Showering Muons in Super Kamiokande

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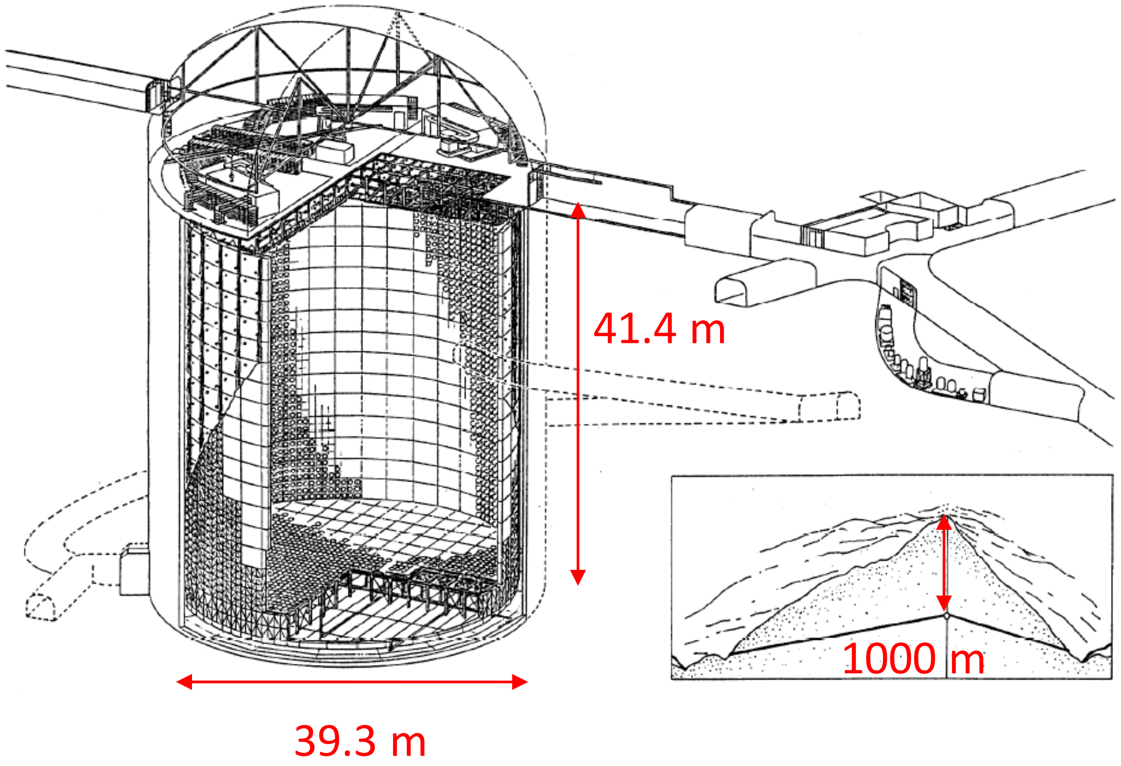
Super Kamiokande Detector

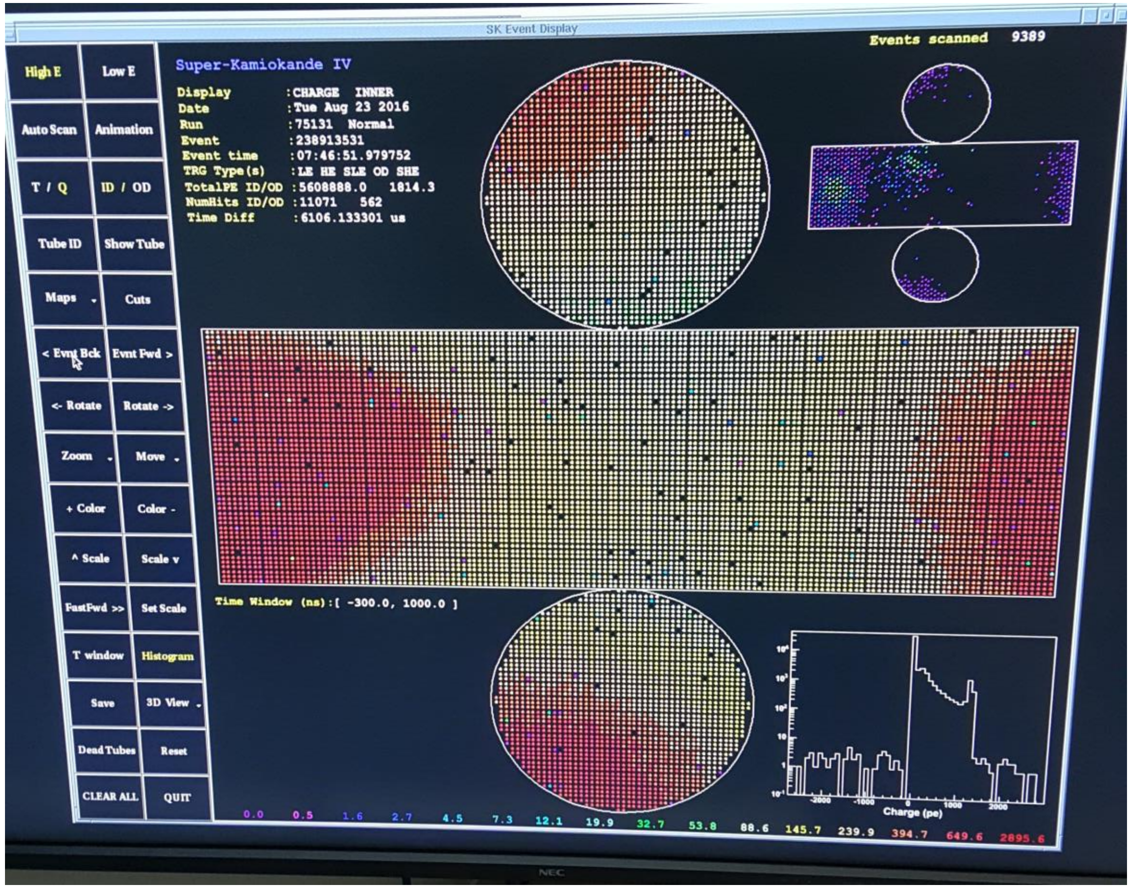


- 50kton water Cherenkov
  - Ultrapure Water
- 22.5 kton fiducial volume (32 kton for SN burst)
- 11, 129 20-inch PMTs (inner), 1885 of 8-inch PMTs (outer)
- Phase Period inner PMTs coverage
- SK-I 1996-2001 11,146 40%
- SK-II 2002-2005 5,182 19%
- SK-III 2006-2008 11,129 40%
- SK-IV 2008-2018 (same as SK-III with new electronics)
- SK-Gd 20XX-
- ~300 kt-years exposure
- Detects neutrinos from many sources
- T2K far detector

Introduction

- ~2 Hz muon rate
- Others usually consider it a MIP, which isn't always the case
  - Large amount of energy can be deposited, especially in the form of a shower
- Issues arise when these cause spallation

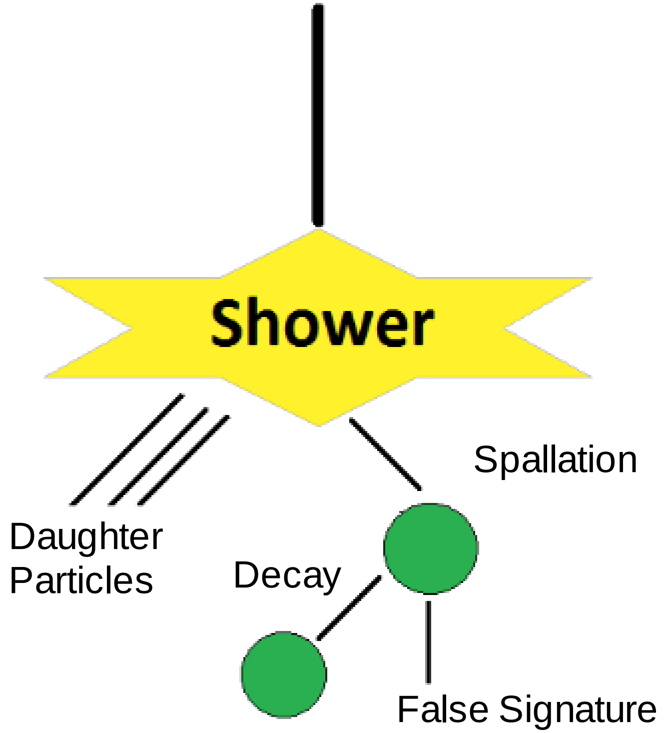
5.6 Mpe ≈ .94 TeV deposited within detector



Picture of Control Room Event Display

Spallation

- Spallation is caused largely by muon induced showers
- It can be long lived (τ ~ O(10s))
  - Troublesome when trying to perform specific analyses
- Shower does not guarantee spallation



Radioactive isotope	τ (s)	Decay mode	$E_{\text{kin.}}$ (MeV)	Primary process
^{11}Be	19.9	β^-	11.51	$^{16}O(n, \alpha + 2p)^{11}Be$
		$\beta^-\gamma$	9.41+2.1(γ)	
^{16}N	10.3	β^-	10.44	$^{16}O(n, p)^{16}N$
		$\beta^-\gamma$	4.27+6.13(γ)	
^{15}C	3.53	β^-	9.77	$^{16}O(n, 2p)^{15}C$
		$\beta^-\gamma$	4.51+5.30(γ)	
^{8}Li	1.21	β^-	~13.0	$^{16}O(\pi^-, \alpha + {}^2H + p + n)^8Li$
^{8}B	1.11	β^+	~13.9	$^{16}O(\pi^+, \alpha + 2p + 2n)^8B$

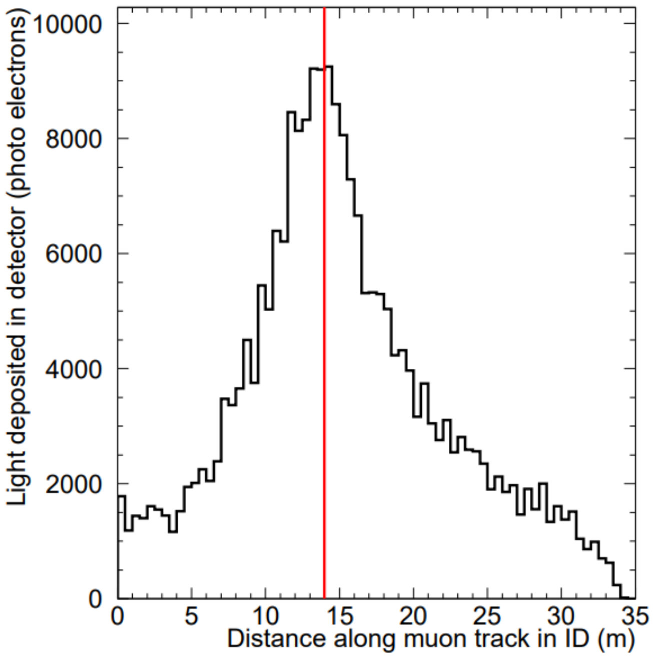
S. W. Li and J. F. Beacom, Phys. Rev. C 89, 045801(2014)

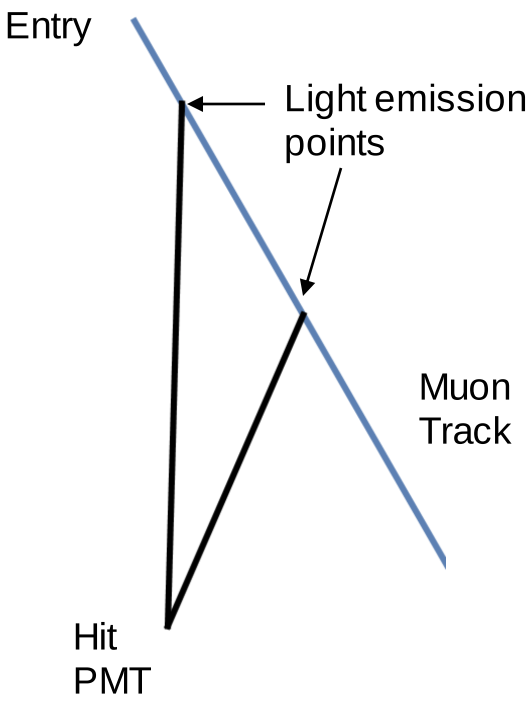
Radioactive isotope	ϵ_i	R_i (kton^{-1}day^{-1})
^{12}B	45.5%	19.8±0.1±1.0
^{12}N	56.2%	2.8±0.1±0.1
^{16}N	45.0%	39.7±3.3±2.8
^{11}Be	38.1%	<16.9
^{9}Li	39.2%	0.9±0.3±0.3
^{8}He/^{9}C	22.2%, 50.2%	<1.4
^{8}Li/^{8}B	42.8%, 51.3%	8.3±0.3±0.3
^{15}C	31.8%	<6.7

Y. Zhang et et al. (Super-Kamiokande Collaboration),Phys. Rev. D 93, 012004 (2016)

Muon Showers

- Shower can be hadronic or electromagnetic
- Both have large EM component
- Look at the energy deposited into detector along muon track
  - dE/dx plots
  - Map PMT hits back to the muon track
- Look for large deposits of energy in these plots





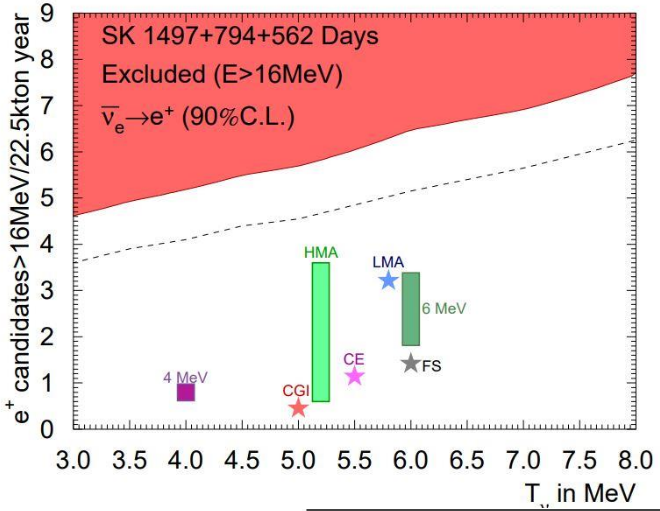
Effects

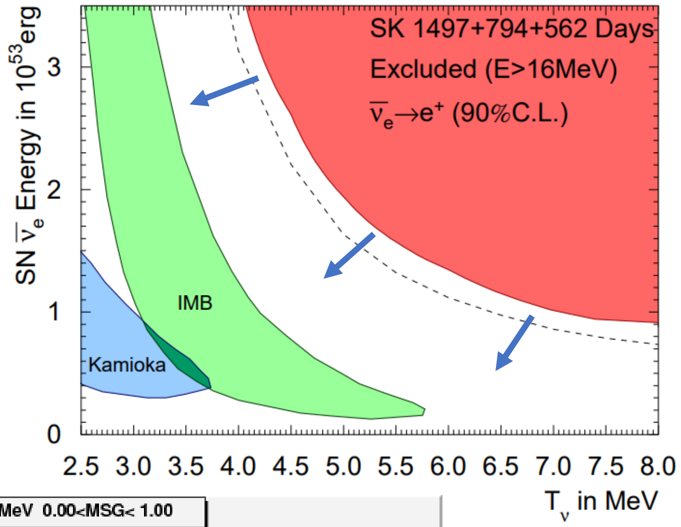
- Acts as a background to major analyses:
  - DSNB
  - Solar neutrinos
- Inhibits us from lowering the threshold for DSNB analysis
- Reducing this background is imperative to enhancing these searches

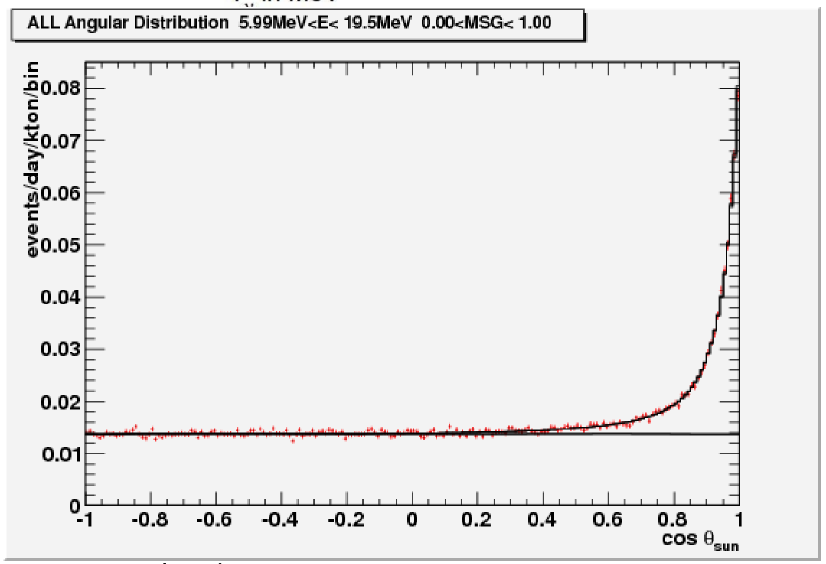
DNSB spallation efficiencies

EFFICIENCY	SK-I/III	SK-II
Low energy	81.8 % (16-18 MeV)	76.2 %(17.5-20 MeV)
High energy	90.8 % (18-24 MeV)	88.2 %(20-26 MeV)

Phys.Rev. D85 (2012) 052007







Personal Work

Hadronic Showers

- Hadn't been seen directly before
- Beacom and Li theorized that a large number of neutrons would be in the shower accompanying a spallation causing muon
- Use WIT (Wideband Intelligent Trigger) system for a lower threshold to see 2.2 MeV gamma from n+p interactions
- All the following is preliminary

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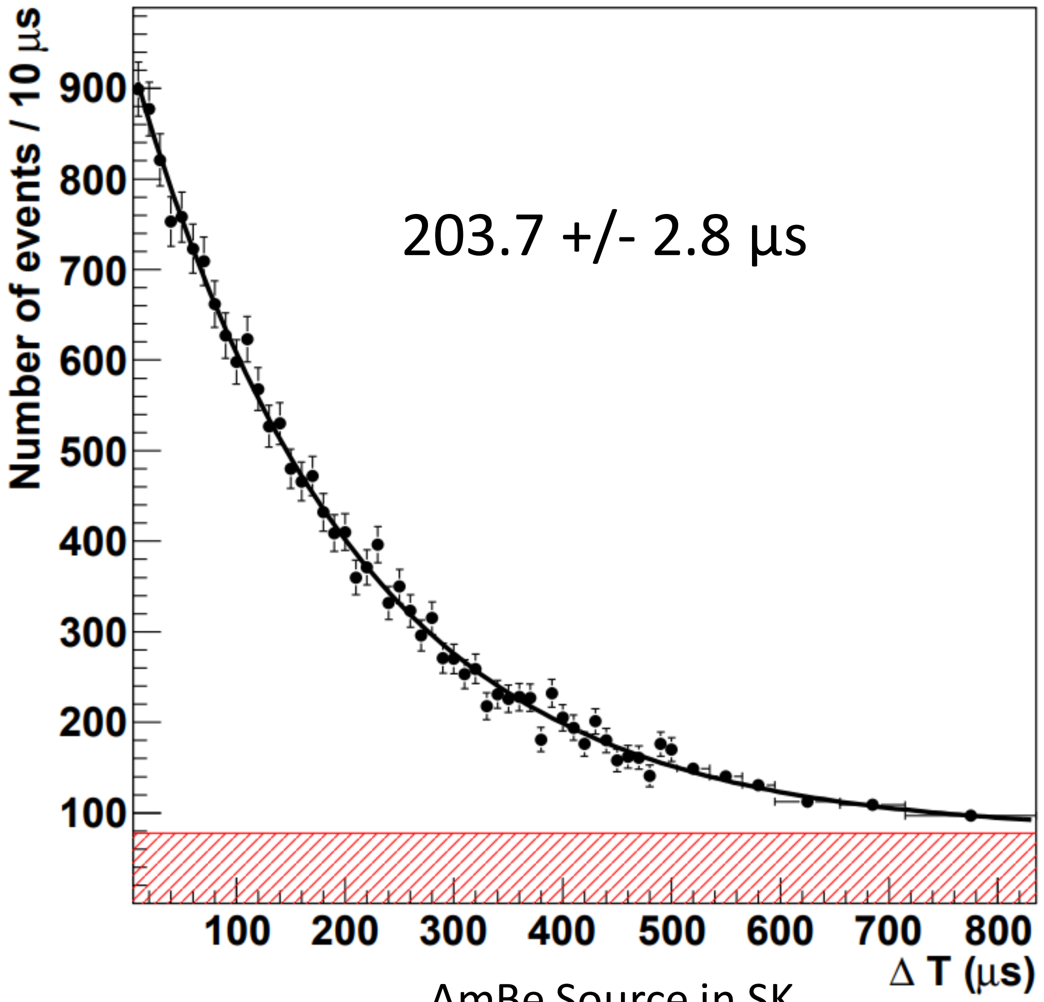
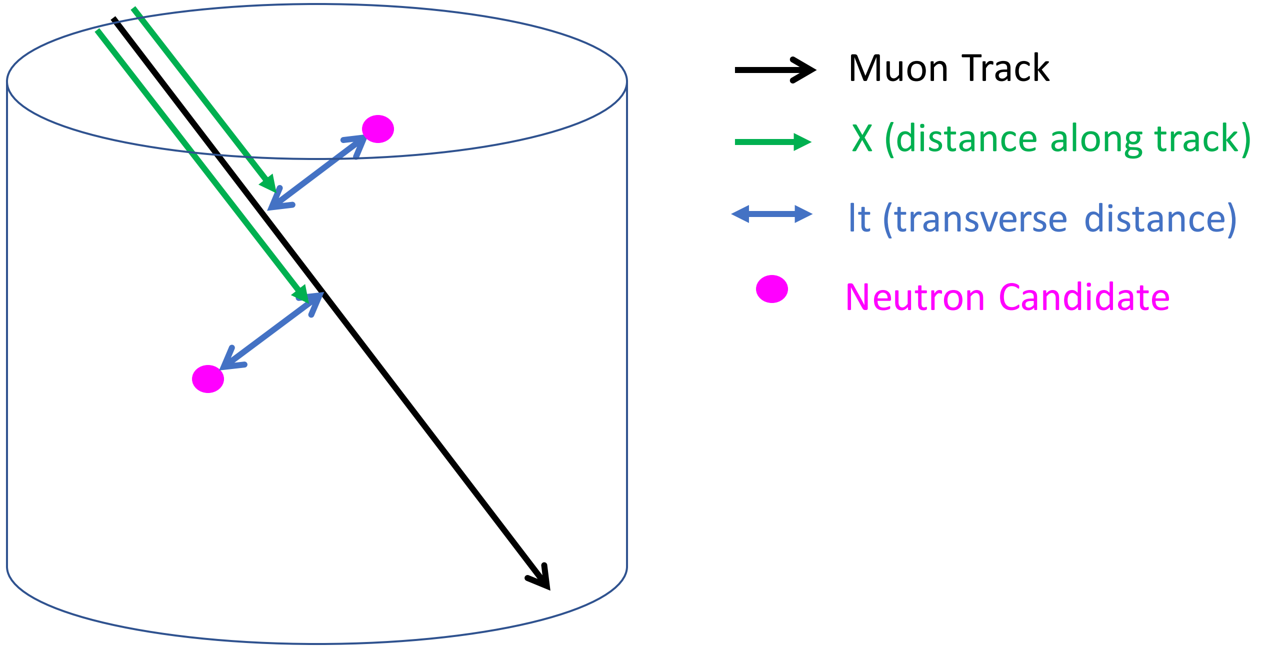


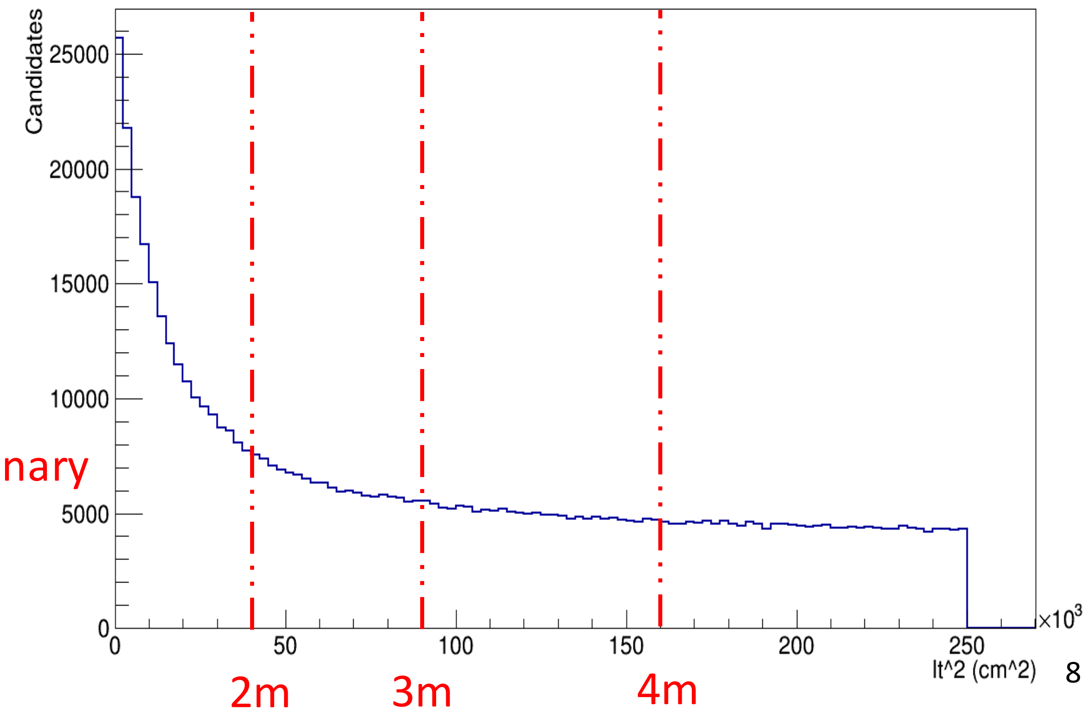
AmBe Source in SK

Neutron Tagging



- Initial Data Set:
  - ~6 weeks of data
  - 20-500 μs after muon
  - E < 5.5 MeV kin
  - <5m from track
  - Anywhere in detector (no FV cut)
  - Basic cut used on some of the data
    - Simple time, goodness, lt cuts
- Sharply peaked closer to the track

SK Preliminary
June 2017



Event Correlation

- Events are tightly correlated
  - Maintain correlation to higher multiplicity
- Look in the future to use this as an isolated cut
  - ~0.7% muons have 2+ events with above cuts
  - A rough calculation finds ~51s a day of dead time for a +/- 2.5m and 60s cut from x_{avg} for events with 2+ candidates

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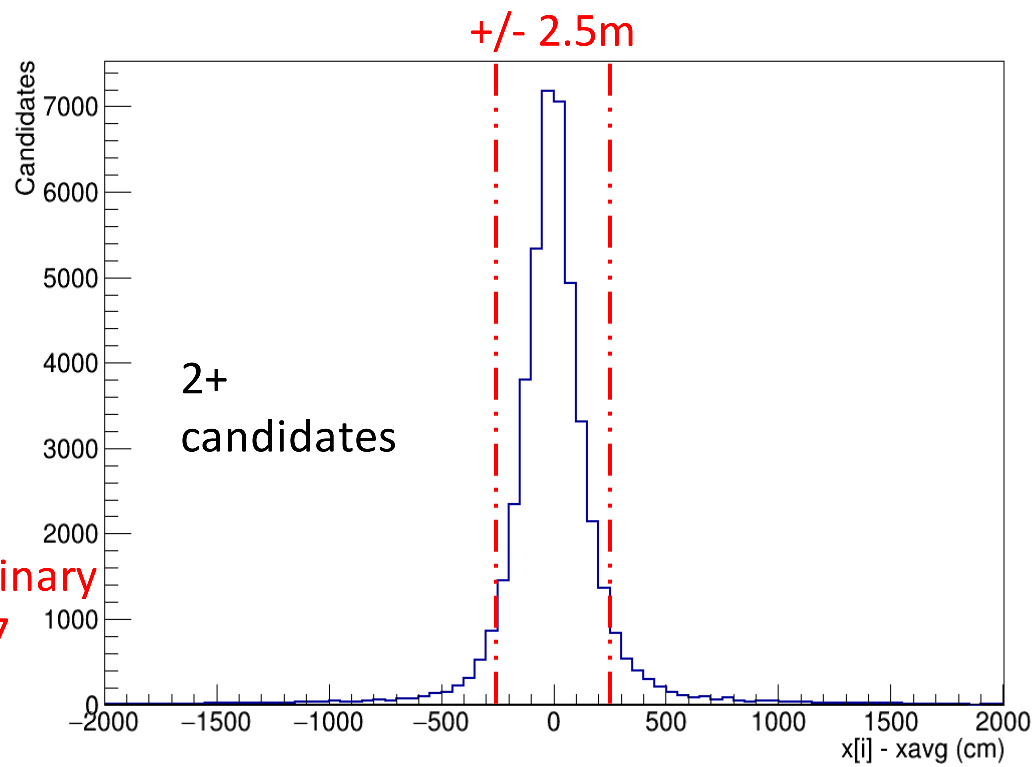
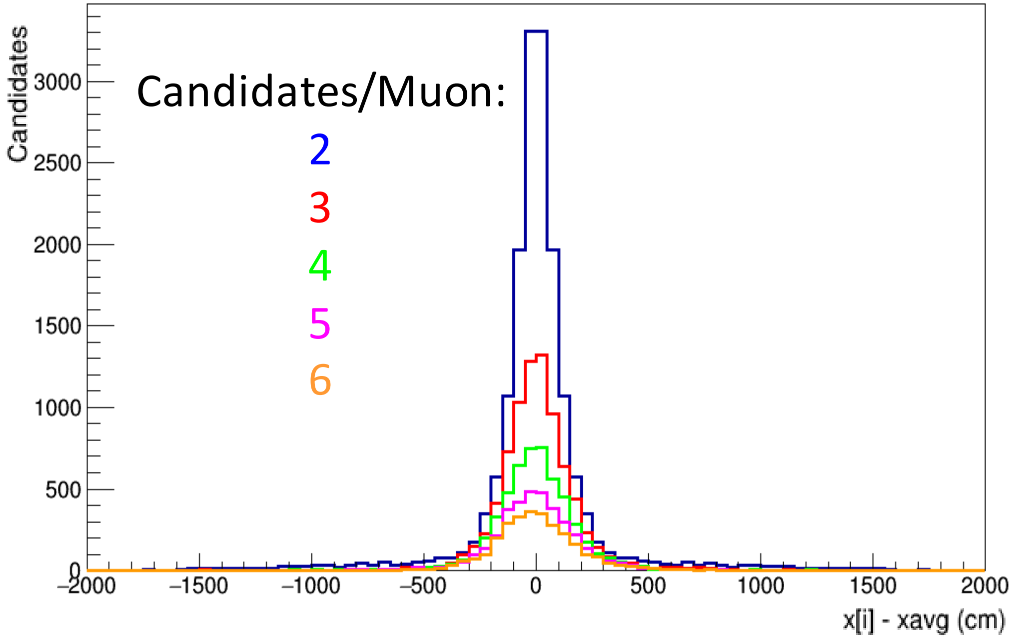
June 2017



Personal
Work



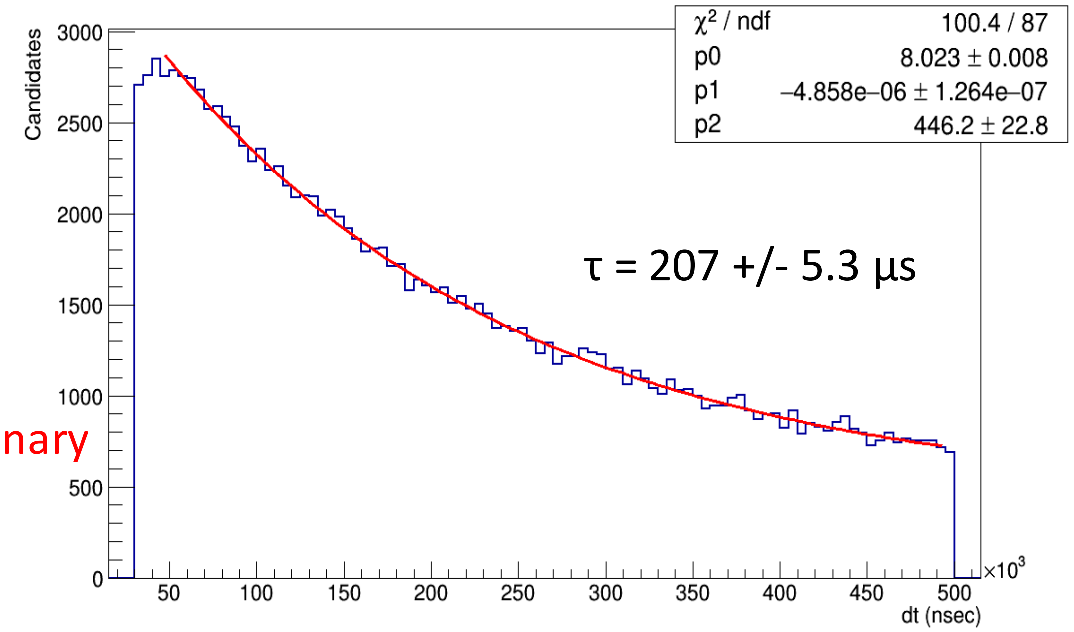
Time Correlation

- Use a simple exponential

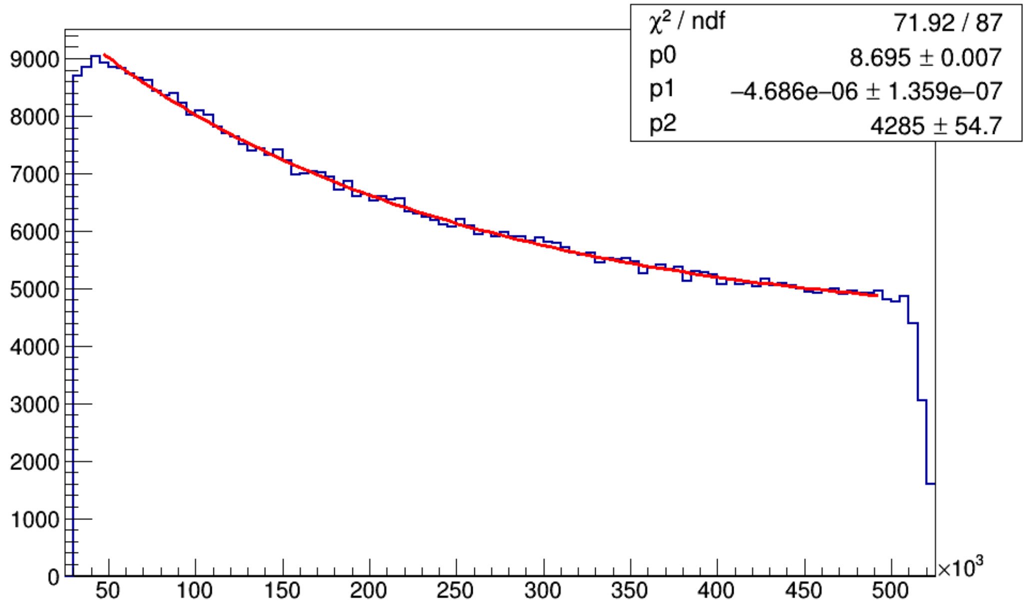
$$N[dt] = e^{p0+p1*dt} + p2$$

- Make a background calculation
  - High purity: ~.0027 accidentals/m of muon track
    - .067 accidentals/25m muon
- Still have good agreement when relaxing the purity cut

SK Preliminary
June 2017



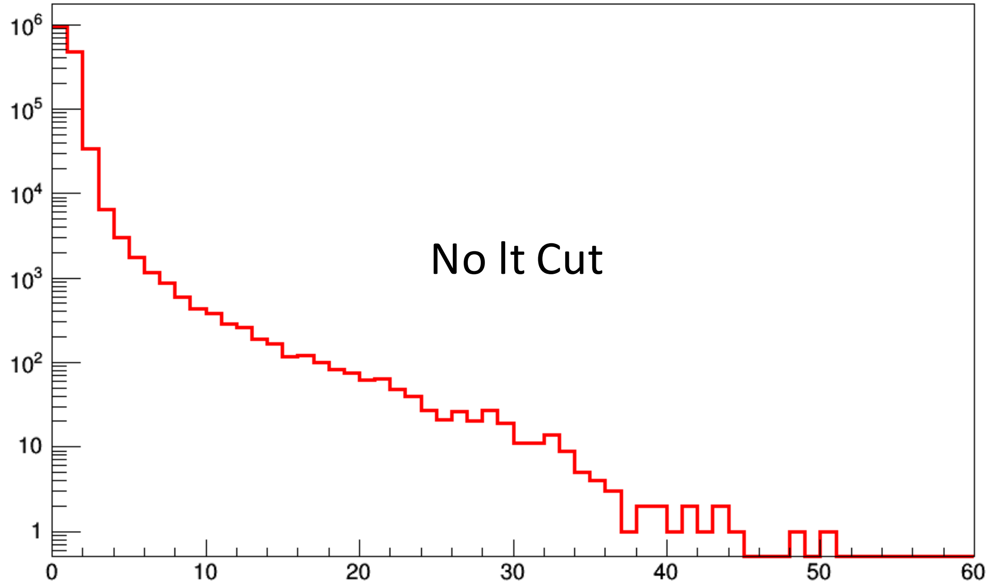
Personal
Work

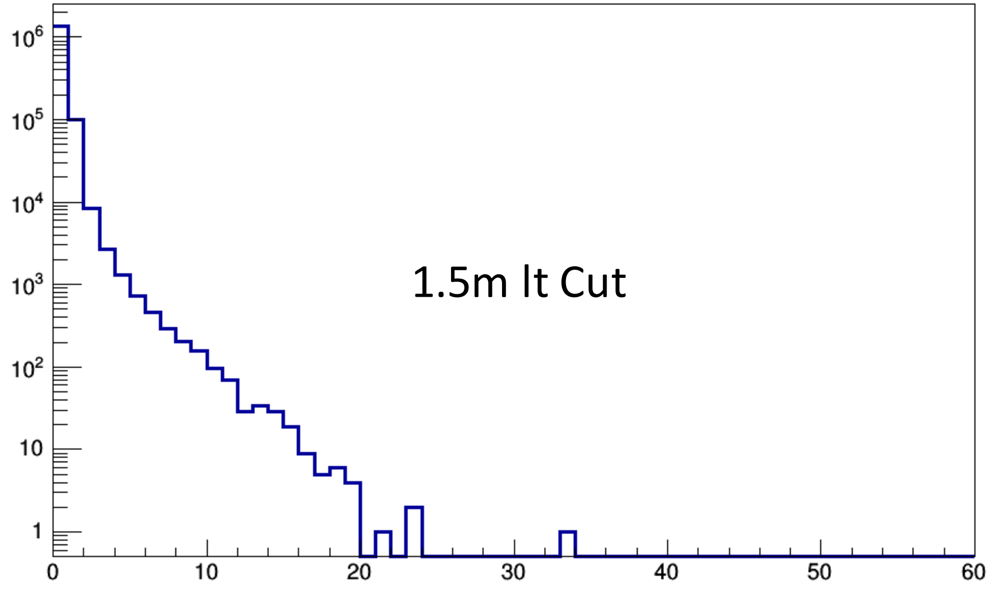


Multiplicity

Personal Work

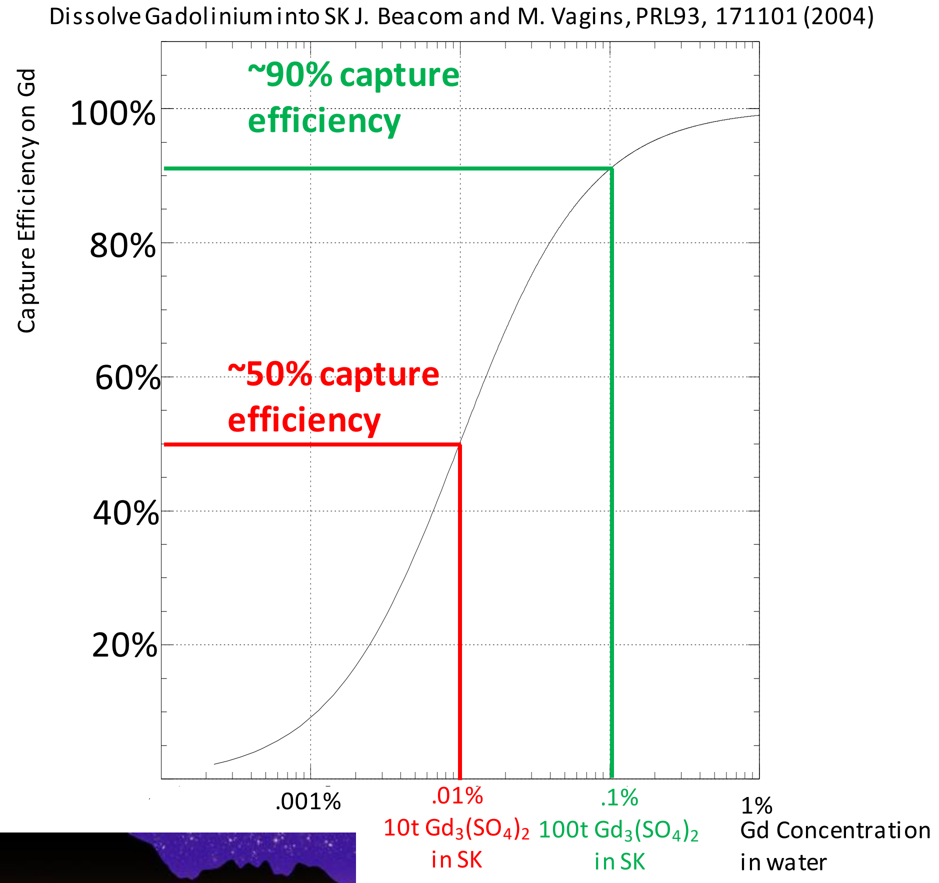
- Note
  - No background subtraction
    - Significantly < 0.5 accidentals/muon, even for low purity
  - Only events from sample
    - 0 bin is a lot bigger with all muons
- Everything shifts, but 0 peak does not grow significantly
- Efficiency:
  - 13.5% (17.2% in FV) efficiency for seeing MC generated neutrons
  - Drops to 4.2% (5.4% in FV) when making goodness and vertex correlation to true location cut

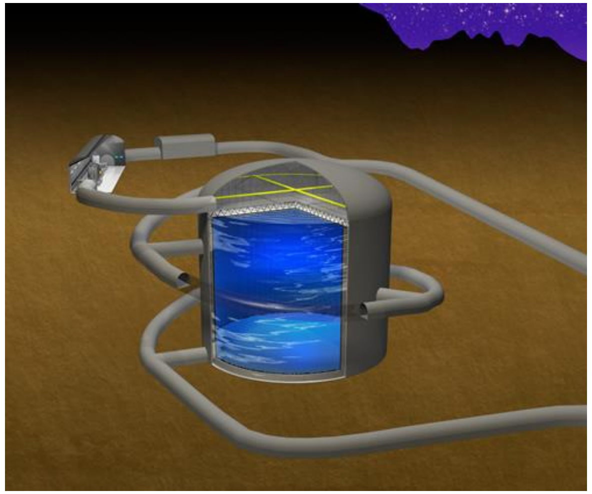




The Future

- SK-Gd
  - Increased capture efficiency on Gd
  - Easier to see the signal
    - Works with increased efficiency to improve tagging
  - Prepare for the signal that SK-Gd should be expecting to see
- Hyper-K
  - Bigger tank with possibly lower overburden
    - Neutrons become even more common as muon rate increases with more volume to interact with





Summary

- Even under 1 km of mountain, still see a non negligible muon rate
  - These muons cause issues in analyses by creating long lived spallation background
- Currently we look at the EM component of both kinds of showers to try and tag this background
- Recent efforts has shown it is possible to directly see the hadronic shower, specifically the neutrons produced
- Events are tightly correlated to each other and the preceding muon
- Efficiency of n capture on H is one of the biggest limiting factors, which should be enhanced with Gd

Super-Kamiokande Collaboration

- 10 nations
- ~42 institutions
- ~160 Researchers
- As of June 2017