High Energy Analysis at KamLAND and Application to Dark Matter Search

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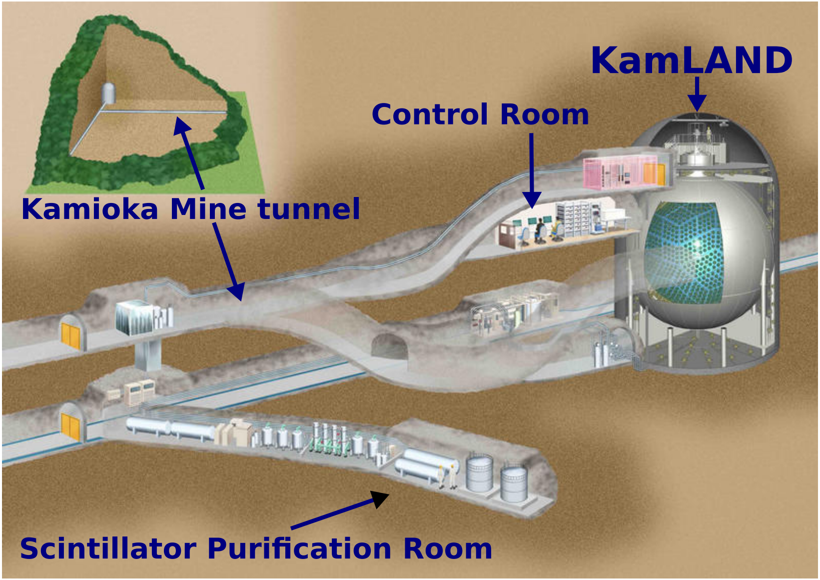
July 19, 2015

Overview

KamLAND: ν detector in Japan



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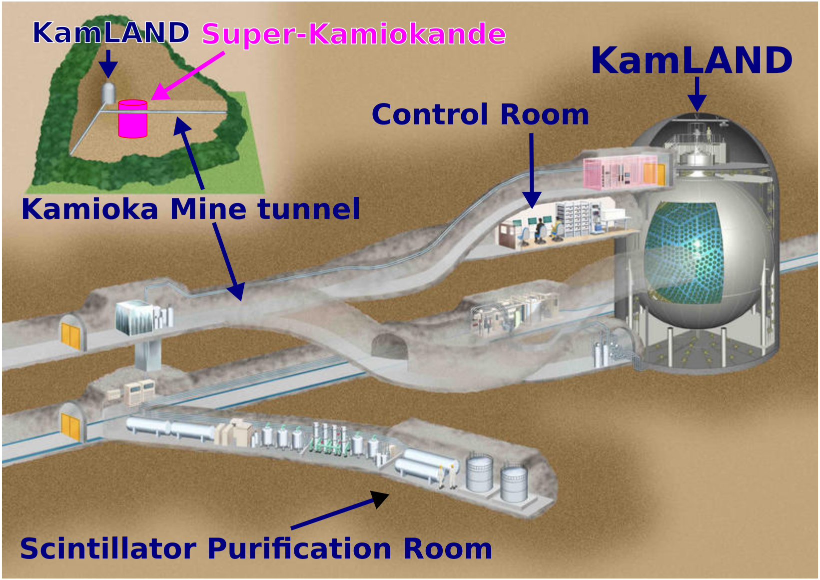

KamLAND: features

- Commissioned: 2001
- Medium: liquid scintillator
  - Decay constants: $\tau_1 = 4.0\,\mathrm{ns}$, $\tau_2 = 8.6\,\mathrm{ns}$
- Size: 1 kt
- Photomultiplier tubes (Hamamatsu):
  - 1325 17-inch, 7 ns rise-time, 3.5 ns TTS
  - 779 20-inch, 10 ns rise-time, 5.5 ns TTS
  - 34 % photo-coverage
- Analysis: $\sim$ MeV $\overline{\nu}_\mathrm{e}$ (inverse-beta decay)
- Energy resolution: $7.0 \pm 0.1\,\%$
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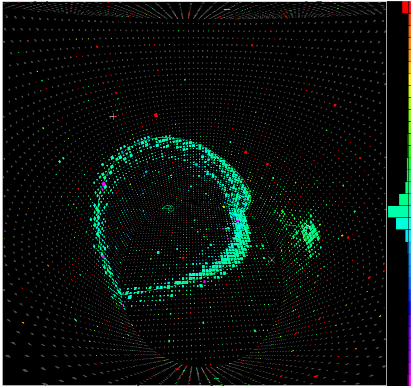
- Directional sensitivity: NONE
- No analysis at higher energies

Directionality in water

Super-Kamiokande



- Cherenkov ring

Directionality in water

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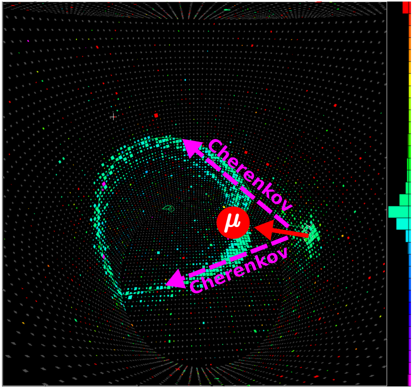

- Cherenkov ring
- shows charged particle direction

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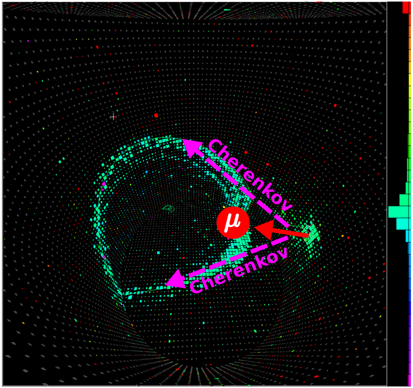
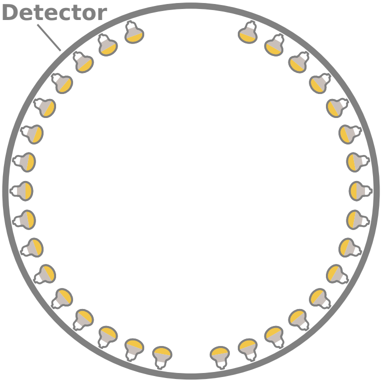


- Cherenkov ring
- shows charged particle direction
- Can we do something similar in scintillator?

In scintillator...

KamLAND



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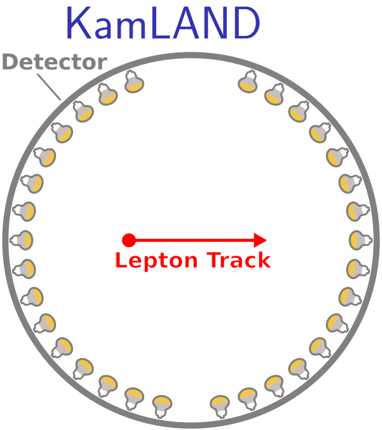

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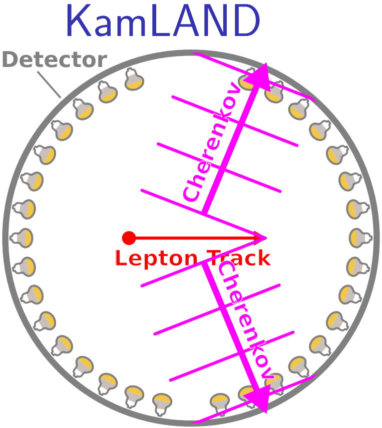
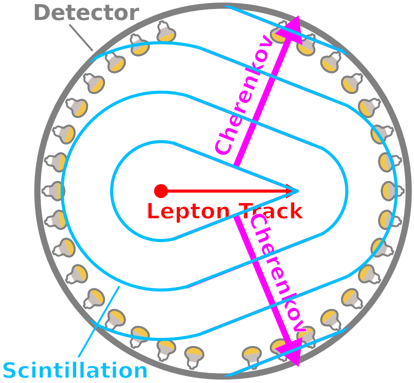


- Cherenkov is emitted

In scintillator...

KamLAND



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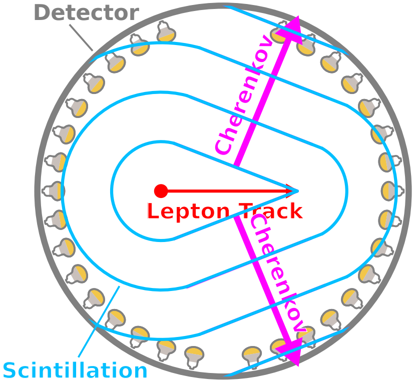
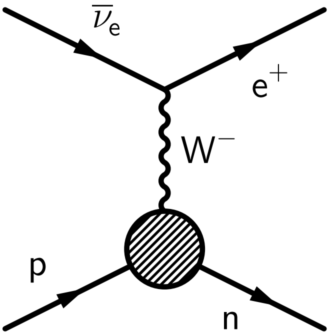


- Cherenkov is emitted
- Along with isotropic scintillation
- $\implies$ Cannot simply use Cherenkov for directionality

Furthermore...

Inverse-beta decay



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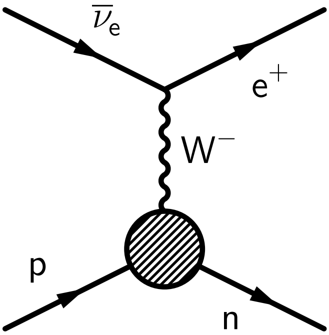

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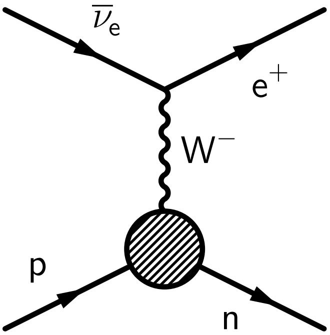
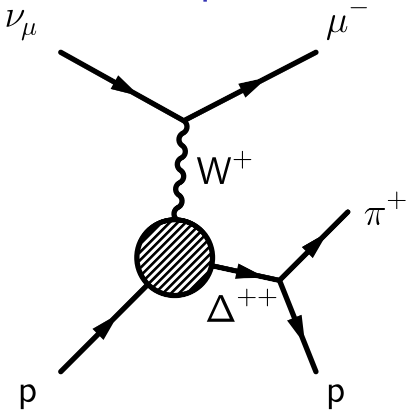


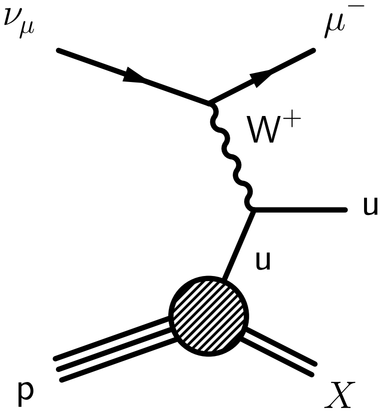
- KamLAND is used to seeing simple kinematics at low energies ($\sim$ MeV)
- Single final-state lepton

But at higher energies, the kinematics is not so simple

Resonance production



Deep inelastic scattering

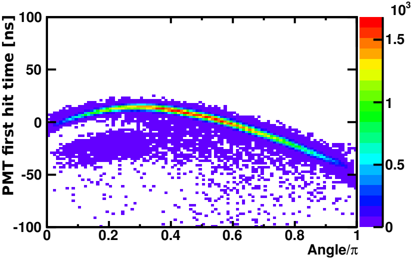


Many photons at high energy in scintillator

Cosmic ray μ

through_going_muon.pdf

Hit time vs angle



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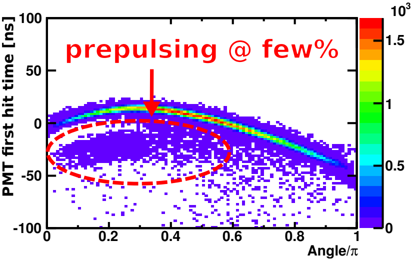

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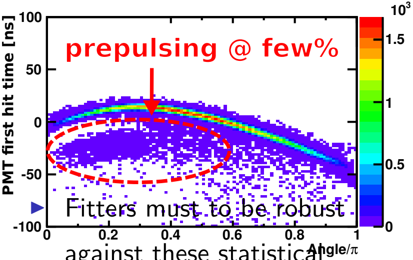

- Fitters must to be robust against these statistical outliers

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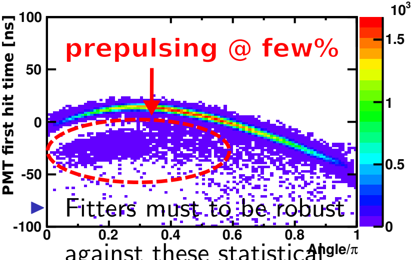

- Fitters must to be robust against these statistical outliers
- Or we can just use **LAPPD**s!

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- 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

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- There are two pieces of information arriving at PMTs

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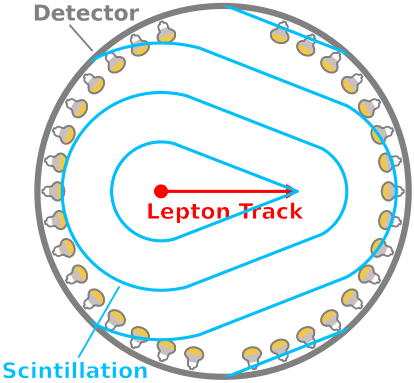
- There are two pieces of information arriving at PMTs
  - Charge
  - Time

Fit direction with charge and time



Idea: John Learned

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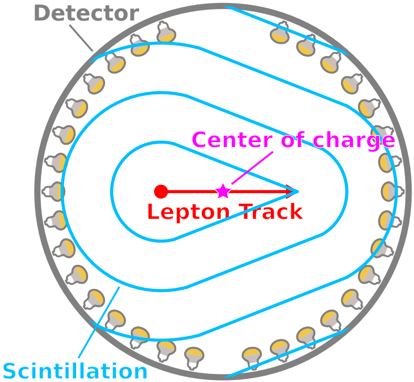
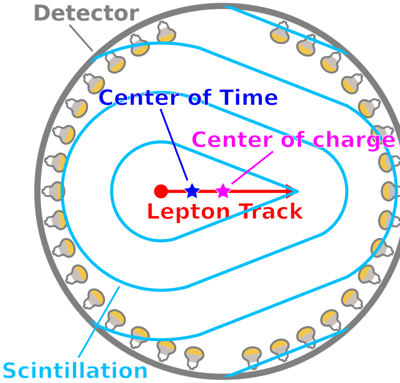


Idea: John Learned

- Use center of charge to fit middle of track

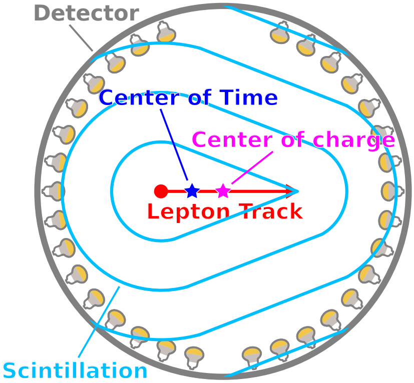
Fit direction with charge and time



Idea: John Learned

- 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



Idea: John Learned

- 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:

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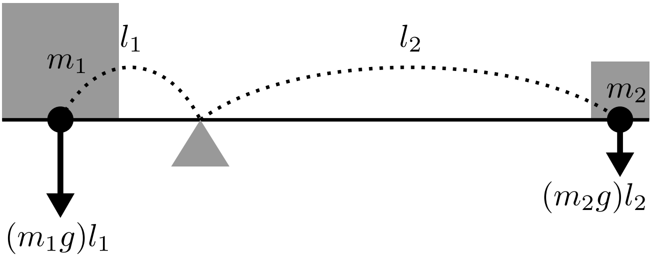
- But, what do we use for the weights in the **weighted mean**:

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

when calculating center of charge and time?

Let's review some basic physics...

What weight is used for *center of gravity*?



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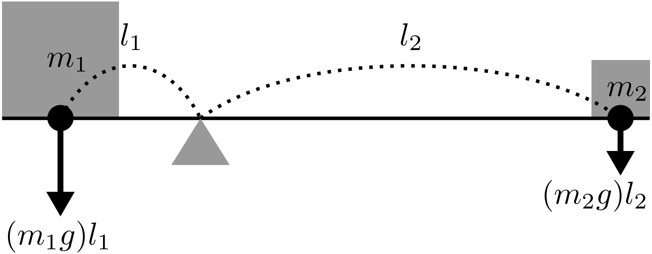

To find center of gravity:

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

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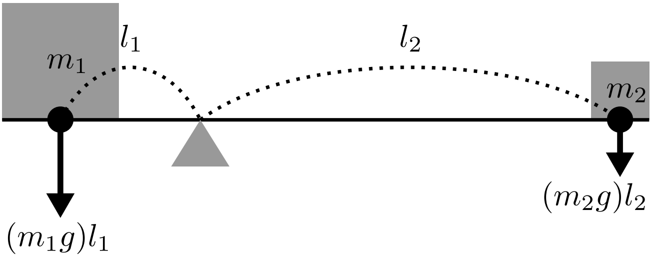

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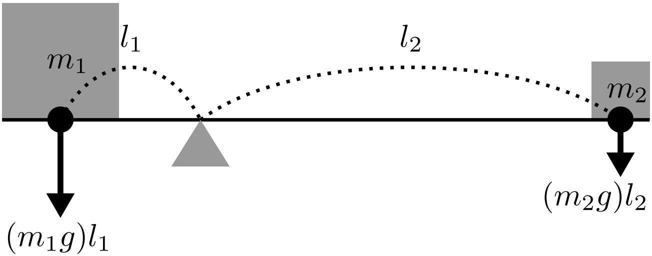

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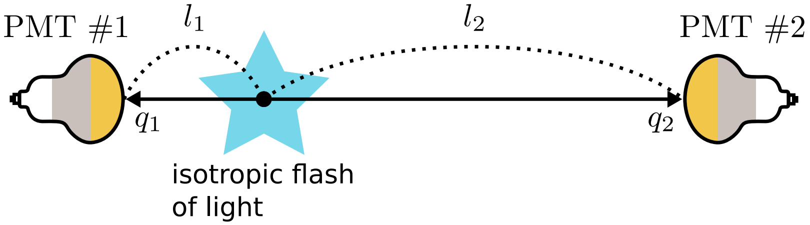
$\therefore$ weight is **mass**: $w_i = m_i$

What weight is used for *center of charge*?



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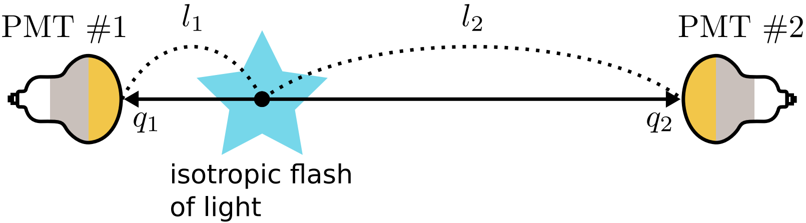

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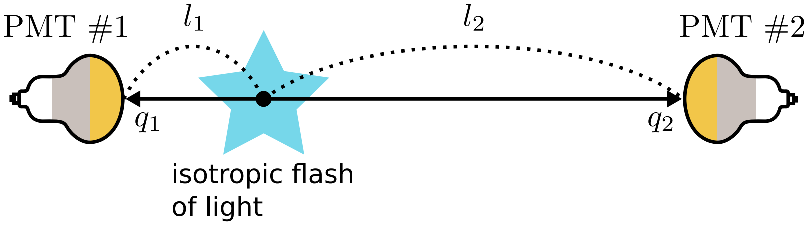

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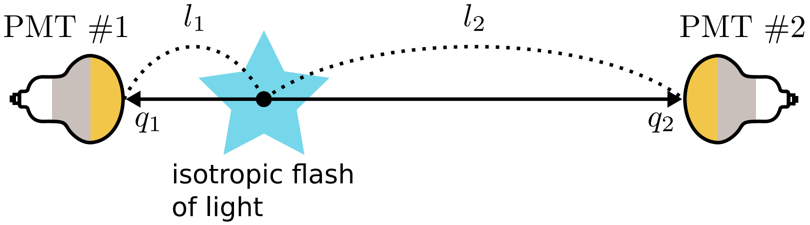

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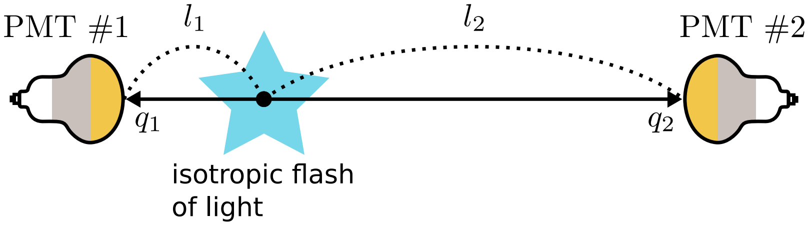

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$\therefore$ weight is $\sqrt{\textbf{charge}}$: $w_i = \sqrt{q_i}$

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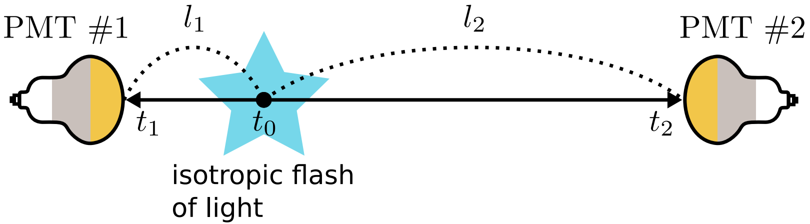

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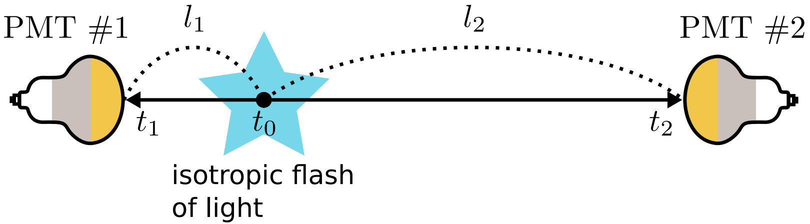

Let $\Delta t_i \equiv t_i - t_0$

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

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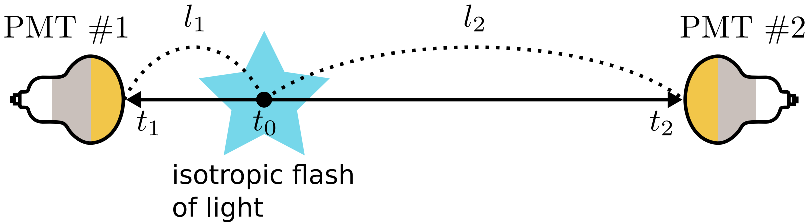

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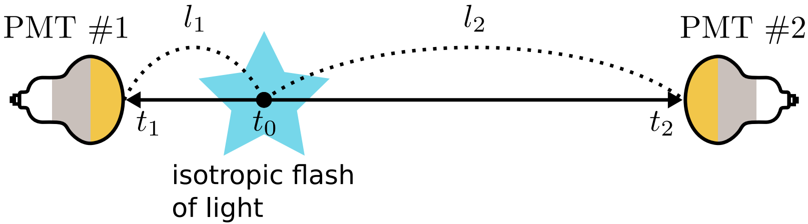

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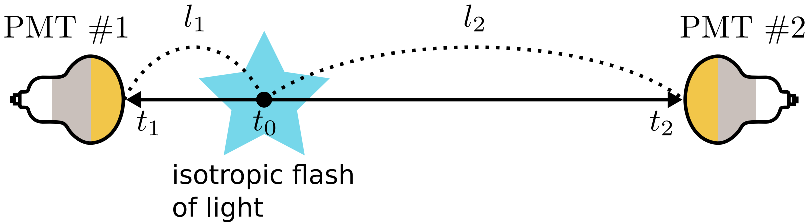

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$\therefore$ weight is **inverse of time**: $w_i = \frac{1}{\Delta t_i}$

Conclusion

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

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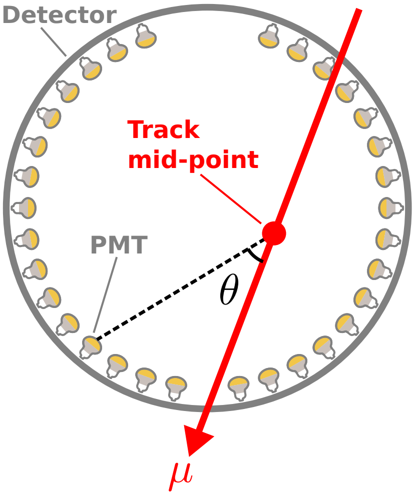
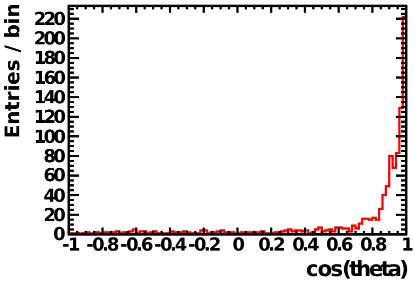
- Use $\sqrt{\textbf{charge}}$ as weight for *center of charge*.
- Use $\left(\frac{1}{\textbf{time}}\right)$ as weight for *center of time*.

Test algorithm against μ (Data)

Cosmic ray μ

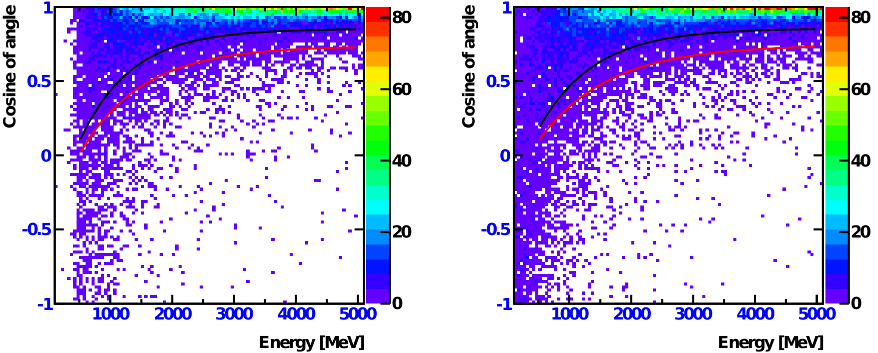


Agreement with μ-fitter
which uses
entry/exit points



Test algorithm against ν (MC)

$\nu_e + {}^1\mathrm{H} \xrightarrow{CC} e^- +$ $\qquad$ $\nu_e + {}^{12}\mathrm{C} \xrightarrow{CC} e^- +$



Legend:

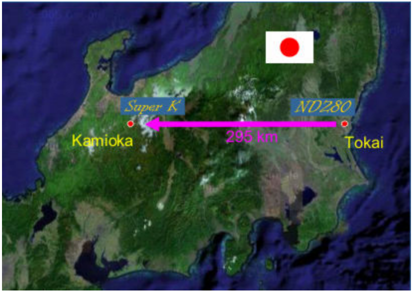
— $1\,\sigma$ of reconstructed angle from ν direction

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

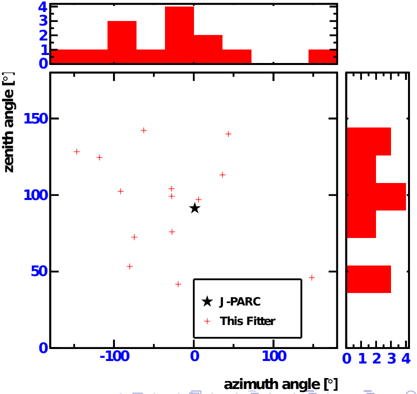
Test algorithm against T2K events (Data)

(Selected with spill-time so no backgrounds)

Map



Agreement with J-PARC direction



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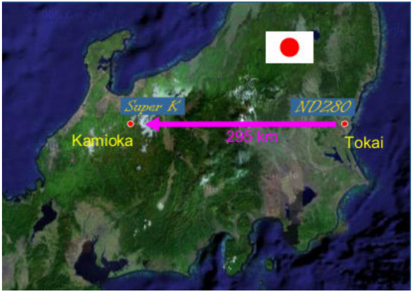
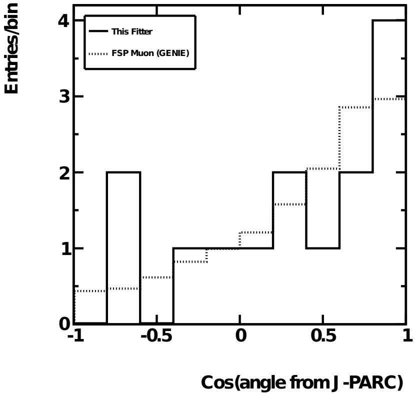


Agreement with MC



Track Reconstruction and Particle ID

Hellgartner's algorithm

(former LENA grad student)

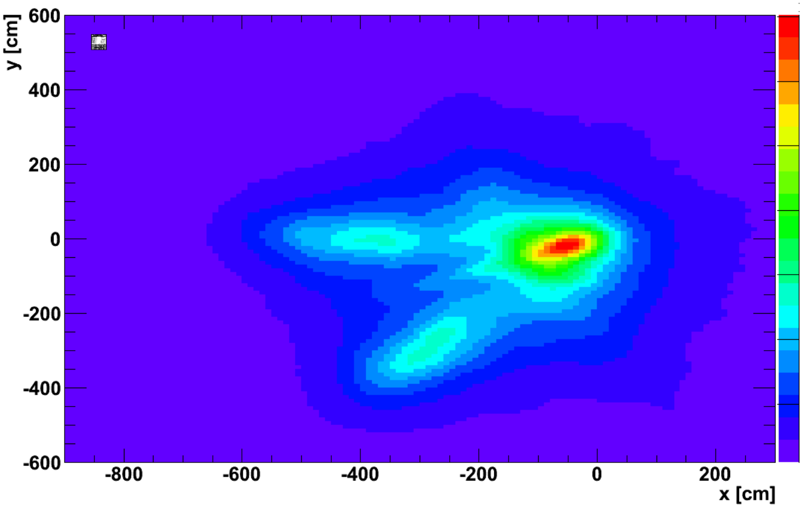
$$h(\vec{x}, t) = \sum_{i=1}^{N_{\text{PMT}}} \Theta(q_i - q_{\text{threshold}}) \sum_{j=1}^{N_\gamma} f(t_{ij} - t_i^{\text{TOF}}, t)$$

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 $\vec{x}$

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

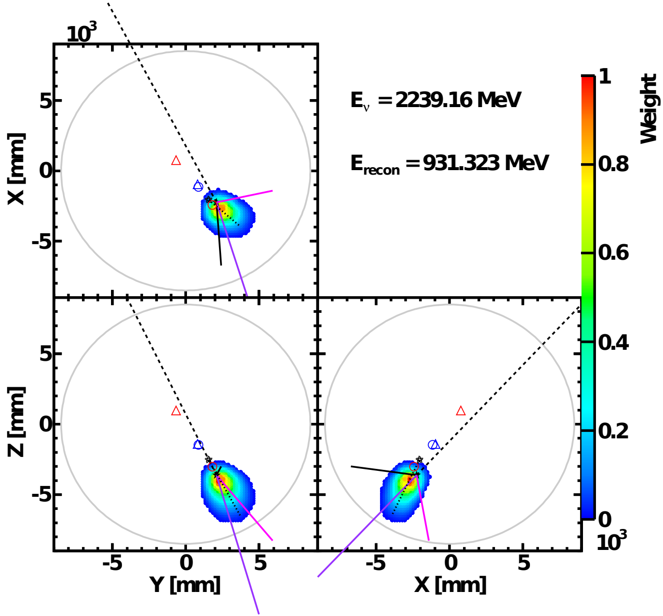
<u>**Figure of merit**</u> for each test point in space $= \int_{-\infty}^{\infty} |h(\vec{x}, t)|^2 \, \mathrm{d}t$

Test Hellgartner on double 1 GeV muons (MC)



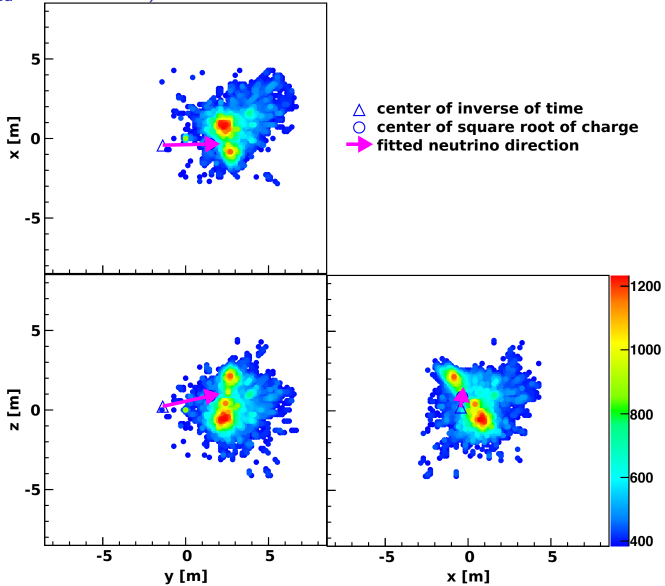
Dominikus Hellgartner

Test Hellgartner on 2 GeV ν_e (MC)



Test Hellgartner on T2K events (Data)

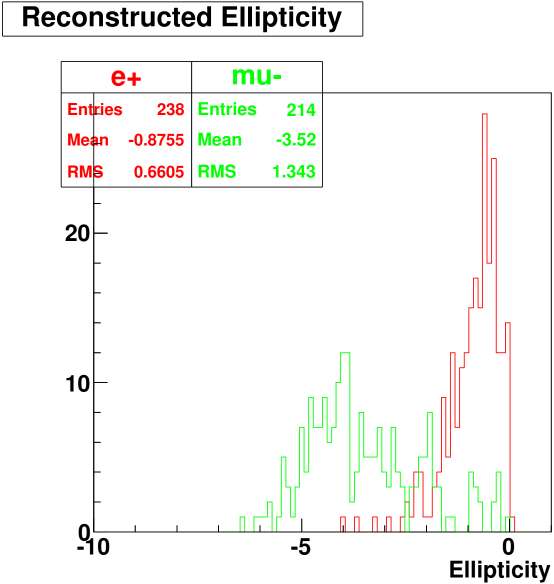
$(E_{\text{reconstructed}} = 363\,\text{MeV})$



Lepton discrimination algorithm

Explanation is here.

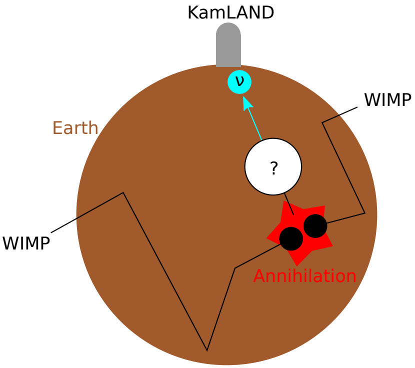
Test lepton discrimination (MC)



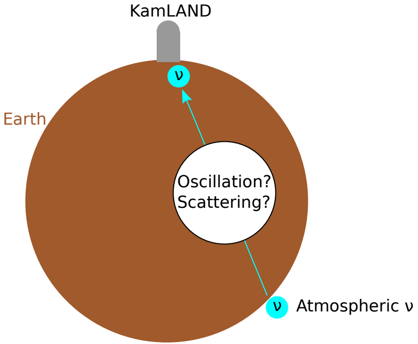
Search for dark matter

Dark matter detection scheme

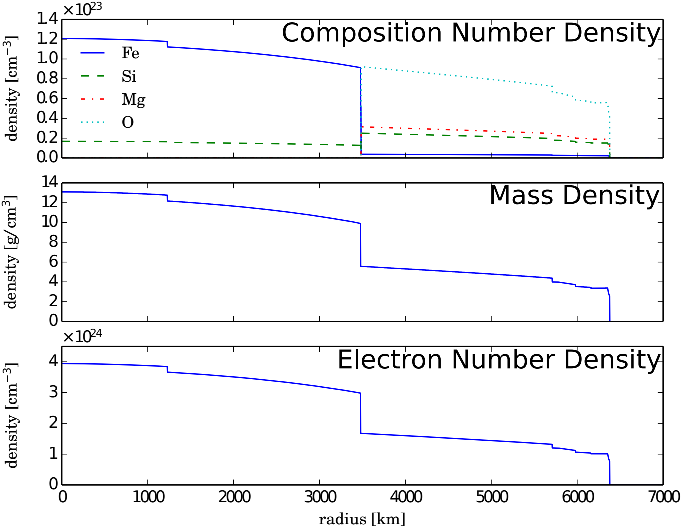
Signal: Dark matter (WIMP) annihilation induced ν



Background: atmospheric ν



Earth Model (PREM)



Neutrino Oscillation Parameters

(normal hierarchy, PDG 2014)

- $\sin^2(2\theta_{12}) = 0.846 \pm 0.021$

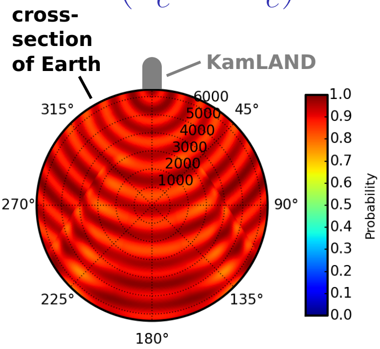
  $\implies \theta_{12} = 33.45^\circ$
- $\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2}$

  $\implies \theta_{13} = 8.88^\circ$
- $\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$

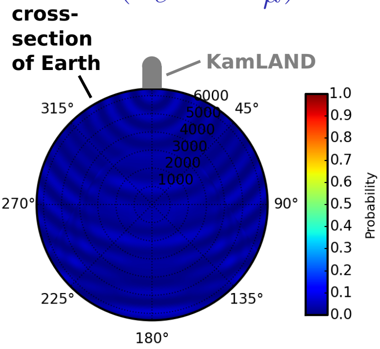
  $\implies \theta_{23} = 44.09^\circ$
- $\Delta m^2_{21} = 7.53 \pm 0.18 \times 10^{-5}\,\text{eV}$
- $\Delta m^2_{31} = 2.52 \pm 0.06 \times 10^{-3}\,\text{eV}$

1 GeV ν_e oscillation probability $P(\nu_e \to \nu_x)$ from inside Earth to KamLAND

$P(\nu_e \to \nu_e)$

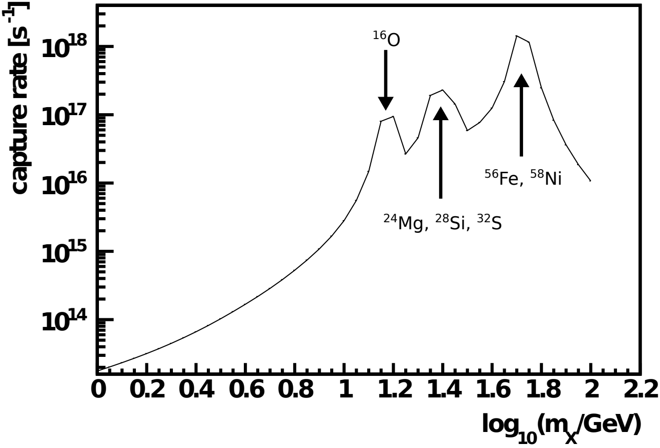


$P(\nu_e \to \nu_\mu)$



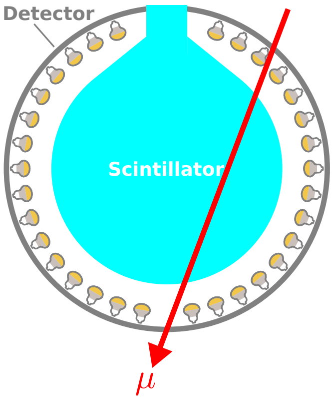
Dark matter capture in Earth vs mass m_x

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

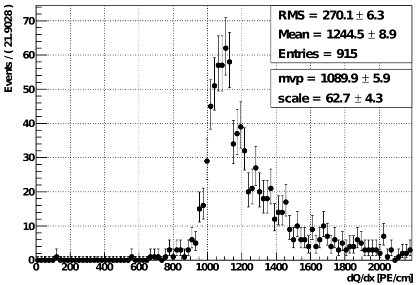


High energy ($\gtrsim$ GeV) calibration

Cosmic ray μ traversing scintillator



$\frac{\mathrm{d}Q}{\mathrm{d}x}$ [p.e./MeV] (data)



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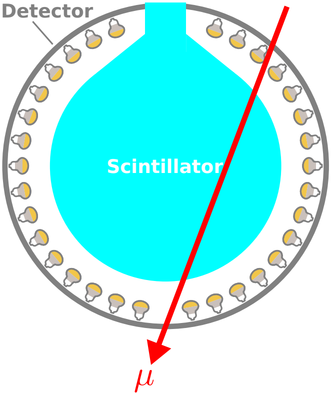
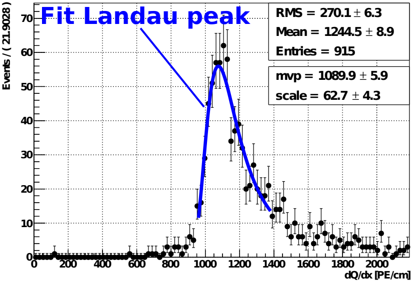
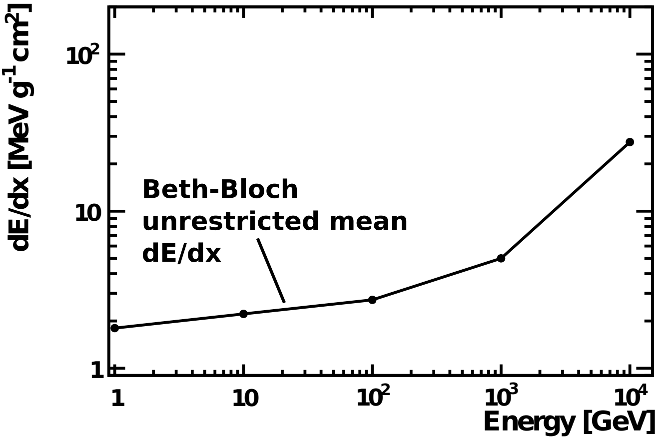


$\frac{\mathrm{d}Q}{\mathrm{d}x}$ [p.e./MeV] (data)



Fit $\frac{\mathrm{d}E}{\mathrm{d}x}$ for μ in scintillator (MC)



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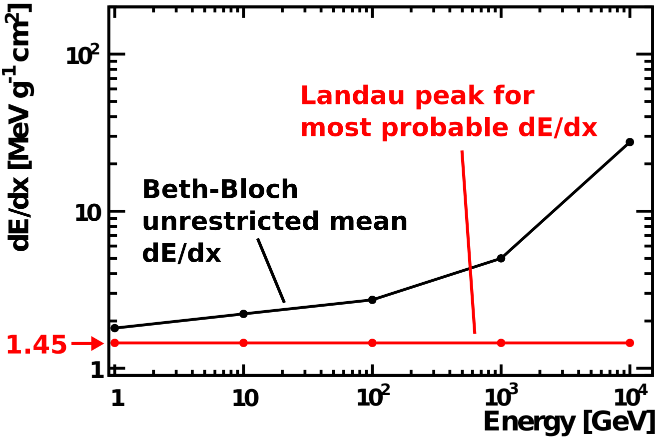
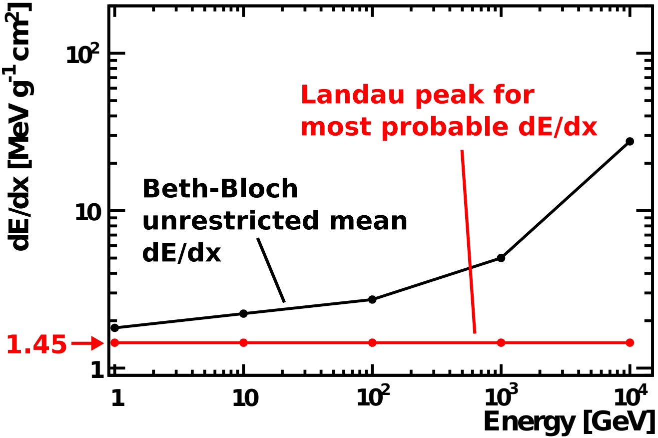


- Peak is stable across huge energy range!

Fit $\frac{\mathrm{d}E}{\mathrm{d}x}$ for μ in scintillator (MC)



- Peak is stable across huge energy range!
- $\Longrightarrow$ Use **peak** instead of mean for calibration

Data selection

- Total live time: 3671 days
- Event selection criteria:

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  - Fully contained events

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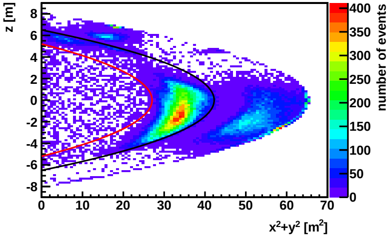
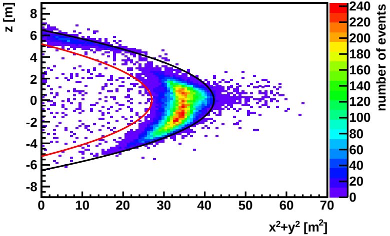
  - $E_{\text{reconstructed}} > 1\,\text{GeV}$ (predicted by theory)

Reconstructed Vertex

$E_{\text{reconstructed}} > 30\,\text{MeV}$



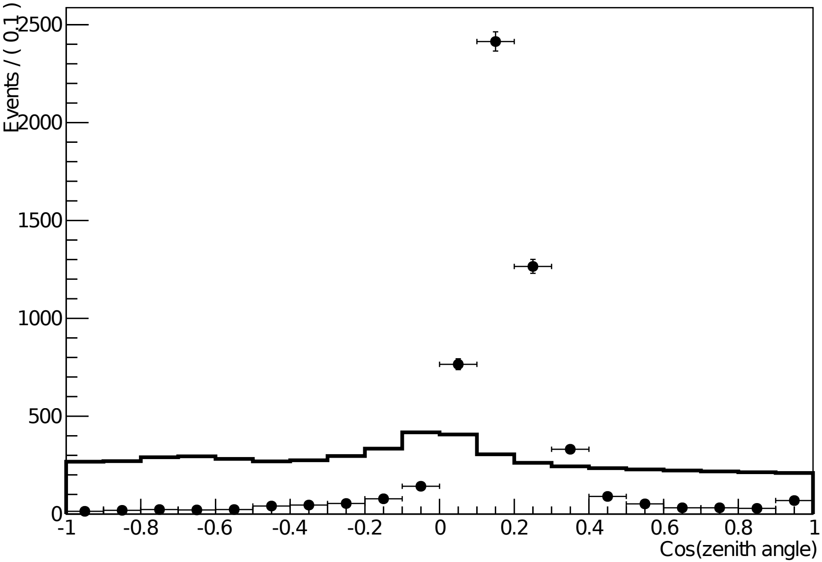
$E_{\text{reconstructed}} > 1\,\text{GeV}$



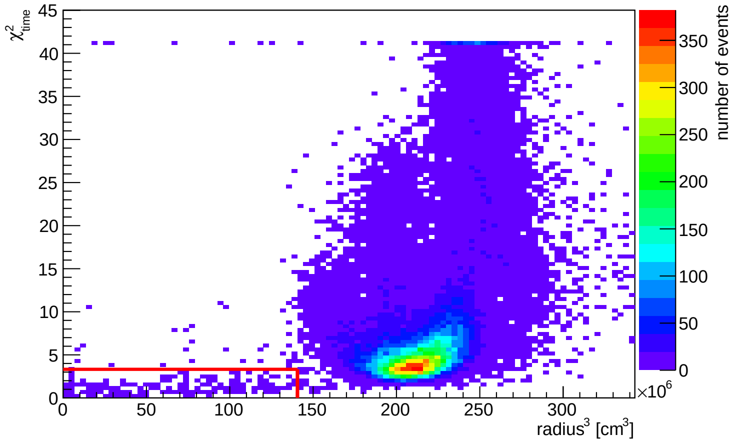
Legend:

- — 6.5 m radius balloon edge
- — 5.2 m radius fiducial volume cut

Fit data to background model



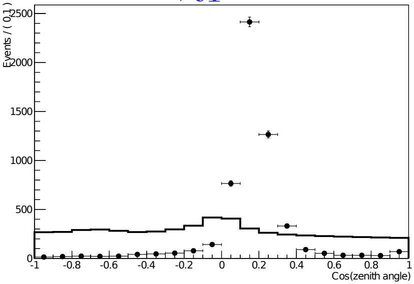
Vertex χ^2_{time} (test of event point-likeness)



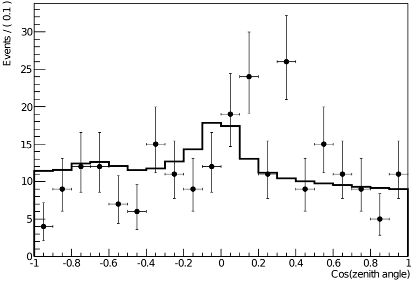
Fit data to background model

(with $\chi^2_T < 3.32$ cut)

No χ^2_T cut



$\chi^2_T < 3.32$



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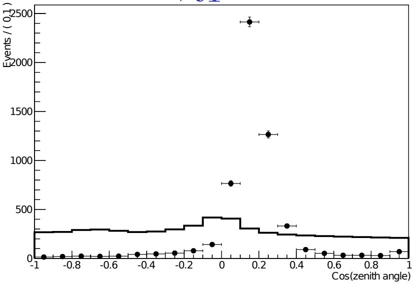

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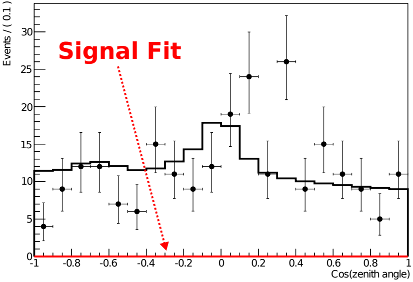


Event rate equation

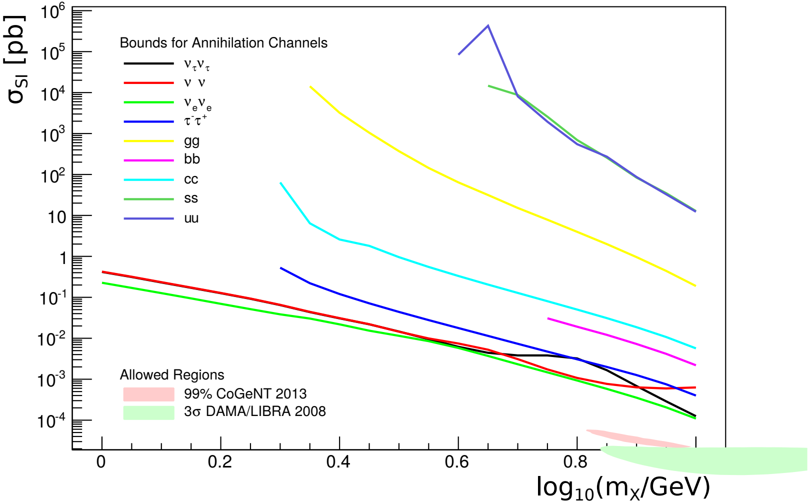
$$\text{rate}_{\text{signal}} = \Gamma_{\text{A}} \times \sum_{\substack{\text{channel}=i \\ \nu-\text{flavor}=\alpha}} \left[B_i \int dE_\alpha \frac{dN_{i,\alpha}}{dE_\alpha} \frac{\sigma_{\text{effective}}(E_\alpha)}{4\pi R_{\text{Earth}}^2} \right]$$

$$\begin{cases} \Gamma_A = \frac{1}{2}\Gamma_C & (\chi\overline{\chi} \text{ annihilation rate at equilibrium}) \\ \Gamma_C = \sigma_{\chi-\text{nucleon}} C_0 & (\chi \text{ capture rate}) \\ E_\alpha & (\text{energy of neutrino for flavor } \alpha) \\ N_{i,\alpha} & (\text{neutrino yield of flavor } \alpha \text{ per annihilation for channel } i) \\ \sigma_{\text{effective},\alpha}(E_\alpha) & (\text{effective detector cross-section}) \\ R_{\text{Earth}} & (\text{Earth radius}) \end{cases}$$

bound on $\text{rate}_{\text{signal}} \implies$ bound on $\sigma_{\chi-\mathrm{nucleon}}$

WIMP $\sigma_{\rm SI}$ bounds

(90 % C.L.)



Summary

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

Thank you for listening!