Rough thoughts about low energy muon signals in ice: Decay, Stopped, Captured.

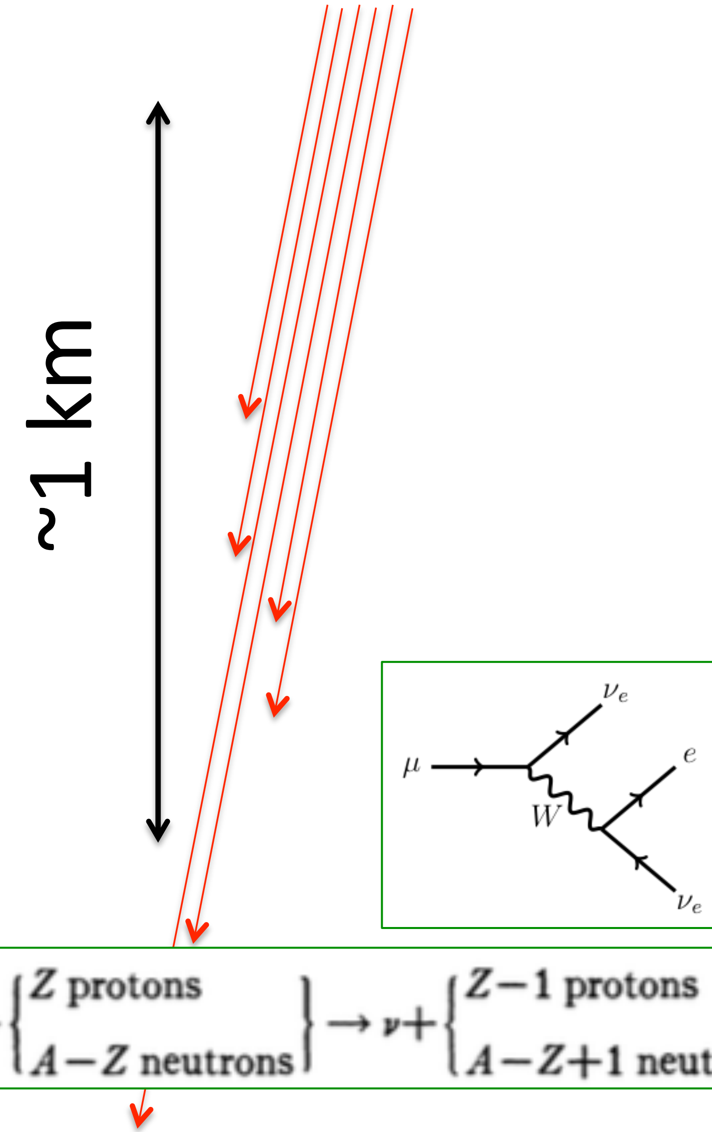
X. Bai, SDSMT

IceCube: Data

- ~280 million cosmic rays events per day
  - Energy from tens of TeV up to about one EeV

- ~500 neutrinos per day
  - Energy from ~10 GeV (DeepCore)/~100 GeV (upper strings) to PeV.
  - Most are atmospheric neutrinos.

Many of them are seen as muons in the deep array.



$$\mu^- + \begin{Bmatrix} Z \text{ protons} \\ A-Z \text{ neutrons} \end{Bmatrix} \to \nu + \begin{Bmatrix} Z-1 \text{ protons} \\ A-Z+1 \text{ neutrons} \end{Bmatrix}$$

π^+/π^- and K^+/K^-

Muon charge ratio $r_\mu = \mu^+/\mu^-$. This ratio can be related to the atmospheric production ratios of π^+/π^- and K^+/K^-.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \qquad \mu^- - capture$$

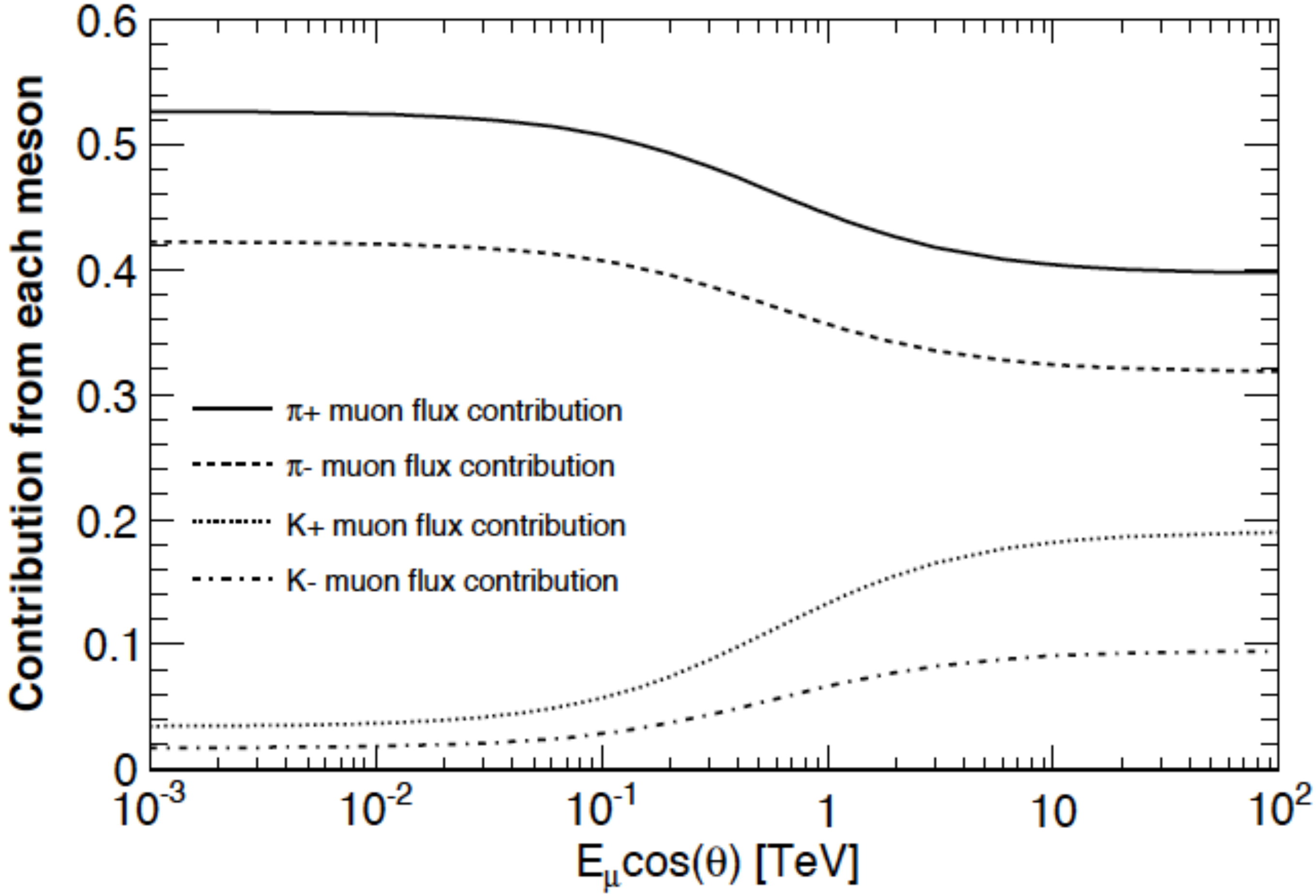
$$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$K_L \rightarrow \pi^\pm + e^\pm + \nu_e(\bar{\nu}_e)$$

Decay from K is the dominant source for ν_e above E_ν~1 GeV.

π^+/π^- and K^+/K^-

Interpretation of the Underground Muon Charge Ratio
P. A. Schreinera, et al. (arXiv:0906.3726v1)



π^+/π^- and K^+/K^-

$$r_\mu \equiv \frac{N^{\mu+}}{N^{\mu-}}$$

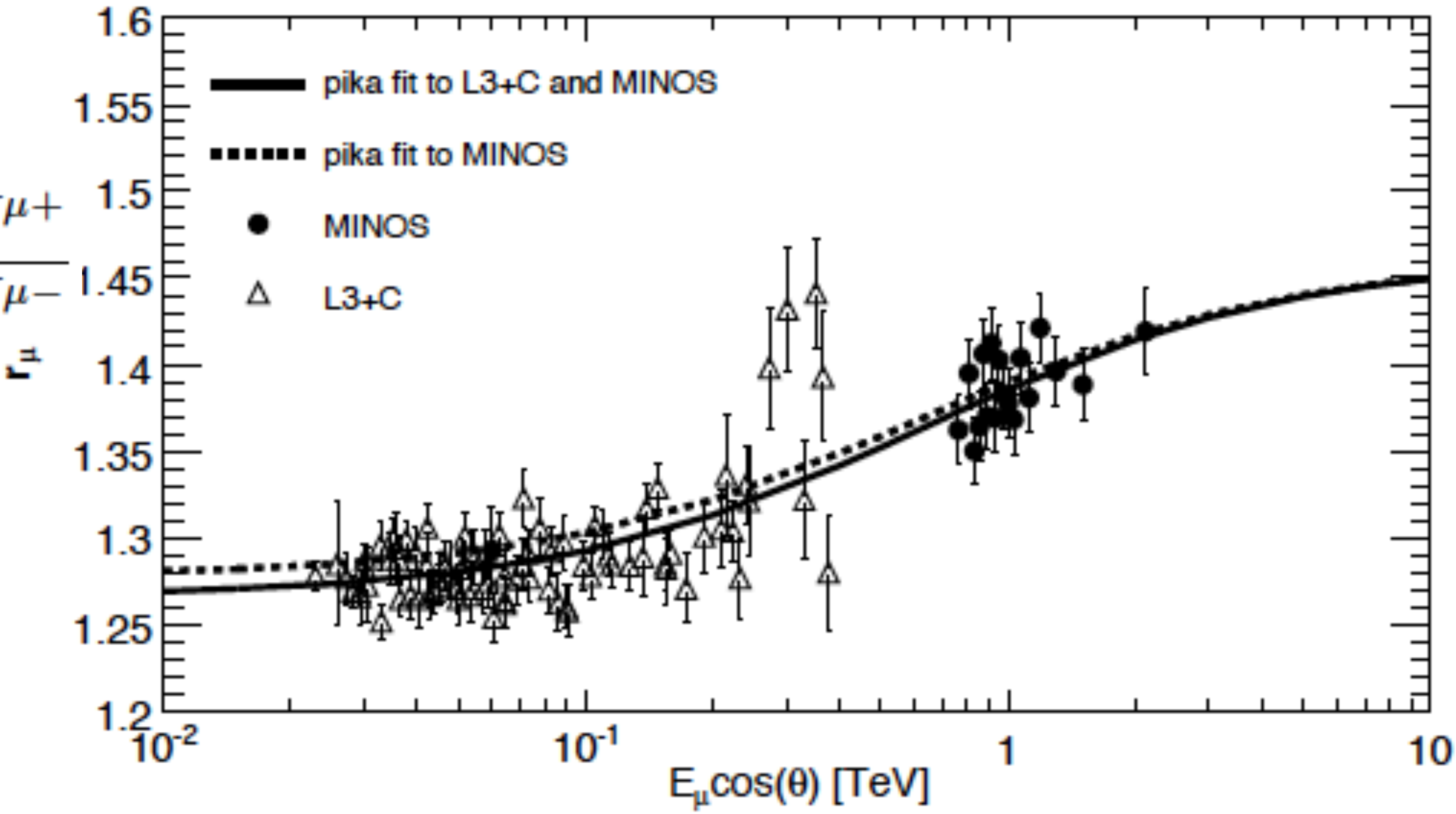
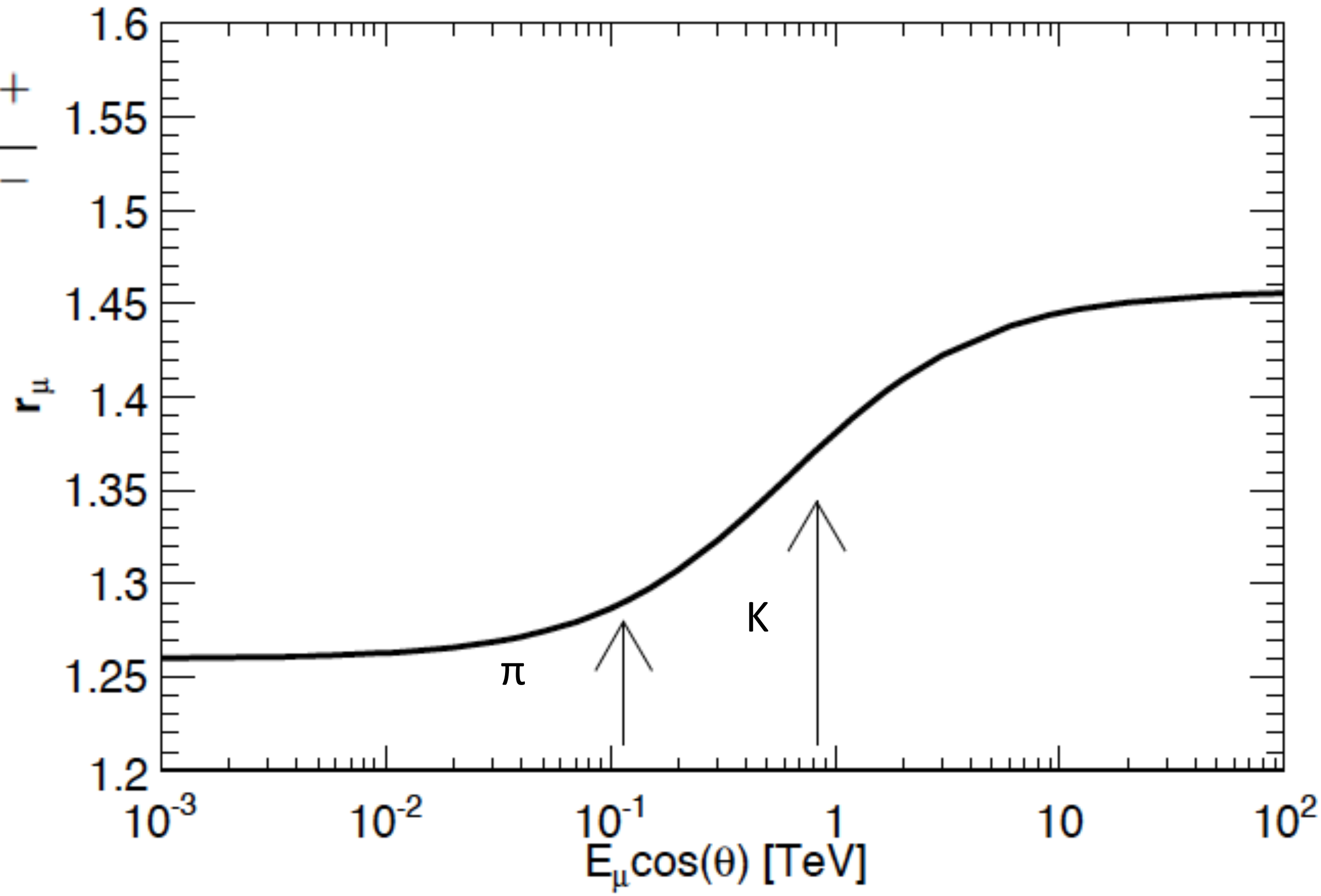


Figure 8: Pika model fitted to L3+C and MINOS (Near and Far) data sets

π^+/π^- and K^+/K^-

$$r_\mu \equiv \frac{N^{\mu+}}{N^{\mu-}}$$



Arrows: The critical energies for π and K decay vs interaction

(The pika model's muon charge ratio for an extended range of energy.)

How about prompt?

- Related to μ^- / μ^+?

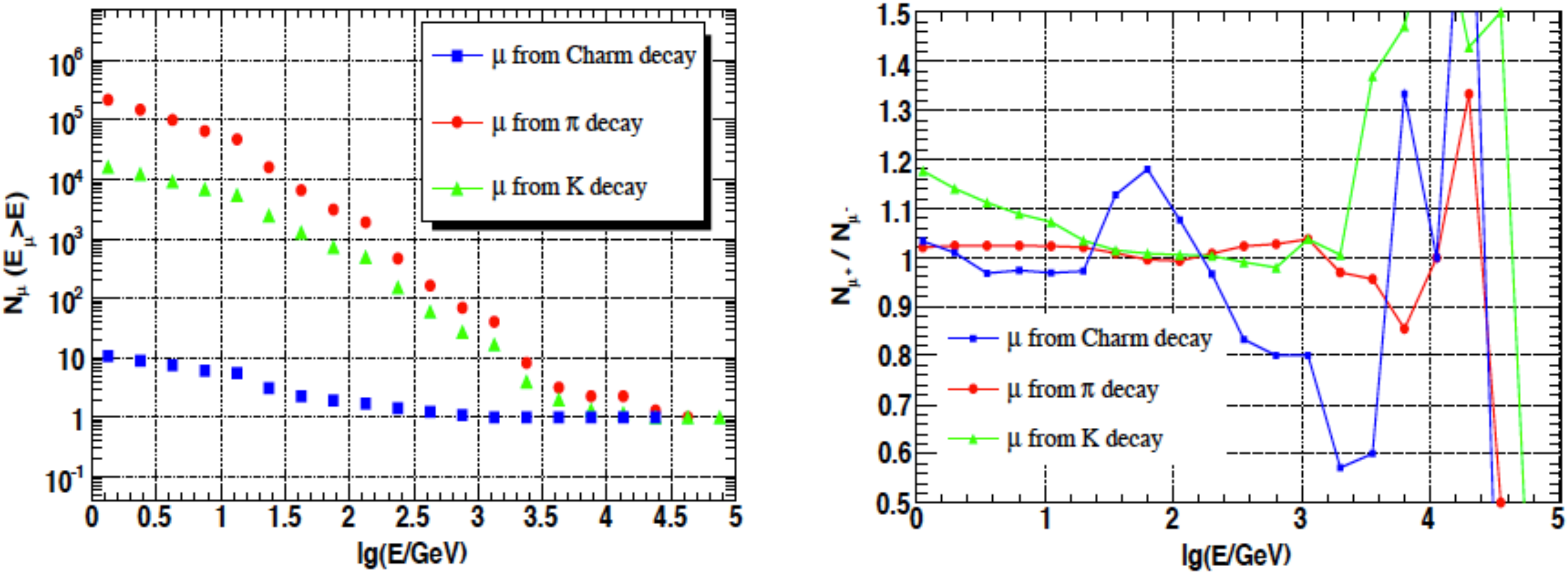
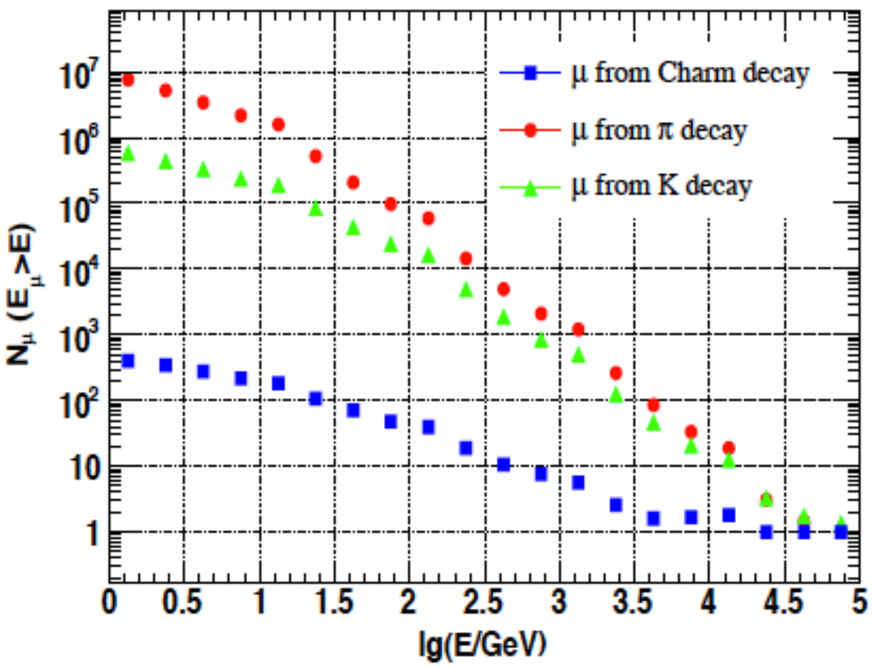


Figure 4: Average energy spectra of μ^+ yield by π meson (red circles), K meson (green triangles) and Charmed particles (blue squres) of 30 showers for 100 PeV (left panel) and the ratio of μ^+ to μ^- (right panel). .

How about prompt?



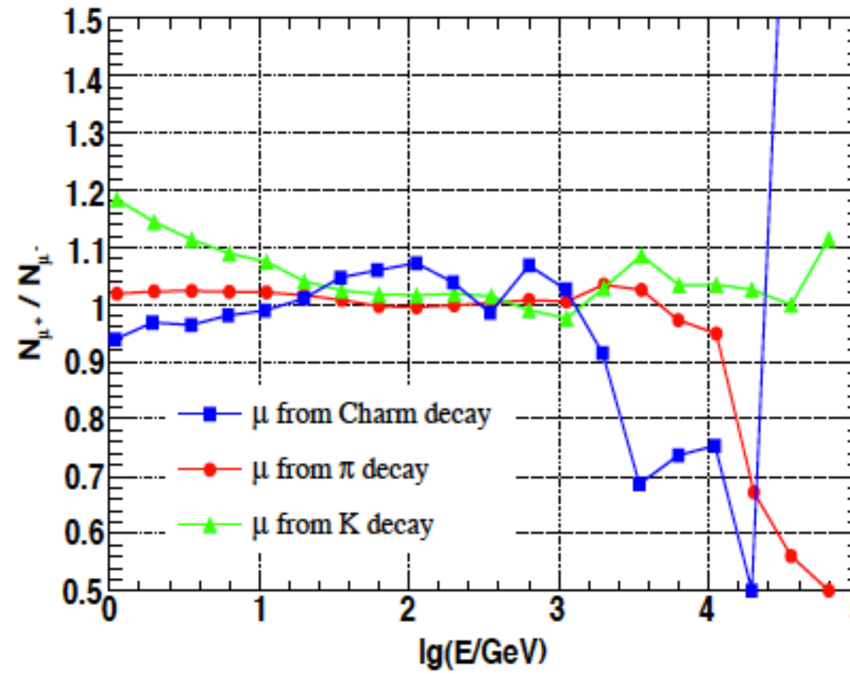
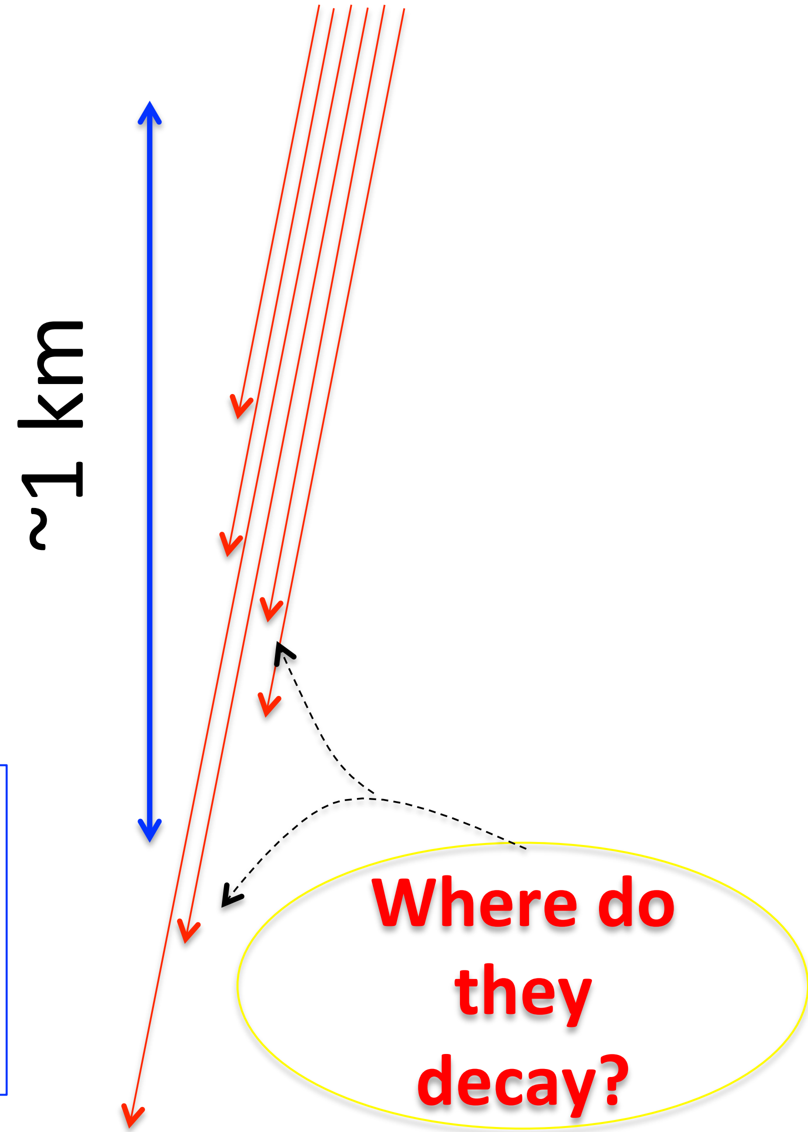


Figure 16: Average energy spectra of μ^+ yield by π meson (red circles), K meson (green triangles) and Charmed particles (blue squres) of 15 showers for 5 EeV (left panel) and the ratio of μ^+ to μ^- (right panel). .

Muon bundle structure

- Number of muons in the bundle
- Energy distribution in the bundle
- Spatial distribution in the bundle

We may learn a lot about these if we know the ending points of muons.



Decay muon signal, Bai, 2010

Table 2. Summary of the Cherenkov detectors used in Auger, IceTop, and the LUX water shield. Auger [47] and IceTop [48] calibration results using through-going muons and Michel electrons (M.E.) from muon decay are listed in the last two columns. In Auger and IceTop tanks, the photoelectron (PE) numbers are the mean values from the fitting to the observed spectra. The lower PE yield (150 PEs) in some IceTop tanks is due to the lower reflectivity of the Zirconium coating used in those tanks. The expected signal sizes in LUX water shield (in ***italic bold***) are derived from the average PE yields in Auger and IceTop tanks. "VEM" stands for Vertical Equivalent Muon.

Project	Tank Size Target Medium Liner	Number of PMTs	Photo-cathode Coverage (%)	Pulse size of through-going muon signal (per VEM)	Pulse size of Michel electron signal (per M.E.)
Auger	Φ3.6m-H1.2m, Filtered Water, Tyvek	3, 9" Photonis XP1805	0.36	90 PEs/PMT	11 PEs/PMT
IceTop	Φ2.0m-H0.9m, Clear ice, Tyvek (Zirconium)	2, 10" Hamamatsu R7081-02	0.80	240 PEs/PMT (150 PEs/ PMT)	45 PEs/PMT
LUX	Φ8.0m-H6.0m, Filtered Water, Tyvek	20, 10" Hamamatsu R7081	0.40	[a] ***>14 PEs/PMT (expected)***	***2 PEs/PMT (expected)***

[a]: The actual signal size per VEM in LUX water shield should be bigger than 14 PEs because of the longer muon track length in the LUX water shield (6 meters compared to about 1 meter in Auger and IceTop tanks).

μ^- / μ^+ : Decay vs Capture

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Total nuclear capture rates for negative muons

T. Suzuki* and D. F. Measday
Physics Department, University of British Columbia, Vancouver, British Columbia, V6T 2A6

J. P. Roalsvig
Department of Physics and Astronomy, State University of New York at Buffalo, Amherst, New York 14260
(Received 16 December 1986)

TABLE III. Compendium of total muon capture results for ligh
timate.)

Z (Z_{eff})	Element	Mean life (ns)
Positive muon		2197.03 ±0.04
1 (1.0)	$^1H^b$	2194.903 ±0.066
	$^1H^b$	
		2194.53 ±0.11
2 (1.98)	^3He	
8 (7.49)	O	1640 ±30
		1812 ±12
		1810 ±20
		1832 ±29
		1795.4 ±2.0

Decay time with captures

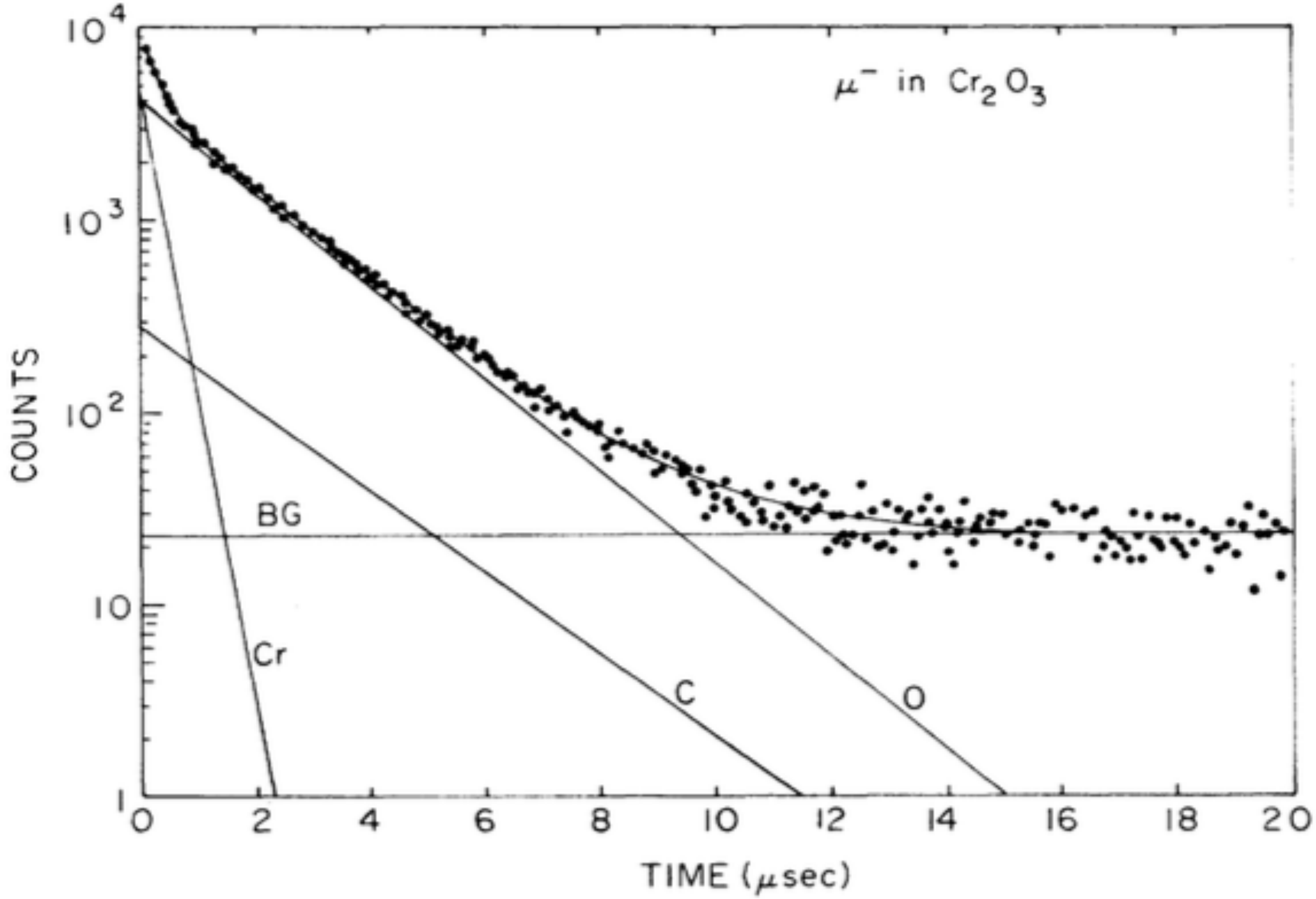


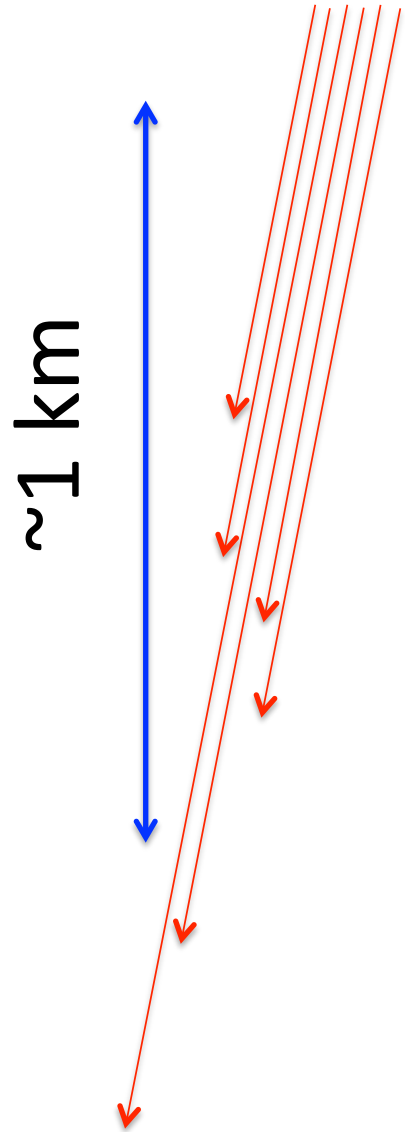
FIG. 3. Decay curve typical for an oxide target.

Flavor oscillations

- Neutrinos: ν_e, ν_μ, ν_τ.
- Charged leptons? e, μ, τ.

On one hand:
- No one has seen.
- Most don't believe.

On the other hand:
- Long muon track
- Wide energy range
- With a nice neutrino tagger (though energy may not right)



Discussions

- Need to estimate the rate and accompanied energy loss.

$$N_i(> E_i, A, E_A, \theta) = C_i \frac{A}{E_i \cos^* \theta} x^{-p_1} (1 - x^{p_3})^{p_2}$$

- How much can IceCube in-ice data do?
- How?