High Energy ($\gtrsim$ GeV) **Neutrino Directionality**, **Event Imaging**, and **Particle ID** in the **KamLAND Liquid Scintillator** **(Preliminary work in progress)**

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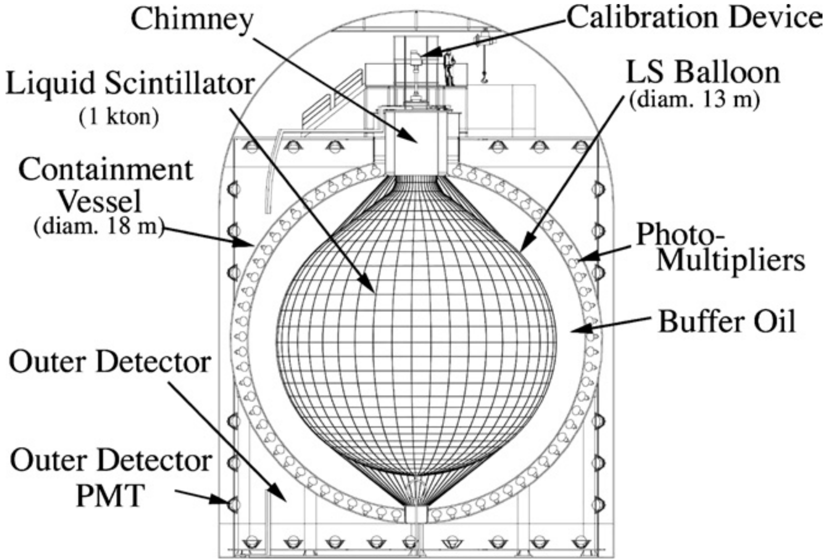
FroST Mar 20, 2016

KamLAND: schematic



KamLAND: features

- Commissioned: 2001
- Medium: liquid scintillator

  Decay constants: $\tau_1 = 4.0\,\text{ns}$, $\tau_2 = 8.6\,\text{ns}$
- Size: 1 kt scintillator, 1.5 kt buffer oil
- Photomultiplier tubes in inner detector (Hamamatsu):

  1325 of 17-inch, 3.5 ns TTS

  554 of 20-inch, 5.5 ns TTS
- Analysis: $\sim$MeV $\overline{\nu}_e$ (inverse-beta decay)
- Energy resolution: $\sigma_E/E = 6.5\,\%/\sqrt{E(\text{MeV})}$
- Vertex resolution: $\sigma_x = 12\,\text{cm}/\sqrt{E(\text{MeV})}$

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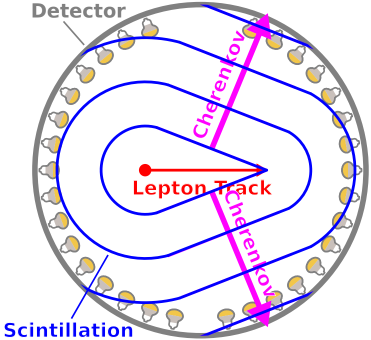
- **Directional sensitivity: never explored**
- **No analysis at higher ($\gtrsim$ GeV) energies**

Direction reconstruction idea

Fit direction with **charge** and **time**



Idea: John Learned

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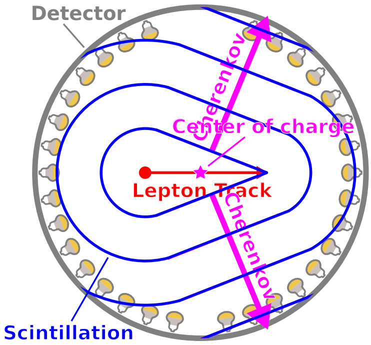
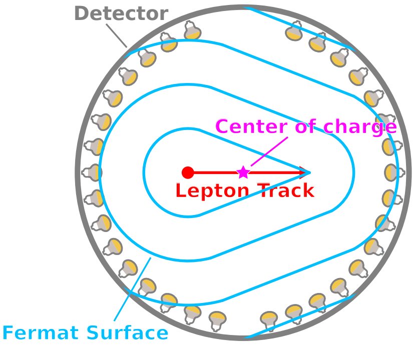


Idea: John Learned

- **Center of charge**
  fits middle of track

Direction reconstruction idea

Fit direction with **charge** and **time**



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- **Fermat surface** $\equiv$ Cherenkov $+$ earliest scintillation

Direction reconstruction idea

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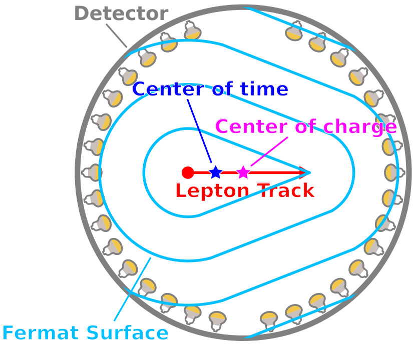

Idea: John Learned

- **Center of charge** fits middle of track
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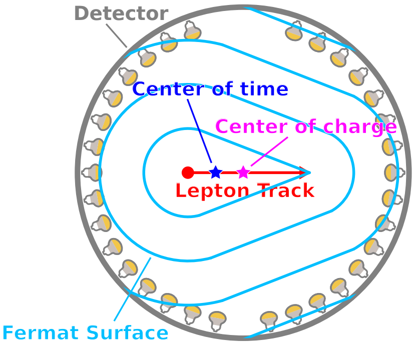
- **Center of time** (using early photons) fits near one end of track

Direction reconstruction idea

Fit direction with **charge** and **time**



Idea: John Learned

- **Center of charge** fits middle of track
- **Fermat surface** $\equiv$ Cherenkov $+$ earliest scintillation
- **Center of time** (using early photons) fits near one end of track
- **And connect dots!**

Question:

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- But, what do we use for the **weights** in the **weighted mean**:

$$\frac{\sum_i w_i x_i}{\sum_i w_i}$$

when calculating **center of charge and time?**

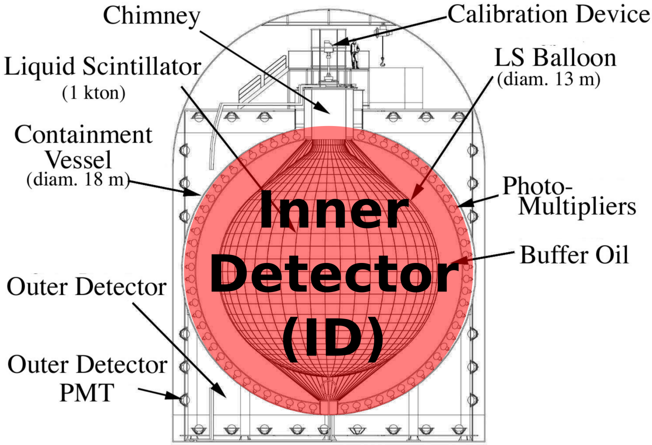
For an idealized **point source of light**, it can be derived to 1st order that...

- Use $\sqrt{\textbf{charge}}$ as weight for **center of charge**.

For an idealized **point source of light**, it can be derived to 1st order that...

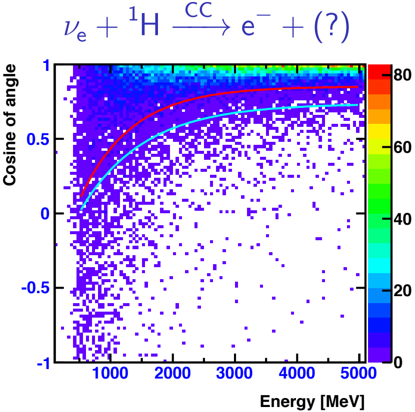
- Use $\sqrt{\textbf{charge}}$ as weight for **center of charge**.
- Use $\textbf{time}^{-1}$ as weight for **center of time**.

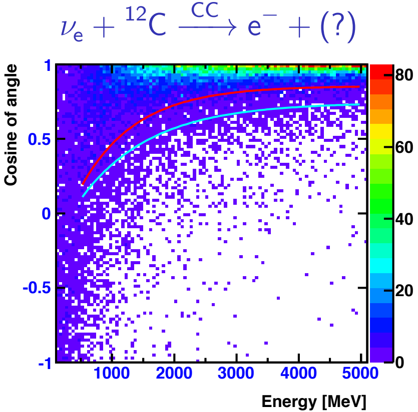
Test with fully contained ν in ID (MC)



Test with fully contained ν in ID (MC)

(Idealized OD efficiency, reconstructed vertex < 6 m radius)





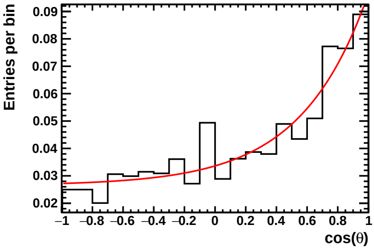
— $1\,\sigma$ of reconstructed angle from ν direction

— $1\,\sigma$ of lepton angle from ν direction

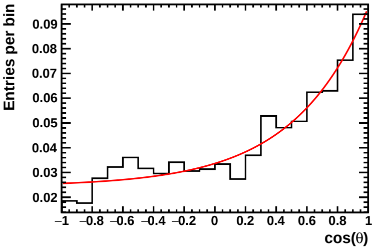
Test with fully contained 1 GeV ν (MC)

(Realistic OD efficiency)

$\nu_e(1\,\text{GeV}) + {}^{1}\text{H} \xrightarrow{\text{CC}} (?)$



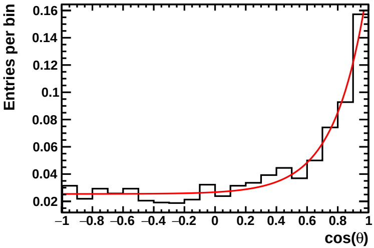
$\nu_e(1\,\text{GeV}) + {}^{12}\text{C} \xrightarrow{\text{CC}} (?)$



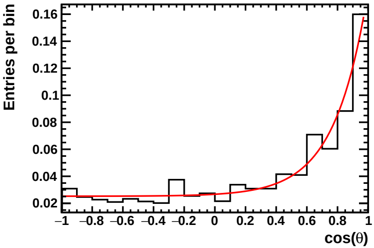
Test with fully contained 10 GeV ν (MC)

(Realistic OD efficiency)

$\nu_e(10\,\mathrm{GeV}) + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} (?)$



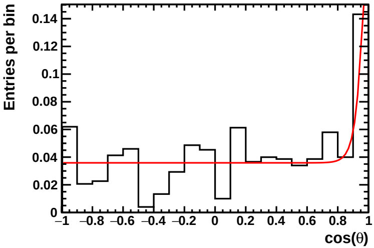
$\nu_e(10\,\mathrm{GeV}) + {}^{12}\mathrm{C} \xrightarrow{\mathrm{CC}} (?)$



Test with fully contained 100 GeV ν (MC)

(Realistic OD efficiency)

$\nu_e(100\,\text{GeV}) + {}^{1}\text{H} \xrightarrow{\text{CC}} (?)$



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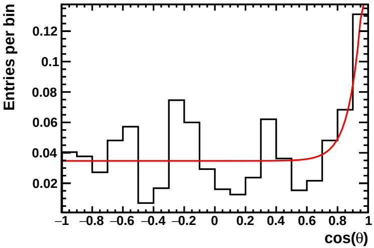

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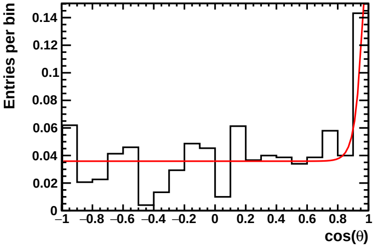

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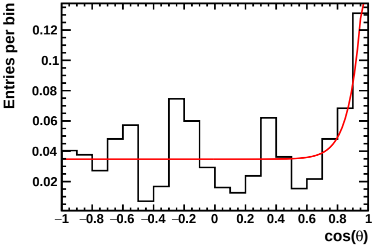
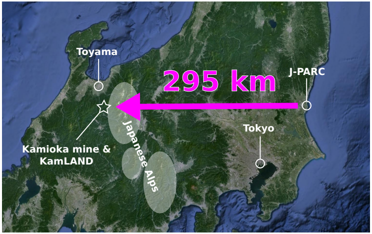


- Lots of noise events due to OD inefficiency to identify fully contained events

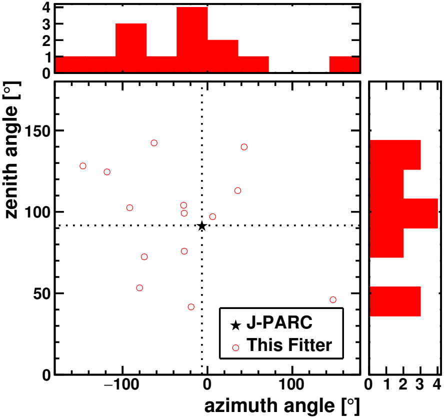
Test with fully contained T2K ν (data)

(Selected with spill-time so no backgrounds)

Map



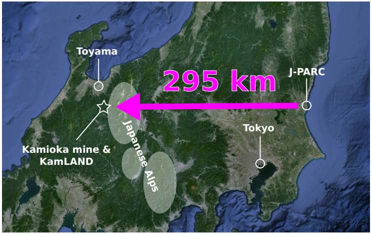
Agreement with J-PARC direction



Test with filly contained T2K ν (data)

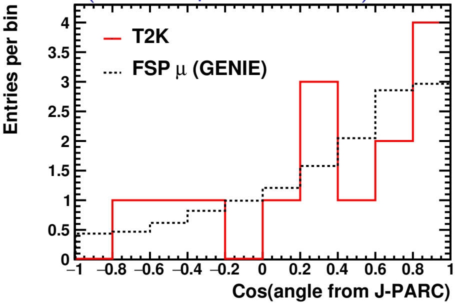
(Selected with spill-time so no backgrounds)

Map



Agreement with MC

(K-S test p-value $= 0.65$)



Event Imaging and Particle ID

Hellgartner's algorithm

(former LENA grad student)

$$h(\vec{x}, t) = \sum_{i=1}^{N_{\mathsf{PMT}}} \Theta(q_i - q_{\mathsf{threshold}}) \sum_{j=1}^{N_\gamma} f(t_{ij} - t_i^{\mathsf{TOF}}, t)$$

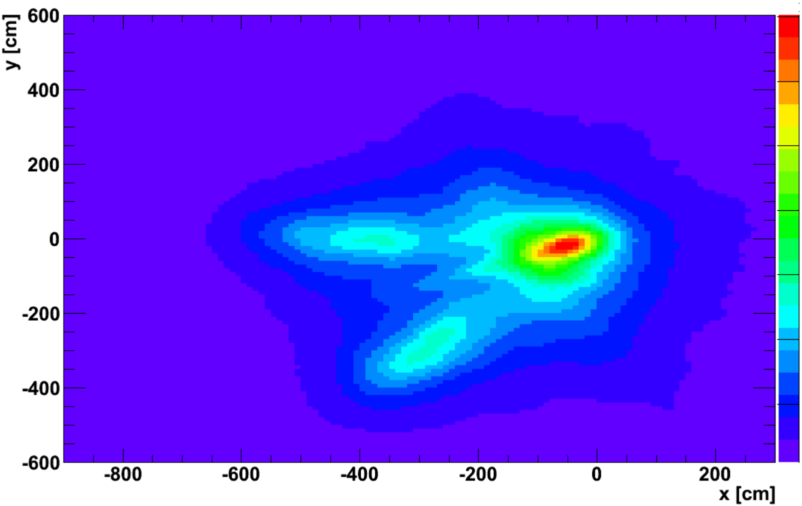
N_{PMT}	number of PMTs
N_γ	number of photon hits to count per PMT
q_i	charge on i-th PMT
$q_{\mathsf{threshold}}$	minimum charge for analysis
t_{ij}	j-th hit time on i-th PMT
t_i^{TOF}	expected time-of-flight between i-th PMT and $\vec{x}$

$$f(\Delta t, t) \propto (t - \Delta t) \exp\left[-\frac{(\Delta t - t)^2}{2\sigma_{\mathsf{tts}}}\right]$$

σ_{tts}	transit time spread

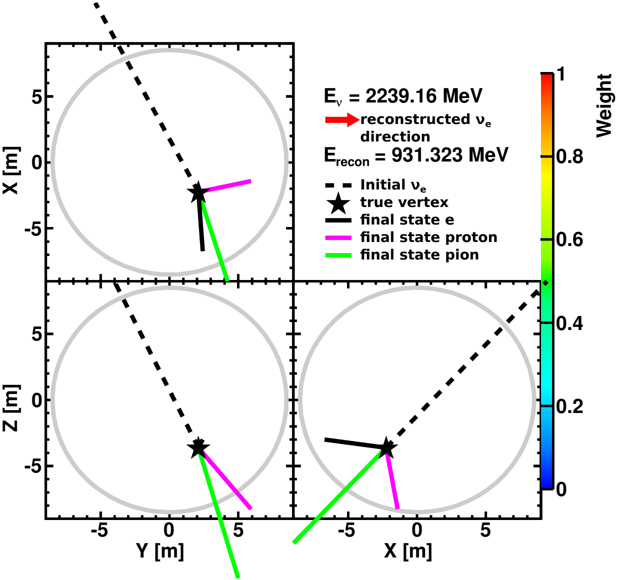
Figure of merit for each test point in space $= \int_{-\infty}^{\infty} |h(\vec{x}, t)|^2 \, \mathrm{d}t$

Test Hellgartner on double 1 GeV muons (MC)

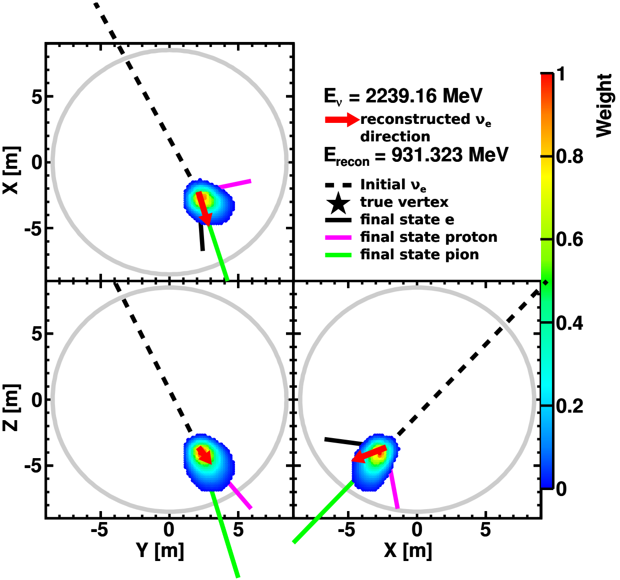


Dominikus Hellgartner

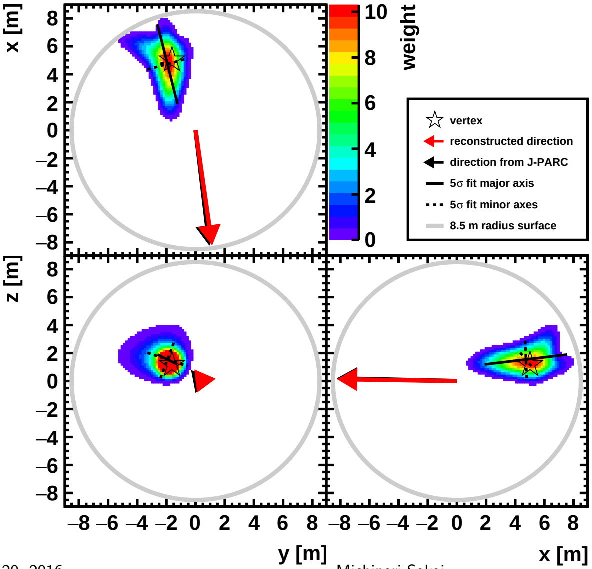
Test Hellgartner on 2 GeV ν_e (MC)



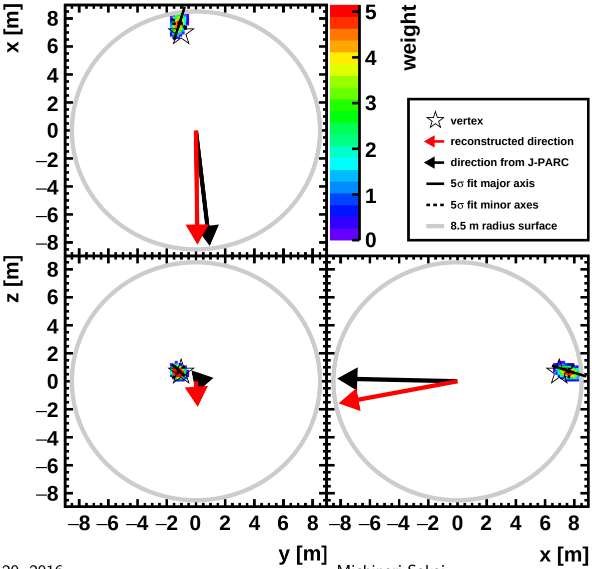
Test Hellgartner on 2 GeV ν_e (MC)



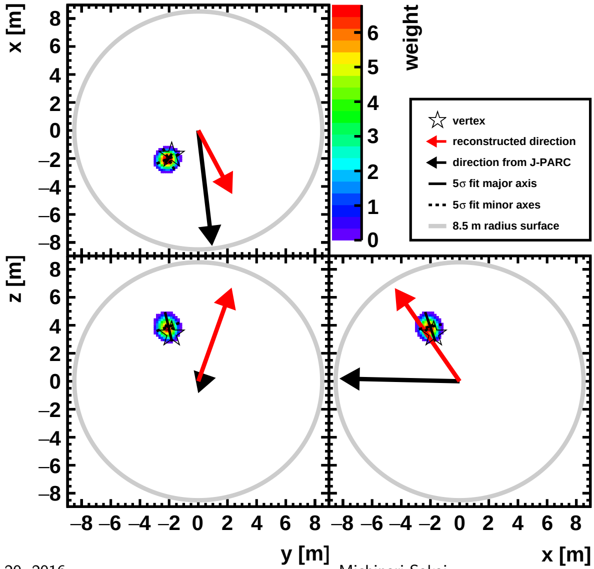
Test Hellgartner on T2K event 1 (data)



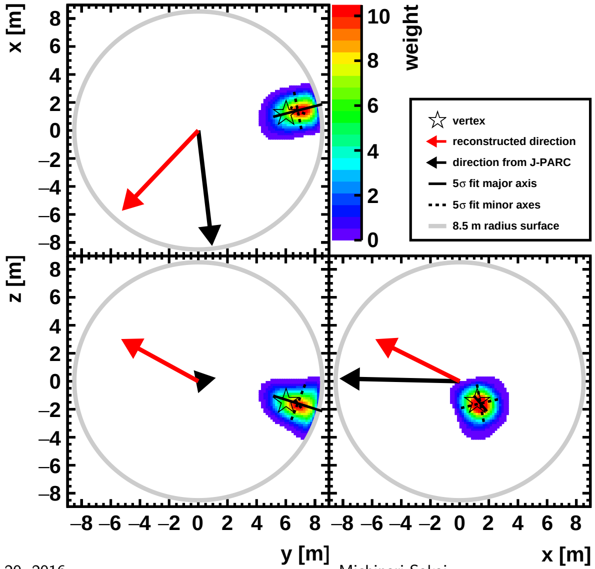
Test Hellgartner on T2K event 2 (data)



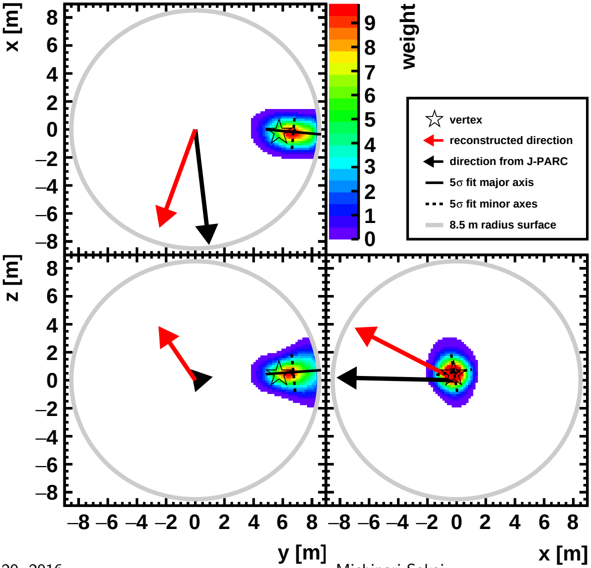
Test Hellgartner on T2K event 3 (data)



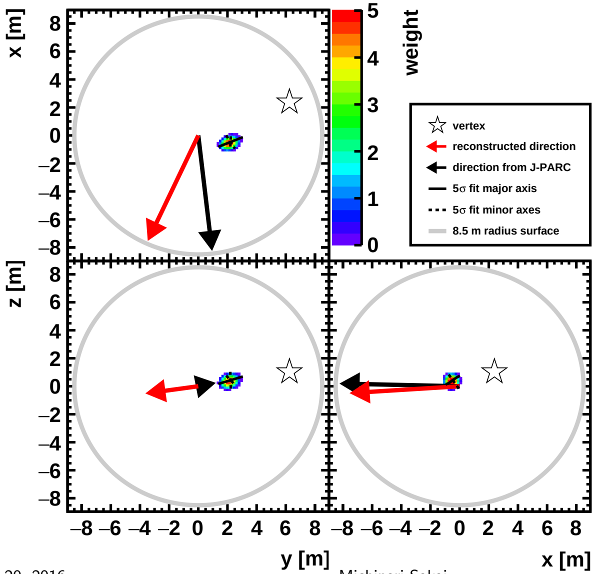
Test Hellgartner on T2K event 4 (data)



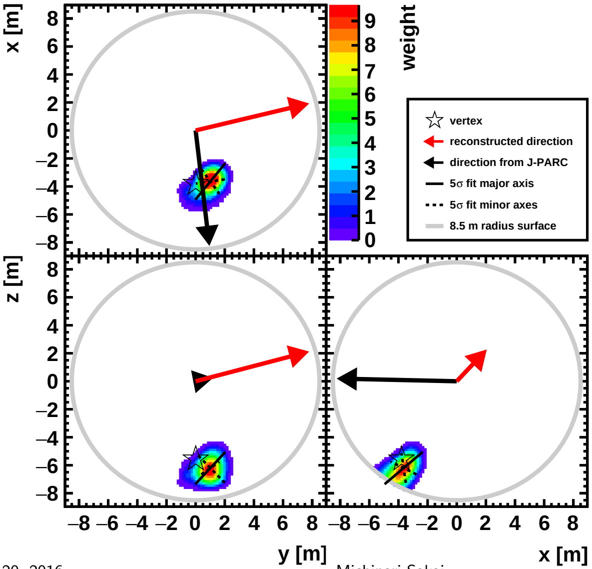
Test Hellgartner on T2K event 5 (data)



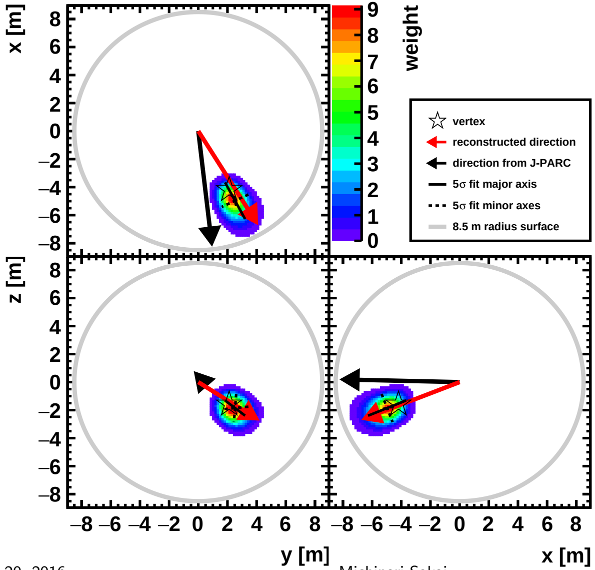
Test Hellgartner on T2K event 6 (data)



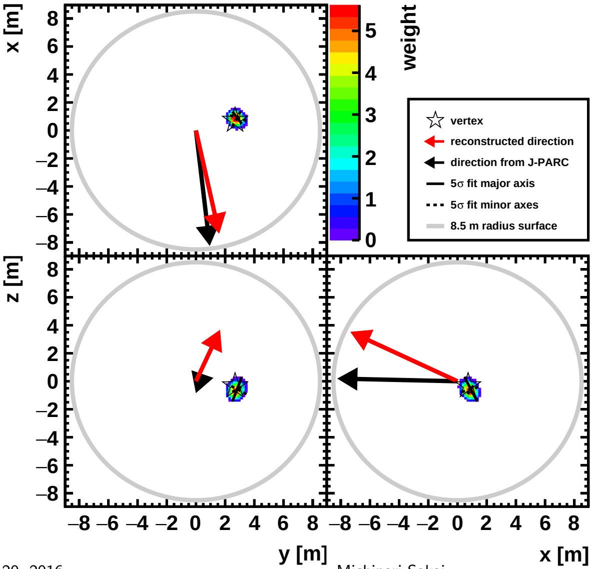
Test Hellgartner on T2K event 7 (data)



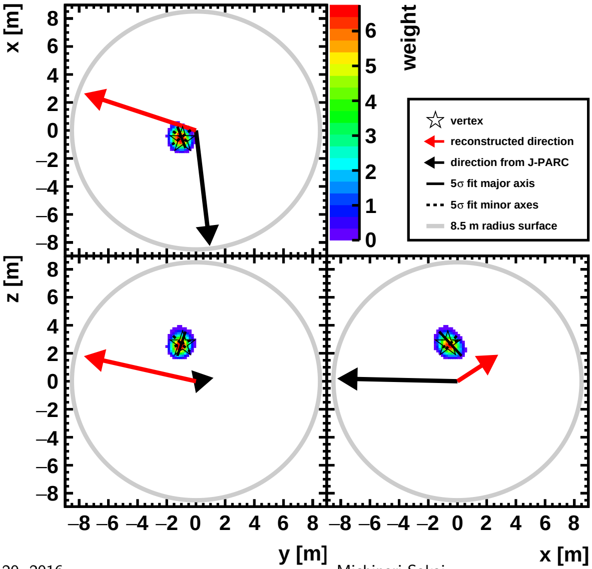
Test Hellgartner on T2K event 8 (data)



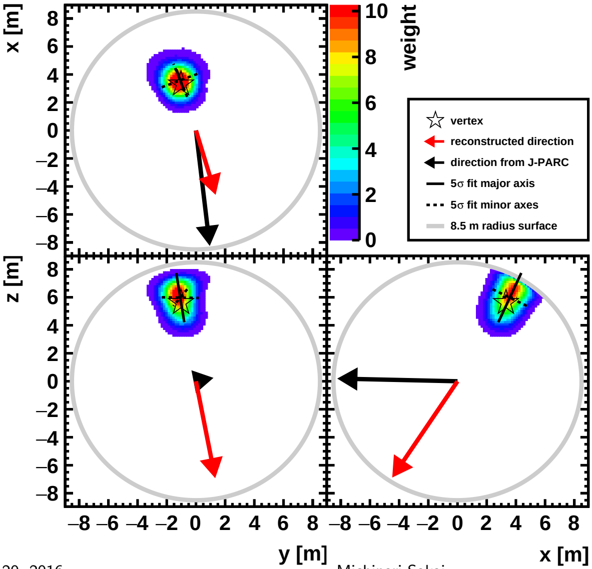
Test Hellgartner on T2K event 9 (data)



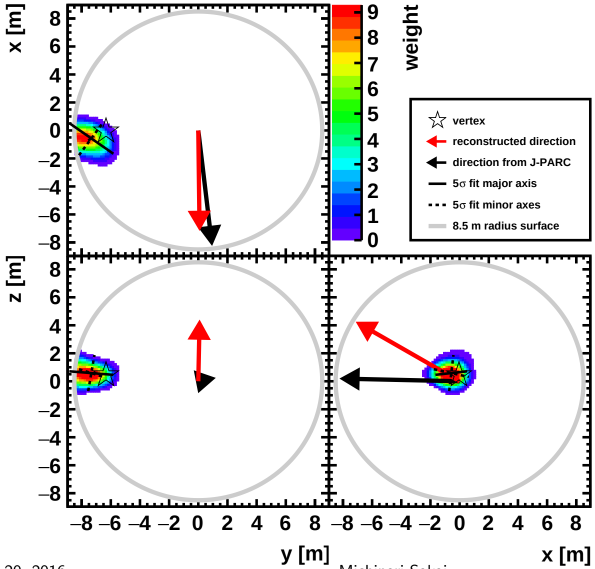
Test Hellgartner on T2K event 10 (data)



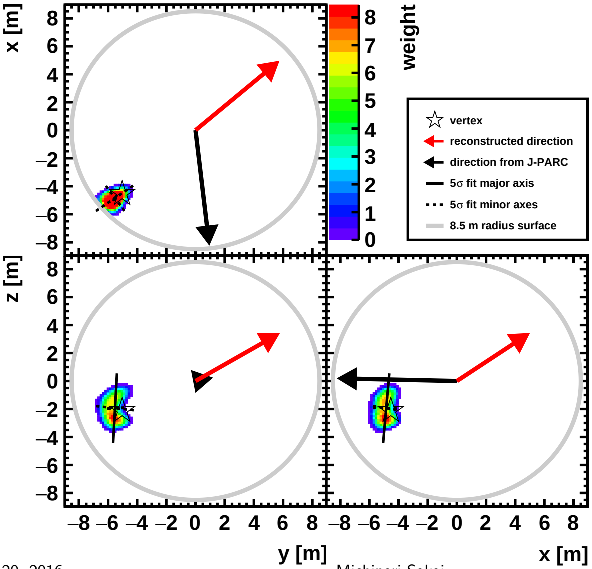
Test Hellgartner on T2K event 11 (data)



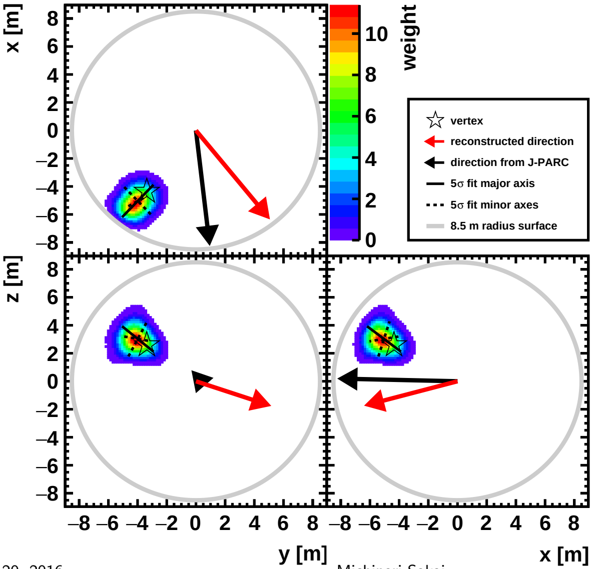
Test Hellgartner on T2K event 12 (data)



Test Hellgartner on T2K event 13 (data)

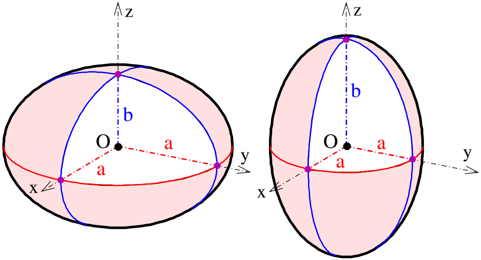


Test Hellgartner on T2K event 14 (data)



Lepton discrimination scheme

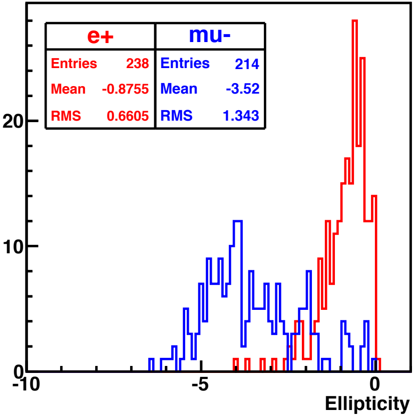
Fit event profile with ellipse



Define ellipticity $\equiv \dfrac{a-b}{a}$

- $\mu^{\mp} \implies$ more elongated
- $e^{\mp} \implies$ less elongated

Test 1 GeV lepton discrimination (MC)



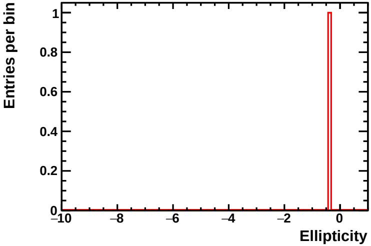
- Fiducial volume cut:

  $< 3\,\mathrm{m}$ radius

- Event selection efficiency:

  $$e^+ \Longrightarrow 2.4\,\%,$$
  $$\mu^- \Longrightarrow 2.1\,\%$$

Reconstructed ellipticity of T2K ν (data)



- Only 1 event in $r < 3\,\mathrm{m}$
- Need more statistics

Summary/Notes

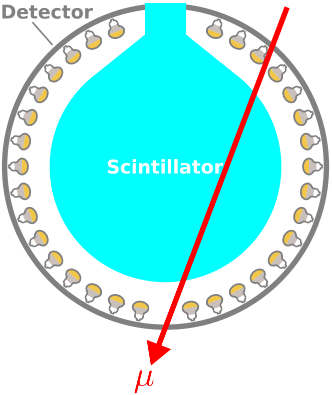
- Developed and tested **directionality** and **track reconstruction** techniques for high energy ν in KamLAND scintillator.
- Studied **lepton flavor discrimination** in KamLAND scintillator.
- Further progress requires **GPUs** for fast simulation (e.g., Chroma)
- **Efficiency of outer detector** is important in identifying fully contained events for clean event reconstruction (KamLAND is now refurbishing/upgrading outer detector)

Thank you for listening!

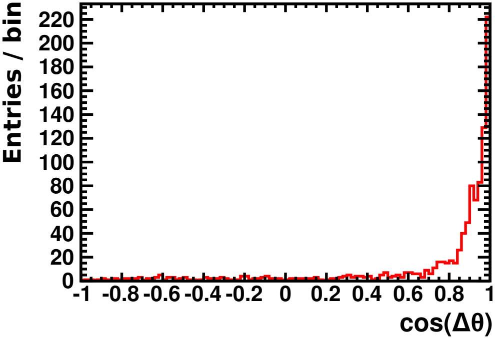
Backup slides

Test algorithm with cosmic-ray μ (data)

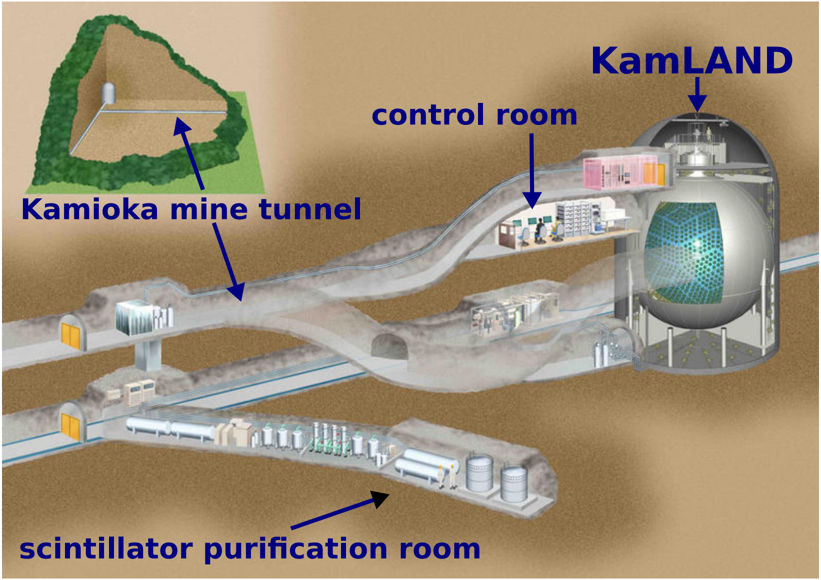
μ track traversing detector



Angle deviation $\Delta\theta$ from entry-exit point μ-fitter



KamLAND: ν detector in Japan



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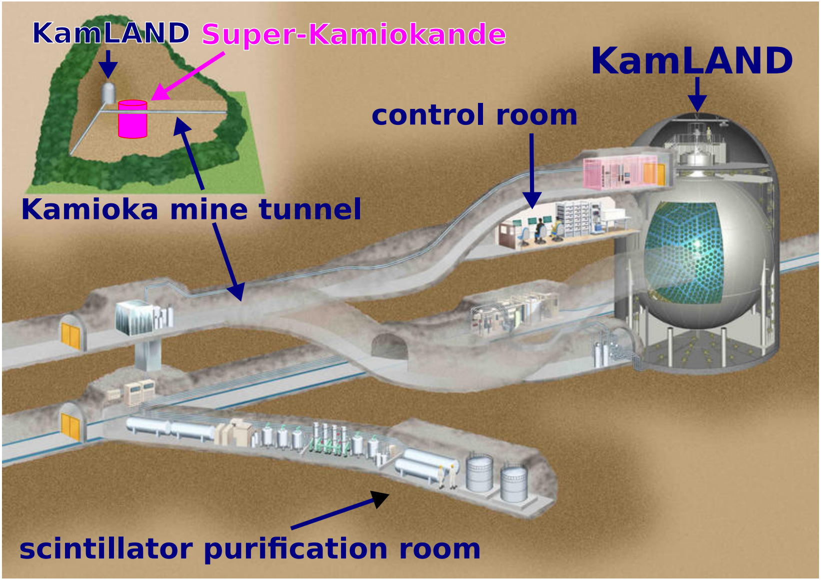


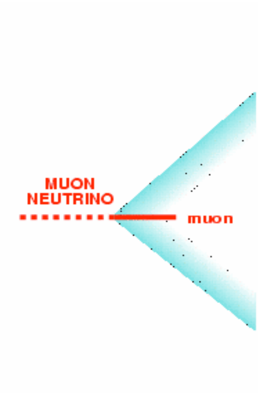
KamLAND: features

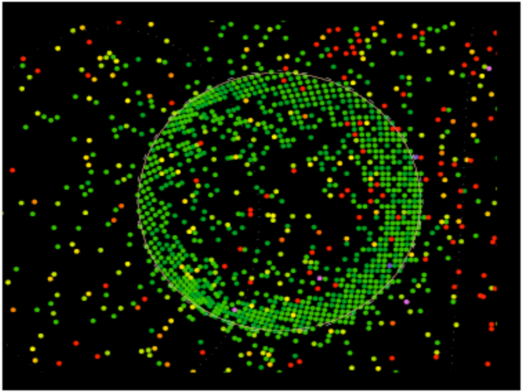
- Commissioned: 2001
- Medium: liquid scintillator
  - Decay constants: $\tau_1 = 4.0\,\mathrm{ns}$, $\tau_2 = 8.6\,\mathrm{ns}$
  - 80.2 % Dodecane ($C_{12}H_{26}$), 19.8 % Pseudocumene (C_9H_{12}), 1.36 g/L PPO ($C_{15}H_{11}NO$)
- Size: 1 kt
- Photomultiplier tubes in inner detector (Hamamatsu):
  - 1325 17-inch, 7 ns rise-time, 3.5 ns TTS
  - 554 20-inch, 10 ns rise-time, 5.5 ns TTS
  - 34 % photocathode coverage
- Analysis: $\sim$MeV $\overline{\nu}_e$ (inverse-beta decay)
- Energy resolution: $7.0 \pm 0.1\,\%/\sqrt{E(\mathrm{MeV})}$
- Vertex resolution: $13.8 \pm 2.3\,\mathrm{cm}$

ν directionality using Cherenkov

(Super-Kamiokande)

Cherenkov ring shows charged particle direction





Joshua Albert

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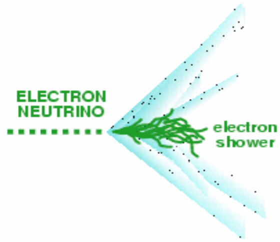
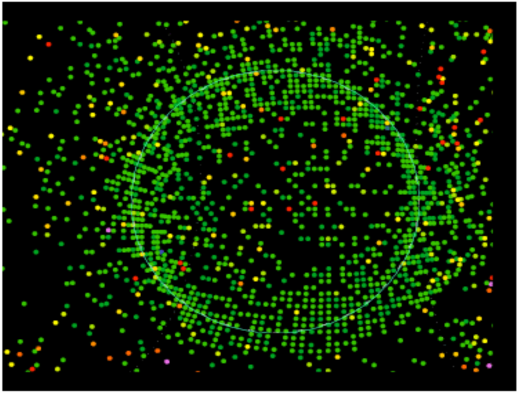
(Super-Kamiokande)

Cherenkov ring shows charged particle direction





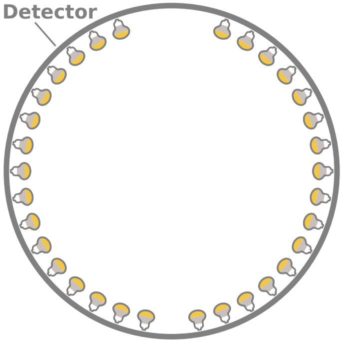
Joshua Albert

Question:

Can we do something similar in scintillator?

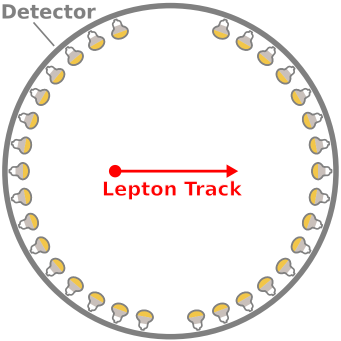
In scintillator...

KamLAND



In scintillator...

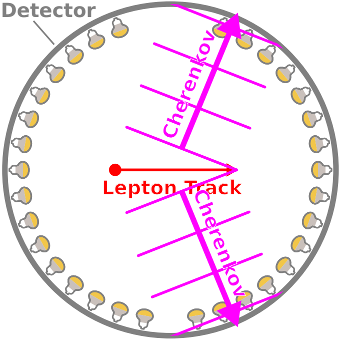
KamLAND



- Charged lepton track

In scintillator...

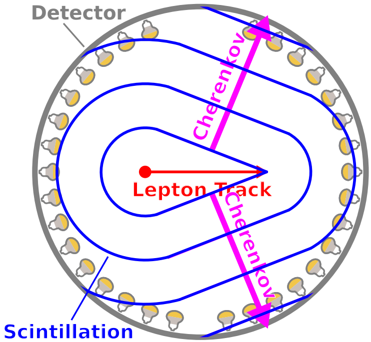
KamLAND



- Charged lepton track
- Cherenkov emitted

In scintillator...

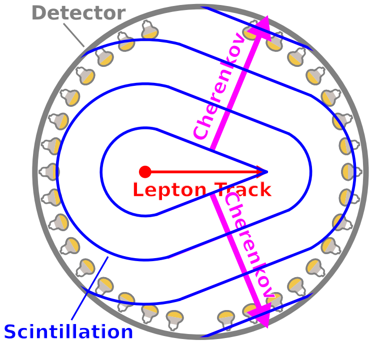
KamLAND



- Charged lepton track
- Cherenkov emitted with isotropic scintillation

In scintillator...

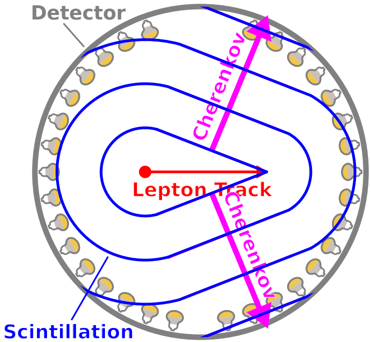
KamLAND



- Charged lepton track
- Cherenkov emitted with isotropic scintillation
- Cherenkov washed out by $\sim 30\times$ brighter scintillation

In scintillator...

KamLAND

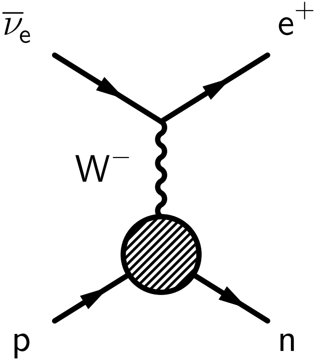


- Charged lepton track
- Cherenkov emitted with isotropic scintillation
- Cherenkov washed out by $\sim 30\times$ brighter scintillation

$\therefore$ **Cannot simply use Cherenkov for directionality**

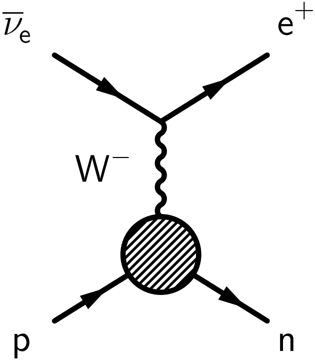
Furthermore...

Inverse-beta decay



Furthermore...

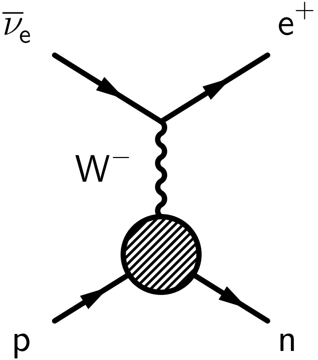
Inverse-beta decay



- KamLAND is used to seeing simple kinematics at low energies ($\sim$ MeV)

Furthermore...

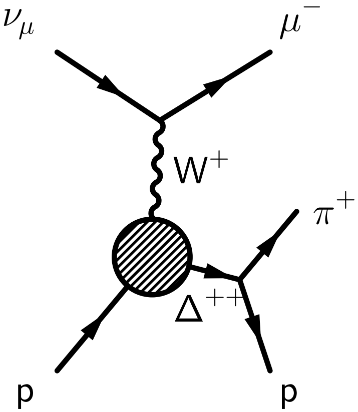
Inverse-beta decay



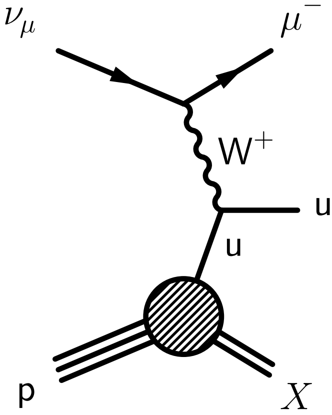
- KamLAND is used to seeing simple kinematics at low energies ($\sim$ MeV)
- Single final-state lepton

But at **higher energies ($\sim$ GeV)**, the kinematics is **not so simple**

Resonance production

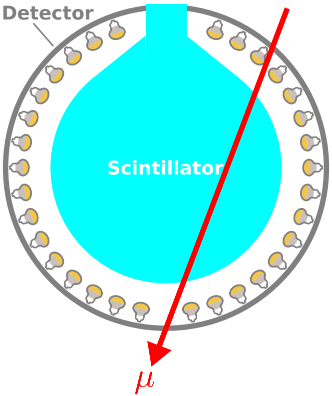


Deep inelastic scattering

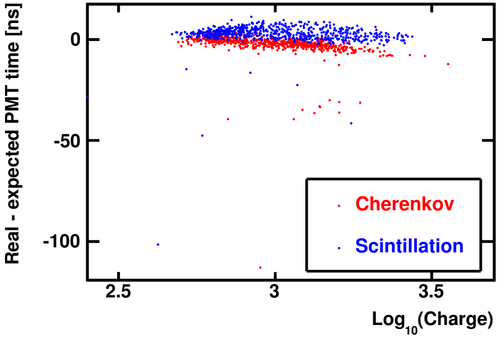


High Energy
$\Longrightarrow$ **many photons** in scintillator

Muon event

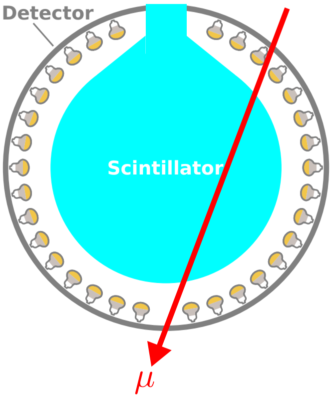


Hit time vs energy (data)



High Energy
$\Longrightarrow$ **many photons** in scintillator

Muon event



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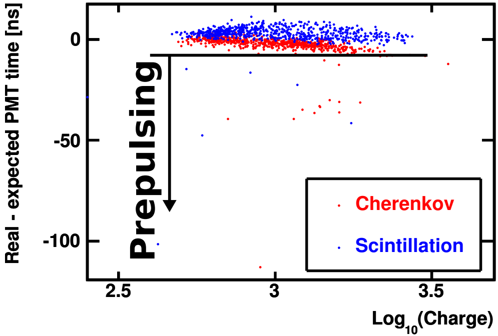

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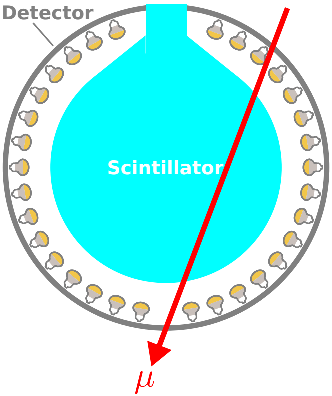

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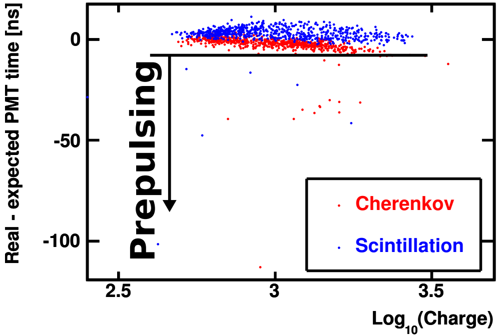
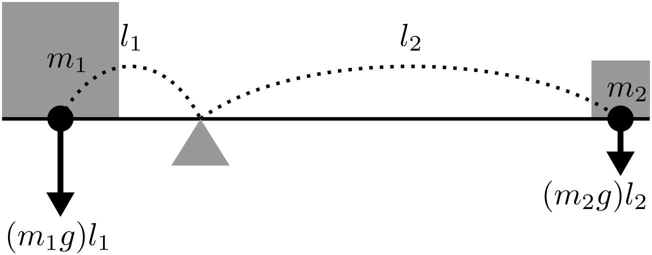


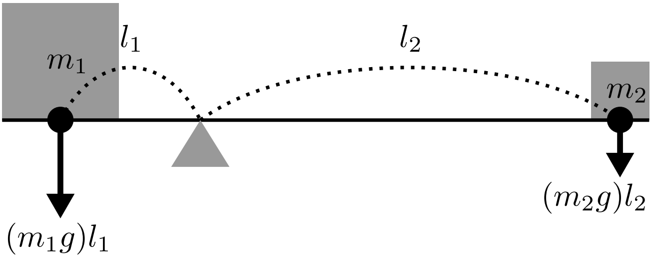
- **Fitter must be robust against prepulsing**

Let's review some basic physics...

What **weight** is used for **center of gravity**?



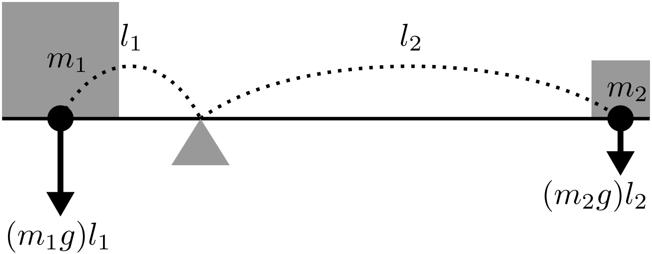
What **weight** is used for **center of gravity**?



To find center of gravity:

net torque $= -(m_1 g) l_1 + (m_2 g) l_2 = 0$

What **weight** is used for **center of gravity**?



To find center of gravity:

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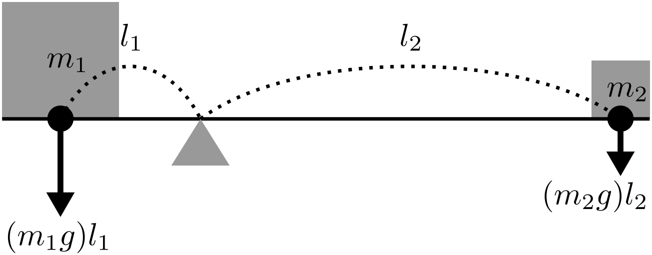
$\implies -(m_1) l_1 + (m_2) l_2 = 0$

What **weight** is used for **center of gravity**?



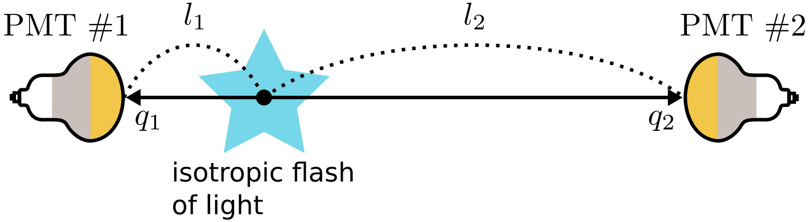
To find center of gravity:

net torque $= -(m_1 g)l_1 + (m_2 g)l_2 = 0$

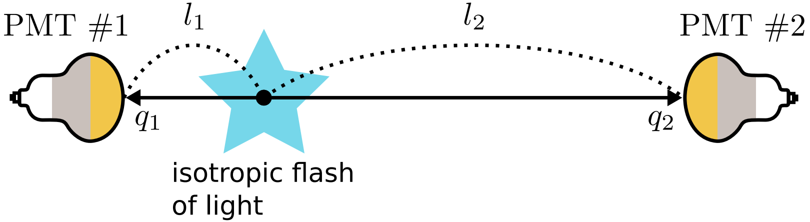
$\implies -(m_1)l_1 + (m_2)l_2 = 0$

$\therefore$ weight is **mass**: $w_i = m_i$

What **weight** to use for **center of charge**?



What **weight** to use for **center of charge**?



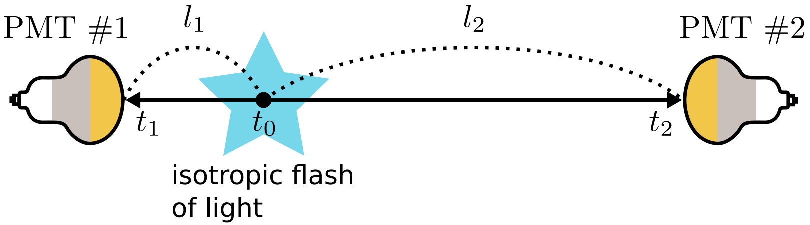
$$q_1 \propto \frac{1}{l_1^2}, \quad q_2 \propto \frac{1}{l_2^2}$$

$$\implies \sqrt{q_1} \propto \frac{1}{l_1}, \quad \sqrt{q_2} \propto \frac{1}{l_2}$$

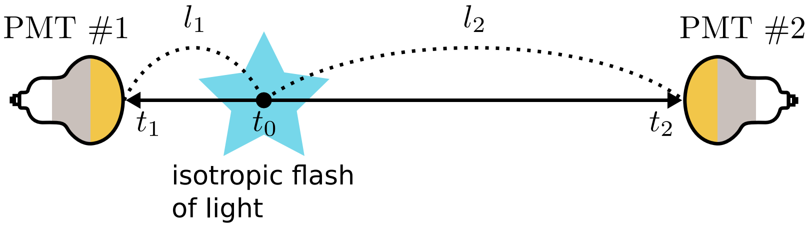
$$\implies -(\sqrt{q_1})l_1 + (\sqrt{q_2})l_2 = 0$$

$\therefore$ weight is $\sqrt{\textbf{charge}}$: $w_i = \sqrt{q_i}$

What **weight** to use for **center of time**?



What **weight** to use for **center of time**?



Let $\Delta t_i \equiv t_i - t_0$

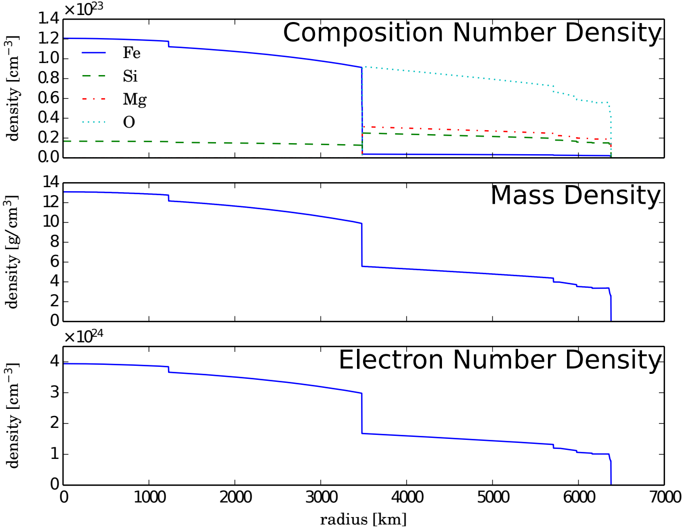
$$\implies \Delta t_1 = \frac{l_1}{c}, \quad \Delta t_2 = \frac{l_2}{c}$$

$$\implies -\left(\frac{1}{\Delta t_1}\right)\frac{l_1}{c} + \left(\frac{1}{\Delta t_2}\right)\frac{l_2}{c} = 0$$

$$\implies -\left(\frac{1}{\Delta t_1}\right)l_1 + \left(\frac{1}{\Delta t_2}\right)l_2 = 0$$

$\therefore$ weight is **inverse of time**: $w_i = \frac{1}{\Delta t_i}$

Earth Model (PREM)



Neutrino Oscillation Parameters

(normal hierarchy, PDG 2014)

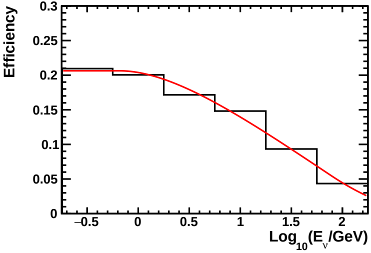
- $\sin^2(2\theta_{12}) = 0.846 \pm 0.021$
  $\Longrightarrow \theta_{12} = 33.45^\circ$
- $\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2}$
  $\Longrightarrow \theta_{13} = 8.88^\circ$
- $\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$
  $\Longrightarrow \theta_{23} = 44.09^\circ$
- $\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\,\mathrm{eV}$
- $\Delta m^2_{31} = 2.52 \pm 0.06 \times 10^{-3}\,\mathrm{eV}$

Assumptions for dark matter properties

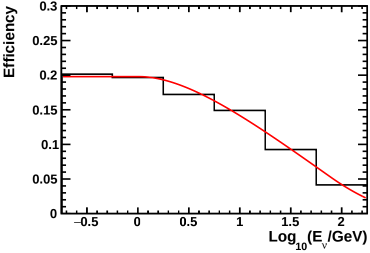
- Spherical density profile (Navarro, Frenk and White): $\propto \frac{1}{\left(\frac{r}{a}\right)^{\gamma}\left[1+\left(\frac{r}{a}\right)^{\alpha}\right]^{\left(\frac{\beta-\gamma}{\alpha}\right)}}, \alpha = 1, \beta = 3, \gamma = 1, a = 20\,\text{kpc}$
- WIMP velocity profile: Maxwell-Boltzmann distribution
- Local WIMP halo density $= 0.3\,\text{GeV}\,\text{cm}^{-3}$
- 3-D WIMP velocity dispersion $\bar{v} \equiv \frac{3kT_\chi}{m_\chi} = 270\,\text{km}$
- Sun effect on WIMP capture by Earth negligible to $\sim 10\,\%$ within $10\,\text{GeV} < m_\chi < 75\,\text{GeV}$
- Galactocentric distance of Sun $= 8\,\text{kpc}$
- Galactocentric speed of Sun $= 220\,\text{km}\,\text{s}^{-1}$
- Average Earth speed wrt halo $= 264\,\text{km}\,\text{s}^{-1}$

Detection efficiency for fully contained events

$\nu_e + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} (?)$



$\nu_e + {}^{12}\mathrm{C} \xrightarrow{\mathrm{CC}} (?)$



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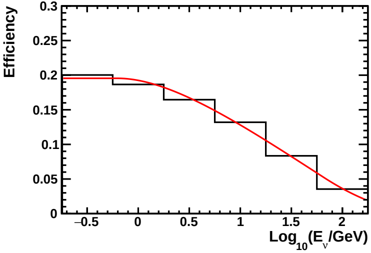

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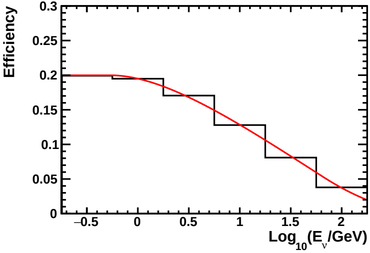
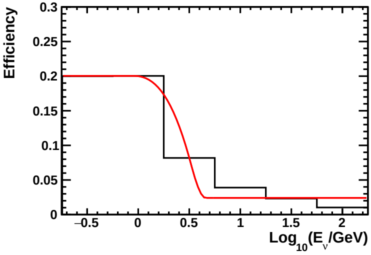


Detection efficiency for fully contained events

$\nu_\mu + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} (?)$



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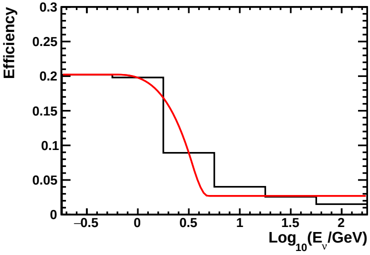

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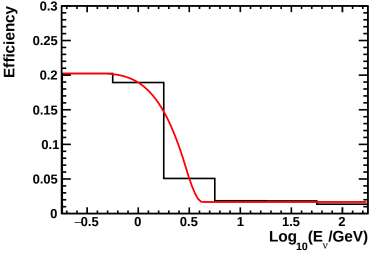

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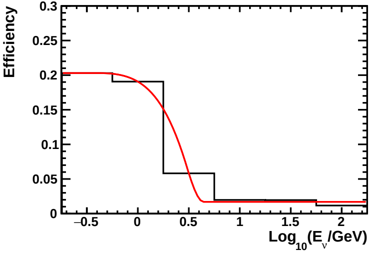
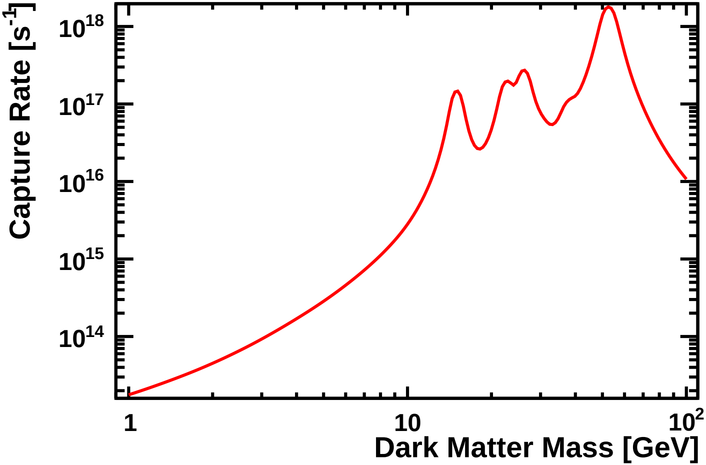


Dark matter capture in Earth vs mass m_x

(Spin-independent cross-section $\sigma_{\mathrm{SI}} = 1 \times 10^{-40}\,\mathrm{cm}^2$)



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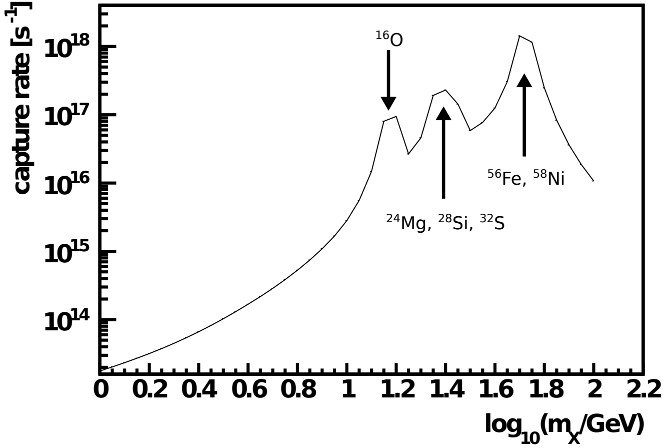
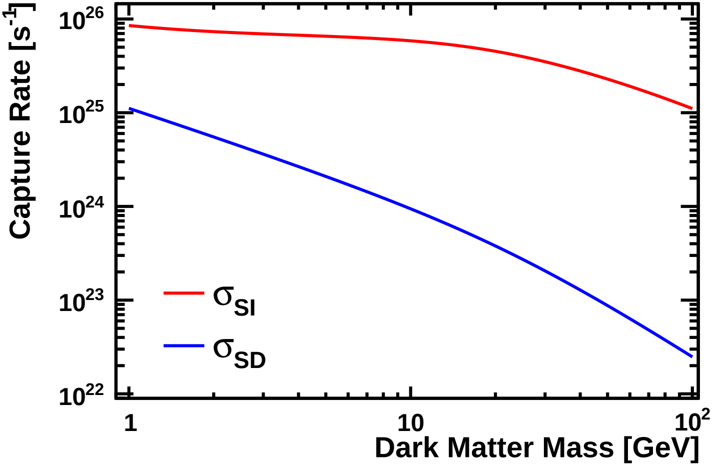


Dark matter capture in Sun vs mass m_x

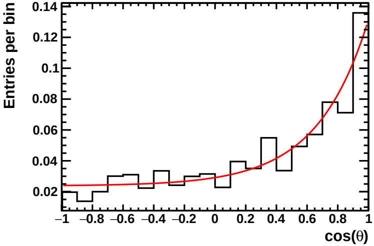
(Spin-independent/dependent cross-sections $\sigma_{\rm SI} = \sigma_{\rm SD} = 10^{-40}\,{\rm cm}^2$)



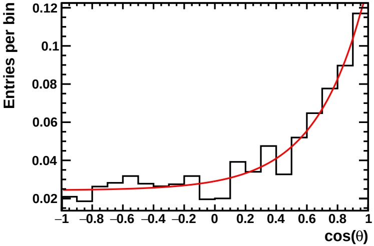
Test with fully contained 1 GeV ν (MC)

Realistic OD efficiency

$\overline{\nu}_e(1\,\text{GeV}) + {}^{1}\text{H} \xrightarrow{\text{CC}} (?)$



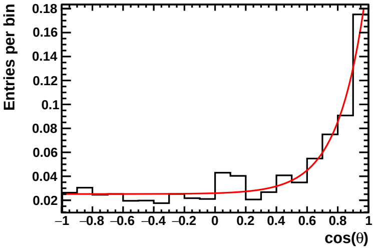
$\overline{\nu}_e(1\,\text{GeV}) + {}^{12}\text{C} \xrightarrow{\text{CC}} (?)$



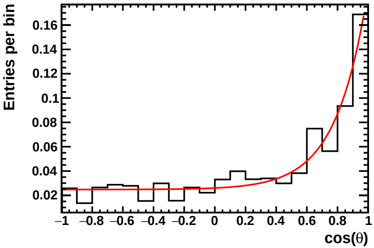
Test with fully contained 10 GeV ν (MC)

Realistic OD efficiency

$\overline{\nu}_e(10\,\mathrm{GeV}) + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} (?)$



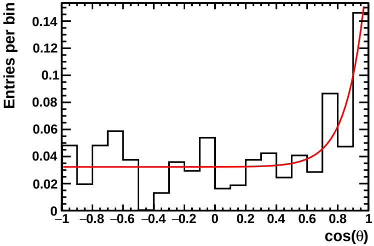
$\overline{\nu}_e(10\,\mathrm{GeV}) + {}^{12}\mathrm{C} \xrightarrow{\mathrm{CC}} (?)$



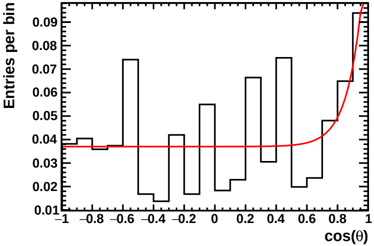
Test with fully contained 100 GeV ν (MC)

Realistic OD efficiency

$\overline{\nu}_{\mathrm{e}}(100\,\mathrm{GeV}) + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} (?)$



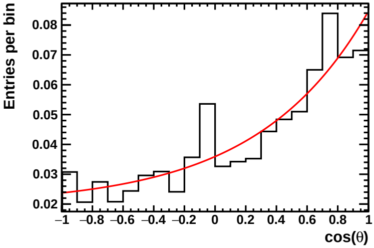
$\overline{\nu}_{\mathrm{e}}(100\,\mathrm{GeV}) + {}^{12}\mathrm{C} \xrightarrow{\mathrm{CC}} (?)$



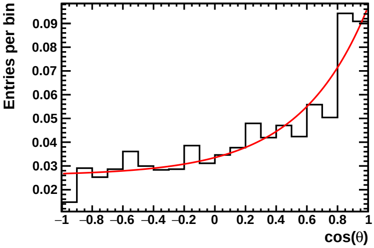
Test with fully contained 1 GeV ν (MC)

Realistic OD efficiency

$\nu_\mu(1\,\mathrm{GeV}) + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} (?)$



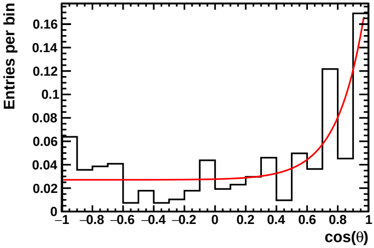
$\nu_\mu(1\,\mathrm{GeV}) + {}^{12}\mathrm{C} \xrightarrow{\mathrm{CC}} (?)$



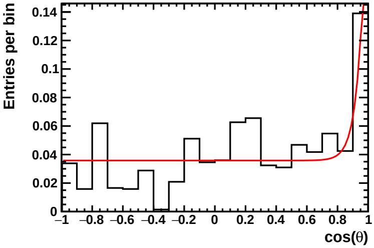
Test with fully contained 10 GeV ν (MC)

Realistic OD efficiency

$\nu_\mu(10\,\text{GeV}) + {}^{1}\text{H} \xrightarrow{\text{CC}} (?)$



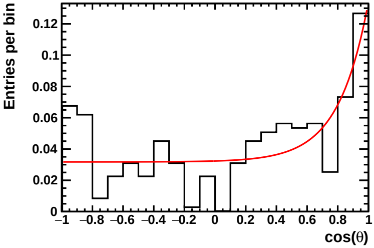
$\nu_\mu(10\,\text{GeV}) + {}^{12}\text{C} \xrightarrow{\text{CC}} (?)$



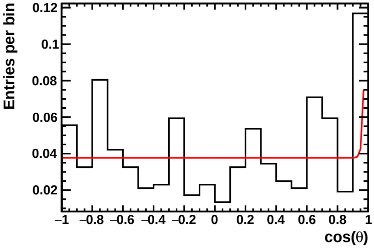
Test with fully contained 100 GeV ν (MC)

Realistic OD efficiency

$$\nu_\mu(100\,\text{GeV}) + {}^1\text{H} \xrightarrow{\text{CC}} (?)$$



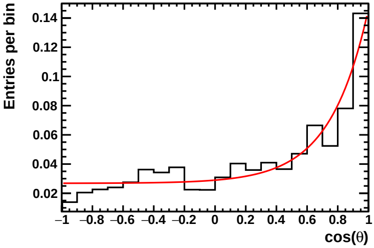
$$\nu_\mu(100\,\text{GeV}) + {}^{12}\text{C} \xrightarrow{\text{CC}} (?)$$



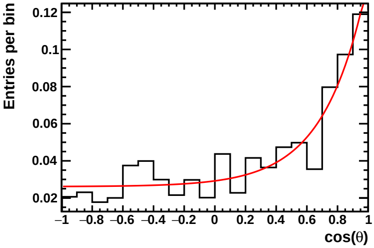
Test with fully contained 1 GeV ν (MC)

Realistic OD efficiency

$\overline{\nu}_\mu(1\,\text{GeV}) + {}^1\text{H} \xrightarrow{\text{CC}} (?)$



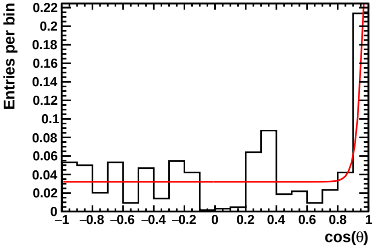
$\overline{\nu}_\mu(1\,\text{GeV}) + {}^{12}\text{C} \xrightarrow{\text{CC}} (?)$



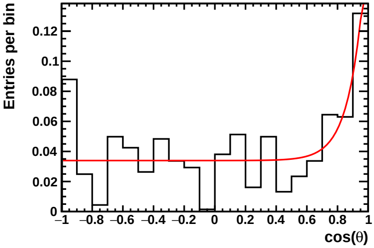
Test with fully contained 10 GeV ν (MC)

Realistic OD efficiency

$\overline{\nu}_\mu(10\,\text{GeV}) + {}^{1}\text{H} \xrightarrow{\text{CC}} (?)$



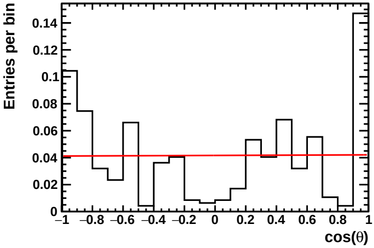
$\overline{\nu}_\mu(10\,\text{GeV}) + {}^{12}\text{C} \xrightarrow{\text{CC}} (?)$



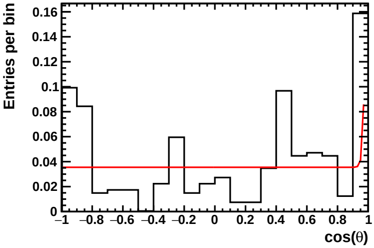
Test with fully contained 100 GeV ν (MC)

Realistic OD efficiency

$\overline{\nu}_\mu(100\,\text{GeV}) + {}^1\text{H} \xrightarrow{\text{CC}} (?)$



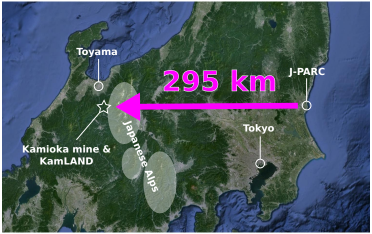
$\overline{\nu}_\mu(100\,\text{GeV}) + {}^{12}\text{C} \xrightarrow{\text{CC}} (?)$



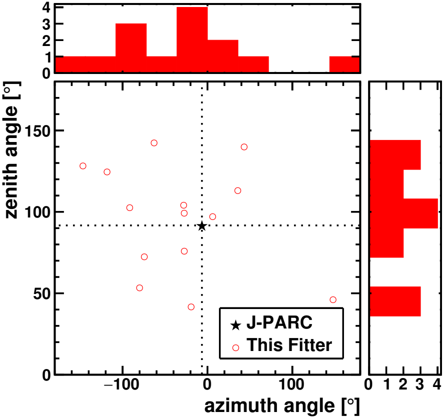
Test algorithm against T2K events (data)

(Selected with spill-time so no backgrounds)

Map



Agreement with J-PARC direction



Summary

- Developed and tested **directionality** and **track reconstruction** techniques for high energy ν in scintillator.
- Studied **lepton flavor discrimination** algorithms in scintillator.
- Performed **high-energy calibration** using cosmic ray μ.
- Placed bounds on **dark-matter-nucleon cross-sections** by looking at annihilation induced ν from Earth and Sun.
- One of **first physics application** of ν directionality in scintillator.