Status of Hyper-K Event Reconstruction (fiTQun)

Mike Wilking

5th Hyper-K Meeting

21-July-2014

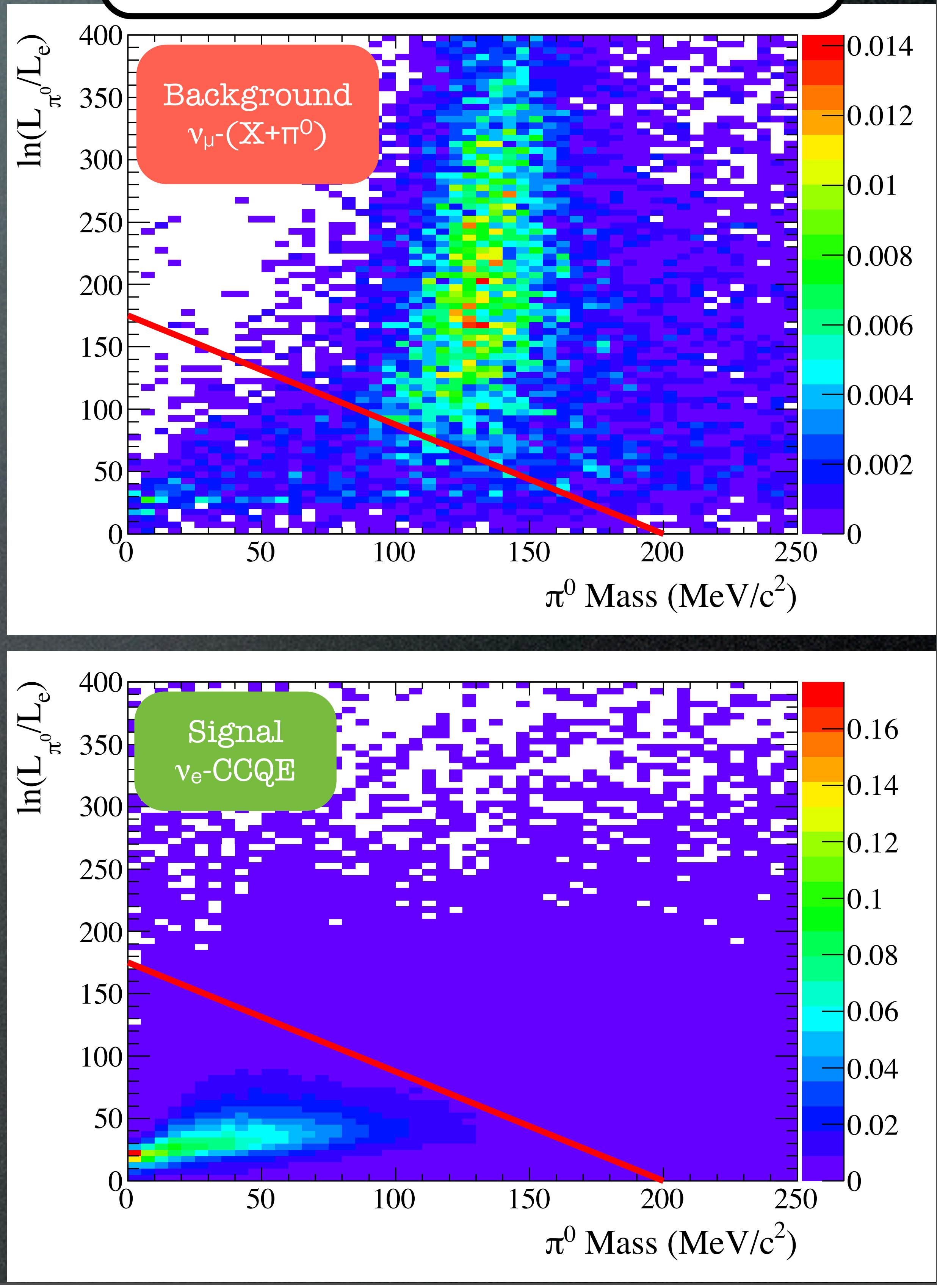
Overview

- Brief reminder of fiTQun capabilities
  - Many of these are typically not reflected in publicly shown Hyper-K sensitivities
- Recent fiTQun developments
- Hyper-K fiTQun integration

π^0 Rejection

- fiTQun can use the **likelihood ratio** and **π^0 mass** to distinguish e^- from π^0
  - Identification of the 2nd photon has significantly improved
- 2D cut **removes 70% more π^0 background** than previous algorithms
  - (2% loss in signal efficiency)
- This is now starting to be used by Hyper-K itself, but not most of the projections made by others
  - Performance should be confirmed with 20% PMT coverage and larger Hyper-K geometry

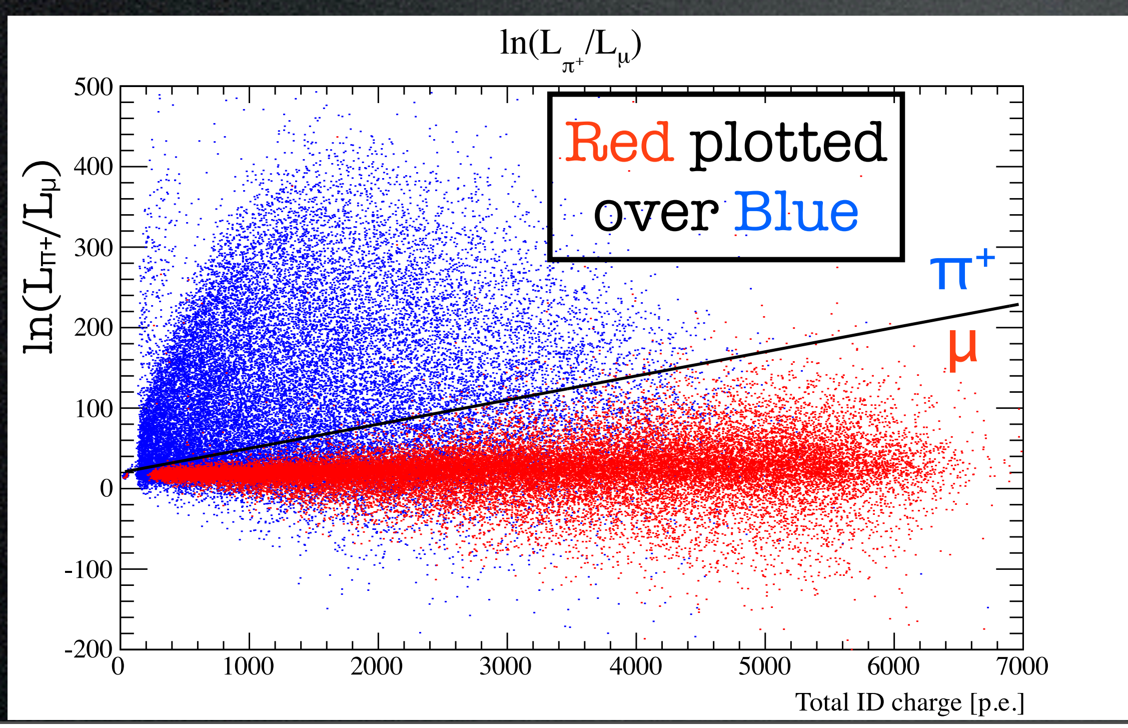
Likelihood Ratio vs π^0 Mass

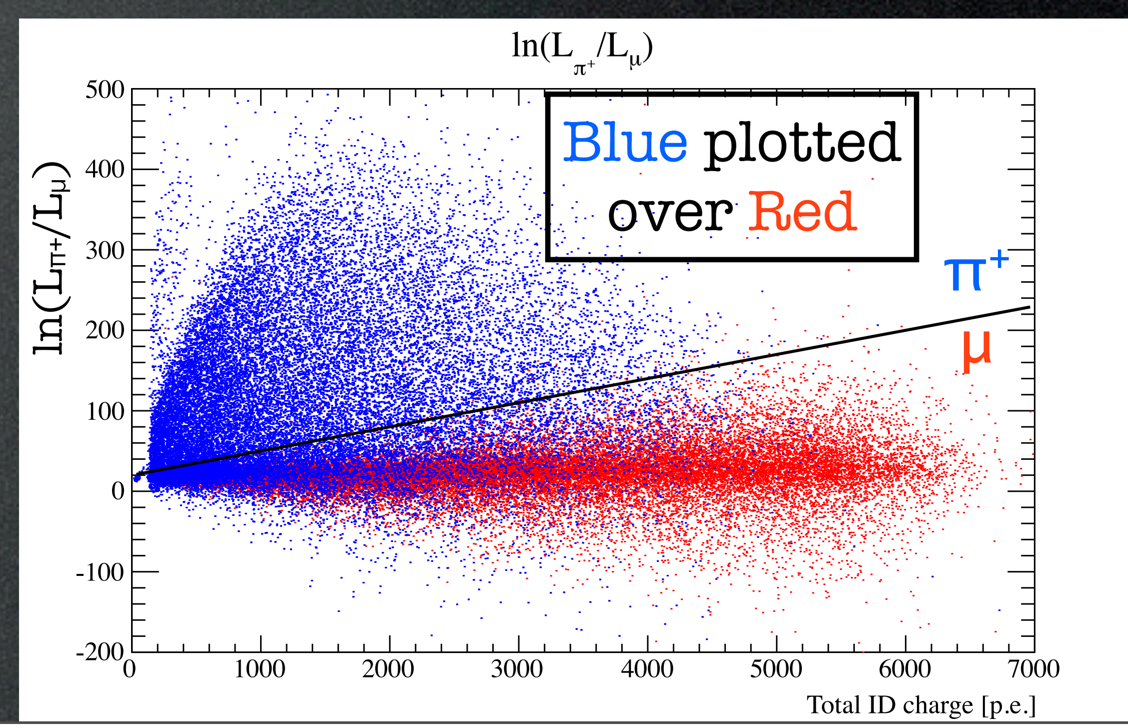


π^+ Fitter

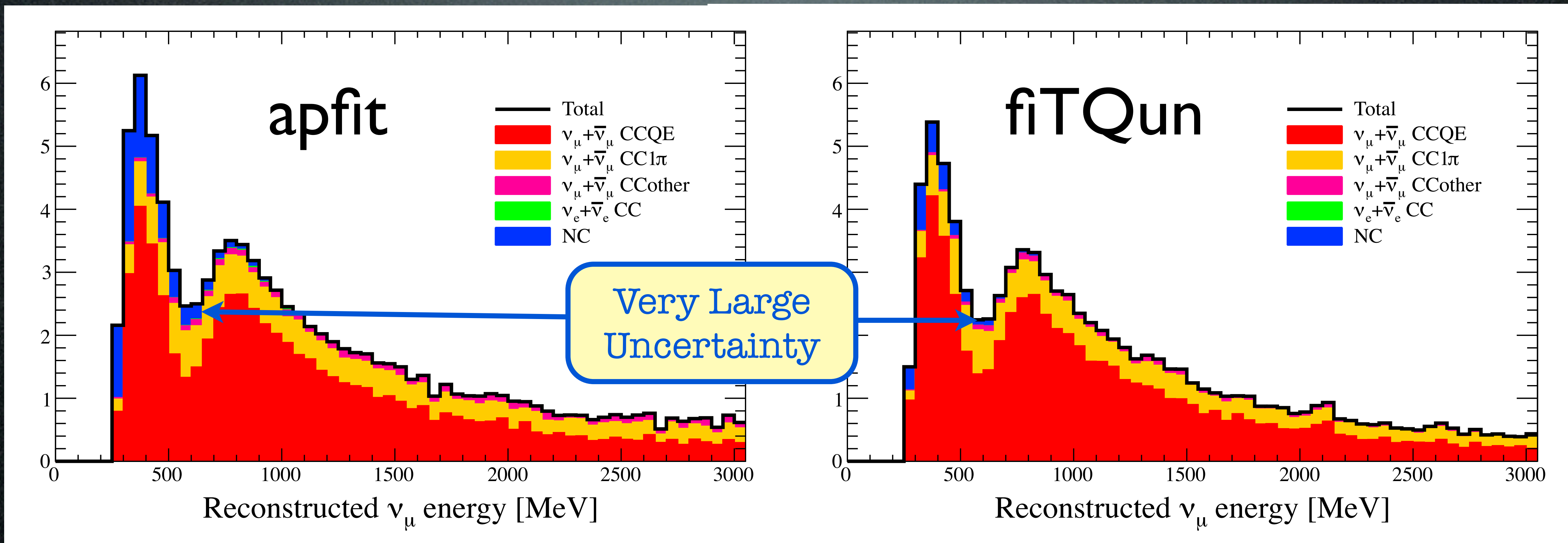
- Pions and muons have **very similar Cherenkov profiles**
  - Main difference is the **hadronic interactions** of pions
- Ring pattern observed is a **"kinked" pion trajectory** (thin ring with the center portion missing)
- π^+ / μ separation is now possible at Super-K!

μ & π^+ particle gun





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
- This cut has **never** been incorporated in **any** Hyper-K sensitivity plot

ν_e Appearance Selection

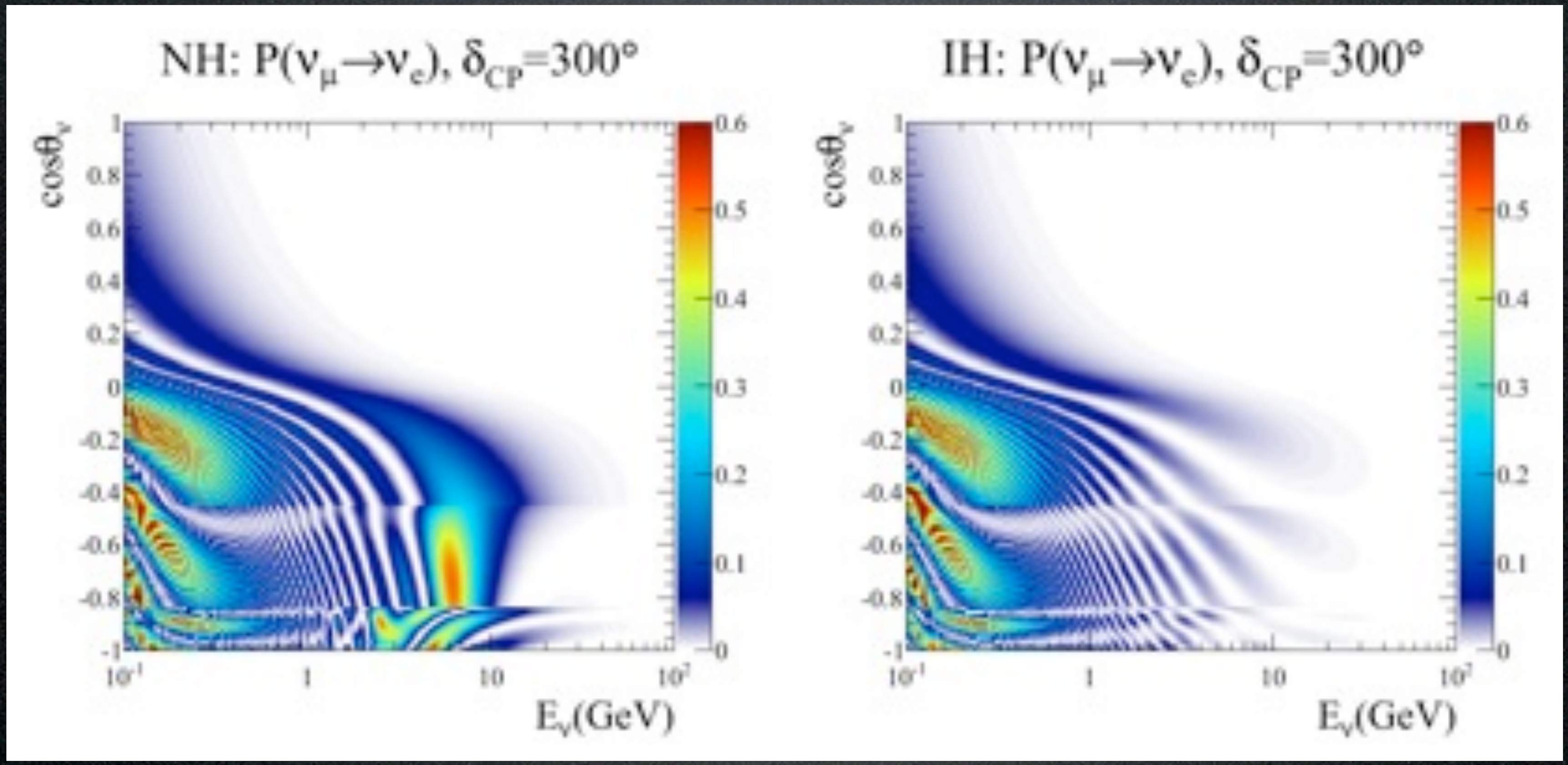
3.01 * 10^{20} POT $\sin^2 2\theta_{13}=0.1$	fiTQun Selection: Signal ($\nu_\mu \rightarrow \nu_e$ CC)	fiTQun Selection: Bkgd (all)	fiTQun Selection: Bkgd (π^0)	fiTQun Selection: Bkgd (ν_μ CC)	fiTQun Selection: Bkgd (beam ν_e CC)	APFit Selection: Signal ($\nu_\mu \rightarrow \nu_e$ CC)	APFit Selection: Bkgd (all)	APFit Selection: Bkgd (π^0)	APFit Selection: Bkgd (ν_μ CC)	APFit Selection: Bkgd (beam ν_e CC)
All other cuts	10.12	8.40	3.88	0.60	4.26	10.04	13.62	8.47	1.75	4.78
≦ 1 Michel	10.11	8.07	3.66	0.42	4.21	10.02	12.92	7.93	1.29	4.70
π^0 Cut	9.21	3.57	0.72	0.079	2.68	9.28	5.51	1.86	0.40	3.15
E_ν < 1250 MeV	**8.99**	**2.42**	**0.42**	**0.058**	**1.82**	**9.00**	**3.68**	**1.31**	**0.296**	**1.92**

- Improved fiTQun μ/e separation allows a looser Michel cut
  - The ν_e-CC signal is **increased by 15%** while the signal/background ratio remains nearly constant
- Loosening this cut does not have a large impact on the APFit sensitivity due to the large increase in ν_μ background
- This has never been included in a Hyper-K sensitivity plot

New fiTQun Capabilities

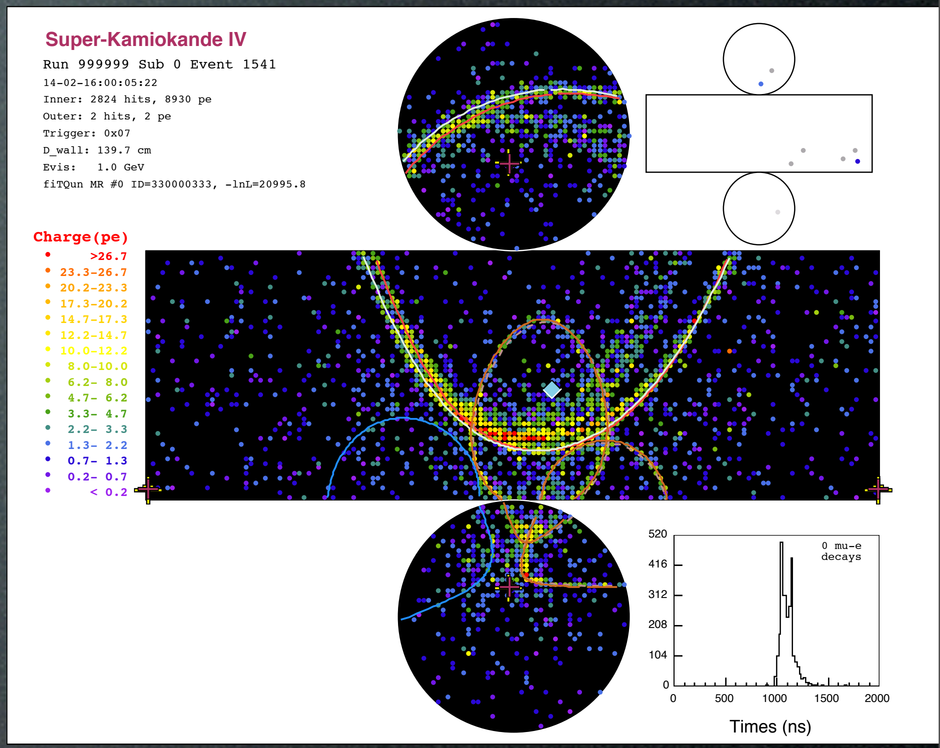
High Energy Events

- Previously, fiTQun has been more focused on single-ring events below 1-2 GeV (T2K selection)
- However, interesting atmospheric neutrino events occur at much higher energies
  - Neutrino mass hierarchy resonance occurs at ~4-6 GeV
- High energy reconstruction can also provide benefits to certain long-baseline neutrino experiment configurations



Multi-ring Fitter Improvements

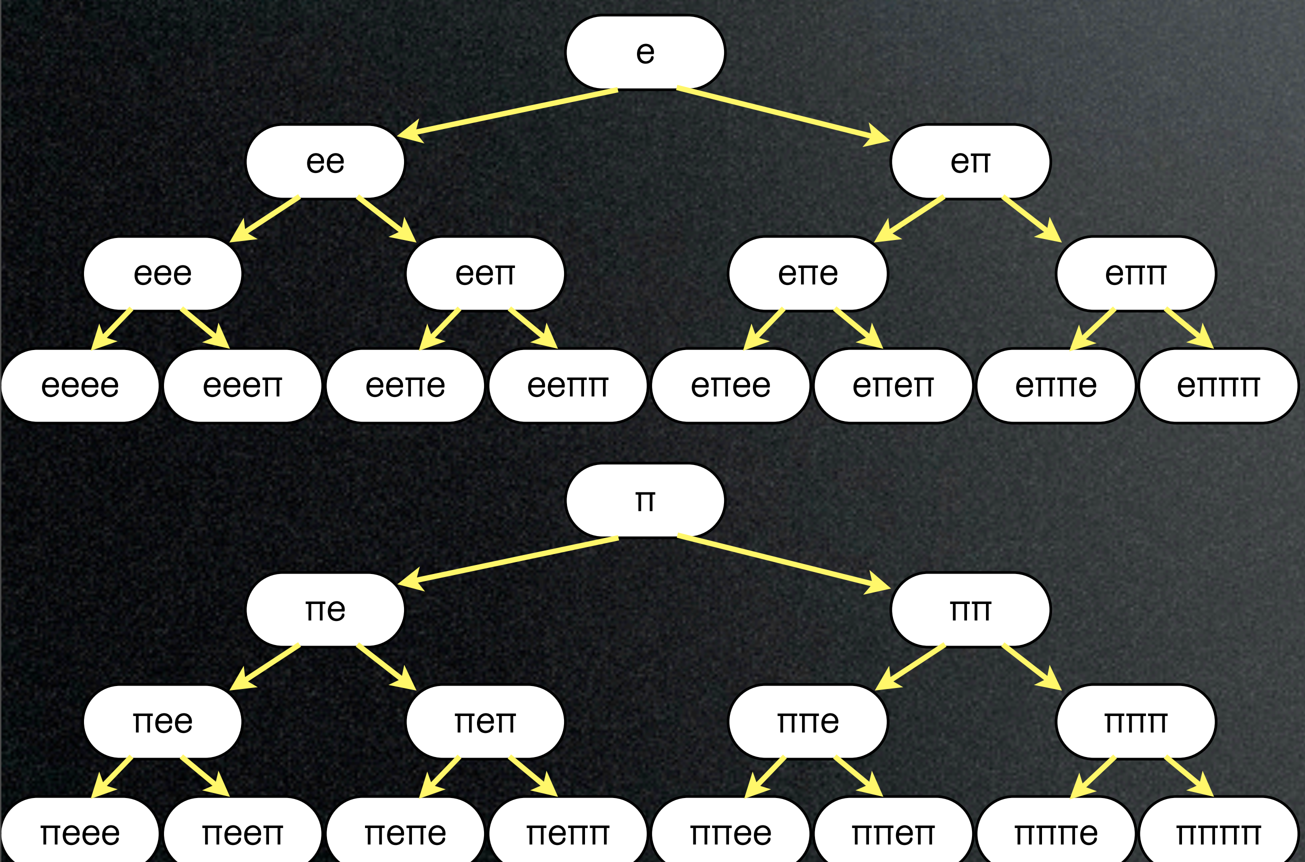
- Previous fiTQun ran every ring permutation up to 4 rings
- New fit sequence terminates branches if no improvement is observed
  - Up to 6 rings are now supported with less total CPU time
- Final hypotheses are refit to remove fake rings and improve PID
  - This is where muon fits are introduced

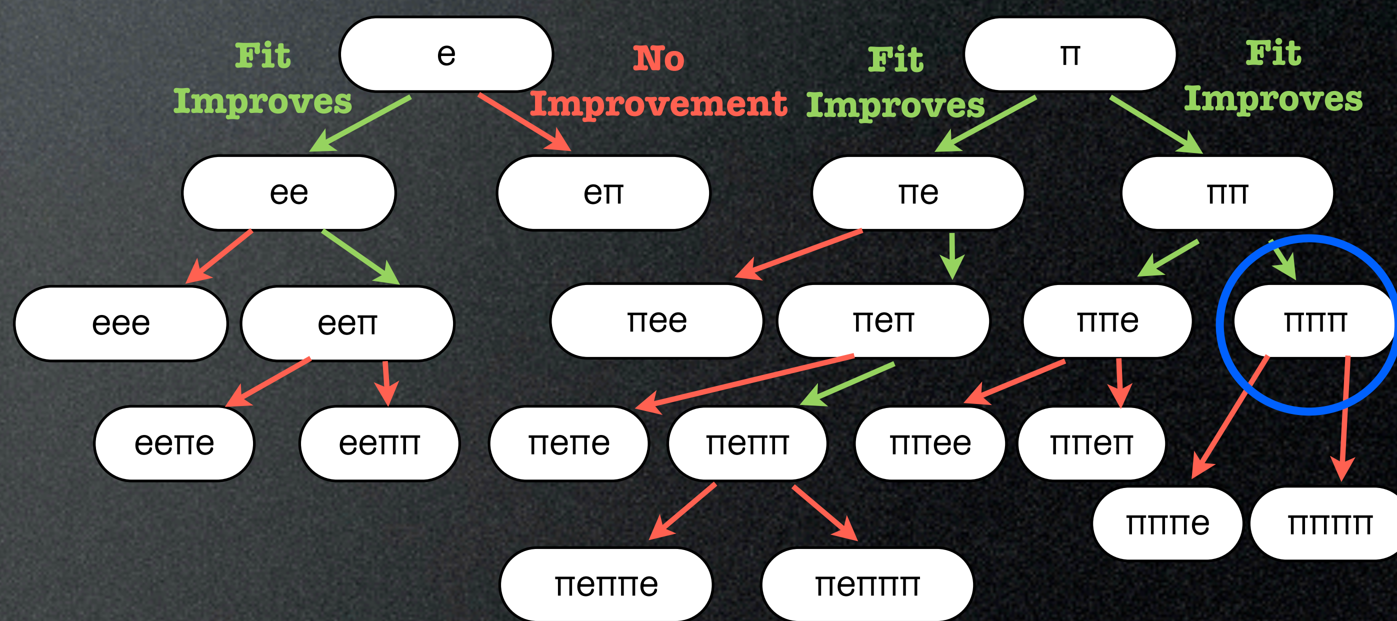


Old Fit Sequence

S. Tobayama

New Fit Sequence





fiTQun now returns best fit number of rings by default

Improved Multi-Ring Performance

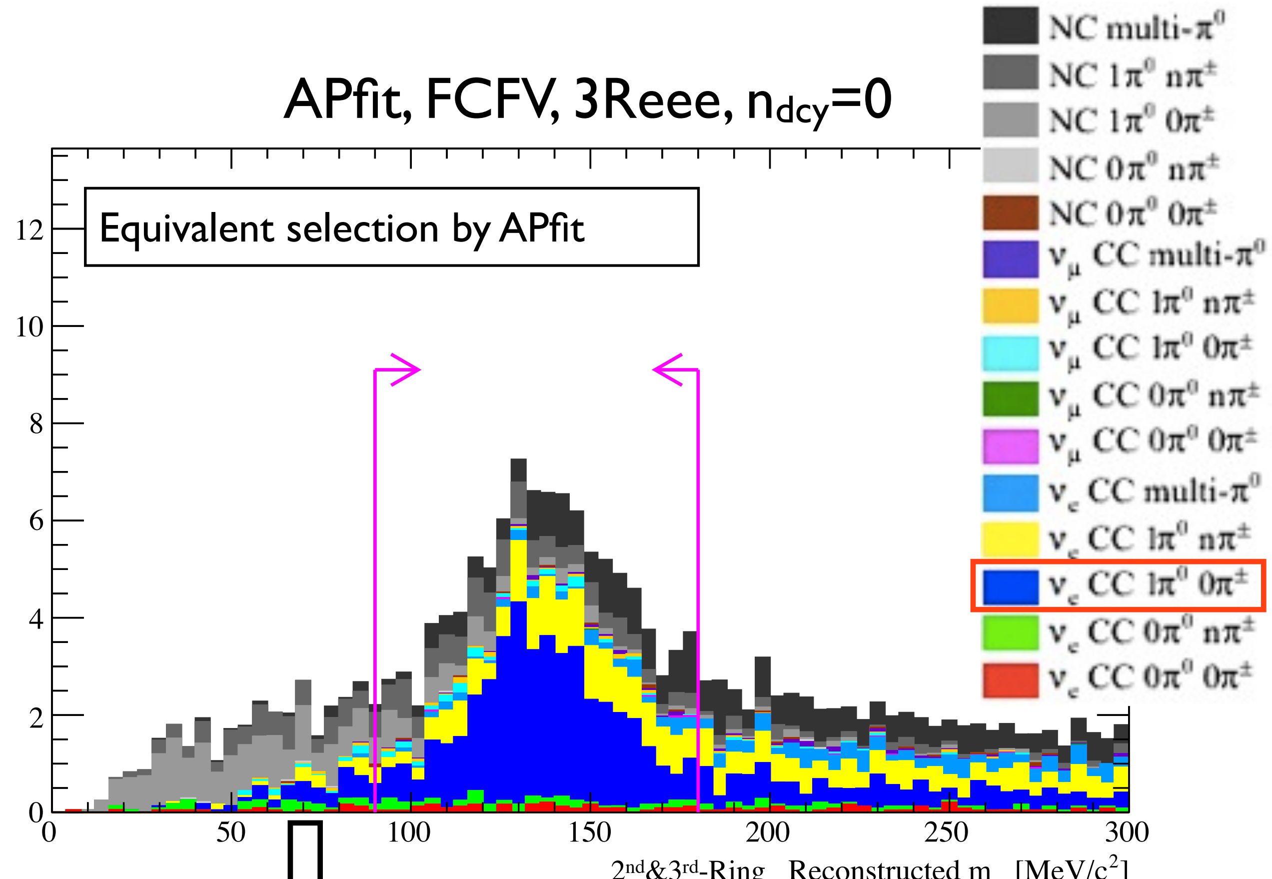
Atm-ν MC 3.5GeV<E_{vis}<7GeV	fiTQun Pre-refit	fiTQun Post-refit	APfit
Average # of true rings found	2.81	2.65	1.86
Average # of fake rings	1.08	0.26	0.14

- fiTQun finds many more rings than APFit
  - However, fake ring rate is higher
- Final refit stage to remove fake rings works very well

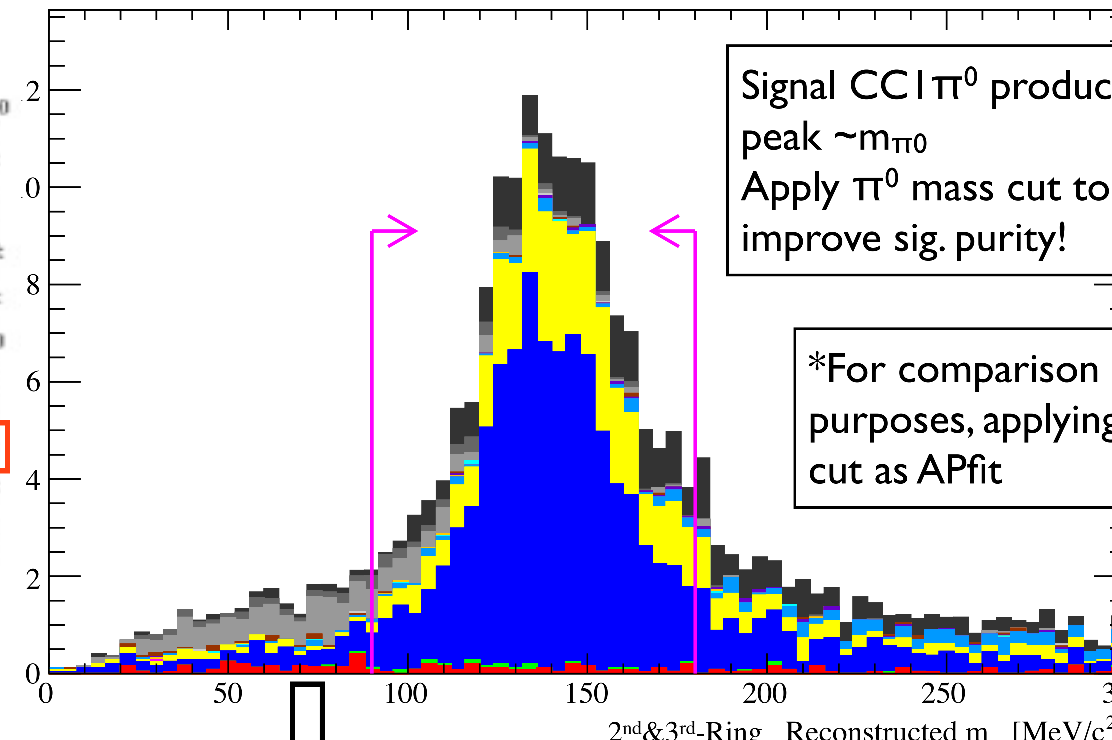
Atm. ν_eCC $1\pi^0$ Selection

*14a SK4 Atm-ν FCMC 1417days

APfit, FCFV, 3Reee, n_{dcy}=0

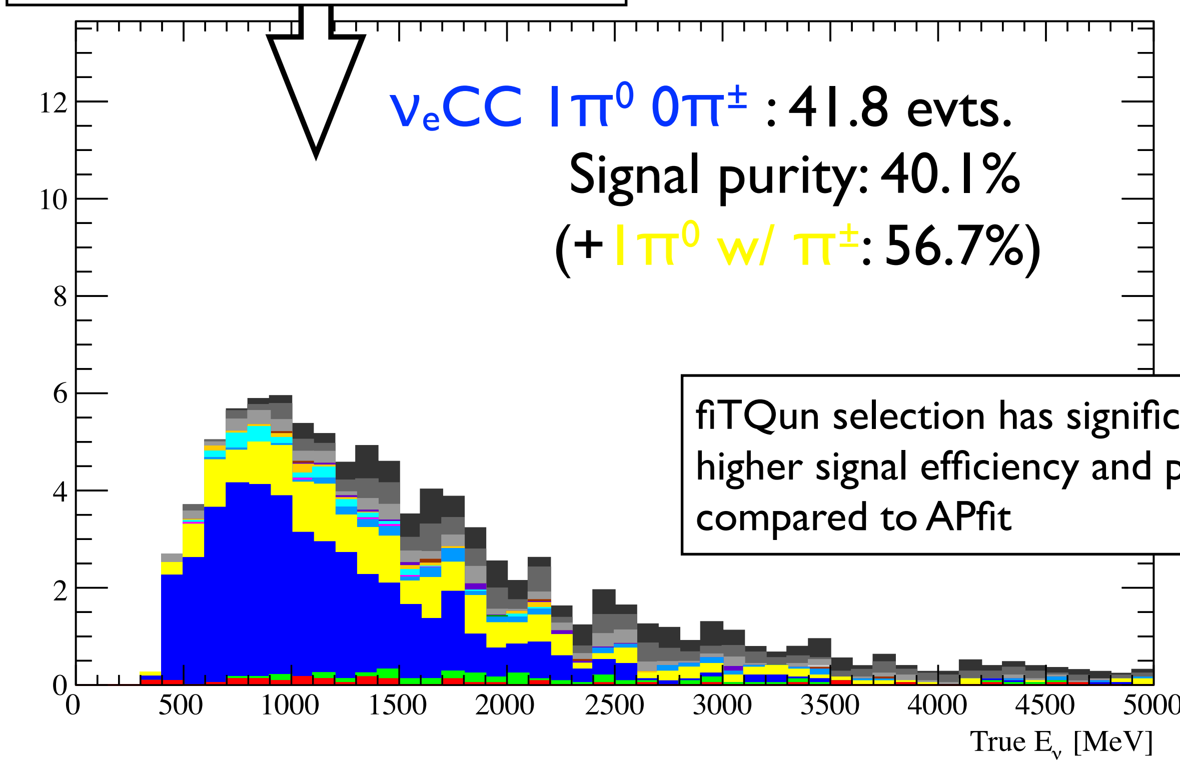


fiTQun, FCFV, 3Reee, n_{dcy}=0

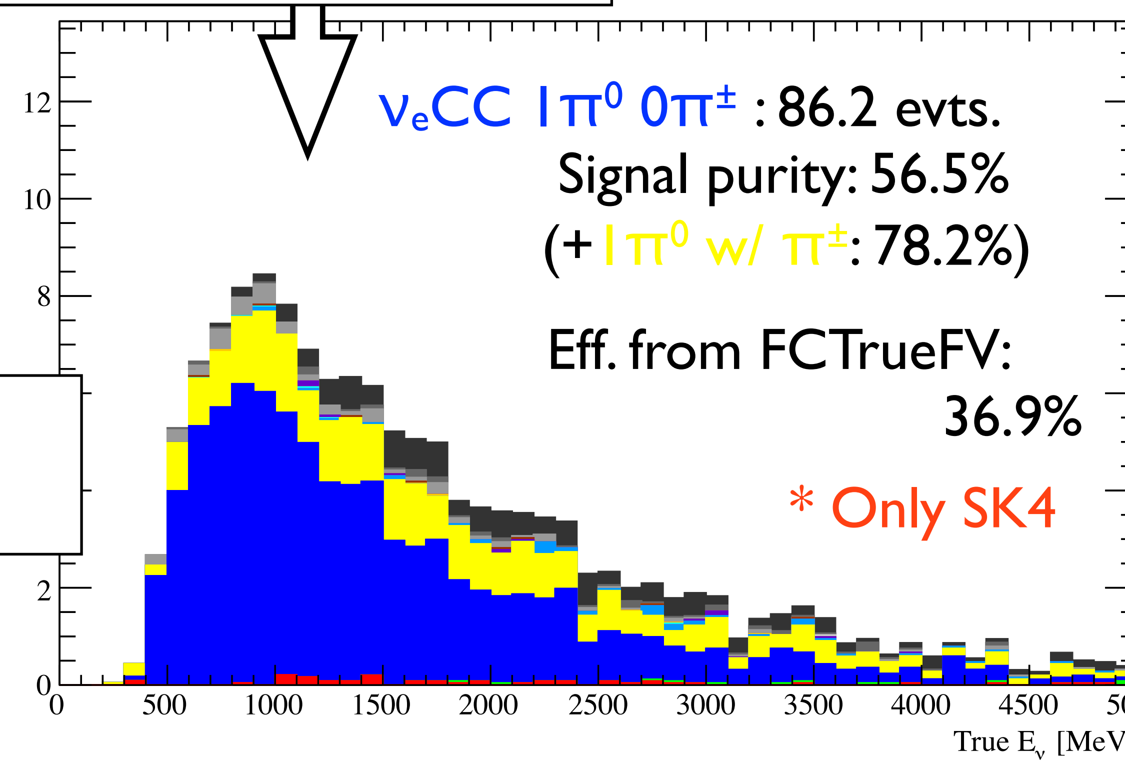


Cut: $90\text{MeV}/c^2 < m_{\gamma\gamma}^{rec} < 180\text{MeV}/c^2$

Cut: $90\text{MeV}/c^2 < m_{\gamma\gamma}^{rec} < 180\text{MeV}/c^2$



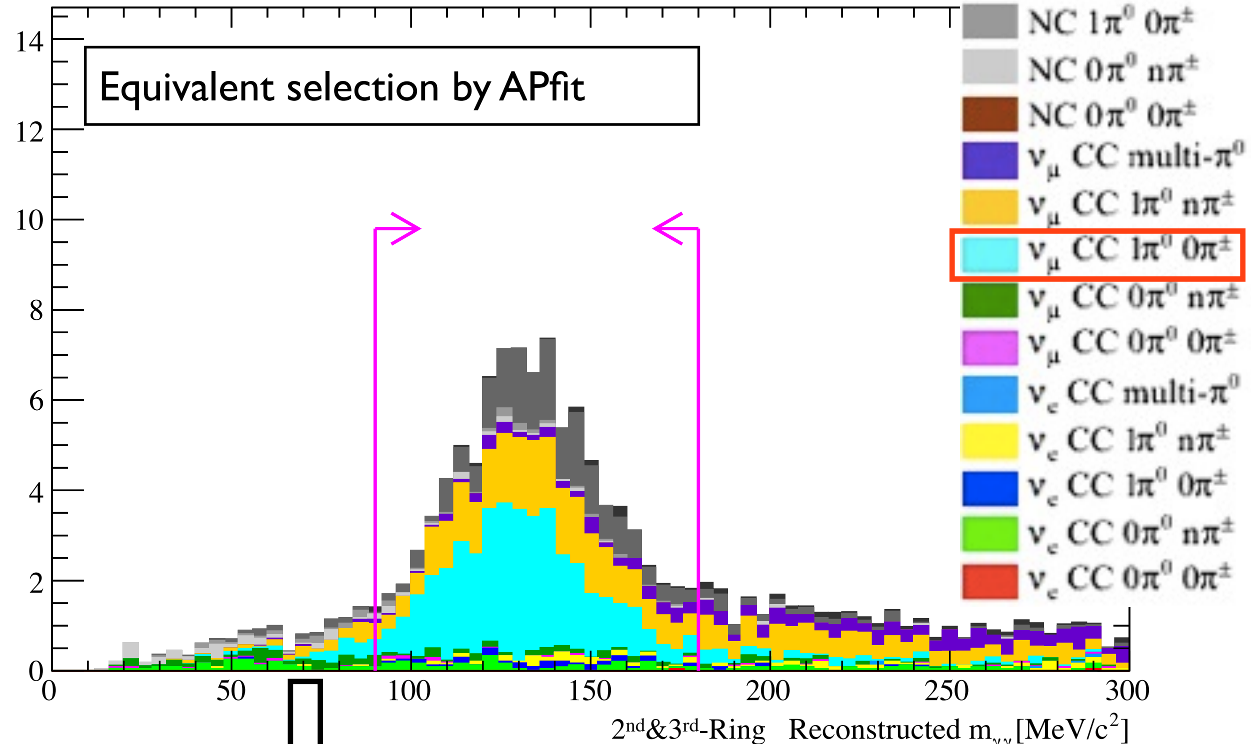
fiTQun selection has significantly higher signal efficiency and purity compared to APfit



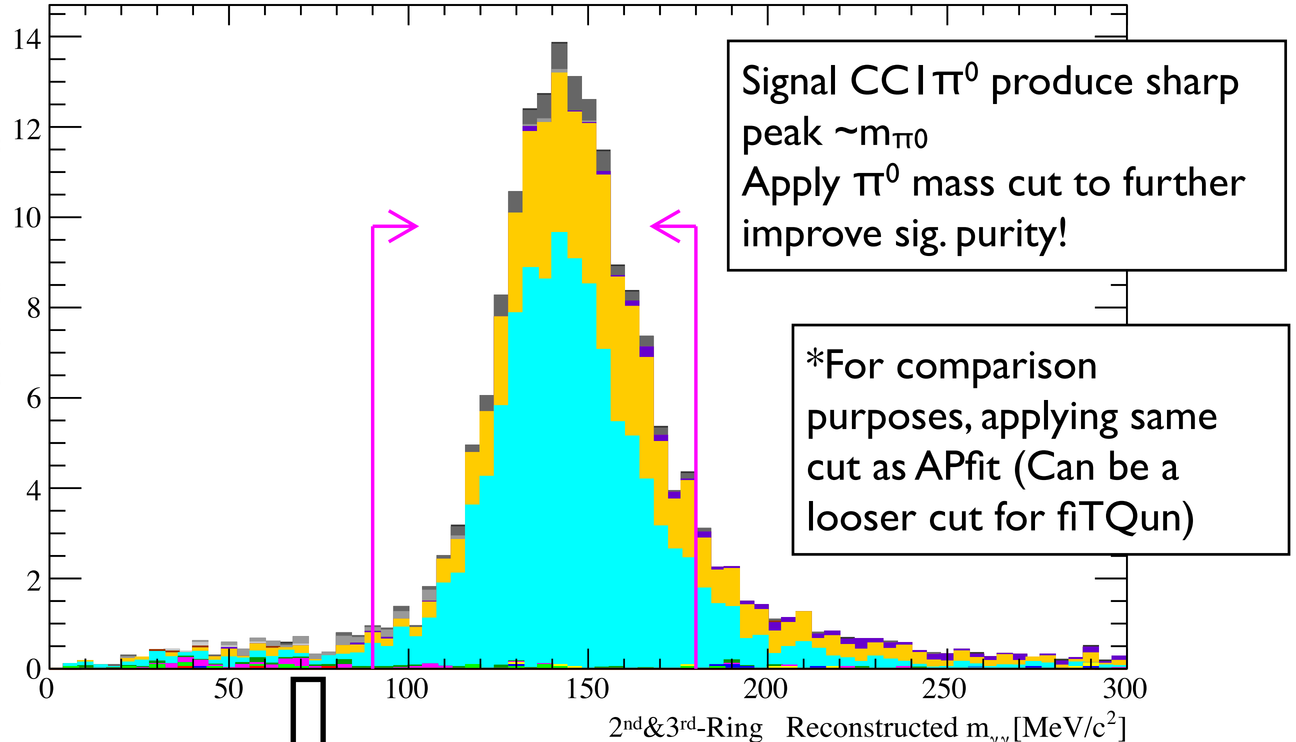
Atm. ν_μCC 1π^0 Selection

*14a SK4 Atm-ν FCMC 1417days

APfit, FCFV, 3Rμee, $n_{dcy} \leq 1$

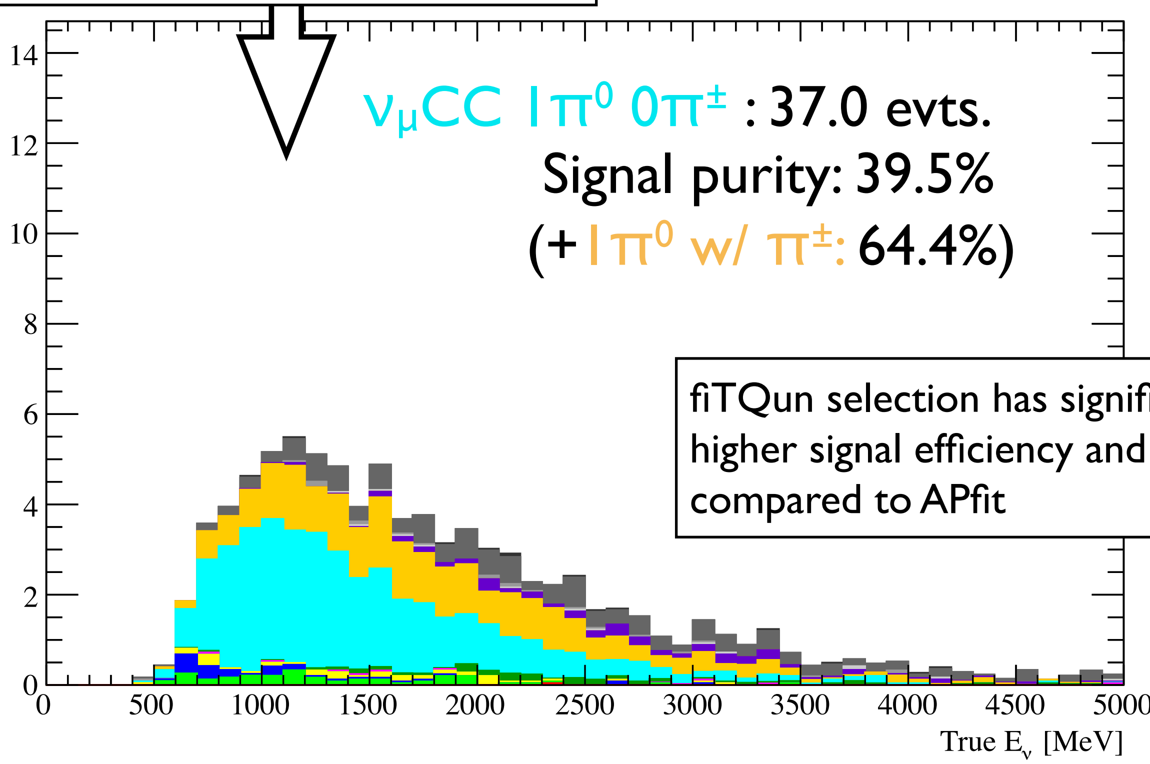


fiTQun, FCFV, 3Rμee, $n_{dcy} \leq 1$

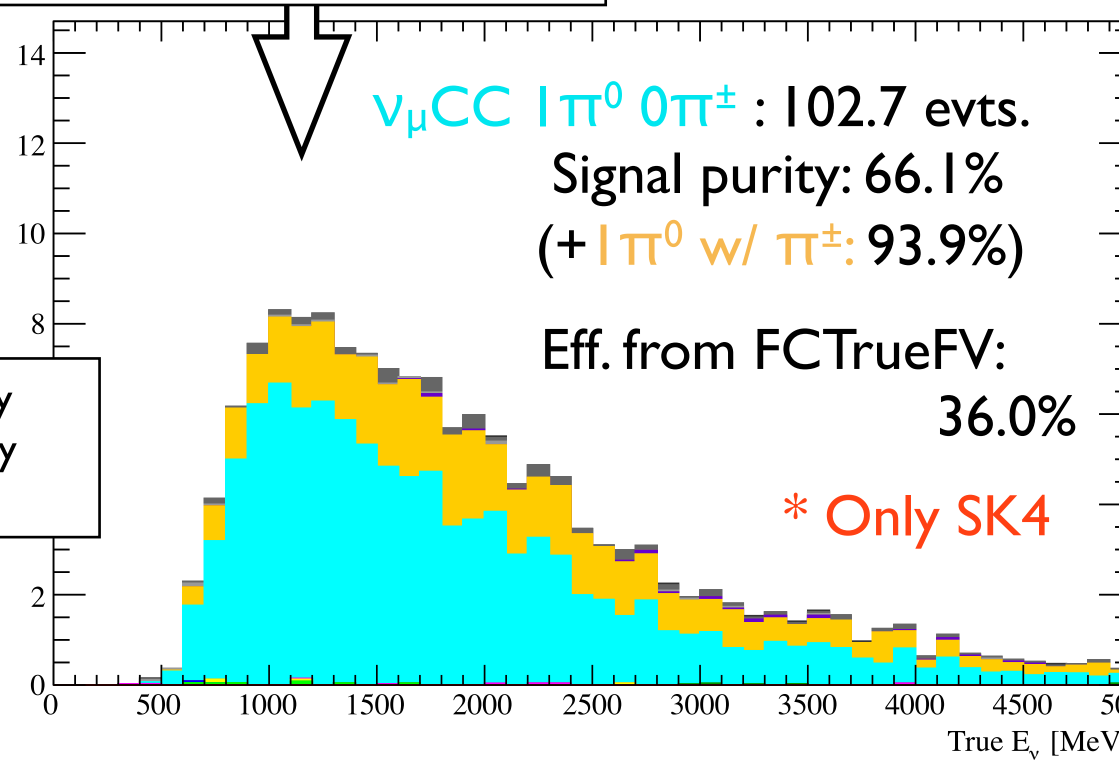


Cut: 90MeV/c² < $m_{\gamma\gamma}^{rec}$ < 180MeV/c²

Cut: 90MeV/c² < $m_{\gamma\gamma}^{rec}$ < 180MeV/c²

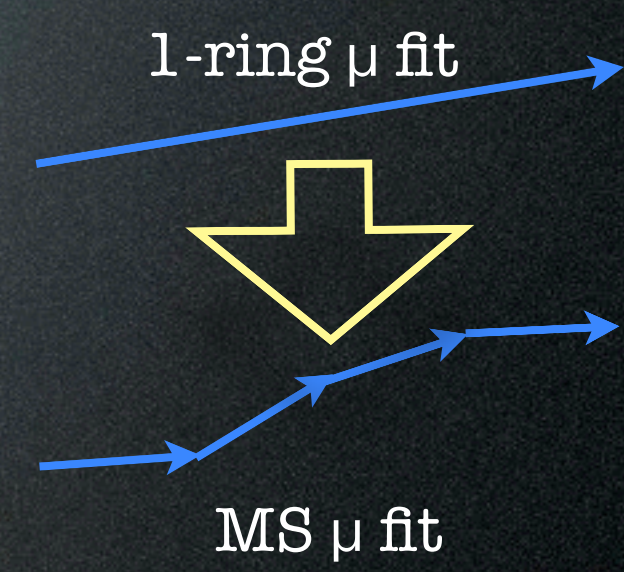


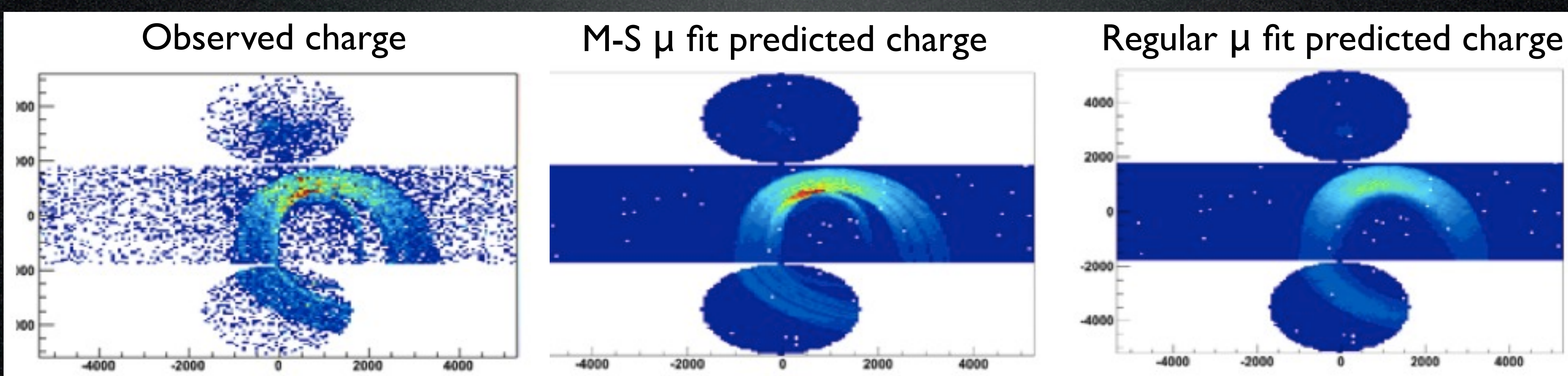
fiTQun selection has significantly higher signal efficiency and purity compared to APfit



Multiple-Scattering Muon Fit

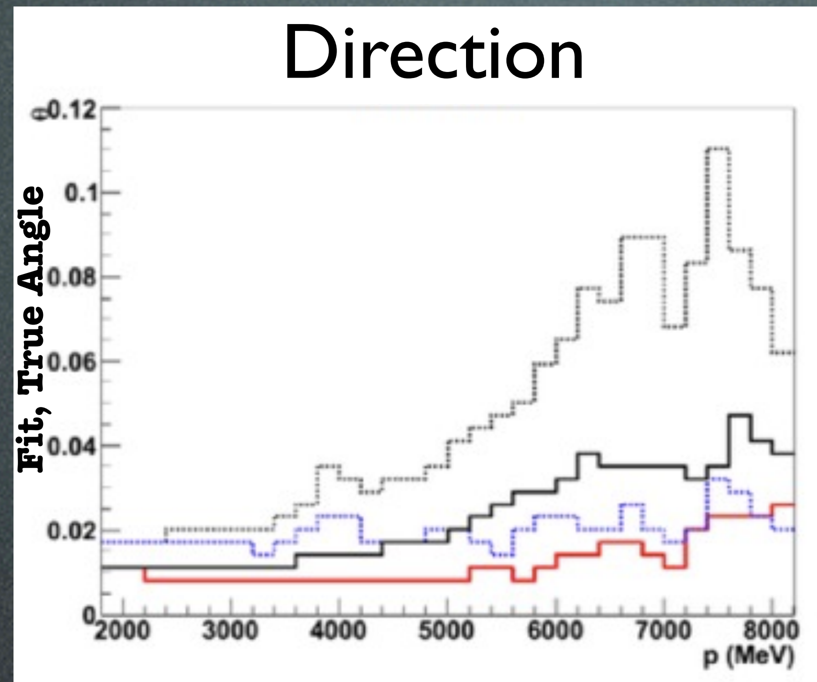
- At high energies, muon scattering distorts the ring center
  - fiTQun assumes azimuthal symmetry
- Track is divided into multiple segments
  - Can now fit structure within rings

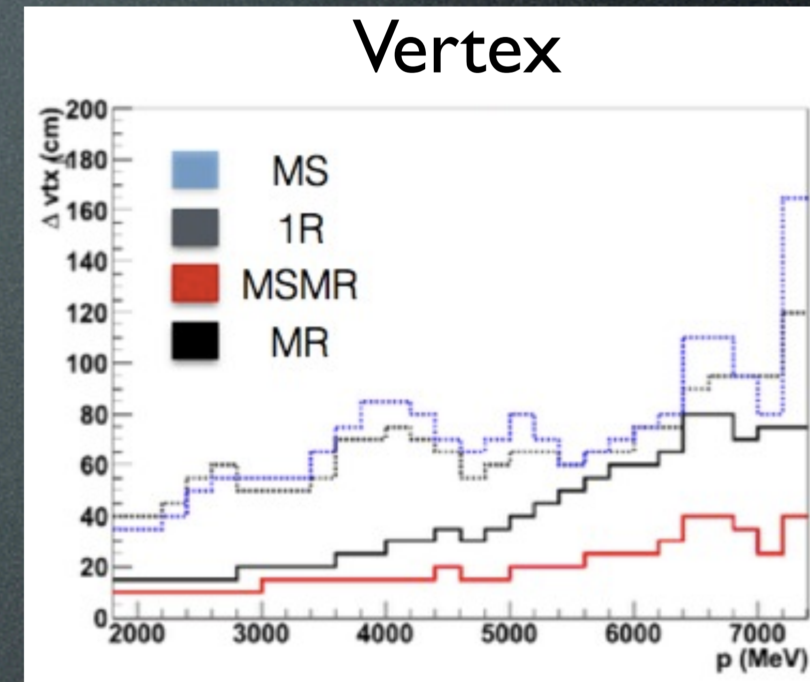




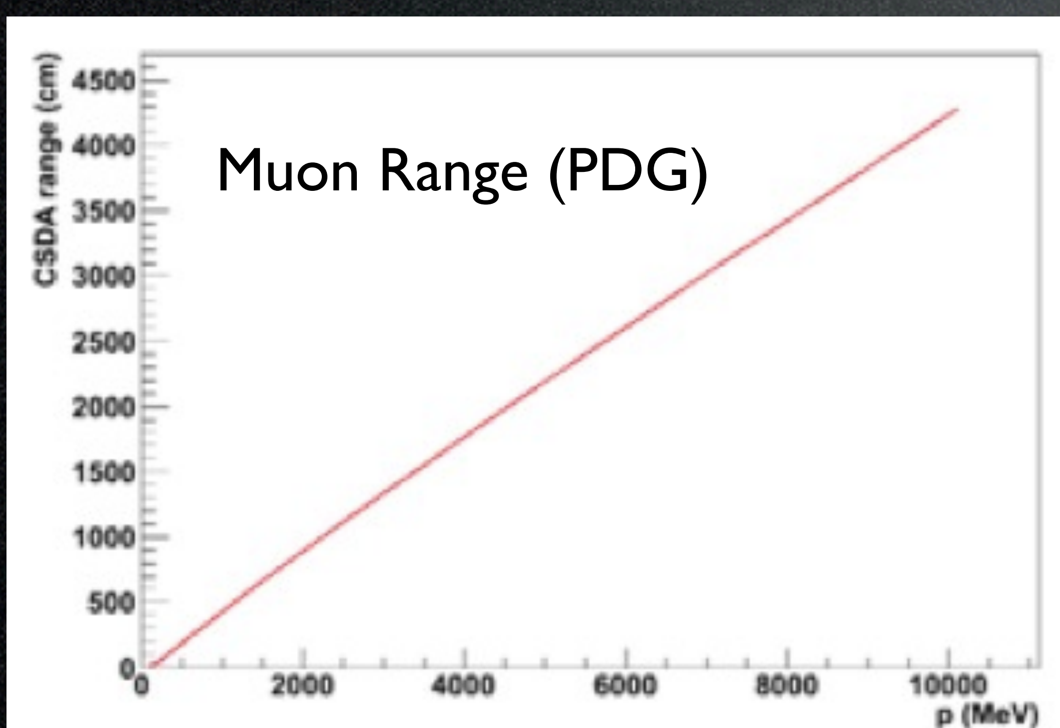
MS Fit Performance

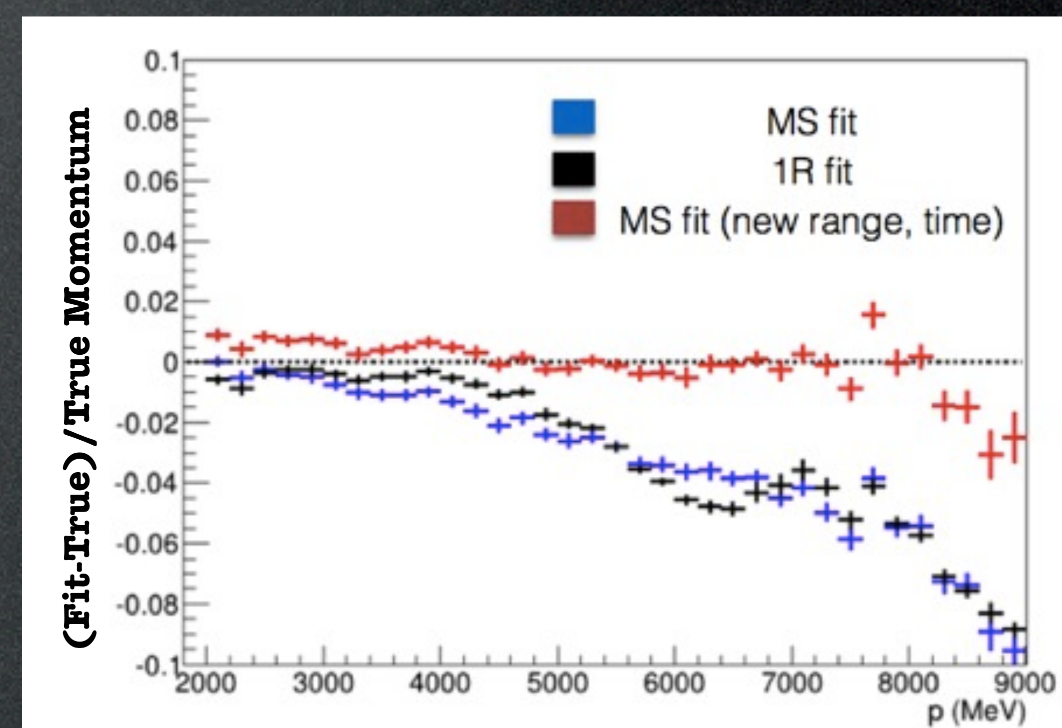
Fit Resolution:





- Using the correct dE/dx is important when piecing together many segments
  - Using PDG range table gave a big improvement in momentum resolution





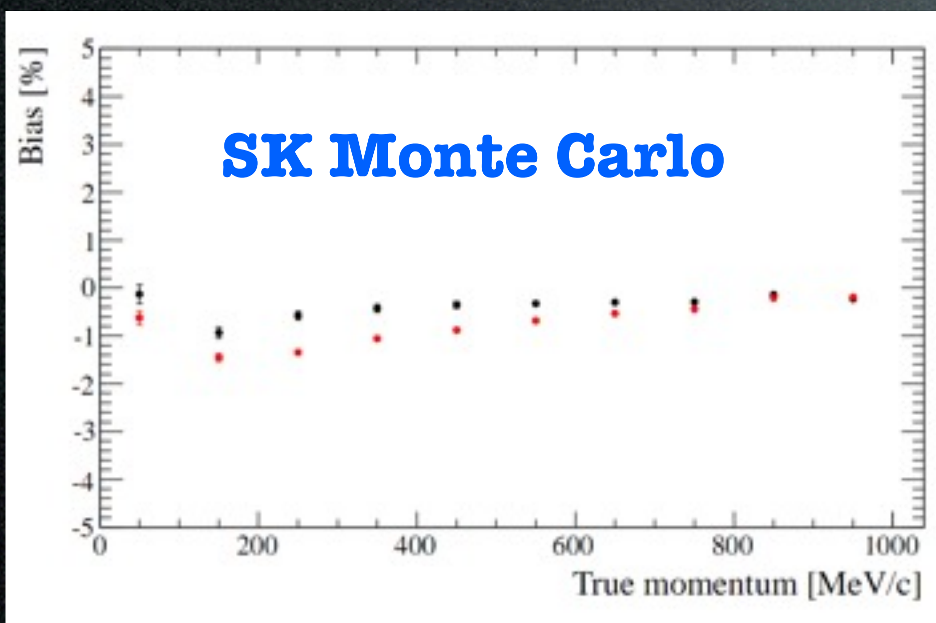
fiTQun in Hyper-K

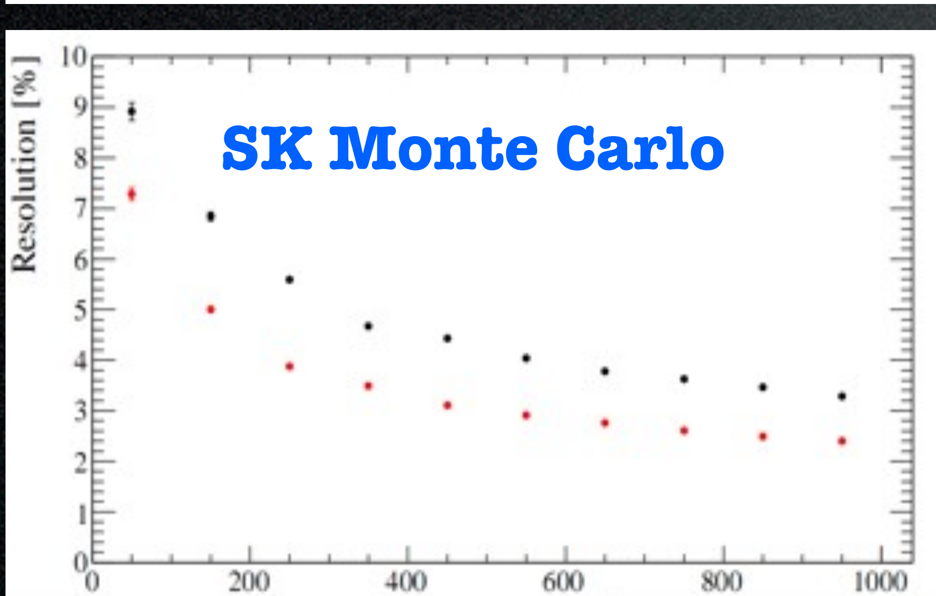
Current Status

- Newest version of fiTQun contains several upgrades for Hyper-K
  - The default root output format is now much more user friendly
    - Matches the Super-K h2root output format
  - Geometry is automatically read from WCSim input file
    - Arbitrary cylindrical geometry is now supported
    - Hyper-K tank with arbitrary z-length is supported
- Additional improvements since the last code freeze:
  - Average quantum efficiency can now be tuned in the parameters file
  - PMT size will automatically be taken into account
    - Useful for Hyper-K near detectors: nuPRISM & Titus

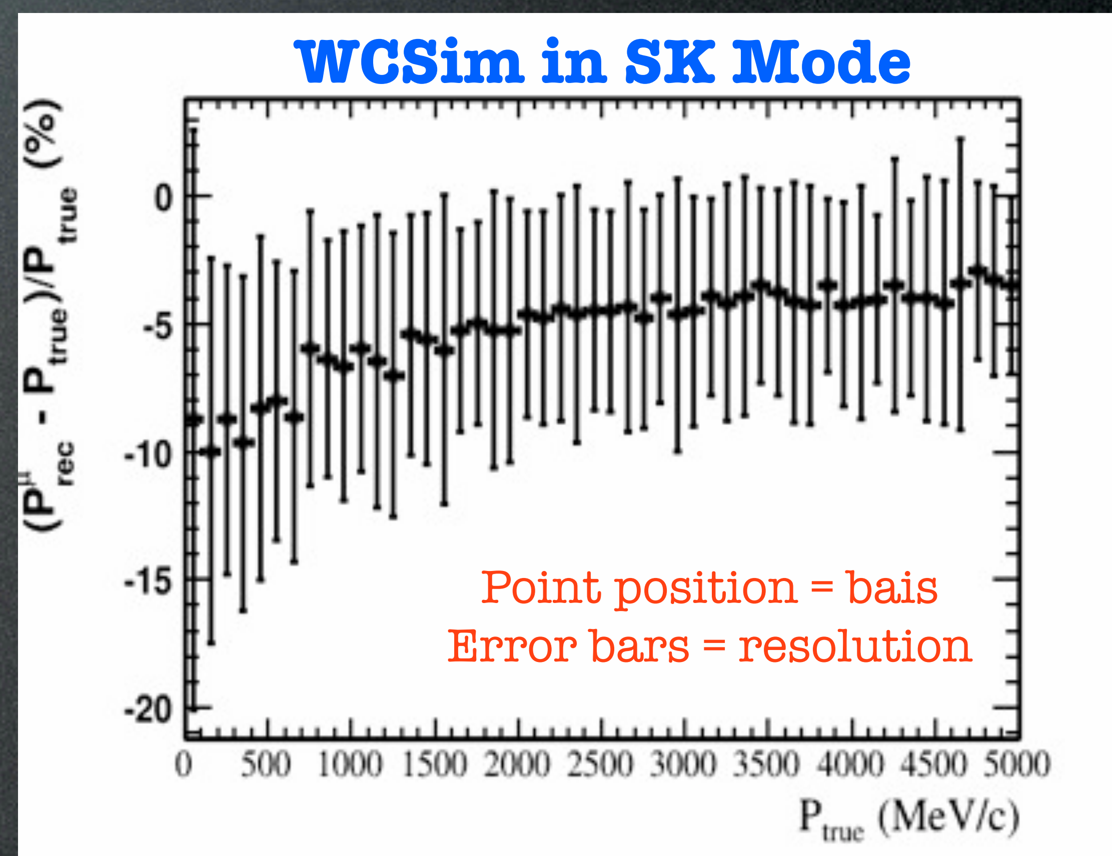
fiTQun HK Performance

- Are reported at the previous meeting, reconstruction of vertex, direction, and PID is working well (close to Super-K values)
  - In theory, fiTQun should work well with minimal change when applied to HK
- However, significant momentum biases are observed
  - Now decided to do a full tuning of fiTQun to HK MC (WCSim)





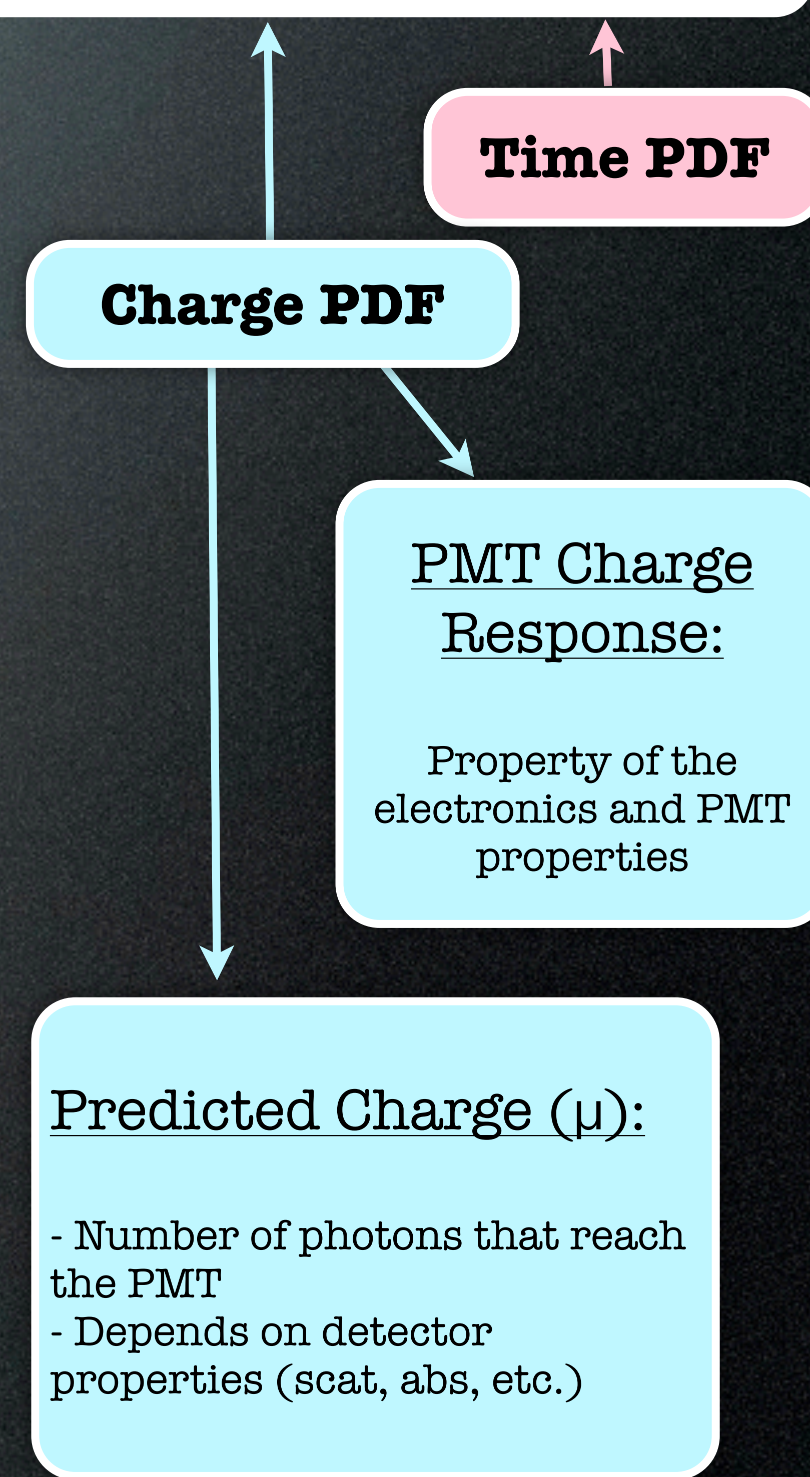
Electron Particle Gun Bias & Resolution



Reminder: fiTQun Components

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

- 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 hit PMT
- The **charge PDF** is factorized into:
  - PMT & electronics response
  - Number of photons reaching the PMT
    - **Predicted charge (μ)**
- All 7 track parameters **fit simultaneously**

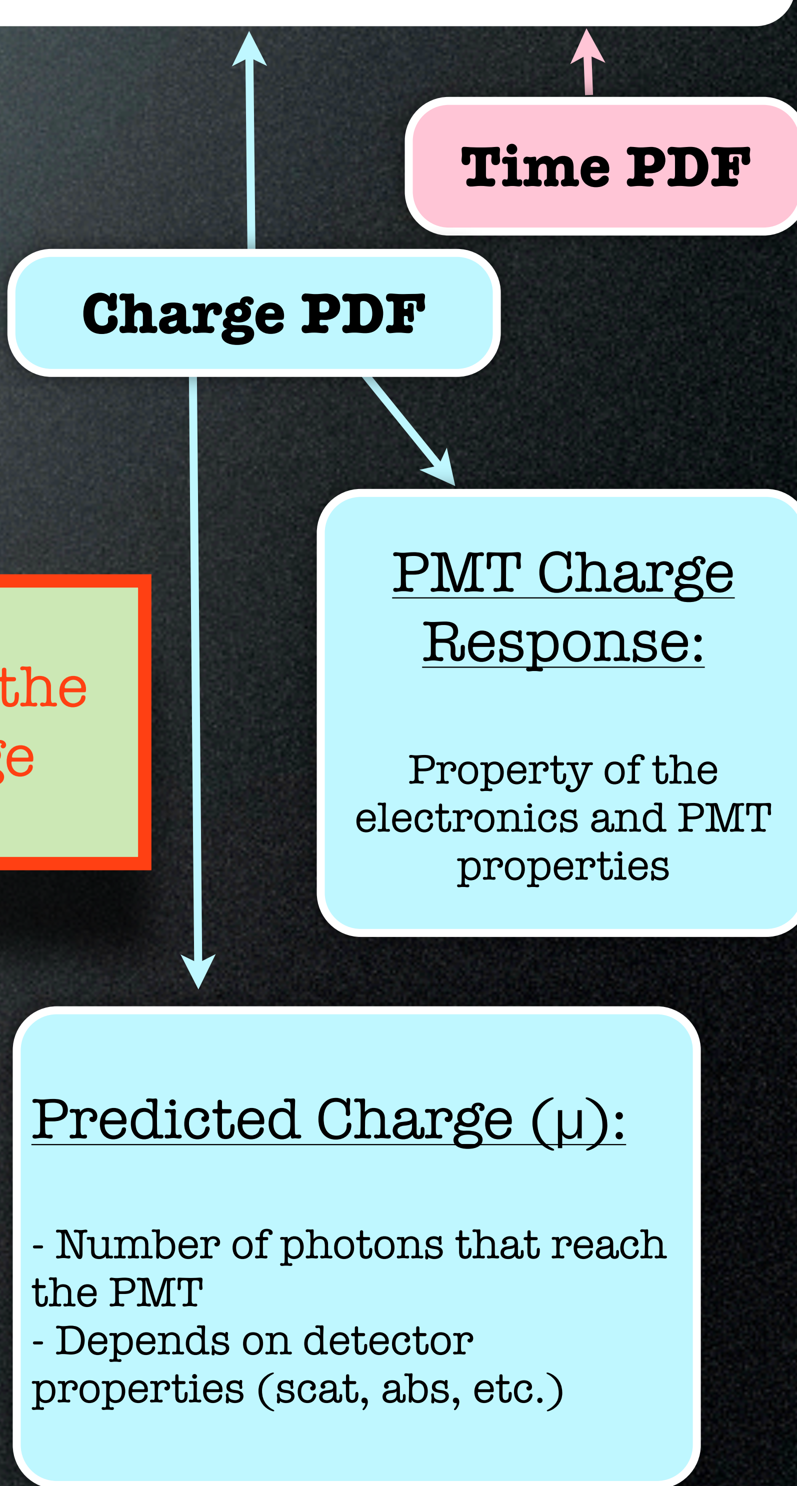


Reminder: fiTQun Components

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

- 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 every hit PMT
- The **charge PDF** is factorized into:
  - PMT & electronics response
  - Number of photons reaching the PMT
    - **Predicted charge (μ)**
- All 7 track parameters **fit simultaneously**

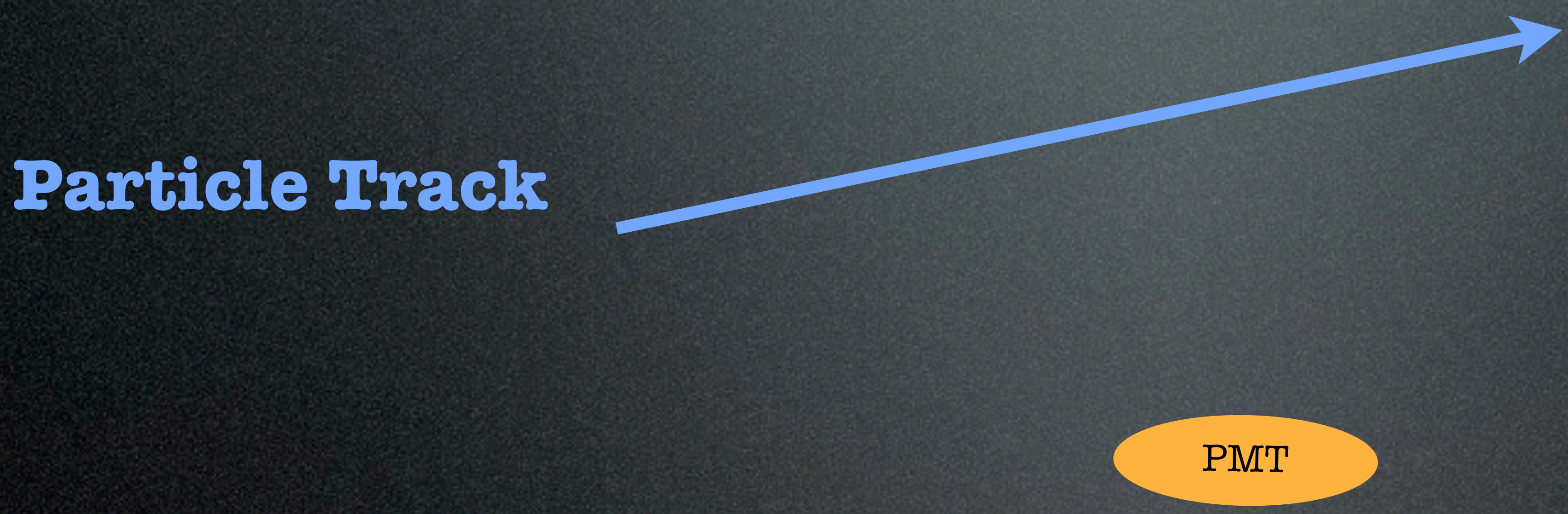
Calculating μ is the main challenge



Predicted Charge (μ)

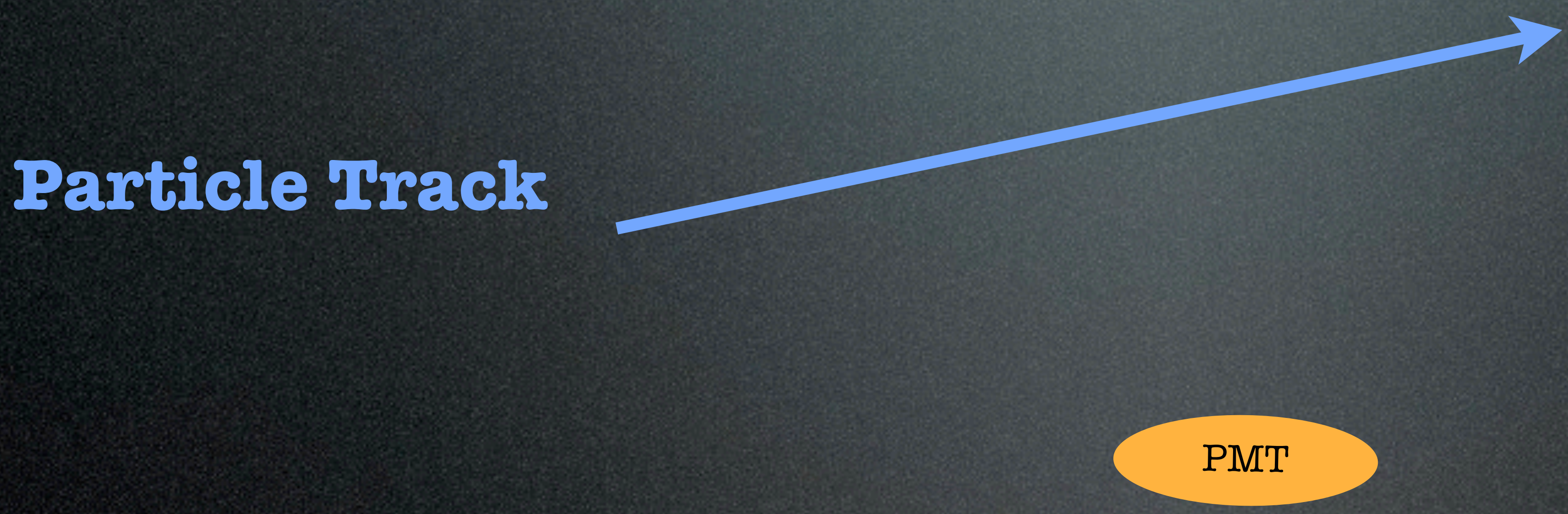
Predicted Charge (μ)

Predicted Charge (μ)



Predicted Charge (μ)

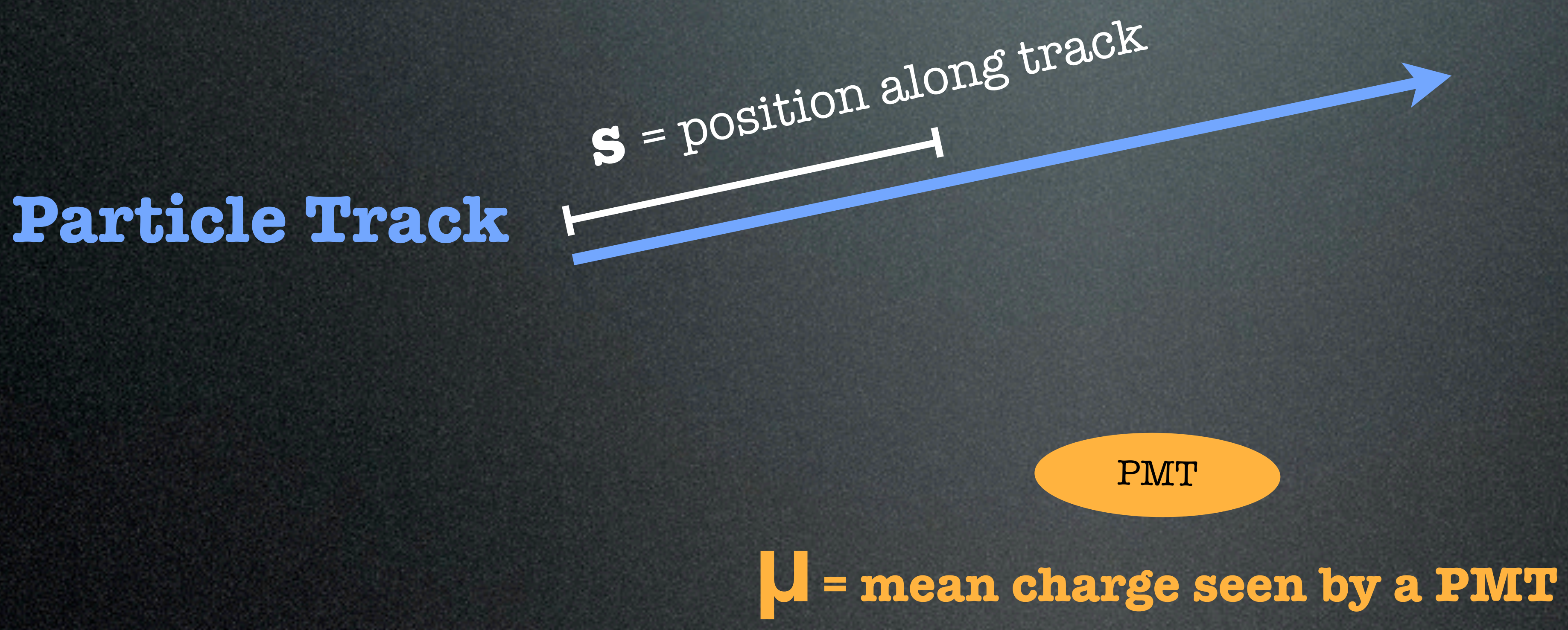
$$\mu =$$



μ = mean charge seen by a PMT

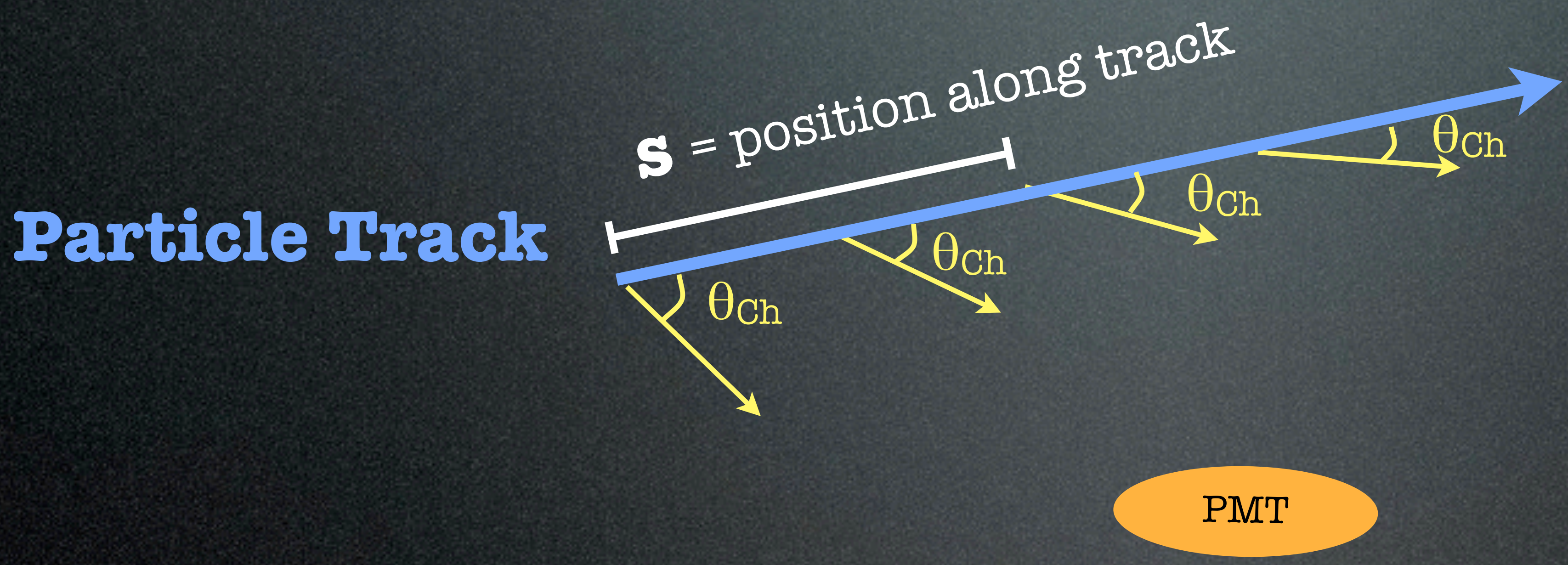
Predicted Charge (μ)

$\mu =$



Predicted Charge (μ)

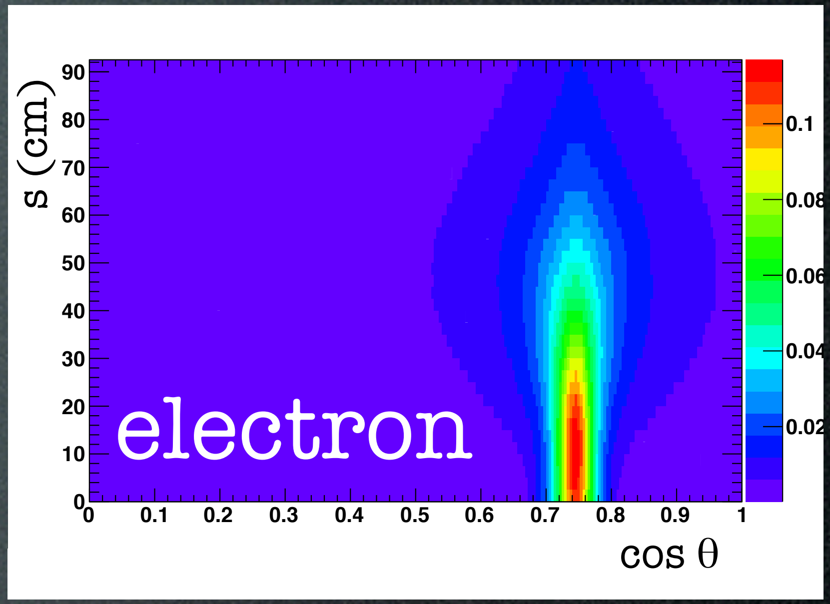
$\mu =$

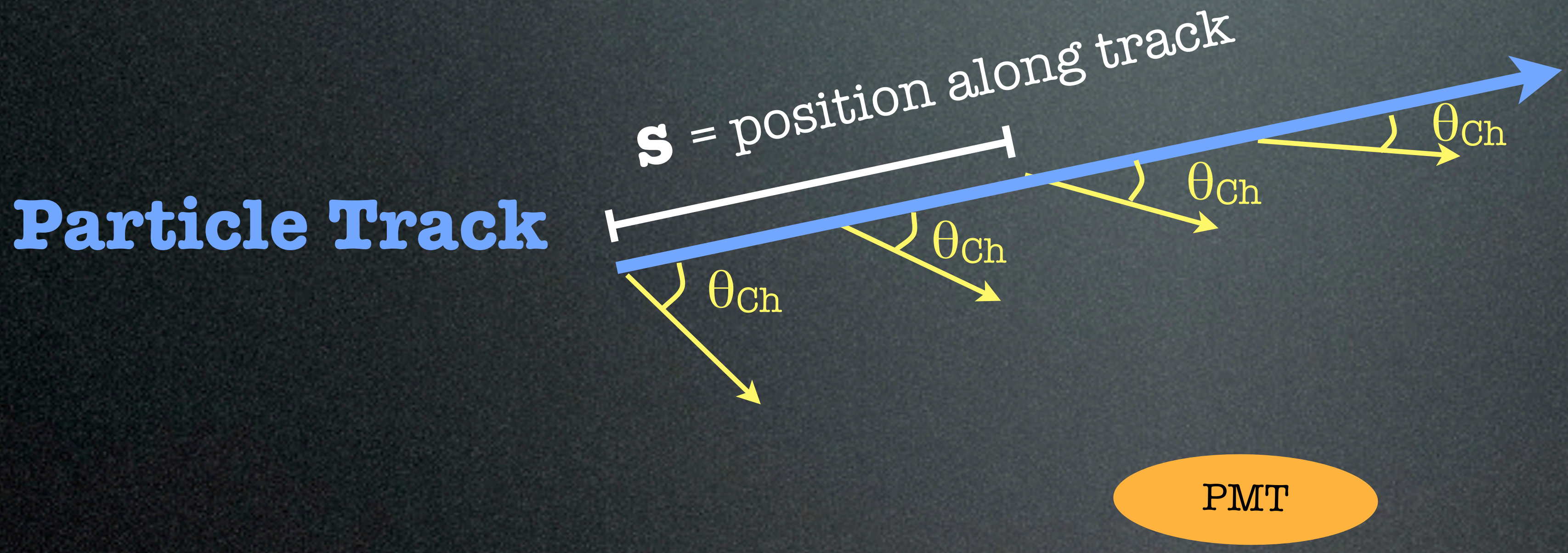


Predicted Charge (μ)

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

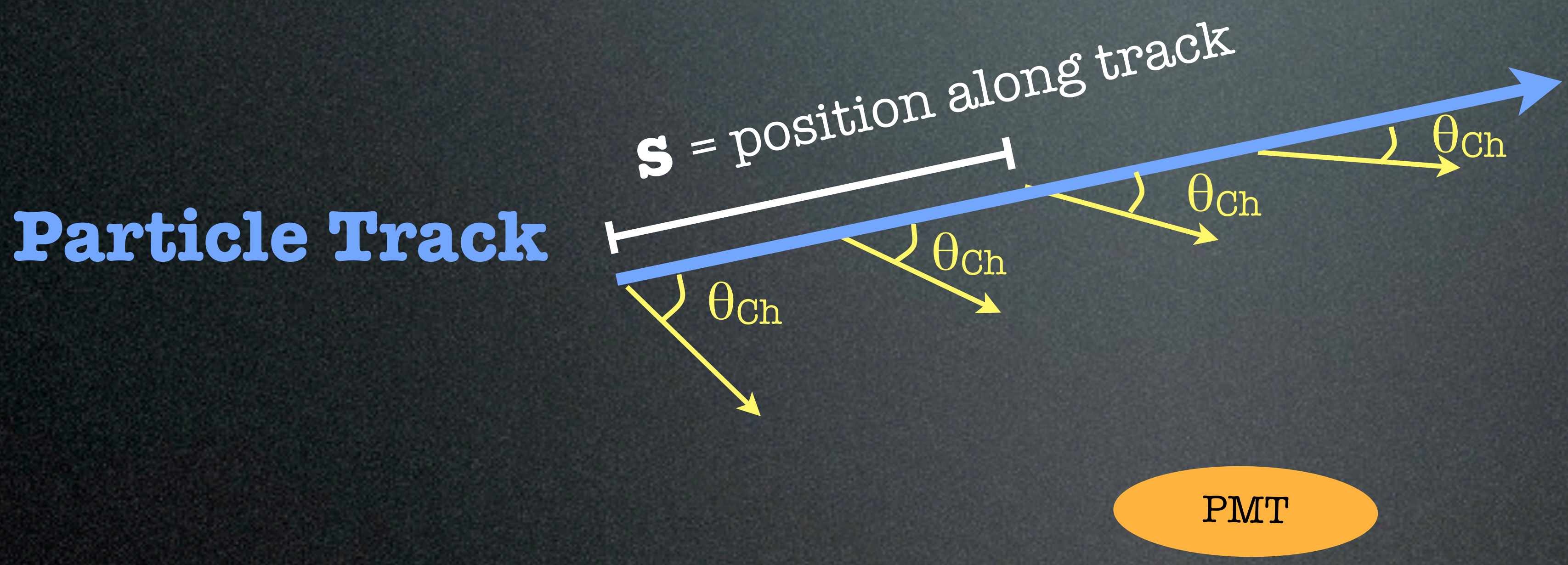
Cherenkov light emission profile



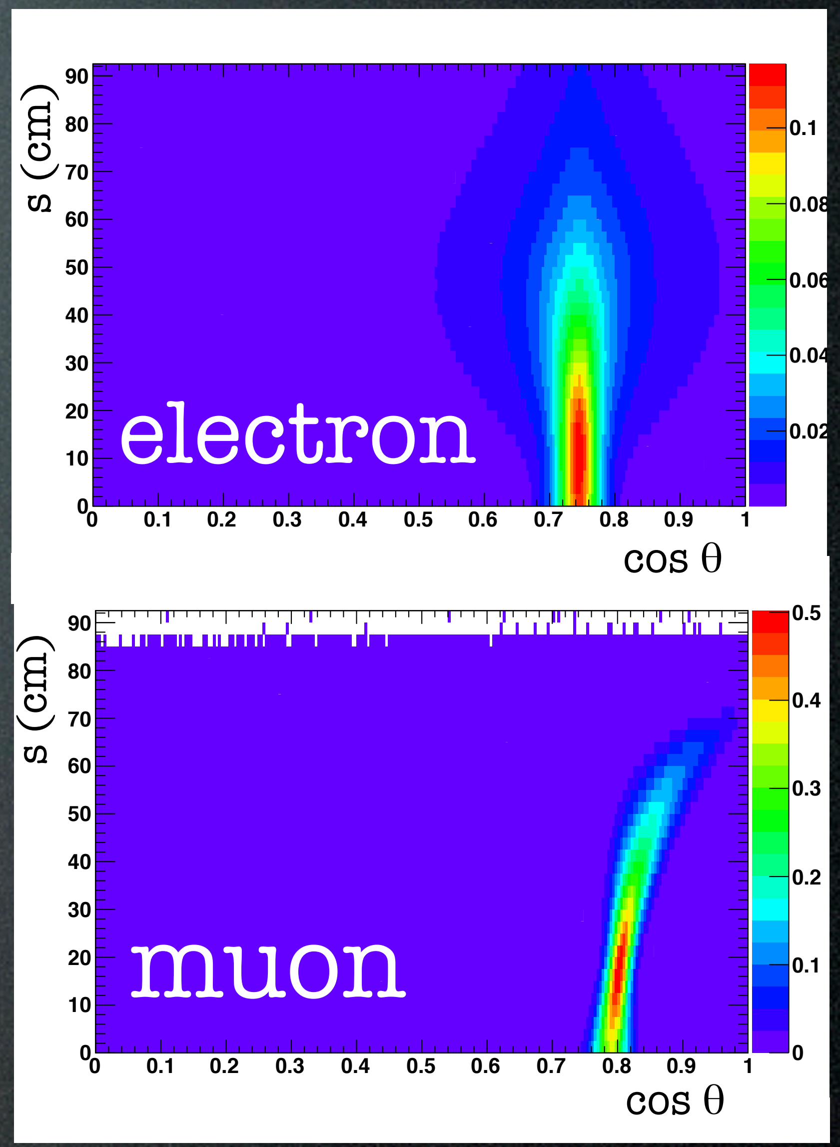


Predicted Charge (μ)

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



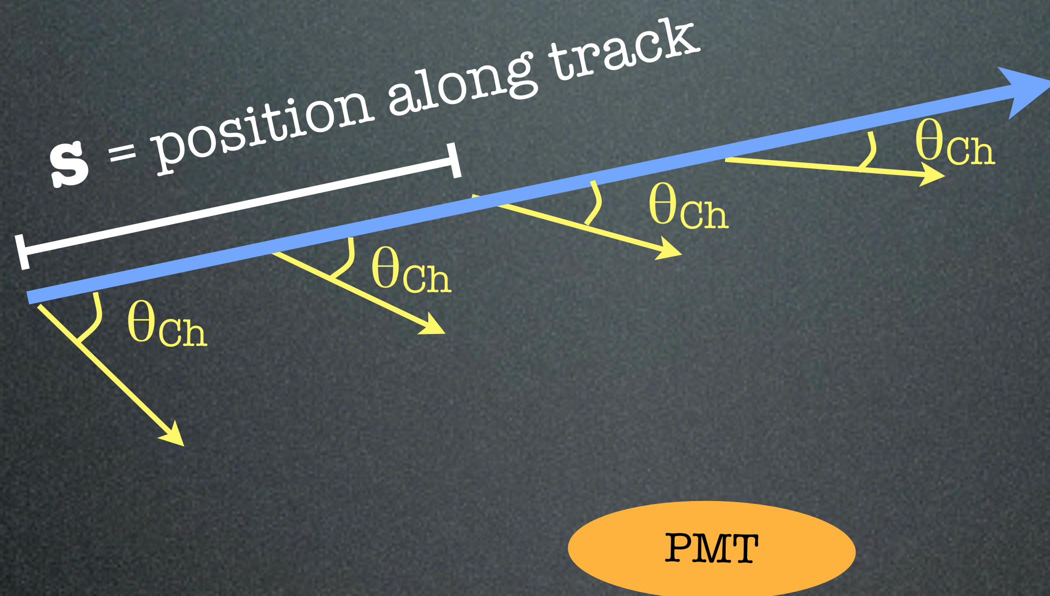
Cherenkov light emission profile



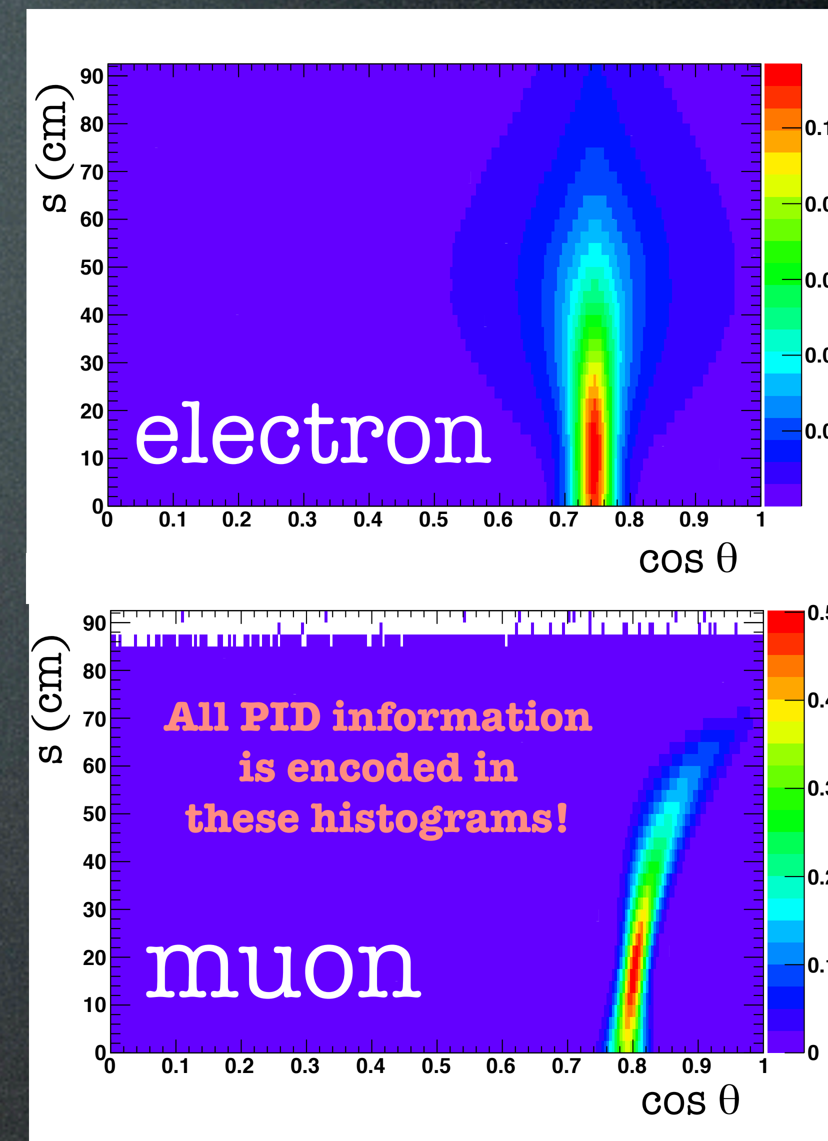
Predicted Charge (μ)

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

Particle Track

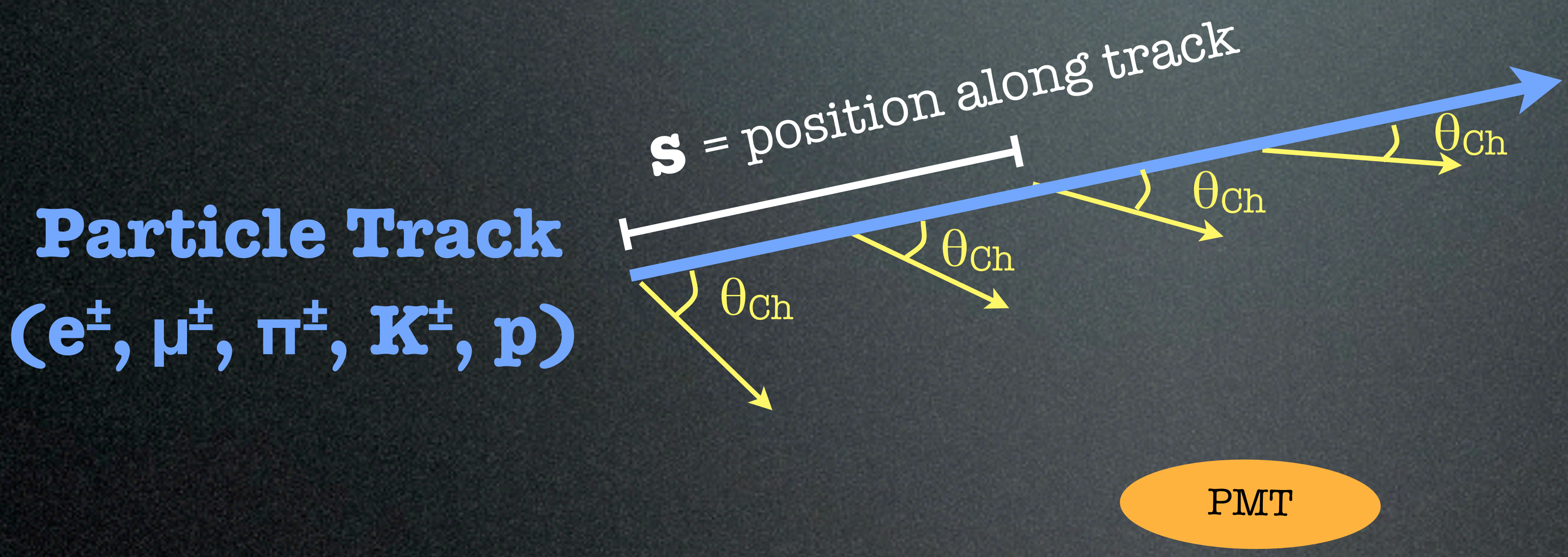


Cherenkov light emission profile

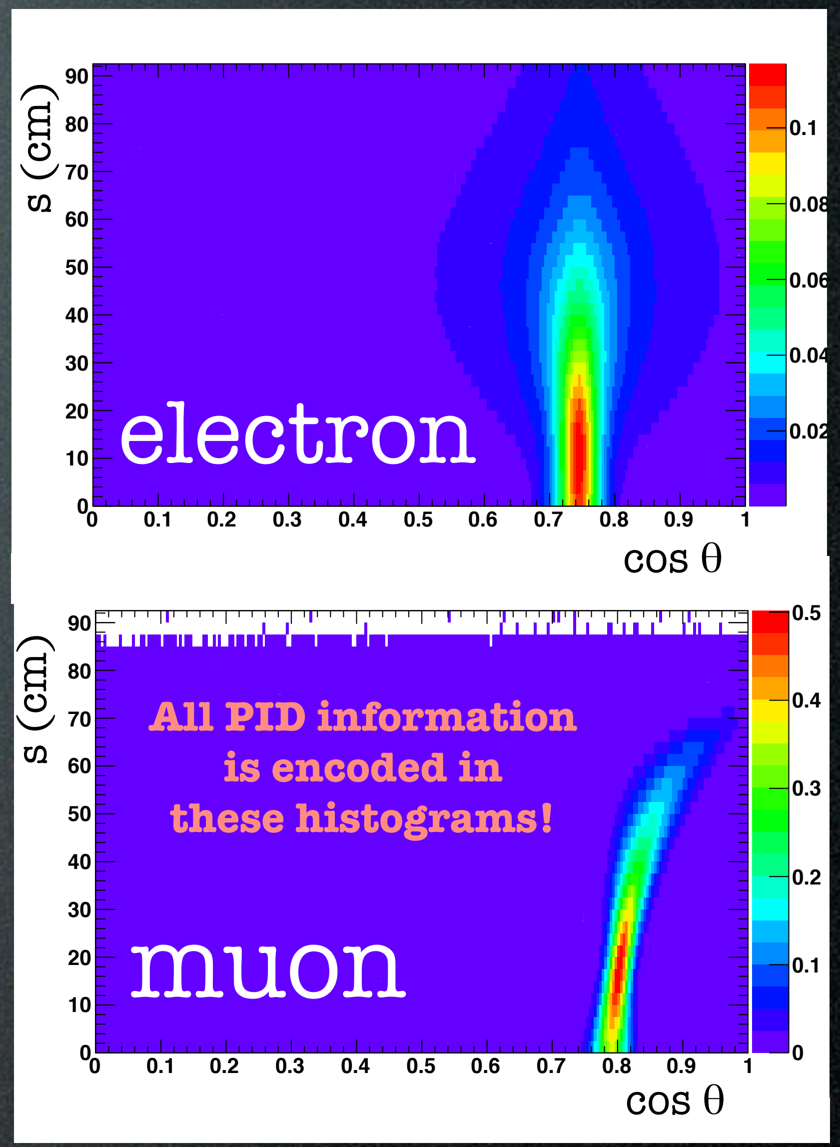


Predicted Charge (μ)

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

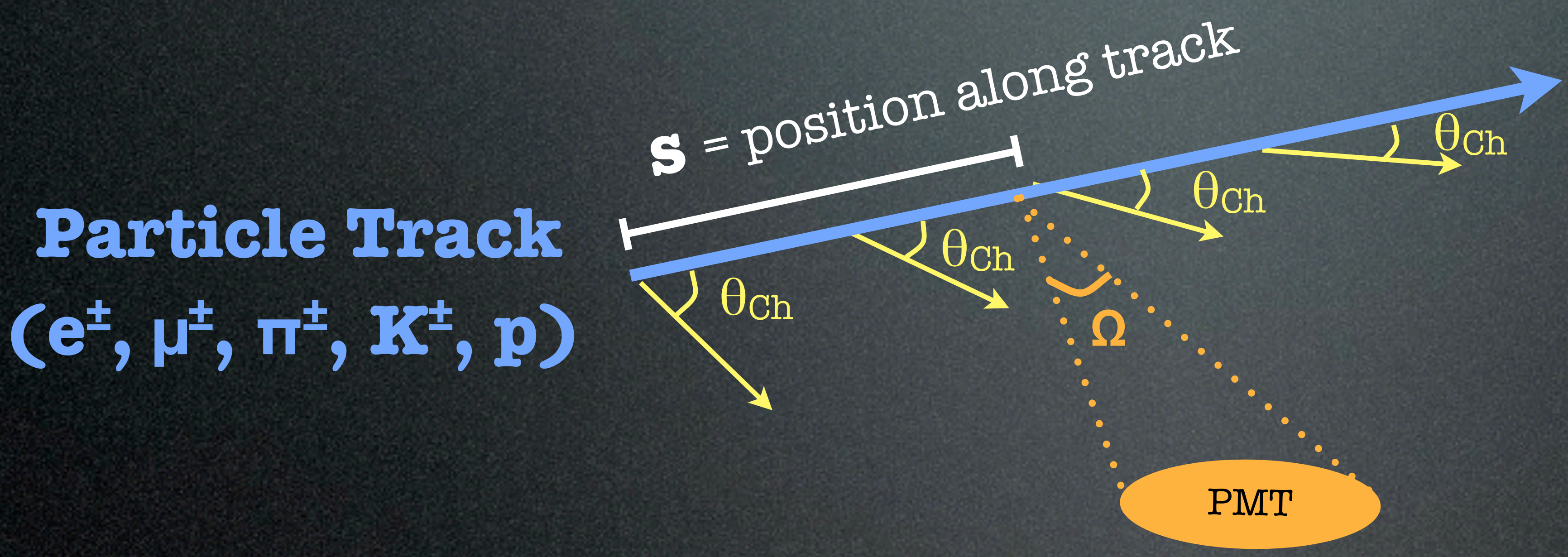


Cherenkov light emission profile

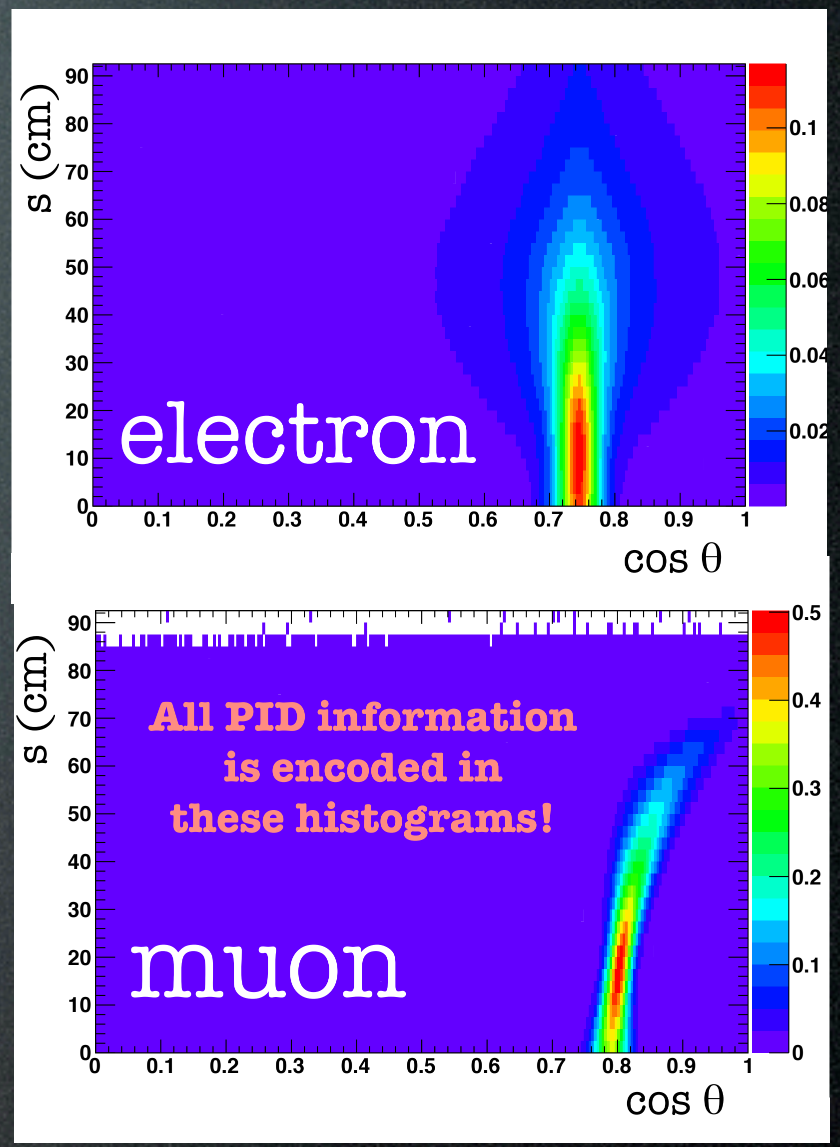


Predicted Charge (μ)

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

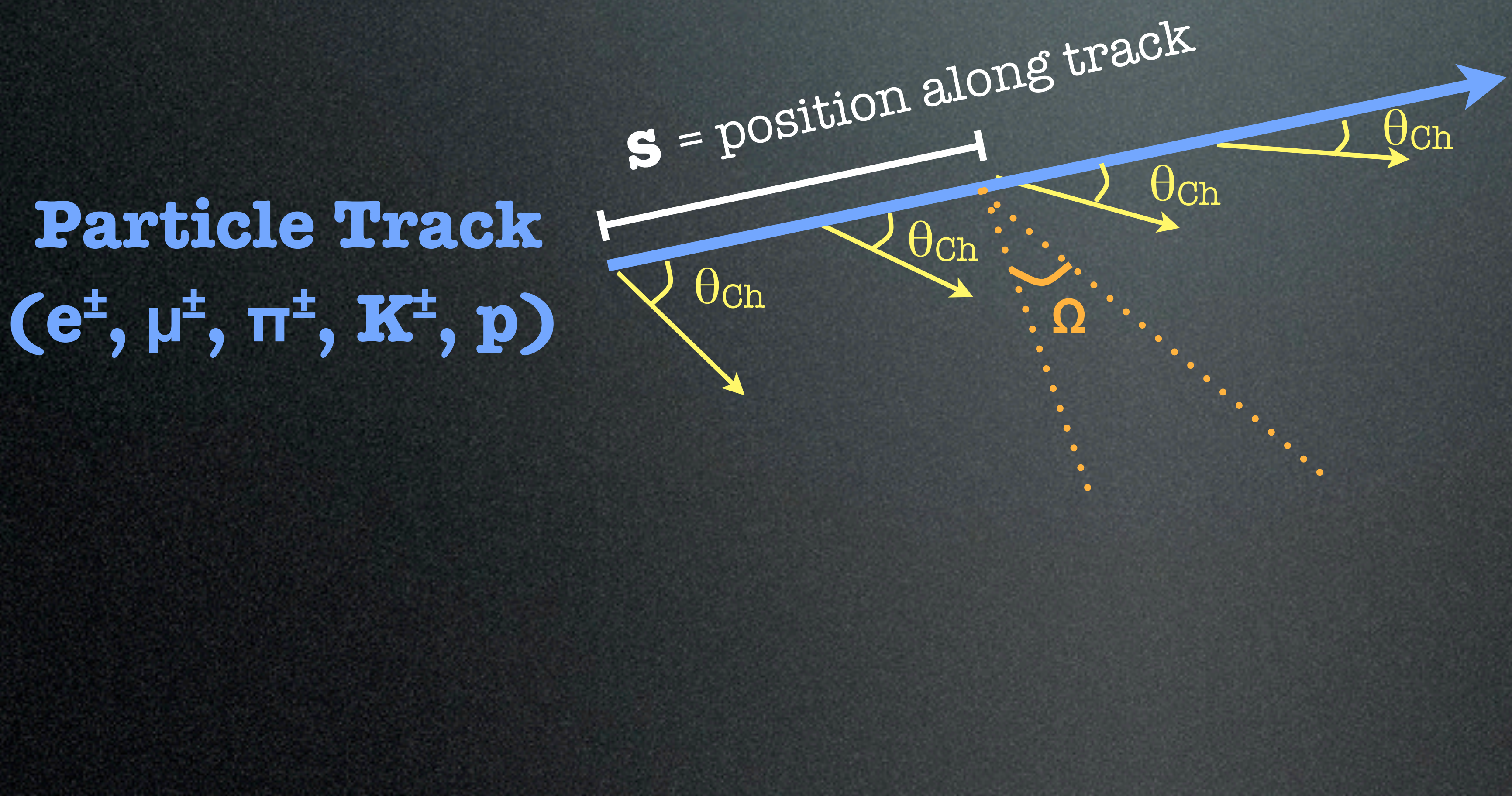


Cherenkov light emission profile

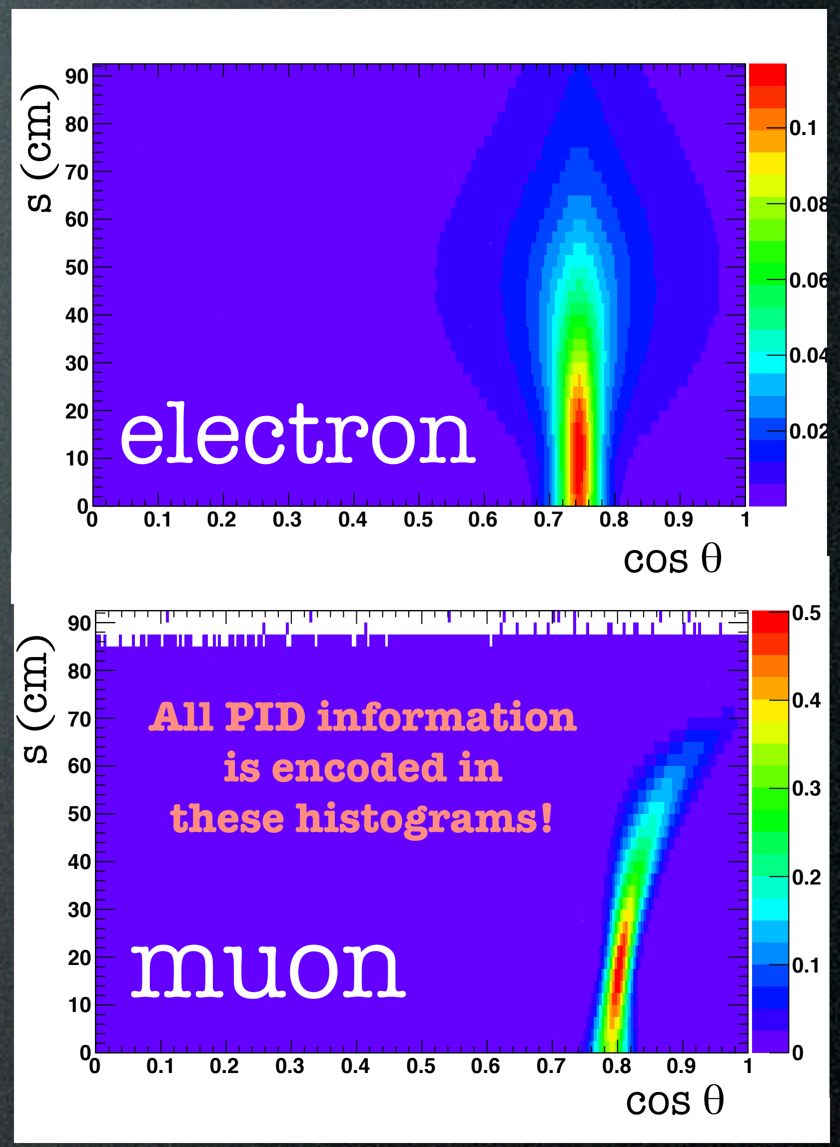


Predicted Charge (μ)

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



Cherenkov light emission profile

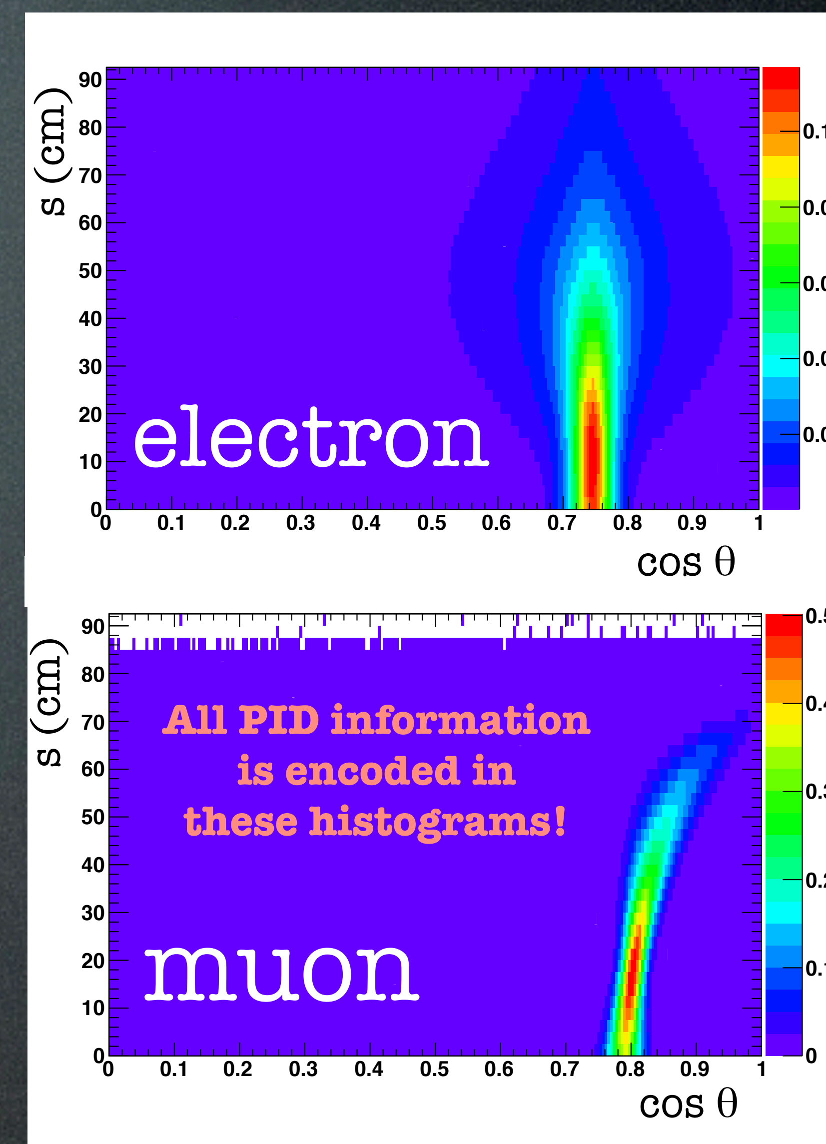


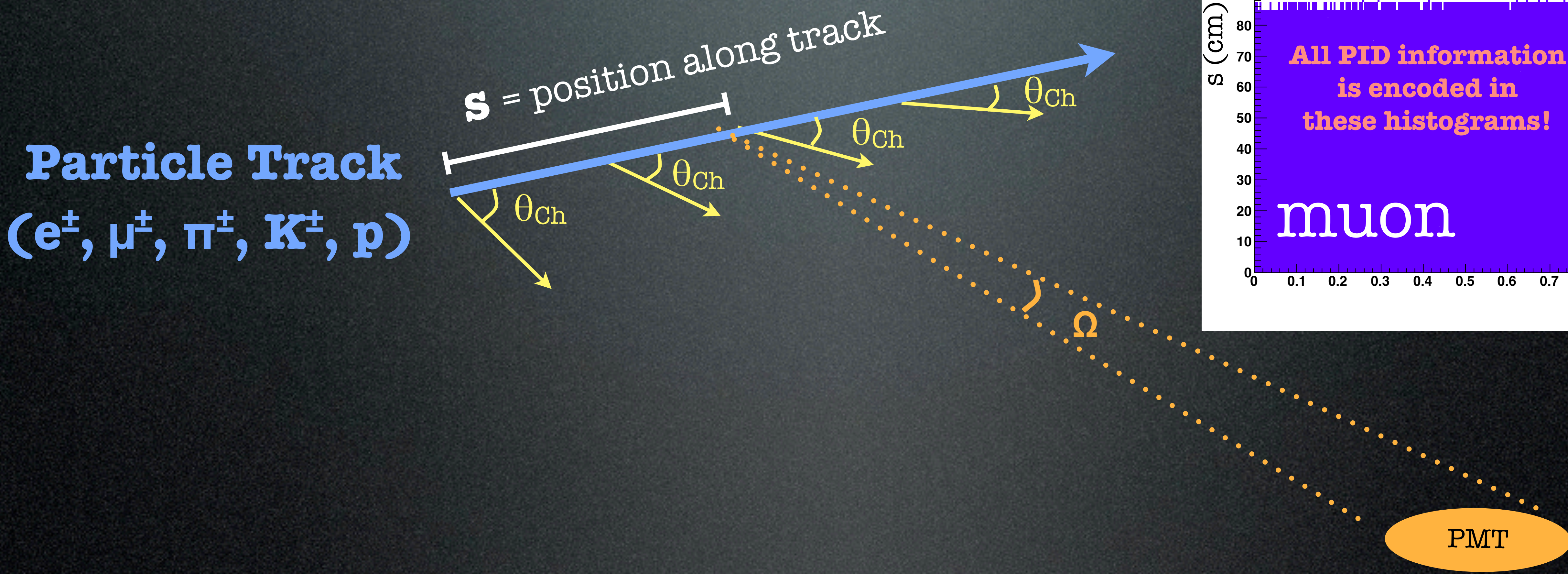
Predicted Charge (μ)

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

PMT solid angle

Cherenkov light emission profile



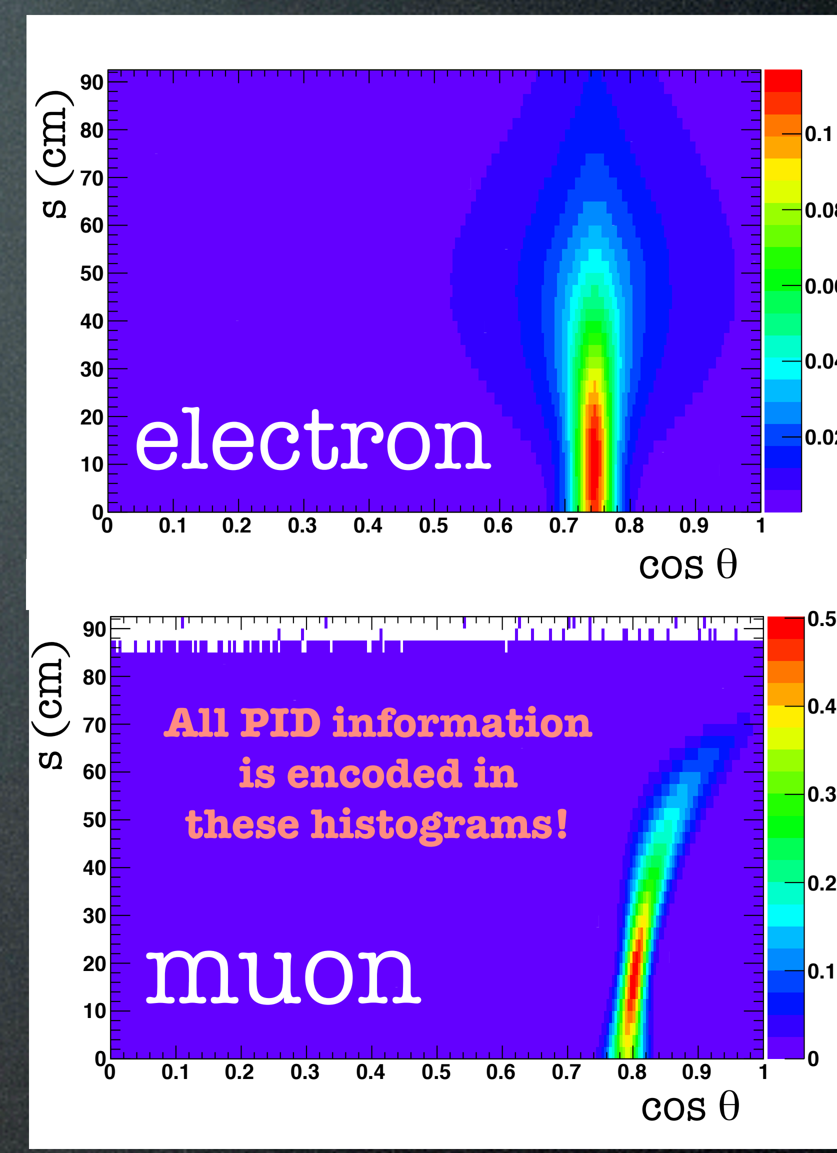


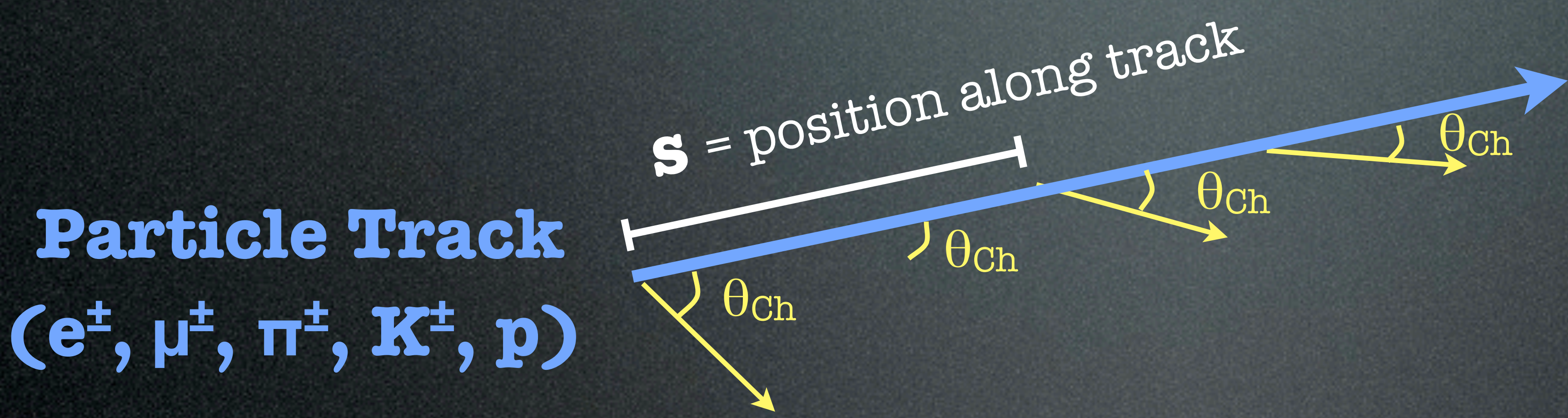
Predicted Charge (μ)

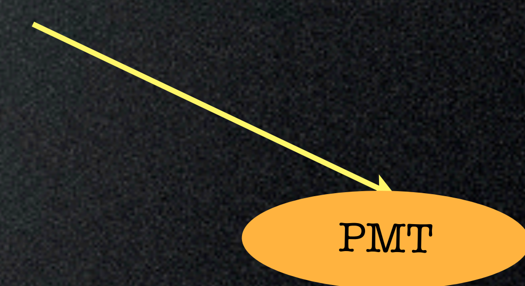
$$\mu = g(s, cos\theta)\Omega(R)$$

PMT solid angle

Cherenkov light emission profile







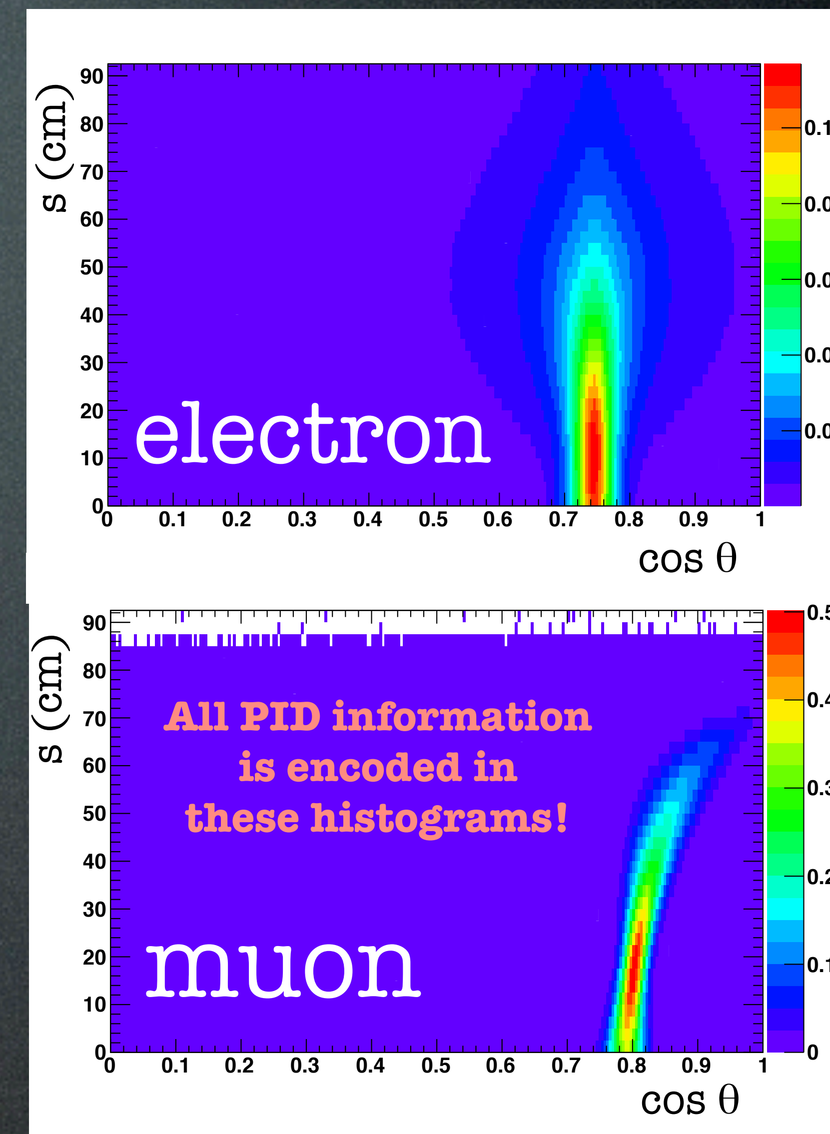
Predicted Charge (μ)

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

PMT solid angle

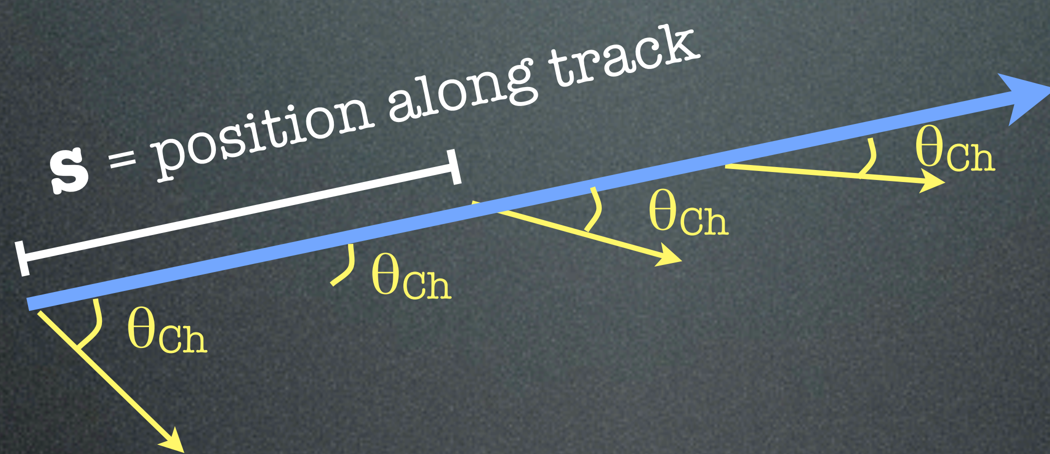
Water attenuation

Cherenkov light emission profile



Particle Track

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

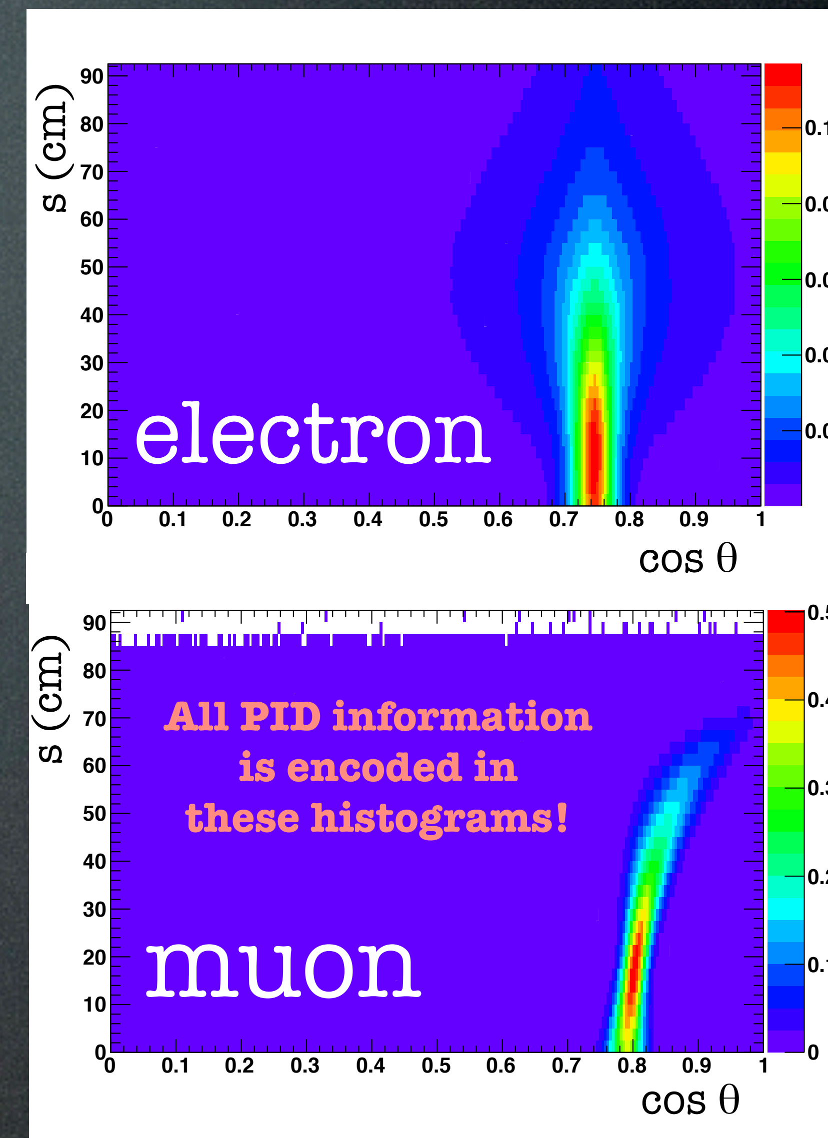


Predicted Charge (μ)

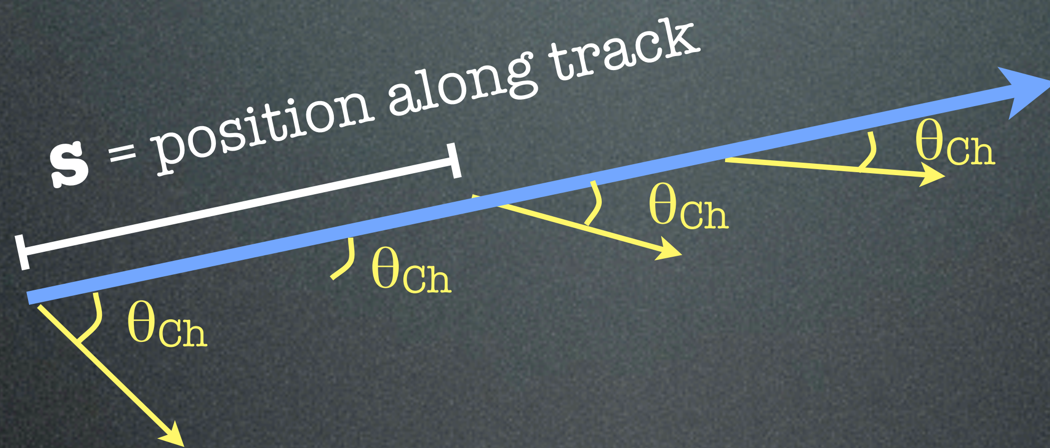
$$\mu = g(s, cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

PMT solid angle — Water attenuation — PMT angular response

Cherenkov light emission profile



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



Predicted Charge (μ)

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

Integral over track length

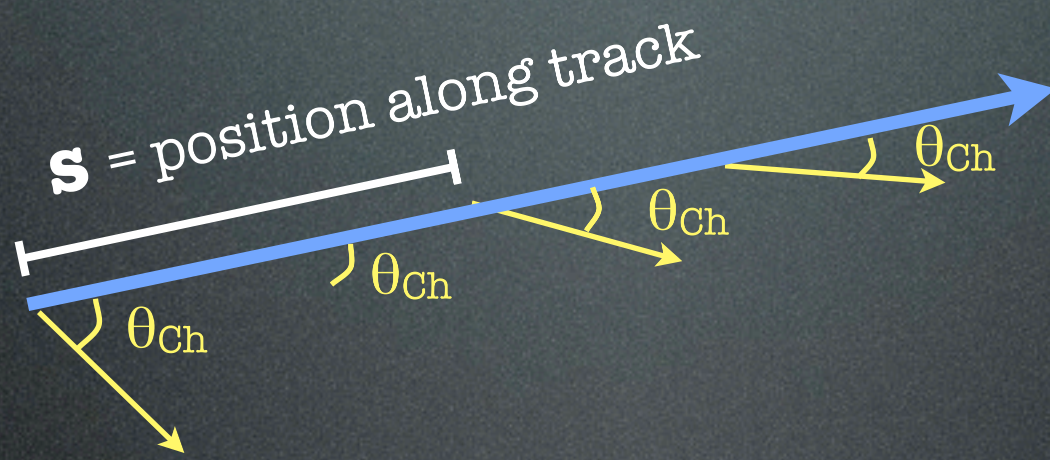
PMT solid angle

Water attenuation

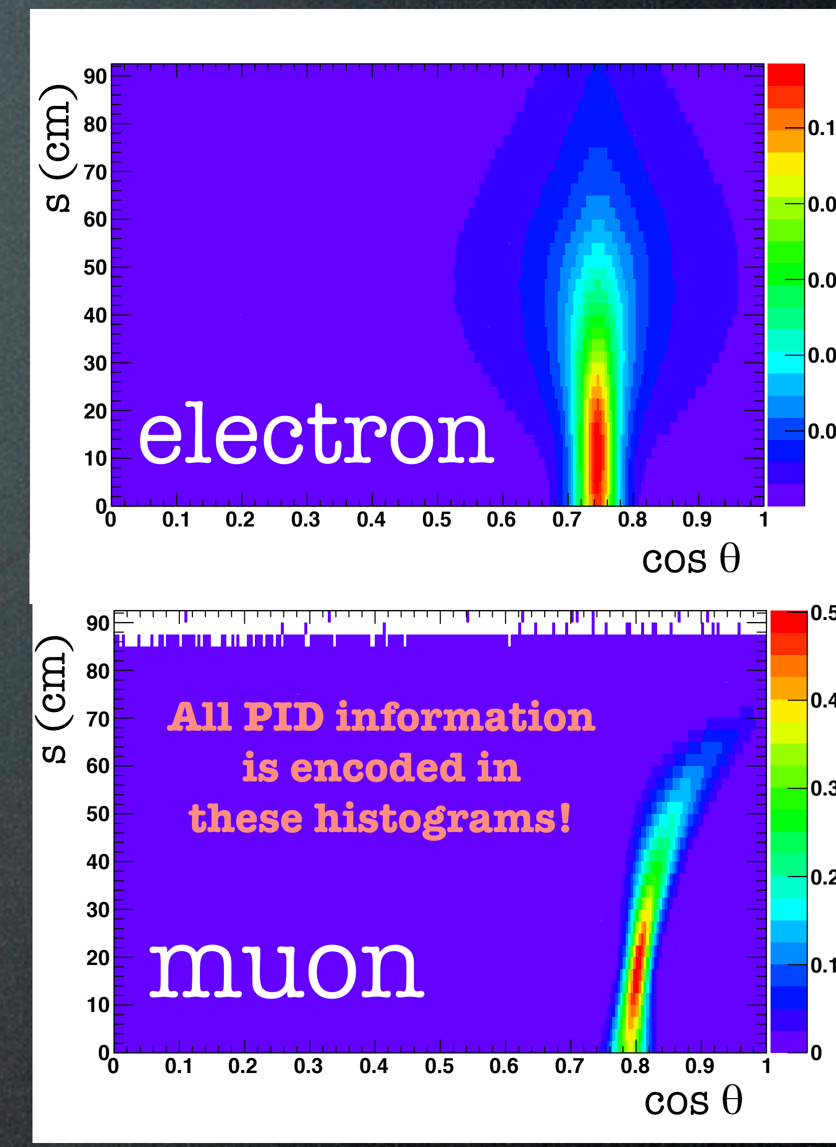
PMT angular response

Particle Track

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



Cherenkov light emission profile



Predicted Charge (μ)

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

Light Yield (normalization)

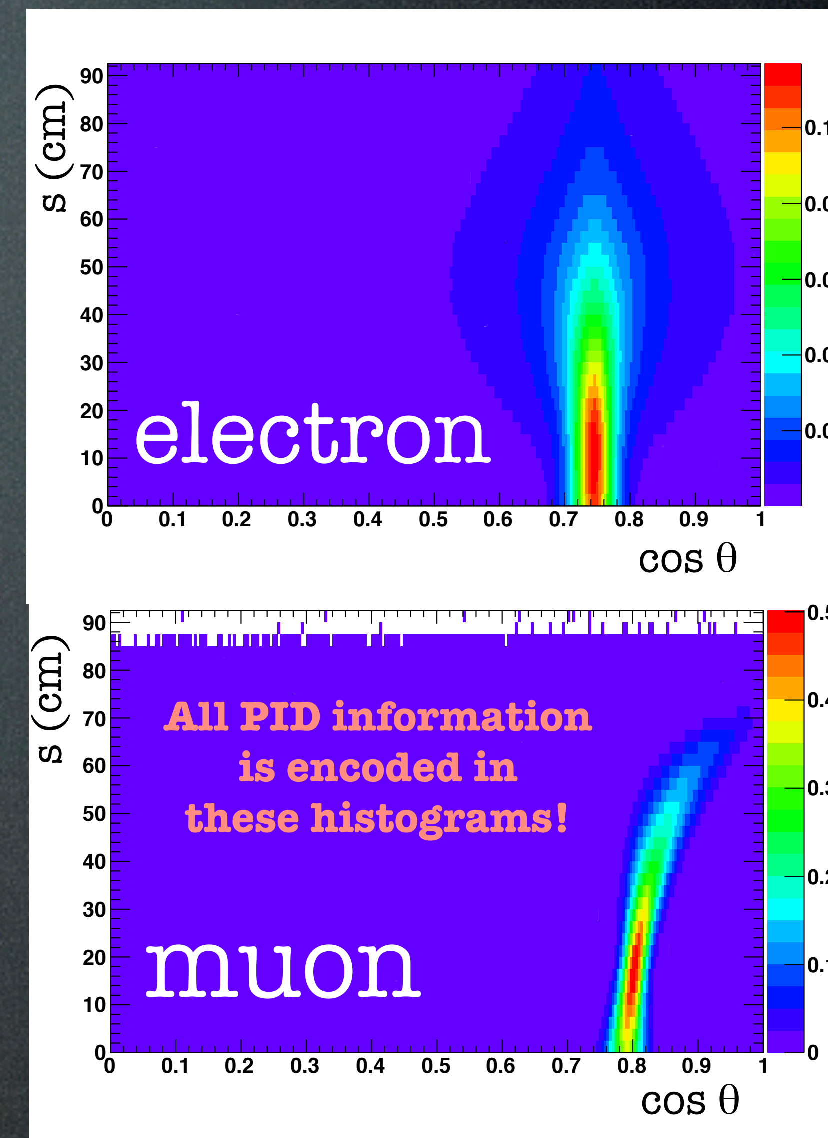
Integral over track length

PMT solid angle

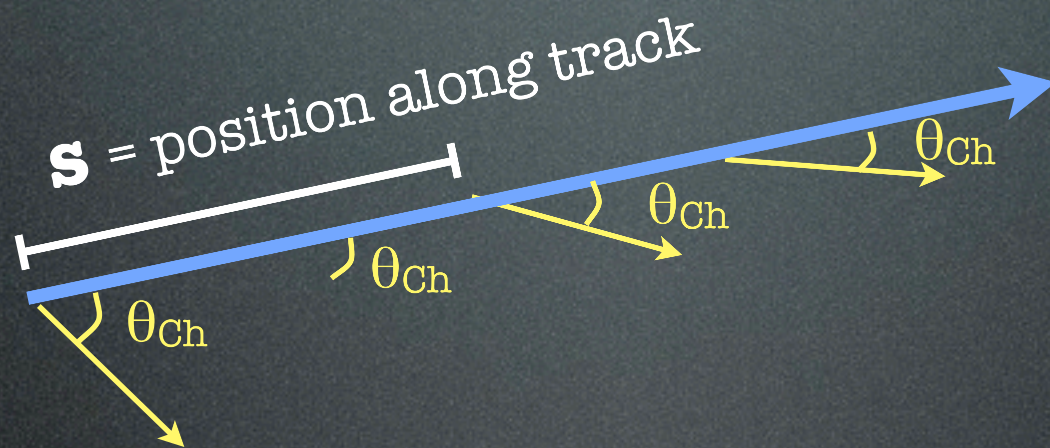
Water attenuation

PMT angular response

Cherenkov light emission profile



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



Predicted Charge (μ)

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

Light Yield (normalization)

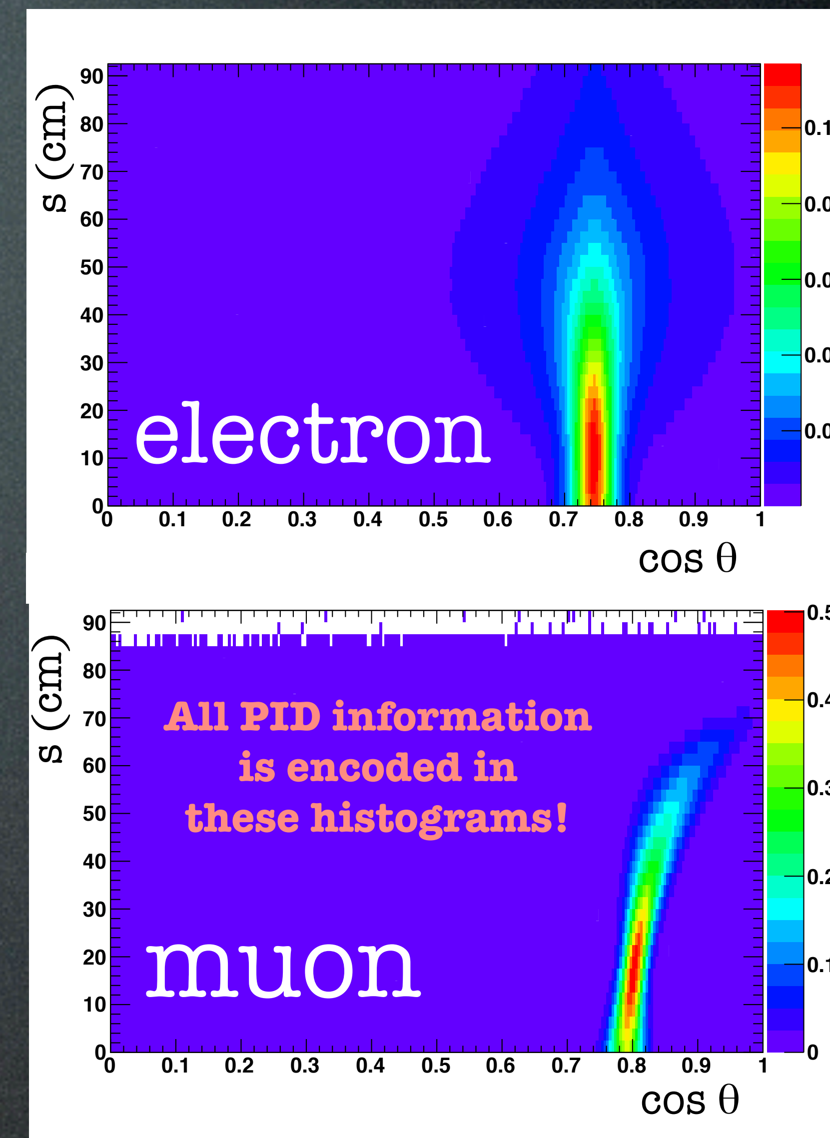
Integral over track length

PMT solid angle

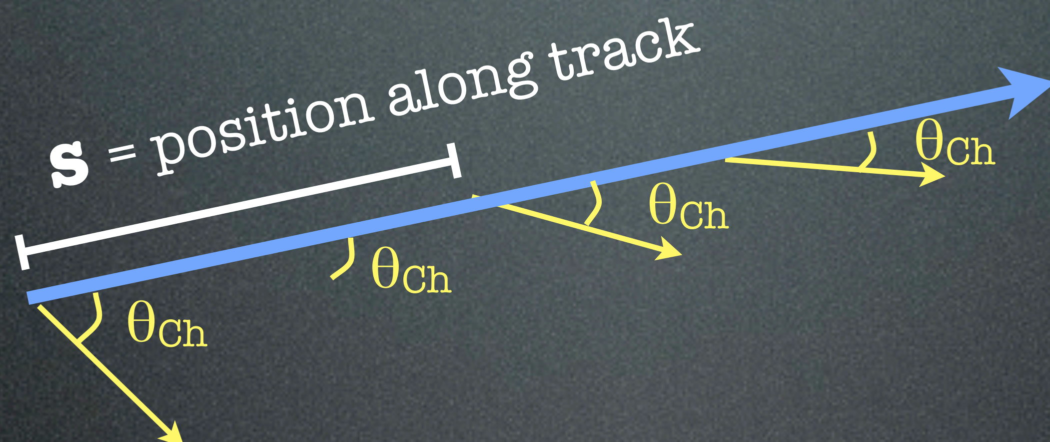
Water attenuation

PMT angular response

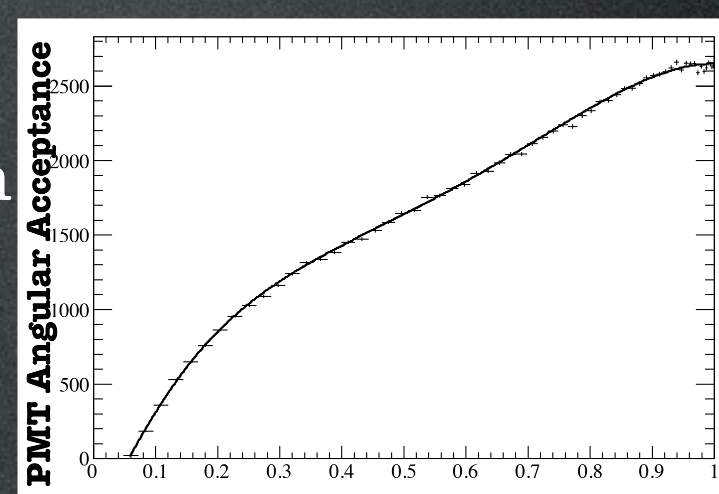
Cherenkov light emission profile

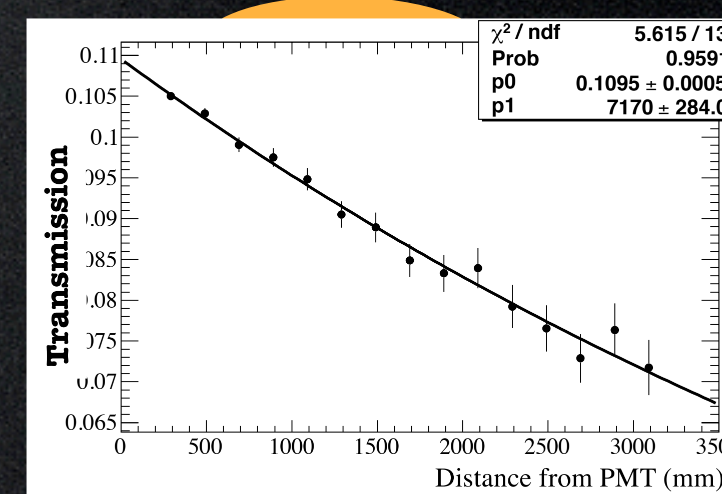


Particle Track
$(e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, p)$



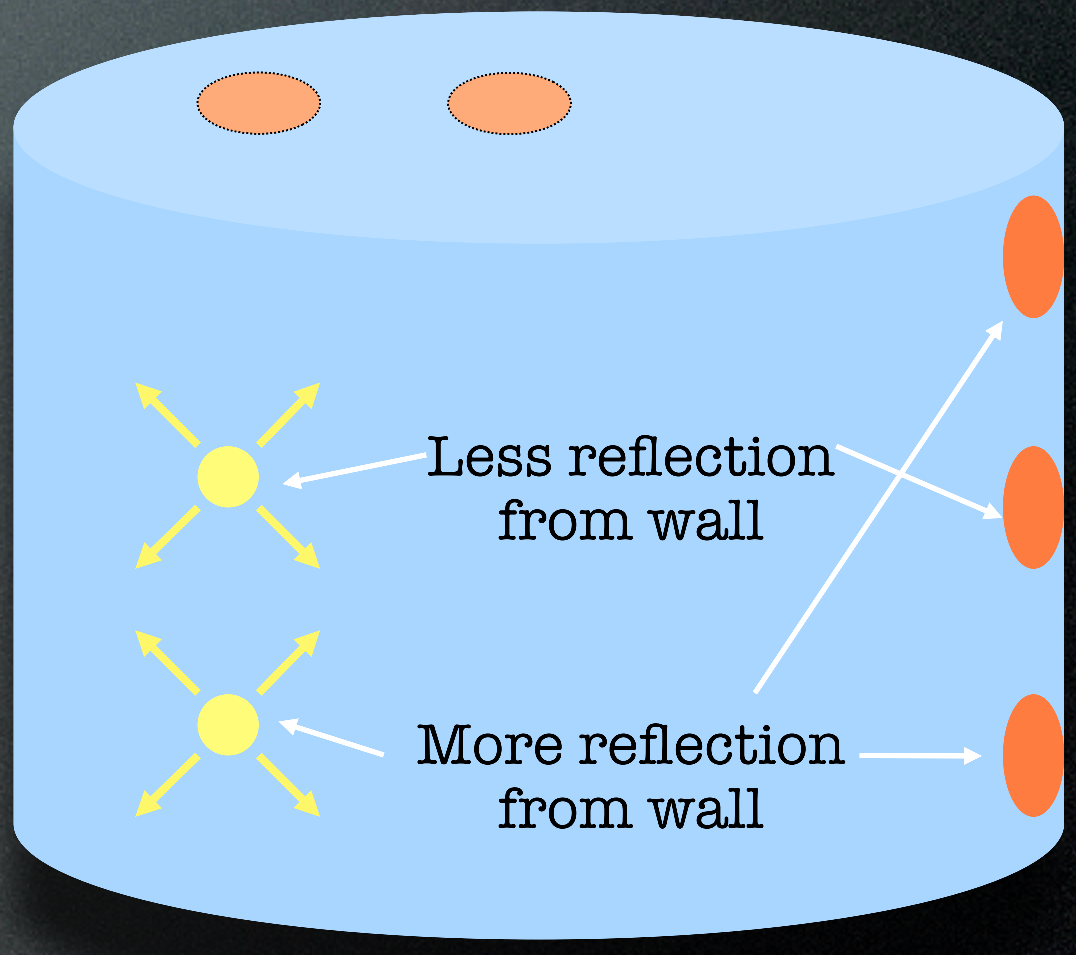
- 80% of detected light is direct
  - Must tune:
    - Angular acceptance function
    - Transmission function
    - Quantum efficiency





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}**



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

Tuning Scattered Light

- Current scattering tables assume cylindrical symmetry
  - For now, we will keep this assumption for Hyper-K (even though it is not a cylinder)
  - Future: new scattering table algorithm is being developed to remove geometric dependence
- To tune, we need to record production point, detection point, and interactions of all photons in MC events
  - Originally, we modified SK MC (GEANT3) to extract this information
  - Now, we have modified HK MC (GEANT4) to extract the same information
- We will begin by making fiTQun work with HK MC in SK geometry mode
  - Then, we will move on to more difficult HK geometry

New Code for fiTQun Tuning

- Added two new classes:
  - WCSimOpticalPhotonTrackInfo
    - A singleton class that stores parent geant id, vertex, direction, and count of scatters and reflections for each optical photon
  - WCSimOpticalPhotonMessenger
    - A messenger class to enable or disable storing this information via a macro file flag:
      - /opInfo/Enabled true or false
- Set of functions in skqfitscat.cc to interface to class
  - Initscattable(), fillscattable(), writescattable()

Other Code Changes

- WCSim.cc:
  - initialize instance of singleton so that the messenger class is created
- WCSimRunAction.cc:
  - Calls initscattable() in begin of run
    - This creates the output TTree "sttree"
  - Calls writescattable() in end of run
    - Writes the TTree to file
- WCSimEventAction.cc:
  - Reset photon track info arrays in begin of event
  - Calls fillscattable() at end of event to fill root tree
    - This fills another entry for each photon that was detected by the PMT to the TTree

Other Code Changes II

- WCSimSteppingAction
  - Calls UserSteppingAction from new photon track information class
  - This allows easier way of checking whether storing photon info is enabled
- WCSimWCSD
  - If photon info is enabled this stores the PMT hit and position of PMT hit (for convenience) in photon info class tagged to the photon track id in G4

Timescales

- Need to generate 1000 M 3 MeV electron events for tuning
- Scripts to generate these events have been written to run this on scinet (U Toronto)
  - Output size is expected to be 1.5 TB
- Expect jobs to be queued this week
- Look at output over next two weeks ~ mid Aug. should have some tables (SK)
  - Some additional analysis code is needed to extract the attenuation function and PMT angular acceptance from this output
- Will also do for HK geometry on this time scale
  - We expect a fully tuned fiTQun for Hyper-K to be ready in September

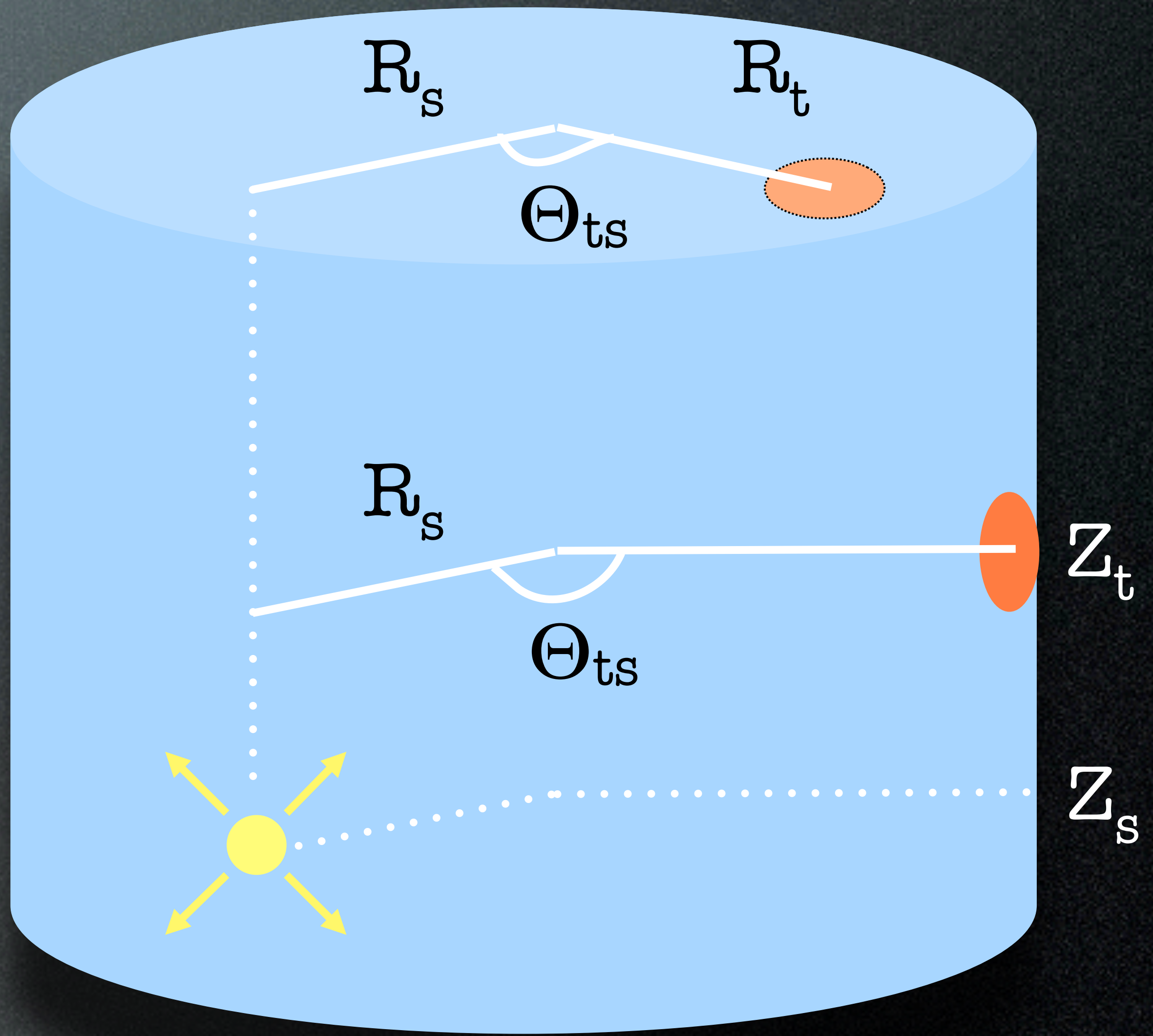
Conclusion

- fiTQun provides many new analysis tools that have not yet been used
    - We should consider employing these in official Hyper-K sensitivities
- Continuous development is taking place in the context of Super-K and T2K
    - Improvements can then be immediately used in Hyper-K
- Integration of fiTQun on Hyper-K MC still needs some tuning
    - New scattered light table
    - Tuning of attenuation length, PMT angular acceptance, and quantum efficiency is needed
- Initial, physics-ready version of fiTQun for HK expected in September

Supplement

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



Tuning Example (500 MeV electrons)

- 500 MeV electrons traveling in the x-direction
  - Starting position at various ToWall values
- Notice at the center of the tank, bias is small
  - Consistent with Okajima-san's studies
- Oddly, both near and far ToWall agree well, but disagree with center of the tank
- Many of these plots exist, varying attenuation length, scattered light fraction, etc.
  - This was not successful; must wait for full tuning