3d-Topological Reconstruction in Liquid Scintillator

Presented by

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on behalf of
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What is 3d Topological Reconstruction?

- **Spatial distribution of the energy deposit**
  - Same abilities as fine grained detector

- **Motivation:**
  - Particle discrimination
  - Identify shower locations
  - Better vetoing of cosmogenics
Why no 3D Tracking (so far)?

Point-like event:

Light emitted in $4\pi$
→ no directional information

Time between emission and detection = distance
→ Circles

Point of light emission
Why no 3D Tracking (so far)?

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Point of light emission
Why no 3D Tracking (so far)?

Point-like event:

Light emitted in $4\pi$
→ no directional information

Time between emission and detection = distance
→ Circles
Why no 3D Tracking (so far)?

Track:

Lots of emission points with different emissions times

→ No association between signal and emission time
My Basic Idea

Assumption:

- One known reference-point (in space & time)
- Almost straight tracks
- Particle has speed of light
- Single hit times available

Concept:

- Take this point as reference for all signal times
The Drop-like Shape

Signal time = particle tof + photon tof

\[ ct = |V_X| + n^*|X_P| \]
The Drop-like Shape

\[ ct = |VX| + n^*|XP| \rightarrow \text{drop-like form} \]
The Drop-like Shape

\[ ct = |VX| + n^*|XP| \rightarrow \text{drop-like form} \]
Working Principle Part I Summary

• For each signal:
  – Time defines drop-like surface
  – Gets smeared with time profile  
    (scintillation & PMT-timing)
  – Weighted due to spatial constraints  
    (acceptance, optical properties, light concentrator, …)

• → Spatial p.d.f. for photon emission points

See B.W. et al., arXiv:1803.08802
Working Principle Part II

- Add up all signals \((\text{Need arrival time for every photon})\)
- Divide result by local detection efficiency
  \(\rightarrow\) Number density of emitted photons
- Use knowledge that all signals belong to same topology to 'connect' their information
  \(\rightarrow\) Use prior results to re-evaluate p.d.f. of each signal

That is what I call probability mask (PM)

See B.W. et al., arXiv:1803.08802
Image Processing

3D Medial line

Medial line XY-Projection

Medial line XZ-Projection

Work of Sebastian Lorenz

Resolution < 20 cm

Future: Machine learning
Performance with Muons in LENA

- Fully contained muons with 1-10 GeV
  - Angular resolution: <1.4° for E ≥ 1 GeV
  - Energy resolution: 10% · sqrt(E/1 GeV) + 2 %
    (Gets better if scattered light is treated correctly)

See B.W. et al., arXiv:1803.08802
Electron/Muon Separation

- **Use longitudinal extent**
  - Clear separation down to 600 MeV
- **Additional Parameters like dE/dx might improve this**

Bachelor thesis of Daniel Hartwig
NC Background

- Started to look at $\pi_0$ in LENA

Caveat:
Used smeared but true $\pi_0$ vertex
Computing Time

- **Full fine grained reconstruction is very time consuming**
  (21 iterations, 12.5 cm binning → a few hours for a few GeV muon in LENA)

- **However:**
  - Easy to implement parallel computing techniques *(already some success)*
  - Reconstruction strategy can be adapted with a configuration file
  - Can use prior track information
  - Already the first iteration with coarse grains includes a lot of information

- **Need to find balance for a given question**
  - Cell size, number of iterations and number of PMTs used

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**GPU could help a lot!**

**Slow: A few hours**

**Fast: 20 min**
Looking for Shower in Cosmic Events

- Result:
  - 40 GeV muon crossing the whole detector
  - With hadronic shower
  - Used PM generated from fast track reconstruction
  - 1m cell size, 1 iteration only → much faster reconstruction

Bachelor thesis of Felix Benckwitz
Tracking at Low Energies
(a few MeV)
• **Central detector**
  - ~78% PMT coverage
  - 18000 20” PMTs + 25000 3” PMTs
    → 1200 photons/MeV

  - Acrylic sphere with liquid scintillator
  - PMTs in water buffer
    → Refraction, but no near field

  - Time resolution < 1.2 ns (σ)
(5000 Hamamatsu PMTs)
Implementation in JUNO

- LENA-MC: Only effective optical model
- JUNO: Full optical model + complex optics due to refraction at acrylic sphere
  Includes Cherenkov-light

Work by Henning Rebber
Electrons vs. Positrons in JUNO

Result after 5th iteration

Electron

Positron

3.6 MeV visible energy
Electron/Positron Discrimination in JUNO

- **So far:** Only 1-dimensional analysis based on contrast
- **Future:** Multivariate decision tree or neural network
- **Effect of Ortho-Positronium already included**

![Histograms showing electron/positron discrimination at 1 MeV and 2.6 MeV energy levels.](image)

<table>
<thead>
<tr>
<th>Energy</th>
<th>e+</th>
<th>95%</th>
<th>90%</th>
<th>80%</th>
<th>75%</th>
<th>68%</th>
<th>50%</th>
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</thead>
<tbody>
<tr>
<td>1 MeV</td>
<td>e-</td>
<td>21%</td>
<td>13%</td>
<td>6%</td>
<td>4%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>2.6 MeV</td>
<td>e-</td>
<td>40%</td>
<td>28%</td>
<td>13%</td>
<td>11%</td>
<td>8%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Work by Henning Rebber
Gamma Discrimination in JUNO

- Used only time based vertex reconstruction to get reference point

Radius containing 80% of light emission probability

Work by Henning Rebber

2 MeV in JUNO

318 electrons
226 gammas

Very preliminary!!!
Eliminating Influence of Scattered Light

• **Idea:** Use probability mask and lookup tables to calculate for each signal the probability to be scattered → Reweigh signals after each iteration

Result **before** removal of scattered light!
**Eliminating Influence of Scattered Light**

- **Idea:** Use probability mask and lookup tables to calculate for each signal the probability to be scattered → Reweigh signals after each iteration

Result *after* removal of scattered light!
Cherenkov Light

• **Much better time information**
  → Good reconstruction without changes to algorithm

• **Additional information from Cherenkov-angle**
  → Need direction dependent local detection efficiency
  → Need dedicated Look-Up-Tables (LUT)

Result without dedicated LUTs

Work in progress!

A few GeV muon
Cherenkov light only
Complication

- Angular distribution of Cherenkov-light modified by multiple scattering
  → Depends on particle typ

- Consequences:
  - Need different photon detection efficiencies
  + hypothesis about particle typ

I do not like this!
→ Another idea!

Idea to Measure Cherenkov Light

- **Assumption:** Already have a 3D topology
- **Observation:** Cherenkov-angle not used yet
- **Strategy:**
  - Go to each point on track/topology
  - Collect signal that match in time
  - Calculate angle of signal against direction towards vertex
    - Angular spectrum
    - Get Cherenkov-angle, Cherenkov-intensity and the spread of its distribution
Cherenkov vs. Scintillation Separation

• What happens if I have both light species?
• Critical point:
  – Both light sources have very different timing behaviors
  – The whole reconstruction is based on good time information
  – Attributing the wrong time distribution to a signal will automatically introduce a bias

Wei, Hanyu et al.
arXiv:1607.01671
Cherenkov vs. Scintillation Separation II

- Could use similar strategy as for scattered light
  - Assign every photon a probability to be Cherenkov-light based on results of previous reconstruction

→ Separation seems possible

- Will depend on:
  - Cherenkov/Scintillation light ratio
  - Time responds of scintillator & sensors
  - Wavelength dependencies

Work in progress!

THEIA
Advantages of Cherenkov Separation

- **Can improve spatial resolution if fast light sensors are used**
- **Contains additional information**
  - Angle and intensity → Particle velocity
  - Sharpness of ring → Showers or multiple scattering
- **Scintillation light delivers**
  - Energy deposition
  - Low threshold
- **Together**: Particle identification + direction

Wei, Hanyu et al. arXiv:1607.01671
First Result Directionality

- **Theia with 5% water-based liquids scintillator (WBLS)**
- **Used directional sum**
- **Angular resolution depends on vertex resolution**
  - Resolution needs to be confirmed with full reconstruction chain

\[
\theta \quad \Delta \theta \quad \text{(Just for illustration, does not include scattering)}
\]

![Graph](image)

- 3 MeV electrons
- Angular resolution 36%

![Graph](image)

- 1000 electrons

(From full Theia MC+Reco including scattering)

(Just for illustration, does not include scattering)
Summary/Conclusion

- **3d topological reconstruction**
  - Versatile tool
  - A lot of potential
  - Needs to get faster *(working on it)*
  - Need to go to waveforms

- **Cherenkov separation**
  - Non-trivial
  - Seams to be feasible
  - Would have a lot of advantages
Backup slides
Solar Neutrinos in JUNO

- **Main challenge:**
  - Radio-purity
  - Cosmogenic background, e.g. long living spallation $^{11}\text{C}$

- **Potential:**
  - $^7\text{Be}$ and low tail $^8\text{B}$ (large mass)
  - Discriminate pp from $^{14}\text{C}$ (energy resolution)

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<table>
<thead>
<tr>
<th>Internal radiopurity requirements</th>
<th>baseline</th>
<th>ideal</th>
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<tbody>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>$5 \times 10^{-24}$ [g/g]</td>
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<tr>
<td>$^{85}\text{Kr}$</td>
<td>$1 \times 10^{-16}$ [g/g]</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
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<tr>
<td>$^{238}\text{U}$</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
<td>$1 \times 10^{-18}$ [g/g]</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
<td>$1 \times 10^{-18}$ [g/g]</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
<td>$1 \times 10^{-18}$ [g/g]</td>
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<tr>
<td>$^{14}\text{C}$</td>
<td>$1 \times 10^{-17}$ [g/g]</td>
<td>$1 \times 10^{-18}$ [g/g]</td>
</tr>
</tbody>
</table>

| Cosmogenic background rates [counts/day/kton] | $^{11}\text{C}$ | 1860 |
|                                             | $^{10}\text{C}$ | 35  |

| Solar neutrino signal rates [counts/day/kton] | pp $\nu$ | 1378 |
|                                             | $^7\text{Be}$ $\nu$ | 517  |
|                                             | pep $\nu$ | 28   |
|                                             | $^8\text{B}$ $\nu$ | 4.5  |
|                                             | $^{13}\text{N}/^{15}\text{O}/^{17}\text{F}$ $\nu$ | 7.5/5.4/0.1 |

Baseline background

JUNO collab., arXiv:1507.05613
Vertex Reconstruction

• Use backtracking-like algorithm to find primary vertex (i.e. signals matching in time corresponding to position)

• Results for low energies already within expectations

• For high energy: Average distance to track 30 cm → Room for improvement
  (likelihoods methods in LENA yielded <10 cm vertex resolution)

Master thesis of David Meyhöfer
What Kind of Detector Would be Best?

• Good balance between amount of Cherenkov and Scintillation light
  → WbLS or lightly doped oil-based LS

• Very fast sensors for Cherenkov separation
  → LAAPD (time resolution 50ps)

• Single photon timing
  → Pixels of LAPPD

• Fast scintillation light, but not too fast for Cherenkov separation
  → THEIA-like detector!
Reconstruction: Overview

- 3D topological reconstruction
  → Spatial distribution of emission density
- Using full time information
- Iterative process
  - Using a probability mask (PM)
  - Usually result of previous iteration
- Operating on a grid → bin size is important
- Only assumptions:
  - One known reference point (in space and time)
  - Single photon hit times available

- Potential at high (GeV) and low (MeV) energies
Mu/e-Separation: Angular Width
Parallel Computing
Example: Real Borexino Data

Significant bins only

Used first hit times only!
But what about the reference point?

**Answer:** Any point on track can be used if I know the time the particle passing!
2GeV Muon, First Hit Information

- **Vertex** (-500.,0.,0.), **Orientation** (1.,1.,0.)

10% of PMTs at +-500 cm in z with respect to vertex
2GeV Muon, First Hit, Backwards

- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**

10% of PMTs at +/-500 cm in z with respect to vertex
2GeV Muon, First Hit, from Middle

- **Vertex (-500.,0.,0.), Orientation (1.,1.,0.)**

![Graph showing 10% of PMTs at ±500 cm in z with respect to vertex]

10% of PMTs at ±500 cm in z with respect to vertex
2GeV Muon, First Hit, Back from Middle

- **Vertex (-500,0,0.), Orientation (1,1,0.)**

![Graph showing PMT signals with mean and RMS values.](Image)

10% of PMTs at +/-500 cm in z with respect to vertex
Vertex Finding/Backtracking

Basic idea: from Domenikus Hellgartner

- Calculate at every point the time correction needed for each first hit signal to match the flight time to that point
- Then look for peaks in this time distribution

\[ \vec{x}_g = (0, 0, 0) \text{ m (on track)} \]
\[ \vec{x}_g = (5, 5, 5) \text{ m (off track)} \]
Vertex Reconstruction I

Uses first hit time of each PMT and gaussian time distribution

Work of D. Hellgartner & K. Loo
How to improve Backtracking

Some regions on track do not produce many 'first hits'

→ Need to look more closely at timing patter (tof corrected)

→ whole track
<table>
<thead>
<tr>
<th></th>
<th>Backtracking</th>
<th>Inner Detector Tracking</th>
<th>Outer Detector Tracking</th>
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</thead>
<tbody>
<tr>
<td>$\sigma_\alpha [^\circ]$</td>
<td>1.63 ± 0.10</td>
<td>2.44 ± 0.19</td>
<td>3.01 ± 0.15</td>
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<tr>
<td>$\sigma_y \text{ [cm]}$</td>
<td>35 ± 4</td>
<td>36 ± 5</td>
<td>28 ± 7</td>
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<tr>
<td>$\sigma_z \text{ [cm]}$</td>
<td>38 ± 4</td>
<td>31 ± 6</td>
<td>45 ± 7</td>
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</table>
Stopped Muon in Borexino
Double Muon Event in Borexino
Double Muon Event in Borexino

Both tracks cut out!
The power of the 4th dimension

4d Canny Algorithm
The Reco Result (266 PMTs)

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<td>Entries</td>
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<td>157.5</td>
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<tr>
<td>RMS x</td>
<td>410</td>
</tr>
<tr>
<td>RMS y</td>
<td>414.3</td>
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</table>
4d-Sobel Result

**hist_slice_z**

<table>
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<tbody>
<tr>
<td><strong>Entries</strong></td>
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<tr>
<td><strong>Mean x</strong></td>
</tr>
<tr>
<td><strong>Mean y</strong></td>
</tr>
<tr>
<td><strong>RMS x</strong></td>
</tr>
<tr>
<td><strong>RMS y</strong></td>
</tr>
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Reco Result divided by 4d-Sobel

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<td>Entries</td>
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<tr>
<td>Mean x</td>
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<tr>
<td>Mean y</td>
<td>-34.22</td>
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<tr>
<td>RMS x</td>
<td>461.7</td>
</tr>
<tr>
<td>RMS y</td>
<td>463.4</td>
</tr>
</tbody>
</table>

09/06/15
Minima of 4d-Sobel
Result after Follow-up
Result for 3GeV Muon Track

Work by B. Wonsak
Electron/Muon Separation

- **Used two parameters:**
  - Length of track
  - Angular width of track (with respect to reference point)

- **Result:** 1.5% impurity, 98% efficiency

Energies: 1-5 GeV
Contained events

Bachelor thesis of Daniel Hartwig
Result 2nd Iteration

z-projection

y-projection

1MeV positron at center
Result 2nd Iteration (Zoom)

1MeV positron at center
Result 2nd Iteration Slice 241

XY-slice of 3d probability density distribution

Y in cm

X in cm
Result 2nd Iteration Slice 240

XY-slice of 3d probability density distribution

Y in cm

X in cm
Result 2nd Iteration Slice 239

XY-slice of 3d probability density distribution

Y in cm

X in cm
Result 2nd Iteration Slice 238

XY-slice of 3d probability density distribution

Y in cm

X in cm
Result 2nd Iteration Slice 237

XY-slice of 3d probability density distribution

Y in cm

X in cm
Result 2nd Iteration Slice 236

XY-slice of 3d probability density distribution

Y in cm

X in cm