A New Method for Event Reconstruction in Large Cherenkov Detectors

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NNN Conference

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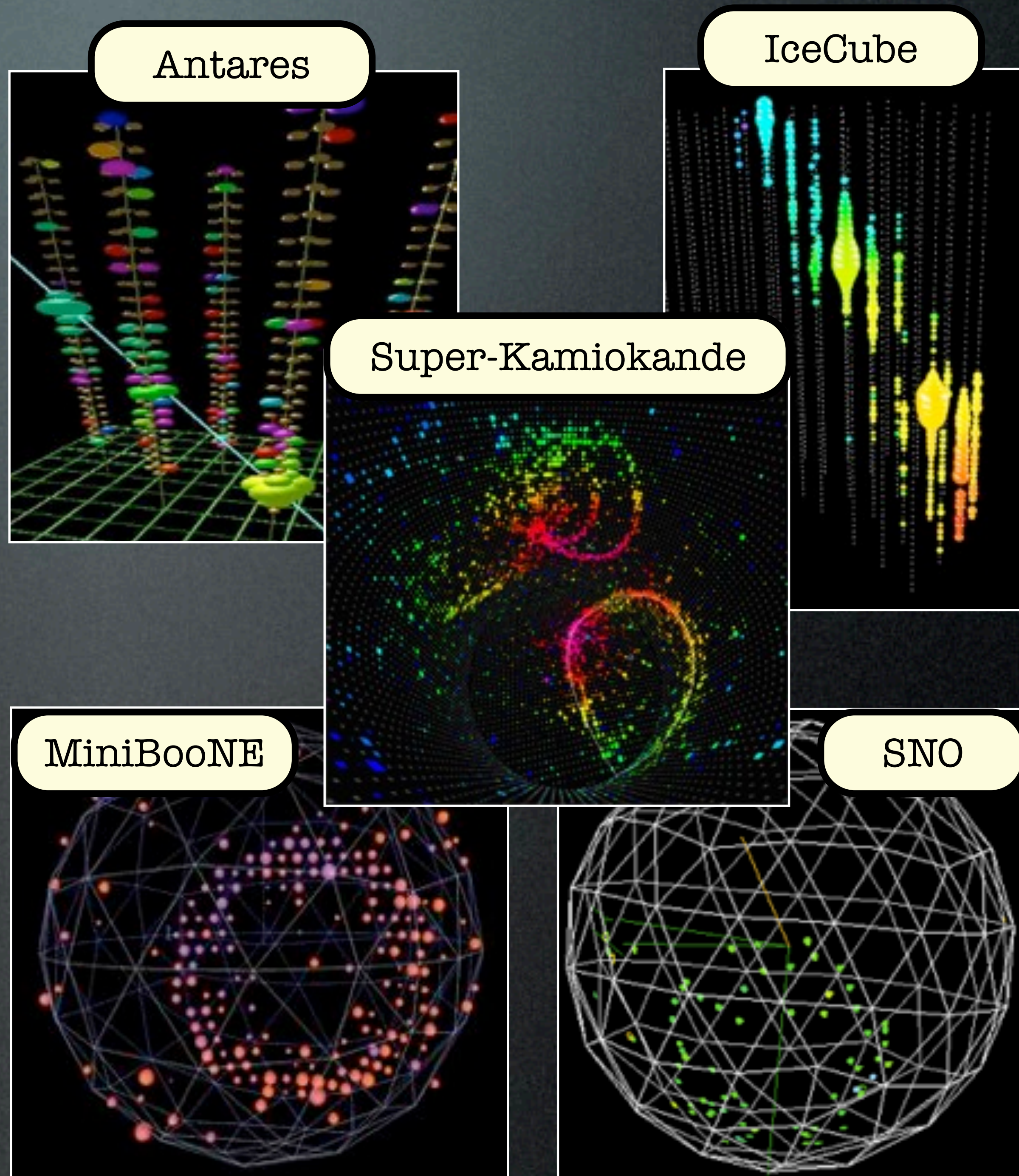
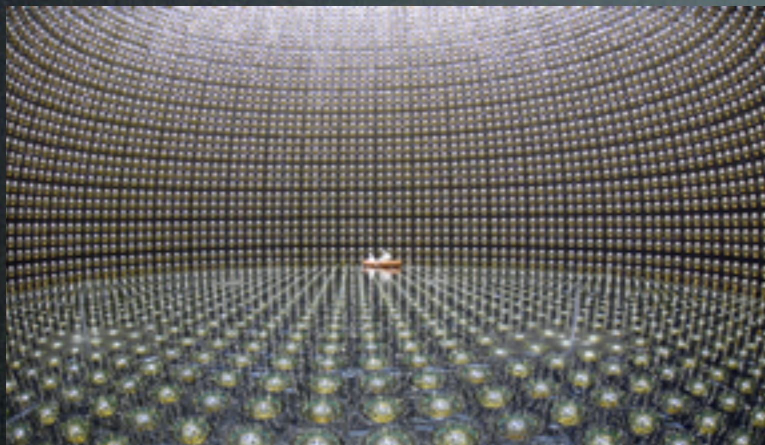
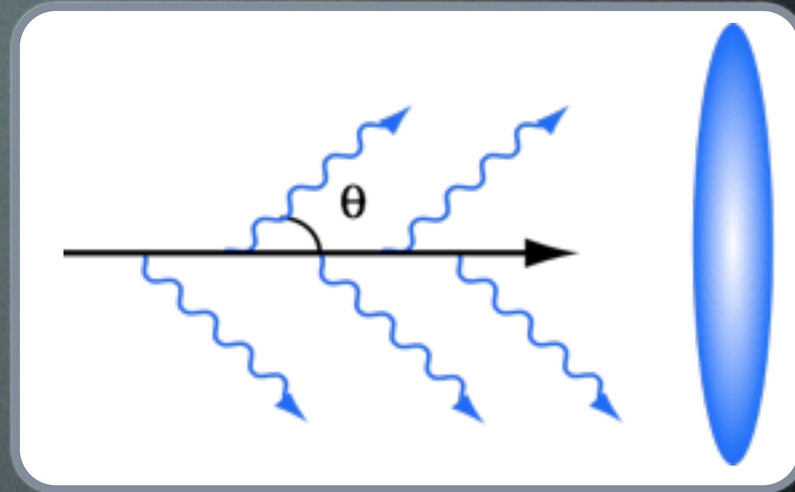
Physics Applications

- Search for proton decay
- Neutrino physics
  - Solar neutrinos
  - Atmospheric neutrinos
  - Accelerator neutrinos
- Supernova neutrinos
- High-energy astrophysical neutrinos
- Indirect dark matter
- ...
- Broad physics reach
  - Much to be gained from better utilizing this technology

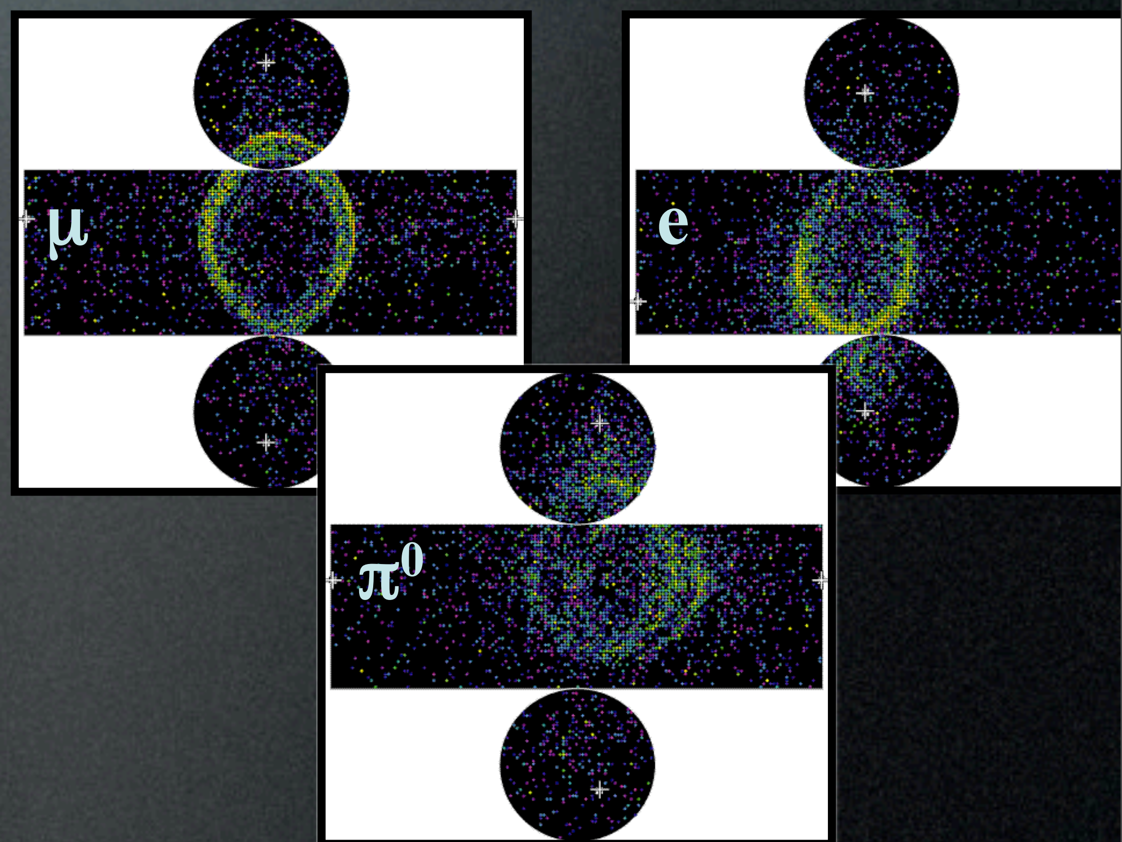


The Super-K Detector





- 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 ($\pi^0 \rightarrow 2\gamma$)
  - 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.)

The Likelihood Fit

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

Time PDF

Charge PDF

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Calculating μ is the main challenge

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)

Predicted Charge (μ)

Particle Track

Predicted Charge (μ)

Predicted Charge (μ)

μ = amount of charge seen by a PMT

Predicted Charge (μ)

$$\mu =$$

μ = amount of charge seen by a PMT

Predicted Charge (μ)

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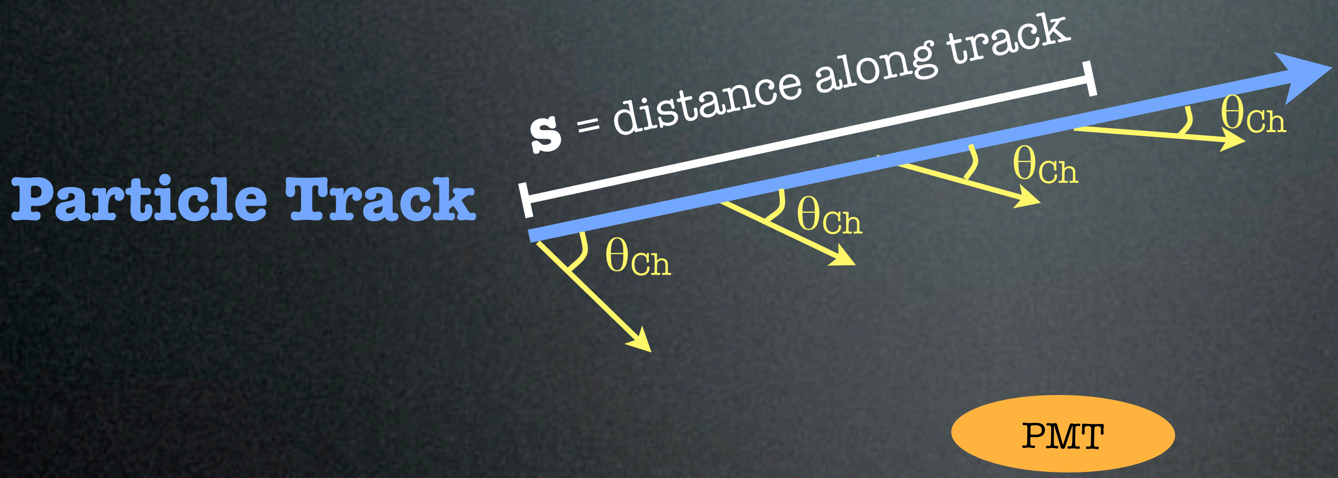
Predicted Charge (μ)

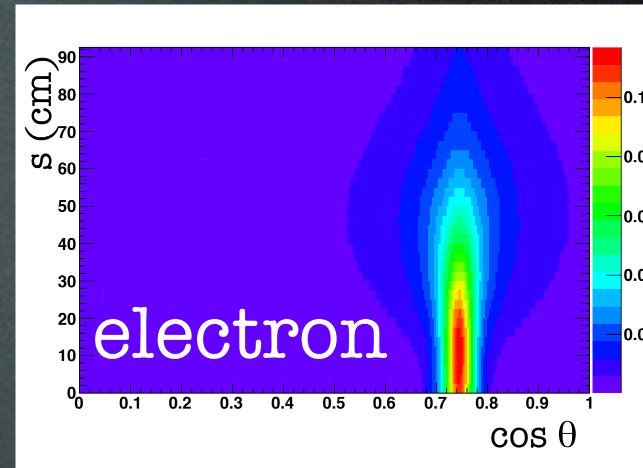
$\mu =$

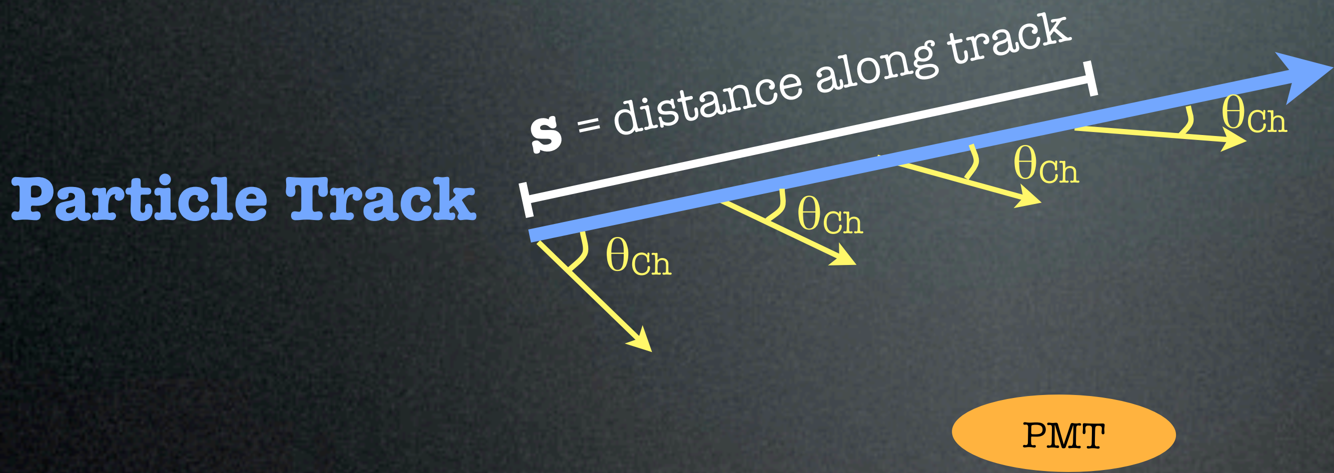


Predicted Charge (μ)

$$\mu = g(s, cos\theta)$$

Cherenkov light emission profile





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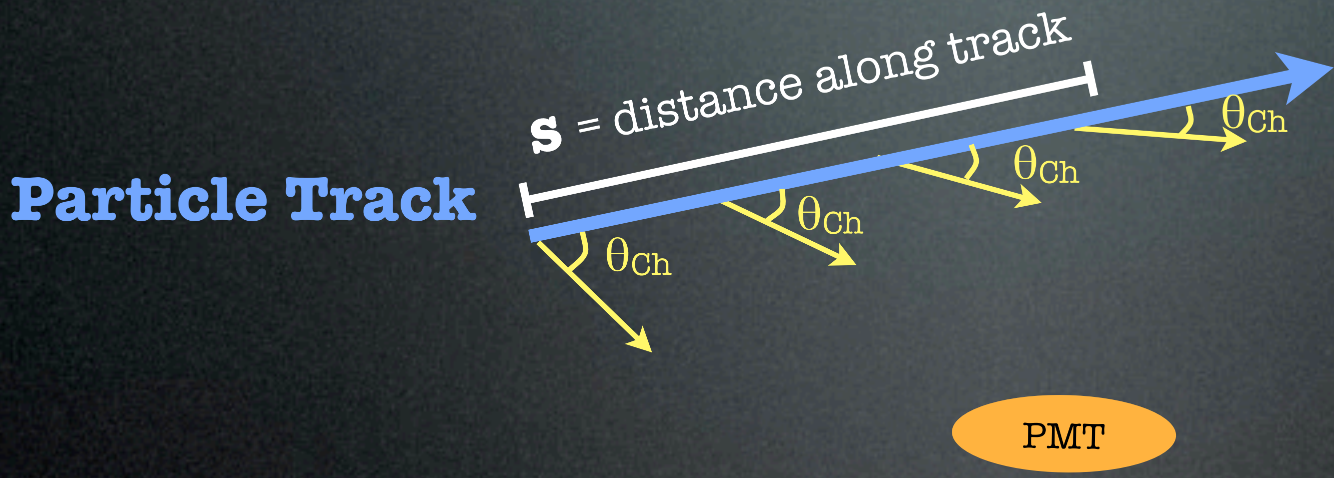

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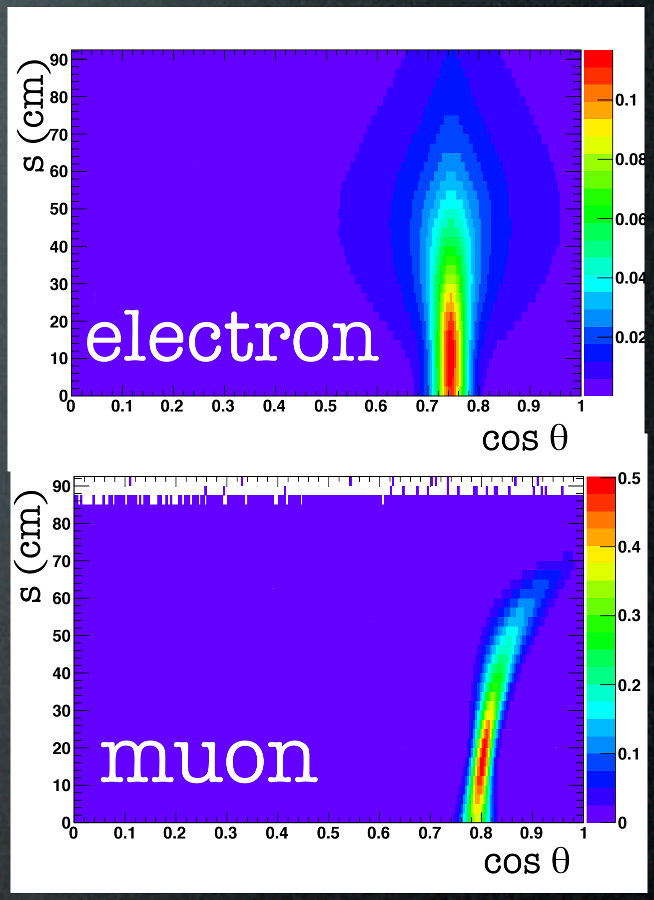

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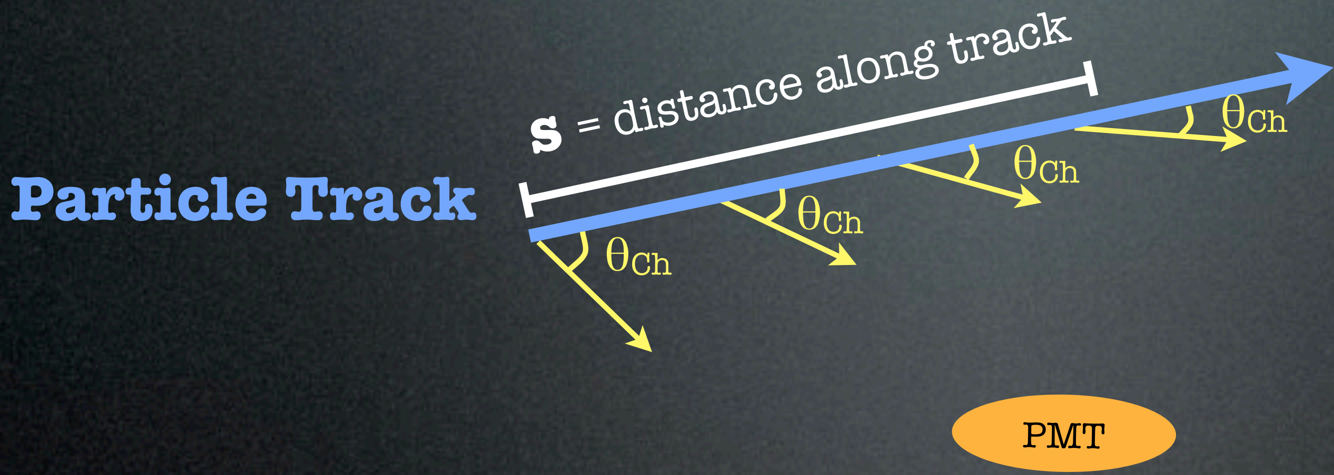

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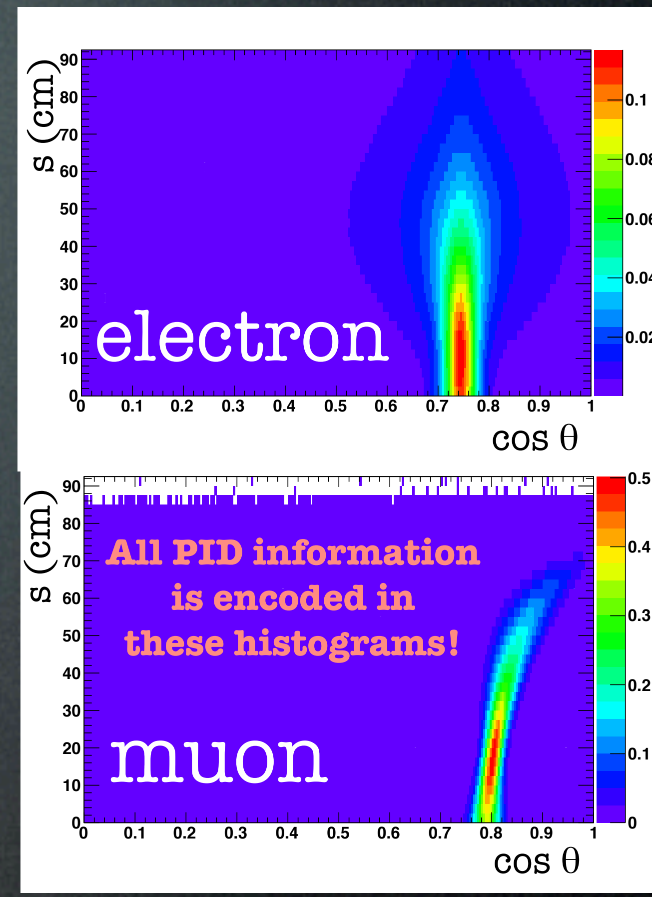
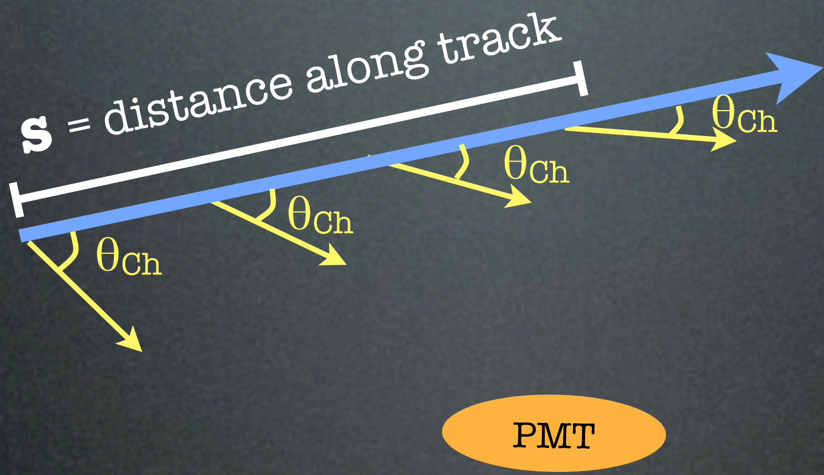


Predicted Charge (μ)

$$\mu = g(s, cos\theta)$$

Particle Track
($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p)



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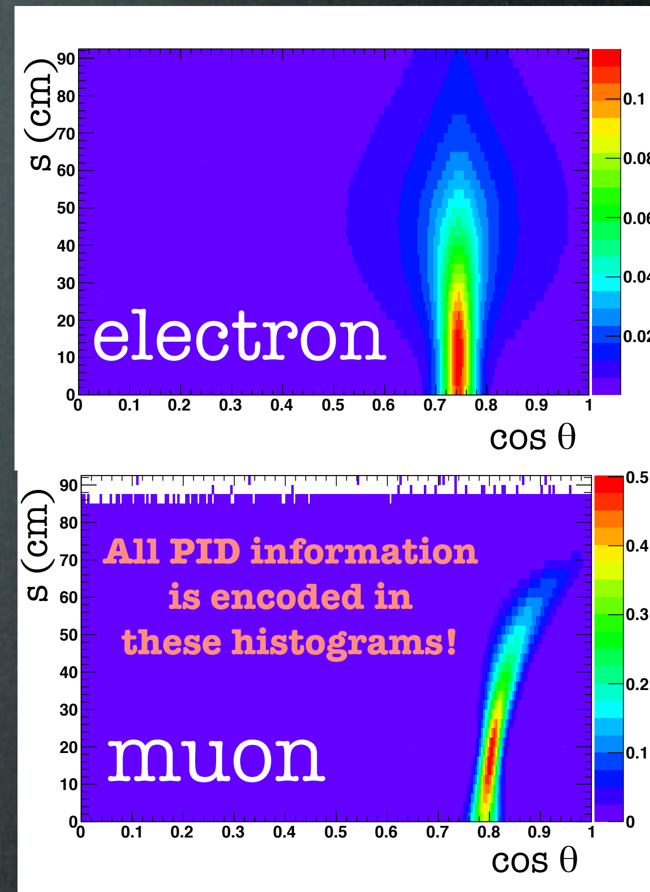

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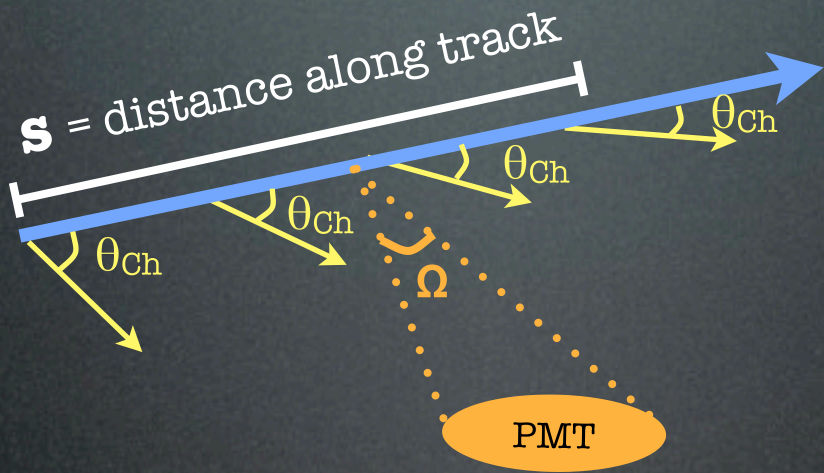

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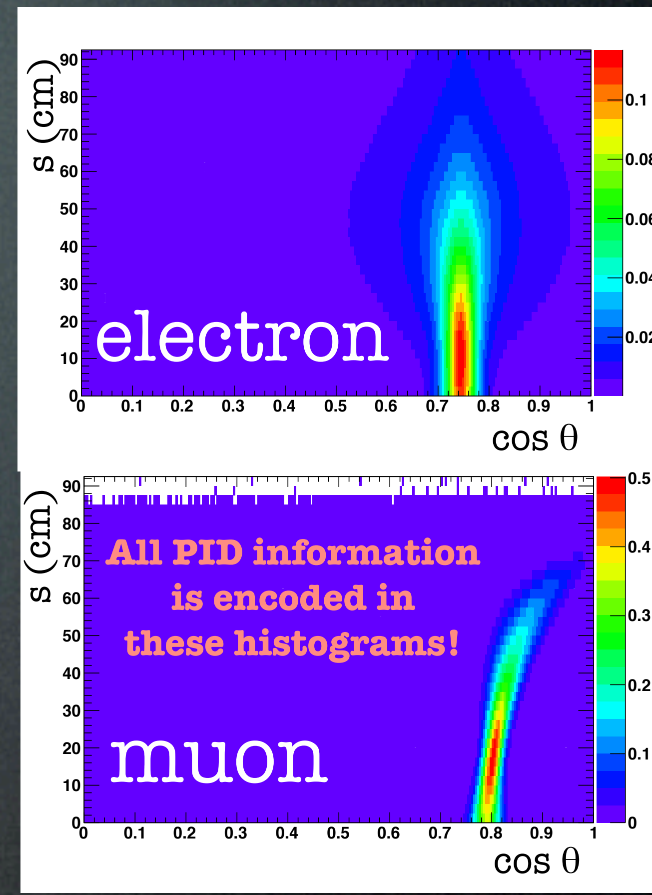

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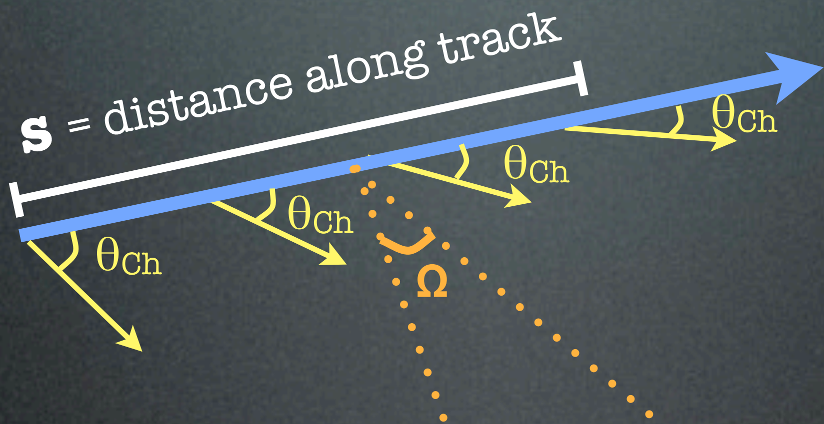

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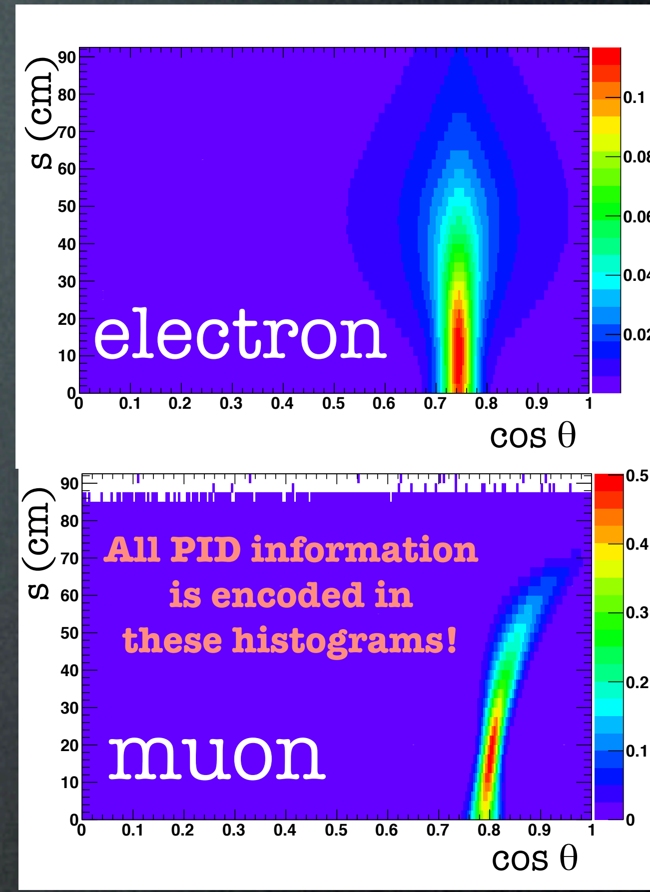
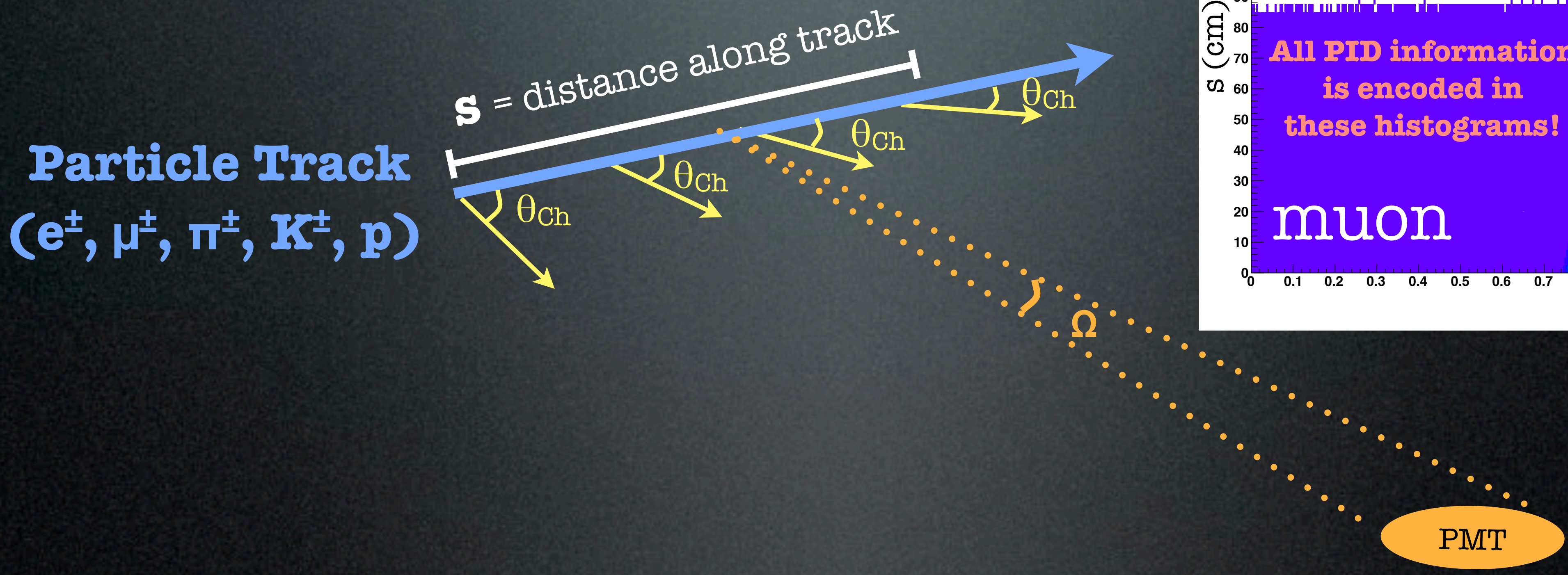


Predicted Charge (μ)

$$\mu = g(s, cos\theta)\Omega(R)$$

PMT solid angle



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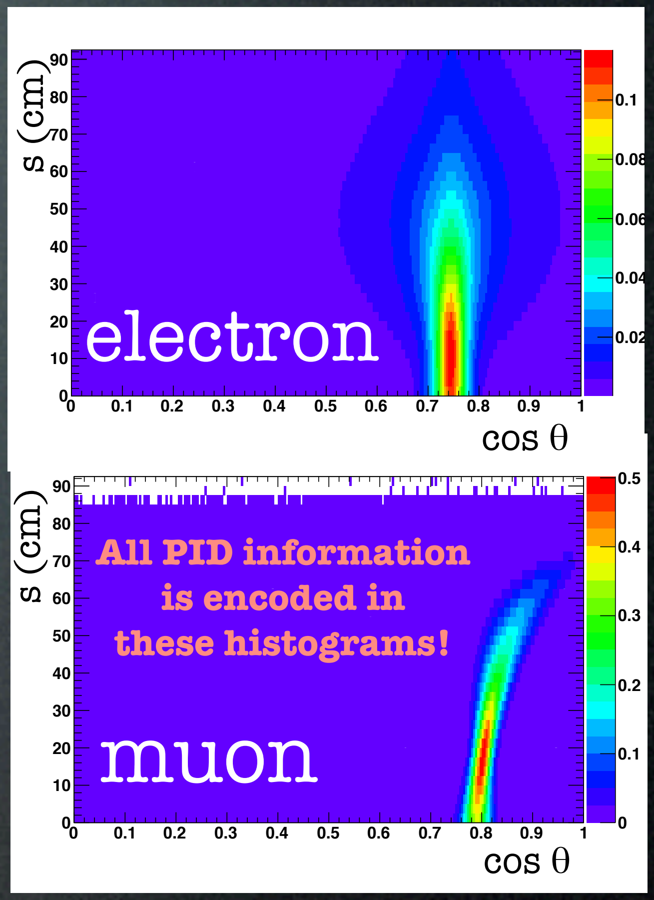

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PMT
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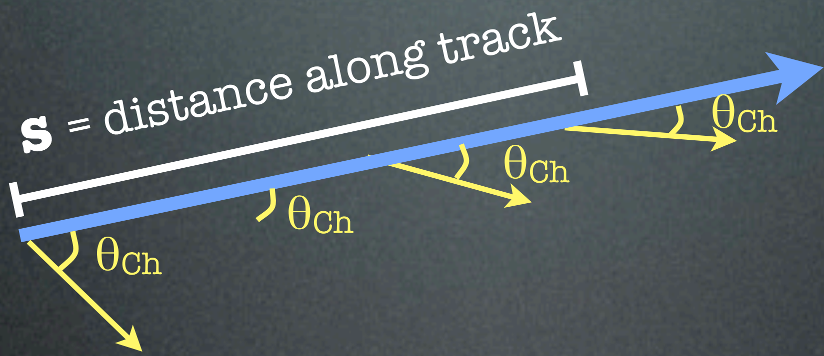
Particle Track
($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p)



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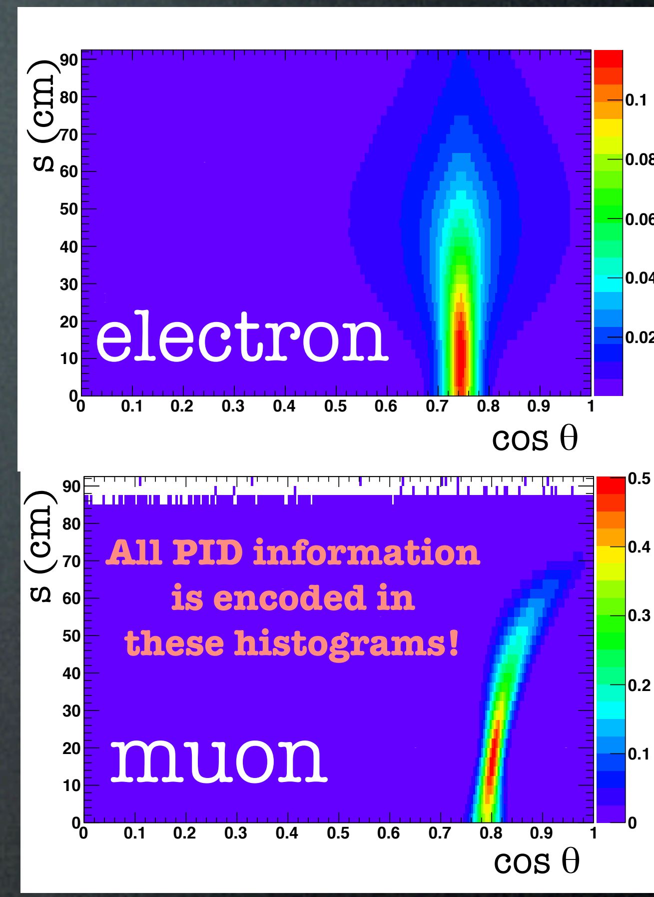
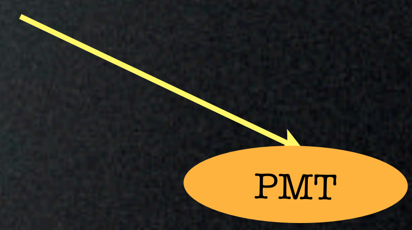




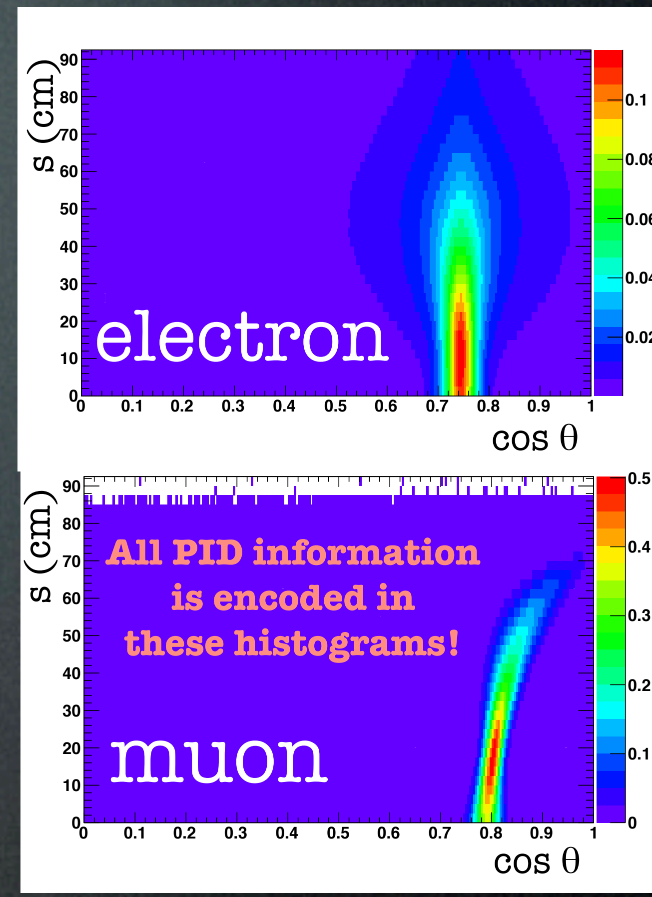
Predicted Charge (μ)

$$\mu = g(s, cos\theta)\Omega(R)T(R)$$

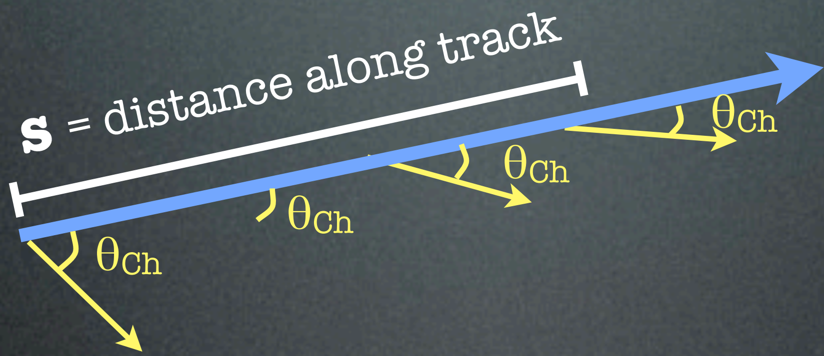
PMT solid angle

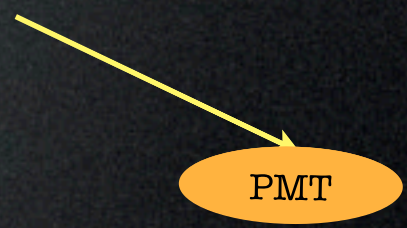
Water attenuation

Cherenkov light emission profile



Particle Track
($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p)



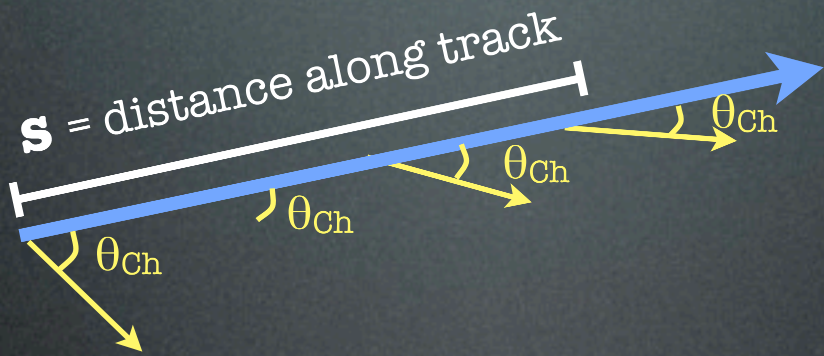


Predicted Charge (μ)

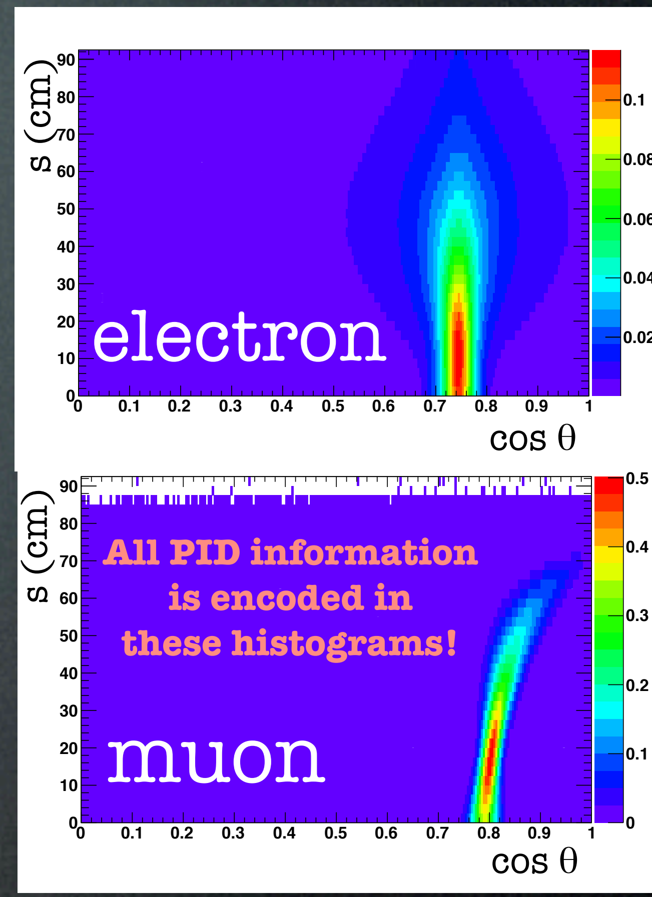
$$\mu = g(s, cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

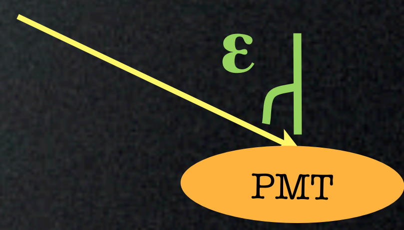
- $\Omega(R)$: PMT solid angle
- $T(R)$: Water attenuation
- $\epsilon(\eta)$: PMT angular response

Particle Track
($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p)



Cherenkov light emission profile



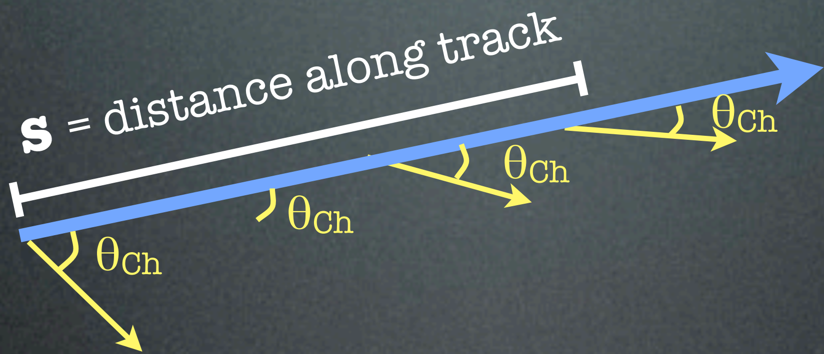


Predicted Charge (μ)

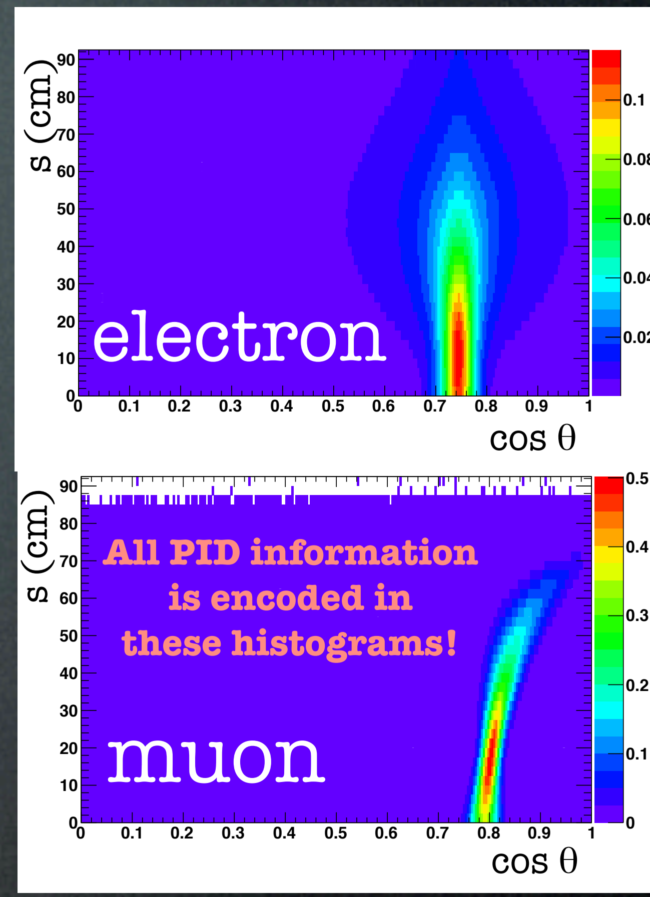
$$\mu = \int ds\, g(s, cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

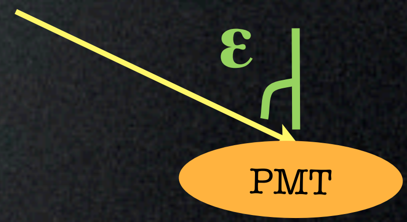
- Integral over track length
- PMT solid angle
- Water attenuation
- PMT angular response

Particle Track
($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p)



Cherenkov light emission profile



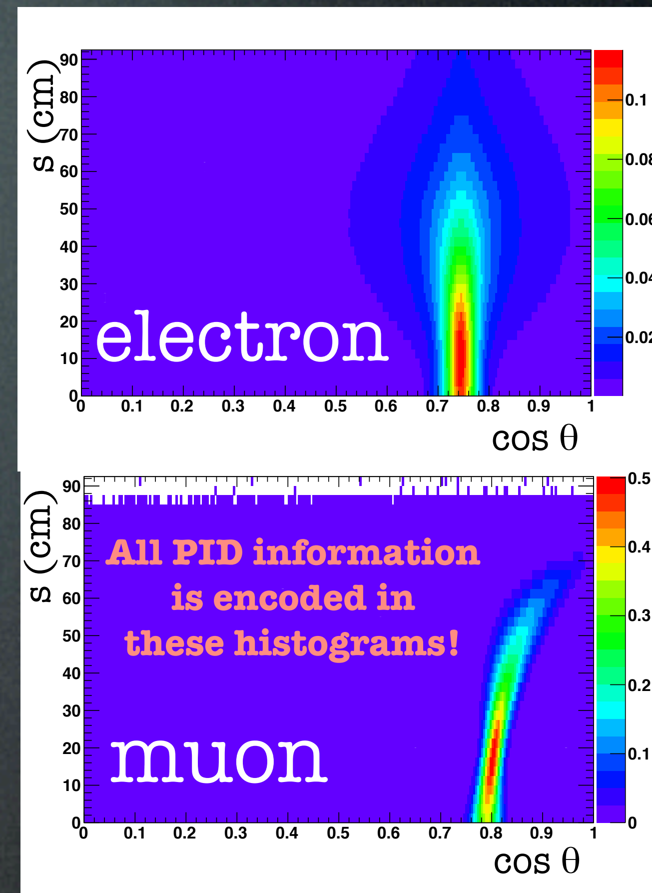


Predicted Charge (μ)

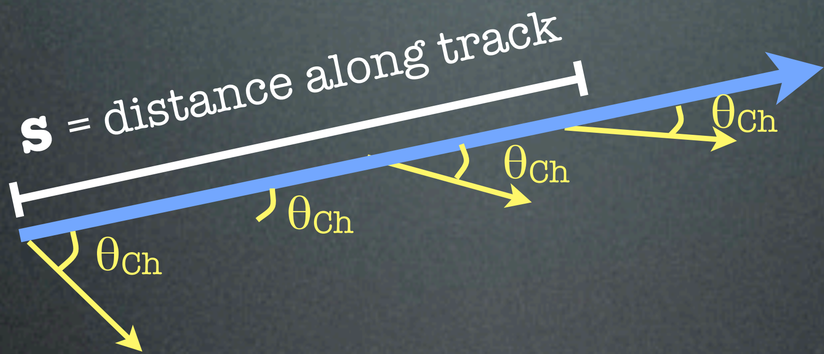
$$\mu = \Phi(p)\int ds\ g(s, cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

- $\Phi(p)$: Light Yield (normalization)
- $\int ds$: Integral over track length
- $g(s, cos\theta)$: Cherenkov light emission profile
- $\Omega(R)$: PMT solid angle
- $T(R)$: Water attenuation
- $\epsilon(\eta)$: PMT angular response

Cherenkov light emission profile



Particle Track
(e±, μ±, π±, K±, p)



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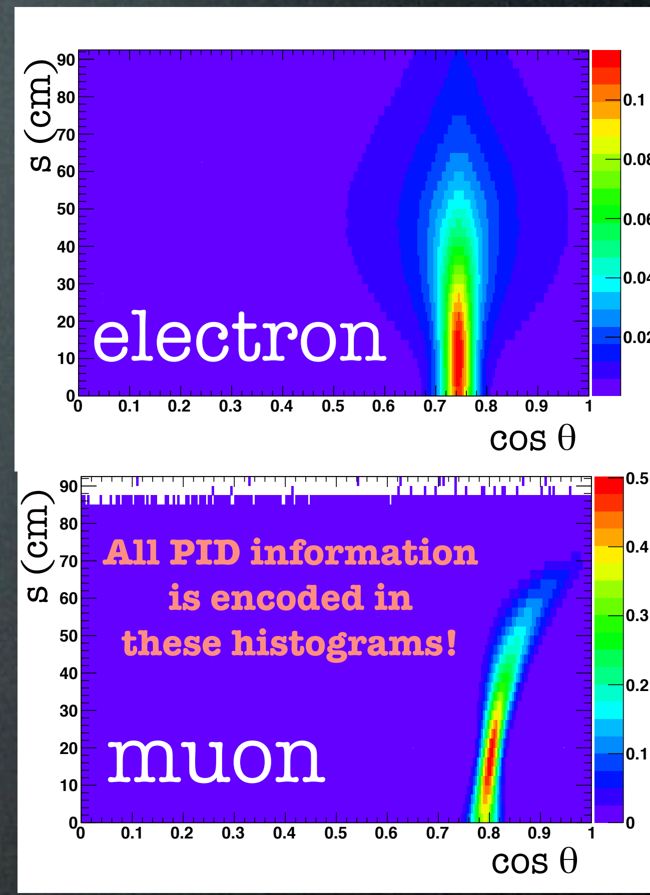
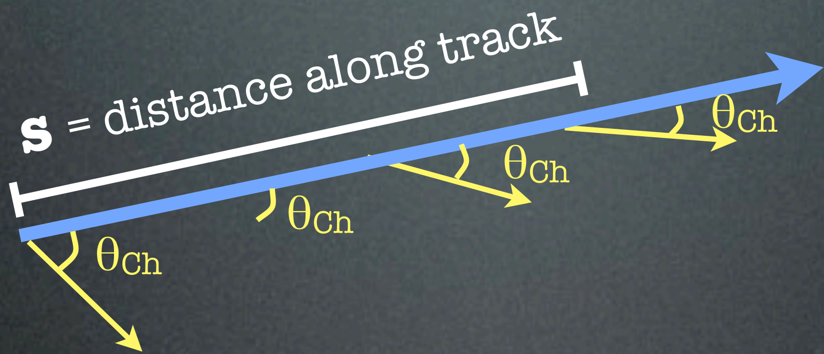
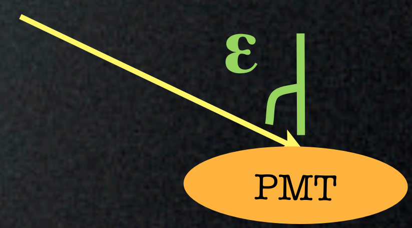
Cherenkov light emission profile



Particle Track ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p)





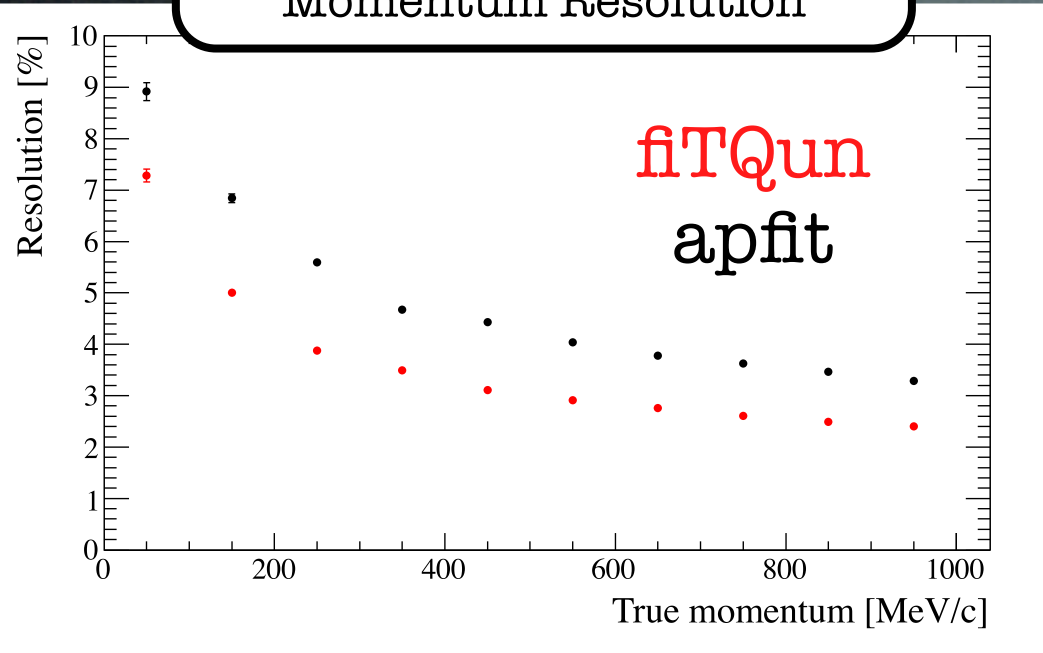
- For multi-particle states, predicted charges are summed
- Scattered and reflected light is treated separately (and more crudely: tabulation)

One-Track Fit Performance

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

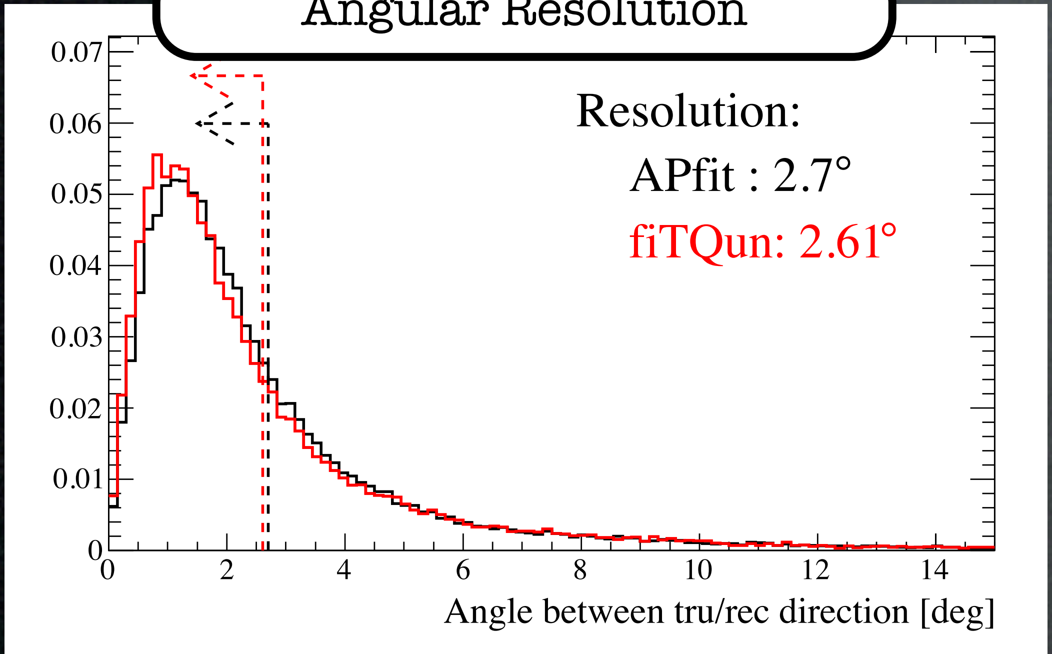
Electrons

Momentum Resolution

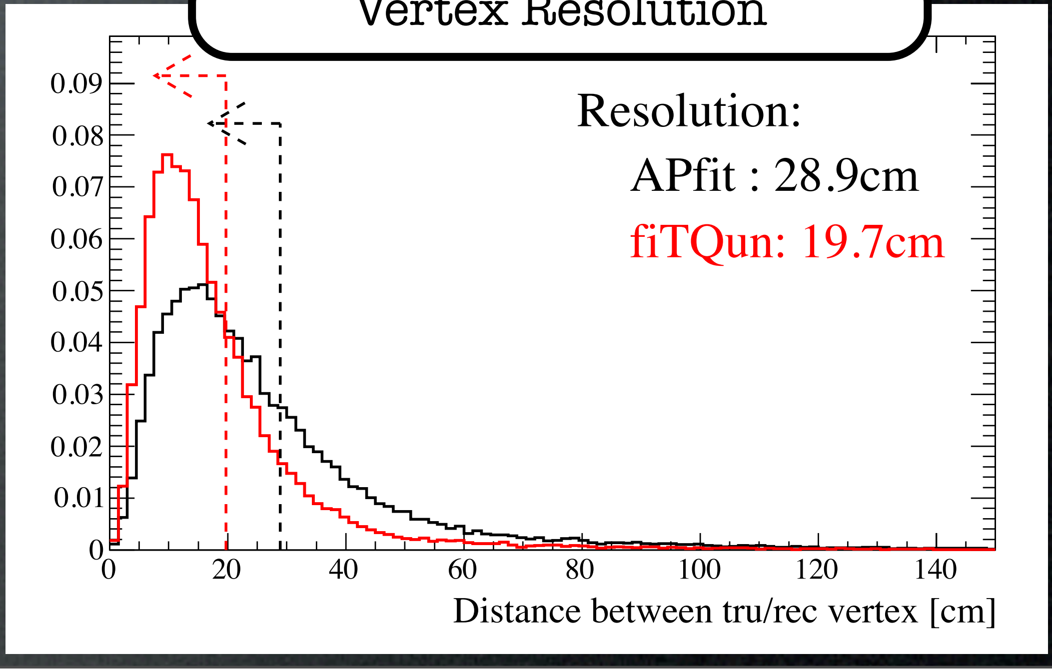


- Tested on a uniform distribution of e⁻ between 0 and 1 GeV/c
  - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution

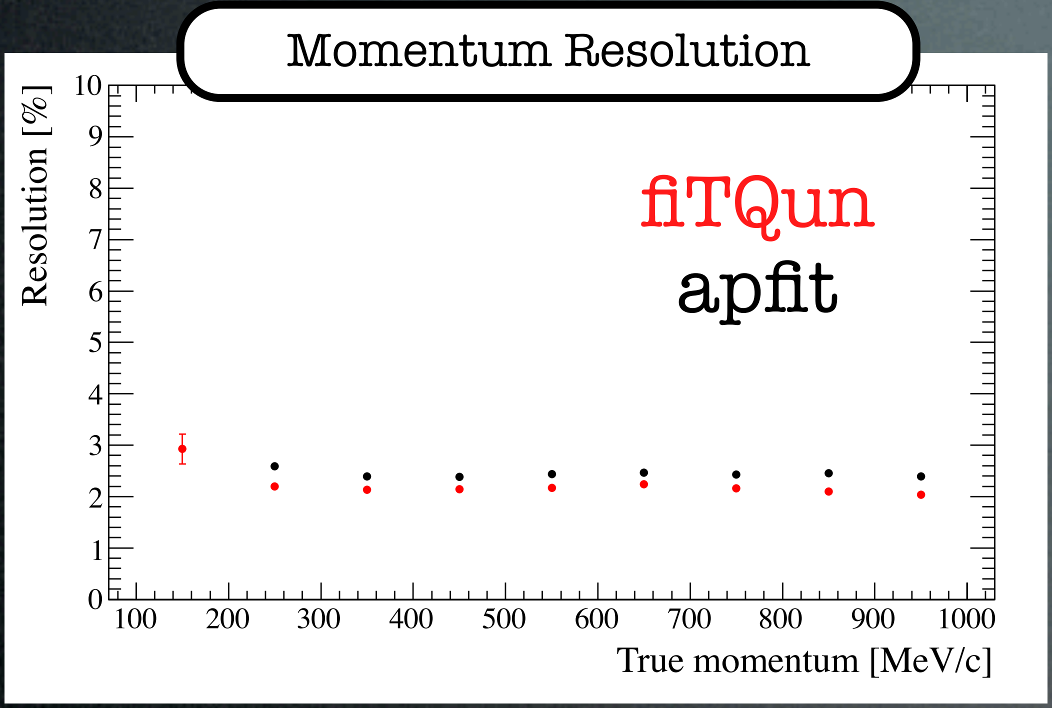
Angular Resolution



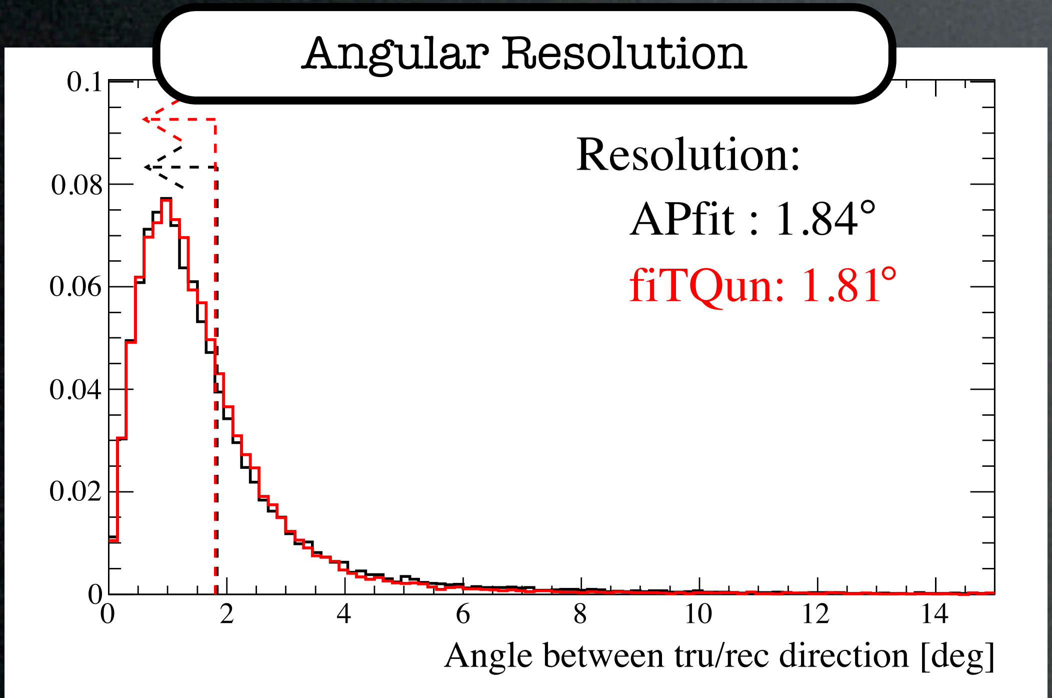
Vertex Resolution

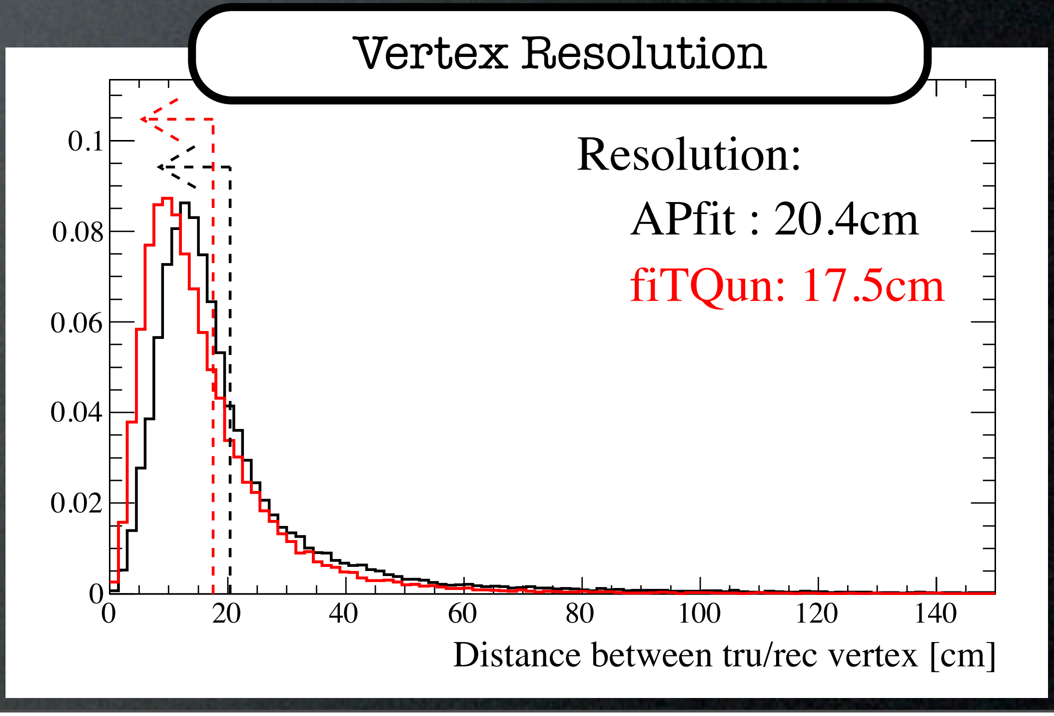


Muons

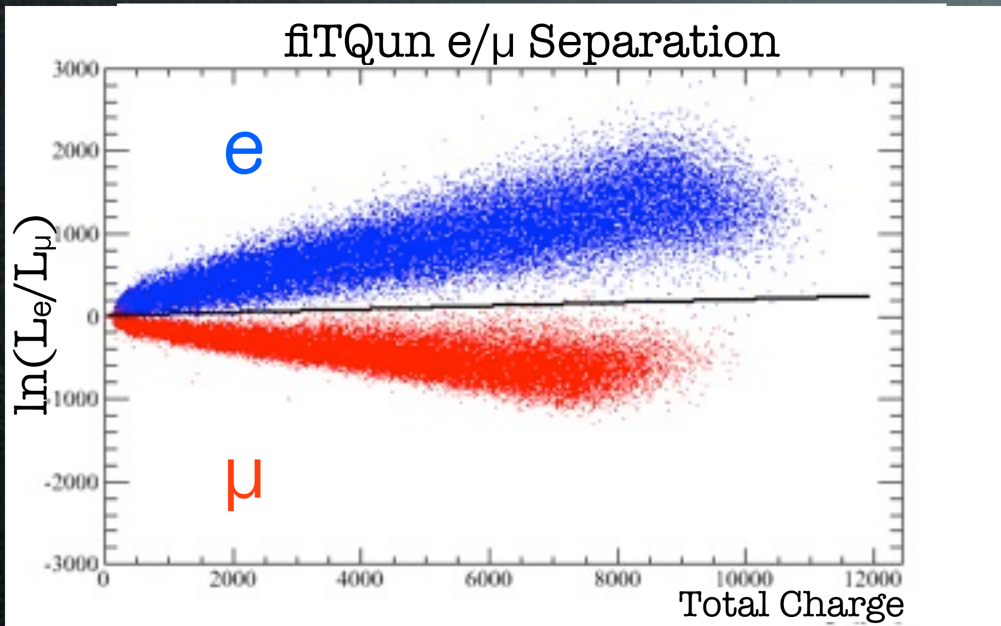


- Tested on a uniform distribution of μ^- between 0 and 1 GeV/c
  - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution

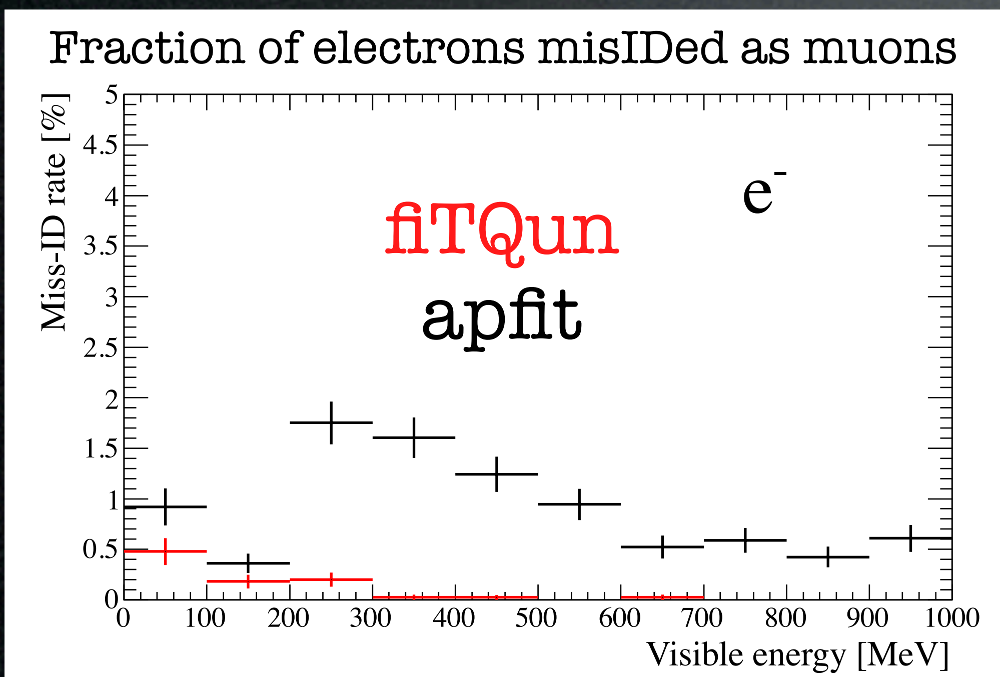


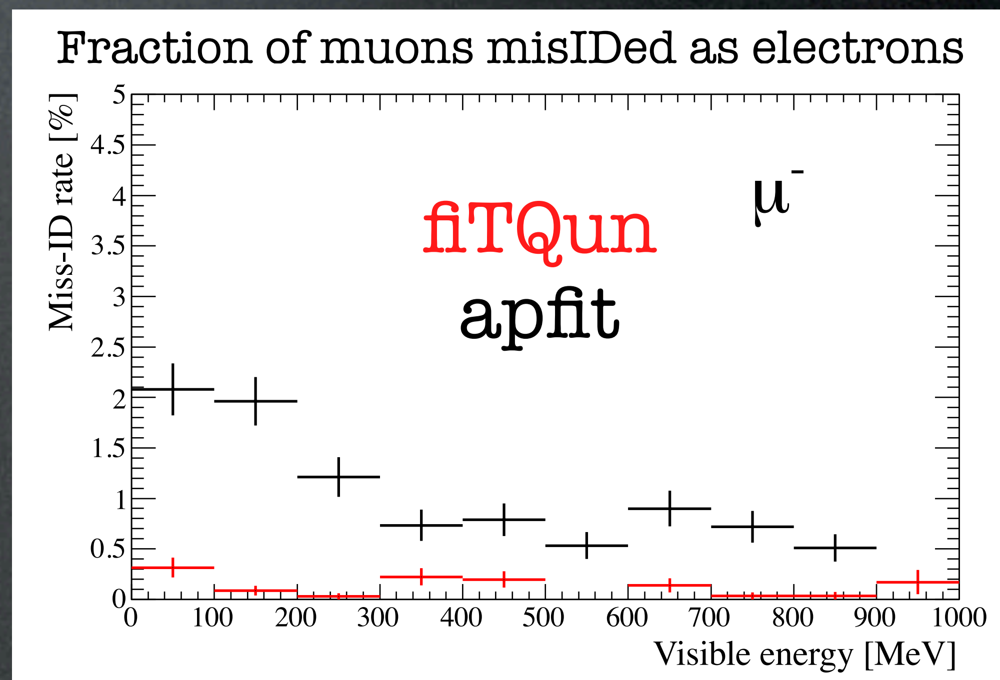


Single Track Particle ID



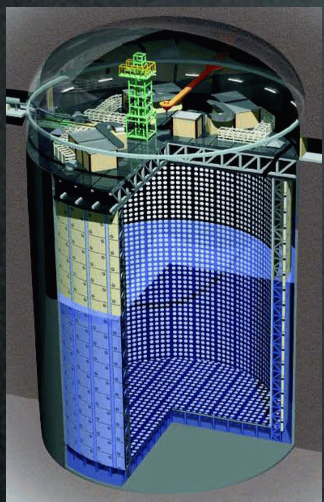
- Simple line cut can be used to separate muons and electrons
- Significantly improved particle ID

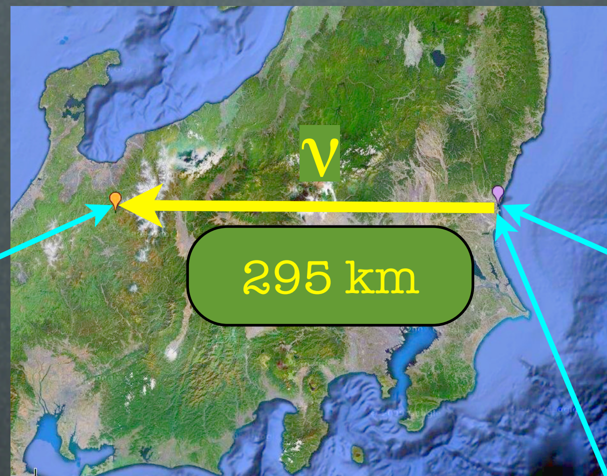




Test Case: The T2K Experiment

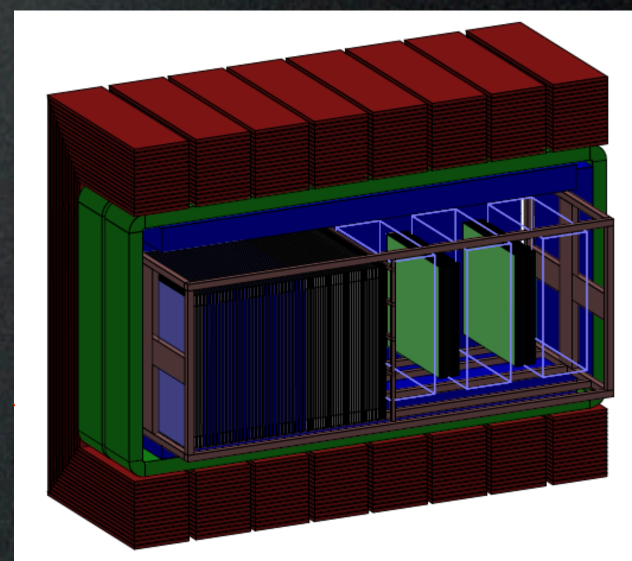
Super-K Detector





J-PARC Accelerator

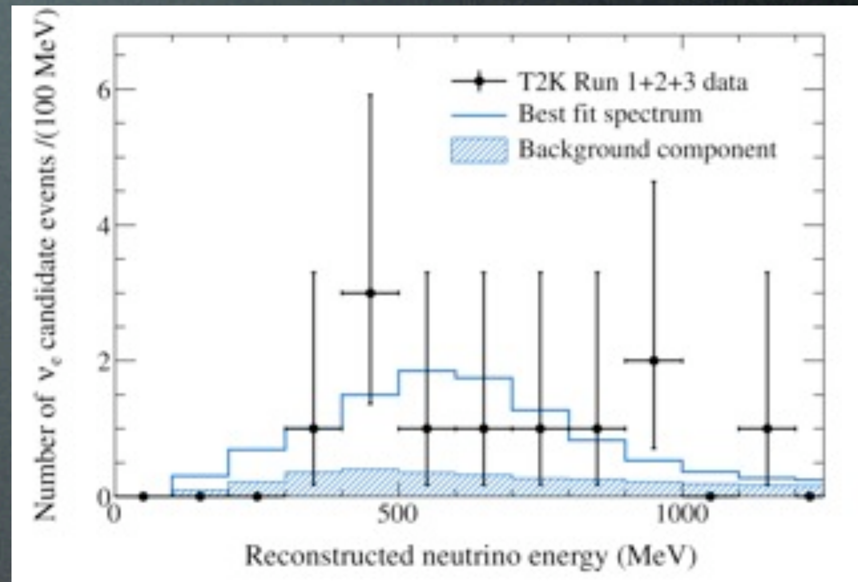
Near Detector



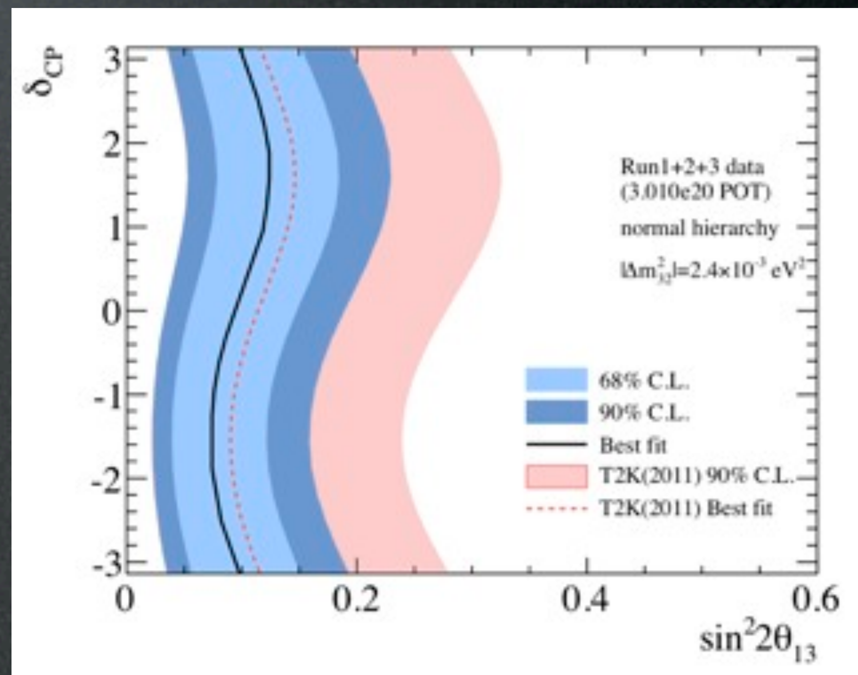
- The T2K experiment searches for neutrino oscillations in a high purity ν_μ beam
- A near detector located 280 m downstream of the target measures the unoscillated neutrino spectrum
- The neutrinos travel 295 km to the Super-Kamiokande water Cherenkov detector
    - For **θ_{13} search**: Super-K looks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

Previous T2K ν_e Results (2012)

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



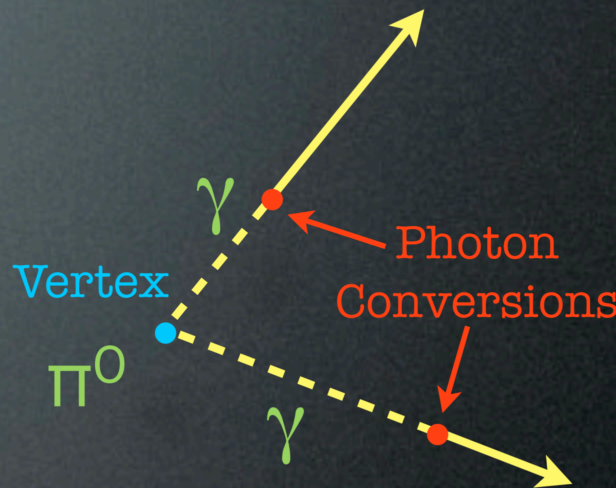
Background Reduction

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

Can fiTQun do better?

fiTQun π^0 Fitter

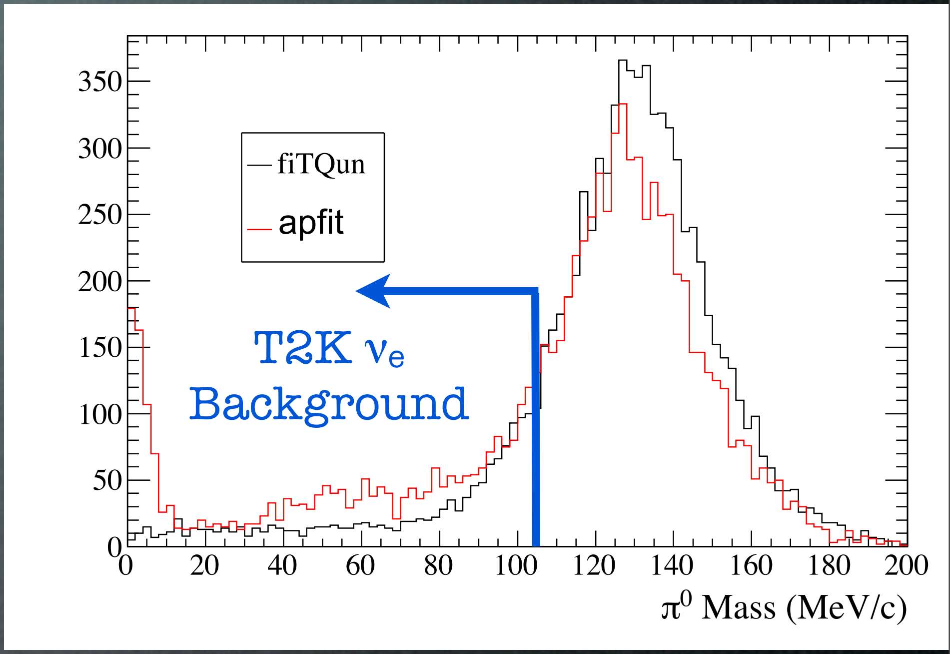
- Assumes two electron hypothesis rings produced at a common vertex
- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, ϕ_1, θ_2, ϕ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)

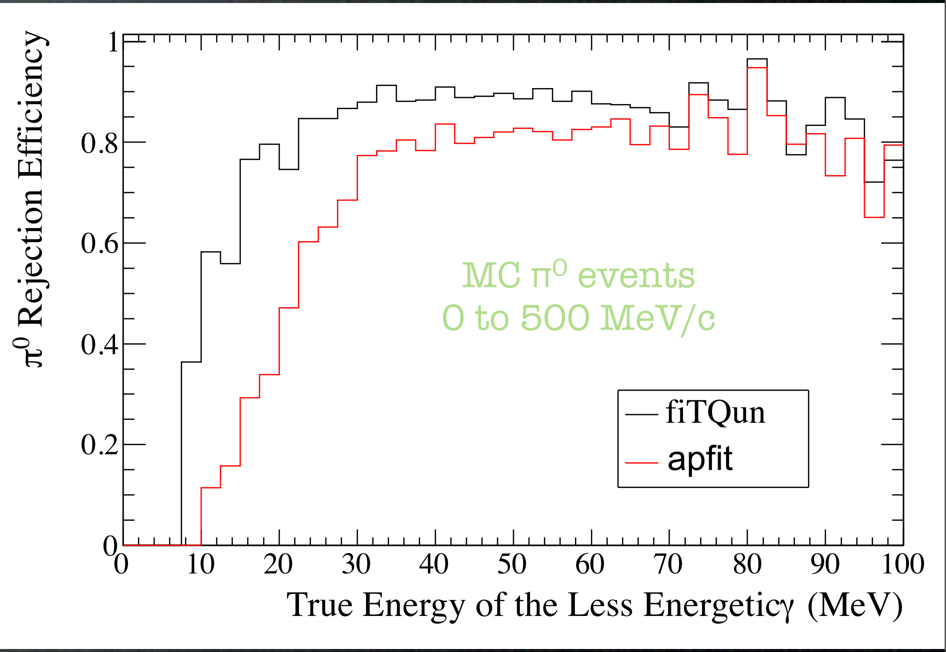


- **Seeding the fit**
  - Use result of single-track electron fit
  - Scan over various directions with a 50 MeV/c electron and evaluate the likelihood function
    - Choose the direction that yields the best likelihood
  - First, fit while floating only p_1 and p_2
- **Do full 12 parameter fit**

π^0 Performance

- Previous T2K ν_e appearance cut: **$m_{\pi 0}$ < 105 MeV**
- The π^0 mass tail is much smaller for fiTQun
  - Significant spike at zero mass in previous 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

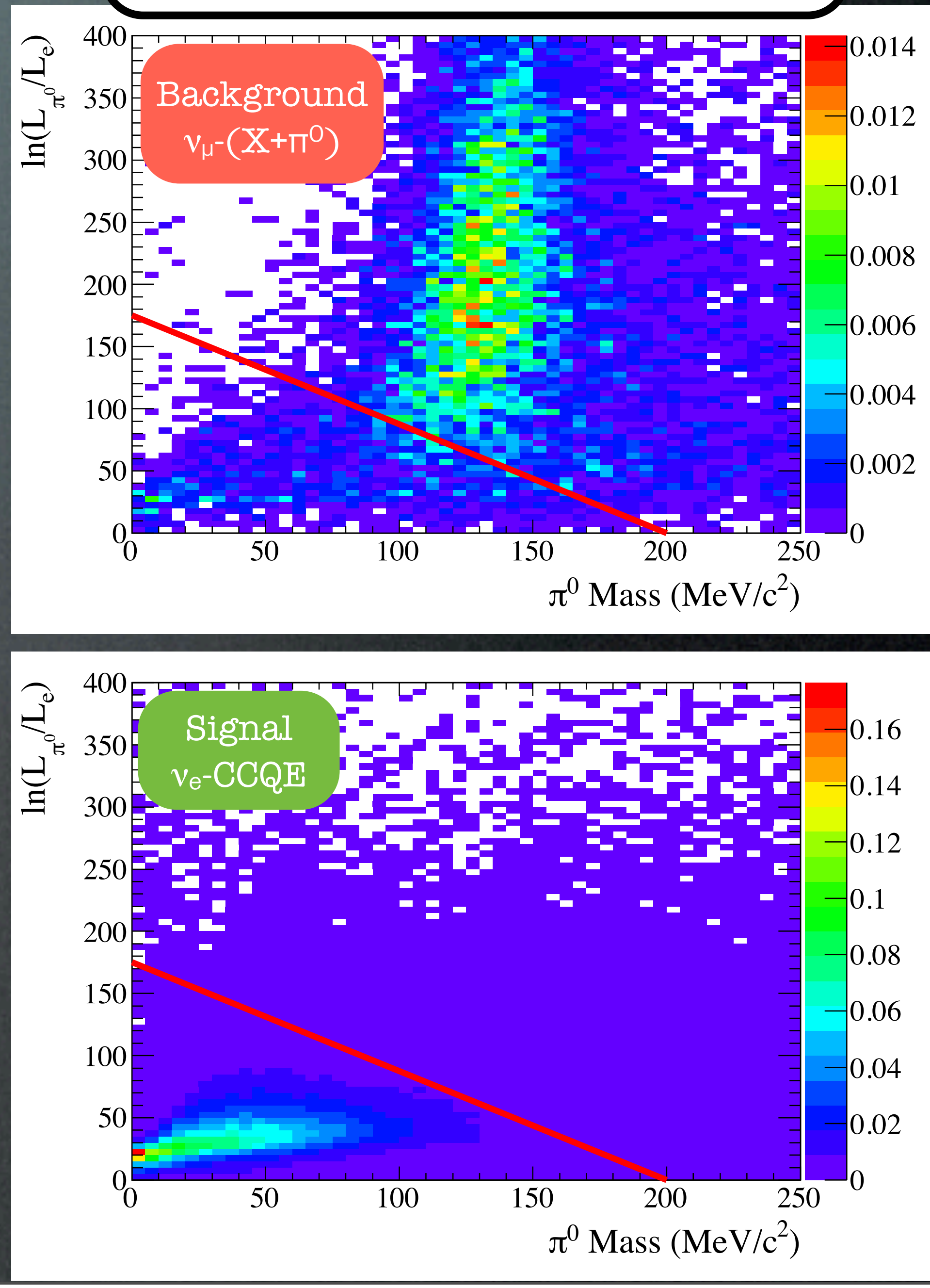




Even Better π^0 Rejection

- 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 70% more π^0 background**
  - (2% loss in signal efficiency)
- Improves ν_e appearance sensitivity from **5.0σ** to **5.5σ**
- More improvements to come!
  - Improved PID, ring counting, etc.

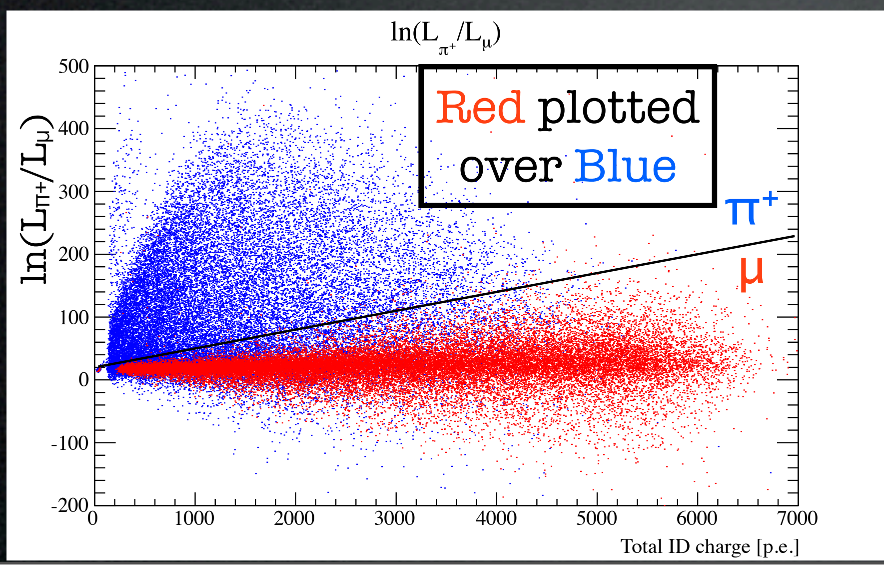
Likelihood Ratio vs π^0 Mass

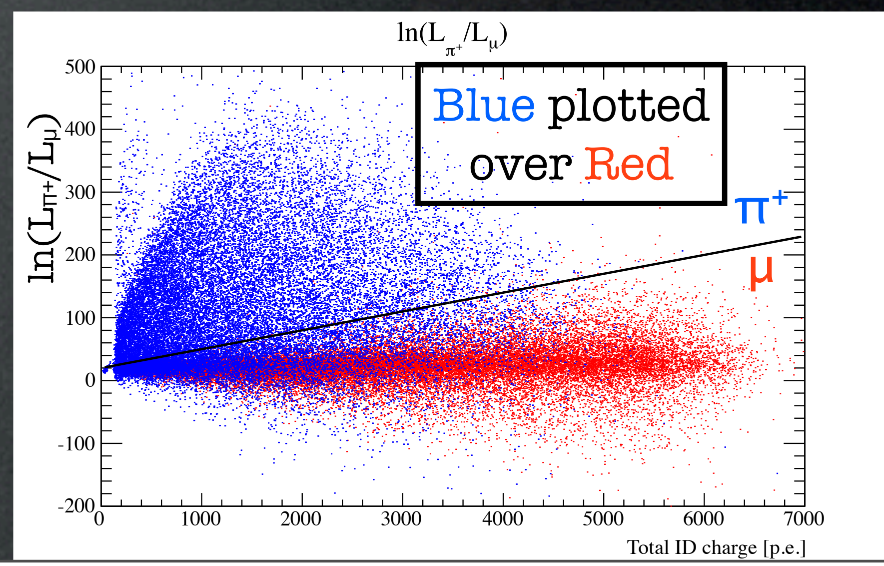


Other fiTQun Tools: π^+ Fitter

- 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)
- First ever π^+ / μ separation at Super-K!

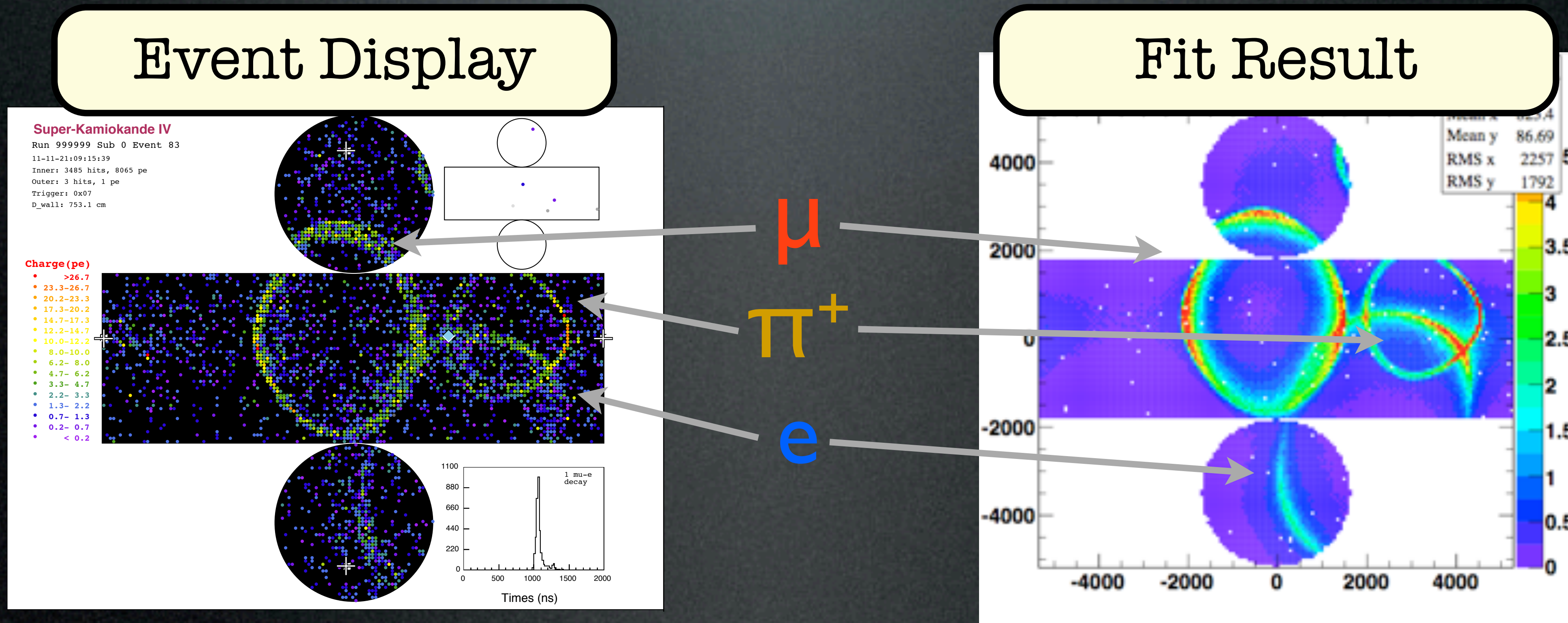
μ & π^+ particle gun





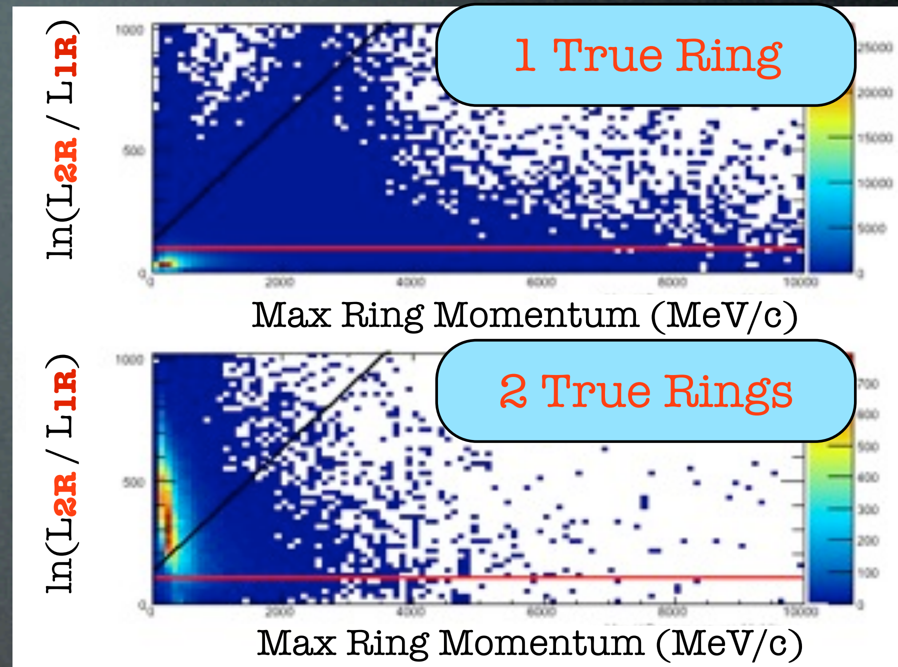
Other Tools: Multi-ring Fitter

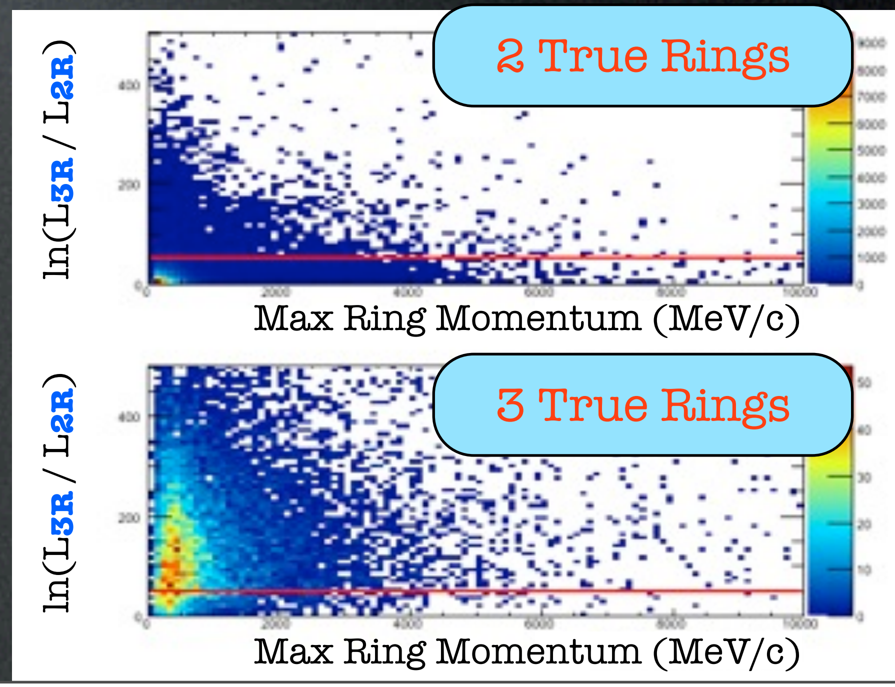
- **Fit up to 4 rings** using e & π^+ hypotheses (soon to be **6**!)
  - 28 fits in total (every possible e/π^+ combination)
- μ hypothesis is a subset of the π^+ hypothesis
  - Just need to move the kink point below Cherenkov threshold



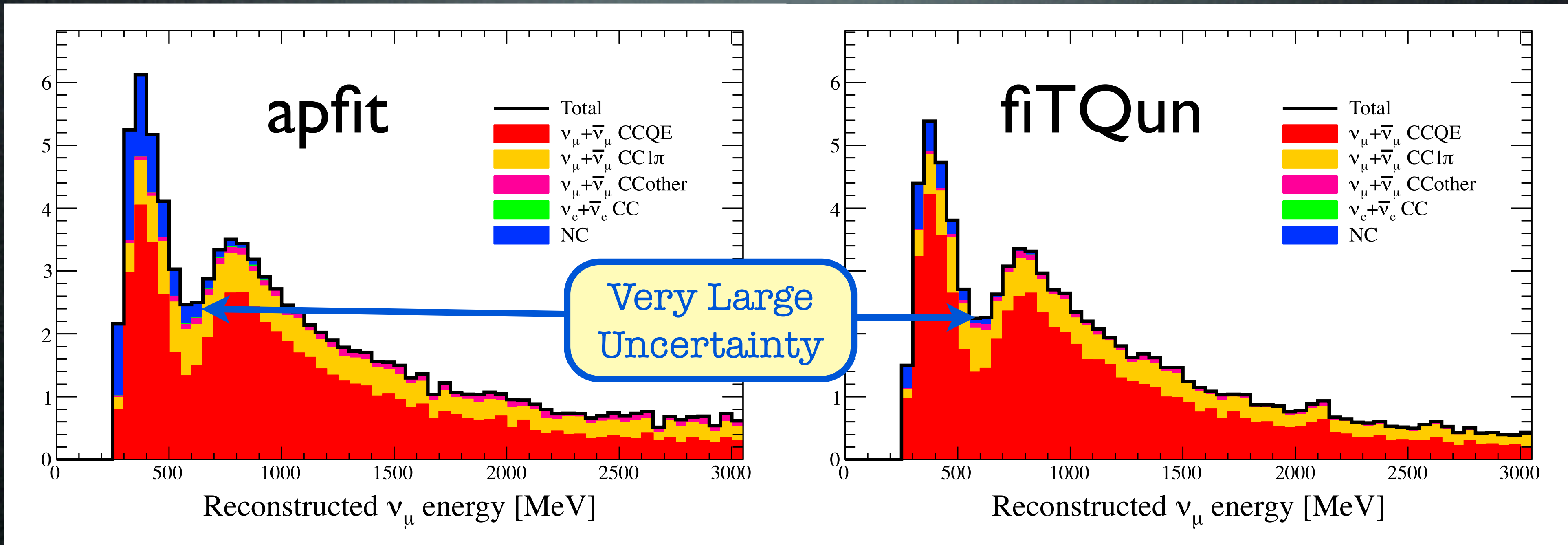
Ring Counting

- 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
  - More improvement on the way





ν_μ Disappearance: 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

$p \to K^+\nu$

- Search via the largest two K^+ decay channels
- **$K^+ \to \mu^+ \nu_\mu$**
  - Search for **6 MeV photon** from nuclear de-excitation
    - Very low energy → current algorithm is very inefficient
      - **Only 6% - 10% efficiency** (>40% have a nuclear photon)
    - **Large potential improvement** if low-energy photon detection can be improved
- **$K^+ \to \pi^+ \pi^0$**
  - **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

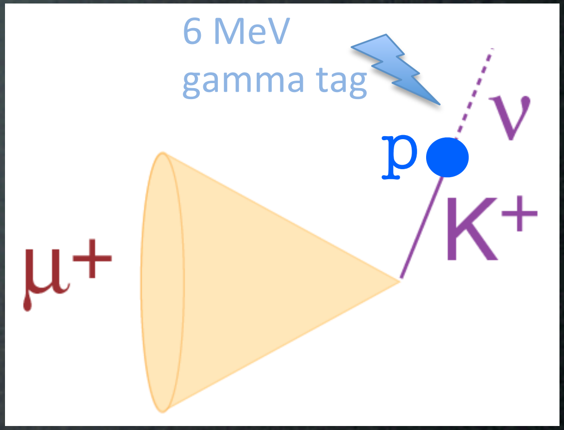
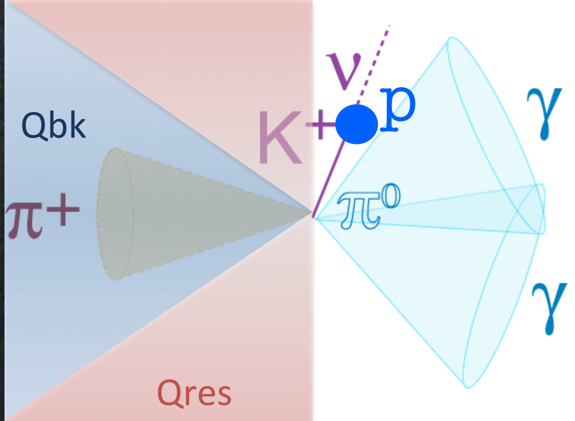
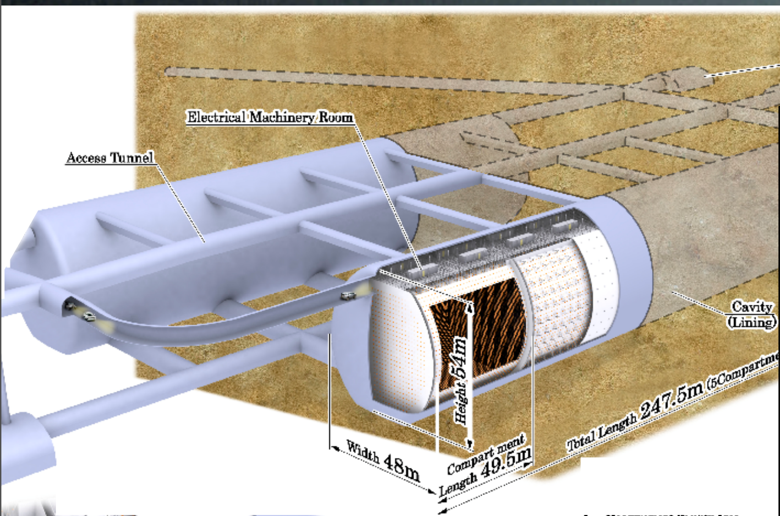
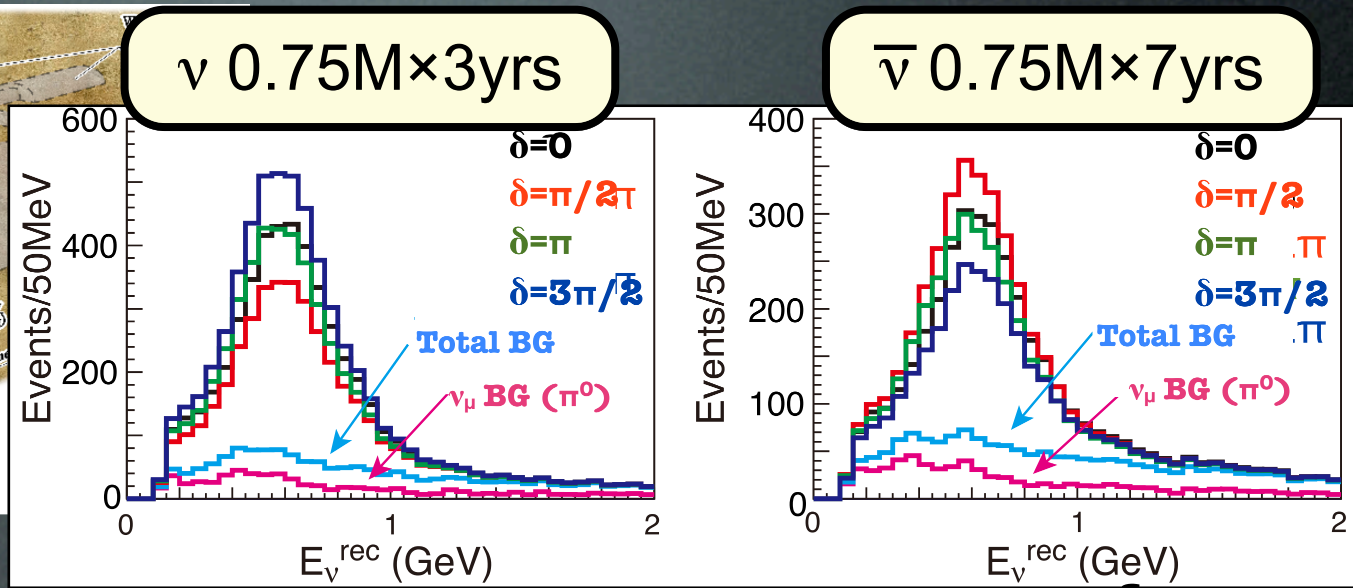


Image credit: Ed Kearns



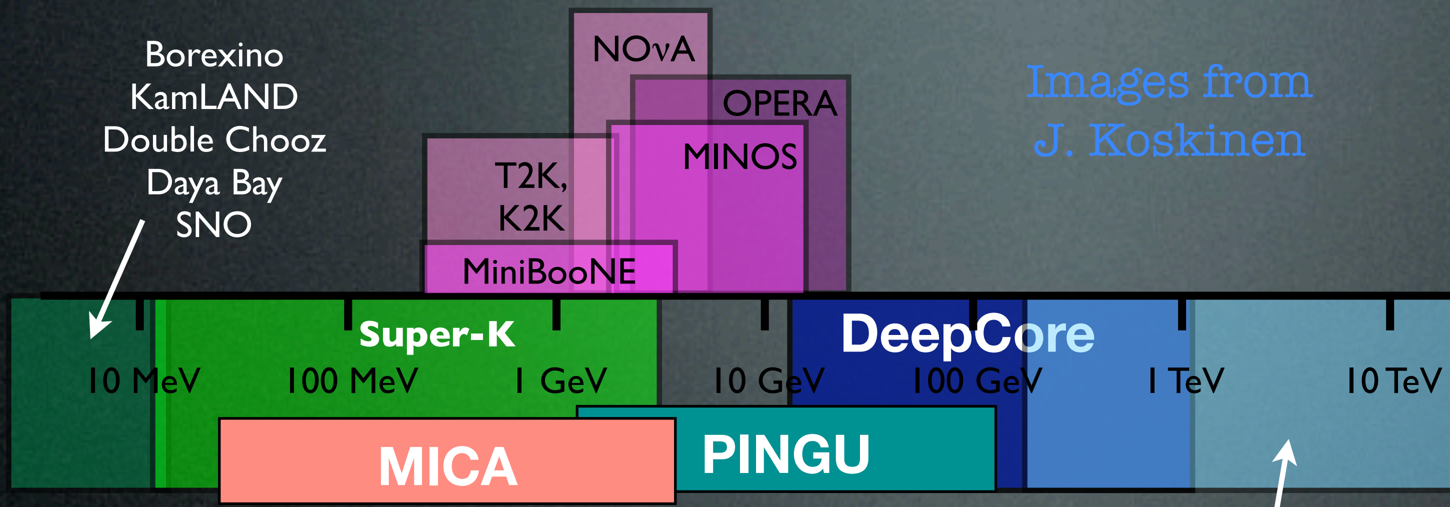
Future Experiments: Hyper-K



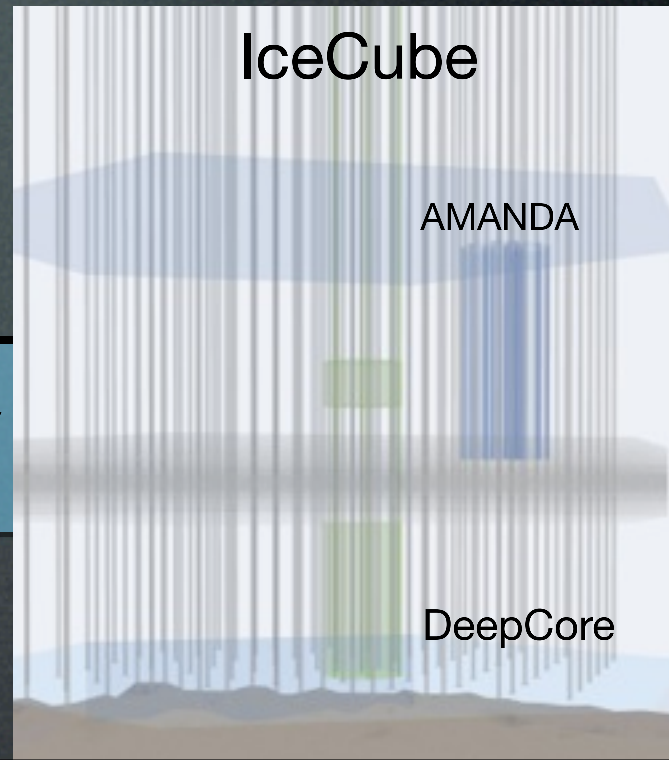


- 0.99 Mton of water (~25 × Super-K fiducial volume)
- Physics goals include proton decay, δ_{CP}, θ_{23} octant, SN-ν, ...
- Same detector design, neutrino beam, backgrounds, etc. as Super-K/T2K
  - Expect similar improvements in performance
- fiTQun is currently being adapted to the Hyper-K software

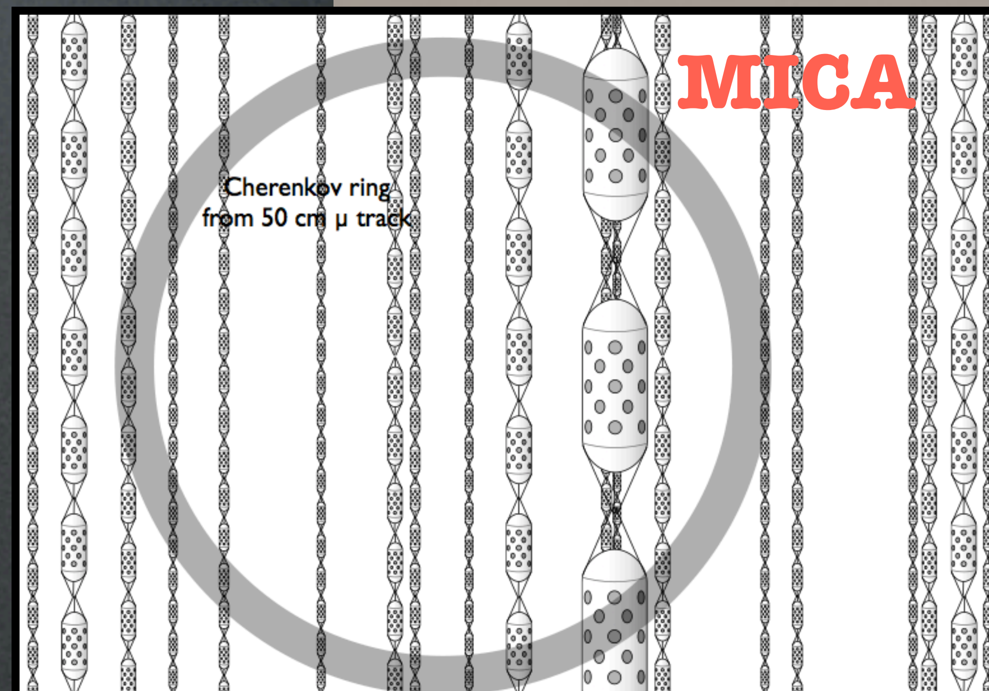
IceCube, DeepCore, Pingu, MICA



Images from
J. Koskinen



- Increasing the number of photosensors lowers the energy threshold
- **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