Water Cherenkov reconstruction with FiTQun

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Introduction

- FiTQun is a maximum likelihood estimation event reconstruction algorithm for water Cherenkov experiments.
- Original developed for Super-K.
  - Based on MiniBooNE reconstruction (NIM A 608, 206)
- Latest T2K results use FiTQun event selection and reconstruction.
  - Work towards a FiTQun-based Super-K atmospheric neutrino oscillation analysis underway.
  - Studies for proton decay searches using FiTQun show promising performance.
- FiTQun is also used to reconstruct high energy events in Hyper-K and its proposed intermediate detector J-PARC E61
  - Good performance on all of these geometries, despite wide range in detector dimensions: 1 – 50 – 260 kton

The FiTQun algorithm

Likelihood-based reconstruction

FiTQun reconstruction is based on maximum-likelihood estimation

Use information from sensors both with and without registered hits in the event

$$\boxed{L(\mathbf{x})} = \boxed{\prod_{i_{unhit}} \mathrm{P}(i_{unhit}|\mathbf{x}) \prod_{i_{hit}} \mathrm{P}(i_{hit}|\mathbf{x})} \boxed{f_q(q_i|\mathbf{x})} \boxed{f_t(t_i|\mathbf{x})}$$

Build likelihood function for event hypothesis **x**

For hit photosensors:

Compare observed charge to prediction and Compare hit time to prediction

Functions f_q and f_t incorporate the photosensor response (σ_t, σ_q, …)

- Event hypotheses can be simple single-particle topologies, in which case:
    - **x** = (t_0, x, y, z, p, θ, φ)
- Or complex, multi-particle events, with an increased number of parameters
- Likelihood ratios are used to distinguish between hypotheses
    - i.e., PID – for single-particle hypotheses

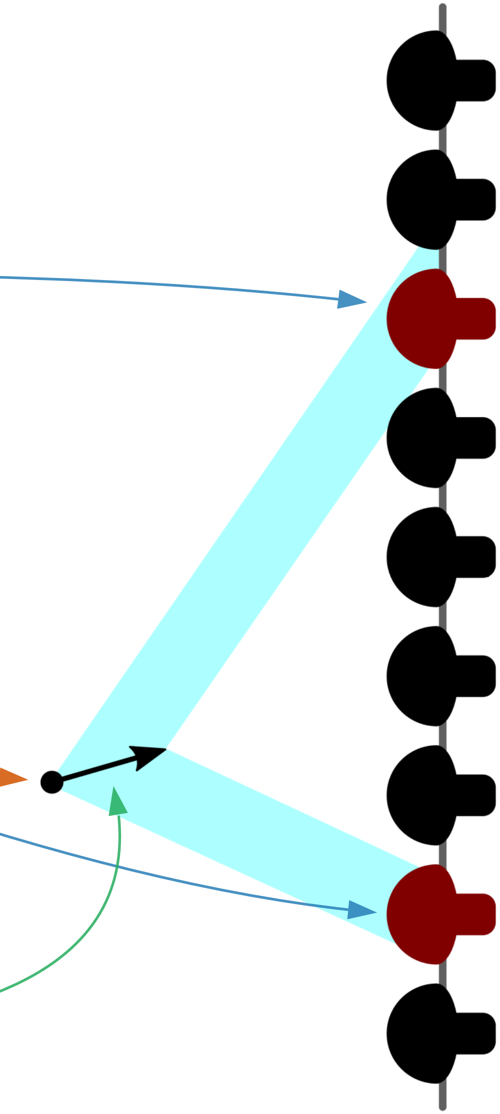
Direct light charge prediction

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

The direct light charge prediction μ is evaluated at each of the hit photosensors

The overall amount of light is governed by the function Φ, which depends on particle type and momentum

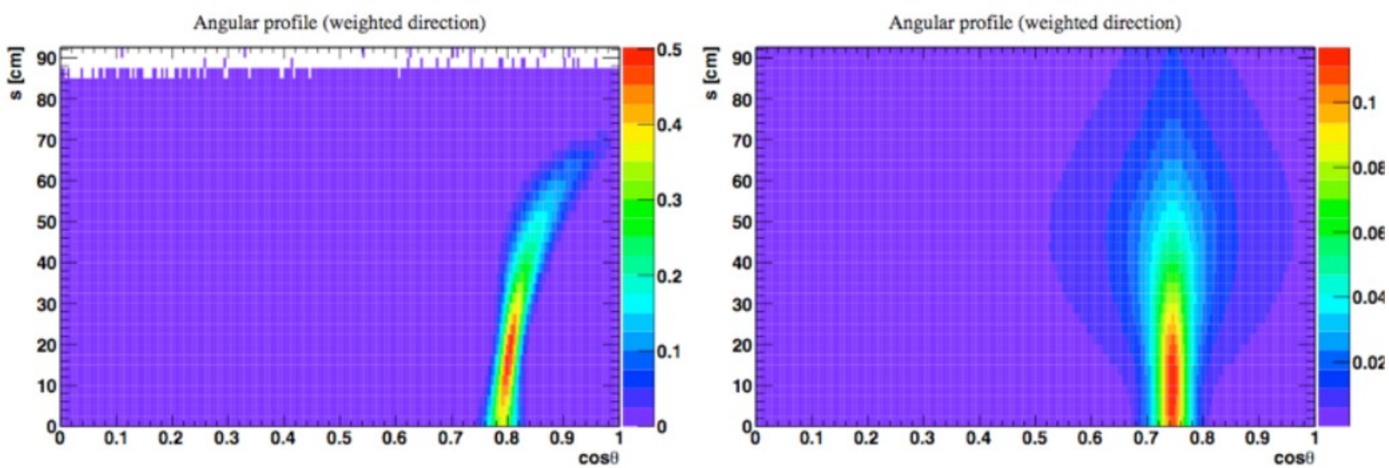
The factors g, Ω, T and ϵ are evaluated in an integral which is computed over the length of the track s



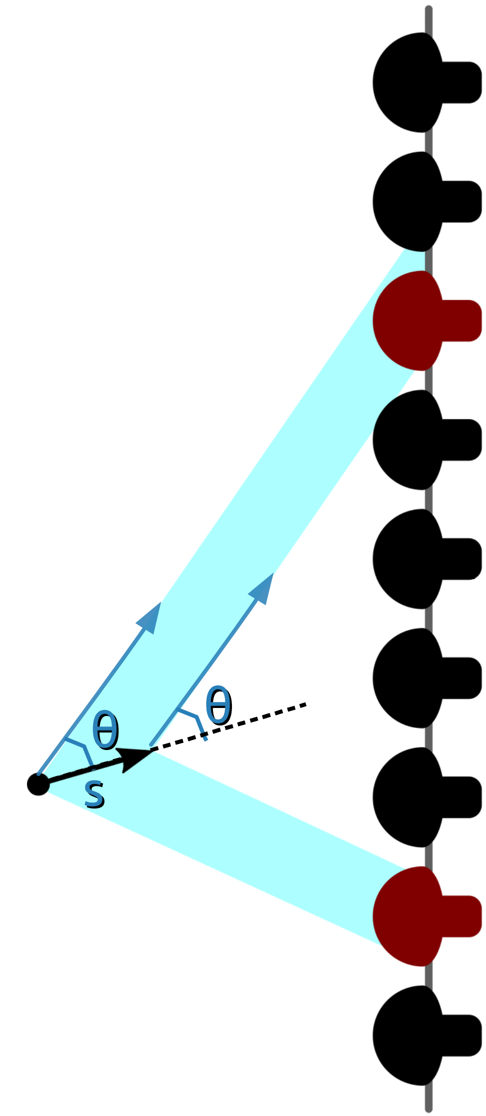
Direct light charge prediction

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

The function g encodes the Cherenkov emission profile



Muon (left) and electron (right) emission profiles at 300 MeV/c



- Cone collapse differs for particles of different mass
- This is all the information used for individual ring PID

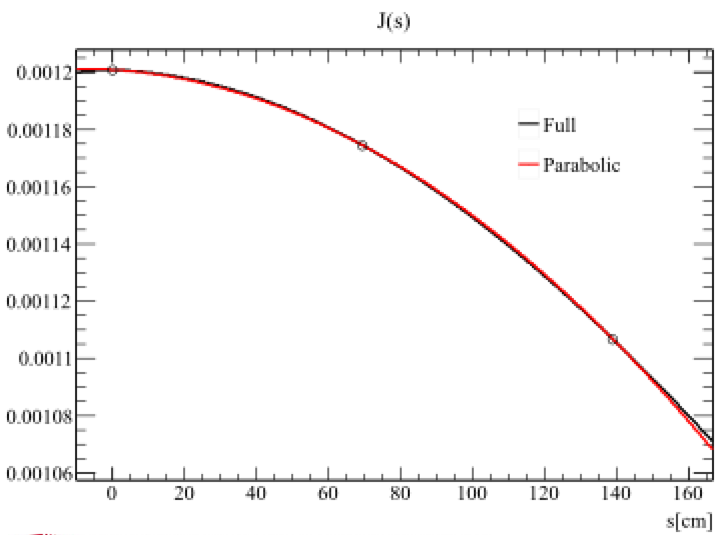
Direct light charge prediction

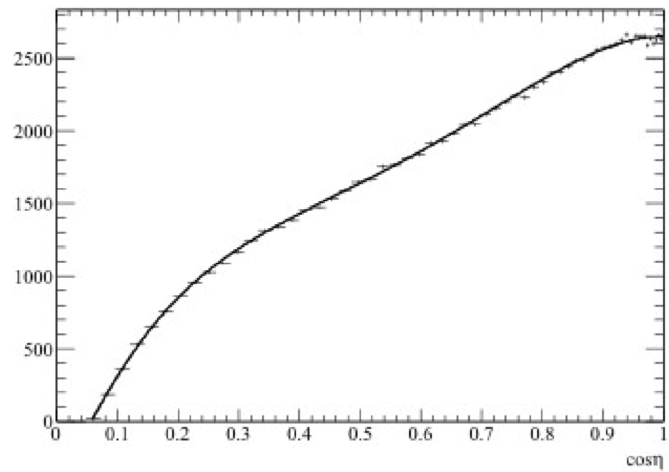
$$\mu^{dir} = \Phi(p) \int ds\; g(p, s, cos\theta)\, \boxed{\Omega(R)}\, \boxed{T(R)}\, \boxed{\epsilon(\eta)}$$

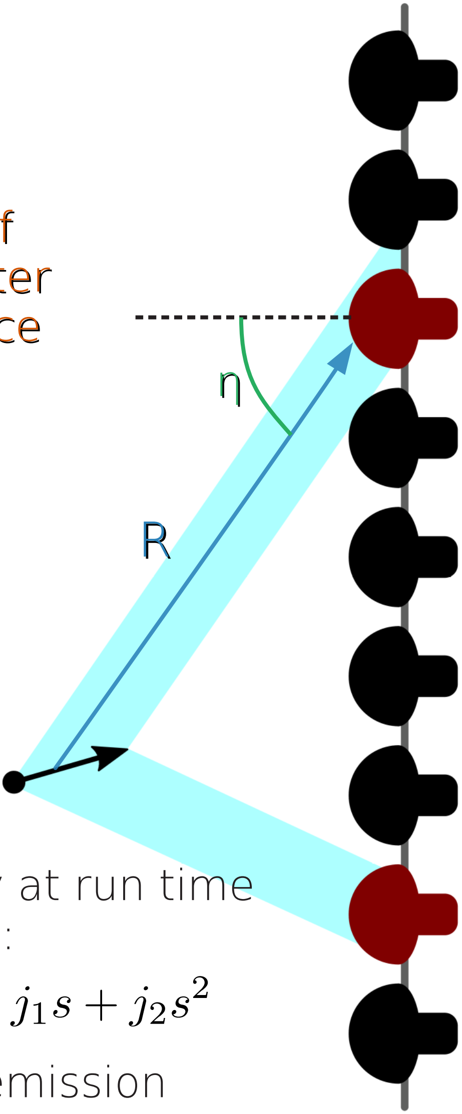
Ω reflects the change in apparent scale of the photosensor as a function of distance

T gives the amount of light attenuation in water as a function of distance

ϵ represents the angular response of the photsensor accounting for effects such as the shadowing due to adjacent PMTs and the shape of the photocathode







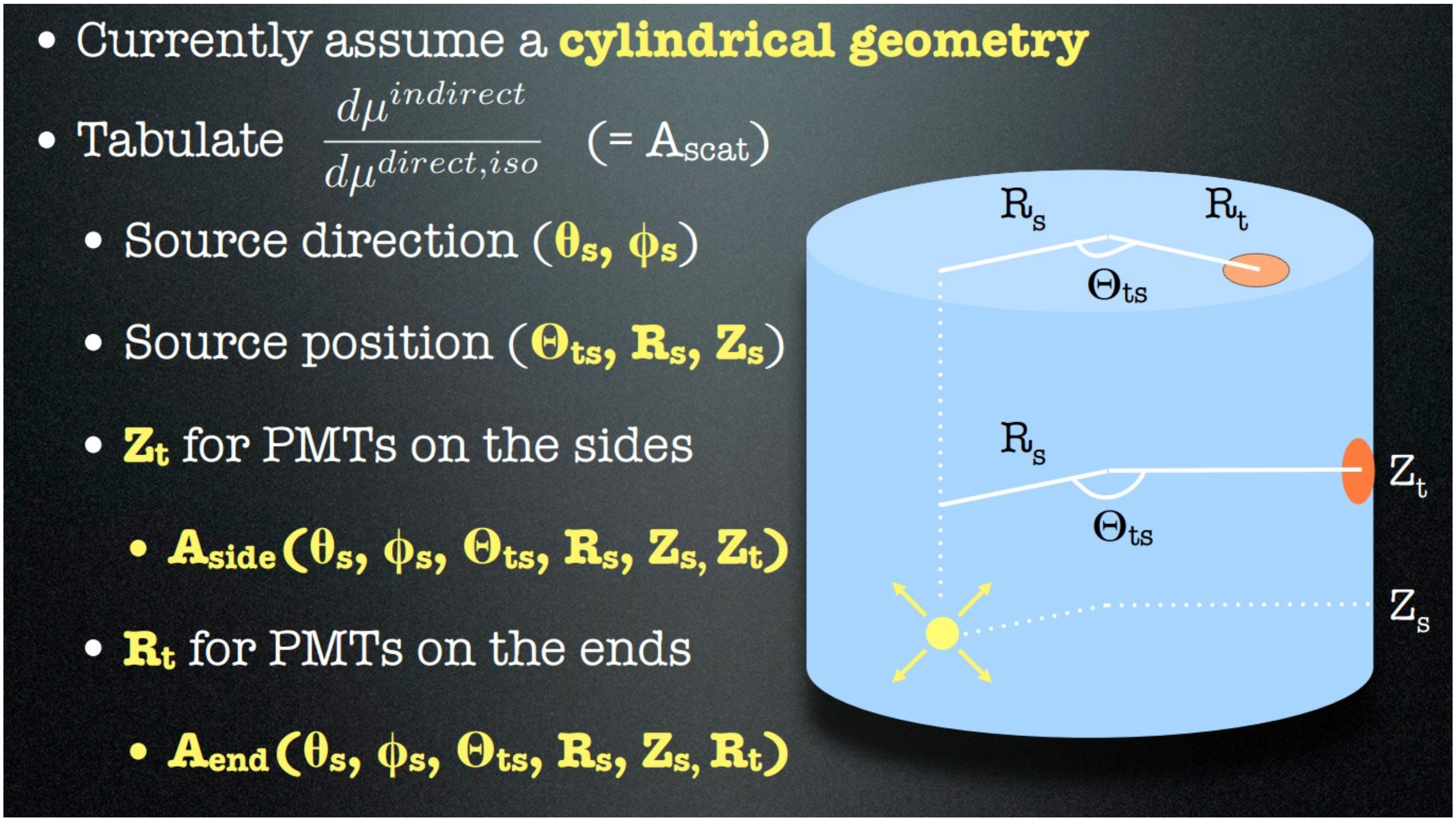
The integral is not computed explicitly at run time

- A parabolic approximation is used:

$$J(s) = \Omega(R)\; T(R)\; \epsilon(\eta) \approx j_0 + j_1 s + j_2 s^2$$

- The integral over the Cherenkov emission profile is tabulated

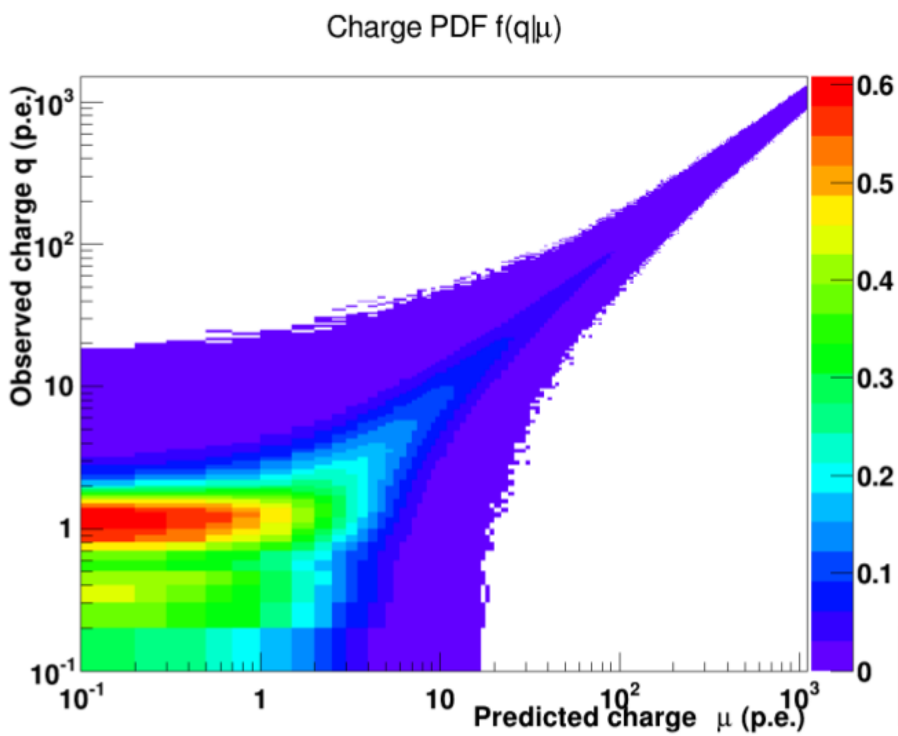
Indirect light charge prediction



Photosensor response

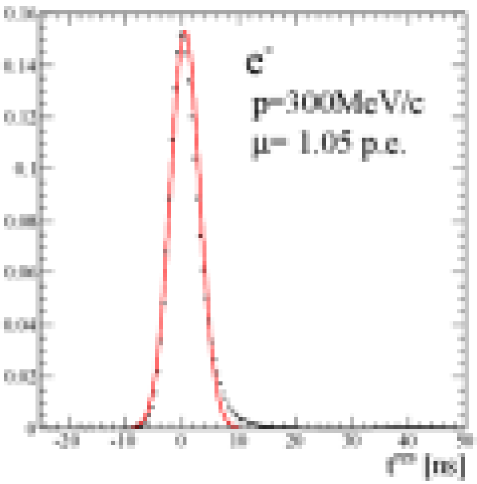
Charge

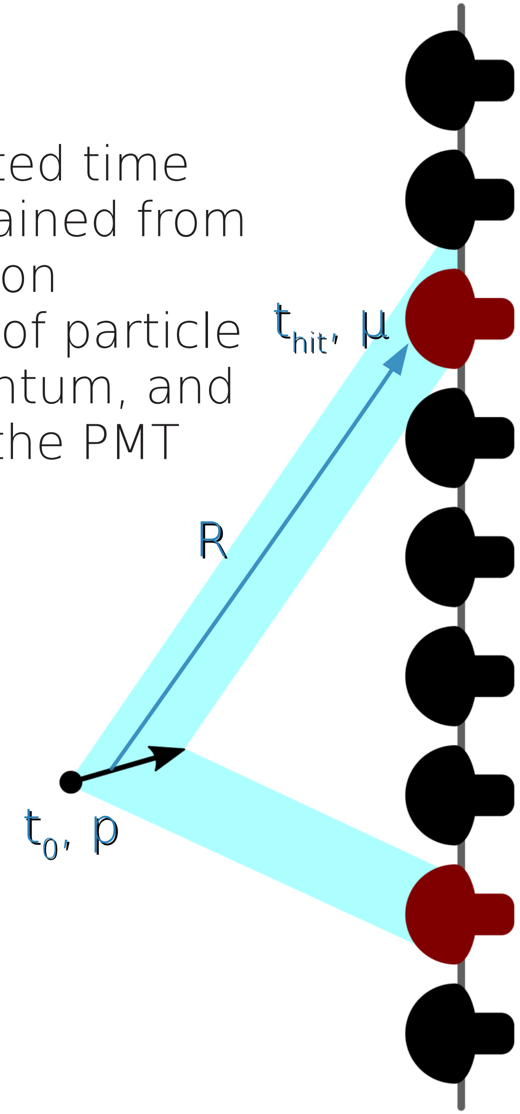
- PDFs of the observed charge for a given true mean obtained from Monte Carlo simulation
- Hit probability functions are extracted from these distributions



Time

- Time-of-flight corrected time distributions are obtained from Monte Carlo simulation
- Stored as a function of particle type, particle momentum, and predicted charge at the PMT

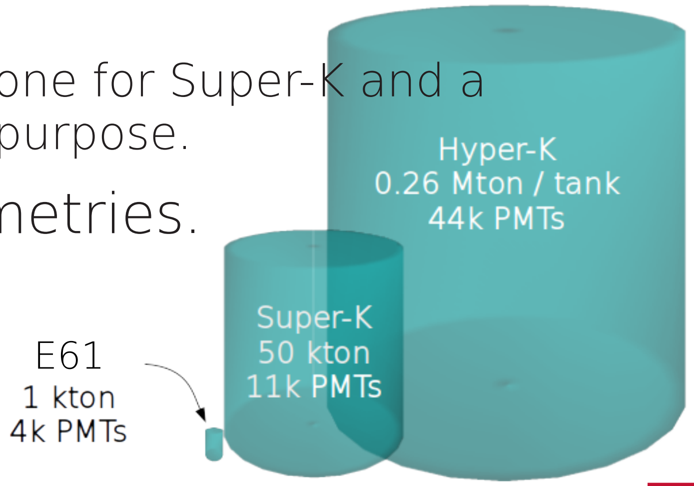




$$t_{corr} = t_0 - \left(t_{hit} - \frac{Rn}{c} - \frac{s}{2c}\right)$$

FiTQun on multiple detector geometries

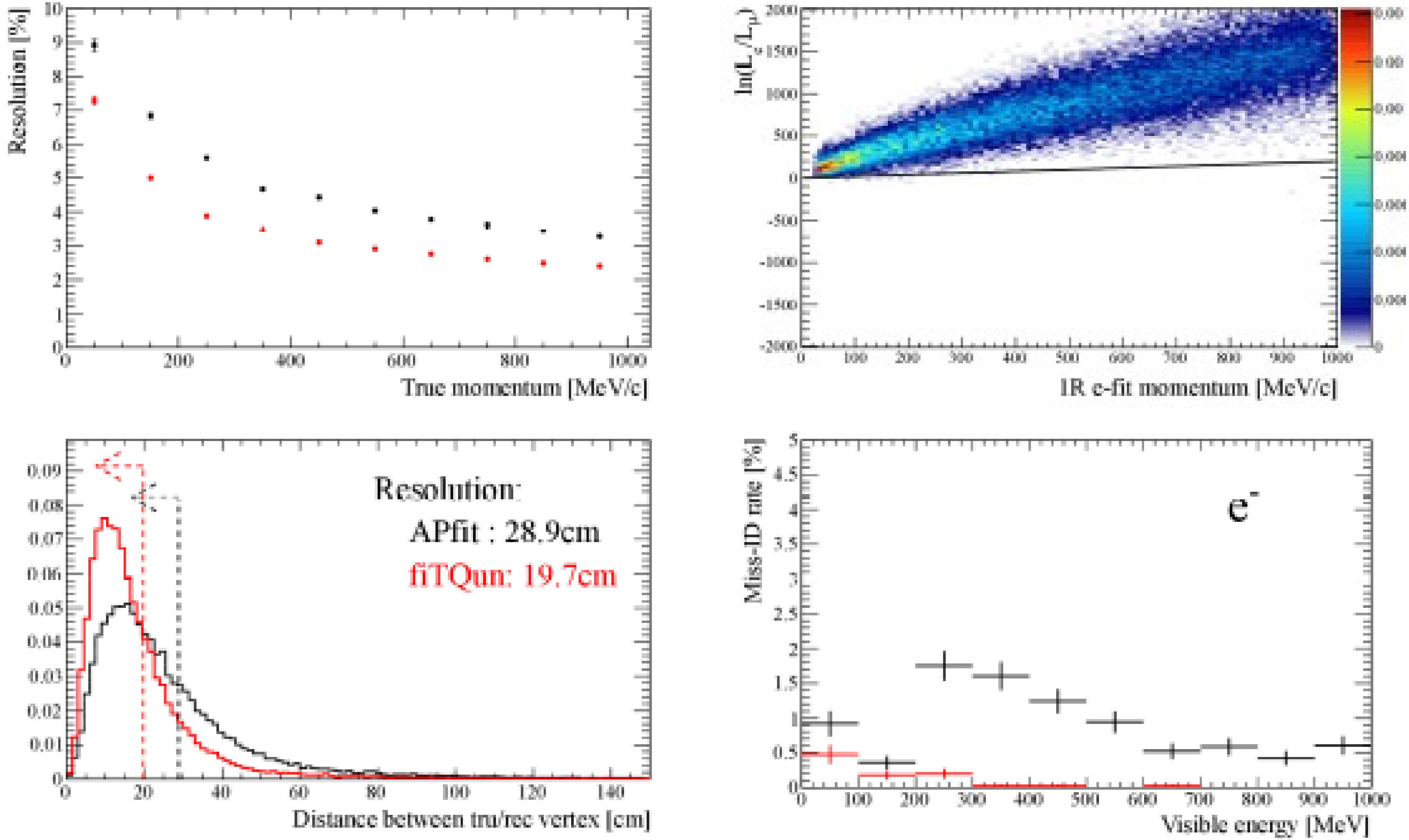
- FiTQun was written for Super-K, with "tunes" available for each of its four eras:
  - Different coverage fraction in SK-II, with additional acrylic covers on PMTs
  - Different electronics in SK-IV
- FiTQun has been adapted to run on events generated with WCSim.
  - Geant4-based simulation for generic water Cherenkov experiments used by Hyper-K and E61.
  - Code-wise very different from the Geant3-based Super-K simulation.
  - WCSimWrapper class allows for fiTQun to be compiled independently of SK software libraries, linked only to WCSim (and ROOT)
  - Tuning procedure was developed based on what was done for Super-K and a collection of utilities and WCSim add-ons exist for this purpose.
- Easy to extend to run on other software / geometries.



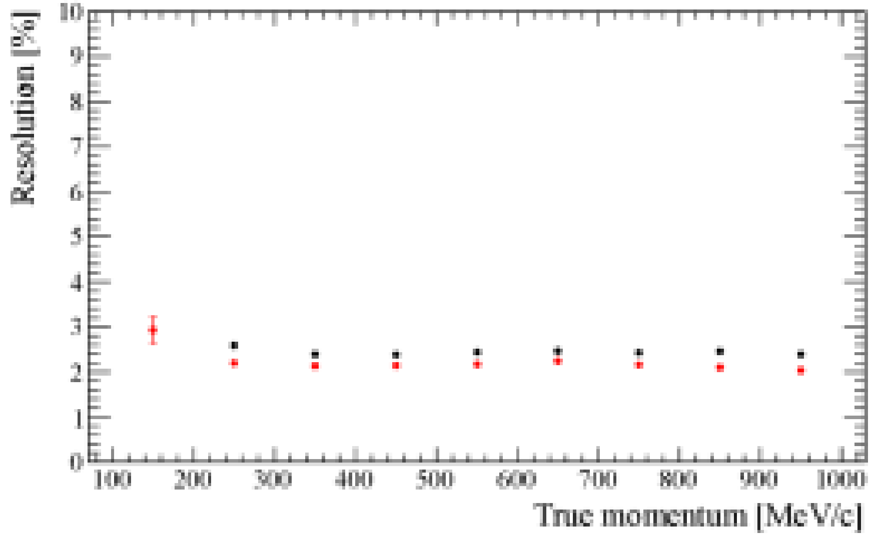
Reconstruction performance

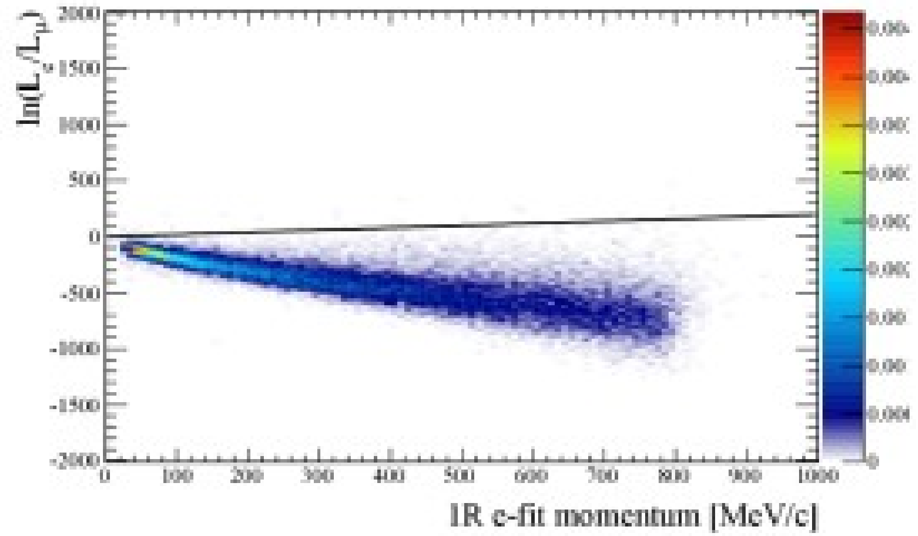
Single-ring fitters: e

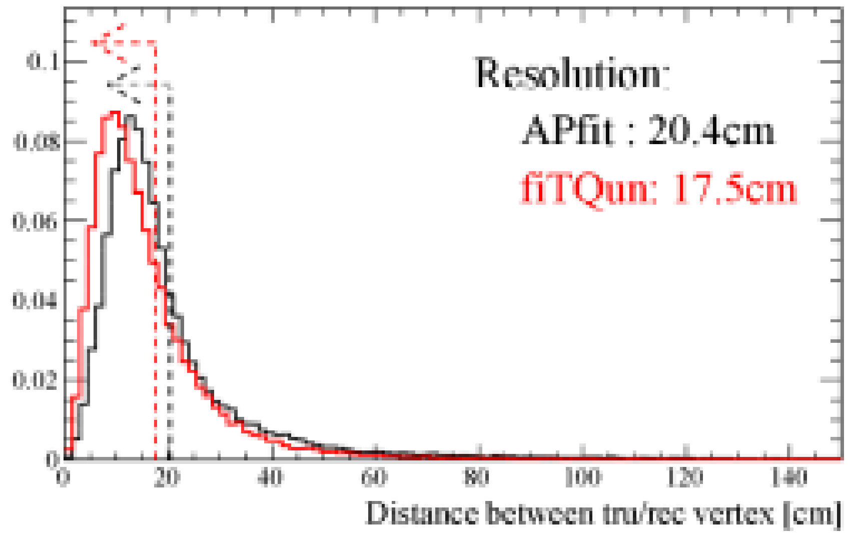
Super-K particle gun performance

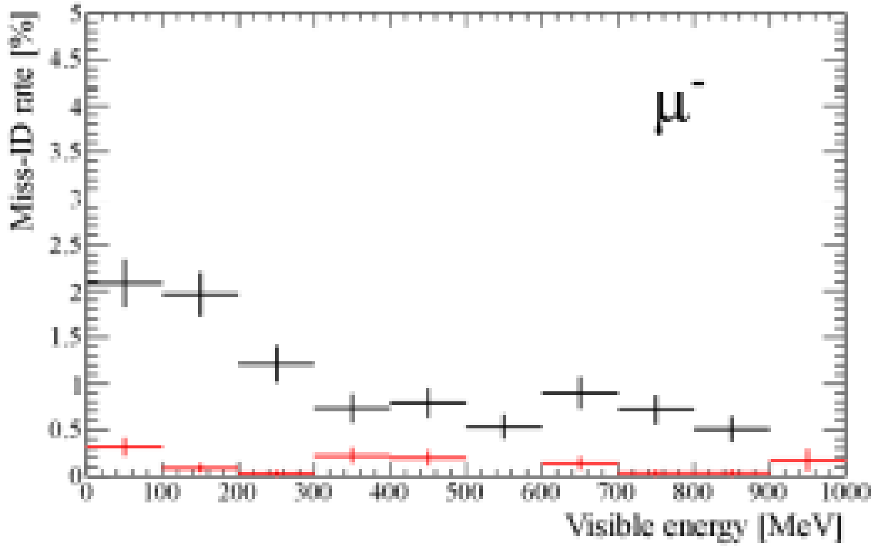


Single-ring fitters: μ
Super-K particle gun performance

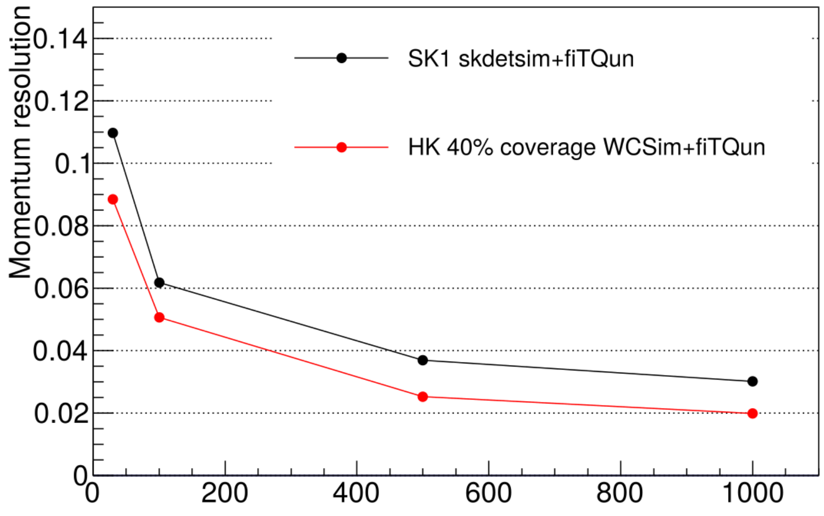


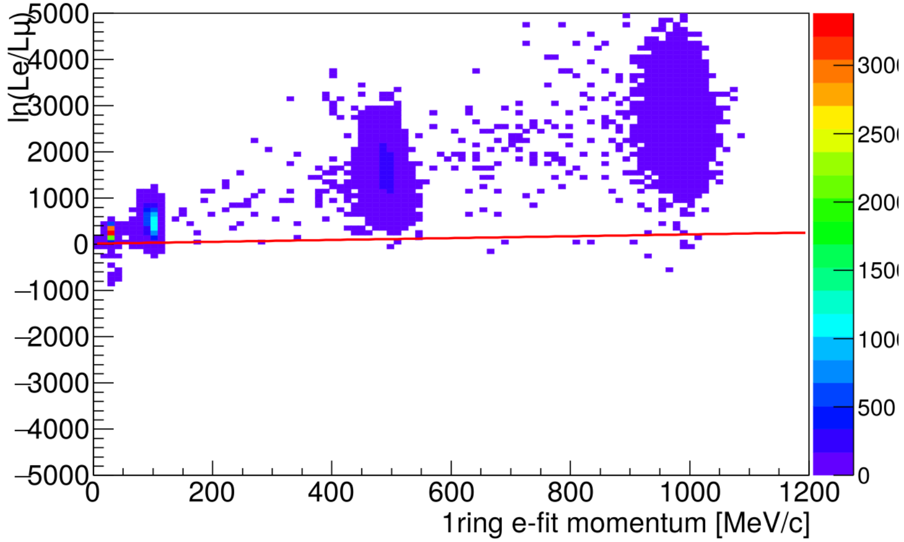


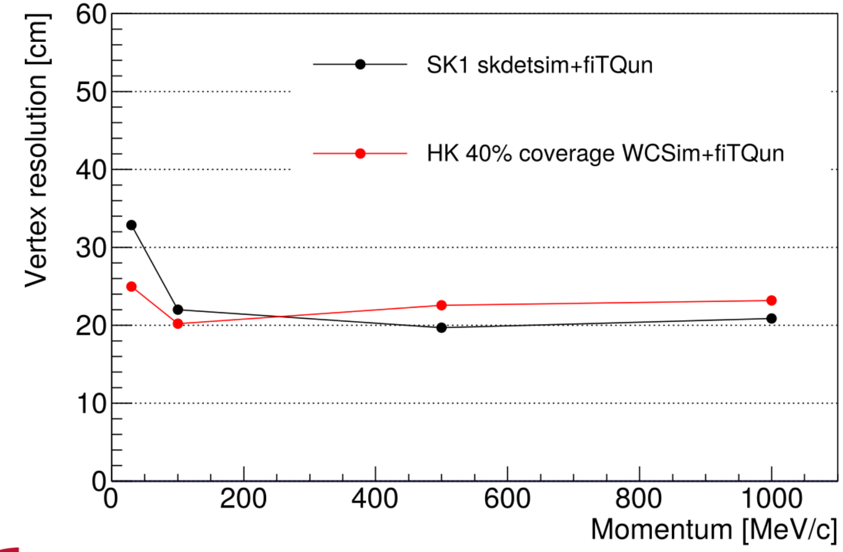


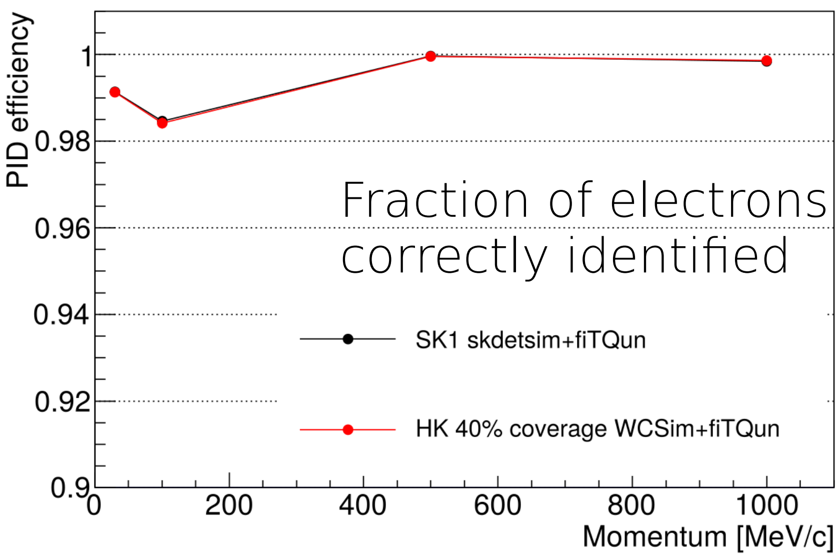


Single-ring fitters: e
Hyper-K particle gun performance

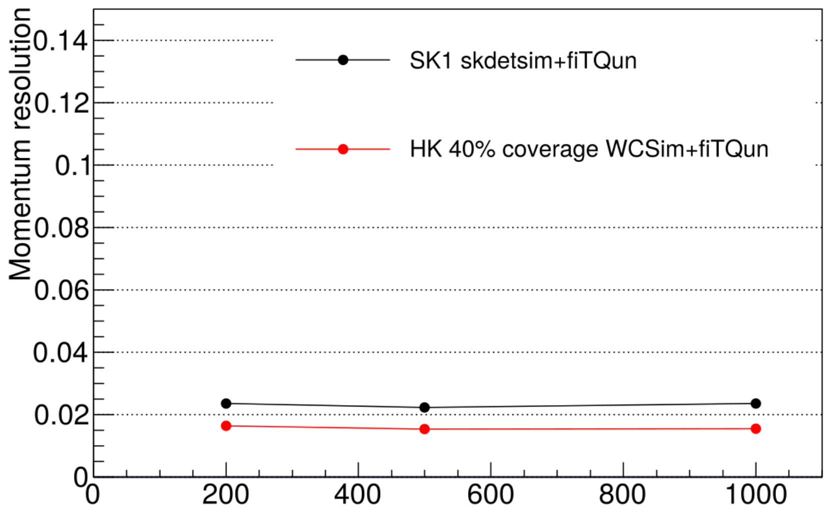


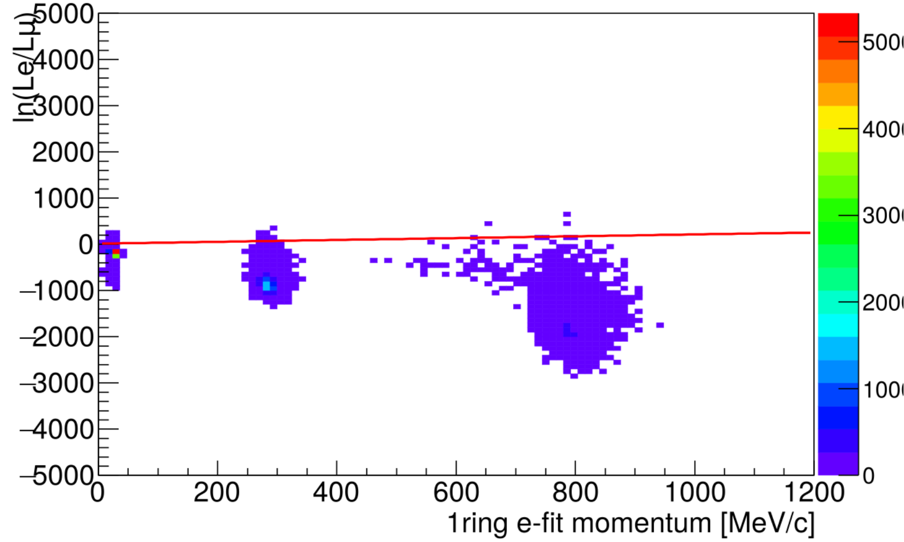


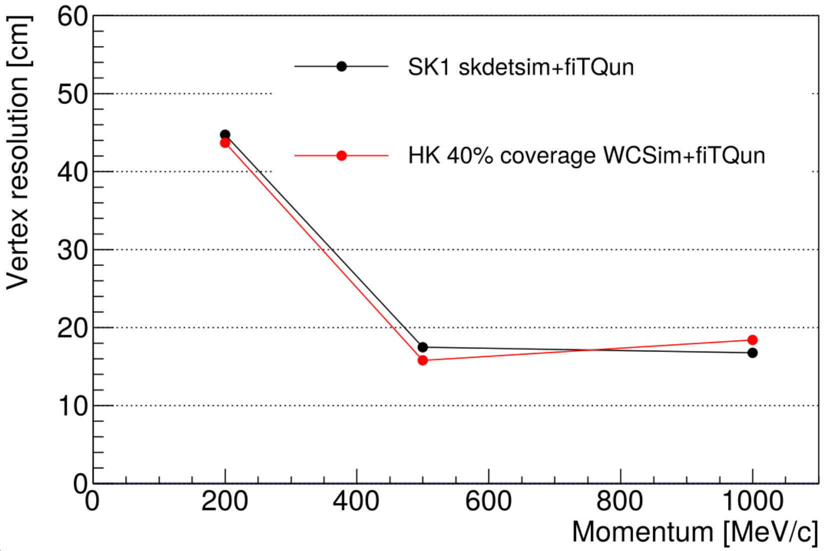


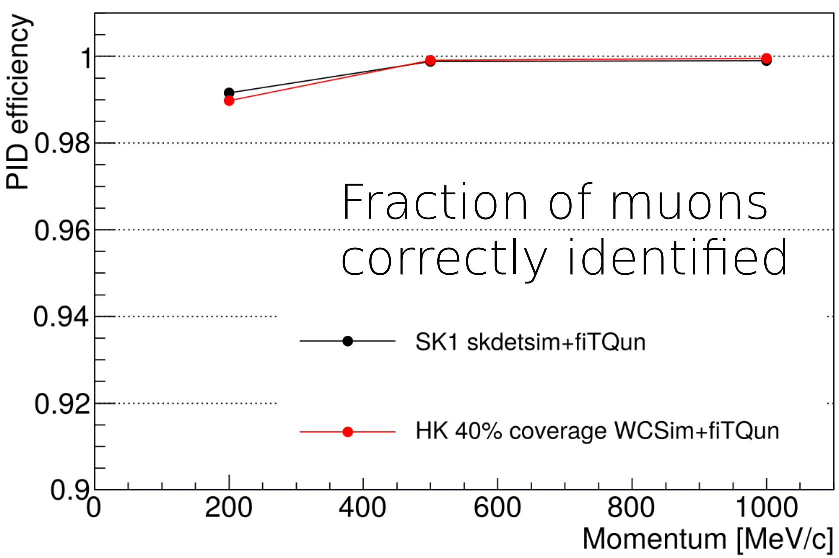


Single-ring fitters: μ
Hyper-K particle gun performance



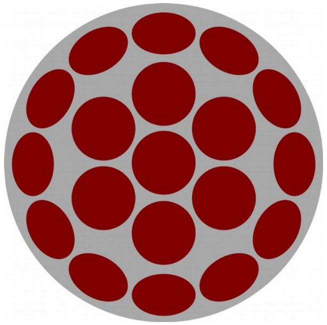


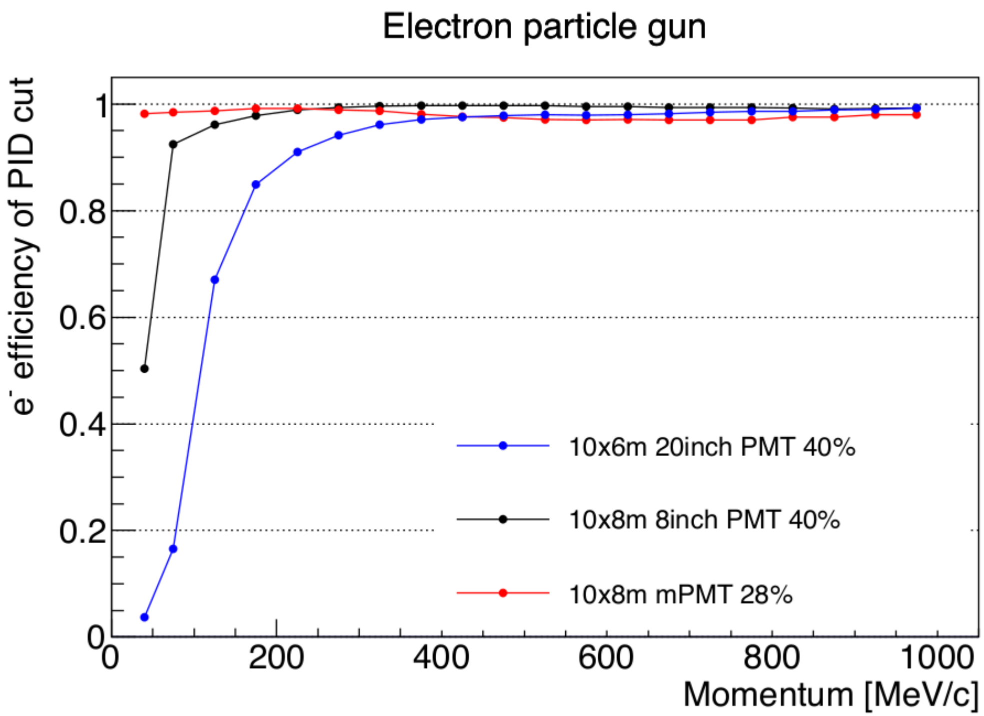


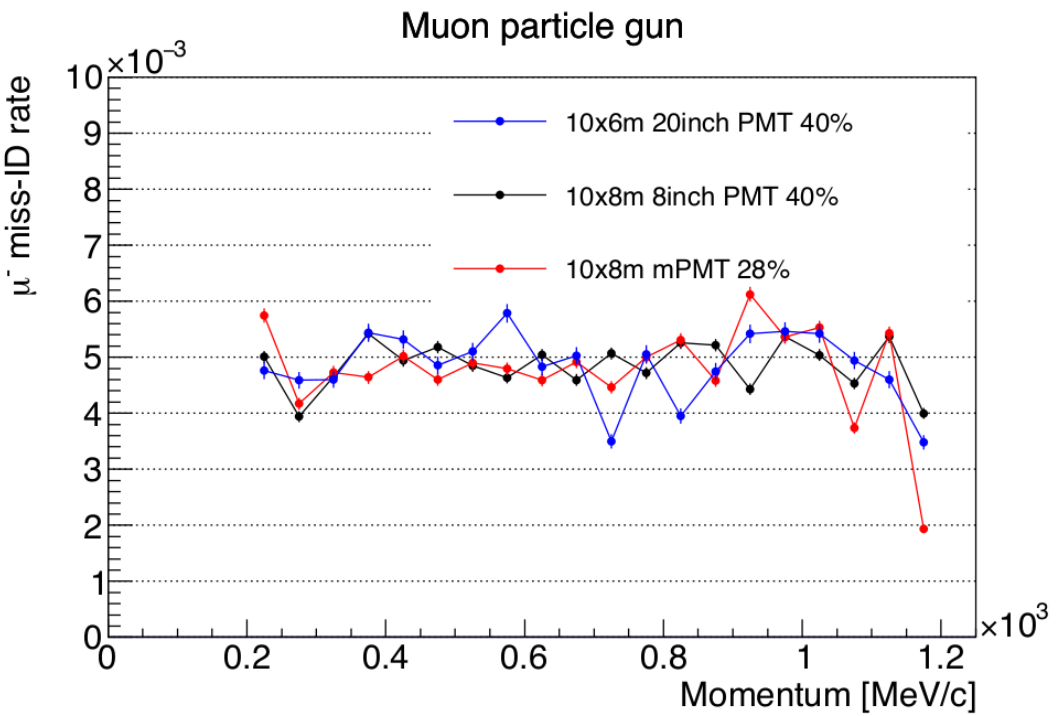


Single-ring fitters
J-PARC E61 experiment

- Small 10 x 8 m tank
- Compare three photosensor options:
  - 20" PMT (for reference only), 8" PMT and multi-PMT modules
    - For multi-PMT module details see G. de Rosa's talk tomorrow am







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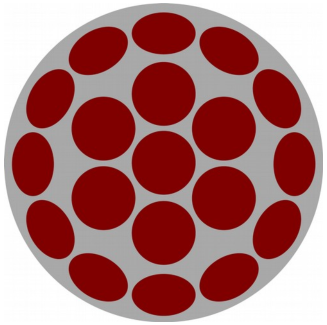
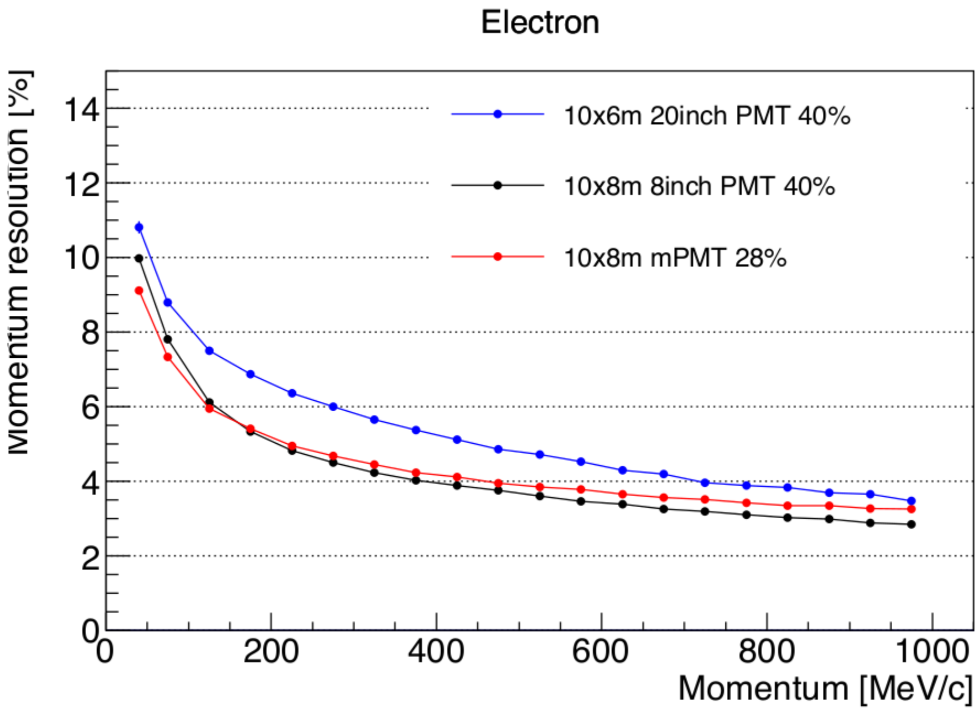
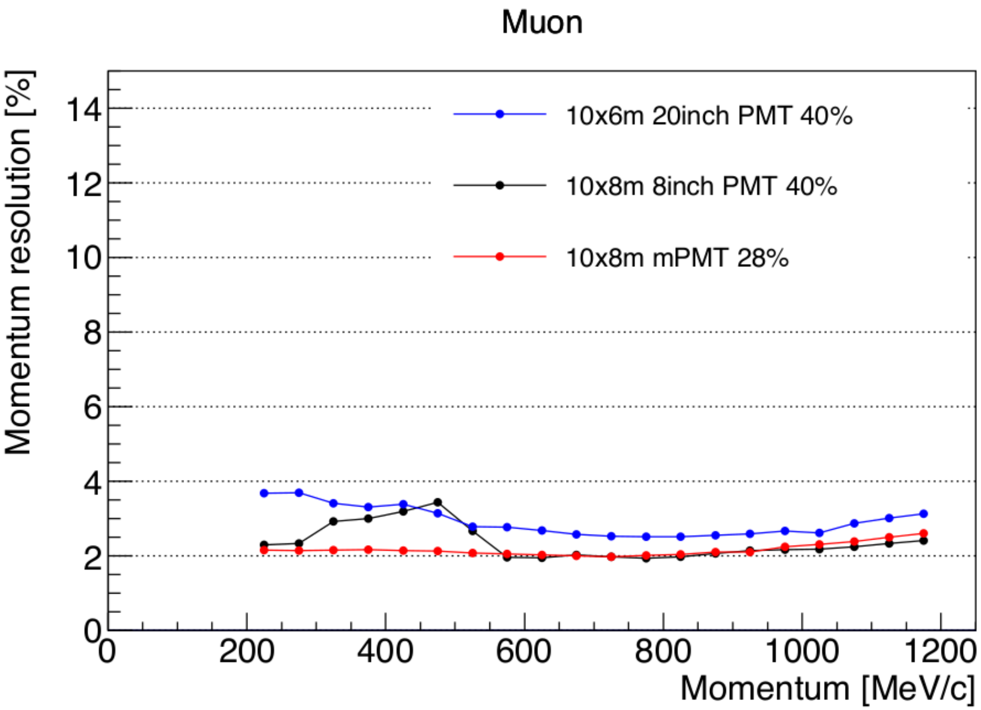
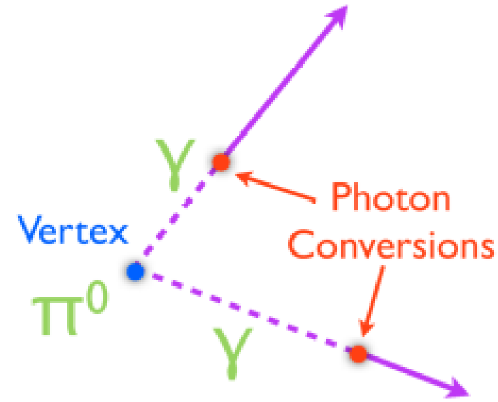


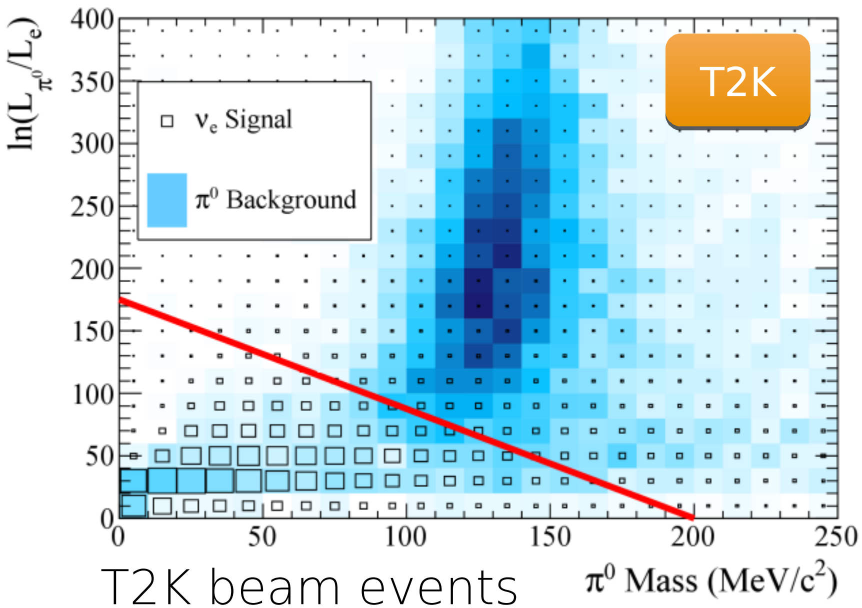




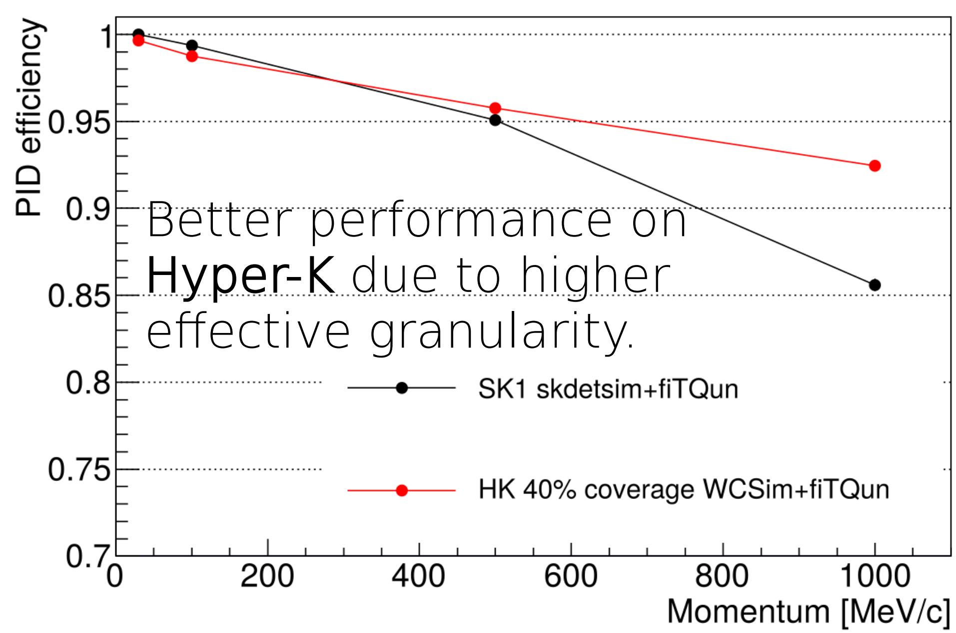
Neutral pions

- Fit two electron-like tracks with common vertex, accounting for photon conversion length
- 15 parameter fit, seeded with single-ring fit result
- Better electron/π^0 separation compared to previous Super-K reconstruction
  - FiTQun better at finding faint rings in busy event.



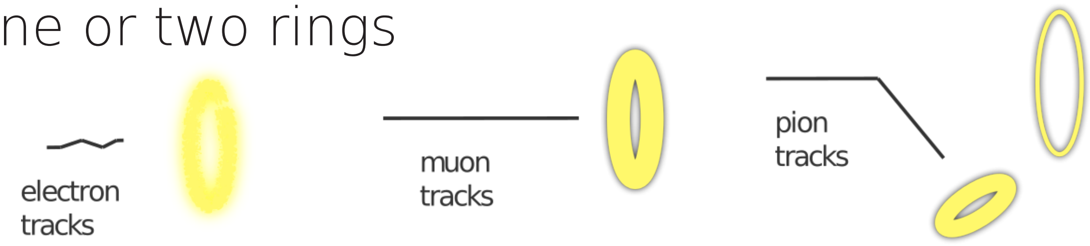


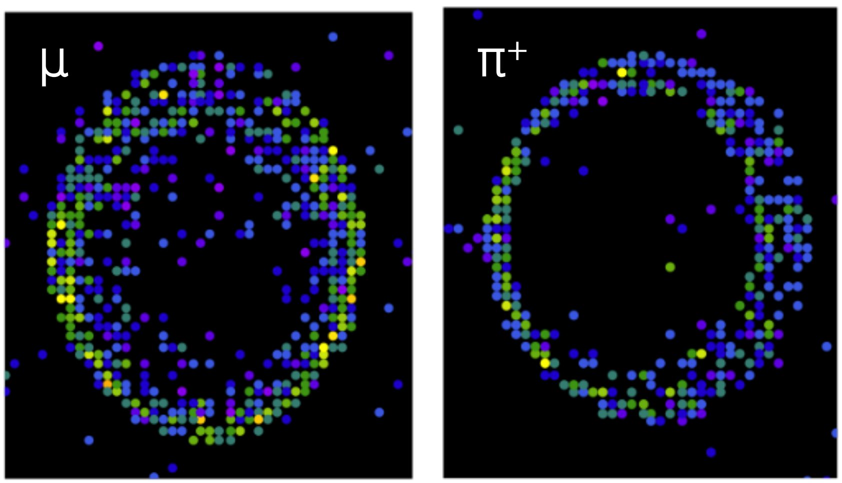
T2K beam events

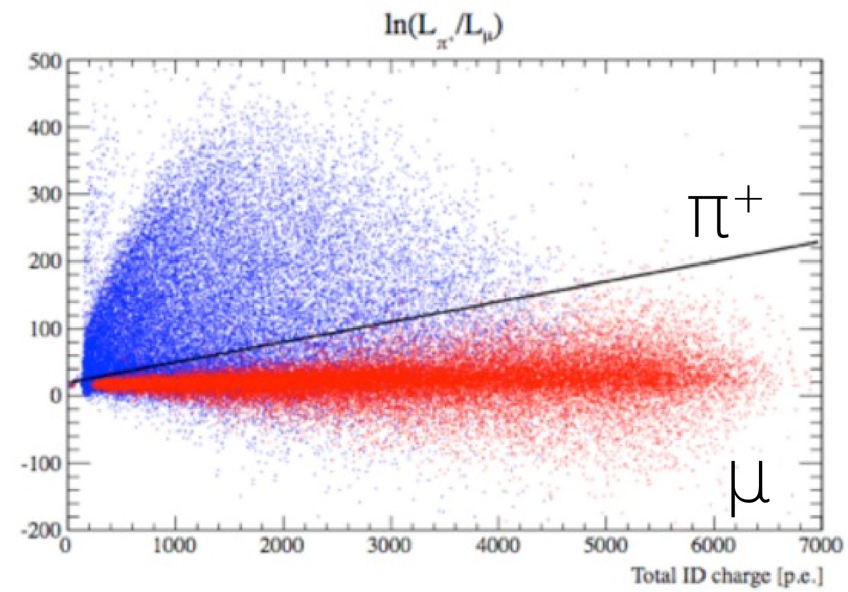


Better performance on Hyper-K due to higher effective granularity.

- Single-ring π^+ difficult to distinguish from μ
- However π^+ are more likely to hard-scatter
- Look for kinked π^+ track with one or two rings
  - "Upstream" ring is thinner
  - "Downstream" ring is fainter or invisible
- New PID handle at Super-K.

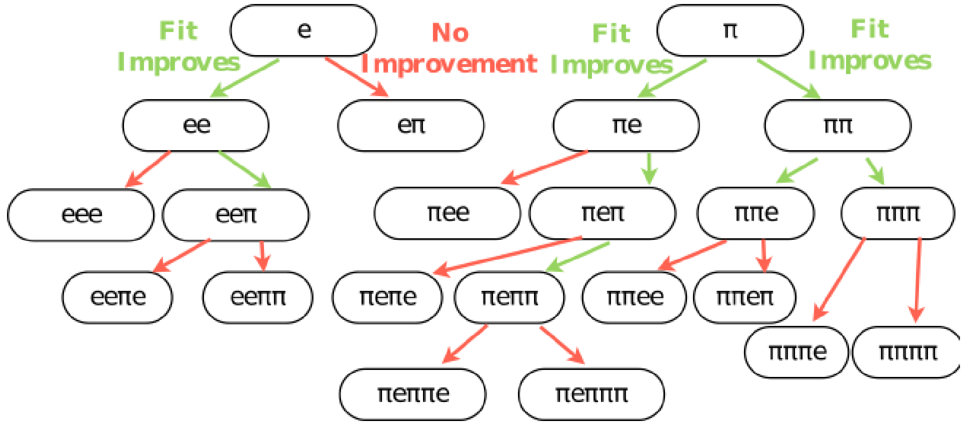


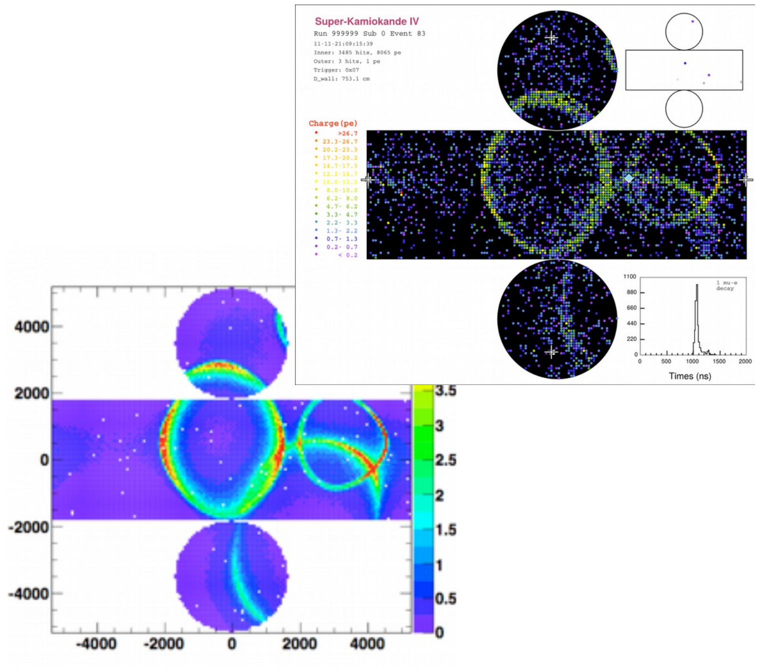


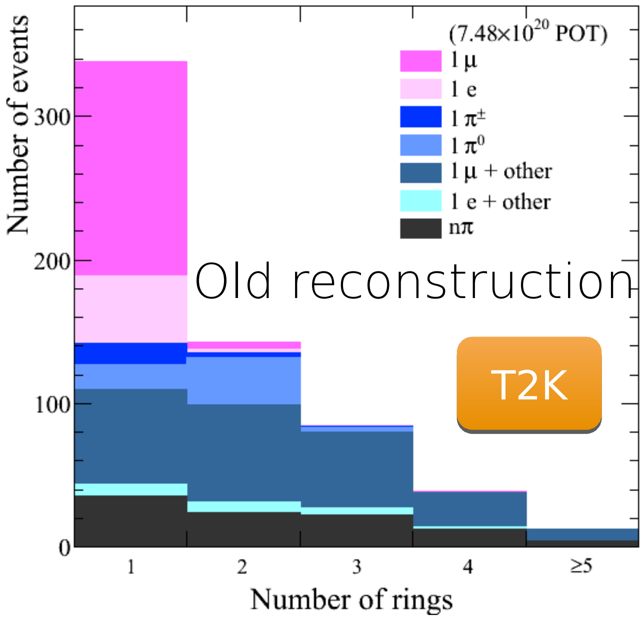


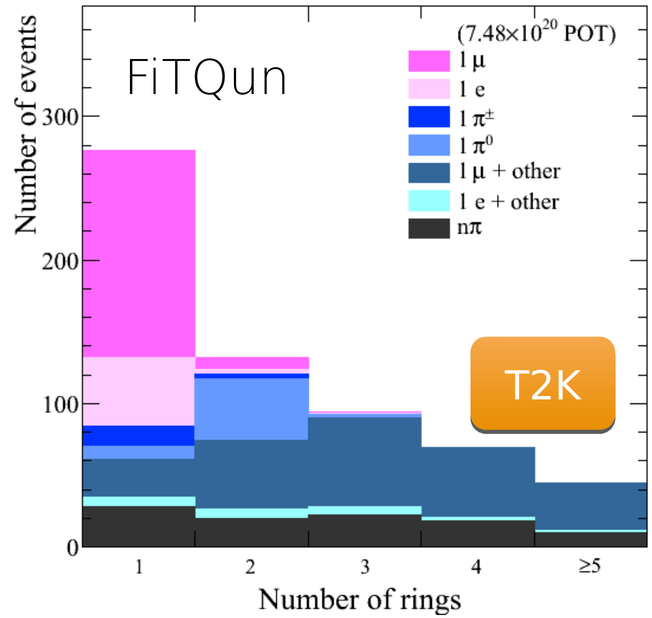
Multi-ring fitter

- Start from single-ring fits and sequentially add e-like or π-like ring until no improvement is seen.
- Once best-fit hypothesis is found, improve by fitting additional particle hypotheses (e.g., μ-like)





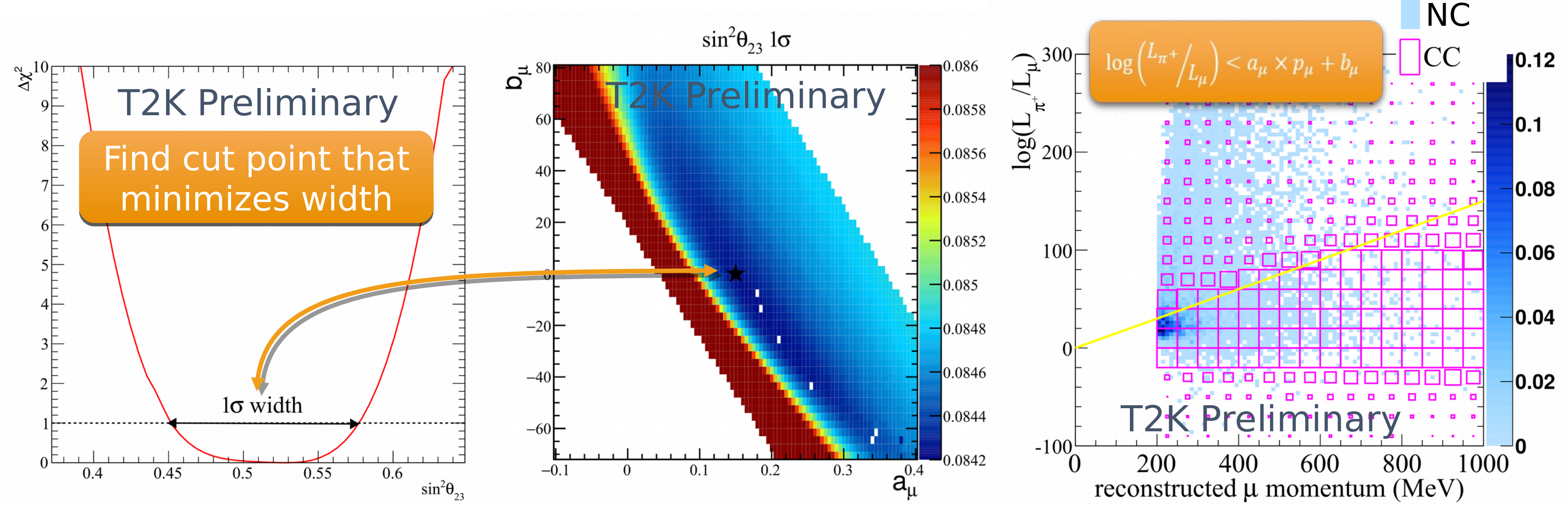




Impact on analyses

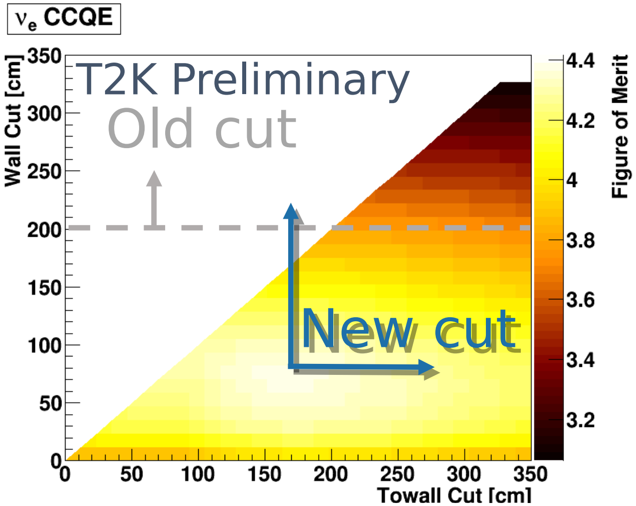
T2K Oscillation analysis – NCπ^+ rejection

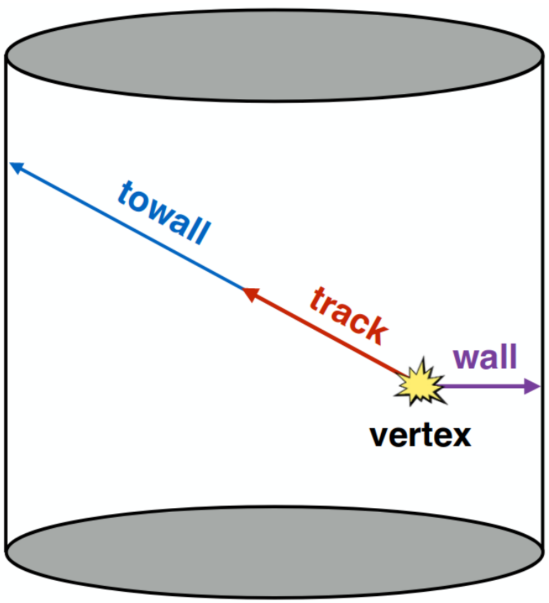
- FiTQun charged pion fits allow for reduction of neutral current backgrounds in T2K disappearance channels.
  - NCπ^+ contribution fills in the oscillation dip and has large cross-section uncertainty
- Cut was optimized for oscillation parameter estimation precision, taking into account statistical and systematic uncertainties.
- With other selection improvements, increased sample purity by 17%

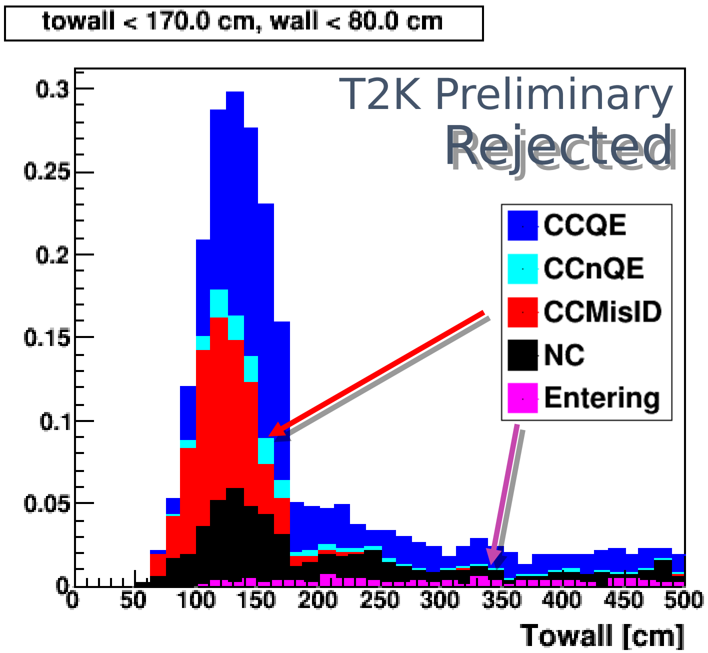


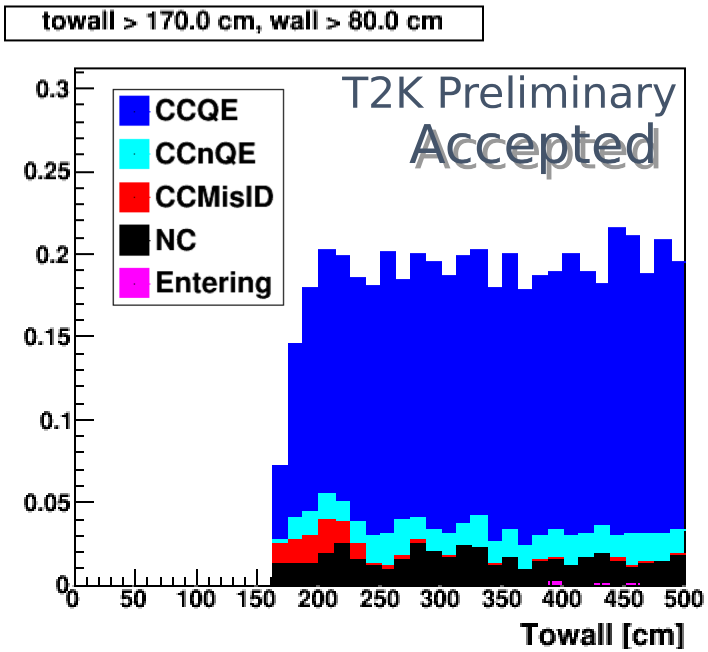
T2K Oscillation analysis – FV expansion

- Reconstruction improvements also allowed for an extension of the fiducial volume criterion.
  - Previously, distance to nearest wall greater than 2 m.
- With FiTQun can relax to 80 cm, while imposing a separate “towall” criterion.
- Leads to a ~20% increase in statistics.



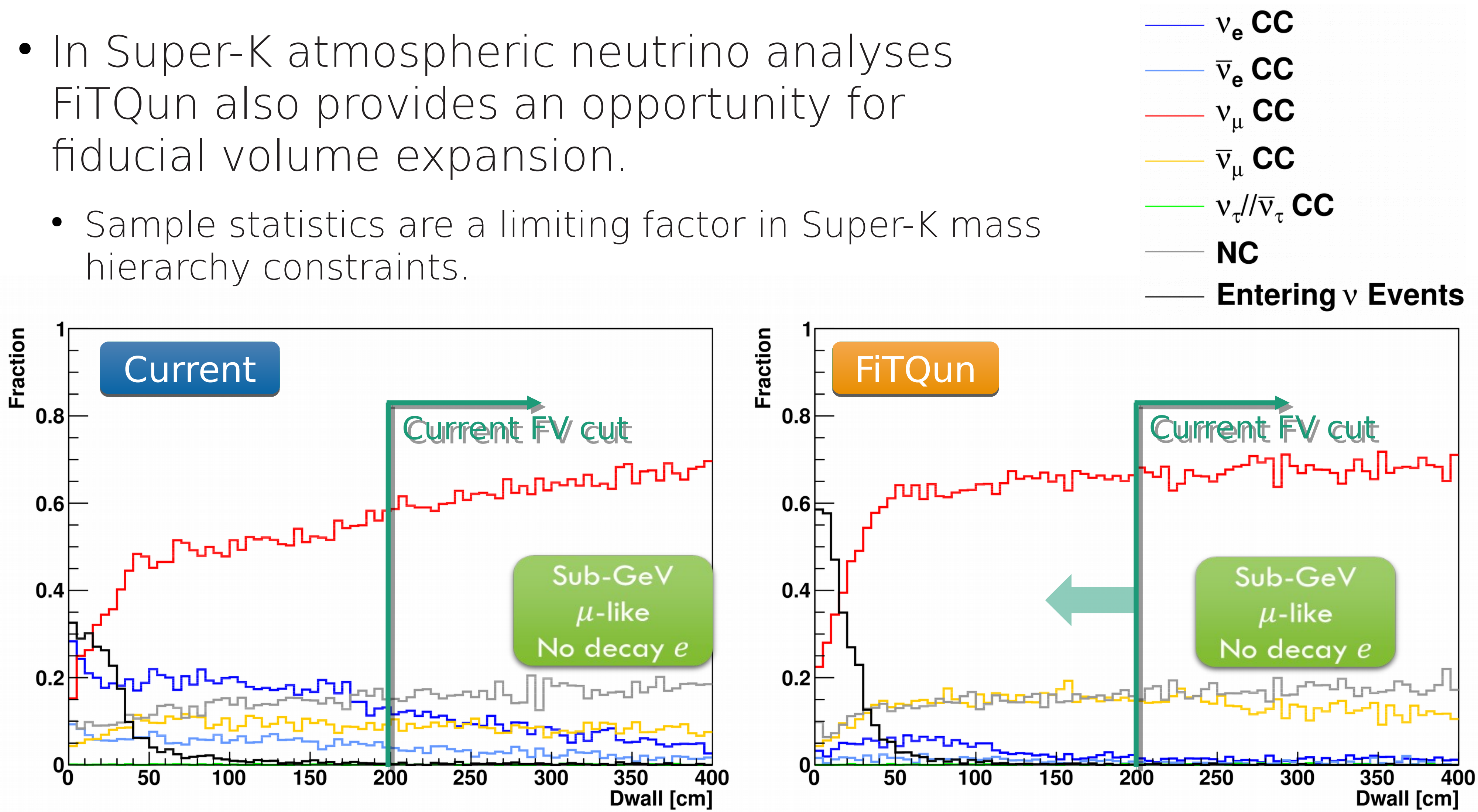






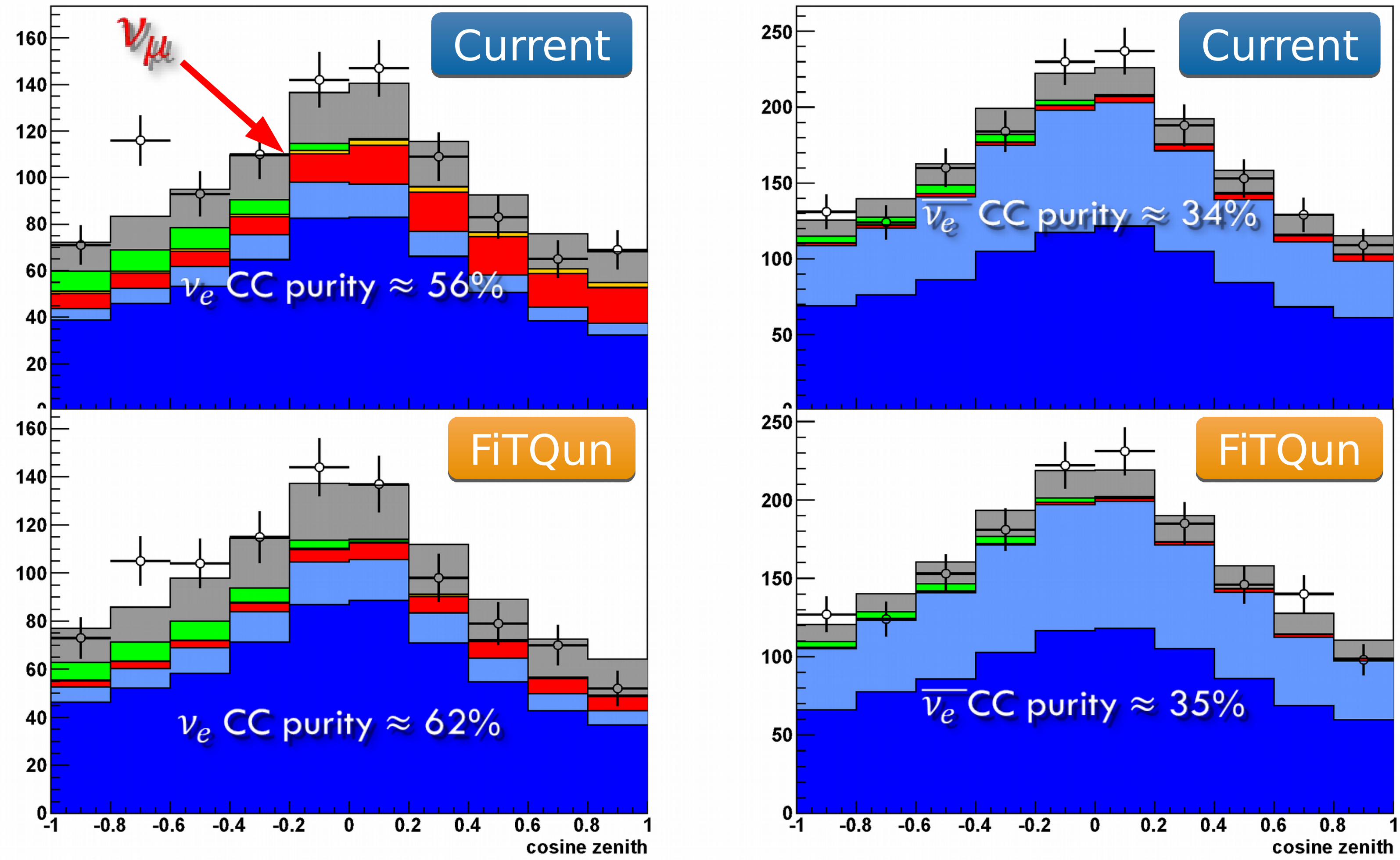
Super-K Atmospheric neutrinos

- In Super-K atmospheric neutrino analyses FiTQun also provides an opportunity for fiducial volume expansion.
  - Sample statistics are a limiting factor in Super-K mass hierarchy constraints.



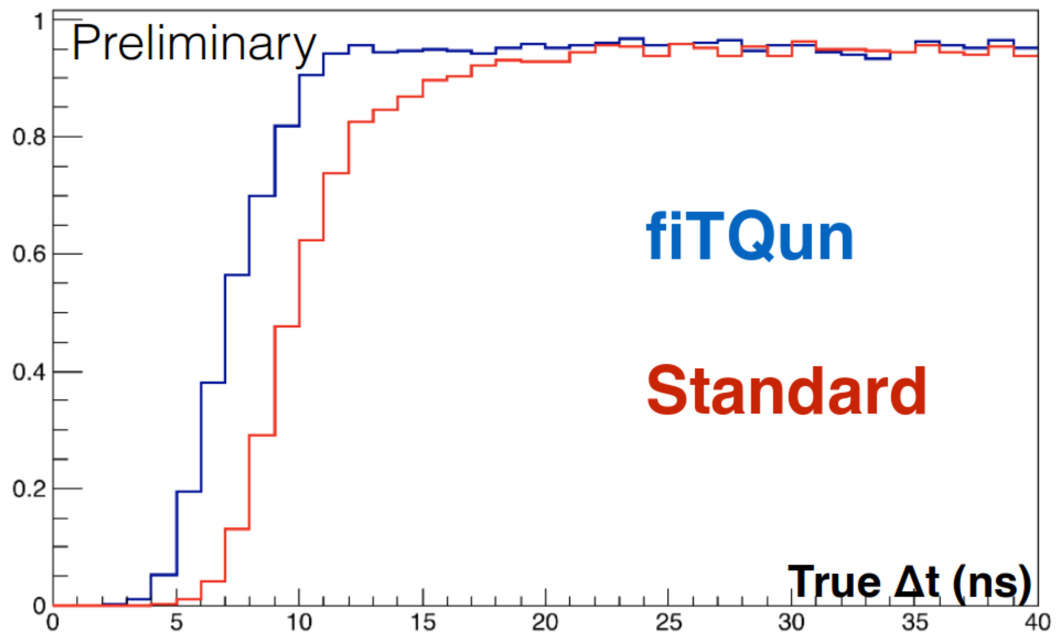
Super-K Atmospheric neutrinos

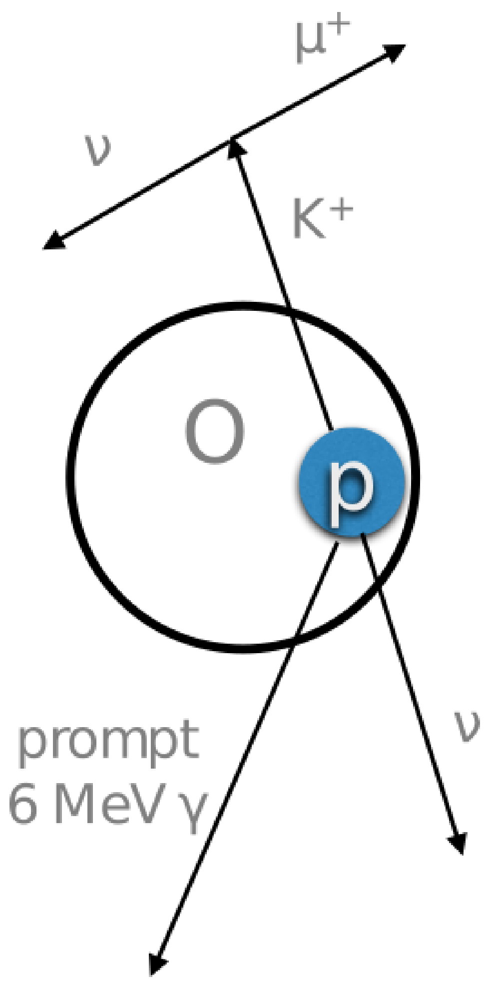
- Particle identification also improves in multi-ring, multi-GeV events.
  - Crucial for constraining the neutrino mass ordering.



Proton decay: $p \rightarrow K^+ \nu$ at Super-K

- Kaon is below Cherenkov threshold: signal is very faint nuclear de-excitation gamma followed (Δt ~12 ns) by monoenergetic muon.
  - Detecting the low energy gamma is challenging.
- FiTQun better at finding the gamma, in particular when very close in time with the muon.
- Expect significant improvement in detection efficiency.



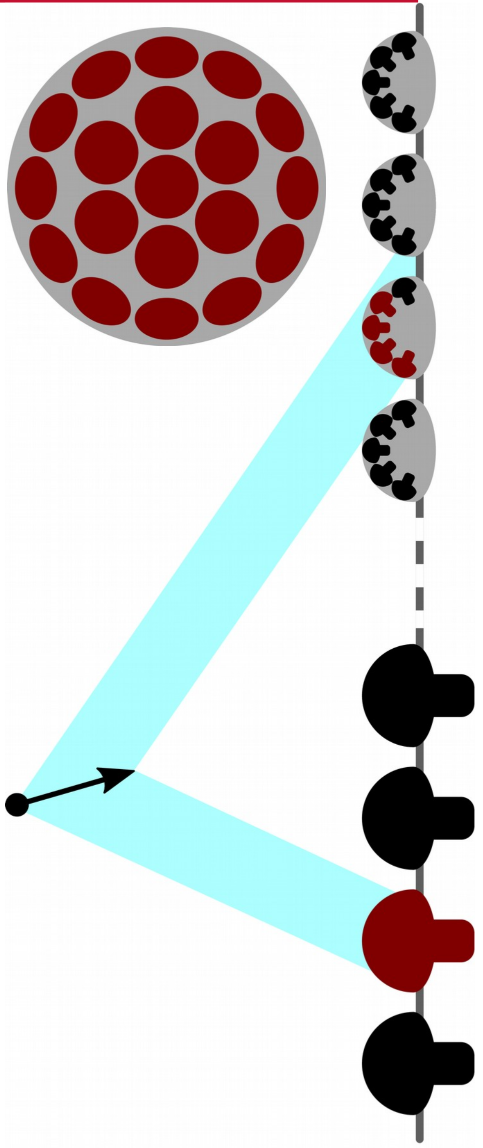


Summary

- New approach to water Cherenkov reconstruction at Super-K has proved very successful.
  - Used for latest T2K oscillation analysis results, where it allowed for an expansion of the fiducial volume.
  - Under study for Super-K atmospheric and proton decay analyses.
  - Used for high energy reconstruction in Hyper-K and E61.
- Current development efforts focused on extending the algorithm to work well with non-Super-K-like geometries.
  - For example, detectors populated with multi-PMT modules.
- The code and algorithm are adaptable to run on different geometries and data formats.
  - Code is currently hosted in a private github repository:
  - https://github.com/fiTQun/
    - If interested in access, get in touch!

Extra

Multi-PMT reconstruction



- Multi-PMT modules are proposed for use in E61 and Hyper-K.
- Their geometry breaks cylindrical symmetry assumed by FiTQun – not all PMTs point towards centre.
  - Angular response depends on PMT position within the module.
  - And so do reflections.
- Initial FiTQun tunes for multi-PMT geometries give reasonable results.
  - Some performance still unsatisfactory, notably the neutral pion fits.
  - Efforts ongoing to add detail to FiTQun predictions, by increasing dimensionality of some parts of the detector model.
    - There might be an opportunity to use machine learning techniques.