DE LA RECHERCHE À L'INDUSTRIE

Geant4 Simulation for the ClearMind Project and Reconstruction of the Gamma Conversion

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for the ClearMind collaboration

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www.cea.fr

Outline

ClearMind Project

- Positron Emission Tomography & Time-of-Flight
- Project Goal & Detector concept

ClearMind Detector Simulation in Detail

- Physics Simulation in Geant4 - Configuration Choice
- Detector Main Features - Optical photons, Photocathodes simulation
- PMT Simulation: Model design - Fitting lab results

Event Reconstruction

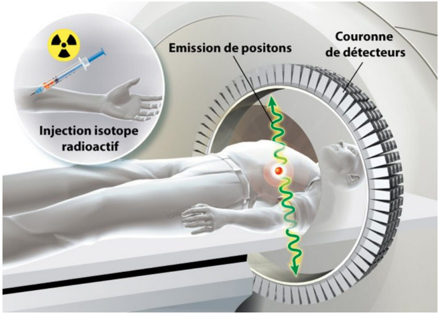
- From Measurement/Simulation to Reconstruction Parameters
- Reconstruction Methods and Results

Conclusion & Perspectives

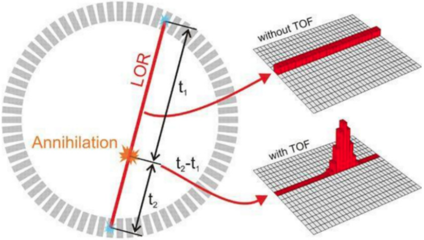
TOF-PET

- Positron Emission Tomography (PET)

  → Diagnosis for Cancers & Cardiac/neurodegenerative diseases



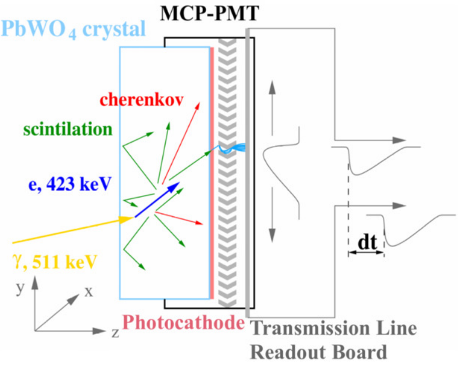
TOF illustration[1]



- Time of Flight (TOF) technique[1] – Requires GOOD time resolution

  Measurement of time difference of signals acquired in coincidence by two detecting modules

  → Enhance image contrast → Reduce patient dose



*with digitized electronics

- Fast detector for TOF in PET
  - $\rightarrow$ Detect efficiently Cherenkov and scintillation lights
  - $\rightarrow$ Direct deposition of the photocathode
  - $\rightarrow$ Detector with monolithic, large surface $PbWO_4$ crystals as the optical window of the Micro-Channel-Plate (MCP) PMT
  - $\rightarrow$ Transmission line readout board + digitized electronics
- Reconstruct 511-keV γ 3D interaction: **a few** mm (FWHM)
  Measure Coincidence Resolving Time: **a few 10s** ps (FWHM)

ClearMind Project Status

- Stage I: Thin detector (5 mm) with 1 detection surface **presented today**
- Stage II: Thick (10 mm) detector with 1 detection surface and optimized efficiency
- Stage III: Detector with 2 detection surfaces and further optimization

Outline

ClearMind Project

ClearMind Detector Simulation in Detail

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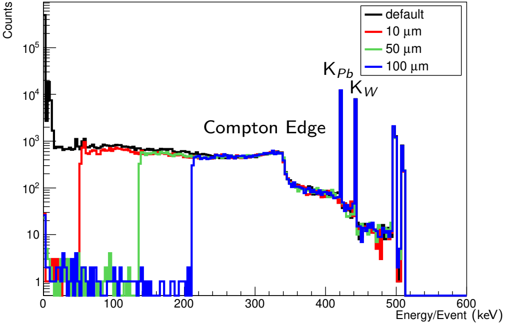
Event Reconstruction

Conclusion & Perspectives

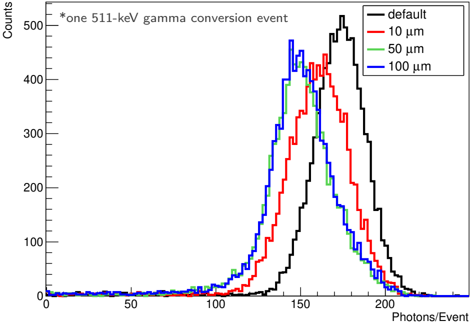
Physics in Geant4 Simulation

- Physics list: **G4EmPenelopePhysics**

Electron Energy Spectrum



Photon Production*

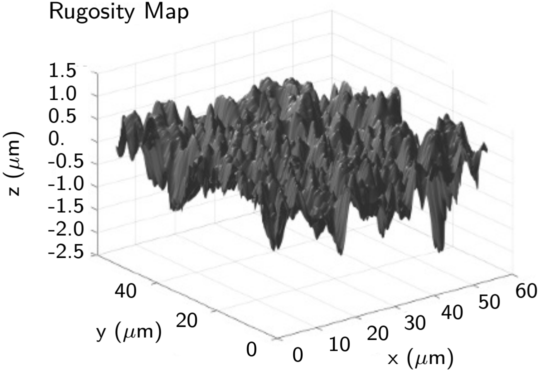


- Step length limit (range cut) of the secondary particles: **Default from Geant4**
  $\rightarrow$ More realistic, similar simulation time

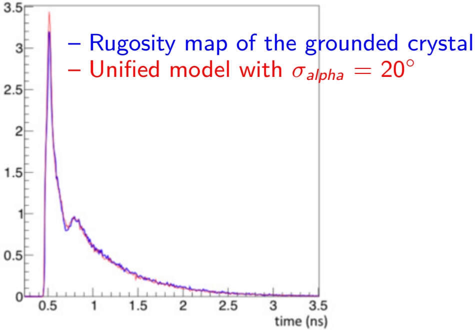
Crystal Surface Configuration

- Crystal: $PbWO_4$
  - Size: $59 \times 59 \times 5$ mm^3
  - Surfaces: 2-sided polished + 4-sided grounded

Rugosity Map



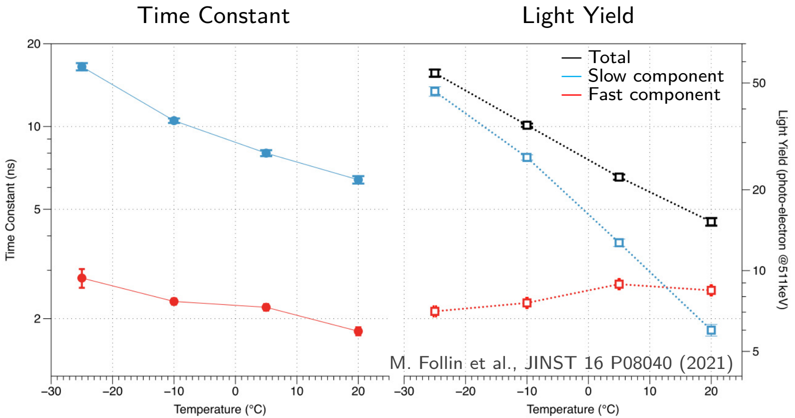
Photon Collection Time



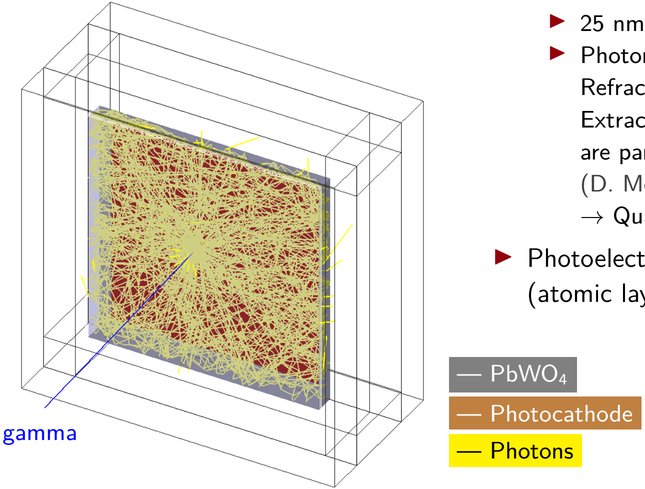
M. Follin et al., JINST 16 P08040 (2021)

Scintillation Yield and Time Constants

- Scintillations (fast/slow)
  - Light yield: 300 photons/MeV
  - Fast component fraction: 58.6%
  - τ_{fast}: 1.79 ns
  - τ_{slow}: 6.41 ns



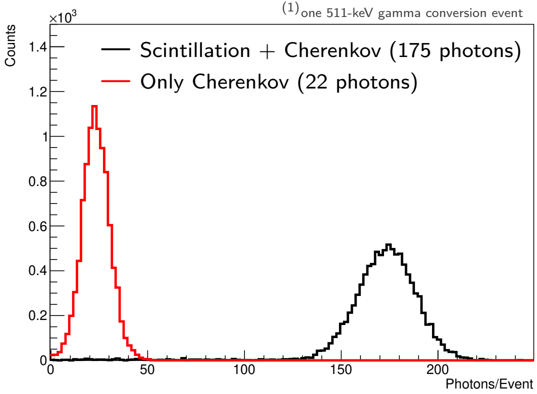
Photocathode Configuration



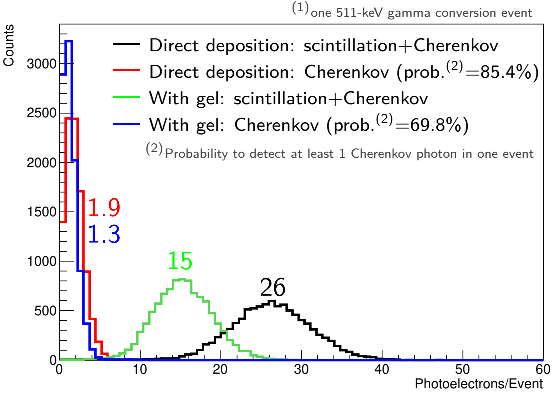
- Bialkali-blue photocathode
  - 25 nm thickness, directly deposited to $PbWO_4$
  - Photon absorption length
    Refractive index
    Extraction probability
    are parametrized as a function of wavelength
    (D. Motta et al, 2005)
    $\rightarrow$ Quantum efficiency: $\simeq$ 30% in 400 nm
- Photoelectron collection efficiency = 90%
  (atomic layer deposited coated MCP)

Photon Production and Photoelectron Detection

Photon Production[1]



Photoelectron Detection[1]

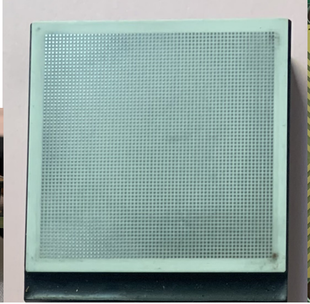


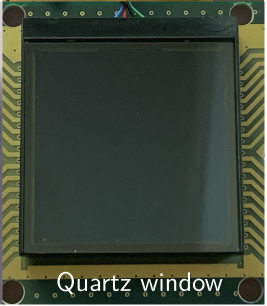
PMT Hardware Setup & Model

- PMT model tuned on the experimental data with parameterised approach
- Measure using PHOTEK detector and pico-second laser in the single photon regime
    - Amplitude gain and fluctuation
    - Charge sharing between lines
    - Time distribution (time transit spread)
    - Digitized signal shape

Transmission line RO board[1]

Anode pads of PMT[2]

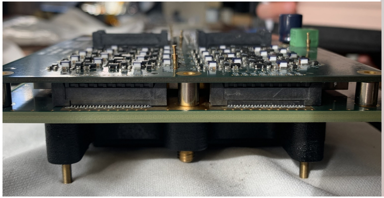




Amplifier board →

Readout board[1] →

$PbWO_4$+PMT[2] →



Detector Composition

PHOTEK, MAPMT253 Standard Detector

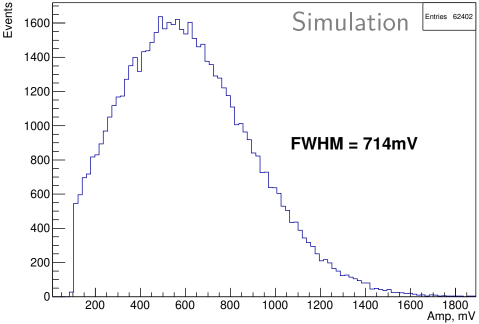
- Amplifier: 40 dB, 1GHz (Bandwidth) (IJC Lab, Orsay, France)
- PMT Gain: $\simeq 10^6$

$$\textit{Charge Density} = e^{-\frac{(X_{pe}-X_{pad})^2+(Y_{pe}-Y_{pad})^2}{2\sigma^2}}$$

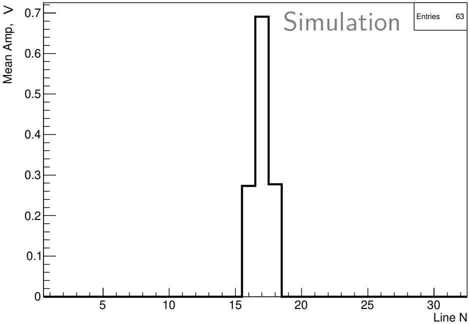
(σ = 0.875 mm)

- Charge is mainly induced on 3 lines

Average Amplitude per Photoelectron*



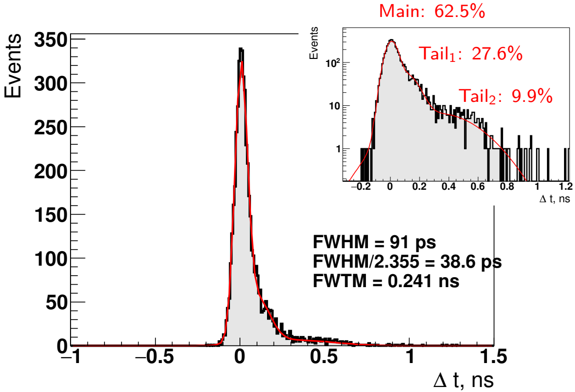
Average Amplitude per Line*



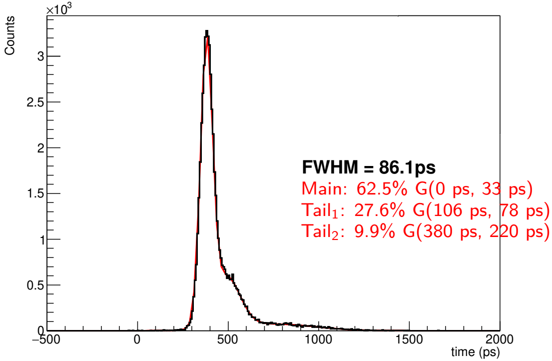
*single photoelectron event

PMT Time Response

Measurement
PMT Time Distribution in single position

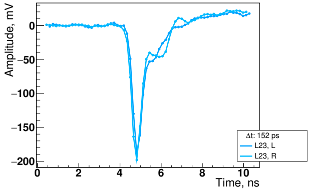


Simulation
Time Transit Spread Implementation



Signal Shape in Detail

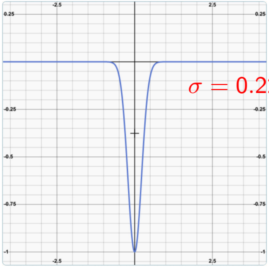
Digitization module: SAMPIC



- Signals pile up on same readout line
- Event reconstruction relies on the signal shape

$$F(t) = -e^{\frac{-t^2}{2\sigma^2}} + A_{rebound} \cdot [B_{rebound} + tanh(C_{rebound} \cdot (t - \Delta t))] \cdot e^{\frac{-(t-\Delta t)}{\tau}}$$

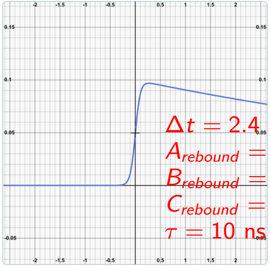
Gaussian



$\sigma = 0.22$ ns

$+$

tanh · exp



$\Delta t = 2.4$ ns

$A_{rebound} = 5\%$

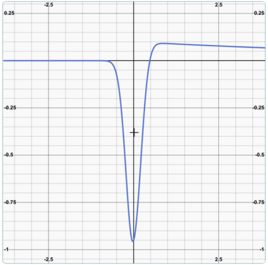
$B_{rebound} = 1$

$C_{rebound} = 10$

$\tau = 10$ ns

$=$

Signal

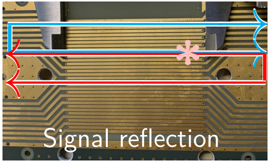


Realistic Signal Shape - with Reflection

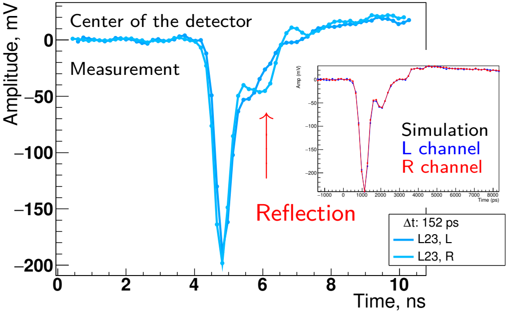
$$F(t) = -e^{\frac{-t^2}{2\sigma^2}} + A_{rebound} \cdot [B_{rebound} + tanh(C_{rebound} \cdot (t - \Delta t))] \cdot e^{\frac{-(t-\Delta t)}{\tau}}$$

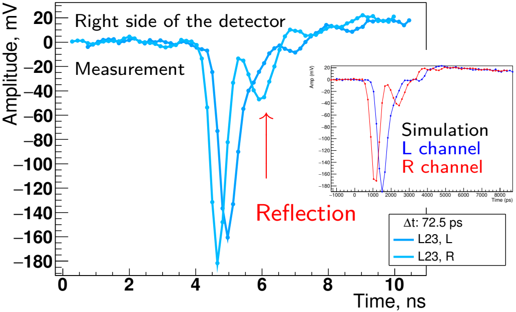
Main peak + Reflection peak = $F(t_{pe}) + 25\% \cdot F(t_{pe} + dt)$

- $\sigma = 0.22$ ns, $\Delta t = 2.4$ ns, $A_{rebound} = 5\%$, $B_{rebound} = 1$, $C_{rebound} = 10$, $\tau = 10$ ns
- t_{pe}: photoelectron detection time
- dt: delay time of the reflection



Digitized using SAMPIC_V3C module

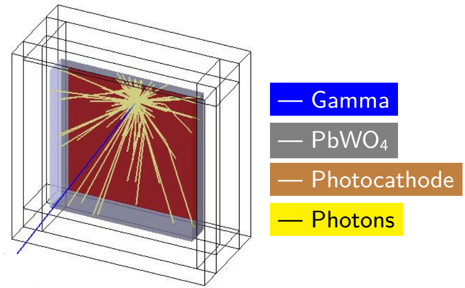


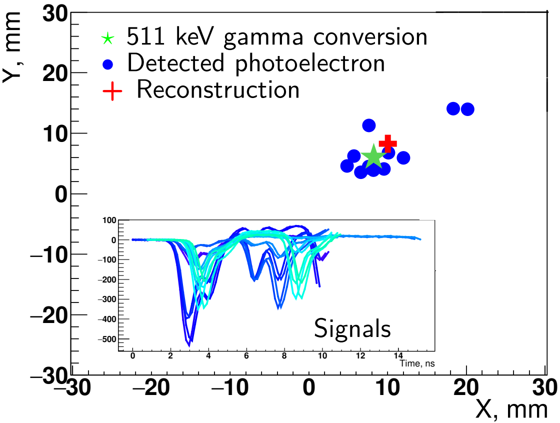


Outline

Sample Data Preparation

- Simplified detector
  - Black surfaces around the crystal → No reflection
- Event reconstruction target
  - x, y, Depth of interaction (DOI) of gamma conversion in each detector



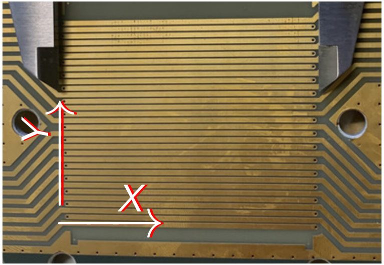


X & Y Reconstruction Method I

Statistical Method

- X reconstruction:
  - dt_i = Time difference of left and right ends on line i
  - $x_\gamma = dt_i/2 \cdot Signal\ Speed$
  - line i: line with maximum charge

- Y reconstruction:
  - $y_i = i^{th}\ line\ coordinate$
  - $y_\gamma = \frac{\sum_{i-1}^{i+1} y_i \cdot w_{charge,i}}{\sum_{i-1}^{i+1} w_{charge,i}}$

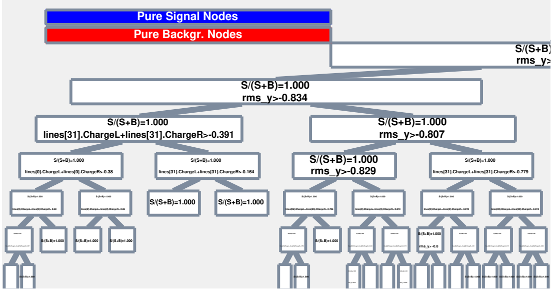


X & Y Reconstruction Method II

Machine Learning/Deep Learning Method

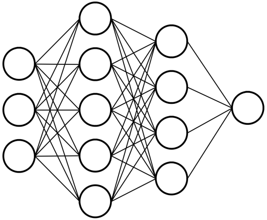
- ROOT-TMVA package: Regression
  - Gradient Boosted Decision Tree (BDTG)[a]
  - Deep Neural Network (DNN)[b]

a. BDTG illustration

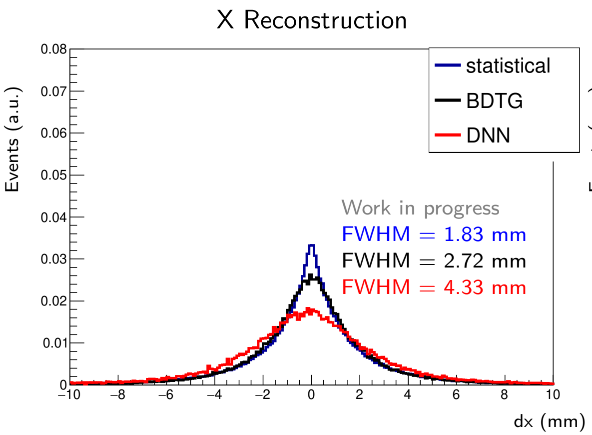


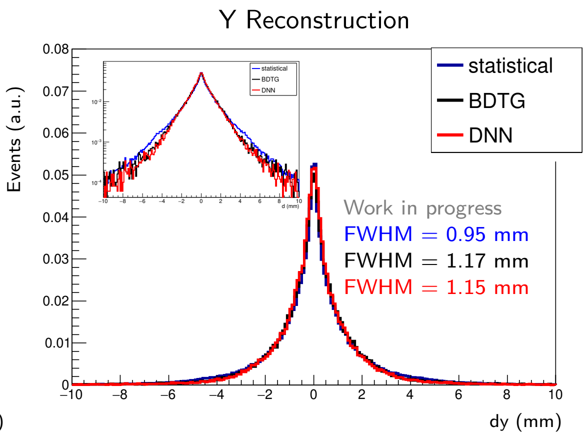
- Input variables: Information from the signals
  - X: Signal charge on each lines
    Time difference between left and right channel signals
  - Y: Signal charge on each lines

b. DNN illustration



X & Y Reconstruction Results

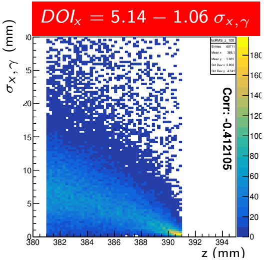




DOI - Reconstruction

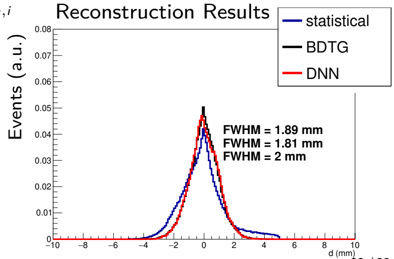
Statistical Method

- Depth-of-Interaction (DOI) reconstruction:
  correlation between σ (spread of photoelectrons) and DOI
  - $x_{pe,i} = dt_i/2 \cdot Signal\ Speed$ $\qquad y_{pe,i} = i^{th}\ line\ position$
  - $x_\gamma = \dfrac{\sum_{i=1}^{32} x_{pe,i} \cdot w_{charge,i}}{\sum_{i=1}^{32} w_{charge,i}}$ $\qquad y_\gamma = \dfrac{\sum_{i=1}^{32} y_{pe,i} \cdot w_{charge,i}}{\sum_{i=1}^{32} w_{charge,i}}$
  - $\sigma_{x,\gamma} = \sqrt{\dfrac{\sum_{i=1}^{32} (x_{pe,i} - x_\gamma)^2 \cdot w_{charge,i}}{\frac{(M-1)}{M} \sum_{i=1}^{32} w_{charge,i}}}$ $\qquad \sigma_{y,\gamma} = \sqrt{\dfrac{\sum_{i=1}^{32} (y_{pe,i} - y_\gamma)^2 \cdot w_{charge,i}}{\frac{(M-1)}{M} \sum_{i=1}^{32} w_{charge,i}}}$



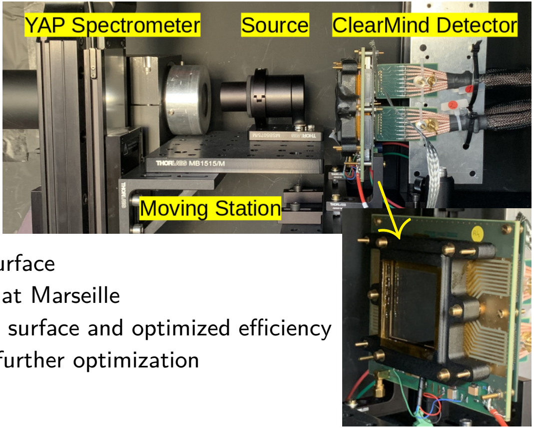
Machine Learning/Deep Learning Method

- Input variables:
  Information extracted form the signal
  - DOI: Charge of lines, $\sigma_{x,\gamma}$, $\sigma_{y,\gamma}$



Conclusion & Perspectives

Measurement Setup for the ClearMind Detector



- Develope a realistic ClearMind detector simulation
- Demonstrate the event reconstruction with statistical and machine learning methods
- ClearMind Project Status

Testing - Stage I: Thin (5 mm) detector with 1 detection surface
Test 2 detectors with the rotating stages at Marseille

In 2022 - Stage II: Thick (10 mm) detector with 1 detection surface and optimized efficiency
Stage III: Detector with 2 detection surfaces and further optimization

- Future work
  - Full PET scanner simulation
  - Using full signal shape for the reconstruction

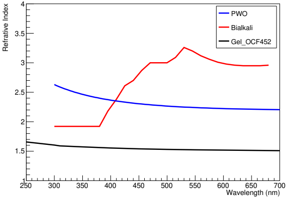
Back up

Parameters

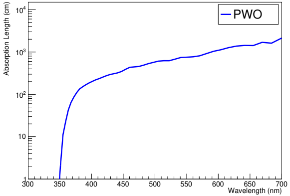
*D. Motta et al, 2005

ClearMind

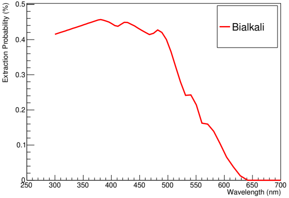
Refrative Index*



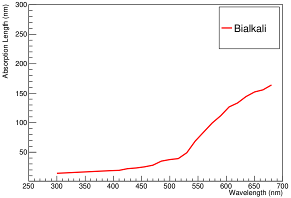
PWO Absorption Length



Extraction Probability*



Photocathode Absorption Length*

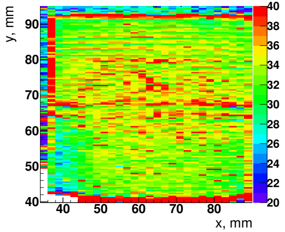


TTS Implementation Details

MAPMT253 Measurement

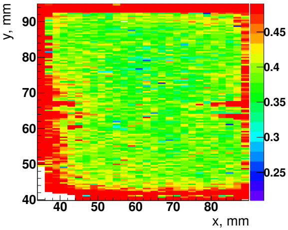
σ of the main peak

$\sigma_{main} = 33ps$ (Work in progress)



Fraction of the tails

$frac_{tail1+tail2} = 38.5\%$



Simulation
Time Transit Spread Implementation