High-energy event reconstruction: FiTQun

Algorithm for Water Cherenkov detectors

Institut de Física d'Altes Energies

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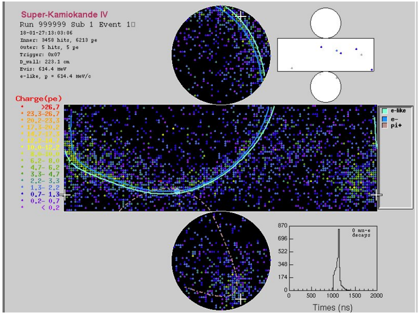
Institut de Física d'Altes Energies

Introduction to fiTQun

- FiTQun is a maximum likelihood estimation event reconstruction algorithm for WC experiments
- The algorithm is based on methods developed for the MiniBooNE experiment
  - additional features such as multi-ring reconstruction for events with multiple final-state particle



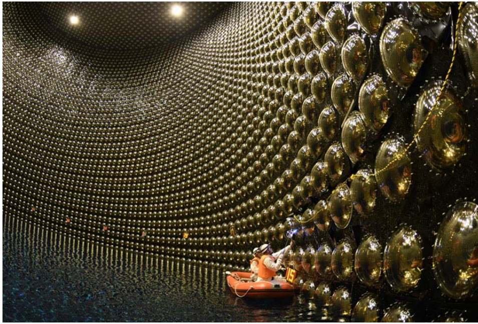
- FiTQun steps:

1. Vertex pre-fitting,
2. Hit clustering,
3. Single-ring reconstruction,
4. Multi-ring reconstruction.

The Likelihood Function

single ring event, i.e. an event with a single electron or a muon

- set of charges and times recorded for every PMT hit (integrated charge within time window)
- use of likelihood functions, in which a PDF is constructed each measurement
- likelihood also a function of the particle parameters specifying initial condition:
  - vertex position x,
  - time t,
  - zenith angle and azimuth of the direction θ, ϕ,
  - and momentum p.
- obtained by searching for global maximum of likelihood function



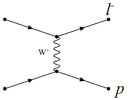
Maximum likelihood method

- designed to extract specific topologies Γ and determine the best set of kinematic parameters

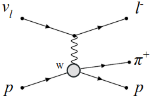
HighE

Interaction Process

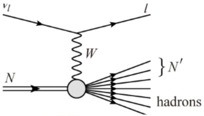
CCQE



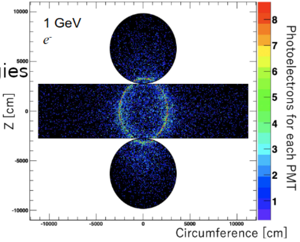
CC RES

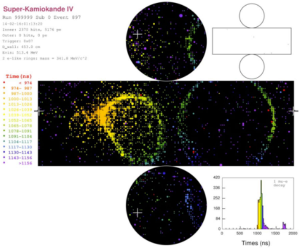


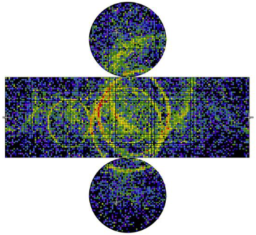
CC DIS



Topologies





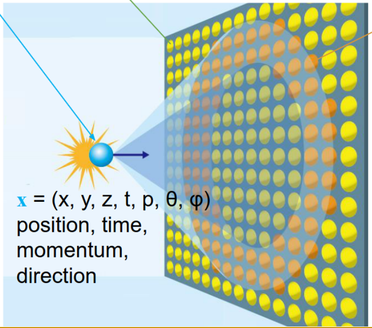


Likelihood-based reconstruction

$$L(\mathbf{x}) = \prod_{j}^{unhit} P_j\left(unhit|\mathbf{x}\right) \prod_{i}^{hit} P_i\left(hit|\mathbf{x}\right) f_q\left(q_i|\mathbf{x}\right) f_t\left(t_i|\mathbf{x}\right)$$

- L: Likelihood to maximise
- $\mathbf{x}$: Candidate track hypothesis
- $P_j(unhit|\mathbf{x})$: Probability of no hit at PMT
- $P_i(hit|\mathbf{x})$: Probability of hit at PMT
- $f_q(q_i|\mathbf{x})$: Hit charge probability density
- $f_t(t_i|\mathbf{x})$: Hit time probability density

Simultaneous fit of all 7 track parameters

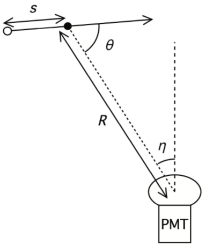


- For a given $\mathbf{x}$, a charge and time PDF is produced for every PMT

Calculation of the Predicted Charge from Direct Light

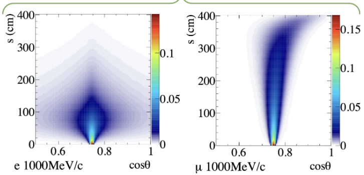
$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

- In practice, "predicted charge" is first calculated: $\mu = \mu^{dir} + \mu^{sct}$ which is used in the likelihood evaluation, where the direct light contribution is:



$$\mu^{\text{dir}} = \Phi(p) \int ds\, g(p, s, \cos\theta)\, \Omega(R)\, T(R)\, \epsilon(\eta)$$

Integral over track length; PMT solid angle; PMT angular response; Light yield; Cherenkov emission profile; Light Attenuation



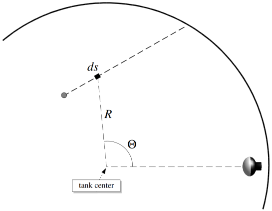
- Particle ID information encoded here and extracted from likelihood comparison of different hypotheses

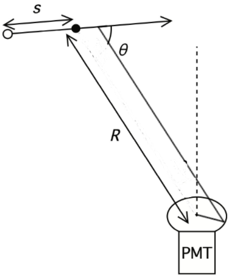
Calculation of the Predicted Charge from Indirect Light
(scattering, fluorescence, reflections)

$$\mu^{sct} = \Phi(p) \int ds \frac{1}{4\pi} \rho(p,s) \Omega(R) T(R) \epsilon(\eta) A(s)$$

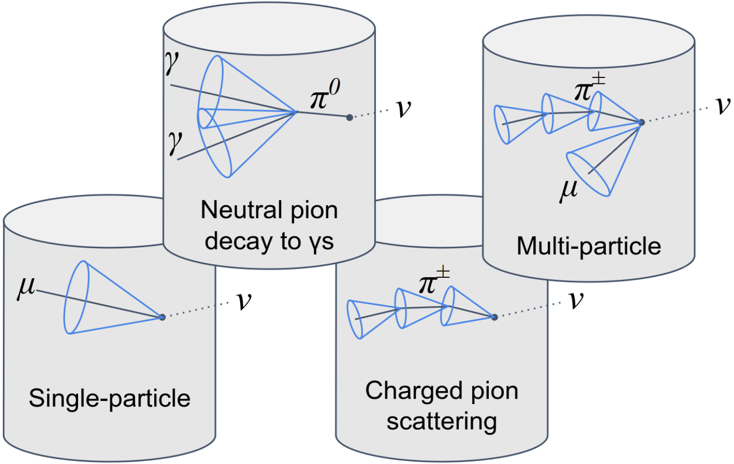
where $\rho(p,s) \equiv \int g(p,s,\cos\theta) d\Omega$ is the fraction of photons emitted per unit track length, at position s along the particle trajectory

- in Indirect light equation, photon emission described in Direct light equation is averaged over all directions at each point on the particle track





Vertices example

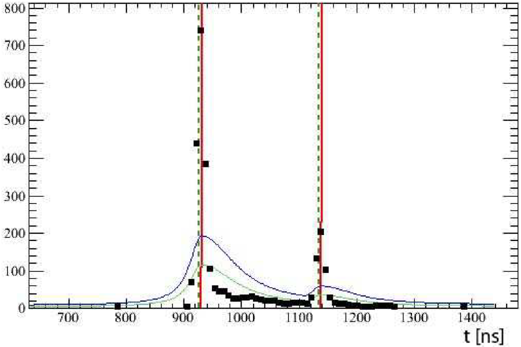


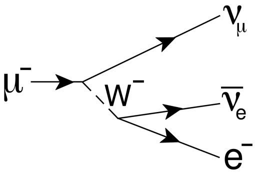
Vertex pre-fitting

- Event reconstruction is done by searching for the global maximum of the likelihood function
- In practice, done by minimizing the negative log likelihood ($-\ln L$) by varying all the fit parameters simultaneously using MINUIT.
- PROBLEM: local minima of $-\ln L$ inevitably exist.
- Important to seed the fit parameters with values which are close to the global minimum
- The vertex pre-fitter is a fast algorithm which uses only the hit time information to estimate the vertex position and time

Sub-event algorithm

- Sub-events represent clusters of PMT hits separated in time from the 1st trigger
- Algorithm search for activity around 1st trigger by **fixing** vertex position x





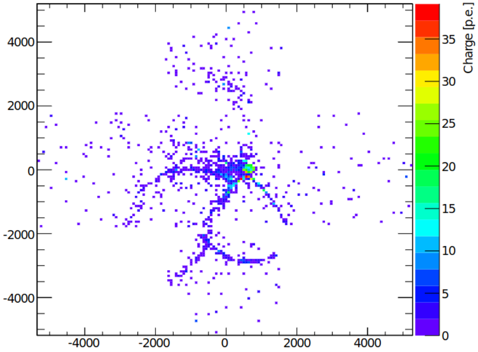
- A MINUIT minimization of $-G(x,t)$ is performed

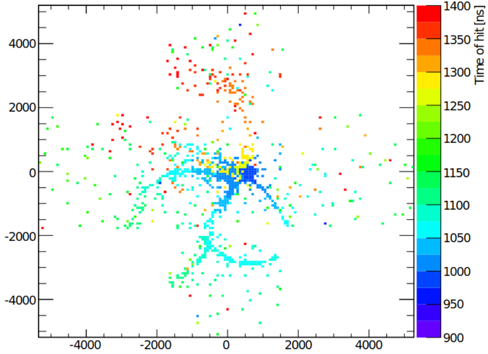
- Searching for the vertex position x and time t, which maximizes the vertex goodness defined as:

$$G(x,t) \equiv \sum_i^{\text{hit}} \exp(-(T^i_{\text{res}}/\sigma)^2/2)$$

Assumption broken

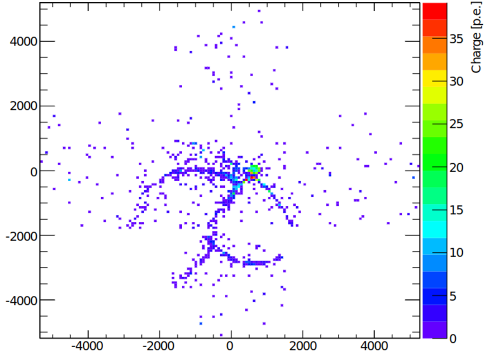
Assumption “vertex positions close to the pre-fit vertex” is broken when the primary particle travels a significant distance from the interaction vertex, as for high momenta muons

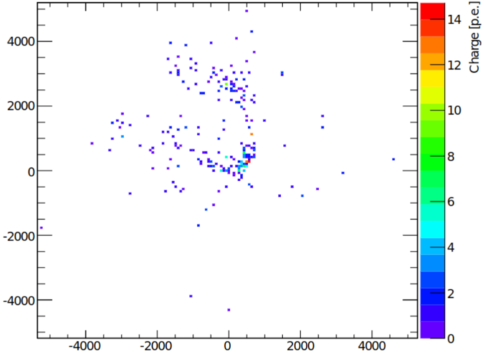




Masking hits

Therefore, the vertex pre-fitting and peak-finding algorithm are rerun after masking the hits caused by the primary particle to improve decay electron reconstruction efficiency



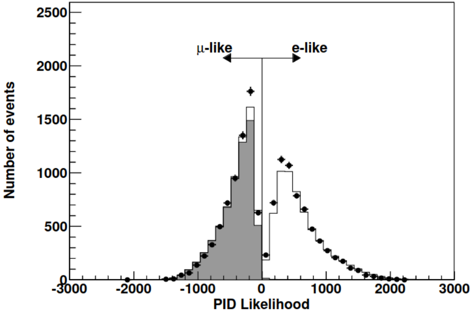


The single-ring fitter

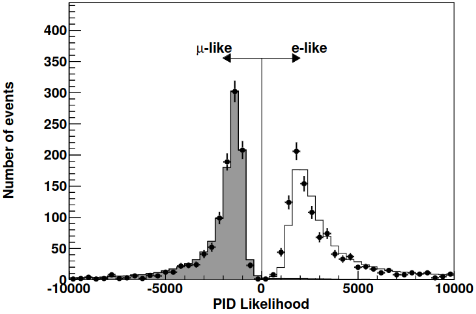
- poses single-particle hypotheses for the likelihood function
- three types of single-ring hypothesis are considered in fiTQun
  1. electron
  2. muon
  3. charged-pion
- the kinematic parameters of the event are varied to maximize the likelihood function against the observation
- Particle identification (PID) is based on the best-fit likelihood values for each of these hypotheses

PID likelihood distribution single-ring

Electrons and muons, for example, are separated by cutting on $\ln(Le/L\mu)$, the logarithm of the likelihood ratio between the best-fit electron and muon hypotheses



(a) Sub-GeV events



(b) Multi-GeV events

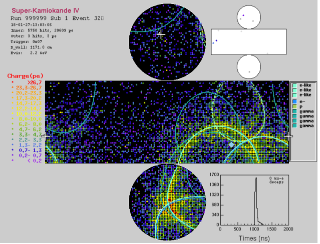
PID results

Summary of the basic performance of fiTQun reconstruction algorithms on the fully contained CCQE single ring event sample with visible energy of 1 GeV

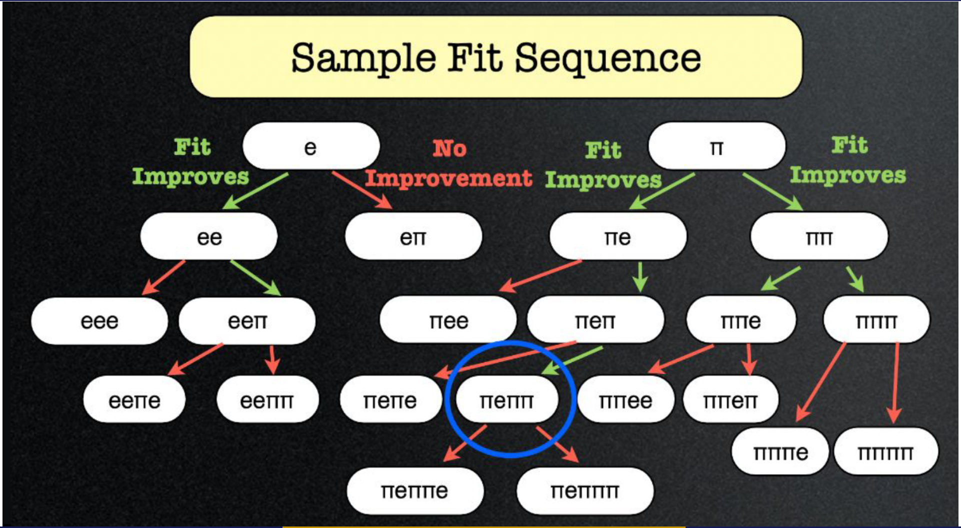
Reconstruction	**True CCQE ν_e sample**	**True CCQE ν_μ sample**
Vertex Resolution	20.64 cm	15.83 cm
Direction Resolution	1.48°	1.00°
Momentum Bias	0.43%	-0.18%
Momentum Resolution	2.90%	2.26%
Mis-PID rate	0.02%	0.05%

Multi-ring reconstruction

- a large fraction of events with multi-GeV energies have multi-particle final state
- is applied only to the time window around the primary event trigger (to save computing time)
- starts by performing an iterative search for an additional ring on top of any existing rings
- likelihood equation is updated to include a new ring and minimized again allowing the kinematic parameters for the rings to vary
- Three hypotheses rings are tested:
  1. e-like
  2. μ-like
  3. π^+-like
- iterates until either a newly added ring fails the likelihood criterion or six rings are found

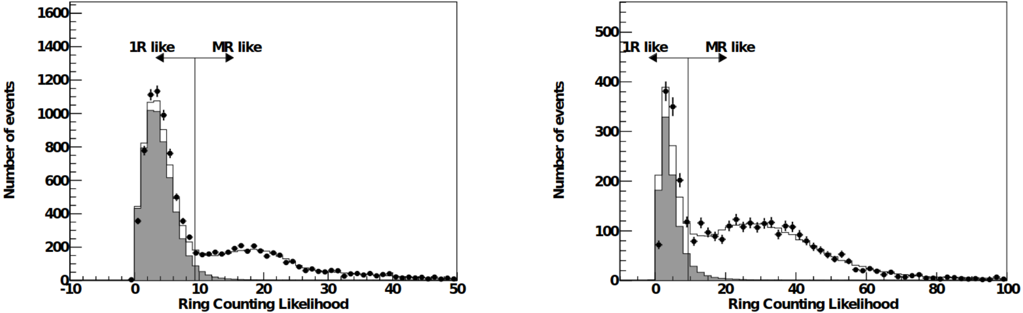


Multi-ring Reconstruction



Distribution of the likelihood ratio between the best-fit single-ring hypothesis and multi-ring hypothesis

cut at 9.35 for e-like, 11.83 for μ-like



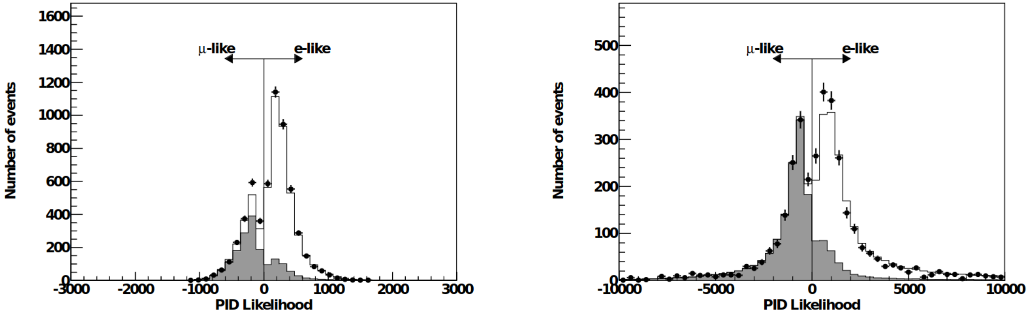
(a) Sub-GeV events (b) Multi-GeV events

Ring counting performance

- Angular separation of less than 20°from the most energetic ring discarded $\rightarrow$ particle scattering
- The two rings are merged and refit as one for all particle hypotheses

True Number of rings	Reconstruction 1R	2R	$\geq$ 3R
True 1R	95.0%	4.64%	0.41%
True 2R	27.8%	66.7%	5.56%
True $\geq$ 3R	7.04%	25.5%	67.5%

PID likelihood variable distribution of the most energetic ring in fully contained multi-ring events



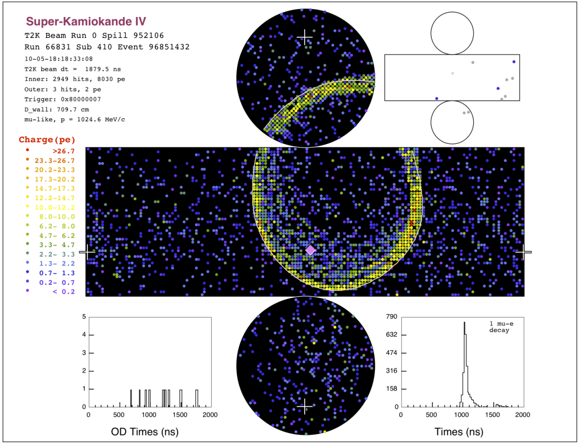
(a) Sub-GeV events

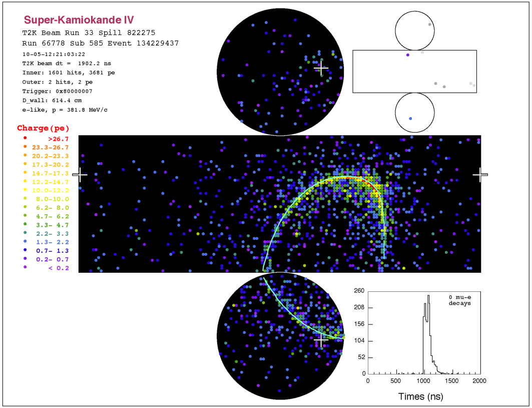
(b) Multi-GeV events

Conclusion

- Reconstruction algorithm for events at Super-K
- FiTQun steps:
  1. Vertex pre-fitting,
  2. Hit clustering,
  3. Single-ring reconstruction,
  4. Multi-ring reconstruction.
- fiTQun is being tuned for HK and WCTE at the moment
- reach limit of the achievable reconstruction precision
- to improve, more complex likelihood function would be required (relaxing assumptions), but would result in increased computational complexity
- alternatives to improve:
  - ML
  - hybrid reconstruction method using ML generated likelihoods with fiTQun-like reconstruction algorithms
- Multi-Vertex fiTQun developed by Matsumoto-san

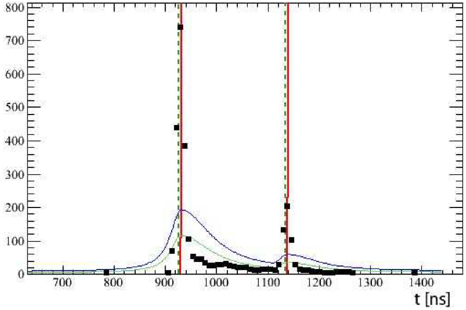
Thank you


Super-Kamiokande IV
T2K Beam Run 0 Spill 952106
Run 66831 Sub 410 Event 96851432
10-05-18:18:33:08
T2K beam dt = 1879.5 ns
Inner: 2949 hits, 8030 pe
Outer: 3 hits, 2 pe
Trigger: 0x80000007
D_wall: 709.7 cm
mu-like, p = 1024.6 MeV/c
Charge (pe)
OD Times (ns)
1 mu-e decay
Times (ns)


Super-Kamiokande IV
T2K Beam Run 33 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:22
T2K beam dt = 1902.2 ns
Inner: 1601 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 381.8 MeV/c
Charge (pe)
0 mu-e decays
Times (ns)

Back-up: Peak Finder

- Peak finder searches for sub-events by fixing vertex position x at the value the vertex pre-fitter returned, and scanning the goodness while varying the time t
  - Assuming vertex positions close to the pre-fit vertex



Peak is defined as first local maximum scan point which lies above blue curve

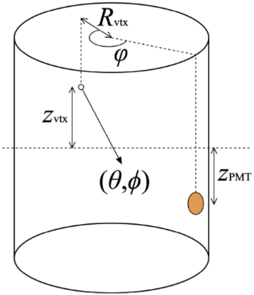
- Threshold curve F(t) defined as

$$F(t) \equiv 0.25 \max_{i \in M} \left\{ \frac{G(x, t_i)}{1 + ((t - t_i)/\gamma)^2} \right\} + \eta$$

$$\text{with } \gamma = \begin{cases} 25\text{ns} & \text{for} \quad t < t_i \\ 70\text{ns} & \text{for} \quad t > t_i \end{cases}$$

- M represents all local maxima of $G(x, t)$
- Offset $\eta = 9$ added to the threshold function to suppress effect of dark hits

Back-up: The indirect light contribution



$$\mu^{\mathrm{sct}} = \Phi(p) \int ds \, \frac{1}{4\pi} \rho(p,s) \Omega(R) T(R) \epsilon(\eta) A(s)$$

$$\rho(p,s) \equiv \int g(p,s,\cos\theta) \, d\Omega$$

$$A(s) = A(x_{\mathrm{PMT}}, z_{\mathrm{vtx}}, R_{\mathrm{vtx}}, \varphi, \theta, \phi) \equiv \frac{d\mu^{\mathrm{sct}}}{d\mu^{\mathrm{iso,dir}}}$$

- Assuming direction-averaged Cherenkov profile
- Scattering table derived from uniformly distributed, isotropic low energy electrons