Application of the Topological Track Reconstruction to an idealized water-based liquid scintillator detector

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Universität Hamburg
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Topological Reconstruction
In unsegmented large-volume liquid scintillator detectors

Outline

1. Motivation and goals
2. Simulation
3. Topological Track Reconstruction
4. Directional information
5. Summary and outlook

Motivation: Theia and ANNIE

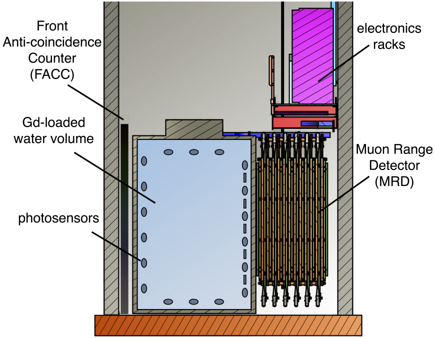
ANNIE

- **A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment currently running at Fermilab
- Cylindrical water-Cherenkov detector (Gd loaded)
- One of the first experiments using **L**arge **A**rea **P**icosecond **P**hoto**D**etectors (LAPPDs)
- Main goal: Measurement of neutron multiplicity; integration and testing of LAPPDs in experiment
- Upgrade to **w**ater-**b**ased **L**iquid **S**cintillator (wbLS)

Theia

- Proposed 50 kt wbLS detector equipped with 100,000 photosensors (PMTs and LAPPDs)
- Main goals: Long-baseline neutrino physics like CP-violation, mass hierarchy; neutrinoless double beta decay

⇒ See E. Drakopoulou et al. "ANNIE Phase I: Neutron Background Measurements" arXiv:1903.11879



⇒ See M. Askins et al. "Theia: An advanced optical neutrino detector" arXiv:1911.03501

Motivation

wbLS

- Mixture of scintillator and water
- Desirable ratio of Cherenkov to scintillation light

Cherenkov light

- Directional and prompt emission
- Direction reconstruction and particle identification

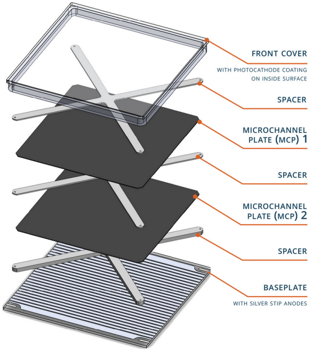
Scintillation light

- Isotropic and emission following exponential decay
- Energy reconstruction and shower identification

$\Rightarrow$ **Study the potential of this (new) technologies in a small detector as test bed.**

LAPPDs

- Sensitive area: $20\,\mathrm{cm} \cdot 20\,\mathrm{cm}$
- Spatial resolution: $\sim 1\,\mathrm{mm}$
- Time resolution: $\sim 0.1\,\mathrm{ns}$



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Goals and mile stones

1. Simulate muon tracks in water and in water-based liquid scintillator in idealized detector.
2. Reconstruct tracks with the **T**opological **T**rack **R**econstruction (TTR) for both cases.
3. Extract directional information of Cherenkov light.
4. Separate Cherenkov and scintillation light and use their advantages.
5. Use the separation for particle identification, shower identification, ring counting.

Simulation: Goal and introduction

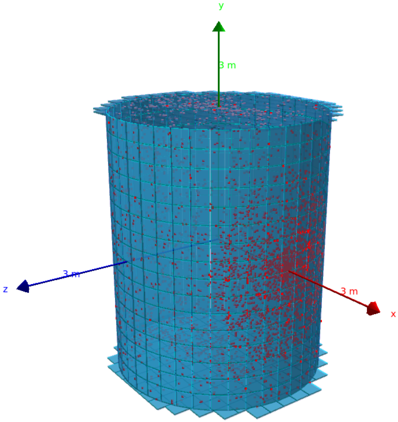
Goal 1: Simulation for muon tracks with adjustable fluid with output usable for the TTR
Goal 2: Simulation for creating **L**ook **U**p-**T**ables (LUTs) needed for the TTR for time reduction

- Geant4 simulation of a small detector (Radius: $\sim 1.5\,\mathrm{m}$, Height: $\sim 3.8\,\mathrm{m}$)

=> comparable to ANNIE

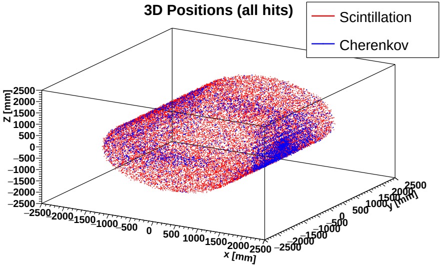
=> little scattering and attenuation

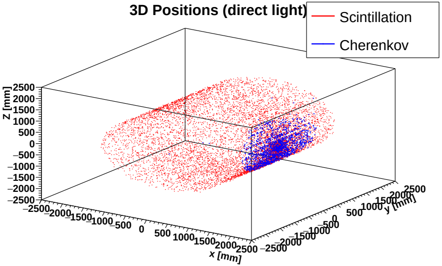
- Detector completely covered with LAPPDs
- LAPPD model taken from ANNIE simulation with minor adjustments
- Tables for wbLS taken from Theia simulation
- Example event: $500\,\mathrm{MeV}$ muon in x direction in water starting at $(0, 0, 0)$.

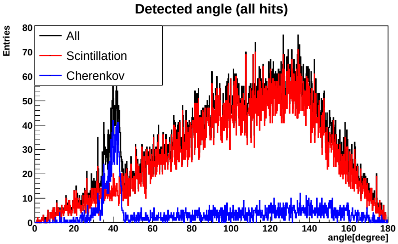


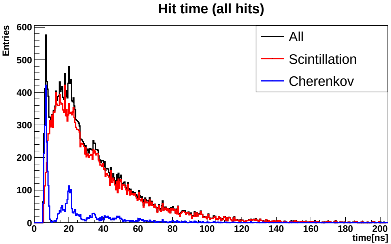
Simulation: Examples

$500\,\mathrm{MeV}$ muon at $(0, 0, 0)$ in x direction in wbLS; ~ 4000 Cherenkov, ~ 27600 scintillation photons

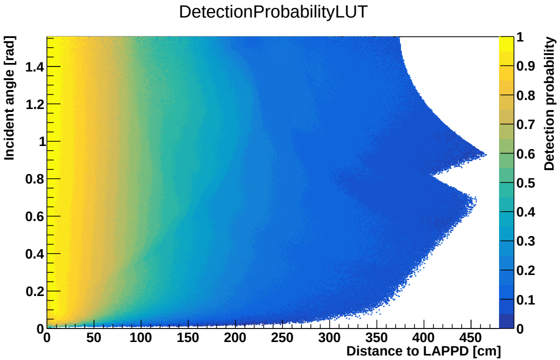


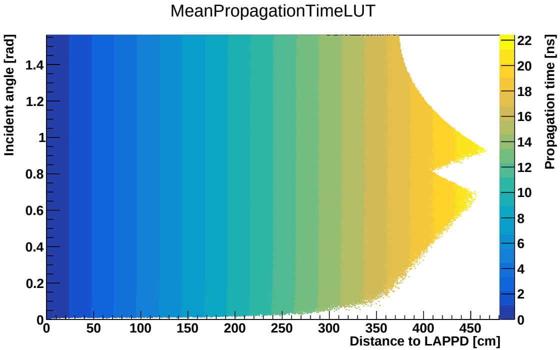






Simulated LUTs and simulation status



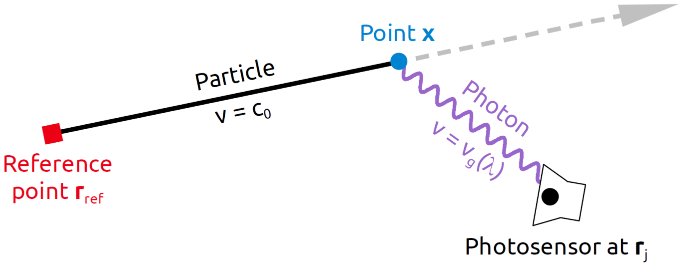


Status 1: Simulating muons (and other particles) work well in water and in wbLS.
Status 2: Simulating the LUTs for Cherenkov light in water works, but adjustments and implementation is needed to simulate LUTs for Cherenkov and Scintillation light in wbLS.
$\Rightarrow$ Expected to finish work at the LUTs this week.

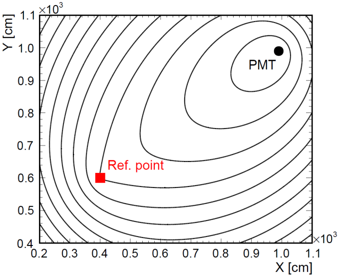
General concept of the Topological Track Reconstruction (TTR)

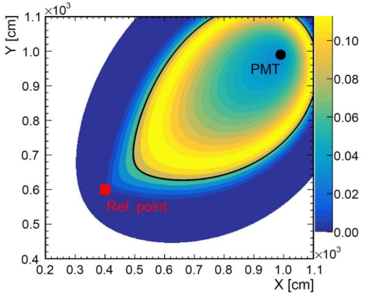
- Known reference point in time t_{ref} and space $\mathbf{r}_{\mathrm{ref}}$
- Assume straight particle path with velocity c_0.
- Calculate possible locations $\mathbf{x}$ of the particle at time $t(\mathbf{x})$.
- Developed by our group in Hamburg. See: Björn Wonsak et al. "Topological track reconstruction in unsegmented, large-volume liquid scintillator detectors" (arXiv:1803.08802)

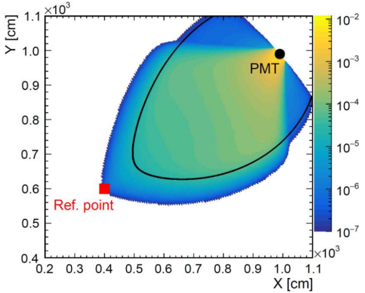
$$t(\mathbf{x}) = t_{\mathrm{ref}} \pm \underbrace{\frac{|\mathbf{x} - \mathbf{r}_{\mathrm{ref}}|}{c_0}}_{\text{particle}} + \underbrace{\frac{|\mathbf{r}_j - \mathbf{x}|}{v_g(\epsilon)}}_{\text{photon}}$$



Probability density functions

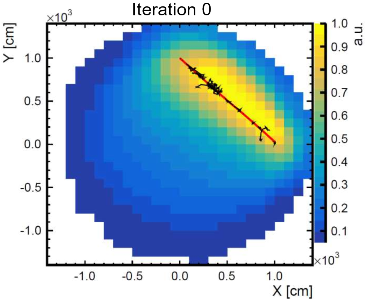


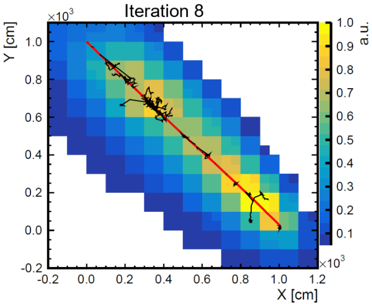




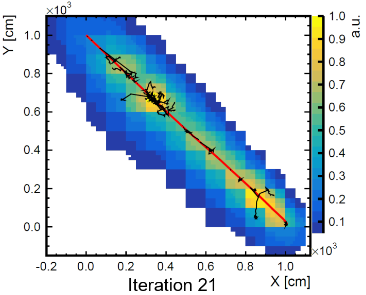
- Develop **p**robability **d**ensity **f**unctions (**p.d.f.**s) when taking more effects into account.
  1. Isochrones come from the inversion of $t(x)$.
  2. Time uncertainty of scintillation light and response of photosensor
  3. Detection and propagation effects like angular acceptance and attenuation

Reconstruction method



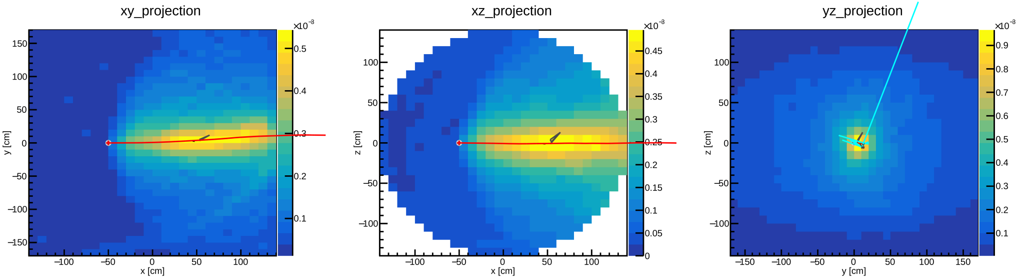


- Create a p.d.f. for every hit and each PMT.
- Superimpose the p.d.f.s for every bin in volume.
- Gain probability mask showing most-likely origin of light.
- Treat prior iteration as truth; cut cells.
- Reconstruct again based on the previous iteration.
- Refine binning for more detailed result.



TTR: Goal and status I

Goal 1: Reconstruct pure Cherenkov events.



Status 1: Reconstruction of several Cherenkov events with decent results.
Goal 2: Reconstruct wbLS events having two reconstructions and outputs, one for Cherenkov and one for scintillation light.
Status 2: TTR is adjusted to produce two outputs, but needs new LUTs and normalisation work.
$\Rightarrow$ Normalisation is next task after producing the LUTs

TTR: Goal and status II

Goal 3: Separate light with algorithms or let the reconstruction do the job.

Algorithm approach

- Use parameters like hit time and angle to develop sorting algorithm.
- Can be based on raw event information and/or on previous iteration of TTR.
- Give every hit a weight and use this in the corresponding reconstruction.

TTR approach

- Scintillation hit in Cherenkov reconstruction would contribute with low probability and vice versa.
- Compare reconstruction results and contribution of hits for separation between iterations.

Status 3: First very simple test with light separation via algorithm was done.
$\Rightarrow$ Testing of algorithm vs. TTR needs to be done via light type flags of simulation.
Goal 4: Use the separation for advanced applications like particle identification.
Status 4: Advanced applications are not started.

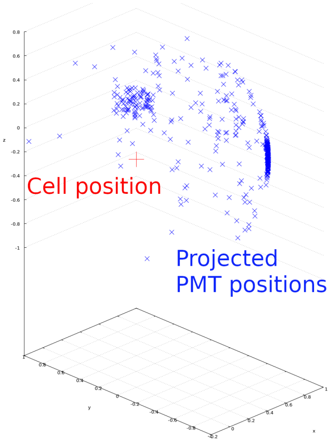
Directional information

Goal

- Use the working principle of the TTR to gain directional information
- Find for every cell in volume direction vectors for secondary/shower identification
- Direction vectors might be usable for Cherenkov light identification

Method

- Project all contributing PMTs to cell on unit sphere.
- Two Methods: Circular Hough transform and directional sum

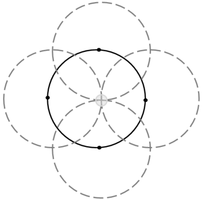


Directional Sum

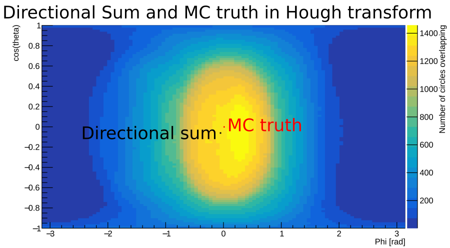
- Add up the unit vectors of contributing PMTs.
- Gives two information:
  - Direction of the directional sum
  - Length of the directional sum
- Both information can be useful.

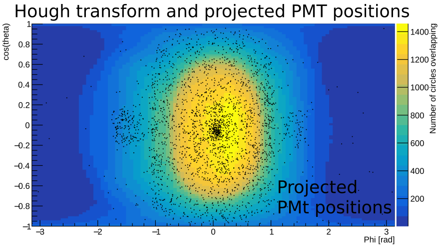
Hough transform

- Project unit sphere on angle plane.
- Draw circle around PMT position with radius corresponding to Cherenkov angle.
- Full circles useful for leaving tracks

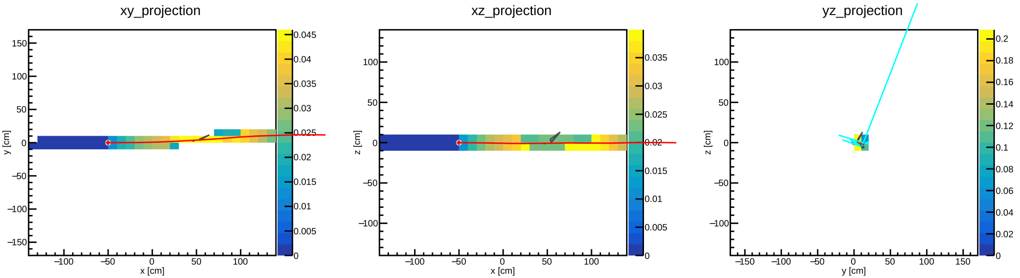


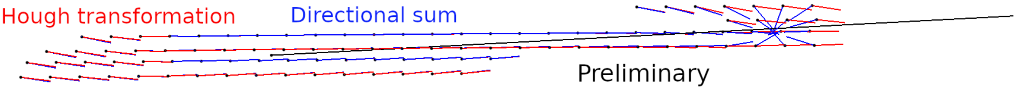
[https://www.mathworks.com]





Preliminary results



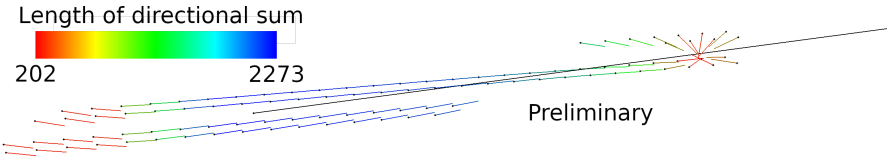


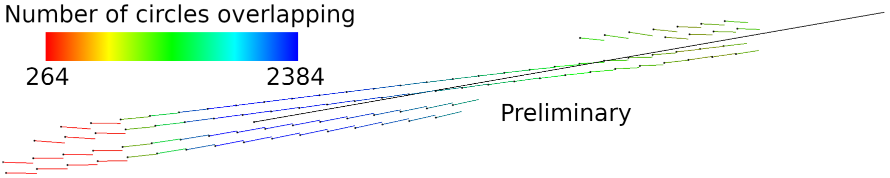
- First information along the track with both methods
- Agreement with the event
- Directional sum needs improvement for end of track.

Preliminary results II and status

- Not only direction, also "quality" of directional sum and Hough transform useful
- Parameters: Length of directional sum and number of circles overlapping for Hough transform
- Indicate amount of Cherenkov light

=> Useful for wbLS application





Status: Directional information can be found and look promising. Needs testing and validation.

Summary

Simulation

- Simulating tracks in water and in wbLS
- Simulating LUTs in water

TTR

- Track Reconstruction works in water.
- Implementation to have two reconstructions in one is done.

Directional information

- The reconstruction can calculate for each cell directional information.
- Hough transform and directional sum are implemented and give first results.

Outlook

Simulation

- LUTs creation for wbLS
- In the future: Simulating of different wbLS mixtures

TTR

- Normalisation for both Reconstruction outputs
- Implementation of light separation and testing
- Particle identification etc. afterwards

Directional information

- Testing and validation of the methods, especially in wbLS

Thank you for your attention.