Identifying CC1π^+ at Super-Kamiokande

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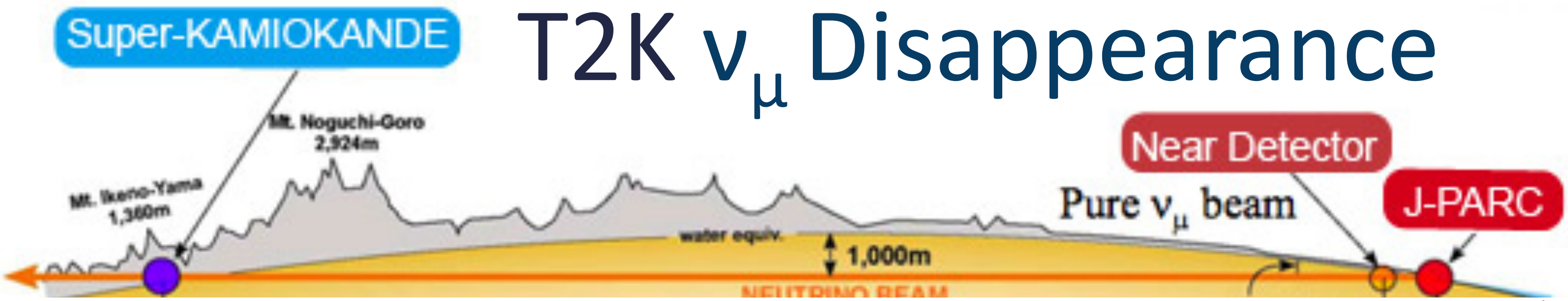
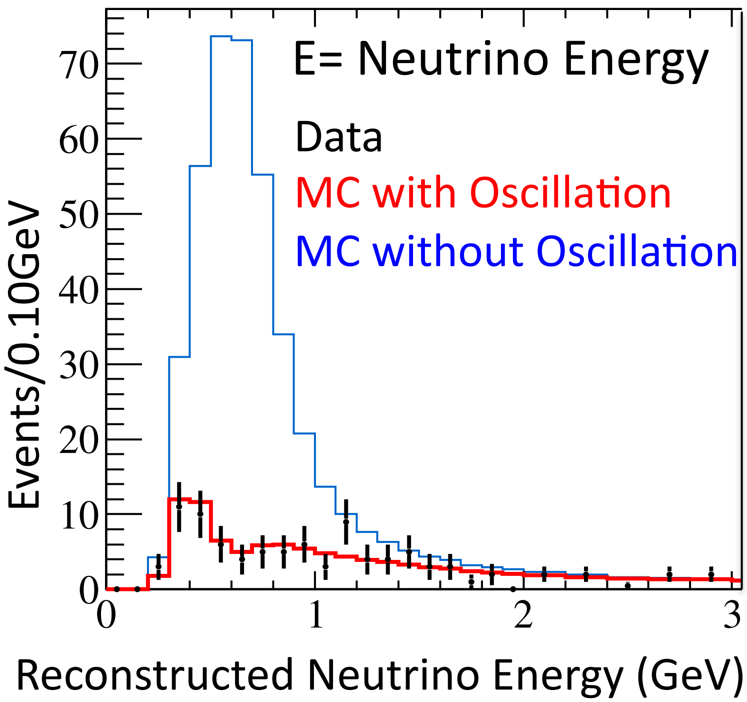
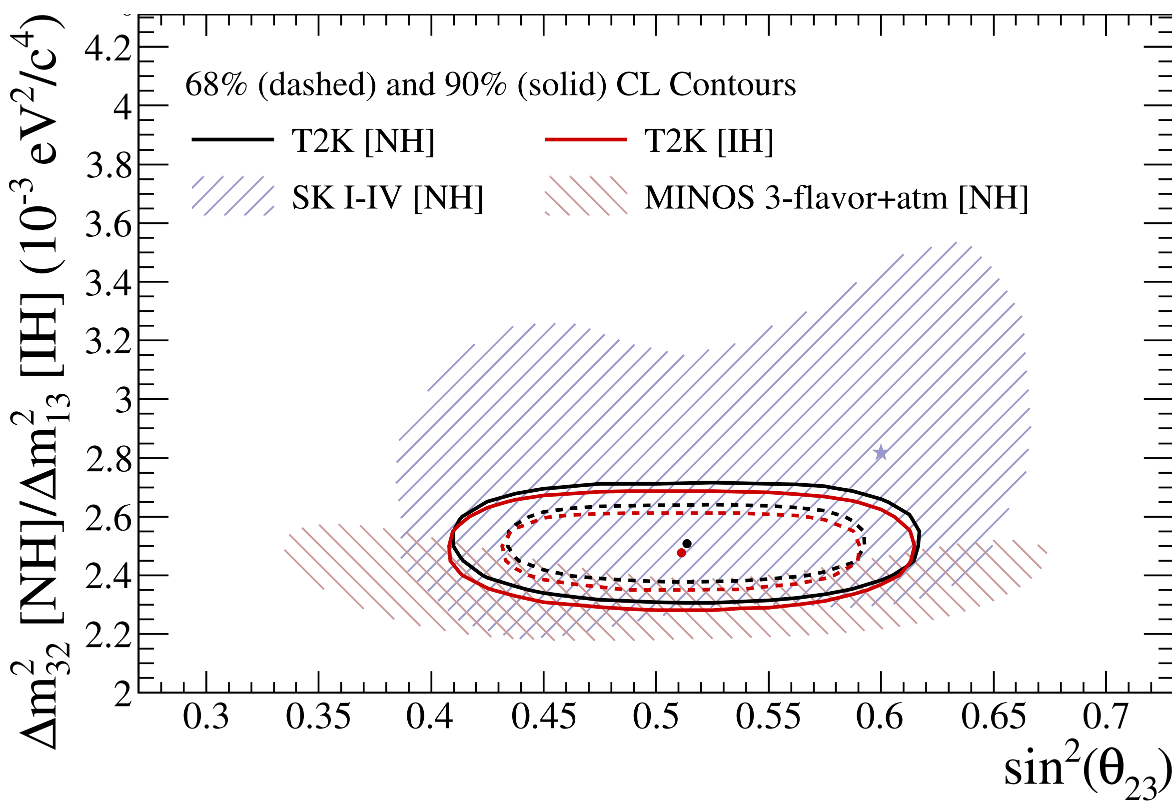
T2K ν_μ Disappearance



$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13})\sin^2(\theta_{23})]\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

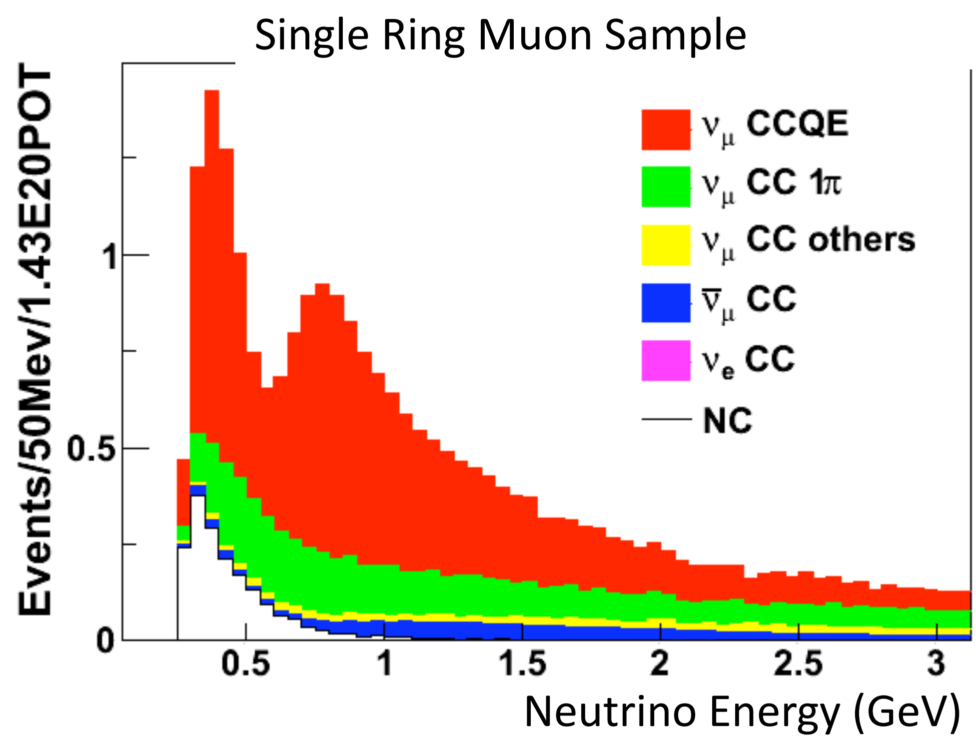


L = 295km



T2K CCQE Signal

- T2K Signal: charged current quasi-elastic
  $$\nu_\mu + n \rightarrow \mu^- + p$$
  - Dominant interaction at T2K energies
  - Look for single muon events at SK
  - Proton is typically below Cherenkov threshold
  - Reconstruct neutrino energy
    - Only depends on muon kinematics (p_μ, $\theta_{\mu\nu}$)



$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_{\mu\nu})}$$

- Largest contribution to background are interactions that produce charged pions

Pion Backgrounds at SK

- Signal:

$$\nu_\mu + n \rightarrow \mu^- + p$$

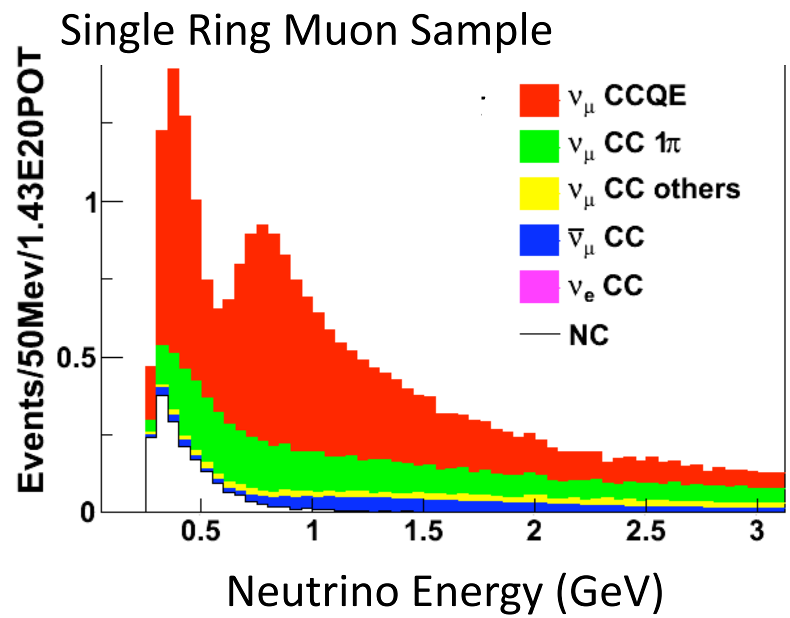
- Neutral Current $1\pi^+$:

$$\nu_\mu + p \rightarrow \nu_\mu + \pi^+ + n$$

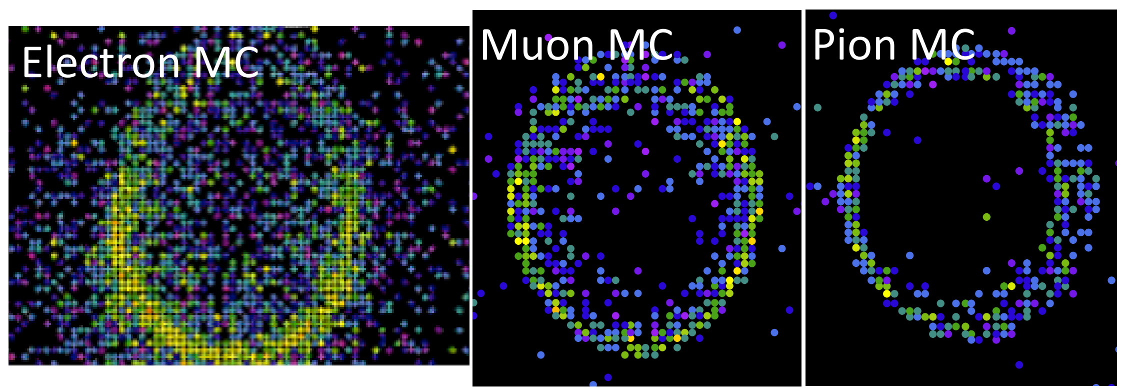
  - Misidentify pion as muon
- Charged Current $1\pi^+$:

$$\nu_\mu + p/n \rightarrow \mu^- + \pi^+ + p/n$$

  - Miss pion and reconstruct as signal
  - Misreconstruct neutrino energy

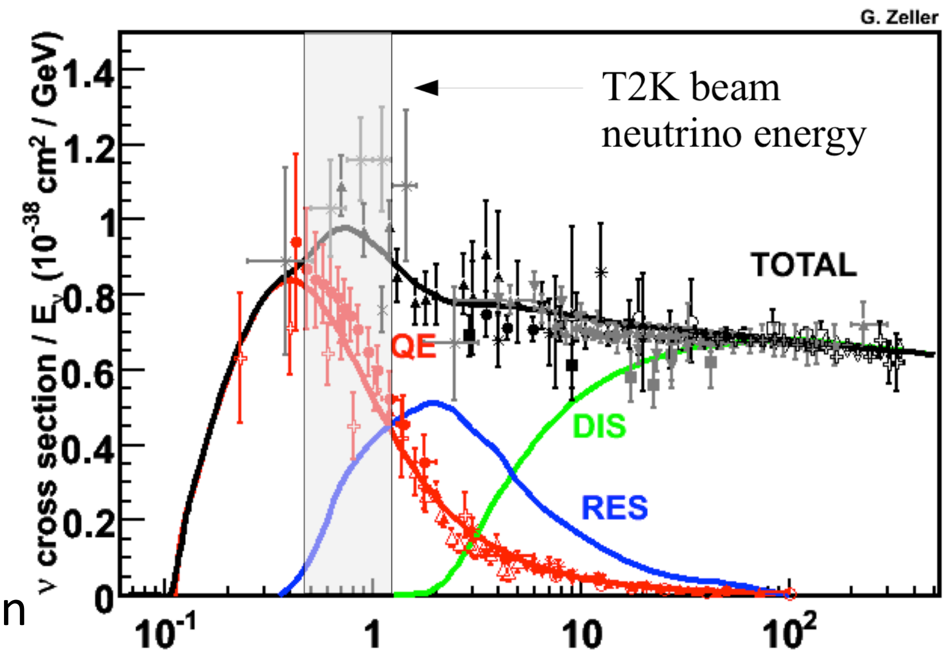


- Current T2K analyses only separate electrons from muons
- Pion and muon rings look similar at SK, except for hadronic interactions



CC1π^+ as SK signal

- Charged current single pion
  $\nu_\mu + p/n \rightarrow \mu^- + \pi^+ + p/n$
  - Second most dominant interaction at T2K energies
  - Look for events with μ^- and π^+
  - Proton or neutron too low energy to reconstruct
  - Reconstruct neutrino energy
    - Analogous to CCQE reconstruction
    - Only depends on muon and pion kinematics
  - Constrain background in single muon sample
  - Additional oscillation signal



Neutrino Energy (GeV)

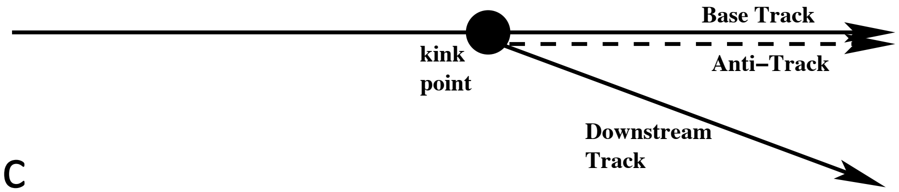
$$E_\nu = \frac{m_l^2 + m_{\pi^+}^2 - 2m_N(E_l + E_{\pi^+}) + 2p_l \cdot p_{\pi^+}}{2(E_l + E_{\pi^+} - |\boldsymbol{p_l}|\cos\theta_{\nu l} - |\boldsymbol{p_{\pi^+}}|\cos\theta_{\nu\pi^+} - m_N)}$$

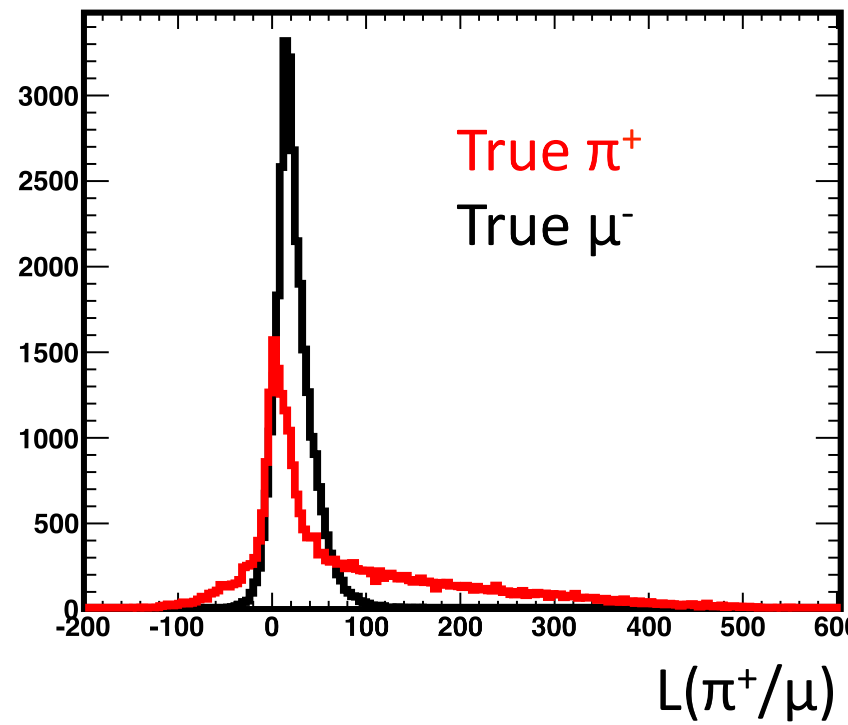
Reconstructing π⁺ and CC1π⁺

- Reconstruct kinematics of particles in SK

$$\mathcal{L}(\boldsymbol{x}) = \prod_{i=1}^{N_{\text{unhit}}} \mathcal{P}_i(\text{unhit};\boldsymbol{x}) \prod_{j=1}^{N_{\text{hit}}} \mathcal{P}_j(\text{hit};\boldsymbol{x}) f_q(q_j;\boldsymbol{x}) f_t(t_j;\boldsymbol{x})$$

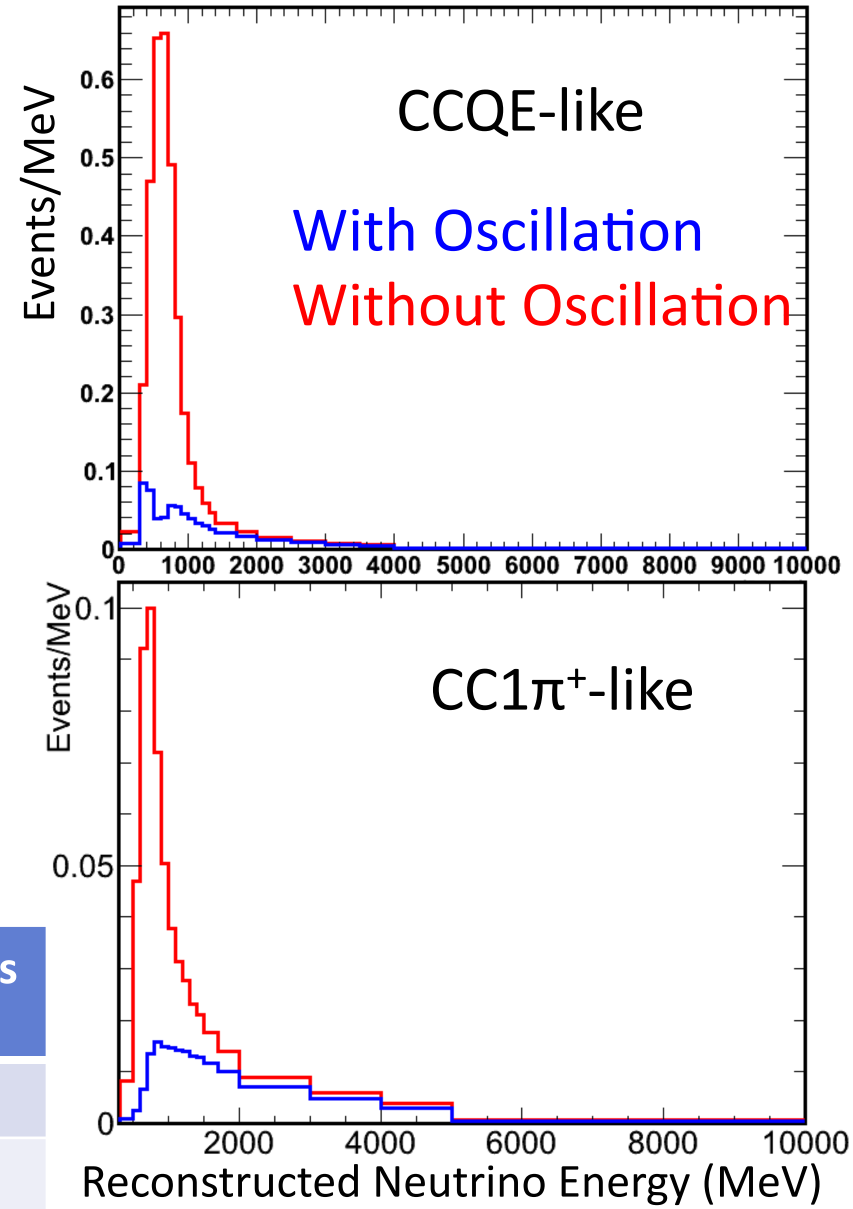
- Charged pions:
  - Kinked track signature: pion changes direction after hadronic interaction
  - Can scatter below Cherenkov threshold so abruptly stops producing light
- Upstream pion reconstruction:
  - Assume below threshold after hadronic interaction
- Multi-ring framework, allows construction of CC1π⁺ hypothesis
  - μ^- and π^+ from same vertex





MC Selection of CCQE and CC1π^+

- Ability to reconstruct CC1π^+ makes it possible to add an additional sample to oscillation signal
- Monte Carlo selection
  - **CC1π^+-like:** 1 π^+ and one μ^- after final state interactions and before secondary interactions
  - **CCQE-like:** one μ^- after final state interactions
- ~40% additional events



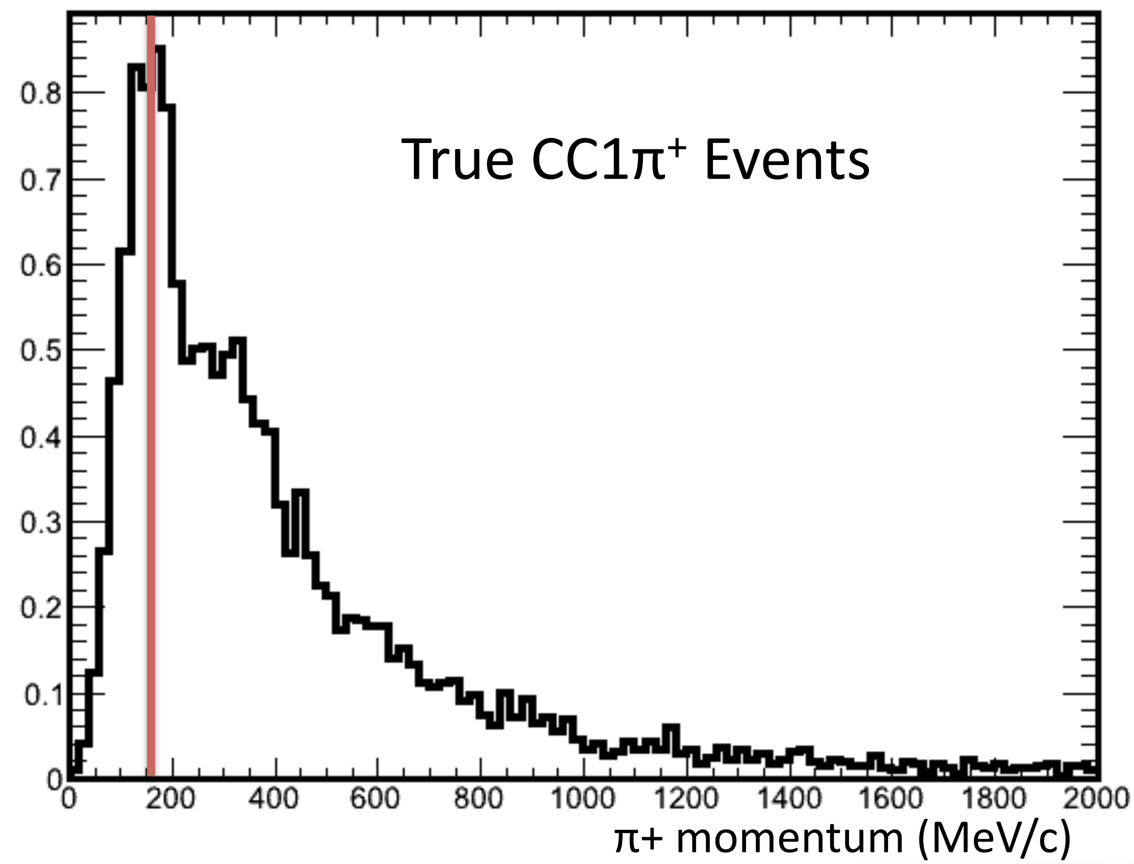
With Current T2K Statistics, 6.57 x 10^{20} POT

Interaction Mode	Number of Events without oscillation	Number of Events with oscillation
CCQE	375.1	86.62
CC1π^+	83.64	35.84

Pion Systematic Errors

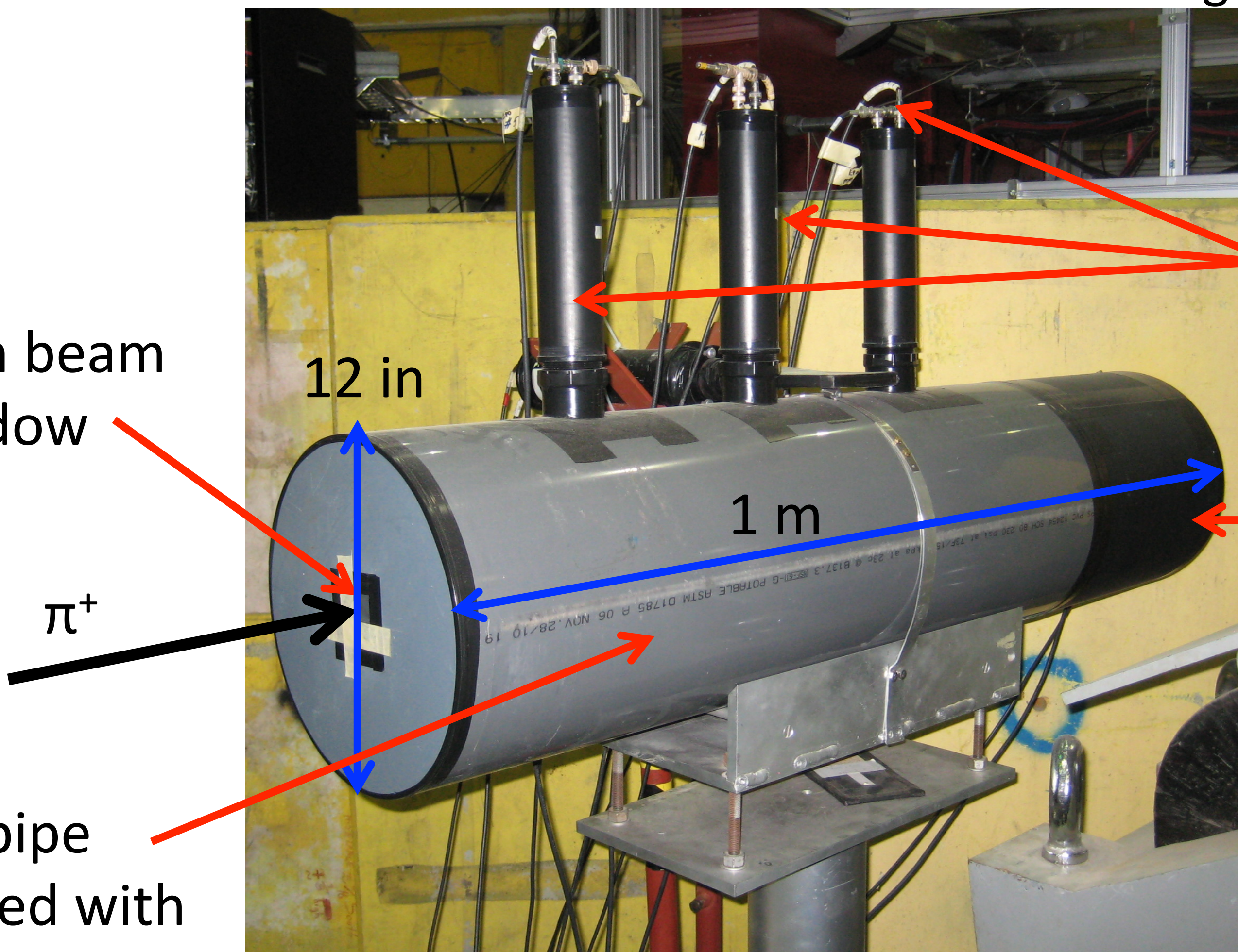
- Existing secondary interaction systematic error
- $CC1\pi^+$ will be a new SK sample
  - Evaluation of systematic errors required for use in analysis
- Studies are especially important for pions close to Cherenkov threshold (160MeV/c)
  - PICCOLO Detector
  - DUET Experiment – See Elder Pinzon's talk tomorrow

Source of uncertainty (number of parameters)	$\delta n_{SK}^{exp} / n_{SK}^{exp}$
ND280-independent cross section (11)	4.9%
Flux and ND280-common cross section (23)	2.7%
SK detector and FSI+SI systematics (7)	5.6%
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{21}, δ_{CP} (4)	0.2%
Total (45)	8.1%



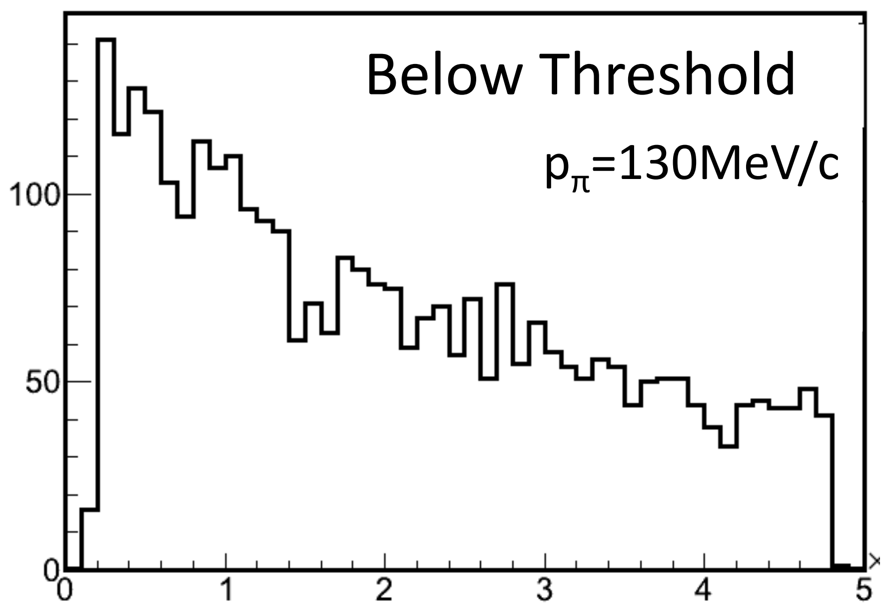
PICCOLO Detector

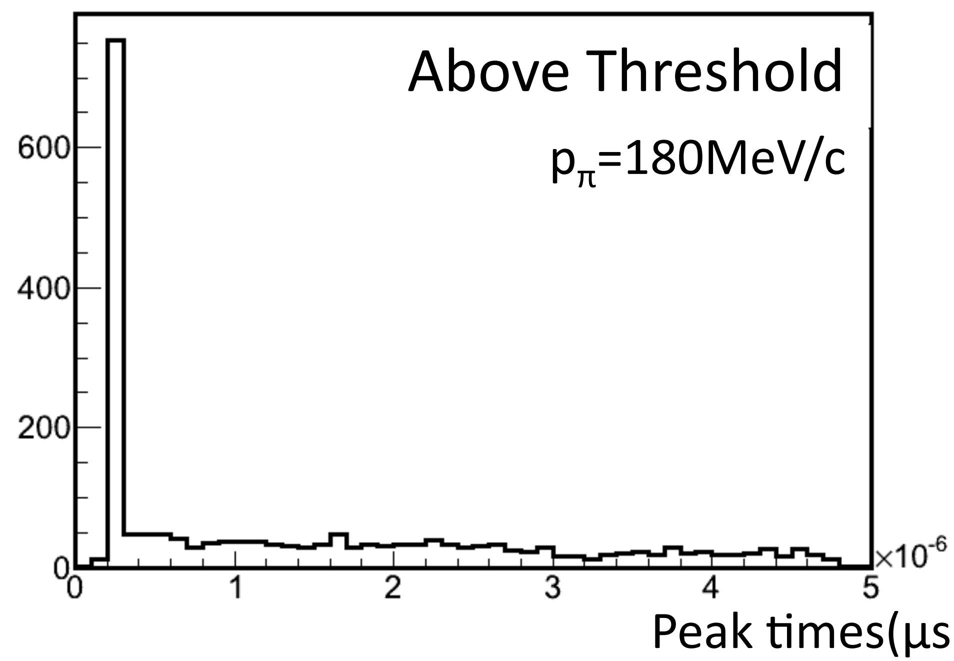
- Understand amount and properties of Cherenkov light produced by pions close to Cherenkov threshold.
  - May be different than for muons/electrons due to hadronic interactions
- Cylinder filled with water with 4 PMTs to collect total light



PICCOLO Data Collection & Analysis

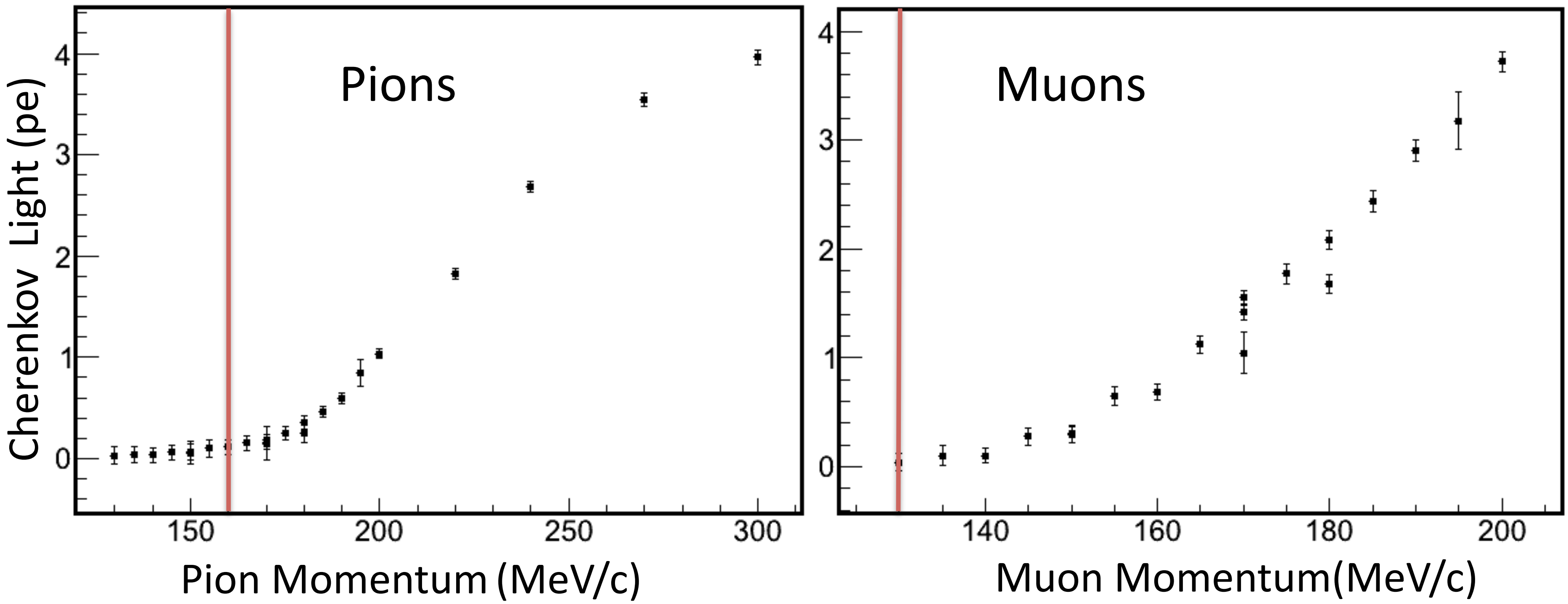
- Data collection in TRIUMF M11 secondary beam-line contains: e^+, μ^+, π^+.
  - ~2% momentum resolution
  - Scan pion Cherenkov threshold from 130-300 MeV/c
  - Separate particle types with time of flight
- To study primary pions, remove light from decay electrons produced





PICCOLO Analysis

- Mean amount of light produced over the momentum range (130-300 MeV/c)
- Evidence of the Cherenkov threshold



Conclusions

- A $CC1\pi^+$ sample at SK can provide a new signal sample for T2K oscillation analyses.
- A framework exists for identifying $CC1\pi^+$ events.
- Use of the $CC1\pi^+$ sample will require better understanding of pion light production in water which can be done using the PICCOLO beam test data.

Backup Slides

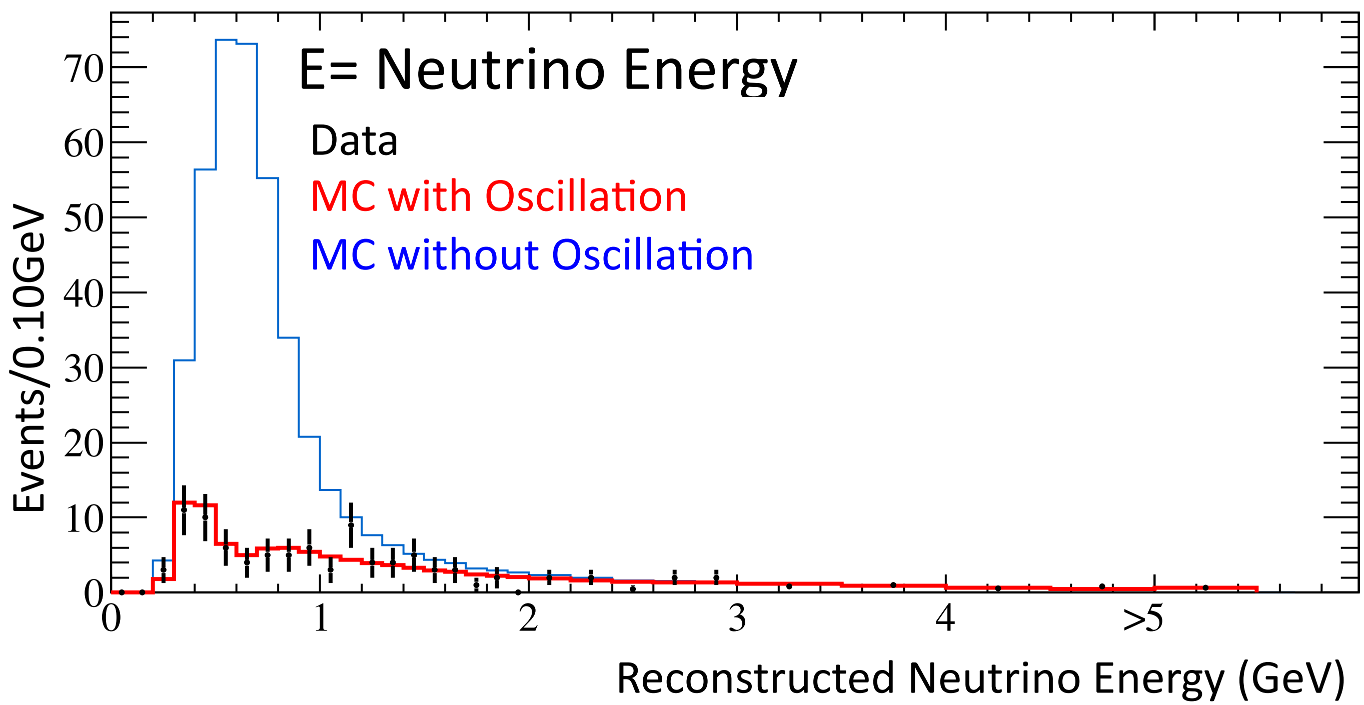
Appearance Formula

- Full formula for electron neutrino appearance

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \; = \;& 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \quad \text{Leading term} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
\text{CP violating term} \quad & -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2\Delta_{21} \quad \text{solar} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& \text{matter effects} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2}(1 - 2S_{13}^2) \sin^2\Delta_{31}
\end{aligned}
$$

T. Nakaya, Neutrino2012

T2K ν_μ Energy Spectrum



Super-Kamiokande & Cherenkov Radiation

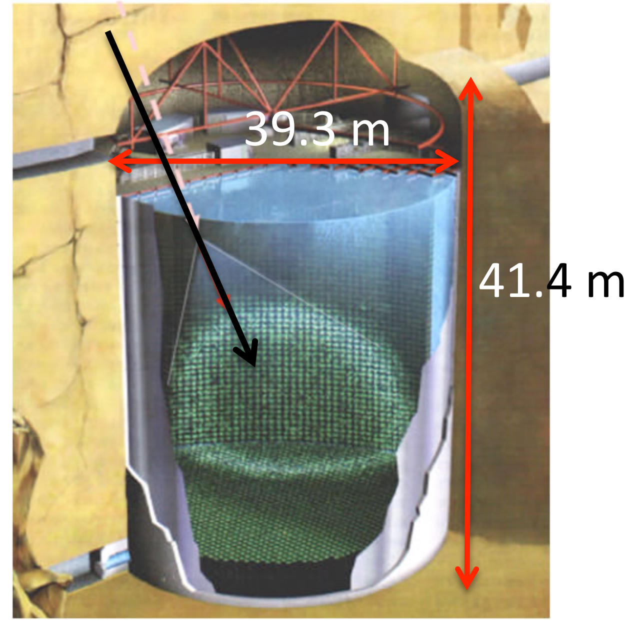
- Super Kamiokande
  - 50 kTon cylindrical water Cherenkov detector
- Cherenkov light is produced when charged particles have speed of

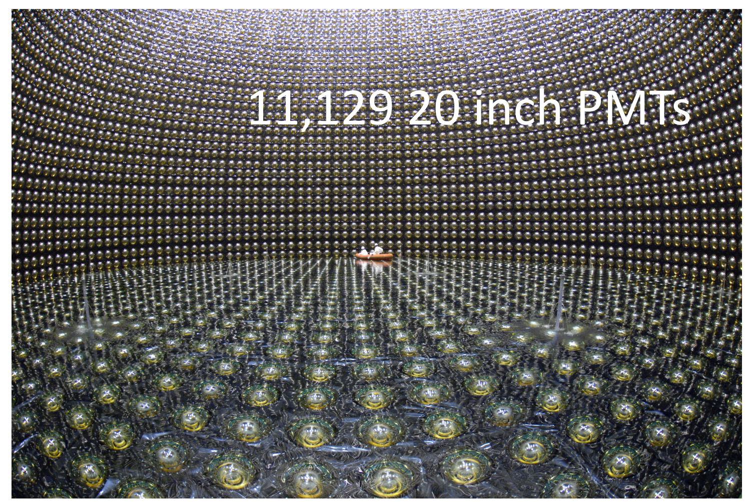
$$v > \frac{c}{n}$$

- Minimum momentum to produce Cherenkov light:

$$p_{min} = \frac{mc}{\sqrt{n^2 - 1}}$$

  - Called "Cherenkov threshold"
- Light is produced in a cone around trajectory of particle
- See rings of light projected on the walls





Event Reconstruction

- Need to reconstruct kinematics of outgoing particles from neutrino interactions to calculate the neutrino energy
- Event: times and charges registered by PMTs
  - Charges are clustered into groups of similar times
  - Clusters arranged into "subevents" with one time, one charge per PMT
- Event Reconstruction for SK (fiTQun):
  - Maximum likelihood algorithm:

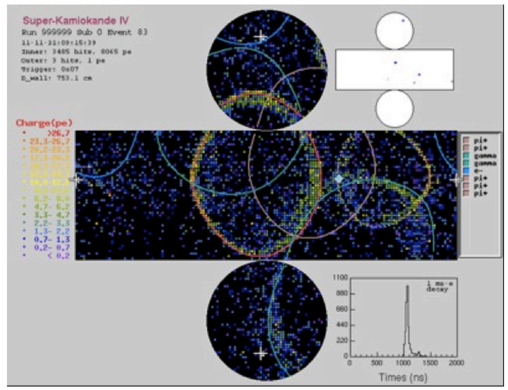
$$\mathcal{L}(\boldsymbol{x}) = \prod_{i=1}^{N_{\mathrm{unhit}}} \mathcal{P}_i(\mathrm{unhit};\boldsymbol{x}) \prod_{j=1}^{N_{\mathrm{hit}}} \mathcal{P}_j(\mathrm{hit};\boldsymbol{x}) f_q(q_j;\boldsymbol{x}) f_t(t_j;\boldsymbol{x})$$

  - Track parameters x: position, time, direction, momentum

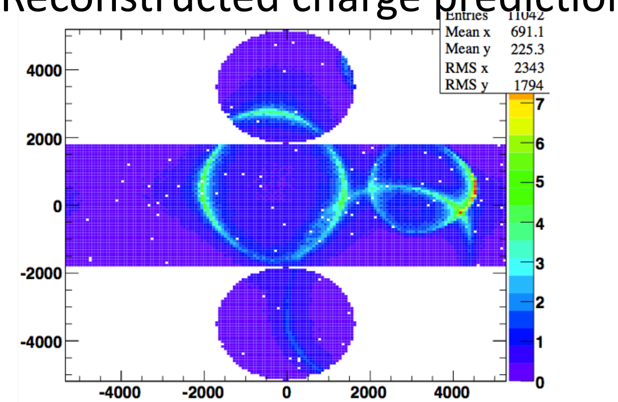
Event Reconstruction

- Charge PDF:

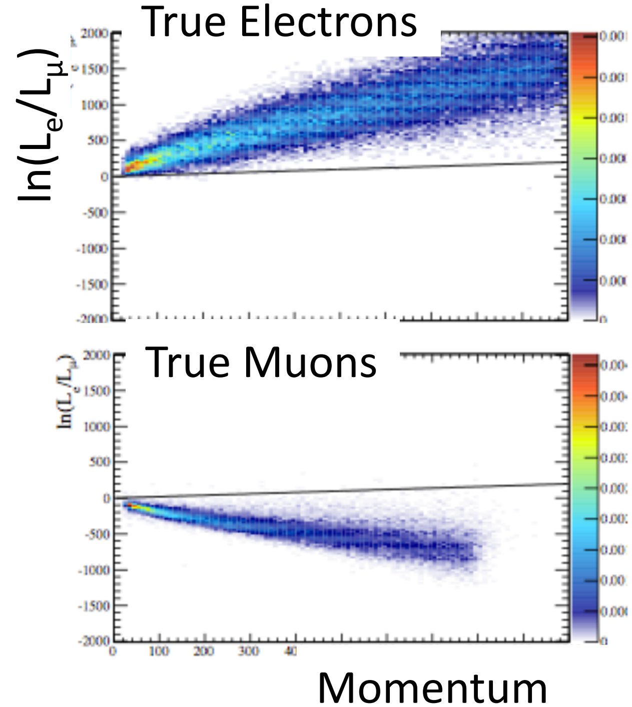
Simulated charge distribution



Reconstructed charge prediction

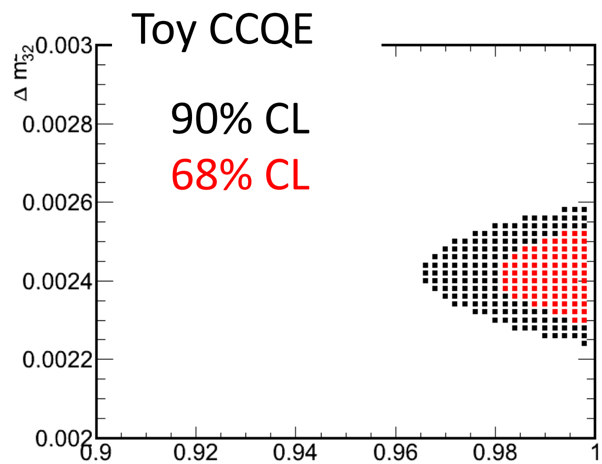


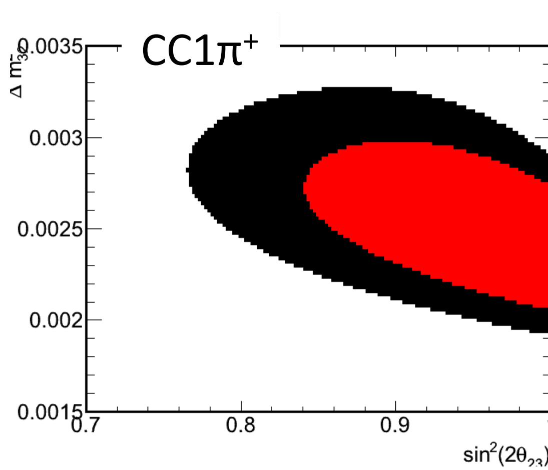
- Determining what happened in an event:
  - Number of rings
  - Kinematics of each ring
  - PID of ring
- Unify these questions by comparing likelihood ratios

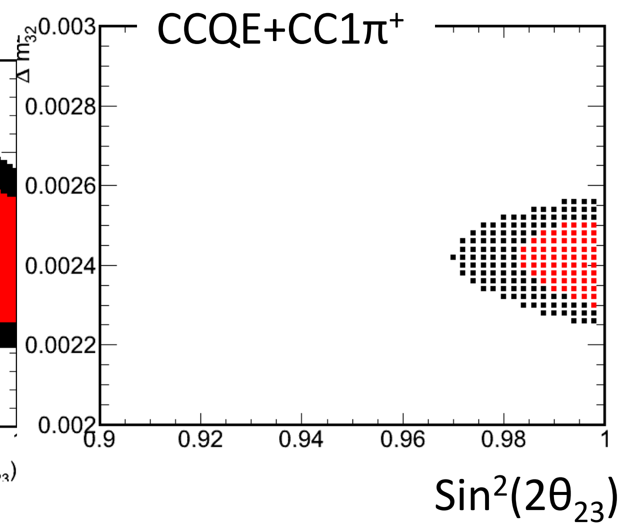


Toy Study Contours

- CCQE is comparable to T2K result for current data set
  - Note different scales
- No systematic errors included





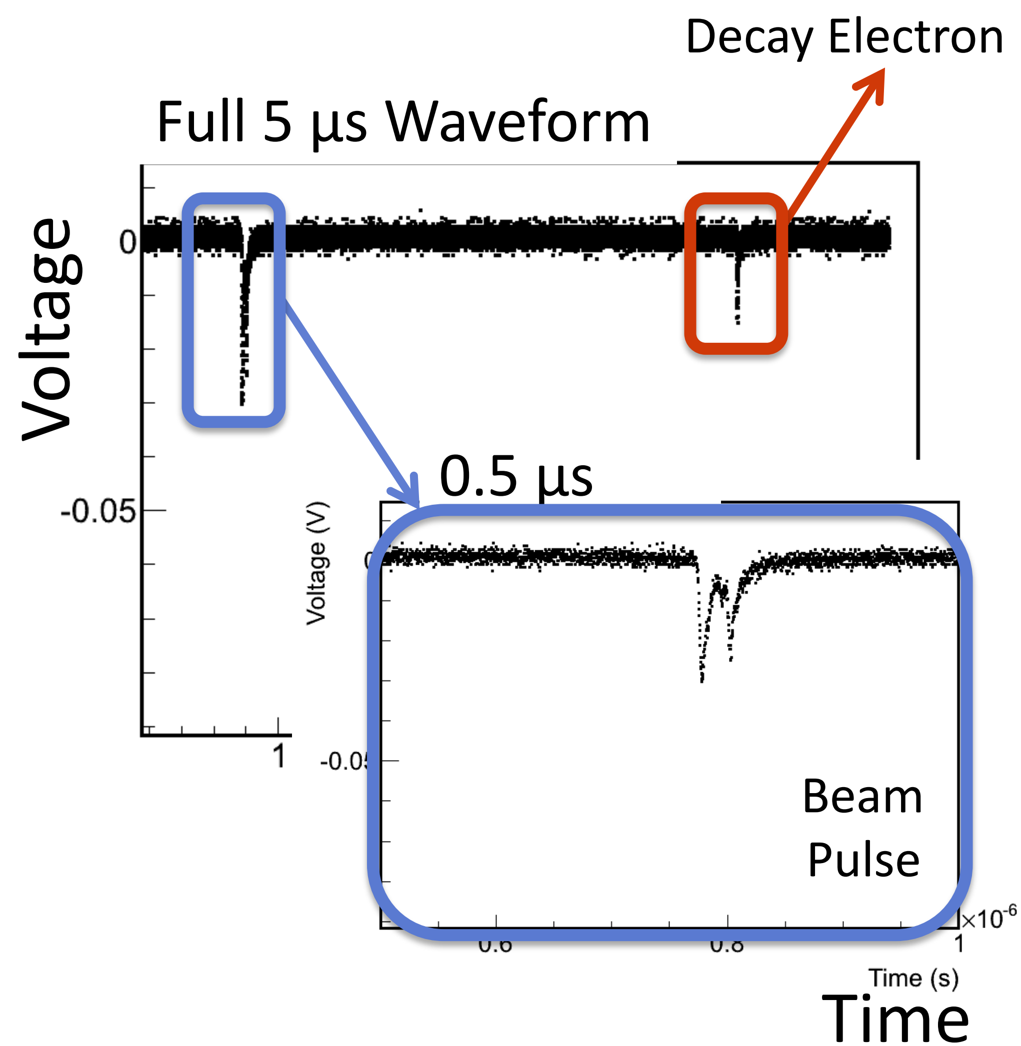


Best Fit Values

Mode	Δm^2_{32} (eV^2)	$Sin^2(2\theta_{23})$
CCQE	0.00242	1
$CC1\pi^+$	0.00240	1
CCQE+ $CC1\pi^+$	0.00240	1

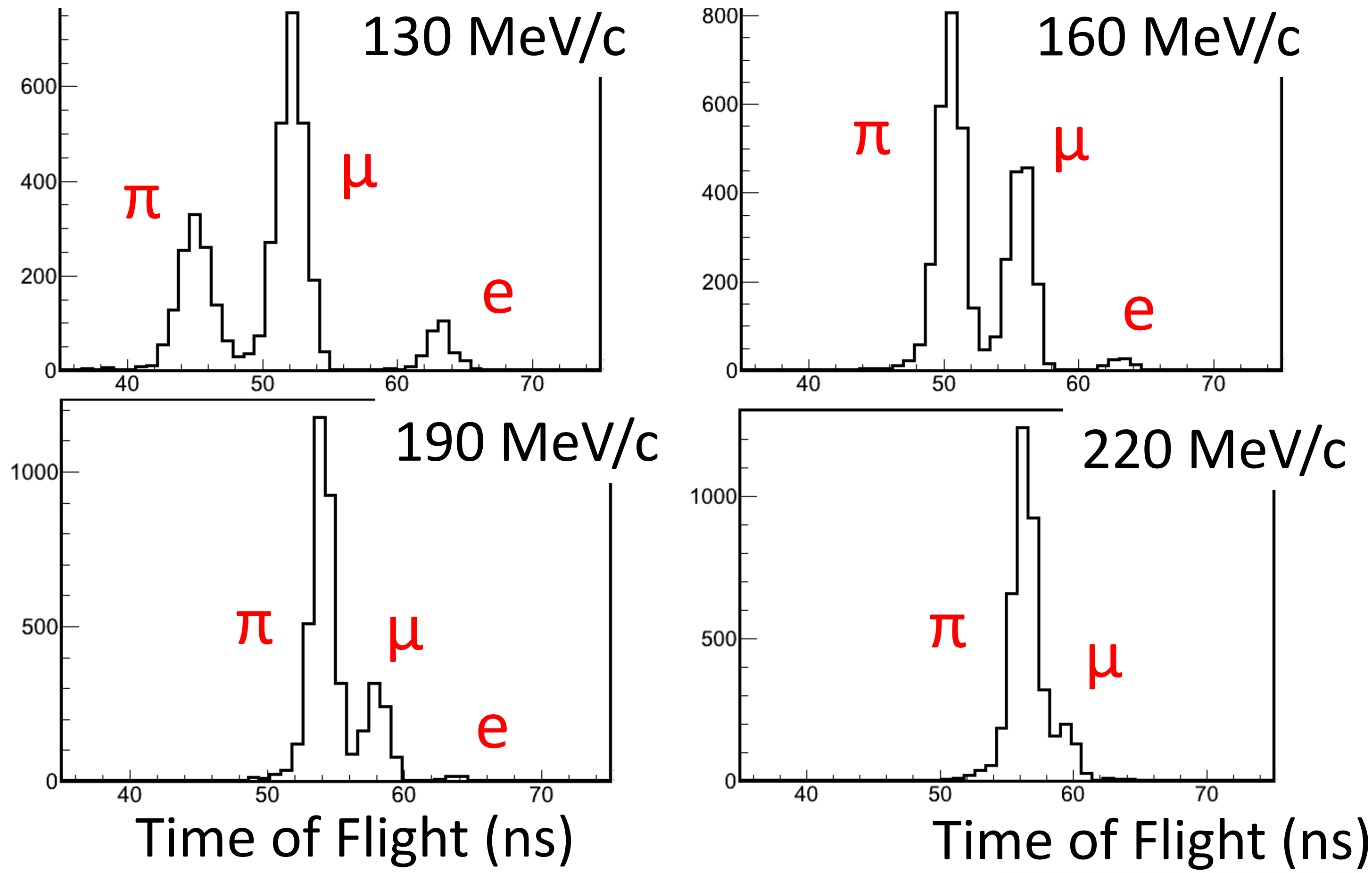
PICCOLO Data Collection

- TRIUMF M11 beam
  - Secondary beamline
  - Contains: e^+, μ^+, π^+
- Select momenta in a range from 130 – 300 MeV/c
- Collected PMT waveform on an oscilloscope



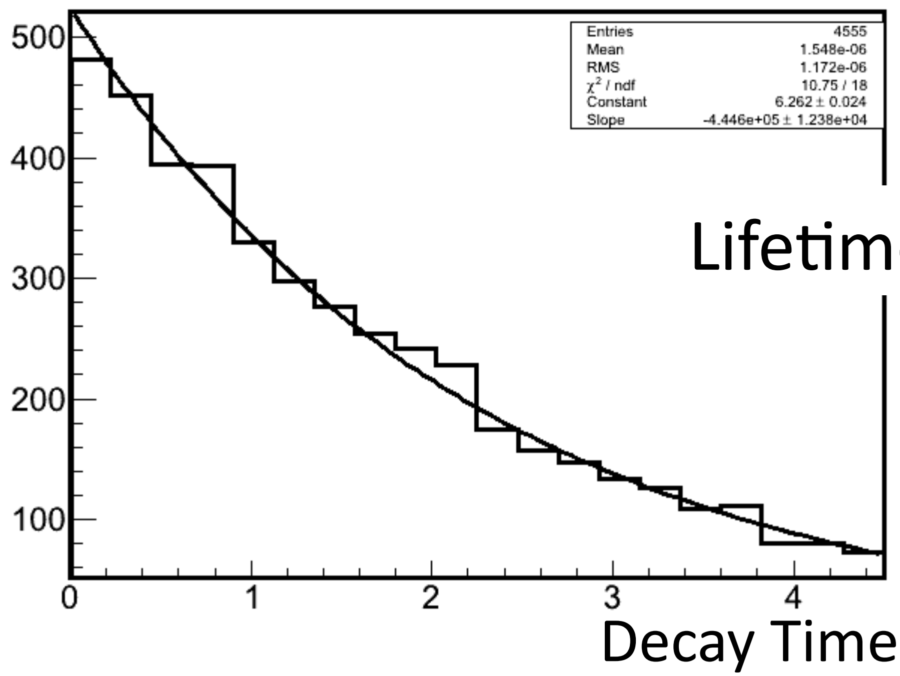
Particle Identification

- Beam contains e^+, μ^+, π^+ so need to separate particles for analysis
- Particles travel at different speeds because of different masses
- Distinguish particles using different flight times from production to detector



Muon Lifetime

- Muons decay as: $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$
- Particle Data Group μ^+ lifetime: ~2.197 μs
  - Ran beam with positive particles so expect lifetime measurement without any muon capture effect
- Extract lifetime as a check of the data
- Identify muons and look for a decay electron peak



Lifetime = 2.24±0.06 μs