Simulation and reconstruction of LBNF events in Theia

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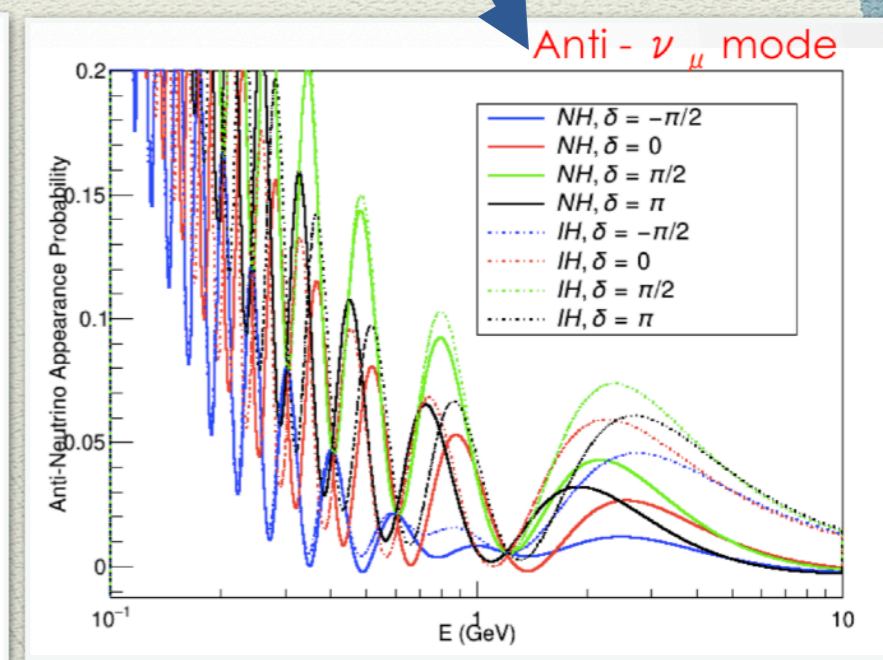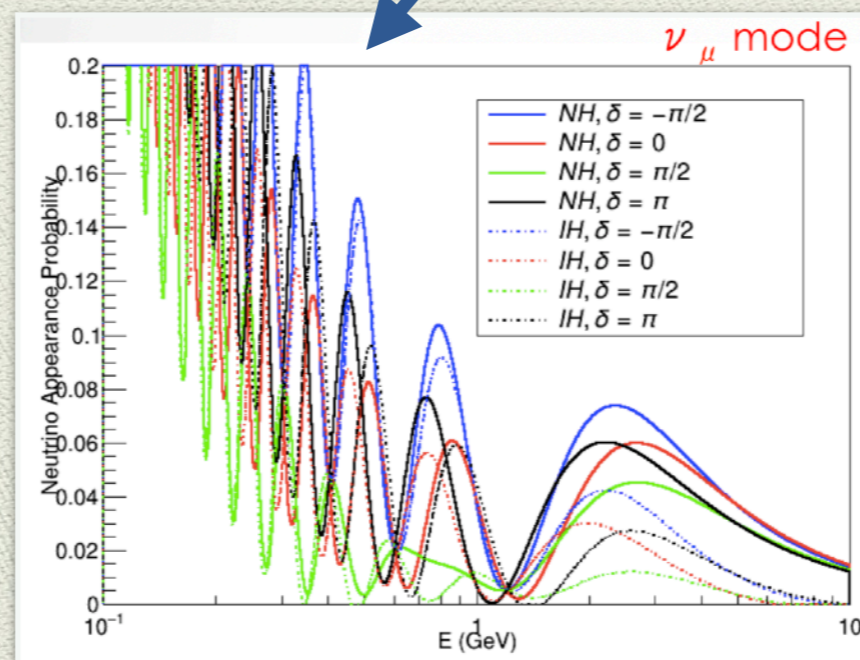 - Energy reconstruction - Theia

Generation of LBNF events

Event production considerations

- To simulate LBNF events in Theia, much has to be considered:

  - Oscillation probabilities

  - Neutrino beam flux

  - Cross-section measurements

  - Detector size

  - Detector composition

  - Baseline

  - Run period

  - Oscillation parameters

Full oscillation probabilities need to be calculated

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31}(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2))$$
$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta_{CP} - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta_{CP}\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$
$$+4S_{12}^2 C_{13}^2(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta_{CP})\sin^2\Phi_{21}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2(1 - 2S_{13}^2)\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31},$$

ν_μ mode

Anti - ν_μ mode

Event production considerations

- To simulate LBNF events in Theia, much has to be considered:

  - Oscillation probabilities

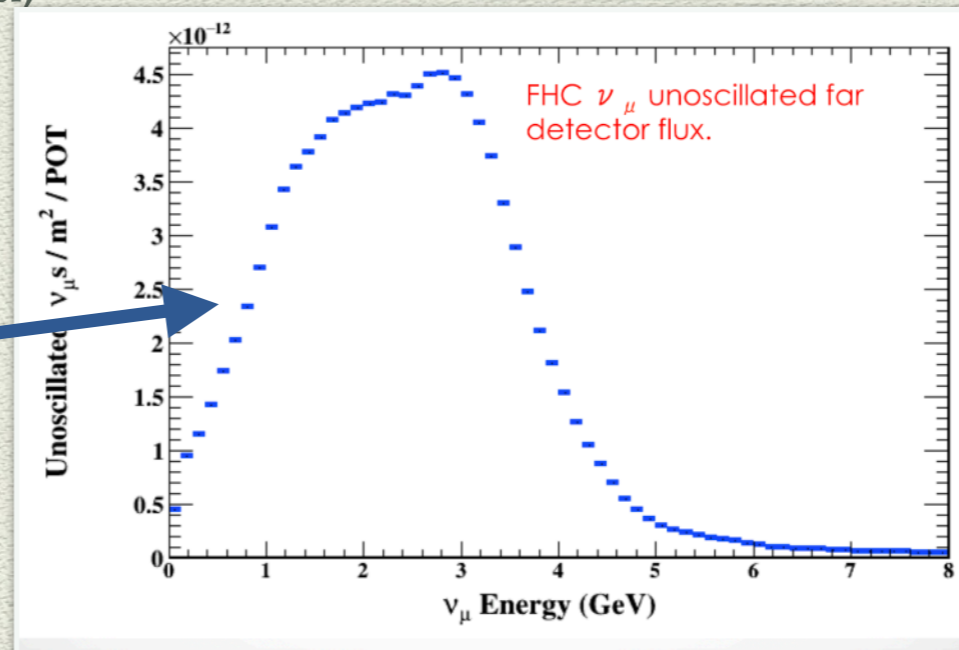 - Neutrino beam flux

  - Cross-section measurements

  - Detector size

  - Detector composition

  - Baseline

  - Run period

  - Oscillation parameters

FHC ν_μ unoscillated far detector flux.

Used LBNF optimised neutrino flux files

ν_μ Cross-sections

Oxygen cc
Oxygen nc
Hydrogen cc
Hydrogen nc

Used GENIE cross-sections. Considered interactions on O and H only (no C)

Event production considerations

- To simulate LBNF events in Theia, much has to be considered:

  - Oscillation probabilities

  - Neutrino beam flux

  - Cross-section measurements
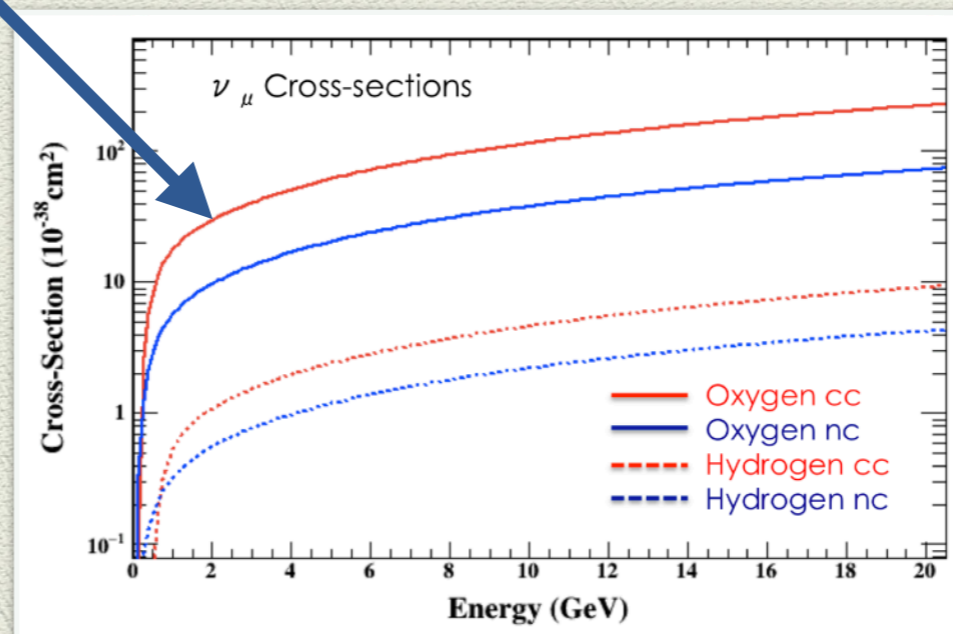
  - Detector size

  - Detector composition

  - Baseline

  - Run period

  - Oscillation parameters

1. 40 kT fiducial volume

2. Generation of events used H and O targets only

3. 3.5 years FHC

4. Normal mass hierarchy

5. $\delta_{CP} = 0$

6. 1300km baseline

7. Intrinsic ν_e background is not simulated

Predicted event numbers in Theia

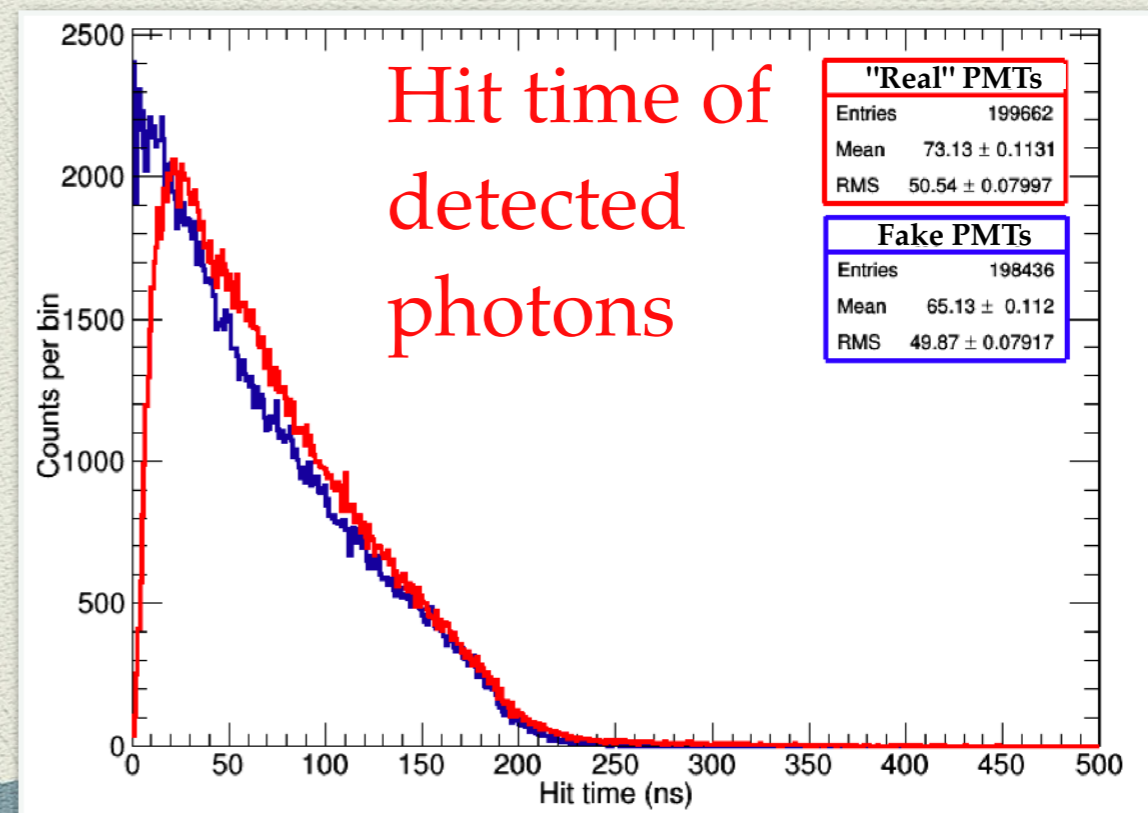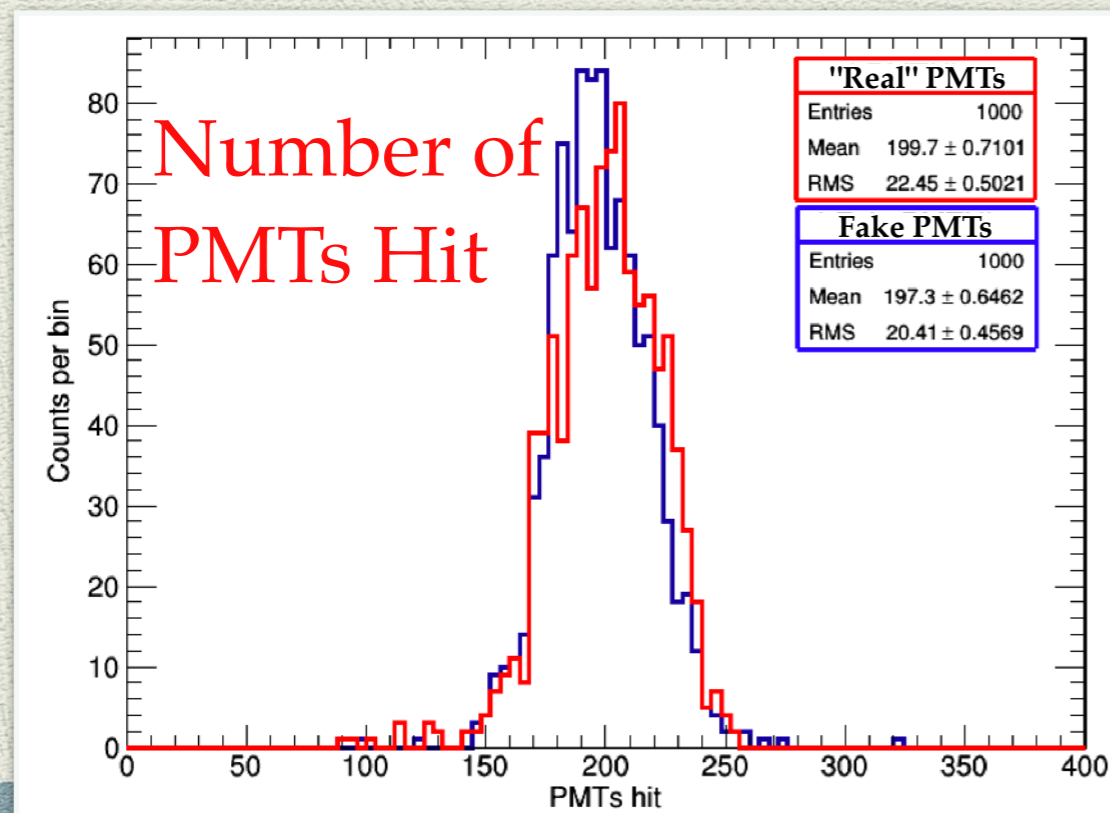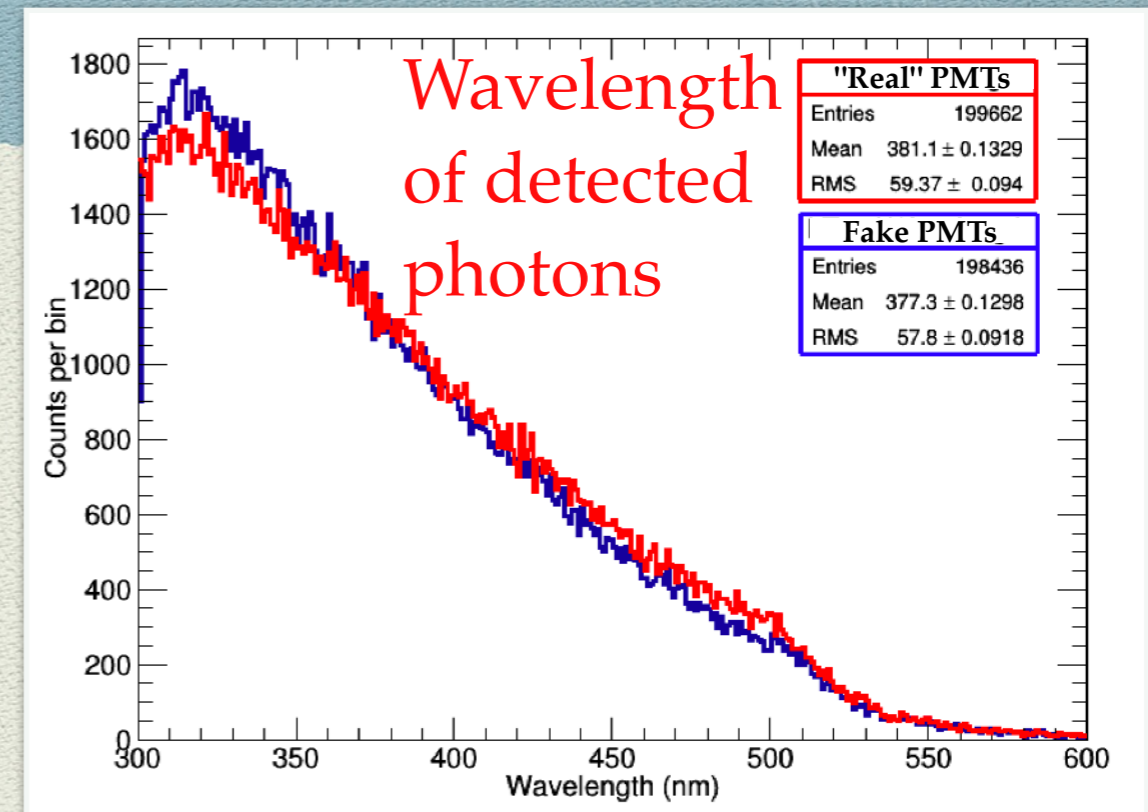| Flavour	Events	CC Events NC Events	CC Event Breakdown - QEL/DIS/RES/Other NC Event Breakdown - QEL/DIS/RES/Other
ν_μ	12454	9255.7 ± 35.7 3289.3 ± 35.7	1857.2 ± 40.1 / 4560.2 ± 45.1 / 2770.9 ± 45.2 / 67.3 ± 11.0 738.3 ± 18.6 / 1546.8 ± 35.9 / 965.7 ± 20.6 / 38.6 ± 4.4
ν_e	1544	1138.9 ± 17.4 404.4 ± 17.4	224.9 ± 10.3 / 497.6 ± 21.6 / 405.9 ± 12.8 / 10.5 ± 3.4 86.7 ± 9.2 / 168.7 ± 8.5 / 144.2 ± 13.0 / 4.8 ± 2.5
anti-ν_μ	898	650.2 ± 12.5 247.8 ± 12.5	109.6 ± 9.9 / 390.9 ± 17.3 / 140.9 ± 8.6 / 8.7 ± 3.5 41.0 ± 5.4 / 144.3 ± 9.2 / 57.8 ± 7.8 / 4.8 ± 2.1
anti-ν_e	13	9.1 ± 1.4 3.9 ± 1.4	3.5 ± 1.6 / 2.7 ± 1.6 / 2.6 ± 1.6 / 0.3 ± 0.4 1.3 ± 1.1 / 1.1 ± 1.0 / 1.5 ± 0.8 / 0.0 ± 0.0

Simulation of events in Theia

RAT-PAC simulation speed

- Tens of thousands of PMTs are required for Theia.

- For GeV LBNF events we create many photons!

- Simulating large numbers of photons interacting with the PMTs is very time consuming.

- For example a GeV muon currently takes ~8 hours to simulate.

  - ~913 years to simulate a million events.

- I have worked on performing the simulations without PMTs enabled in RAT-PAC, then reintroducing them within the analysis framework.

  - Already have parameters such as the PMT positions and efficiencies as a function of wavelength from the ratdb framework.

- This should speed up the simulations considerably, so we can produce MC sooner than ~900 years after Theia has been built.

Testing methodology - use photon bombs!

- After changing the framework by removing PMTs, we need to ensure we have the same detector response:
  - Used photon bombs as they are quick to simulate (both for enabled and disabled PMTs) to give large statistics.
  - Simulated a $1/\lambda^2$ photon bomb distribution.
    - 1000 events each of 10000 photons.
- Further subtle tuning is needed. However, in general, this method performs comparably to the full simulation.

Wavelength of detected photons

"Real" PMTs	
Entries	199662
Mean	381.1 ± 0.1329
RMS	59.37 ± 0.094

Fake PMTs	
Entries	198436
Mean	377.3 ± 0.1298
RMS	57.8 ± 0.0918

Number of PMTs Hit

"Real" PMTs	
Entries	1000
Mean	199.7 ± 0.7101
RMS	22.45 ± 0.5021

Fake PMTs	
Entries	1000
Mean	197.3 ± 0.6462
RMS	20.41 ± 0.4569

Hit time of detected photons

"Real" PMTs	
Entries	199662
Mean	73.13 ± 0.1131
RMS	50.54 ± 0.07997

| Fake PMTs	
Entries	198436
Mean	65.13 ± 0.112
RMS	49.87 ± 0.07917

How has the speed changed?

- New method replicates "PMT enabled" Theia simulation well.
  - Some small remappings are required to match the samples.
  - Implementation of "glass bulbs".
  - Implementation of transit time spread.
- Old method took ~8 hours to simulate a 1 GeV muon.
  - Years to produce 1000000 events.
- New method takes ~100 seconds.
  - 1000000 events can be simulated in ~week.
- Testing different PMT configurations can be done with the same MC sample!

Reconstruction of high energy events

Position reconstruction in WATCHMAN

Position reconstruction

- First stage of reconstruction is to produce a time residual PDF for Cherenkov and for scintillation light.
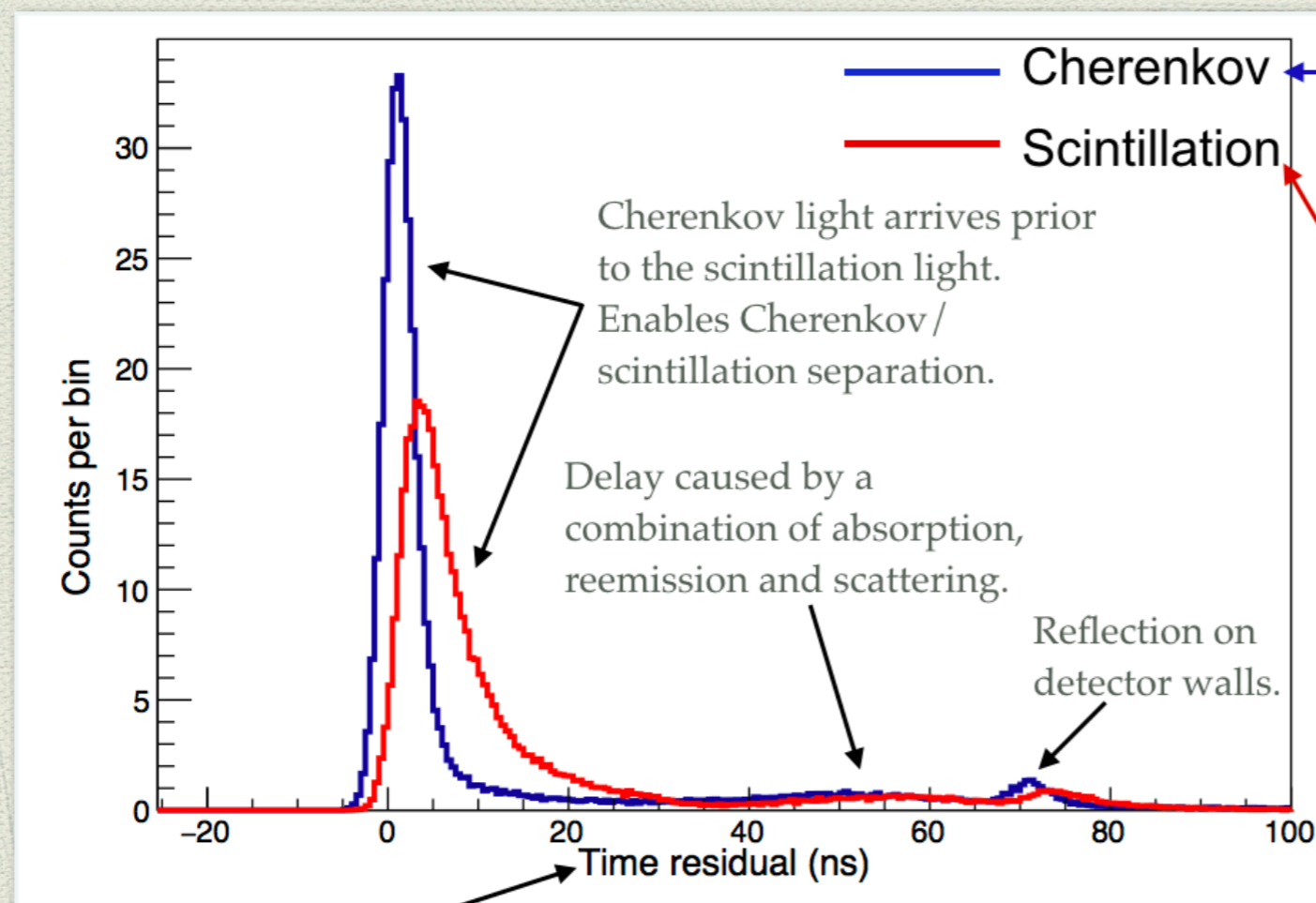
Cherenkov light timing information is a function of vertex position (x,y,z) and particle direction (ϱ, ϕ).

Scintillation light timing information is a function of vertex position only (x,y,z).

For a "test vertex", calculate a likelihood.

- Once we have the PDFs, we can begin to reconstruct event information.

- For a "test vertex" and a "test particle direction", iterate through the first hit times on each PMT.

- For each PMT hit time, calculate BOTH the Cherenkov AND scintillation timing residuals.
    - Both are calculated as we do not know which mechanism produced the photon.

- Whichever production mechanism yields the highest likelihood, is the "hypothesized mechanism" and the corresponding likelihood value is added to the "test likelihood" for this test vertex.

Now, test other vertices throughout the detector.

- We now have our first "test likelihood". However, we must repeat this process for positions throughout the detector AND for all particle directions.

- To do this (in the most non-computationally intensive way possible) we voxelise the detector.
  - Initially, scan over large increments in x, y, z, ϱ, ϕ.

- After the first scan, we have an approximate region of test parameter space that yields the largest "test likelihood".

  - Now, repeat this scanning process, with smaller increments centered around the parameters that gave this largest "test likelihood".

  - Continue to repeat for as many iterations as time permits and/or resolution requires.
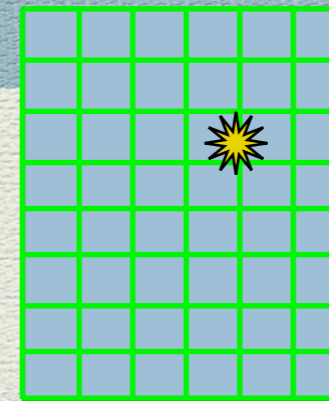
Initial, course, scan is undertaken.
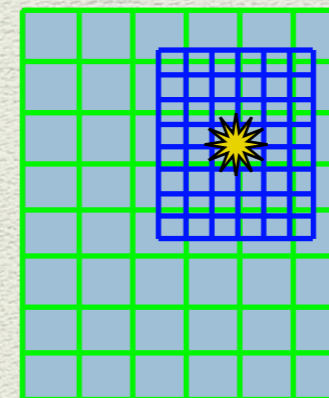
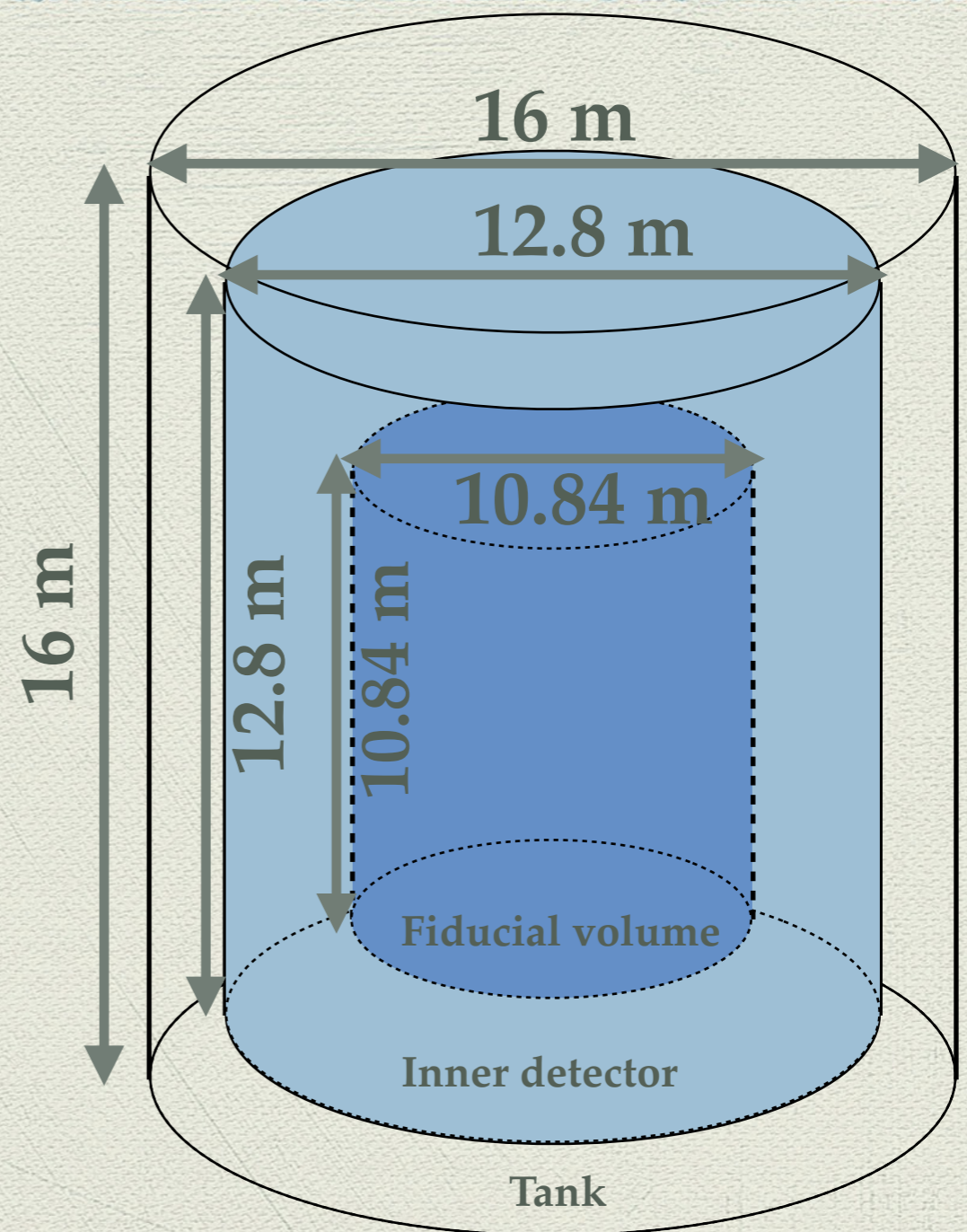Once the sweet spot is found, a finer scan can be undertaken.
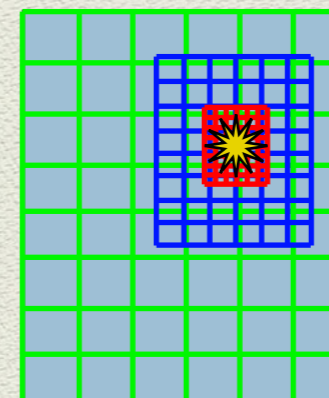
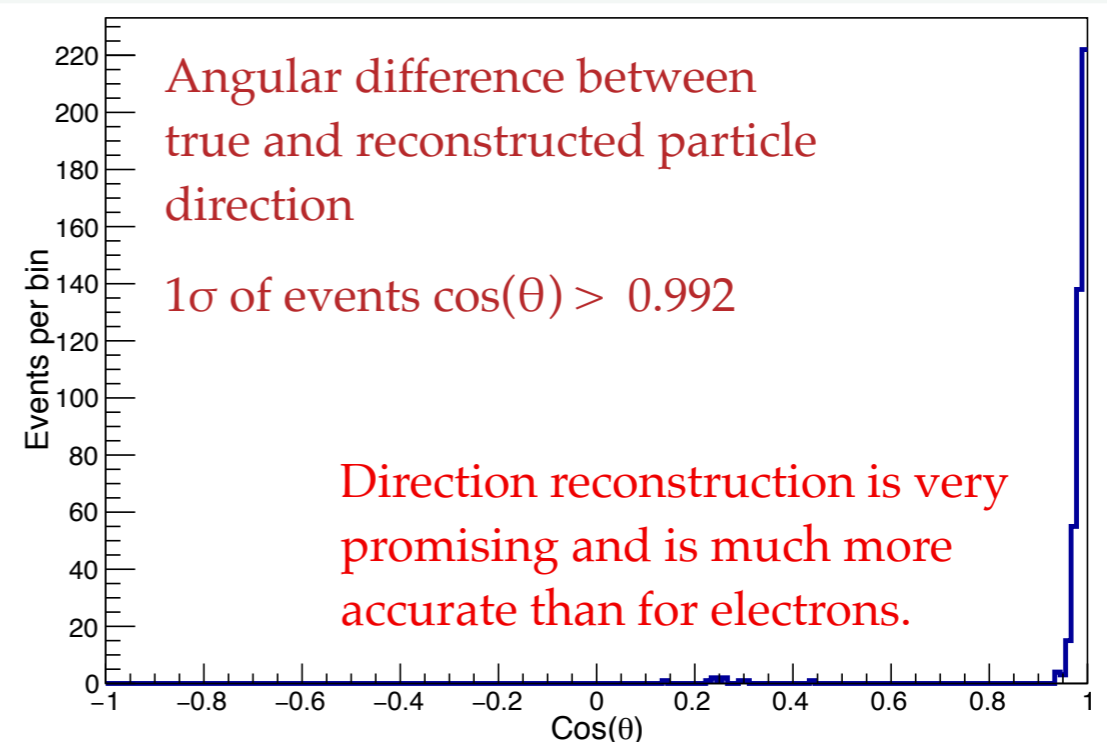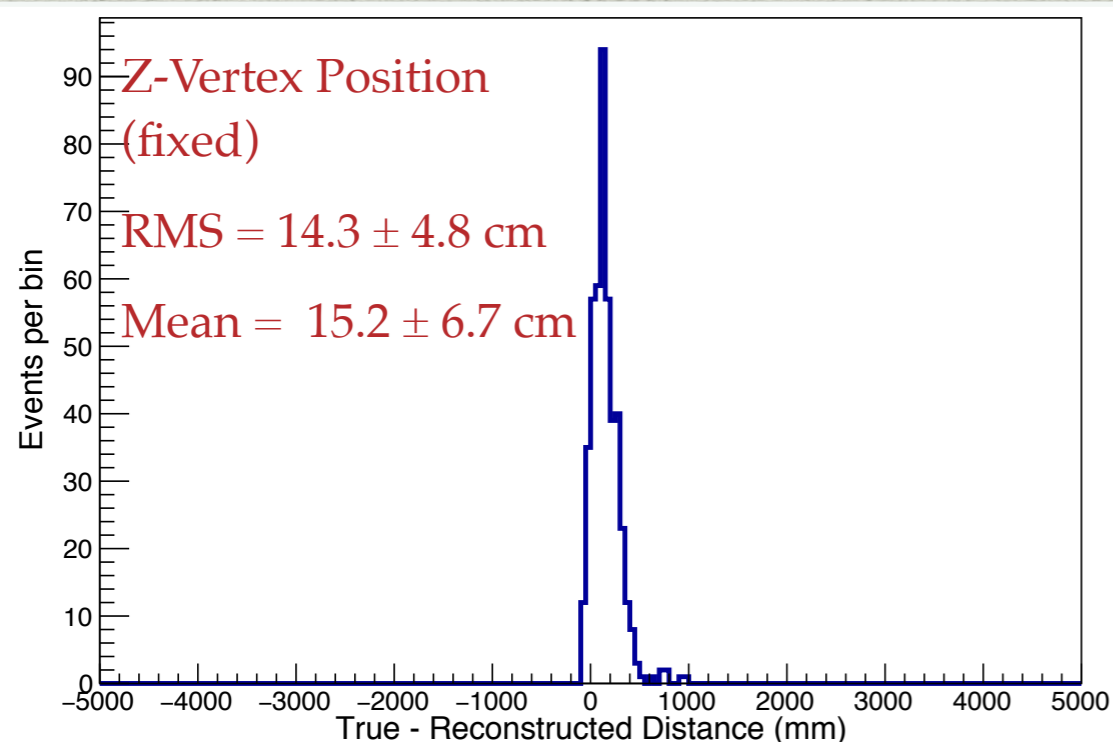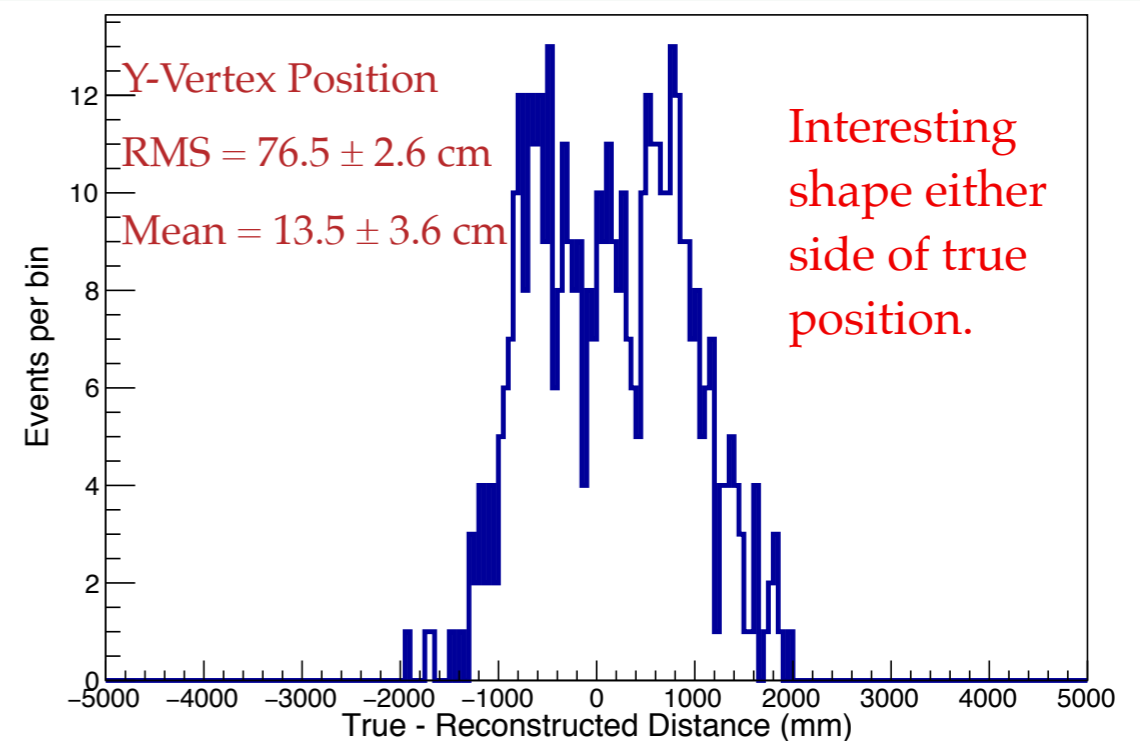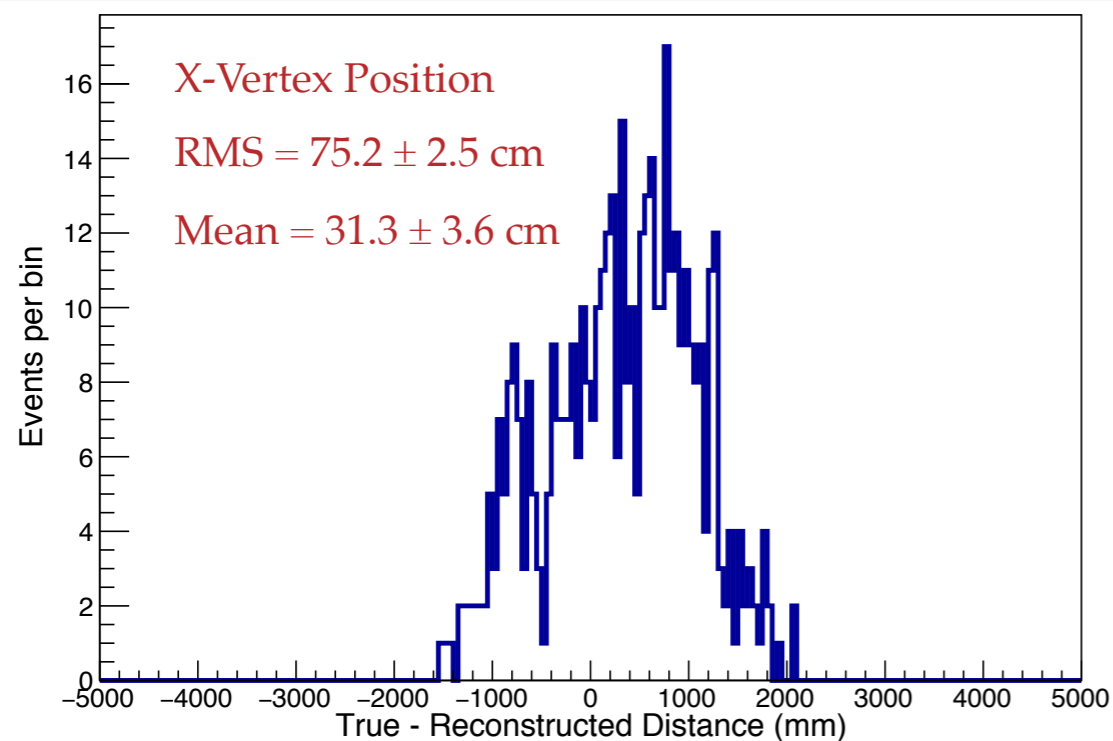This process can be repeated as many times as needed.

☀ Interaction vertex
▢ Detector volume
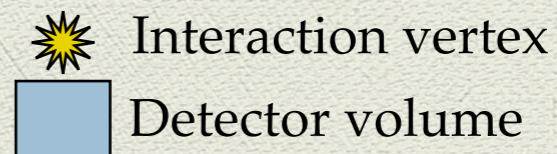
WATCHMAN simulation setup with WbLS

Volume	Width (m)	Diameter (m)
Tank size	16	16
Inner detector size	12.8	12.8
Fiducial size	10.84	10.84

- 4330 x R7081 10" Hamamatsu pmts (27.5% coverage).
- Filled with WbLS 1%.
- 5 GeV muons starting at the top of the inner detector and exiting at the bottom.

# Directionality of through going muons is impressive.

X-Vertex Position

RMS = 75.2 ± 2.5 cm

Mean = 31.3 ± 3.6 cm

Events per bin

True - Reconstructed Distance (mm)

Y-Vertex Position

RMS = 76.5 ± 2.6 cm

Mean = 13.5 ± 3.6 cm

Interesting shape either side of true position.

Events per bin

True - Reconstructed Distance (mm)

Z-Vertex Position (fixed)

RMS = 14.3 ± 4.8 cm

Mean = 15.2 ± 6.7 cm

Events per bin

True - Reconstructed Distance (mm)

Angular difference between true and reconstructed particle direction

1σ of events cos(θ) > 0.992

Direction reconstruction is very promising and is much more accurate than for electrons.

Events per bin

Cos(θ)

Particle identification in Theia

Particle identification using ring imaging

- Superkamiokande uses ring imaging techniques to determine ν_e or ν_μ events.

- Look for "fuzzy" electron-like Cherenkov rings and "well defined" muon-like Cherenkov rings.

- WbLS may make this more challenging...

 - Added scintillation light component will make everything "fuzzier".
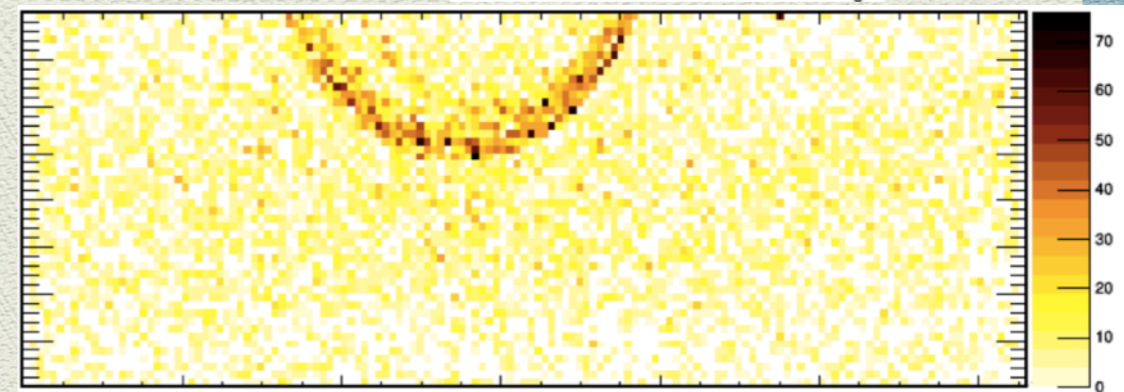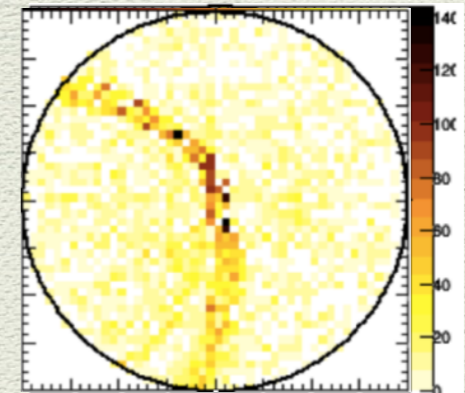
Simulated ν_μ CC event display in Theia loaded with 5% WbLS. Note the sharp muon Cherenkov ring alongside the homogenous scintillation light component.
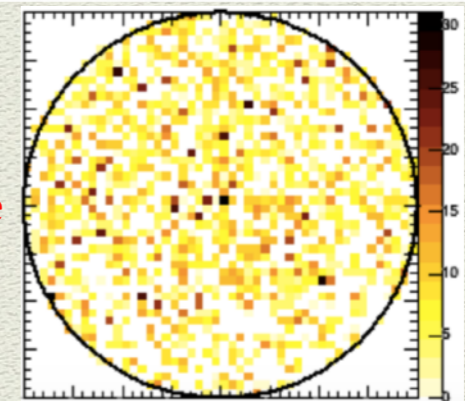
Particle identification in WbLS - methodology

- Using 1 GeV electron and muon events fired along the z-axis, produce separate PMT hit map PDFs.

- Then for a range of WbLS loadings (0.1%, 1% and 5%) find the efficiency at correctly identifying the particle types using a log-likelihood method.

- Does the scintillation component make this task much more difficult?
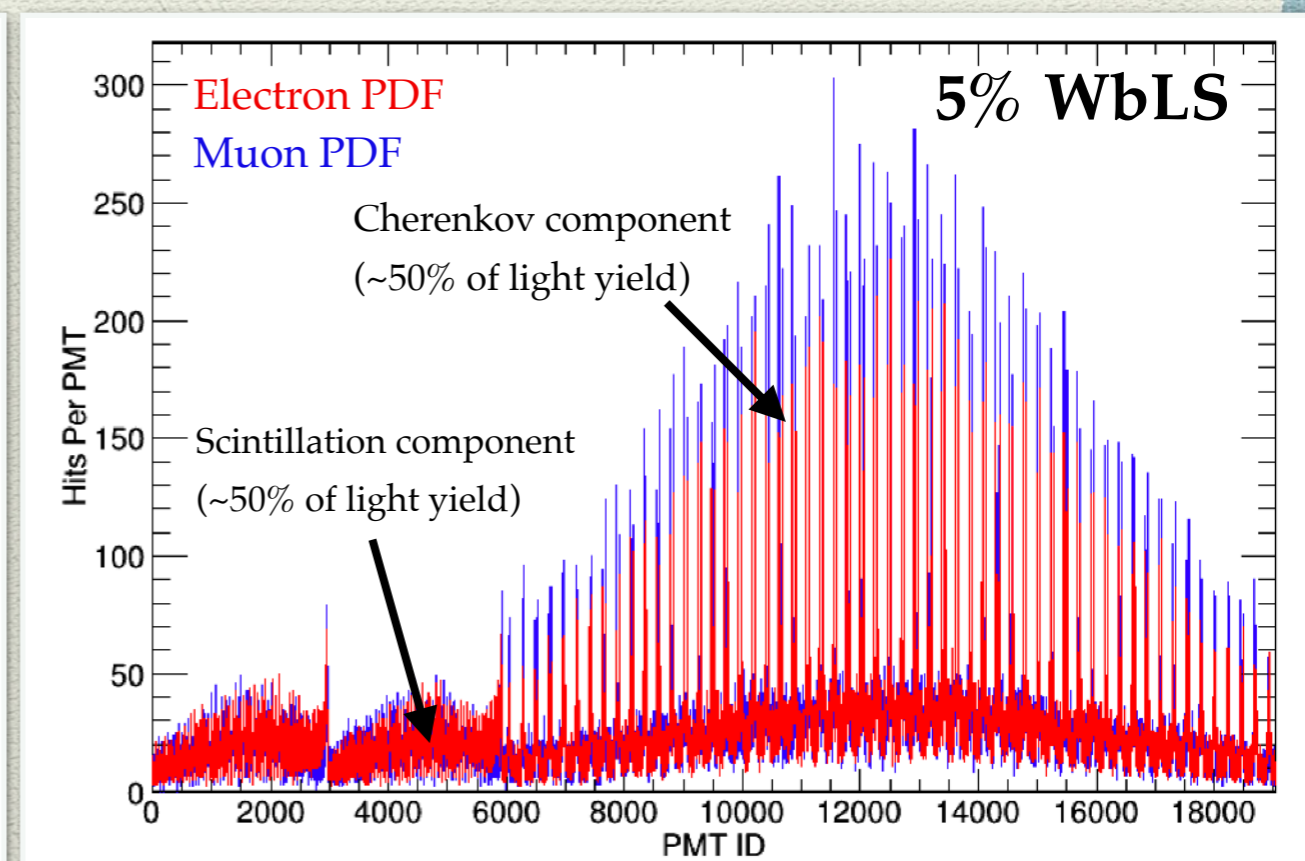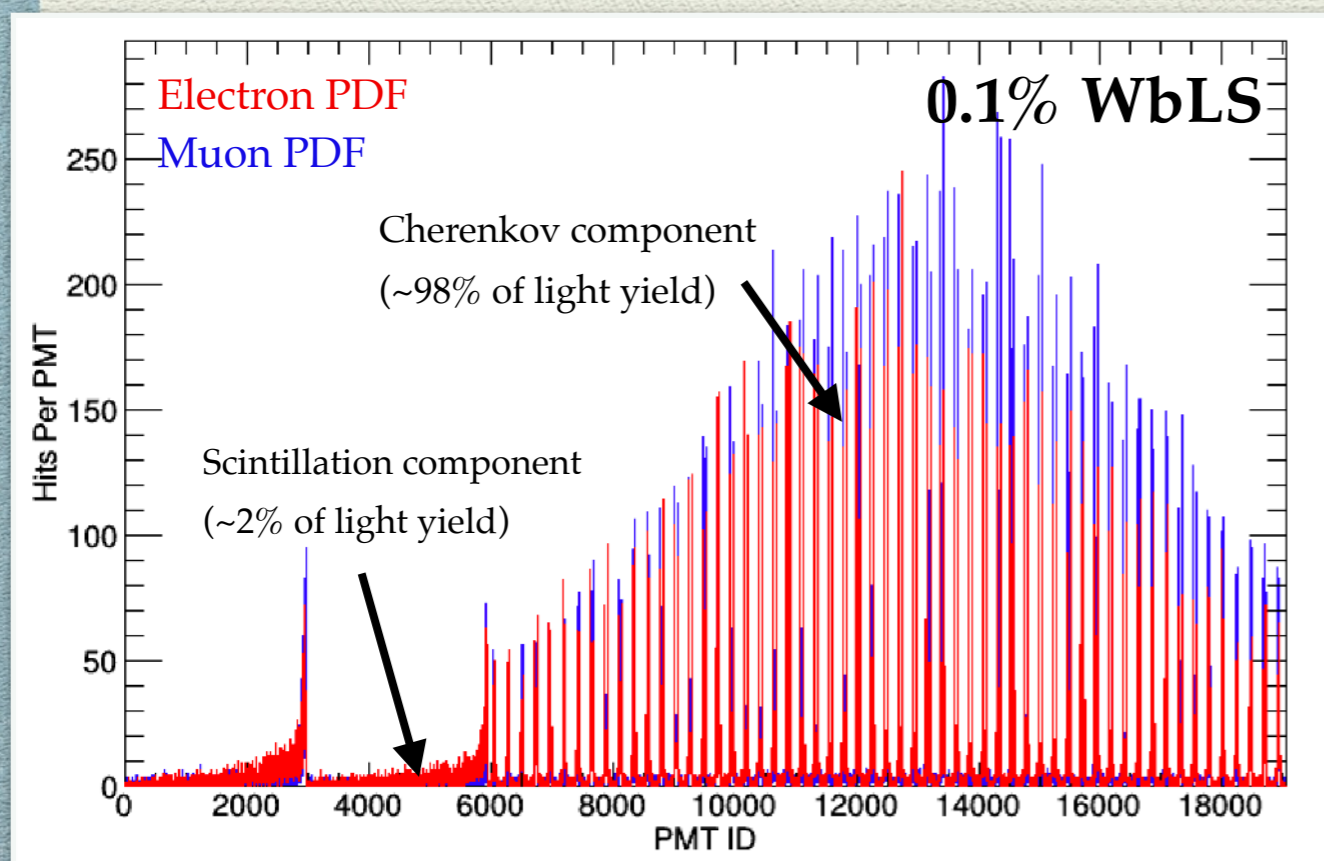
Example PID PMT hit map PDFs for electron and muon events.

Particle identification is made more difficult with increased WbLS loading

Detector Setup	0.1% WbLS	1% WbLS	5% WbLS	5% WbLS (15ns)	5% WbLS (10ns)	5% WbLS (5ns)	5% WbLS (5ns + 4ns Jitter)
PID Efficiency	99.0%	97.5%	90.7%	83.6%	94.0%	95.6%	94.1%

* Increasing the liquid scintillator component reduces PID capabilities!

* This is because the scintillation component makes all rings "fuzzier".

* Introducing even a crude time cut significantly improves PID efficiency!

* PMT transit time spread obviously effects the timing cut.

* Fast timing is beneficial!

Energy reconstruction in Theia

Energy reconstruction methodology

- Method adapted from IceCube's"fast" reconstruction algorithm.

- Process is to maximise the natural logarithm of the following likelihood:

Mean number of photons detected by a PMT →

Observed number of photons in a single PMT →

$$\mathcal{L} = \frac{\lambda^k}{k!} . e^{-\lambda}$$

- To predict the mean number of photons for a given PMT, a template function Λ is used:

$$\lambda = \Lambda E$$

- Then:

$$0 = \frac{\partial \Sigma ln \mathcal{L}}{\partial E} = \Sigma_{PMTs\ j}(k_j \Lambda_j / E\Lambda_j - \Lambda_j)$$
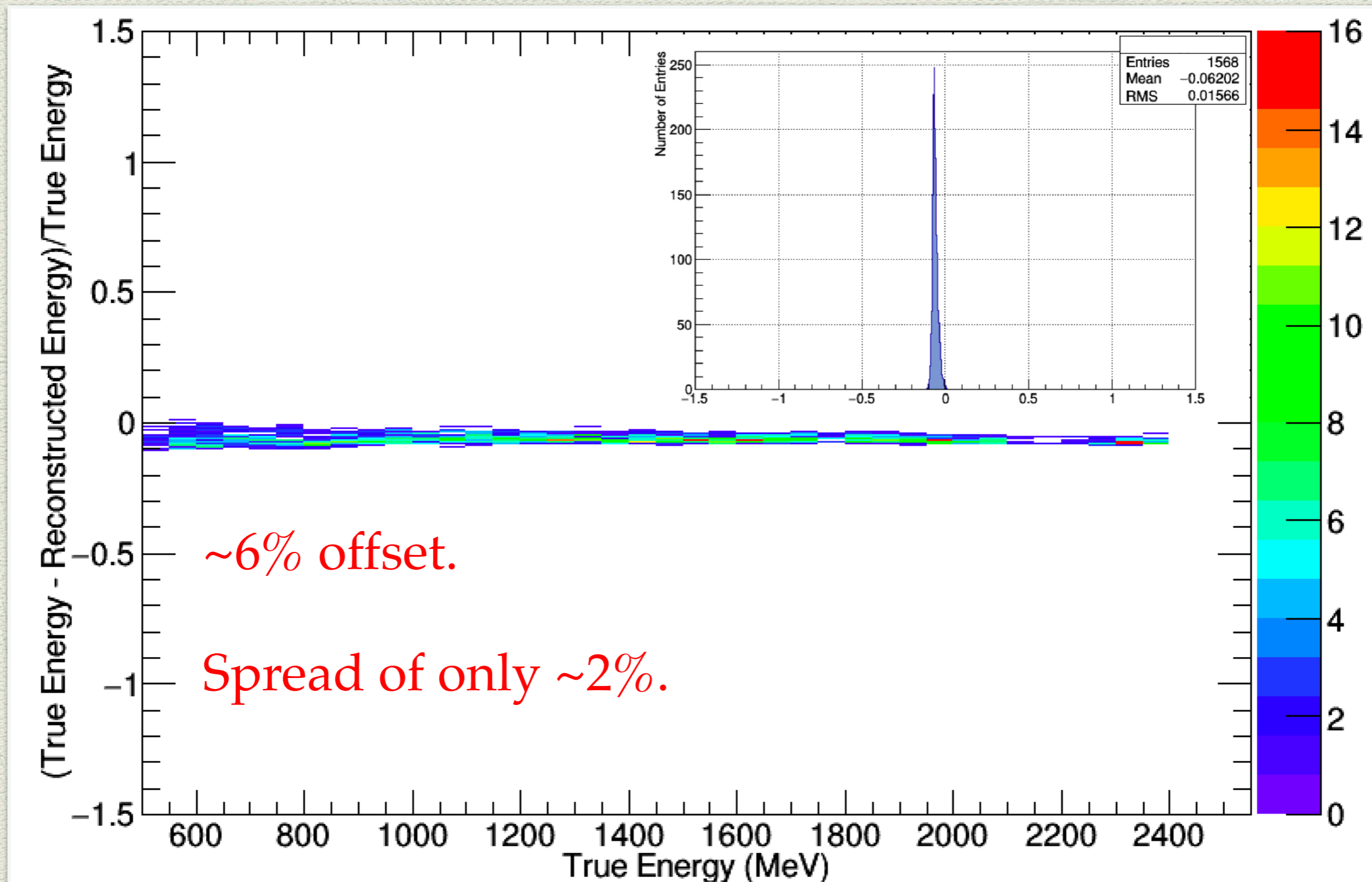
- Calculating Λ is by far the most challenging part of this reconstruction method.

Calculating Λ

- Most challenging part of this methodology is determining the template function.

- The template function encapsulates the probability of a photon being detected by a PMT, given the distance from the vertex to that PMT.

- To deduce Λ, I simulated photons bombs that replicated the photon wavelength distribution produced by a muon.

  - It was found that subtle changes in the template can have large impacts - tuning for different event topologies is needed.
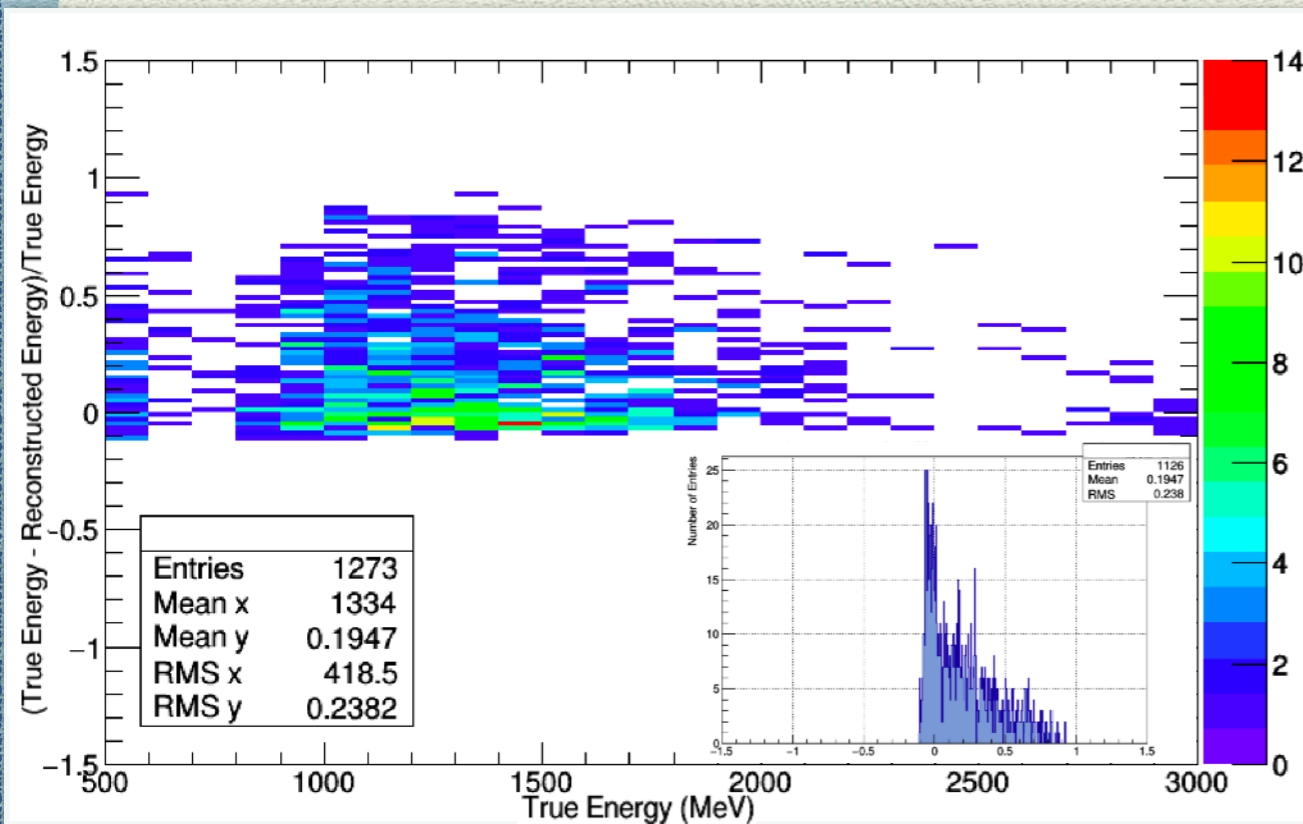

Photon distribution from a muon

Corresponding template function
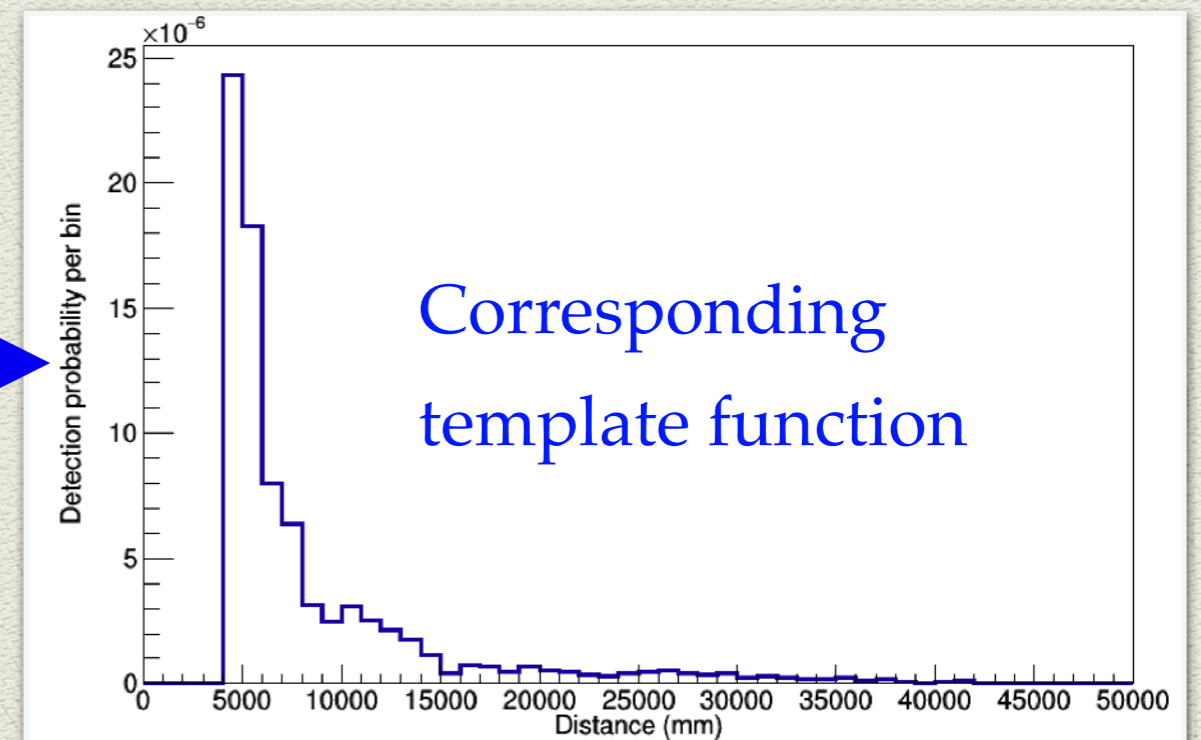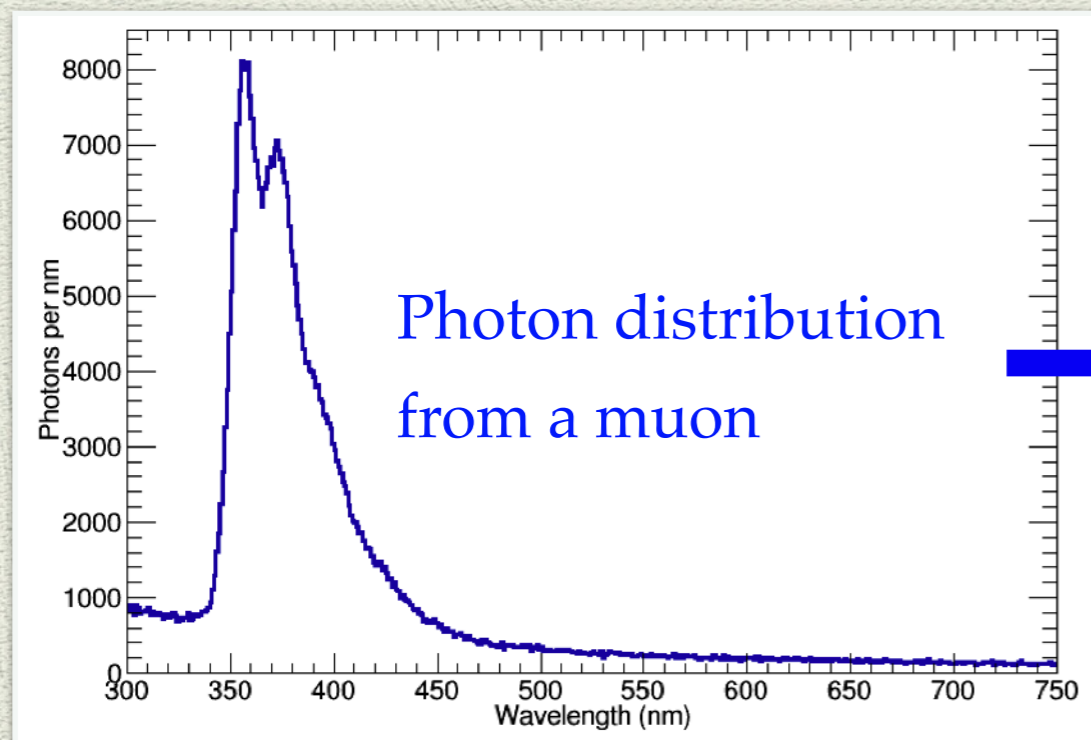
Energy reconstruction of high energy muons is impressive!

~6% offset.

Spread of only ~2%.

LBNF events prove more troublesome to reconstruct

ν_μ CCQE Events

ν_μ CCQE Events (1P in final state)

* Residual RMS is 0.238!

* Underprediction of event energy is now an issue.

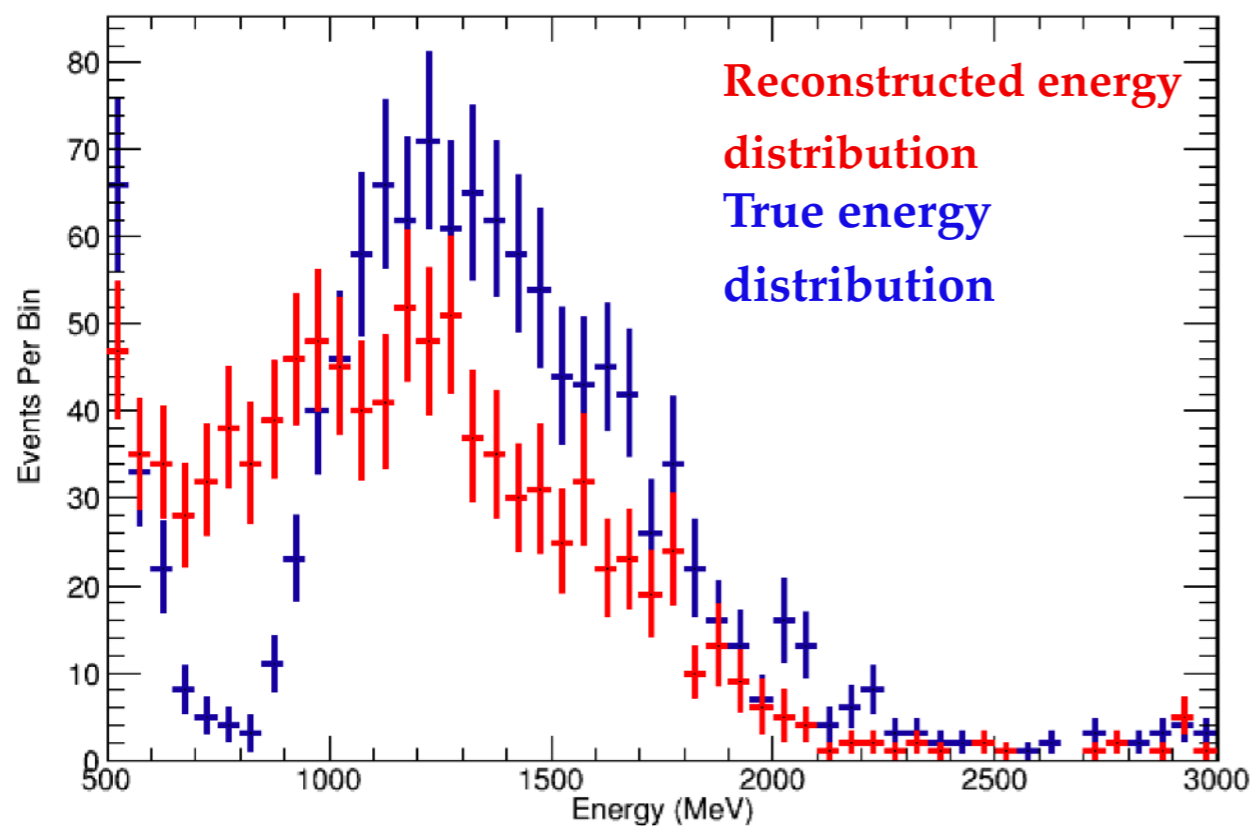* Clearly the complexity of the events is causing some issues.
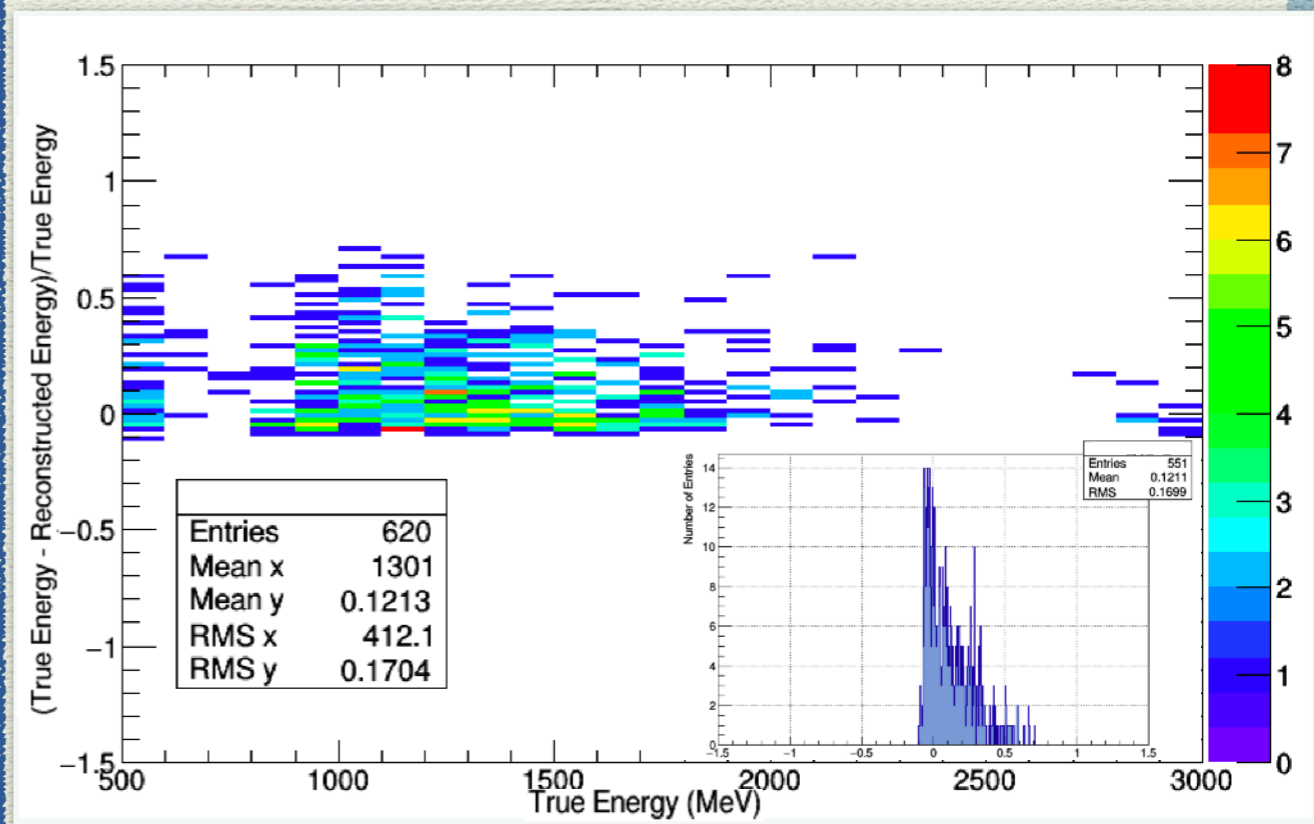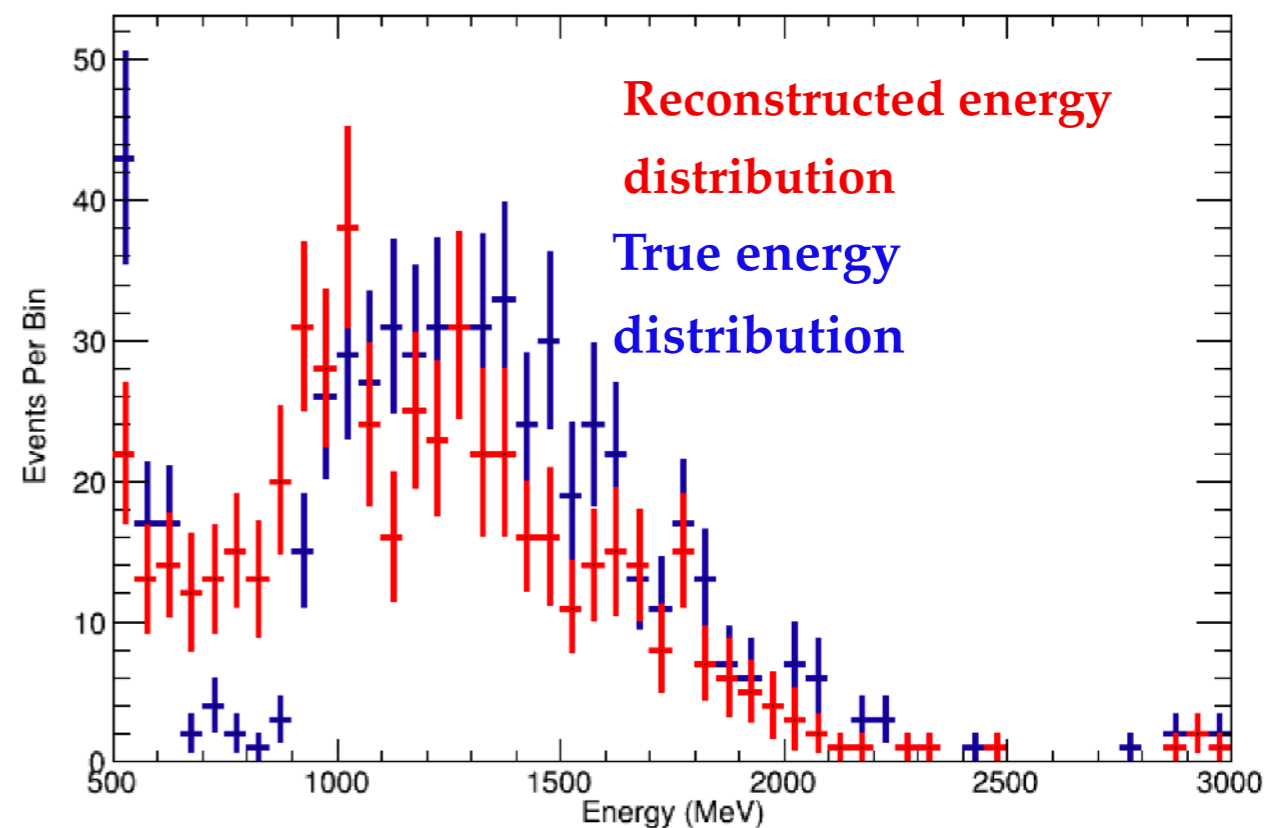
* Residual RMS is 0.170.

* Energy underprediction is reduced slightly here.

* This reduction compared to all CCQE events suggest neutrons are troublesome!

How well can we reconstruct the event energy?

ν_μ CCQE Events

ν_μ CCQE Events (1P in final state)

- Underpredicting event energy causes a smearing to the left!

- New template function for ν_μ CCQE Events?

- A better understanding of how final state particles affect the reconstruction capabilities is needed.

Conclusions

- Infrastructure is in place to generate LBNF events in Theia using the latest flux files.

- Now have an updated framework to simulate such high energy events within reasonable timescales - considerably less than a millenium.

- Position reconstruction algorithm uses timing residual information - results are promising.

  - Many improvements can be made such as position dependent PDFs.

- Initial particle identification using hit map PDFs has been explored to asses the effect of WbLS loading.

  - Increasing the loading cause increased misidentification as the Cherenkov rings look "fuzzier".

  - Simple timing cuts improve the identification efficiency significantly - gives confidence at reaching Superkamiokande capabilities.

- Fast energy reconstruction algorithm adpated from IceCube has been implemented.

  - Muon events are reconstructed with impressive energy resolution over a wide range of energies.

  - The complexity of LBNF events begins to cause issues.

Particle identification is made more difficult with increased WbLS loading

	0.1% WbLS	1% WbLS	5% WbLS	5% WbLS (15ns)	5% WbLS (10ns)	5% WbLS (5ns)	5% WbLS (5ns + 4ns Jitter)
Electron correctly identified	100.0%	100.0%	81.6%	100.0%	99.7%	99.7%	99.3%
Muon correctly identified	98.0%	95.0%	99.9%	67.2%	88.3%	91.6%	89.0%
Total correctly identified	99.0%	97.5%	90.7%	83.6%	94.0%	95.6%	94.1%

- Increasing the liquid scintillator component reduces PID capabilities!
- This is because the scintillation component makes all rings "fuzzier".

- Introducing even a crude time cut significantly improves PID efficiency!

- PMT transit time spread obviously effects the timing cut.
- Fast timing hugely beneficial!

LBNF events prove more troublesome to reconstruct