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

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Bundesministerium für Bildung und Forschung

Topological Reconstruction
In unsegmented large-volume liquid scintillator detectors

Outline

Motivation: Introduction

Motivation for this work

- Idealised detector ⇒ full potential of new and advanced techniques:
  Large Area Picosecond Photodetectors (LAPPDs) and Water-based liquid scintillator (WbLS)
- Reconstructions and light separation algorithms for this detector
  ⇒ experience and results for future experiments like Theia
- Theia: Planned long-baseline beam neutrino experiment with a broad physics program
- Aiming to use WbLS as well as LAPPDs and PMTs

For Theia see also: M. Askins et al. "Theia: An advanced optical neutrino detector" (arXiv:1911.03501)

Motivation: Water-based liquid scintillator

Cherenkov light

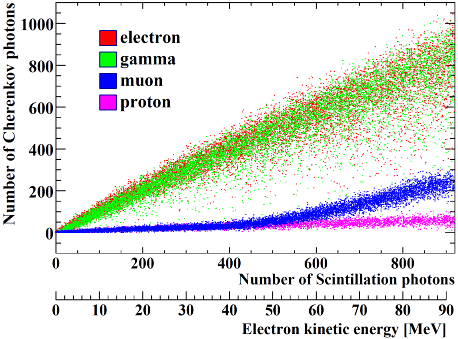
- Prompt and directional emission
- Directional information with ring location and shape
- Particle identification via ring structure

Scintillation light

- Delayed and isotropic emission
- Low threshold and good energy reconstruction
- Shower reconstruction

WbLS

- Separation of light types gives access to all advantages.
- Further particle identification with the ratio of Cherenkov to scintillation light



[arXiv:1607.01671]

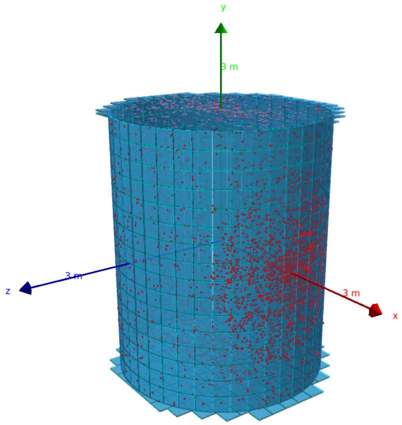
Simulation: Introduction

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

=> comparable to ANNIE

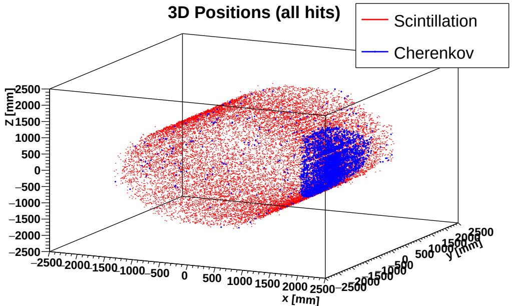
=> little scattering and attenuation for optical photons

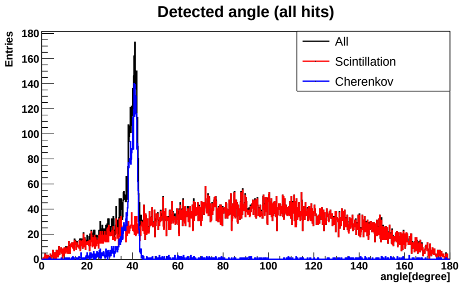
- Detector completely covered with LAPPDs
- Volume is filled with water or WbLS.
- LAPPD model taken from ANNIE simulation with minor adjustments
- Optical properties of WbLS taken from the Theia simulation
- Example event: $500\,\mathrm{MeV}$ muon in x direction in water starting at detector center.

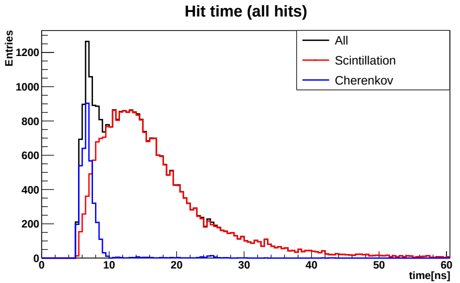


Simulation: WbLS examples plots

- 500 MeV muon in x direction starting at detector center
- Resulting in ∼ 3900 Cherenkov and ∼ 28,000 scintillation hits.
- Little scattering due to small detector (∼ 6 % of hits are scattered or reflected.)
- Cherenkov disk due to exiting muon



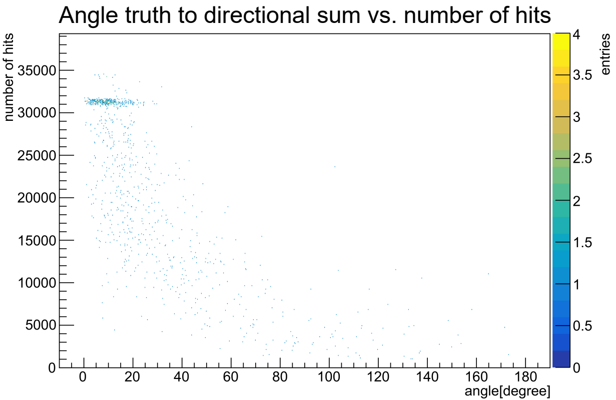




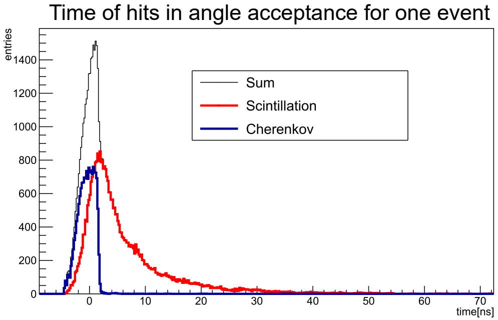
Light Separation: Concept

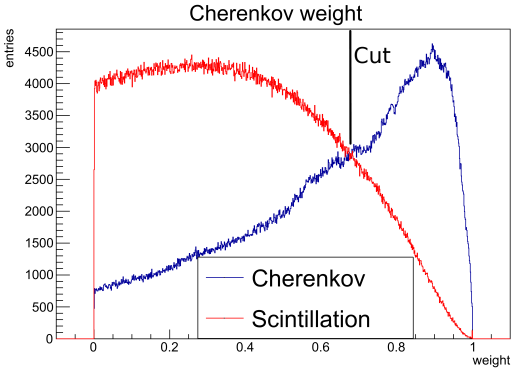
Method for separating Cherenkov and scintillation light

1. Cut hits later than 100 ns.
2. Smear vertex with an accuracy possible for vertex reconstructions: 20 cm and 1 ns
3. Reconstruct particle direction via directional sum.
4. Use direction for Cherenkov angle acceptance in samples on the track.
5. Calculate expected time and compare with hit time.
6. Weight hits according to the timing spectrum.



Light Separation: First result





- 12.9 % of all hits are Cherenkov hits.
- 71 % of remaining hits with a cut at 0.66 are Cherenkov.

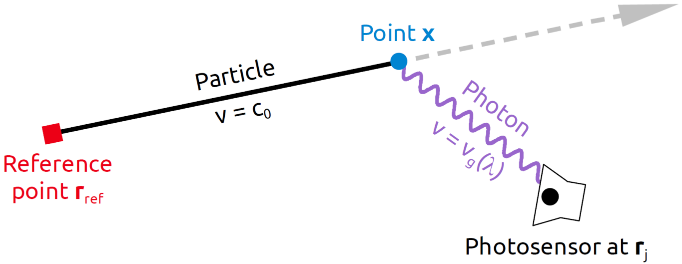
=> 58 % Improvement

- 33.5 % of all Cherenkov, 2 % of all scintillation photons remain.
- Room for improvement in angle acceptance, sampling of particle track and weighting function.

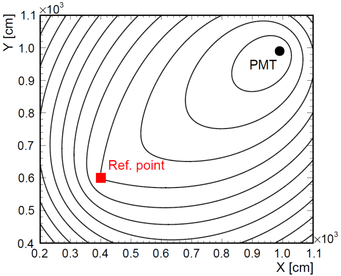
General concept of the Topological Track Reconstruction (TTR)

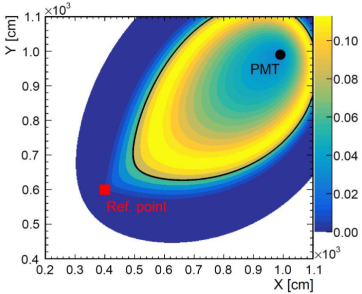
- Known reference point in time t_{ref} and space $\mathbf{r}_{\mathrm{ref}}$
- Assume straight particle path with velocity c_0.
- Calculate possible locations $\mathbf{x}$ of the particle at time $t(\mathbf{x})$.
- Developed by our group in Hamburg. See: Björn Wonsak et al. “Topological track reconstruction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

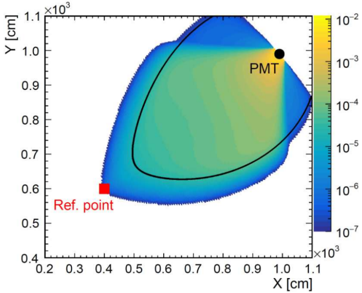
$$t(\mathbf{x}) = t_{\mathrm{ref}} \pm \underbrace{\frac{|\mathbf{x} - \mathbf{r}_{\mathrm{ref}}|}{c_0}}_{\text{particle}} + \underbrace{\frac{|\mathbf{r}_j - \mathbf{x}|}{v_g(\epsilon)}}_{\text{photon}}$$



Probability density functions

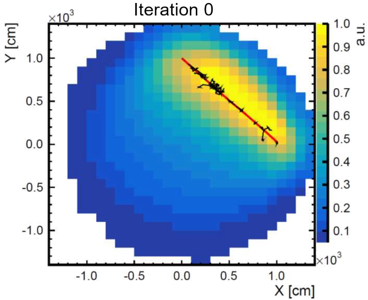


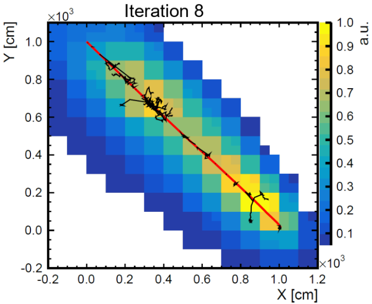


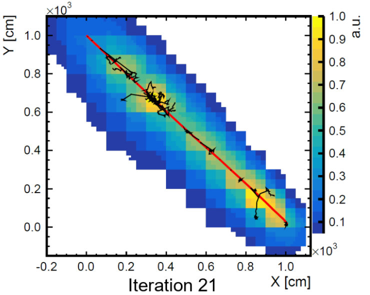


- Develop **p**robability **d**ensity **f**unctions (**p.d.f.**s) when taking more effects into account.
  1. Isochrones come from the inversion of $t(x)$.
  2. Time uncertainty of scintillation light and response of photosensor
  3. Detection and propagation effects like angular acceptance and attenuation

Reconstruction method



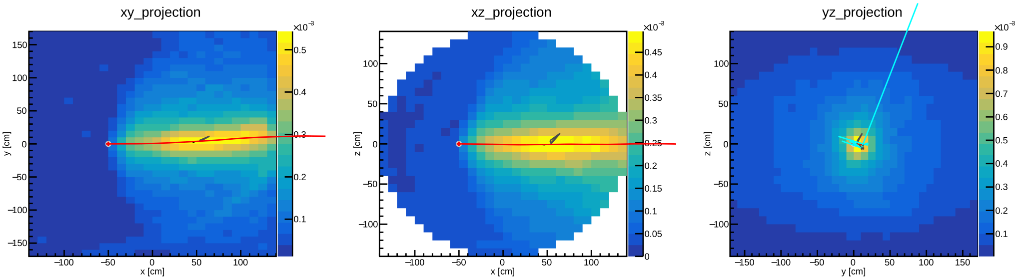




- Create a p.d.f. for every hit and each PMT.
- Superimpose the p.d.f.s for every bin in volume.
- Gain probability mask showing most-likely origin of light.
- Treat prior iteration as truth; cut cells.
- Reconstruct again based on the previous iteration.
- Refine binning for more detailed result.

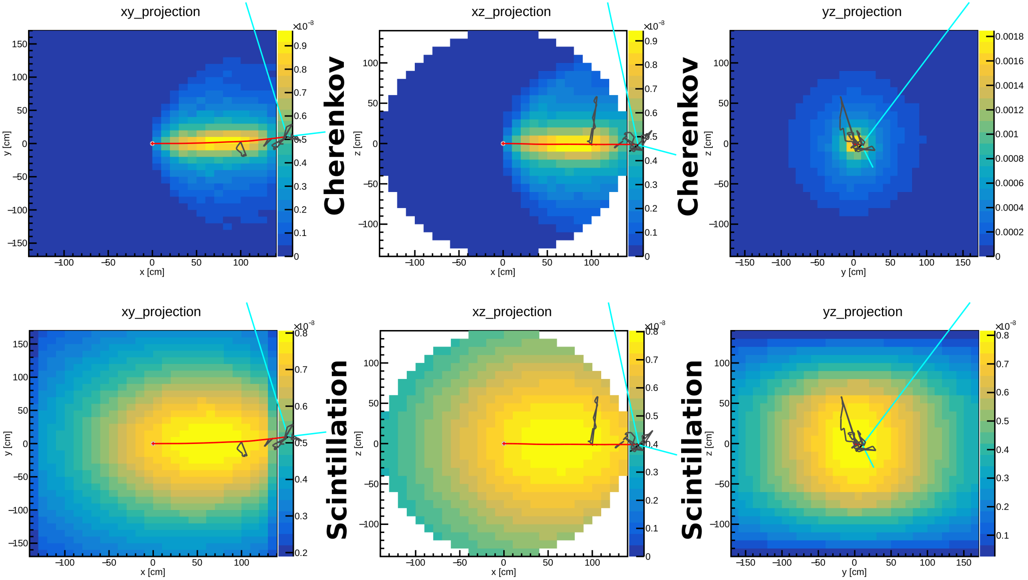
TTR: Two reconstructions in one

- Modify the reconstruction to work with pure Cherenkov detectors.
- Reconstruct pure Cherenkov event for proof of principle.

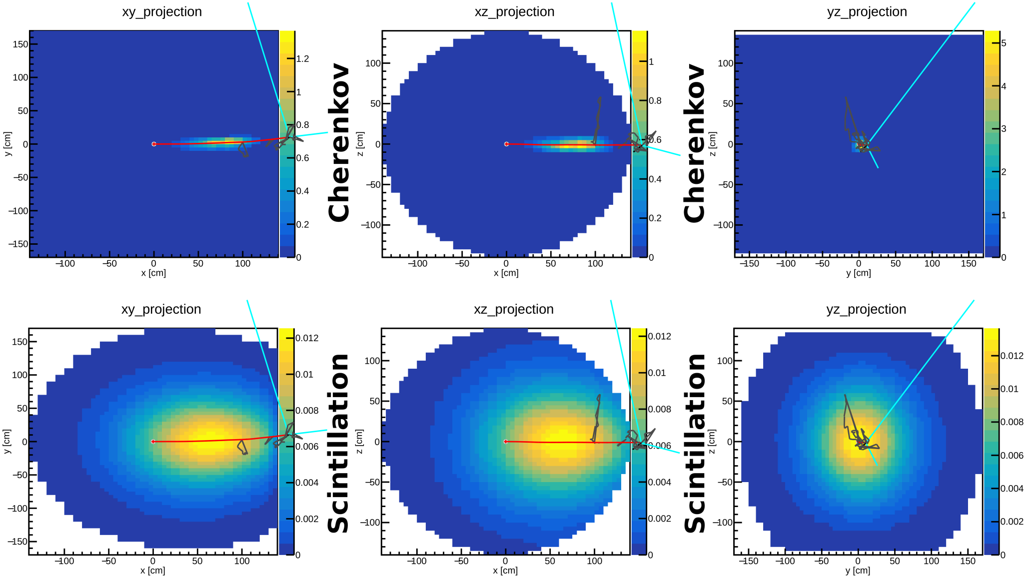


- Modify the reconstruction to have a scintillation and a Cherenkov part.
- With every iteration two reconstructions are performed:
  One considers hits to be Cherenkov photons, the other assumes hits to be Scintillation photons.
- Next slides: Perfect ordering from MC truth, Cherenkov reconstruction reconstructs only Cherenkov hits and vice versa.

Reconstruction result WbLS: Iteration 0



Reconstruction result WbLS: Iteration 5



TTR: Status

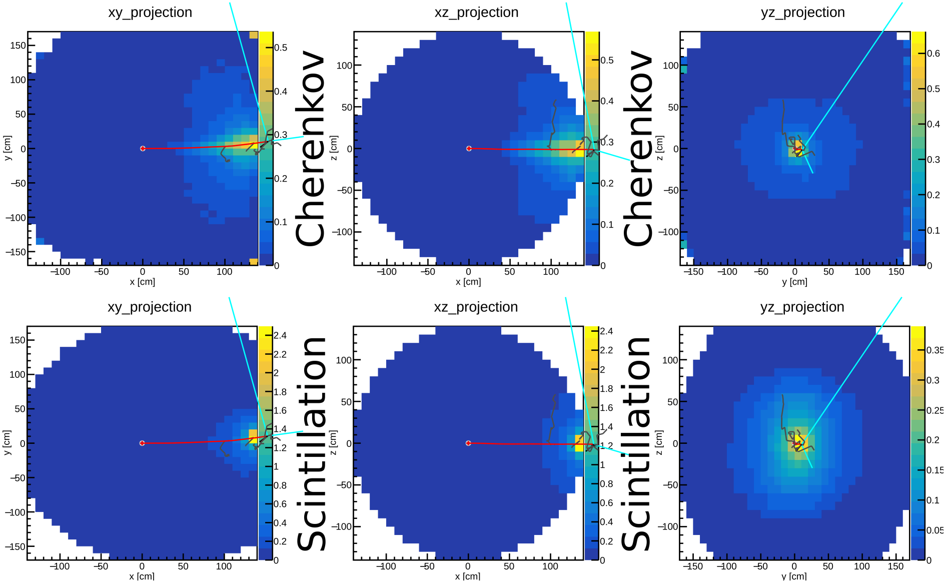
Status

- Splitting of the reconstruction worked well; results for the raw reconstruction look like expected.
- Raw reconstruction: no usage of propagation effects except angular acceptance of photodetectors
- Characteristics of both light types can be distinguished.
- Probability mask too confined on middle of the track

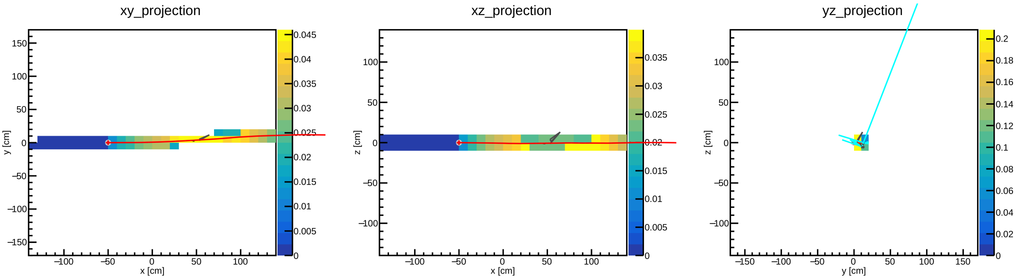
Issue

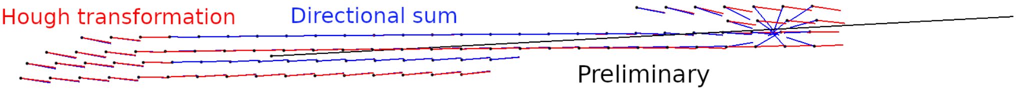
- Results for emitted light look unexpected; probability mask has high entries at edge, artefacts.
- Emitted light algorithm: use all propagation effects and the Look-Up-Tables (LUTs) to calculate the number of emitted photons for each cell.
- Worked well for larger detectors like LENA, problematic with this small WbLS detector for particles leaving detector.
- Currently under investigation

TTR problem: Emitted light at iteration 5



Reminder: Directional information in pure water





- For each cell take hits giving a contribution to cell content into account.
- Project hits on unit sphere around cell.
- Gain directional information via circular Hough transform and directional sum.
- Needs adjustments and improvements in the new version of the TTR.

Machine Learning I: Direction reconstruction in JUNO

Work of Hauke Schmidt

- JUNO has $\sim 3\,\%$ Cherenkov light $\Rightarrow$ direction reconstruction
- Motivation: background suppression for sources with known location, especially solar neutrinos

- Assumption of known vertex

=> Time of flight correction

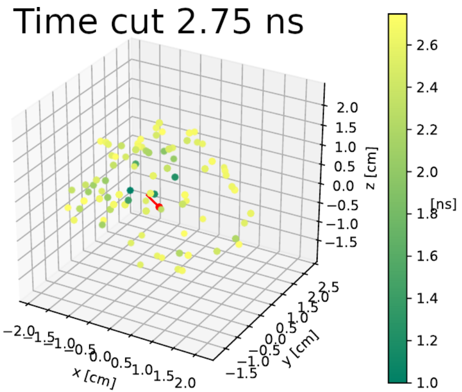
- Projection of hit coordinates on unit sphere around the vertex

=> Angular coordinate for every hit

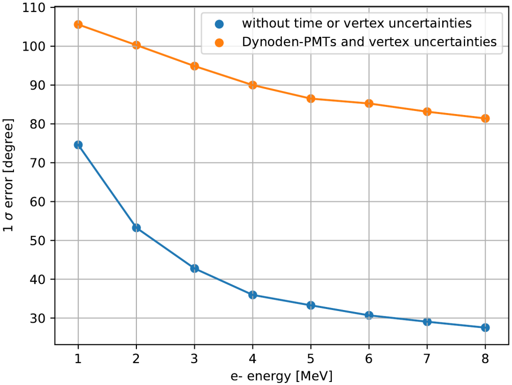
- Modification of distance of hit point to origin according to time information

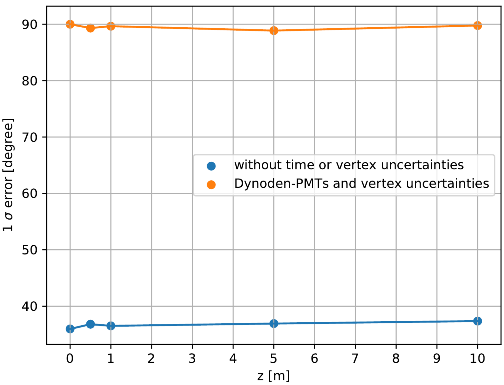
=> Time deformed sphere around vertex

- Network PointNet (see arXiv:1612.00593)
- Data represented as PointCloud (PMT positions, hit times)



Results





- No dependence on position: energy of 8 MeV gives with vertex uncertainty and TTS error of 90 $^\circ$.

=> Direction can be confined to half of the detector at 8 MeV.

=> Great result for amount of Cherenkov light in JUNO

=> Expected to be very useful in a WbLS-detector.

Machine learning II: introduction and simulated data

Work of Rosmarie Wirth

Goal

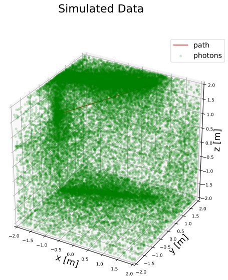
- Reconstruct track and find shower with Machine Learning.

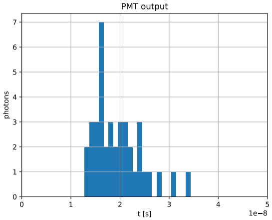
Simulation

- Toy MC simulating scintillation along random track with a high emission point (Peak)
- Cubic detector with 4 m edge length
- 100 PMTs with 1 ns time resolution per wall
- First stage: Dynamic Graph CNN
  (Yue Wang et al. "Dynamic Graph CNN for Learning on Point Clouds" arXiv:1801.07829)
- Second stage: fully connected layers

Output goals

1. Coordinate reconstruction (start, peak, end)
2. Voxel reconstruction



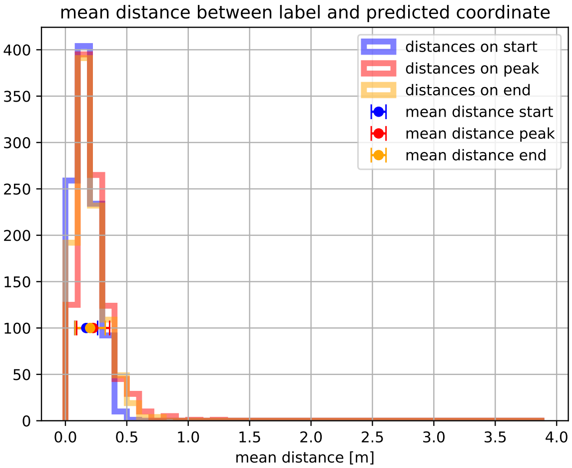


Goal I: Coordinate reconstruction

Promising results:

Position	**Mean distance**
Start	$0.16 \pm 0.20\,\mathrm{m}$
Peak	$0.22 \pm 0.14\,\mathrm{m}$
Exit	$0.21 \pm 0.11\,\mathrm{m}$

$\Rightarrow$ Track and shower identification work.

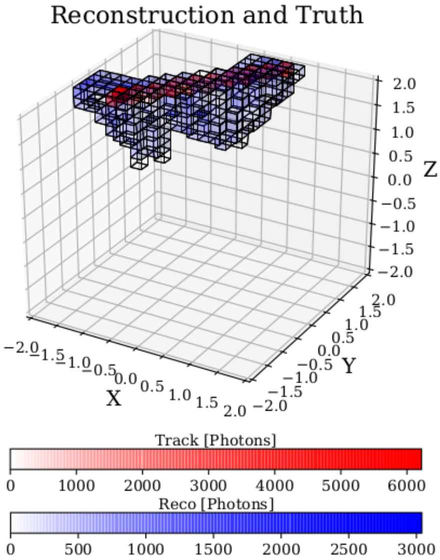


Outlook

- Implementation for OSIRIS sub-detector of JUNO
- More realistic data
- Use case: Muon flux and veto validation

Goal II: Voxel reconstruction

- $(99.24 \pm 2.84)\,\%$ of the path voxels discriminated to $7\,\%$ of detector volume (empty means ≤ 200 photons)
- Mean distance reconstructed peak to label $(0.36 \pm 0.47)\,\mathrm{m}$
- For $85\,\%$ of the analysed peaks, distance reconstructed peak to label $\leq 0.5\,\mathrm{m}$
- Reconstructed photon emission distribution is not reliable: number of photons in empty voxels too high and vice versa



Summary

Summary

- Simulation in place for simulating events and LUTs
- Light separation algorithm shows first results.
- TTR works well with WbLS in raw reconstruction.
- Directional information can be extracted within the TTR.
- ML: Direction reconstruction can confine direction to half of the detector for $8\,\mathrm{MeV}$ electron events in JUNO.
- ML II: Coordinate and voxel reconstruction are working well with toy MC data.
- Additional work for LAPPD simulation in ANNIE and other service work (not shown here)

Outlook

Outlook

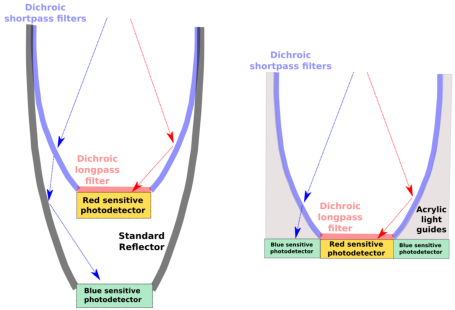
- Improve light separation algorithms and study different energies and particles.
- Fix problems with emitted light algorithm in TTR.
- Use TTR for separation.
- Adjust directional information algorithms to new TTR version.
- Use advantages of light separation.
- Contract is extended for 6 months.

Thank you for your attention.

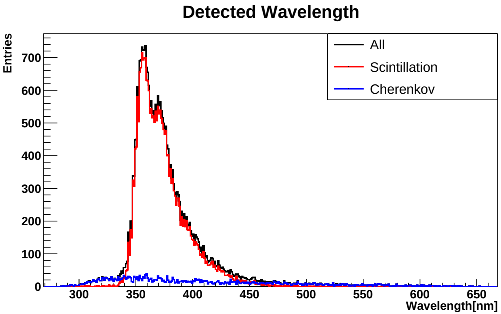
Light Separation I: Wavelength

- Cherenkov photons in blue/green wavelengths
- Scintillation photons in UV/blue wavelengths

=> Use wavelength filtering for separation.



[arXiv:1912.10333]



Dichroicon

- Dichroic filter: Reflection/Transmission dependent on wavelength
- Two photosensor with Winston cones: One for Cherenkov wavelengths, one for scinitllation wavelengths

Light Separation II: Position

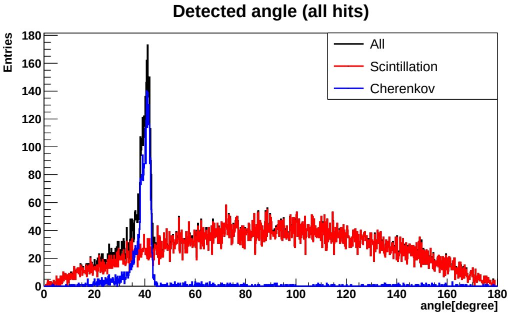
- Cherenkov photons emitted at a characteristic angle of $\sim 38 - 40^\circ$.
- Scintillation photons emitted isotropic.

=> Use spatial information for separation.

- In an experiment excellent granularity in direction of Cherenkov cone is needed.

=> LAPPDs are capable of this feature.

- For non-beam events: Track reconstruction is necessary to get direction.



Light Separation III: Timing

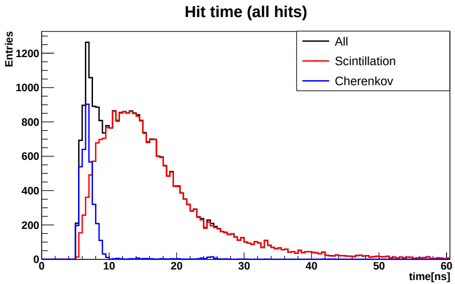
- Cherenkov photons emitted prompt.
- Scintillation photons emitted delayed.
- Velocity dependent on wavelength: Scintillation light travels slower

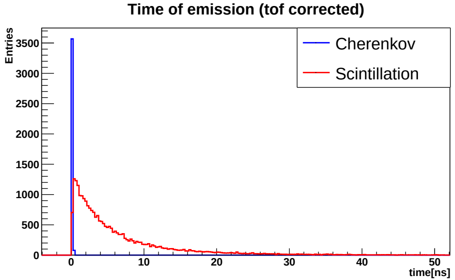
=> Use time information for separation.

- Need for fast photosensors

=> LAPPDs are fast enough.

⇒ **LAPPDs are a good tool for Cherenkov and scintillation light separation using spatial and timing information!**





Light Separation IV: outlook

Two main ideas:

1. Use algorithms before or in reconstruction to sort hits.
2. Use probability information within the reconstruction.

Algorithm way

- Generate several hundreds of events for looking into overall timing/spatial profile.
- Reconstruct track direction for using spatial information or use the topological track reconstruction for this purpose.
- Combination of timing and spatial cuts/weights for separation.

Separation within reconstruction

- Scintillation hits get less weight in Cherenkov reconstruction and vice versa at track.
- This information might be usable for separation.
- Furthermore, directional information like directional sum to estimate amount of Cherenkov versus scintillation light in cells.

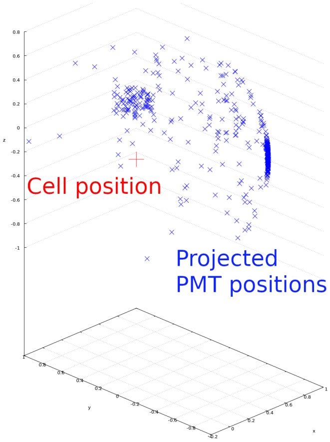
Directional information

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



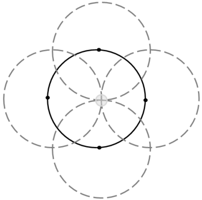
Directional sum and Hough transform

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.

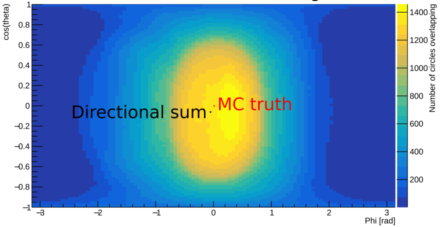
Hough transform

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

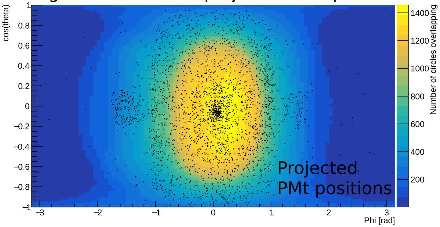


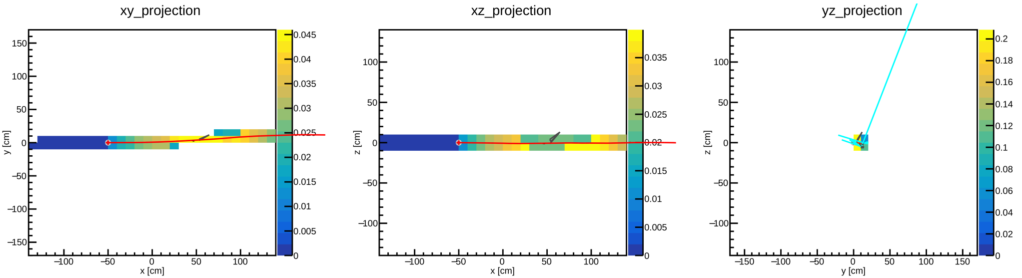
[https://www.mathworks.com]

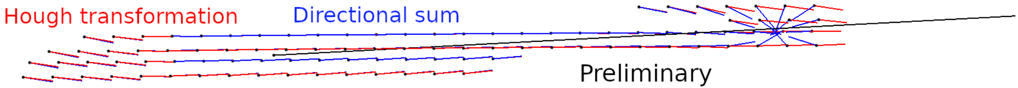
Directional Sum and MC truth in Hough transform



Hough transform and projected PMT positions





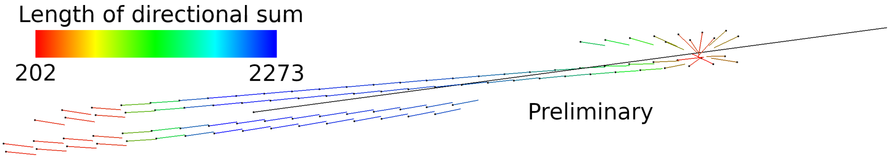


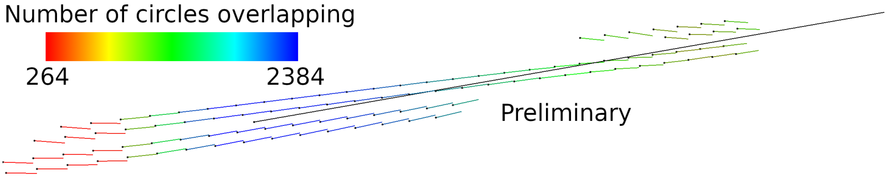
- First information along the track with both methods
- Agreement with the event
- Directional sum needs improvement for end of track.

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

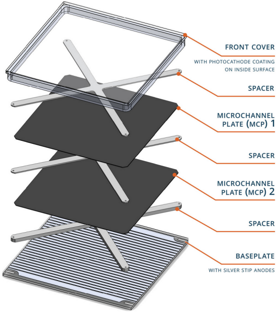




Status: Directional information can be found and look promising. Needs testing and validation.

Motivation III: Large Area Picosecond Photodetectors (LAPPDs)

- Photodetectors with two Microchannel Plates and 30 anode strips with $20\,\mathrm{cm} \cdot 20\,\mathrm{cm}$ size
- Excellent time resolution of $< 100\,\mathrm{ps}$
  JUNO PMTs have $\sim 1\,\mathrm{ns}$
- Spatial resolution of $< 1\mathrm{cm}$
  JUNO PMTs no granularity: $> 50\,\mathrm{cm}$
- Quantum efficiency $> 20\,\%$
  JUNO PMTs $\sim 30\,\%$



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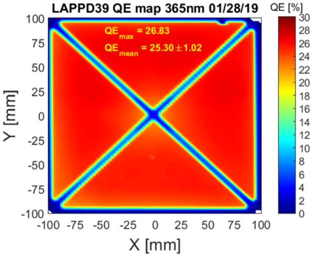
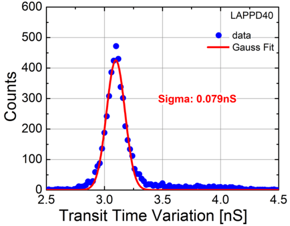
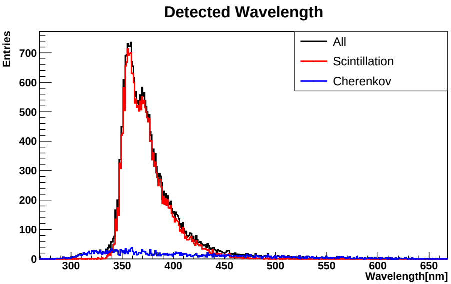


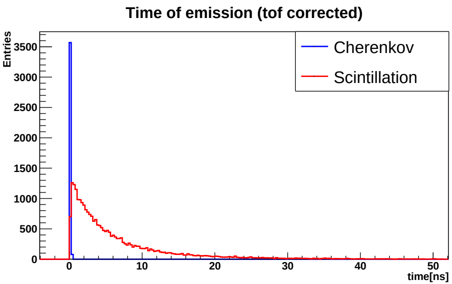
[arXiv:1909.10399]

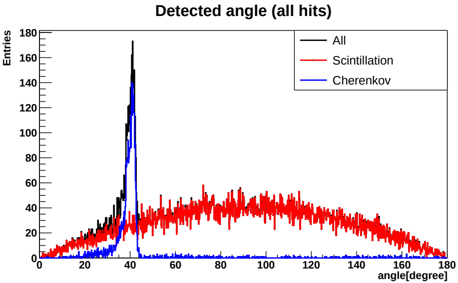


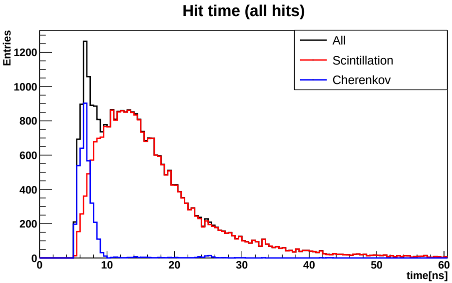
[arXiv:1909.10399]

Simulation: wbLS examples plots II





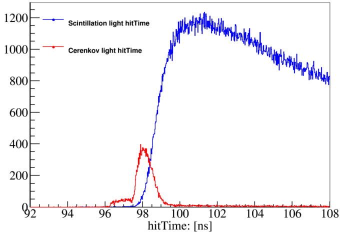




Direction reconstruction

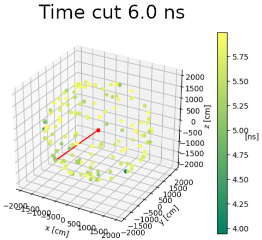
- In JUNO $\sim 3\,\%$ of the emitted light is Cherenkov light.
- This opens an opportunity for a direction reconstruction.
- Motivation: background suppression for neutrinos of sources with known location, especially solar neutrinos

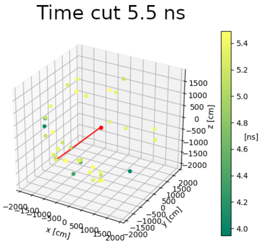
- **No usage of the TTR**
- Training sample: 100,000 electron events ($3\,\mathrm{MeV}$) at the center of JUNO (using detector simulation)
- Validation and evaluation: 10,400 events for every $1\,\mathrm{Mev}$ step between 1 and $8\,\mathrm{MeV}$
- Time of flight correction
- Time cut $5.5\,\mathrm{ns}$ after time of flight correction
- Usage of known vertex position



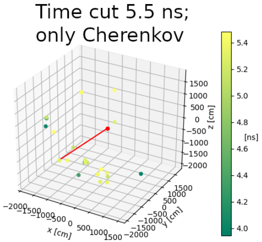
[Determination of Supernovae Direction with Reconstructed Positron Information; DOI: 10.22323/1.244.0067]

Hit distribution

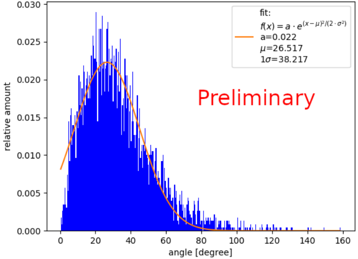


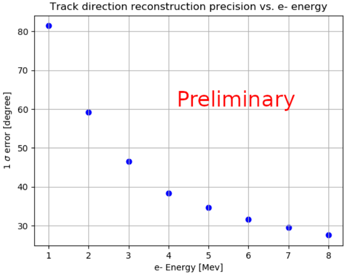


- Not using a CNN because
  - Edge effects if trying to parameterize the 3D sphere to 2D cartesian coordinates
  - 3D CNN would contain lots of entries with a zero
    $\Rightarrow$ massive amount of memory and running time



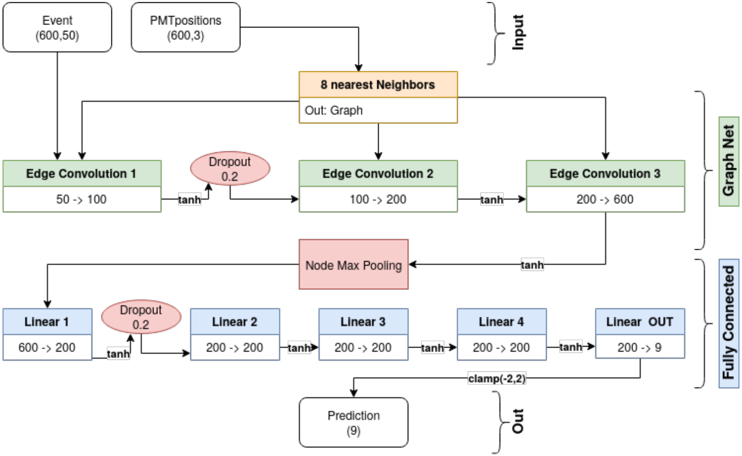
- Network PointNet (see arXiv:1612.00593); Framework: **TensorFlow**
- Data represented as PointCloud (PMT positions, hit times)
- Implementation based on **Dynamic Graph** CNN with modifications:
  - No rotation and moving of input
  - Reduce output to three values
  - Add quadratic normalisation to output
  - Cosine function as loss function
  - Use Convolution, MaxPooling and Dense layer instead of ReduceMax and fully connected layer





Network architecture

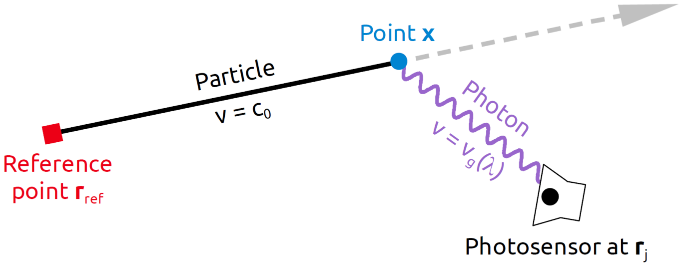
- First stage: Dynamic Graph CNN (see arXiv:1801.07829)
- Second stage: Fully connected layers
- Notable feature: Node max pooling (take maximum of each node)



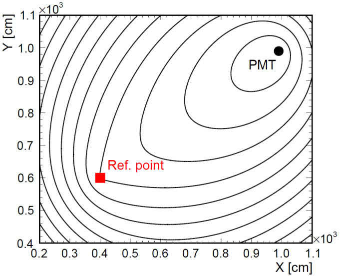
General concept of the Topological Track Reconstruction (TTR)

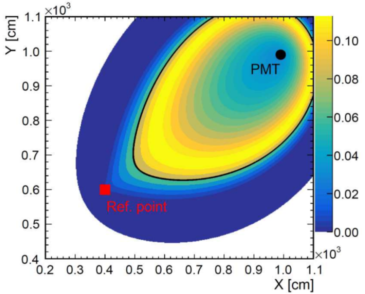
- Known reference point in time t_{ref} and space $\mathbf{r}_{\text{ref}}$
- Assume straight particle path with velocity c_0.
- Calculate possible locations $\mathbf{x}$ of the particle at time $t(\mathbf{x})$.
- Developed by our group in Hamburg. See: Björn Wonsak et al. "Topological track reconstruction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

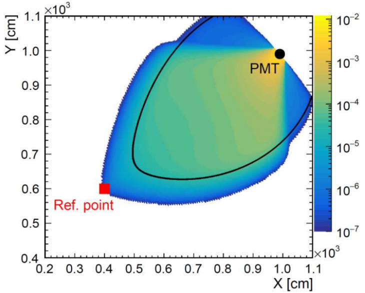
$$t(\mathbf{x}) = t_{\text{ref}} \pm \underbrace{\frac{|\mathbf{x} - \mathbf{r}_{\text{ref}}|}{c_0}}_{\text{particle}} + \underbrace{\frac{|\mathbf{r}_j - \mathbf{x}|}{v_g(\epsilon)}}_{\text{photon}}$$



Probability density functions

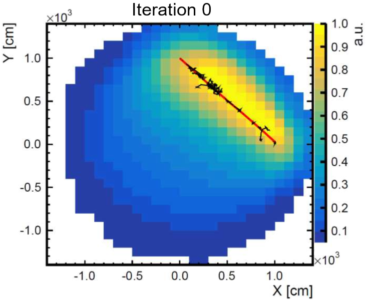


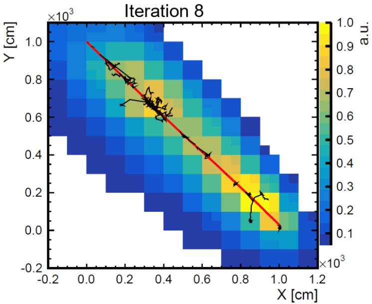




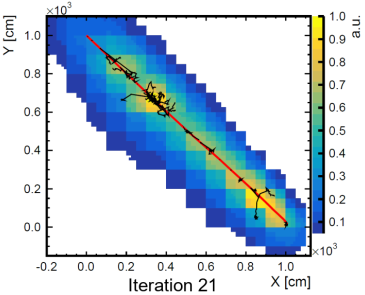
- Develop **p**robability **d**ensity **f**unctions (**p.d.f.**s) when taking more effects into account.
    1. Isochrones come from the inversion of $t(x)$.
    2. Time uncertainty of scintillation light and response of photosensor
    3. Detection and propagation effects like angular acceptance and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

Reconstruction method

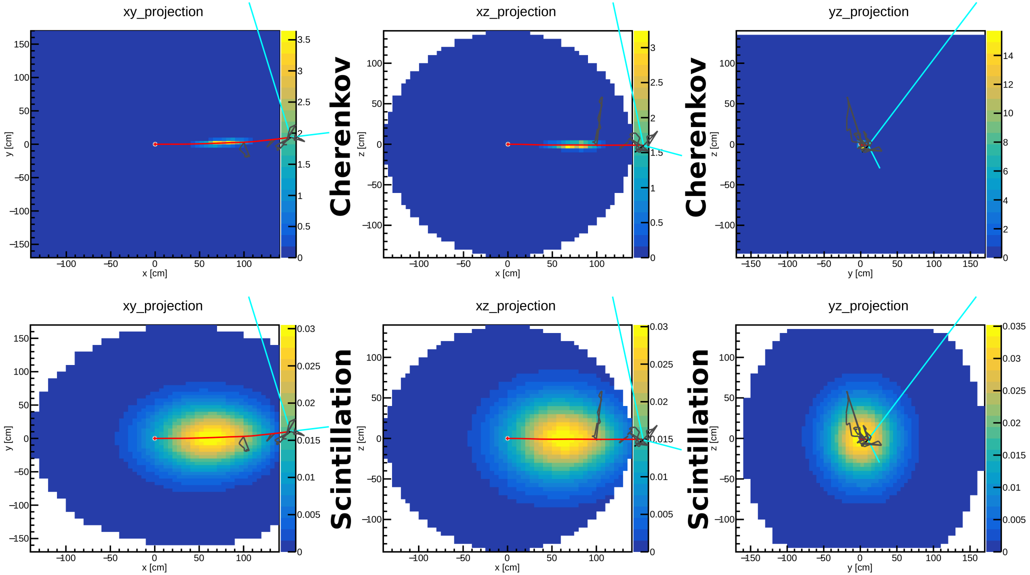




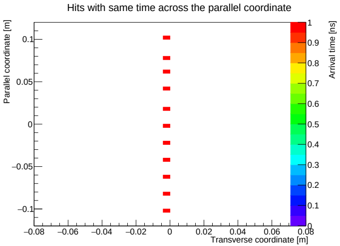
- Create a p.d.f. for every hit and each PMT.
- Superimpose the p.d.f.s for every bin in volume.
- Gain probability mask showing most-likely origin of light.
- Treat prior iteration as truth; cut cells.
- Reconstruct again based on the previous iteration.
- Refine binning for more detailed result.

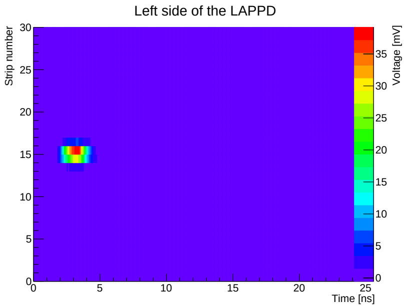


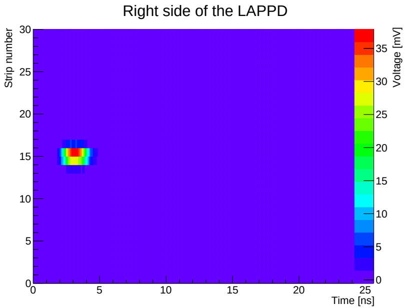
Reconstruction result wbLS: Iteration 10



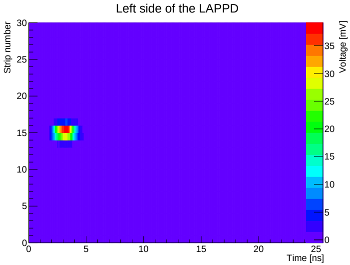
Hits across the parallel coordinate I

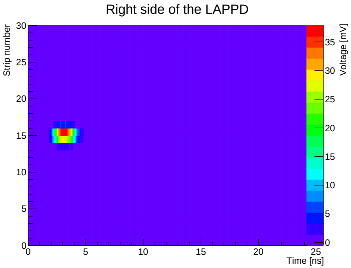


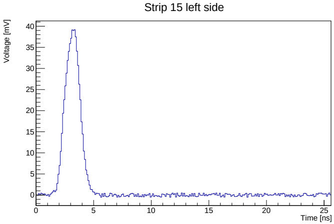


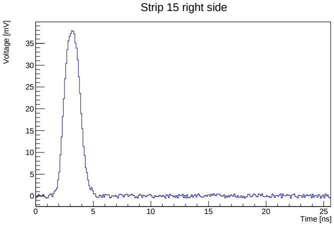


Hits across the parallel coordinate II

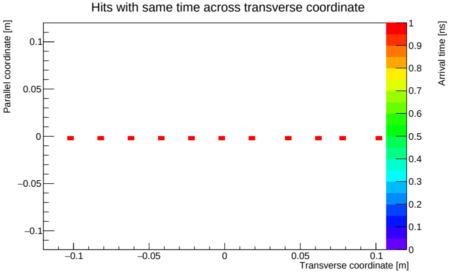


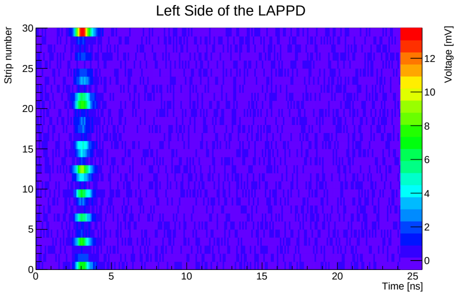


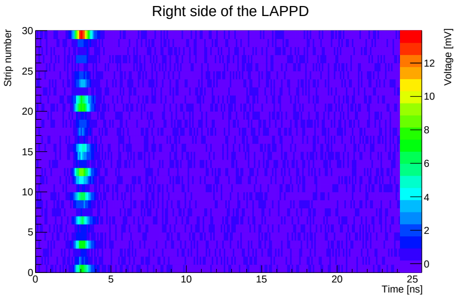




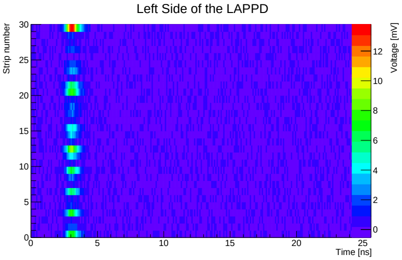
Hits across transverse coordinate

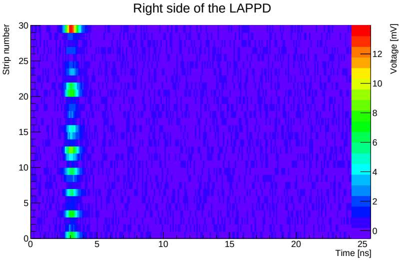


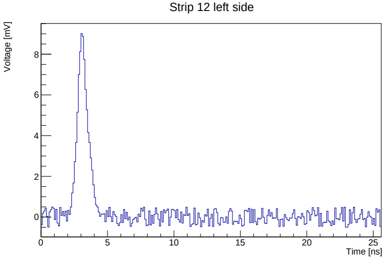


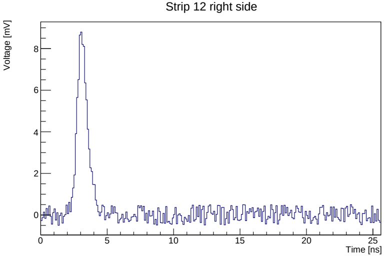


Hits across transverse coordinate II

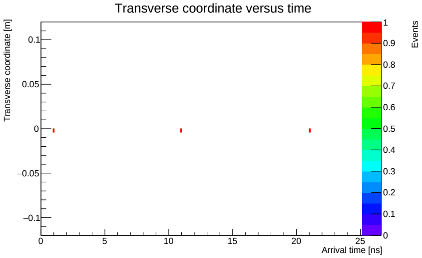


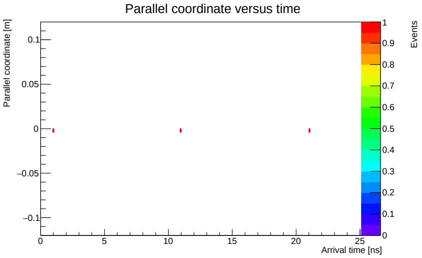


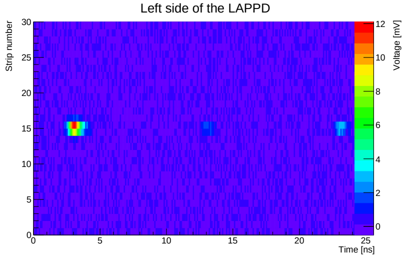


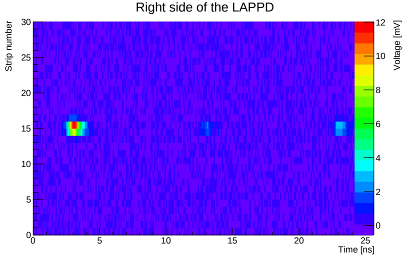


Hits with different time at same spot

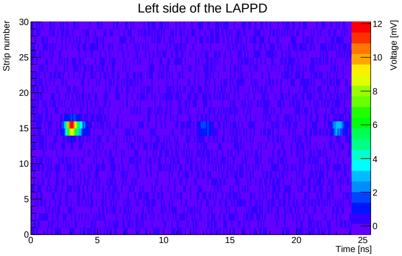


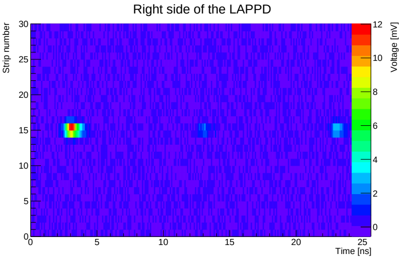


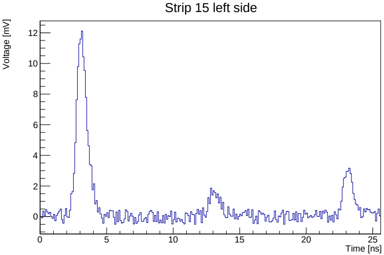


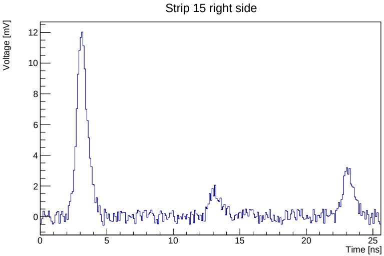


Hits with different time at same spot II

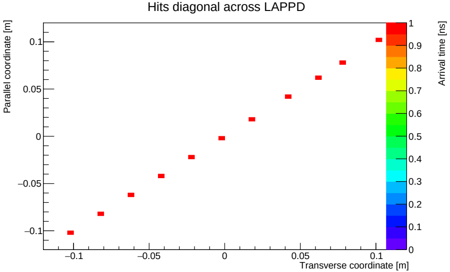


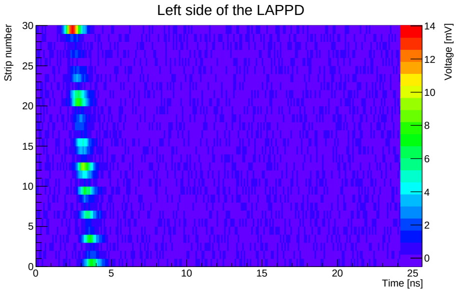


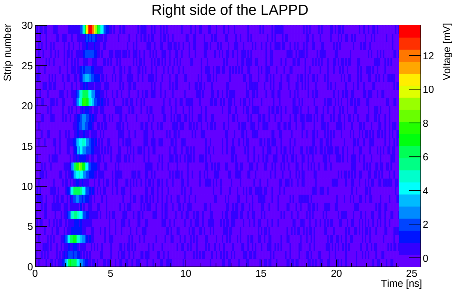




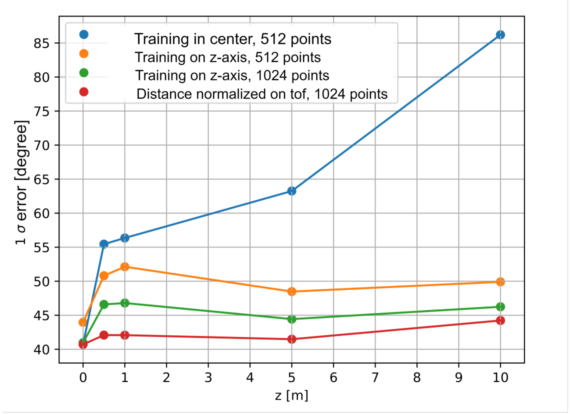
Diagonal Hits across LAPPD

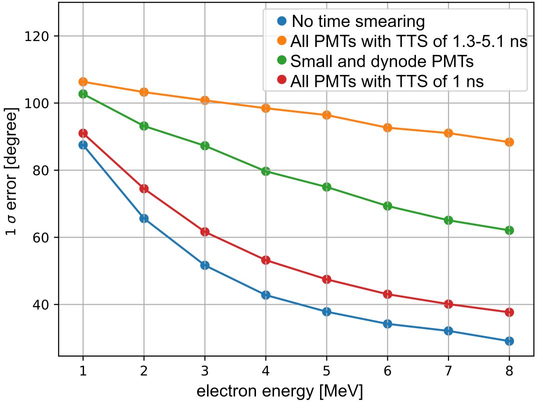






Influence of training and time resolution





- Training in center yields worse results, especially farther outside.
- Training on z-axis normalised to the time of flight is best option.
- Performance improves with time resolution of the PMTs.