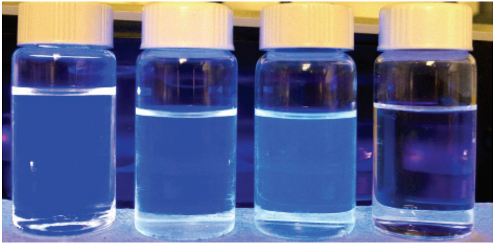
Benefits of and progress towards massive water-based liquid scintillator detectors

David E. Jaffe



LS WbLS(1) WbLS(2) Water
with UV illumination

Outline

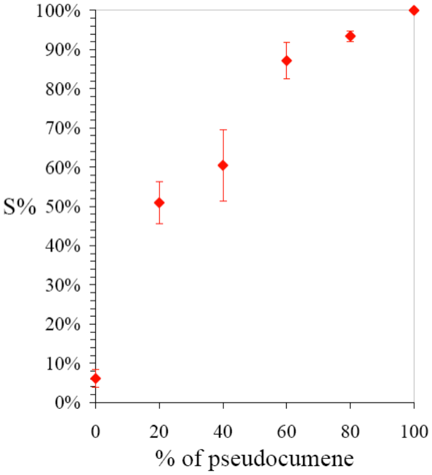
1. Current knowledge of Water-based Liquid Scintillator (WbLS)
    - Formulation
    - Performance
2. Scientific applications
    - $p \rightarrow K^{+}\nu$ sensitivity
    - Low energy $\bar{\nu}_e$ detection
    - Near-site WbLS-based detector
3. Research and Plans
    - Quenching/time-response/attenuation length
    - Purification/re-circulation
    - Long-term performance & stability
    - 1-ton demonstrator

WbLS Formulation: "Do oil & water mix?"

- Organic solvents, such as liquid scintillator (LS), are immiscible in water mainly due to the differences in polarities.
- A surfactant that contains lypophilic and hydrophilic groups is necessary to emulsify (or aggregate) the organic liquid scintillator into the water solvent.
- Engineering of a complexing medium to stabilize the lypophilic and hydrophilic molecules in a water medium with appropriate optical transmission and long stability is the key to WbLS development.
- Non-ionic surfactants of linear alkyl benzene derivatives (sulfonate and amine) were identified for different applications. Linear Alkylbenzene Sulfonic acid (LAS) is used.
- A stable, first-generation, WbLS with sufficient scintillation light has been developed.

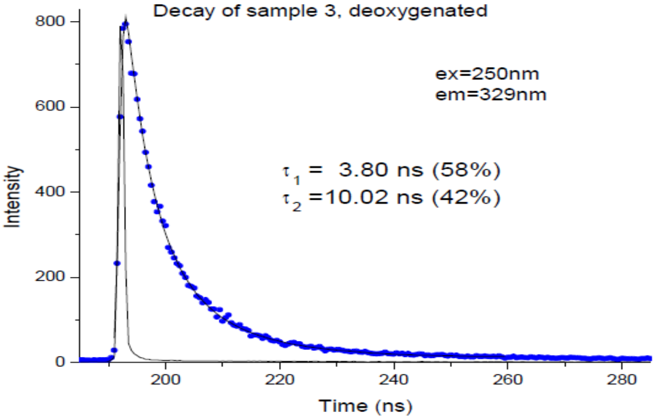
WbLS performance

Light Yield as a function of PC% in Dodecane



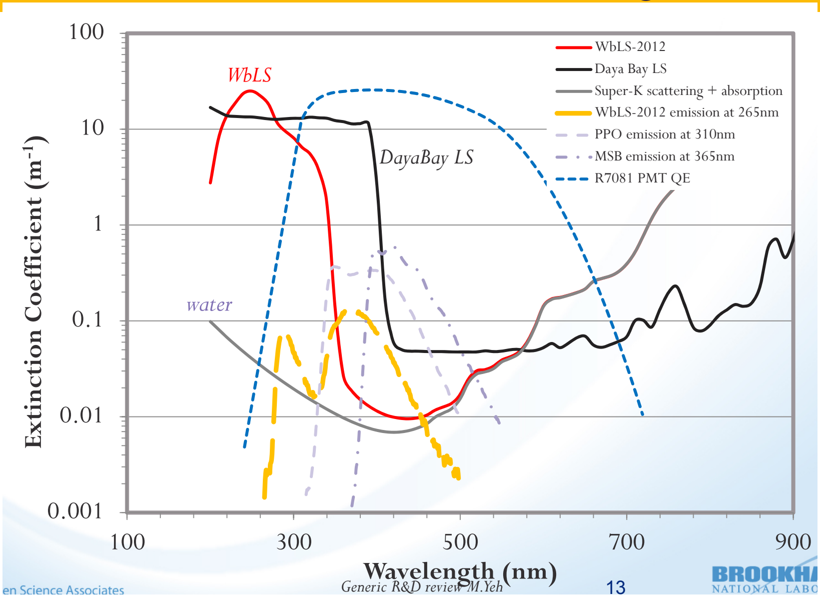
- *Adjustable light yield.* Non-linear dependence of light yield and LS concentration (left figure)
- Scintillation decay time (next pages)
- Extinction length (next pages)
- Stability (First gen. WbLS stable for 2+ years)

WbLS scintillation decay time

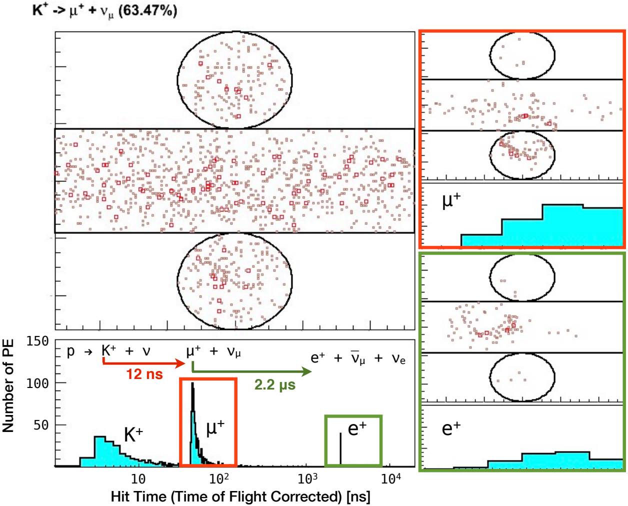


Scintillation measured at 329 nm, excited by 250 nm light using time-resolved fluorescence spectrometry

WbLS emission and attenuation length



Detection of $p \rightarrow K^+\nu$



Simulation of SK-like geometry with 40% PMT coverage (WCsim).

Scintillation yield: **90 optical photons/MeV**

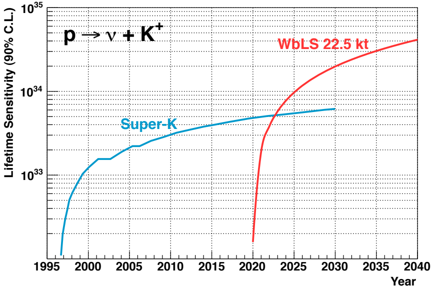
Triple-coincidence:

	E(MeV)	τ	ring?
K^+	105	12ns	no
μ^+	152	2.2μs	yes
e^+	< 50	—	yes

$p \to K^+\nu$ sensitivity estimate

Cut	Gold (Time)	Silver (Time+Energy)
PE($K^+ + \mu^+$)	96.8%	
One Michel e^+	99.2%	
μ^+ decay $>$ 100ns	95.6%	
K^+ decay $\geq$ 10ns	54.0%	
K^+ decay $<$ 10ns, PE(K^+)$>$ 150		42.4%
Product	49.6%	38.9%
Free $p(10^{33})$	1.53	
Bound $p(10^{33})$	5.98	3.0[a]
Run time	10 years	
Current limit	2.3×10^{33} years	
Predicted evts	10.3	4.9

[a]Effective

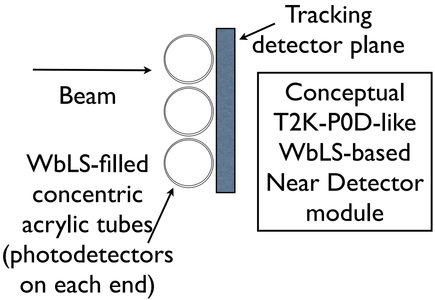


Expected atm ν background $\sim 0.1/10$ years.
Sensitivity includes performance estimate for $K^+ \to \pi^+\pi^0$

Low-energy $\bar{\nu}_e$ detection

- Low-energy physics could be accessible with $\sim$10% LS/water solution that is expected to produce $\sim$**2000 Optical Photons/MeV**; however, ring-imaging ability would be lost or severely impaired.
- Hyper-K LOI estimates 83 (10-30 MeV) supernova relic anti-neutrinos (SRN) detected per year with 0.1% Gd-loaded water.
- Comparable performance might be possible for a future, WbLS-enhanced HK with 20% Photo-Coverage:
  $2000\ \mathrm{OP/MeV} \times 0.2(PC) \times 0.22(QE) \times 1/e(att.len.) \approx 32\ \mathrm{PE/MeV}$
  or $\sim$70 PE for neutron capture on $^{1}\mathrm{H}$. Could be some loss due to longer capture time ,$\tau(n\mathrm{H}) \sim 200\mu$s, $\tau(n\mathrm{Gd}) \sim 30\mu$s, but the e^{+} energy resolution would be superior.

Conceptual near site WbLS-based detector



Possibility to measure energy and identify process at interaction point.

$\nu_\mu n \longrightarrow \nu_\mu n \pi^0$	tag *n*-capture?
$\nu_\mu p \longrightarrow \nu_\mu p \pi^0$	measure *p*
$\bar{\nu}_\mu p \longrightarrow \mu^+ n$	*n*-capture id's $\bar{\nu}/\nu$

Multiple modules along beam direction.

Concentric acrylic tubes:

- total internal reflection,
- WbLS compatibity,
- cost,
- ability to empty/fill WbLS.

R and D: WbLS properties

- Near-term research will enable understanding WbLS response as a function of proton velocity in a low energy proton BNL beam.
- Proton velocities of $\beta = 0.57$ and $\beta \approx 0.52$ correspond to the K^+ velocity in $p \rightarrow K^+\nu$ for free and bound protons, respectively.
- Examination of light yield in water, WbLS and LS as a function of β will allow absorption and re-emission effects to be disentangled from scintillator quenching.
- Establish light yield vs LS concentration
- Beam time scheduled for October 2012.

WbLS stability and purification(1)

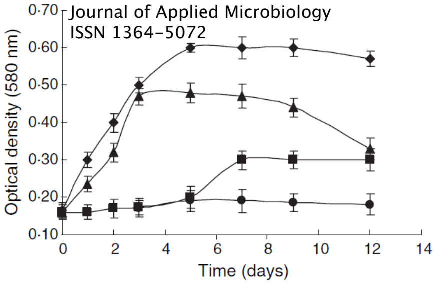


Figure 5 Time-course analysis of consortium growth at different linear alkylbenzene sulfonate concentrations (in mg l^{-1}): (◆) 10; (▲) 20; (■), 50; and (●) 100. Values are means ± standard deviations for three replicates.

- LAS degradation only occurs at <50mg/L
- LAS stability and compatibility (acrylic) stable for 2+ years since formulation
- LAS at ≥100mg/L completely inhibits bacteria growth (extensive studies by environmental-research groups in academia and industry).

WbLS stability and purification(2)

- Micro-organism growth is known to degrade attenuation length in water detectors and requires constant circulation
- Inorganic metallic ions can be removed either by vacuum distillation (SNO+) or multi-filtration (GADZOOKS)
- WbLS, a mix of LAS, PC, water and PPO can simplify the online-purification process
  - WbLS can be vacuum distilled
  - 10% LS-loaded water can pass 0.1μ teflon filter without loss. Testing with ultra/nanofilters planned.
  - Testing with ion exchange and reverse osmosis also planned
- Purification plan
  - All raw materials will be purified before synthesis
  - LAS/PC inhibits bio-activity; is circulation needed? If so, apply filtration and/or distillation.

R & D: 1-ton demonstrator

- 1-ton prototype to evaluate capability to detect neutrino interactions, resolve Cerenkov and scintillation light, serve as a veto detector and maintain long-term stability
- Possible test scenarios:
  - WbLS detector in few GeV neutrino beam at FNAL
  - Gd-WbLS in few MeV reactor neutrino flux
  - WbLS detector in 0.1 - 1 GeV proton beam at BNL (mimics kaon kinematics from $p \to K^+\nu$)
  - WbLS detector in conjunction with another detector to tag incoming muons
  - WbLS test after EGADS completion?

Summary

- Water-based Liquid Scintillator is a new detection medium with high stability, fast pulse, long attenuation length and Cerenkov/scintillation light capability.
- The potential enhancement to proton decay sensitivity of a WbLS is established
- Extensive studies of WbLS properties in particle beams underway
- Studies of purification and stability ongoing

Many thanks to Milind Diwan, Brett Viren, Minfang Yeh, Chao Zhang for their contributions to this presentations..

References:

- "A new water-based liquid scintillator and potential applications", M.Yeh *et al.*, Nucl.Instrum.Meth. A**660** (2011) 51.
- "Water-based Liquid Scintillator for Large-Scale Physics", M.Yeh, ANT 2011
- "A New Water-based Liquid Scintillator for Large Neutrino Physics", M.Yeh, APS April Meeting 2012

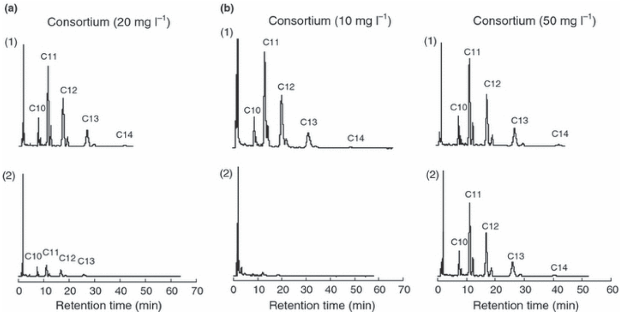
Backup

Choice of LAS as surfactant

LAS = Linear Alkylbenzene Sulfonic acid

- Very safe to handle
- Binding strength for LS and water is better than other surfactants studied
- Another surfactant (TX) is not as stable. Liquid goes into two phases in a few months

Biodegradation



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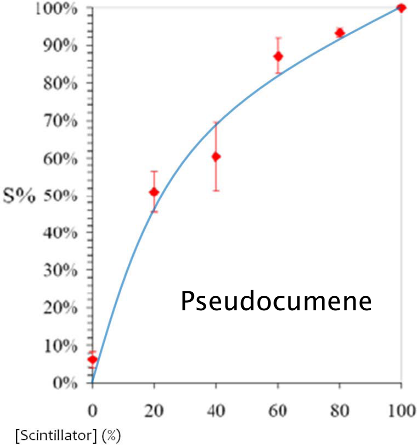
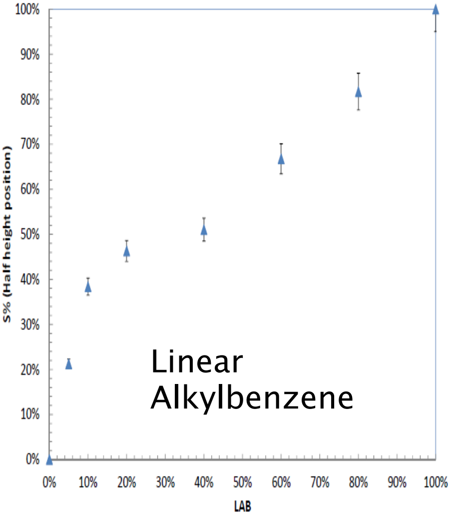
- LAS degradation only occurs at 50mg/L (0.05%) or lower
- Stability and compatibility (acrylic) are under monitoring; no change since synthesis (2-years+)

Cn: n = # of carbons hooked to benzene ring.

“Retention time” analogous to column height in chromatograph.

A little LS gives lots of light



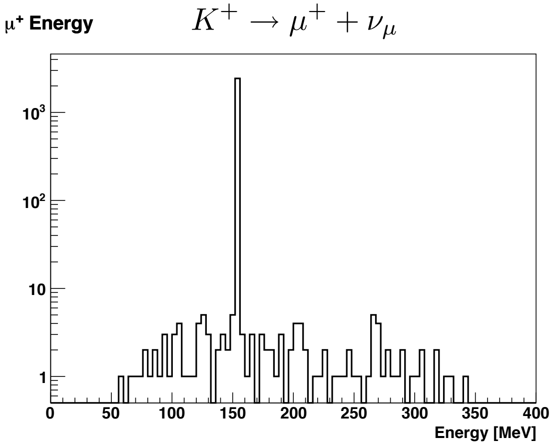


Now Look at Details on This Mode

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

(63%, primary signal channel)

Muon Energy Distribution



When Kaon decays on flight (4.2%), the muon energy cease to be mono-energetic

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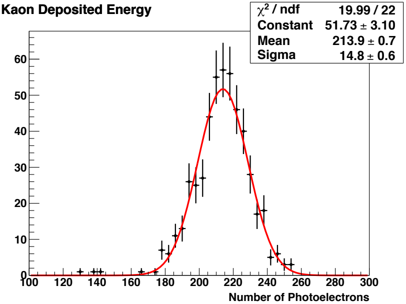
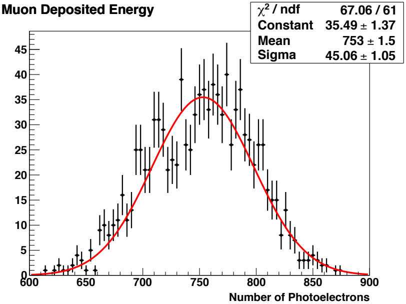
Photo-Electron Distribution

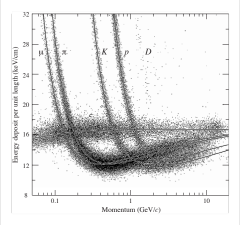




Kaon: 105 MeV -> 213 PE

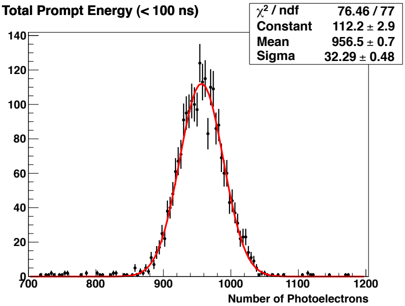
Muon: 152 MeV -> 753 PE

- higher light yield for muon caused by
  - Cherenkov contribution: muon only
  - Quenching: muon has lower stopping power



PEP4/TPC 27

Prompt Energy Cut



- Develop the first cut on total prompt light < 100 ns
  - 800 < PE < 1100
  - Efficiency: 96.8%
- To avoid the Michel positron light leak into the prompt time window (t < 100 ns), require muon decay later than 100 ns.
  - Assuming muon decay time can be reconstructed by pulse edge
  - small/too-early muon decay signals violate this assumption, will discuss later
  - Efficiency: 95.6%

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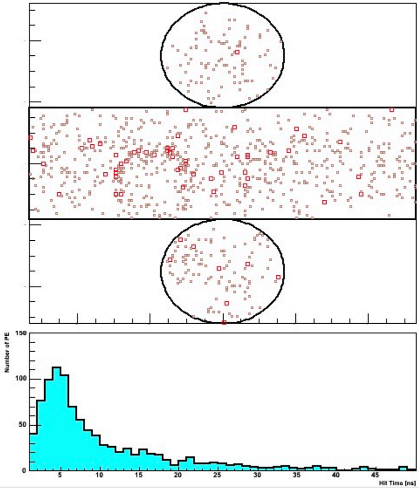
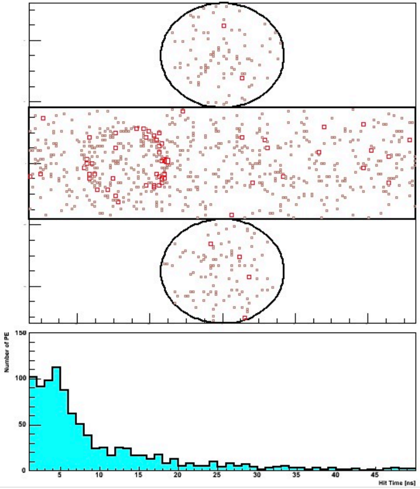
Background: Atmospheric Muon-neutrino

$K^+ \rightarrow \mu^+ + \nu_\mu$ (63.47%)

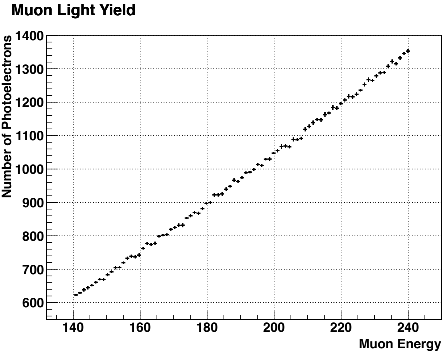


Background: Muon



If nu_mu has the 'right' energy, it becomes a background to 'early-decay' kaons 29

Background: Atmospheric Muon-neutrino



From 4000 muon background event simulation

- Prompt energy cut 800 < PE < 1100 corresponds to 170 MeV < muon energy < 210 MeV
- The atmospheric neutrino background in this energy window is about 2 event/kt/year (scaled from SK and LENA paper)

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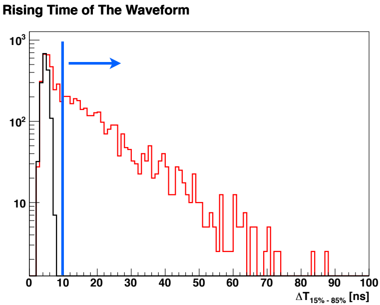
Pulse Shape Discrimination



- Red: Signal Black: Background
- A cut at rising time > 10 ns gives
  - Signal Efficiency: 54.0%
  - Background Acceptance: 0

- Define a PSD variable to distinguish 'two-pulse' signal from 'one-pulse' background
  - Rising time from 15% of the maximum pulse to 85% of the maximum pulse
  - A timing spread of 2.2 ns has been applied to make the timing more realistic
    - PMT TTS (jitter): 2 ns
    - vertex recon resolution: 20 cm

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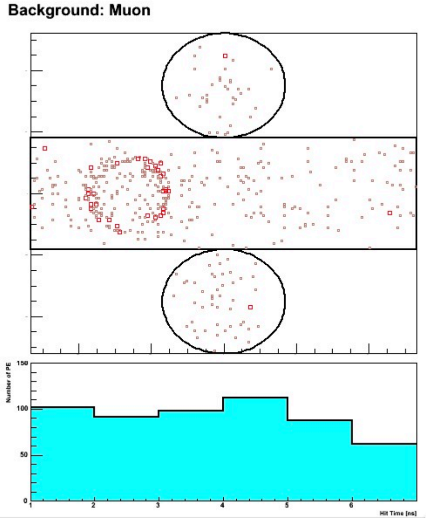
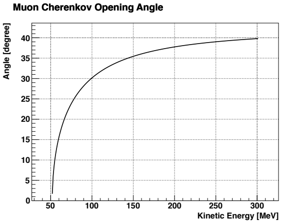
Muon Energy Reconstruction



- It's also possible to reconstruct the muon energy using
  - the early light from Cherenkov
  - the (reconstructed) opening angle of the Cherenkov ring
- A ML based reconstruction is needed to use the full information of timing and spacial pattern



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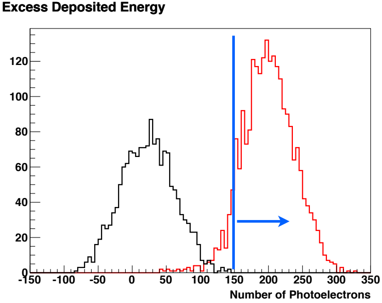
Kaon Energy Reconstruction



- Red: Signal Black: Background
- A cut at Kaon PE > 150 gives
  - Signal Efficiency: 91.9%
  - Background Acceptance: 0

- Assuming a resolution of 10% at 100 MeV can be achieved with such a reconstruction. We can plot the 'Prompt Energy - Reconstructed Muon Energy' (i.e. Kaon Energy) distribution.
- The non-zero bias for the background channel is caused by the linear energy scale used in my simple reconstruction. Background rejection will improve if we can understand correctly the non-linearity
- This method strongly depends on the reconstruction resolution.

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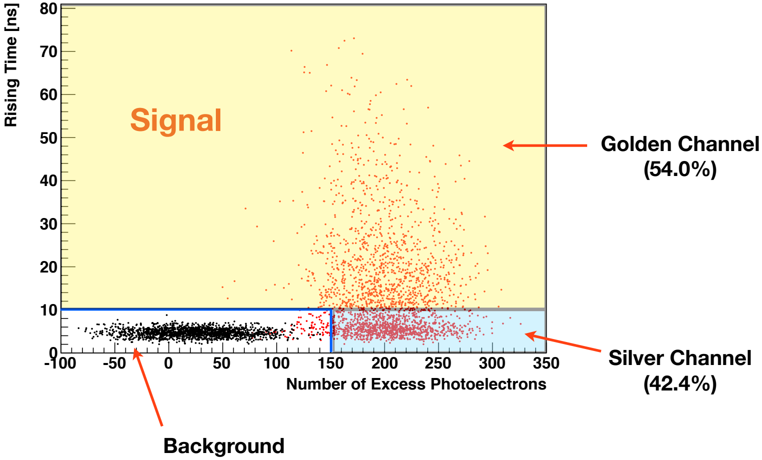
Illustration of Signal / Background Region



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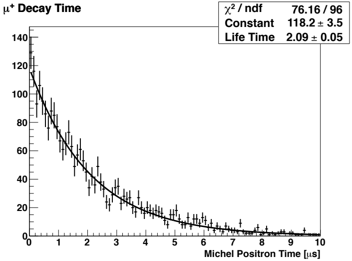
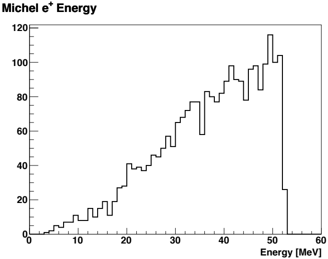
Michel Positron Cut





- For signal events, we require one and only one Michel positron be identified
- From scintillation light curve we assume that if muon decays within 10 ns, the Michel Positron signal cannot be separated from the parent muon signal. The inefficiency due to t_decay < 10 ns is 0.45%
- To reduce the random coincidence from radioactive background, we require the energy of Michel positron > 6 MeV (~50 PE). The efficiency of the cut is 99.7%

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Summary of Efficiency

$K^+ \to \mu^+ + \nu_\mu \quad (63.47\%)$	Golden Channel	Silver Channel
800 < PE in first 100 ns < 1100	96.8%	
One Michel positron	99.2%	
Muon decay later than 100 ns	95.6%	
Rising time >= 10 ns	54.0%	-
Rising time < 10 ns Kaon Recon PE > 150	-	42.4%
Total	49.6%	38.9%

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Number of Protons

- Assuming 22.5 kton fiducial volume, H : O : C = 0.659 : 0.309 : 0.031
  - Free protons (H): 1.53e33
  - Bound protons (O, C): 5.98e33
- For now treat bound protons the same as free protons
  - total protons: 7.5e33
  - due to the nuclear effects such as binding energy and Fermi motion, the kinetic energy of the kaons from bound proton decay will be modified
  - [LENA Paper]: limiting range for kaon KE is (25.1 - 198.8) MeV for s-state and (30.0 - 207.2) MeV for p-state
  - This has marginal effects on the golden channel but will have considerable effects on the silver channel which relies on the reconstruction of the kaon kinetic energy. Assuming 50% efficiency (flat distribution of KE).

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Signal Prediction

$K^+ \to \mu^+ + \nu_\mu \quad (63.47\%)$	Golden Channel	Silver Channel
Free Protons	1.53E+33	
Bound Protons	5.98E+33	3.0e33 (effective)
Efficiency	49.6%	38.9%
Running Time	10 years	
Current limit	2.3e33 years	
Predicted Events	10.3	4.9

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Muon Background

- The atmospheric neutrino generated muon need to be in the energy range of (170, 210) MeV to mimic the prompt signal. The event rate is ~2 events/kt/year
- With the 4000 simulated muon events in this energy range, none passed the signal selection (timing cut / kaon energy recon cut). This means a background rejection > 99.975%
- At this rejection level, the expected muon background after 10 years running is ~0.1 events