Simulation and reconstruction for Theia LBL

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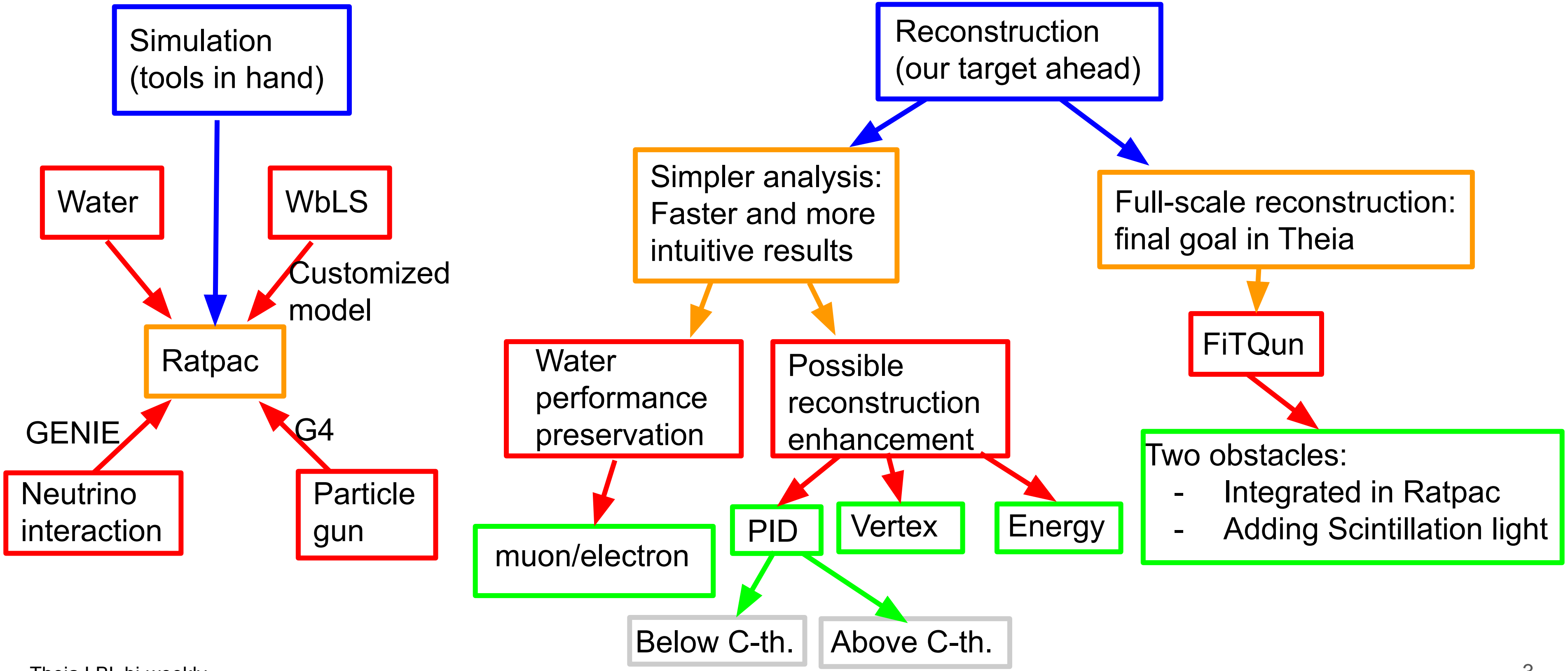
Beyond the Theia white paper

In the Theia white paper, we assumed the same reconstruction performance as water.

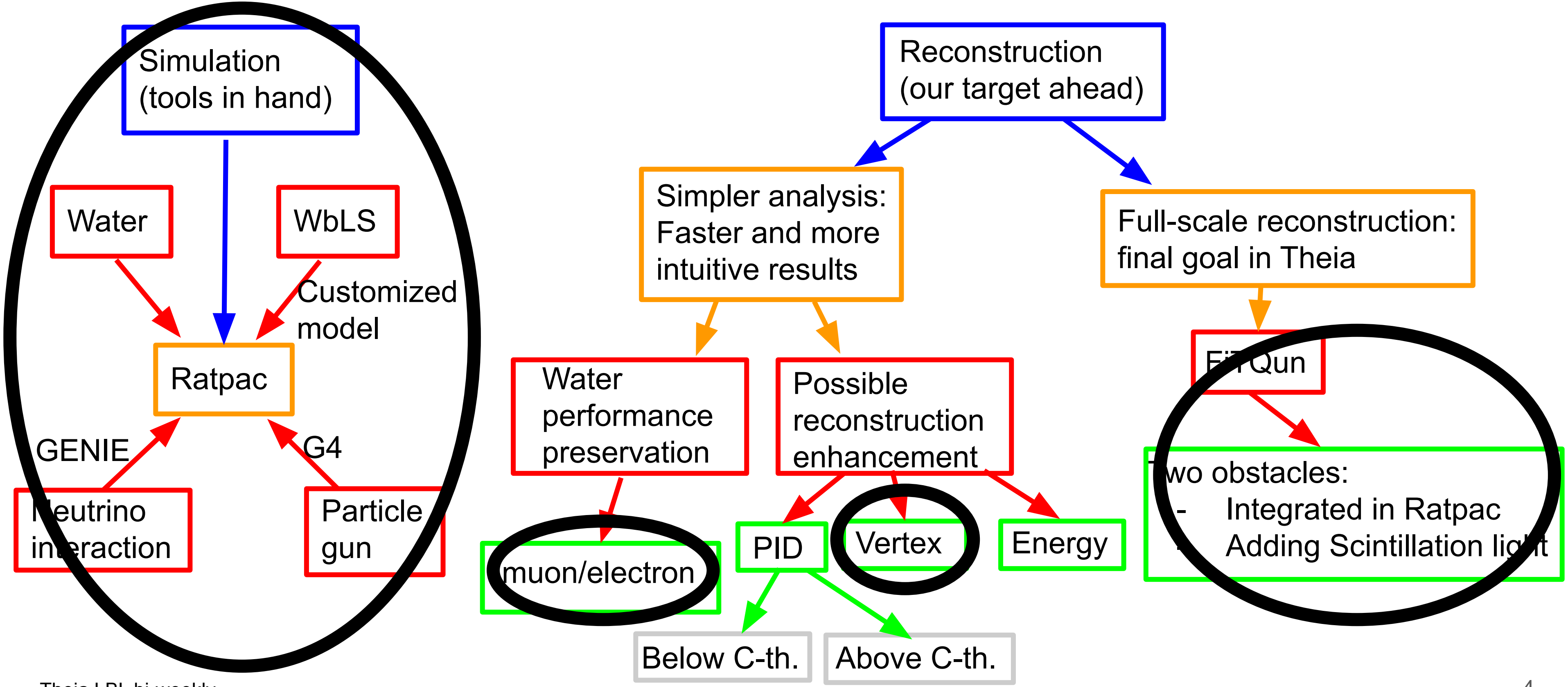
- Did not simulate and reconstruct WbLS events.
- Use existing FiTQun reconstruction on SK samples and weight the flux. The main work was including more x-ring y-decay samples and reducing the background with multi-variable technique.

To work on the actual WbLS, simulation and reconstruction from scratch are needed.

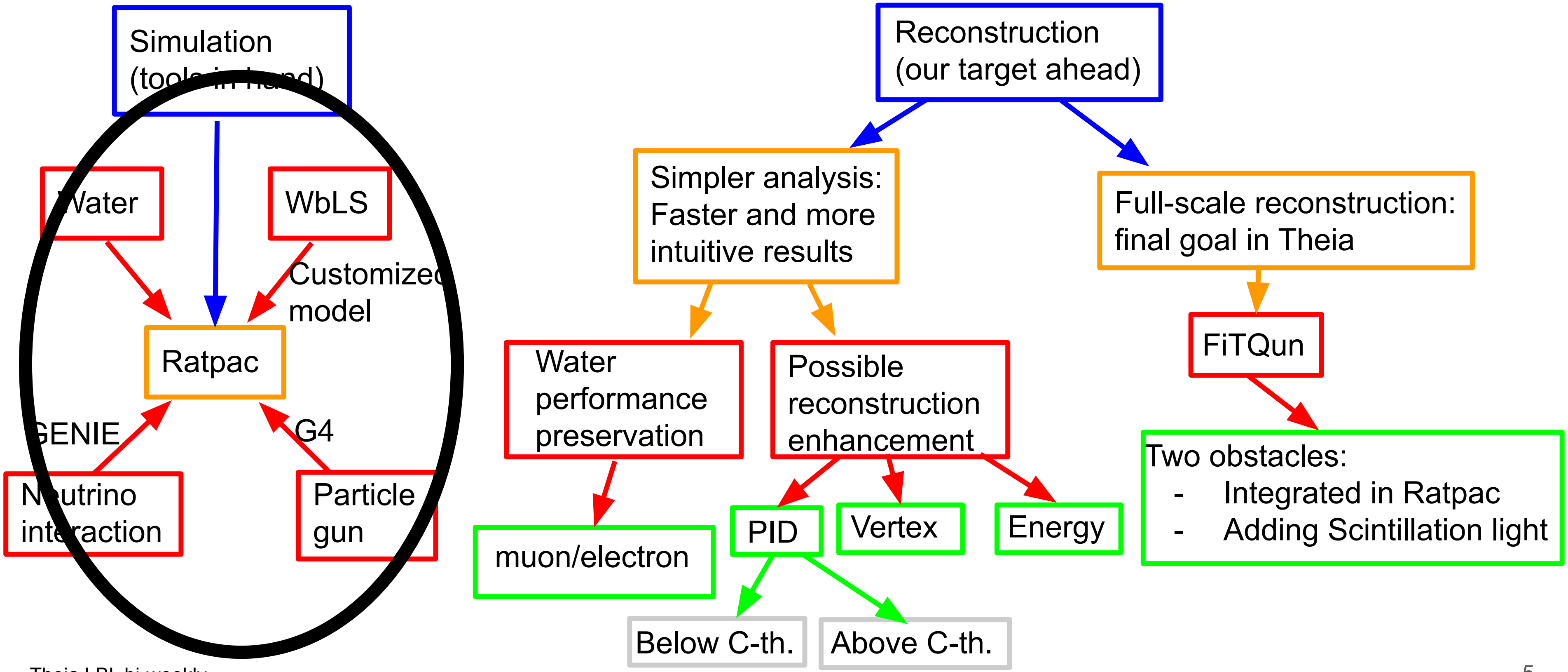
Simulation and reconstruction highlight



Simulation and reconstruction highlight



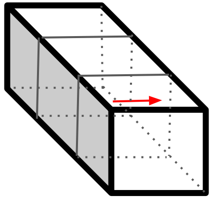
Simulation and reconstruction highlight



Simulation with ratpac

Geometry

- Considering a 25-kt Theia, 40% coverage results in >46,000 20-inch PMTs -> too heavy for simulation.
- Instead, having 14 big sensitive regions and look at the detailed location of each hit.



Physics model

- Various GENIE versions and tunings are ready for the neutrino interaction.
- Various G4 models are ready for the particle propagation, default QGSP_BERT.

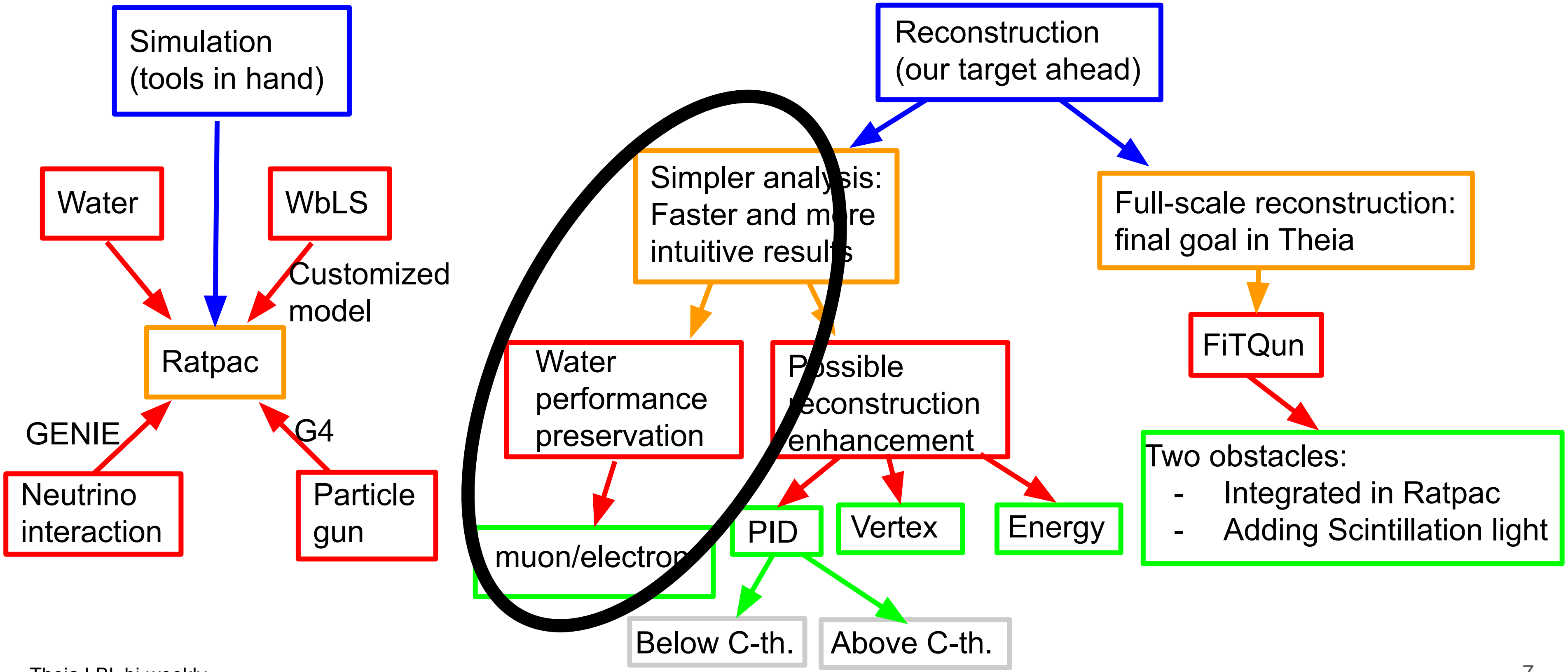
WbLS Optical model

- Scintillation code in RAT is based on GLG4Sim with model parameter inputs.
- Light yield from measurement: here.
- Rayleigh scattering from BNL measurement.
- *Absorption length from combination of BNL LABPPO measurement and Pope+Smith for water.*
- Refractive index, scintillation rise time and spectrum are from measurements.

Output information

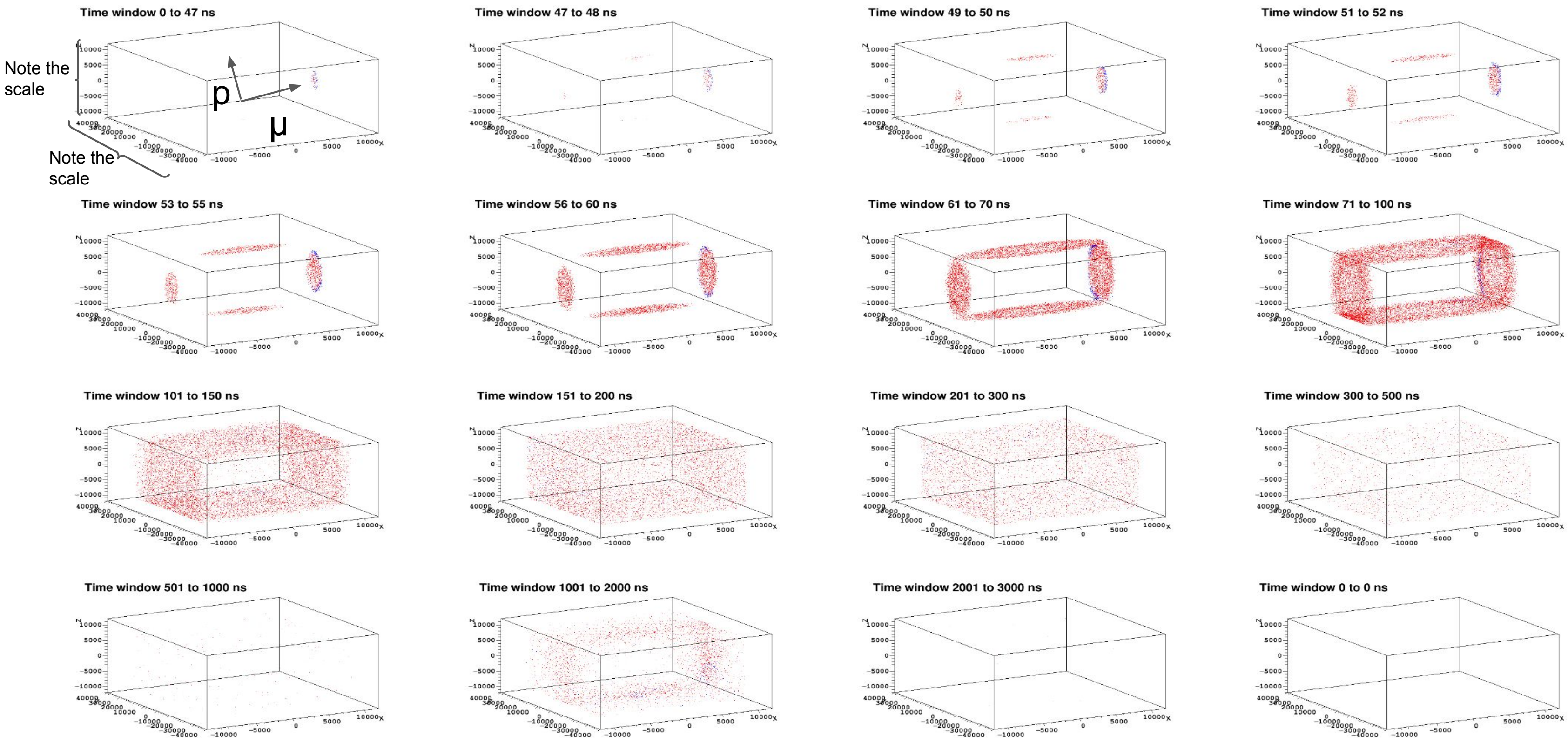
- Ratpac output root with true PE location and time.
- PMT Transit time spread, charge can be added, but not at the moment.

Simulation and reconstruction highlight

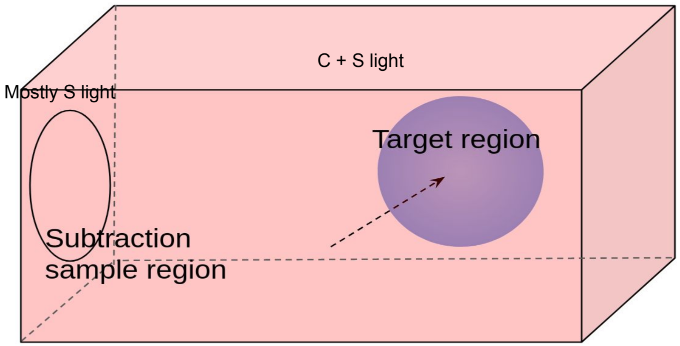


How does a 1 GeV neutrino event looks like

375 KE u- and
493 KE Proton



Clarity of the water detector information-> muon ring

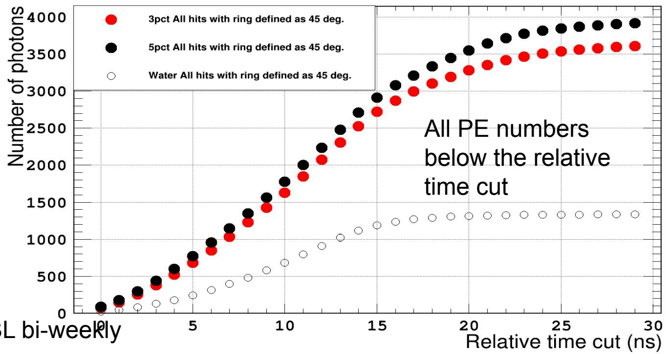


-Define ring clarity as:

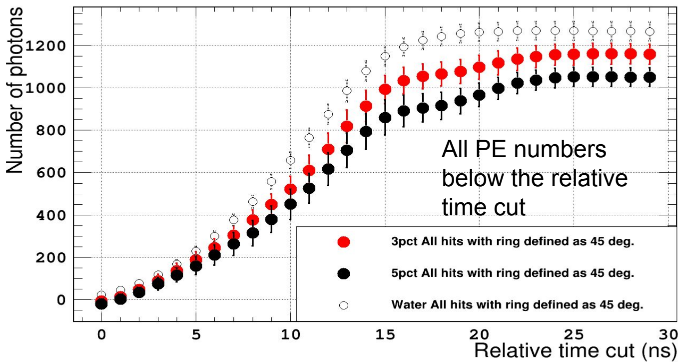
Total light in ring - light in far region

- In-ring light will be C+S
- Far region will be primarily S
- The (solid-angle corrected) subtraction should yield the net C signal
- Demonstrate clean identification of Cherenkov ring at few % LS loading for 500-MeV muons

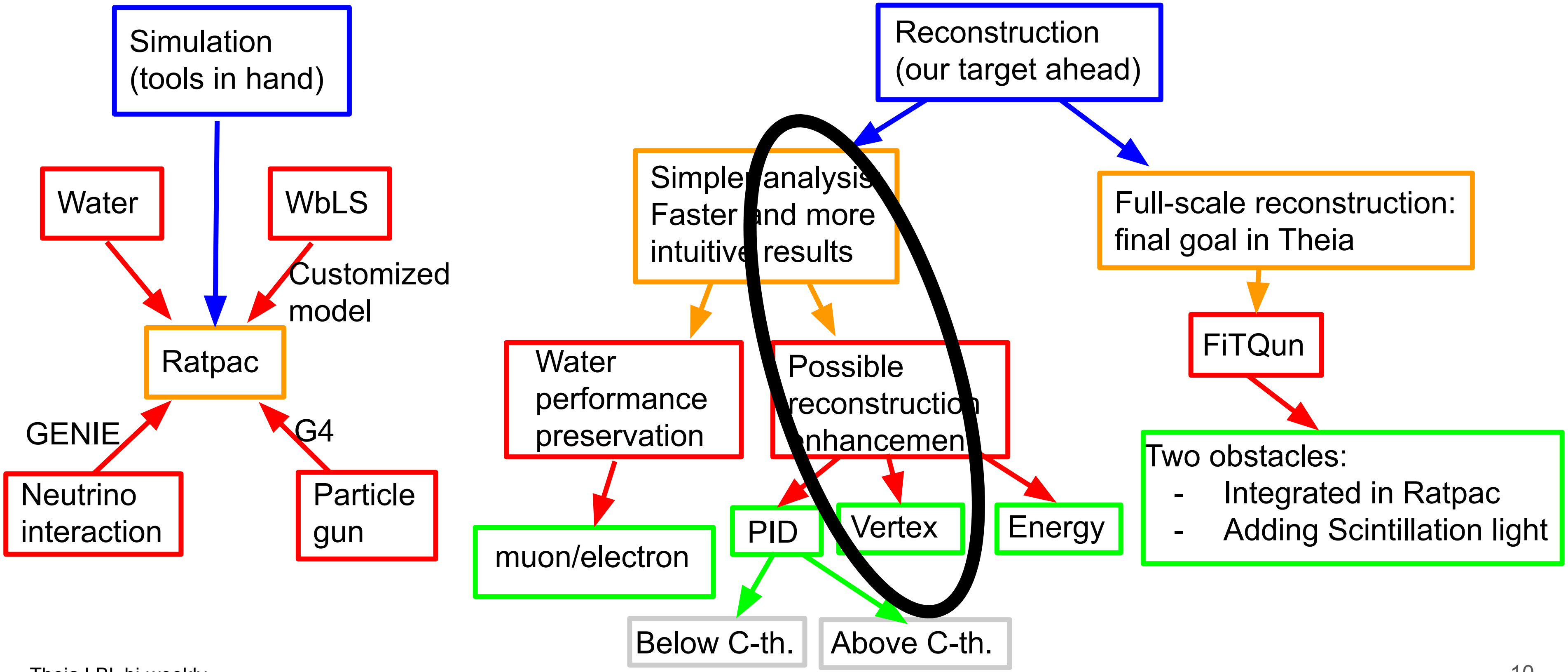
Total number of photons in ring (500 MeV muon)



Total number of photons in ring - light in far away region (500 MeV muon)

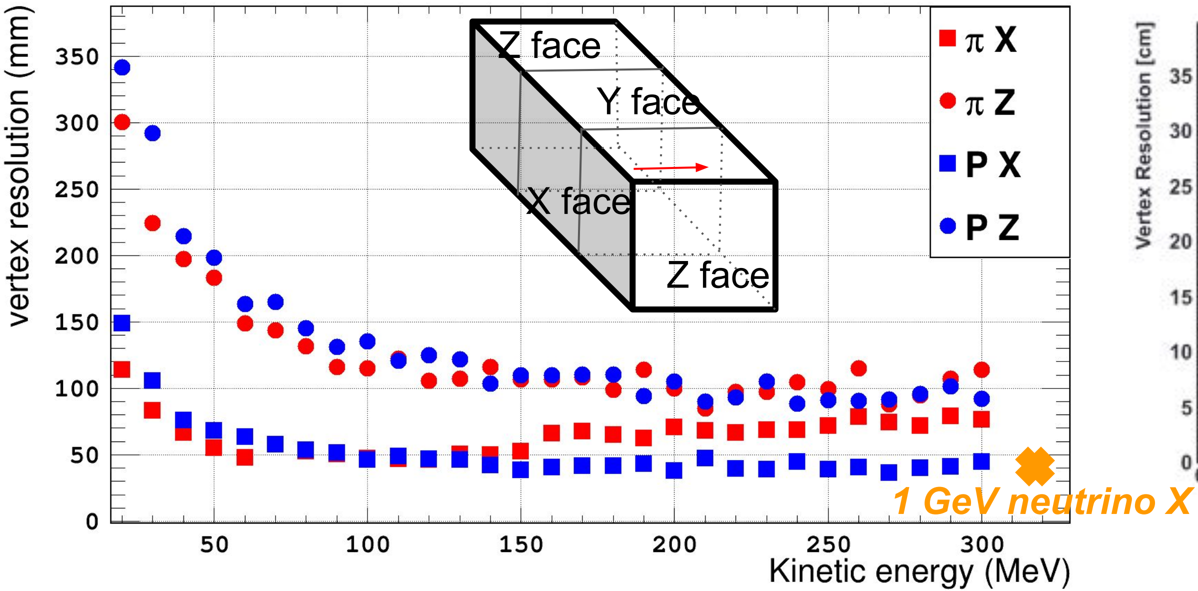


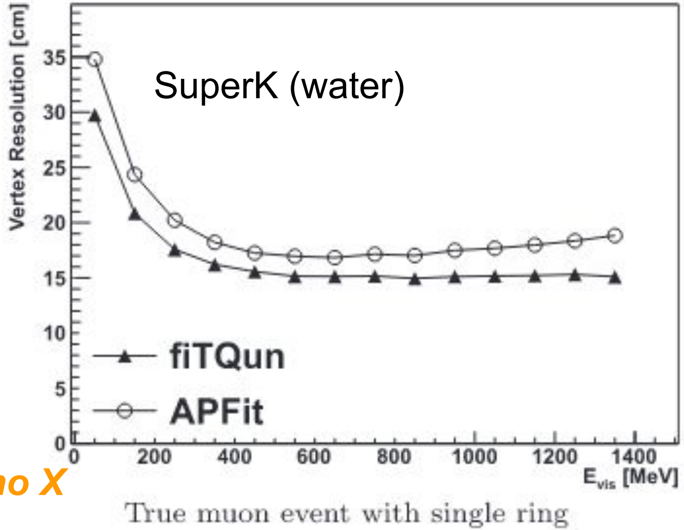
Simulation and reconstruction highlight



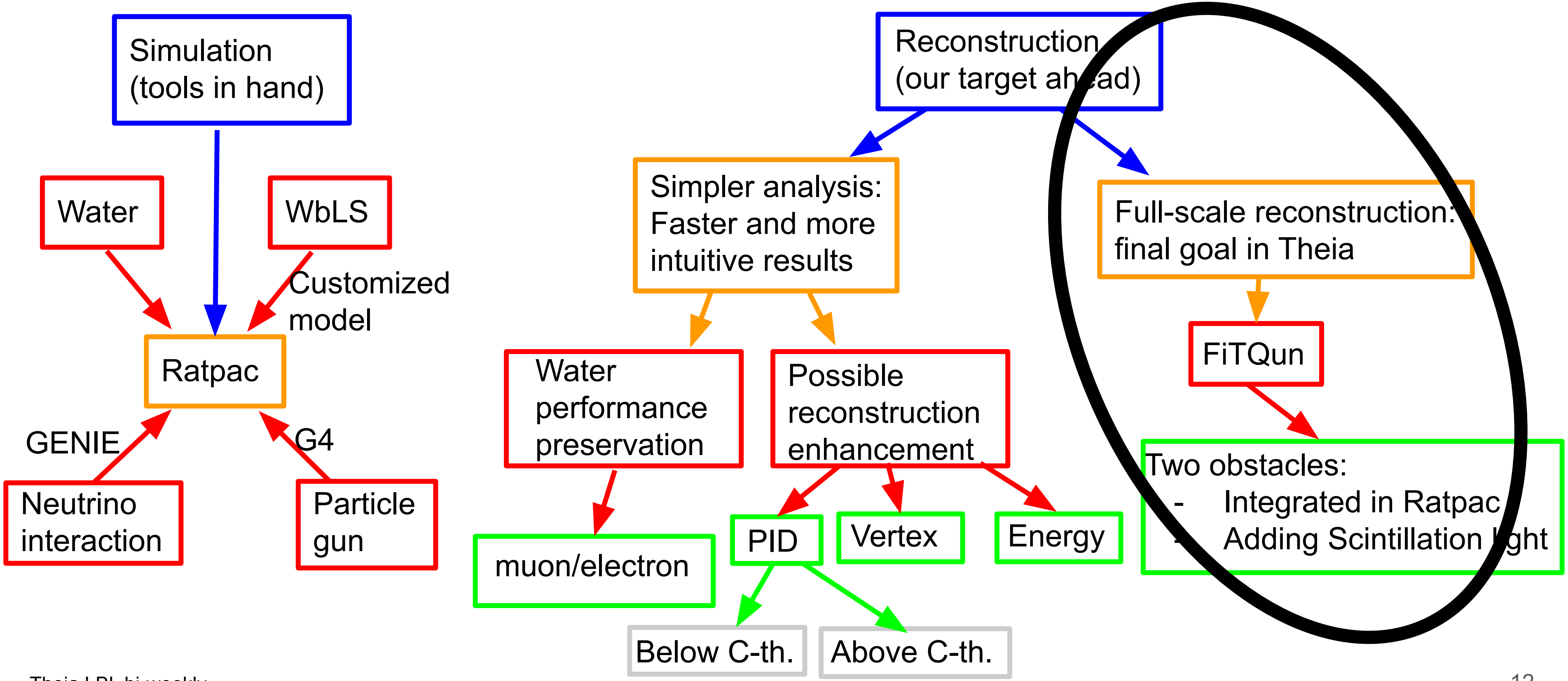
Vertex resolution for 5% WbLS with proton/pion

Use the earliest light on each face to determine the vertex location (true at 0)





Simulation and reconstruction highlight



FiTQun

A full reconstruction providing information of neutrino interaction vertex, number of rings, and momentum and PID of each ring.

For a single ring, there are seven reconstructed quantities: location (3), momentum (1), direction (2), time (1), denoted as **x**.

$$\mathcal{L}(\mathbf{x}) = \prod_{\text{unhit}} (1 - P(i\ \text{hit}; \mathbf{x})) \times \prod_{\text{hit}} P(i\ \text{hit}; \mathbf{x})\ f_q(q_i; \mathbf{x})\ f_t(t_i; \mathbf{x})$$

P is the likelihood the PMT got hit;
q,t are measured charged and time in pmts;
fq is the charge profile;
ft is the time profile;

Four steps

1. Simulate different kinds of events
2. Extract needed information from the simulation
3. Convert to the FiTQun-style input
4. Run FiTQun with test samples

Input for FiTQun

Cherenkov profile

Charge profile

Time profile

Indirect light ratio table

Need a “tuner” to provide all these information. Currently FiTQun is compatible with two softwares:

- SuperK library -> too old, we don’t want to use it.
- WCSim library -> pretty modern, but there is no scintillation light in it.

Need to extract these from Ratpac

Since we are using different material and detector geometry, all these might need to be re-generated, although would be nice to use existing profiles..

Workflow: each step can be called a milestone

Need to extract information from Ratpac -> a big chunk of hack, tested part of them, they seem to work.

Simulate a large amount of events for each profiles.

Expand FiTQun to include the scintillation light

Need a lot of validations: looking at water first.

Summary

Simulation is ready for event reconstruction studies.

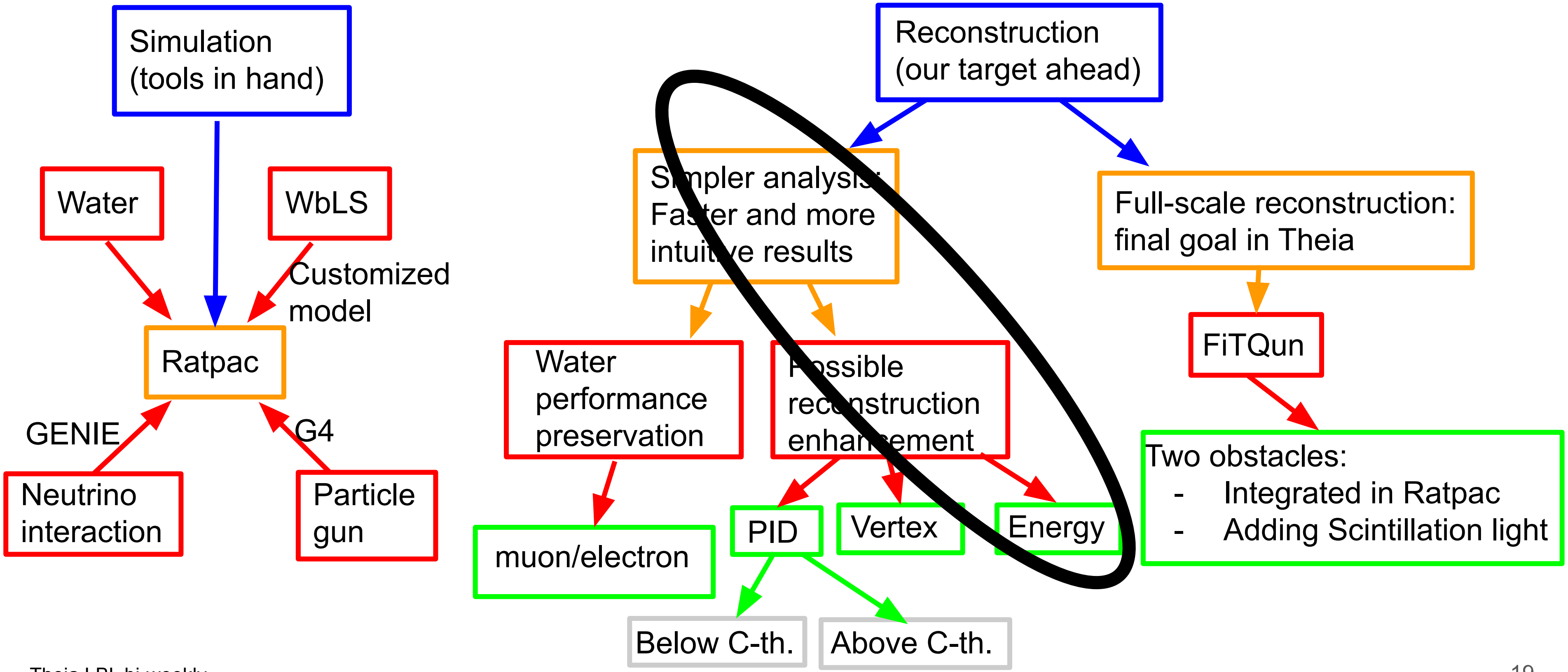
Largely, the there are two streams:

- **Simple physics studies about basic performance: fast but isolated**
- **FiTQun full reconstruction: complete but difficult**

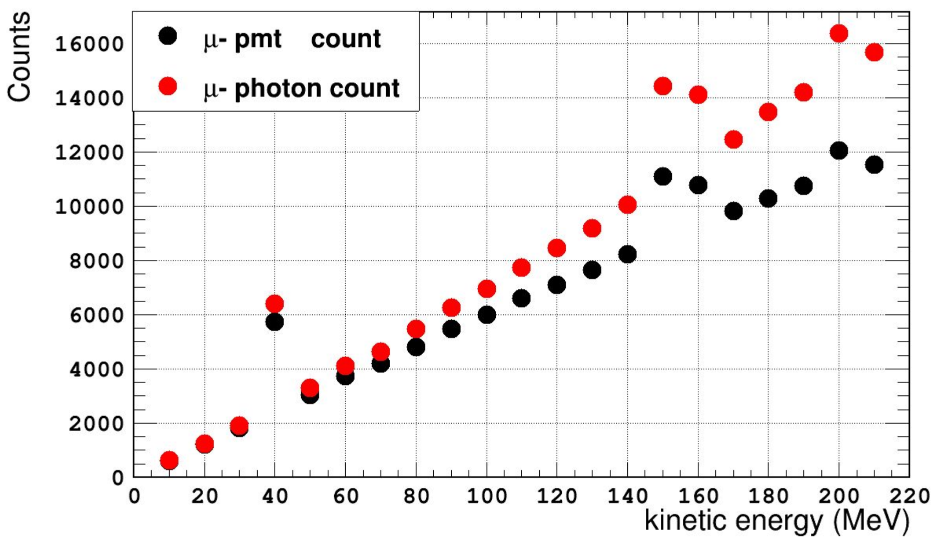
In the future meetings, Gian and I may present some detailed work on some branches.

Backups

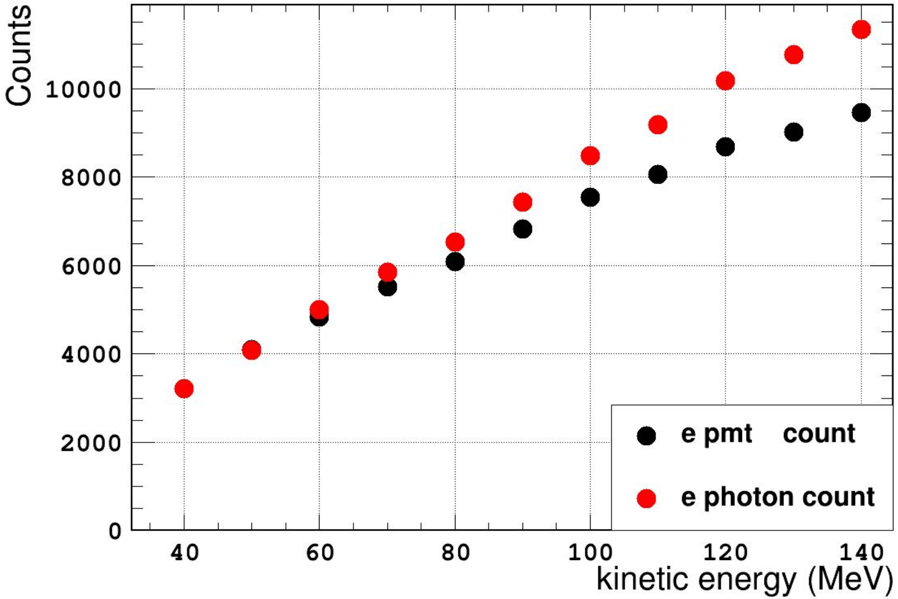
Simulation and reconstruction highlight



Particle gun with muon and electron



5% WbLS



Single event at each KE used, so fluctuation is strong.

Particle gun with Proton/π+

Each charged particle's PE-KE looks linear.
A workflow for CCQE could be:

- C light: muon
- S light: total - muon ->proton KE

CC1π+ with pion above C threshold:

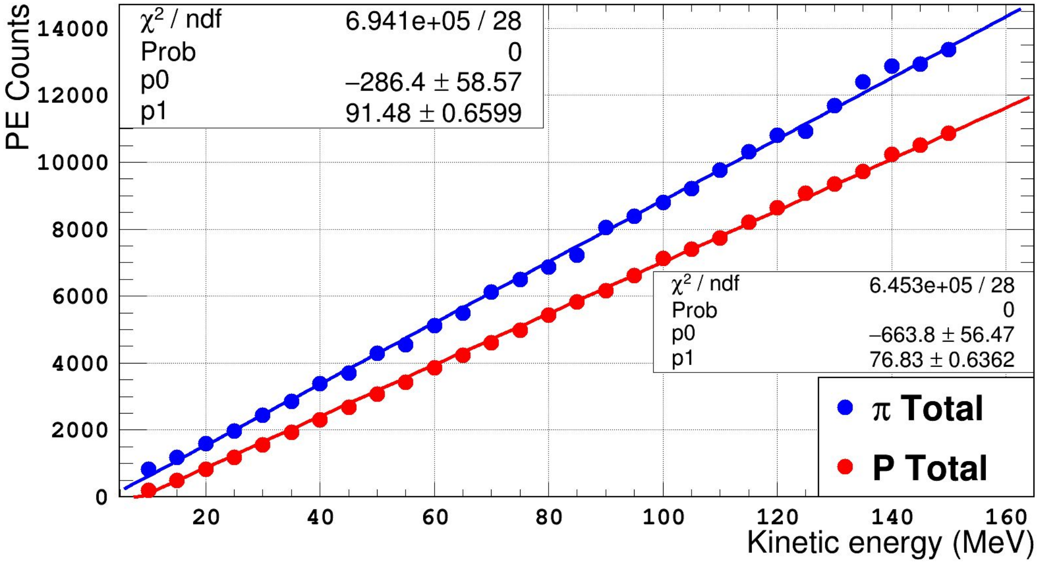
- Similar to QE

CC1π+ with pion below C threshold:

- C light: muon
- S light: total - muon-> sum of light from proton and pion
- Either assume proton/pion have the same PE-KE

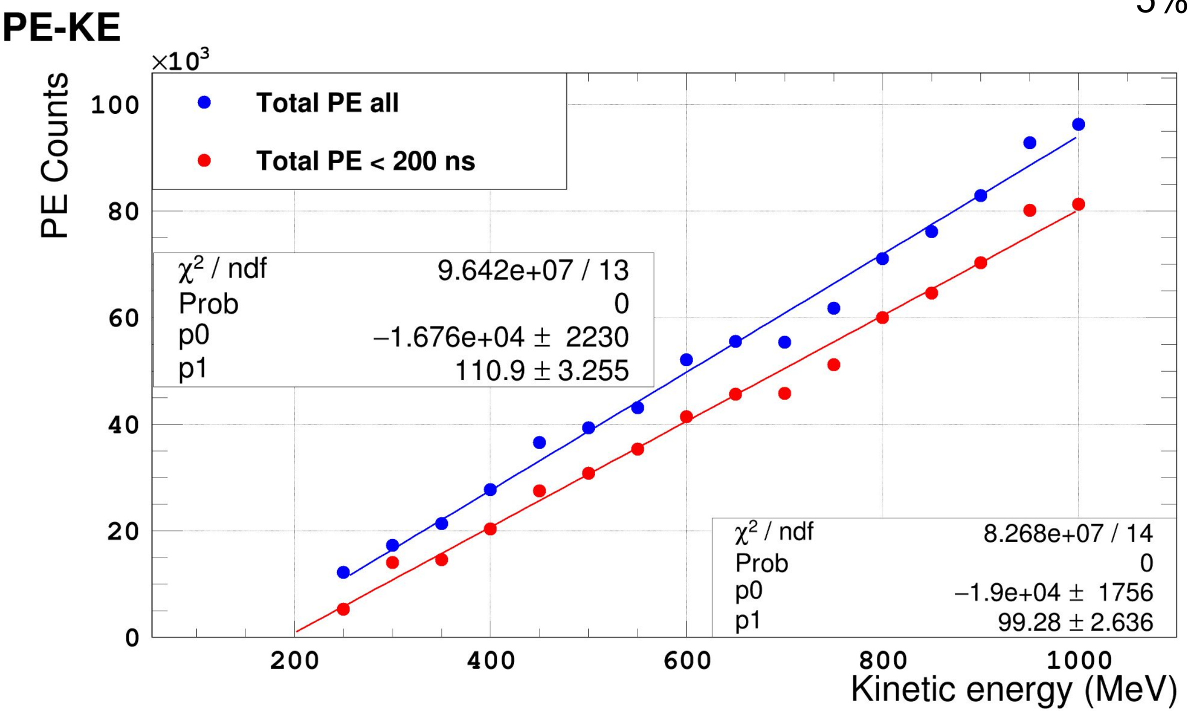
Need PID to identify interaction channel.

5% WbLS



PE-KE for true CC0π

5% WbLS



Parameter	Name in ratdb	Measured (yes/no)	Comment	Reference
Light yield	LIGHT_YIELD	yes		https://doi.org/10.1140/epjc/s10052-020-8418-4
Rayleigh Scattering	RSLENGTH	yes		private communication with BNL
Absorption Length	ABSLENGTH	no	combination of BNL data for LABPPO and Pope+Smith for water	
Refractive index	RINDEX	yes		
Reemission probability	REEMISSION_PROB	no	0.8 for w< 345nm, 0 for w >370	
Scintillation rise time	SCINT_RISE_TIME	yes		
Scintillation time profile for betas	SCINTWAVEFORM	yes		https://doi.org/10.1039/D0MA00055H
Scintillation time profile for alphas	SCINTWAVEFORMalpha	no	used same as SCINTWAVEFORM	
Birk's constant for betas	SCINTMOD	no	SNO+ (measurements for WbLS undergoing)	
Birk's constant for alphas	SCINTMODalpha	no	SNO+ (measurements for WbLS undergoing)	
Birk's constant for neutrons	SCINTMODneutron	no	SNO+ (measurements for WbLS undergoing)	
Scintillation emission spectrum	SCINTILLATION	yes		https://doi.org/10.1039/D0MA00055H
Scintillation emission spectrum for wavelength shifters	SCINTILLATION_WLS	yes	used same as SCINTILLATION, LAB->PPO energy transfer should be non-radiative, so	

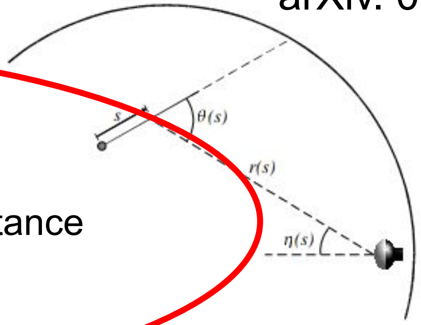
https://docs.google.com/spreadsheets/d/1QqpolQU69itKQxvAd-bvHCZZQVoRMGxC6zsBcNU4Yfo/edit?usp=sharing

$$F(\mathbf{x}) \equiv -\log \mathcal{L}(\mathbf{x}) \equiv F_q(\mathbf{x}) + F_t(\mathbf{x})$$

$$F_q(\mathbf{x}) \equiv -\sum_{\text{unhit}} \log(1 - P(i \text{ hit}; \mu_i)) - \sum_{\text{hit}} \log(P(i \text{ hit}; \mu_i) f_q(q_i; \mu_i))$$

The μ is the predicted mean charge.

arXiv. 0902.2222



Scintillation light

$$\mu_{\text{point,sci}} = \Phi_{\text{sci}}\, \Omega(r)\, T_{\text{sci}}(r)\, \epsilon(\eta)$$

LY　Solid angle　Transmission acceptance

$$\mu_{\text{sci}} = \Phi_{\text{sci}} \int_{-\infty}^{\infty} ds\; \rho_{\text{sci}}(s)\, \Omega(s)\, T_{\text{sci}}(s)\, \epsilon(s)\ .$$

Similarly,

$$\mu_{\text{Ch}} = \Phi_{\text{Ch}} \int_{-\infty}^{\infty} ds \rho_{\text{Ch}}(s)\, \Omega(s)\, T_{\text{Ch}}(s)\, \epsilon(s)\, g(\cos\theta(s); s)$$

Ch. angular profile

Indirect light

Scintillation

$$A_{\rm sci}(R, \cos\Theta) \equiv \frac{d\mu_{\rm sci}^{\rm indirect}}{d\mu_{\rm sci}^{\rm direct}} .$$

$$\mu_{\rm sci} = \Phi_{\rm sci} \int_{-\infty}^{\infty} ds\, \rho_{\rm sci}(s)\, \Omega(s) T_{\rm sci}(s) \epsilon(s) \left[1 + A_{\rm sci}\left(R(s), \cos\Theta(s)\right)\right]$$

Cherenkov

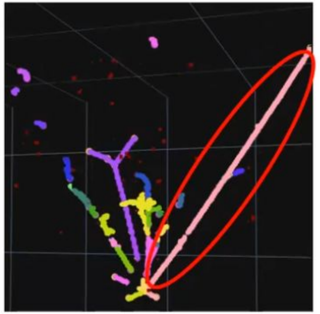
$$A_{\rm Ch}(R, \cos\Theta, \cos\theta, \phi) \equiv \frac{d\mu_{\rm Ch}^{\rm indirect}}{d\mu_{\rm Ch}^{\rm direct,iso}}$$

$$\mu_{\rm Ch}^{\rm indirect} = \Phi_{\rm Ch} \int_{-\infty}^{\infty} ds\, [\rho_{\rm Ch}(s)\, \Omega(s)\, T_{\rm Ch}(s)\, \epsilon(s) \times A_{\rm Ch}\left(R(s), \cos\Theta(s), \cos\theta(s), \phi(s)\right)]$$

Energy reconstruction

How DUNE LAr works

$$E_\nu(\nu_\mu) =$$



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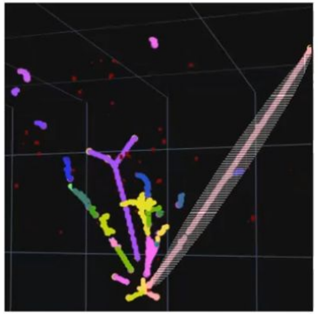
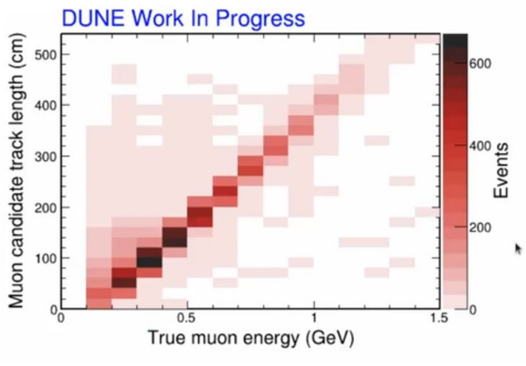
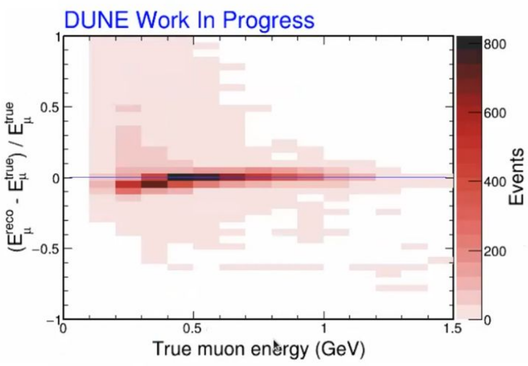
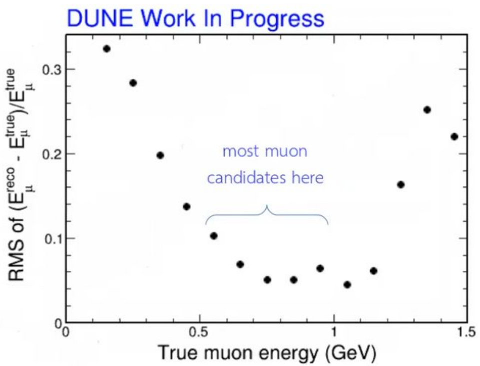


muon energy
(range)

everything else
(calorimetric)

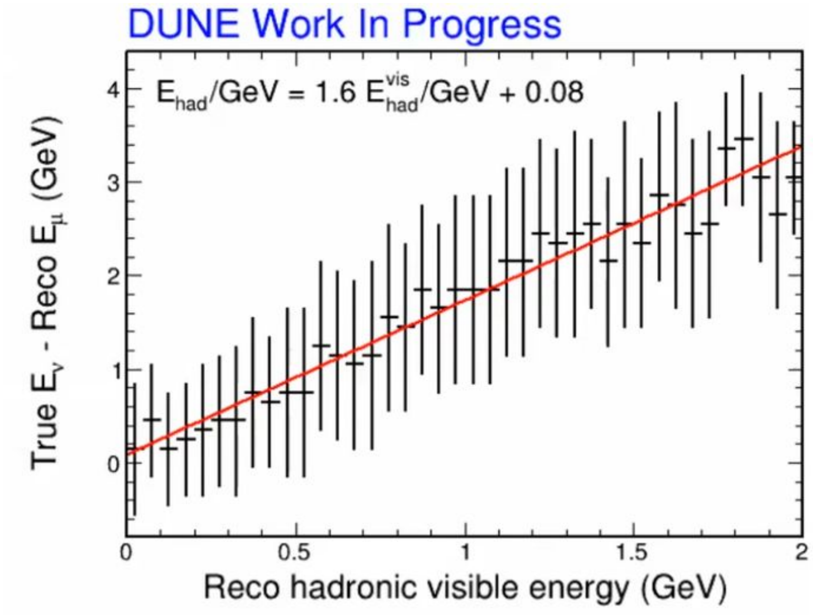


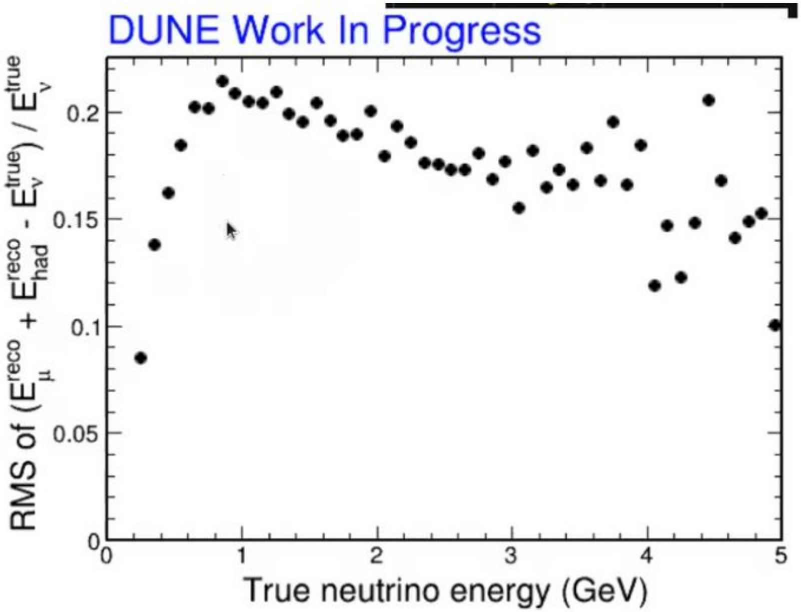




Energy reconstruction

DUNE hadronic energy

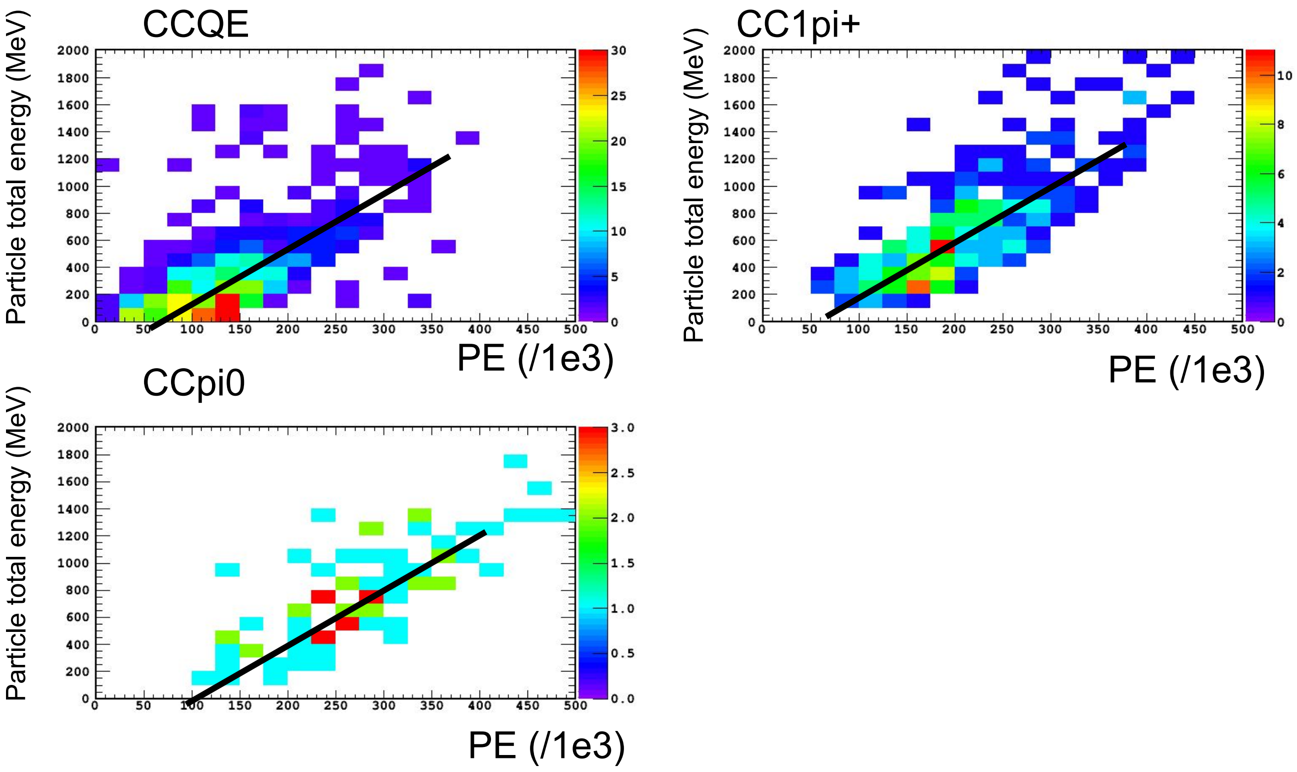




With any michel info. in 5% WbLS

Taking out muon energy and PE.

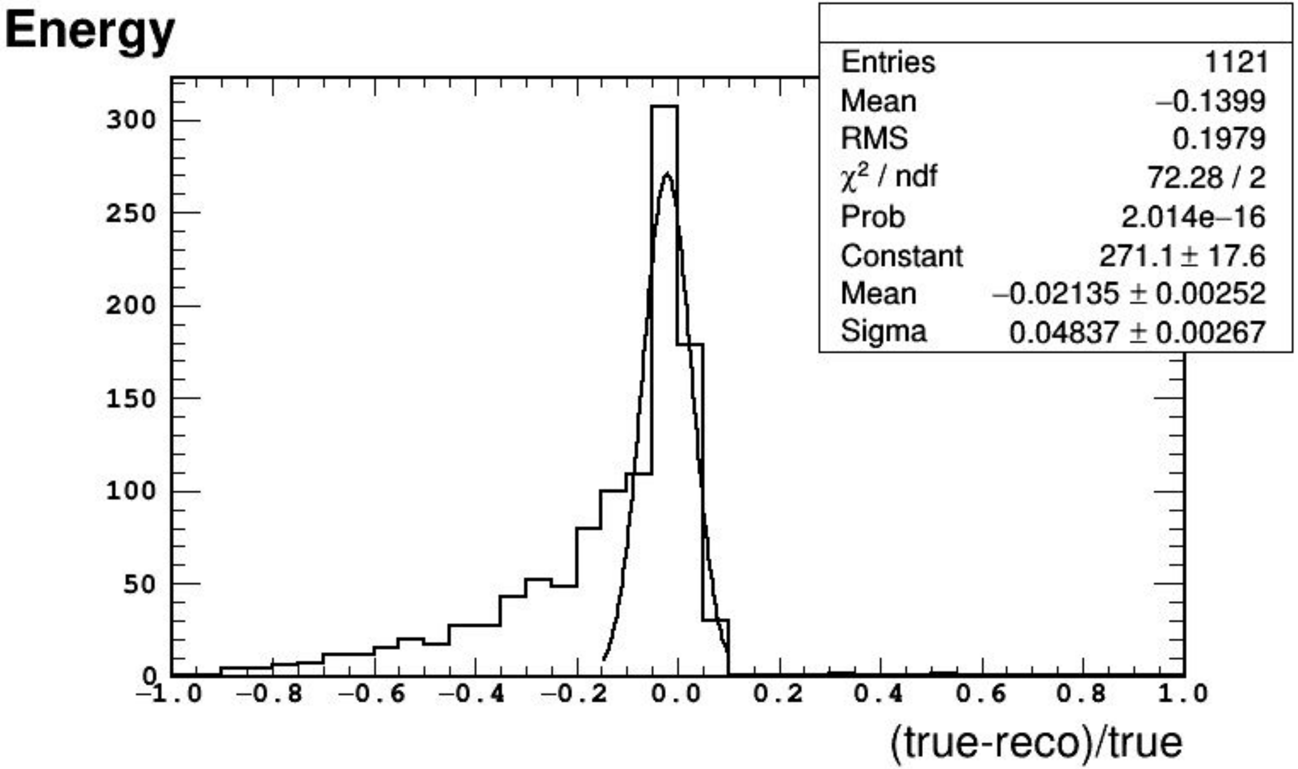
Fit a line and use the linear PE-Energy relation.



Resolution

CCQE + CC1pi+ + CC1pi0 combined

I don’t have any correction like what DUNE does. Will look into that. I expect at least similar resolution.



Two layers of questions

- How can we use the scintillation information?

  -> As soon as we can separate out the Cherenkov light largely, we can use all the remaining light.

- How would the Slow-Scintillator help?

  -> Slow-scintillator may give additional information, but how?

Obviously, show-scintillator can separate out the Cherenkov light better.

What do we do with water? -> T2K

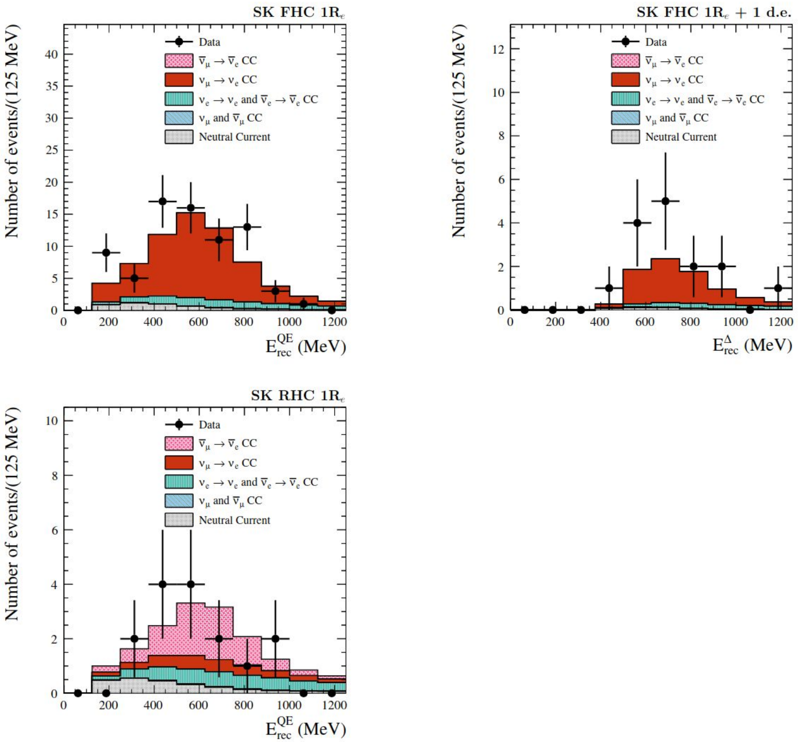
CP: nue appearance

Nu mode

- 1 e-like ring 0 decay
- 1 e-like ring 1 decay

Antinu mode

- 1 e-like ring 0 decay



What do we do with water? -> Theia white paper

CP sensitivity

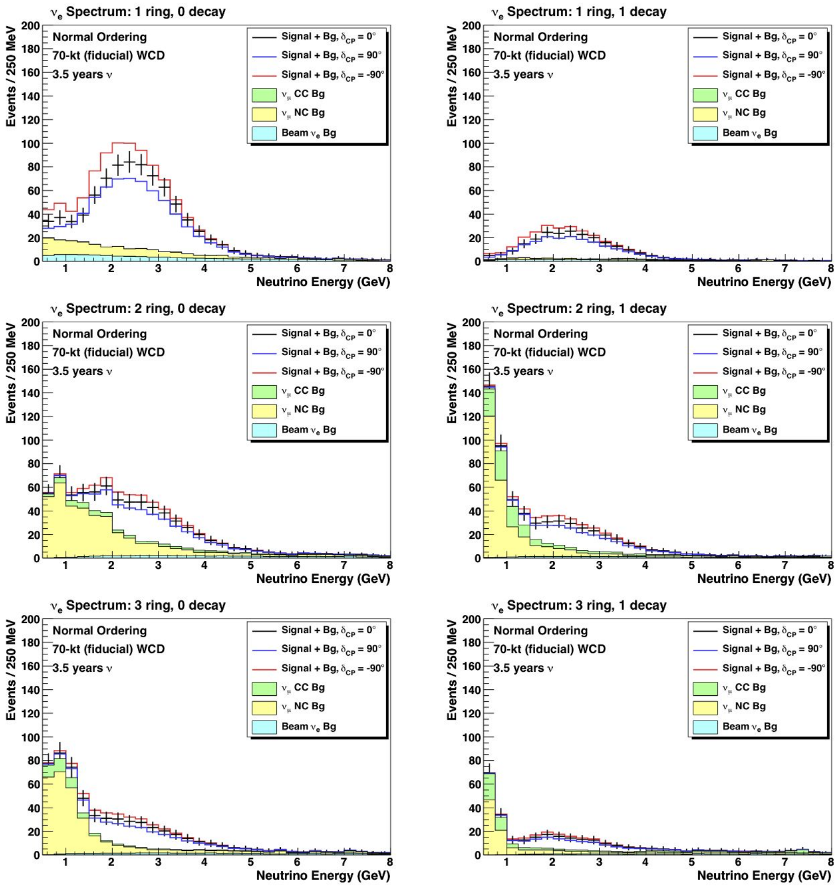
Nu mode:

- 1,2,3 rings with 0,1 decays

Antinu mode:

- 1,2,3 rings with 0 decay

We have information of the primary Cherenkov ring and decay Cherenkov ring.

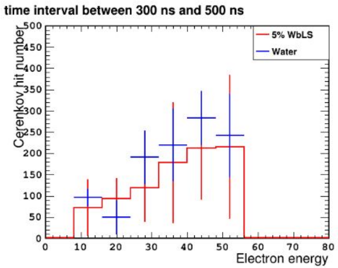


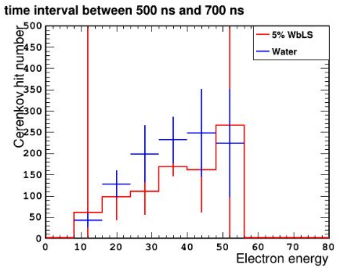
Clarity of the water detector information-> michel ring

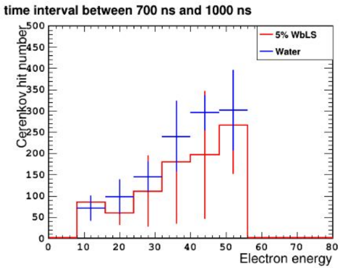
The same trick as the muon ring, 1 GeV neutrino

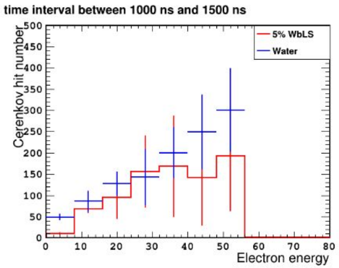
All light in ring - light in an away region with the same solid angle

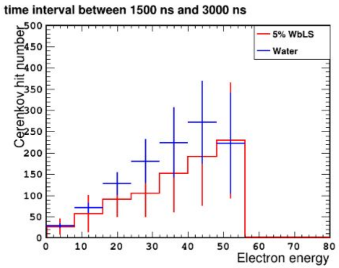
Error bar shows the event-by-event deviation
Note that the neutrino energy spectrum is broad.

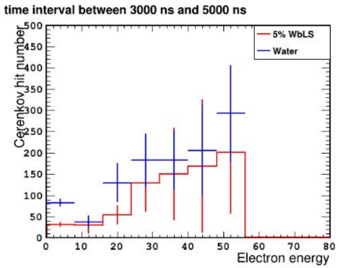








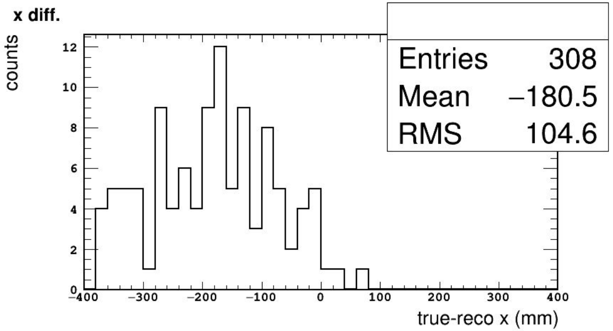


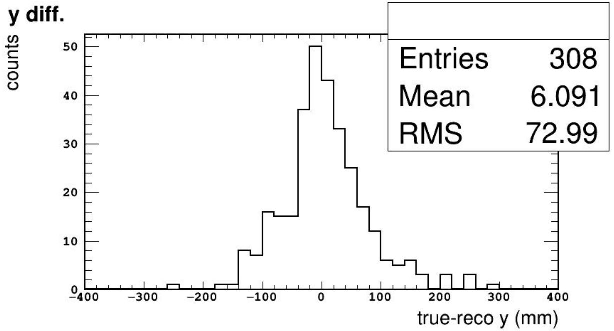


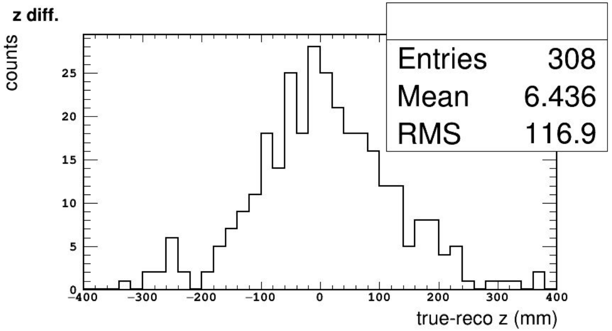
A clear improvement -> vertex resolution

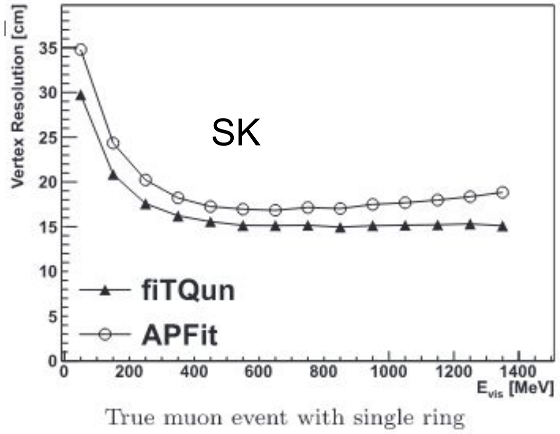
Only for true CC1π+ channel with DUNE flux;

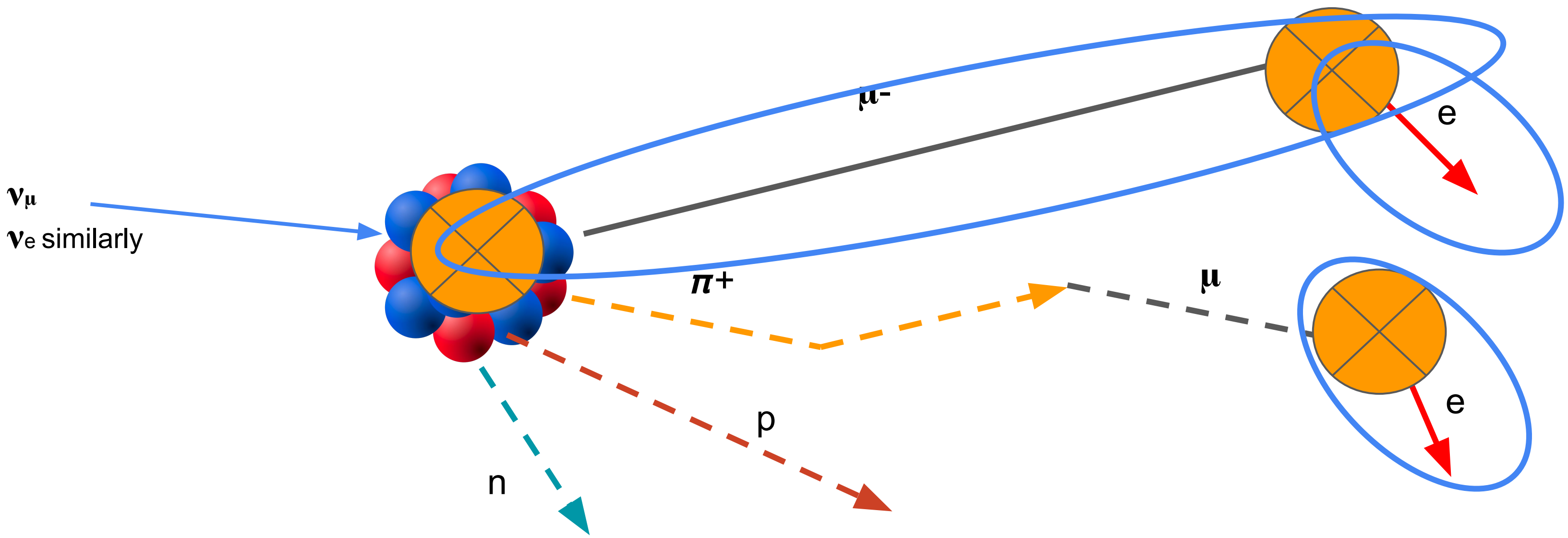
vertex determined by the first hit on each face.







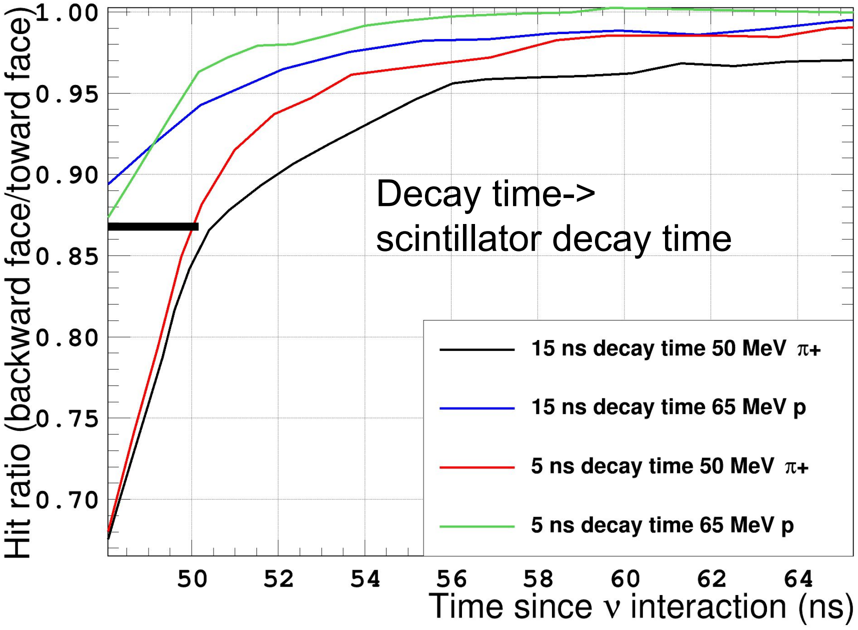




- Without the slow scintillator, we may be able to identify the muon and michels.
- We might aim to improve the reconstruction of the particles below the Cherenkov threshold -> keep in mind the neutrino energy is our final goal.

PID : proton/pi+

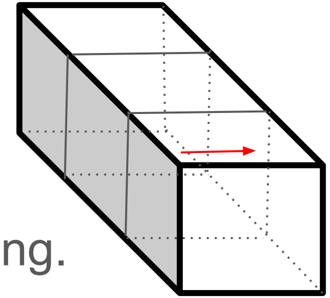
Study the proton/pi+ separation in a more systematic way -> In the Neutrino 2022, we just showed one specific case.



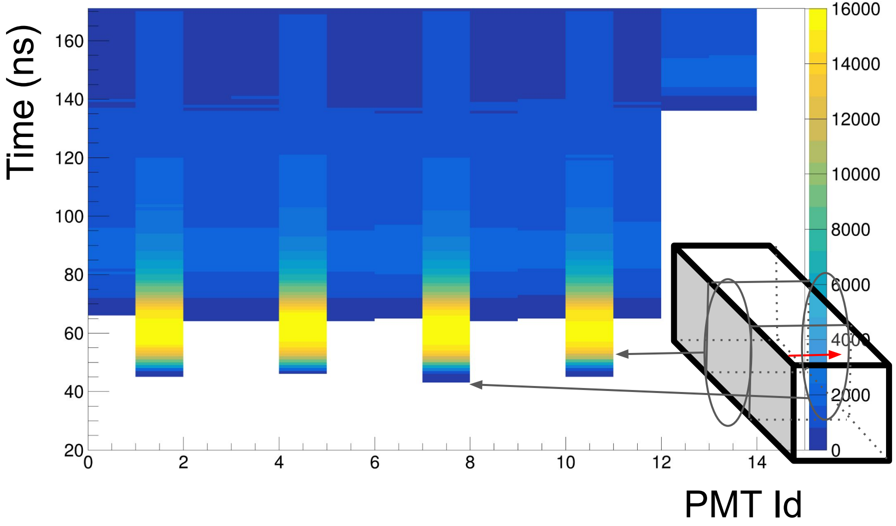
1. Given a decay time, for each proton energy, find the corresponding pi+ energy that produce similar light amount (typically about 20 MeV lower).
2. Set the hit ratio cut at a few time slices.
3. Obtain efficiency and purity for proton with each hit ratio cut for each energy.

Proton/π+ separation

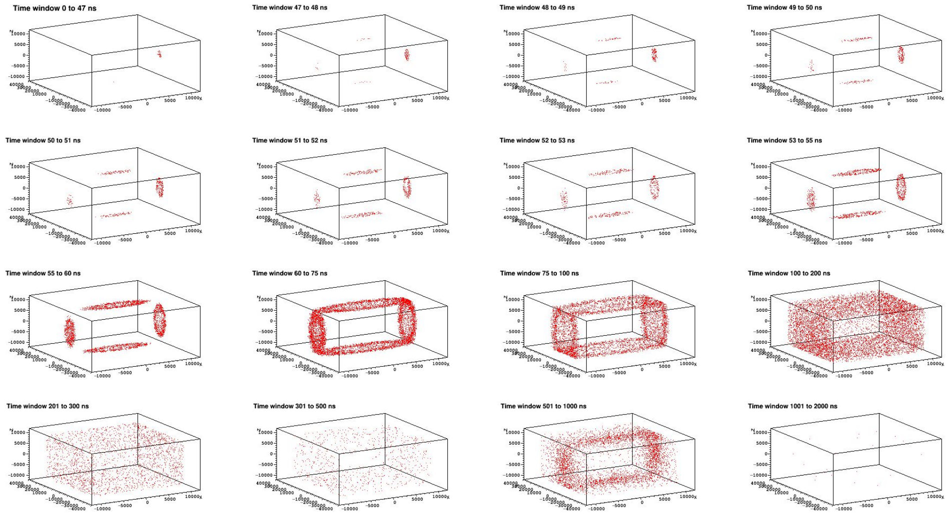
As a start, separate the whole detector to 14 “PMTs”



Hope is to use the scintillation light asymmetry due to particle traveling.

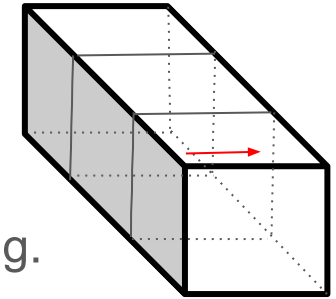


80 MeV π+



Proton/π+ separation

As a start, separate the whole detector to 13 “PMTs”



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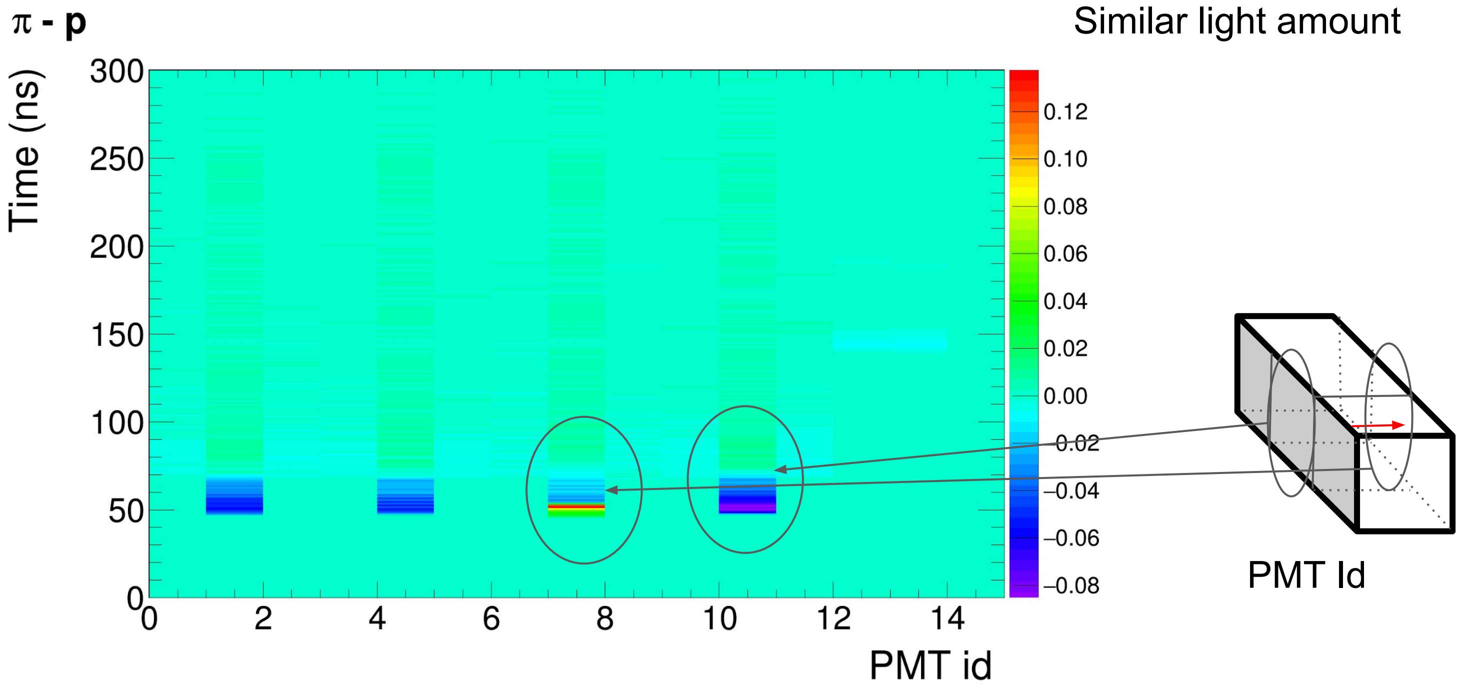
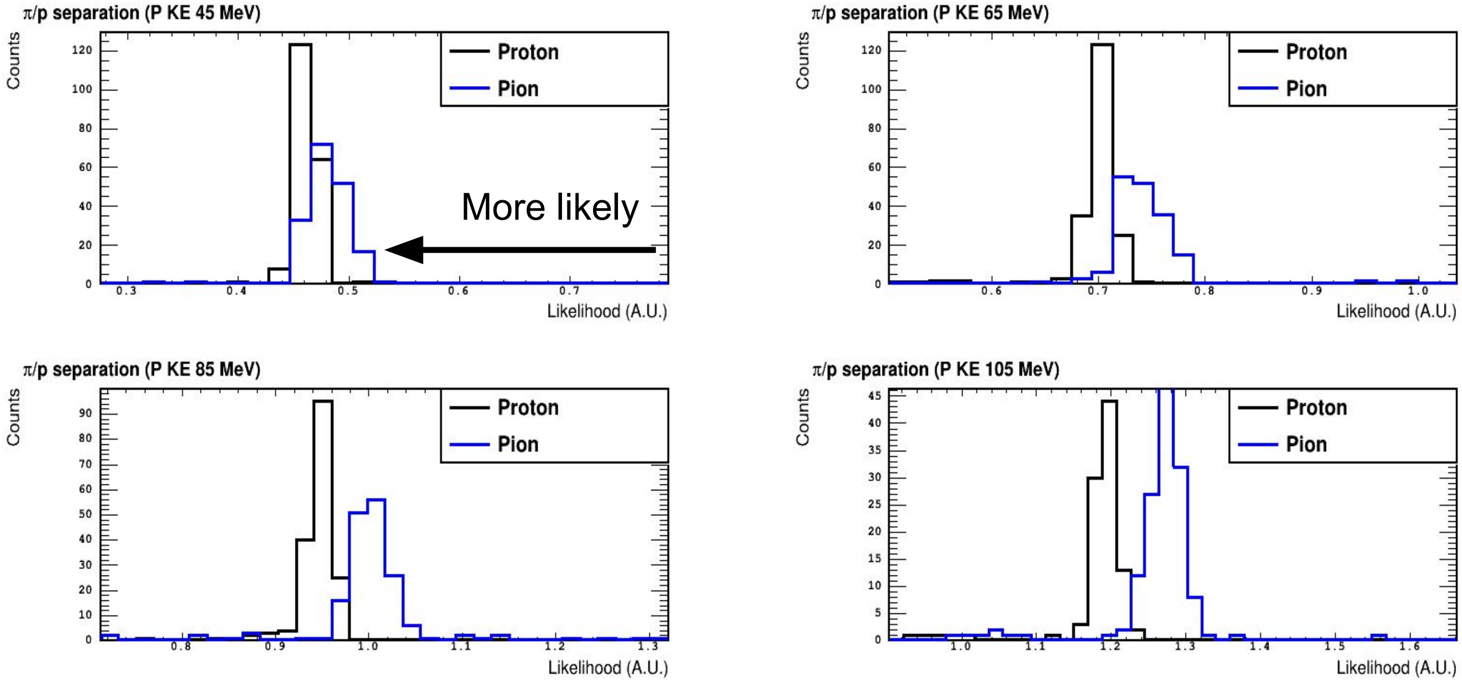


Using the Eos likelihood framework

Taking proton PDFs to fit for proton and pion sample (5 ns decay time).



FiTQun

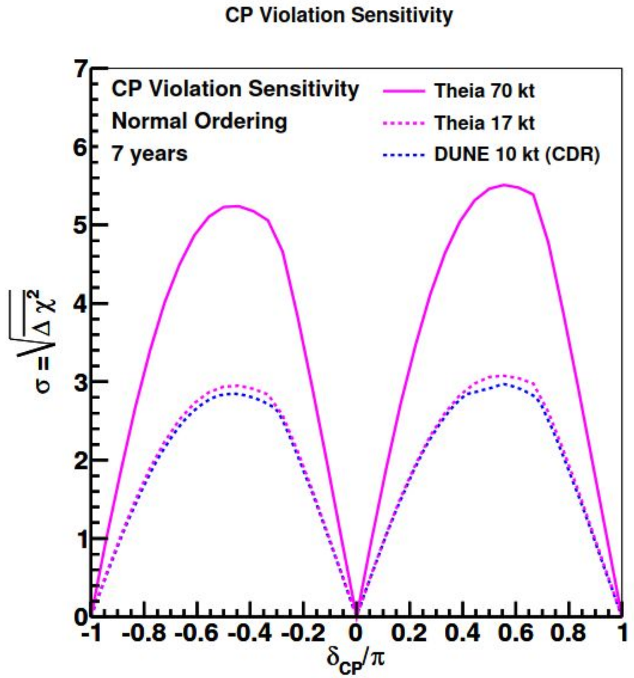
Being used in Super-K, T2K and WCSim

It has also been used in the Theia long-baseline result.

Performance -> Atmospheric Neutrino Oscillation Analysis with Improved Event Reconstruction in Super-Kamiokande IV: arXiv. 1901.03230

Principle -> The extended-track reconstruction for MiniBooNE: arXiv. 0902.2222

Theia white paper



Beyond that

Even with all the input information, previously, although FiTQun contains scintillation light information for each track, it did not really work with the particles below the threshold.

We will have low energy proton, pion etc. -> it needs some effort to look into those events below the Cherenkov threshold in FiTQun. In principle, it should be straightforward.

Geometry

Theia 25 kt letter box inside DUNE cavern: 20 m x 18 m x 69 m

500 MeV muons at the end of the detector