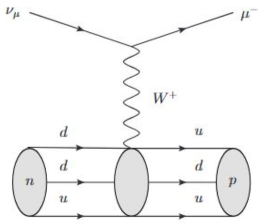
# Hyper-Kamiokande : reconstruction and selection of events

Arthur Choquet

# Studying neutrinos

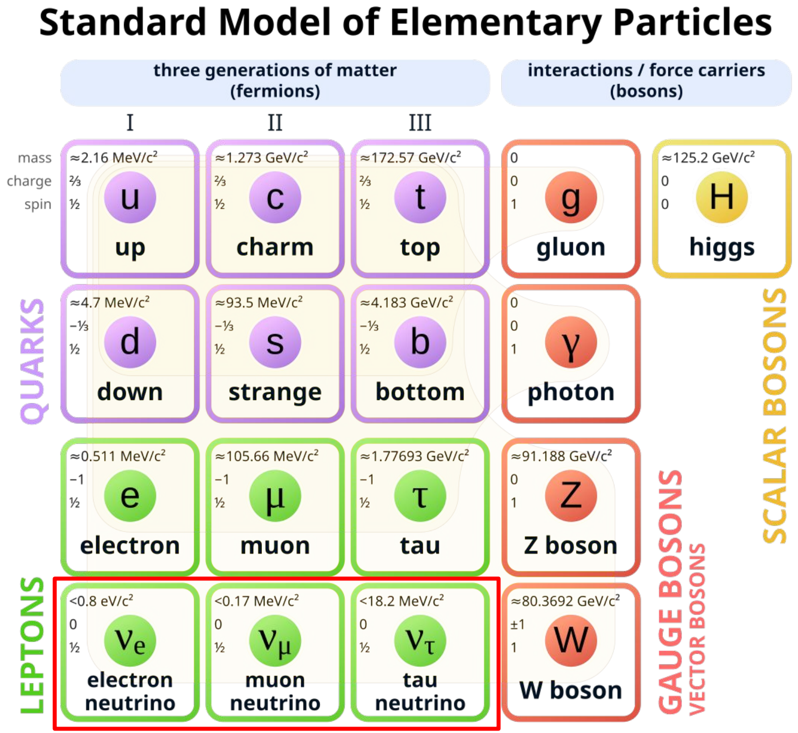
Very light particles interacting only through **weak interaction** (W and Z bosons).

Interesting and not yet completely understood phenomena like **neutrino oscillation.**




(a) CCQE

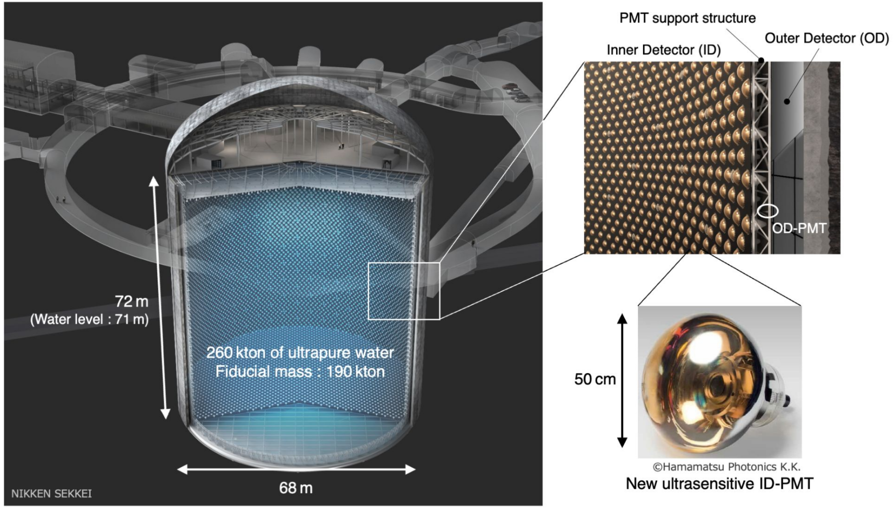
One possible neutrino interaction with matter, **creating a charged lepton** (here a muon).



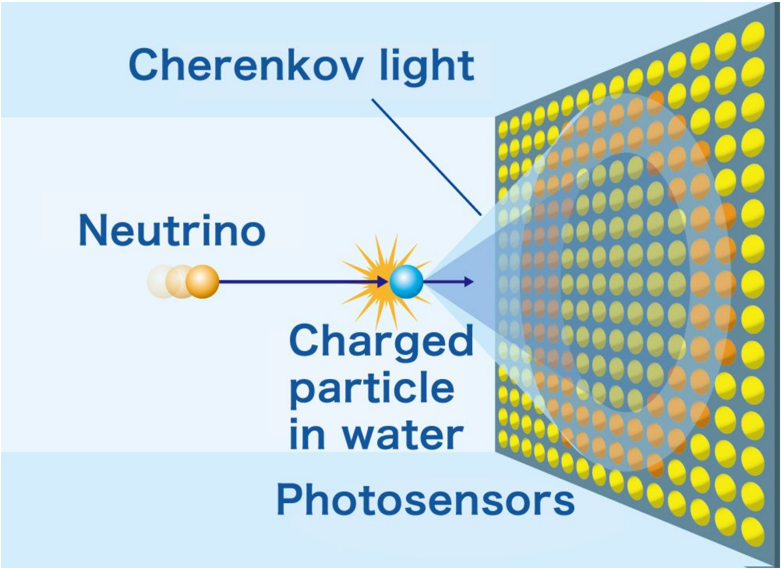

**Standard Model** of particle physics.

# The Hyper Kamiokande neutrino detector

# Water Cherenkov detectors

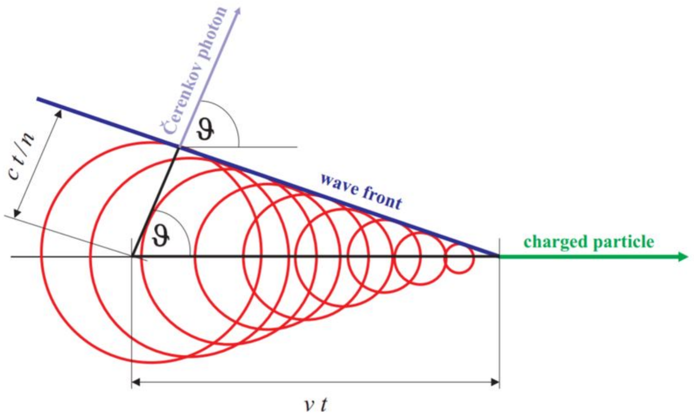



The **Hyper Kamiokande** detector (experiment starting in 2028) with its Photomultiplier Tubes (PMTs).

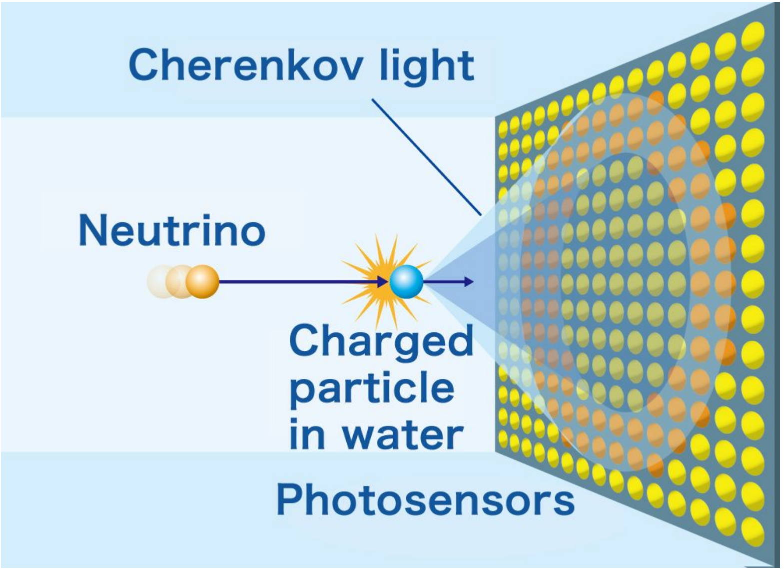



Capturing this light with photosensors.

# Water Cherenkov detectors

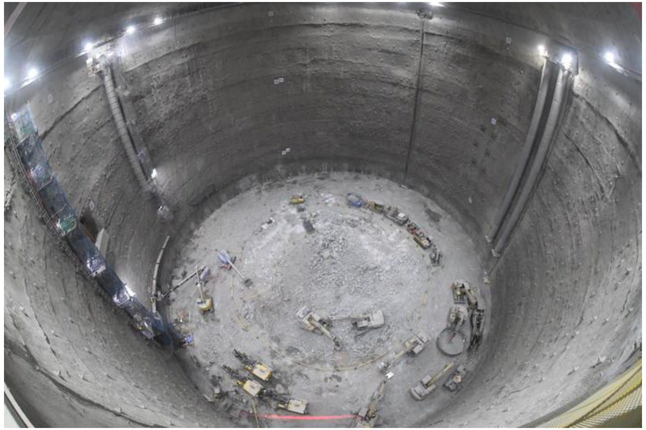



Cherenkov radiation emitted at a fixed angle for particles going at speeds **higher than the speed of light in the medium**.




Capturing this light with photosensors.

# Hyper Kamiokande's construction

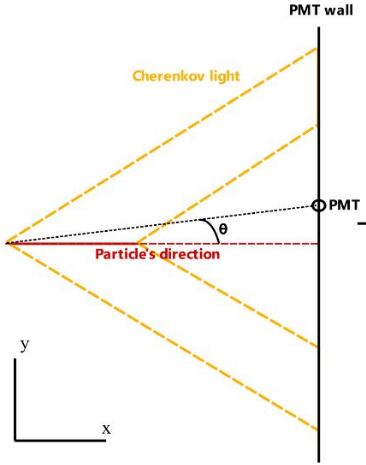


HK's tank being drilled.

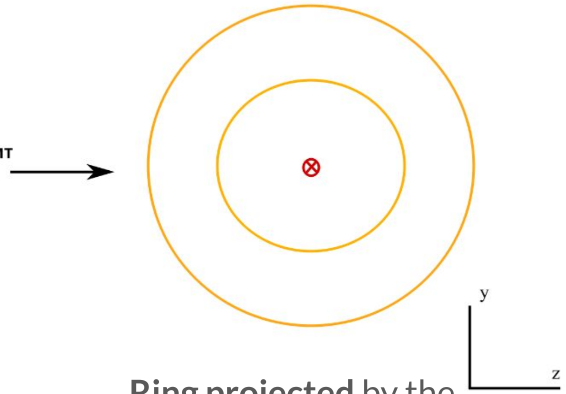
PMTs on their **testing bench** being handled by a skilled worker.

# Reconstruction of the events

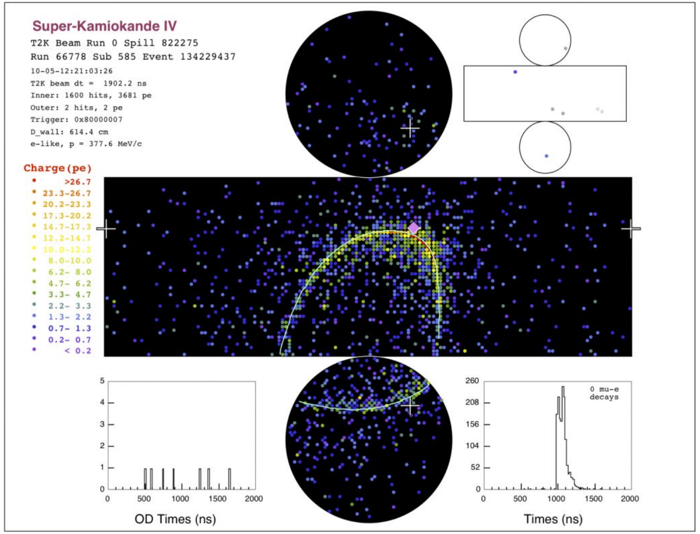
# Raw data : Cherenkov rings




**Cone of light** generated by Cherenkov radiation.




**Ring projected** by the Cherenkov radiation on the wall of the detector.



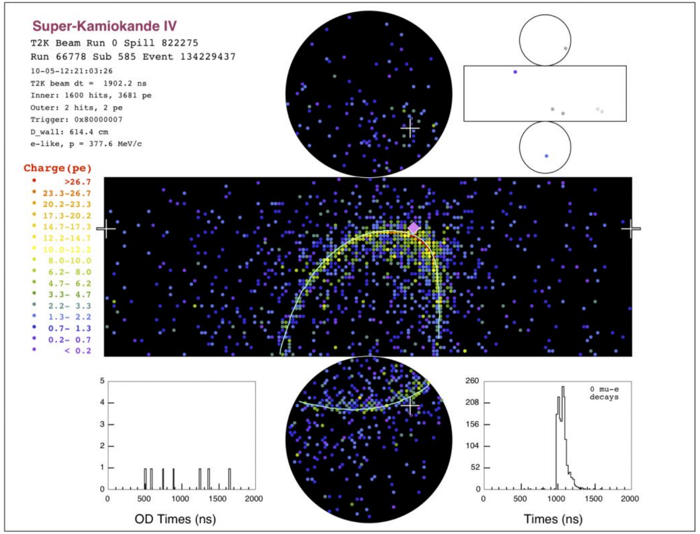

Actual **electron event** detected by Super Kamiokande.

# Reconstructing the physical properties of the events

**Main physical properties** we need to reconstruct :

- Type of particle (electron, muon, pion, photon, …)
- Momentum of the particle
- Vertex (starting point) of the particle
- Direction of the particle

One of the goal of my work : study the possibility of **separating gamma (photon) and electron events.**




Actual **electron event** detected by Super Kamiokande.

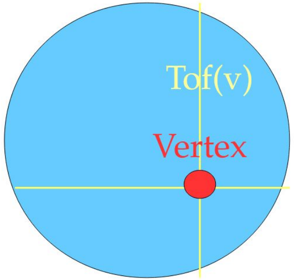
# Reconstructing the physical properties of the events

Statistical method based on know distributions.

Parameters used by the fit :

- Distribution of the **Cherenkov charge** emitted by the particle

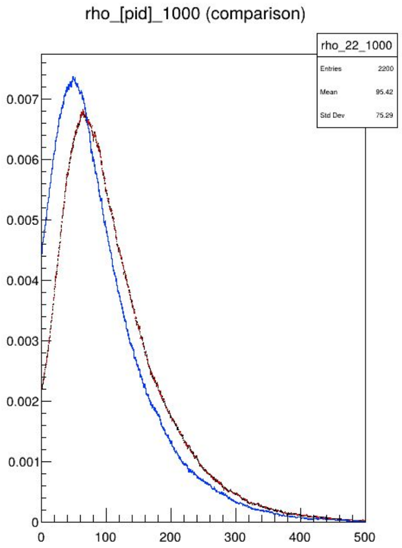
**Monte-Carlo simulations** are used to generate these distributions.




First reconstruction of the vertex by calculating the **time of flight** of Cherenkov photons and finding the best fit with the actual observed data.

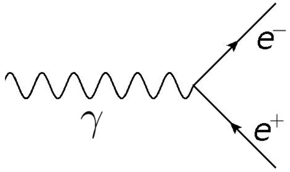
$$L(\mathbf{x}) = \prod_{j}^{\text{unhit}} P_j(\text{unhit}|\mathbf{x}) \prod_{i}^{\text{hit}} \{1 - P_i(\text{unhit}|\mathbf{x})\} f_q(q_i|\mathbf{x}) f_t(t_i|\mathbf{x}).$$

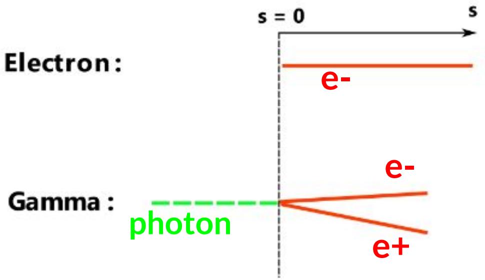
Then a more precise reconstruction : **likelihood method** on every parameters.




Example of charge distribution.

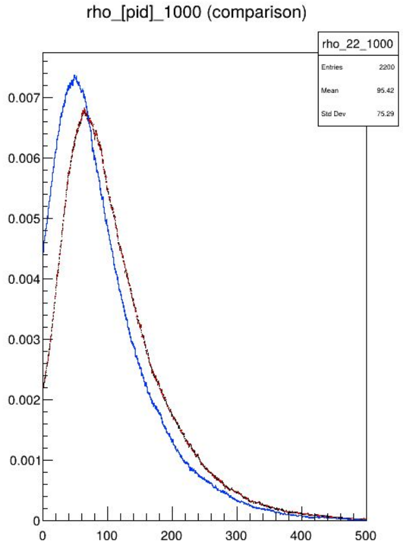
# Separation of gamma and electron events



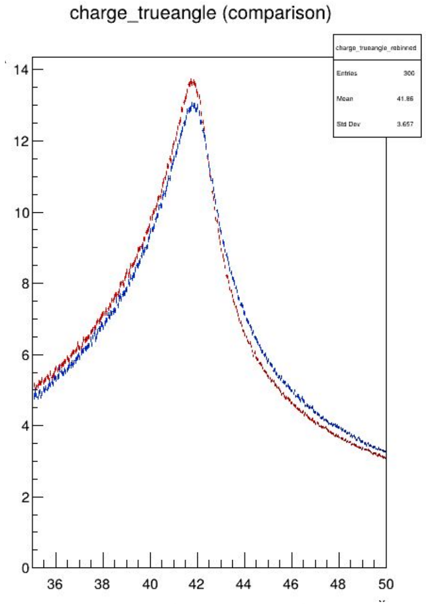




- Inside the tank, high energy photons decay into a **pair of e+/e-.**
- The order of magnitude of the angle of separation is m_e/k ~ 2° for 500 MeV photons, so the Cherenkov rings **superimpose into a single ring.**

Charge profiles :



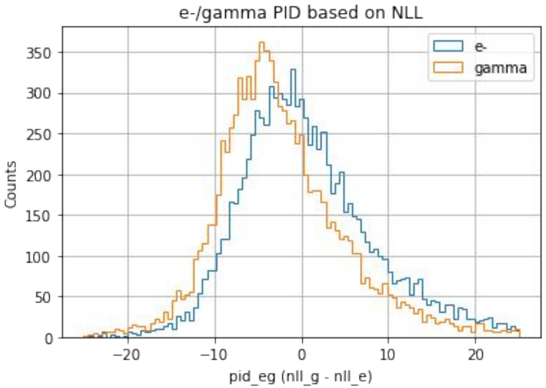

Distance along the particle directory (**s**)

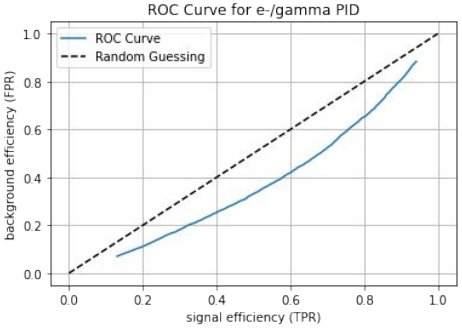



Angle between the particle's directory and the PMT (**θ**)

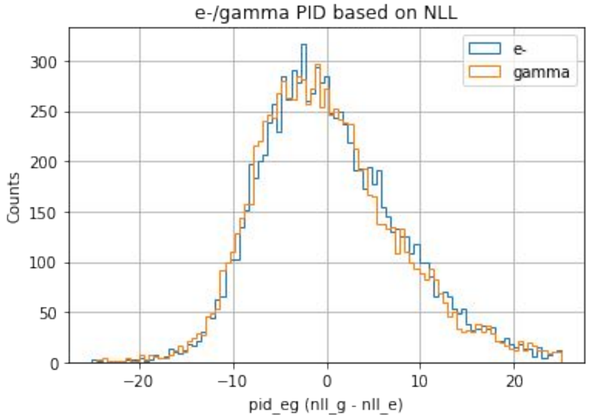
**Red is e- events**
**Blue is gamma events**

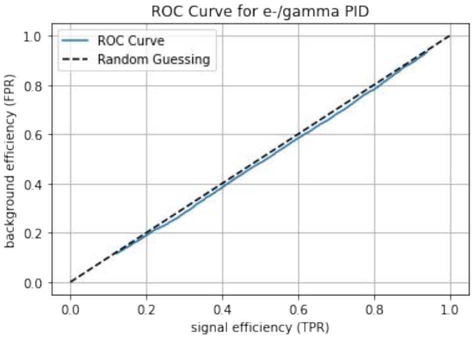
# Separation of gamma and electron events



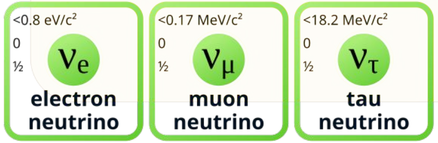

Using reconstructed properties, **the separation power is lost.**



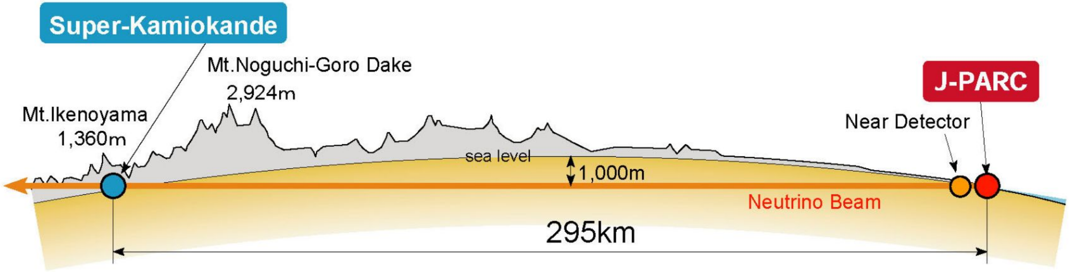



# Event selection

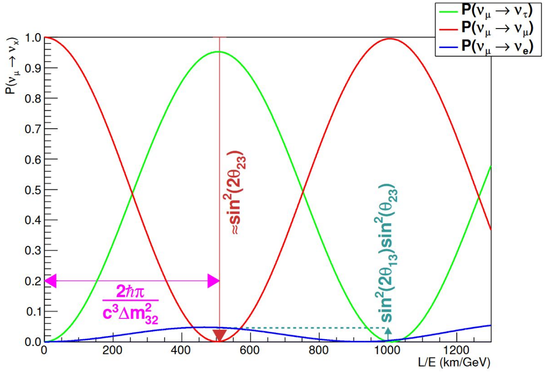
# The T2K experiment




Different **flavors** of neutrino.




The T2K experiment layout : **a beam of pure muon neutrinos** is produced and intercepted by our detector.




Neutrino oscillation : the flavor (muon, electron, tau) of the neutrino can change over time.

# Different kind of interactions

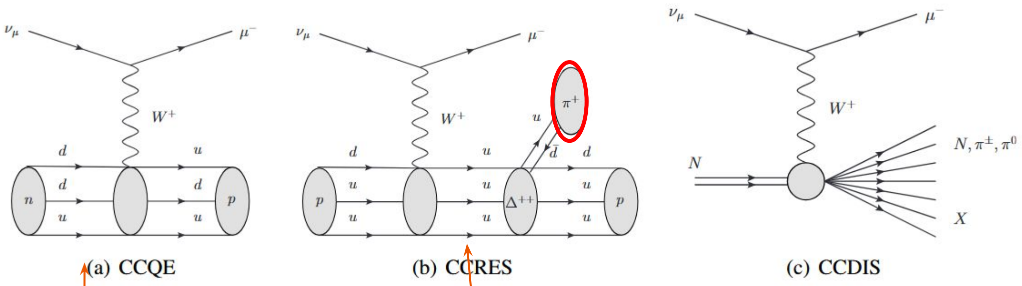



Figure 5.2: Neutrino charged current interaction with a nucleus through quasi-elastic (left), resonant (center) and DIS processes.

1 lepton produced : **Charged Current Quasi Elastic (CCQE) interactions**

CC1π (1 lepton + 1 charged pion produced) : **Charged Current Resonant interaction**

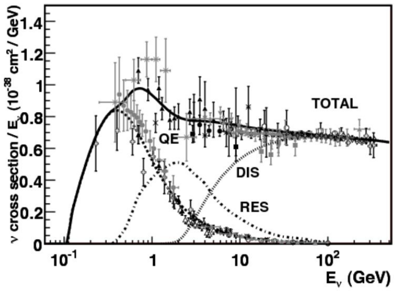



Figure 5.1: Total neutrino CC cross sections per nucleon **divided by neutrino energy** and plotted as a function of energy. The important increase from $E_\nu \sim 100$ MeV to 1 GeV is due to the kinematics of the process which should produce a muon. Taken from [65]. See Figure 5.3 for the legends of the different data sets.

At the energy of T2K (~600 MeV), **CCQE** interactions are predominant followed by **CCRes** interactions.

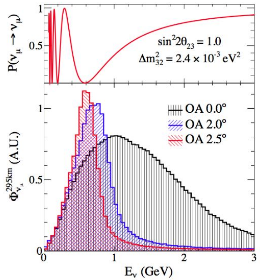



Figure 7.2: T2K $\nu_\mu$ beam spectrum at different off-axis angles. The $\nu_\mu$ survival probability at SK is also shown on the top. Figure taken from [86].

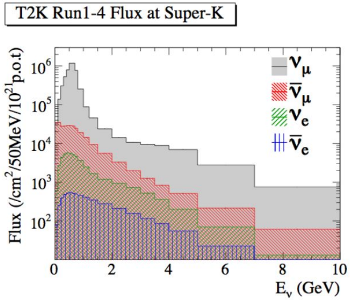



Figure 7.4: Predicted T2K neutrino flux at SK. Figure provided by the T2K beam working group.

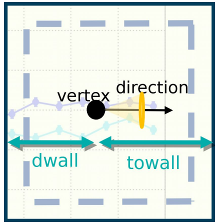
# Different kind of interactions

Our signal for oscillation analysis is :

- **CCQE nu_mu** and **CCQE from oscillated nu_e -> 1Re and 1Rmu samples**
- **CC1pi nu_mu** and **CC1pi from oscillated nu_e -> MRmu, 1Re+pi, MRe samples**

Everything else is background :

- Neutral current
- Non oscillated nu_e (beam contamination)
- CCDIS (high energy neutrino interactions)



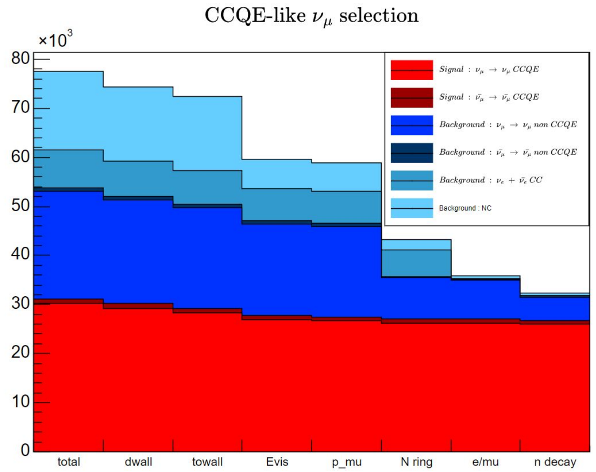

Particles outside the fiducial volume are ignored.

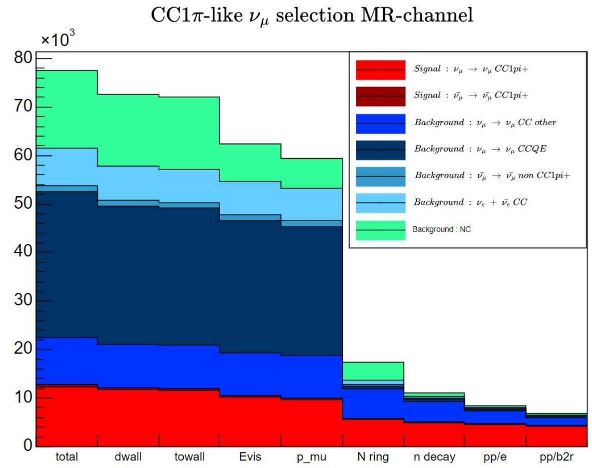
First study of this kind for Hyper Kamiokande : a lot of parameters needs to be optimized, especially the **fiducial volume** (maximum volume containing all the events that we accept).

# Some results

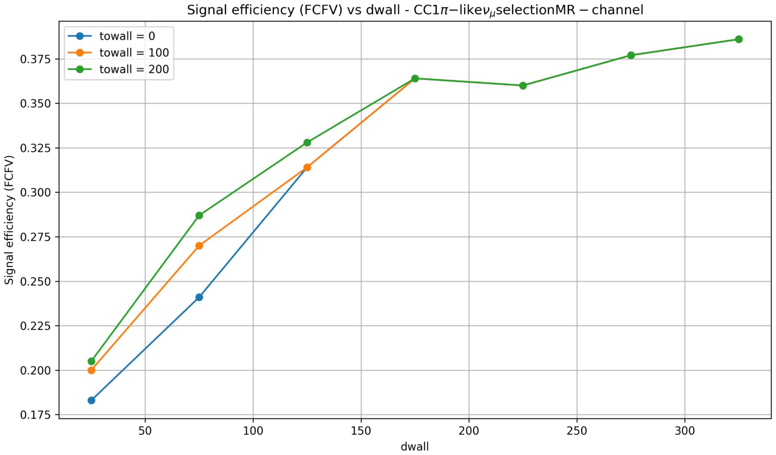
Using the properties reconstructed by fiTQun, we can find criteria to **select only our signal events** among all the events :

- Number of rings
- Number of decay electrons (from muon decay)
- Particle identification
- ...

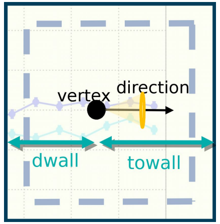


# Some results




Impact of the **fiducial volume** on the selection;




| Samples | | Signal efficiency (FCFV) | Signal purity | Background acceptance | Main background |
|---|---|---|---|---|---|
| CCQE nu_e | T2K (2020) | 69.4% | 80.4% | 1.6% | nu_e beam, NC |
| | **HK** | **90.6%** | **80.0%** | **1.3%** | **oscillated nu_e CC, nu_e beam, NC** |
| CCQE nu_mu | T2K (2020) | 84.2% | 76.3% | 7.3% | nu_mu CC non QE, NC |
| | **HK** | **92.2%** | **80.4%** | **13.0%** | **nu_mu CC non QE, NC** |

**Sample statistics** obtained during this work (here for CCQE samples).

# Final word

Other subjects I worked on during my internship :

- Phenomenology : study of the possibility of experimentally validating theoretical model of neutrino physics like **leptogenesis, discrete flavor symmetry.**
- Exploring the impact of an electron/gamma separation on the background of **proton decay** analysis.

# Thank you for listening