

Measurement of the muon flux at SNOLAB using the DEAP-3600 experiment

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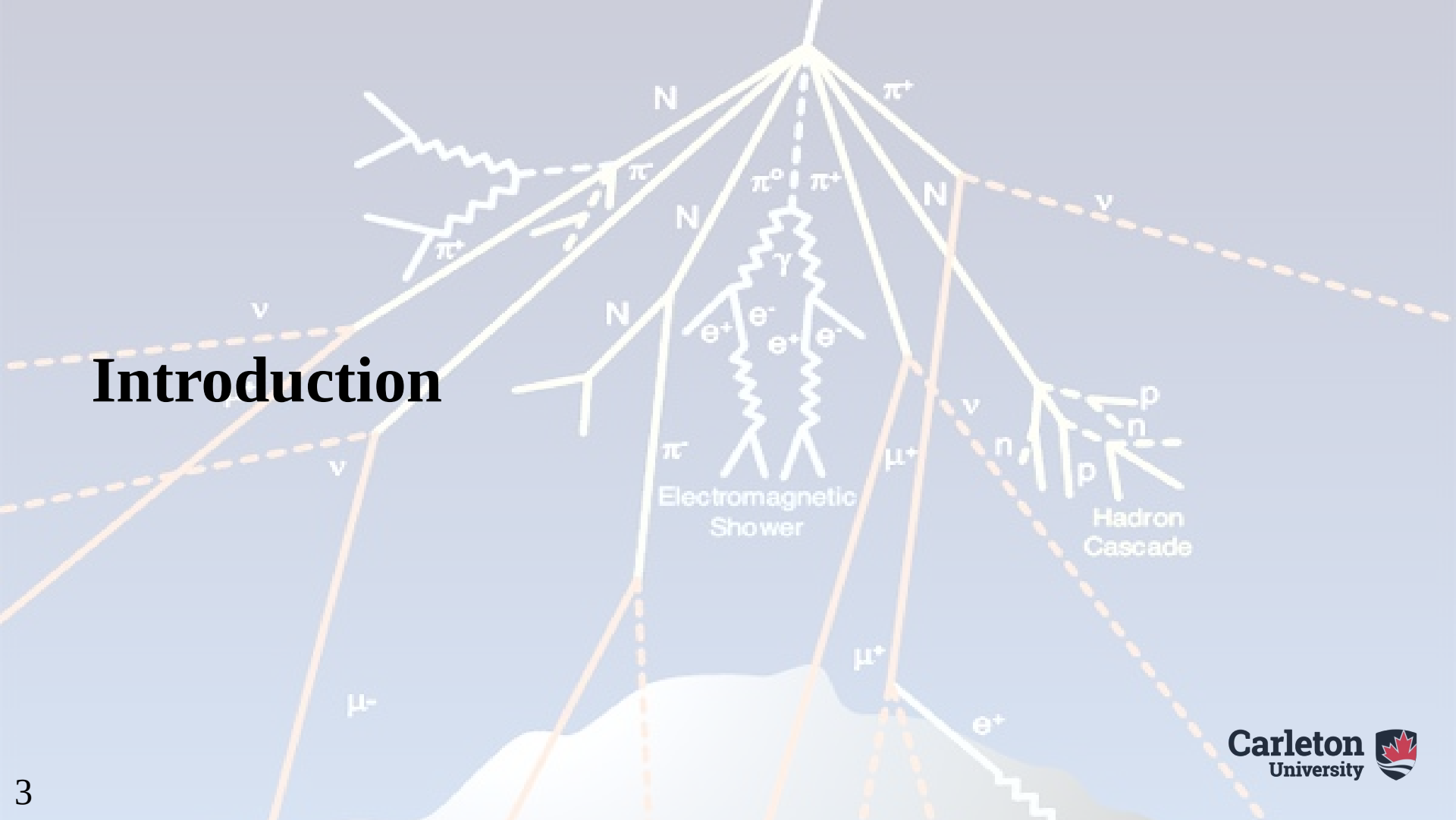


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Outline

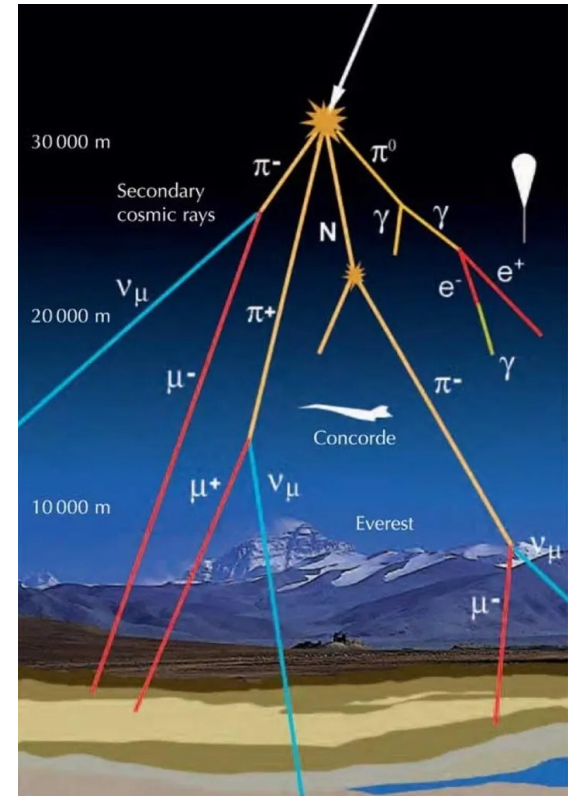
- Introduction
- DEAP-3600 experiment
- Water tank muon flux calculation
 - N_{events} , effective area, live time, acceptance
- Coincidence muon flux calculation
 - N_{events} , effective area, live time, acceptance
- Conclusion

Introduction



Cosmic Rays

- Production of muons in the atmosphere:
 - $\pi^\pm \rightarrow \mu^\pm + \nu_\mu / \bar{\nu}_\mu$ ($\sim 100\%$)[†]
 - $K^\pm \rightarrow \mu^\pm + \nu_\mu / \bar{\nu}_\mu$ ($\sim 63.5\%$)[†]
- Flux of muon at sea level $\sim 1 \text{ muon} / \text{cm}^2 / \text{min}$



[†]S. Cecchini & M. Spurio, Atmospheric muons: experimental aspects, arXiv:1208.1171v1 [astro-ph.EP], 6 Aug 2012

Muon-Induced Background Study for Underground Laboratories

D.-M. Mei and A. Hime
 Physics Division, MS H803,
 Los Alamos National Laboratory,
 Los Alamos, NM 87545, USA

(Dated: December 5, 2005)

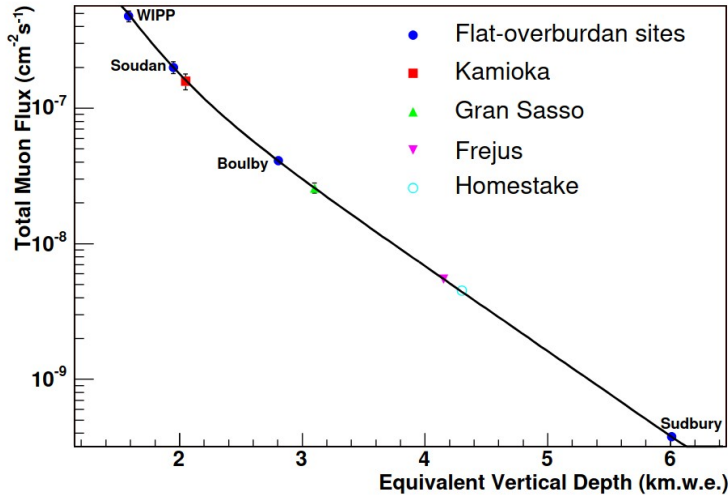


TABLE I: Summary of the total muon flux measured at the underground sites and the equivalent vertical depth relative to a flat overburden.

Site	Total flux $\text{cm}^{-2}\text{sec}^{-1}$	Depth km.w.e.
WIPP	$(4.77 \pm 0.09) \times 10^{-7}$ [6]	1.585 ± 0.011
Soudan	$(2.0 \pm 0.2) \times 10^{-7}$ [15]	1.95 ± 0.15
Kamioka	$(1.58 \pm 0.21) \times 10^{-7}$ [8]	$2.05 \pm 0.15^\dagger$
Boulby	$(4.09 \pm 0.15) \times 10^{-8}$ [9]	2.805 ± 0.015
Gran Sasso	$(2.58 \pm 0.3) \times 10^{-8}$ [this work]	$3.1 \pm 0.2^\dagger$
	$(2.78 \pm 0.2) \times 10^{-8}$ [16]	$3.05 \pm 0.2^\dagger$
	$(3.22 \pm 0.2) \times 10^{-8}$ [17]	$2.96 \pm 0.2^\dagger$
Fréjus	$(5.47 \pm 0.1) \times 10^{-9}$ [14]	$4.15 \pm 0.2^\dagger$
	$(4.83 \pm 0.5) \times 10^{-9}$ [this work]	$4.2 \pm 0.2^\dagger$
Homestake	$(4.4 \pm 0.1) \times 10^{-9}$ [this work]	4.3 ± 0.2
Sudbury	$(3.77 \pm 0.41) \times 10^{-10}$ [12]	6.011 ± 0.1

Mei-Hime paper link

Measurement of the Cosmic Ray and Neutrino-Induced Muon Flux at the Sudbury Neutrino Observatory

(Dated: October 23, 2018)

Results are reported on the measurement of the atmospheric neutrino-induced muon flux at a depth of 2 kilometers below the Earth's surface from 1229 days of operation of the Sudbury Neutrino Observatory (SNO). By measuring the flux of through-going muons as a function of zenith angle, the SNO experiment can distinguish between the oscillated and un-oscillated portion of the neutrino flux. A total of 514 muon-like events are measured between $-1 \leq \cos \theta_{\text{zenith}} \leq 0.4$ in a total exposure of $2.30 \times 10^{14} \text{ cm}^2 \text{ s}$. The measured flux normalization is 1.22 ± 0.09 times the Bartol three-dimensional flux prediction. This is the first measurement of the neutrino-induced flux where neutrino oscillations are minimized. The zenith distribution is consistent with previously measured atmospheric neutrino oscillation parameters. The cosmic ray muon flux at SNO with zenith angle $\cos \theta_{\text{zenith}} > 0.4$ is measured to be $(3.31 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (sys.)}) \times 10^{-10} \mu/\text{s}/\text{cm}^2$.

	Cosmic ray muons	ν -induced muons
	$(\times 10^{-10}) \mu/\text{cm}^2/\text{s}$	
Muon flux at SNOLAB	3.31	0.02

[SNO paper link](#)

Muon flux measurements

- What do we need?

$$\text{Muon Flux} = \frac{\text{No. of Muons}}{\text{Acceptance} \cdot \text{Livetime} \cdot \text{Effective Area}}$$

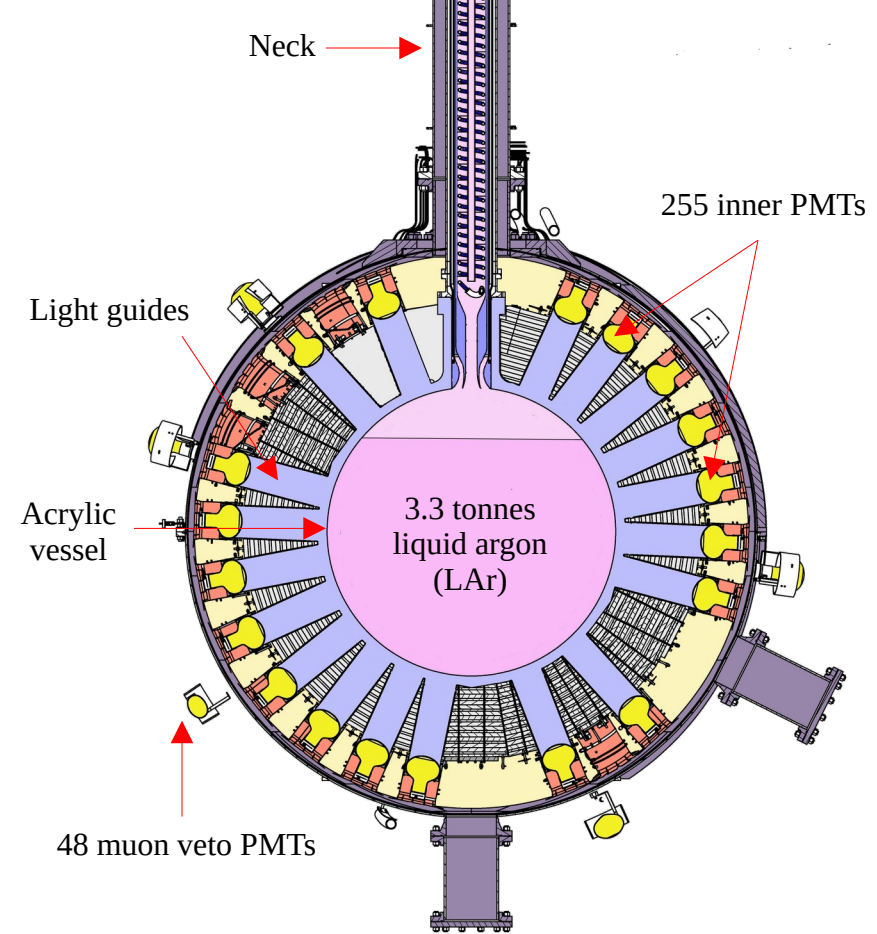
- Why do we need it?
 - Provide an independent measurement of the muon flux at SNOLAB
 - Understand the response of DEAP-3600 to events with very high energy deposited in liquid argon
 - Study the production of cosmogenic neutrons that mimic DM signals → Bad!



DEAP-3600 experiment

Detector

- Direct dark matter search experiment
 - **D**ark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination (DEAP)
- (3269 ± 24) kg liquid argon (LAr)
- Located at SNOLAB, Sudbury
- ~ 2 km rock overburden
 - 6000 m.w.e



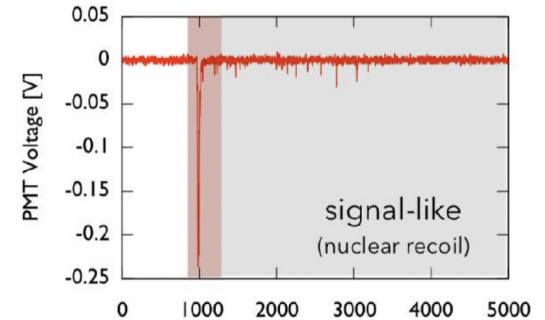
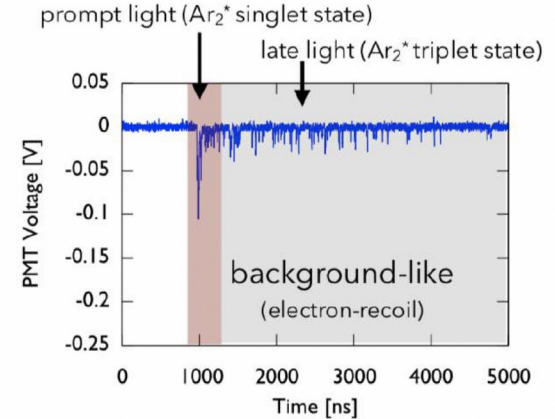
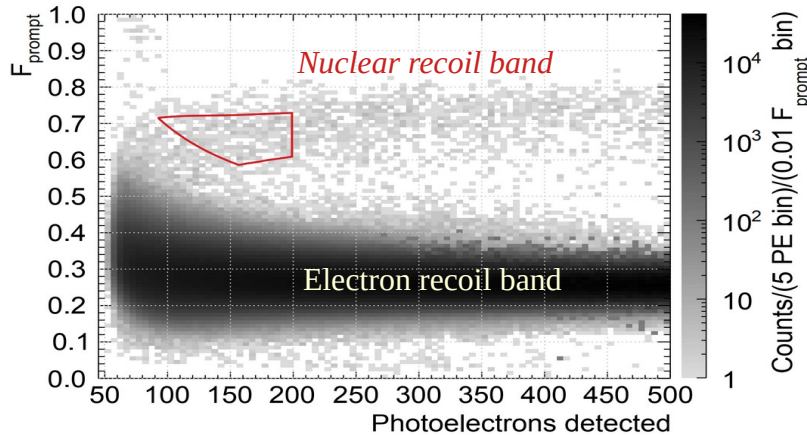
Water shielding

Pulse-shape discrimination (PSD)

- Pulse shape model:
- Nuclear recoil band and electron recoil band can be easily distinguished using this method
- Need to study the backgrounds thoroughly

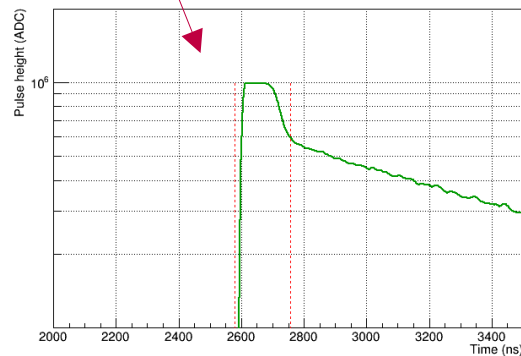
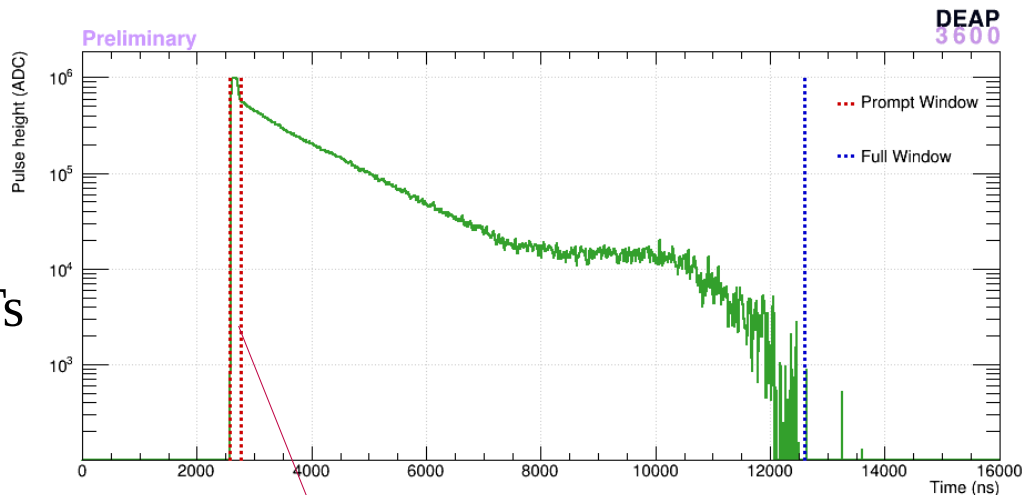
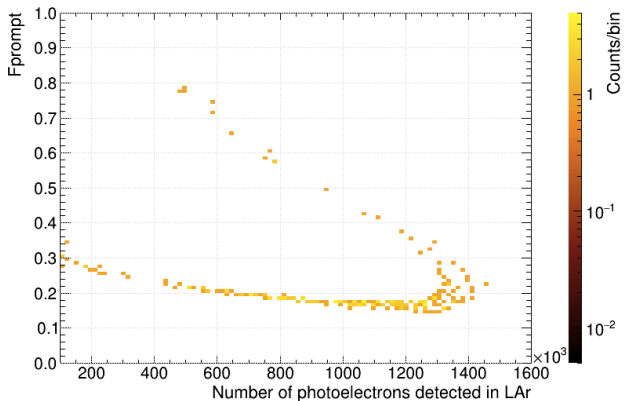
$$PSD = \frac{\text{Prompt light}}{\text{Prompt light} + \text{Late light}}$$

$$F_{\text{prompt}} = \frac{\sum_{t=-28 \text{ ns}}^{t=150 \text{ ns}} Q(t)}{\sum_{t=-28 \text{ ns}}^{t=10 \text{ } \mu\text{s}} Q(t)}$$



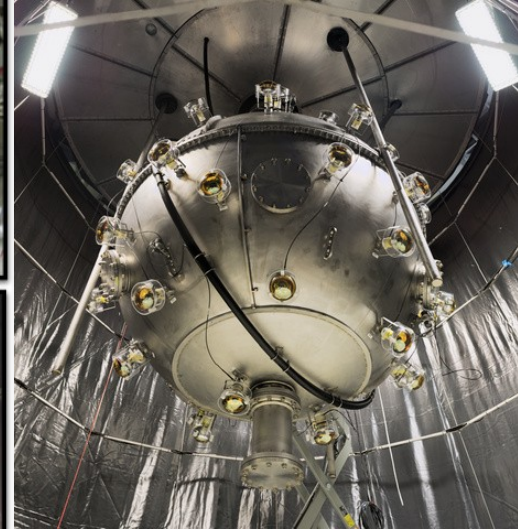
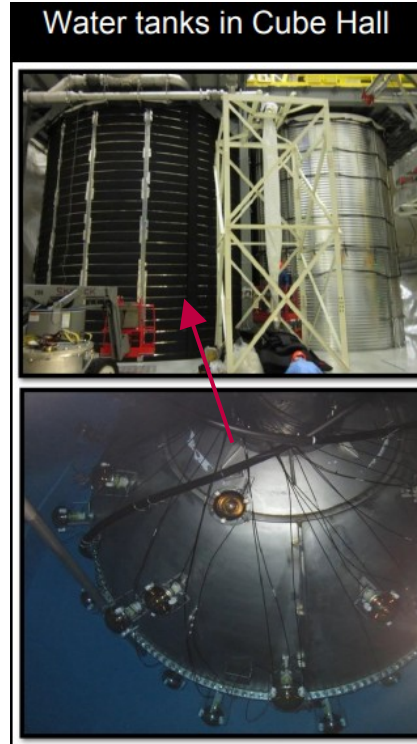
Muon event in LAr

- Muons in LAr produce a lot of scintillation light
- Clips V1720 digitizers
- Saturates the inner detector PMTs
 - Very high energy events have higher F_{prompt} and lower PE



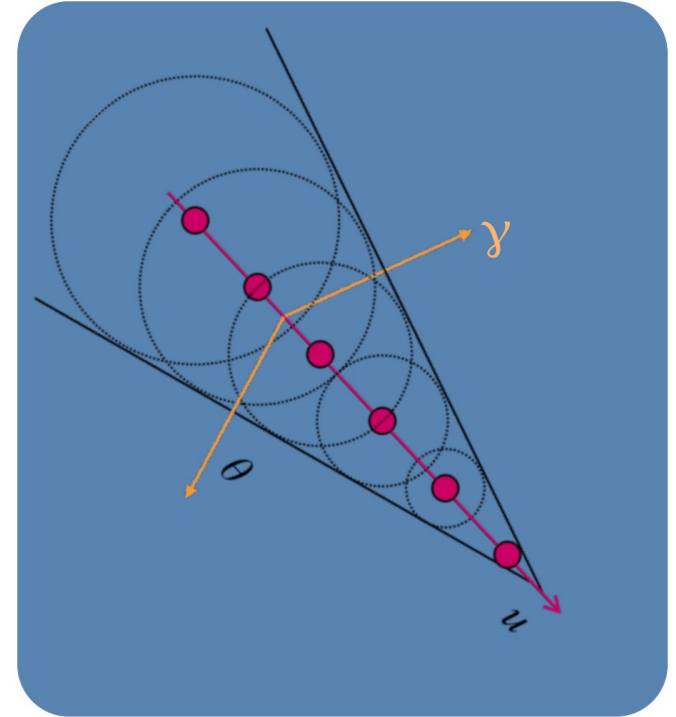
Water tank

- 48 veto PMTs
- Dimensions of the tank:
 - Diameter: 780 cm
 - Height: 779 cm
- Water shielding acts as a neutron moderator
- Detects muons through Cherenkov radiation in water



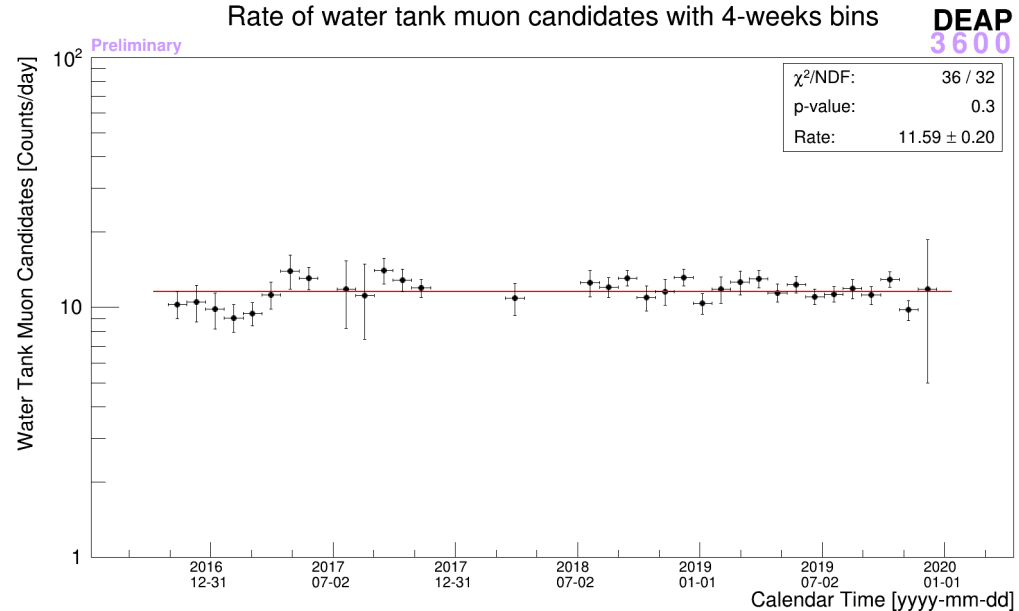
Water tank muon flux calculation

Cherenkov radiation in water



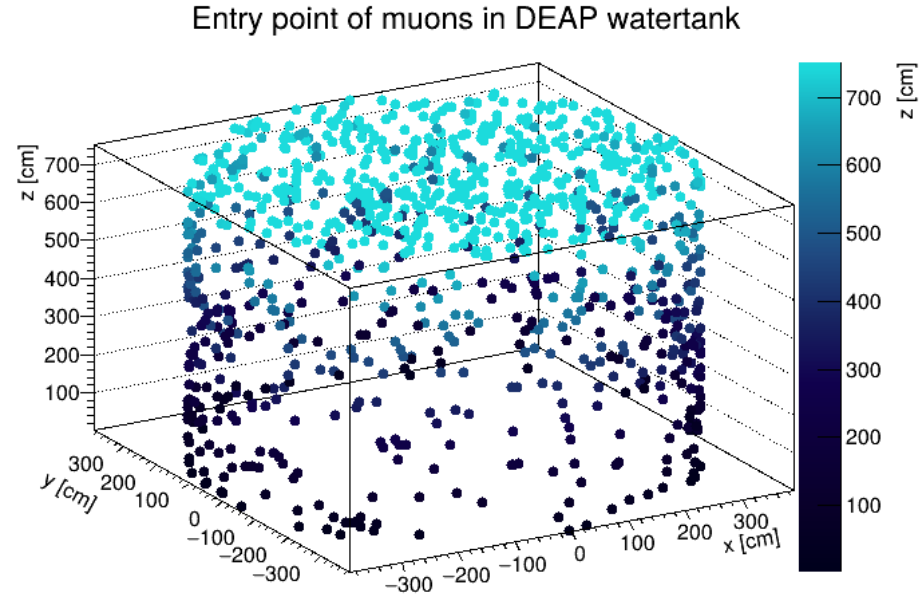
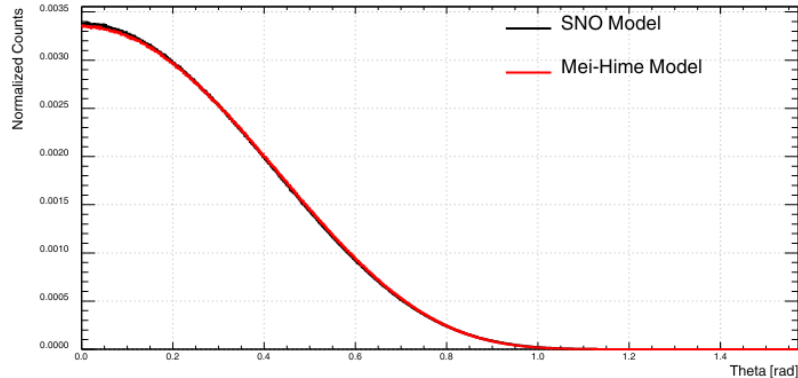
Muon candidates in water tank

- Event selection criteria
 - Improve dataset purity by rejecting noise and non-physical events
 - Developed through studies of detector response
 - Validated using comparisons between data and simulations
- Rate = $(11.59 \pm 0.20) \mu/\text{day}$
- Live time:
 - Run time $\sim 20\text{-}22$ hr
 - **323** runs in the water tank dataset
 - ~ 282 live days



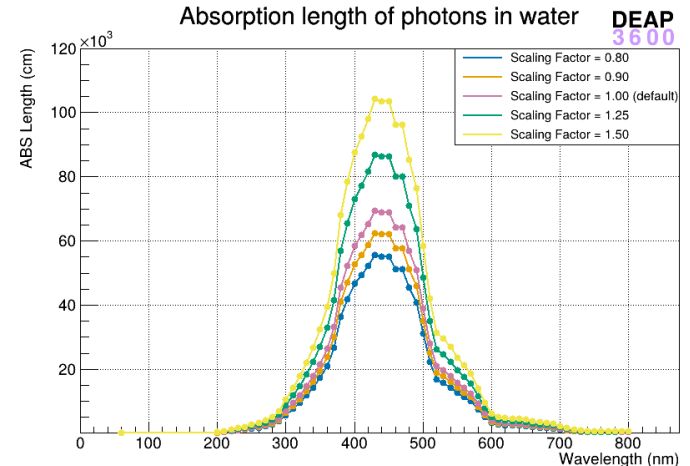
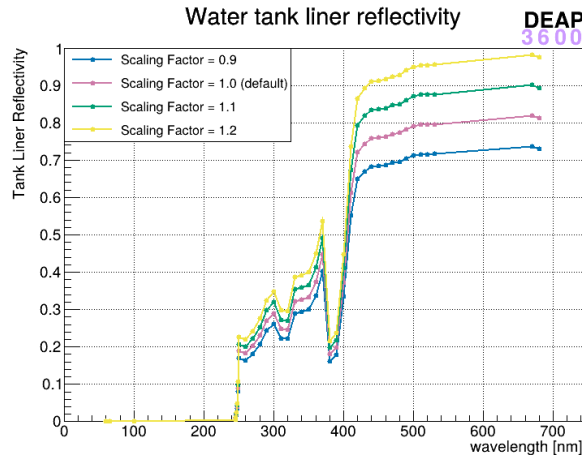
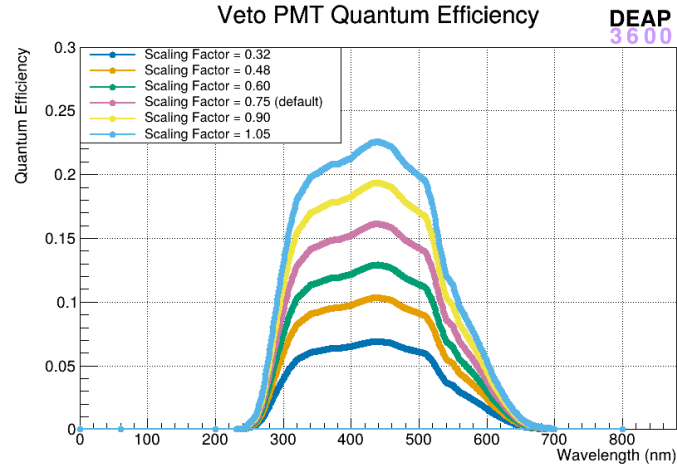
Effective area of the water tank – Toy MC

- Generating muons from a large plane above the detector
- Traversing muons from the plane and counting the hits
- Using SNO and Mei-Hime models for angular intensity distribution of muons



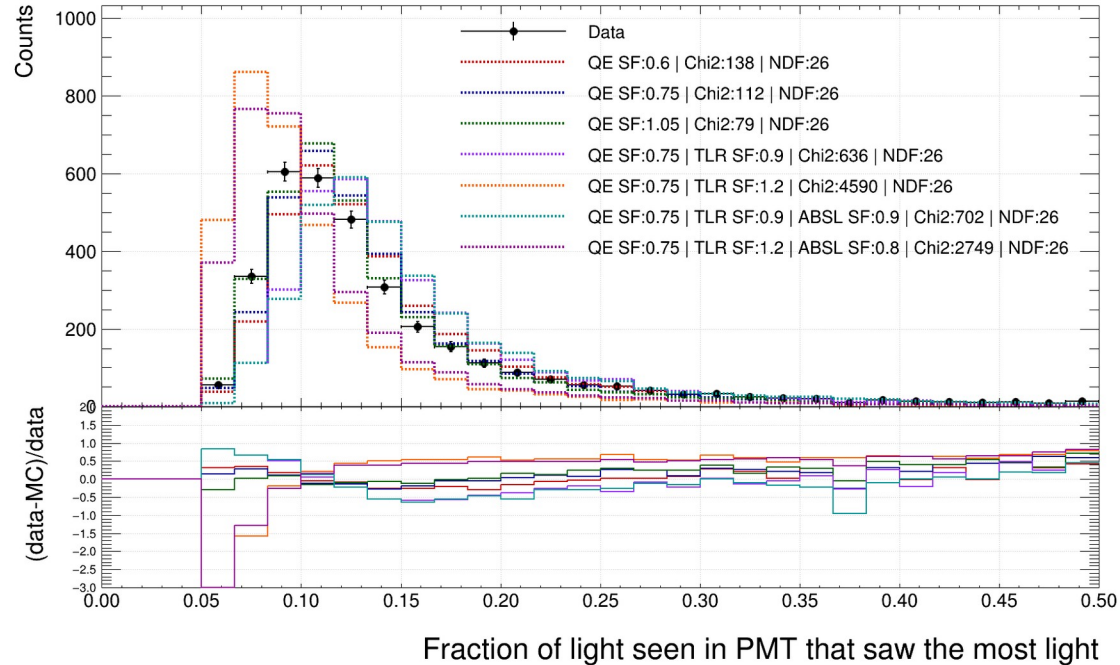
Acceptance

- Scaling the optical parameters
 - Quantum efficiency of veto PMTs (QE)
 - Tank liner reflectivity (TLR)
 - Absorption length of photons in water (ABSL)



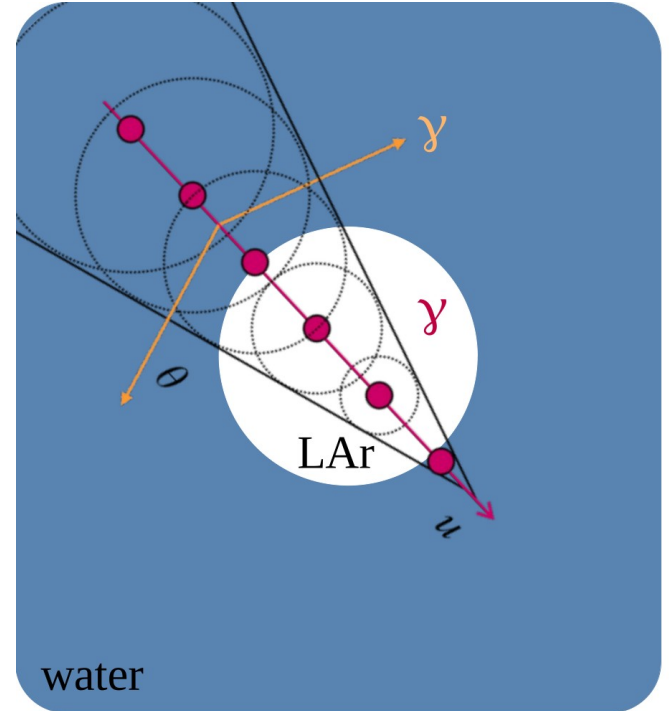
Acceptance

- Final set of selected simulation models to match with data
- Calculating acceptance for each model and evaluating systematic uncertainty



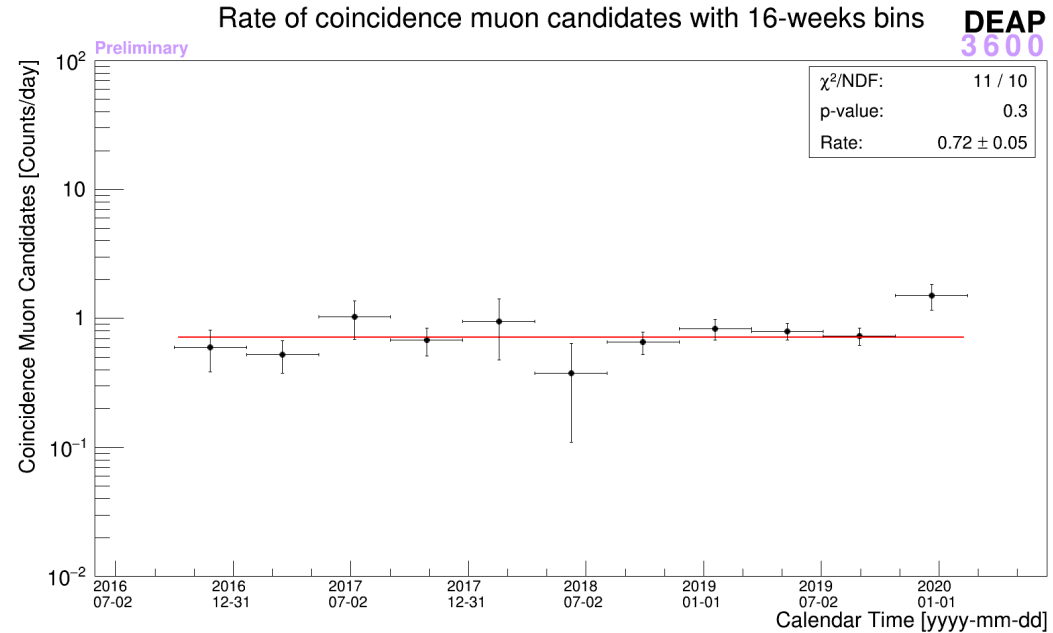
Coincidence muon flux calculation

Cherenkov and scintillation photons in LAr



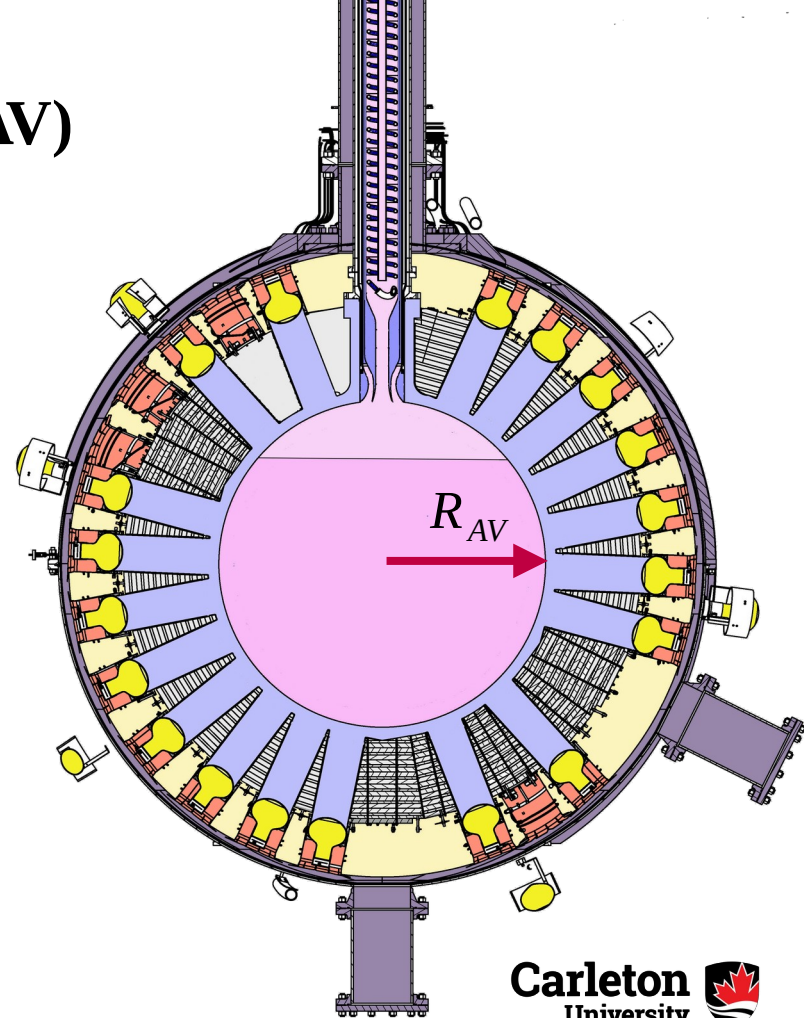
Tagging muon candidates in coincidence

- Tagging MV events with LAr events
- Time difference = $t_{\text{LAr}} - t_{\text{MV}} - t_{\text{offset}}$ ($4 \mu\text{s}$)
- Select tagged veto events within $1 \mu\text{s}$ window
- Rate = $(0.72 \pm 0.05) \mu/\text{day}$
- Live time:
 - **376** runs in the coincidence dataset
 - ~330 live days



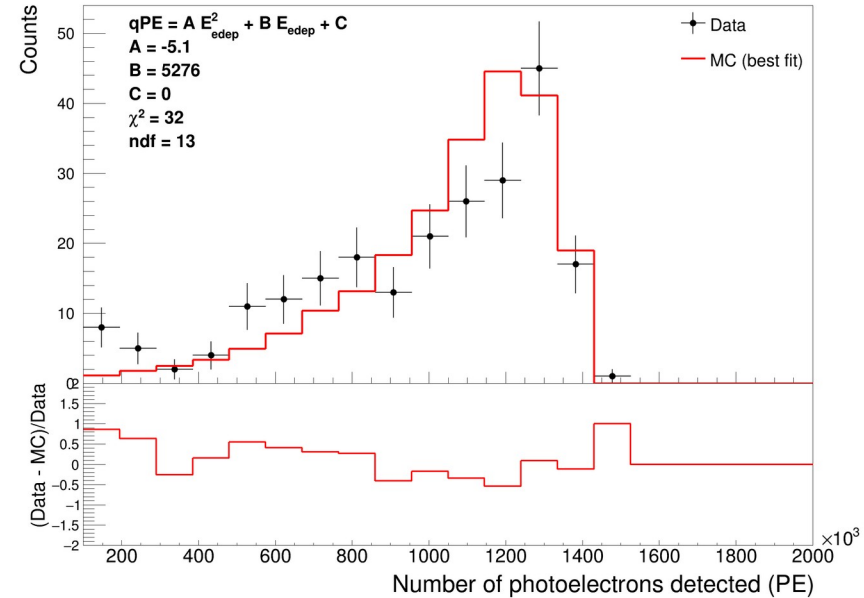
Effective area of the acrylic vessel (AV)

- AV radius = (845.6 ± 0.9) mm
- Takes into account the thermal contraction of AV due to cooling
- Muon flux decreases with increasing zenith angle
- Near vertical muons dominate the flux at detector depth
- Effective area is taken as a disk of AV radius



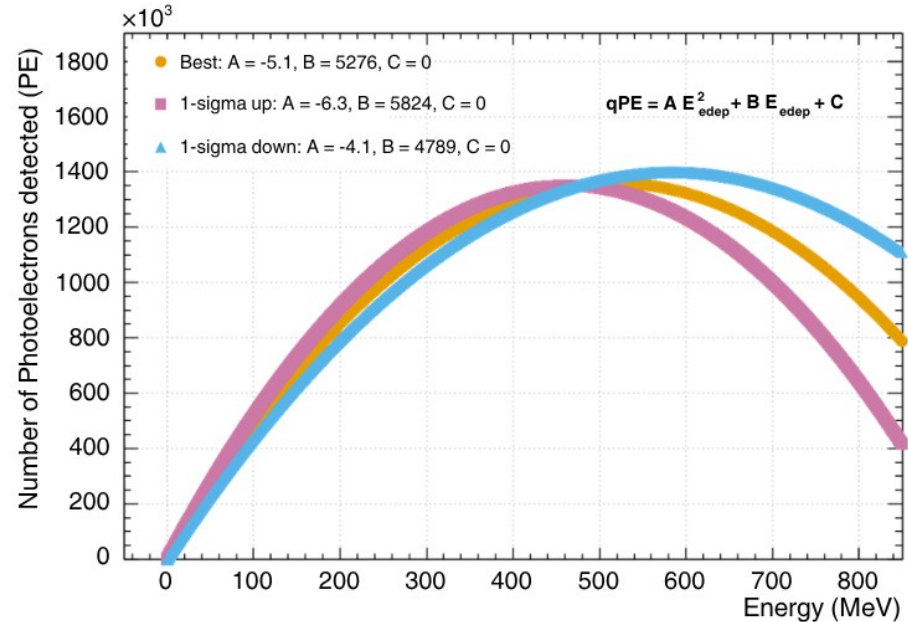
Acceptance

- qPE = Number of photoelectrons in LAr
- Parameterize qPE as per the quadratic energy response model with best fit:
 - $qPE = A \cdot E_{edep}^2 + B \cdot E_{edep} + C$
 - $A = -5.1 \text{ PE/MeV}^2$
 - $B = 5276 \text{ PE/MeV}$
 - $C = 0 \text{ PE}$
- E_{edep} is the MC truth variable for the energy deposited by muon in LAr



Acceptance

- The low energy region follows approximately as linear response
- The detector limit has a maximum of 1.5 million PE
- At high energies, the quadratic model breaks down
- Systematic uncertainties are found from the spread between these models



Conclusion

- The muon flux obtained is consistent with the previous SNO measurements
- The analysis is undergoing collaboration review
- Paper will be written next month
- Stay tuned for new results!

Thank you!

The End

Questions?

Backup

Finalized Muon Event Selection – Water tank Muons

- Low level cuts:
 - Number of PE seen by veto PMTs > 50
 - Integrated charge in the waveform above baseline < 2000
 - A boolean flag to select events passing a set threshold in the waveform
 - Data only:
 - Select events after two trigger windows after an earlier event to prevent late light in the dataset
 - A low level cut to select events which passes the cuts in data processing
 - Select events which contain muon veto triggers
 - Simulation only:
 - Path of muons in water > 0
 - A boolean to trigger on muon events
- High level cuts:
 - Fraction of light seen to the most light seen in a PMT < 0.4
 - Fraction of light seen to the most light seen in a PMT > 0.05
 - Waveform threshold < -1.0
 - Number of hit veto PMTs \leq Number of Active veto PMTs
 - Number of hit veto PMTs/Number of Active veto > 0.7
 - Number of hit PMTs greater than 30
 - Integrated charge in the waveform above baseline < 1000
 - Number of PE seen by veto PMTs > 250
 - Peak of the PMT waveform between {1600, 2000} ns

Finalized Muon Event Selection – Coincidence muons

- LAr data
 - Number of PE detected in LAr scintillation > 100000
 - Select events which contain muon triggers
 - $0 \leq$ Time difference between event in LAr and watertank $\leq 1\mu\text{s}$
- MV data
 - Select events after two trigger windows after an earlier event to prevent late light in the dataset
 - A low level cut to select events which passes the cuts in data processing
 - Select events which contain muon veto triggers
 - A boolean flag to select events passing a set threshold in the waveform
 - Number of PE detected in the watertank > 10
 - Fraction of light seen by a PMTs to the most light in the PMT < 0.5
 - Number of PMTs hit in an event > 3

Live time

- Trigger counting
- Run time \sim 20-22 hr
- Need to subtract dead time between two events
- Live time = run time – dead time

