A New Method for Event Reconstruction in Large Cherenkov Detectors

Michael Wilking, TRIUMF

New Directions in Neutrino Physics

Aspen, CO

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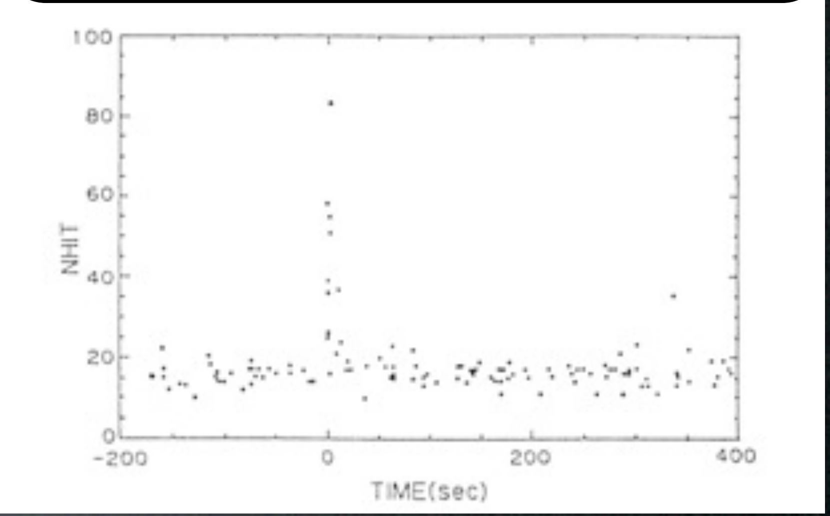
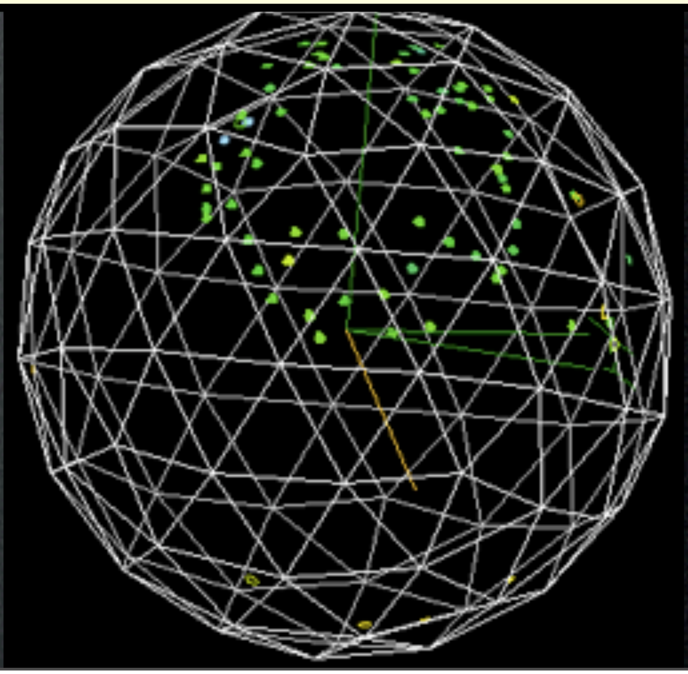
Physics Applications

- Search for proton decay
- Supernovae
  - SN burst
  - Relic SN background
- Neutrino physics
  - Solar neutrinos
  - Atmospheric neutrinos
  - Accelerator neutrinos
  - High-Energy astrophysical neutrinos
  - ...
- Broad physics reach
  - Much to be gained from better utilizing this technology

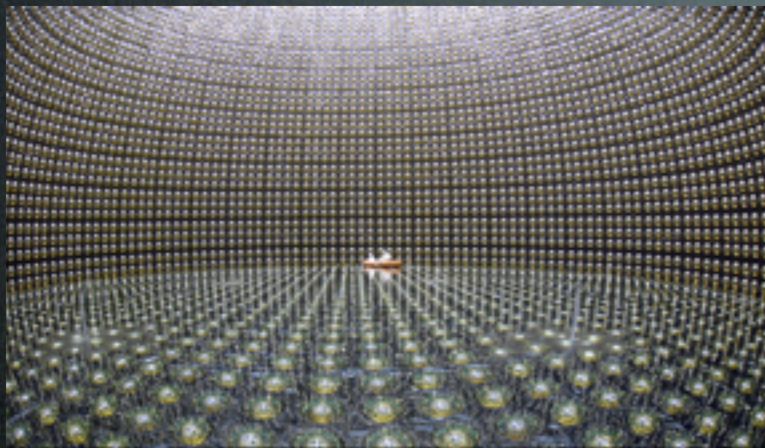
Kamiokande SN 1987a Signal

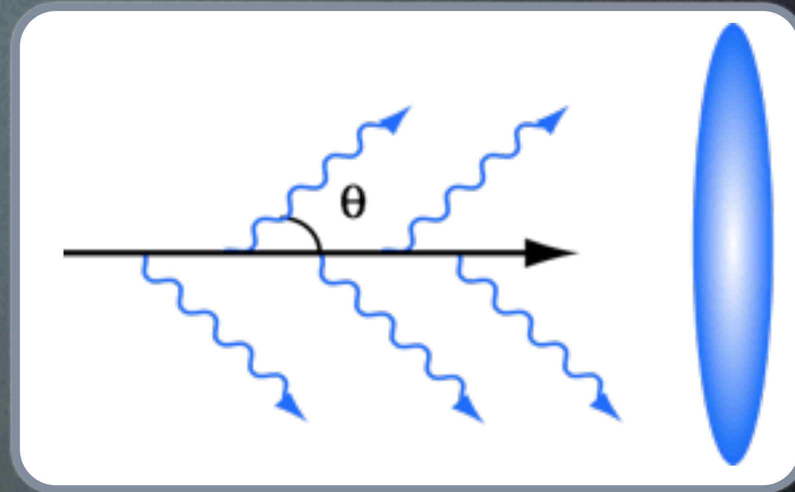


SNO Single-Electron Event

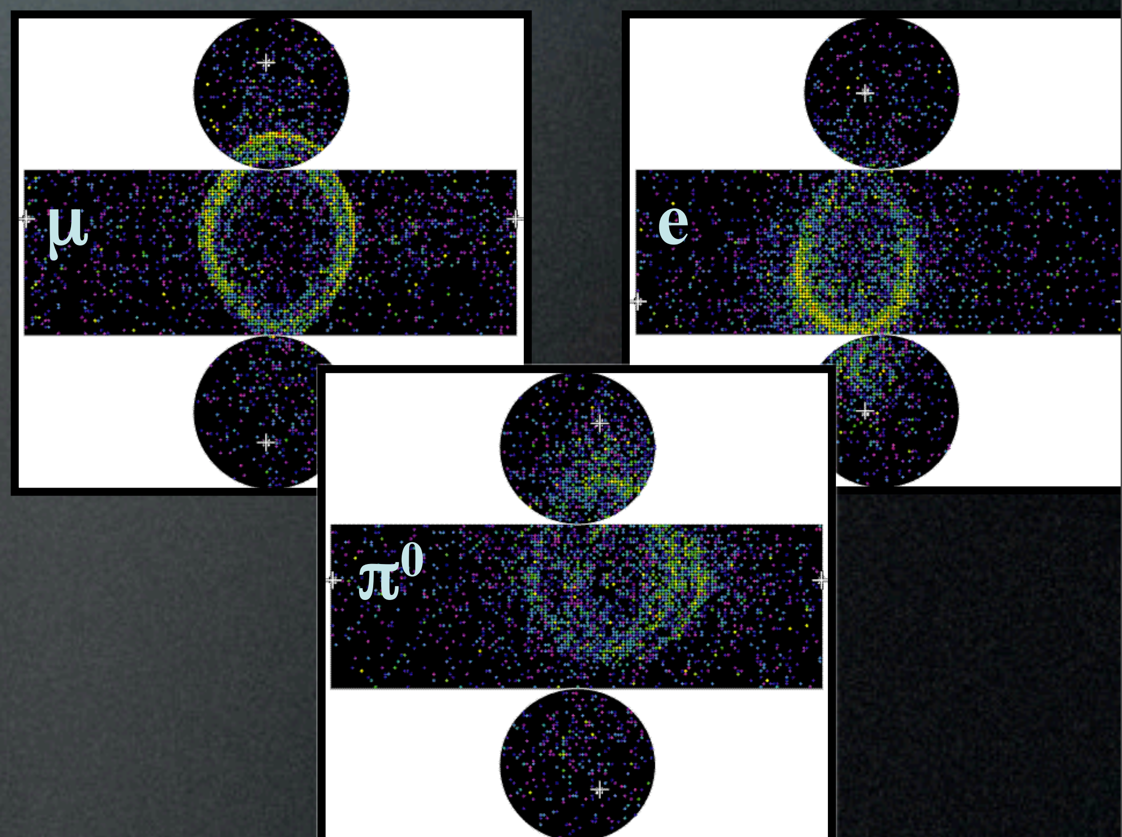


The Super-K Detector





- 50 kton water Cherenkov detector
- **$\mu^{\pm}$ detection**
  - Less scattering ⇒ sharp rings
- **$e^{\pm}$ detection**
  - More scattering ⇒ fuzzy rings
- **π^0 detection**
  - 2 electron rings ($\pi^0 \to 2\gamma$)
  - To separate from electrons, **MUST** detect 2nd ring



fiTQun: A New Event Reconstruction Algorithm for Super-K

- For each Super-K event we have, for every hit PMT
  - **A measured charge**
  - **A measured time**
- For a given event topology hypothesis, it is possible to produce a **change and time PDF for each PMT**
  - Based on the likelihood model used by MiniBooNE (NIM A608, 206 (2009))
- Framework can handle **any number of reconstructed tracks**
  - Same fit machinery used for all event topologies (e.g. e^- and π^0)
- Event hypotheses are distinguished by **comparing best-fit likelihoods**
  - electron / π^0
  - electron / muon / π^+ / K^+ / p / ...
  - 1-ring / 2-ring / 3-ring ...

The Likelihood Fit

$$L(\mathbf{x}) = \prod_{\text{unhit}} P(i\text{unhit}; \mathbf{x}) \prod_{\text{hit}} P(i\text{hit}; \mathbf{x}) f_q(q_i; \mathbf{x}) f_t(t_i; \mathbf{x})$$

- A single track can be specified by a **particle type**, and **7 kinematic variables** (represented above as the vector **x**):
  - A vertex position **(X, Y, Z, T)**
  - A track momentum **(p)**
  - A track direction **(θ, φ)**
- For a given **x**, a charge and time PDF is produced for every PMT
- The **charge PDF** is factorized into:
  - Number of photons reaching the PMT
    - **Predicted charge (μ)**
  - PMT & electronics response
- All 7 track parameters **fit simultaneously**

Time PDF

Charge PDF

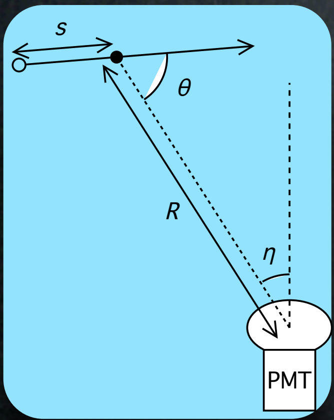
PMT Charge Response:

Property of the electronics and PMT properties

Predicted Charge (μ):

- Number of photons that reach the PMT
- Depends on detector properties (scat, abs, etc.)

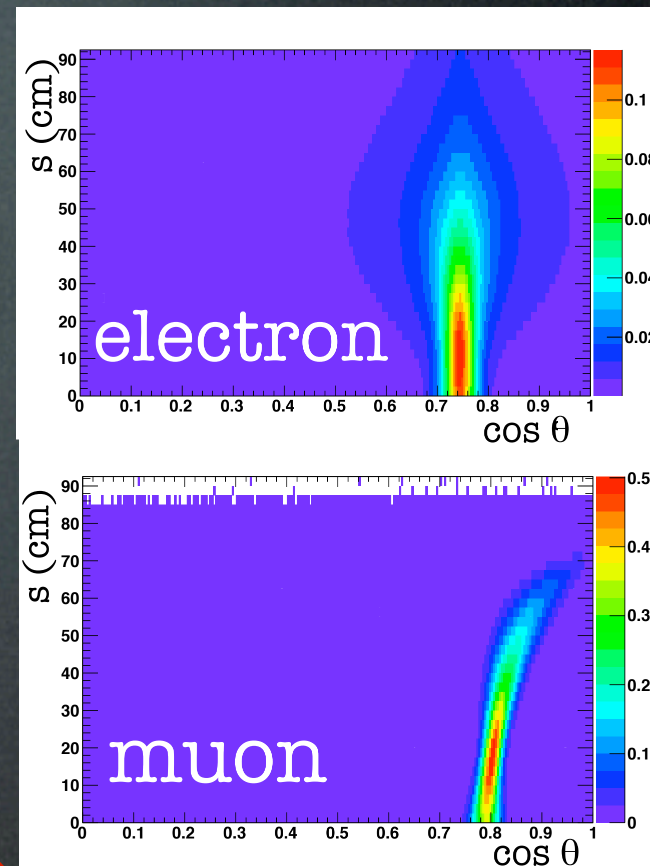
Predicted Charge (μ)



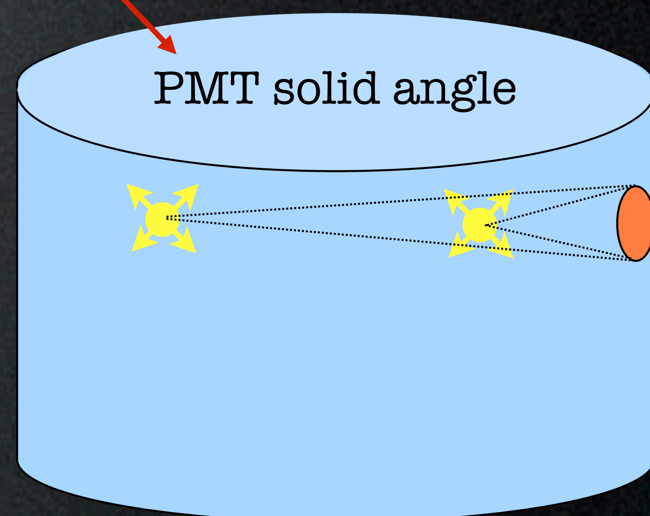
$$\mu^{\text{dir}} = \Phi(p)\int ds\, g(s, \cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

Light Yield — Integral over track length — PMT solid angle — Water attenuation — PMT angular response

Cherenkov light emission profile



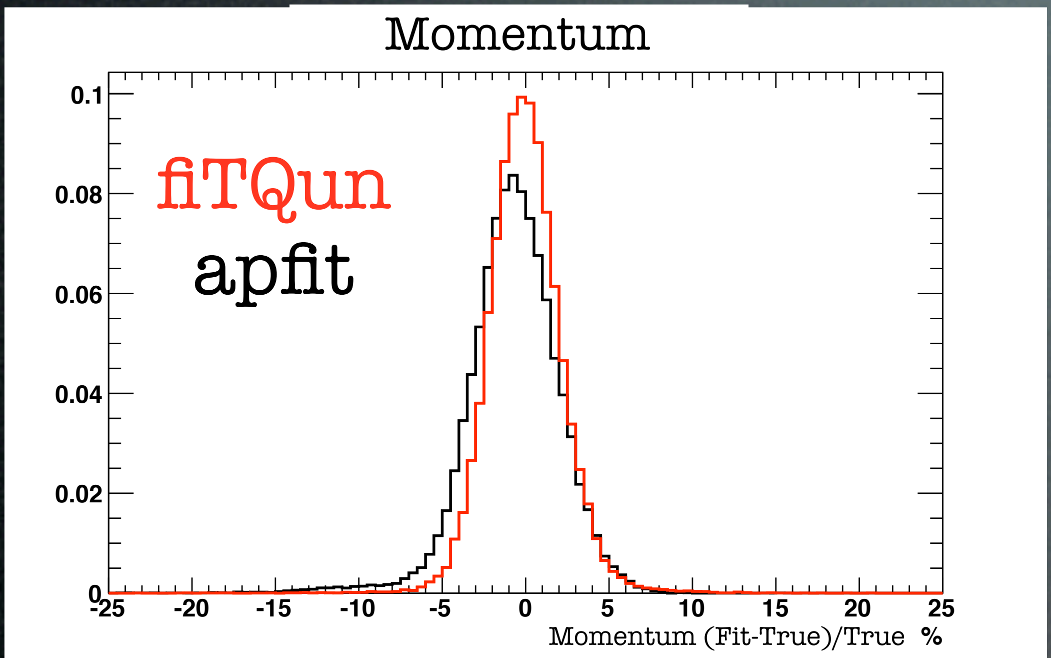
- μ^{dir} is the predicted charge due to "direct light" only (scattered light is handled separately)
- μ is an integral over the length of the track (parameterized by the momentum, p)
- Cherenkov light emission is characterized by g(s,cosθ)
  - These functions must be generated separately for each particle type
  - All particle ID comes from these distributions
- Ω, T, and ε depend on the geometry and detector properties
  - Can be used for all particle hypotheses



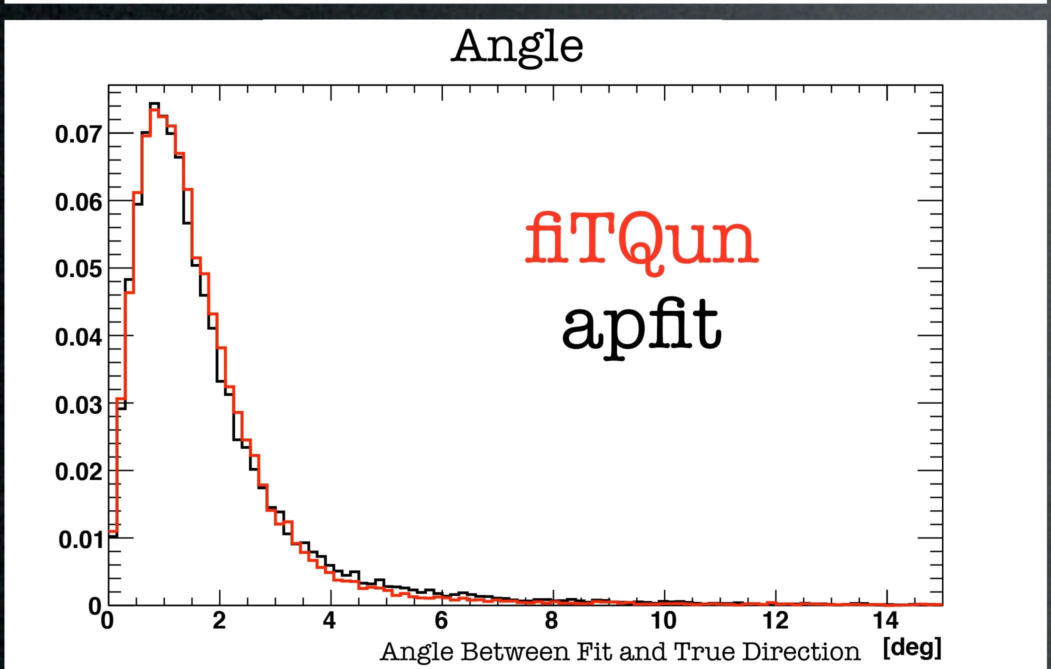
One-Track Fit Performance

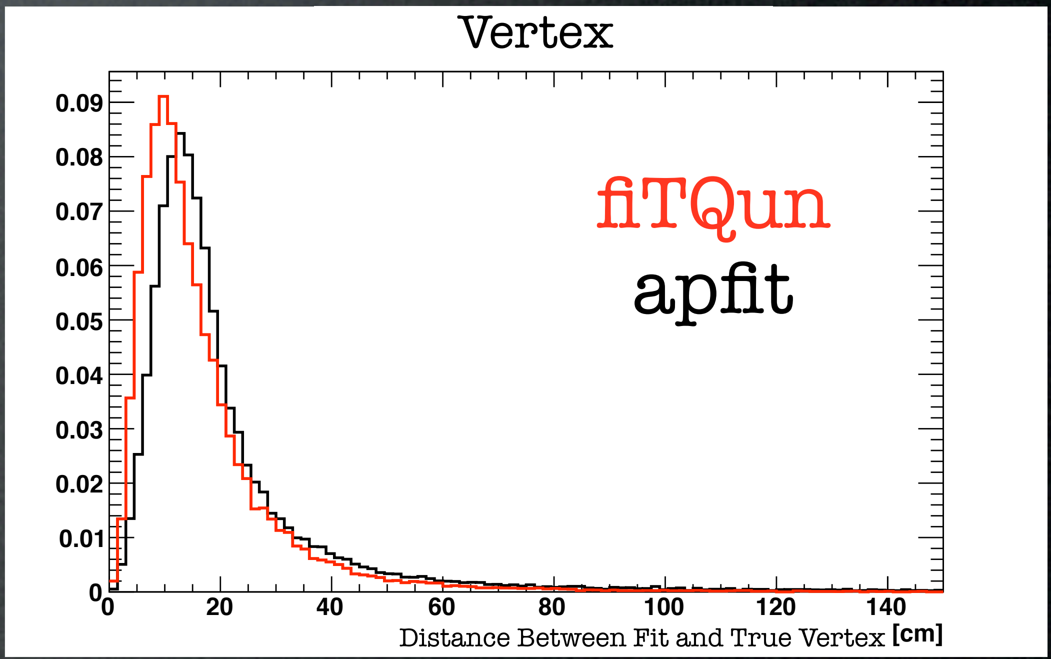
Shown with default Super-K reconstruction, **apfit**, for comparison

Muons

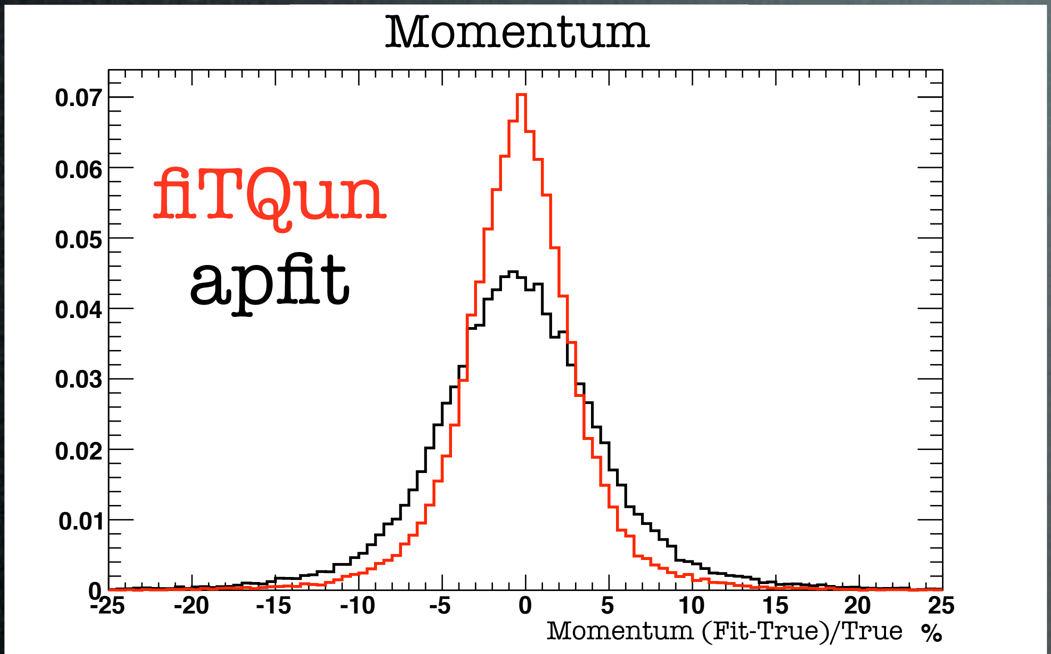


- Tested on a uniform distribution of muons between 0 and 1 GeV/c
    - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution

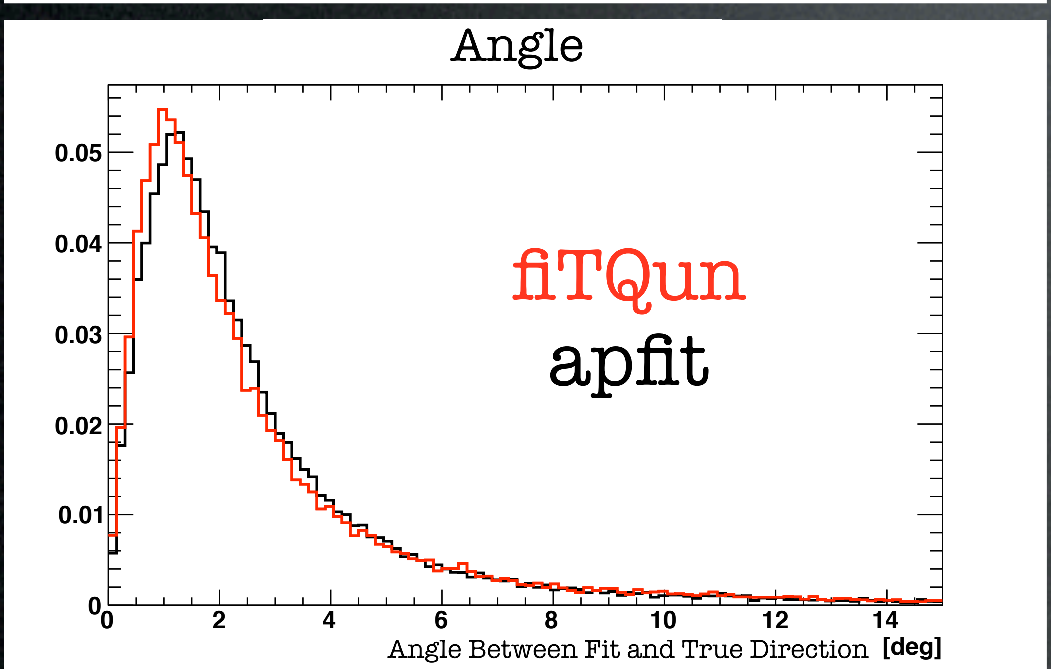


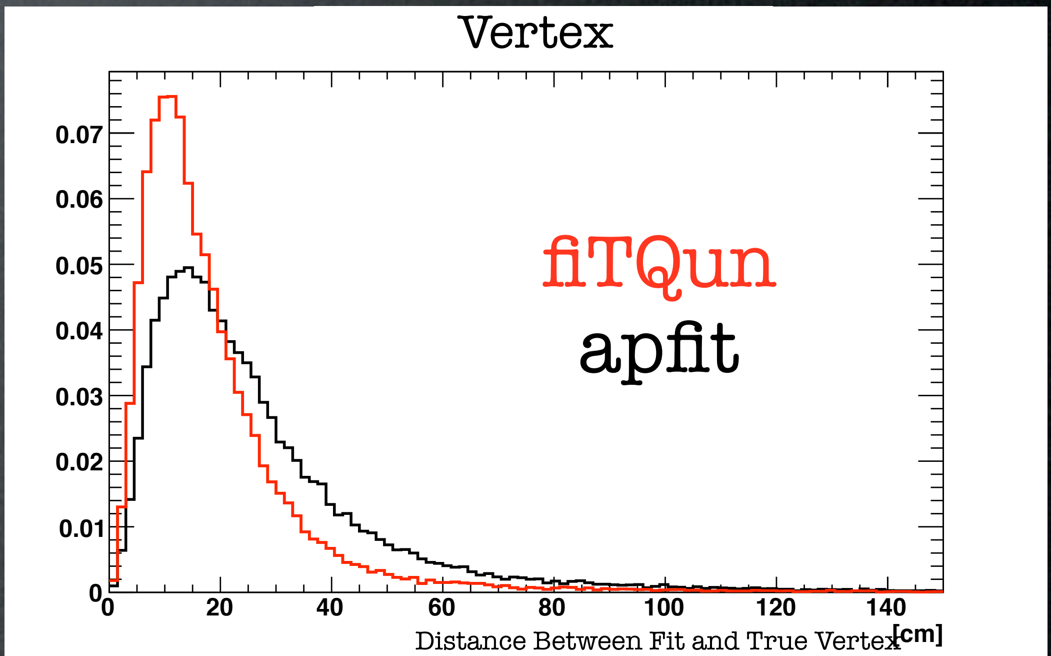


Electrons

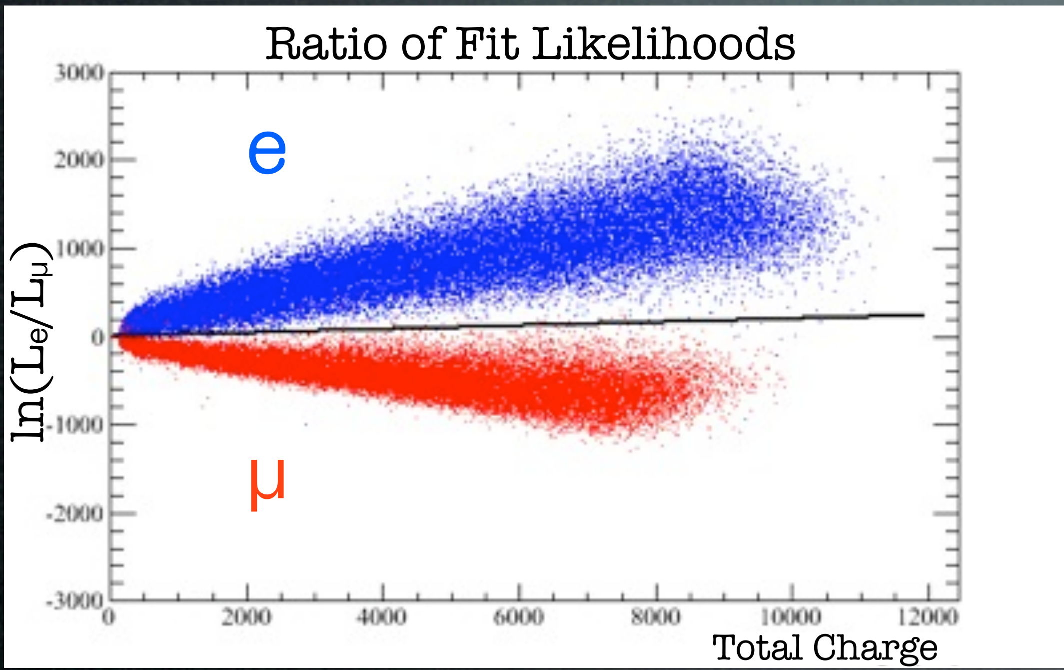


- Tested on a uniform distribution of e⁻ between 0 and 1 GeV/c
  - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution

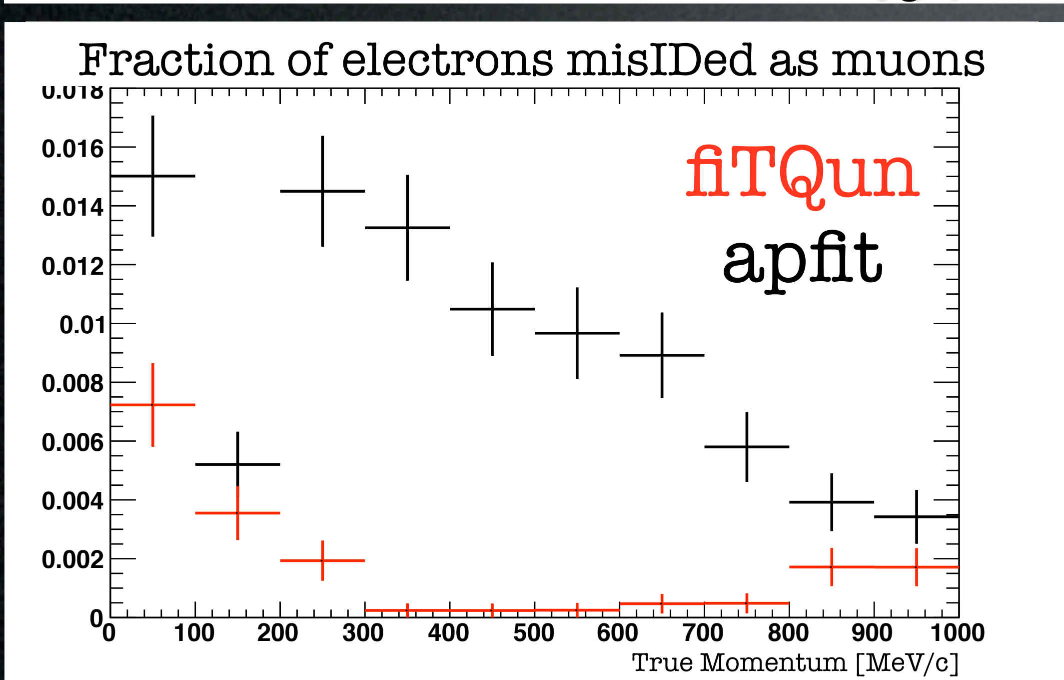


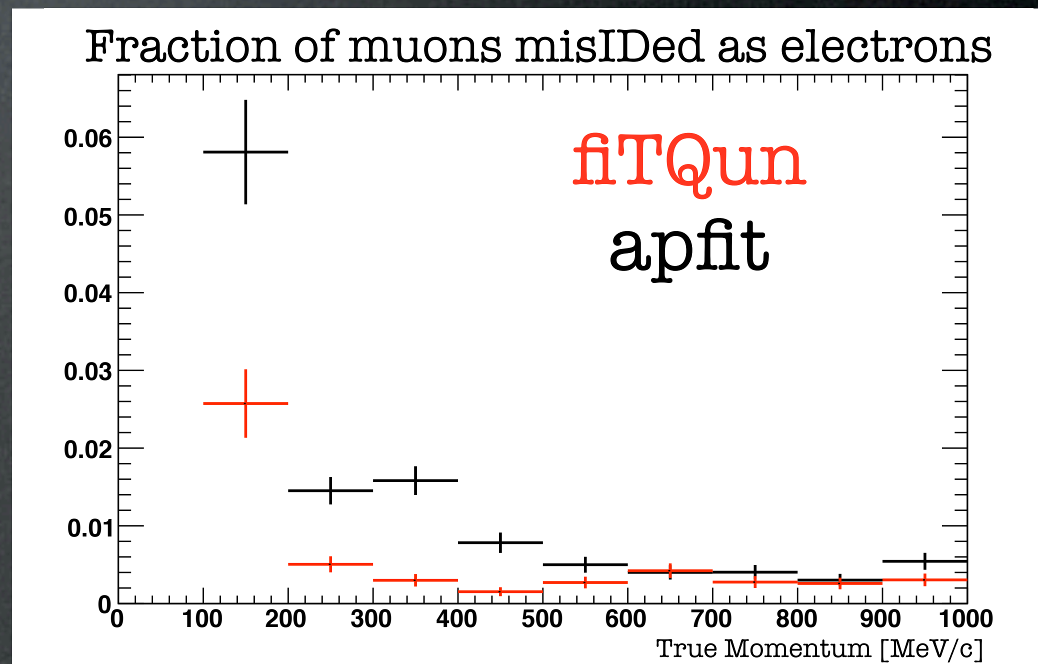


Single Track Particle ID



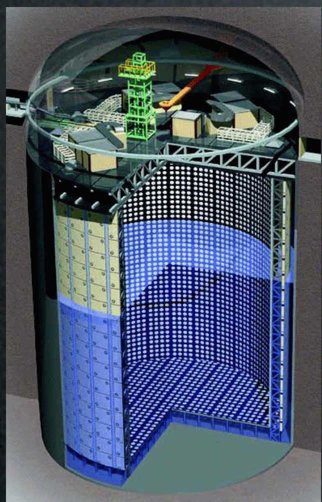
- Simple line cut can be used to separate muons and electrons
- Significantly improved particle ID

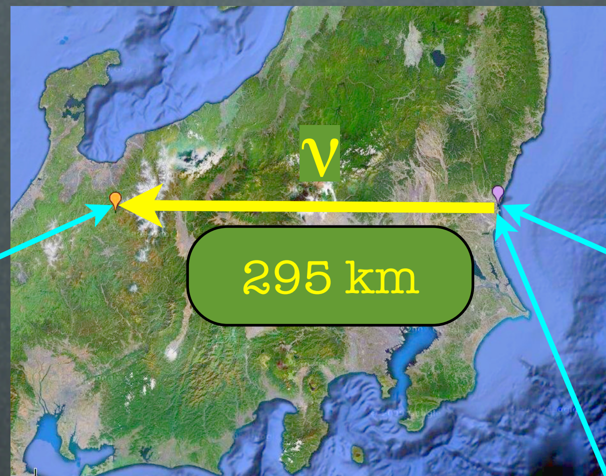




Test Case: The T2K Experiment

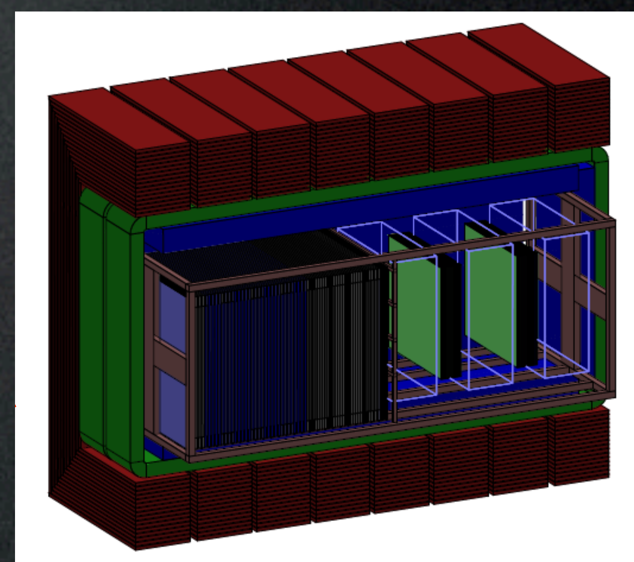
Super-K Detector





J-PARC Accelerator

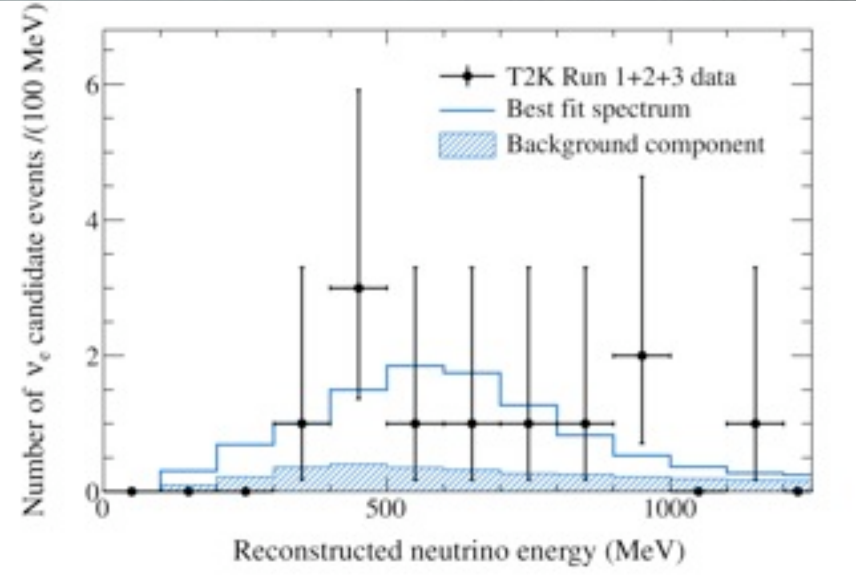
Near Detector



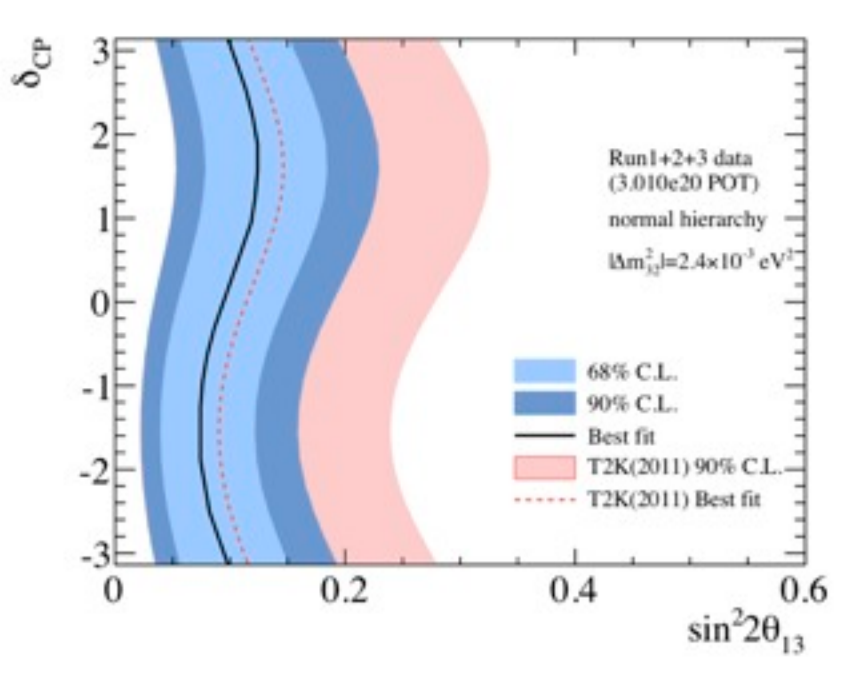
- The T2K experiment searches for neutrino oscillations in a high purity ν_μ beam
- A near detector located 280 m downstream of the target measures the unoscillated neutrino spectrum
- The neutrinos travel 295 km to the Super-Kamiokande water Cherenkov detector
  - For **θ_{13} search**: Super-K looks for the **appearance of ν_e**
  - For **θ_{23} measurement**: The ν_μ at the near and far detectors are compared to search for ν_μ **disappearance**

Latest T2K ν_e Results (2012)

- 11 events observed
- $\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$
- 3.2σ exclusion of $\theta_{13}=0$



- 3.22 ± 0.43 background events
  - 1.56 ± 0.20 **intrinsic beam ν_e**
    - **Irreducible**
  - 1.26 ± 0.35 ν_μ neutral current (**mostly π^0**)
    - **Reducible?**



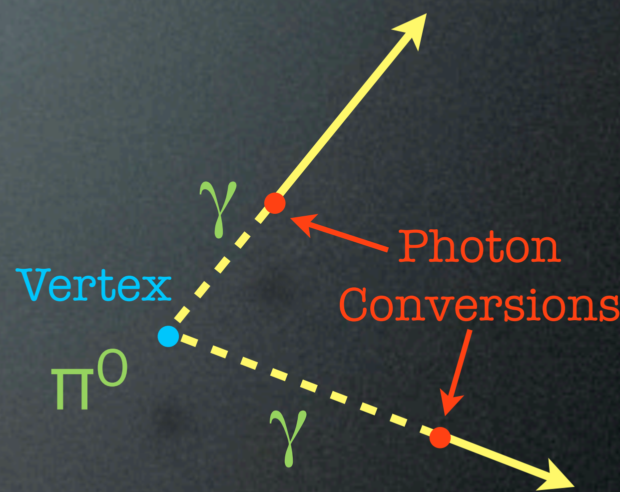
Background Reduction

40% of the ν_e appearance background is from π^0 where the 2nd photon was missed

Can fiTQun do better?

fiTQun π^0 Fitter

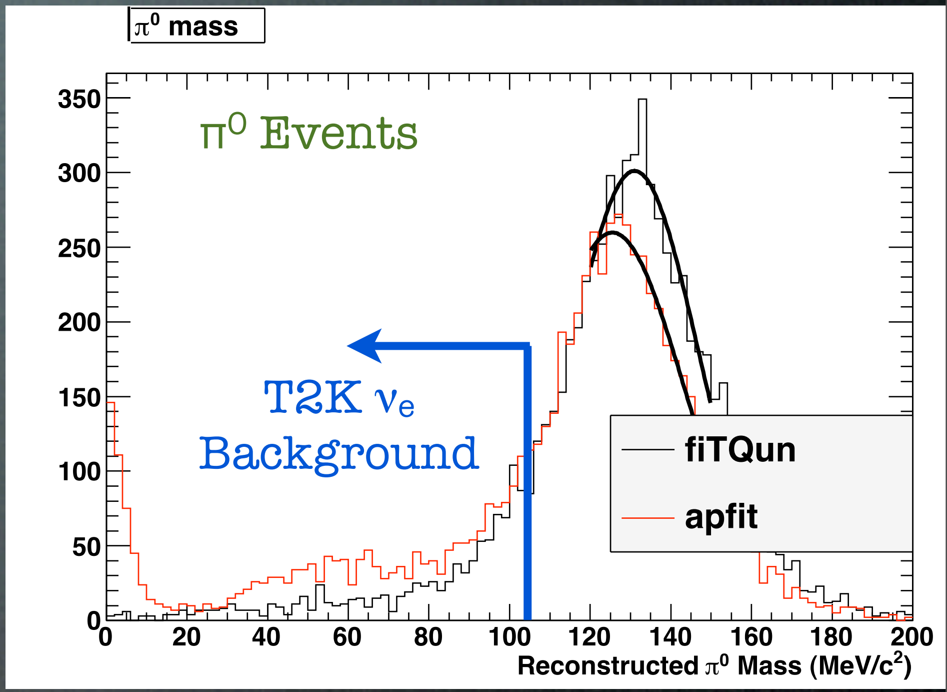
- Assumes two electron hypothesis rings produced at a common vertex
- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, ϕ_1, θ_2, ϕ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)

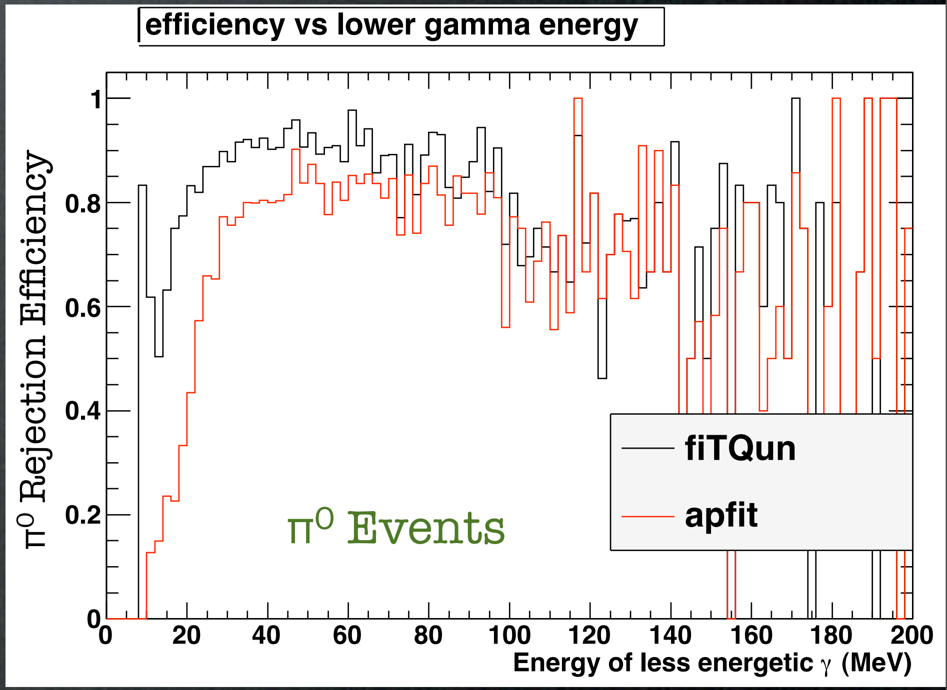


- **Seeding the fit**
  - Use result of single-track electron fit
  - Scan over various directions with a 50 MeV/c electron and evaluate the likelihood function
    - Choose the direction that yields the best likelihood
  - First, fit while floating only p_1 and p_2
- **Do full 12 parameter fit**

π^0 Performance

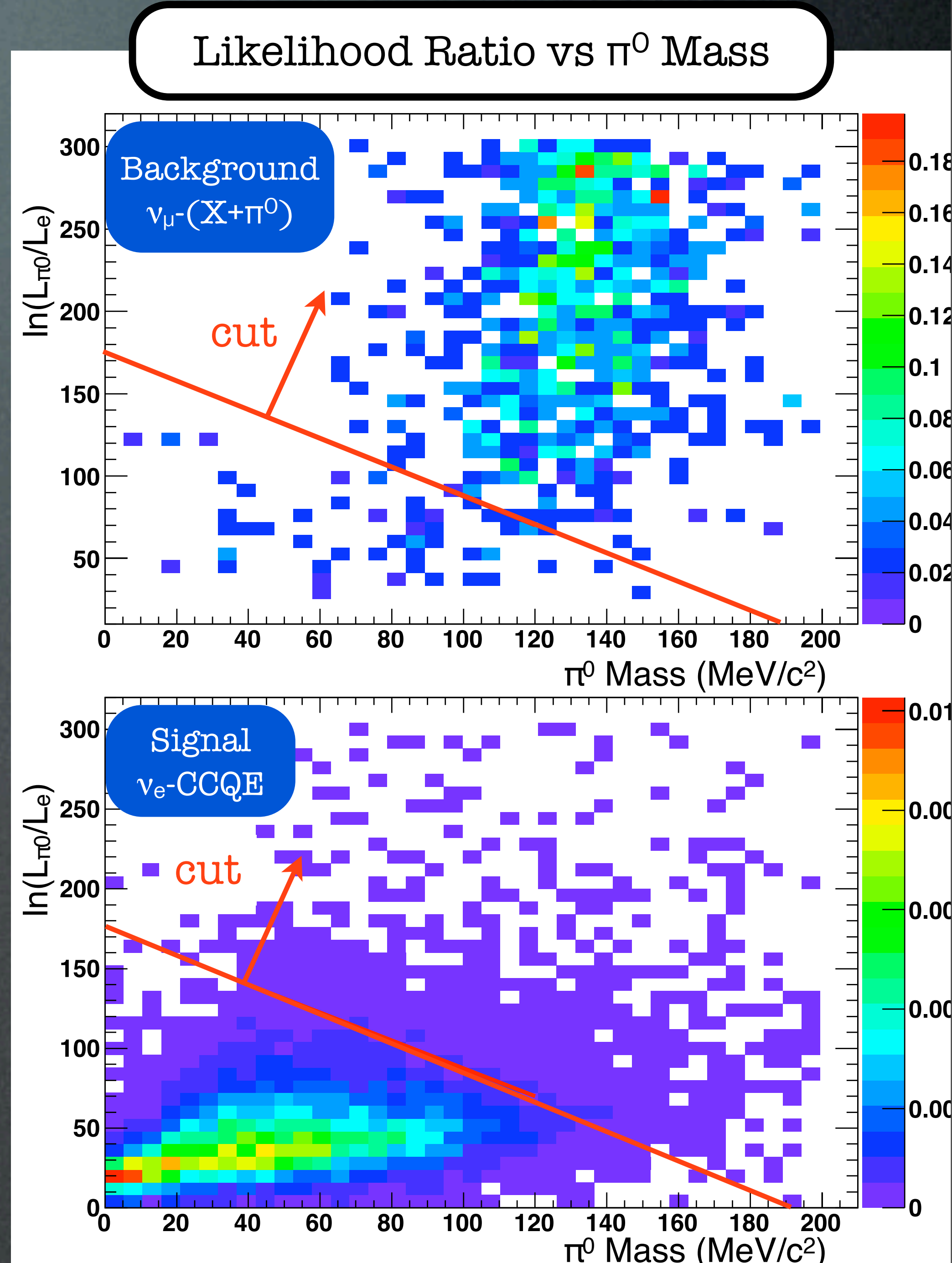
- T2K ν_e appearance cut:
  m_{π^0} < 105 MeV
- The π^0 mass tail is much smaller for fiTQun
  - Significant spike at zero mass in standard fitting algorithm (**apfit**)
    - **All events in the spike are background**
    - **fiTQun shows no spike**
- Lower plot:
  π^0 rejection efficiency vs **lower γ energy**
  - fiTQun is more sensitive to lower energy photons





Even Better π^0 Rejection

- fiTQun can also use the **likelihood ratio** to distinguish e^- from π^0
  - Even if 2nd photon is identified, it may be on the tail of the π^0 mass resolution
  - In this case, the 2-ring likelihood will still be preferred
- 2D cut **removes 75% more π^0 background**
  - For the same electron signal efficiency



Effect on ν_e Appearance

- π^0 background has **>30% error (flux + cross section)**
  - Error on **beam ν_e** background is only ~**12%**
- Background due to π^0 is reduced by ~75%

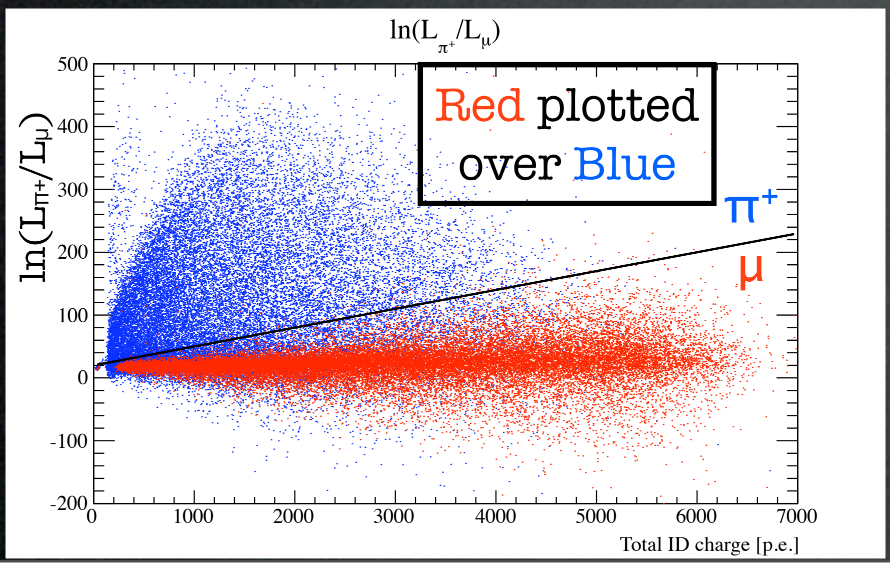
For 3.01 * 10^{20} POT	fiTQun	apfit
# π^0 bkgd	0.29	1.13
# Total bkgd	1.94 ± 0.24	2.93 ± 0.46

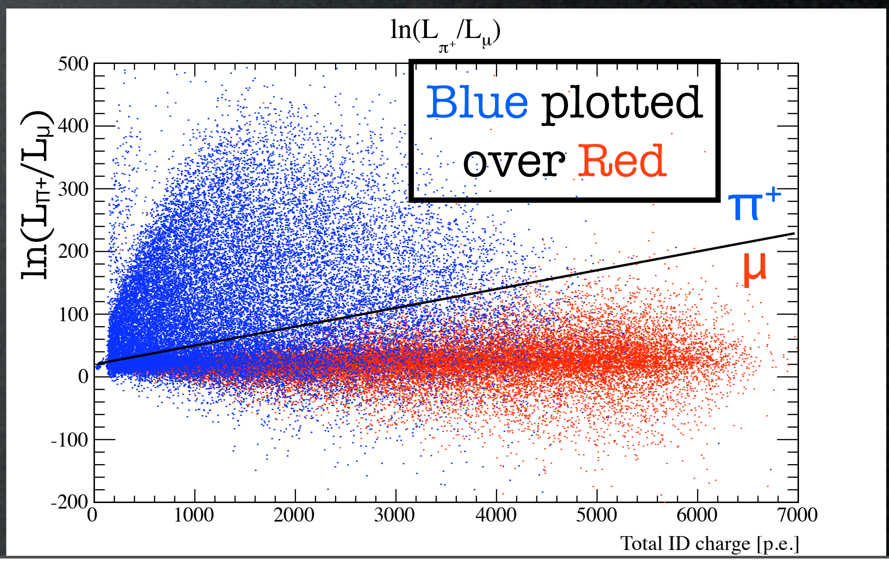
- Total background is reduced by 33%
  - More importantly, **background error is halved**
  - Significant improvement in $\sin^2 2\theta_{13}$ sensitivity
- Other fiTQun improvements (e.g. e^- PID, ring counting) improve the sensitivity further

Other fiTQun Tools: π^+ Fitter

- Pions and muons have **very similar Cherenkov profiles**
  - Main difference is the **hadronic interactions** of pions
- Ring pattern observed is a **"kinked" pion trajectory** (thin ring with the center portion missing)
- π^+ tracks have never been reconstructed before at Super-K

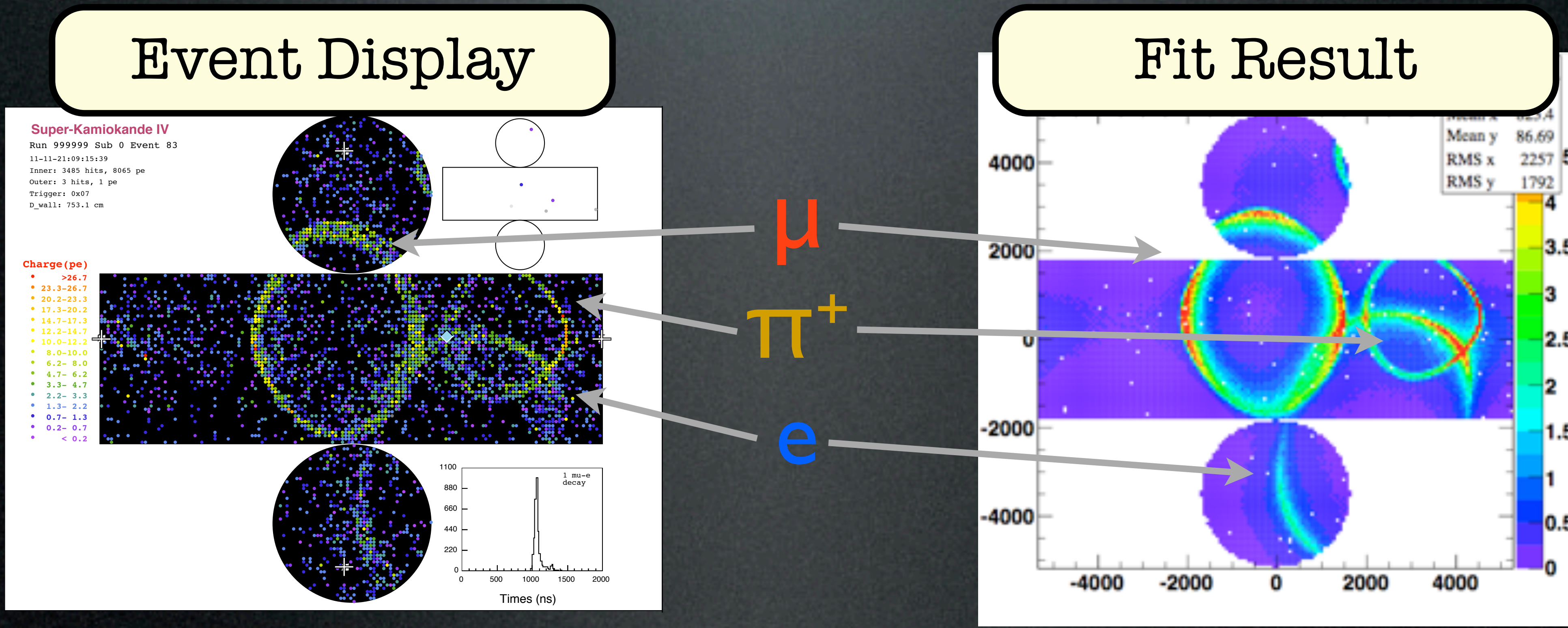
μ & π^+ particle gun





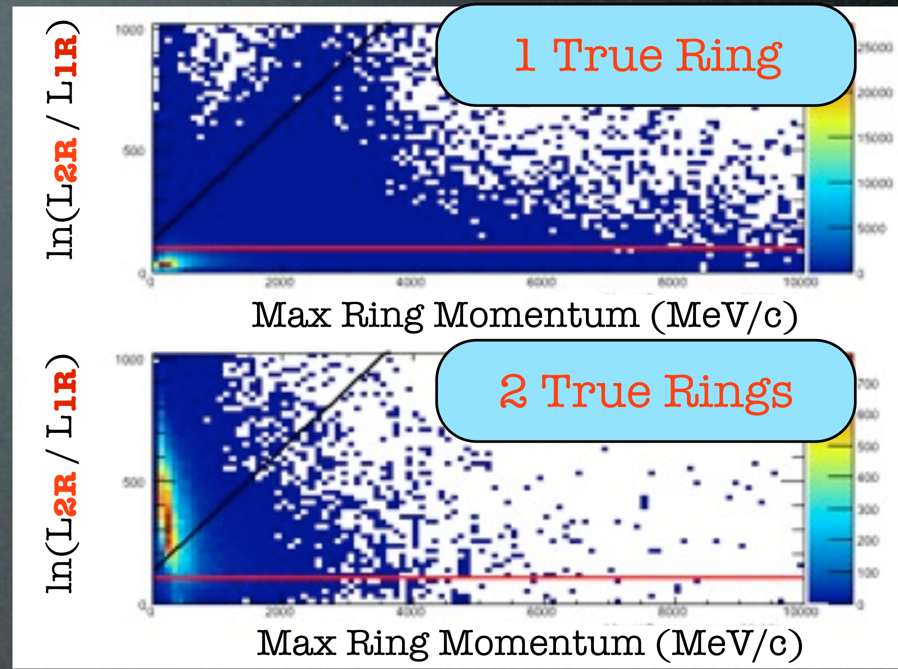
Other Tools: Multi-ring Fitter

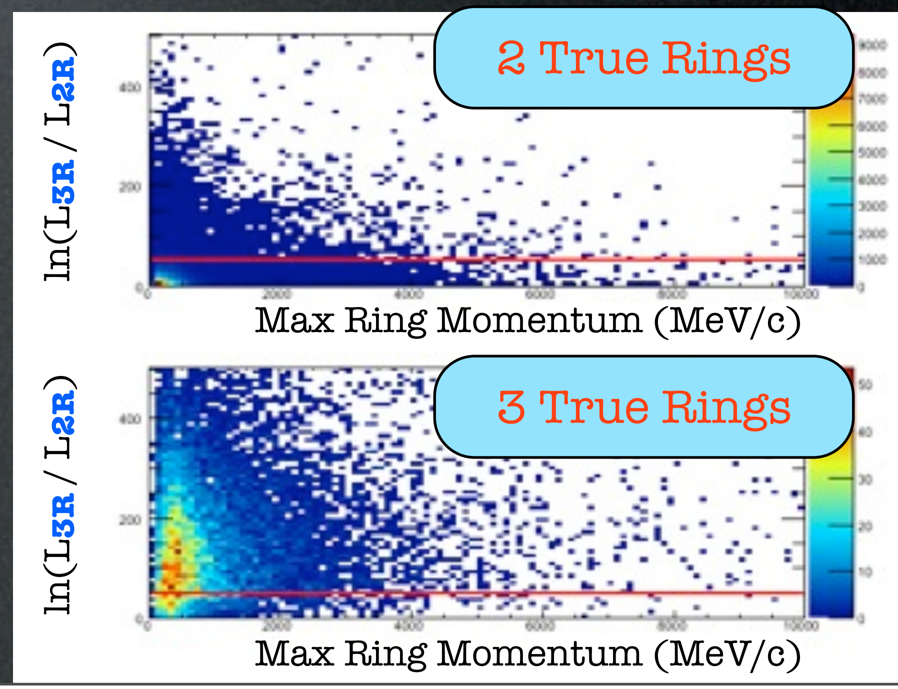
- **Fit up to 4 rings** using e & π^+ hypotheses
  - 28 fits in total (every possible e/π^+ combination)
- μ hypothesis is a subset of the π^+ hypothesis
  - Just need to move the kink point below Cherenkov threshold



Ring Counting

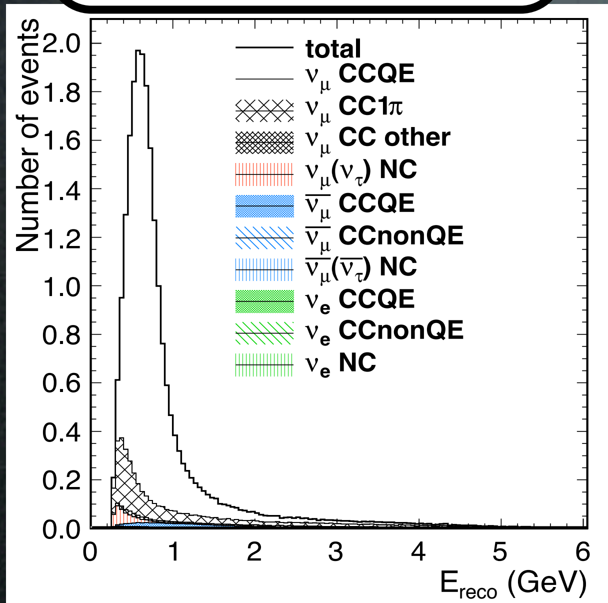
- Compare best **(n)-ring** likelihood to best **(n+1)-ring** likelihood
  - Ring counting now depends on particle ID
- Can test performance on atmospheric neutrino sample
  - Higher energy neutrinos = **more rings**
  - Define a “true ring”
    - Any particle >10 MeV/c above Cherenkov threshold
- Good performance seen up to 4 rings





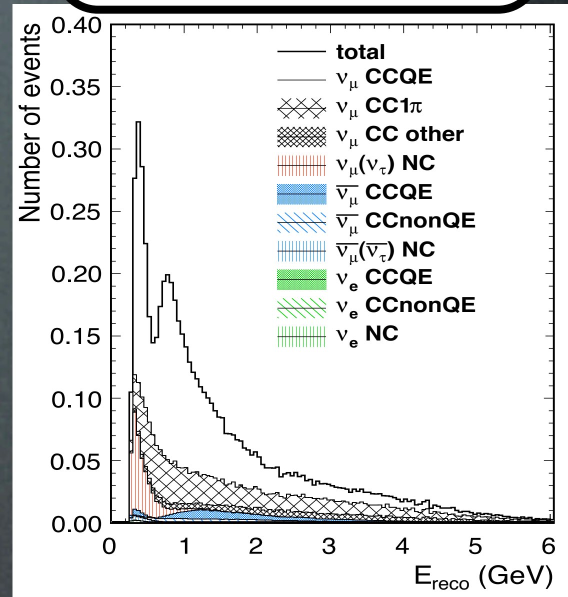
T2K ν_μ Disappearance

Unoscillated Number of events at Super-K



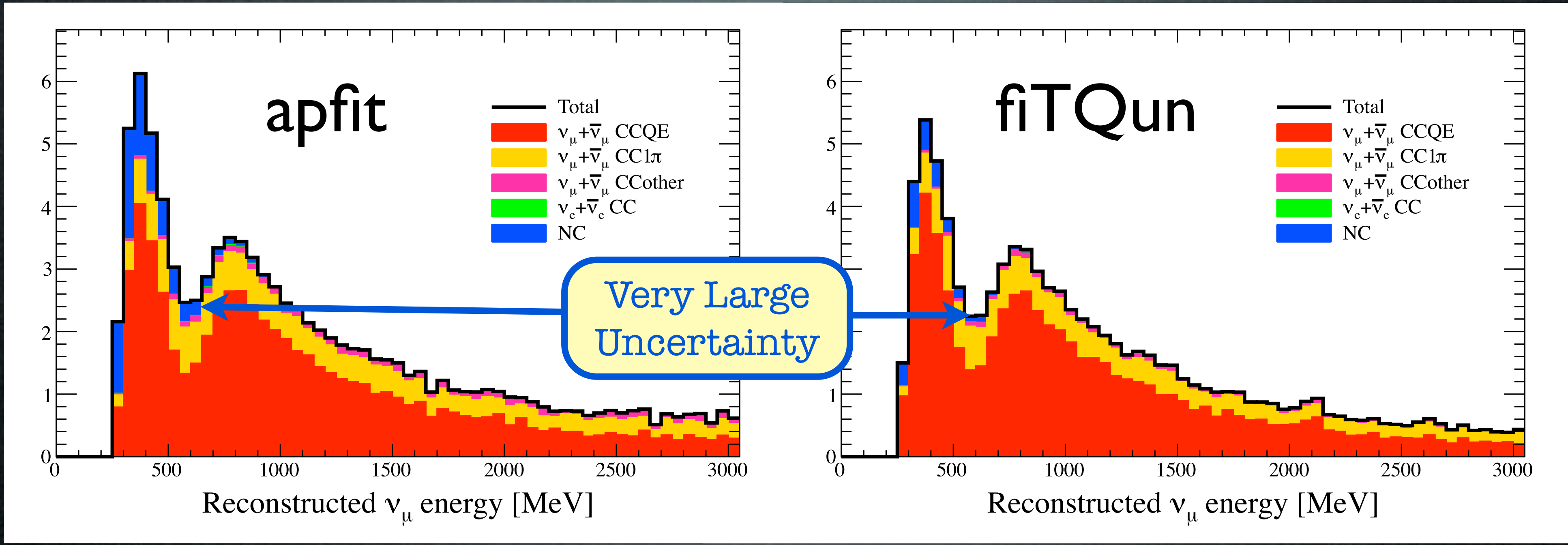
oscillation

$\sin^2(2\theta_{23})=1$
$\Delta m_{32}^2 = 2.4 * 10^{-3}\ eV^2/c^4$



- Largest backgrounds are from $CC\pi^+$ and $NC\pi^+$
  - **$NC\pi^+$**: pion is misidentified as a muon
    - Super-K reconstruction **uncertainty on π^+ is large (>100%)**
  - **$CC\pi^+$**: pion is unobserved
    - The fiTQun can now reconstruct π^+
      - If properly reconstructed, **$CC\pi^+$ can be treated as signal**

ν_μ Selection: fiTQun vs apfit



Fraction of apfit selected events removed:

$\nu_\mu+\bar{\nu}_\mu$ CCQE	4.8%
$\nu_\mu+\bar{\nu}_\mu$ CC1π	21.5%
$\nu_\mu+\bar{\nu}_\mu$ CCother	53.7%
$\nu_e+\bar{\nu}_e$ CC	92.1%
NC	61.2%

- fiTQun signal efficiency is higher below 1 GeV
- Significant reduction of NC background due to π^+ rejection
  - **NCπ^+ background has a very large uncertainty (>100%)**
    - NCπ^+ piles up near the oscillation dip
- Expect significant enhancement in **θ_{23} and Δm^2_{32} sensitivity**

Other Uses for fiTQun

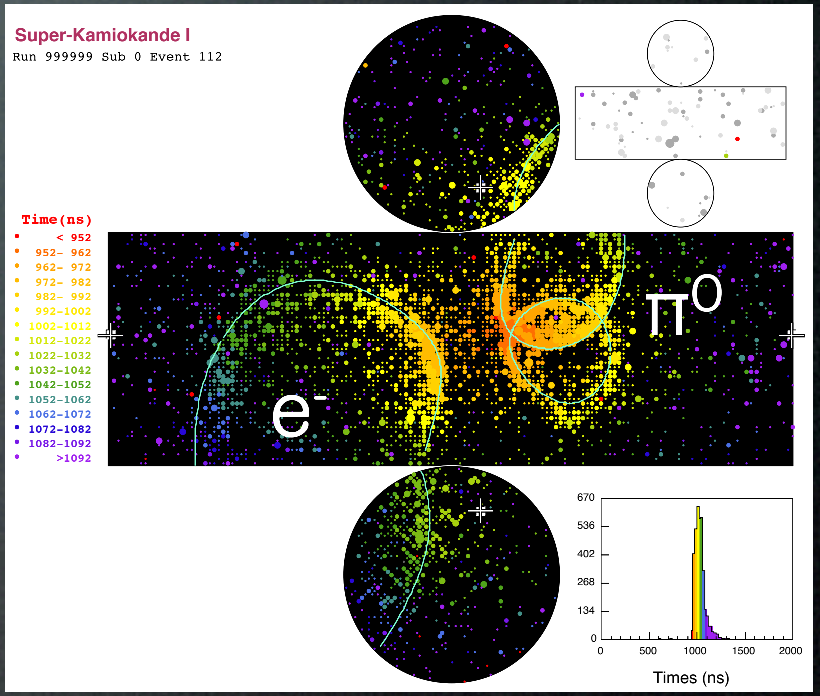
In principle, any Super-K physics analysis can benefit from fiTQun

Particularly, Proton Decay

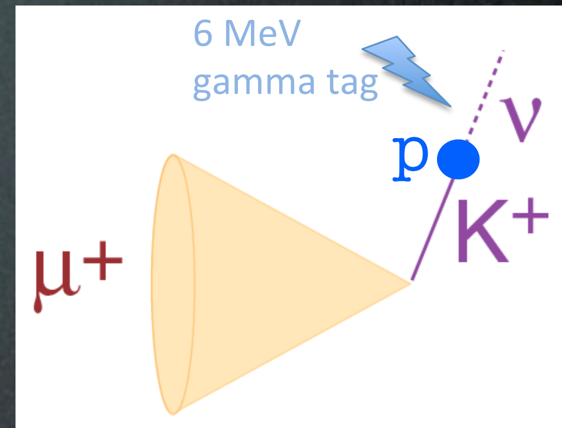
Reconstruction requirements are very similar to T2K ν_e appearance requirements

$p \rightarrow e^+\pi^0$

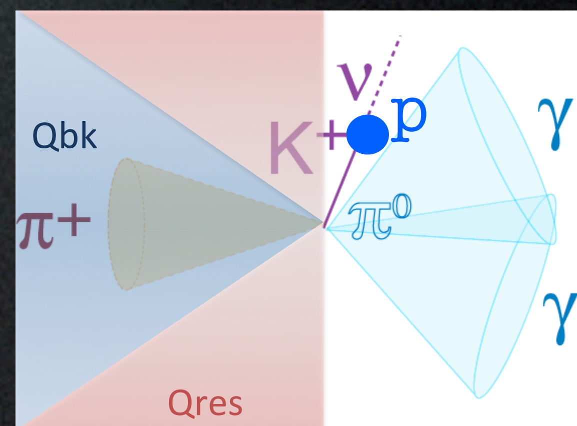
- 45% reconstruction efficiency with current Super-K tools
  - Selection allows for 2- or 3-ring reconstructed rings
- fiTQun has **improved identification of faint photon rings**
  - Should **improve signal efficiency** (for 3-ring events)
  - Analogous to T2K π^0 search
- Improved electron resolution
  - Better constraints on momentum balance and reconstructed π^0 and p masses
  - Can tighten cuts to improve background rejection



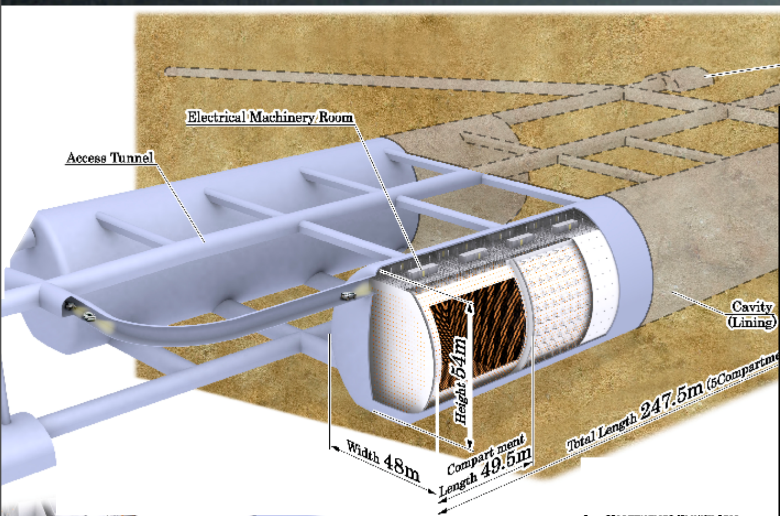
$p \rightarrow K^{+}\nu$

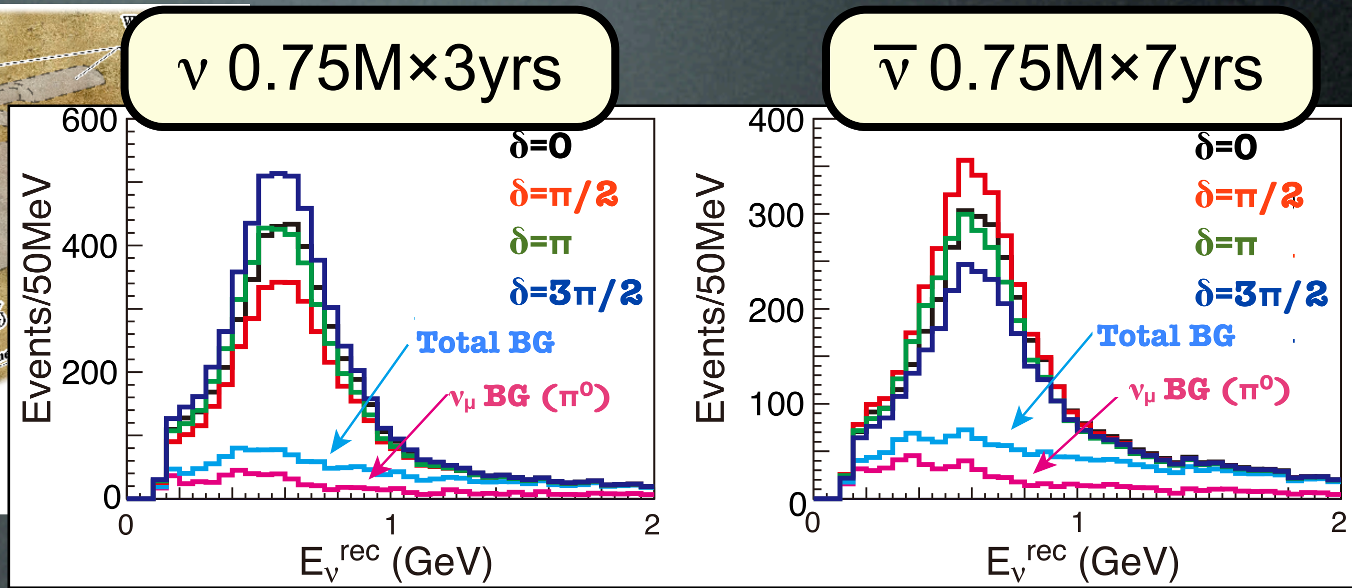


- Search via the largest two K^+ decay channels
- **$K^+ \rightarrow \mu^+ \nu_\mu$**
  - Search for a mono-energetic muon
    - fiTQun has improved muon momentum resolution
  - Search for **6 MeV photon** from nuclear de-excitation
    - Very low energy → current algorithm is very inefficient
      - **Only 6.4% efficiency** (44% have a nuclear photon)
    - **Large potential improvement** if low-energy photon detection can be improved
- **$K^+ \rightarrow \pi^+ \pi^0$**
  - **No previous ability to reconstruct π^+**
    - Instead, sum charge in 40 degree cone opposite the π^0 direction
    - veto on any other charge in the event
  - **fiTQun can reconstruct charged pions**
    - Can also do **simultaneous $\pi^+\gamma\gamma$ fit** and compare likelihood with background hypotheses



Future Experiments: Hyper-K

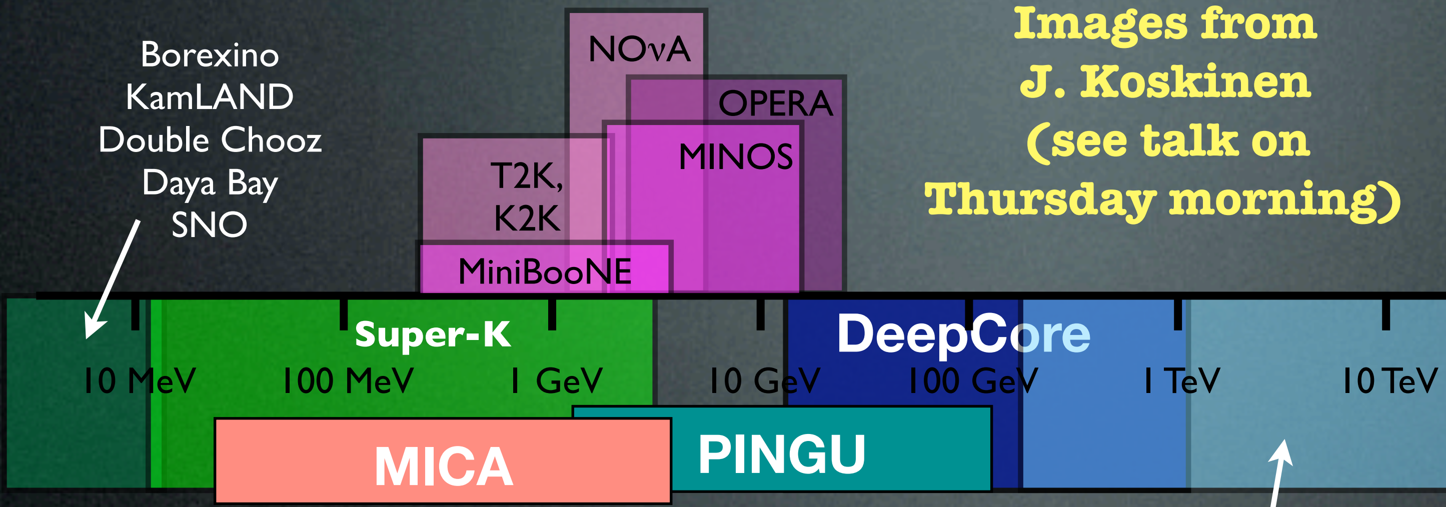


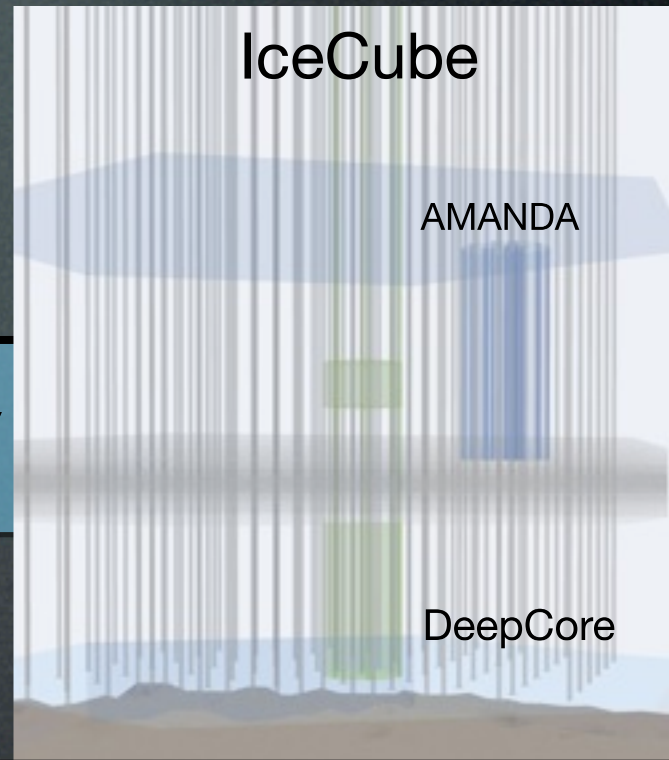


- 0.99 Mton of water (~25 × Super-K fiducial volume)
- Physics goals include proton decay, δ_{CP}, θ_{23} octant, SN-ν, ...
- Same detector design, neutrino beam, backgrounds, etc. as Super-K/T2K
    - Expect similar improvements in performance
- fiTQun has recently been adapted to the Hyper-K software

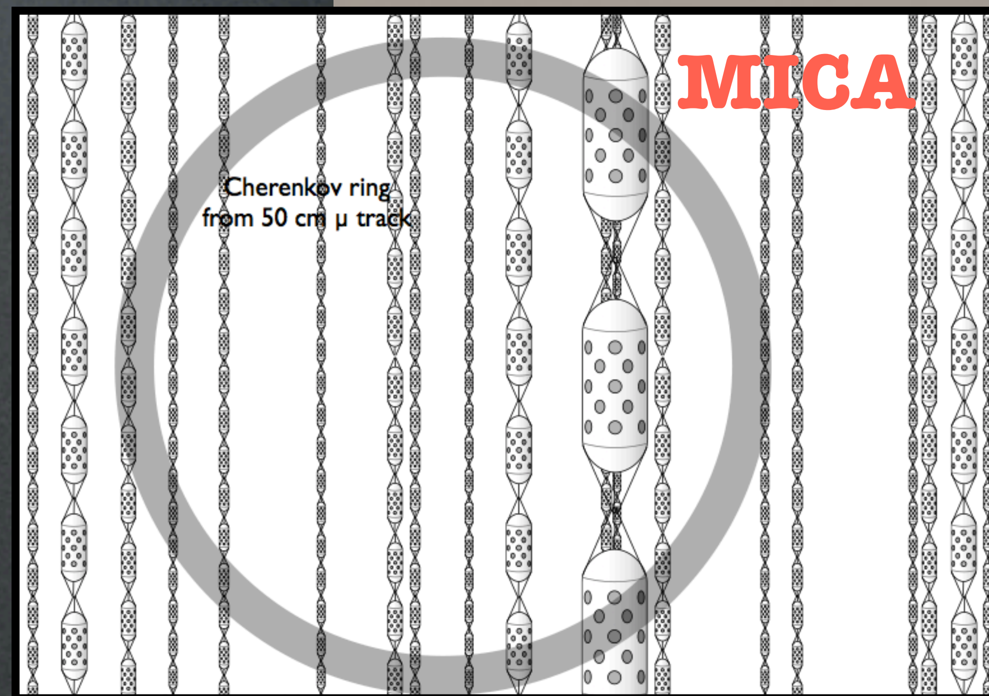
IceCube, DeepCore, Pingu, MICA

Images from J. Koskinen (see talk on Thursday morning)





- There are plans to increase the number of photo-detectors in the ice
  - See talks Thursday morning
- **This is a problem fiTQun is even better suited to solve**
  - Arbitrary phototube locations are naturally accommodated
  - No reflections from tank walls
    - Treatment of non-direct light is greatly simplified
- Proton decay, atmospheric ν, ...

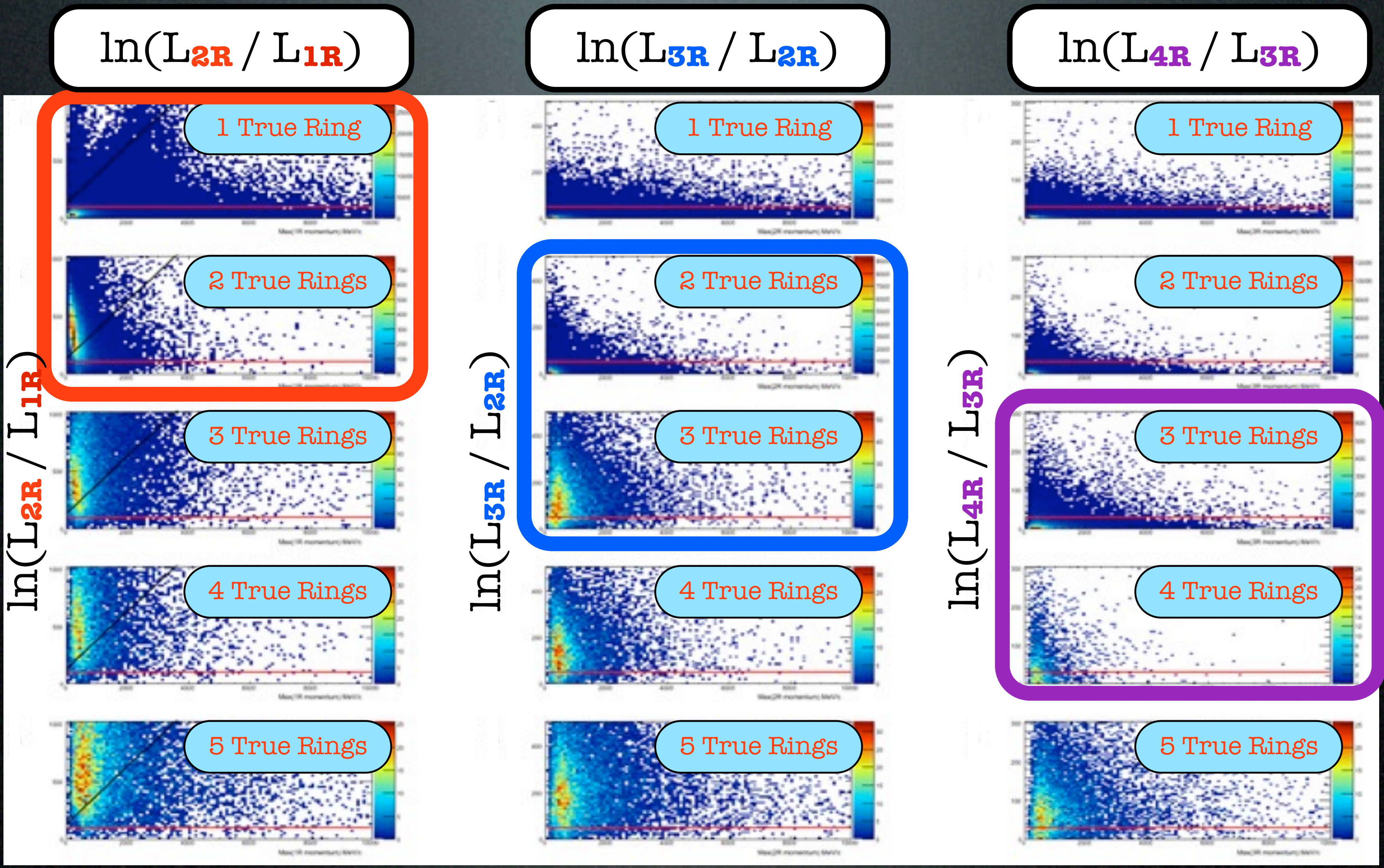


Summary

- fiTQun is a new reconstruction algorithm for large Cherenkov Detectors
- Significant improvements are seen over previously used algorithms
  - Large reductions in poorly understood backgrounds for T2K ν_e appearance and ν_μ disappearance measurements
- fiTQun is beginning to seep into other Super-K analyses
  - Atmospheric neutrinos
  - Proton Decay
- fiTQun can make important contributions to future Cherenkov detectors, such as Hyper-K and PINGU/MICA

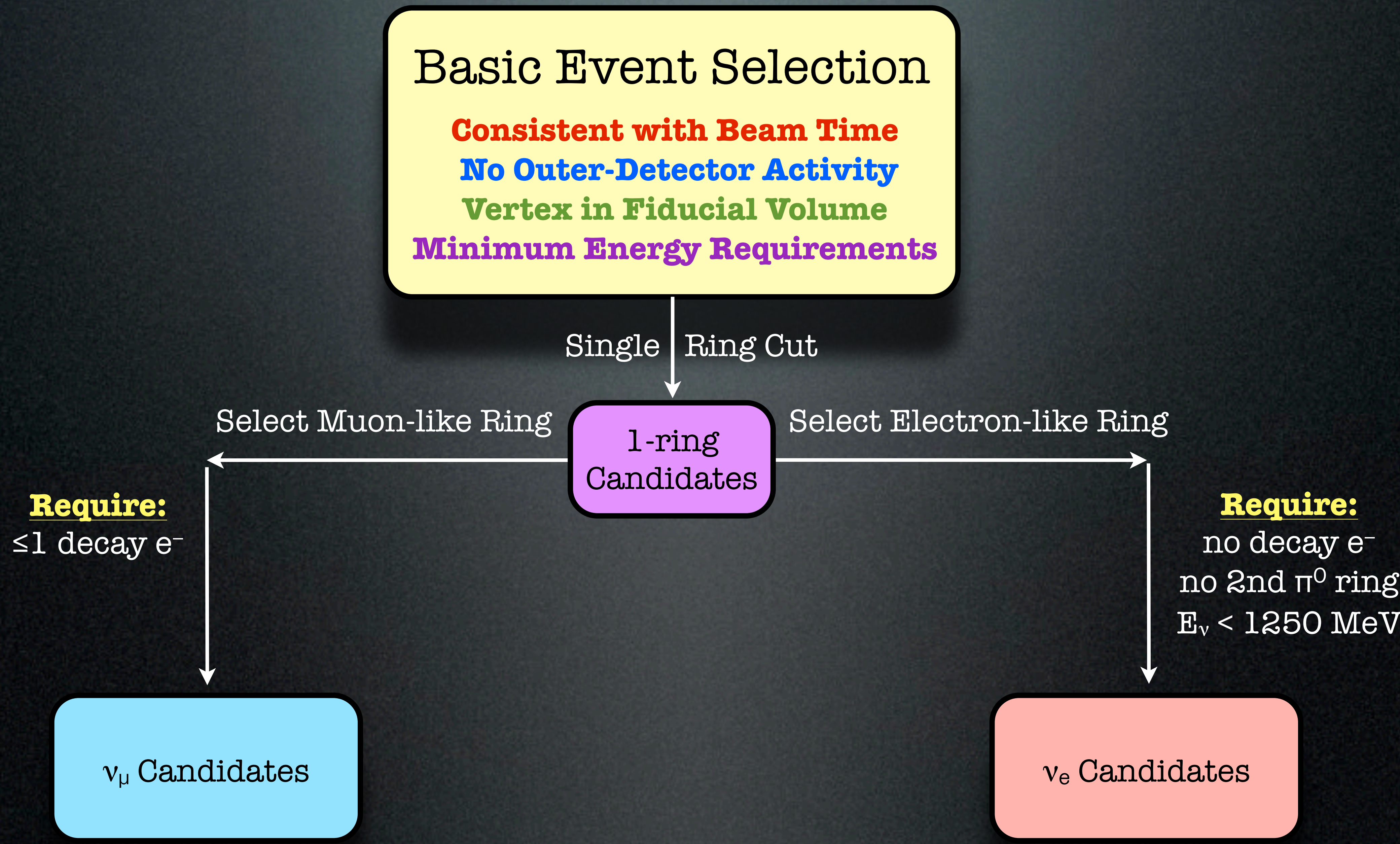
Backups

Ring Counting



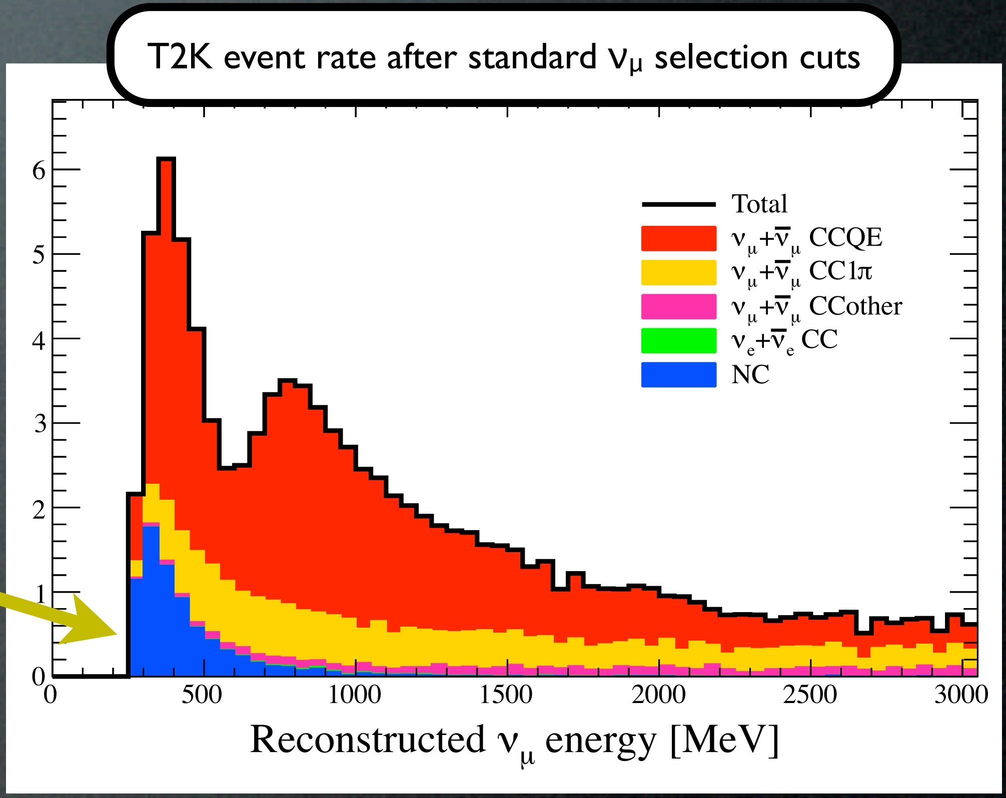
- Good discrimination seen up to ~4 rings

T2K Event Selection



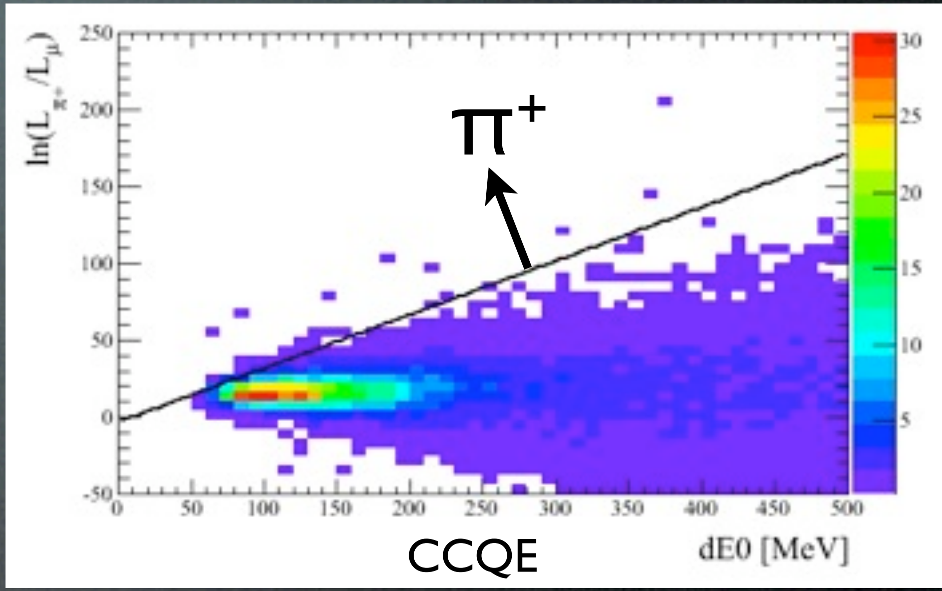
T2K ν_μ Sample

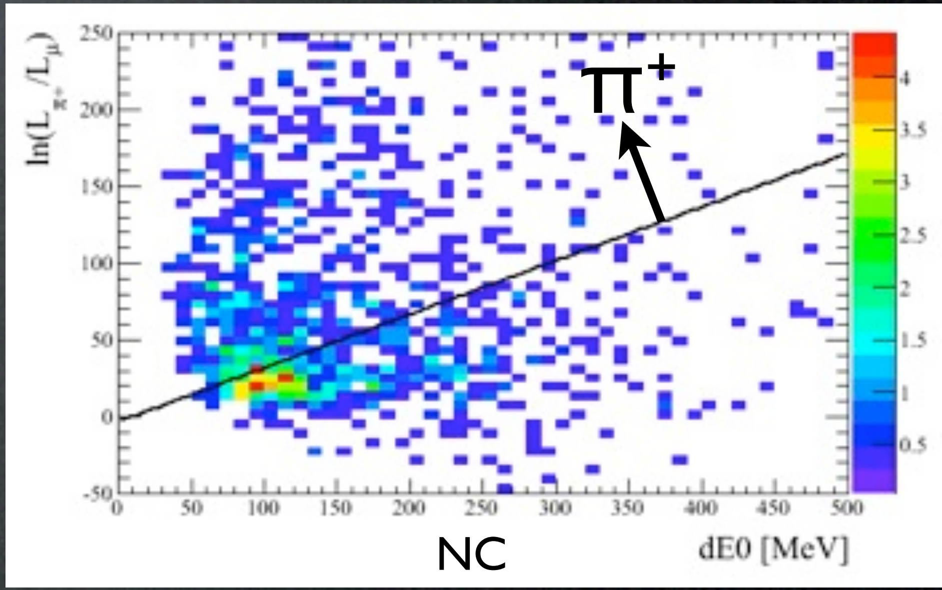
- Large neutral-current (NC) background at low energy
  - Affects the **position (Δm^2)** and **depth ($\sin^2 2\theta$)** of the oscillation dip
  - Uncertainty in Super-K π^+ reconstruction is **very large (> 100% error)**
    - No previous algorithm to reconstruct charged pions
- **fiTQun π^+ rejection** can be very helpful



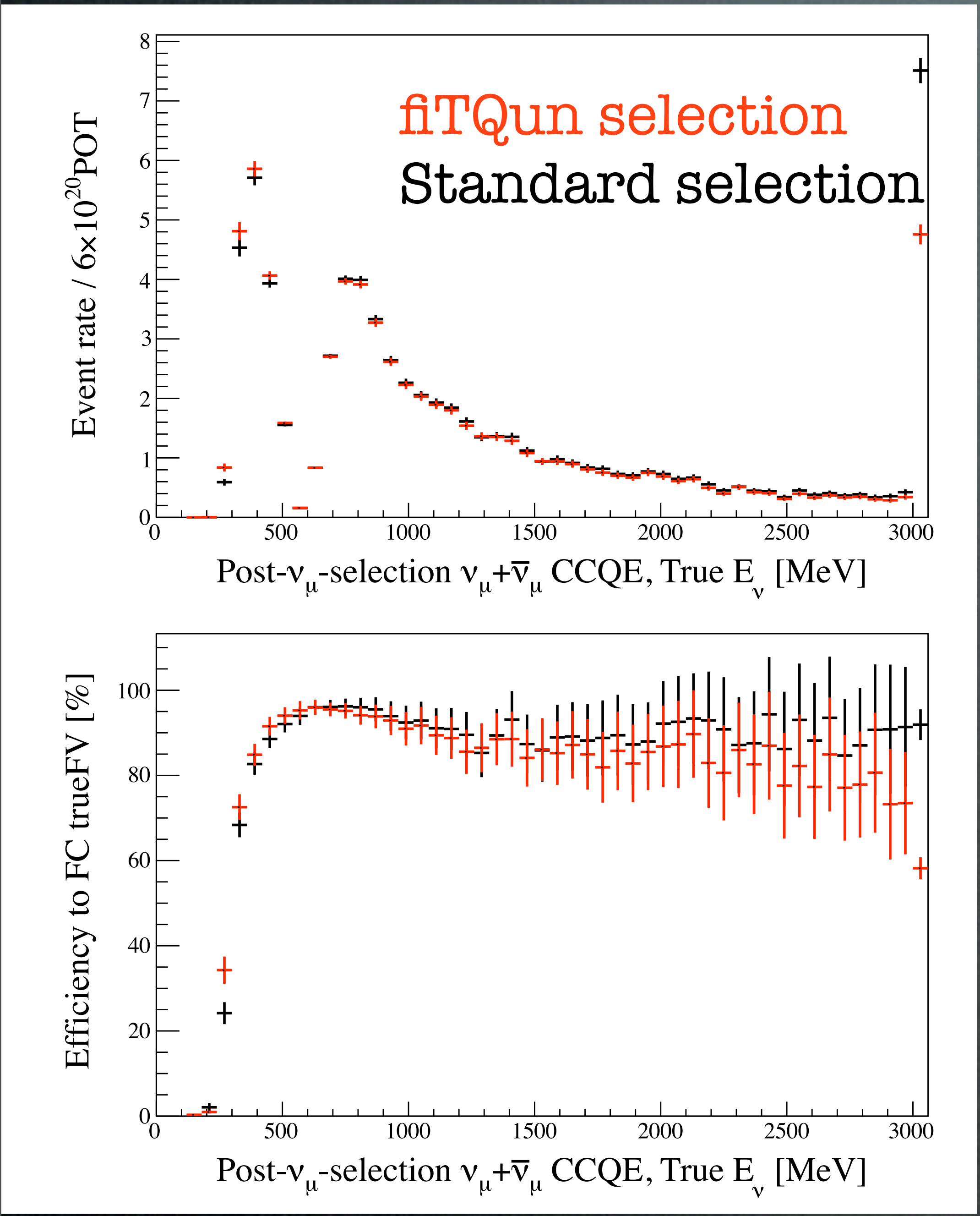
Neutral Current (NC) Rejection

- Use π+/μ likelihood ratio
- CCQE signal looks muon-like
- A large fraction of the NC background lies above the cut line
    - NC background is mostly due to NCπ^+
    - Also a small contribution from NC-proton





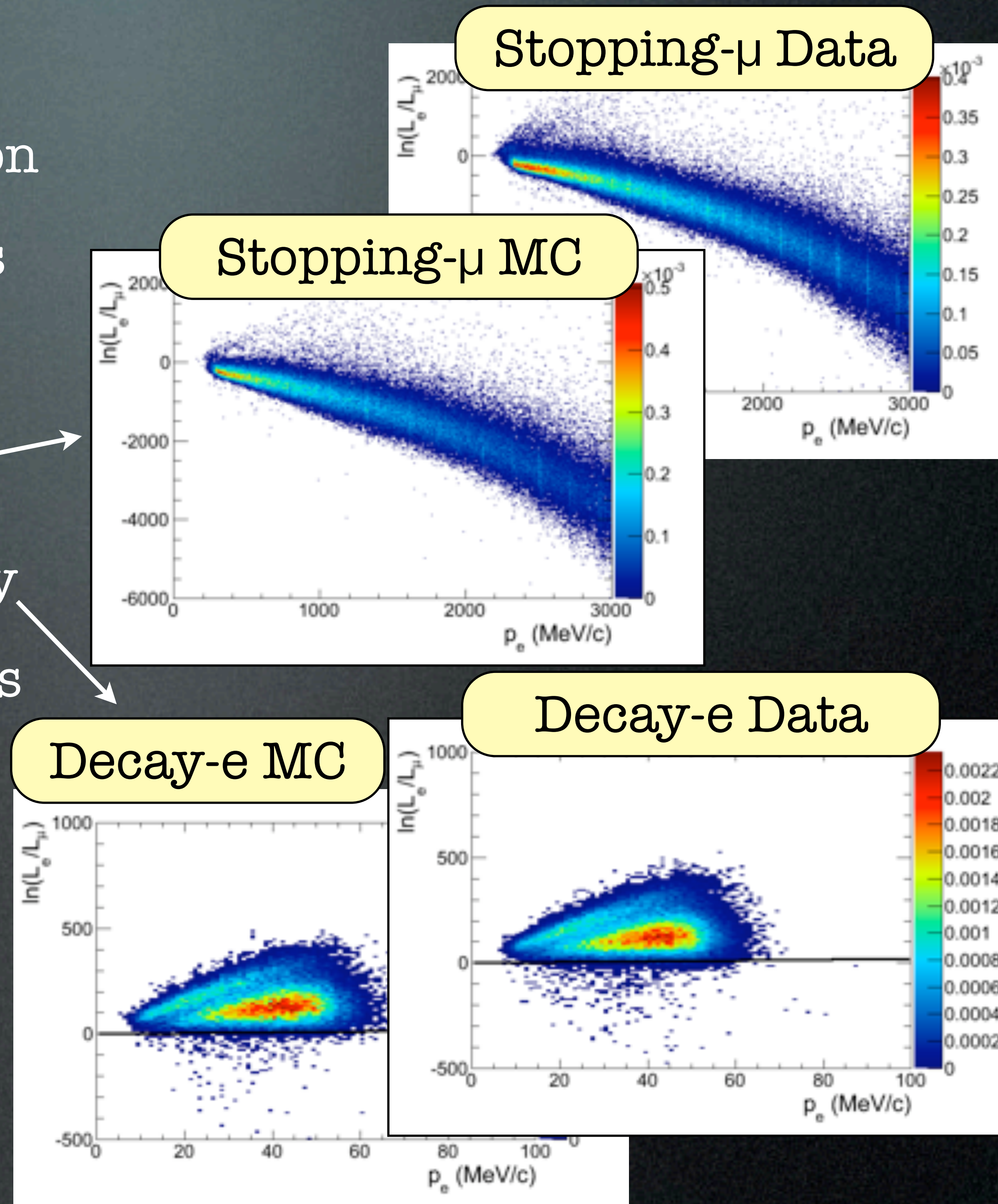
ν_μ Signal Efficiency Comparison



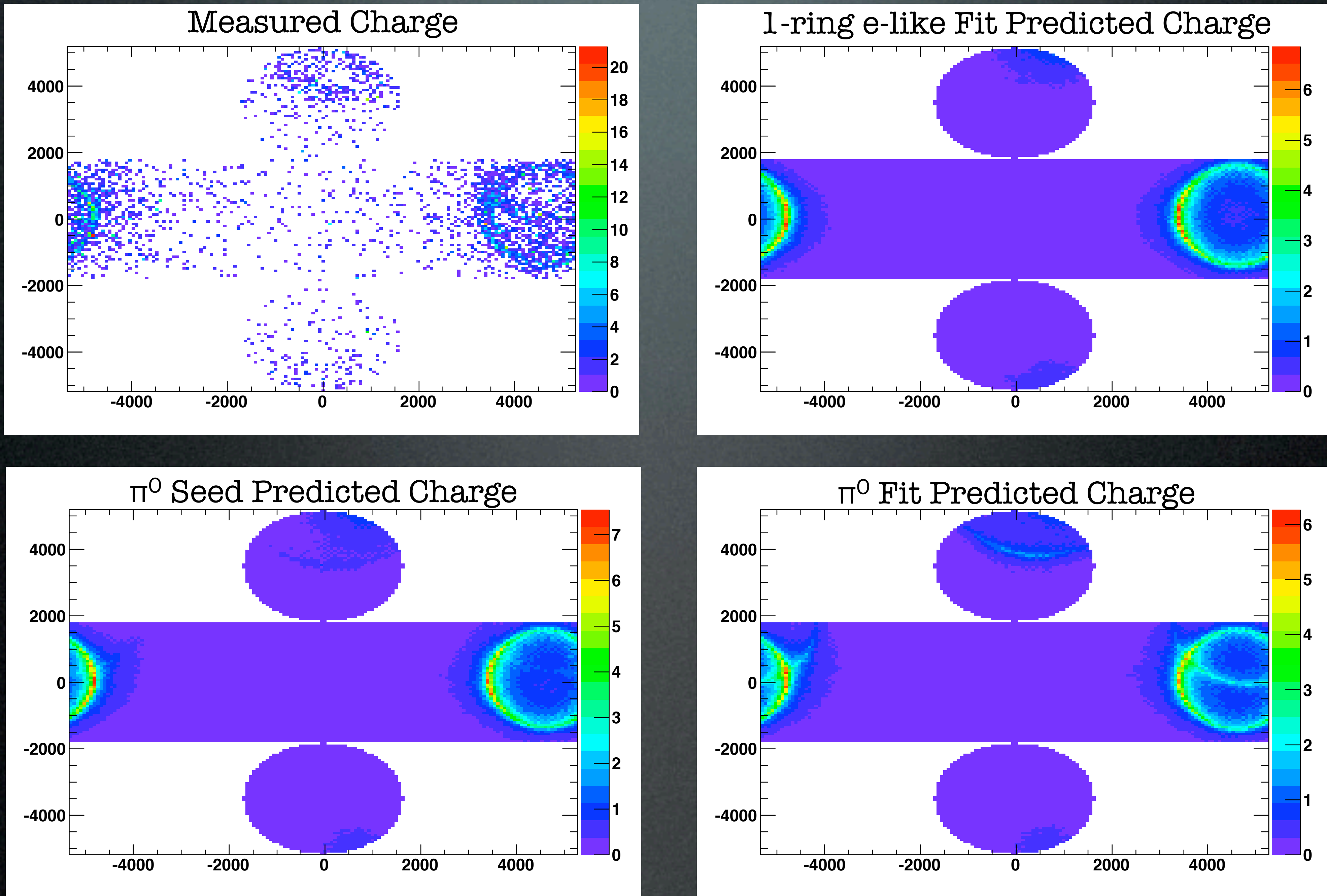
- Around the oscillation dip, fiTQun has higher signal efficiency
- Signal loss by fiTQun selection is mostly in the high-energy tail region (>3GeV)

Data Validations

- We have begun a program for data-based fit validation
- Plan to test fiTQun over as many data samples as possible
  - Stopping cosmics
  - Electrons from μ-decay
  - Atmospheric neutrinos
  - Detector calibration samples
  - Cone generator
  - Calibration sources (e.g. Nickel ball)



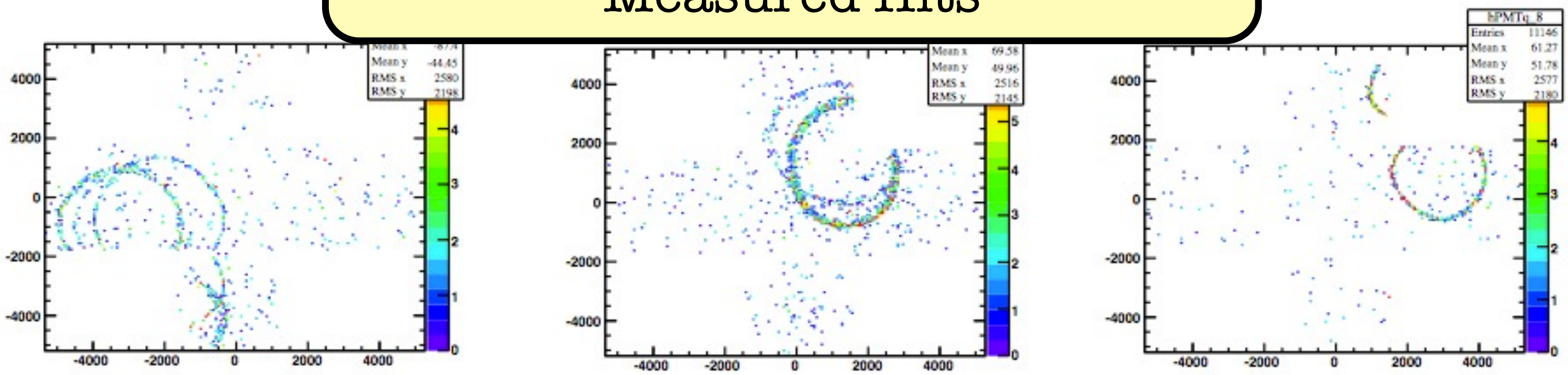
Event Display: π^0 Fit



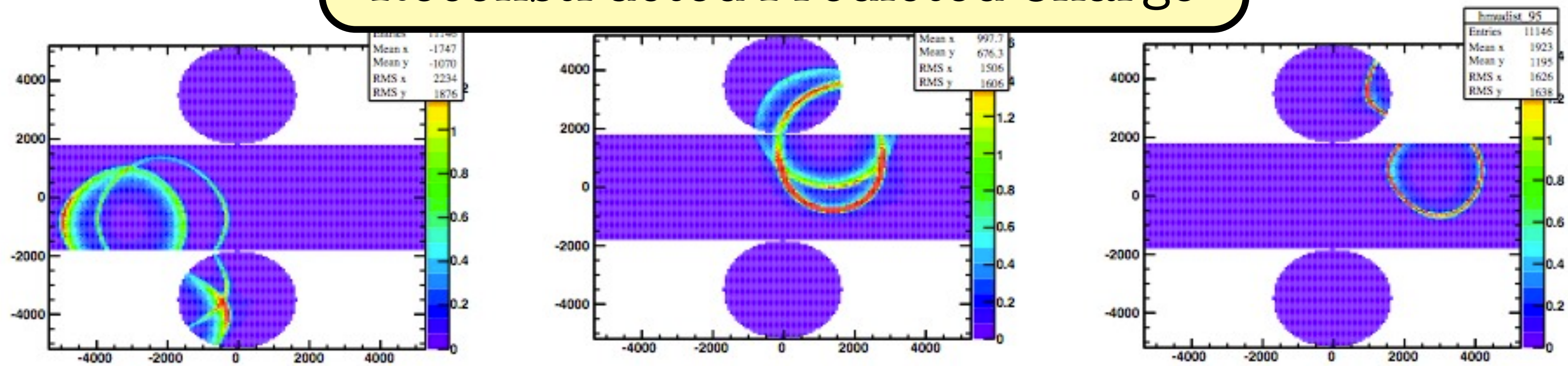
Event Display

Kinked-track π^+ Fitter

Measured Hits



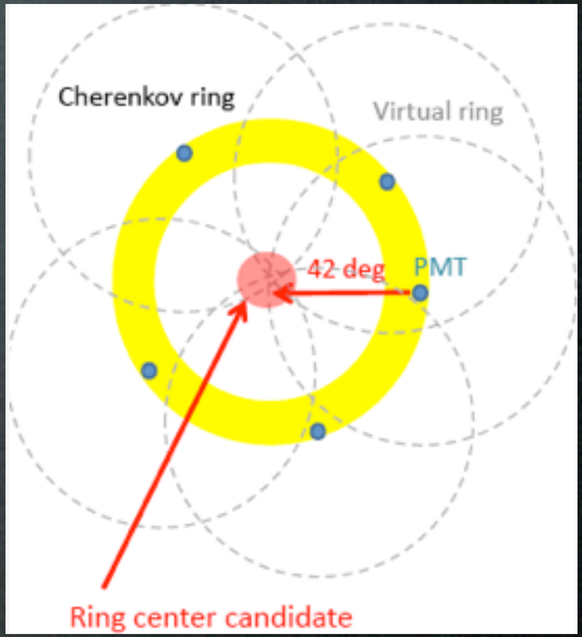
Reconstructed Predicted Charge

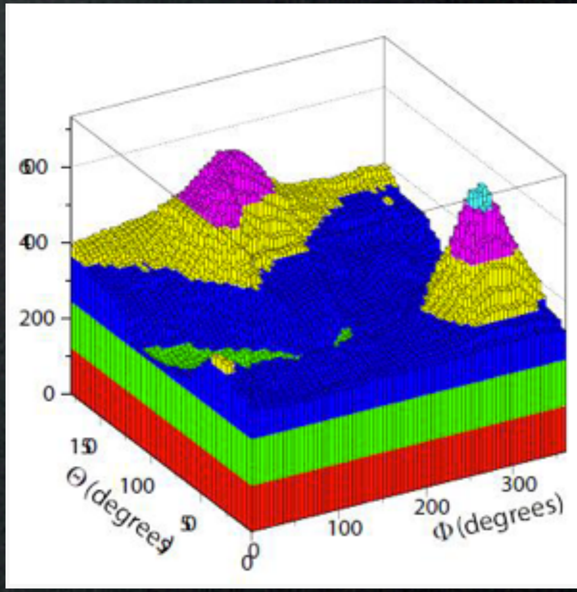


Old Super-K Reconstruction

1. Find the **event vertex** with hit timing information
2. Determine **number & direction** of rings
   - Assume a 42° Cherenkov angle (maximum for water)
   - Use Hough transform to find hits belonging to a common ring
   - Discard dimmer rings if with 15° of another ring
3. Calculate the **particle type for each ring**
   - Use a Gaussian PDF for charge in each PMT based on expected charge pattern
   - Angle can be readjusted to improve fit
4. Sum all charge within 70° cone to **determine the ring momentum**
   - (where rings overlap, try to separate the charge based on expected ring pattern)

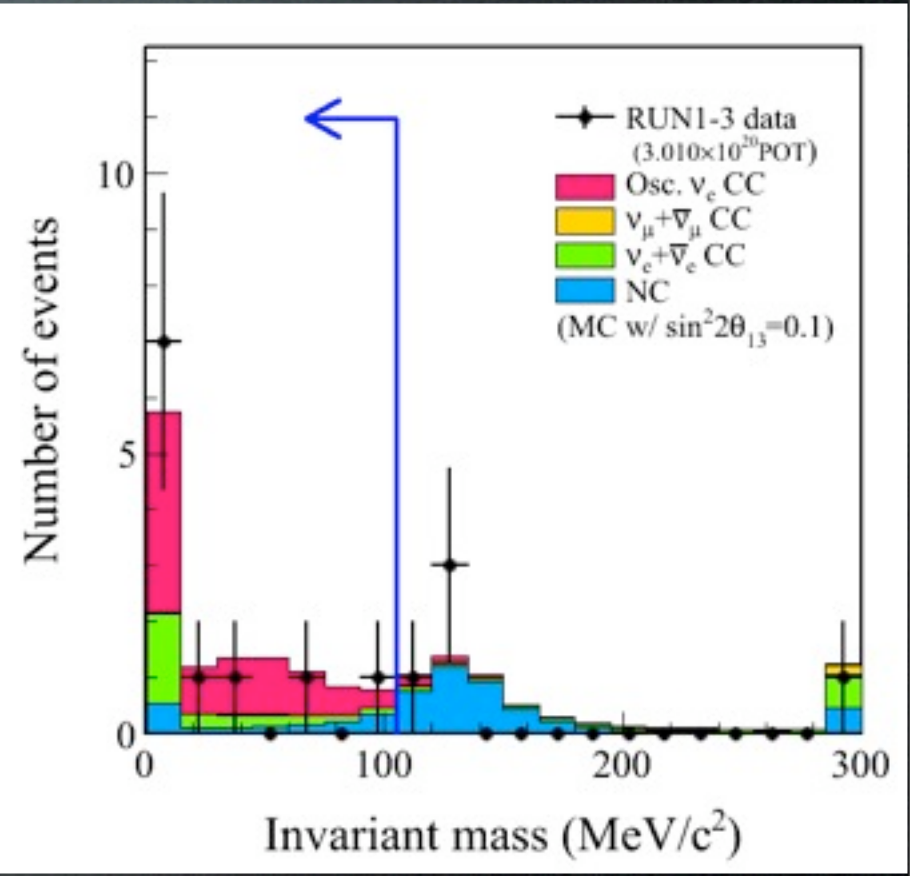
- This is a multi-step fitting procedure (**apfit**)





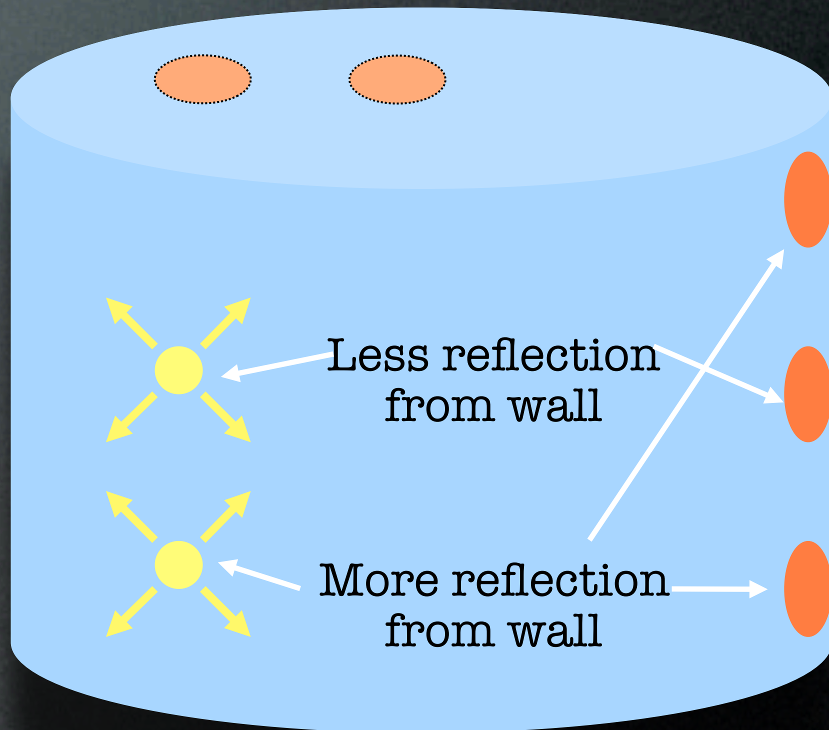
Default π^0 Rejection

- Specialized algorithm is used to **find soft photons**
  - POLFit "Pattern-Of-Light Fit"
  - Finds photons **missed by ring counting** in apfit
- POLFit uses a "fiTQun-esqe" predicted-charge fit method
  - **Several approximations are made**:
    - Coarse scattered-light matrix
    - No photon conversion lengths
    - No reflections
    - No time likelihood
- POLFit **always returns a 2nd photon** momentum and direction
  - Cut on reconstructed invariant mass to remove π^0 background



Scattered Light

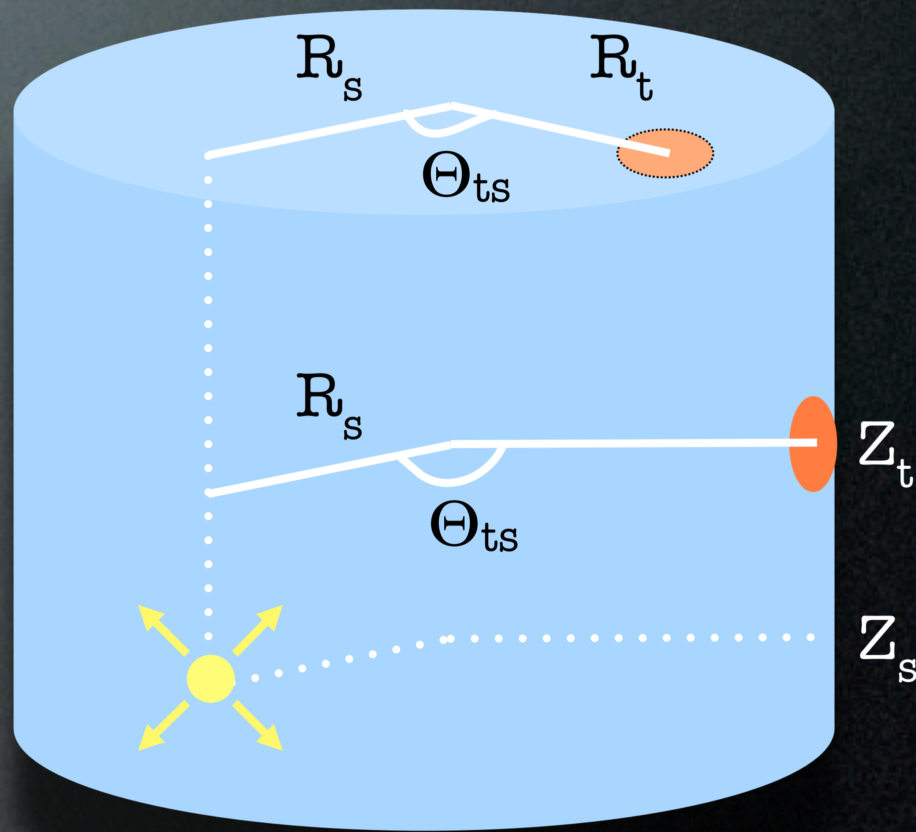
- **More scattered light** is detected for sources that are **close to the wall**
  - The same is true for PMTs near corners
- The scattered light in each PMT depends on:
  - **Light source intensity**
  - **Track direction**
  - **PMT and source geometry**
- Scattered light for each PMT is **normalized to direct light**
  - Accounts for the source intensity
  - Tabulate in advance: **"Scattering Table", A_{scat}**



$$A_{scat}\,(\theta_{source},\ \varphi_{source},\ \text{geometric variables}) \equiv \frac{d\mu^{indirect}}{d\mu^{direct,iso}}$$

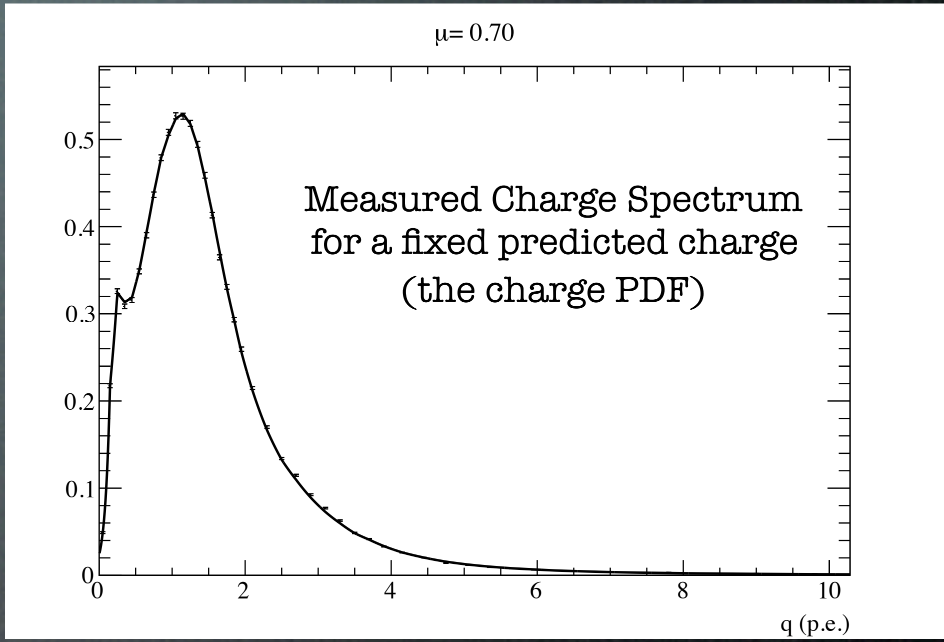
Scattering Tables

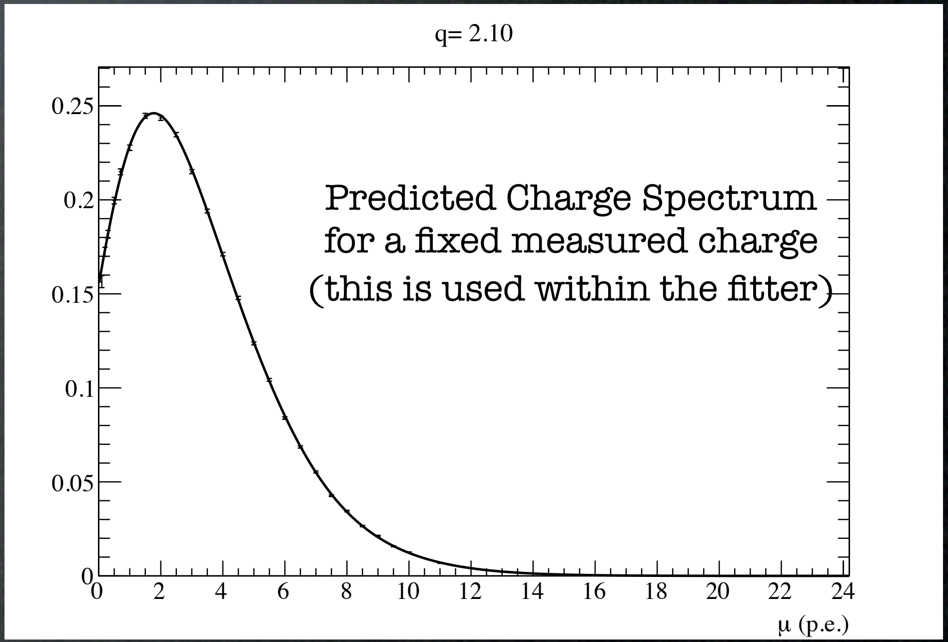
- Take advantage of **cylindrical geometry**
- A_{scat} will depend on
  - Source direction (**θ_s, ϕ_s**)
  - Source position (**Θ_{ts}, R_s, Z_s**)
  - **Z_t** for PMTs on the sides
    - **$A_{side}(\theta_s, \phi_s, \Theta_{ts}, R_s, Z_s, Z_t)$**
  - **R_t** for PMTs on the ends
    - **$A_{end}(\theta_s, \phi_s, \Theta_{ts}, R_s, Z_s, R_t)$**
- Must tabulate 6-dimensional scattering tables using the detector MC



PMT Charge Response

- For a given predicted charge, μ, we need a PDF for the measured charge, q
- Use skdetsim to generate a Poisson distributed charge in each PMT with mean μ
- This gives a 2D histogram of measured charge vs predicted charge
    - Each bin of measured charge is normalized to 1 (to make proper charge PDF)
    - During the fit, charge is fixed (only predicted charge varies)
        - Use distribution of μ at fixed q
- Use smoothed (i.e. fit) curves to improve minimization performance





Time Likelihood

- For every PMT, we have calculated:
  - Predicted charge from direct light
  - Predicted charge from scattered light
- For a predicted amount of direct light, need a PDF for the first hit arrival time
  - Also need a PDF for scattered light first hit time
- For a given particle hypothesis, particle guns are run at many different momenta
  - Hit times (corrected for time of flight) are recorded in bins of predicted charge and momentum
- Give priority to direct light, since it should reach the PMT first
  - $f_t = P(hit_{dir}) * f_{t,dir}(\mu) + (1-P(hit_{dir})) * f_{t,scat}(\mu)$
  - If there is a lot of direct light, the time PDF should default to the direct light time PDF