Event reconstruction in Super-Kamiokande

M.Miura

Kamioka observatory, ICRR

TMEX2018

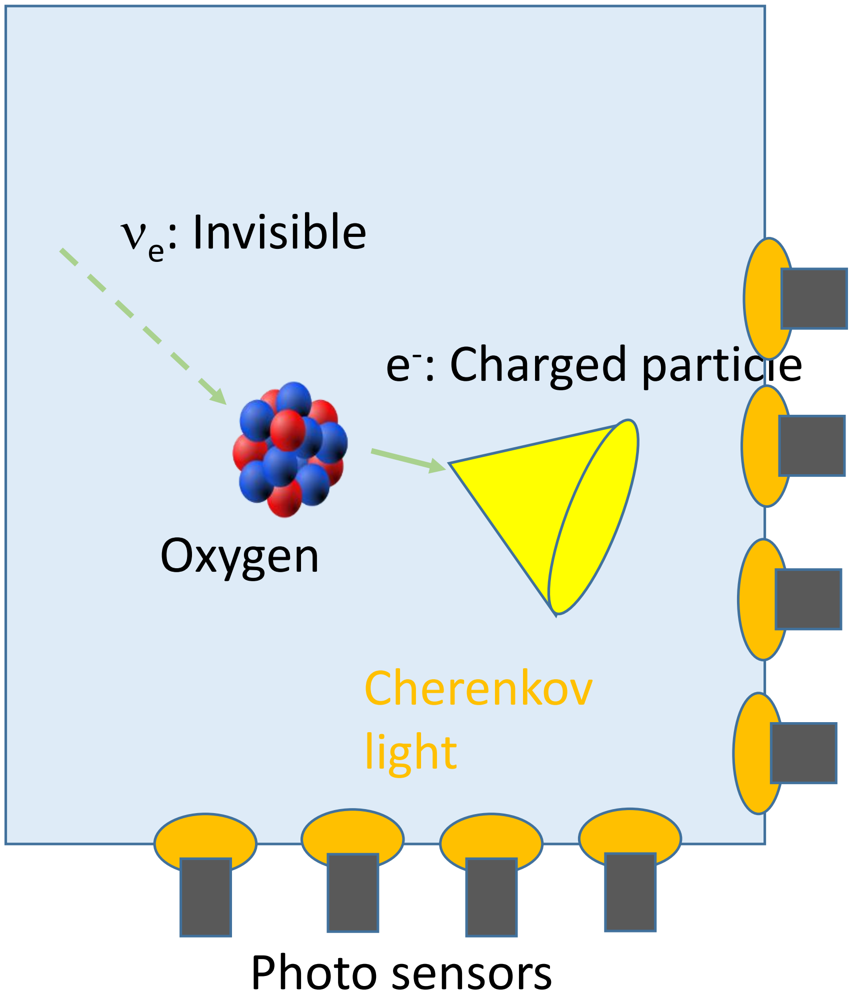
September 19th,2018, Warsaw University of Technology

Contents

1. Overview of event reconstruction in SK

How neutrino can be detected in SK?

- Neutrino itself can not be seen, but it rarely interacts with nucleon or electron.
- Kicked out charged particle emits Cherenkov light in water.
- Cherenkov light propagates in water and it is detected by PMTs.
- From amount of photons and arrival time, the event can be reconstructed.

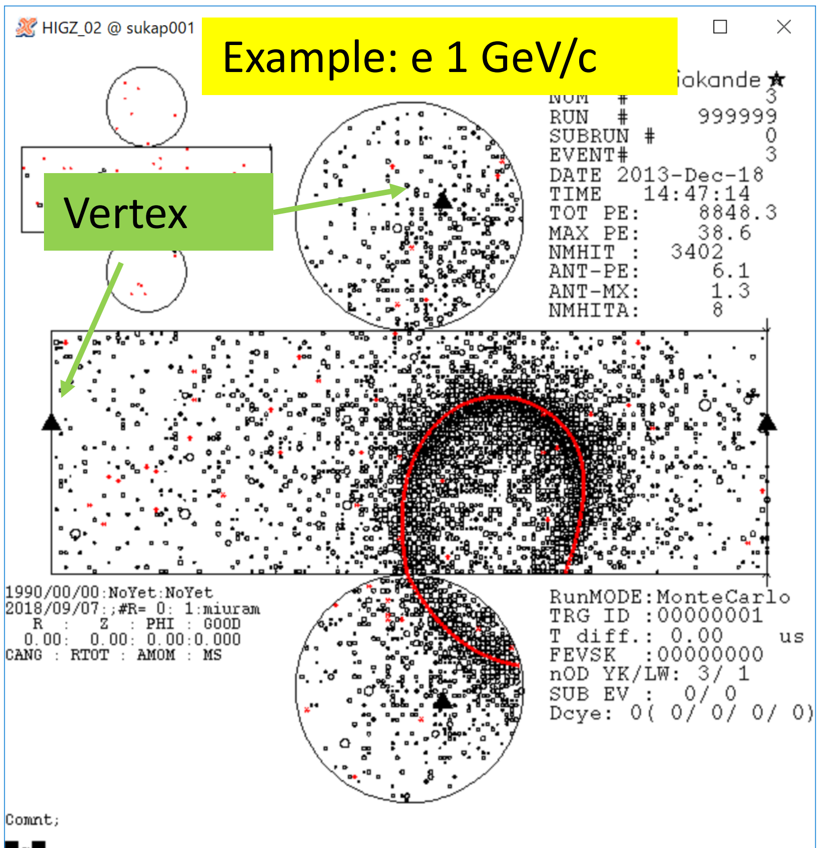


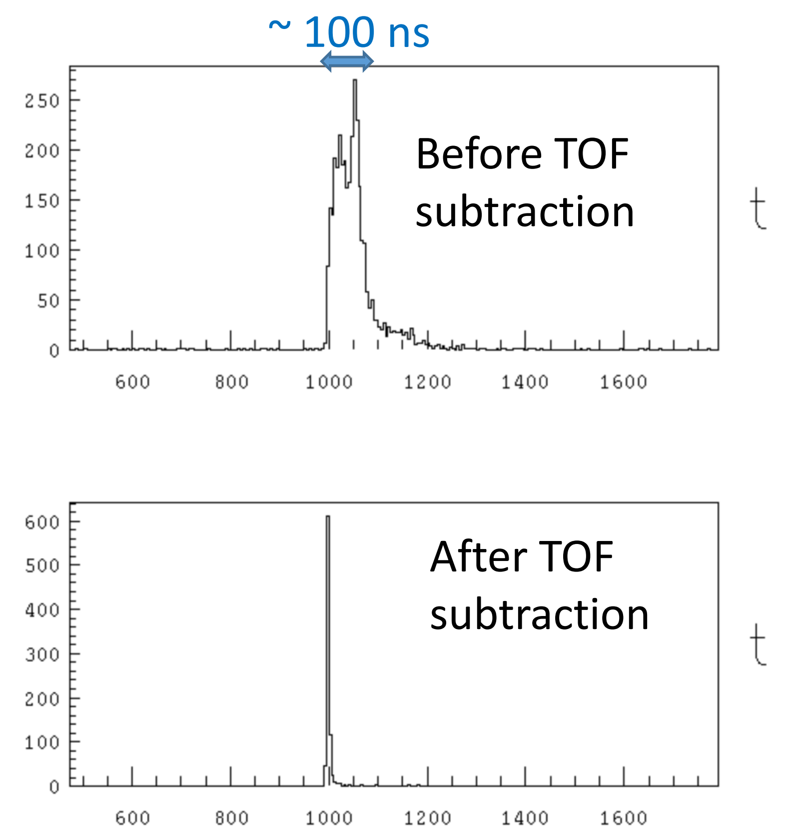
Conventional event reconstruction: Apfit

- Physics quantities are determined step by step. There are many steps but here I pick up major ones;
  1. Determine event vertex from time information.
  2. Count number of rings.
  3. Determine particle type.
  4. Calculate momentum of each ring.
- Now a new method is developing (see next talk).

2. Vertex reconstruction

- Assumption: All rings are generated at one event vertex.
  ➔ Search for a point where time distribution becomes sharpest after time of flight (TOF) subtraction.





Step 1. Simple fit (assuming all photons from a point)

Time residual: $t_i = t_i^0 - \frac{n}{c} \times |\vec{P}_i - \vec{O}|$

t_i^0 : time information of i-th PMT

$\vec{P}_i$: position of i-th PMT $\vec{O}$: vertex position

Definition of goodness: $G_p = \frac{1}{N} \sum_i \exp\left(- \frac{(t_i - t_0)^2}{2\,(1.5 \times \sigma)^2} \right)$

t_0: event time (free parameter),
σ: typical time resolution (2.5 ns), N: number of PMT

Search the point where G_p becomes maximum.

Step 2. TDC fit (more precise fit)

Track length and scattered light are taken into account.

photon emission point

$$t_i = \begin{cases} t_i^0 - \frac{1}{c} \times |\vec{X}_i - \vec{O}| - \frac{n}{c} \times |\vec{P}_i - \vec{X}_i| & \text{for PMTs inside the Cherenkov ring} \\ t_i^0 - \frac{n}{c} \times |\vec{P}_i - \vec{O}| & \text{for PMTs outside the Cherenkov ring} \end{cases}$$

For inside the Cherenkov ring, goodness G_f:

$$G_I = \sum_i \frac{1}{\sigma_i^2} \exp\left(- \frac{(t_i - t_0)^2}{2\,(1.5 \times \sigma)^2} \right)$$

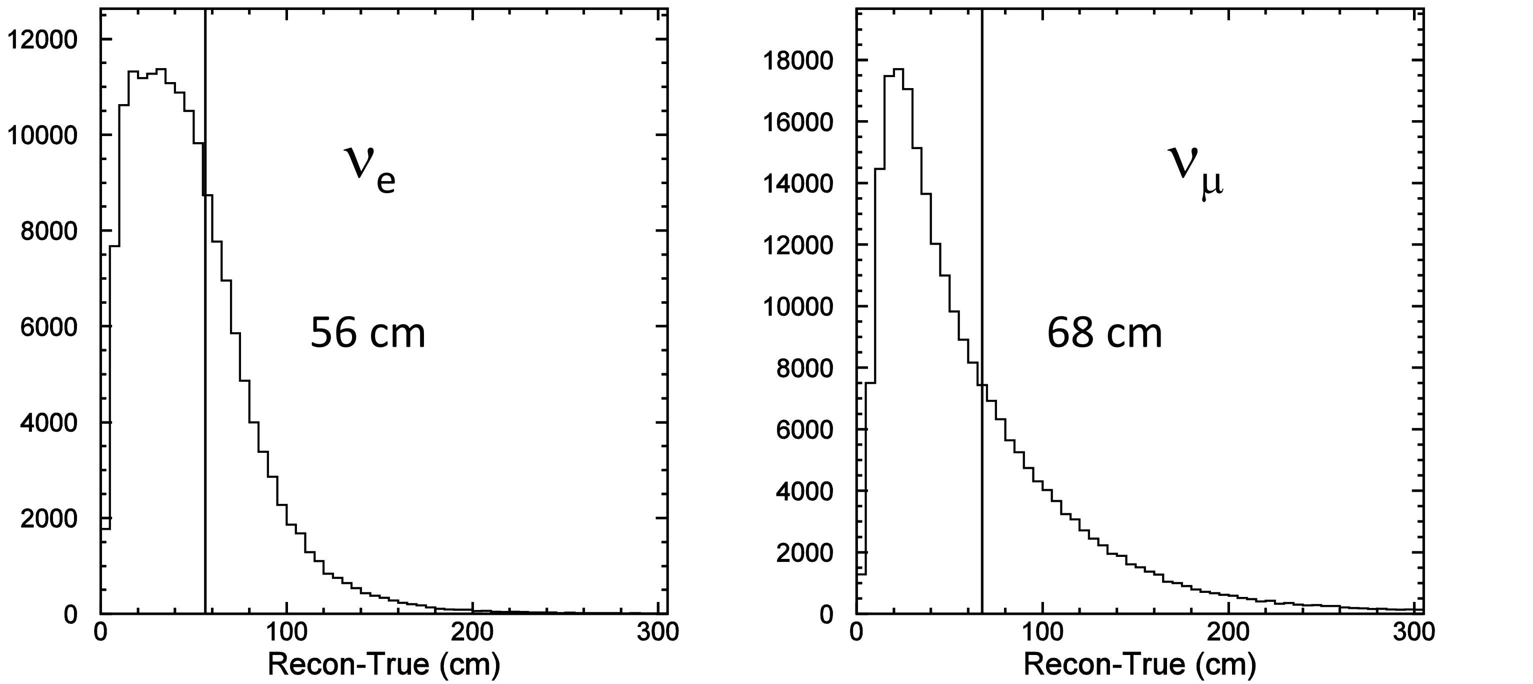
σ_i: time resolution of i-th PMT depends on detected p.e.

For outside the Cherenkov ring, scattered light is taken into consideration to calculate G_O (see backup). Then decide the vertex which gives maximum total goodness G_T:

$$G_T = \frac{G_I + G_O}{\sum \frac{1}{\sigma_i^2}}$$

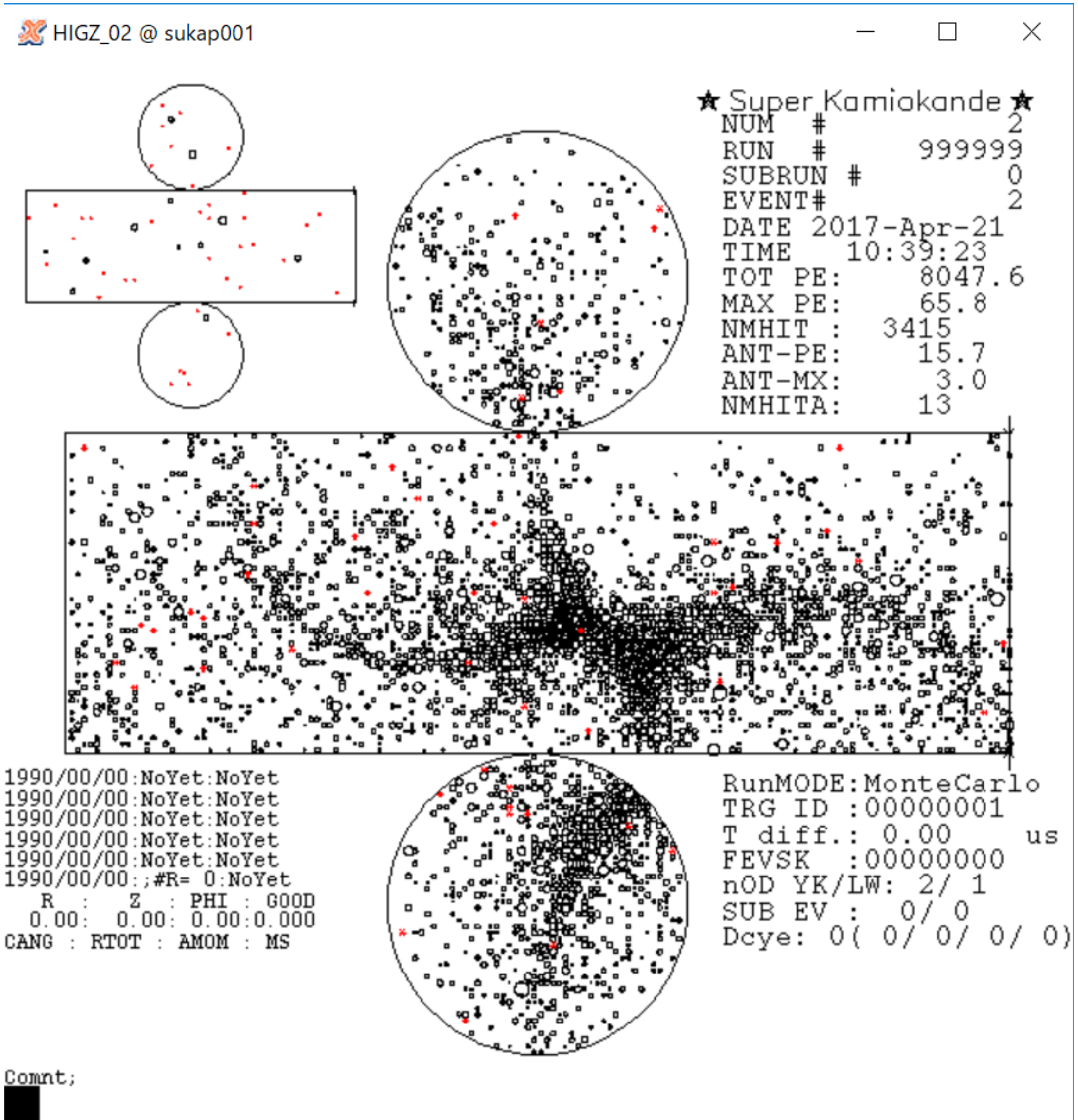
The 1st ring is defined by TDC fit.

Distance between reconstructed and true vertex
Sample: FCFV, Sub-GeV, CCQE



NOTE: For 1R sample, another precise fit using hit pattern is applied in the later step
(σ < 30cm for Sub-GeV).

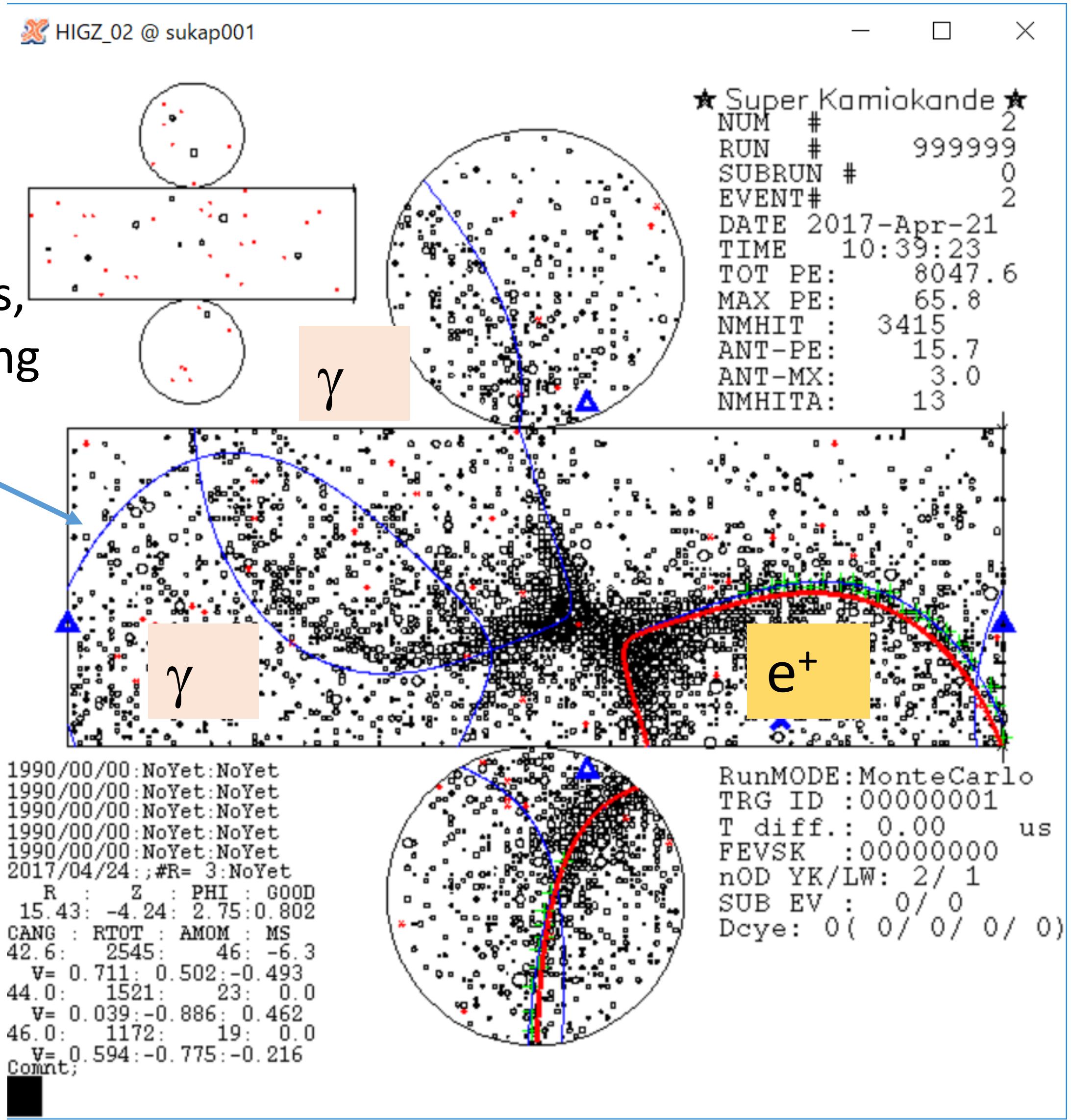
3. Ring counting



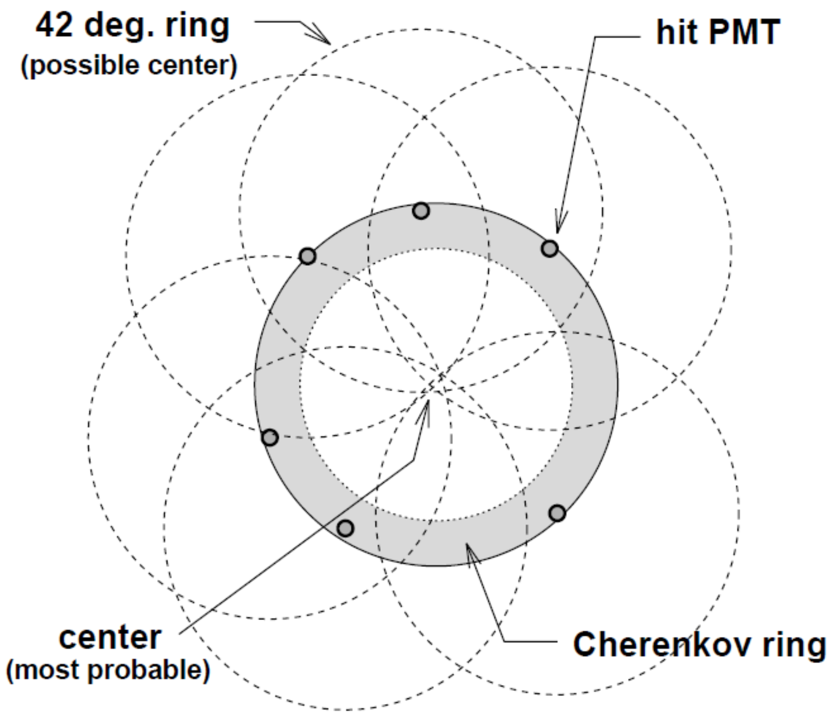
Q. How many rings can you find ?

Ans. 3 rings ($p \rightarrow e^+\pi^0$)

Difficult for eyes, but Ring counting routine found it correctly.



How to find ring candidates



- Spherical coordinate centered by vertex.
- Draw 42° circle from hit PMTs.
- Direction of Cherenkov ring could be identified as intersection of these virtual circles.

- N-th ring has been already observed, N+1 th ring candidates are examined by likelihood.

$$L_{N+1} = \sum_i \log\left(prob\left(q_i^{\text{obs}},\, \sum_{n=1}^{N+1} \alpha_n \cdot q_{i,n}^{\text{exp}}\right)\right)$$

q_i^{obs} : Observed charge in i-th PMT

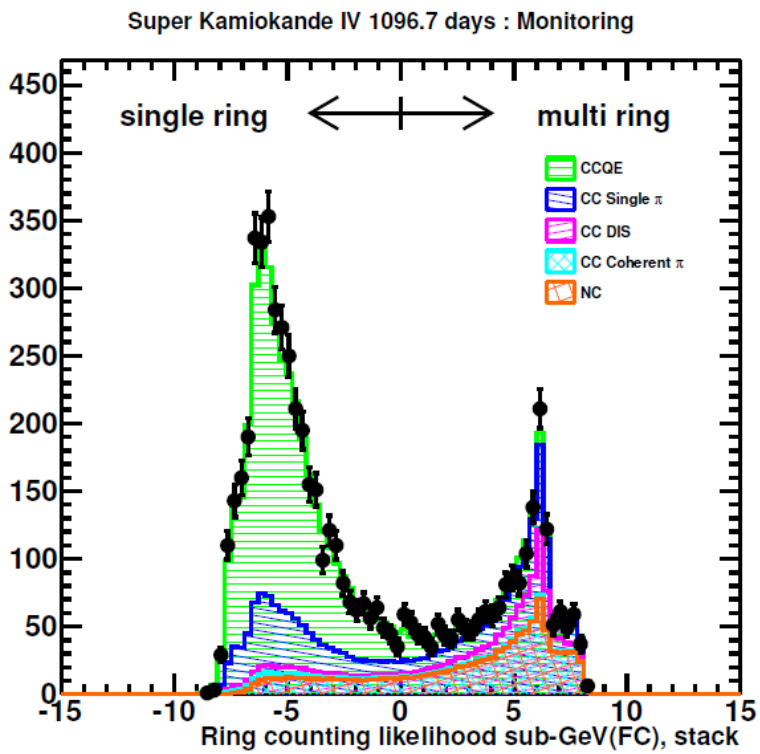
$q_{i,n}^{\text{exp}}$: Expected charge in i-th PMT from n-th ring

α_n: Normalization factor

prob: Gaussian for > 20 pe, or Poisson for less charge.

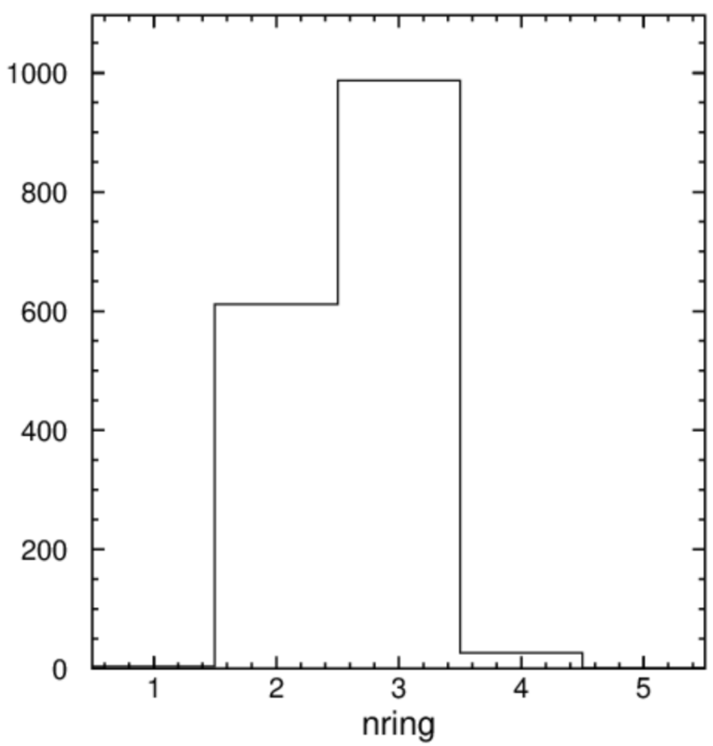
- If $L_{N+1} > L_N$ case, N+1-th candidate is taken as ring.

L2 –L1 distribution



- More than 90 % of CCQE events are identified as single ring event.

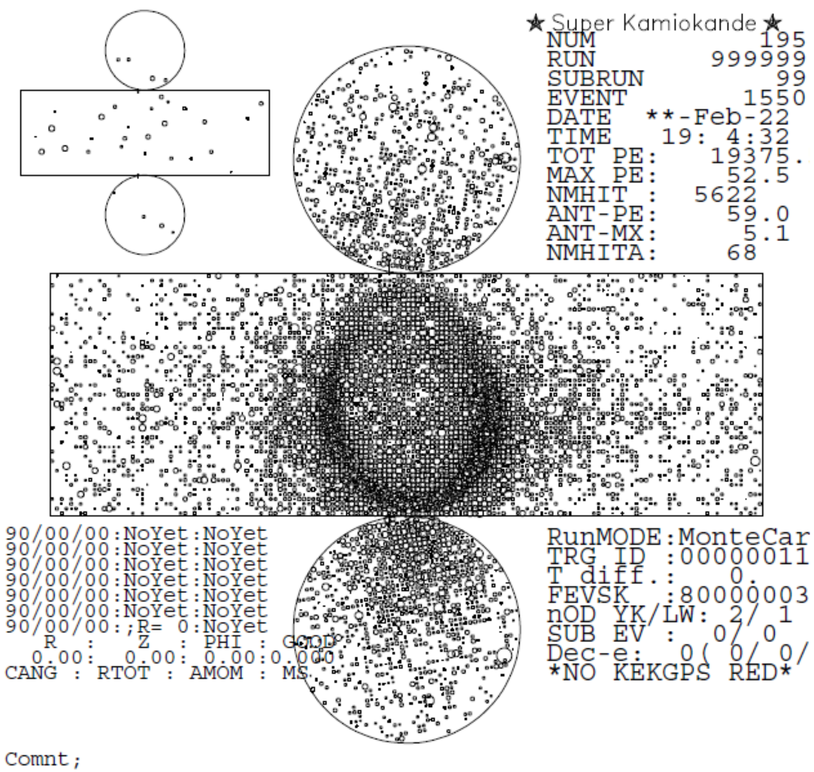
Free proton → $e^+\pi^0$

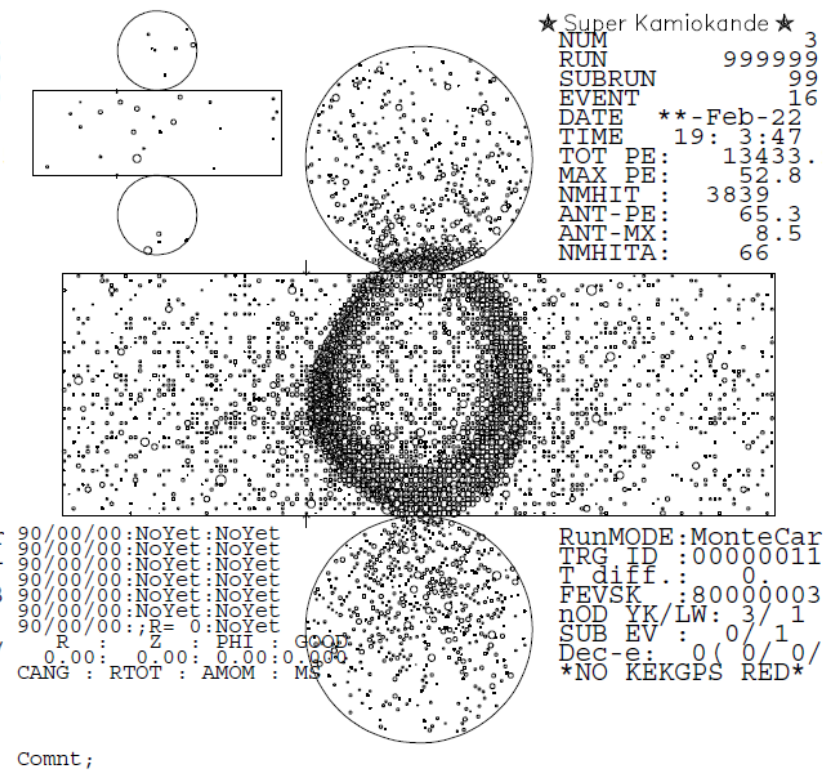


- About 2/3 of free proton decay into $e^+\pi^0$ are identified as 3 ring events.
- Inefficiency is caused by small opening angel and smaller charge of γ from π^0.

4. Particle ID

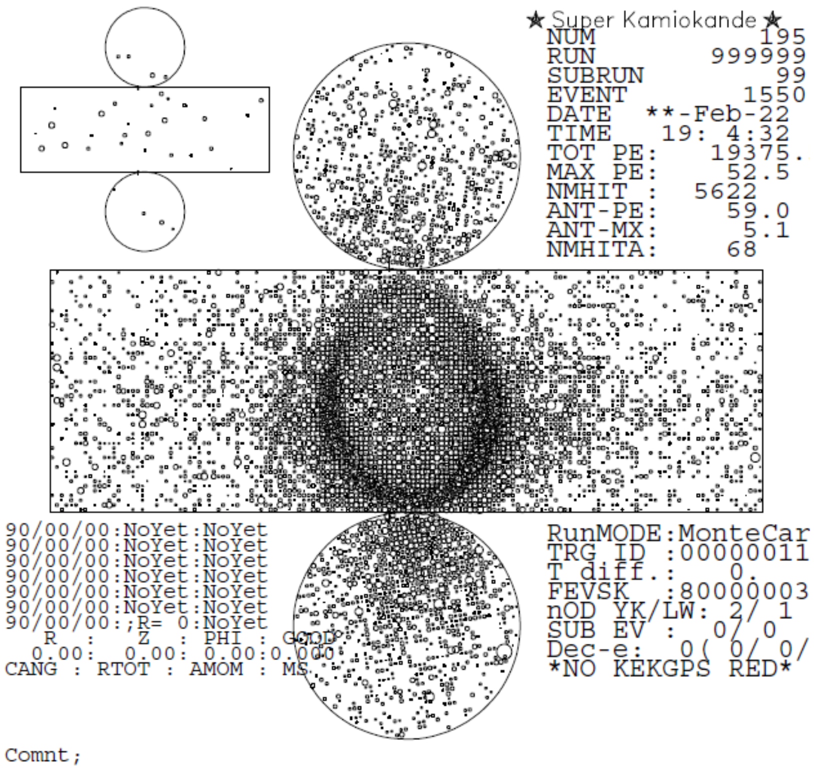
Q. Can you identify electron and muon by eye ?



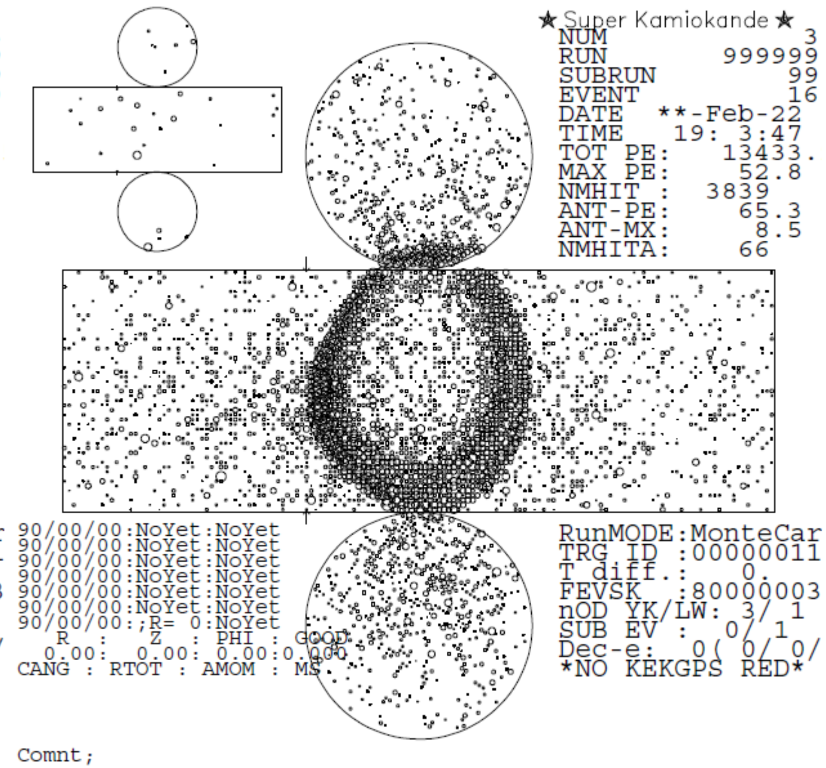


Answer

Electron

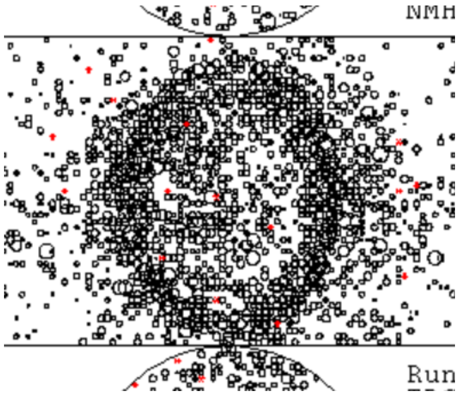


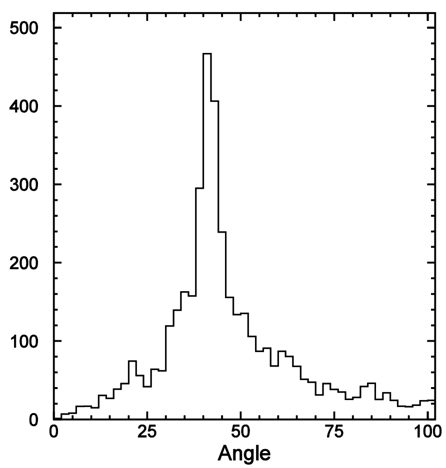
Muon



Electron:

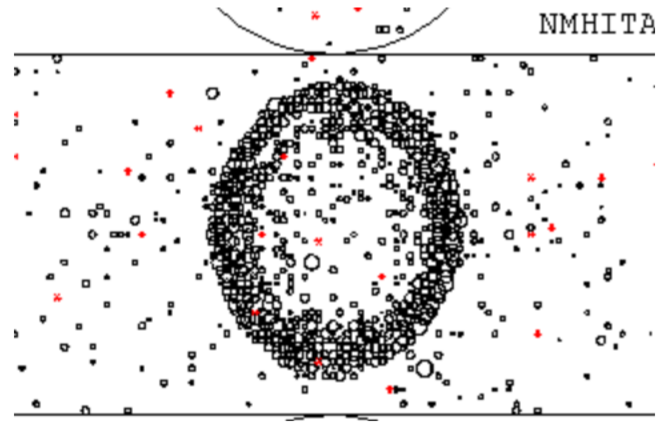
Ring edge is fuzzy due to EM shower.

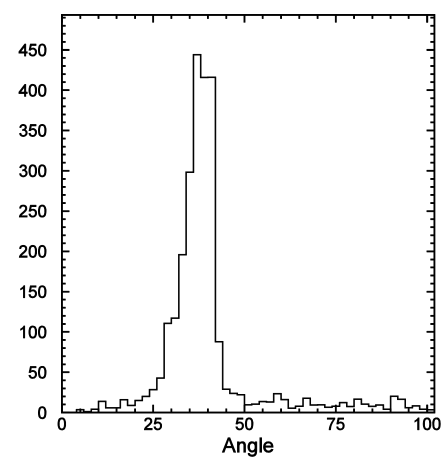




Muon:

Ring edge is more sharp.
Smaller Cherenkov opening angle in low momentum.





Can distinguish them by hit pattern and opening angle.

Likelihood function is constructed by observed and expected charge distributions;

$$L_n(e \text{ or } \mu) = \prod_{\theta_i<(1.5\times\theta_c)} prob\left(q_i^{\rm obs}\ ,\ q_{i,n}^{\rm exp}(e \text{ or } \mu) + \sum_{n'\neq n} q_{i,n'}^{\rm exp}\right)$$

$q_i^{\rm obs}$:Observed charge in i-th PMT

$q_{i,n}^{\rm exp}(e \text{ or } \mu)$: Expected charge of n-th ring in i-th PMT assuming electron or muon

Likelihood function is transformed to probability:

$$P_n^{\rm pattern}(e \text{ or } \mu) = \exp\left(-\frac{\left(\ \chi_n^2(e \text{ or } \mu) - \min\left[\chi_n^2(e)\ ,\ \chi_n^2(\mu)\right]\ \right)^2}{2\,\sigma^2_{\chi_n^2}}\right)$$

where

$$\chi_n^2(e \text{ or } \mu) = -2\ \log L_n(e \text{ or } \mu) + \text{constant}$$

- Cherenkov opening angle is also used for PID;

$$P_n^{\mathrm{angle}}(e \ \mathrm{or} \ \mu) = \exp\left(- \frac{\left(\theta_n^{\mathrm{obs}} - \theta_n^{\mathrm{exp}}(e \ \mathrm{or} \ \mu) \right)^2}{2\,(\delta\theta_n)^2} \right)$$

θ_n^{obs} : Observed Cherenkov angle of n-th ring

$\theta_n^{\mathrm{exp}}(e \ \mathrm{or} \ \mu)$: Expected Cherenkov angle of n-th ring assuming e or mu.

- Total probability function is ;

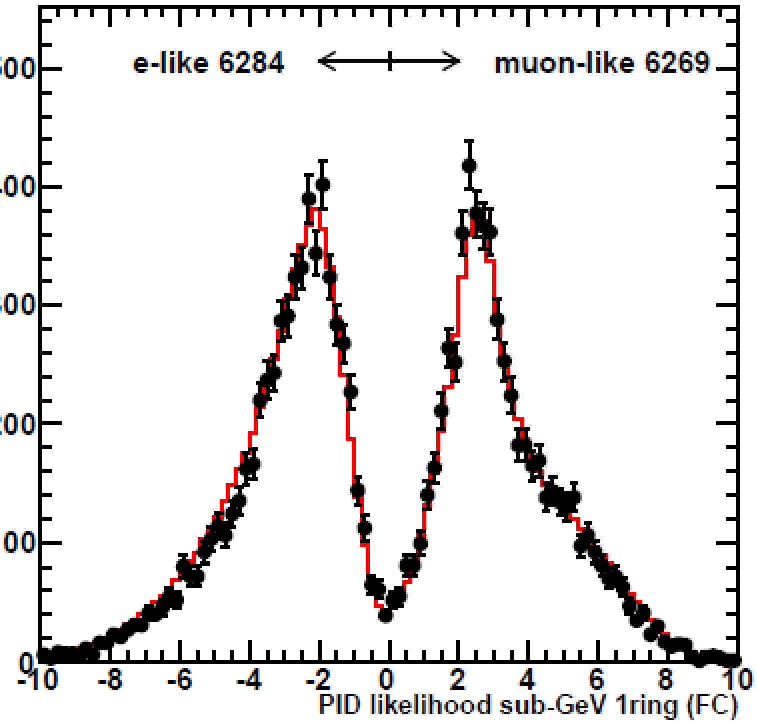
$$\begin{aligned} P_{single}(e,\mu) &= P_{single}^{\mathrm{pattern}}(e,\mu) \times P_{single}^{\mathrm{angle}}(e,\mu) \\ P_{multi}(e,\mu) &= P_{multi}^{\mathrm{pattern}}(e,\mu) \end{aligned}$$

- Then PID likelihood function is defined as;

$$P_{PID} \equiv \sqrt{-\log P(\mu)} - \sqrt{-\log P(e)},$$

P_{PID} <0 → e-like, P_{PID} >0 → mu-like

Sample: FCFV SubGeV 1R



Black: Data

Red: Atm.ν MC

- mis-PID for CCQE sub GeV sample is ~ 1 %.

5. Momentum Determination

- Momentum of each ring is determined from observed charge in 70° cone and [-50 ns: +250ns] from event time.
- Observed charge in each PMT is corrected by attenuation length in water, PMT acceptance, scattered photons.

$$RTOT_n = \frac{G_{\rm MC}}{G_{\rm data}} \left[\alpha \times \sum_{\substack{\theta_{i,n}<70^\circ \\ -50{\rm nsec}<t_i<250{\rm nsec}}} \left(q_{i,n}^{\rm obs} \times \exp\left(\frac{r_i}{L}\right) \times \frac{\cos\Theta_i}{f(\Theta_i)} \right) - \sum_{\theta_{i,n}<70^\circ} S_i \right]$$

Acceptance

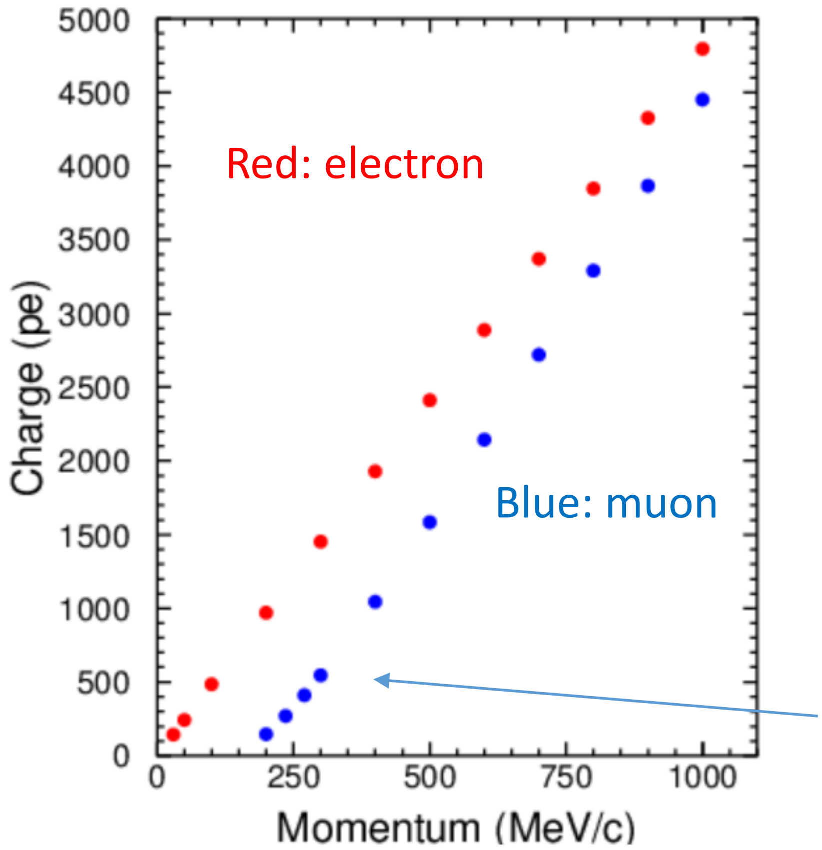
Attenuation

Scattered photon

where

α	:	normalization factor
$G_{\rm data}$, $G_{\rm MC}$	:	relative PMT gain parameter for the data and the Monte Carlo simulation
$\theta_{i,n}$	:	opening angle between the n-th ring direction and the i-th PMT direction
t_i	:	TOF subtracted hit timing of the i-th PMT position
L	:	light attenuation length in water
r_i	:	distance from the vertex position to the i-th PMT
$f(\Theta_i)$	:	correction function for the PMT acceptance as a function of the photon incidence angle Θ_i
S_i	:	expected p.e.s for the i-th PMT from scattered photons

Momentum vs corrected charge



- Make momentum vs corrected charge table based on MC with monochromatic momentum.
- Corrected charge of the ring is transformed to momentum by the table.
- Momentum resolution at 1 GeV/c
  - 3.4% for electron
  - 2.1 % for muon

Not linear in lower momentum.

6. Summary

- Basic idea how to reconstruct major physics quantities in conventional method is shown.
- There are more items about event reconstruction:
  - precise fitter for single ring,
  - decay electron search,
  - neutron tagging,
  - …….
- The next speaker will explain new method of reconstruction. Stay tuned !

Backup

Goodness for scattered light in TDC fit

For the hit PMTs outside the Cherenkov ring, the definition of the estimator changes with the time residual. If the hit timing is later than t_0, the contribution from the scattered photons are considered. The definitions of the estimator for hit PMTs outside the Cherenkov ring are as follows :

$$G_{O1} = \sum_i \frac{1}{\sigma_i^2}\left(\exp\left(-\frac{(t_i - t_0)^2}{2\,(1.5\times\sigma)^2}\right)\times 2 - 1\right) \qquad (\text{ for } t_i \le t_0 \text{ }) \tag{5.6}$$

$$G_{O2} = \sum_i \frac{1}{\sigma_i^2}\left(\max\left[\exp\left(-\frac{(t_i - t_0)^2}{2\,(1.5\times\sigma)^2}\right),\ G_{\text{scatt}}(t_i, t_0)\right]\times 2 - 1\right) \qquad (\text{ for } t_i > t_0 \text{ }) \tag{5.7}$$

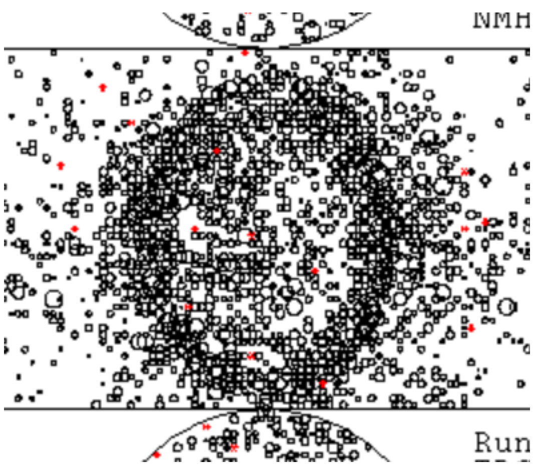
where

$$G_{\text{scatt}}(t_i, t_0) = \frac{R_q}{1.5^2}\times\exp\left(-\frac{(t_i - t_0)^2}{2\,(1.5\times\sigma)^2}\right) + \left(1 - \frac{R_q}{1.5^2}\right)\times\exp\left(-\frac{t_i - t_0}{60\text{nsec}}\right) \tag{5.8}$$

R_q is the fraction of the charge detected inside the Cherenkov ring. The numerical factors in the equations are chosen to optimize the fitter performance.

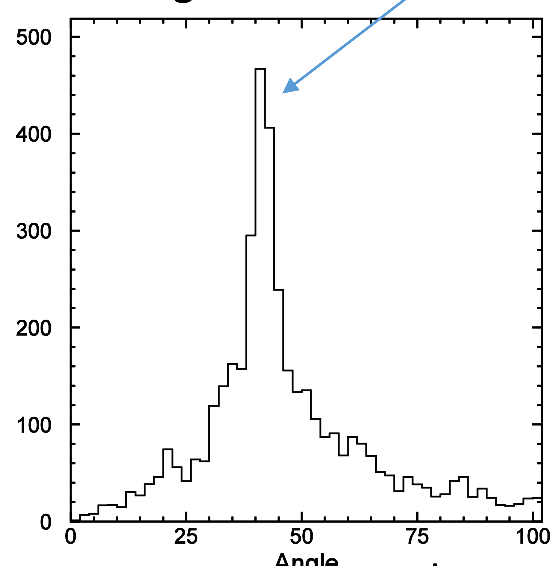
Electron case

- High energy electron loose energy in water by emitting photon (Bremsstrahling), and the photon creates electron-positron pairs. It repeats until all energy lost and electro-magnetic shower is formed.
- Thus, in electron case, many Cherenkov rings are overlapped and its ring edge becomes fuzzy.



Cherenkov edge (42 degree).

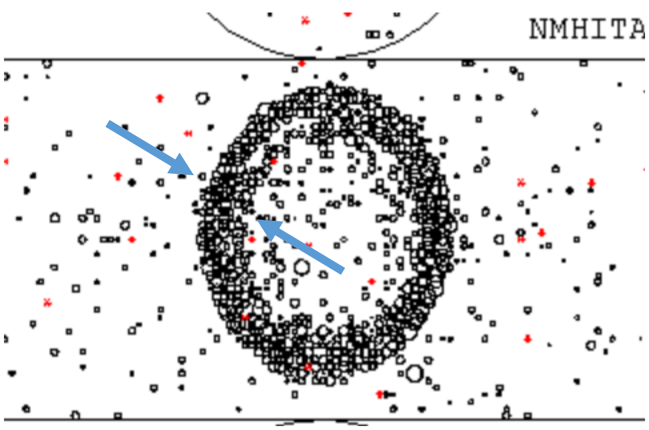
Charge distribution



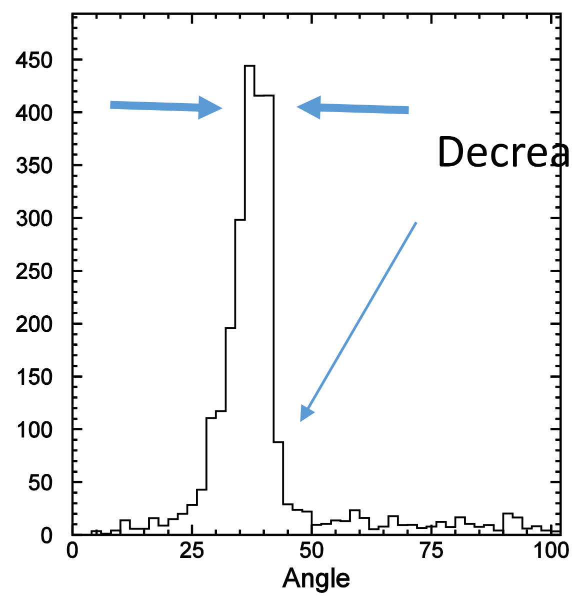
degree

Muon case

- Muon is 200 times heavier than electron and it looses energy mainly by Cherenkov photon emission. Thus, ring edge is clear than electron.
- High energy muon can run longer and Cherenkov photons are emitted each point.

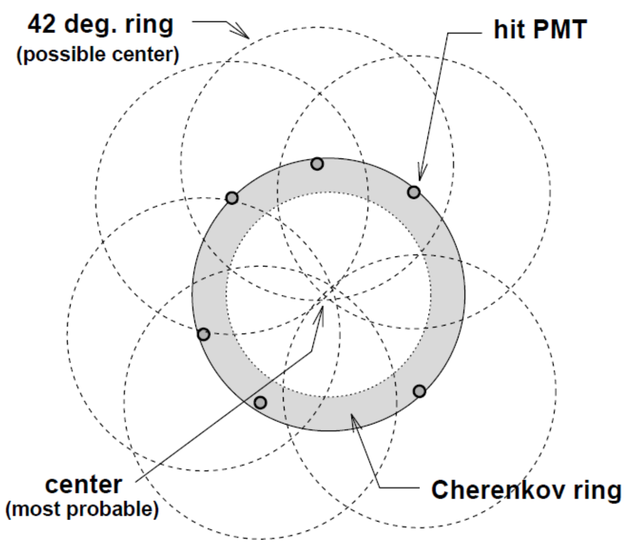


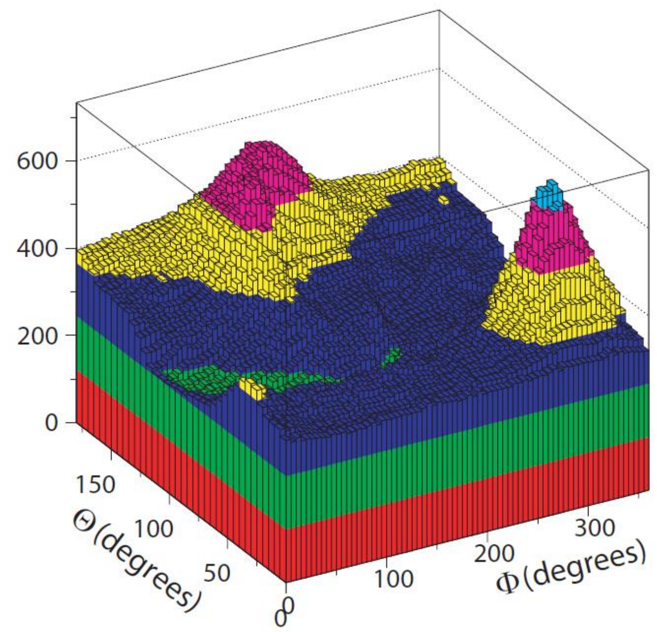
Charge distribution



Decreased sharply.

How to find rind candidates





- Spherical coordinate centered by VTX.
- Draw 42° circle from hit PMTs.
- Direction of Cherenkov ring could be identified as intersection of these virtual circles.

- In practice, instead of the virtual circles , expected charge distribution function f(θ) weighted by charge is mapped on Θ-Φ plane.
- Ring center candidates can be identified as peaks on the map.