High Energy Analysis at KamLAND and Application to Dark Matter Search

Michinari Sakai

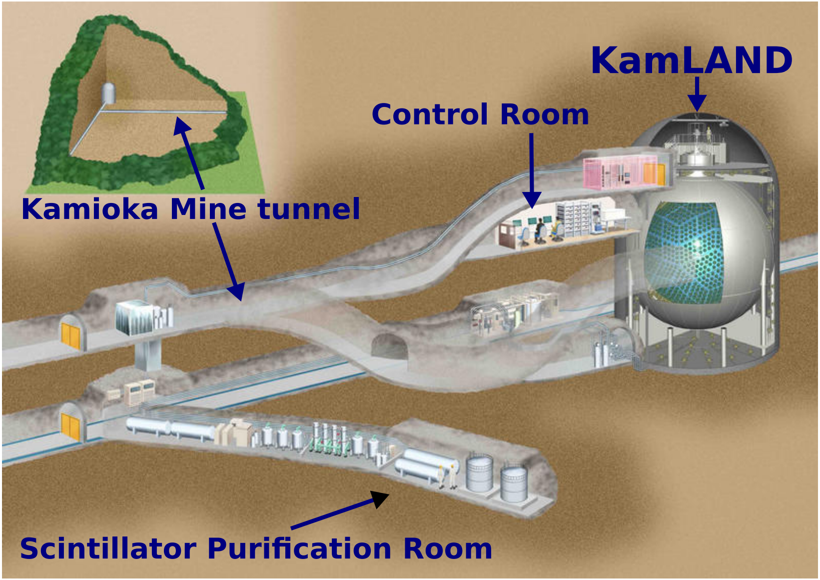
University of Hawaii, Manoa

michinar@hawaii.edu

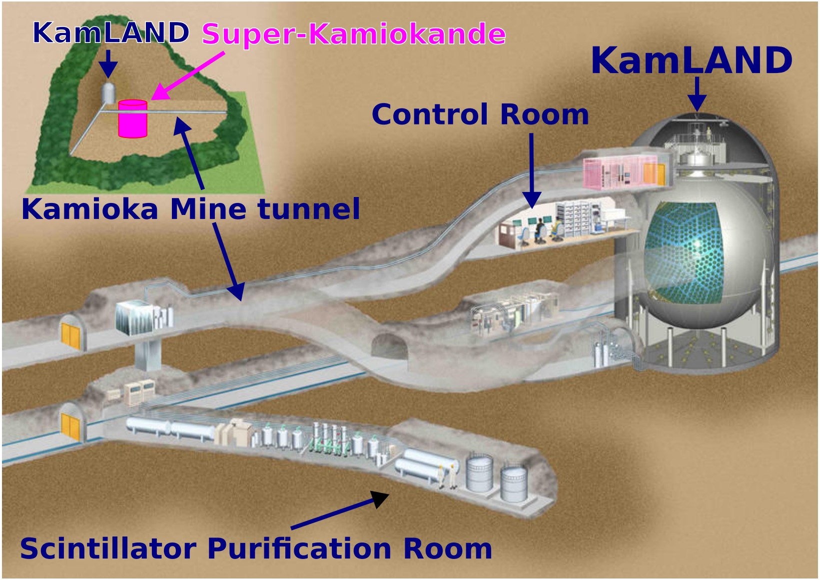
July 17, 2015

Overview

KamLAND: ν detector in Japan



KamLAND: ν detector in Japan



KamLAND: features

- Commissioned: 2001
- Detector medium: liquid scintillator
- Size: 1 kt
- Photomultiplier tubes (Hamamatsu):
  - 1325 17-inch, 7 ns rise-time
  - 779 20-inch, 10 ns rise-time
  - 34 % photo-coverage
- Analysis ν energy: $\sim$ MeV
- Energy resolution: $7.0 \pm 0.1\,\%$
- Vertex resolution: $13.8 \pm 2.3\,\mathrm{cm}/\sqrt{\mathrm{E(MeV)}}$

KamLAND: features

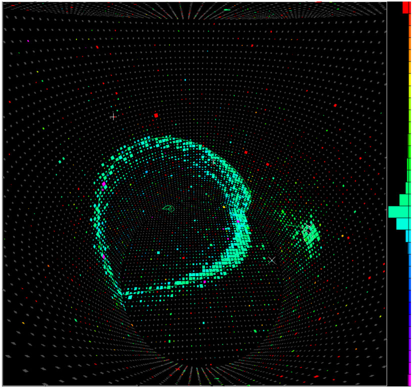
- Commissioned: 2001
- Detector medium: liquid scintillator
- Size: 1 kt
- Photomultiplier tubes (Hamamatsu):
  - 1325 17-inch, 7 ns rise-time
  - 779 20-inch, 10 ns rise-time
  - 34 % photo-coverage
- Analysis ν energy: $\sim$ MeV
- Energy resolution: $7.0 \pm 0.1\,\%$
- Vertex resolution: $13.8 \pm 2.3\,\mathrm{cm}/\sqrt{\mathrm{E(MeV)}}$
- Directional sensitivity: NONE

KamLAND: features

- Commissioned: 2001
- Detector medium: liquid scintillator
- Size: 1 kt
- Photomultiplier tubes (Hamamatsu):
  - 1325 17-inch, 7 ns rise-time
  - 779 20-inch, 10 ns rise-time
  - 34 % photo-coverage
- Analysis ν energy: $\sim$ MeV
- Energy resolution: $7.0 \pm 0.1\,\%$
- Vertex resolution: $13.8 \pm 2.3\,\mathrm{cm}/\sqrt{\mathrm{E(MeV)}}$
- Directional sensitivity: NONE
- No analysis at higher energies

Directionality in water

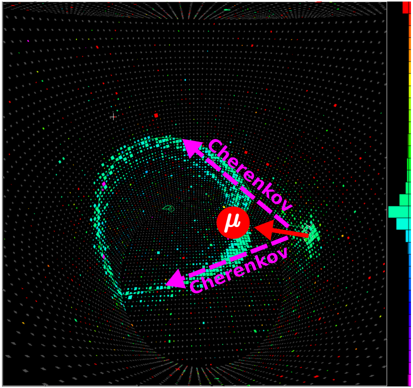
Super-Kamiokande



- Cherenkov ring

Directionality in water

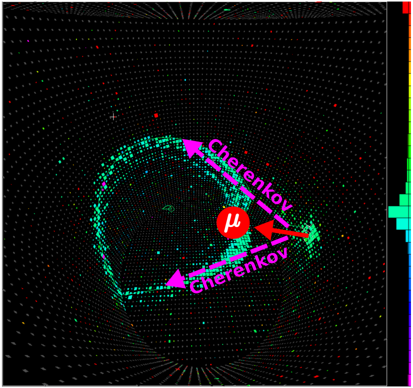
Super-Kamiokande



- Cherenkov ring
- shows charged particle direction

Directionality in water

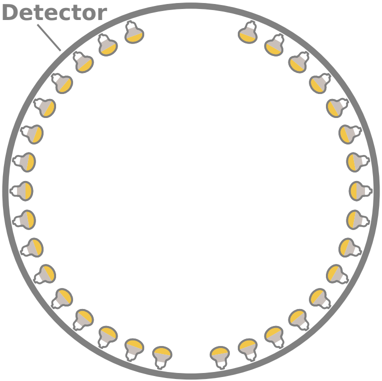
Super-Kamiokande



- Cherenkov ring
- shows charged particle direction
- Can we do something similar in scintillator?

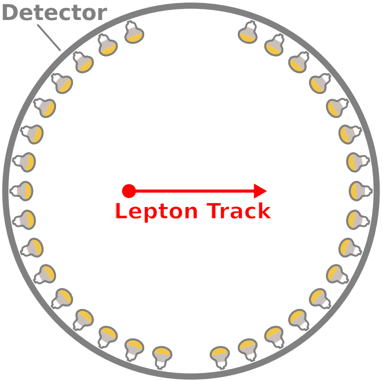
In scintillator...

KamLAND

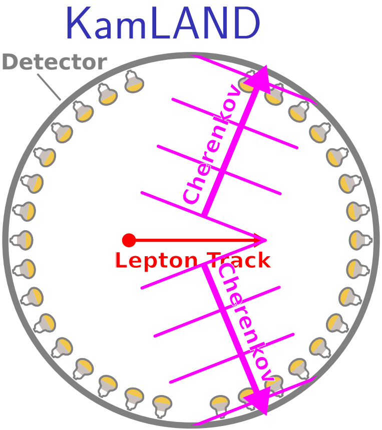


In scintillator...

KamLAND

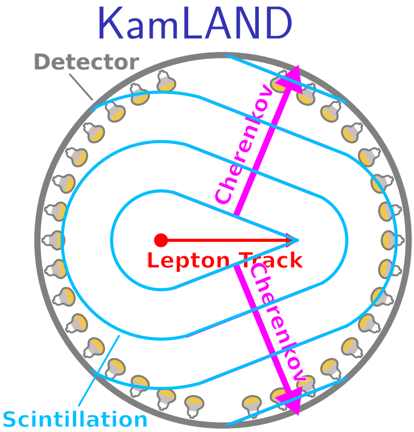


In scintillator...



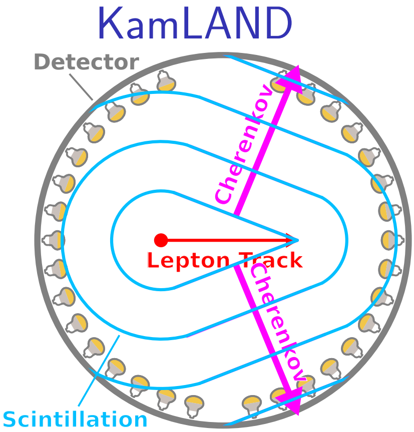
- Cherenkov is emitted

In scintillator...



- Cherenkov is emitted
- Along with isotropic scintillation

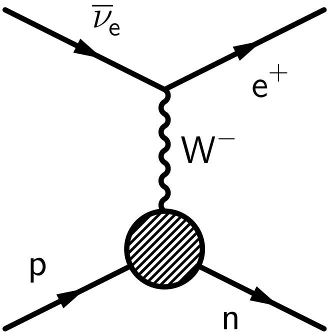
In scintillator...



- Cherenkov is emitted
- Along with isotropic scintillation
- $\implies$ Cannot simply use Cherenkov for directionality

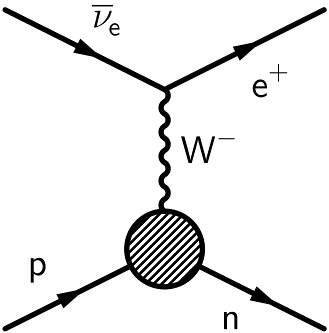
Furthermore...

Inverse-beta decay



Furthermore...

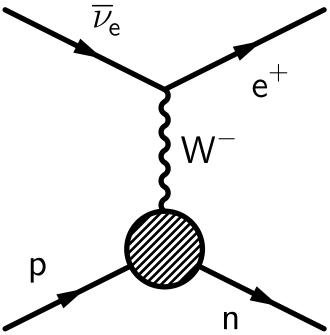
Inverse-beta decay



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

Furthermore...

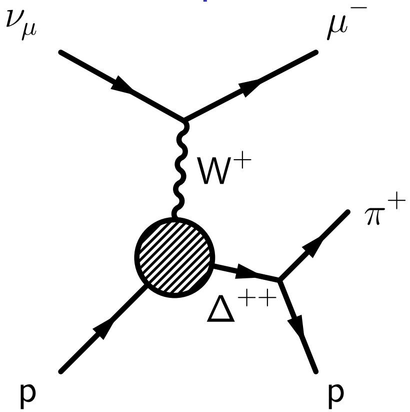
Inverse-beta decay



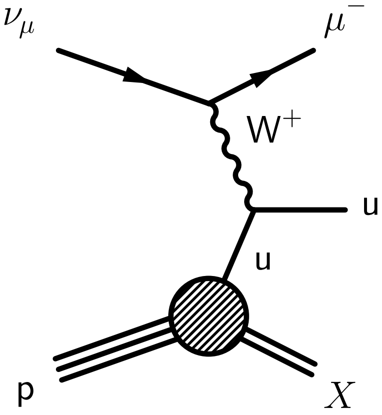
- KamLAND is used to seeing simple kinematics at low energies (MeV)
- Single final-state lepton

But at higher energies, the kinematics is not so simple

Resonance production

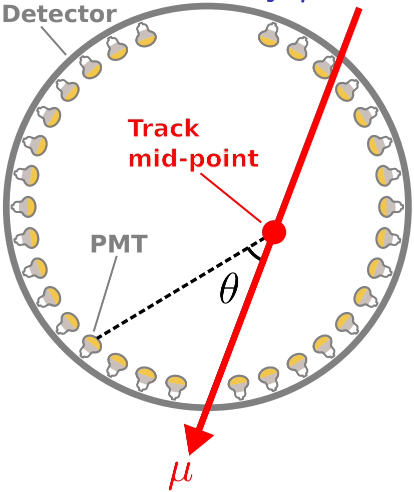


Deep inelastic scattering

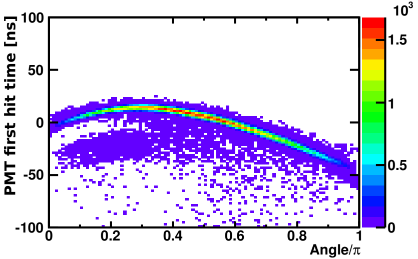


Many photons at high energy in scintillator

Cosmic ray μ

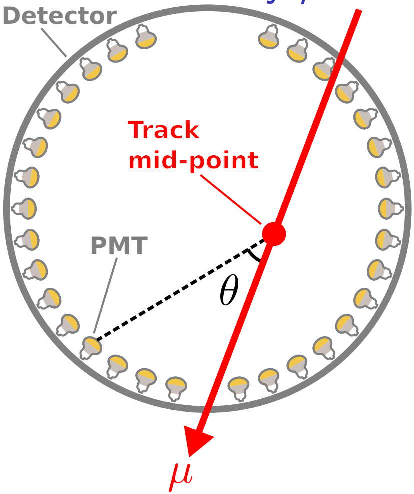


Hit time vs angle

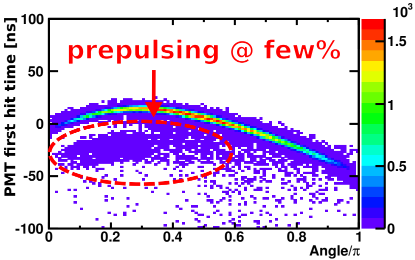


Many photons at high energy in scintillator

Cosmic ray μ

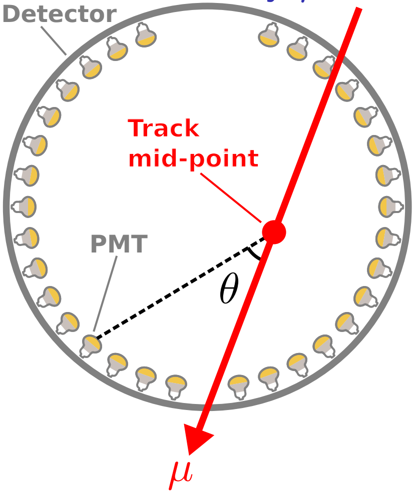


Hit time vs angle

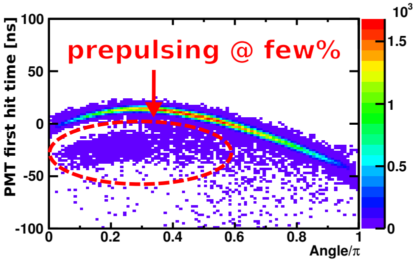


Many photons at high energy in scintillator

Cosmic ray μ



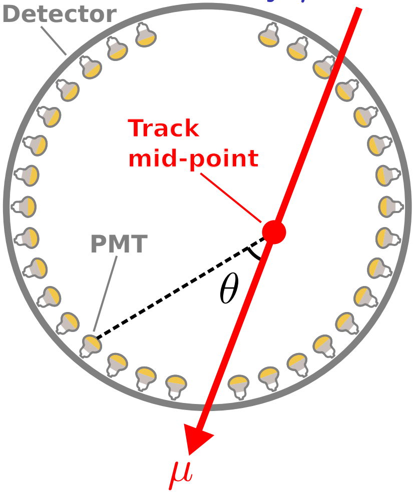
Hit time vs angle



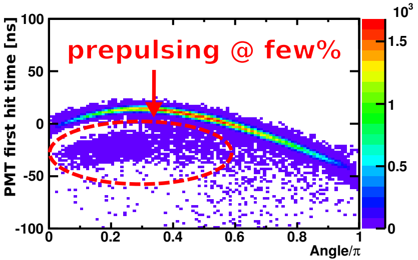
- Fitters must to be robust against these statistical outliers

Many photons at high energy in scintillator

Cosmic ray μ



Hit time vs angle



- Fitters must to be robust against these statistical outliers
- Or we can just use **LAPPD**s!

There are many problems...

- Light is emitted isotropically

There are many problems...

- Light is emitted isotropically
- At high energies:

There are many problems...

- Light is emitted isotropically
- At high energies:
  - complicated kinematics
  - multiple final-state particles

There are many problems...

- Light is emitted isotropically
- At high energies:
  - complicated kinematics
  - multiple final-state particles
- Many photons $\implies$ pre-pulsing

Let's change perspective and think more simple

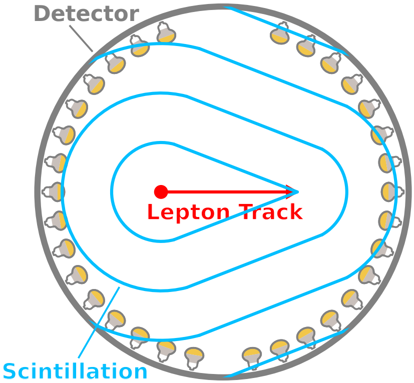
Let's change perspective and think more simple

- There are two pieces of information arriving at PMTs

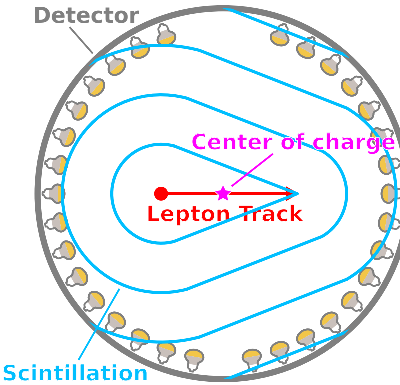
Let's change perspective and think more simple

- There are two pieces of information arriving at PMTs
  - Charge
  - Time

Fit direction with charge and time

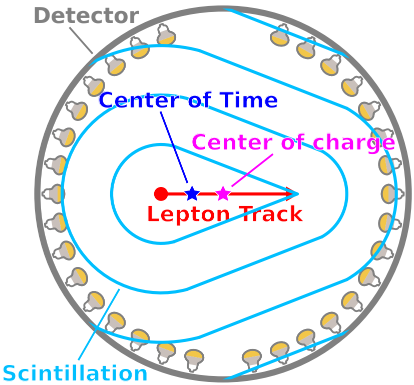


Fit direction with charge and time



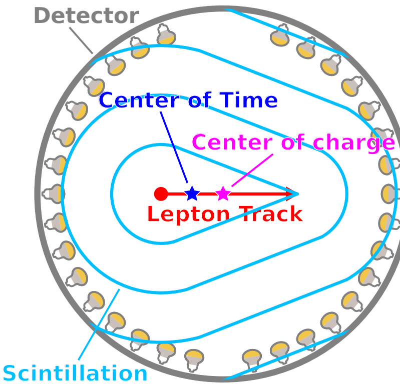
- Use center of charge to fit middle of track

Fit direction with charge and time



- Use center of charge to fit middle of track
- Use center of time to fit near end of track

Fit direction with charge and time



- Use center of charge to fit middle of track
- Use center of time to fit near end of track
- And just connect dots to find direction!

Question:

Question:

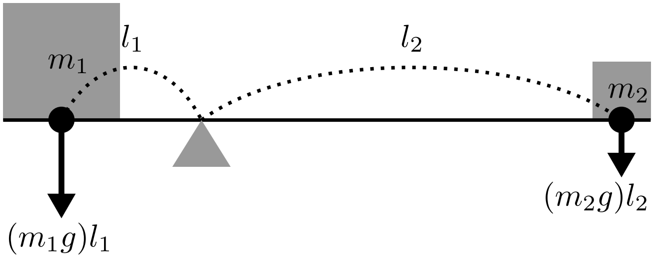
- But, what do we use for the weights in the **weighted mean**:

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

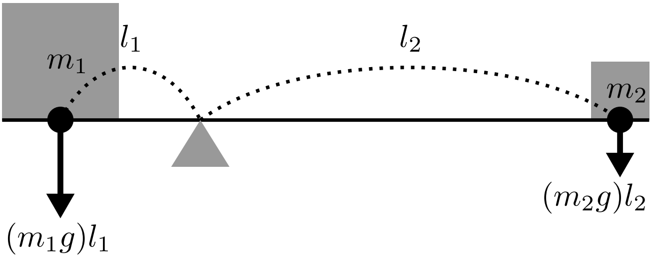
when calculating center of charge and time?

Let's review some basic physics...

What weight is used for *center of gravity*?



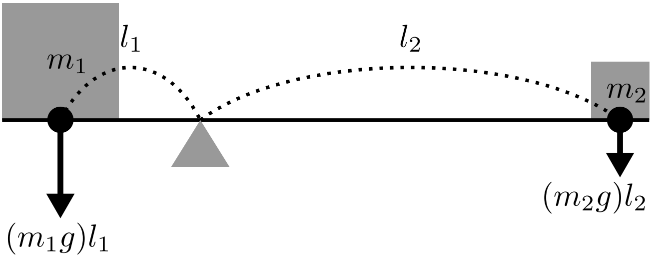
What weight is used for *center of gravity*?



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*?

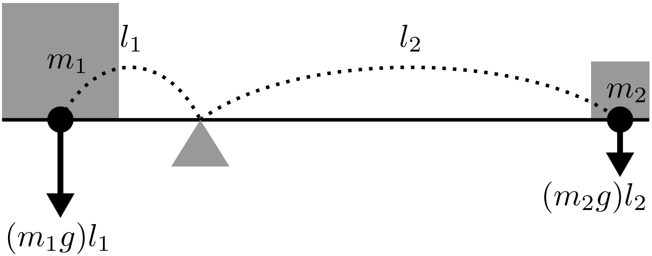


To find center of gravity:

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

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

What weight is used for *center of gravity*?



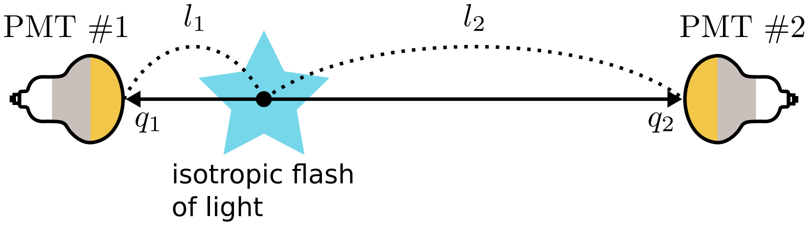
To find center of gravity:

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

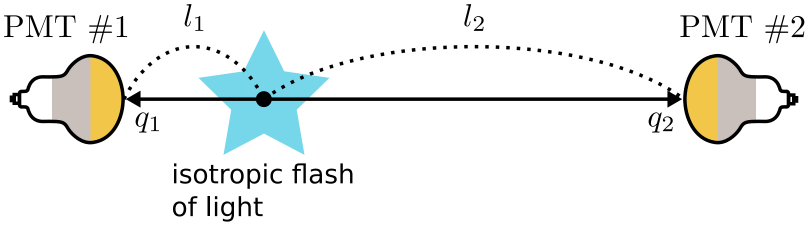
$\implies -(m_1)l_1 + (m_2)l_2 = 0$

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

What weight is used for *center of charge*?

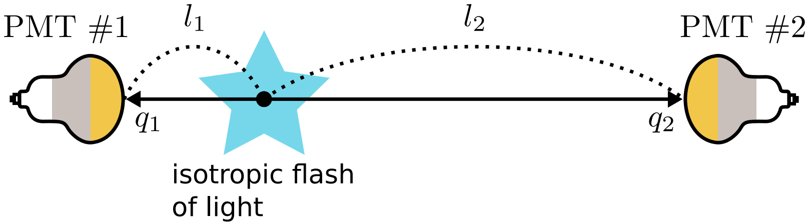


What weight is used for *center of charge*?



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

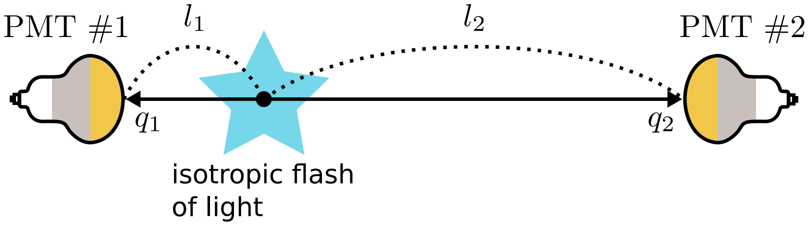
What weight is used for *center of charge*?



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

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

What weight is used for *center of charge*?

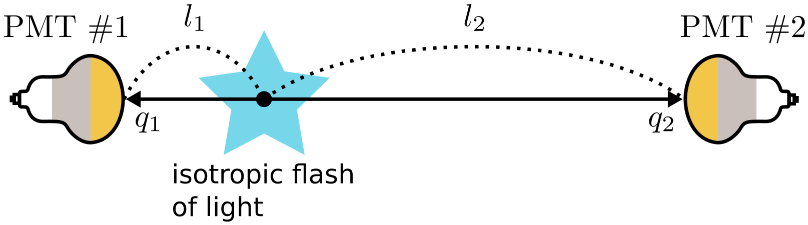


$$q_1 \propto \frac{1}{l_1^2}, \quad q_2 \propto \frac{1}{l_2^2}$$

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

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

What weight is used for *center of charge*?



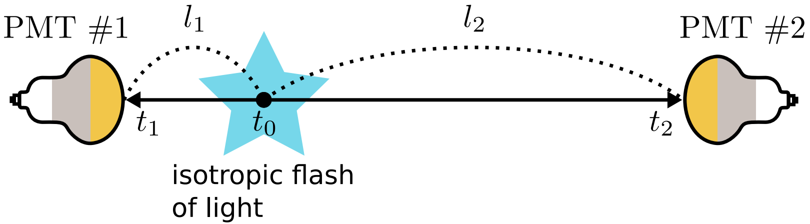
$$q_1 \propto \frac{1}{l_1^2}, \quad q_2 \propto \frac{1}{l_2^2}$$

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

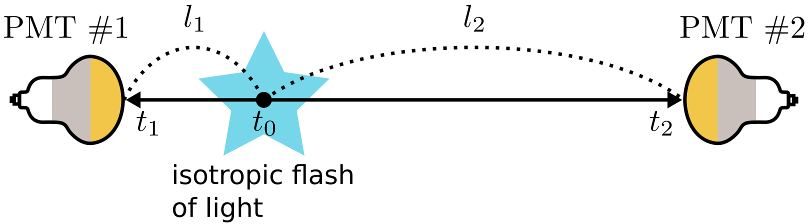
$$\implies -(\sqrt{q_1})l_1 + (\sqrt{q_2})l_2 = 0$$

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

What weight is used for *center of time*?



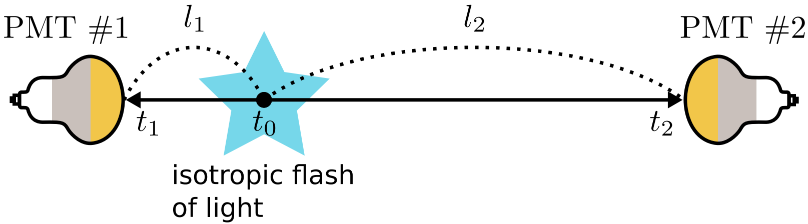
What weight is used for *center of time*?



Let $\Delta t_i \equiv t_i - t_0$

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

What weight is used for *center of time*?

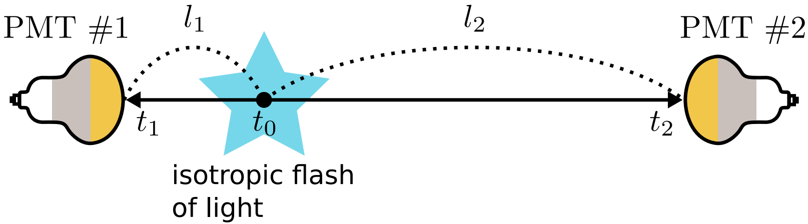


Let $\Delta t_i \equiv t_i - t_0$

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

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

What weight is used for *center of time*?



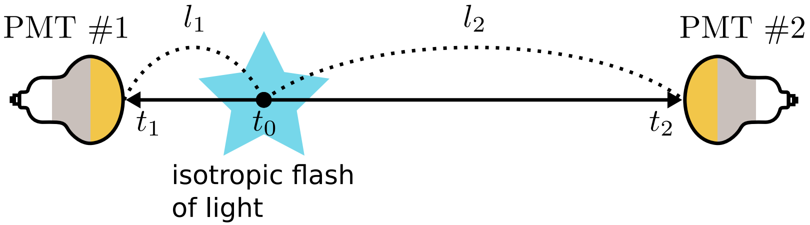
Let $\Delta t_i \equiv t_i - t_0$

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

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

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

What weight is used 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**: $w_i = \frac{1}{\Delta t_i}$

Conclusion

- Use **mass** as weight for *center of gravity*.

Conclusion

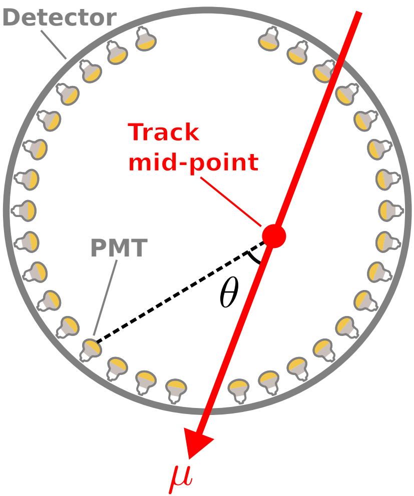
- Use **mass** as weight for *center of gravity*.
- Use $\sqrt{\textbf{charge}}$ as weight for *center of charge*.

Conclusion

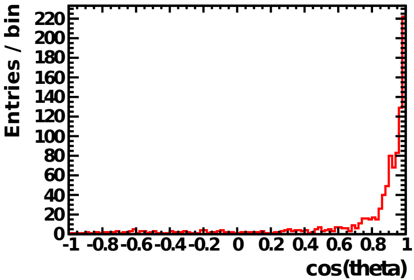
- Use **mass** as weight for *center of gravity*.
- Use $\sqrt{\textbf{charge}}$ as weight for *center of charge*.
- Use $\left(\dfrac{1}{\textbf{time}}\right)$ as weight for *center of time*.

Test algorithm against μ (Data)

Cosmic ray μ

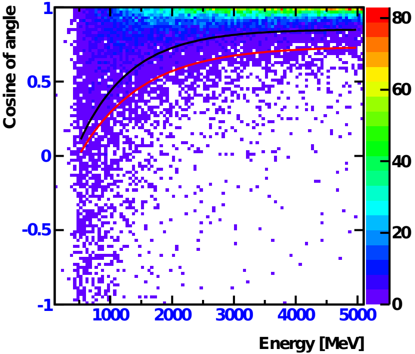


Agreement with μ-fitter
which uses
entry/exit points

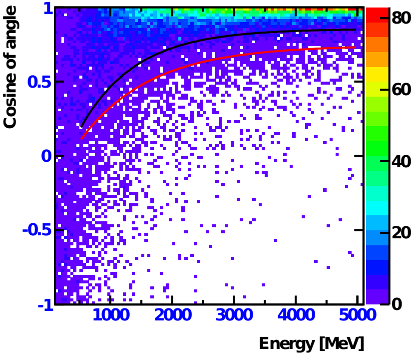


Test algorithm against ν (MC)

$\nu_e + {}^{1}\mathrm{H} \xrightarrow{\mathrm{CC}} e^- +$



$\nu_e + {}^{12}\mathrm{C} \xrightarrow{\mathrm{CC}} e^- +$

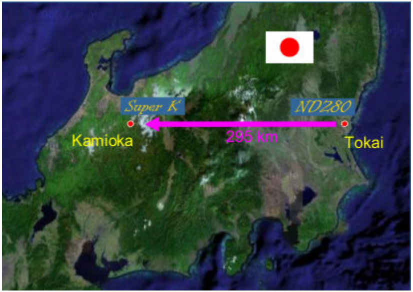


- Black line: $1\,\sigma$ of reconstructed angle from ν direction
- Red line: $1\,\sigma$ of lepton angle from ν direction

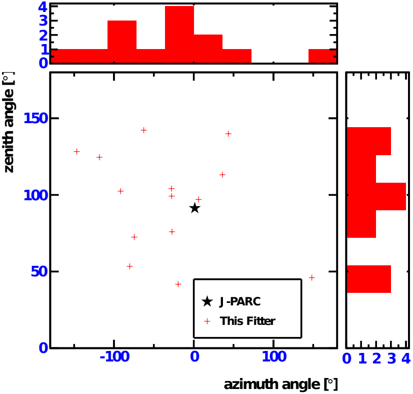
Test algorithm against T2K events (Data)

(Selected with spill-time so no backgrounds)

Map



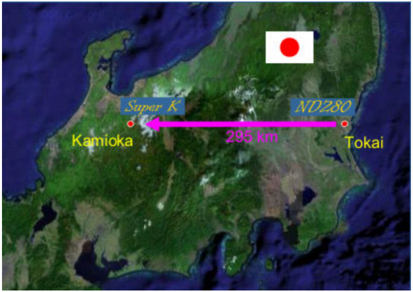
Agreement with J-PARC direction



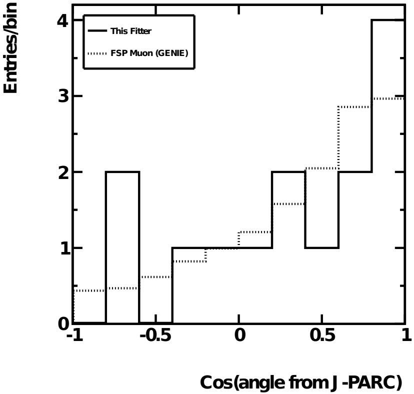
Test algorithm against T2K events (Data)

(Selected with spill-time so no backgrounds)

Map



Agreement with MC



Track Reconstruction and Particle ID

Hellgartner's algorithm

(former LENA grad student)

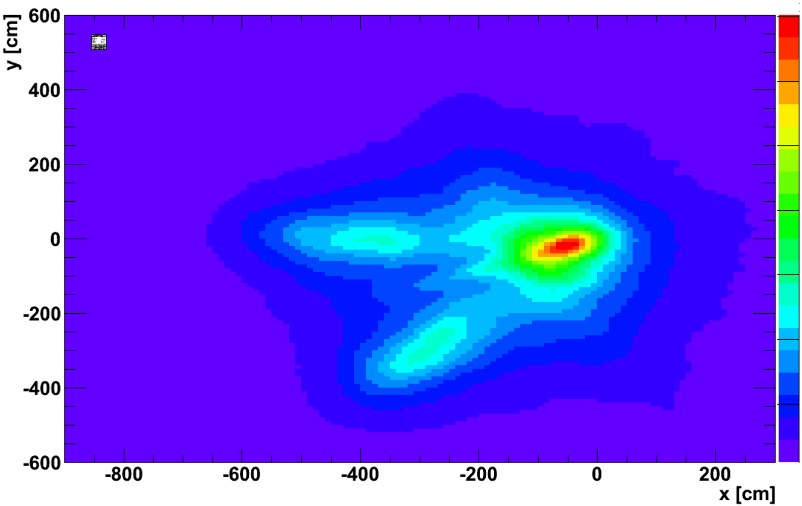
$$h(\vec{x}, t) = \sum_{i=1}^{N_{\text{PMT}}} \Theta(q_i - q_{\text{threshold}}) \sum_{j=1}^{N_\gamma} f(t_{ij} - t_i^{\text{TOF}}, t)$$

where N_{PMT}: number of PMTs
N_γ: number of photon hits to count per PMT
q_i: charge on i-th PMT, $q_{\text{threshold}}$: 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 $\vec{x}$

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

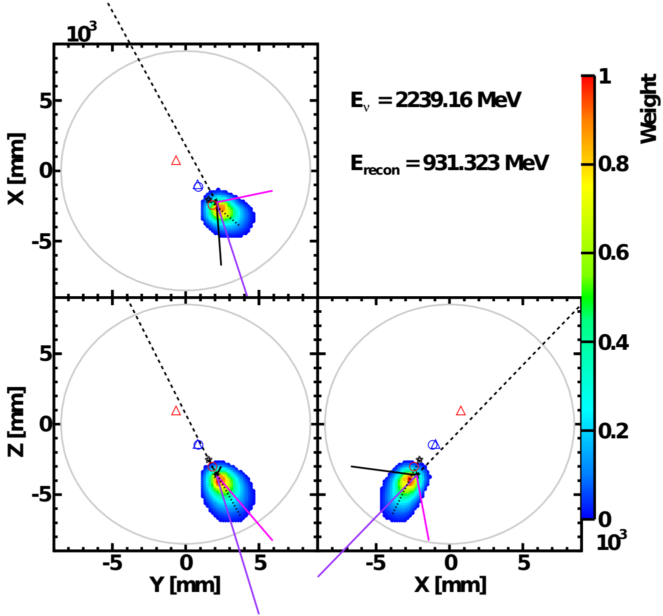
Figure of merit for each test point in space $= \int_{-\infty}^{\infty} |h(\vec{x}, t)|^2 \, \mathrm{d}t$

Test Hellgartner on double 1 GeV muons (MC)

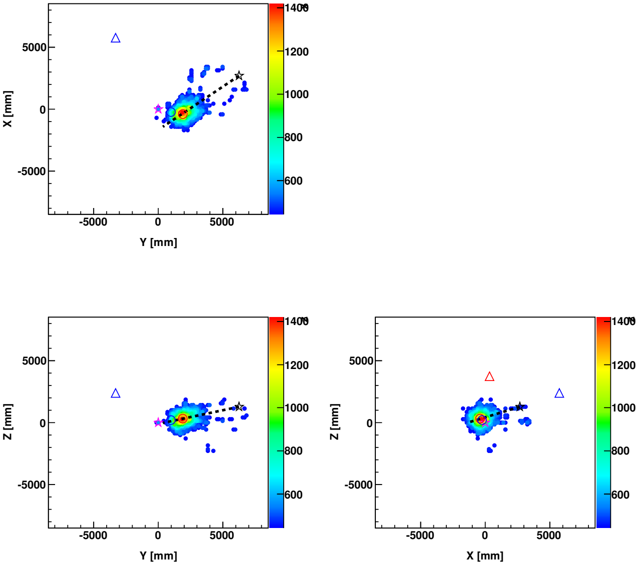


Dominikus Hellgartner

Test Hellgartner on 2 GeV ν_e (MC)



Test Hellgartner on T2K events (Data)



Lepton discrimination algorithm

Explanation is here.

Test lepton discrimination (MC)