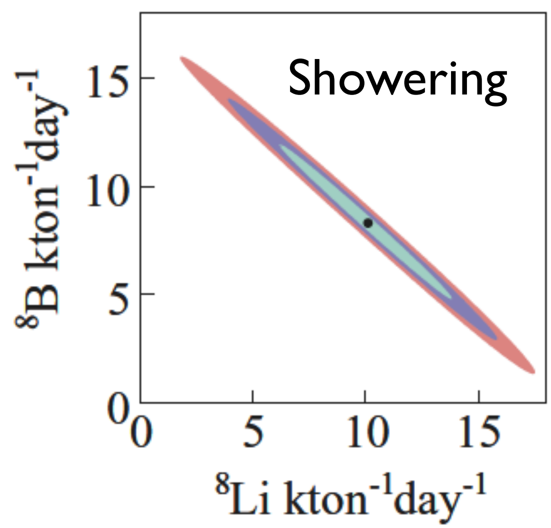
The Medium Lived Isotopes: ^{8}Li and ^{8}B

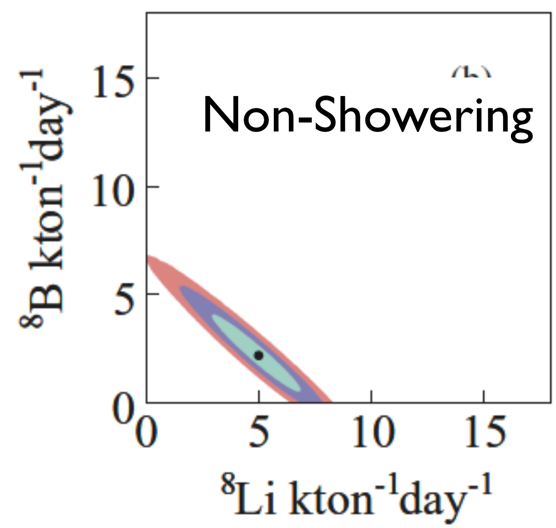
The time window is chosen to be long enough that ^{12}B, ^{12}N, ^{9}Li, ^{8}He and ^{9}C have decayed.

Unlike the shorter lived isotope, these two isotopes are not easily separated so a combined binned maximum likelihood to the time and energy spectra are used.



Y(^{8}Li)=12.2±2.6×10^{-7} μ^{-1}g^{-1}cm^{2}





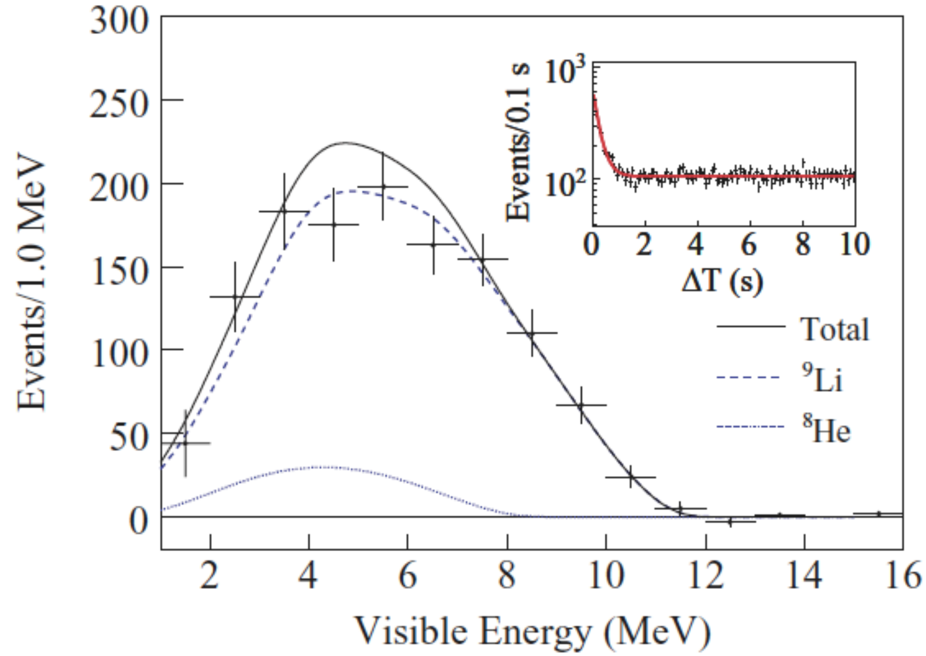
Y(^{8}B)=8.4±2.4×10^{-7} μ^{-1}g^{-1}cm^{2}

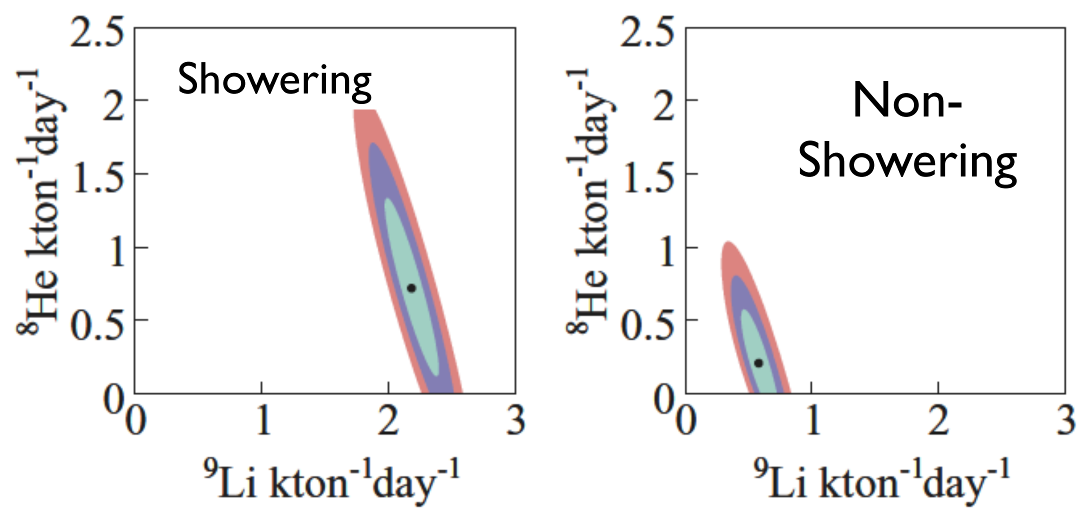
Delayed Neutrons: ^{9}Li and ^{8}He

These two nuclei are delayed neutron emitters so a triple coincidence of muon, beta decay and then neutron capture.

A combined time and energy fit is needed to differentiate the two nuclei.

The neutron efficiency is calculated as before.





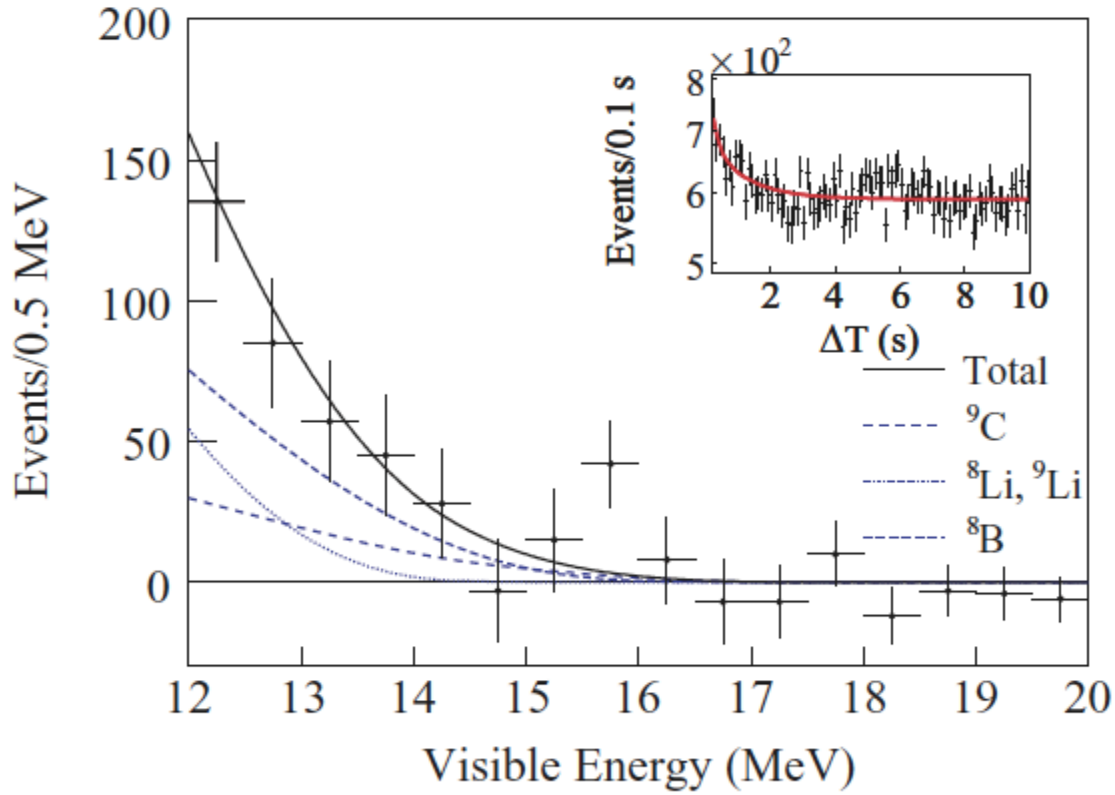
$Y(^{9}Li)=2.2\pm0.2\times10^{-7}\ \mu^{-1}g^{-1}cm^{2}$

$Y(^{8}He)=0.7\pm0.4\times10^{-7}\ \mu^{-1}g^{-1}cm^{2}$

Short but not too Short: ^{9}C

The extraction of the ^{9}C yield requires inputs from the previous analyses. A combined time and energy fit with ^{9}Li, ^{8}Li, ^{8}B as backgrounds is used.

The time range was chosen such that shortest lived isotopes, ^{12}B and ^{12}N can be neglected and the energy range above the ^{8}He endpoint.



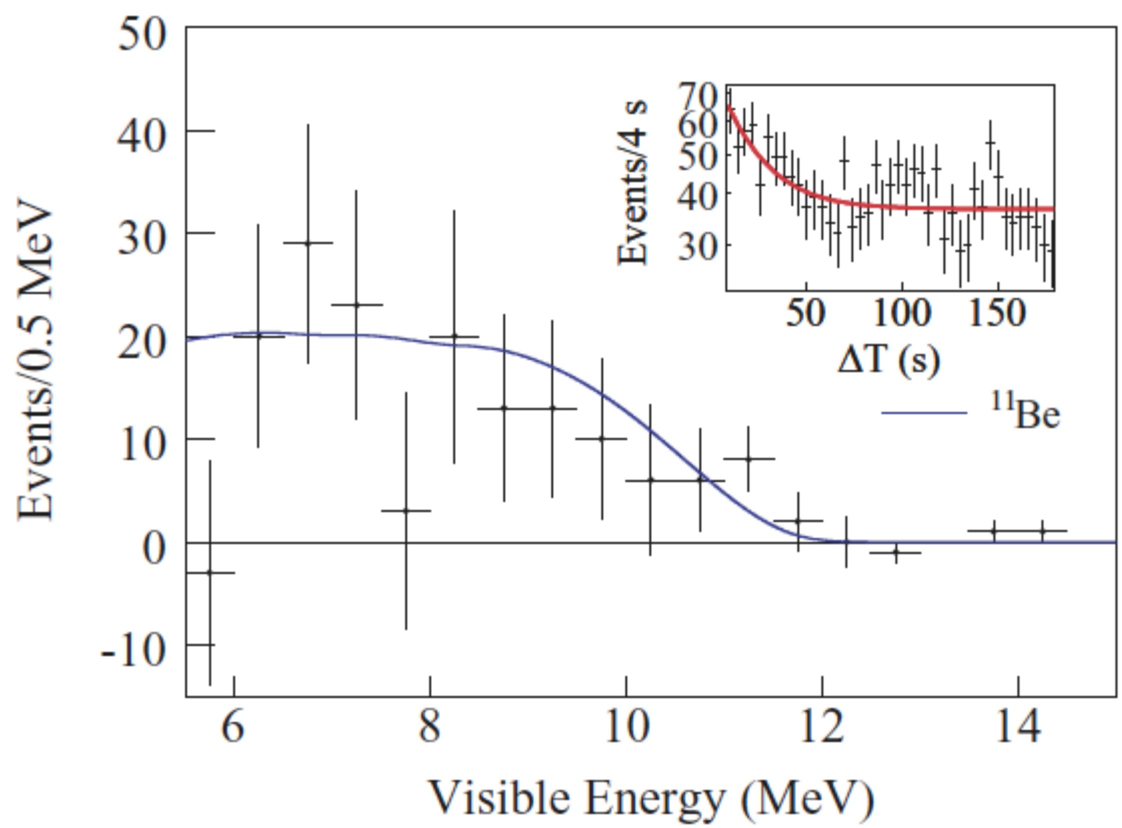
$$Y(^{9}C)=3.0\pm1.2\times10^{-7}\ \mu^{-1}g^{-1}cm^{2}$$

Long Lived Isotope: ^{11}Be

The time window is chosen to be long enough that ^{12}B, ^{12}N, ^{9}Li, ^{8}He, ^{9}C, ^{8}Li and ^{8}B have decayed.

A time only maximum likelihood fit is sufficient to extract the rate, but the accidental background is high.

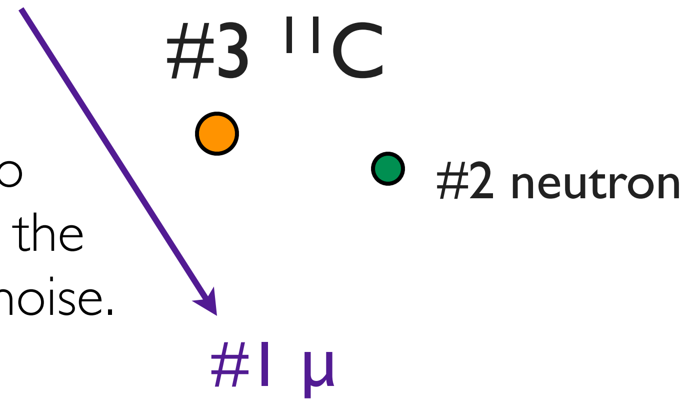
A 1m cylinder cut around the muon track is used to improve the signal to noise.

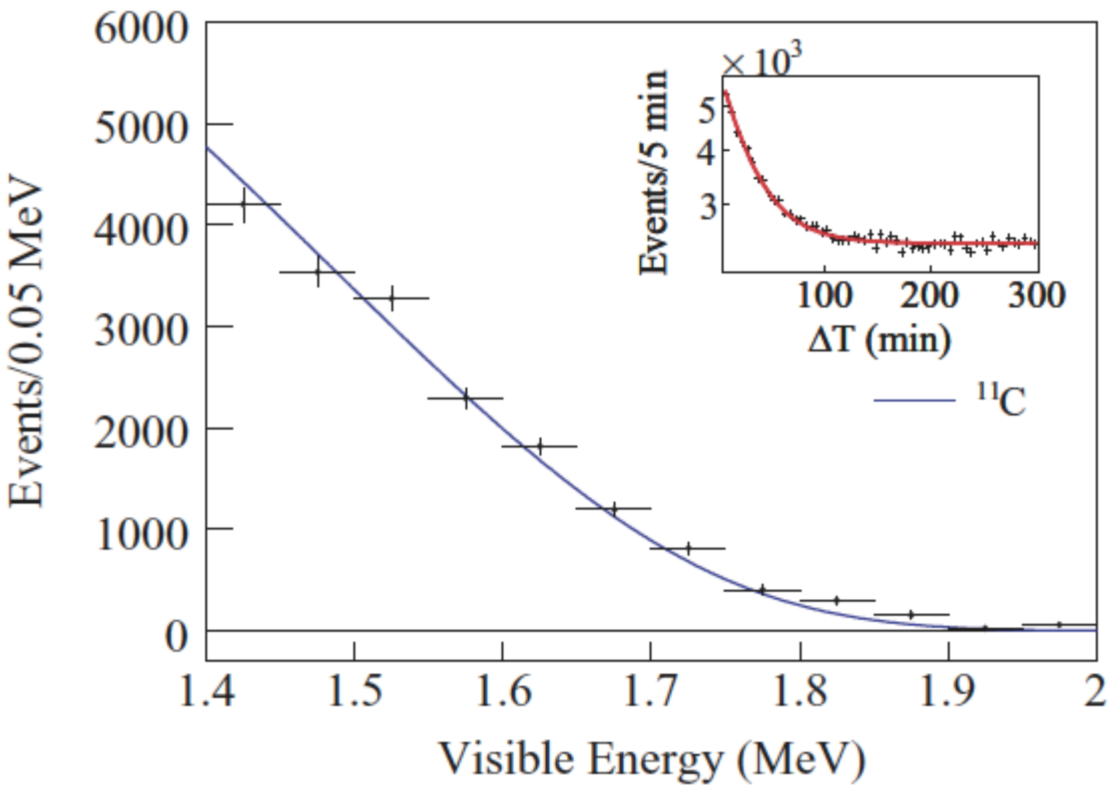


$$Y(^{11}Be)=1.1\pm0.2\times10^{-7}\ \mu^{-1}g^{-1}cm^{2}$$

The Triple Coincidence: ^{11}C

This lowest endpoint decay which we attempt to extract. A reduced fiducial volume, R<3.5m, and the triple coincidence is key for improving signal to noise.





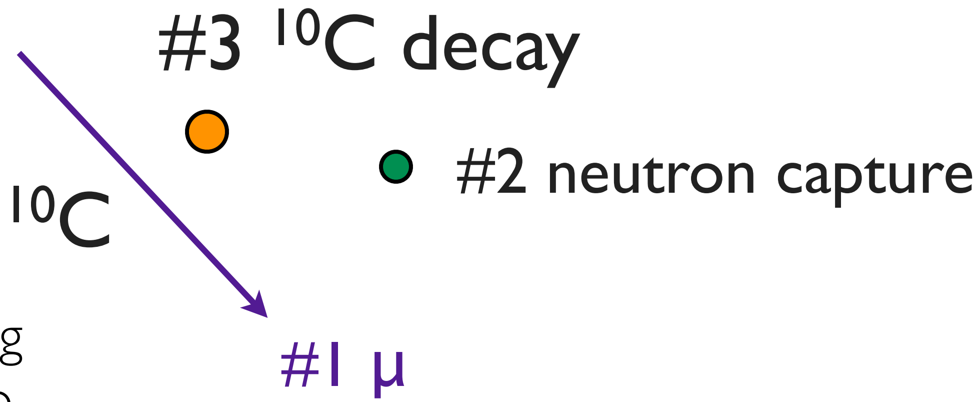
$Y(^{11}C)=866\pm153\times10^{-7}\ \mu^{-1}g^{-1}cm^{2}$

However, not all possible production modes produce a neutron. To quantify this another analysis was done without the neutron requirement but with 50cm cylinder cut around the muon track. The result is:

96.3±2.0%

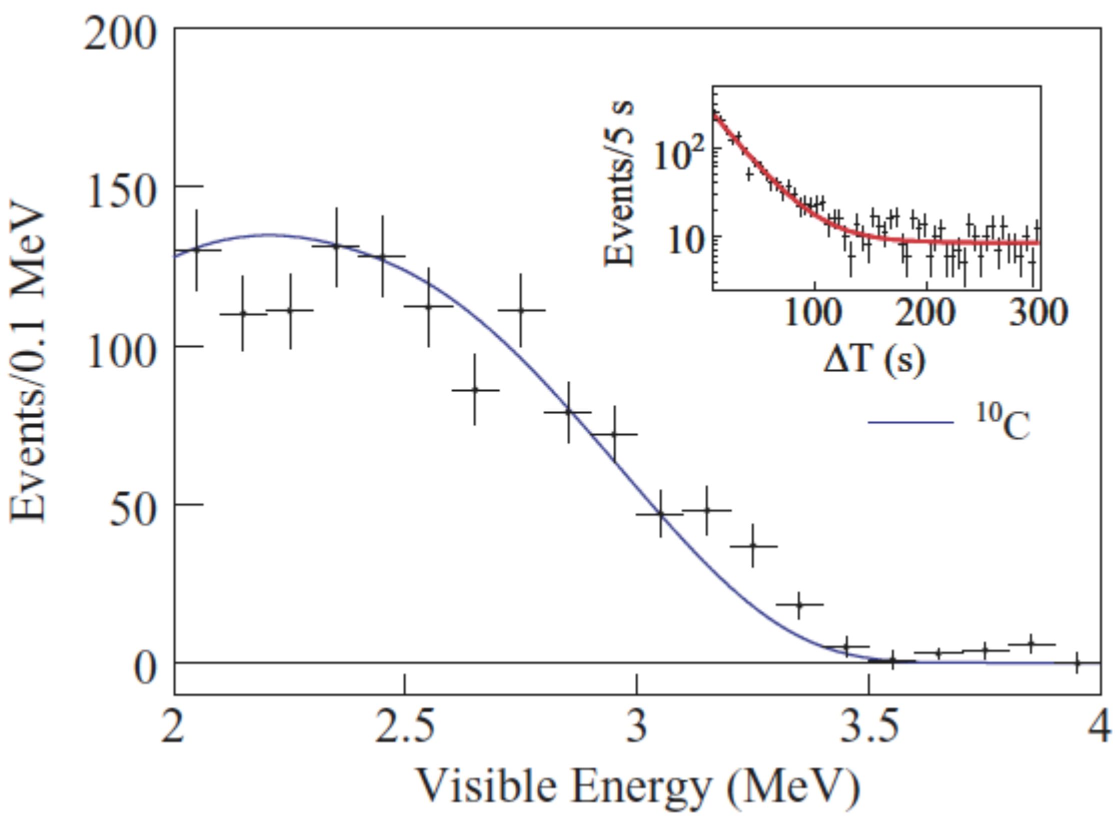
of ^{11}C are accompanied by a neutron.

The is agreement with the 95.6% calculated by Galbiati et. al. in Phys. Rev. C 71:055805 (2005) and scaling the yield to Borexino depth agrees with the numbers reported in Phys. Rev. Lett. 101:0191302 (2008) though not the CTF measurements.



Shorter Triple Coincidence: ^{10}C

Though not as low in energy or as long lived, the triple coincidence is needed to extract the ^{10}C yield as well.



Using the same method as for ^{11}C:

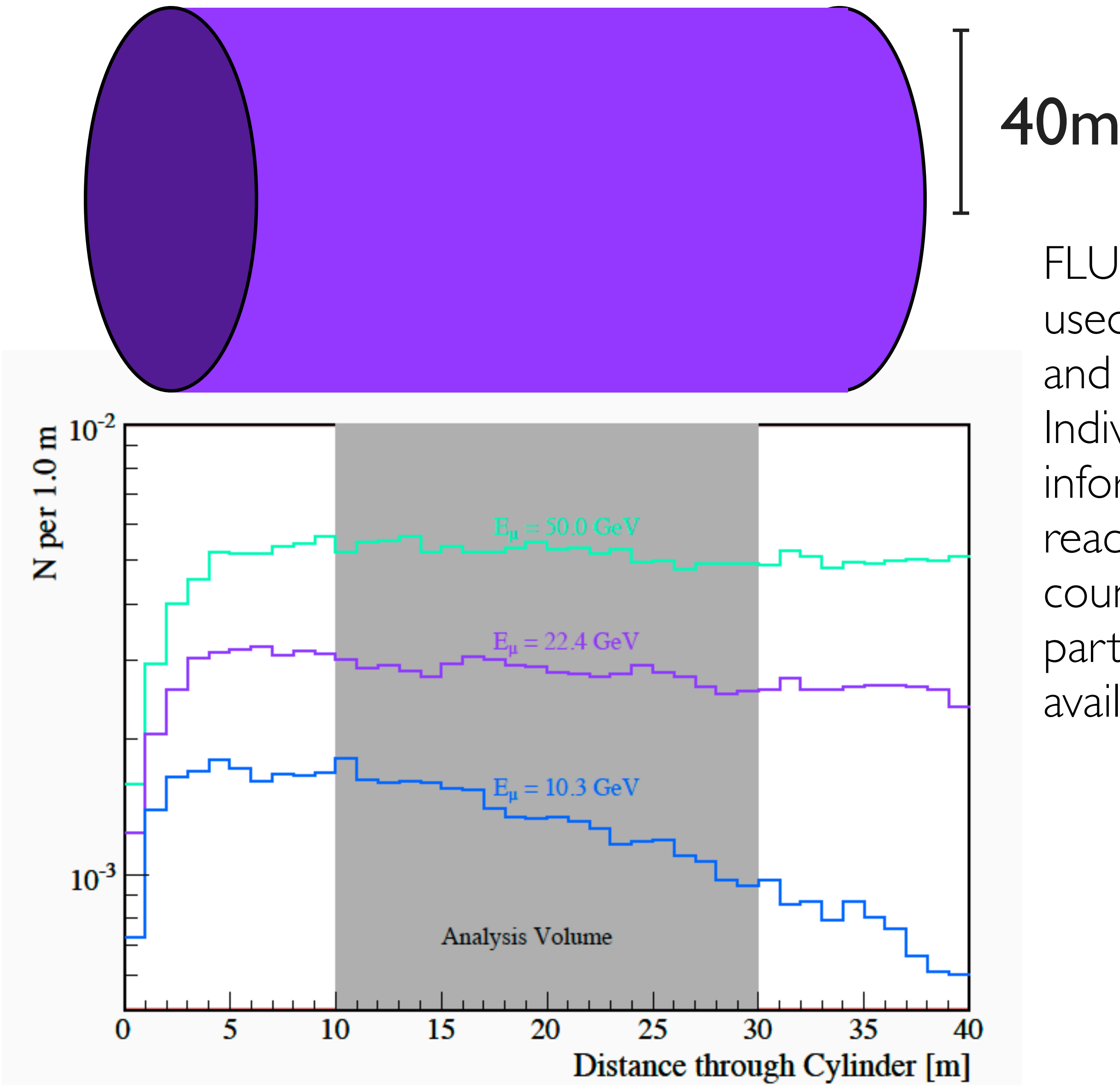
90.7±5.5%

of the ^{10}C produced are accompanied by a neutron.

$Y(^{10}C)=16.5\pm1.9\times10^{-7}\ \mu^{-1}g^{-1}cm^2$

Note that ^{11}Be is a background for this analysis but the small production rate makes it negligible.

FLUKA Simulation:



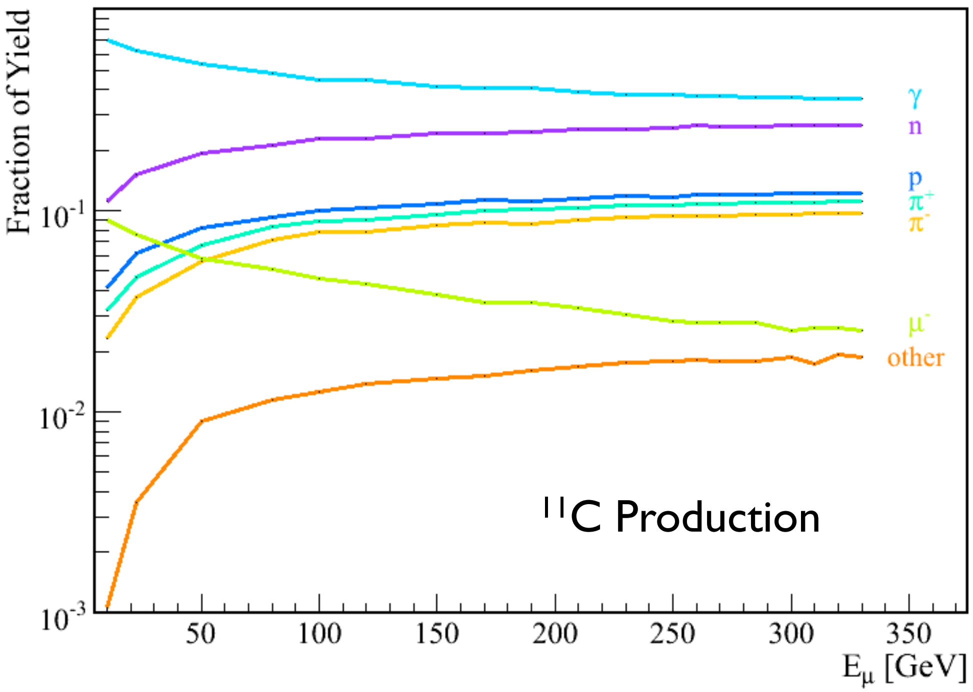
FLUKA version 2006.3b was used to simulate both neutron and isotope production. Individual particle tracking information was output so that reactions like (n, 2n) could be counted correctly, and parent particle information would be available.

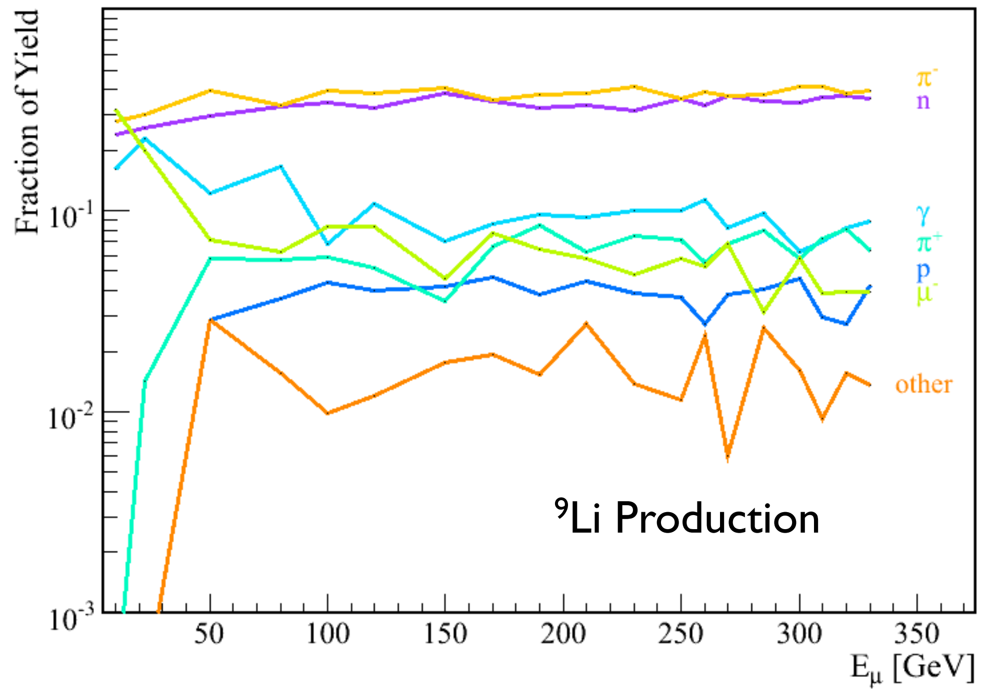
Corrections for Muon Charge Ratio and Muon Spectrum:

	Simulated production yield ($\times 10^{-7}\ \mu^{-1}\ \mathrm{g}^{-1}\ \mathrm{cm}^2$)	Ratio of simulated production yields		Power-law exp.	Primary process
		μ^+/μ^-	Spectrum/monoenergetic		
n	2344 ± 4	0.969 ± 0.002	0.912 ± 0.003	0.779 ± 0.001	$\pi^- + {}^1\mathrm{H}, {}^{12}\mathrm{C}$
$^{11}\mathrm{C}$	460.8 ± 1.7	0.971 ± 0.005	0.913 ± 0.006	0.703 ± 0.002	$^{12}\mathrm{C}(\gamma, n)$
$^{7}\mathrm{Be}$	116.8 ± 0.9	0.986 ± 0.011	0.945 ± 0.011	0.684 ± 0.004	$^{12}\mathrm{C}(\gamma, n\alpha)$
$^{10}\mathrm{Be}$	44.63 ± 0.53	0.960 ± 0.018	0.891 ± 0.019	0.825 ± 0.007	$^{12}\mathrm{C}(n, {}^3\mathrm{He})$
$^{12}\mathrm{B}$	30.85 ± 0.44	0.970 ± 0.021	0.936 ± 0.022	0.828 ± 0.009	$^{12}\mathrm{C}(n, p)$
$^{8}\mathrm{Li}$	23.42 ± 0.39	0.927 ± 0.026	0.936 ± 0.025	0.821 ± 0.010	$^{12}\mathrm{C}(n, p\alpha)$
$^{10}\mathrm{C}$	21.13 ± 0.37	0.982 ± 0.025	0.915 ± 0.027	0.810 ± 0.010	$^{12}\mathrm{C}(\pi^+, np)$
$^{6}\mathrm{He}$	13.40 ± 0.29	0.916 ± 0.035	0.918 ± 0.035	0.818 ± 0.013	$^{12}\mathrm{C}(n, 2p^3\mathrm{He})$
$^{8}\mathrm{B}$	6.40 ± 0.20	0.996 ± 0.045	0.915 ± 0.050	0.804 ± 0.019	$^{12}\mathrm{C}(\pi^+, {}^2\mathrm{H}^2\mathrm{H})$
$^{9}\mathrm{Li}$	3.51 ± 0.15	0.856 ± 0.074	0.842 ± 0.078	0.801 ± 0.026	$^{12}\mathrm{C}(\pi^-, {}^3\mathrm{He})$
$^{9}\mathrm{C}$	1.49 ± 0.10	0.850 ± 0.114	0.949 ± 0.102	0.772 ± 0.039	$^{12}\mathrm{C}(\pi^+, {}^3\mathrm{H})$
$^{12}\mathrm{N}$	0.86 ± 0.07	0.963 ± 0.128	1.006 ± 0.120	0.921 ± 0.045	$^{12}\mathrm{C}(p, n)$
$^{11}\mathrm{Be}$	0.94 ± 0.08	0.842 ± 0.145	0.804 ± 0.161	0.753 ± 0.051	$^{12}\mathrm{C}(n, 2p)$
$^{8}\mathrm{He}$	0.35 ± 0.05	0.964 ± 0.200	0.576 ± 0.372	0.926 ± 0.078	$^{12}\mathrm{C}(\pi^-, n3p)$
$^{13}\mathrm{B}$	0.31 ± 0.04	1.020 ± 0.197	1.062 ± 0.176	0.742 ± 0.075	$^{13}\mathrm{C}(n, p)$
$^{15}\mathrm{O}$	0.05 ± 0.02	1.250 ± 0.379	1.635 ± 0.234	0.793 ± 0.244	$^{16}\mathrm{O}(\gamma, n)$
$^{13}\mathrm{N}$	0.06 ± 0.02	1.500 ± 0.272	1.190 ± 0.401	1.120 ± 0.220	$^{13}\mathrm{C}(p, n)$

A quick note on primary production process:

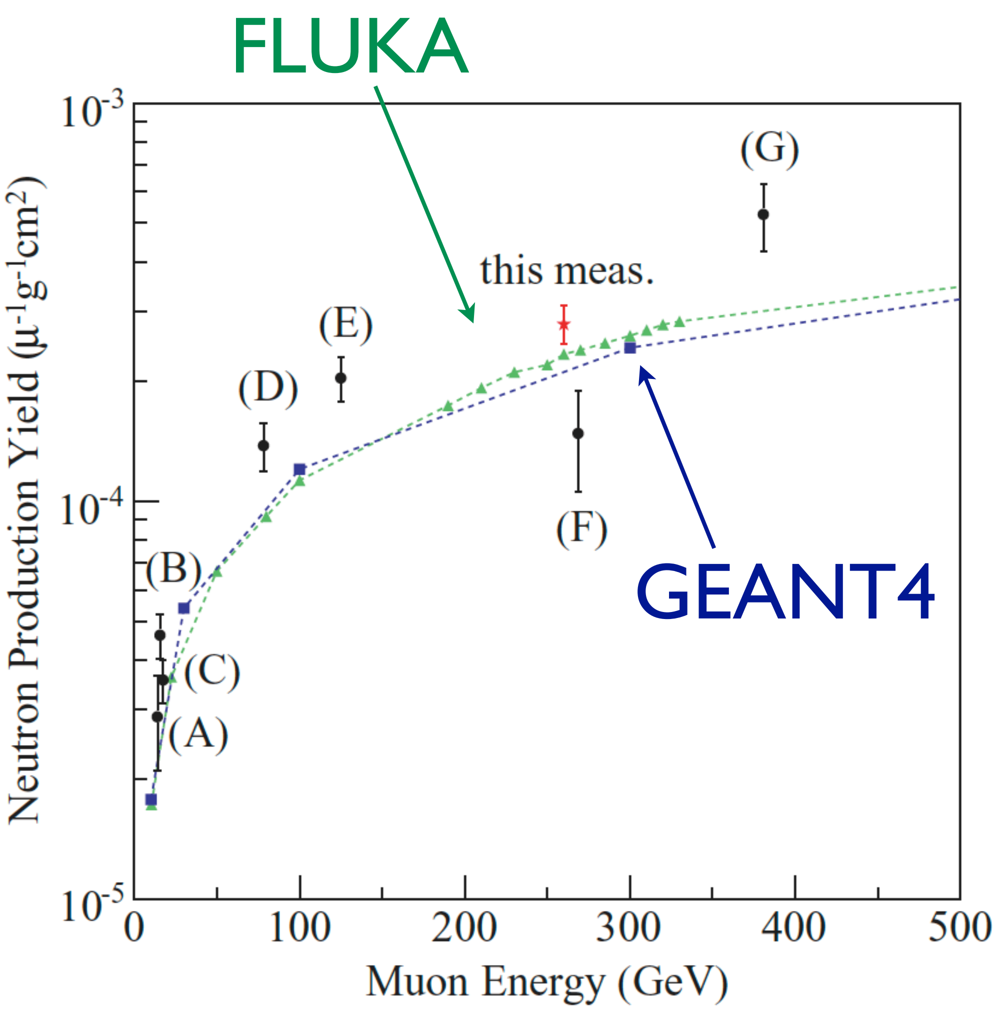
For some of the isotopes, one process dominates while for others we see multiple processes contributing.

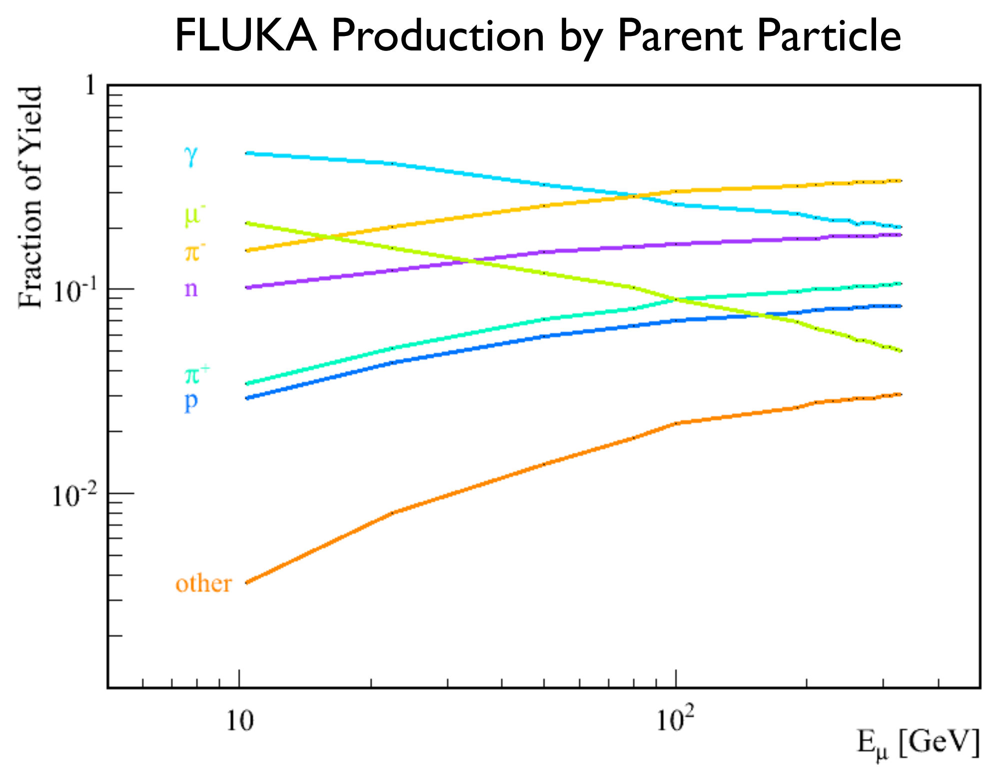




Neutrons Again:

These are the classic plots for benchmarking the performance of the simulation. These are consistent with other work and show that the simulation consistently underestimates the yield.





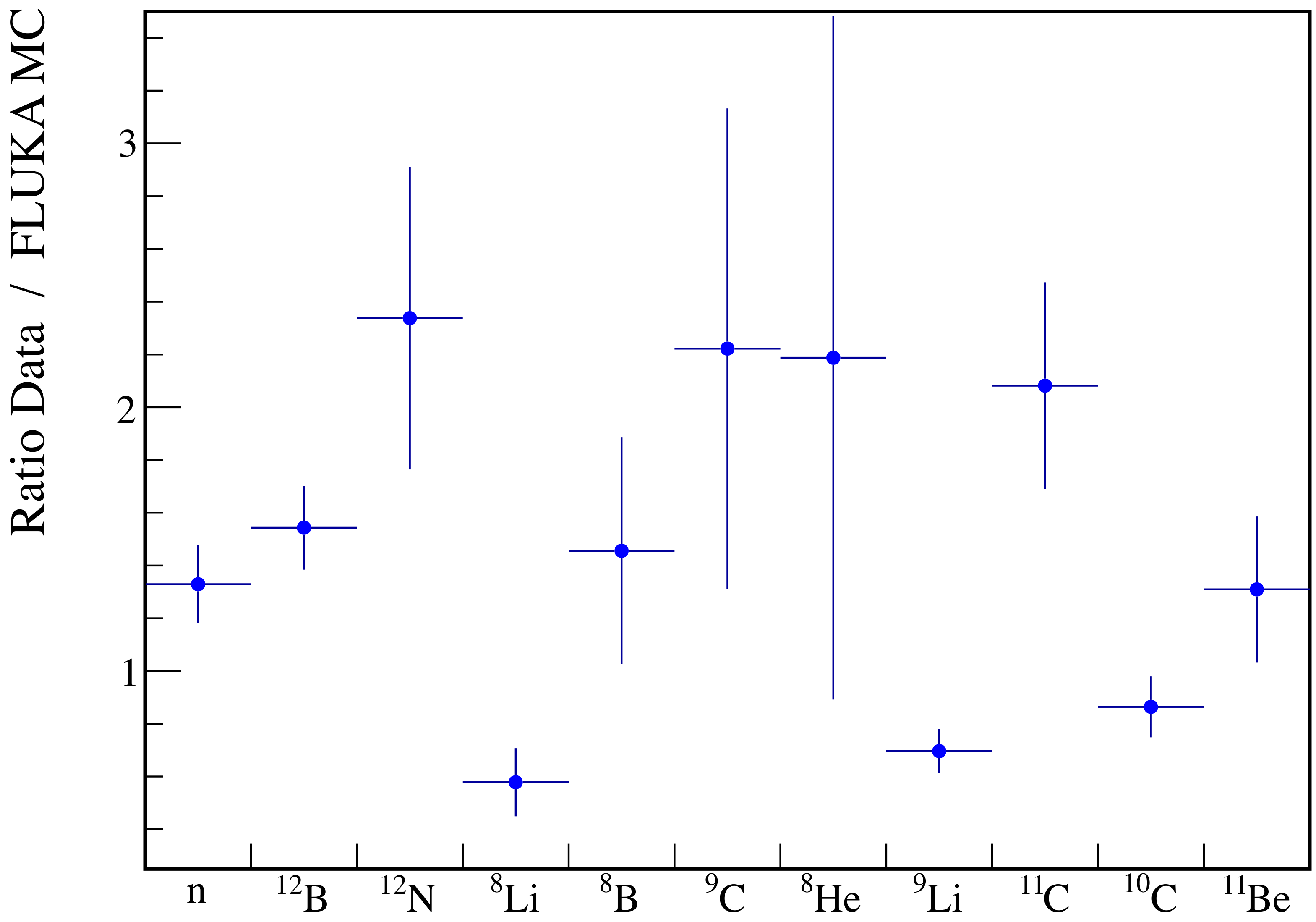
And Now the Isotopes...

The comparisons of isotope production to simulation are not so clear cut, and do not divide nicely along the lines of parent production process.

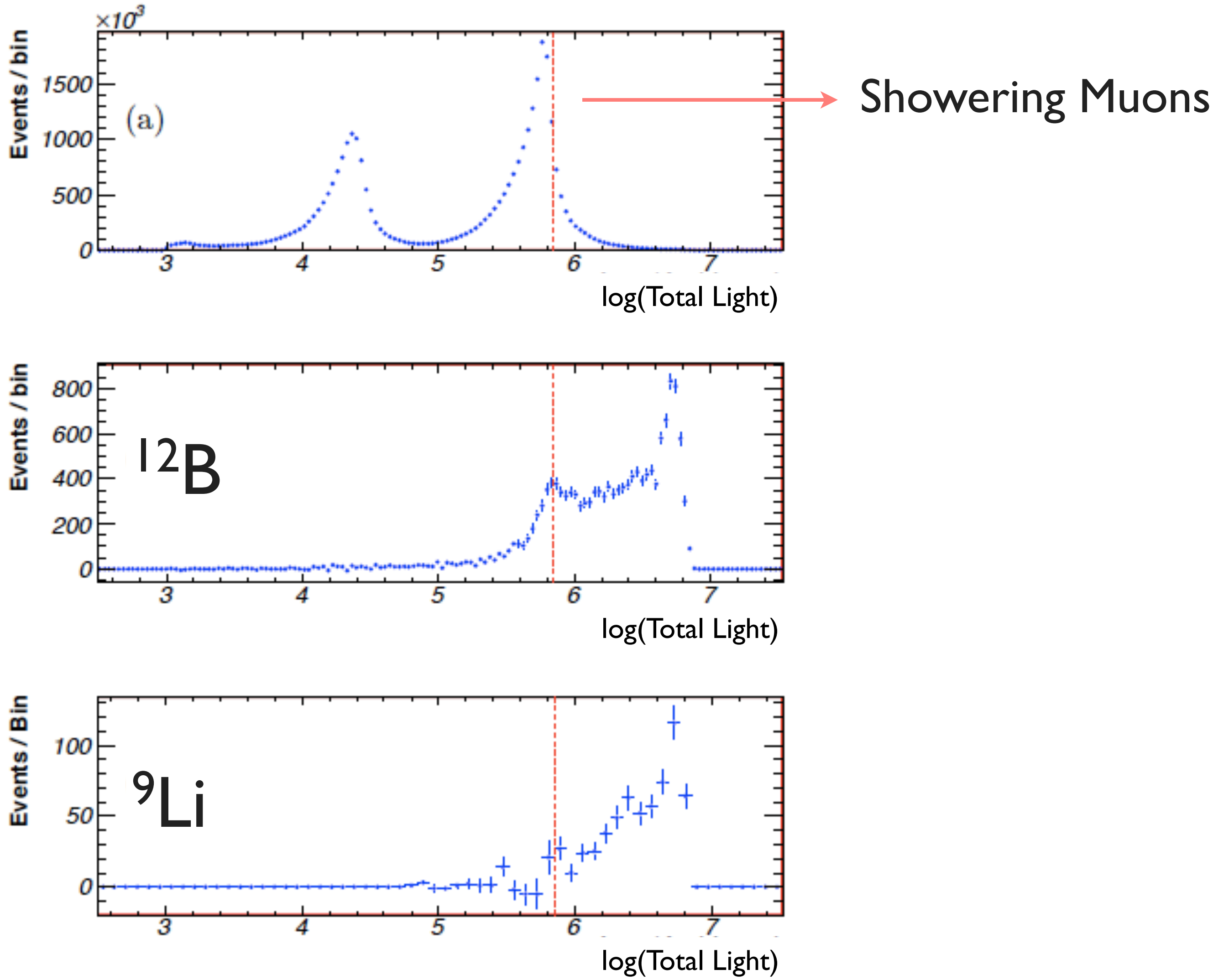
	Lifetime in KamLAND LS	Radiation energy (MeV)	Yield ($\times 10^{-7} \mu^{-1}$ g^{-1} cm^2)		
			Ref. [10]	FLUKA calc.	This measurement
n	207.5 μs	2.225 (capt. γ)	–	2097 ± 13	2787 ± 311
^{12}B	29.1 ms	13.4 (β^-)	–	27.8 ± 1.9	42.9 ± 3.3
^{12}N	15.9 ms	17.3 (β^+)	–	0.77 ± 0.08	1.8 ± 0.4
^{8}Li	1.21 s	16.0 ($\beta^- \alpha$)	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6
^{8}B	1.11 s	18.0 ($\beta^+ \alpha$)	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4
^{9}C	182.5 ms	16.5 (β^+)	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2
^{8}He	171.7 ms	10.7 ($\beta^- \gamma n$)	} 1.0 ± 0.3 (8He + 9Li)	0.32 ± 0.05	0.7 ± 0.4
^{9}Li	257.2 ms	13.6 ($\beta^- \gamma n$)		3.16 ± 0.25	2.2 ± 0.2
^{11}C	29.4 min	1.98 (β^+)	421 ± 68	416 ± 27	866 ± 153
^{10}C	27.8 s	3.65 ($\beta^+ \gamma$)	54 ± 12	19.1 ± 1.3	16.5 ± 1.9
^{11}Be	19.9 s	11.5 (β^-)	<1.1	0.84 ± 0.09	1.1 ± 0.2
^{6}He	1.16 s	3.51 (β^-)	7.5 ± 1.5	12.08 ± 0.83	–
^{7}Be	76.9 day	0.478 (EC γ)	107 ± 21	105.3 ± 6.9	–

Muon beam experiment at CERN scaled to KamLAND depth, consistently underestimates the observations.

or instead of the table a plot...



A plot that should have made it into the paper:



From the thesis of D.A.Dwyer

And Finally....

	Lifetime in KamLAND LS	Radiation energy (MeV)	Yield ($\times 10^{-7} \mu^{-1}$ g^{-1} cm^2)			Fraction from showering μ (%) This measurement
			Ref. [10]	FLUKA calc.	This measurement	
n	207.5 μs	2.225 (capt. γ)	–	2097 ± 13	2787 ± 311	64 ± 5
^{12}B	29.1 ms	13.4 (β^-)	–	27.8 ± 1.9	42.9 ± 3.3	68 ± 2
^{12}N	15.9 ms	17.3 (β^+)	–	0.77 ± 0.08	1.8 ± 0.4	77 ± 14
^{8}Li	1.21 s	16.0 ($\beta^- \alpha$)	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6	65 ± 17
^{8}B	1.11 s	18.0 ($\beta^+ \alpha$)	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4	78 ± 23
^{9}C	182.5 ms	16.5 (β^+)	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2	91 ± 32
^{8}He	171.7 ms	10.7 ($\beta^- \gamma n$)	} 1.0 ± 0.3	0.32 ± 0.05	0.7 ± 0.4	76 ± 45
^{9}Li	257.2 ms	13.6 ($\beta^- \gamma n$)		3.16 ± 0.25	2.2 ± 0.2	77 ± 6
^{11}C	29.4 min	1.98 (β^+)	421 ± 68	416 ± 27	866 ± 153	62 ± 10
^{10}C	27.8 s	3.65 ($\beta^+ \gamma$)	54 ± 12	19.1 ± 1.3	16.5 ± 1.9	76 ± 6
^{11}Be	19.9 s	11.5 (β^-)	<1.1	0.84 ± 0.09	1.1 ± 0.2	74 ± 12
^{6}He	1.16 s	3.51 (β^-)	7.5 ± 1.5	12.08 ± 0.83	–	–
^{7}Be	76.9 day	0.478 (EC γ)	107 ± 21	105.3 ± 6.9	–	–