A New Method of Event Reconstruction for the Hyper Kamiokande Detector

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Physics Goals

- All Hyper-K physics goals depend on the quality of the event reconstruction, especially at higher energy
- CP violation
  - Electron momentum/angular resolution
  - π^0 rejection (i.e. π^0 detection efficiency)
  - Additional signal channels? ν_e-CCπ^+?
- Proton decay
  - $e^+\pi^0$: electron/photon kinematics
  - $K^+\overline{\nu}$: timing resolution; efficiency to detect low energy particle in the presence of high energy particles

A New Algorithm: **fiTQun**

- For each SK event, we have, for every hit PMT
  - A measured charge
  - A measured time
- For a given track(s) hypothesis, a charge and time PDF can be produced for every PMT
  - Fitter modifies the track parameters to maximize the correspondence between the measured values and the PDFs
  - Based on the algorithm use by MiniBooNE (NIM A608, 206 (2009))
- Multi-track fits are possible using the same procedure
  - e.g. electron and π^0 fits use the same machinery
    - Can directly compare fit likelihoods
    - Current reconstruction (**apfit**) uses different techniques for π^0s
  - Can fit π^+ tracks as well (more later)

The Likelihood Fit

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

- A single track in the detector 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 probability distribution function (PDF) is produced for every PMT
  - Charge PDF can be factorized into **Predicted charge, μ** and **PMT charge response**
- The fitter maximizes the likelihood to determine **x**
  - **For particle ID**: compare final likelihoods for different particle hypotheses

Time PDF

Charge PDF

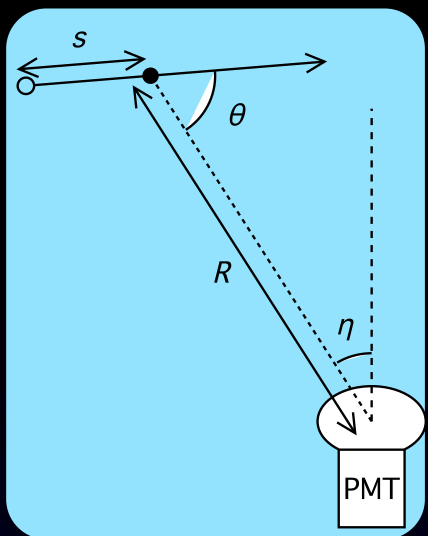
PMT Charge Response:

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

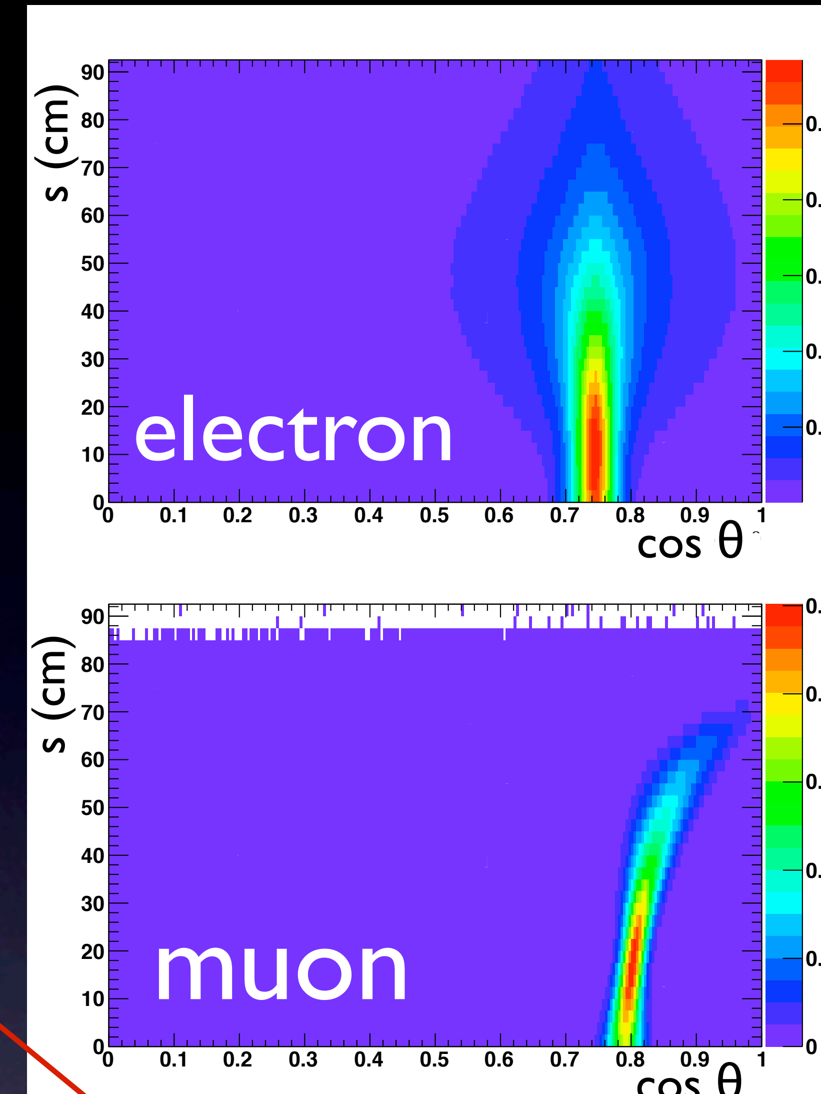
Integral over track length

PMT solid angle

Water attenuation

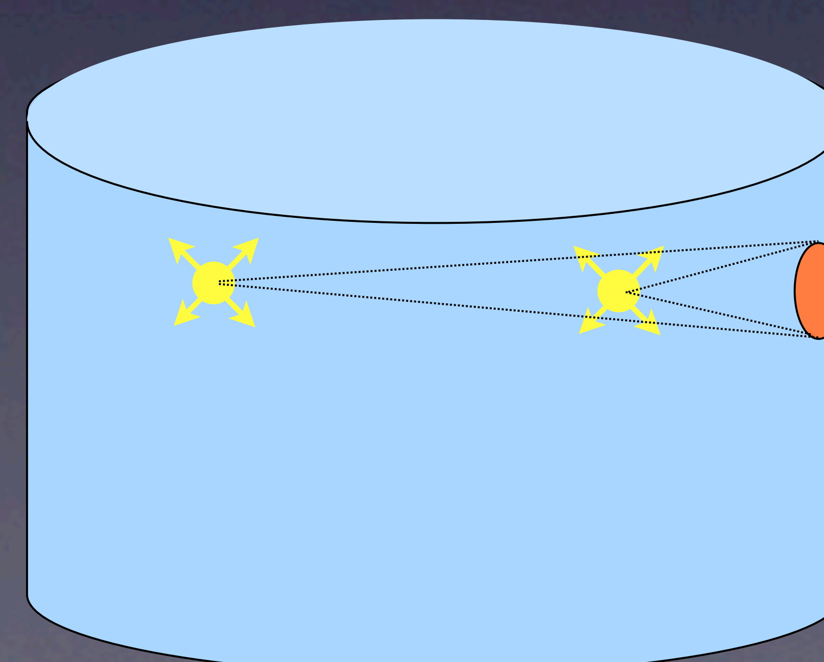
PMT angular response

Cherenkov light emission profile



- μ^{dir} is the predicted charge due to “direct light” only (scattered light is handled separately & less important)
- 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

PMT solid angle



Integral Calculation

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

Light Yield

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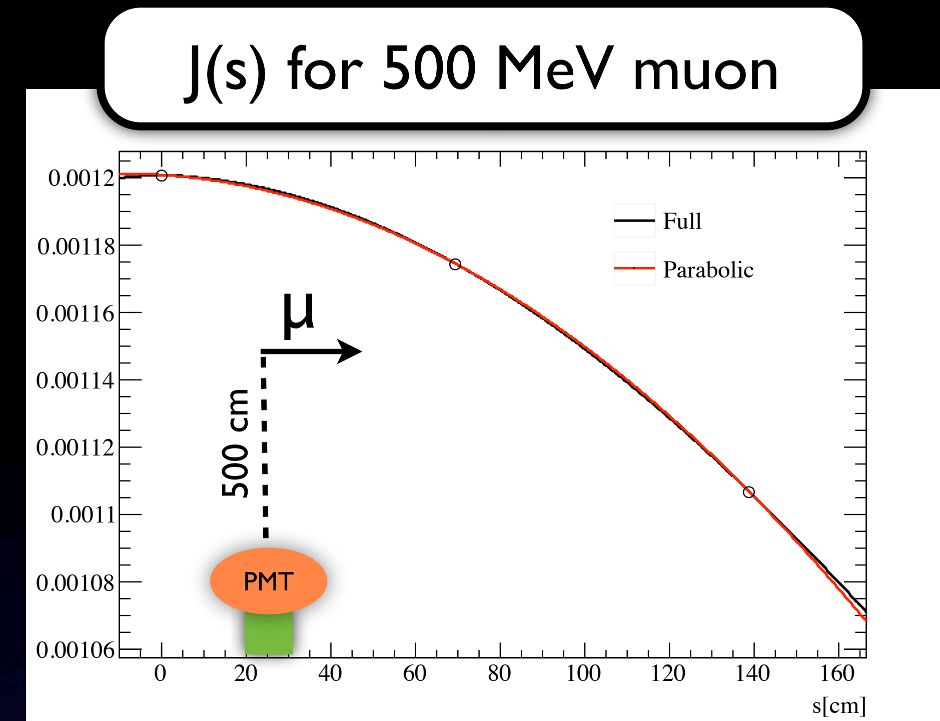
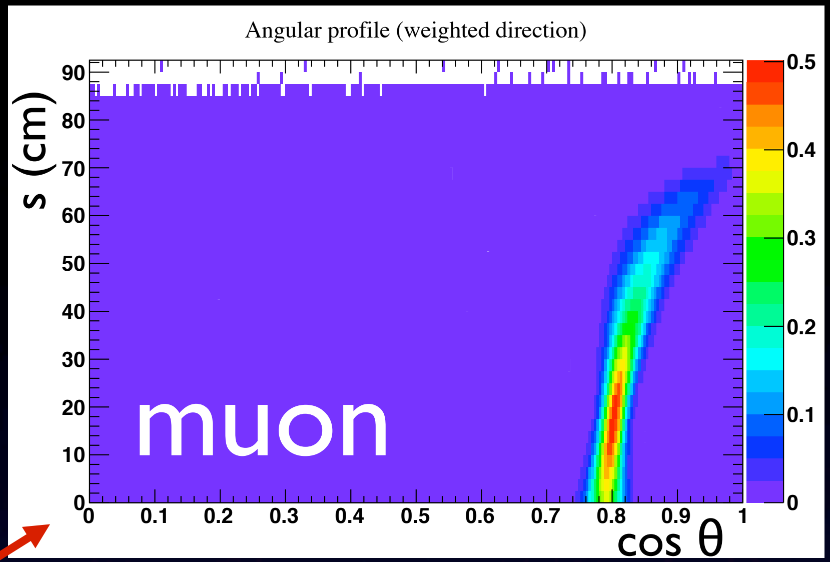


- g(s) can vary rapidly as a function of s
    - e.g. when PMT moves into or out of the Cherenkov cone
- However, **$J(s) \equiv \Omega(s)T(s)\varepsilon(s)$** varies slowly as a function of s
    - Can approximate as **$J(s) = j_0 + j_1 * s + j_2 * s^2$** (“**parabolic approximation**”)
    - Evaluate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

Modularized Design

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

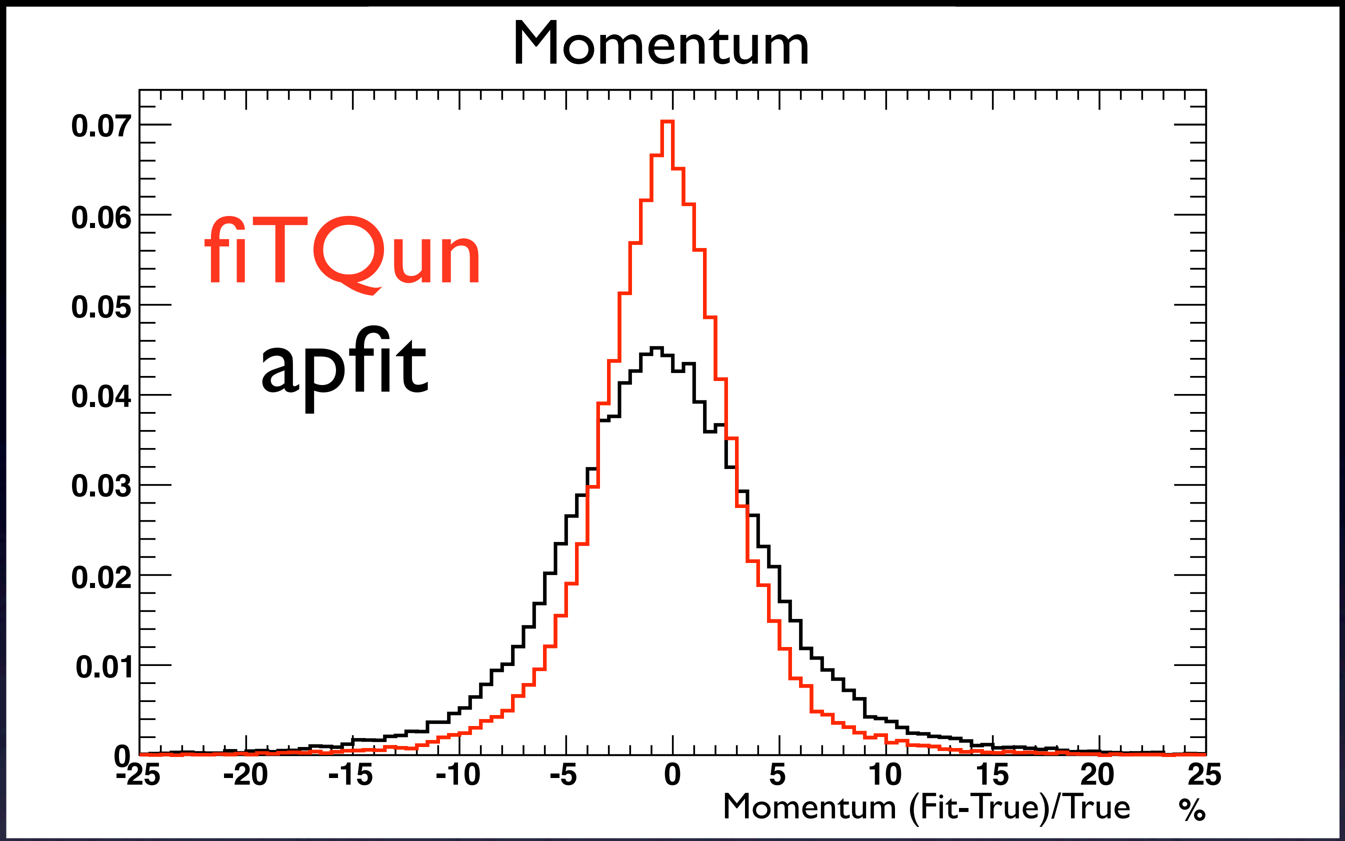
Light Yield | Integral over track length | Cherenkov emission profile | PMT solid angle | Water attenuation | PMT angular response



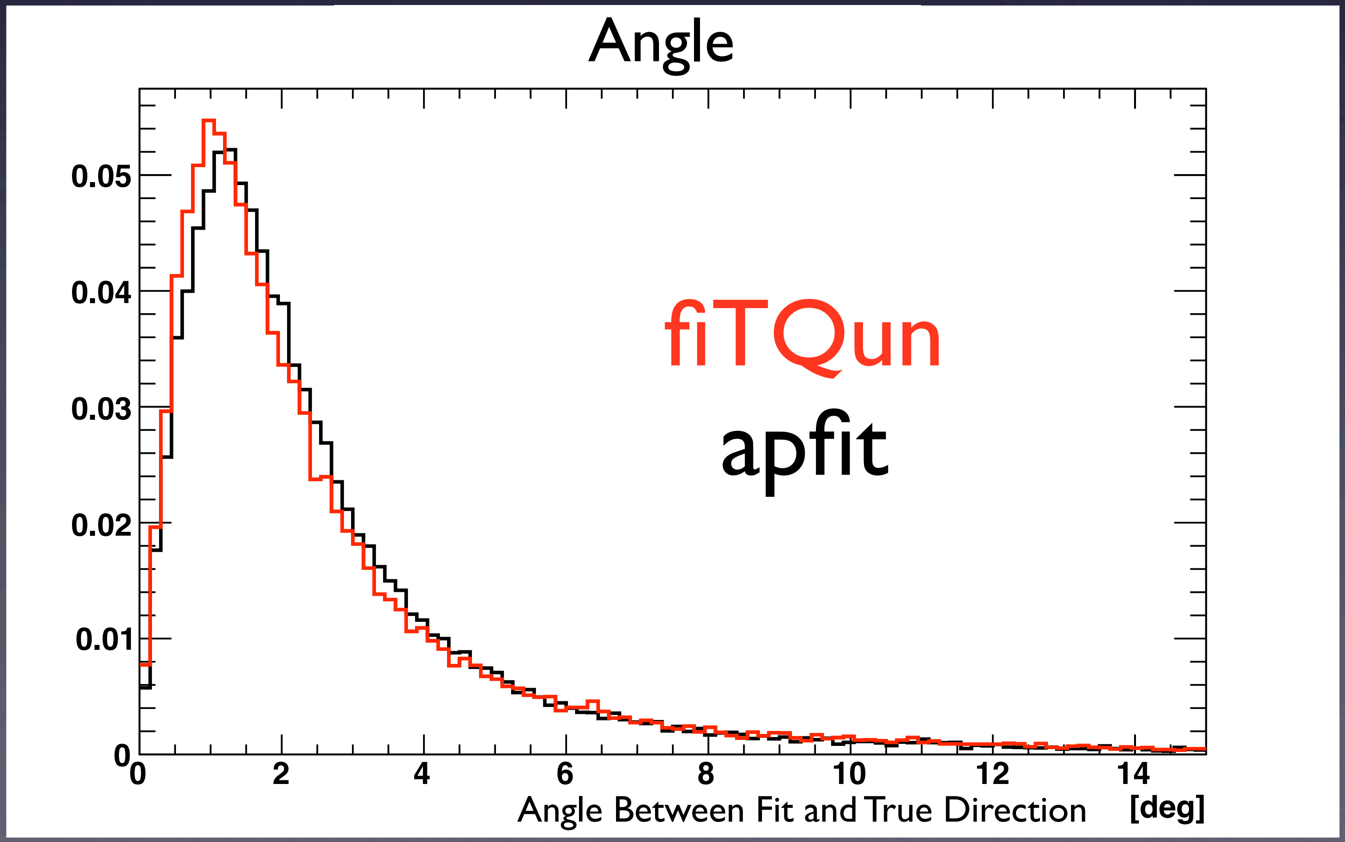
- To add a new particle type, only need to generate a new g(s,cos)
- To change the water quality, only need to modify T(R)
- To change the PMT size/type, only need to modify Ω(R)/ε(η)
- To change the tank geometry, only need to generate a new scattering table
- To change the photocathode coverage, no modifications are required

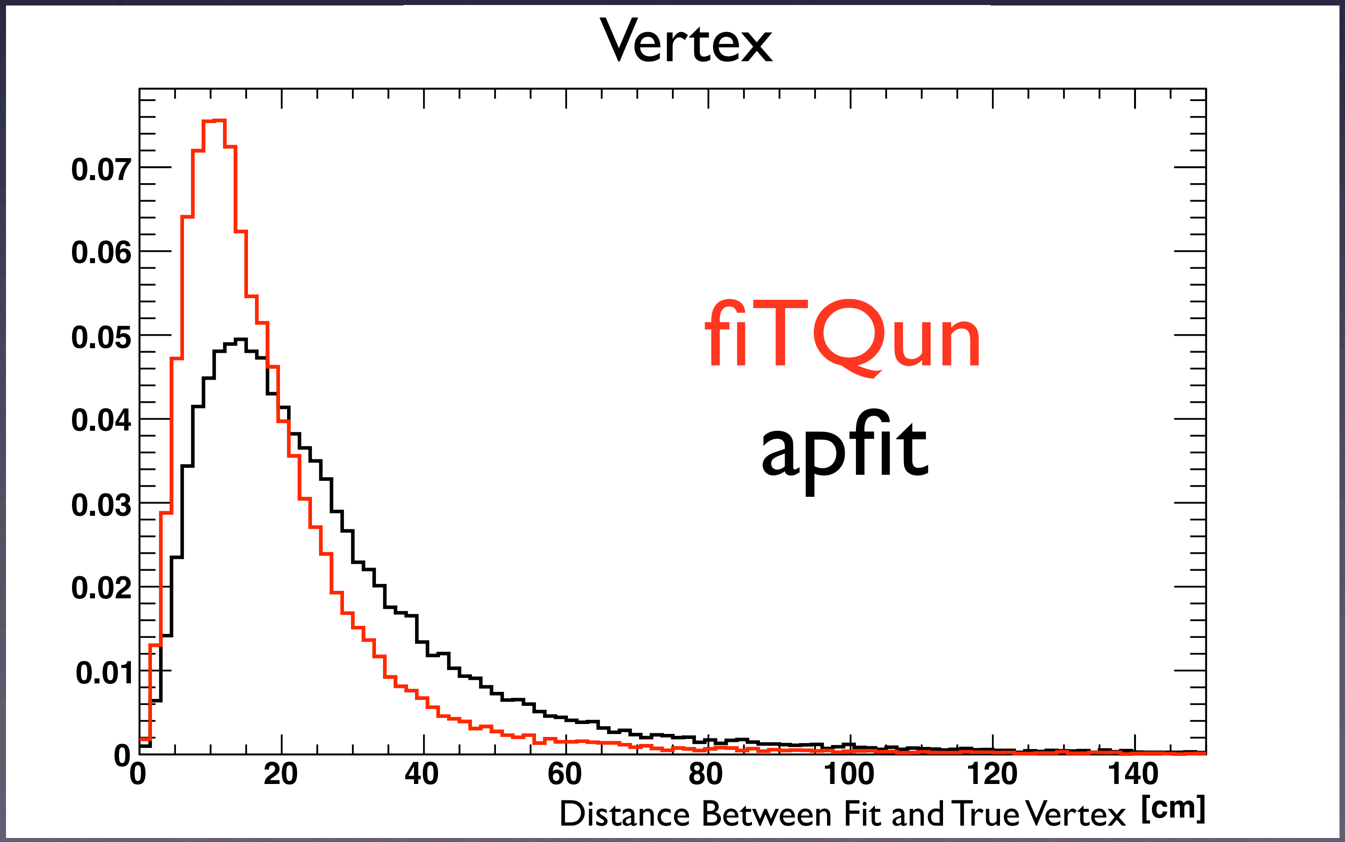
One-Track Fit Results (MC Only)

Electrons

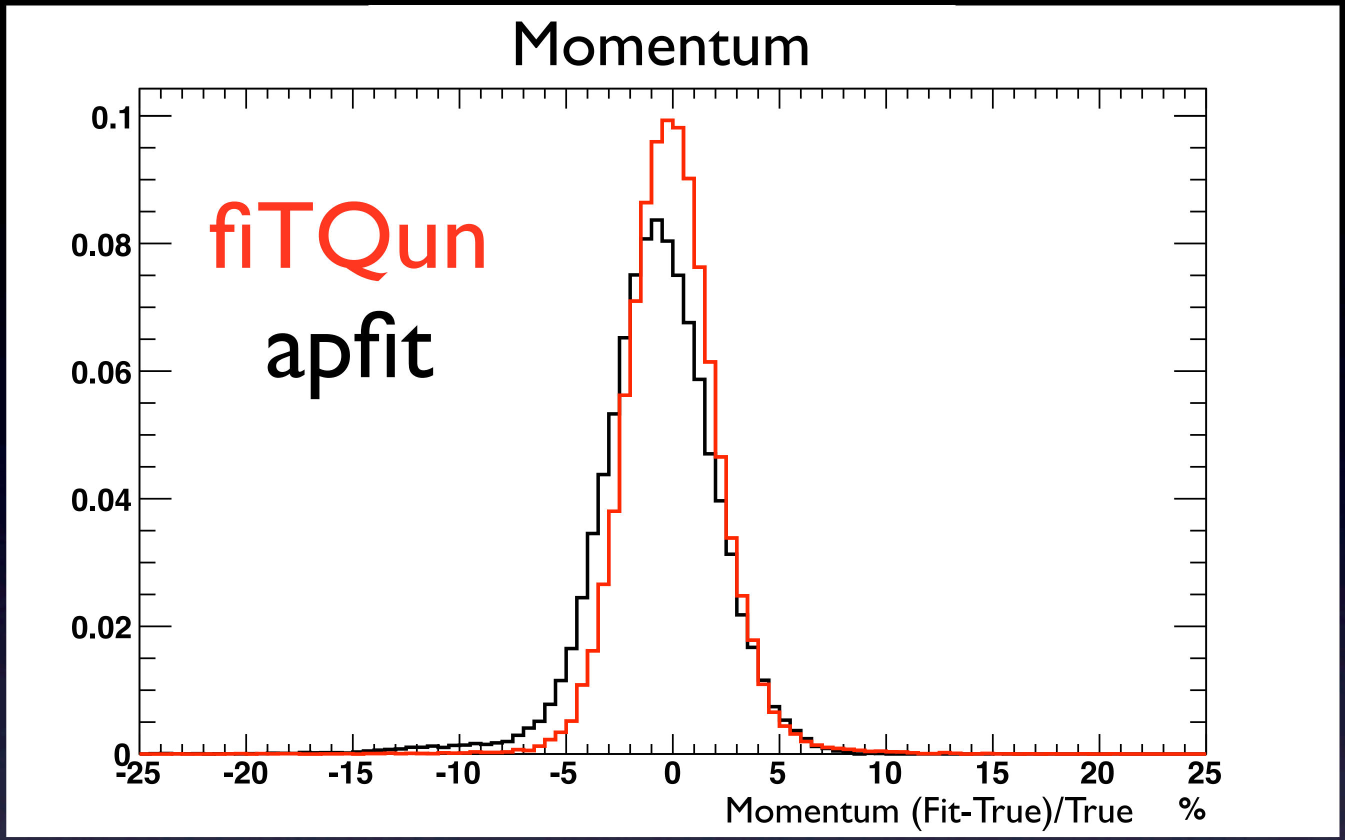


- Uniform distribution of electrons between 0 and 1 GeV/c
  - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution

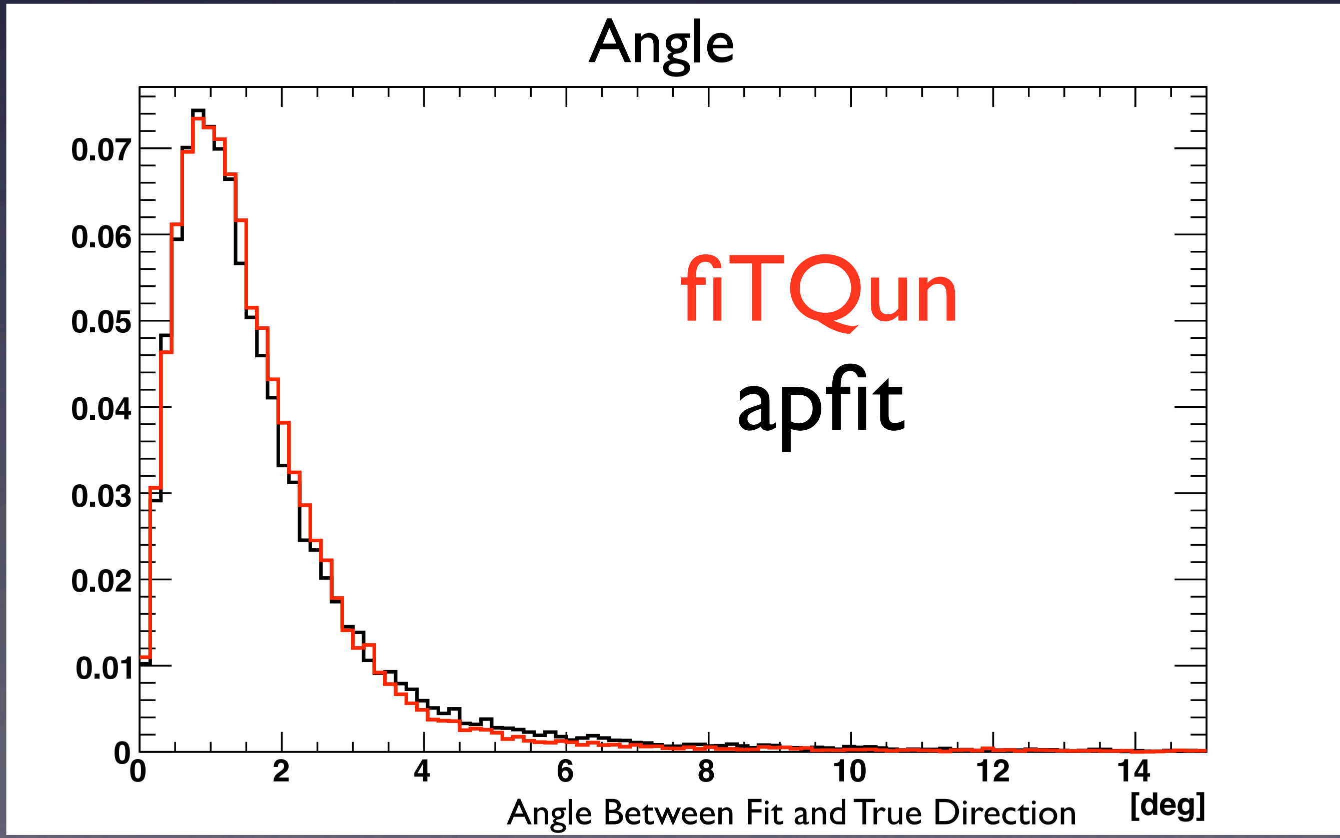


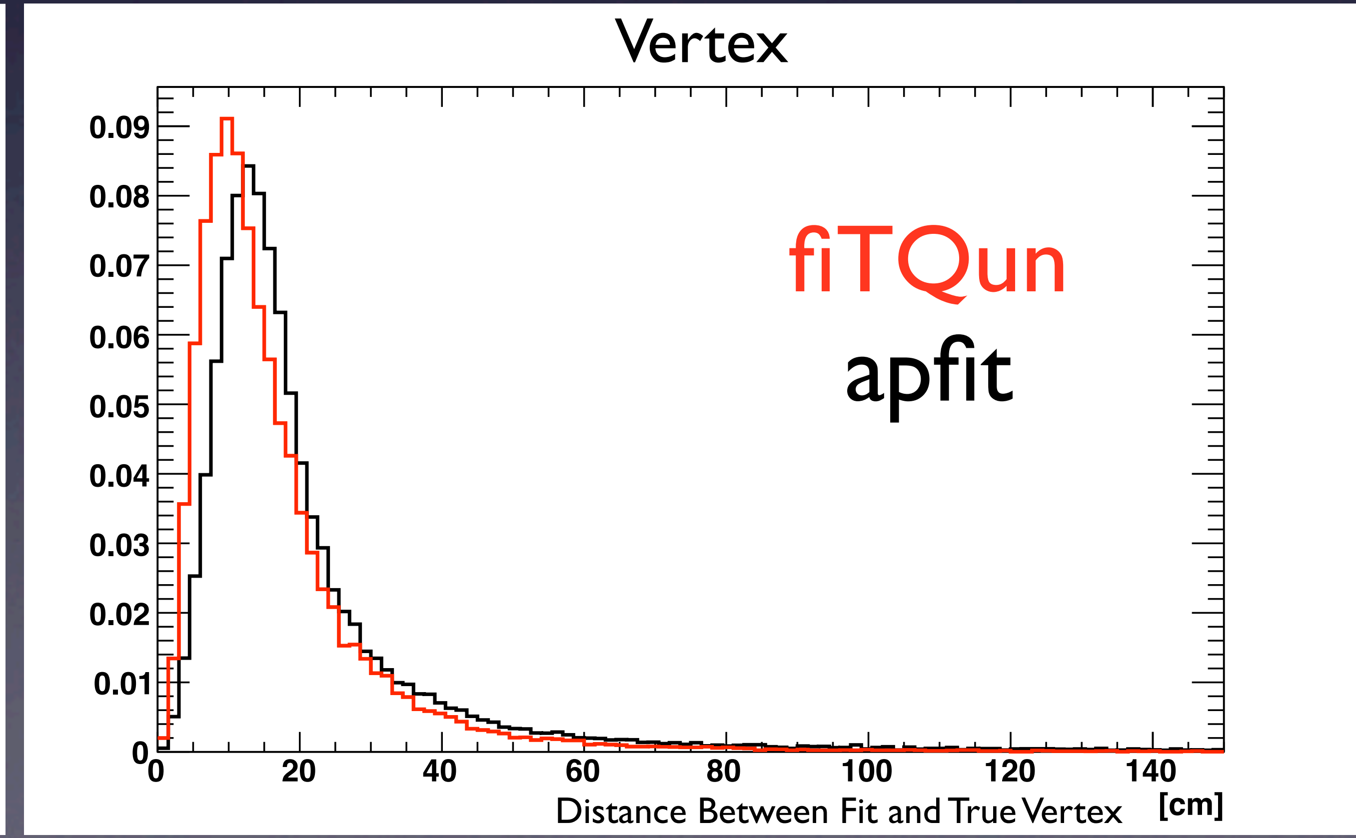


Muons

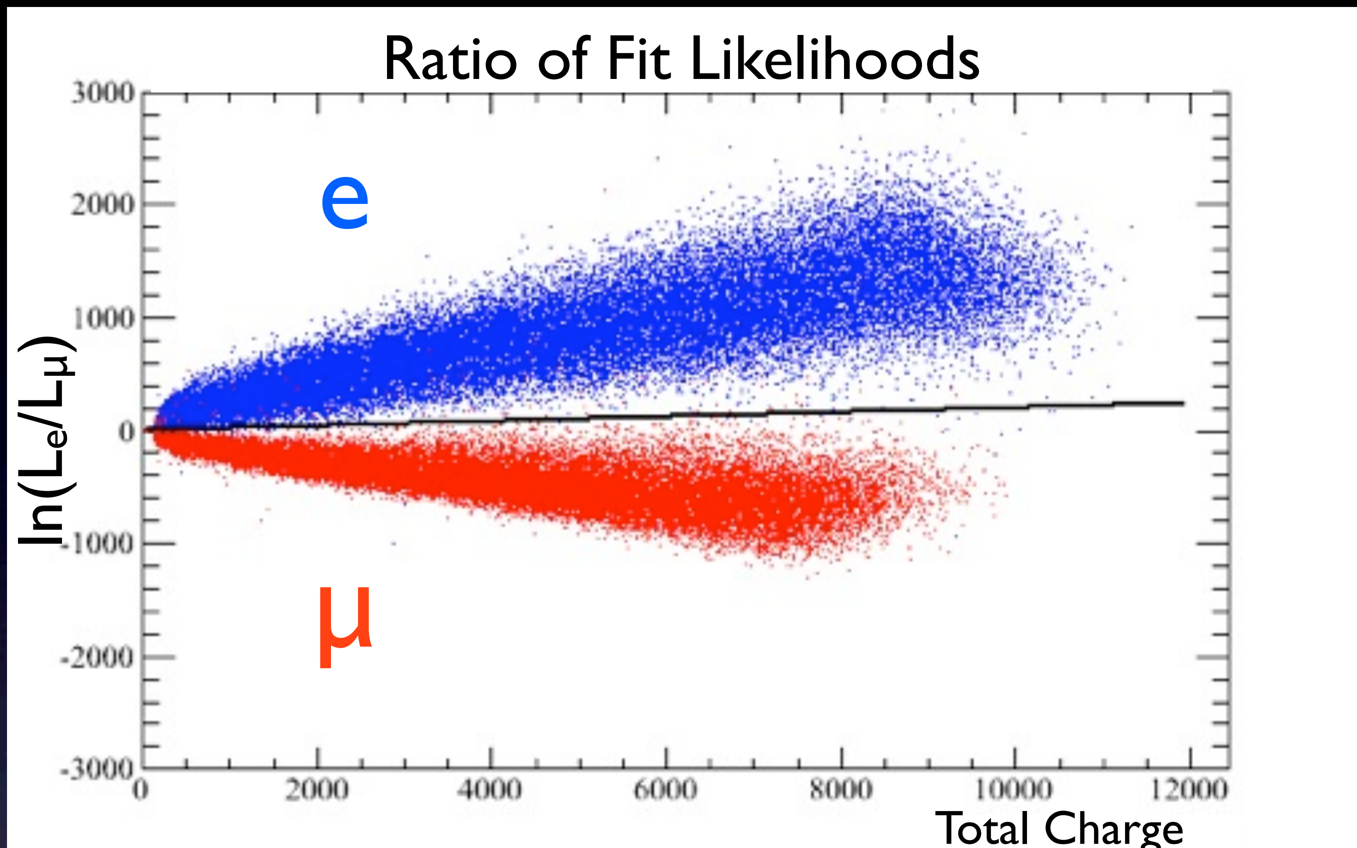


- Uniform distribution of muons between 0 and 1 GeV/c
  - Isotropic & random position (inside FV & charge>200pe)
- Significant improvements in the vertex and momentum resolution

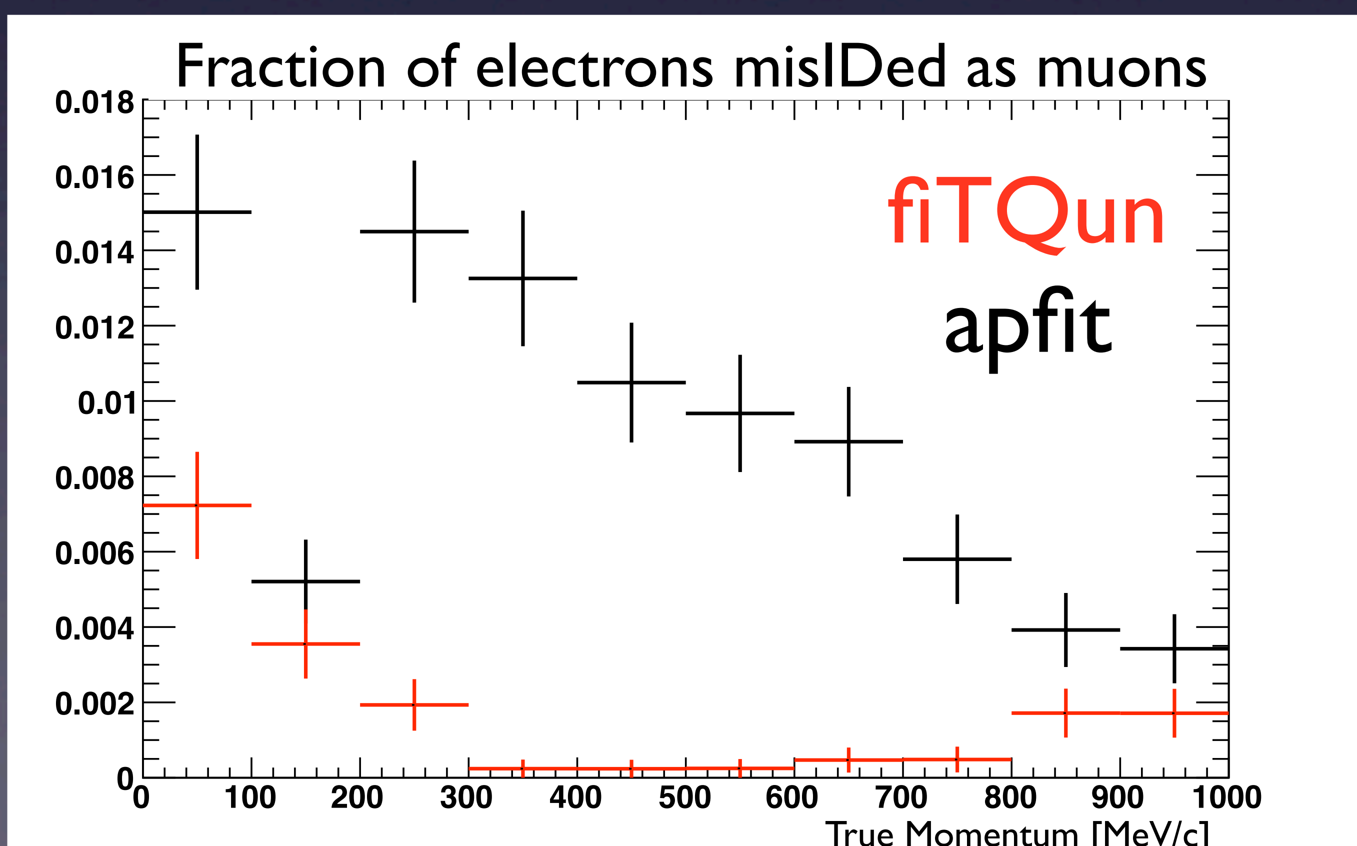


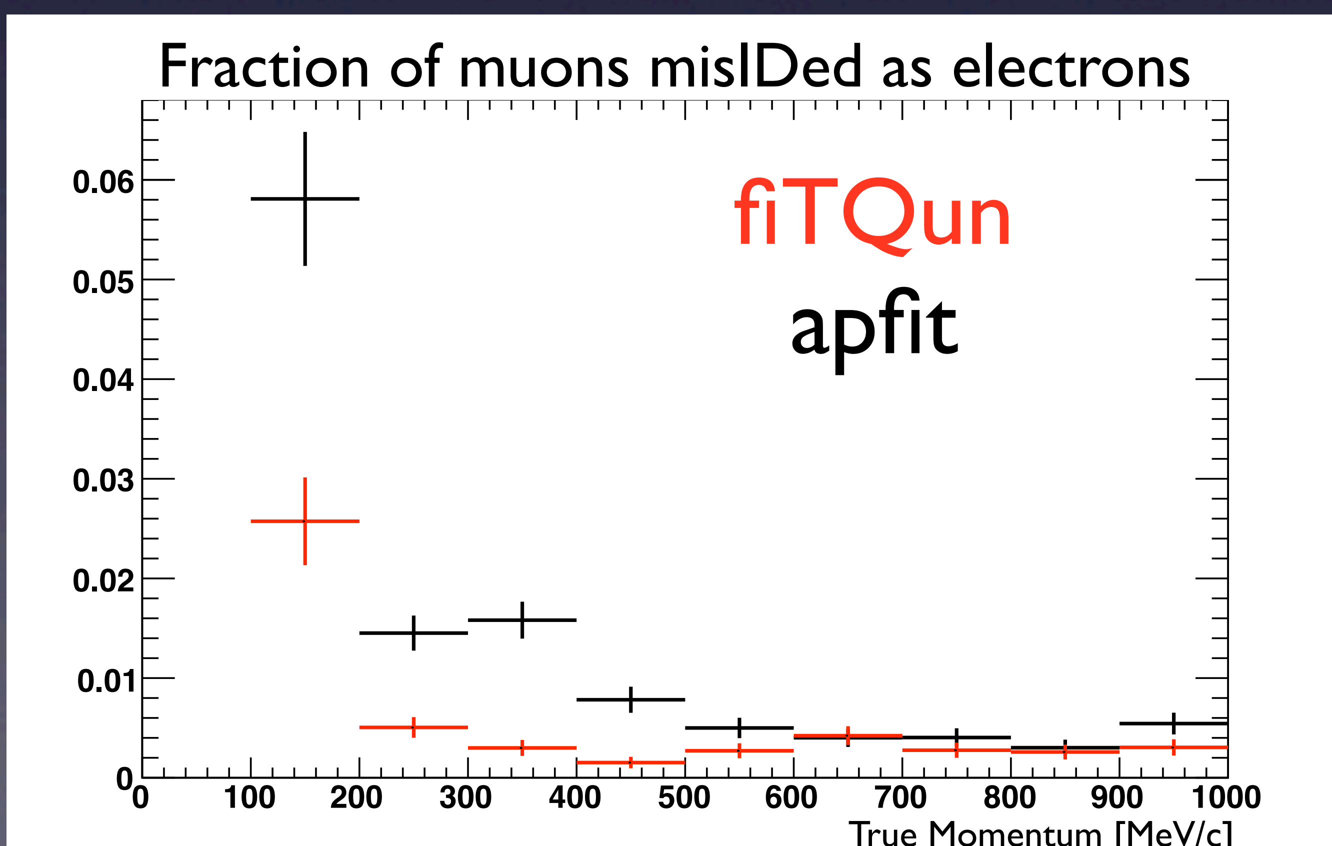


Single Track Particle ID



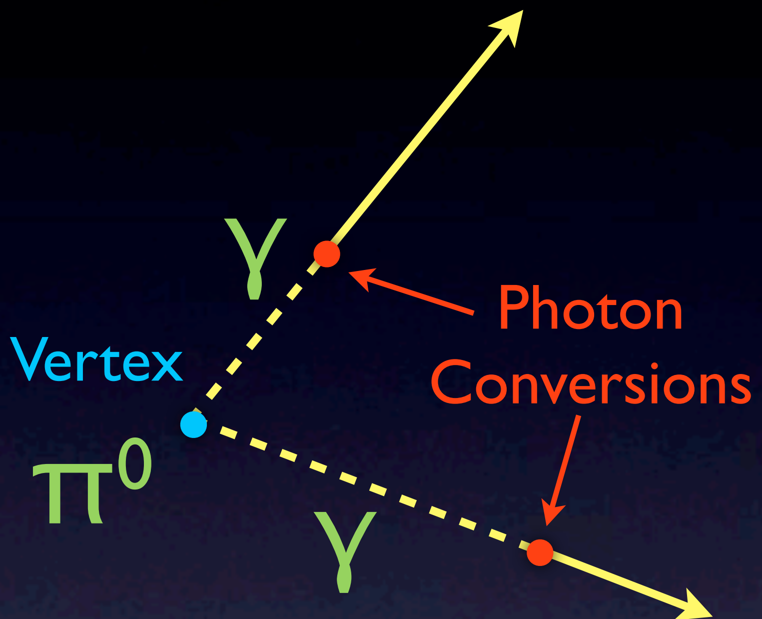
- Simple line cut can be used to separate muons and electrons
- Significantly improved particle ID





π^0 Fitter

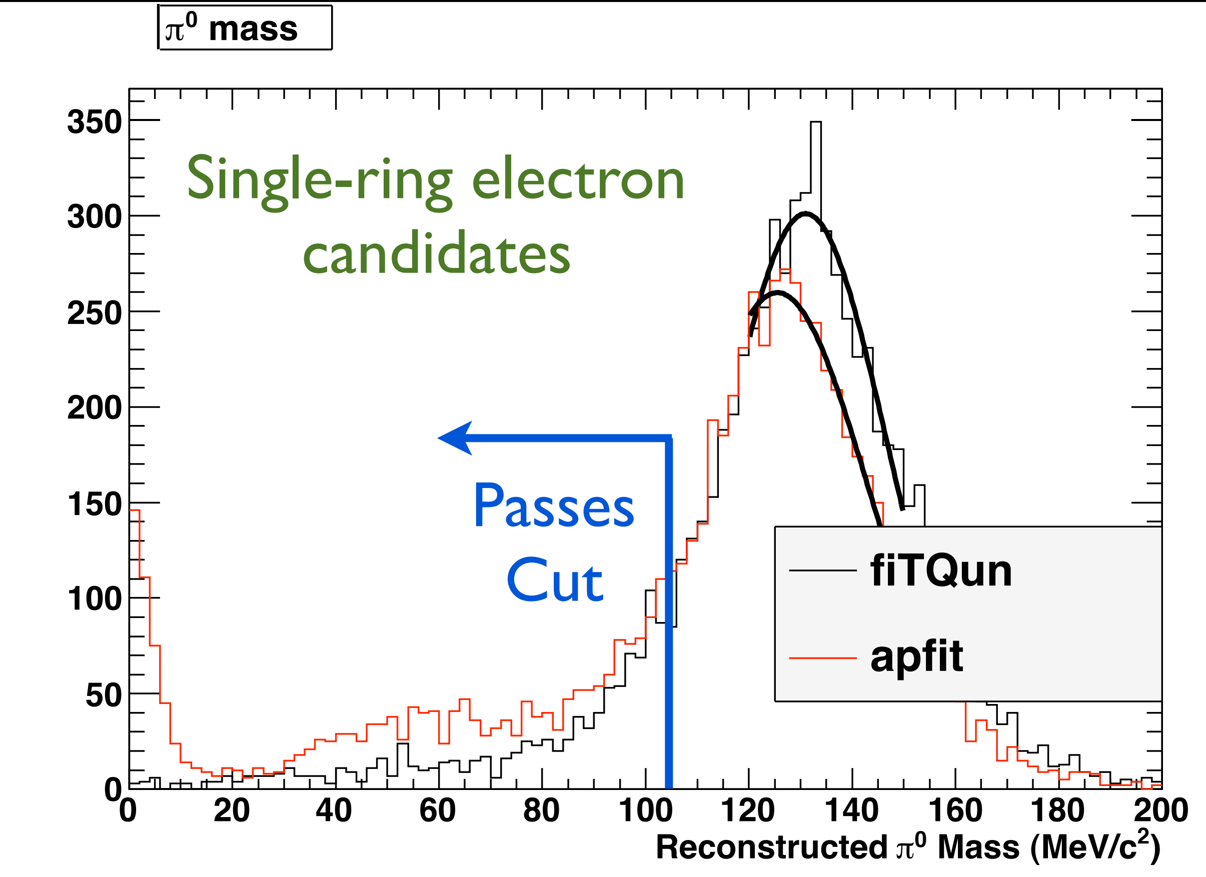
- Assumes two electron hypothesis rings produced at a common vertex
- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions ($\theta_1, \varphi_1, \theta_2, \varphi_2$)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)

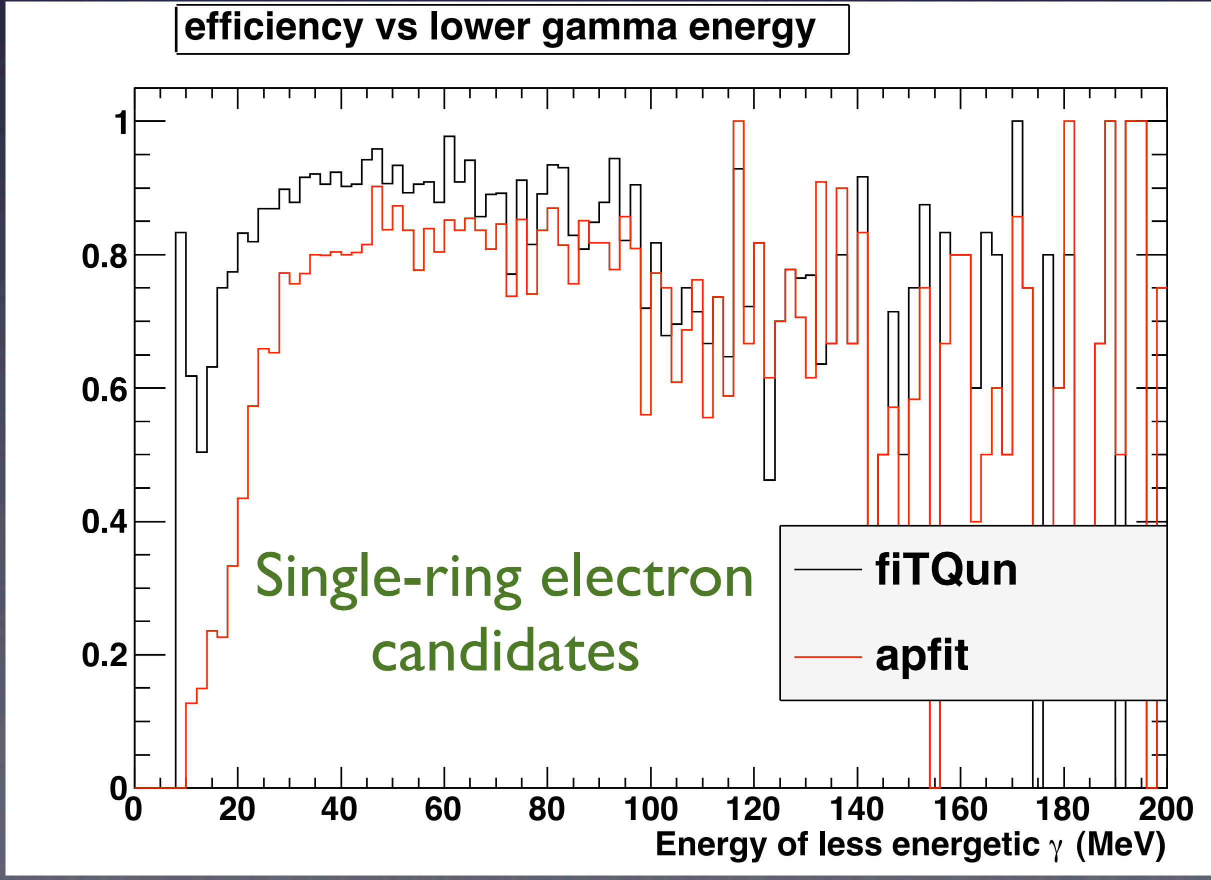


- **Seeding the fit**
  - Use result of single-track electron fit
  - Scan over various angles with a 50 MeV/c electron and evaluate the likelihood function
  - First, fit while floating only p_1 and p_2
  - Do full 12 parameter fit
- **Tested on ~50,000 MC π^0 events ~30,000 electron events**
  - Random momenta between 0 and 500 MeV/c, random vertex position, and isotropic directions

True π^0's

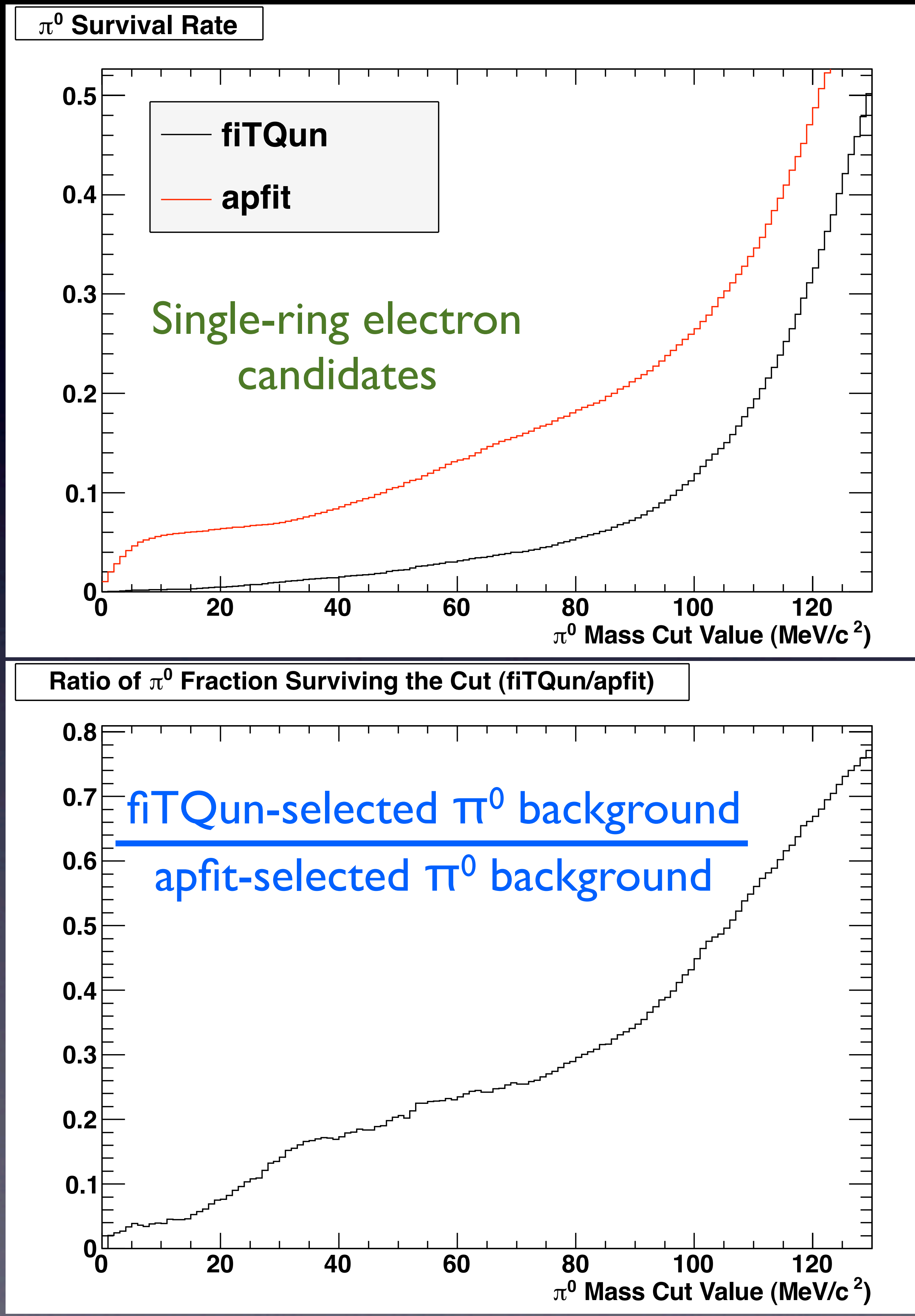
- In the Hyper-K LOI, ν_e appearance measurements cut on π^0 mass to remove π^0 background
- The π^0 mass tail is much smaller for fiTQun than standard SK reconstruction
  - Significant spike at zero mass in apfit
- Lower plot:
  π^0 rejection efficiency after 105 MeV/c^2 cut (T2K cut value)
  - fiTQun is more sensitive to lower energy photons





π^0 Rejection Cuts

- Can check fraction of π^0 that survive various values of the π^0 mass cut
  - T2K ν_e appearance measurement uses 105 MeV/c^2 cut
- Lower plot: ratio of upper plot (fiTQun / apfit)
  - For a cut of ~60-80, fiTQun selects <30% of the background selected by apfit

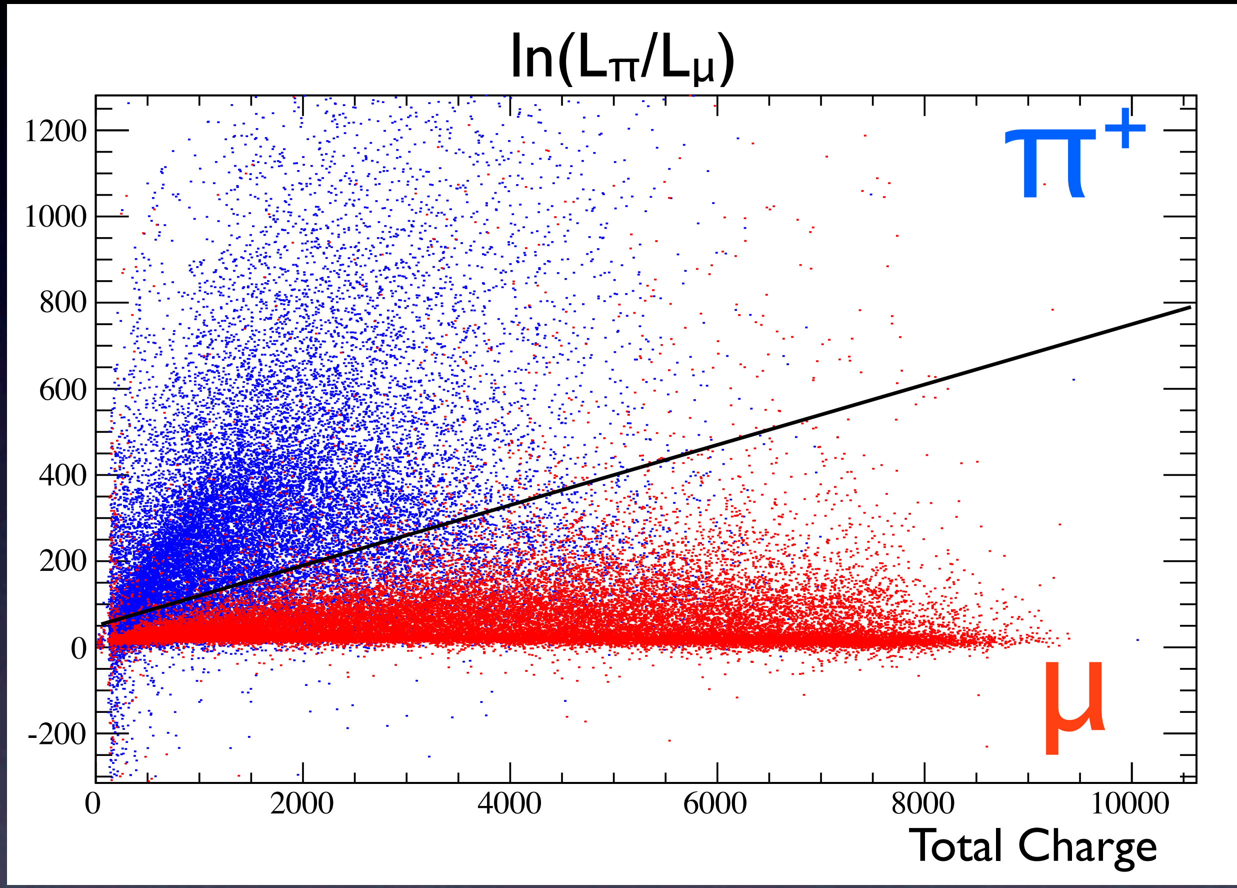


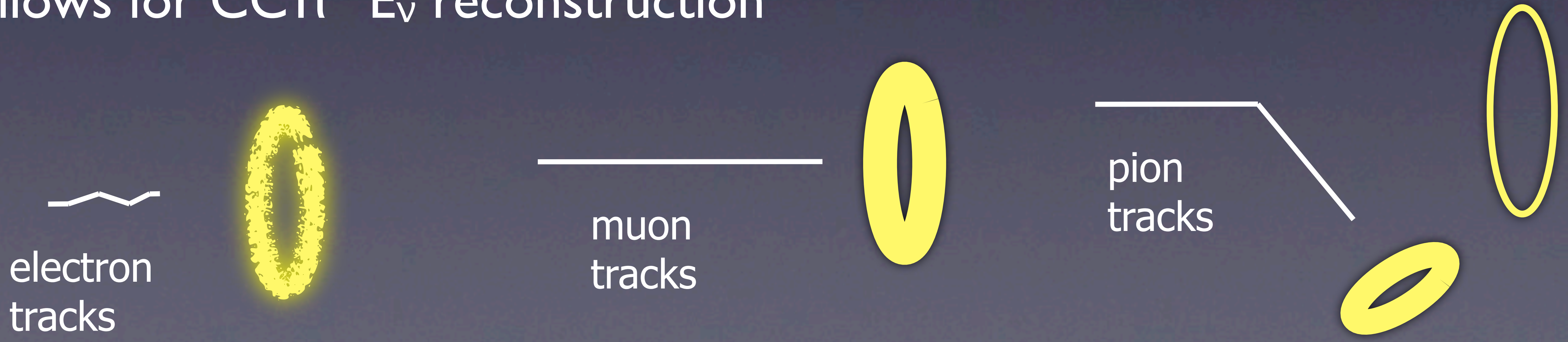
π^0 Rate Measurement

- ν_μ-NC events (mostly π^0s) are currently ~40% of the T2K ν_e appearance background
  - Also the largest contribution to the uncertainty on the background
  - 43% rate uncertainty assumed for T2K oscillation analysis based on fits to MiniBooNE data
- Can also use reconstructed π^0 events at the far detector to constrain this uncertainty
  - Even the ~15 events in the current T2K data set can provide a useful constraint on the π^0 background
  - For a Tokai-to-Hyper-K experiment, external data and near detector measurements will likely not be necessary

π^+ Fitter

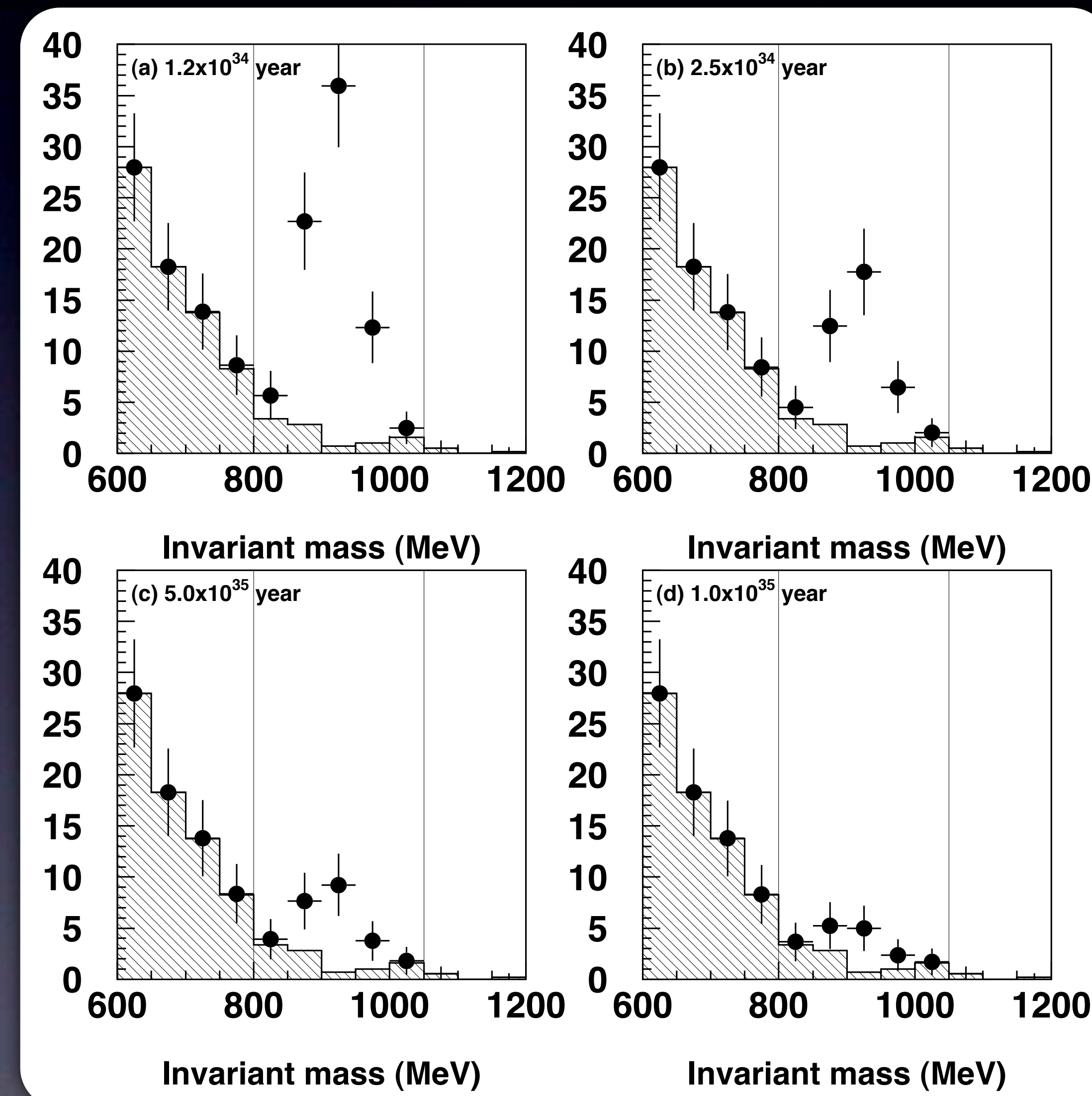
- Pions and muons propagate and produce Cherenkov light in a very similar manner (similar masses)
- The main difference is due to hadronic interactions
- Ring pattern observed is a "kinked" pion trajectory
- This is the first demonstration of pion/muon separation at SK (in MC)
- Allows for CCπ^+ E_ν reconstruction





Proton Decay: $e^+\pi^0$

- Improved reconstruction can have significant consequences on proton decay searches
- Current SK $e^+\pi^0$ measurement has low background (0.3 events; 141 kton*year)
  - At Hyper-K, background is much larger at 10 years of exposure (9 events; 5.6 Mton*year)
  - Backgrounds are controlled with cuts on π^0 and proton mass
    - Improved resolution allows these cuts to be tightened
  - π^0 mass cut can only be used if both photon rings are detected
    - fiTQun has improved detection of low energy photons



Proton Decay: $K^+\bar{\nu}$

- Hyper-K LOI claims a 90% CL of $2.5*10^{34}$ years after 10 years of running
- 7.1% efficiency for $K^+ \to \mu^+$ channel (with γ tag)
  - Absolute efficiency limited to 25% (fraction of ^{15}N decays that produce a 6.3 MeV photon)
  - Hits in a 50 degree region around the muon track are removed from gamma search
  - fiTQun improves ability to detect low energy photons, even in the presence of a high energy ring
- 6.7% efficiency for $K^+ \to \pi^+\pi^0$
  - No attempt to reconstruct π^+ ring (205 MeV/c)
    - Instead, look for charge in opposite direction of π^0, veto on any other charge
  - fiTQun has improved low energy ring detection as well as a new π^+ hypothesis ring fit to search for the dim π^+ ring
- Opportunity for significant efficiency gains using fiTQun
  - For comparison, 28 kt fiducial LAr detector gives a 90% CL of $3.5*10^{34}$ years after 10 years of running

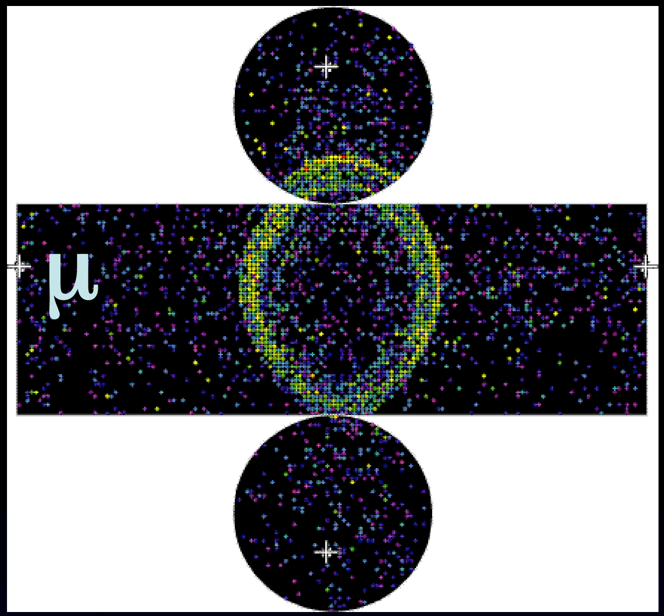
Summary

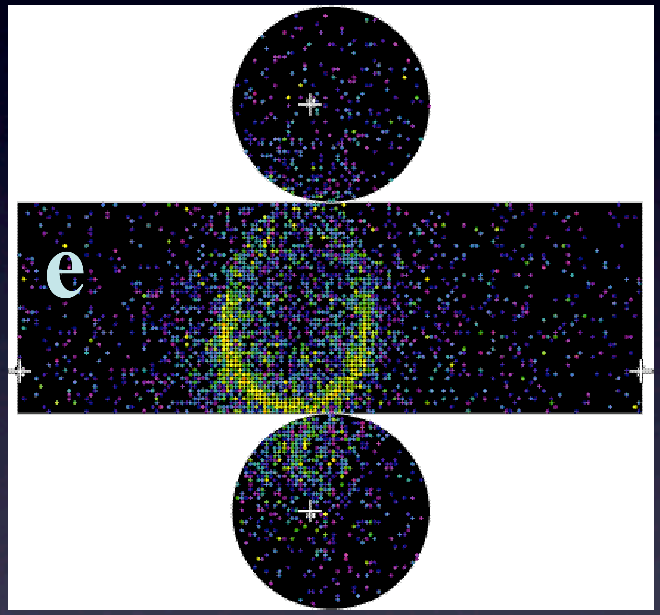
- We now have new reconstruction for single track muon and electron hypotheses, as well as first implementations of π^0 and π^+ fitters
  - All fitters are out-performing current SK reconstruction (only on MC so far)
  - A π^+ hypothesis fit has never been used before
- fiTQun can significantly reduce the π^0 background in a CP violation measurement
  - Not only using cuts on π^0 mass, but also $L(\pi^0)/L(e)$ vs various reconstructed parameters
- Improvements expected for proton decay sensitivity
  - Will be particularly interesting for $p \rightarrow K^+ \bar{\nu}$

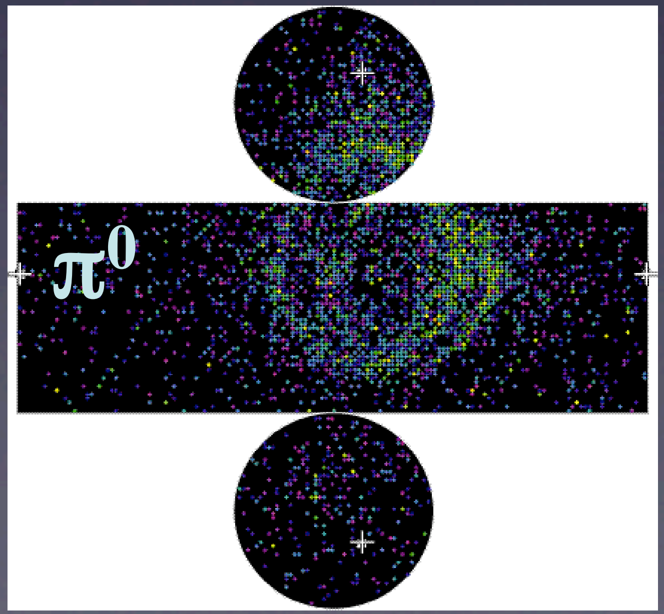
Backups

Super K Particle ID

- Muons rings are thick with sharp edges
  - Long straight tracks (less scattering)
- Electrons produce fuzzy rings
  - More scattering, EM showers
- Photons from π^0 decay convert to e^+/e^- pairs
  - 2 electron-like rings
  - If 1 ring is lost, π^0 will mimic single-electron oscillation signal
- ν_μ neutral current events (mostly π^0s) are currently 42% of the ν_e appearance background
  - Improvements to π^0 rejection can have a significant impact on sensitivity to θ_{13}

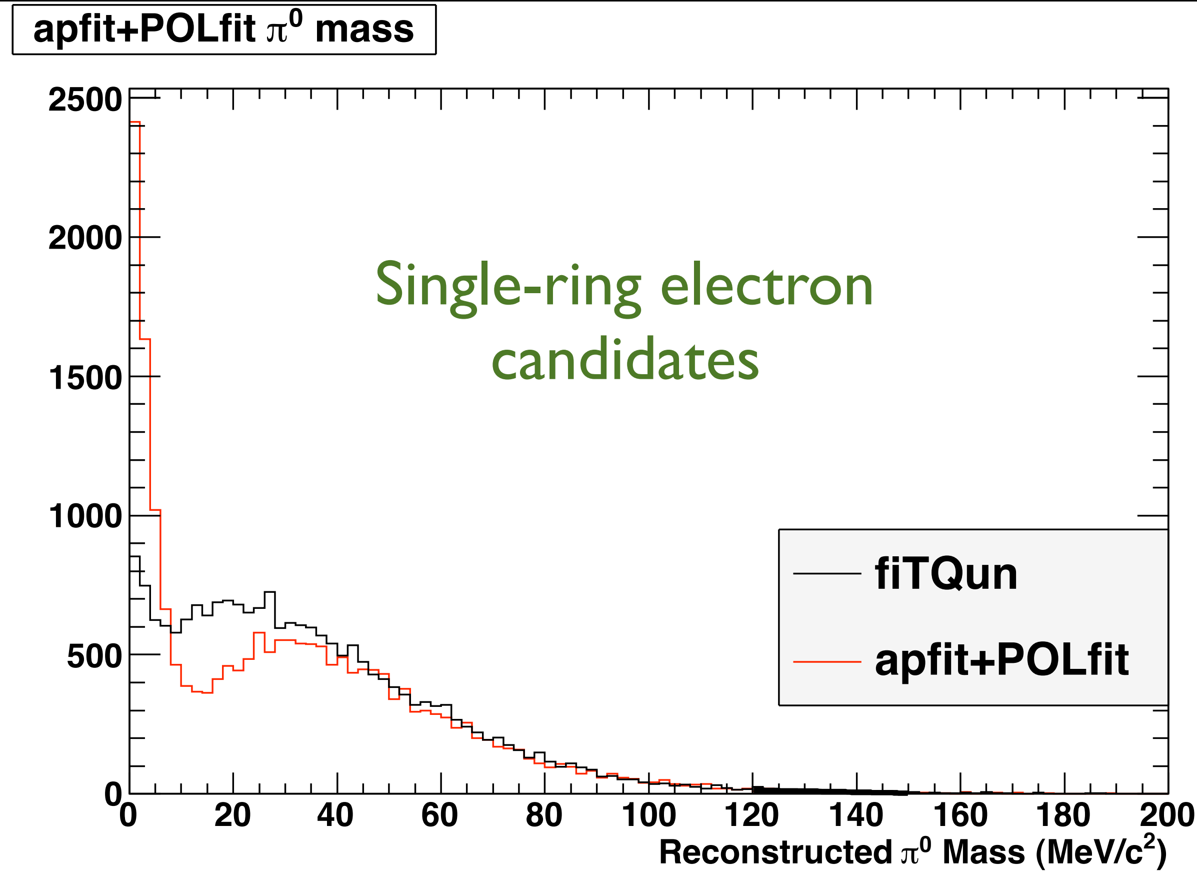


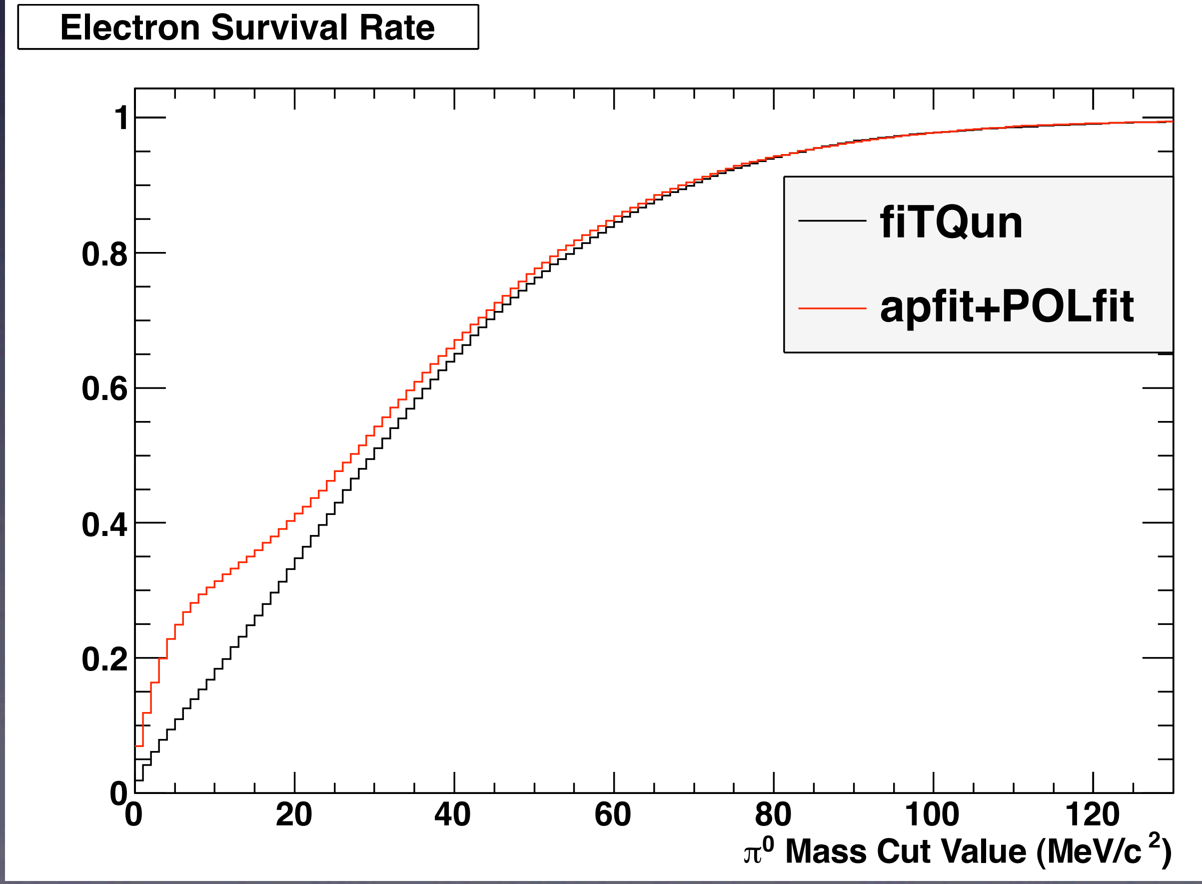




True Electrons

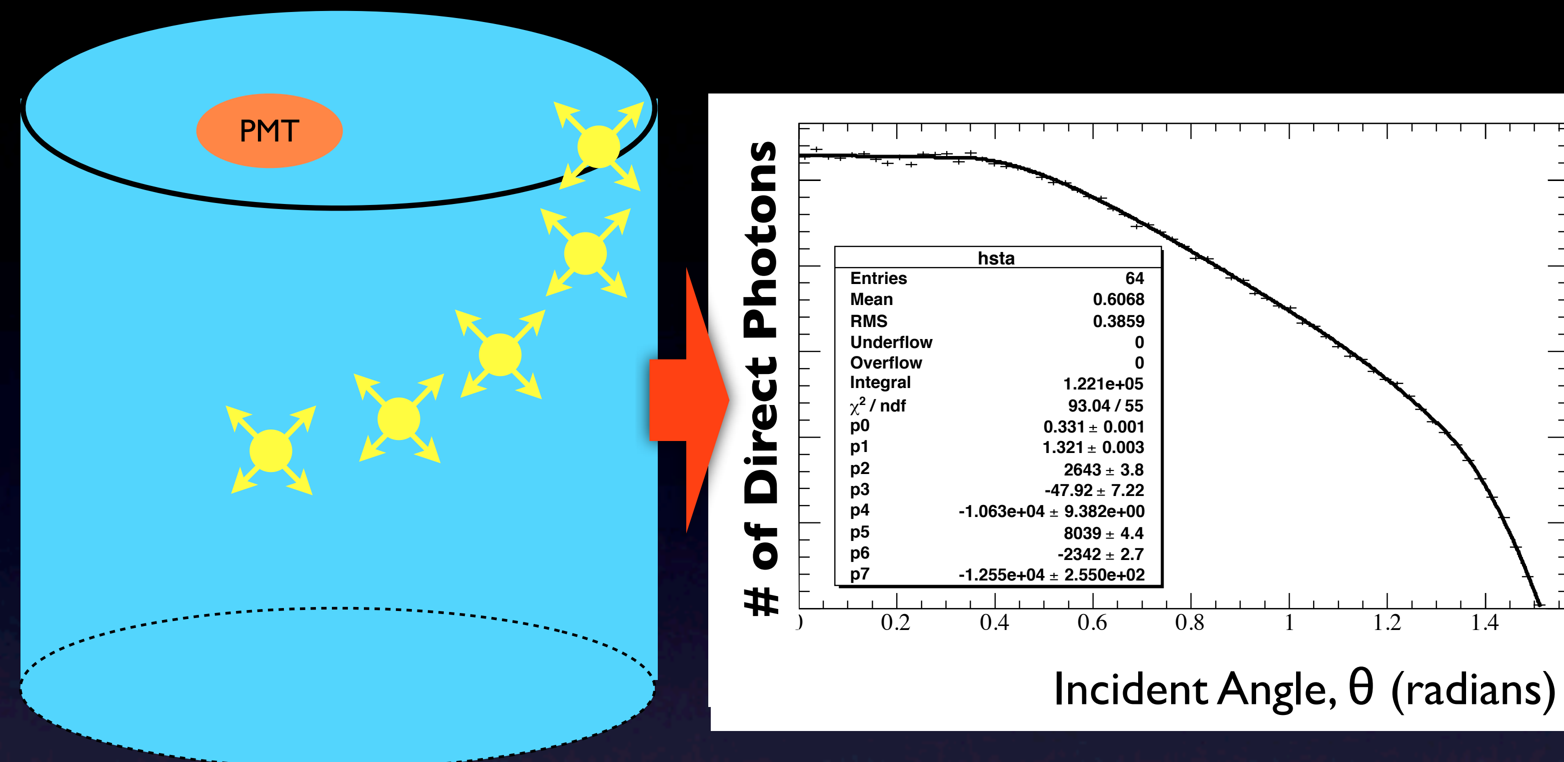
- T2K ν_e appearance measurement cuts on π^0 mass to remove π^0 background
- apfit has a large peak at zero mass
  - Very good if cutting on mass to identify π^0 events
- Lower plot: electron survival rate for various $M_{\pi 0}$ cut values
  - Electron efficiency is the same above ~50-60 MeV/c^2
  - Cut value for current ν_e appearance measurement is 105 MeV/c^2

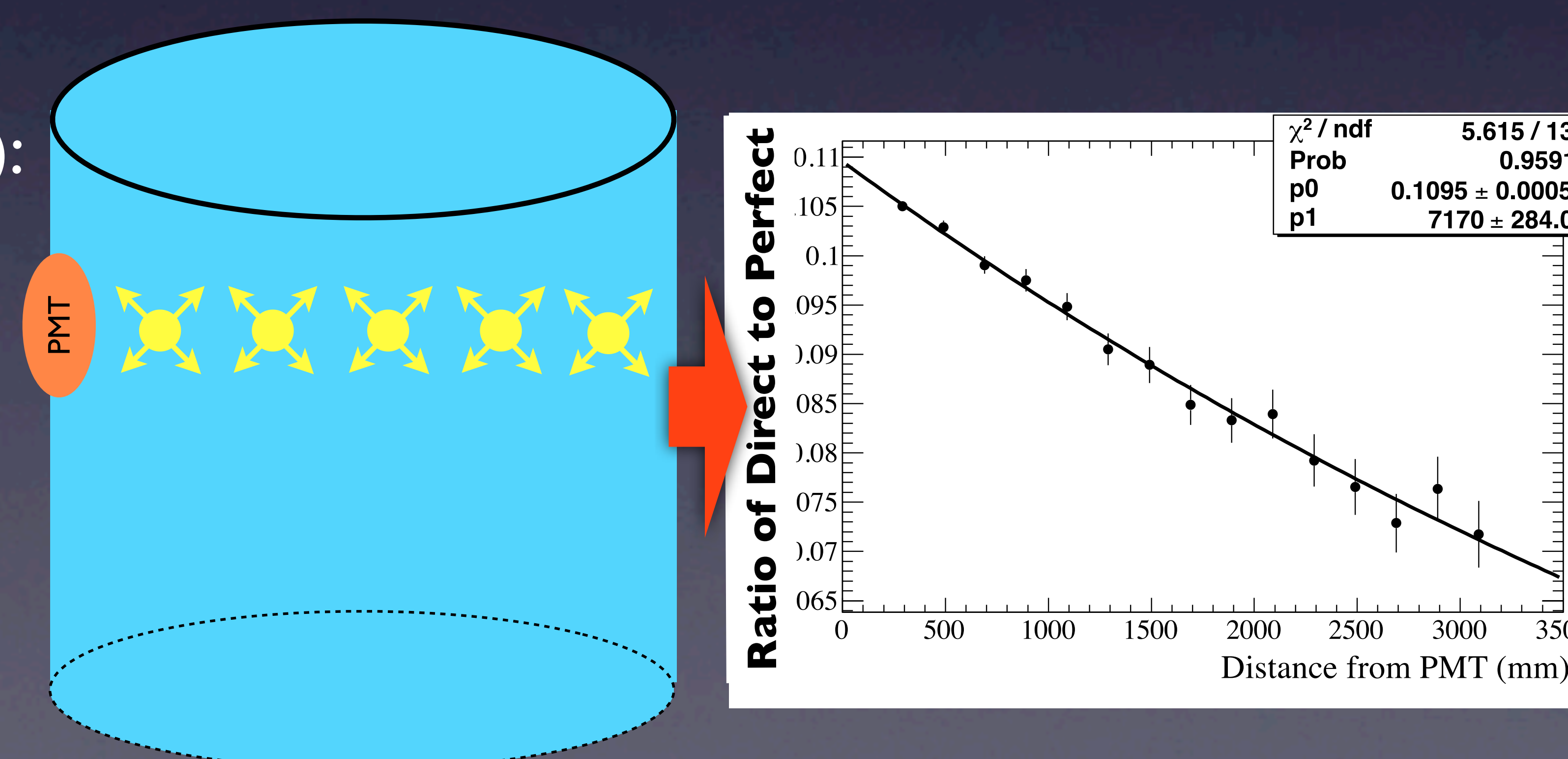




Calculating T and ε

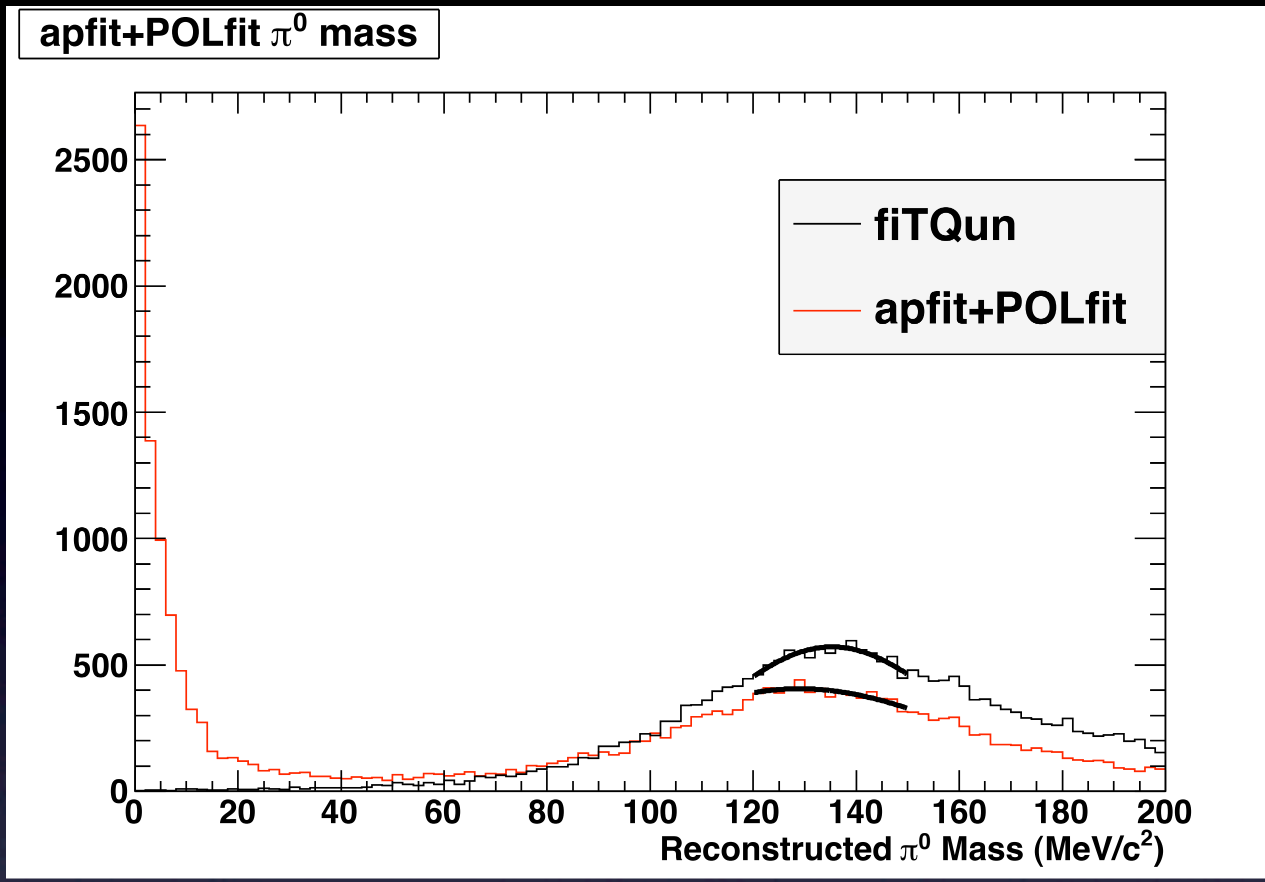
- Use the detector MC:
  - Direct light only (no scat light)
  - Perfect Trans. (no scat/abs)
- Produce a "point sources" of Cherenkov light
  - 100 simultaneous 3 MeV electrons ("electron bombs")
- For ε (PMT angular acceptance):
  - Bombs vs angle
- For T (water transmission):
  - Bombs vs distance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

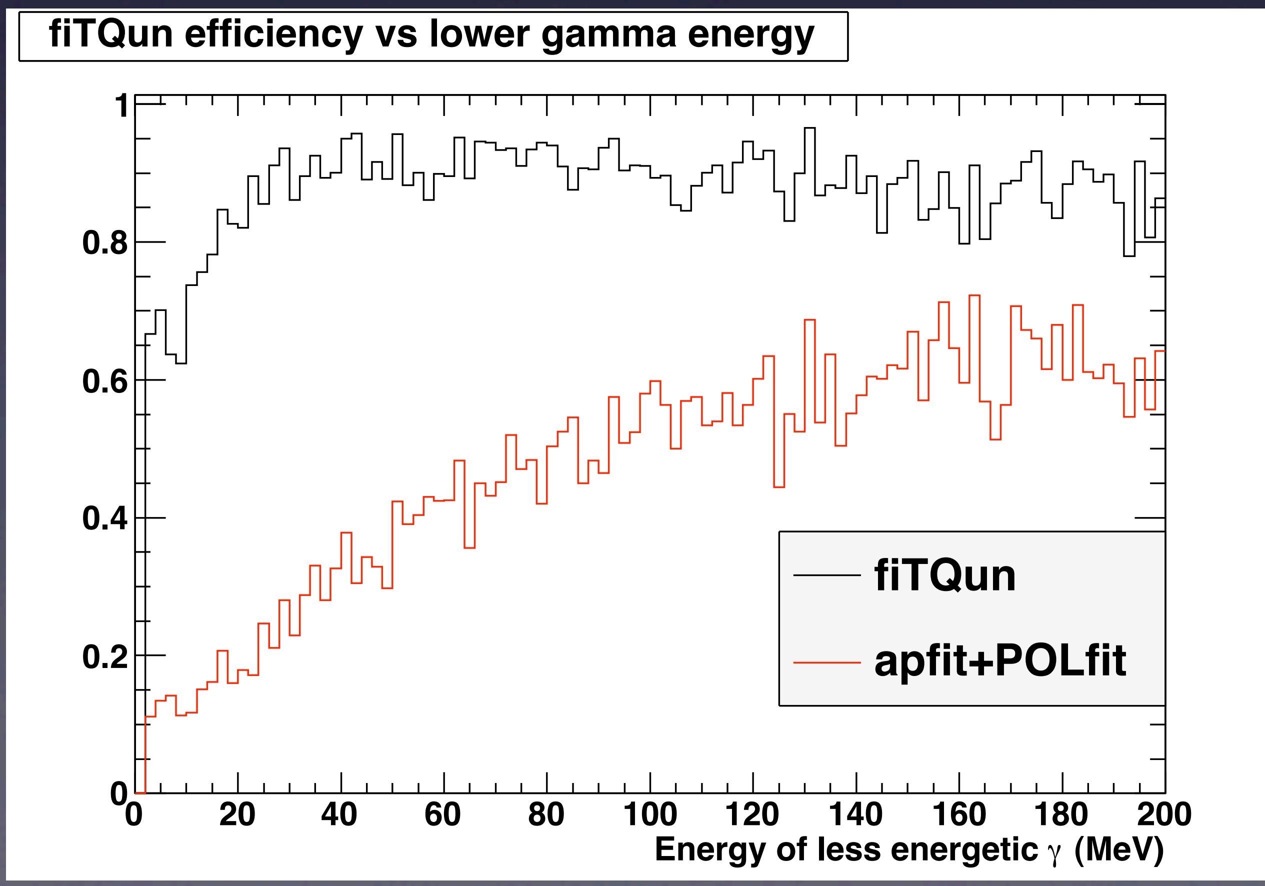




Higher Momentum π^0's

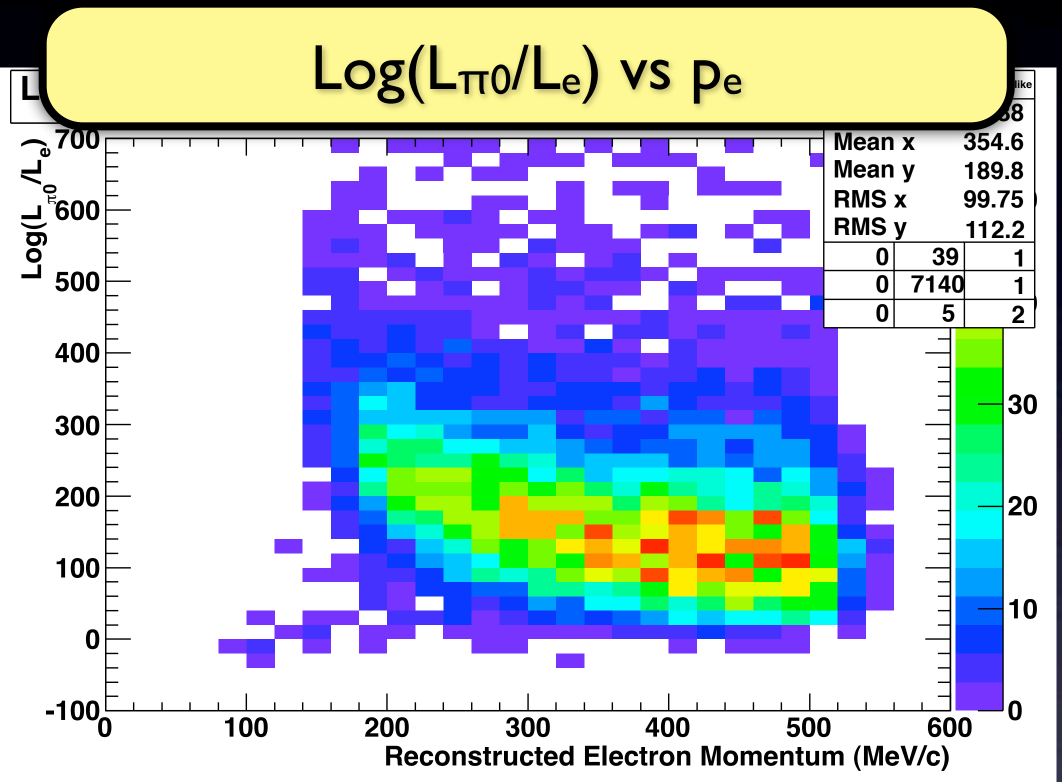
- Randomly generated from 500 to 1500 MeV/c
  - Want to check lower energy photons
- Efficiency to be rejected by 105 MeV/c^2 $M_{\pi 0}$ cut is much better for fiTQun

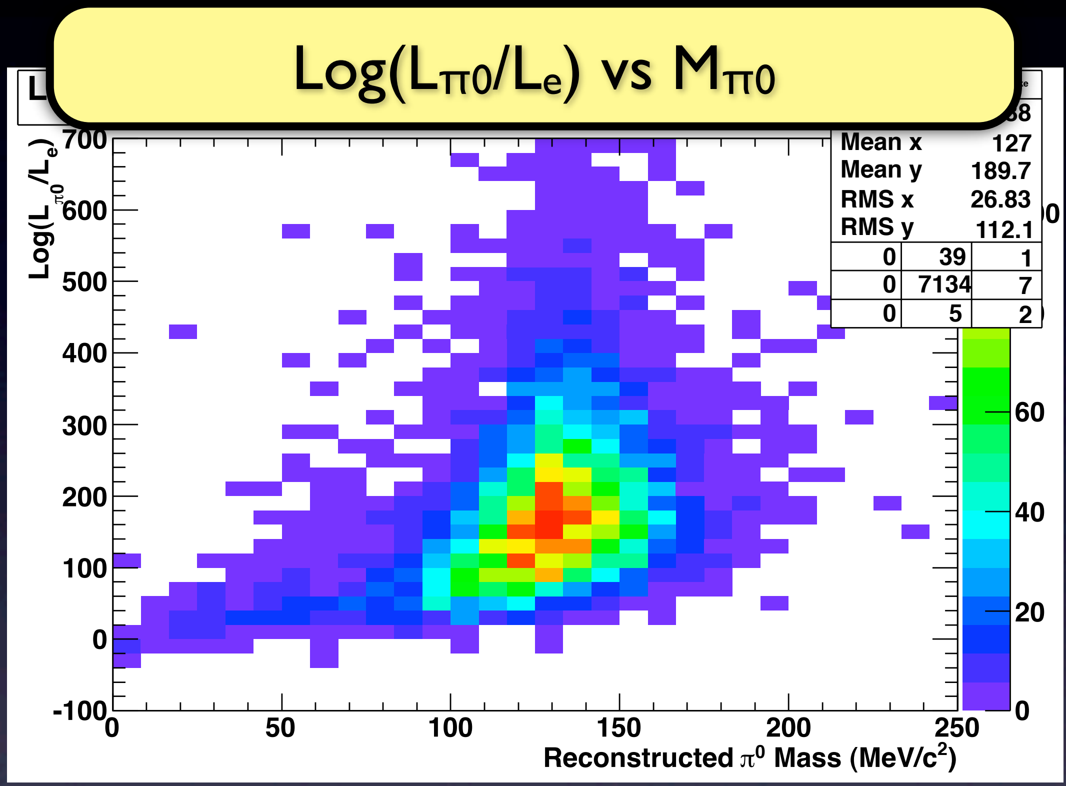




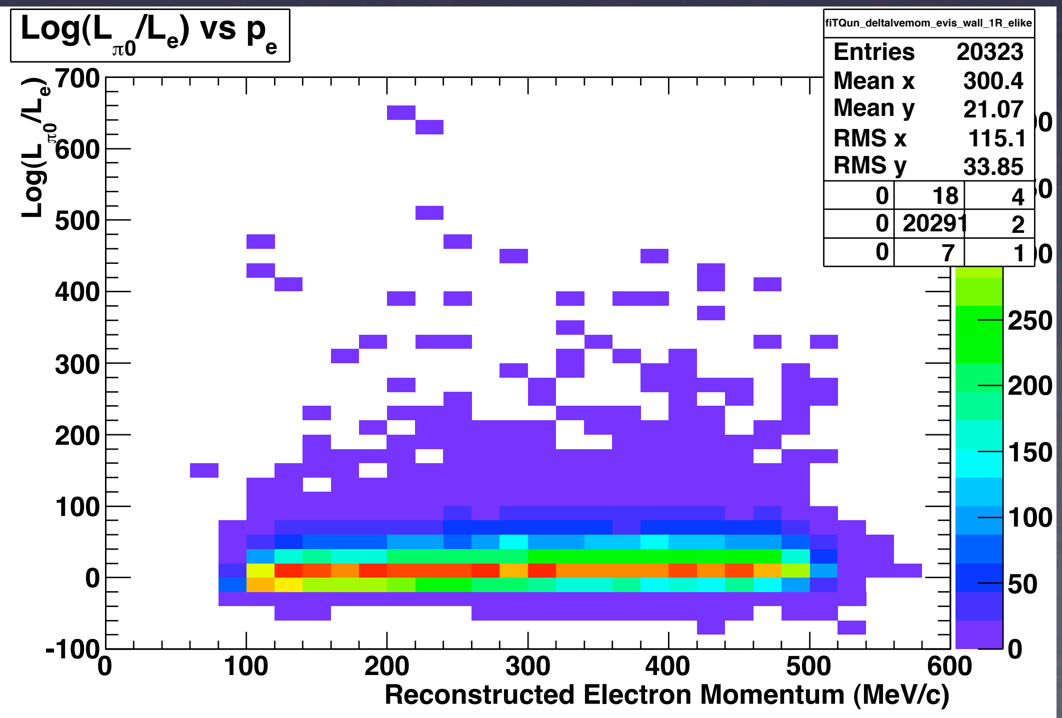
Likelihood Ratios

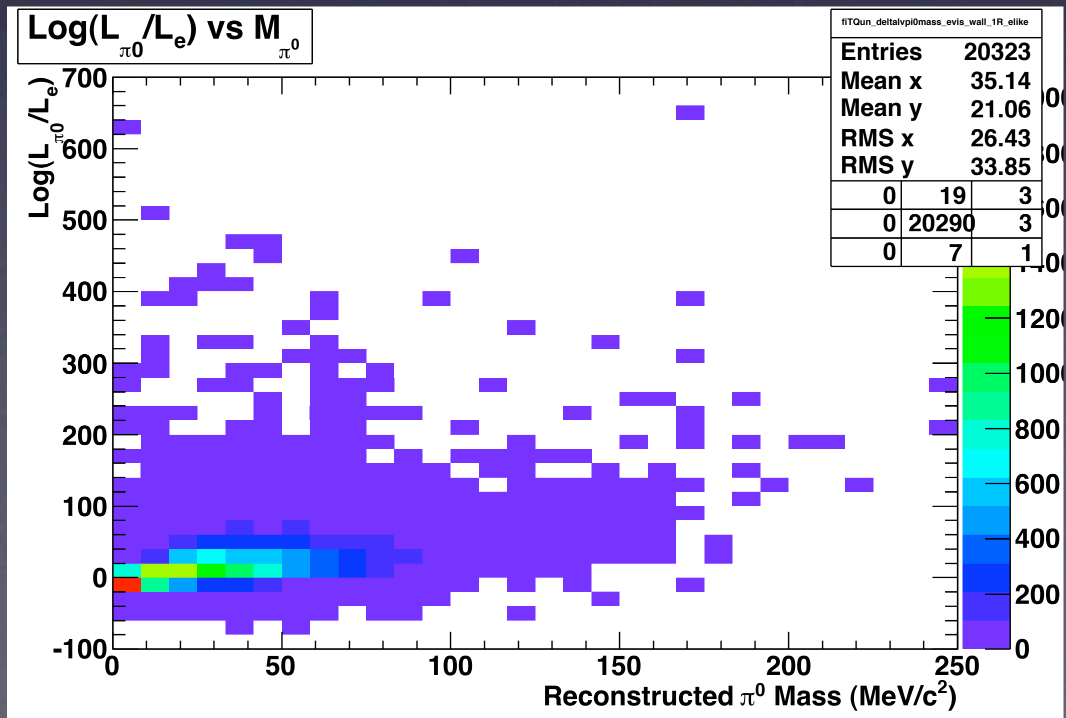
- For the new reconstruction, we don't want to make a 1D mass cut
  - Will eventually cut on likelihood ratios vs electron momentum, $M_{\pi 0}$, etc





π^0's



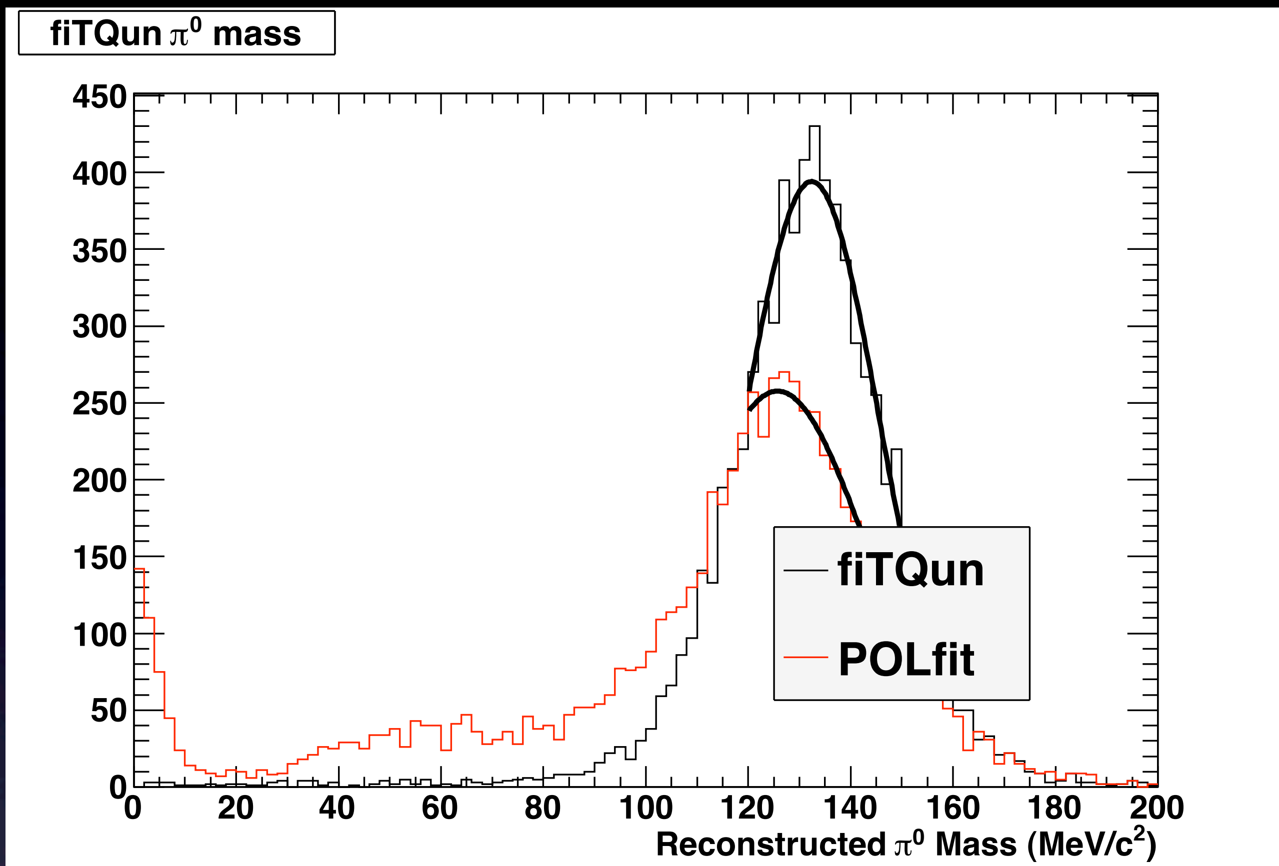


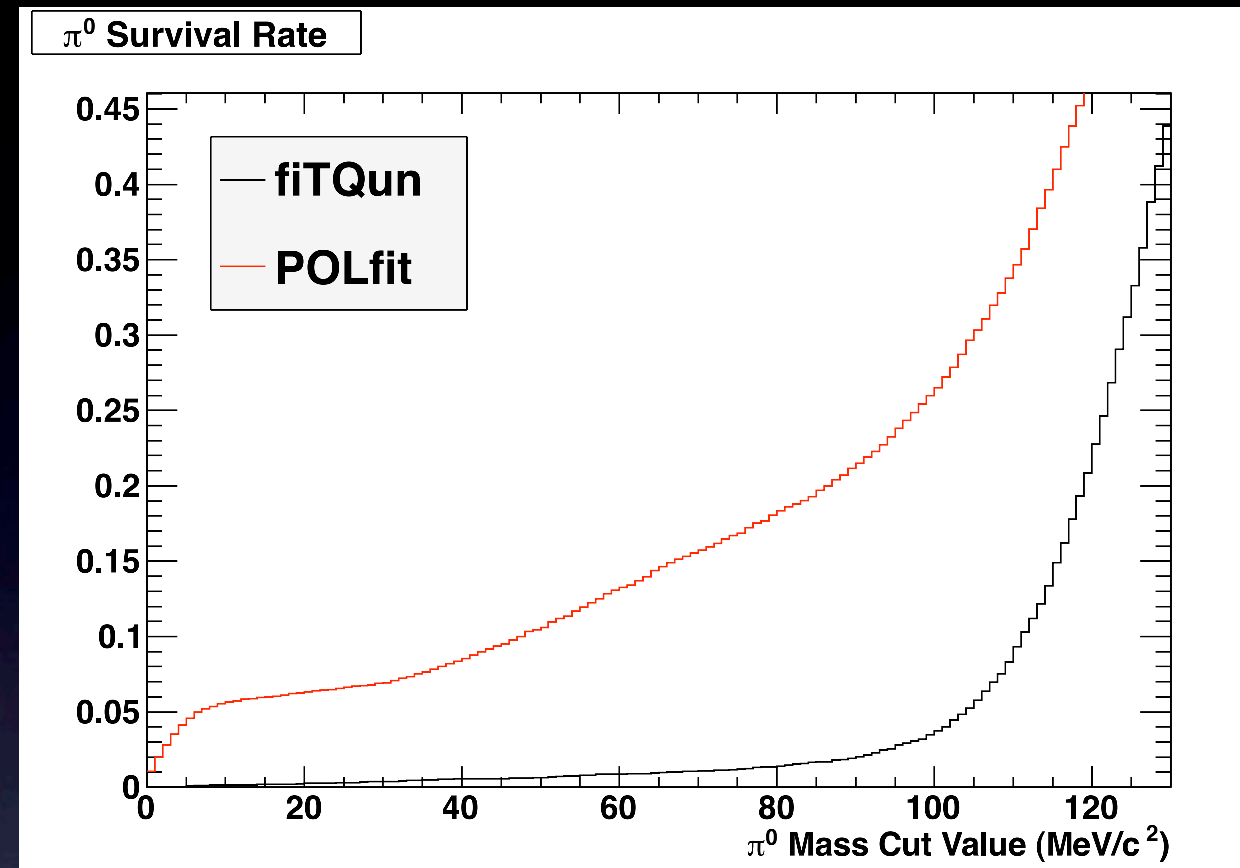
electrons

Future Improvements

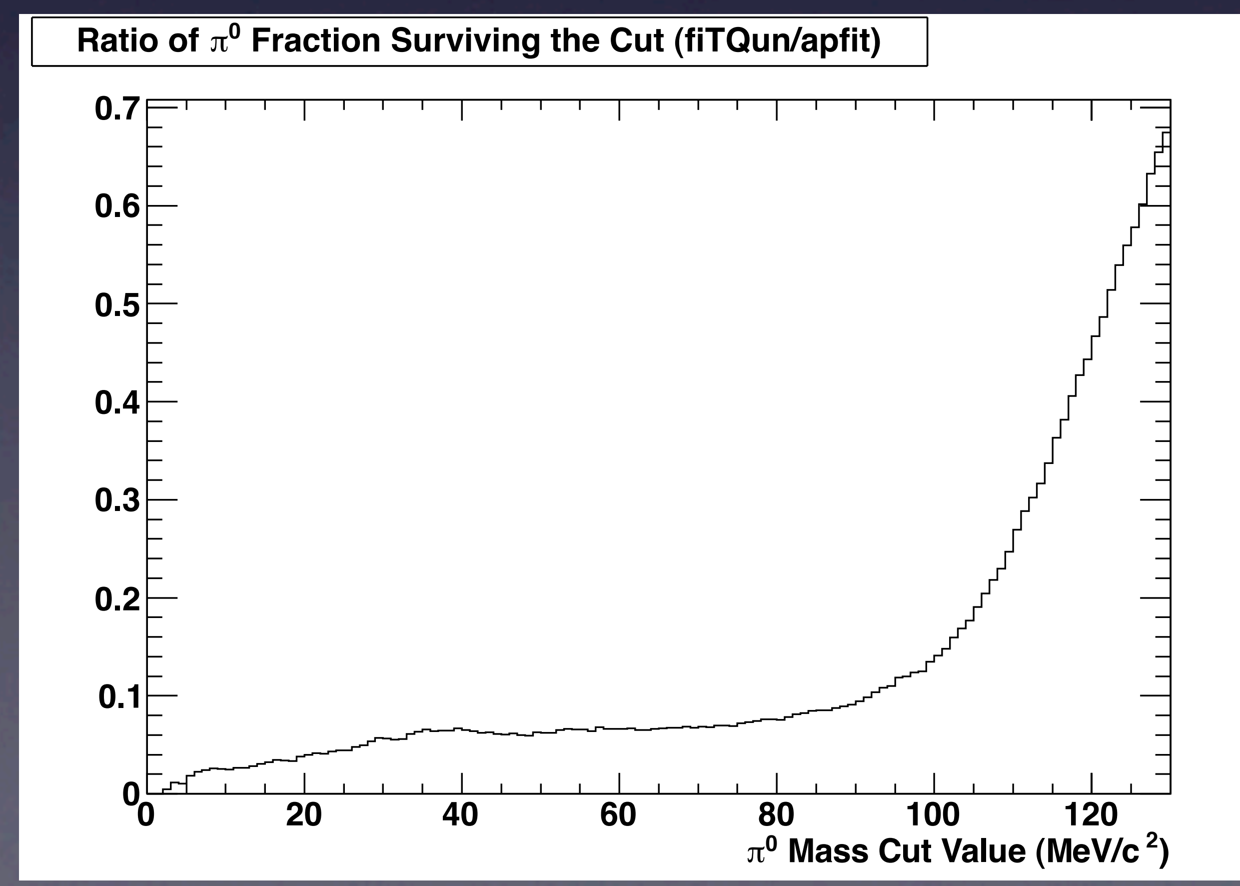
- To understand how well we can do by improving the seeding, the fit can be seeded with the true information
  - This tells us if there is a proper maximum in the likelihood surface
- Several improvements to the seeding are possible
  - e.g. use π^0 mass improve the guess of the second photon energy

Best Case Scenario (Truth Seed)





- If we could perfectly seed the fitter, we could reduce the π^0 background below ~10% of current level



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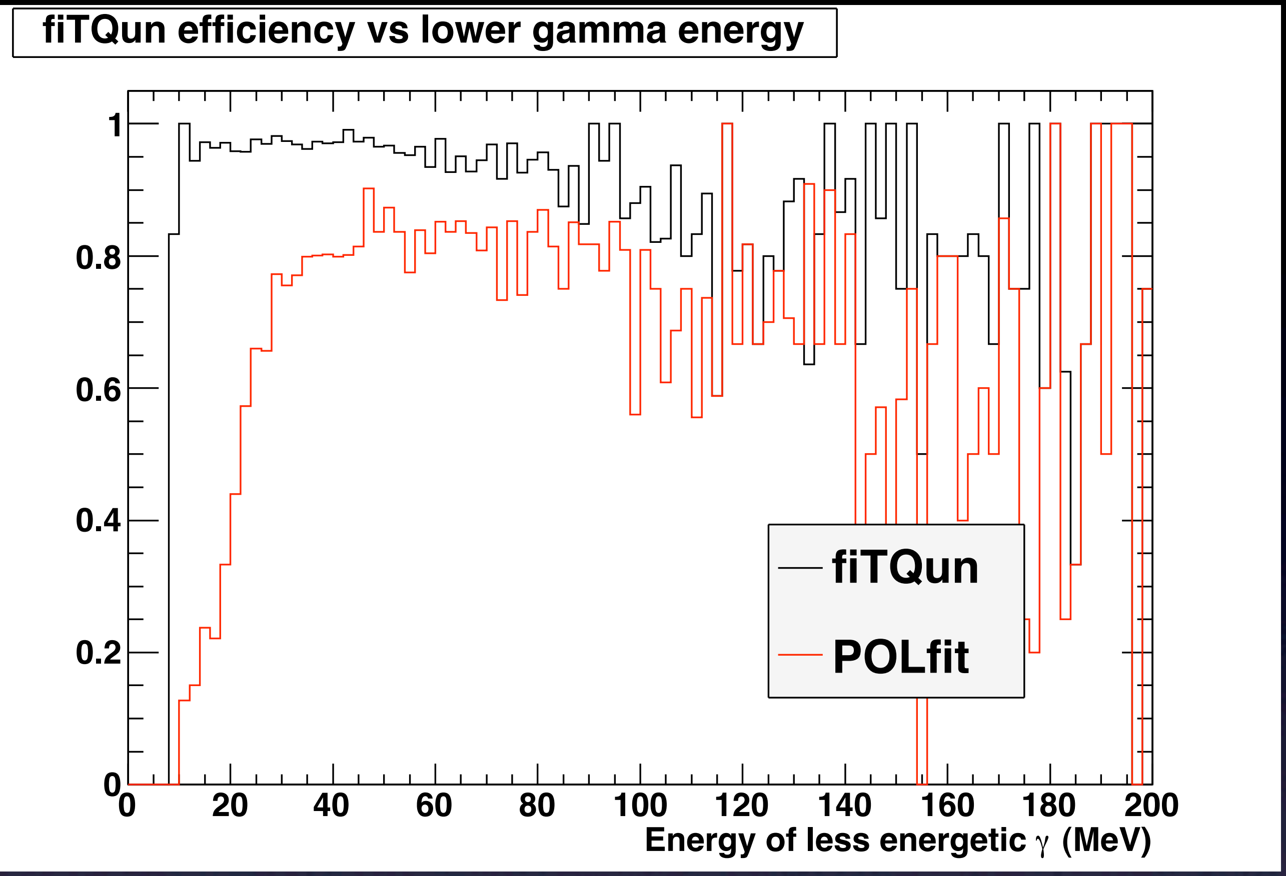
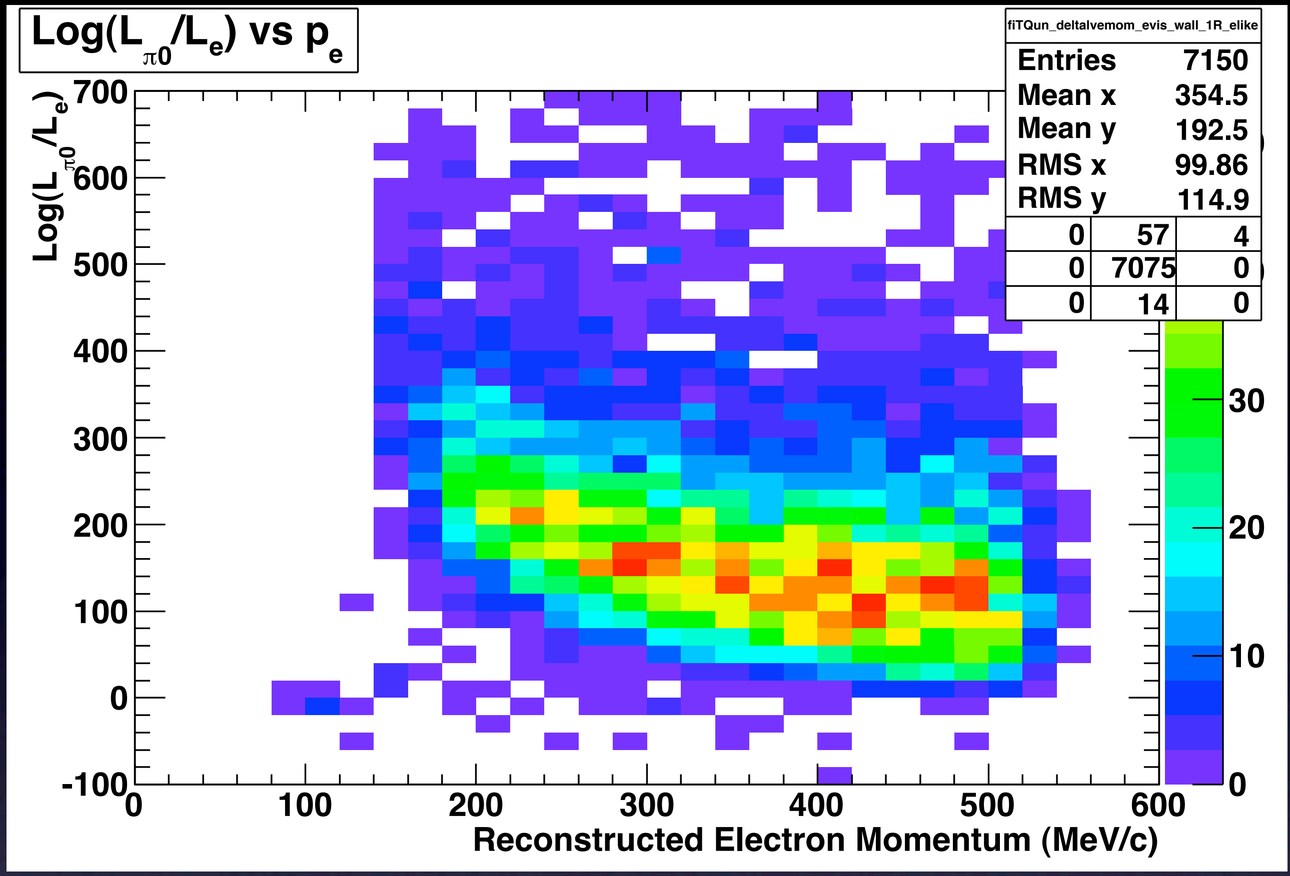
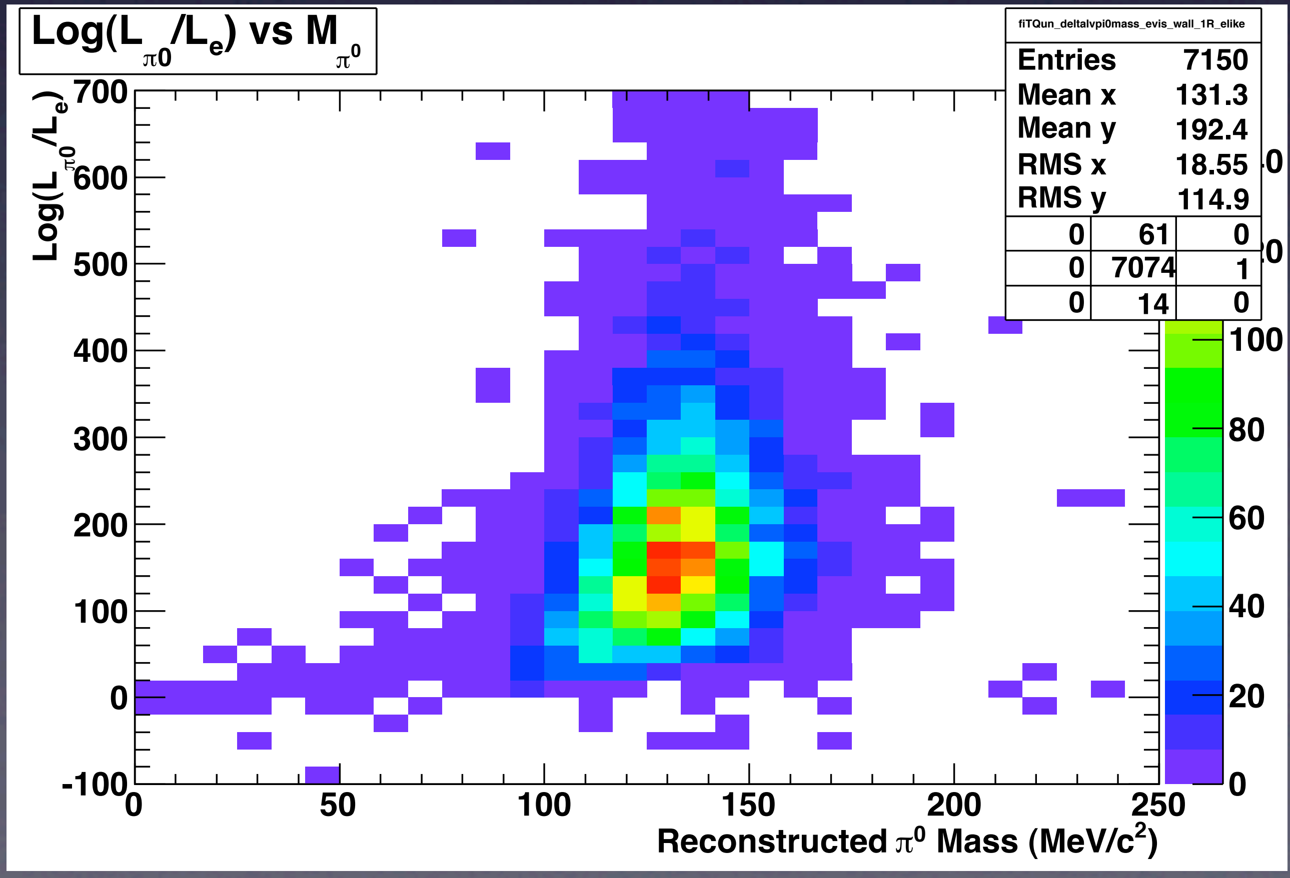
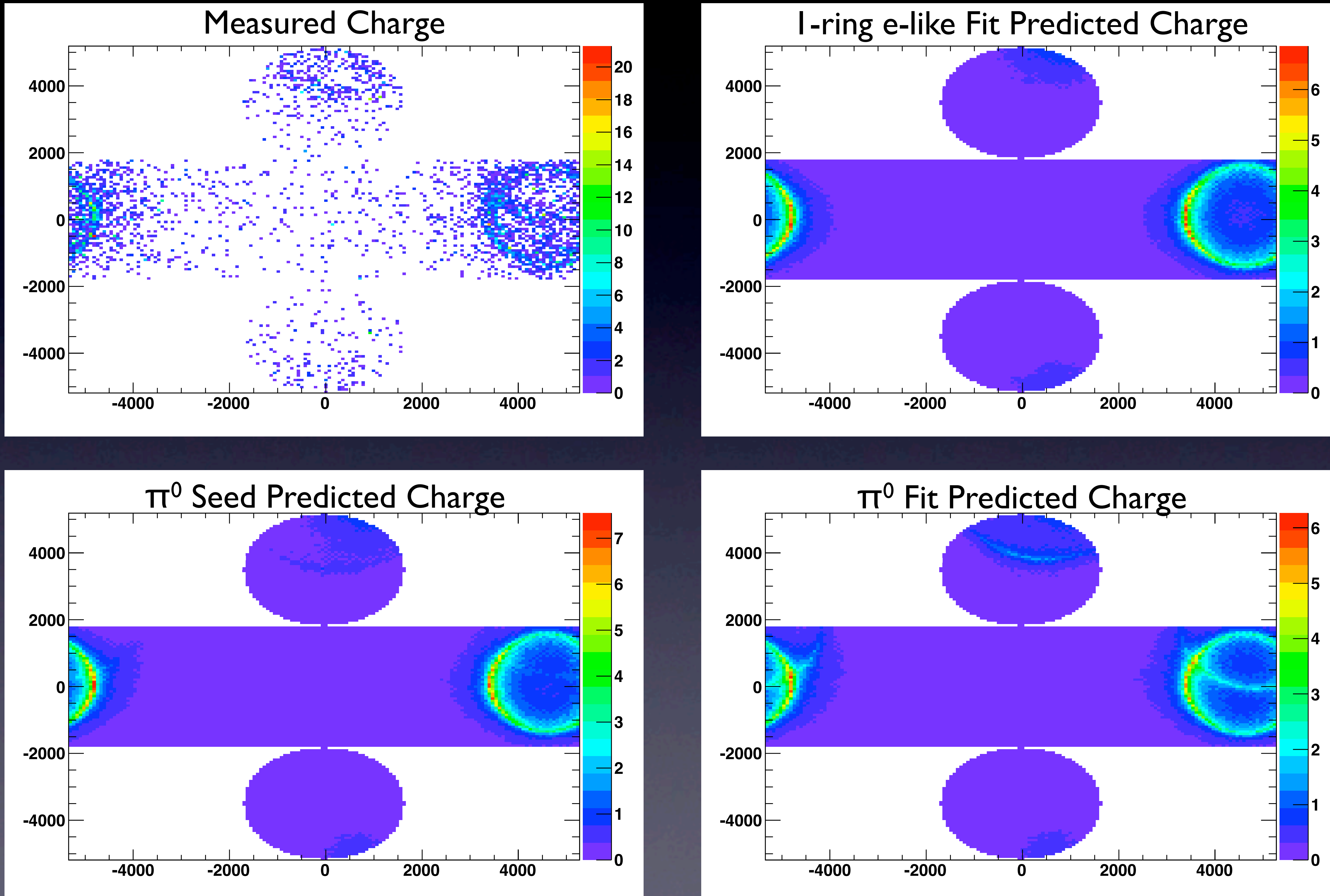






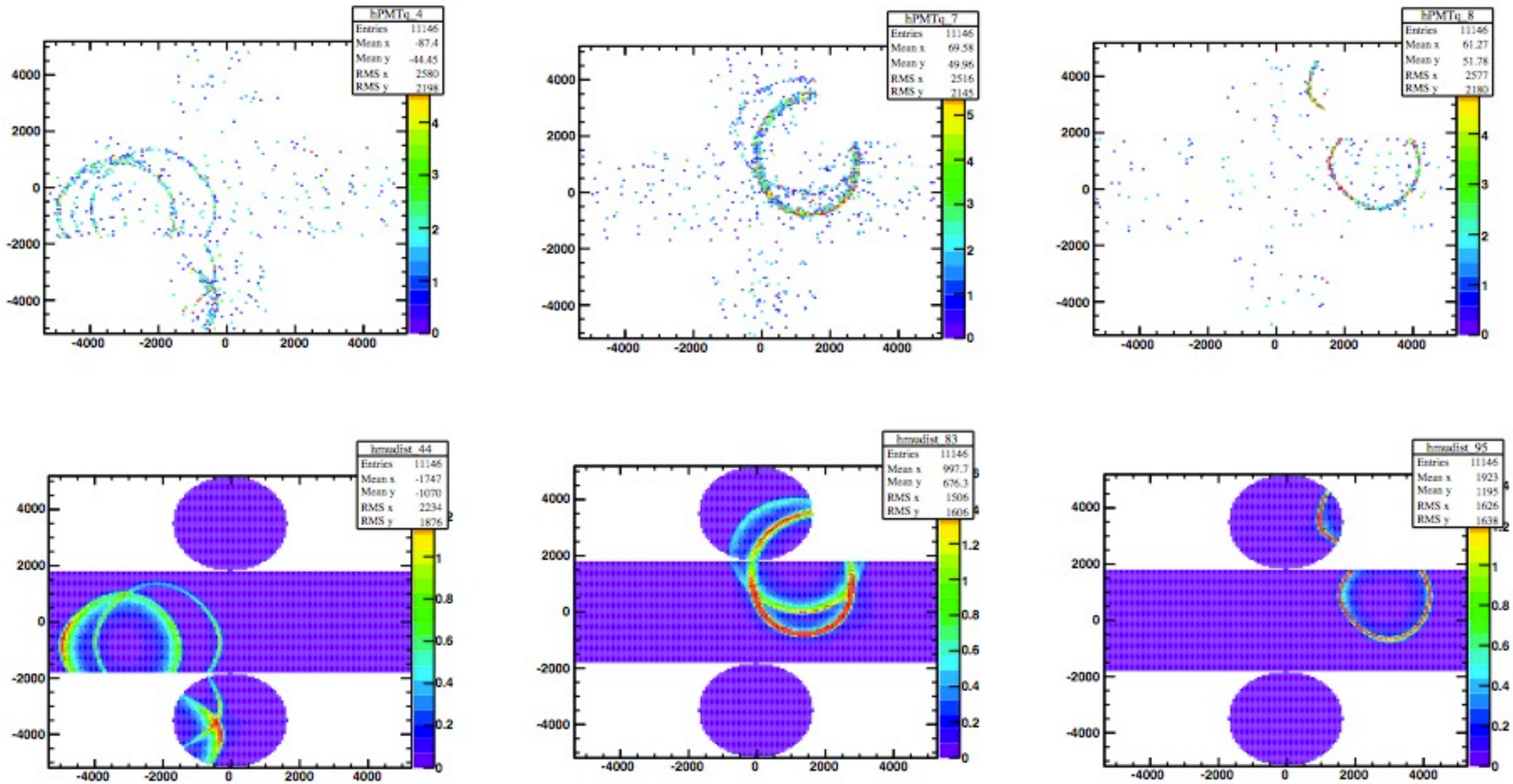
- π^0's can be found down to photon energy threshold (for 500 MeV/c π^0's)

Event Display: π^0 Fit



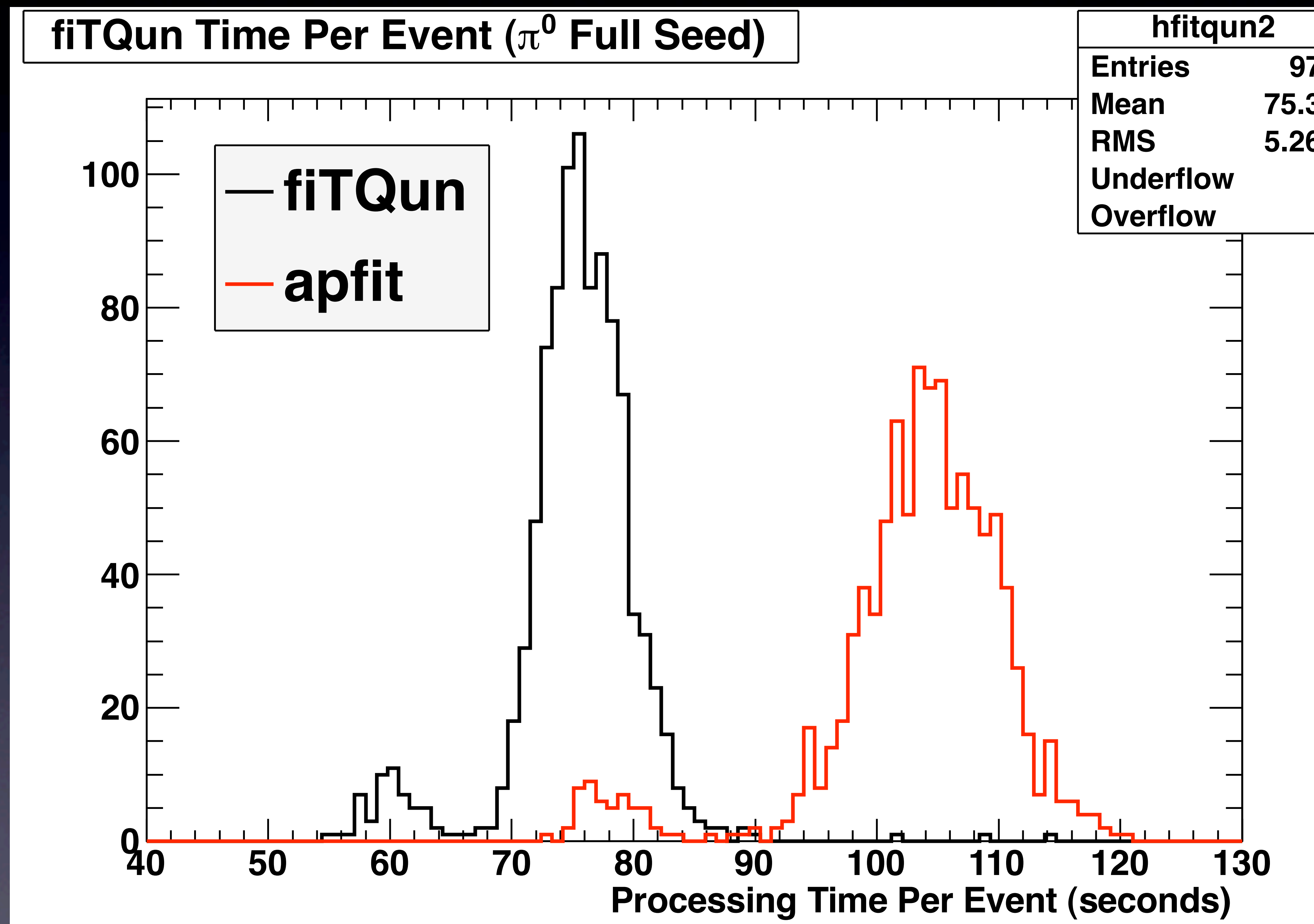
Event Displays

Kinked-track π^+ Fitter



Processing Time

- If fiTQun runs only:
    - 1-track electron fit
    - 1-track muon fit
    - π^0 fit



Reconstruction Challenges

- The main issue to overcome will be differences in the fitter performance on data and MC
  - This fitter uses more information than previous reconstruction algorithms
  - Parts of the fitter are determined from the MC
- Several validation studies will be needed
  - Stopping cosmics
  - Michel electrons
  - Atmospheric neutrinos
  - Detector calibration samples
    - Cone generator
    - Ni data, laser, etc.
- Significant work left to do!