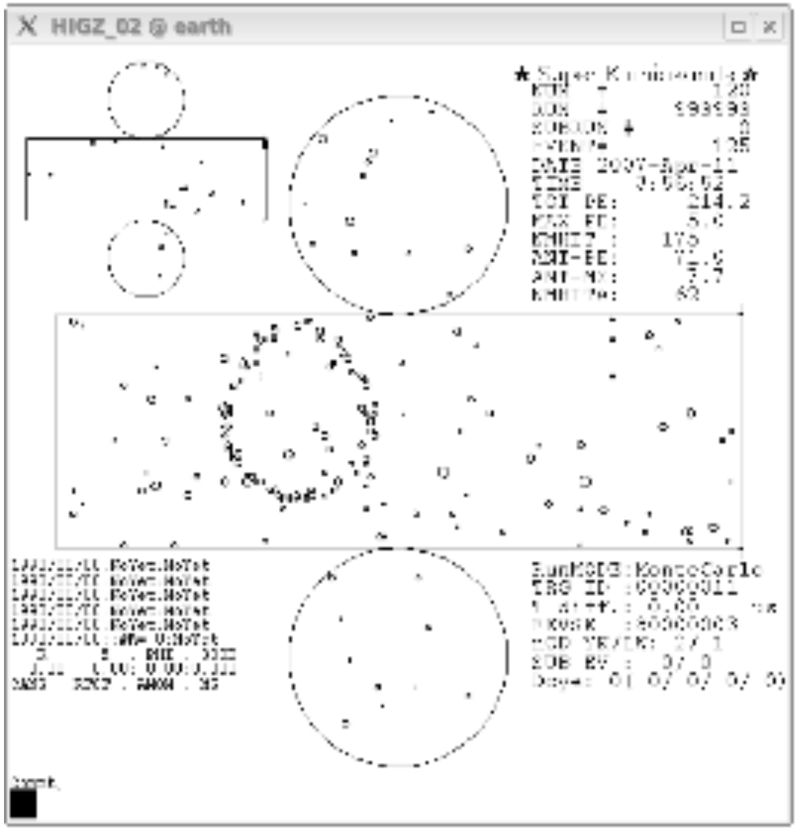
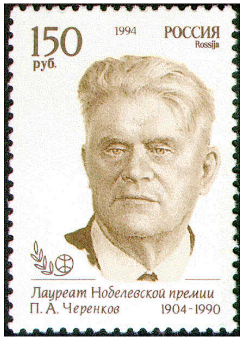
The physics impact of proton track identification in future megaton-scale water Cherenkov detectors.



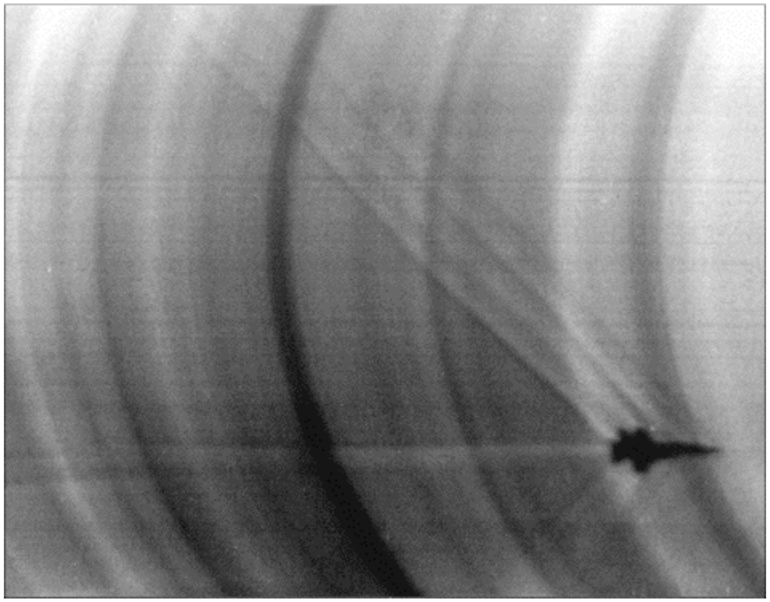
C.W. Walter and M. Fechner
NuFact09, IIT July 2009

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.

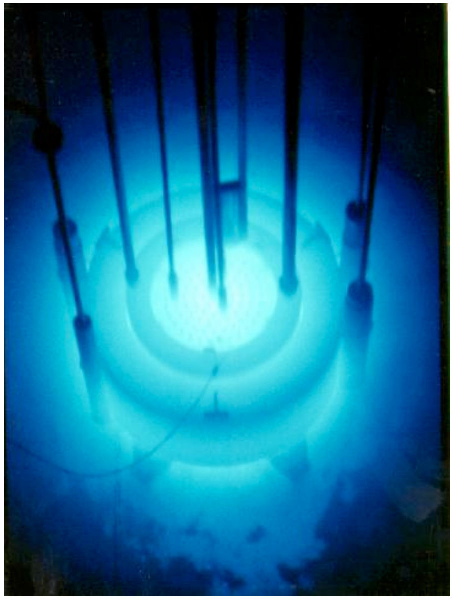


Hypersonic Jet



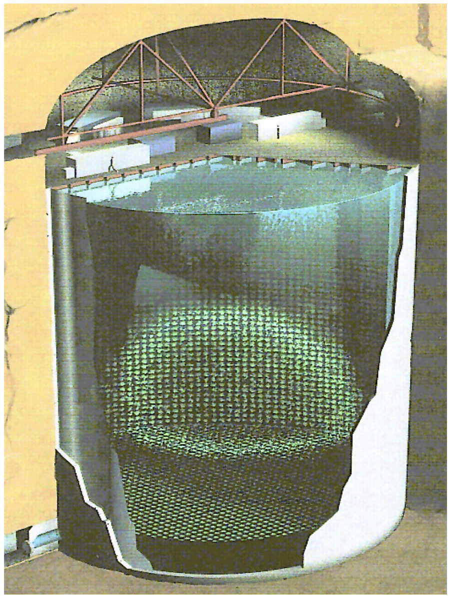
Moving faster than the speed of sound in air makes a sonic boom.

Reactor Core



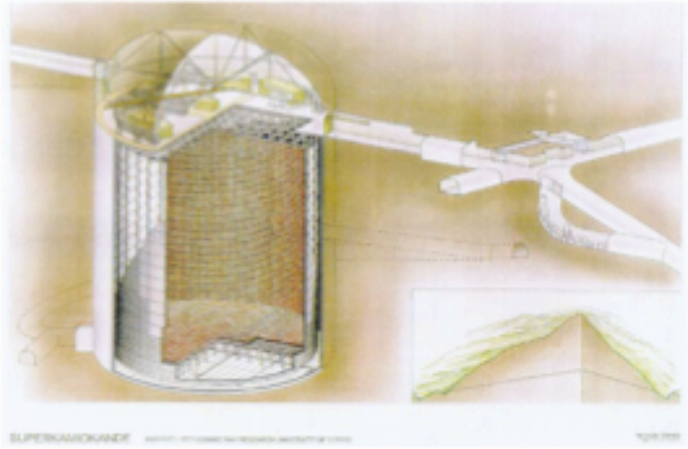
Electrons moving faster than c/n in water make light.

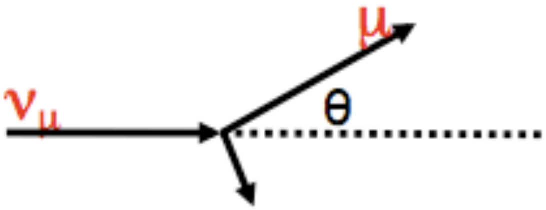
Super-K



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

E_ν Reconstruction (assuming QE)





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

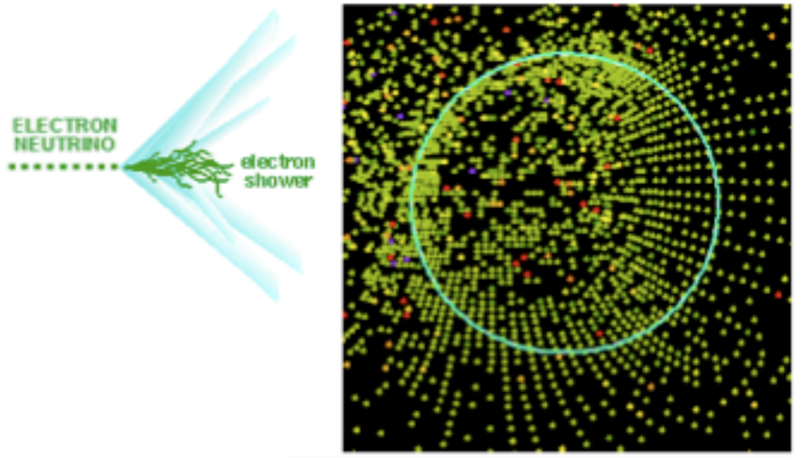
m_N = Neutron Mass
E_μ = Muon Energy
m_μ = Muon mass
p_μ = Muon momentum
θ_μ = Muon angle wrt beam

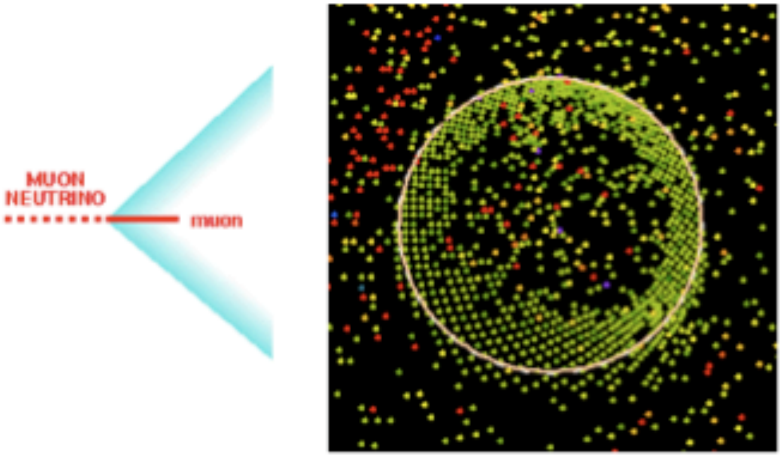
In Water Cherenkov detectors not every particle is above Cherenkov threshold. Luckily, in a Quasi-Elastic reaction, even if only the muon is visible we can reconstruct the neutrino energy!
[Case for most events in K2K/T2K Energies]

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

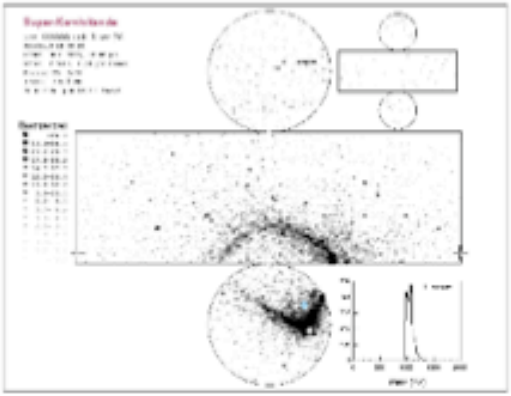
With atmospheric neutrinos we don´t know the direction of the beam.

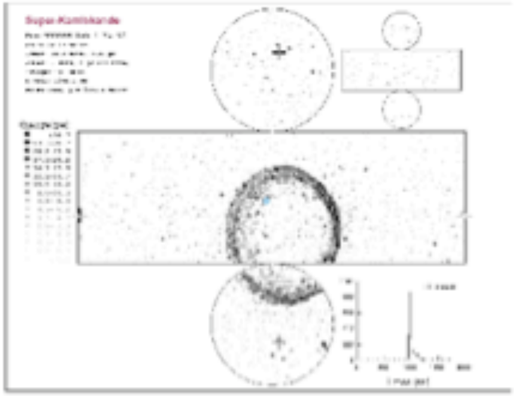
Telling Electrons from Muons





Compare profile of ring against a shape likelihood.





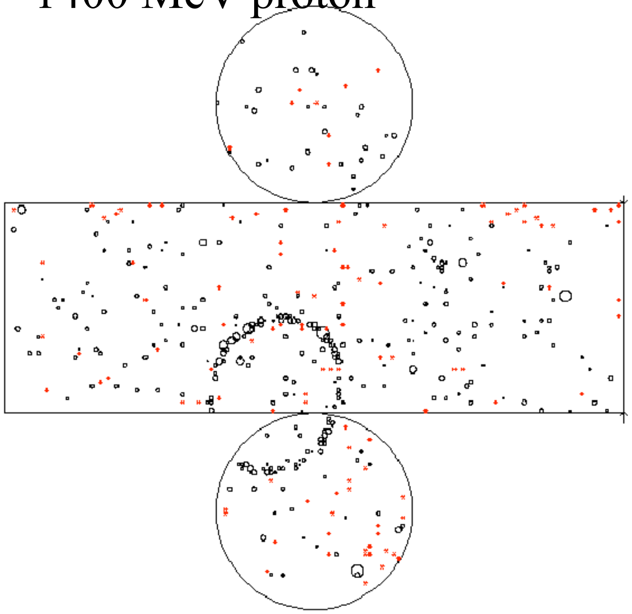
Electrons bremstrahlung and pair produce making many particles each making light.

Thickness gives momentum

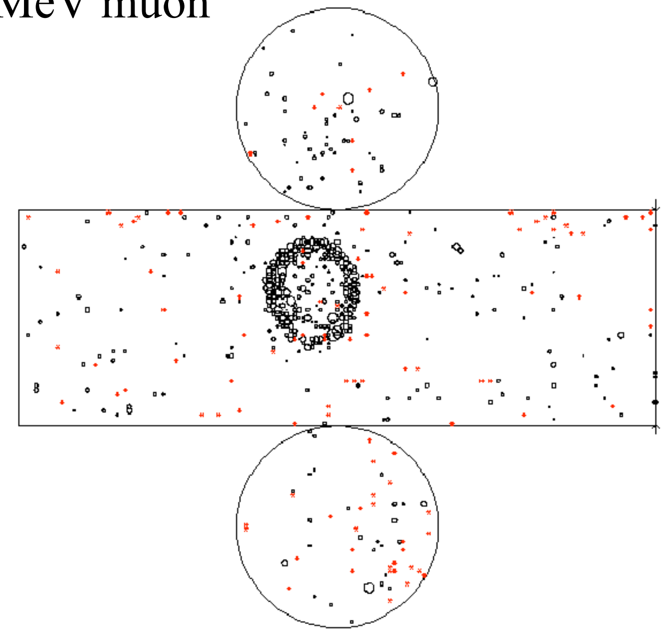
Muons move forward producing a single cone of light.

Proton vs muon

~ 1400 MeV proton



~ 300 MeV muon



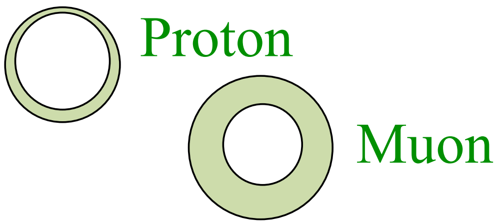
Proton ID relies on :

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 : ν + n⟶ ν + p are sensitive to all neutrinos and sterile oscillations.
- We applied a set of cuts + neural network to select NC elastic events.

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



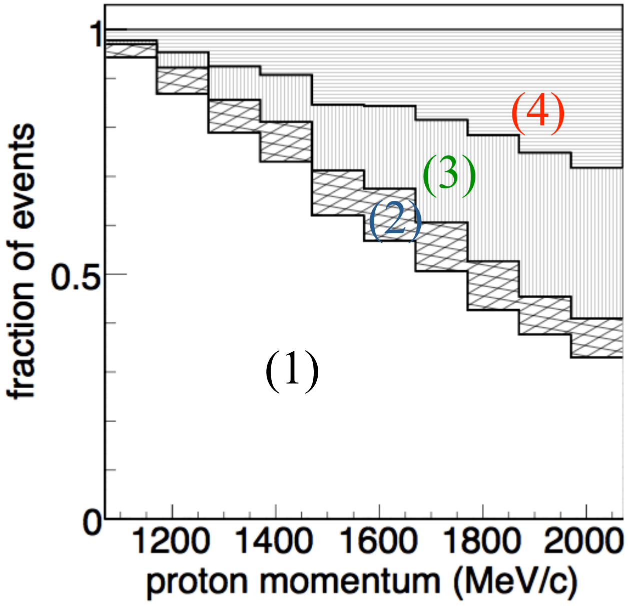
New light pattern engine includes hadronic interactions

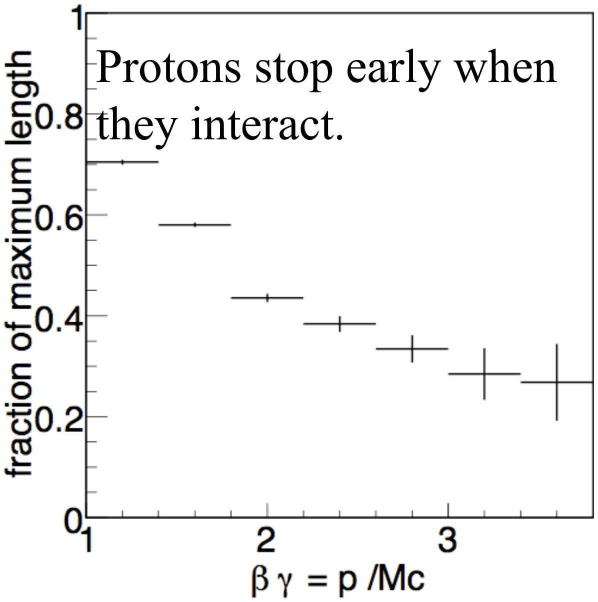
  - makes proton patterns for any vertex + direction + momentum + path length
- **Proton fitter :**
  - Same idea as regular PID : test proton hypothesis vs muon hypothesis
    - Maximizes the proton pattern likelihood $\mathcal{L}_p$ while fitting for proton momentum P & path length L
    - Calculates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

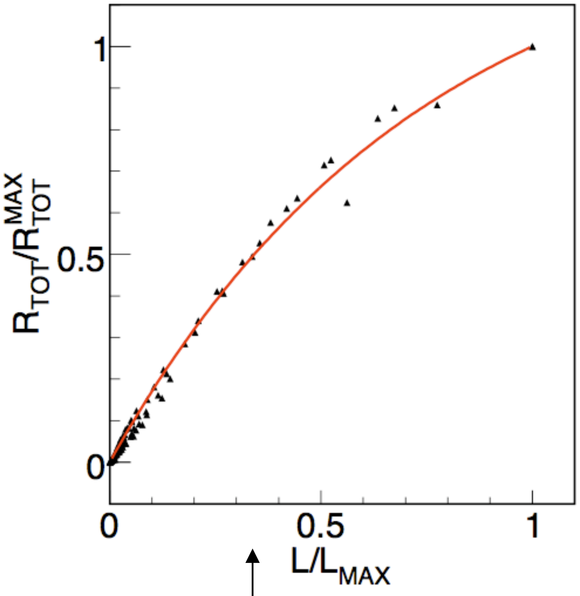
OUTPUTS OF FITTER

Hadronic Interactions

Protons traveling in the water produce secondary particles



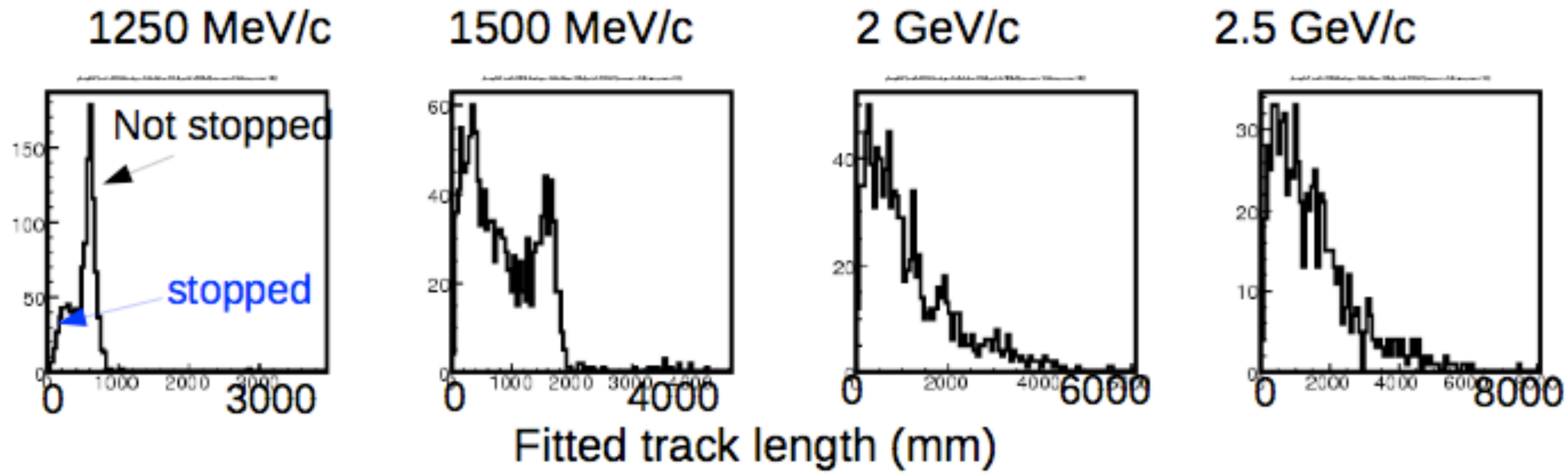

Protons stop early when they interact.



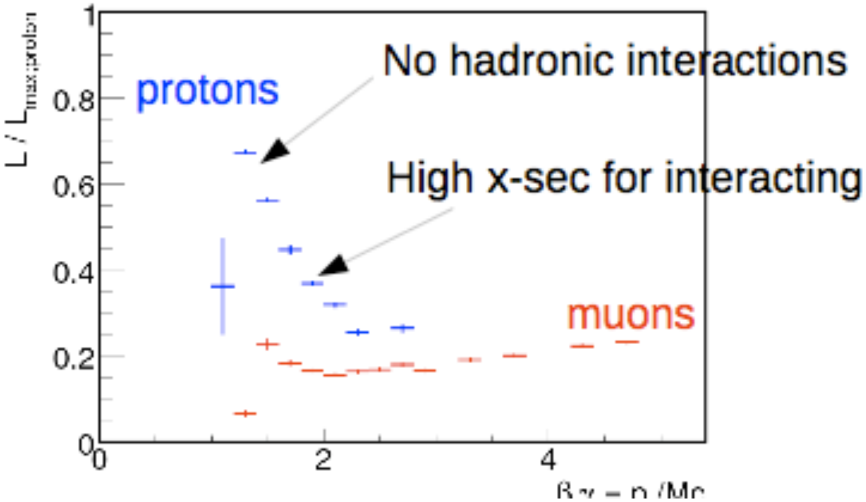
1) No secondaries
2) Below threshold secondaries
3) Above threshold charged pions
4) hadronic pizero production

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

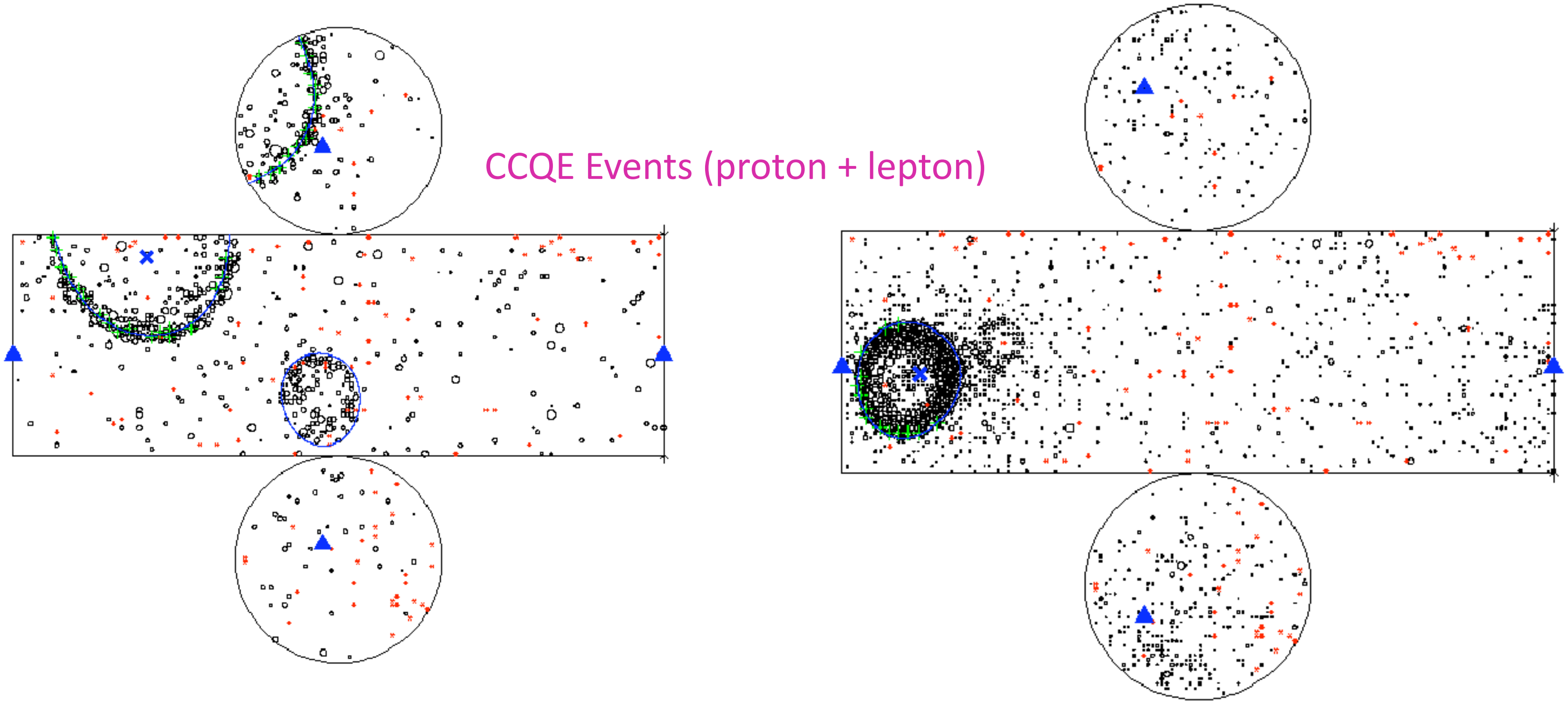
Interacting protons: Examples



- 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



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 (ν + p → p + l) can be fully reconstructed because all kinematics are constrained.
- CC events with a visible proton come only from neutrinos.

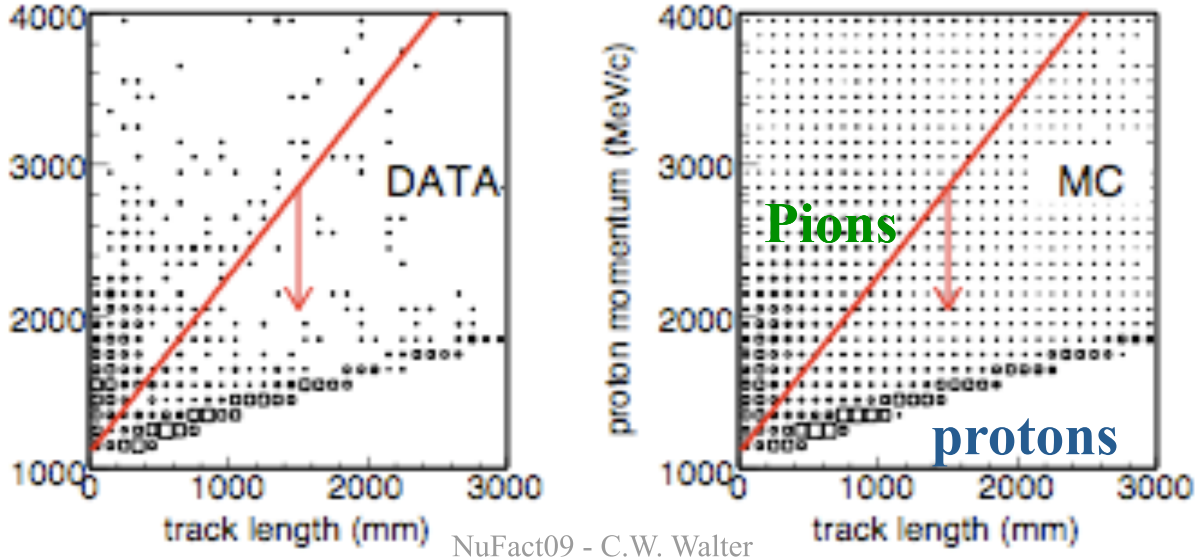
Don´t need to know the direction of the beam!

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

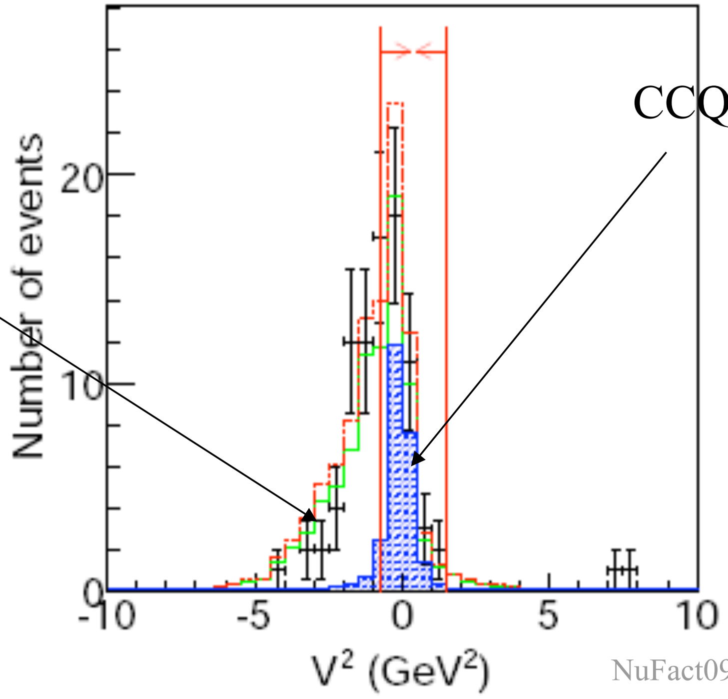
Let V be the 4-vector

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

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 $m_\nu^2 \approx 0$ eV^2/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.

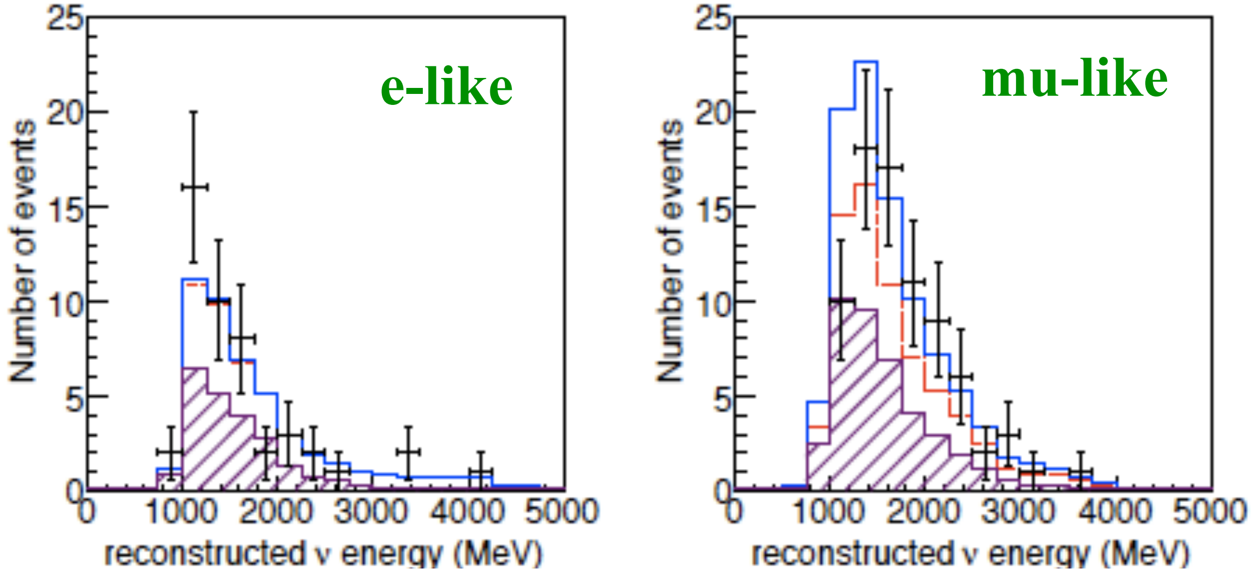
$$P_{tot} = \sqrt{(\mathbf{P}_{\mathrm{p}} + \mathbf{P}_{\mathrm{l}})^2},$$

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%)

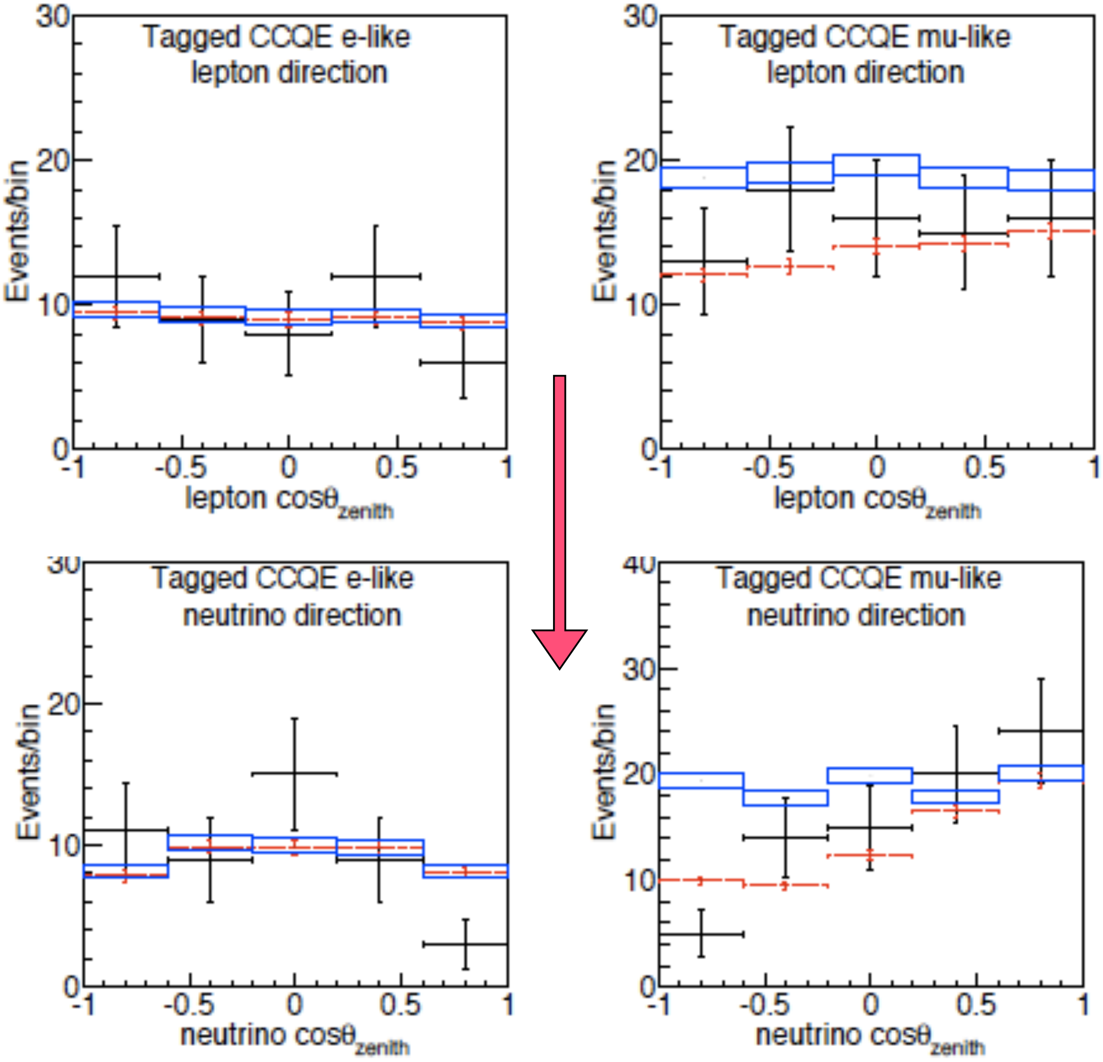
Lepton vs neutrino zenith direction

Note: In oscillation analysis multi-ring events are with leading e-like ring are normally not included. They are included here and still have a high CC purity.

From Lepton direction

To

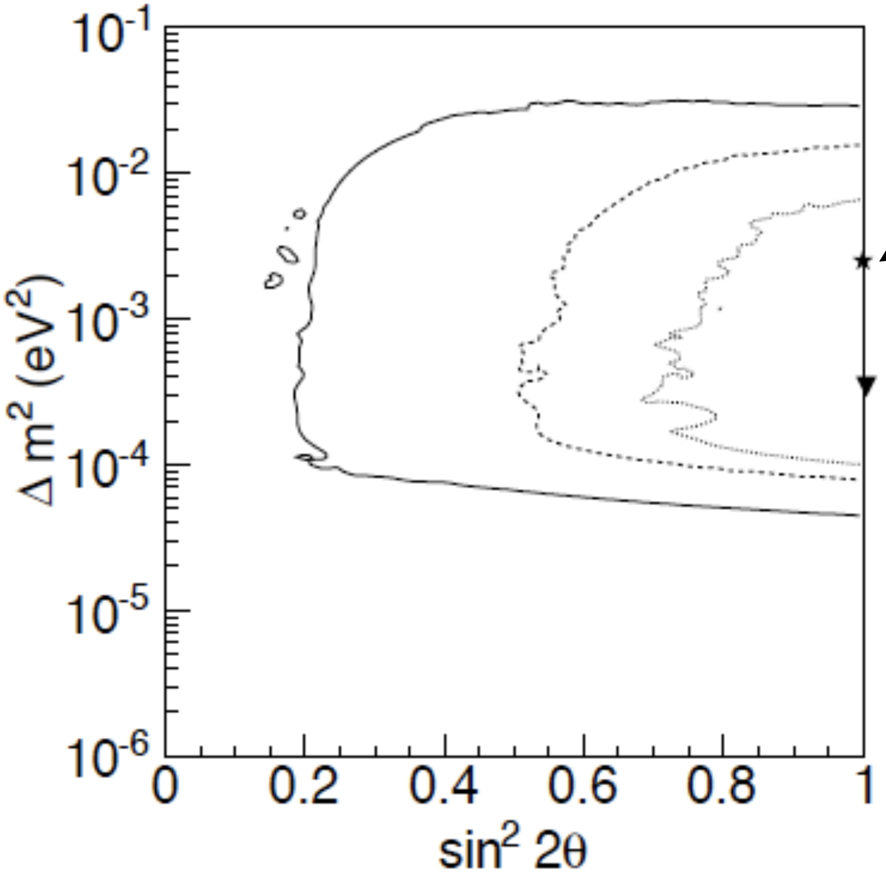
Neutrino direction



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

Results of kinematically reconstructed L/E fit

An important cross-check of both our technique and the oscillation hypothesis



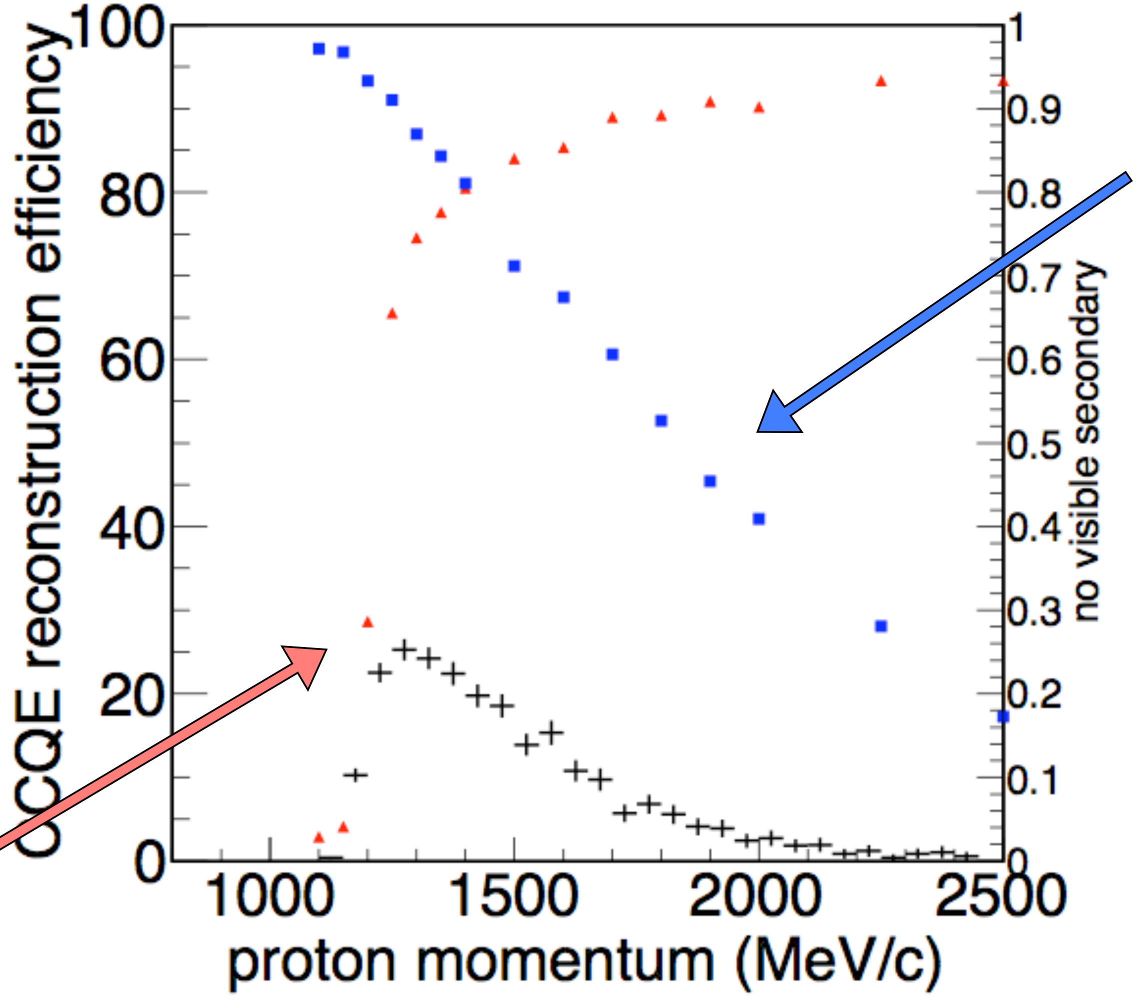
Usual best fit

This analysis

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

Observability Conditions

What beams and fluxes will this technique work for?



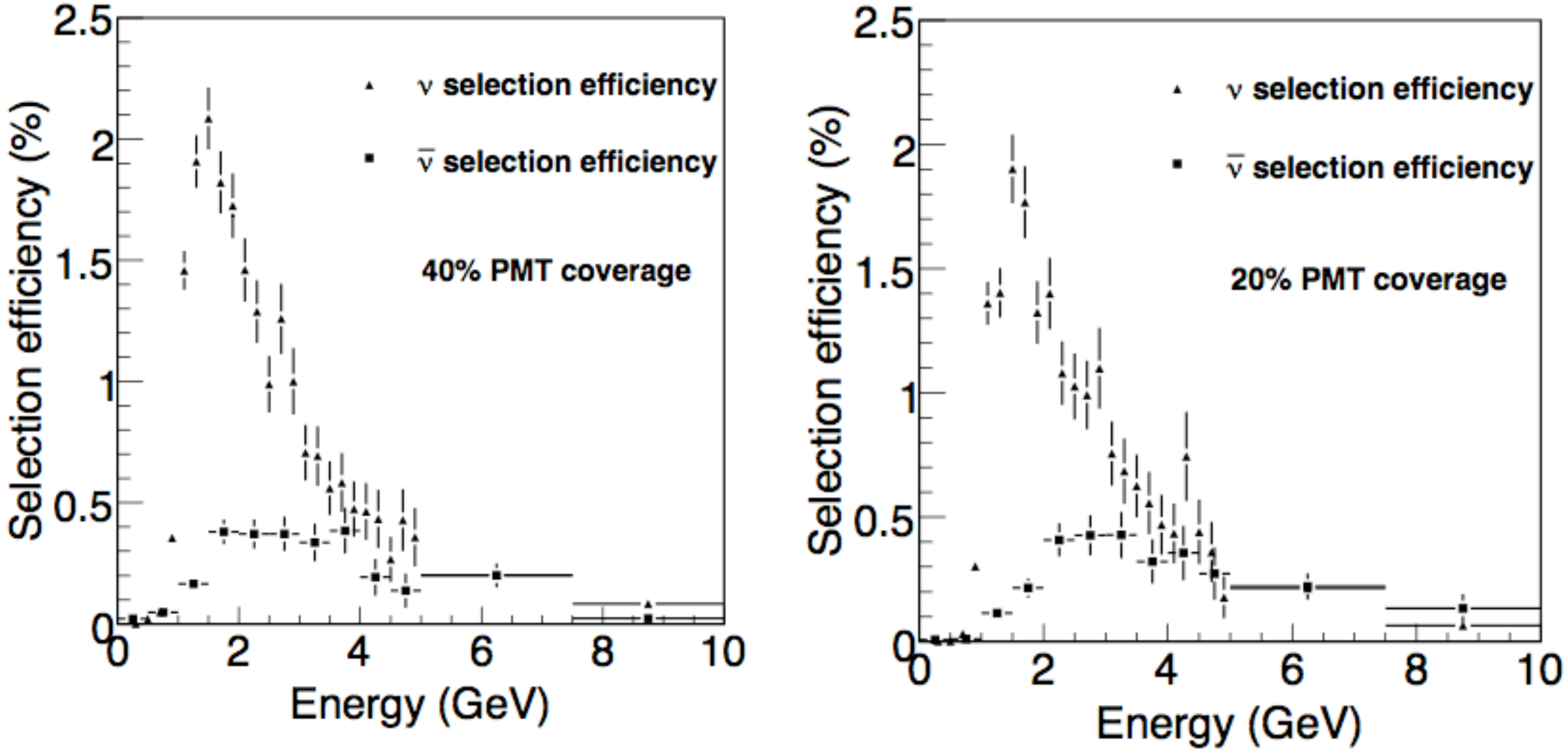
Hadronic Interactions

Cherenkov Threshold.

ν vs anti-ν tagging

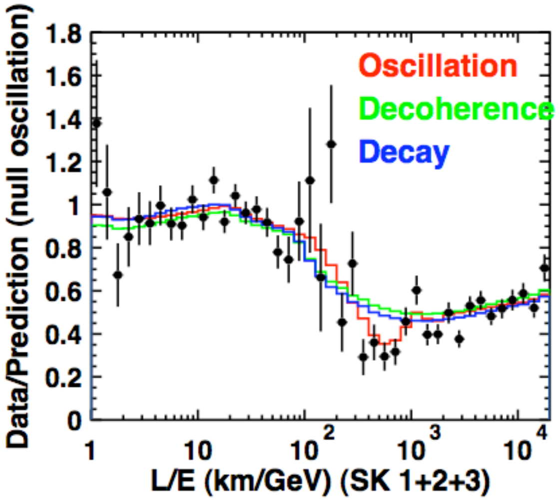
$\nu + n \rightarrow$ p + l only happens for **neutrinos** not **anti-neutrinos**

The selected CCQE atmospheric sample is 92% neutrino pure.

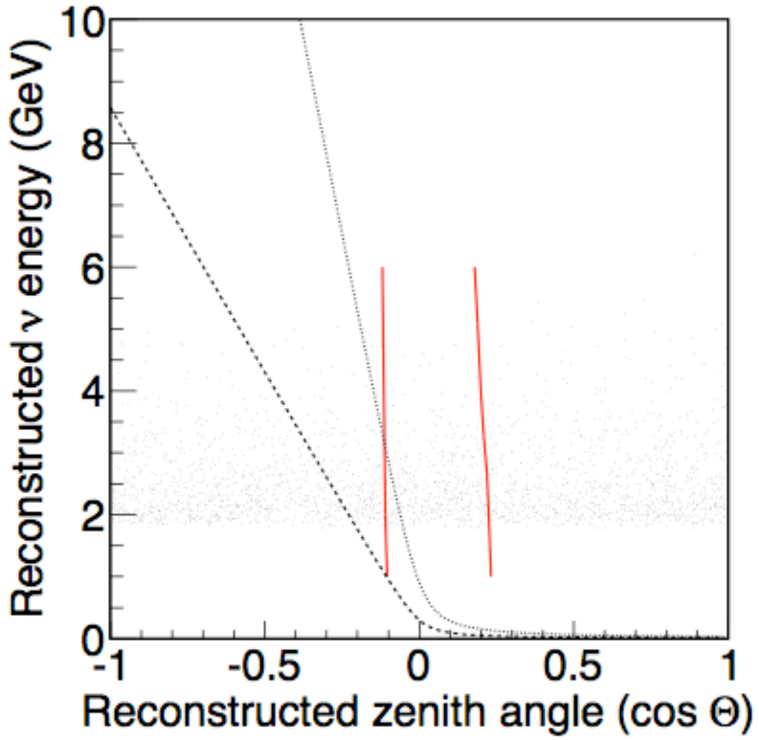


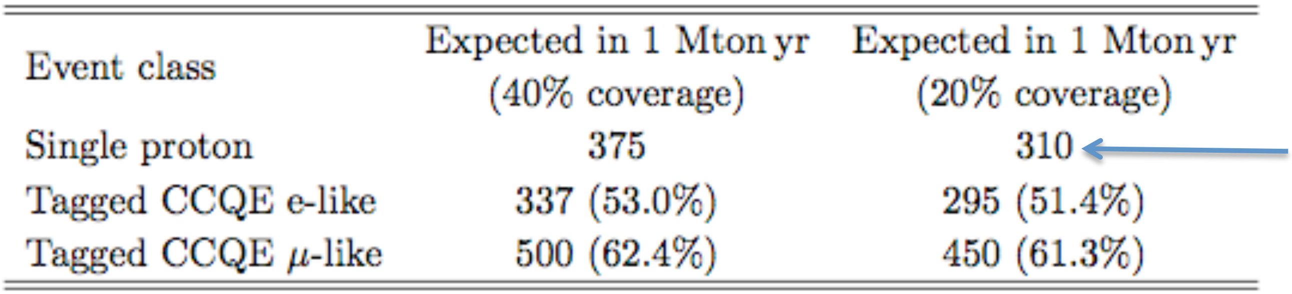
Also preferentially selects neutrino events for non-CCQE events.

Tagging atmospheric neutrinos



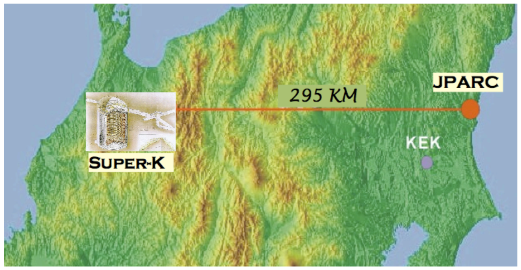
Very good L and E resolution:
E ~ 15, Direction ~ 12%.
Q: Can we make L/E better? A: No.



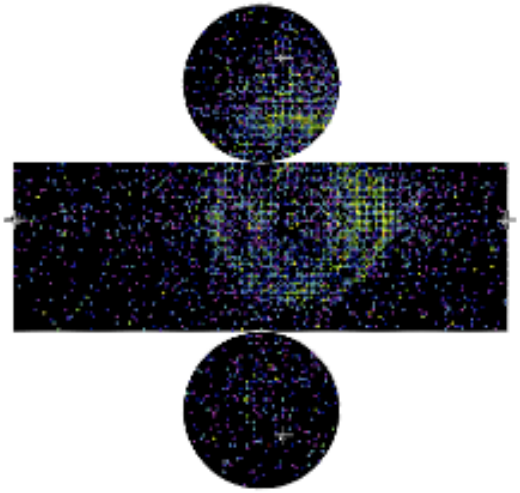


Event class	Expected in 1 Mton yr (40% coverage)	Expected in 1 Mton yr (20% coverage)
Single proton	375	310
Tagged CCQE e-like	337 (53.0%)	295 (51.4%)
Tagged CCQE μ-like	500 (62.4%)	450 (61.3%)

Would help
constrain
sterile admixture
searches



Rates in T2K



Due to the relatively low neutrino energy usually the protons are below threshold.

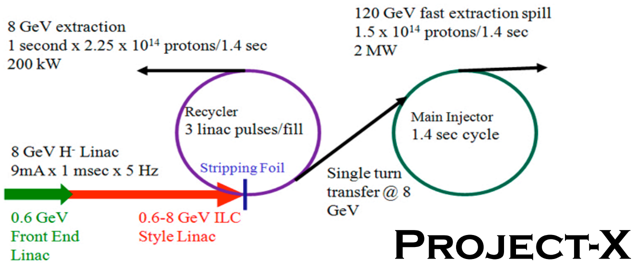
With 5 x 10^{21} POT we estimate only 24.4 CCQE events with 13 events selected.

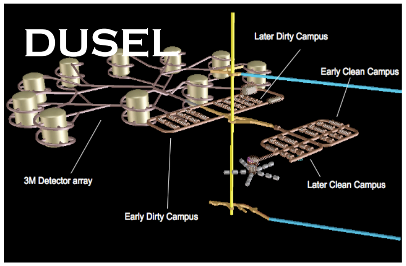
Lepton Flavor	Selected	True CCQE
E-like	2.0	0.5
μ-like	10.9	5.9

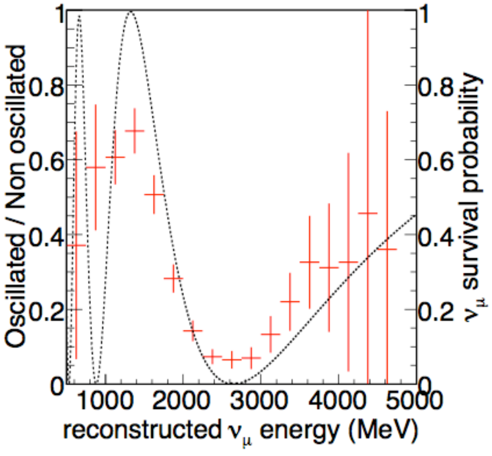
This technique will unfortunately not be useful for T2K.

Project-X to DUSEL

Assume a 300kton SK like detector at DUSEL and a 2.3MW beam of 120 GeV protons.







How many fully reconstructed events?

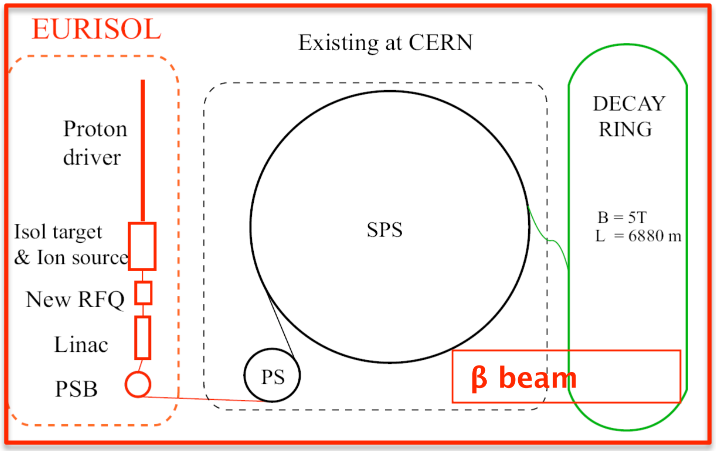
lepton flavor	Selected	true-CCQE	Selected	true-CCQE
photo-coverage	40%	40%	20%	20%
e-like	91 ± 15	13 ± 2	106 ± 15	20 ± 4
μ-like	698 ± 26	464 ± 20	648 ± 26	422 ± 20

- 750 to 800 events in 3 years of running (3 x 10^7 seconds) of which ~ 500 are CCQE.
- CCQE purity is 60% and the neutrino energy resolution of the sample is ~15%
- Could use V^2 in addition to beam direction to further purify the sample.
- As θ_{13} varies from 0 to 4°, the number of selected ν_e events varies ~15%
- Could run with the anti-neutrino beam to tag and confirm the expected neutrino contamination (30%).

High Energy Beta Beams

Assume a 300kton SK like detector with L = 700km and $\beta=350$

^{18}Ne for ν_e with E_0 = 3432.7 keV and ^{6}He for anti-ν_e with E_0 =3506.7 keV



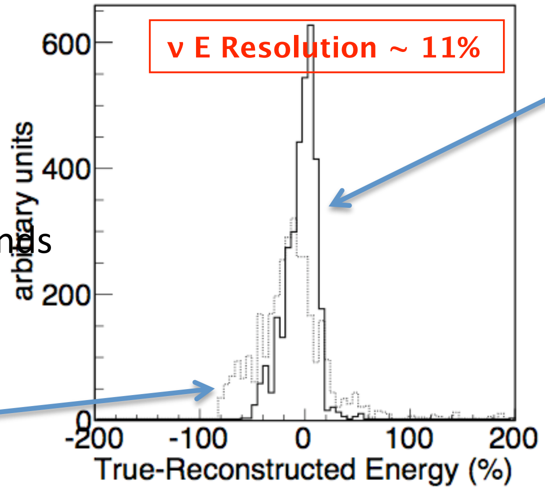
Could use a refurbished SPL at CERN or the Tevatron at FNAL.

- Followed EUROSOL guidelines
- 2.9 x 10^{18} decays/year for He and 1.1 x 10^{18}/year for Ne ions
- This gives flux peaked ~ 1.6 GeV with an spectrum endpoint of 2.4 GeV
- For both ions calculate for neutrino and anti-neutrino.

Beta Beam - Continued

With the neutrino beam you get a 66% pure CCQE beam with very good energy resolution.

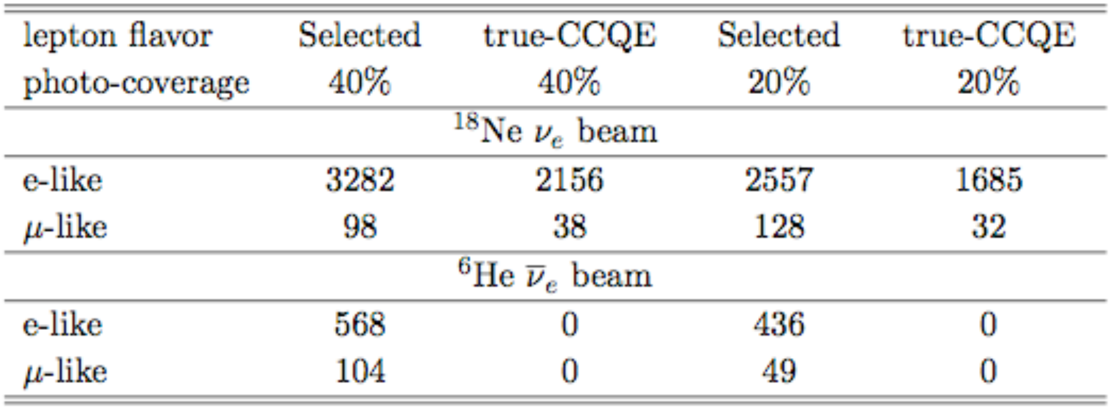
By applying the technique to the pure anti-neutrinos Mode we get a separate measurements of backgrounds In the neutrino running.



CCQE sample

Lepton only

Rates for 1Mton-yr of exposure



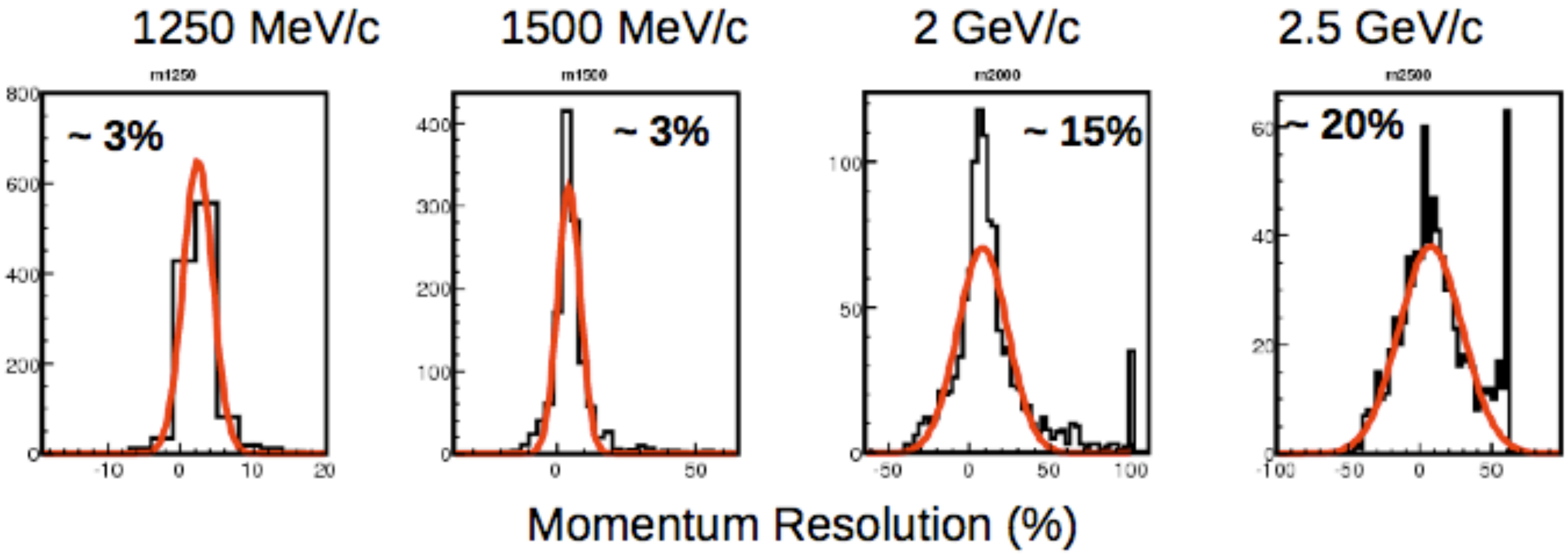
lepton flavor photo-coverage	Selected 40%	true-CCQE 40%	Selected 20%	true-CCQE 20%
		^{18}Ne ν_e beam		
e-like	3282	2156	2557	1685
μ-like	98	38	128	32
		^{6}He $\overline{\nu}_e$ beam		
e-like	568	0	436	0
μ-like	104	0	49	0

Conclusions

- We successfully identified and reconstructed protons in the Super-K experiment (see Phys.Rev.D79:112010,2009. e-Print: arXiv:0901.1645) and applied this technique for future facilities (see arXiv:0901.1950**)**
- To be useful for beams the neutrinos should be in the few GeV range.
- A wide band-beam coupled with a 300 kton water Cherenkov detector such as the LBNE project would achieve statistics of the order of 800 events with a CCQE purity of ≈ 60%, good energy resolution, fully reconstructed kinematics, and the ability to confirm the neutrino contamination in the anti-neutrino beam.
- Using a high energy beta-beam this technique can reject non-CCQE events very efficiently, and produce a sample of thousands of events with very good energy resolution while achieving an ≈ 66% pure CCQE sample.
- The ability to select neutrino events without lepton sign-selection, the full kinematic reconstruction of neutrino events, and the rejection of non-CCQE background are all important additions to the capabilities of water Cherenkov detectors.
- We have shown that large, well reconstructed samples are possible using this technique. Detailed future simulations of experiments searching for CP violation and measuring the mass hierarchy in the neutrino sector should consider this technique when determining their sensitivities.

Backup

- Proton momentum constrained by opening angle



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

Searching for single protons

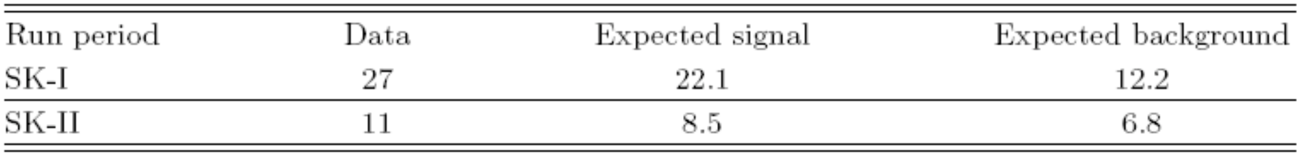
- Identify NC elastic interactions : ν + p → ν + p
- Other NC modes also contribute if other particles are below threshold
- Because of the atmospheric neutrino spectrum & high Cherenkov threshold, only ~10 interactions/year are potentially visible...
- Strategy :
  - Apply cuts on sample to enhance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

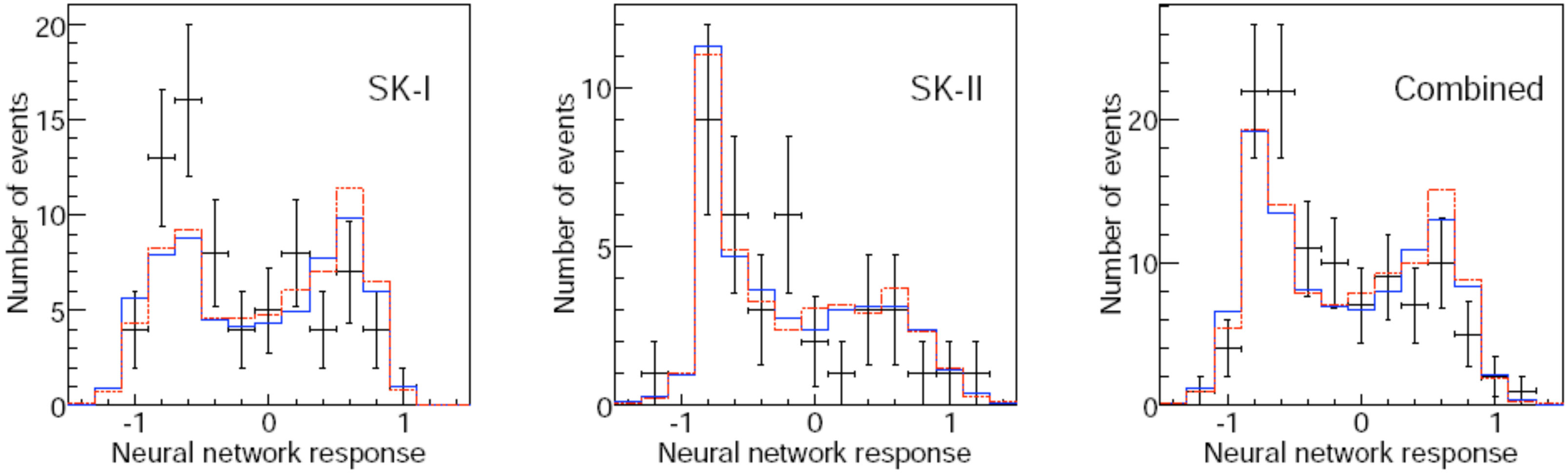
Super-Kamiokande-I	Data	Total MC NEUT	Signal MC NEUT	Total MC NUANCE	Signal MC NUANCE
FC, FV, single-ring, spallation removed	8946 (100%)	8138.1(100%)	45.1 (100%)	8031.5 (100%)	41.2 (100%)
Sparse ring removal cut	8509 (95.1%)	7729.7 (95.0%)	31.7 (70.4%)	7673.4(95.5%)	29.3 (71.1%)
$E_{vis} < 200$ MeV	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)

Neutrino kinematic reconstruction

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

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

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

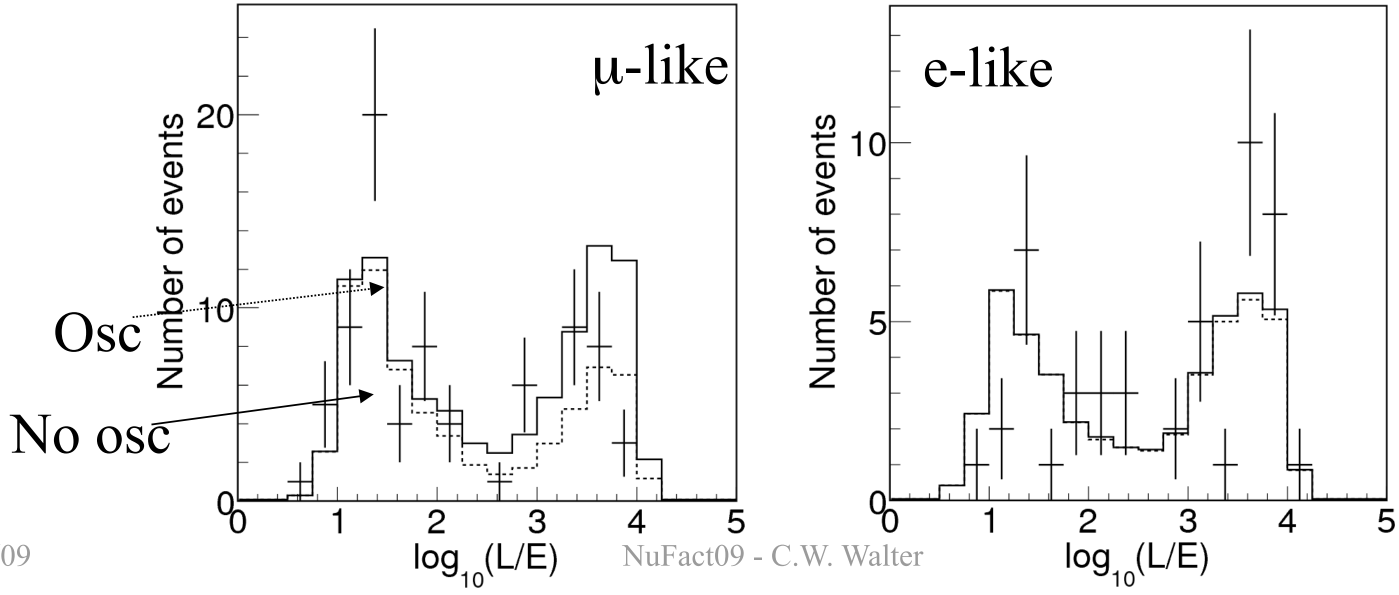
The sample has CC purity of 88% for e-like and 95% for mu-like events.
The sample is 92% neutrino as opposed to anti-neutrino.

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.

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)



Fit to L/E distributions

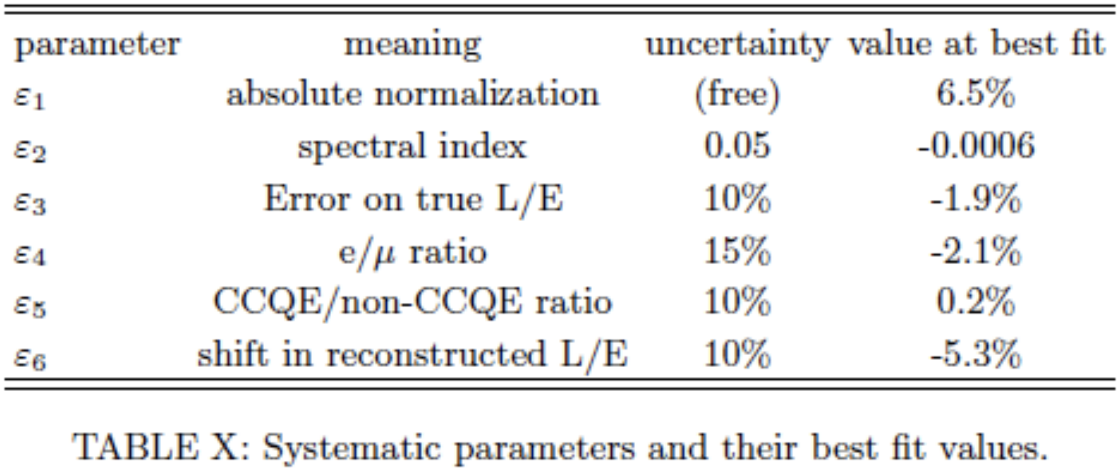
- 2 flavor oscillation hypothesis
- Use Poisson likelihood ratio instead of chi2
- Use only 5 bins in log(L/E) for each distribution following Shiozawa-san's comment
- Fit e-like & mu-like together

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

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.

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.