Event Reconstruction for an Opaque Liquid Scintillator

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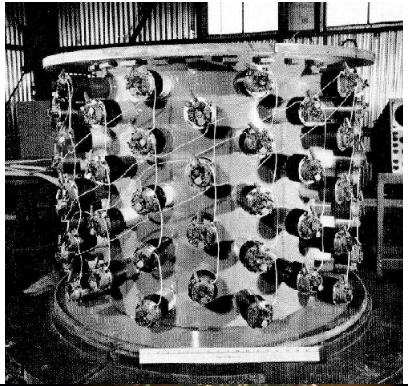
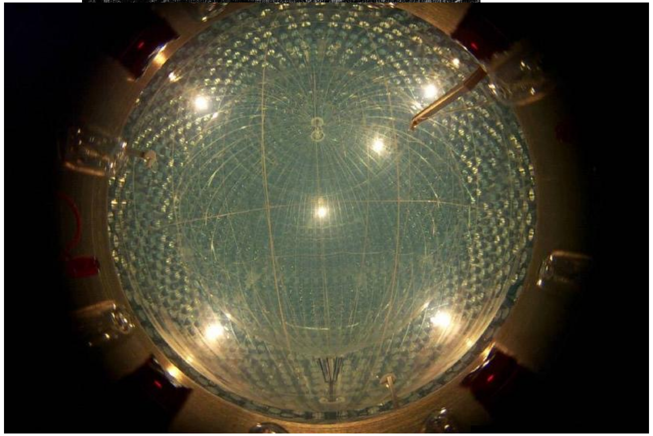
Transparent Liquid Scintillator Detectors for Neutrino Physics



[The Savannah River neutrinos detector. C. Cowan and F. Reines]



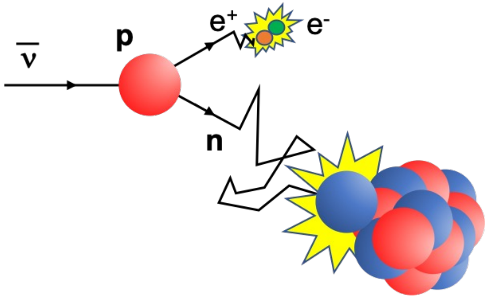
[Credit:Borexino Collaboration]

- Charged particles pass through the **material** exciting its **molecules** and **producing light.**

Carbon and Hydrogen

Organic liquid scintillators (e.g Linear Alkylbenzen (LAB) or pseudocumene (PC).

- **Well-established** technology for neutrino experiments.
- For **neutrino detection** → scintillation photons from **positron annihilation** and **neutron capture.**



Transparency ensures efficient photon detection.

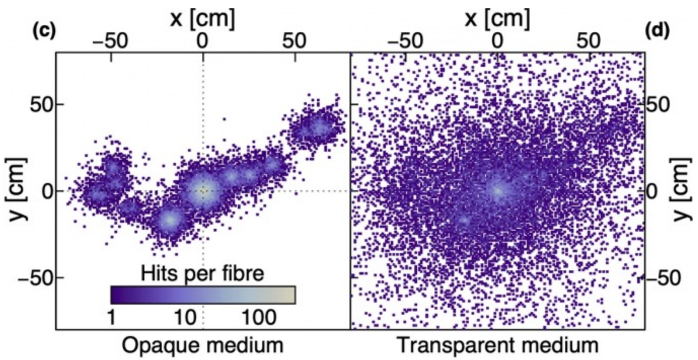
Limitation on the detector size.

Opaque Liquid Scintillator Detectors

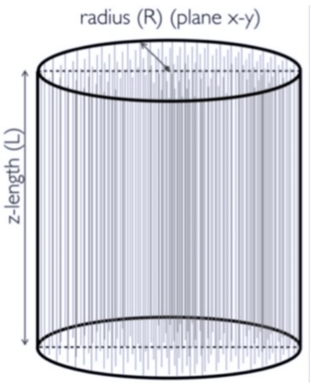
- Liquid scintillator that introduces opacity by **doping transparent scintillator** like Linear alkylbenzene (LAB) with different materials (e.g. wax).
- The light becomes **stochastically confined around the interaction point** and collected by fibers.
- The **topology** of the event is conserved

  → **powerful particle discrimination capabilities**

  (identify positron annihilation by detecting the e^+ itself along the $\gamma\gamma$)



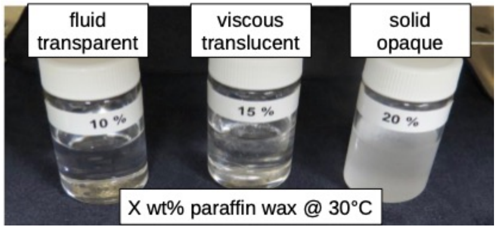
[Example of a 1 MeV e+ simulated event in an opaque scintillator(left) and in a transparent scintillator(right). Source: Nature's Communication Physics 4 273 2021 Credit: LiquidO Consortium]



[Credit: J. Pedro Ochoa-Ricoux]

Basic detector design:

Scintillator Volume + Wavelength shifting fibers + Photosensors



[LAB with different concentrations of wax resulting in a wax-based (NoWaSH) opaque scintillator (Source: JINST 14 (2019) P11007)
Credit: S. Schoppmann]

The Chooz LiquidO Ultranear Detector (CLOUD)

The first opaque scintillator (LiquidO) neutrino experiment that will address neutrino fundamental research and reactor monitoring using **reactor neutrinos** at Chooz.

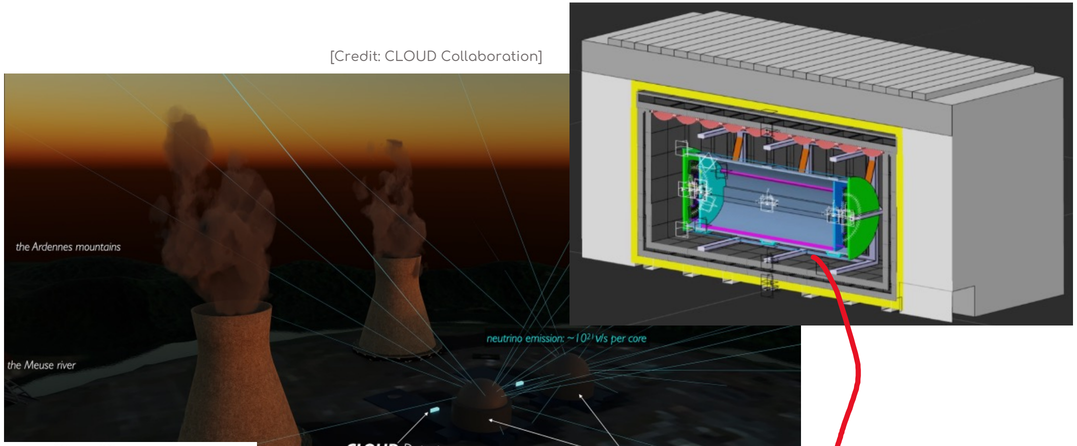
produced when the radioactive products of nuclear fission undergo beta decay:

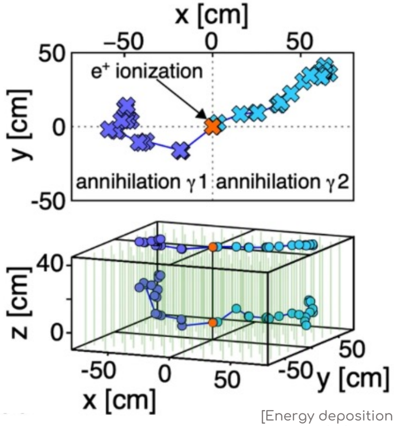
$$(A,Z) \longrightarrow (A,Z+1) + e^- + \bar{\nu}$$

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

Take advantage of LiquidO imaging potential to improve background control and sensitivity → directly identify positron annihilation

[Credit: CLOUD Collaboration]





[Energy deposition from a 1 MeV e+ simulated event in LiquidO. Source: Nature's Communication Physics 4 273 2021 Credit: LiquidO Consortium]

Inner detector:

- 5-10 tons cylindrical volume of 90 cm radius and 4 m length filled with opaque scintillator.
- ~ 10,000 WLS fibers along the volume and SiPMS at both ends of the fibers

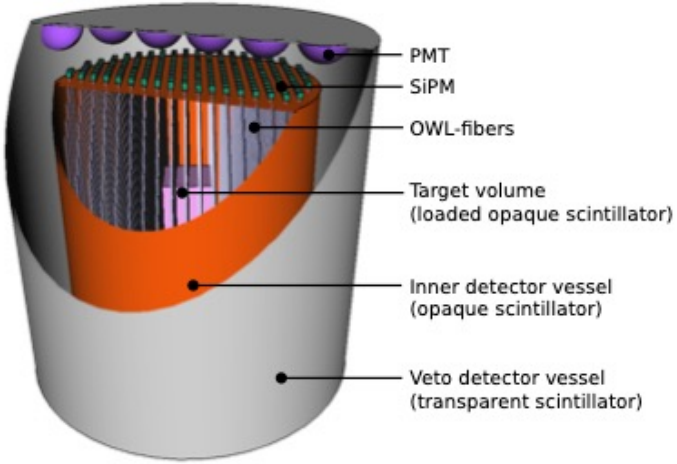
Neutrino Double beta plus plus (NuDoubt++) detector

A novel isotope-loaded (Kr-78) liquid scintillator detector that plans to combine **hybrid** (WbLS/slow LS) and **opaque scintillators** for double beta decay searches [arXiv:2407.05999v2].

Two main modes: $2\nu\beta\beta$ and $0\nu\beta\beta$.
Also: **double electron capture ($2\nu ECEC$) and electron capture + positron emission ($2\nu\beta^+EC$)**

Proposed design:

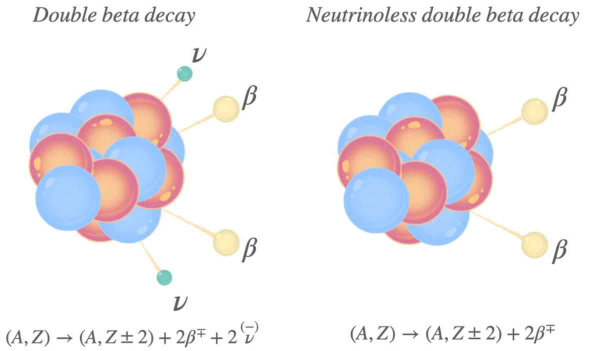
- 1-ton cylindrical volume of 110cm diameter and 110 cm length filled with hybrid + opaque scintillator.
- Optimized Wavelength-shifting-fibers parallel to the detector.
- SiPMs on both ends



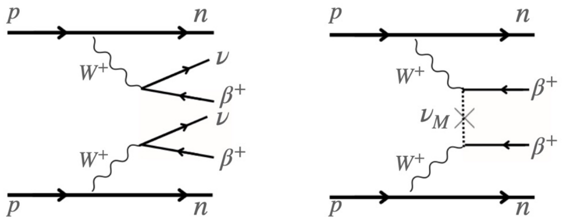
[Proposed design for the NuDoubt++
Credit: NuDoubt++ collaboration]

$2\nu\beta^+EC$, $2\nu\beta^+\beta^+$ and the $0\nu\beta\beta$ variants **have not been observed yet** → physics beyond the SM (Majorana masses, lepton number conservation)

Same signatures for **signal** and backgrounds (e^+, e^-, γ) → **requires excellent background suppression.**



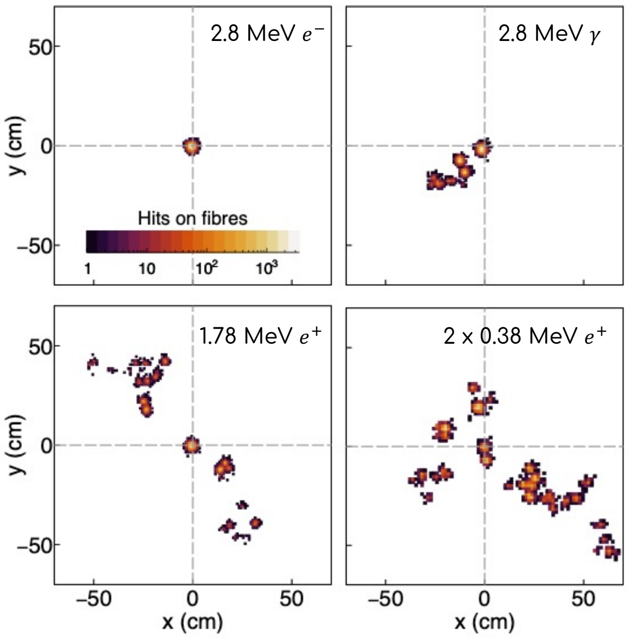
[Credit: V. Palusova]



[Feynman diagrams for double beta decay and neutrinoless decay. Credit: V. Palusova]

Event Reconstruction for an Opaque Liquid Scintillator Detector

- Develop **reconstruction methods** adapted to the characteristics of opaque scintillators to **exploit their detection capabilities → different event topologies depending on the particle.**



[Particle discrimination in opaque scintillator based on the topology of the event. Credit: NuDoubt++ collaboration]

- Focus on **discriminating low-energy** (< 10 MeV) $\boldsymbol{e^-}$**,** $\boldsymbol{e^+}$ **and** $\boldsymbol{\gamma}$ events.
- Different approaches such as **GNNs** are also being studied within the CLOUD collaboration.
- Explore the idea of adapting **jet clustering algorithms** as a classical reconstruction alternative.

Why jet clustering algorithms?

- ✓ Well established
- ✓ They can handle complex event topologies

Sequential recombination algorithms (k_t-algorithms)

The idea behind **the k_t algorithms** is to examine four-vector inputs pairwise and construct jets **hierarchically based on some distance measure.**

$$\boxed{d_{ij} = \min\left(k_{ti}^{2p}, k_{tj}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2}}$$

$$\boxed{d_{iB} = k_{ti}^{2p}}$$

$\boldsymbol{k_t}$: transverse momentum of the *i-th* and *j-th* particles.

$\boldsymbol{\Delta R_{ij}^2}$: distance between particles *i* and *j*.

$\boldsymbol{R}$: resolution parameter.

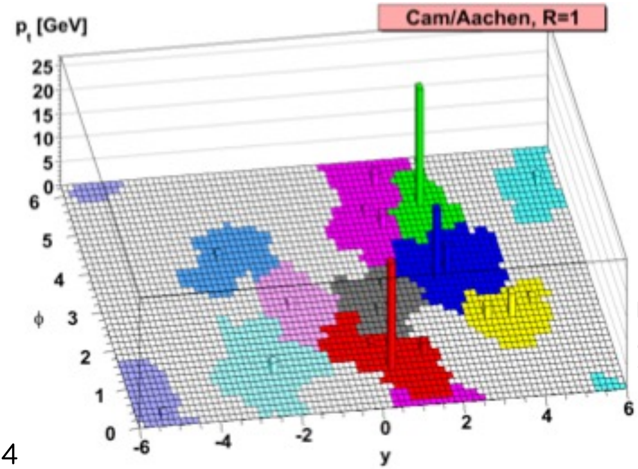
$\boldsymbol{d_{iB}}$: "beam distance" (distance between particle *i* and *beam*)

For $\boldsymbol{p = 1}$ one get the k_t algorithm, $\boldsymbol{p = -1}$ results in the anti- k_t algorithm and with $\boldsymbol{p = 0}$ one obtain the Cambridge-Aachen algorithm:

$$\boxed{d_{ij} = \frac{\Delta R_{ij}^2}{R^2}}$$

$$\boxed{d_{iB} = 1}$$

$\Rightarrow$ implement the Cambridge-Aachen algorithm for an opaque liquid scintillator.



[Example of the clusters found by the C-A algorithm in the context of high-energy jets. Source: arXiv:0802.1189]

Adapting the Cambridge-Aachen algorithm

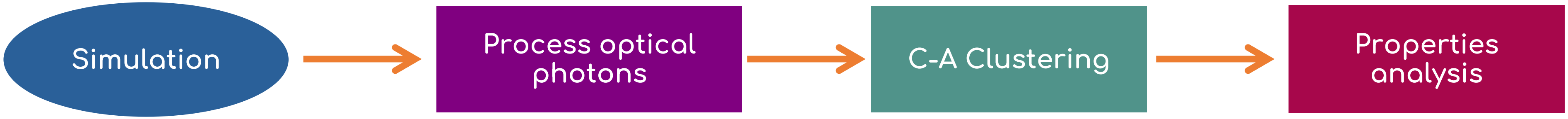
To implement the Cambridge-Aachen algorithm in the context of an opaque liquid scintillator:

$$d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$$

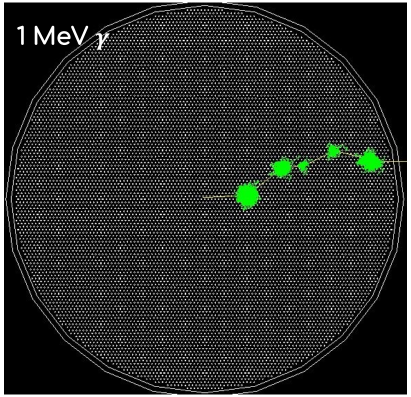
$$d_{iB} = 30\ mm$$

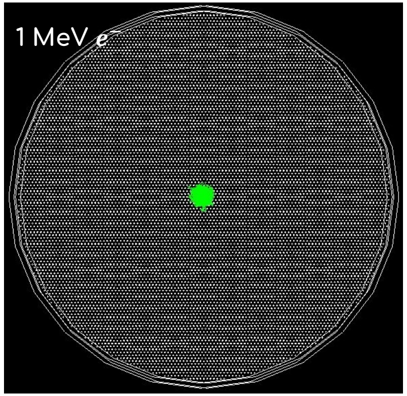
- Take the **distance measure** as the 2D Euclidean distance: $\Delta R_{ij}^2 = \Delta x_{ij}^2 + \Delta y_{ij}^2$ and $R = 1$
- **Optical photons** instead of particles.
- Reconstruct **blobs (bulky light objects)** instead of jets.
- Instead of $d_{iB} = 1$, choose a **reasonable** d_{iB} constant for all photons as the **distance threshold** for deciding when a photon should no longer be merged, and the cluster formed is considered a final cluster.
- Do not consider coordinate z yet since one needs a more refined strategy to determine the resolution on z.

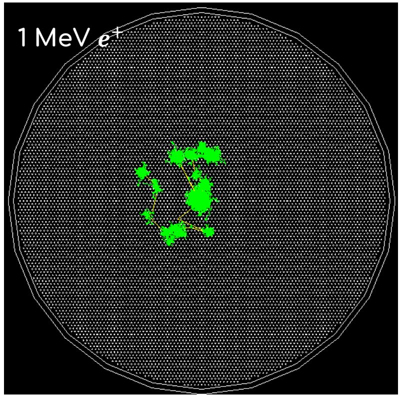
Reconstruction pipeline



Reconstruction pipeline: Simulation





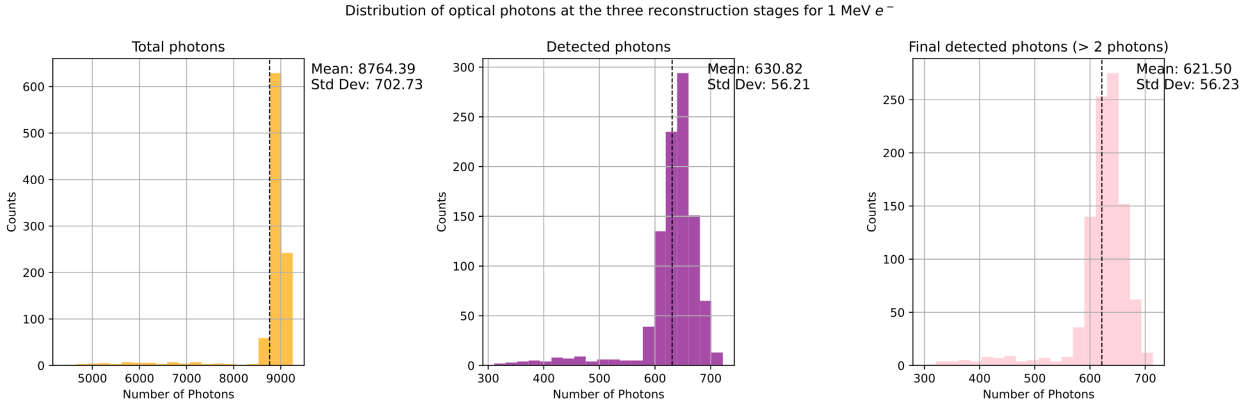


Geant4 simulation of **1 MeV e^-, e^+ and γ (1000 events each)** in the **NuDoubt++ like** configuration:

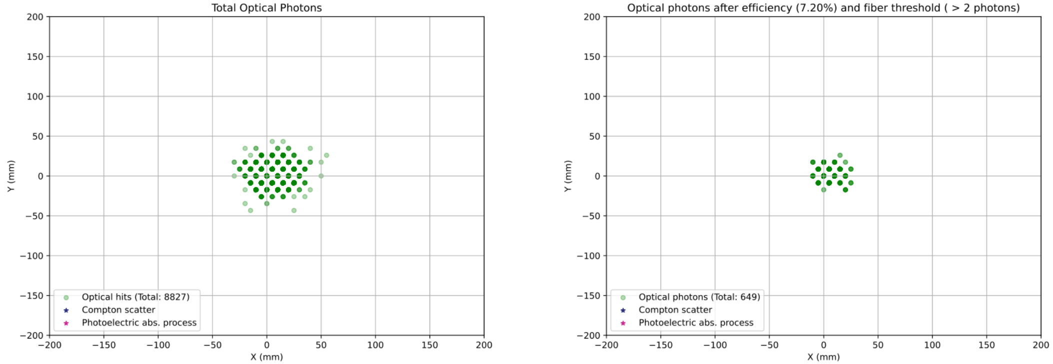
- Cylindrical detector of 110 cm long and 110 cm diameter.
- Fiber diameter (3 mm) and fiber spacing (1 cm).
- Fiber array: hex z-parallel.
- Detector material: 98% LAB, 2% paraffin wax detector.
- Scattering length = 2mm, Absorption length = 2m, Scintillation yield = 9000 photons/MeV

Reconstruction pipeline: Process optical photons

- Distribute photons (top and bottom SiPMs).
- Apply **detection efficiency** based on the OWL fiber properties **(~ 7.20%).**
- Select fibers with > 2 photons to account for **noise removal effect.**



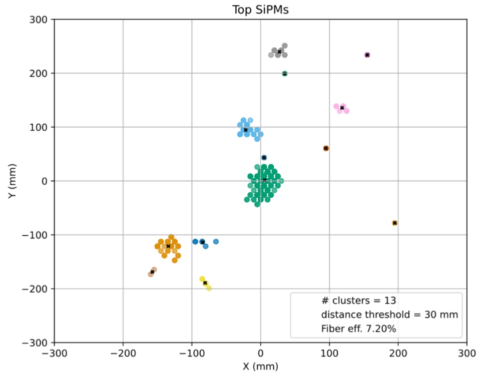
Example of the visualization of the optical photons produced by a 1 MeV e^- event before and after fiber efficiency.



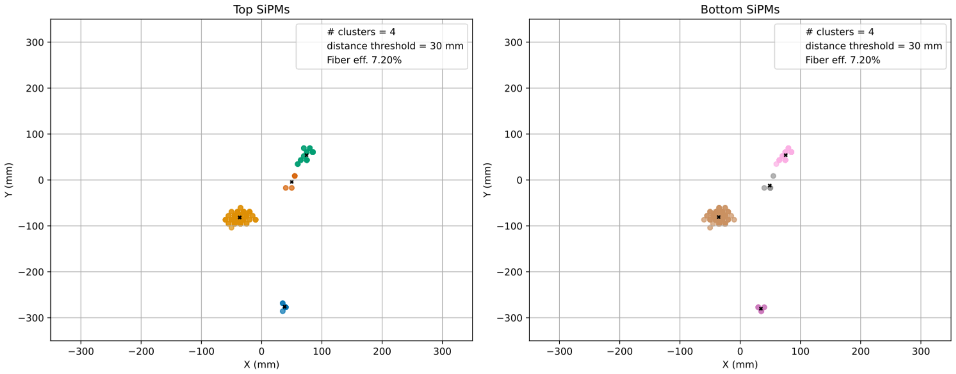
Reconstruction pipeline: Clustering

Apply the Cambridge-Aachen algorithm to top and bottom SiPMs photons.

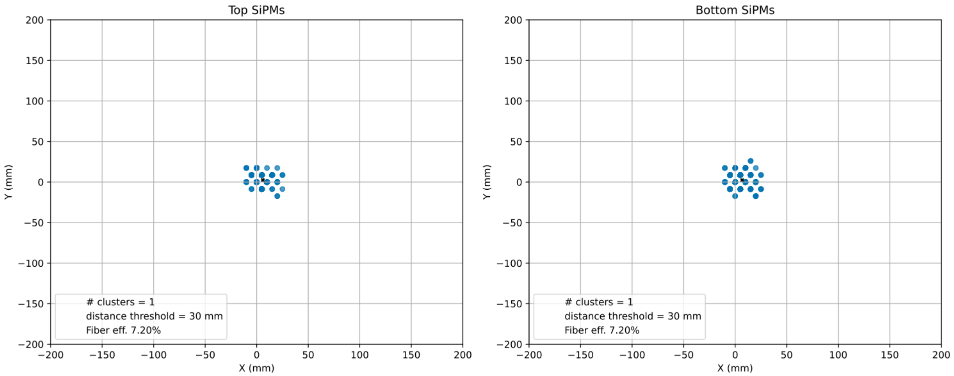
Cluster visualization for a 1 MeV e^+ event



1 MeV γ cluster visualization



Cluster visualization for a 1 MeV e^- event



Cluster visualization in the x-y plane for an event of 1 MeV e+(left), γ (right), and e- (center). Each black mark represents the COM of that cluster.

Reconstruction pipeline: Properties analysis

As a **result of the clustering,** we have different properties that can aid in the **reconstruction and/or discrimination of an event:**

- **Number of clusters per event.**
- The center of mass coordinates (x,y) of each cluster.
- Time of each cluster.
- The energy of each cluster.
- RMS (x, y, time, energy)

→ Consider the number of clusters as the number of blobs in the event

Additionally, we have the **true information** from the simulation that includes:

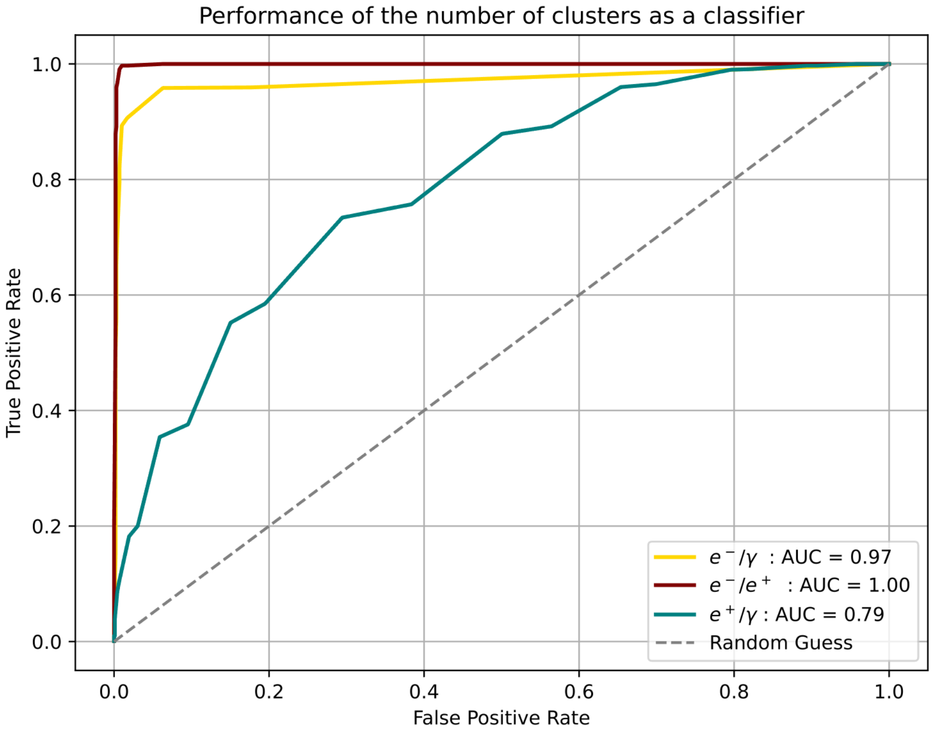
- **Compton scattering information** (position, time, angle, energy deposited).
- Photoelectric process information (position, time, energy deposited)

→ Compton scattering is the main energy loss mechanism thus we expect to be able to reconstruct the chain of scatters

Properties analysis: Discrimination via number of clusters

To have a first approximation of the event discrimination capabilities of this method:

- Choose the number of clusters as a classifier.
- Perform a simple binary classification.
- Obtain ROC curve for the cases: e^-/γ, e^+/γ, and e^-/e^+.
- This method can also be used to get a first estimate of the signal/background ratio.

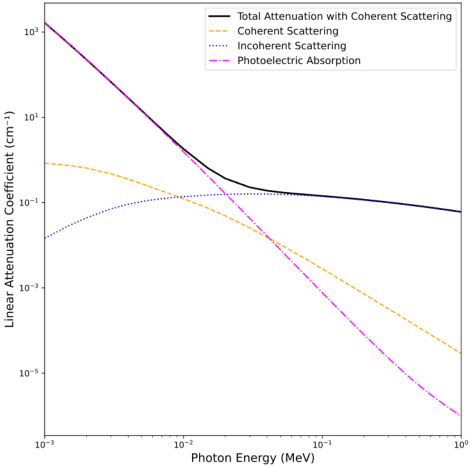


ROC curves for the three different discrimination scenarios. The AUC represents how well we can distinguish between event topologies.

Properties analysis: Comparing with true information

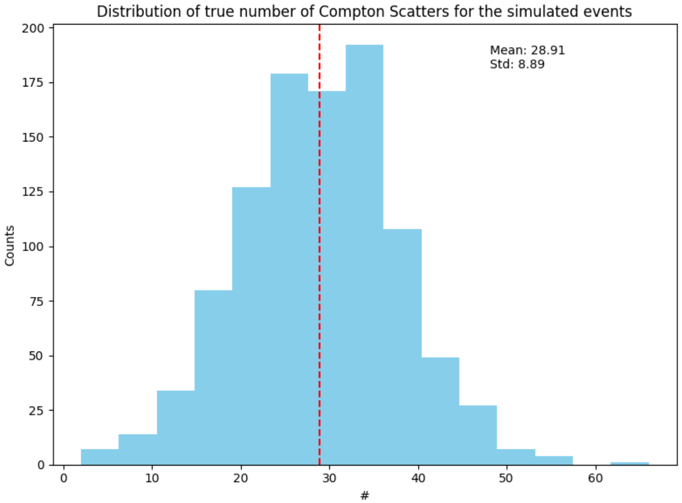
One of the main ideas is to use the cluster properties to reconstruct the chain of Compton scatters produced by the particle interaction (e^+ or γ).

Linear attenuation coefficient for gammas in LAB [NIST-XCOM data-base].



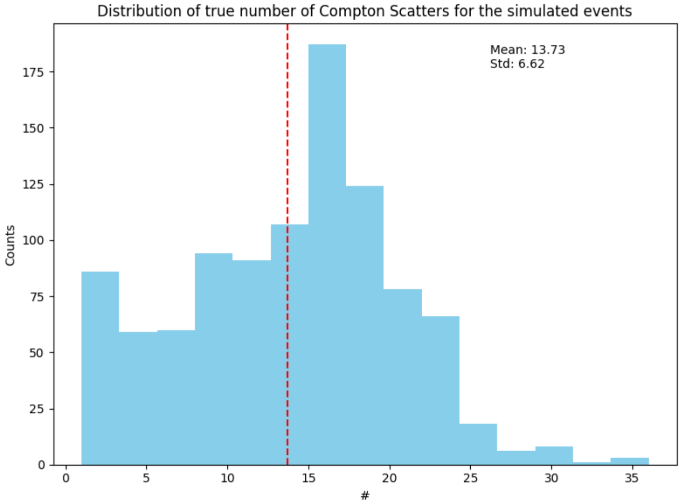
In the range of energies we are interested in, incoherent scattering (Compton) is the predominant effect. The inverse of the linear attenuation coefficient corresponds to the distance traveled by gammas in LAB.

True Compton scattering information for the 1 MeV e^+ simulated events.



Distribution of the true number of Compton scatters for 1 MeV e^+. The mean agrees with the typical extension (distance traveled) for the two gammas originating from positron annihilation.

True Compton scattering information for the 1 MeV γ simulated events.

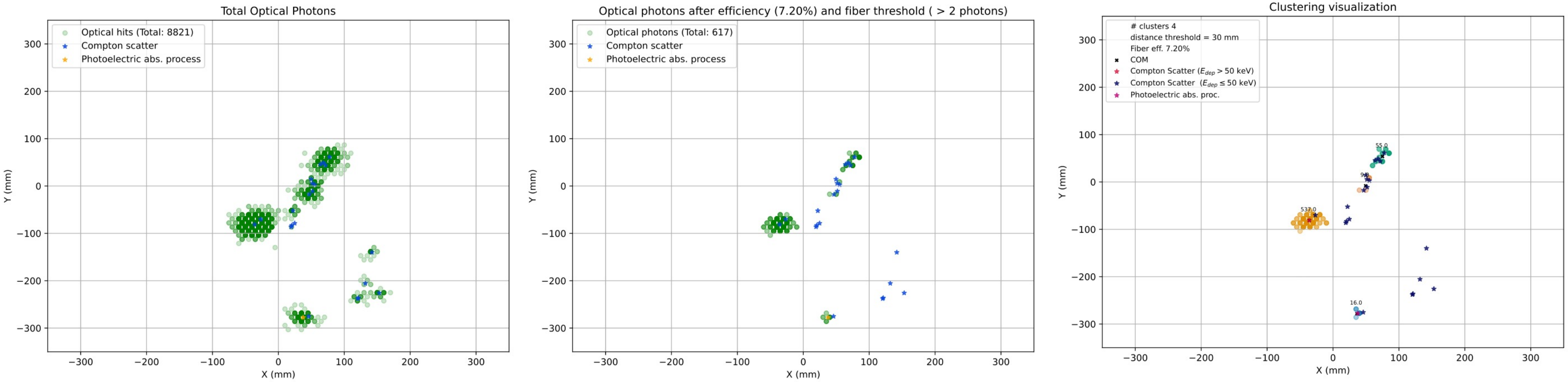


Distribution of the true number of Compton scatters for 1 MeV γ. The mean agrees with the typical extension (distance traveled) for a gamma in LAB.

Properties analysis: Comparing with true information

To **compare the true information with the clustering** results, one must match the clusters at each side of the detector this is done via the **closest distance**.

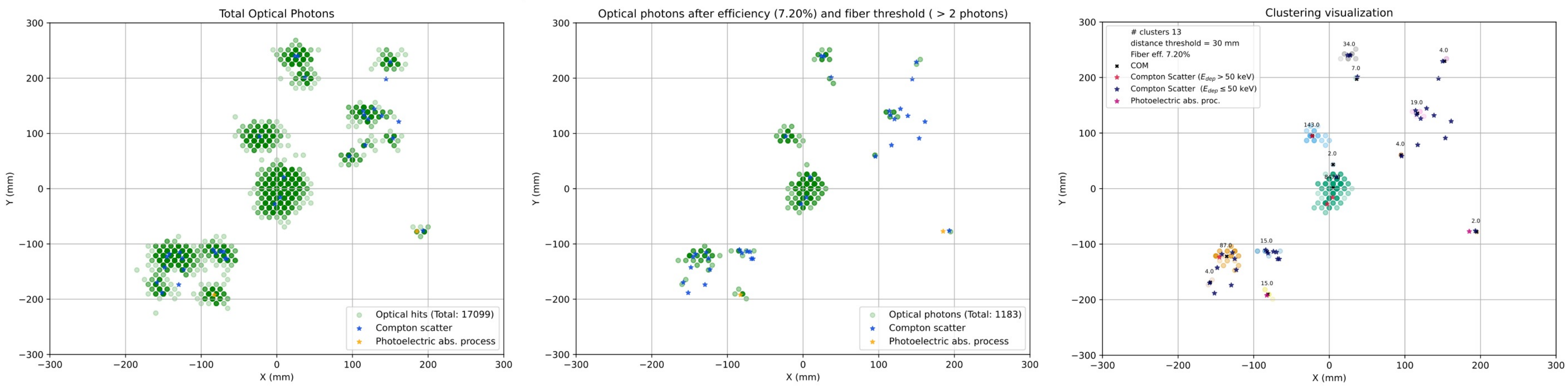
Visualization of the optical photons along the true Compton scattering information produced by a 1 MeV γ event at the three different stages of the reconstruction



The position where a Compton scattering or photoelectric process happens is marked along the three stages. In the clustering, we made the distinction between the Compton scatters that deposited > 50 keV (since is approximately the minimal energy required to produce scintillation light on the detector).

Properties analysis: Comparing with true information

Visualization of the optical photons along the true Compton scattering information produced by a 1 MeV e^{+} event at the three different stages of the reconstruction



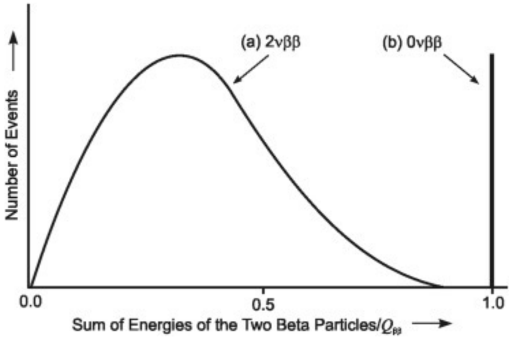
The position where a Compton scattering or photoelectric process happens is marked along the three stages. In the clustering, we made the distinction between the Compton scatters that deposited > 50 keV (since is approximately the energy required to produce scintillation light on the detector).

Summary

- **Opaque scintillators** are a promising technology that offers several advantages like higher light yield, improved energy resolution, and **particle discrimination based on event topology.**
- The **Cambridge-Aachen** algorithm can be implemented in the context of an opaque liquid scintillator detector with encouraging results.
- It can function as a **baseline** to compare with more sophisticated reconstruction methods such as **neural networks**.
- The results presented were done in the context of the NuDoubt++ detector but one can **tune the algorithm for specific geometries** like CLOUD.
- Only using **the number of clusters** per event allows an insight into the capabilities of event discrimination of these detectors.
- More detailed analyses to **compare the cluster properties with the true Compton Scattering information** are still in progress.
- There is still room for improvement; optimize the algorithm, include fiber simulation, electronics noise, etc.

Backup Slides

NuDoubt++



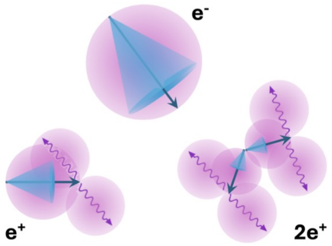
Goal:
Observe two-neutrino double beta plus decay modes:

$$2v2\beta^{+}: (A, Z) \rightarrow (A, Z-2) + 2e^{+} + 2v$$

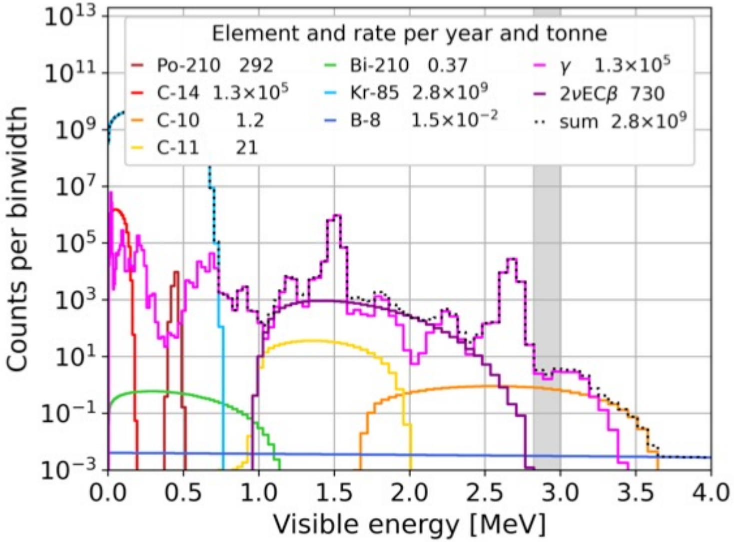
$$2\nu EC\beta^{+}: (A, Z) + e^{-} \rightarrow (A, Z-2) + e^{-} + 2v$$

$$2v2EC: (A, Z) + 2e^{-} \rightarrow (A, Z-2) + 2v$$

Improve the detection limits for neutrinoless double beta decay.



The ratio of Cherenkov and Scintillation light produced can be used as particle discrimination in a hybrid scintillator.



Expected spectra for a NuDoubt++ detector located at the LNGS. Expected signal spectrum for $2\nu EC\beta^{+}$ for isotope loading at 5 bar overpressure with 50% enriched Kr-78. [arXiv:2407.05999v2]

Reconstruction pipeline: Process optical photons

- **Separate the photons into fibers:** Check if they are within the radius of the center of the fiber.
- **Calculate the efficiency of the fiber** (~ 7.20%) by considering the trapping efficiency for the OWL fiber, the QE, and the optical coupling.
- Assign a **50%** probability for the photon going to the top or bottom SiPM.
- With the distance from the the hit position to the SiPM and the attenuation length (5 mt) calculate the **total detection efficiency** as:

$$\boxed{total\ efficiency = \varepsilon_{fiber} e^{-\frac{d}{l_{att}}}}$$

- Assign a random probability to the photon being detected based on the total efficiency.
- Considering the decay time of the fiber, the time spread and the speed of light on the fiber calculate the arrival time of the hit.
- Apply threshold: only keep fibers with < 2 photons.

Cambridge-Aachen algorithm

1. Calculate the distances between the particles
   - Create initial clusters from hits
   - Initialize distance matrix
2. Calculate the beam distances
3. Identify the smallest of the distances and if it is a recombine particles *i* and *j* (merge two particles via four vector summation), if it is , call particle *i* a jet and remove it from the list of particles.
   - Find the clusters with the minimum distance from the matrix and merge them (update the centroid properties).
4. Recalculate the distances and repeat the procedure until no particles are left.
   - Update distance matrix and repeat procedure.

Potential issues: Speed (O(N^3))
It can be optimized up to O(NlnN)
(FastJet algorithm)