# FiTQun for THEIA

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# Overview

- Brief introduction
- Reminder (with more details) of FiTQun functionality and performance
- Upgrades for THEIA
  - Opportunities for new contributors

# **fiTQun**: An 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 $\pi^0$)
- Event hypotheses are distinguished by **comparing best-fit likelihoods**
  - electron / $\pi^0$
  - electron / muon / $\pi^+$ / $K^+$ / 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**

Calculating μ is the main challenge

**Time PDF**

**Charge PDF**

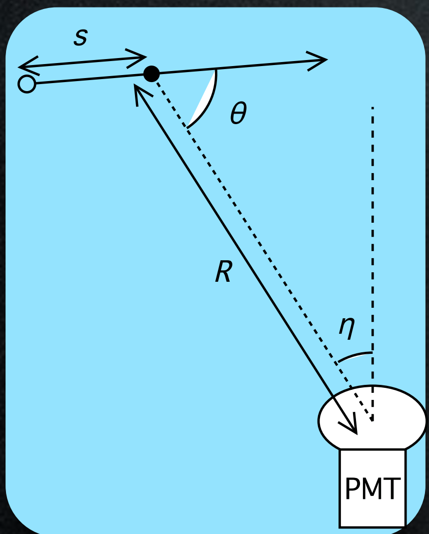
PMT Charge Response:

Property of the electronics and PMT properties

Predicted Charge (μ):

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

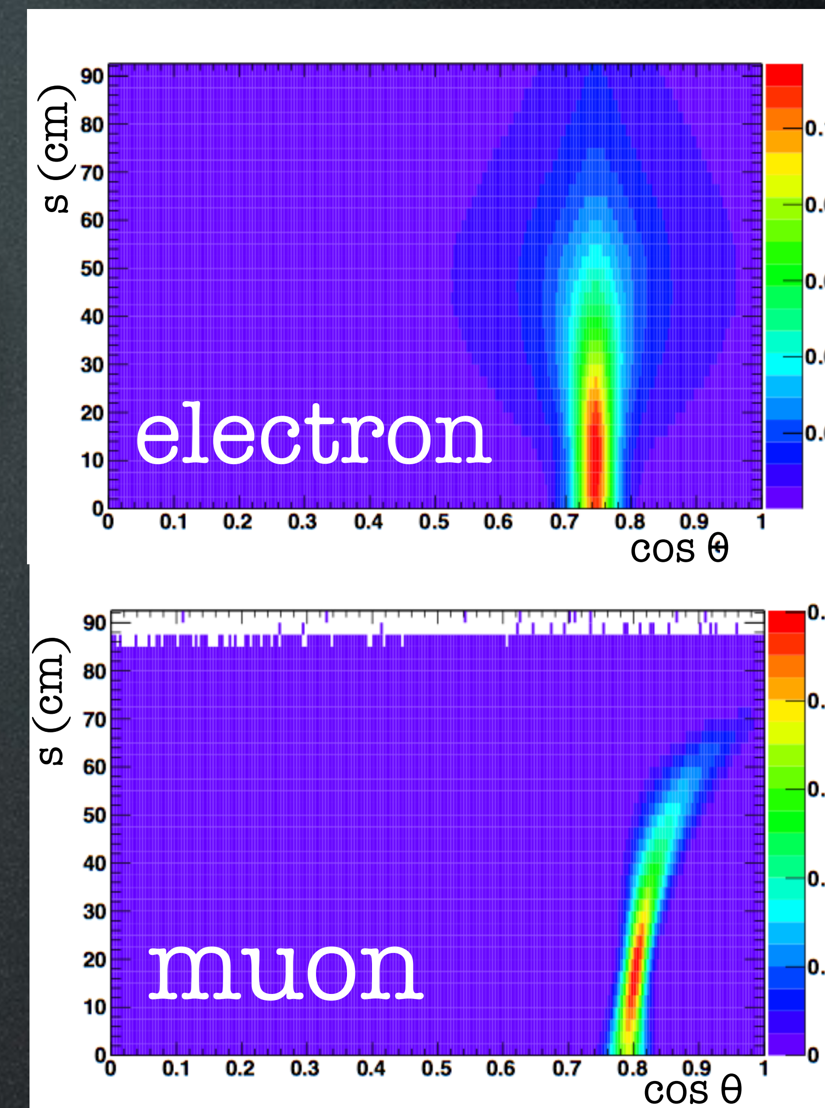
# Predicted Charge (μ)



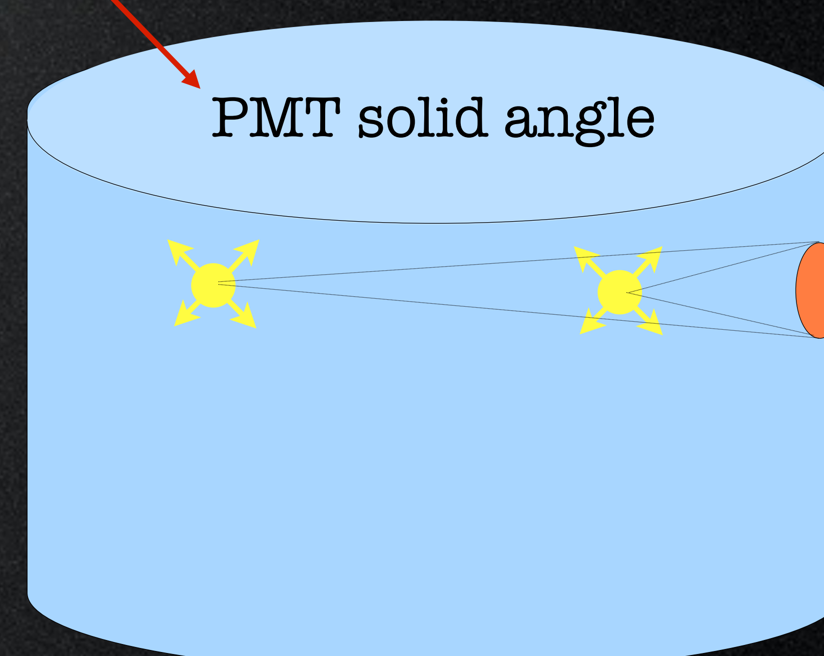

$$\mu^{\mathrm{dir}} = \Phi(p) \int ds\, g(s, \cos\theta)\,\Omega(R)\,T(R)\,\epsilon(\eta)$$

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

Cherenkov light emission profile




- $\mu^{\mathrm{dir}}$ is the predicted charge due to "direct light" only (scattered light is handled separately)
- μ is an integral over the length of the track
- 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

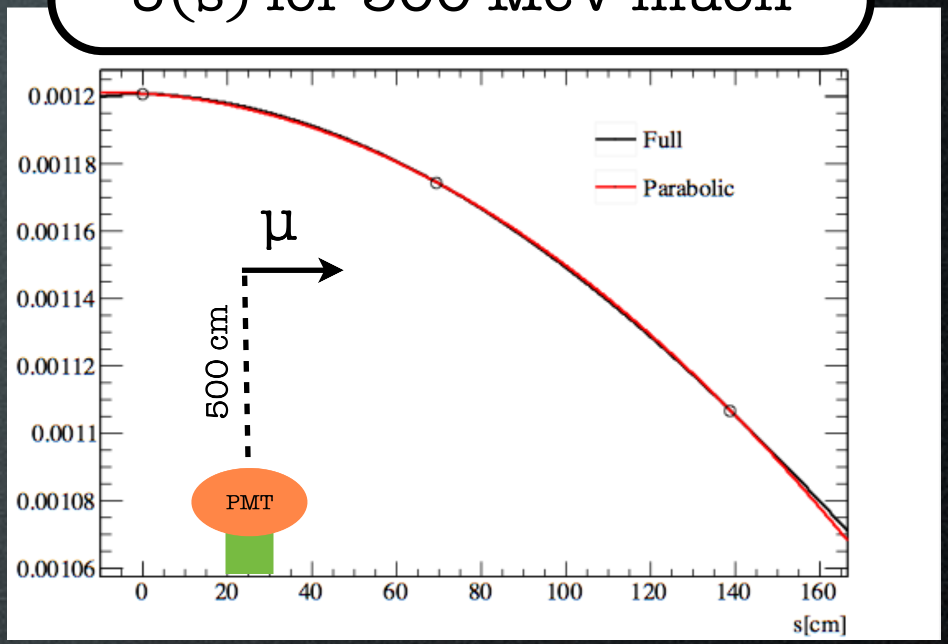


# Integral Calculation

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

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

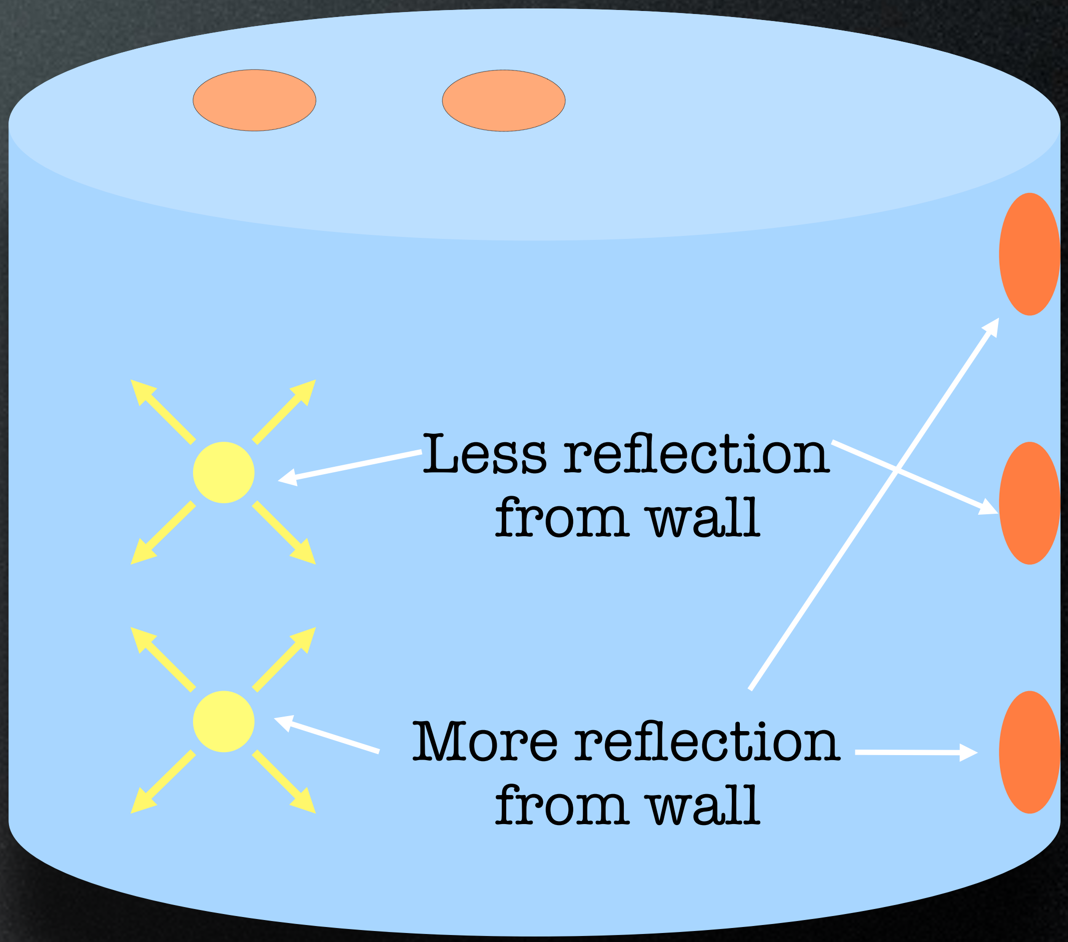
J(s) for 500 MeV muon




- Performing an integral in a minimization loop is prohibitively slow
  - Need a faster way to calculate $\mu^{\text{dir}}$
- **g(s) can vary rapidly** as a function of s
  - e.g. when PMT moves into or out of the Cherenkov cone
- However, **$J(s) \equiv \Omega(s)T(s)\varepsilon(s)$ varies slowly** as a function of s
  - Can approximate as **$J(s) = j_0 + j_1 * s + j_2 * s^2$** (“**parabolic approximation**”)
  - **Evaluate integrals in advance**: $I_i(R_0, \cos\theta_0) = \int ds * g(s, \cos\theta) * s^i$
- Now, **$\mu^{\text{dir}} = \Phi(p) * (I_0 * j_0 + I_1 * j_1 + I_2 * j_2)$**
  - No need to integrate within fitter minimization

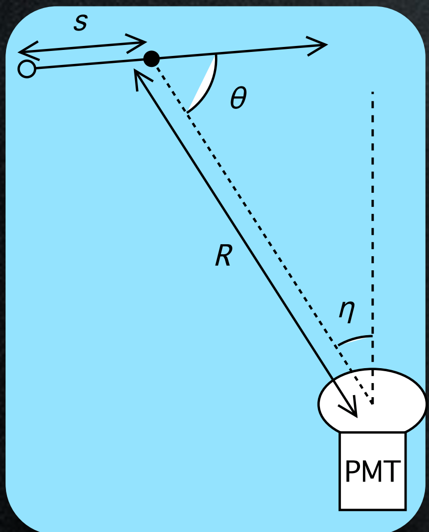
# Scattered Light

- **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", $A_{scat}$**




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

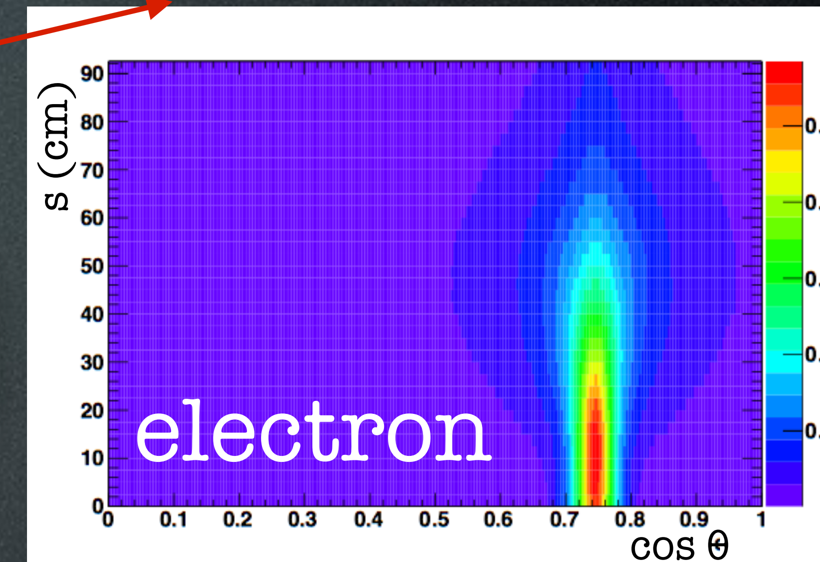
# Scintillation Light



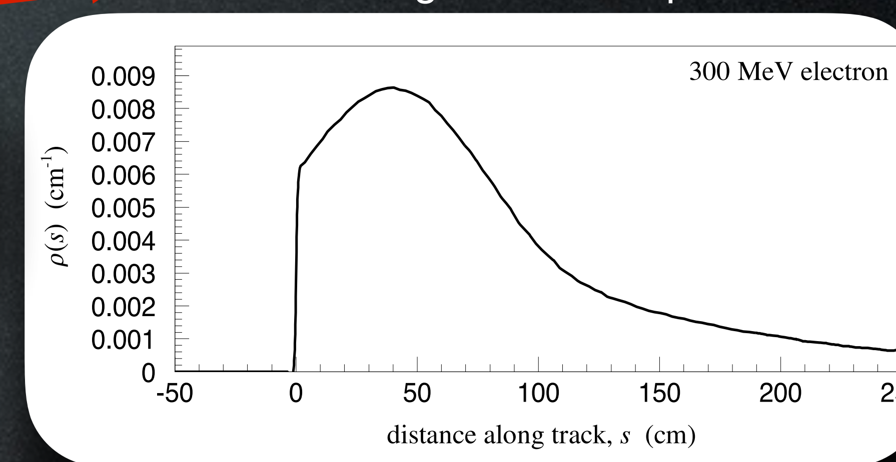

$$\mu^{dir}_{Cher} = \Phi(p) \int ds\ g(s, \cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

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

Cherenkov light emission profile




Scintillation light emission profile

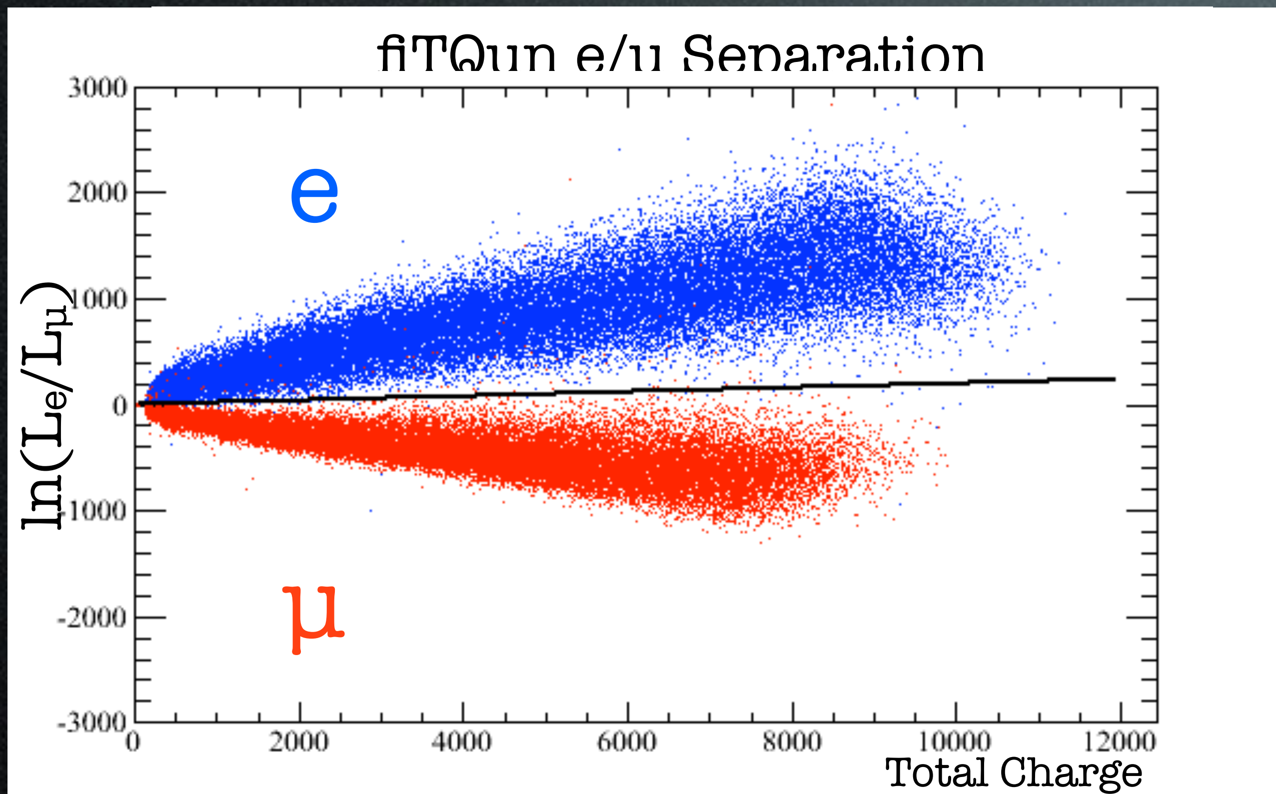



$$\mu^{dir}_{Sci} = \Phi(p) \int ds\ \rho(s)\Omega(R)T(R)\epsilon(\eta)$$

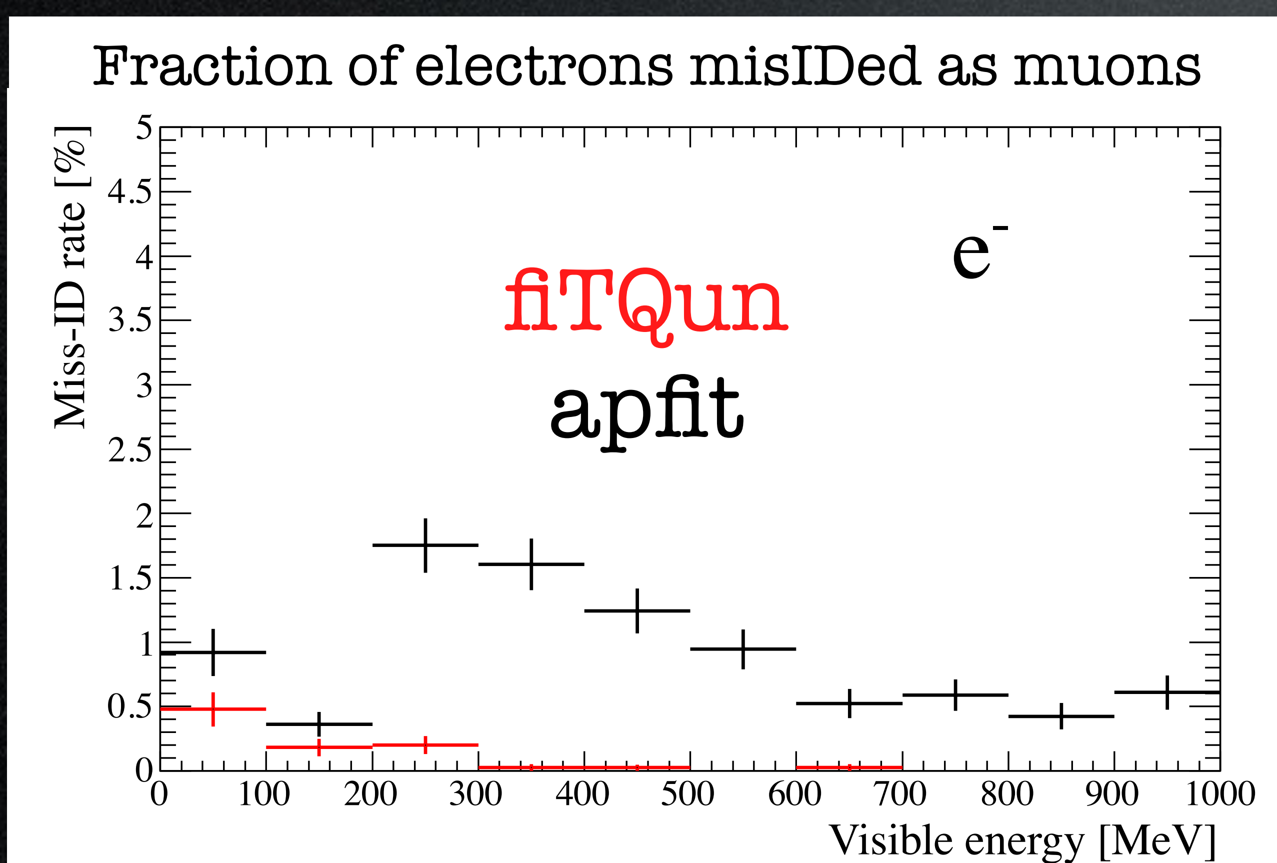
Light Yield — Integral over track length — PMT solid angle — Water attenuation — PMT angular response

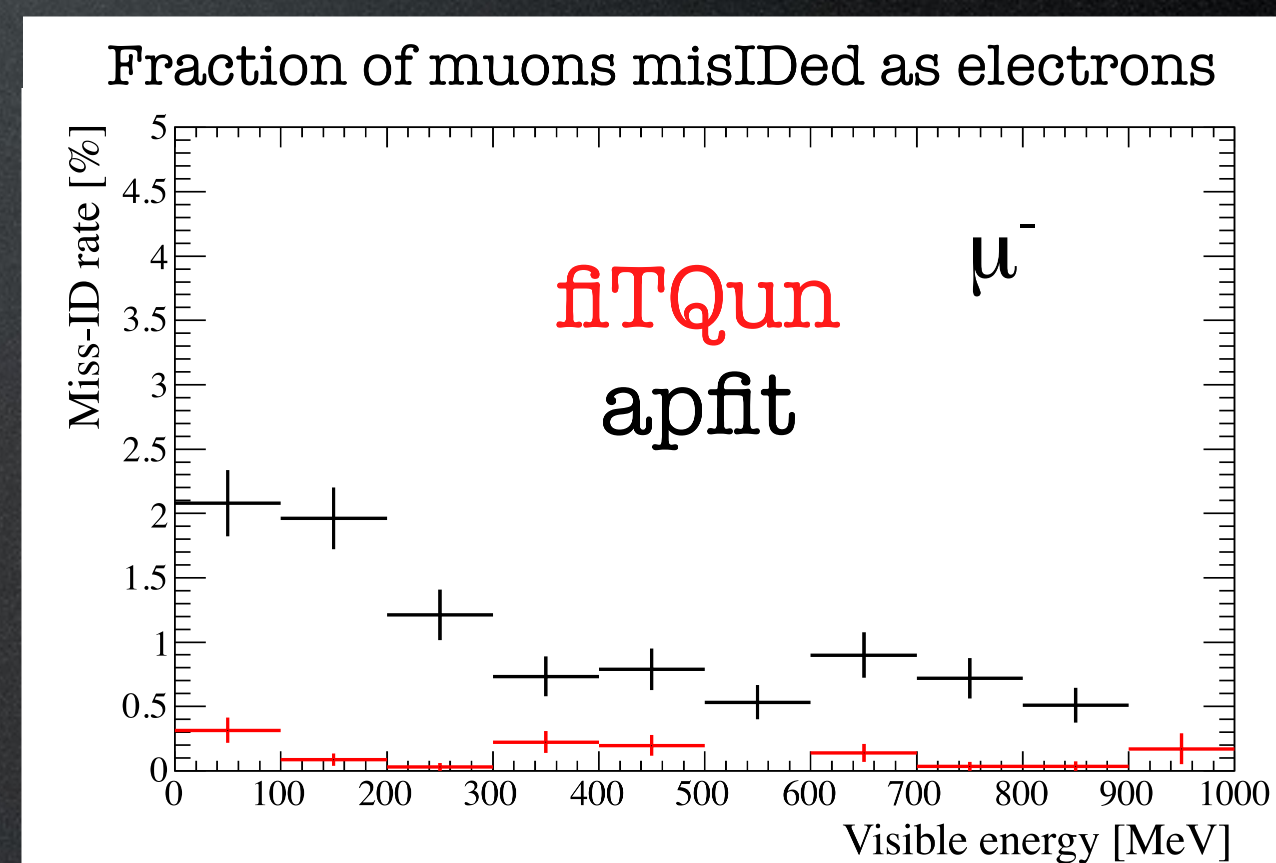
- Original mathematical formulation of FiTQun for MiniBooNE contained scintillation light
    - Assumed to be isotropic, so integral computation is much simpler
- Total predicted charge is $\mu^{dir}_{Sci} + \mu^{dir}_{Cher} + \mu^{indir}_{Sci} + \mu^{indir}_{Cher}$ for all tracks

# Single Track Particle ID



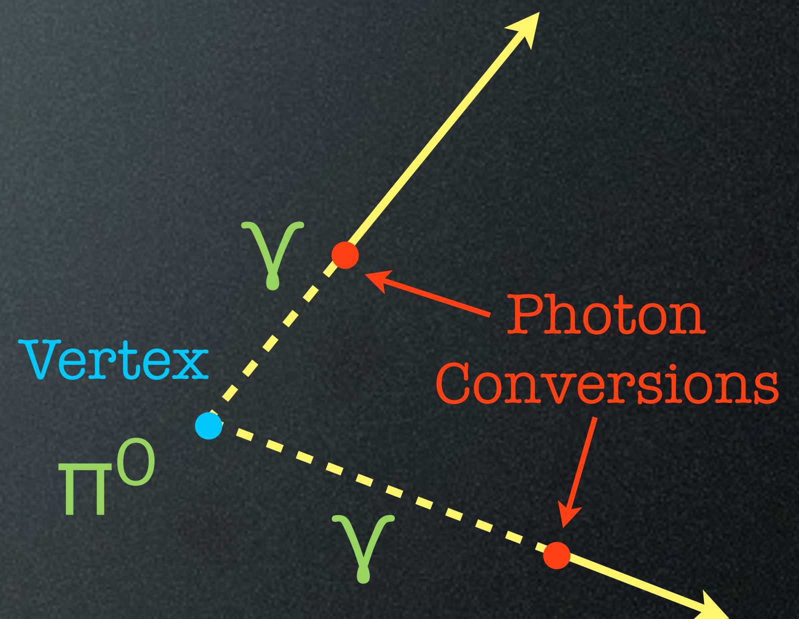

- Simple line cut can be used to separate muons and electrons
- Significantly improved particle ID

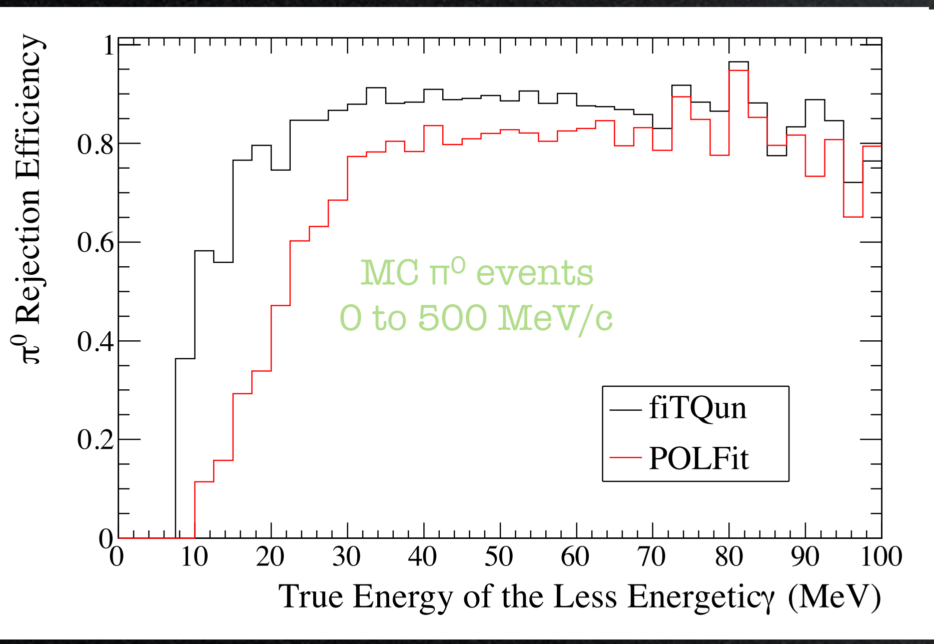


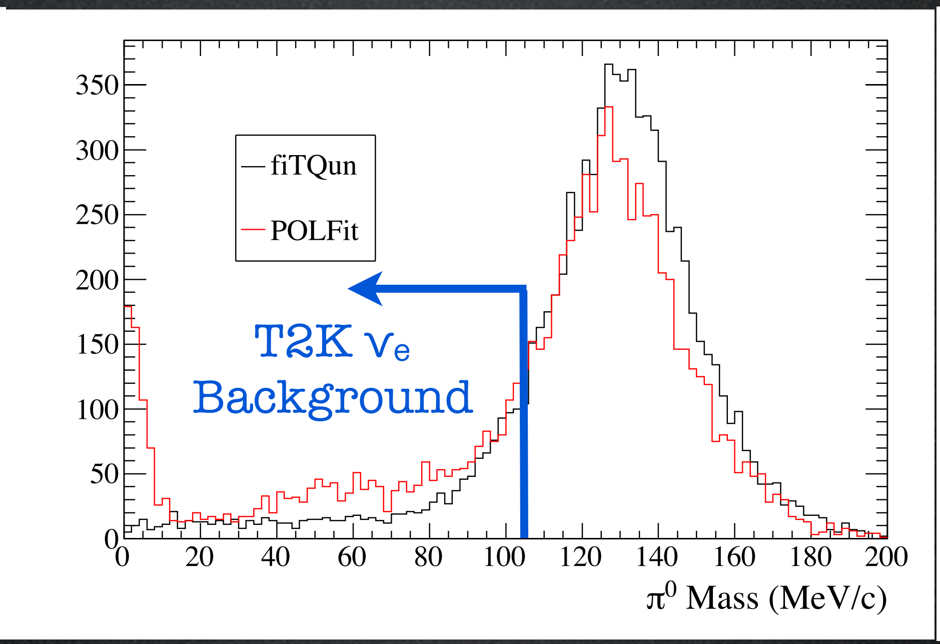



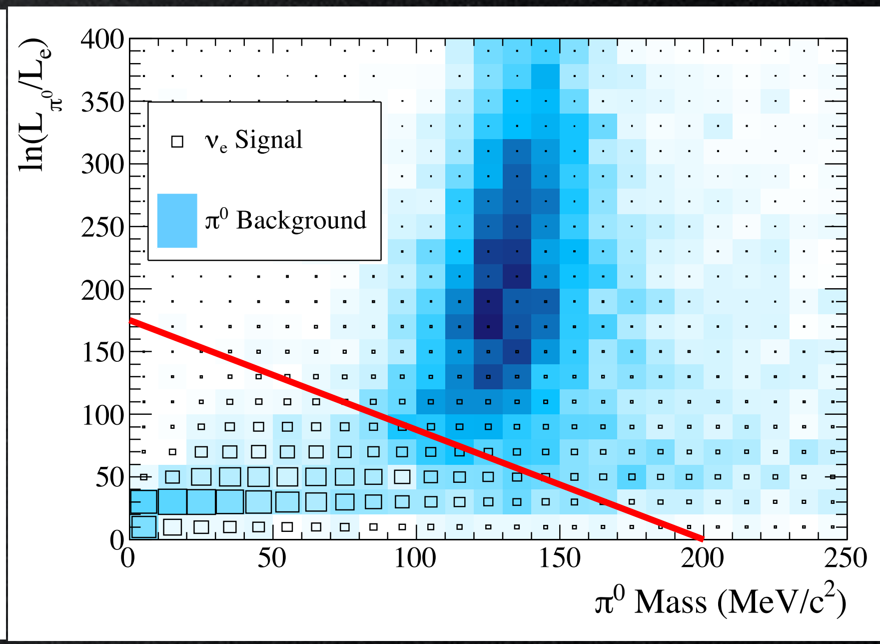
# FiTQun $\pi^0$ Fitter

- Assumes two electron hypothesis rings produced at a common vertex
- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions ($\theta_1$, $\varphi_1$, $\theta_2$, $\varphi_2$)
  - Momenta ($p_1$, $p_2$)
  - Conversion lengths ($c_1$, $c_2$)
- Large improvement in finding low energy 2nd ring
  - ~70% reduction in $\pi^0$ background relative to POLFit (not used in LBNE studies)



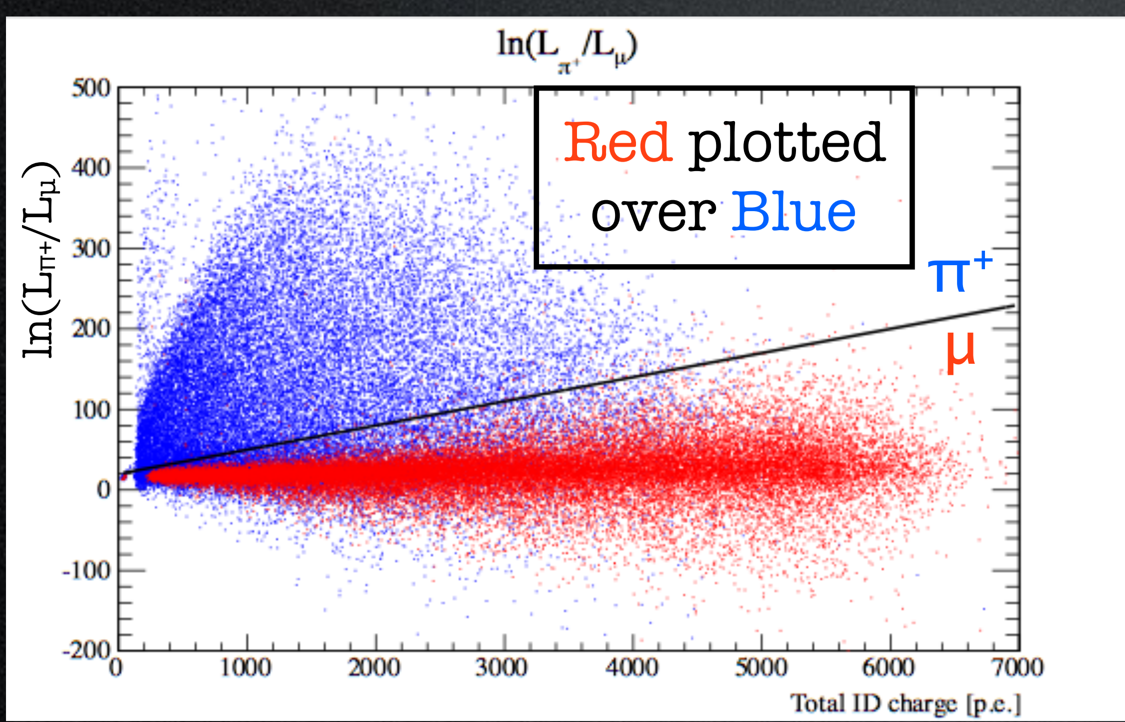



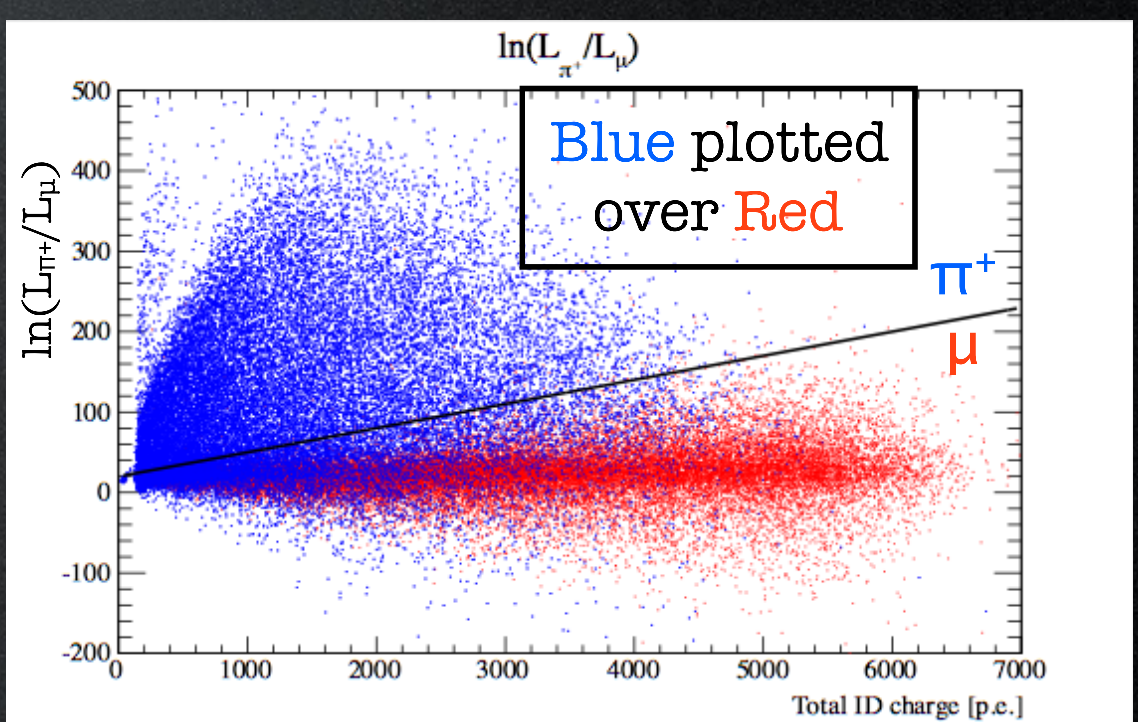



# Other fiTQun Tools: $\pi^+$ Fitter


- 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)
- New ability to separate charge pions from muons

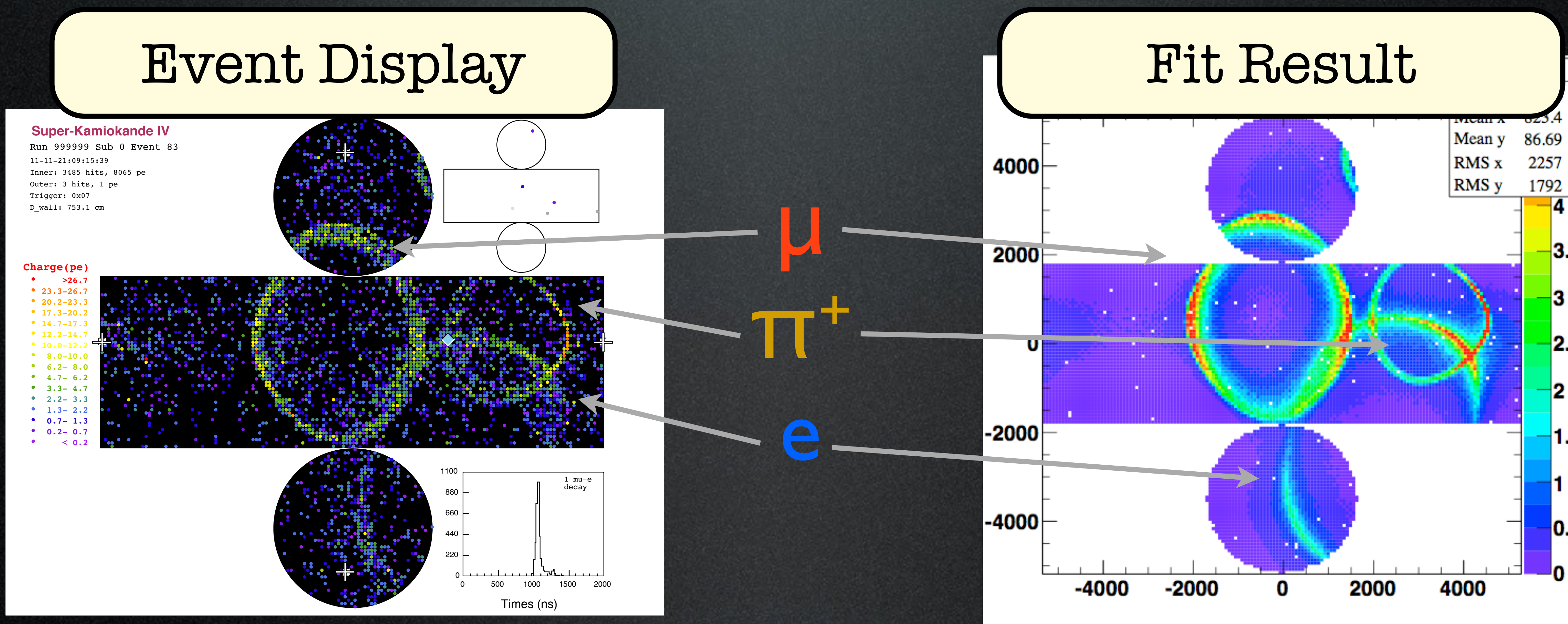
$\mu$ & $\pi^+$ particle gun



# Multi-ring Fitter

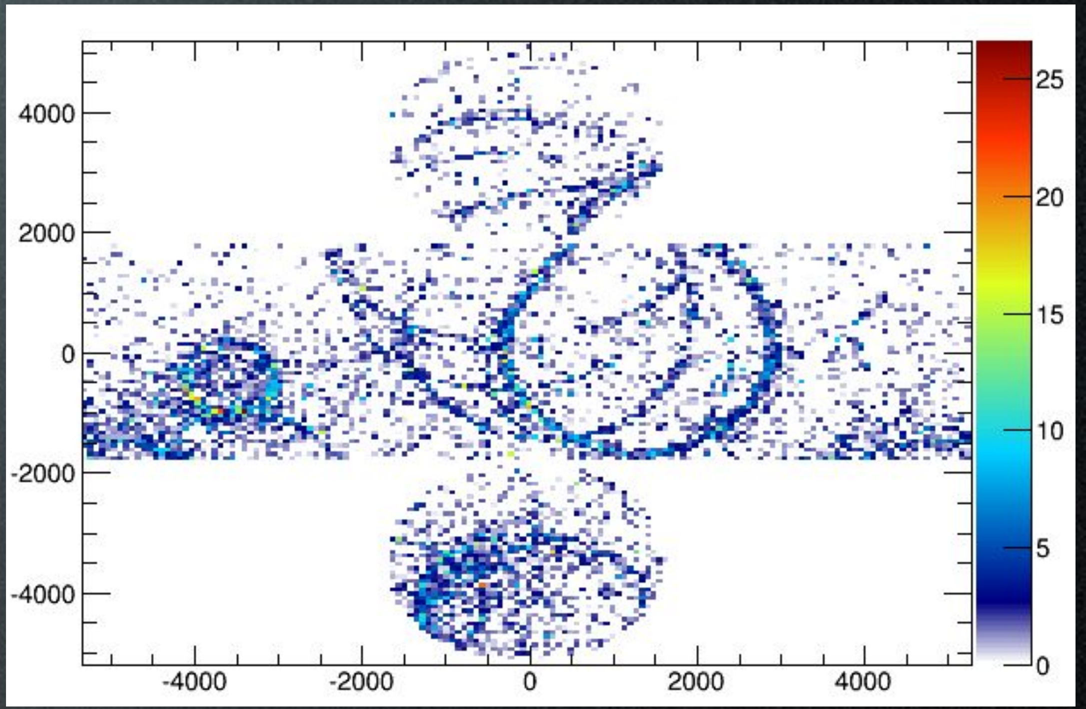
- **Fit up to 6 rings** using e & $\pi^+$ hypotheses28 fits in total (every possible e/$\pi^+$ combination)
- μ  hypothesis is a subset of the $\pi^+$ hypothesis (no “thin” ring from hadronic interactions)
- Can now separate pion, muon, and electron rings



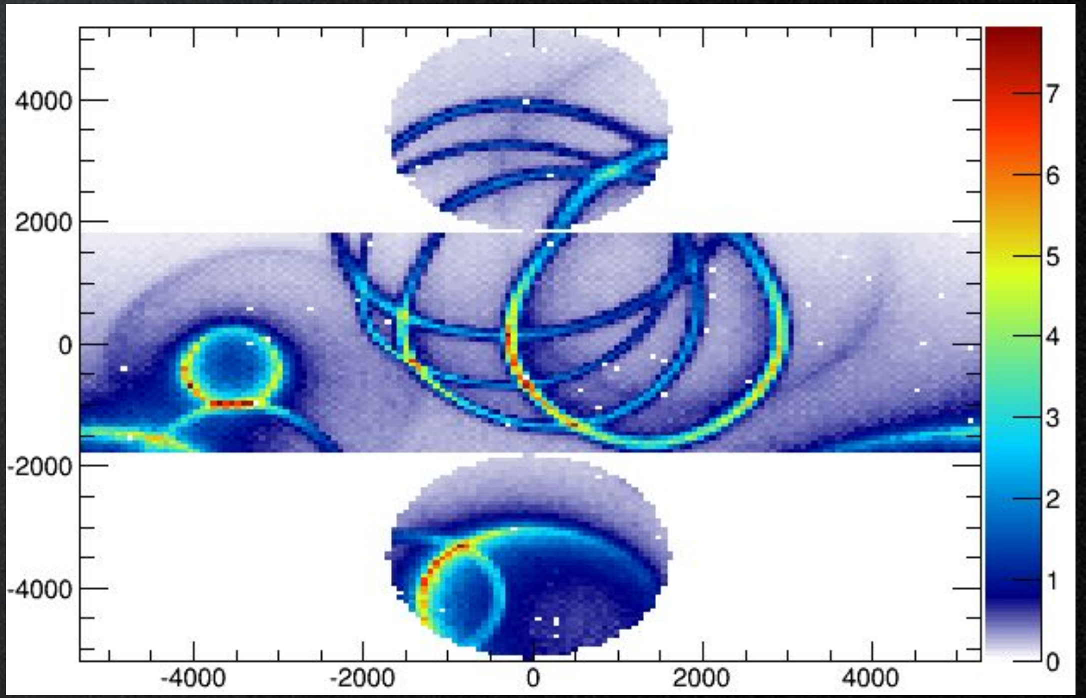
# Multi-Ring Events


- Complicated event topologies can now be fit (up to 6 rings)
    - High energy $\pi^+$ often scatter several times, producing several “thin” rings
- Important for $CC\pi^+$ events in the 2-3 GeV range
    - (DUNE energies; see LBL talk this afternoon)

**Hit Charge Distribution**




**Reconstructed Predicted Charge**

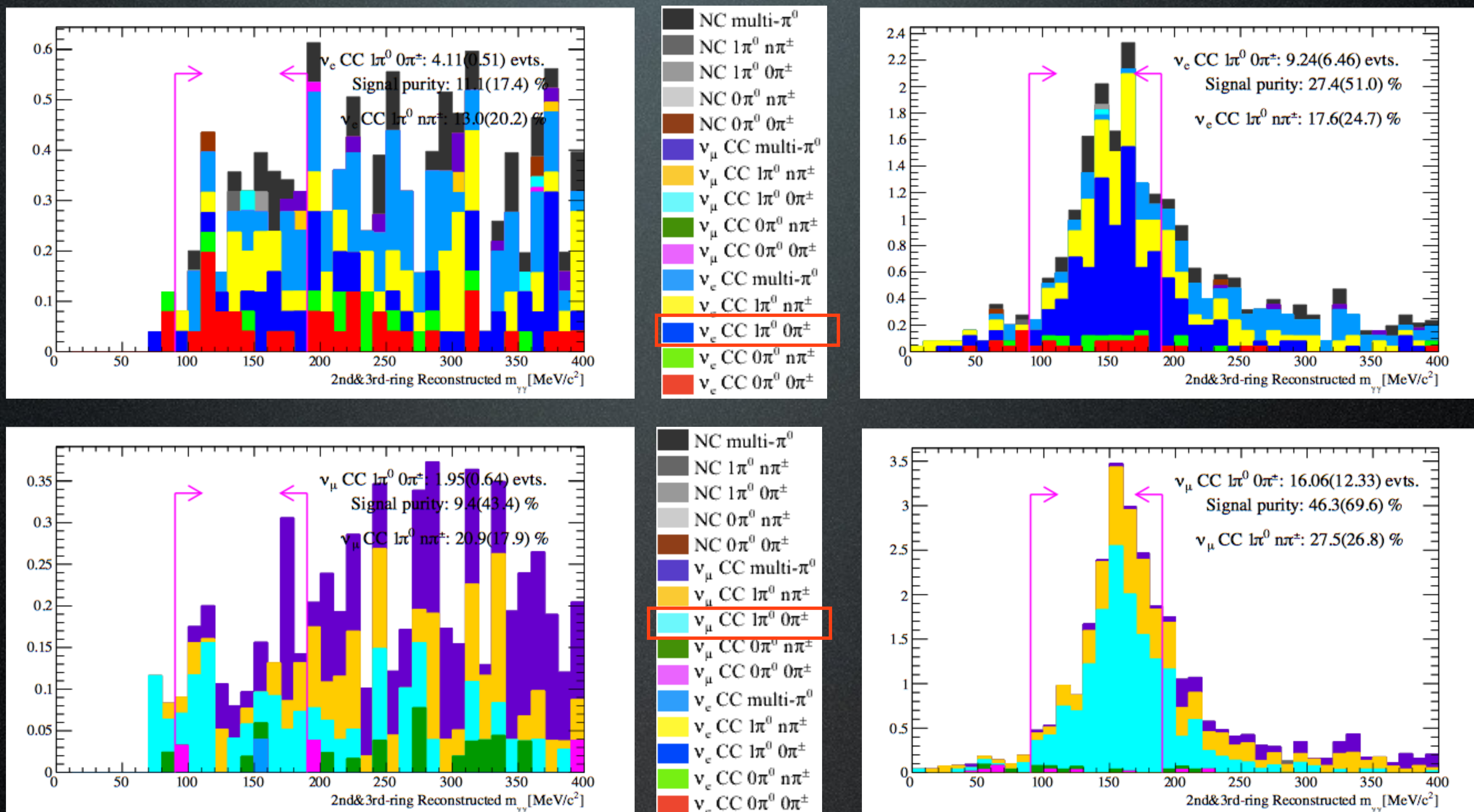


# High Energy Ring Counting

APfit FiTQun

$\nu_e CC1\pi^0$ ($E_\nu > 3$ GeV)

$\nu_\mu CC1\pi^0$ ($E_\nu > 3$ GeV)




- FiTQun ring counting provides significant improvement at higher energies

# FiTQun Status

- FiTQun is currently maintained by Stony Brook on GitHub
- This summer, T2K will fully transition to a FiTQun-only analysis
  - Detailed vetting using atmospheric neutrinos, cosmic muons, and Michel electrons
  - Super-K MC is based on GEANT3/Fortran
- FiTQun is the "official" high-E reconstruction algorithm for Hyper-K and NuPRISM
  - Detector MC is based on GEANT4/C++ (WCSim)

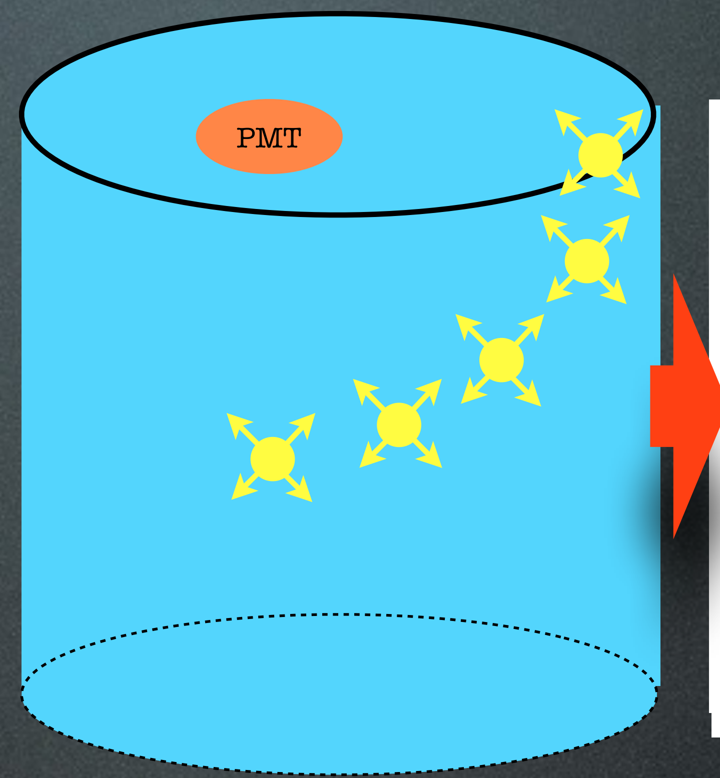
# Plans for THEIA

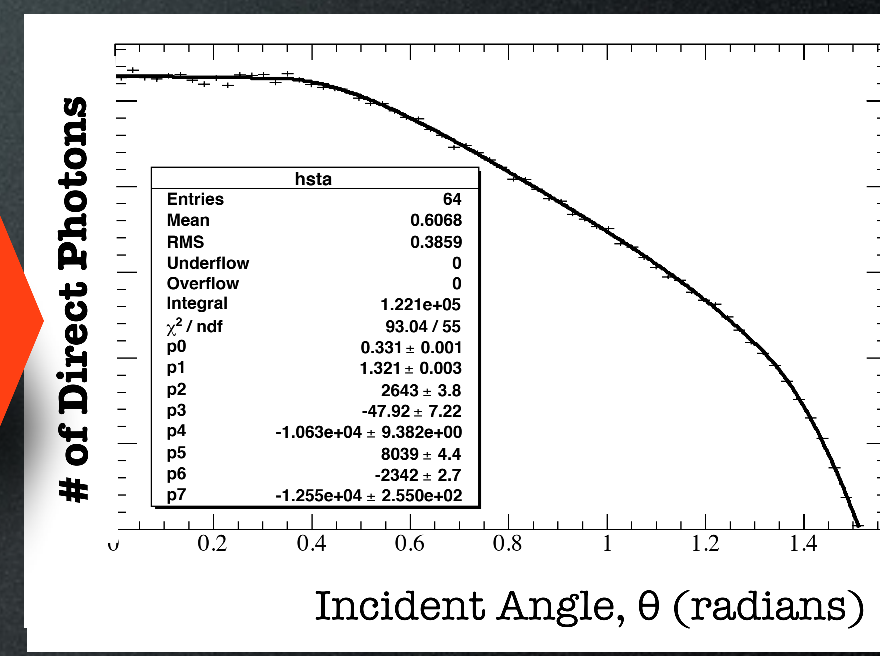
- Our group is collaborating on the BNL 1 ton prototype (for WbLS)
  - One of our students spent last summer working on the rat-pac simulation
- The next step is to adapt FiTQun to run on rat-pac simulation output
  - This should be straightforward, as this has already been done for c++ based Hyper-K MC
  - Additional participation is welcome!
- We now have a well established procedure for tuning FiTQun to various detector geometries, photosensors, etc.
  - We are happy to train new people interested in studying various detector configurations

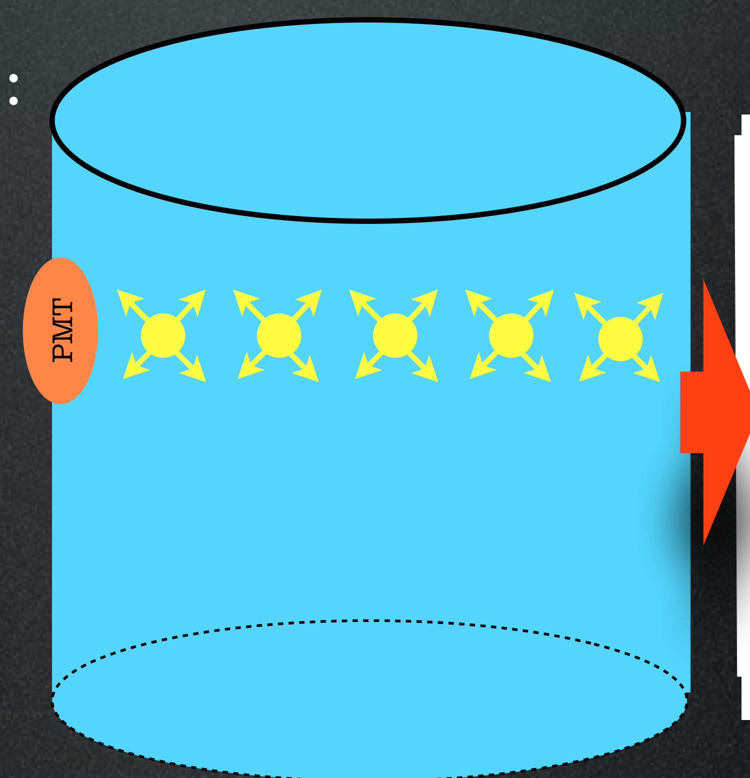
# Supplement

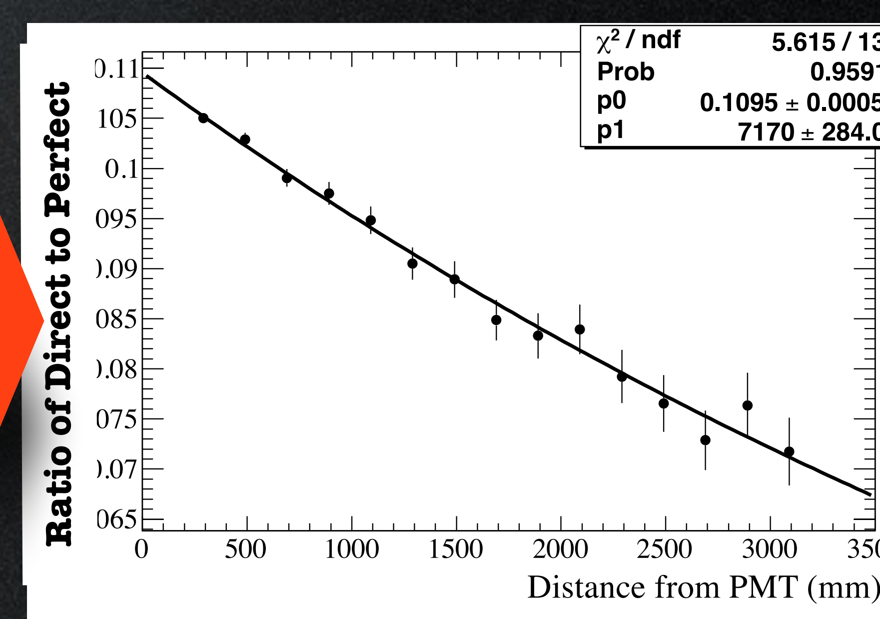
# Calculating T and ε

- Use the detector MC:
    - Direct light only (no scat light)
    - Perfect Trans. (no scat/abs)
- Produce a "point sources" of Cherenkov light
    - 100 simultaneous 3 MeV electrons ("electron bombs")
- For ε (PMT angular acceptance):
    - Bombs vs angle
- For T (water transmission):
    - Bombs vs distance
    - Ratio of Direct Light to Perfect Trans.



# 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