# Advanced Reconstruction in Large Volume Liquid Scintillator Detectors 

Applied to LENA

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UH<br>it<br>Universität Hamburg der forschung । der lehre । der bildung

## Overview

- Tracking at high energies (GeV)
- Basic algorithm
- Performance
- Application to low energies (MeV)
- New techniques to improve robustness
- Positron discrimination


## Motivation: Tracking at High Energies

$v_{\mathrm{e}}$ appearance experiments:
NC-background
$\rightarrow$ Is it possible to identify the $\pi_{0}$ ?

## Reactor experiments

Short-lived cosmogenics $\left({ }^{9} \mathrm{Li} /{ }^{8} \mathrm{He}\right)$ dangerous background

Full veto produces too much deadtime
$\rightarrow$ Identify places of high energy deposition (showers induced by muon)

## Why no 3D Tracking (so far)?

## Point-like event:

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

Time between emission and detection = distance
$\rightarrow$ Circles

Point of light emission

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## Why no 3D Tracking (so far)?

## Track:

Lots of emission points with different emissions times
$\rightarrow$ 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


## Concept:

- Take this point as reference for all signal times


## The Drop-Ife Shape

## Signal time $=$ particle tof $\boldsymbol{+}$ photon tof

$$
\rightarrow \mathbf{c t}=|V X|+n^{*}|X P|
$$



## The Drop-Ife Shape

## ct $=|\mathbf{V X}|+\mathbf{n}$ * $|X P| \rightarrow$ drop-like form




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## Time Distribution




## Convolution of Gaus and Exponential-Function

## Time Distribution




## Convolution of Gaus and Exponential-Function

## Result 1 PMT



## Result a Few PMTs



## Result 266 PMTs



## Light Distribution (LD) Effects

Some parts of each drop-like shape are more likely the origin of light, because:

- they are closer
- directly in front of the PMT
$\rightarrow$ Need to consider:
- solid angle of PMT area
- attenuation
- angular acceptance


## Light Distribution (LD) Effects

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- they are closer
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$\rightarrow$ Need to consider:
- solid angle of PMT area
- attenuation
- angular acceptance

Finally I have to normalise the resulting pdf !

## Result all PMTs



## Probability Mask

So far probabilities have been added!
$\rightarrow$ correct for independent information

## However:

Light signals are not completely independent from each other, because they belong to the same track.
$\rightarrow$ Use "Result l" to weight all the single light contribution and re-normalise each of them!

## Result I



## Result 2nd Iteration



## Result 3rd Iteration



## Result 9th Iteration



## 3D Topology

Probability distribution projected into the xy plane


Color: Total photon emission probability in arbitrary units
$\rightarrow \mathrm{dE} / \mathrm{dx}$ seems accessible

## Image Processing





## Resolution < 20 cm

## Computing

One 3 GeV event, 20 cm bins, full light, 22 iterations in LENA $\rightarrow$ several hours (despite usage of adaptive mesh refinement)

## However:

- I'd like to go to 2 cm bins
- because there should be enough light for this resolution
- In principle many more iterations are allowed


## But algorithm highly parallisable $\rightarrow$ GPUs, etc.

## Gurrent Status

## Large reconstruction campaign ongoing!

Muons with 1-5 GeV: (first results)

- Robustness $\rightarrow$ okay
- Angular resolution: $\sim 1.5^{\circ}$

Electron events under production
Other event classes still to be studied
Paper under preparation!



Ph. D. student Sebastian Lorenz

## Can also do it with Cherenkov Light

3 GeV muon, initial direction $(1,-1,0)$


A few \% of light in liquid Scintillator is Cherenkov light
$\rightarrow$ using both could help pattern and partical identification
Also suitable for water Cherenkov detectors! Perfect for WbLS!

## Tracking at Low Energies (a few MeV)

## Robust Iterations!?



## New Procedure

- Divide detector in different parts
- Do reconstruction for each part
- Multiply results
- Use this as Probability Mask
- Go back to first step


## Result 2nd Iteration

z-projection

y-projection


1 MeV positron at center

## Result 2nd Iteration (Zoom)



1 MeV positron at center

## Result 2nd Iteration Slice 241



## Result 2nd Iteration Slice 240



## Result 2nd Iteration Slice 239



## Result 2nd Iteration Slice 238



## Result 2nd Iteration Slice 237



## Result 2nd Iteration Slice 236



## Grystalisation of the Result

- Use well defined probability mask
- Do reconstruction for each photon
- Identify bin with highest probability
- Associate photon with this bin
$\rightarrow$ number of photons from that bin


## Grystalisation: 1 MeV Positron



## Crystalisation: 2 MeV Electron



## Crystalisation: 2 MeV Electron



# Electron vs. Positron Discrimination: First Try Results I 

Ratio R of light reconstructed near vertex vs. total light


- 3343 events of electron and positron events each
- Visible energy $1-5.5 \mathrm{MeV}$
- At the center of the detector $\rightarrow$ worst place

Notice: Used perfect vertex position for this analysis

- LENA-MC $\rightarrow 250$ photons per MeV


# Electron vs. Positron Discrimination: At C-11 Energy Region 

## Ratio R of light reconstructed near vertex vs. total light



- 111 events of electron and positron events each
- Visible energy 1-2 MeV
- At the center of the detector $\rightarrow$ worst place
- LENA-MC $\rightarrow 250$ photons per MeV

Notice: Used perfect vertex position for this analysis

## Remarks on Potential

- Possible improvements:
- So far only 250 p.e/ MeV
$\rightarrow$ Borexino: 500 p.e/ MeV, JUNO: 1200 p.e/ MeV
- Faster scintillator
- Remove scattered light statistically
- Multivariate analysis
- Other ideas:
- Use time as 4th dimension
- Gradient information (Sobel-Filter)


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## Eliminating Influence of Scattered Light

- Idea: Use probability mask and lookup tables to calculate for each signal the probability to be scattered
$\rightarrow$ reweigh signals after each iteration


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Result before removal of scattered light!

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Result after removal of scattered light!

## Using the 4th Dimension

## - Observation:

- Contrast limited by influence of neighbour bins


## - Idea:

- Use time distribution at each point
- Fit signal-function + background from neighbours


Example of a bad bin with a lot of noise!

Scattered light not removed!

## Using the 4th Dimension: Result

## First result:

- Very preliminary!


This now respresents a real $\mathrm{dE} / \mathrm{dx}$ !

## Using the 4th Dimension: Result

## First result:

- Very preliminary!
- Background estimate must be more robust
- One possibility is to use probability mask to calculate background from neighbour bins


This now respresents a real $\mathrm{dE} / \mathrm{dx}$ !

## Other Possible Applications

- Improvement of:
- Position reconstruction
- Energy reconstruction

Influence on non-stochastic term of energy resolution

- IBD directional information Supernova neutrinos
- Gamma identification
${ }^{8} \mathrm{~B}$ neutrinos
$\left({ }^{208} \mathrm{TI}\right.$ background at 2.6 MeV )
- Charge of stopping muons Atmospheric neutrinos
- Background reduction for $0 v \beta \beta$-experiments $\gamma$-cacade vs. point-like
(e.g. ${ }^{110 \mathrm{~m}} \mathrm{Ag}$ in KamLAND-Zen)


## Conclusion I

- My Tracking:
- Powerful new tool to increase physics potential
- At both high and low energies
- Wide range of applications

Liquid Scintillator, Water Cherenkov, Water based Liquid Scintillator, even Liquid Argon

- Performance:
- Spatial resolution of less than 20cm
- dE/dx accessible
- Angular resolution for 1-5 GeV muon tracks $\sim 1.5^{\circ}$

Used realistic vertex information
$\rightarrow$ As expected from backtracking algorithm

## Conclusion II

- Positron-Discrimination:
- Promising first results
- Separation seems possible at low energies
- Tracking at low energies:
- Topological $\mathrm{dE} / \mathrm{dx}$ will be challenging
- Many possible applications

Used perfect vertex information so far
$\rightarrow$ Need to use existing vertex finding algorithms

## Thanks for your attention!

## Backup slides

## Example: Real Borexino Data



## Comment on Ortho-Positronium

## - Longer lifetime

$\rightarrow$ Additional time-offset
$\rightarrow$ Annihilation photons not (or badly) reconstructable

- But:
- Better separation in inside vs. outside analysis expected
- Residual asymmetry expected
(deviation from spherical symmetry)


## 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.)

$10 \%$ 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.)

$10 \%$ 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.)


So if I have an outer detector and a particle leaves the LS volume I will have a starting point!

$10 \%$ of PMTs at +-500 cm in z with respect to vertex

## Vertex Finding/Backtracking

## Basic idea:

- 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



## Vertex Reconstruction I

Uses first hit time of each PMT and gaussian time distribution


## How to improve Backtracking

Some regions on track do not produce many 'first hits'
$\rightarrow$ Need to look more closely at timing patter (tof corrected)


## $\rightarrow$ whole track




## 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)



## 4d-Sobel Result



## Reco Result divided by 4d-Sobel



## Minima of 4d-Sobel



## Result after Follow-up



## Some early examples with different particles

## $465 \mathrm{MeV} \pi_{0}$

## - Vertex (0.,0.,0.), Orientation (-1.,0.,0.)


$10 \%$ of PMTs at +-500 cm in z with respect to vertex

## $465 \mathrm{MeV} \pi_{0}$

## - Vertex (0.,0.,0.), Orientation (-1.,0.,0.)


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## Muon 800 MeV

## - Vertex (200.,100.,0.), Orientation (-1.,-1.,0.)


$10 \%$ of PMTs at +-500 cm in z with respect to vertex

## 2 Muons with 750 MeV each

## - Vertex (300.,0.,0.), Orientation +-45 ${ }^{\circ}$


$10 \%$ of PMTs at +-500 cm in z with respect to vertex

## Ridge-Line Analysis

- Remark:
- The pictures seem to give only rough spatial information
- This is only because the single photon resolution is poor But we have a lot of light
$\rightarrow$ mean value should be very accurate
$\rightarrow$ Need method to increase contrast/use the picture to find the track position


## Ridge-Line Analysis

- Idea: Track should be a kind of ridge (in 3d) $\rightarrow$ Take only bins, with more than 17 smaller neighbour bins


## Resultat: 500 MeV Electron

## - Vertex (0.,0.,0.), Orientation (-1.,0.,0.)



## $465 \mathrm{MeV} \pi_{0}$

## - Vertex (0.,0.,0.), Orientation (-1.,0.,0.)



## Muon 800 MeV

## - Vertex (200.,100.,0.), Orientation (-1.,-1.,0.)


$10 \%$ of PMTs at +-500 cm in $z$ with respect to vertex

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## Event Signature for Tracking

## Charge


(First) Hit time


Simulated distributions over detector surface!

