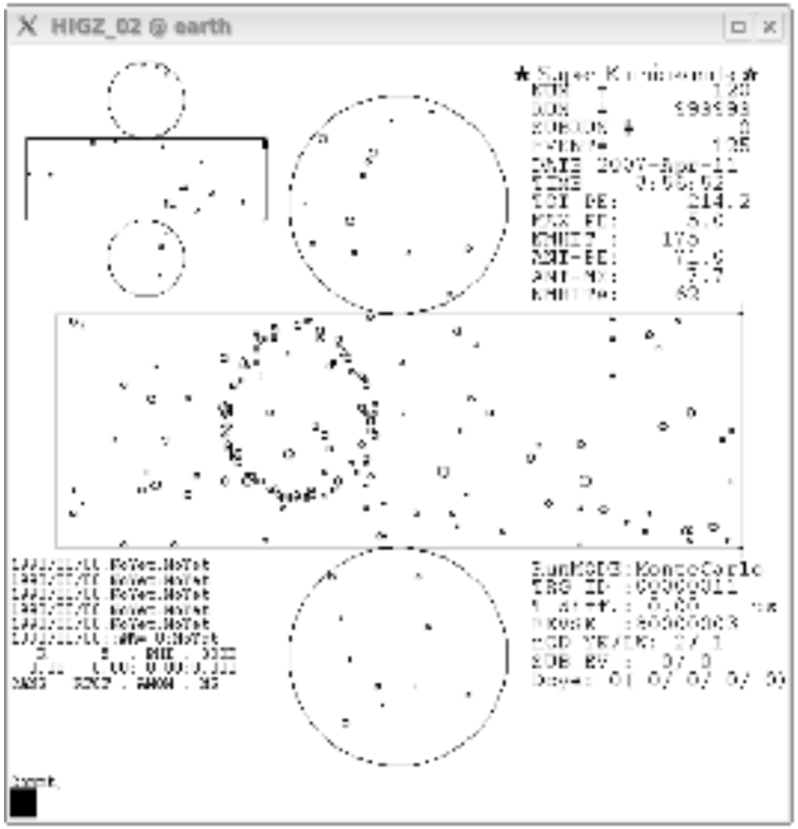
CCQE and NCEL in Super-K

using proton identification

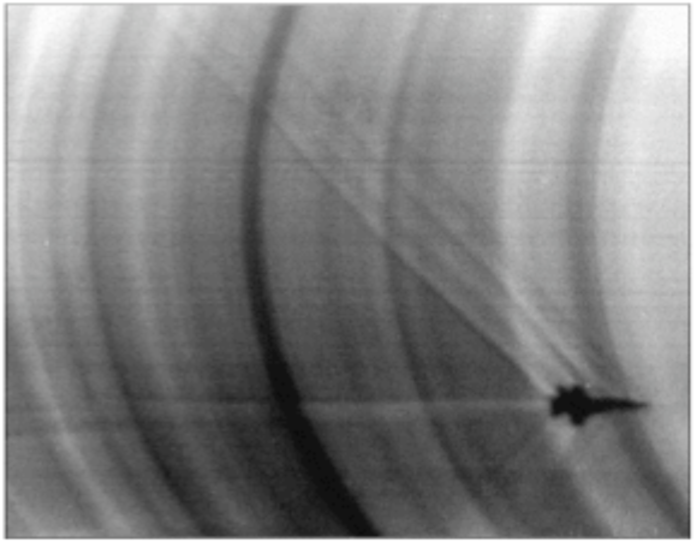


C. Walter and M. Fechner for the Super-Kamiokande Collaboration
NuInt09 Sitges, Spain

Cherenkov Radiation

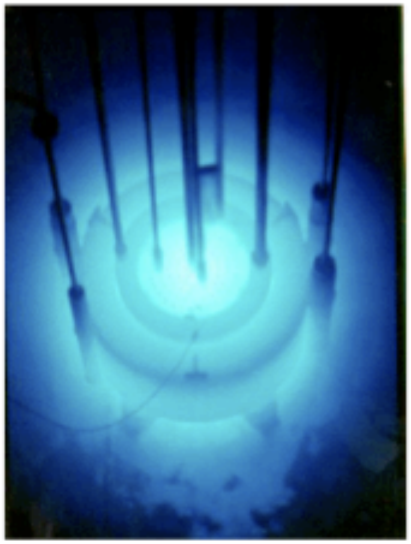
Cherenkov light is emitted when a charged particle, like a muon or an electron goes faster than the speed of light in some medium. The Cherenkov light is emitted like a shockwave, in a cone along the direction of particle motion.

Hypersonic Jet



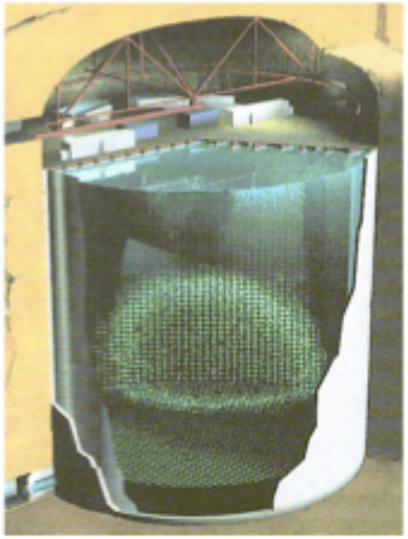
Moving faster than the speed of sound in air makes a sonic boom.

Reactor Core



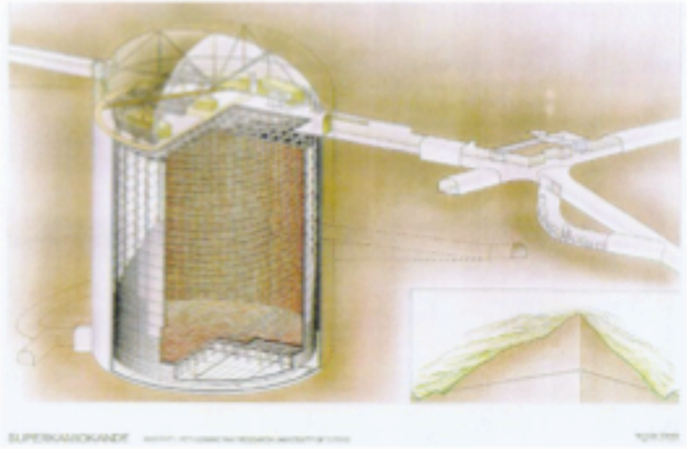
Electrons moving faster than c/n in water make light.

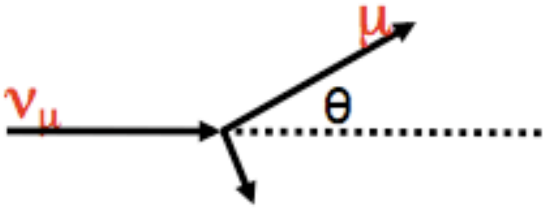
Super-K



Particles **moving faster than c/n** make cones of light.

E_ν Reconstruction (assuming QE)





$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\theta_\mu)}$$

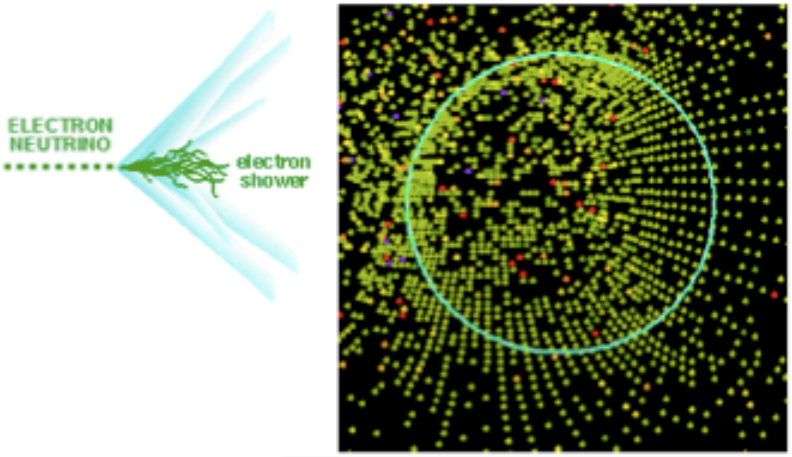
m_N = Neutron Mass
E_μ = Muon Energy
m_μ = Muon mass
p_μ = Muon momentum
θ_μ = Muon angle wrt beam

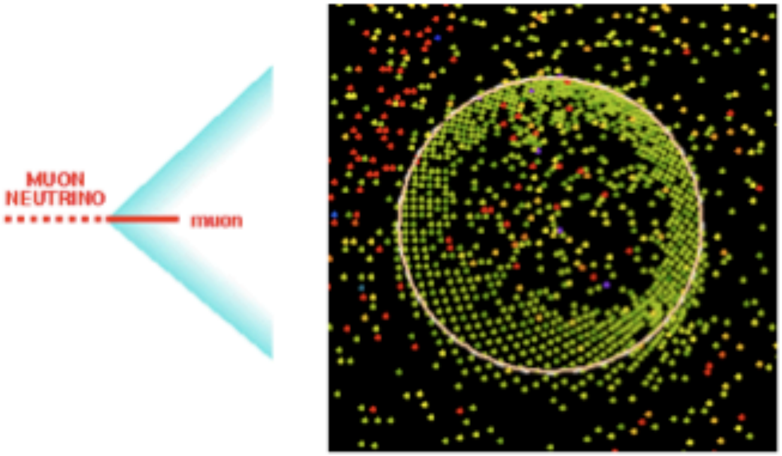
In Water Cherenkov detectors not every particle is above Cherenkov threshold. Luckily, in a Quasi-Elastic reaction, even if only the muon is visible we can reconstruct the neutrino energy!
[Case for most events in K2K/T2K Energies]

If the interaction is non Quasi-Elastic then the reconstructed energy will be incorrect.

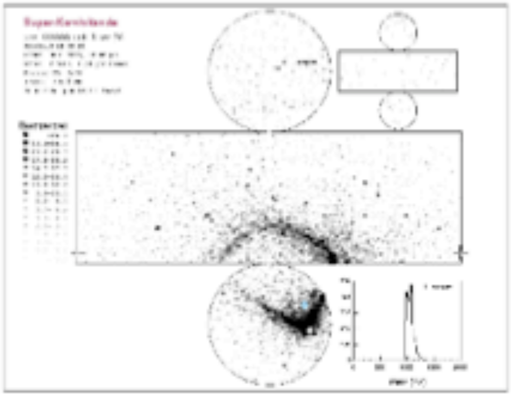
With atmospheric neutrinos we don´t know the direction of the beam.

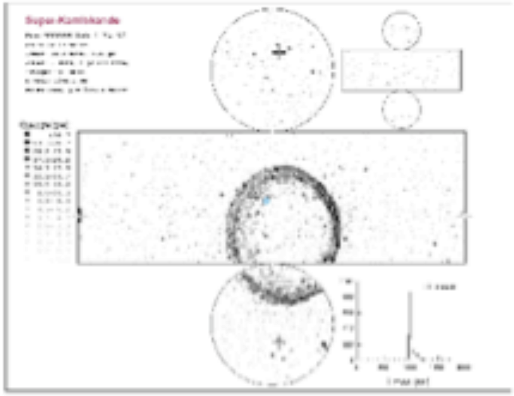
Telling Electrons from Muons





Compare profile of ring against a shape likelihood.





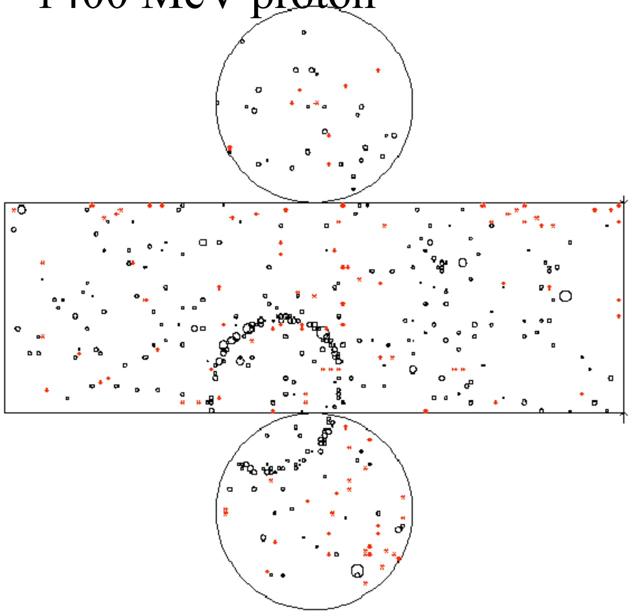
Electrons bremstrahlung
and pair produce making many
particles each making light.

Thickness gives momentum

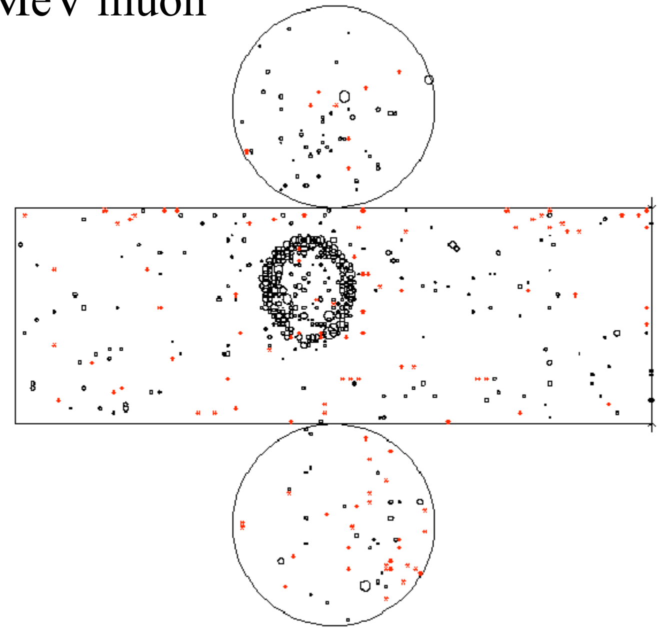
Muons move forward
producing a single cone
of light.

Proton vs muon

~ 1400 MeV proton



~ 300 MeV muon

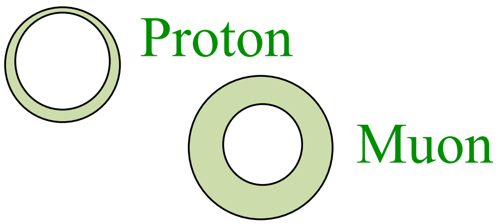


Proton ID relies on :
- smaller opening angle
- “thinness” of the ring
- different light density

- First successful identification and reconstruction of protons in a water Cherenkov detector.
- NC Elastic events : $\nu + p \rightarrow \nu + p$ are sensitive to all neutrinos and sterile oscillations.

The single proton fitter

- **Protons have distinctive characteristics :**
  - Cherenkov threshold >~ 1070 MeV/c
  - Small opening angle
  - Sharp edges on the outside of the cone
- **Interactions in the water → short tracks**
  - Thin rings with sharp edges on the inside



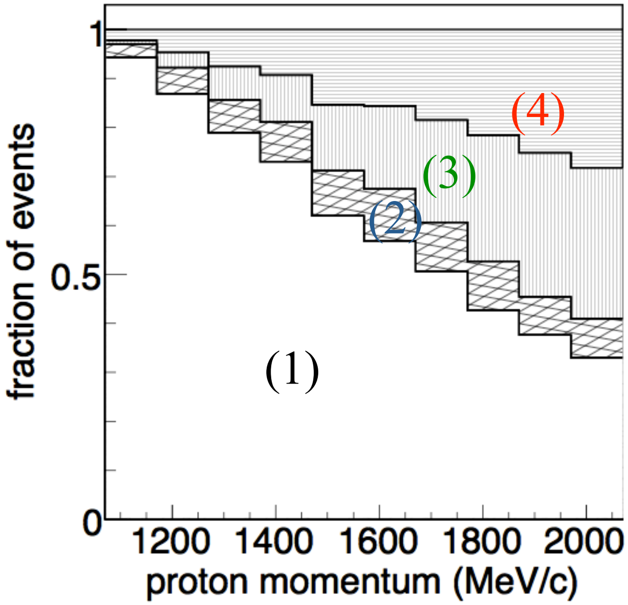
New light pattern engine includes hadronic interactions

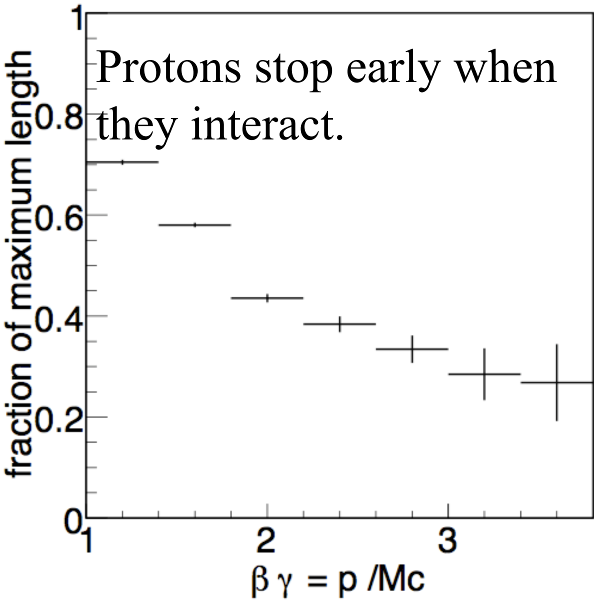
  - makes proton patterns for any vertex + direction + momentum + path length
- **Proton fitter :**
  - Same idea as regular PID : test proton hypothesis vs muon hypothesis
    - Maximizes the proton pattern likelihood $\mathcal{L}_p$ while fitting for proton momentum P & path length L
    - Calculates the muon pattern likelihood $\mathcal{L}_\mu$ assuming event is single muon
  - Adaptable to other particles (pions)

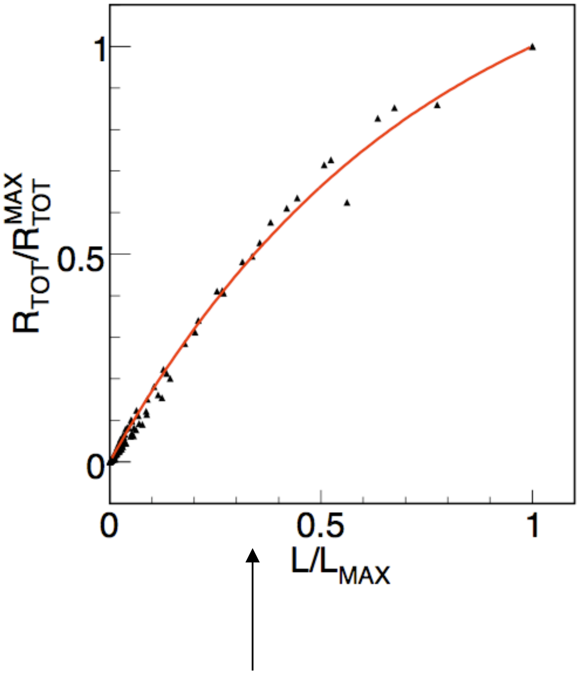
OUTPUTS OF FITTER

Hadronic Interactions

Protons traveling in the water produce secondary particles



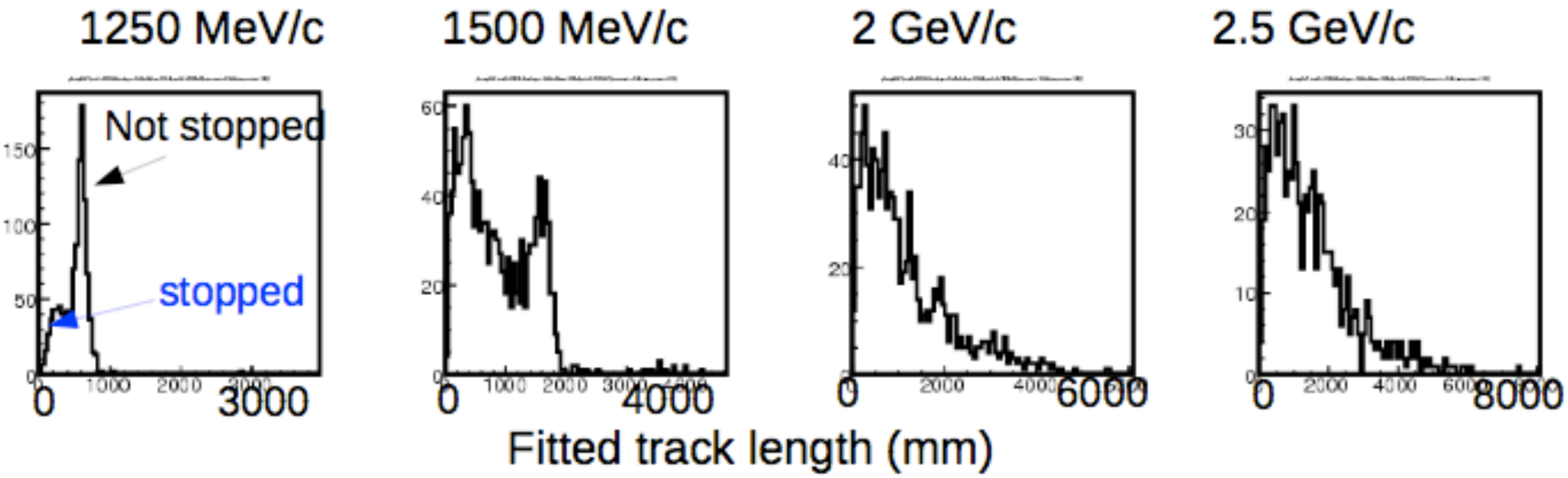

Protons stop early when they interact.



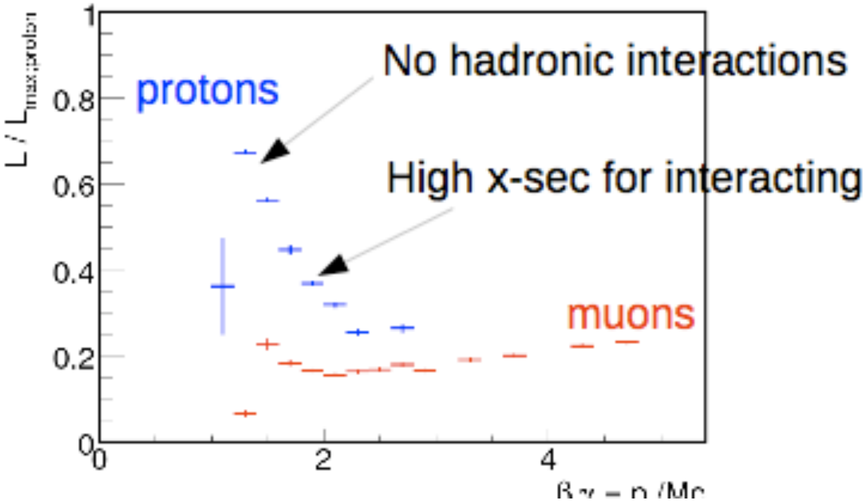
How do you normalize the amount of light in a pattern for a proton that stops?

1) No secondaries
2) Below threshold secondaries
3) Above threshold charged pions
4) hadronic pizero production

Interacting protons: Examples



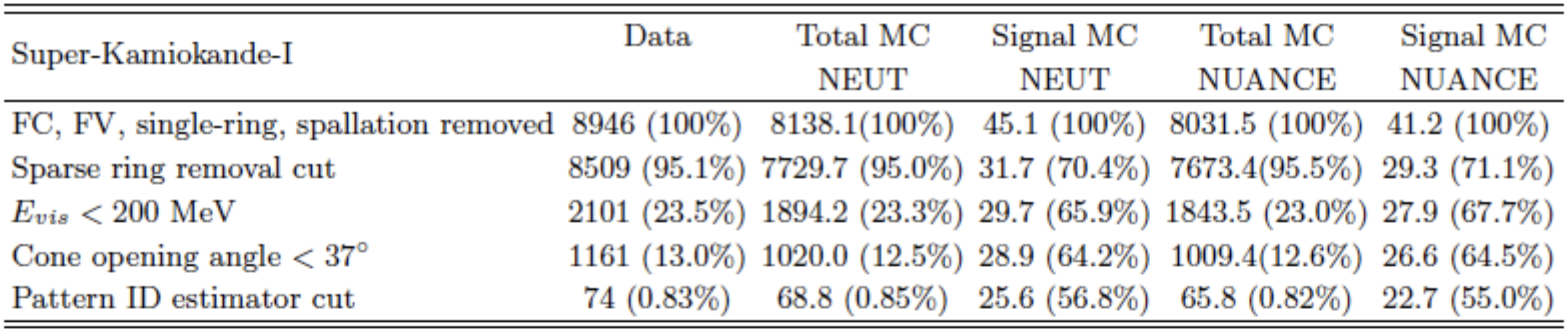
- We can "see" the hadronic interactions in the water of high-P protons
- Ratio of L/Lmax(P) important for mu/p separation : can see the fraction of Lmax decreasing when hadronic interactions increase for protons



Searching for single protons

- Identify NC elastic interactions : ν + p → ν + p
- Other NC modes also contribute if other particles are below threshold
- Because of the atmospheric neutrino spectrum & high Cherenkov threshold, only ~10 interactions/year are potentially visible...
- Strategy :
  - Apply cuts on sample to enhance signal component
  - Pass remaining events to neural network to get rid of remaining background

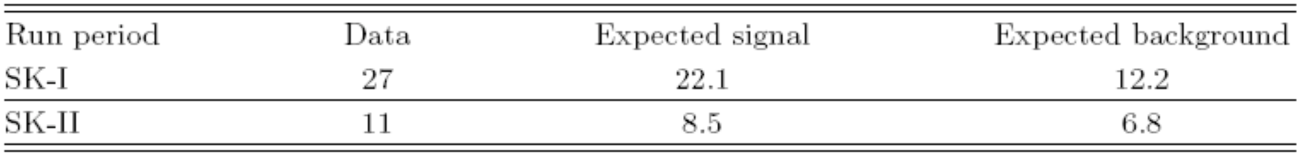
This analysis was done with
1489.2 days of SK-I (~ 40% photocathode coverage)
798.6 days of SK-II (~ 20% photocathode coverage)
= 141 kton*yr



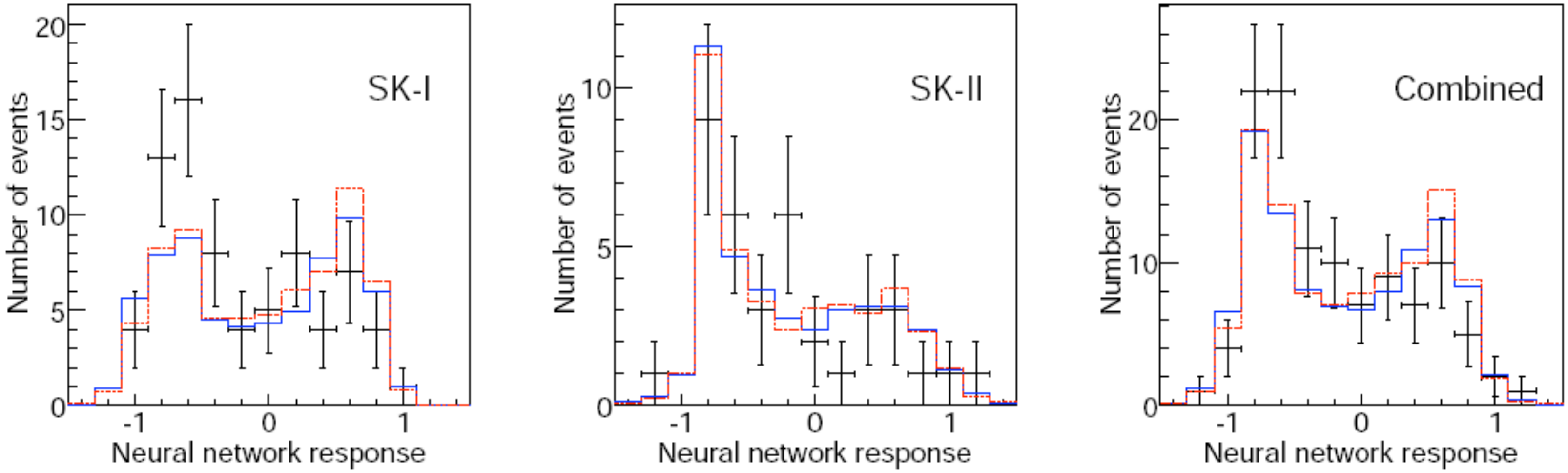
Super-Kamiokande-I	Data	Total MC NEUT	Signal MC NEUT	Total MC NUANCE	Signal MC NUANCE
FC, FV, single-ring, spallation removed	8946 (100%)	8138.1(100%)	45.1 (100%)	8031.5 (100%)	41.2 (100%)
Sparse ring removal cut	8509 (95.1%)	7729.7 (95.0%)	31.7 (70.4%)	7673.4(95.5%)	29.3 (71.1%)
$E_{vis} < 200$ MeV	2101 (23.5%)	1894.2 (23.3%)	29.7 (65.9%)	1843.5 (23.0%)	27.9 (67.7%)
Cone opening angle $< 37^\circ$	1161 (13.0%)	1020.0 (12.5%)	28.9 (64.2%)	1009.4(12.6%)	26.6 (64.5%)
Pattern ID estimator cut	74 (0.83%)	68.8 (0.85%)	25.6 (56.8%)	65.8 (0.82%)	22.7 (55.0%)

Search for NC elastic events

- About 30 events with a single visible proton will be visible in the data
- Proton PID + neural network to extract small signal out of backgrounds



Run period	Data	Expected signal	Expected background
SK-I	27	22.1	12.2
SK-II	11	8.5	6.8

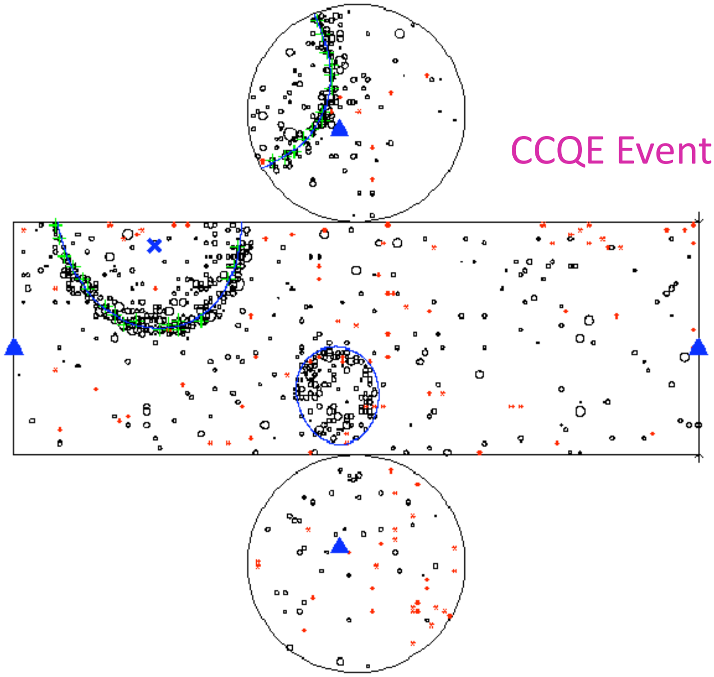


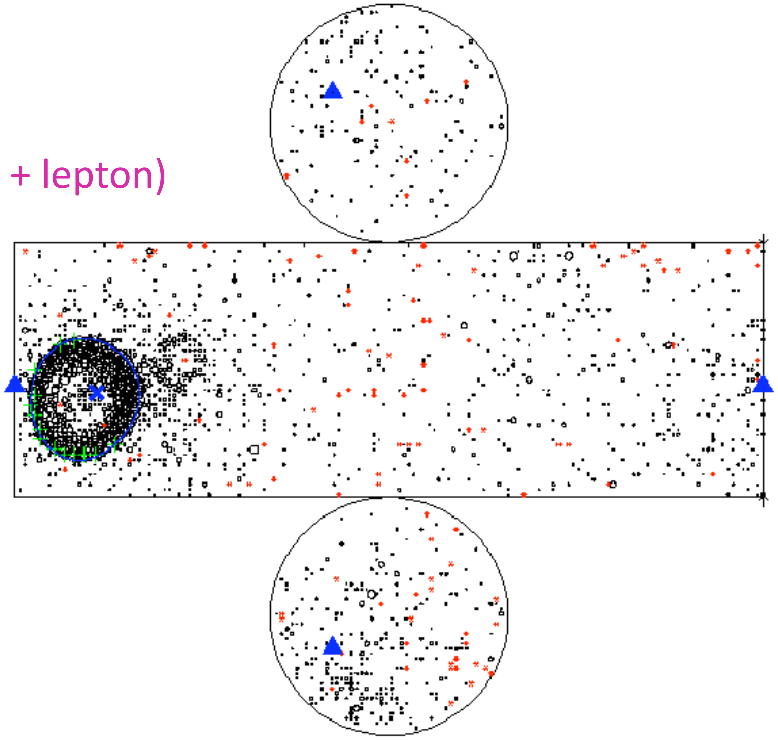
- χ^2 of Data to MC with protons = 9.3 for 6 bins → Probability = 15.7 %
- χ^2 of Data to MC with no visible protons = 15.8 for 6 bins → Probability = 1.5 %
- Observed up-down asymmetry = -0.1±0.19

Data favors proton observation Data compatible both with and w/o sterile osc

Signal: 55% NCEl rest absorbed single pions / Sample is 85% NC (SKI)

CCQE search





CCQE Events (proton + lepton)

There are two types of CCQE events in SK if the proton is above Cherenkov threshold :

- 2 rings are found by standard ring finder
- Identified as 1 ring but 2nd is found by new dedicated CCQE search algorithm

- CCQE events ($\nu + p \rightarrow p + l$) can be fully reconstructed because all kinematics are constrained.
- CC events with a visible proton come only from neutrinos.

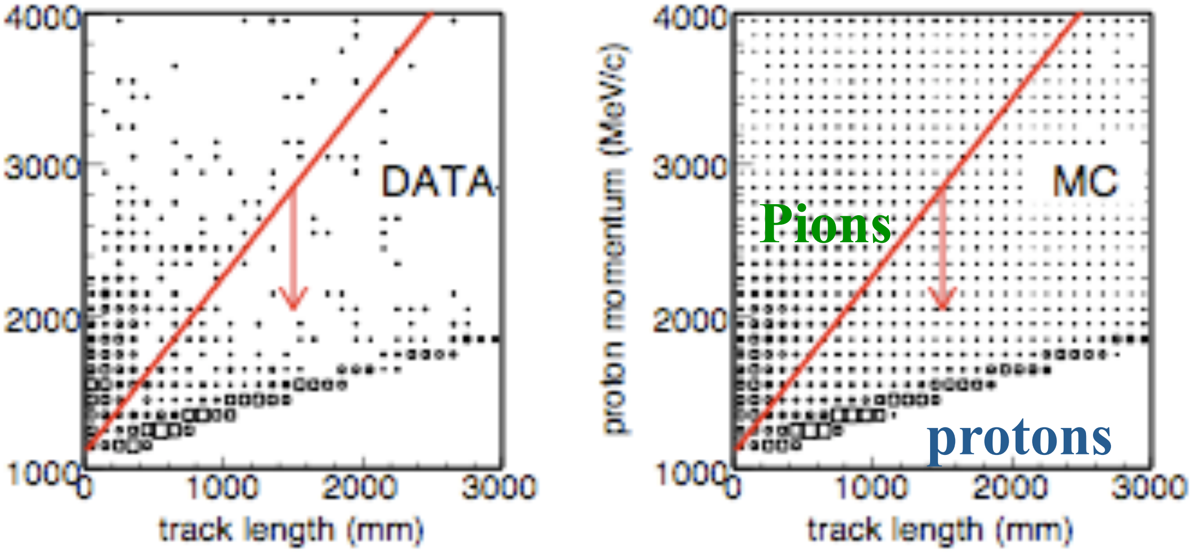
Don´t need to know the direction of the beam!

Search for CCQE events

- Use 2 ring events (1 lepton, 1 proton) : identify proton & get its momentum
- Use 1 ring events (only lepton found but p visible) : reconstruct & identify proton

This doubles the statistics.

- Selection cuts
  - use proton likelihood information
  - Use specialized cut to remove pions.
    - Protons : any length, but peak toward max track length
    - Pions : very short path length



Kinematically enhance CCQE

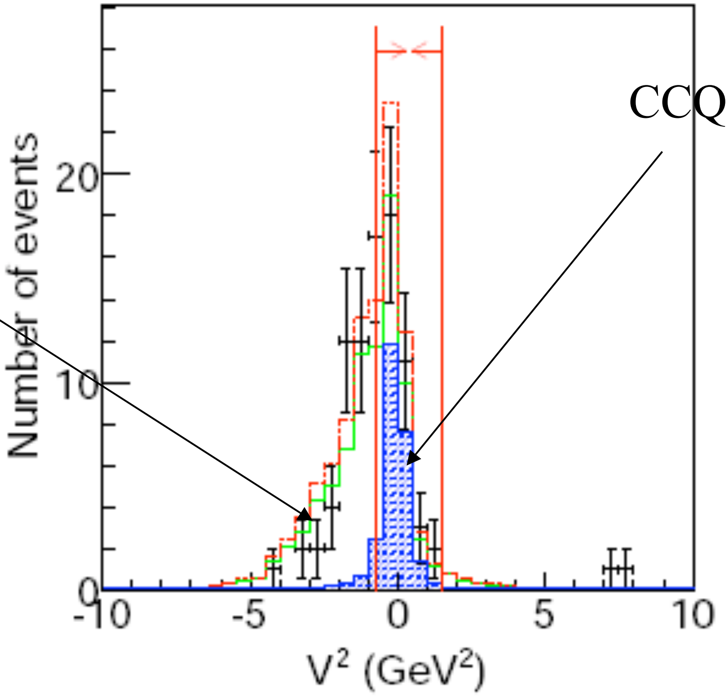
Let V be the 4-vector

$$V = P_p + P_l - P_n,$$

where P_p, P_l, and P_n are the 4-momenta of the proton, lepton, and target neutron.

Lorentz invariant quantity V^2 must be $m_\nu^2 \approx 0 \text{ eV}^2/\text{c}^4$

How can we do it without knowing the beam direction??



non-CCQE

CCQE (mass~0)

With a beam:
Try this AND direction!

Reconstructed Neutrino Energy.

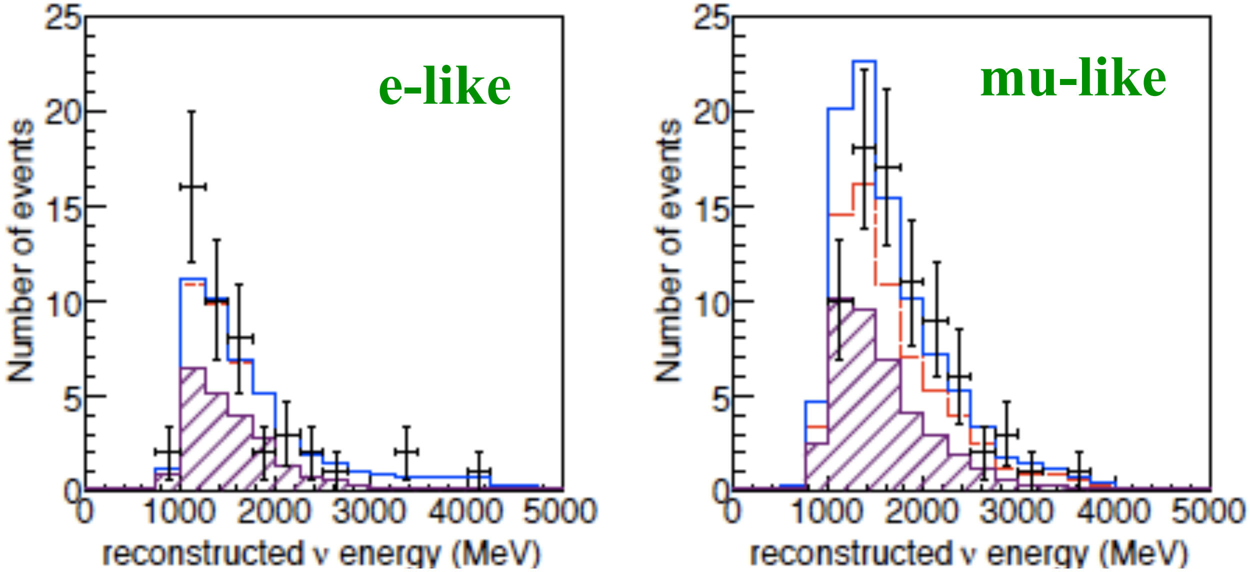
$$P_{tot} = \sqrt{(\mathbf{P}_{\mathrm{p}} + \mathbf{P}_{\mathrm{l}})^2},$$

Neutrino energy

and

$$\mathbf{d} = \frac{1}{P_{tot}}(\mathbf{P}_{\mathrm{p}} + \mathbf{P}_{\mathrm{l}}),$$

Neutrino direction



Event class	SK-I data	SK-II data
NC elastic (expected NC elastic fraction)	27 (64.7%)	11 (55.6%)
CCQE e-like (expected CCQE fraction)	31 (53.0%)	16 (51.4%)
CCQE μ-like (expected CCQE fraction)	60 (62.4%)	18 (61.3%)

Neutrino kinematic reconstruction

- **Proton + lepton – immobile neutron = incoming neutrino track**
- ~ 14% energy resolution for sample (8% for CCQE events)
- Angular resolution: 12° on νμ tracks, 16° on νe tracks

The CCQE sample is 70-80% sub-GeV.

the neutrino is > 1 GeV but evis is < 1.3 GeV

The sample has CC purity of 88% for e-like and 95% for mu-like events.
The sample is 92% neutrino as opposed to anti-neutrino.

The **lepton** doesn't point back to the neutrino direction but the **neutrino** does!

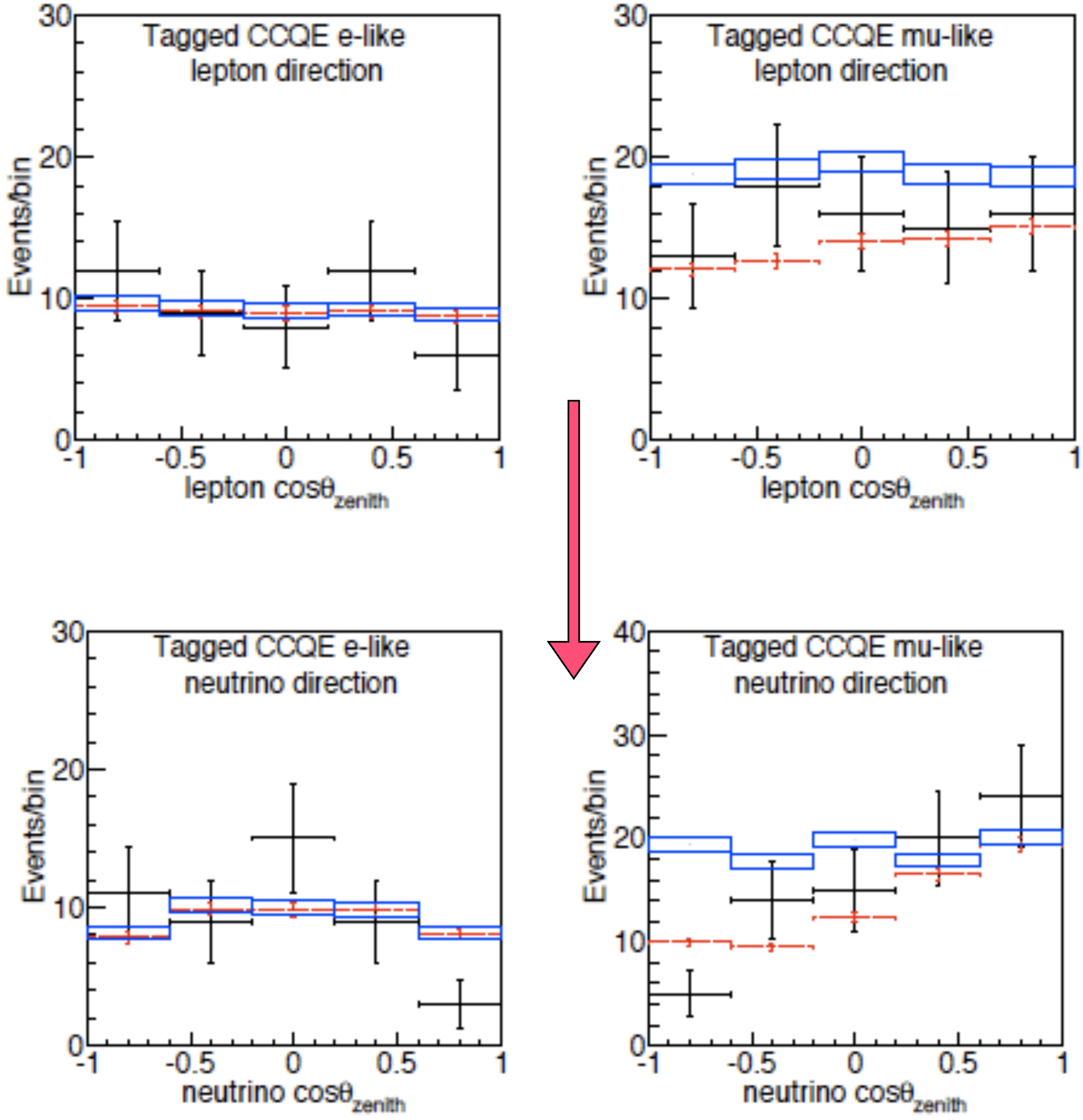
Using proton ID restores zenith angle pointing to a low energy portion of the data which had no observed zenith angle distortion and adds events to the sample which were not previosly considered.

Lepton vs neutrino zenith direction

From Lepton

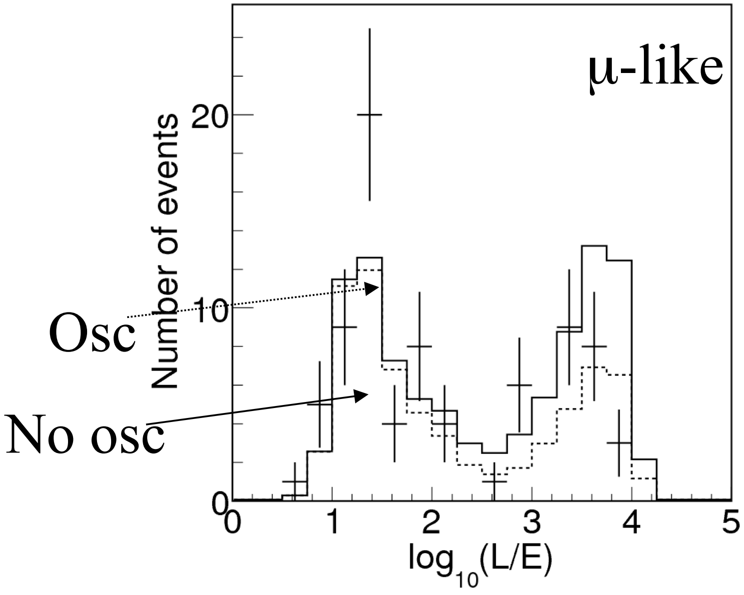
To

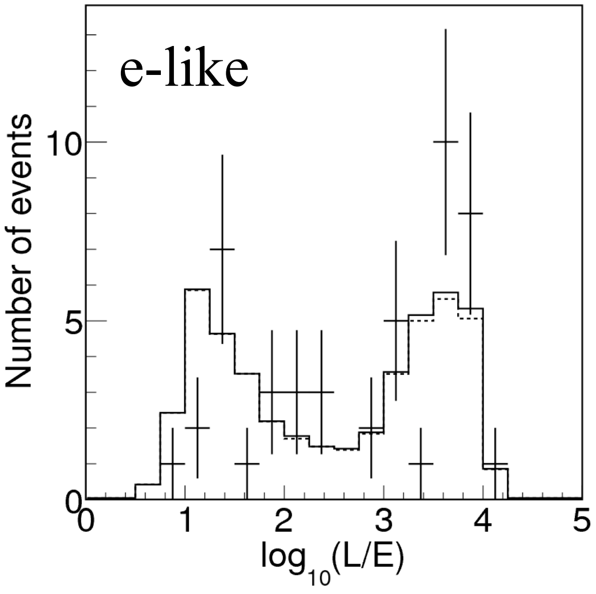
Neutrino



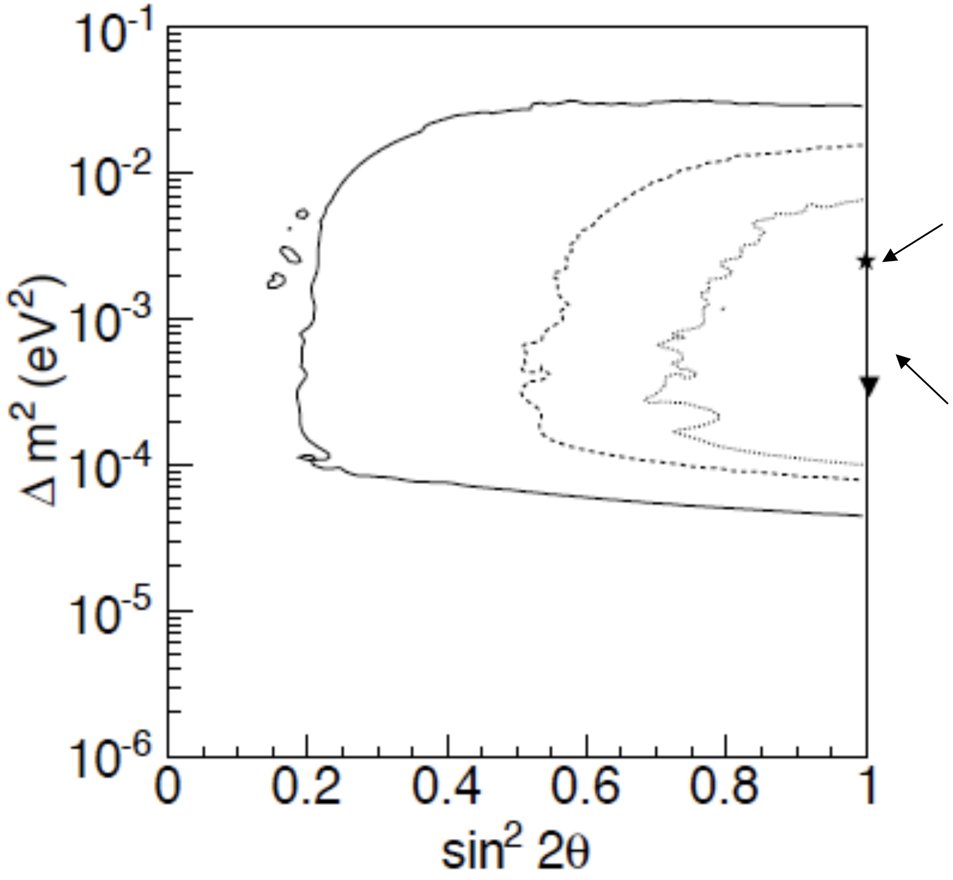
L/E distributions

- **Kinematically reconstruct incoming neutrino direction & energy, and calculate L/E with the neutrino parameters**
- **Do 2 flavor oscillation fit**
- Several remarks :
  - Soudan-2 did something similar with twice the stats, but this is the 1st time in a large water Cherenkov
  - NOT competitive with our other analyses. It is an extra confirmation of our analysis technique and the oscillation hypothesis using a precisely reconstructed sample
  - This sample is almost pure ν (as opposed to anti-ν) : ν fraction is 91.7±3% (syst) With larger detector, very good for CP odd effects (mass hierarchy, etc)





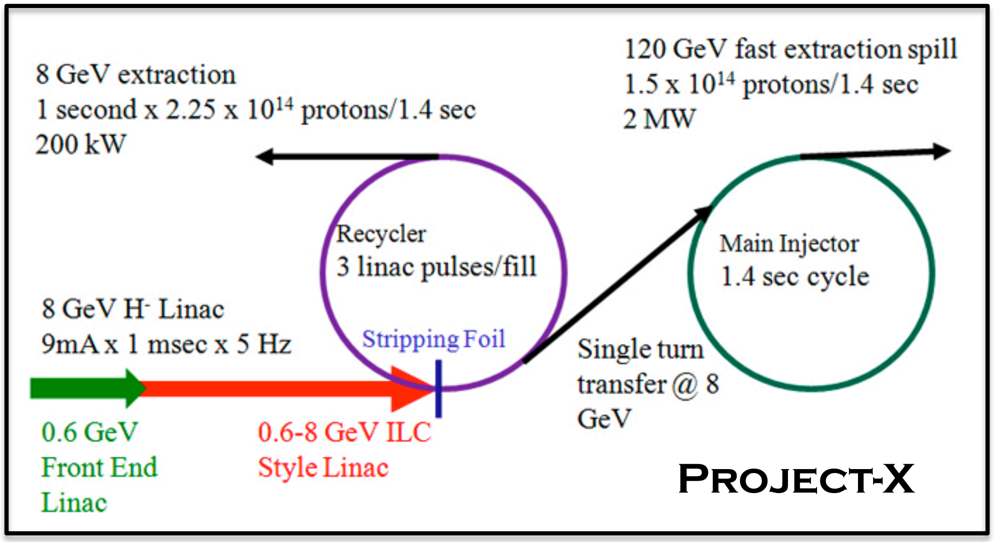
Results of L/E fit



Usual best fit

This analysis

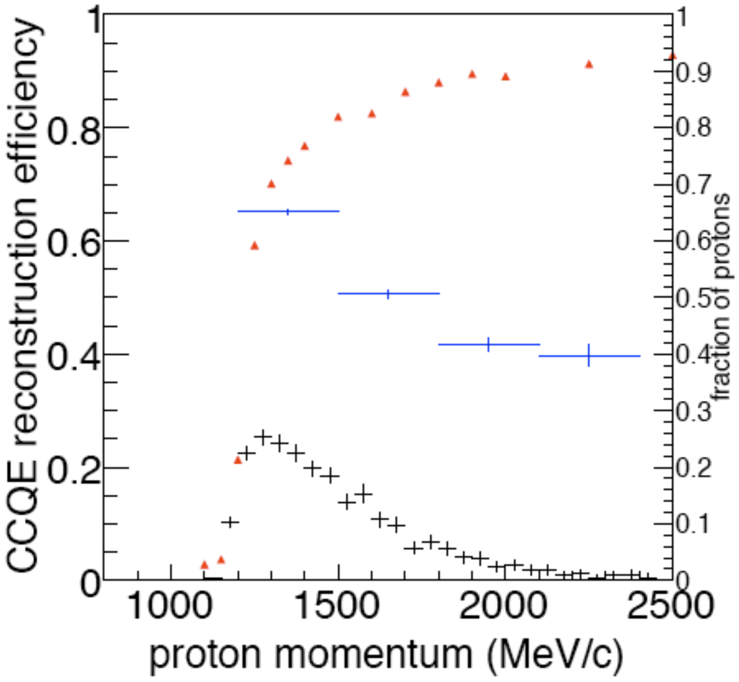
No oscillation : $\Delta\chi^2 = 12.95$ → excluded at 3 σ

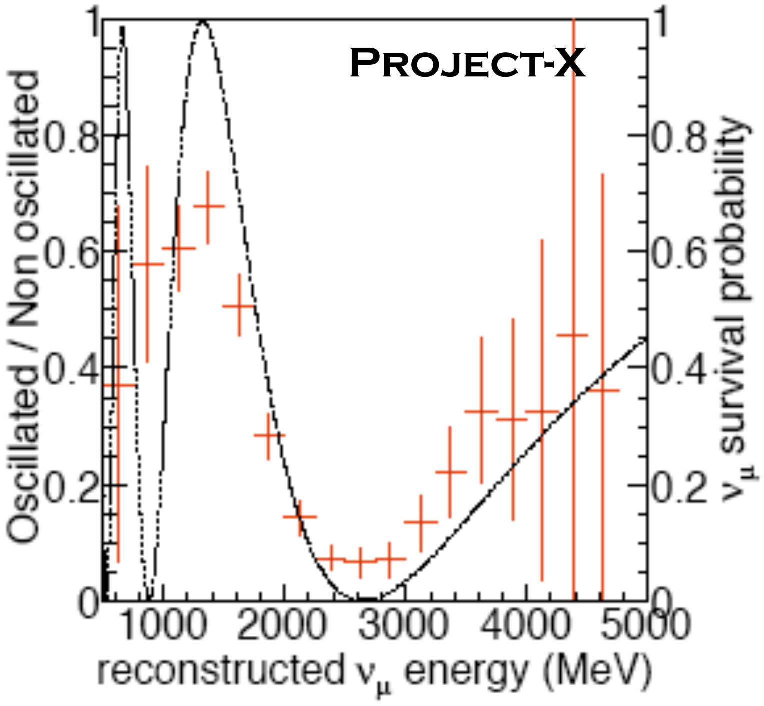


Also can apply technique to studies of future beams and large detectors

Calculated for large WC detectors with atmospheric and T2K/Project-X/ and beta beams.

COME TO NUFACT. IF MY LAPTOP IS NOT RUN OVER BY A BUS I WILL TELLYOU ABOUT IT.



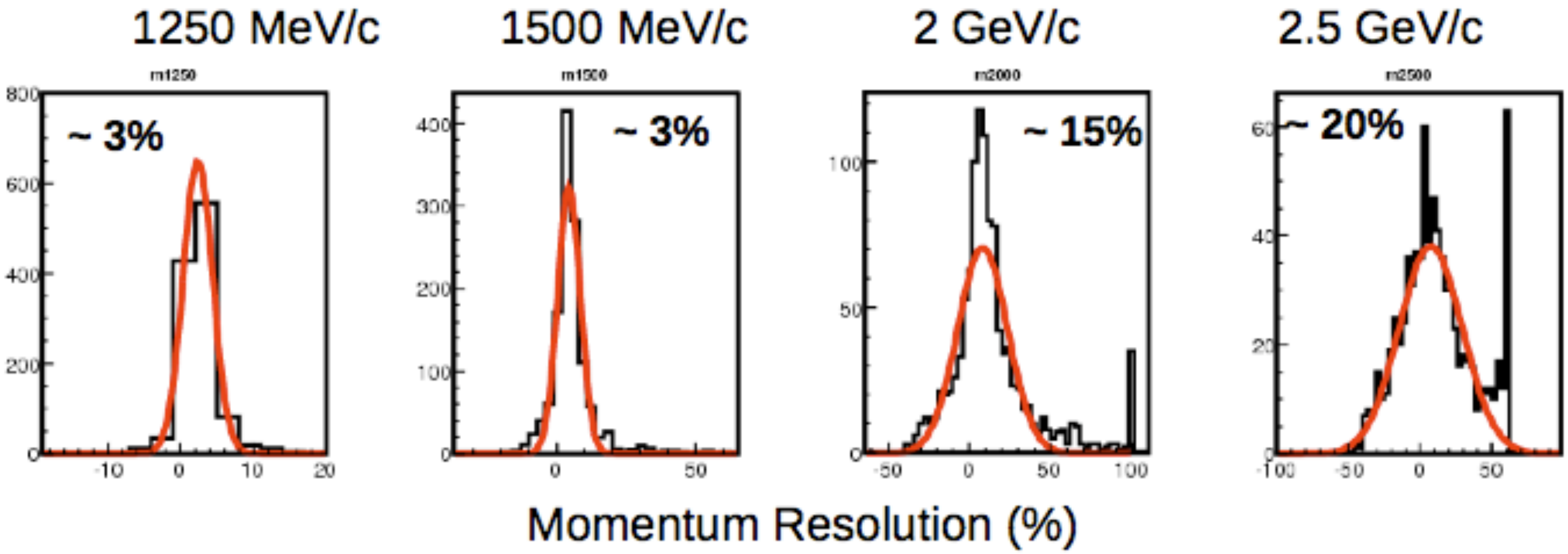


Conclusions

- We sucessfully identified and recontructed protons in the Super-K experiment.
- We obtained a high purity NC sample.
- We also obtained a sample of fully kinematically reconstructed atmospheric neutrinos by selecting CCQE events from neutrino interactions.
- The CCQE fraction of the sample is 55% and its neutrino fraction is 92%.
- A clear zenith angle distortion in the neutrino direction itself was seen.
- An L/E analysis confirmed our previous result and excluded the no-oscillation hypothesis at three sigma.
- This technique will be usefull in future large WC detectors and some of the ideas might also be profitbly used in other detectors as well.

Backup

- Proton momentum constrained by opening angle



- Very good precision in the momentum measurement < 15 % for p<2GeV/c

Fit to L/E distributions

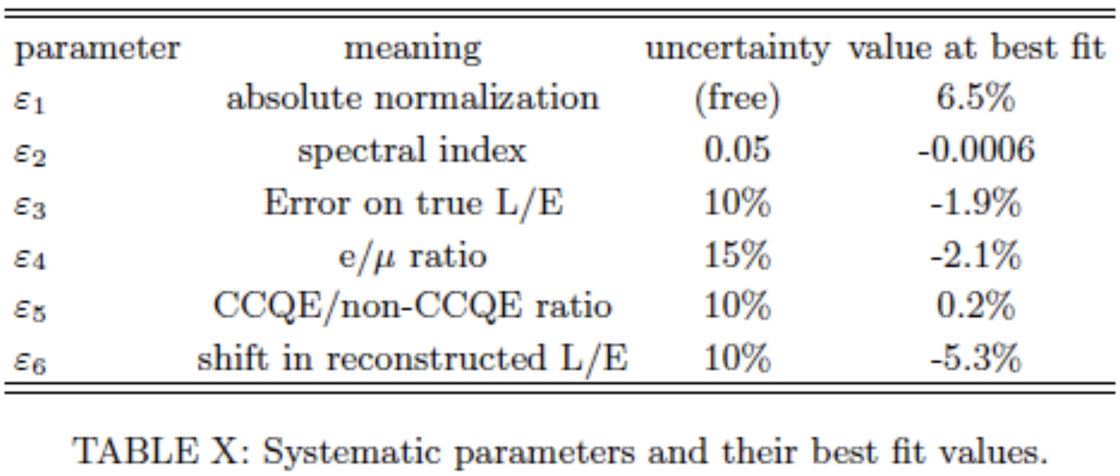
- 2 flavor oscillation hypothesis
- Use Poisson likelihood ratio instead of chi2
- Use only 5 bins in log(L/E) for each distribution following Shiozawa-san's comment
- Fit e-like & mu-like together

$$\chi^2 = \sum_{i=1}^{N_{bins}} 2\left(N_i^{exp} - N_i^{obs} + N_i^{obs}\ln\frac{N_i^{obs}}{N_i^{exp}}\right) + \sum_{j=1}^{N_{sys}}\left(\frac{\varepsilon_j}{\sigma_j^{sys}}\right)^2$$

Systematics

- Cannot use Fij(too many) → **follow same procedure as 1998 oscillation paper**
- **Each of the 6 terms ε_i is a combination of the relevant systematic sources:**
  - **“theoretical” effects (ie flux, cross-sections),**
  - **errors from CCQE selection: overall efficiency (#1),**
    background selection efficiency (#5)
    bias in measured ν L/E from proton & lepton track reconstruction (#6)
- **List of the 6 systematic terms :**
  - **Absolute normalization**
  - **Neutrino spectral index** (width=0.05) as in Nuosc98
  - **Error on true L/E** when calculating oscillation probas (prod height, true E) : 10% as in nuosc 98 [flux, path length etc. effects]
  - **Error on e/mu ratio** : uncertainty in flavor content AND PID ; set to 15% (conservative) because SK-I and SK-II are combined
  - **Error on CCQE / non-CCQE ratio**, uncertainty in background selection efficiency [as well as x-section effects]. Set to 10% (conservative).
  - **Systematic bias in reconstructed L/E** from neutrino track reconstruction errors
    (error in momentum & direction reconstruction of proton and lepton)
    Set to 10% from MC studies.

Systematics at best fit



parameter	meaning	uncertainty	value at best fit
ε_1	absolute normalization	(free)	6.5%
ε_2	spectral index	0.05	-0.0006
ε_3	Error on true L/E	10%	-1.9%
ε_4	e/μ ratio	15%	-2.1%
ε_5	CCQE/non-CCQE ratio	10%	0.2%
ε_6	shift in reconstructed L/E	10%	-5.3%

TABLE X: Systematic parameters and their best fit values.