Status and upcoming steps for ECal calorimeter reconstruction

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ECAL overview

From DUNE-It last year

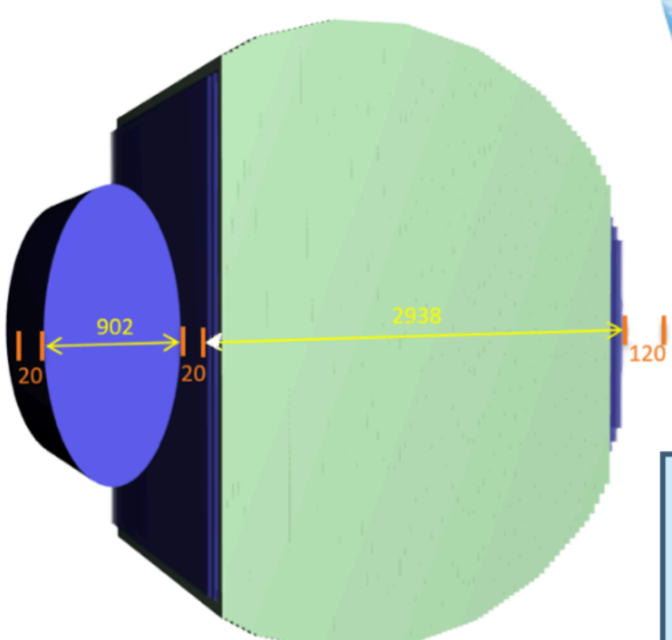
SAND employs an existing superconducting magnet successfully operated at INFN-LNF for the KLOE experiment.

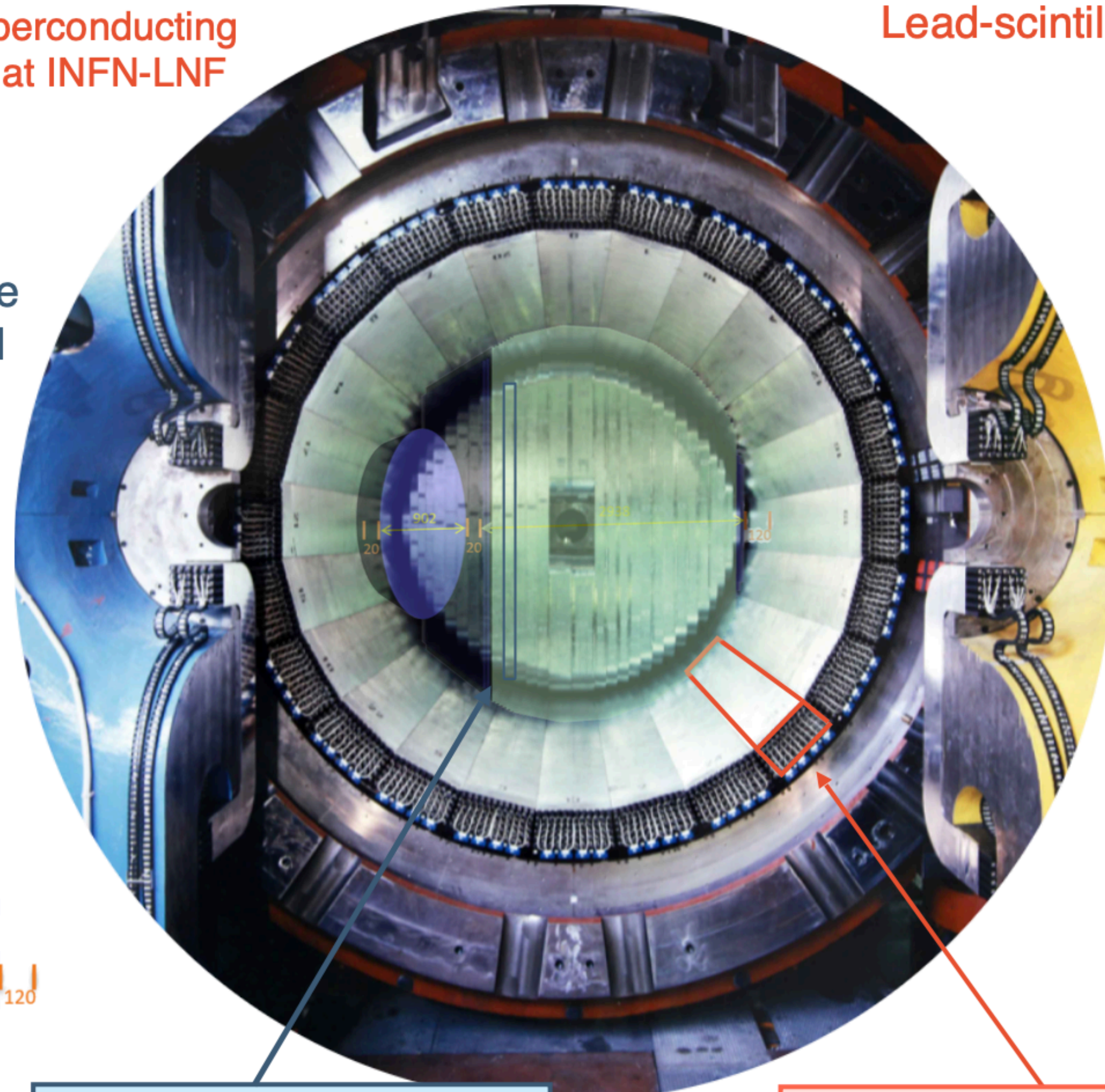
- Coil

Superconducting to produce 0.6 T over a 4.3 m long and 4.8 m diameter volume. located inside a cryostat.

- Iron yoke

~ 470 t





Lead-scintillating fiber sampling calorimeter.

All modules are composed of alternated foils

- 200 lead foils, 0.5 mm thick, grooved to host fibers.
- 200 layers of cladded fibers glued together with special epoxy, 1mm diameter.

Average density $\sim 5g/cm^3$, for an overall thickness of ~15 radiation lengths.

Readout at both ends of each module via PMTs

Endcap

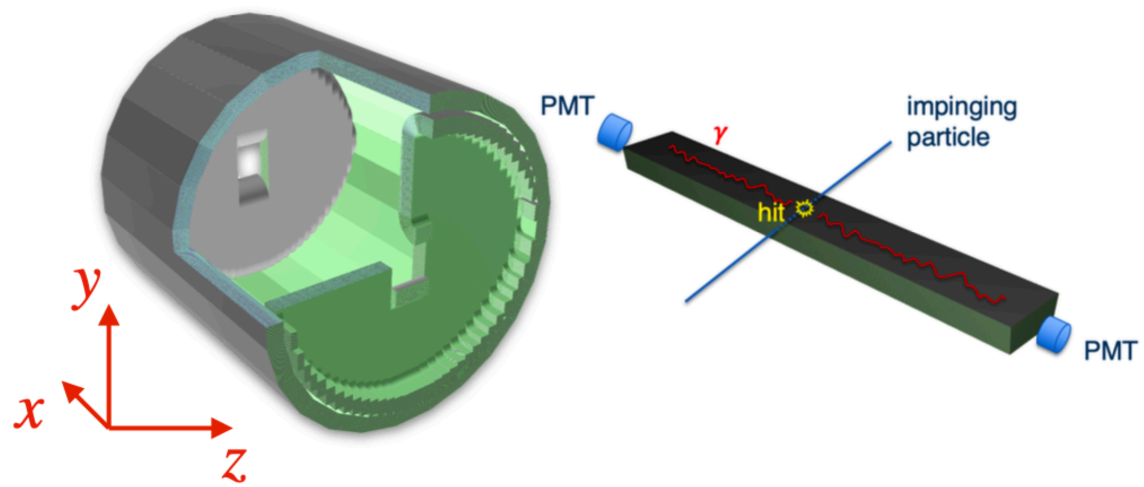
32 C-shaped, different dimensions.

Barrel

24 modules, same dimensions.

Ecal signal reconstruction workflow

Reconstruction of the signal position and time



- Modules segmented in 5 layers w/ cells of 4.4 x 4.4 cm²: 4880 readout channels

- The coordinate along the barrel x(y) is extracted from the time difference between signals at the two ends, z(x) and y(z) are derived from the geometrical center of the fired cell

$$t^e = \frac{t^A + t^B}{2} - \frac{L}{2v}, \quad x^e = \frac{v}{2}\left(t^A - t^B\right)$$

I) Monte Carlo simulation [*edep-sim*]

with MC deposited energy hits,
N_{pe} from Poisson ($\mu_e = \mathrm{dE} \cdot \mathrm{E_{pe}} \cdot \mathrm{A_l}$)
arrival time [ns]

$$\mathrm{t_{pe} = t_{cross} + t_{decay} + \frac{d_{1,2}}{v_{ph}} + Gauss(1ns)}$$

II) Ecal digitisation [ADC, TDC]

from photoelectrons generating the (hit) signal we build digitised photo-signals for each cell-side (A,B): ADC and TDC
DAQ digits stored into a ROOT TTree

III) Ecal clustering

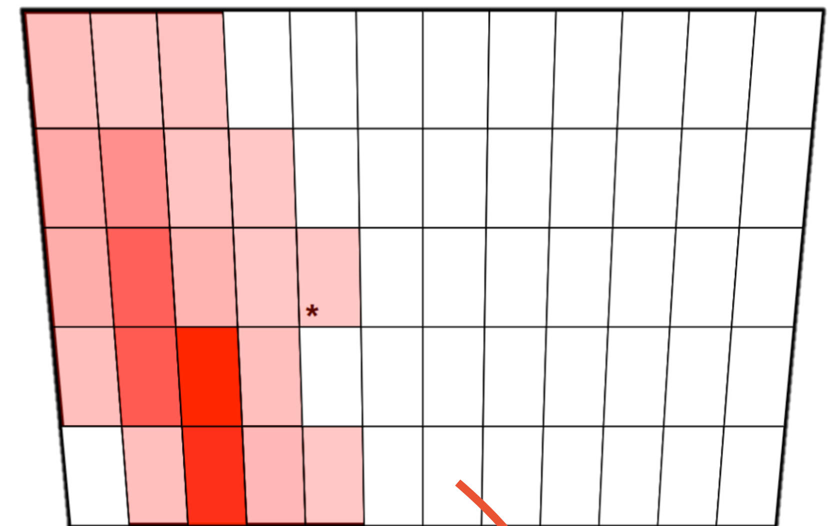
for each event a *cluster* cointaining all the fired cells w/ non-null photo-signal is created and stored into a ROOT TTree

Ecal reconstruction: clustering

Cluster of cells are built up followind these criteria:

- Pre-clustering
  Cells geometrically nearby are merged together
- Splitting
  Pre-clusters are divided in time quadrants relying on time spread
- Merging
  Re-join together clusters with distance < 30 cm and time difference < 2.5 ns

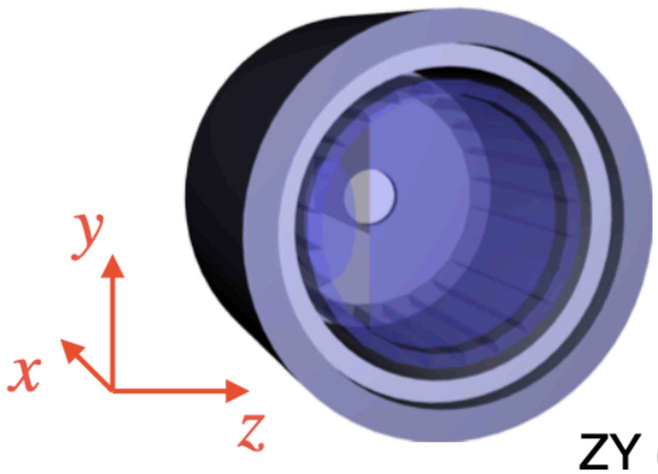
Both complete (PMTs on side A,B measure a signal) and incomplete (single photo-signal) cells are used to generate clusters.



Cluster output structure

- Energy.
- Position.
- Time.
- Collection of reco cells:
  - Cell geo info.
  - Reco energy.
  - Reco time.
  - Photo-signal$_{A,B}$.

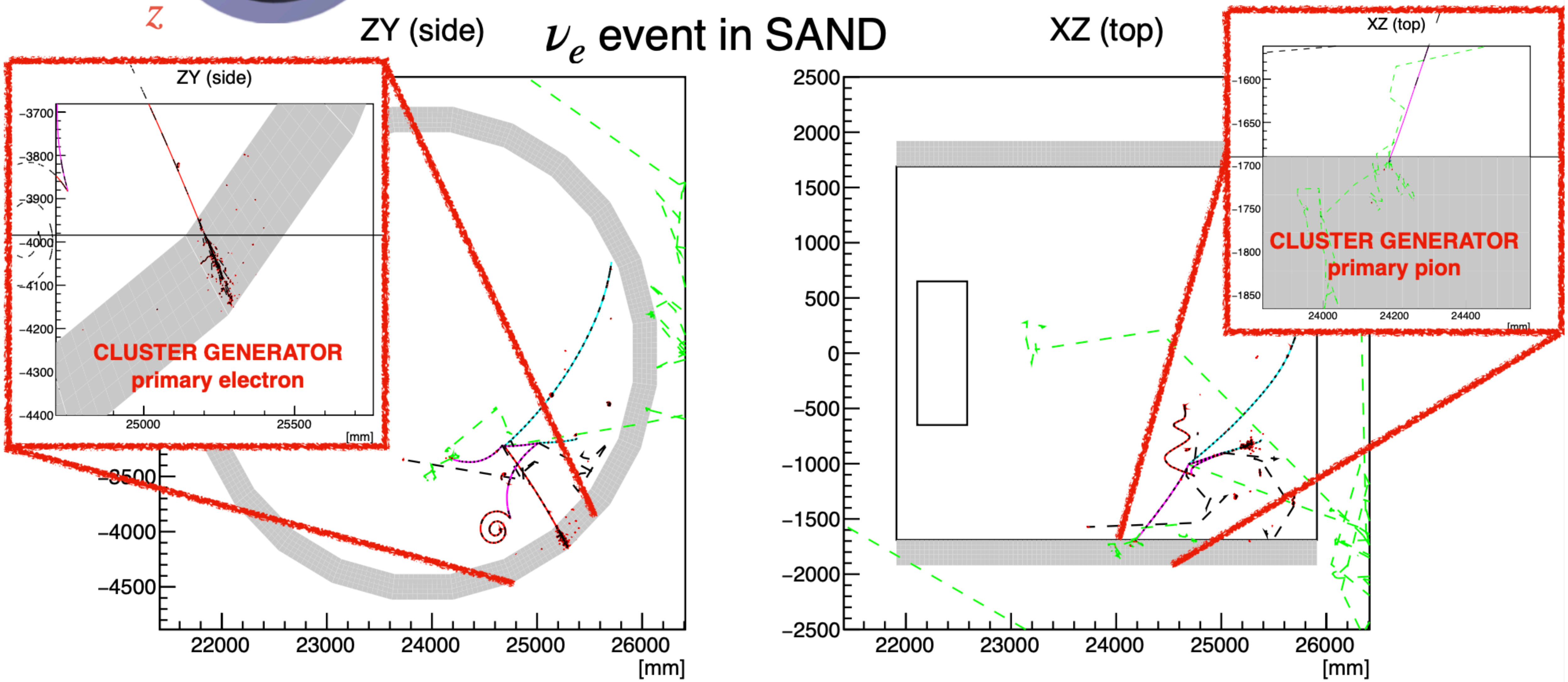
Ecal reconstruction: association cluster/MC



Twofold target:

- **Validate** clustering algorithm.
- **Analysis** for ECAL particle reconstruction performances.

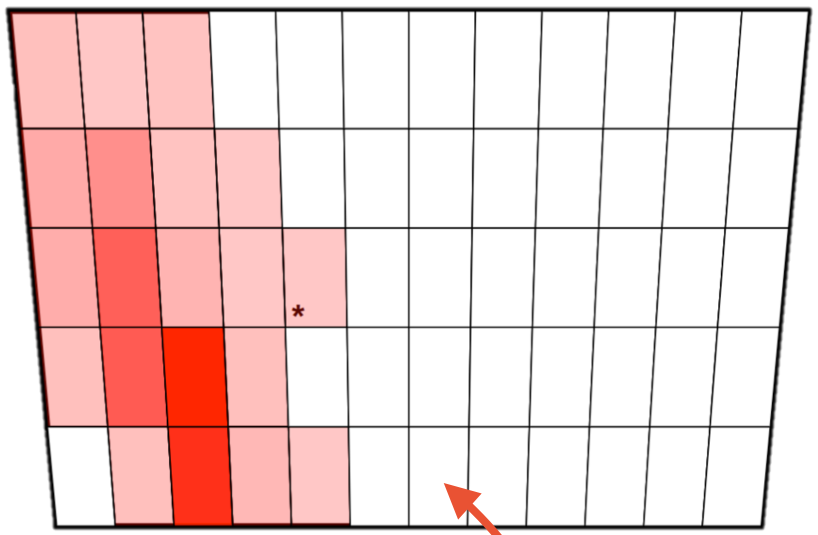
First step: MC - cluster association

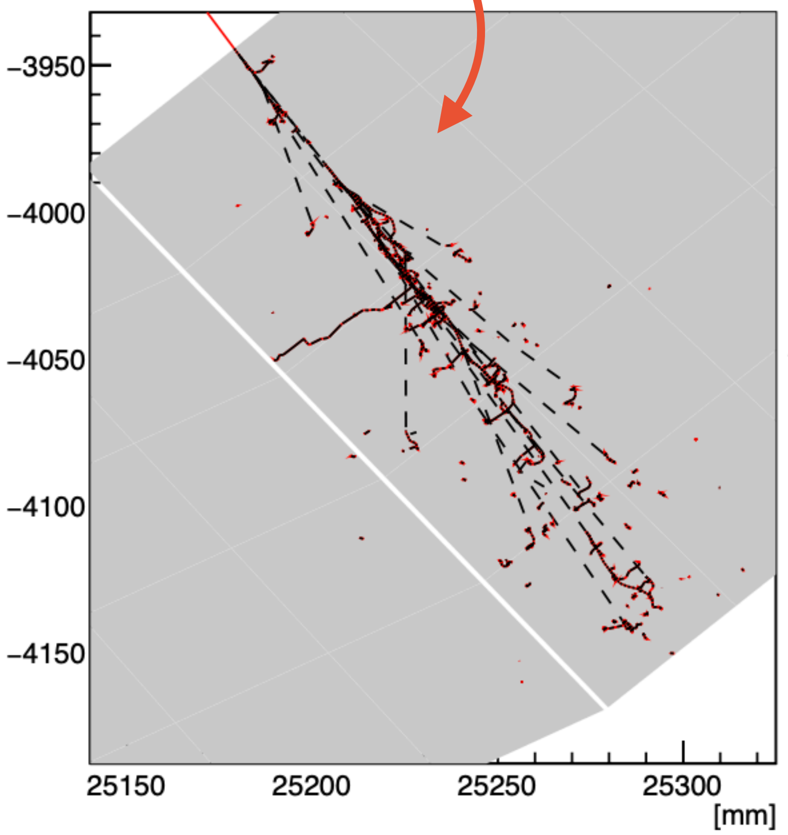


Ecal reconstruction: association cluster/MC

- Reconstructed cluster:
  - Energy, position, time
  - Collection of cells
- Monte Carlo information on the event:
  - Hits with deposited energy
  - Particle trajectories
- Match information from reco & MC with backtracking: build a true cluster with all *generators*, i.e. cluster cells where multiple true particles contribute to E deposition
  - True particle:
    Track-id/PDG, $\vec{p}_0$, first point in the cluster

Method: all trajectories with hits are checked to find if they have (trajectory) points entering the reco cluster

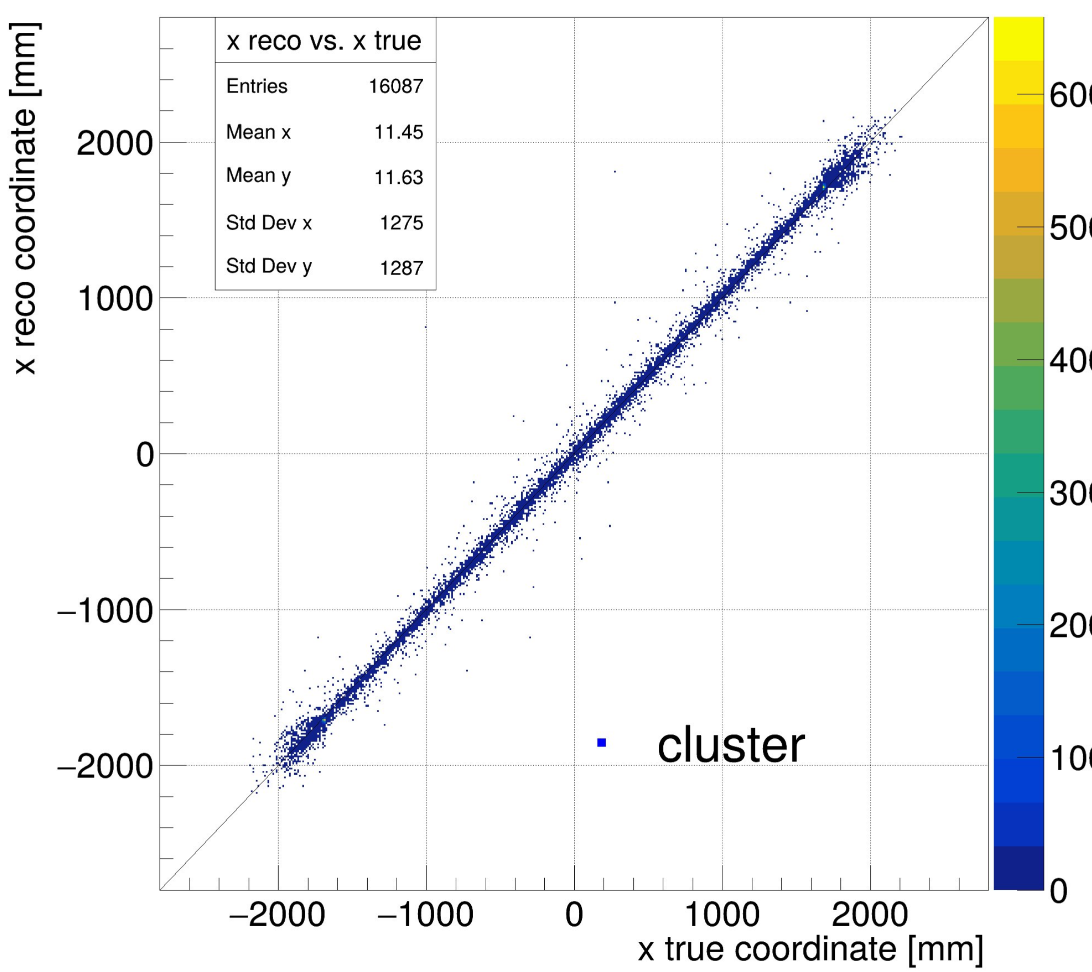




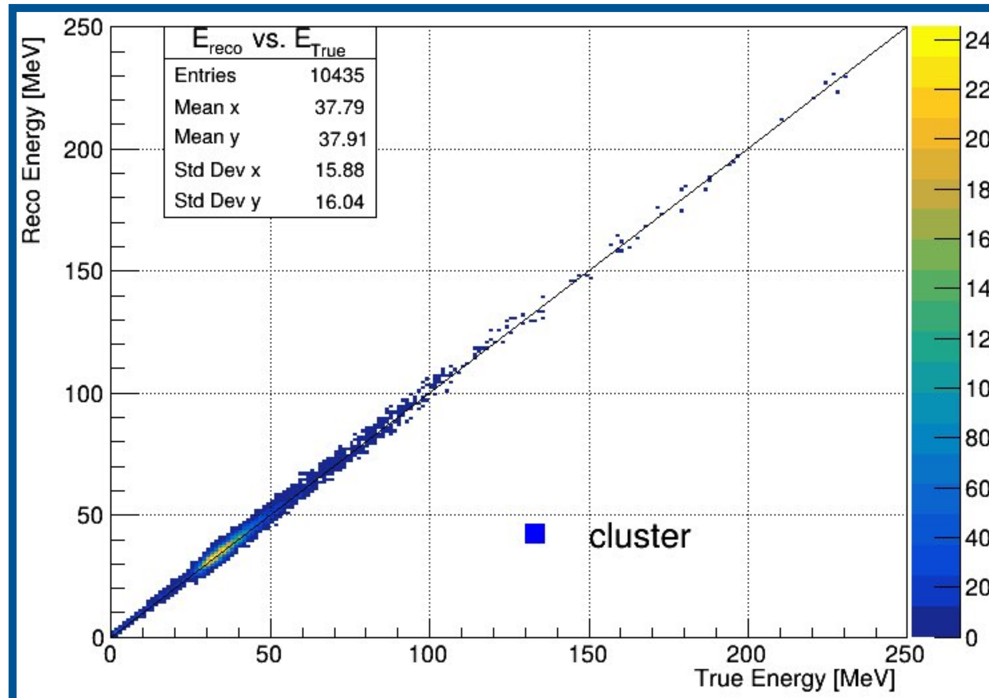
Ecal reconstruction: clustering validation

Validation of the clustering step with MC *backtracking* comparing true and reco cluster **coordinates** and **energy**

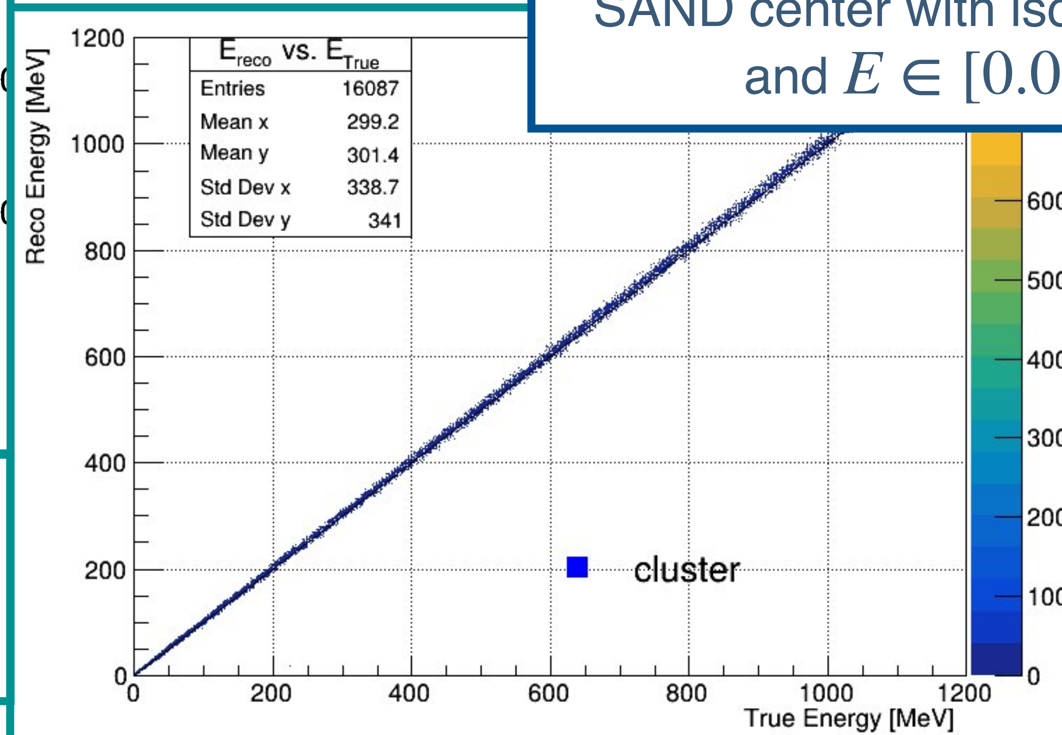
SAND center: (0.0, -2384.73, 23910.0)mm



Sample: $3 \cdot 10^4$ electrons generated in the SAND center and near barrel module with isotropic initial angle and $E \in [0.001, 6]$ GeV.



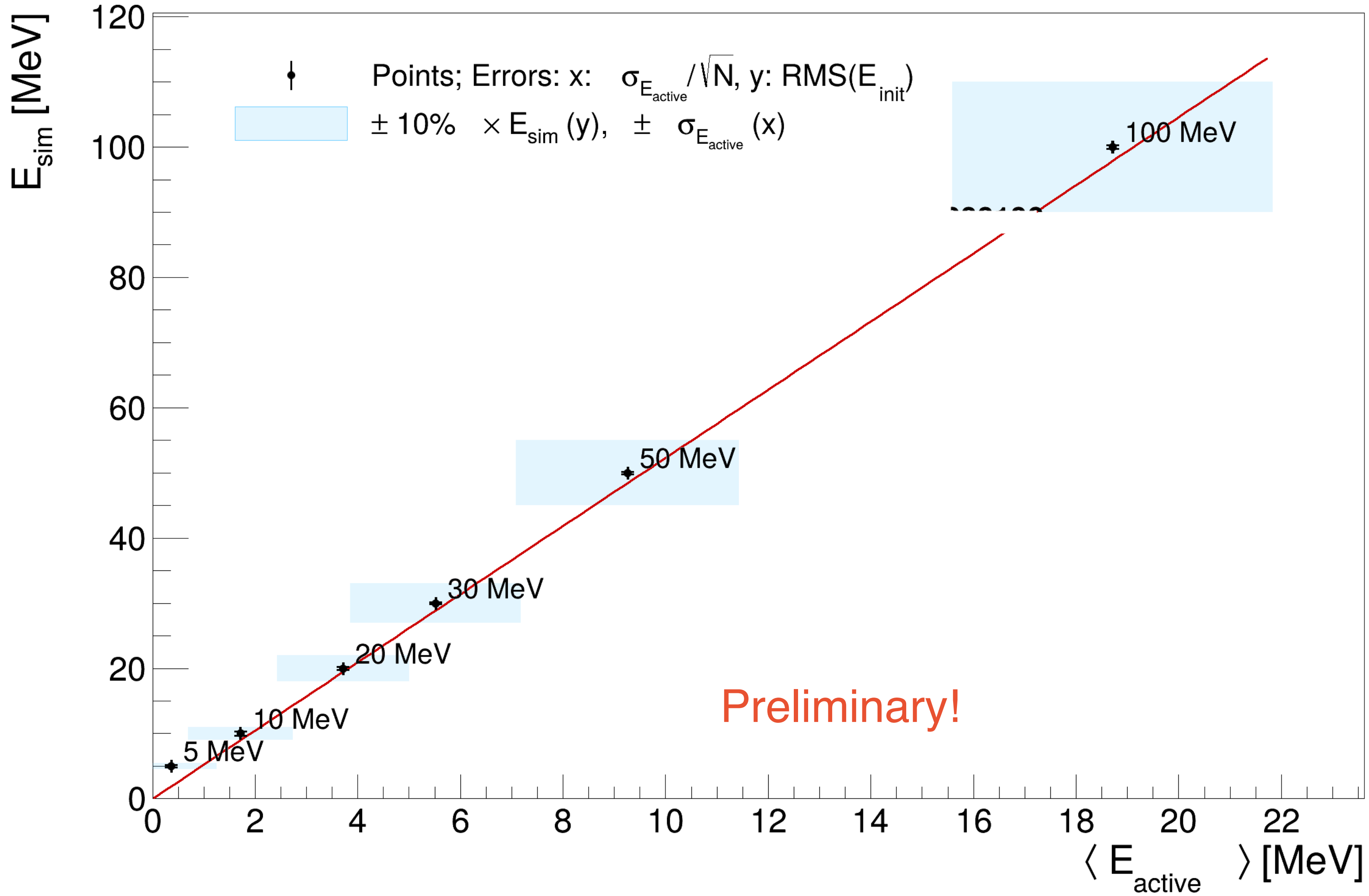
Sample: $3 \cdot 10^4$ muons generated in the SAND center with isotropic initial angle and $E \in [0.001, 6]$ GeV.



Ecal reconstruction: preliminary results on calibration

- Sample of electrons from the vertex from $30\mathrm{k}\ \nu_e$ interactions in the SAND tracker volume with E_ν distributed according to the beam spectrum

E_{sim}
True initial particle energy from MC as a function of
E_{active}
Reconstructed (cluster) energy from the deposition in the active material



Preliminary results are compatible with expectations from KLOE

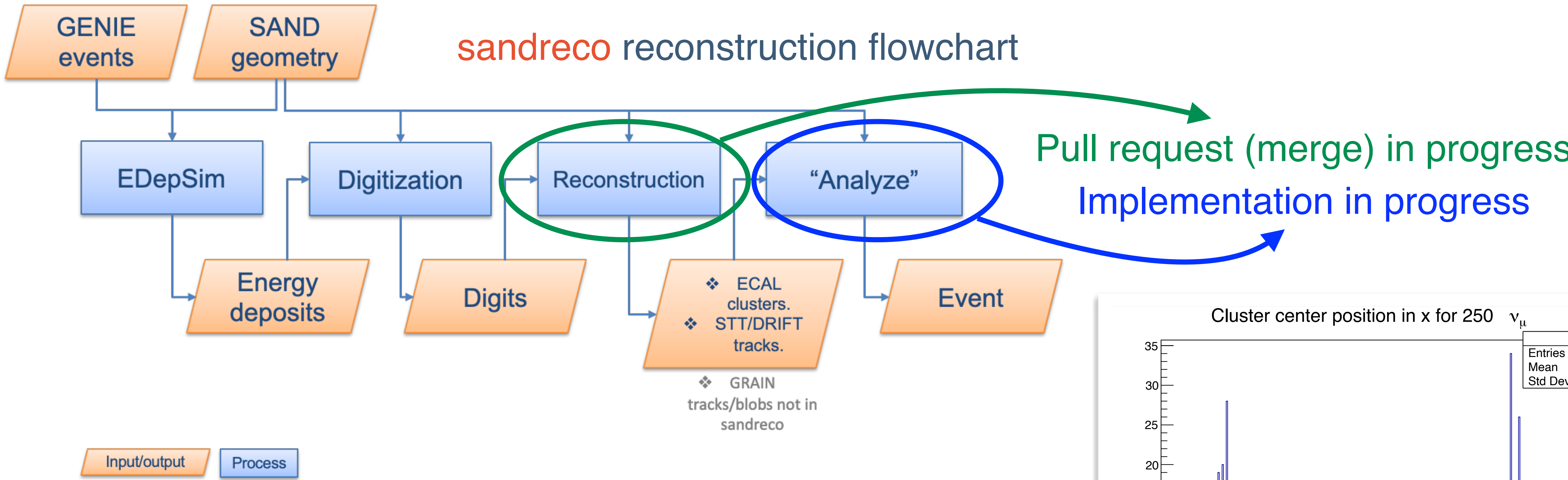
Ecal reconstruction: software infrastructure status

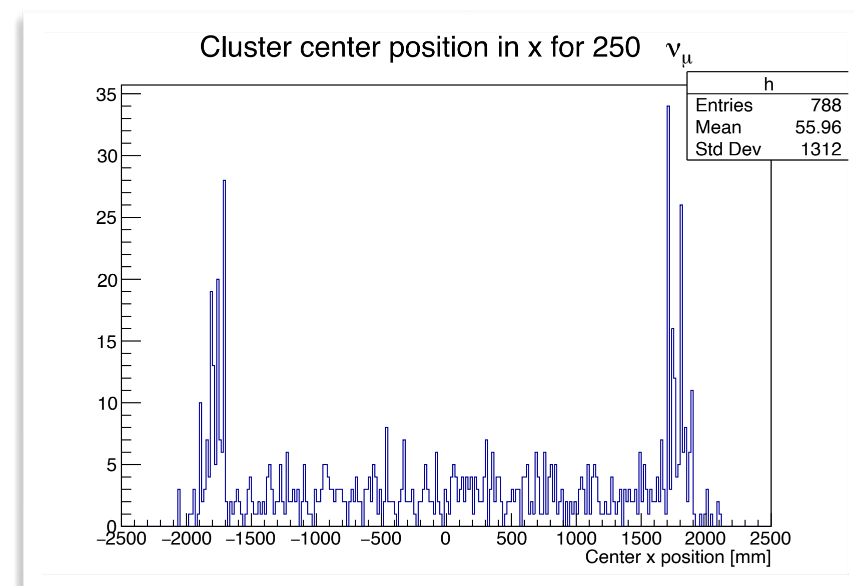
- All the sand reco branches containing development on:
  - Geometry and SANDGeoManager
  - Digitization
  - Clustering

  are now merged in *develop* (see Pull Request)
- Full Ecal simulation/reconstruction chain including edep-sim, digitization, clustering, MC/cluster association available in sand reco
  - Clustering tested and validated
- First version of CAF files (see next slide) for calorimeter (& tracker) is ready
- Analyses for PID (e/π separation with ML techniques) and neutron detection

Ecal reconstruction: CAF files & integration within ND

sandreco reconstruction flowchart





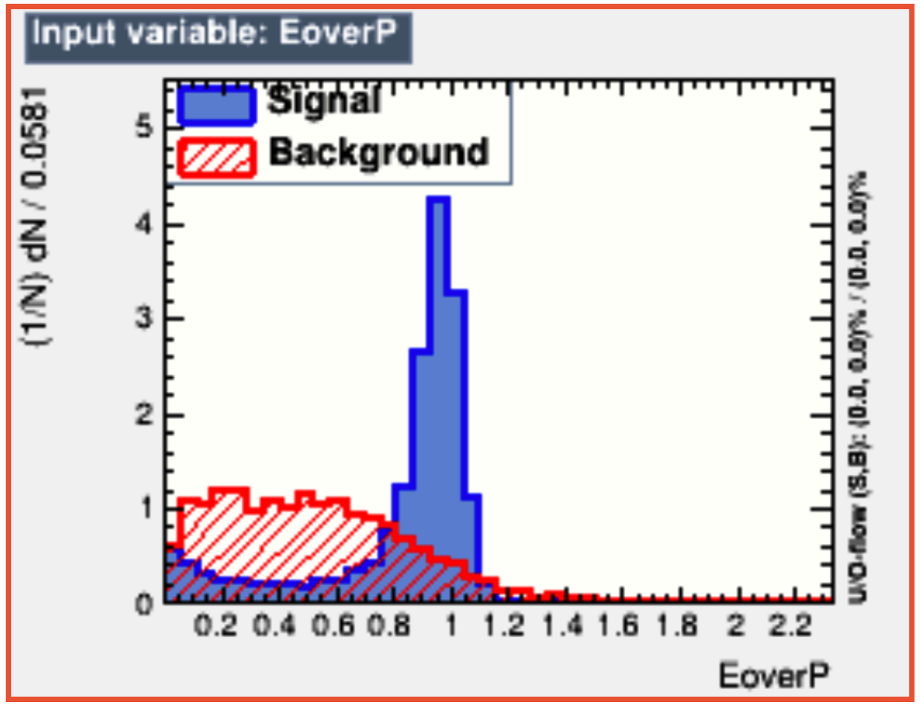
- Common Analysis Files (**CAF**s) to be used for DUNE analyses involving all ND detectors
  - sand-reco variables filled and validated for (Ecal) *cluster* and to be tested for (STT Tracker) *track* - PR (merge) in progress
  - *Event* (ν candidate) info (interaction vertex, hierarchy of reco particles, …) work in progress
  - Temporary workaround to ND CAF maker to handle SAND: standardized solution as the next step in sandreco

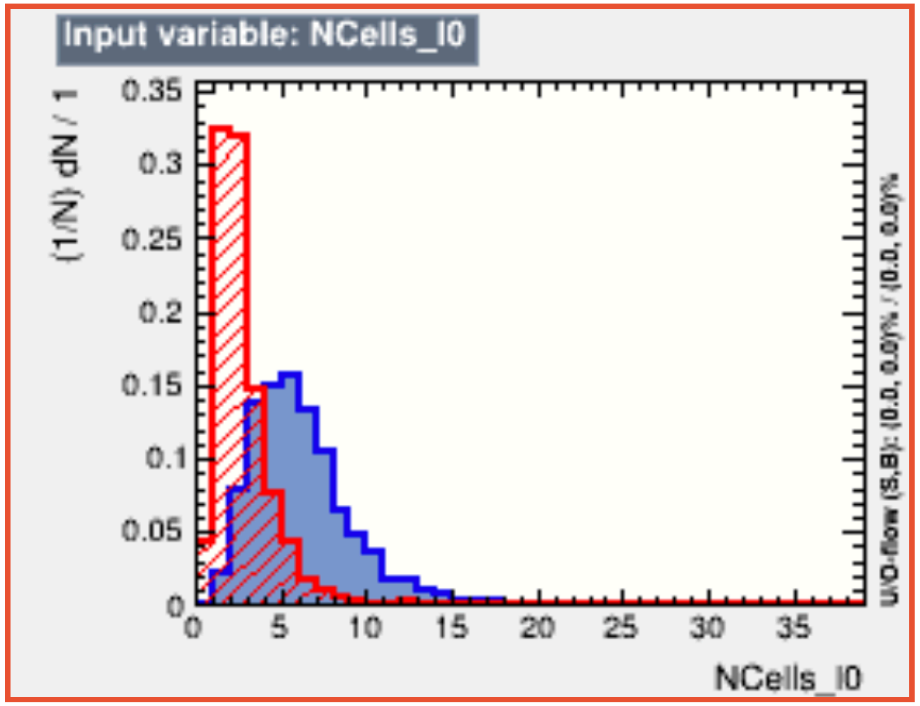
```
struct cluster {
  int tid;
  double x;
  double y;
  double z;
  double t;
  double e;
  double ax;
  double ay;
  double az;
  double sx;
  double sy;
  double sz;
  double varx;
  double vary;
  double varz;
  std::vector<reco_cell> reco_cells;
  std::vector<incomplete_cell> incomplete_cells;
};
```

Ecal reconstruction for physics-driven analysis: PID

- Idea: use Ecal + tracker reconstruction to implement a **ML-based approach** to do particle identification, tests in particular for e/π **separation**
  - Sample: 30k ν_e with beam energy spectrum, interacting in the STT
  - Candidate event selection:
    - one generator/cluster
    - generator primary particles: $e^{\pm}, \pi^{\pm}$ with ν_e as parent
    - reconstructed variables from Ecal clustering (cluster energy, N_{cells}, …)
    - MC + (4%) smearing variables (momentum) from the tracker
  - Input variables used for the classification:

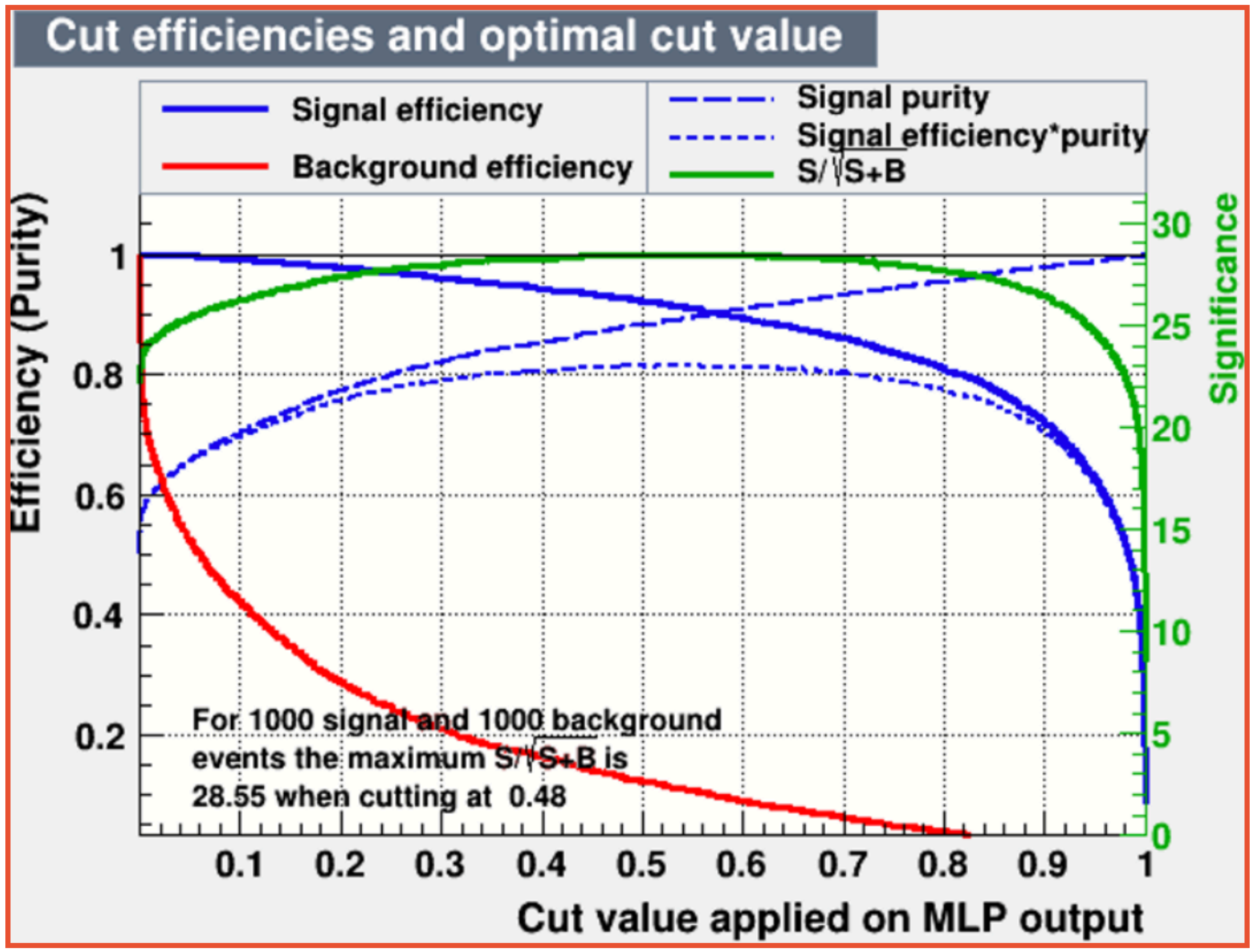
ratio $\frac{E_{cluster}}{p_{gen,\ MC}}$, N_{cells} w/ signal for each Ecal layer, …

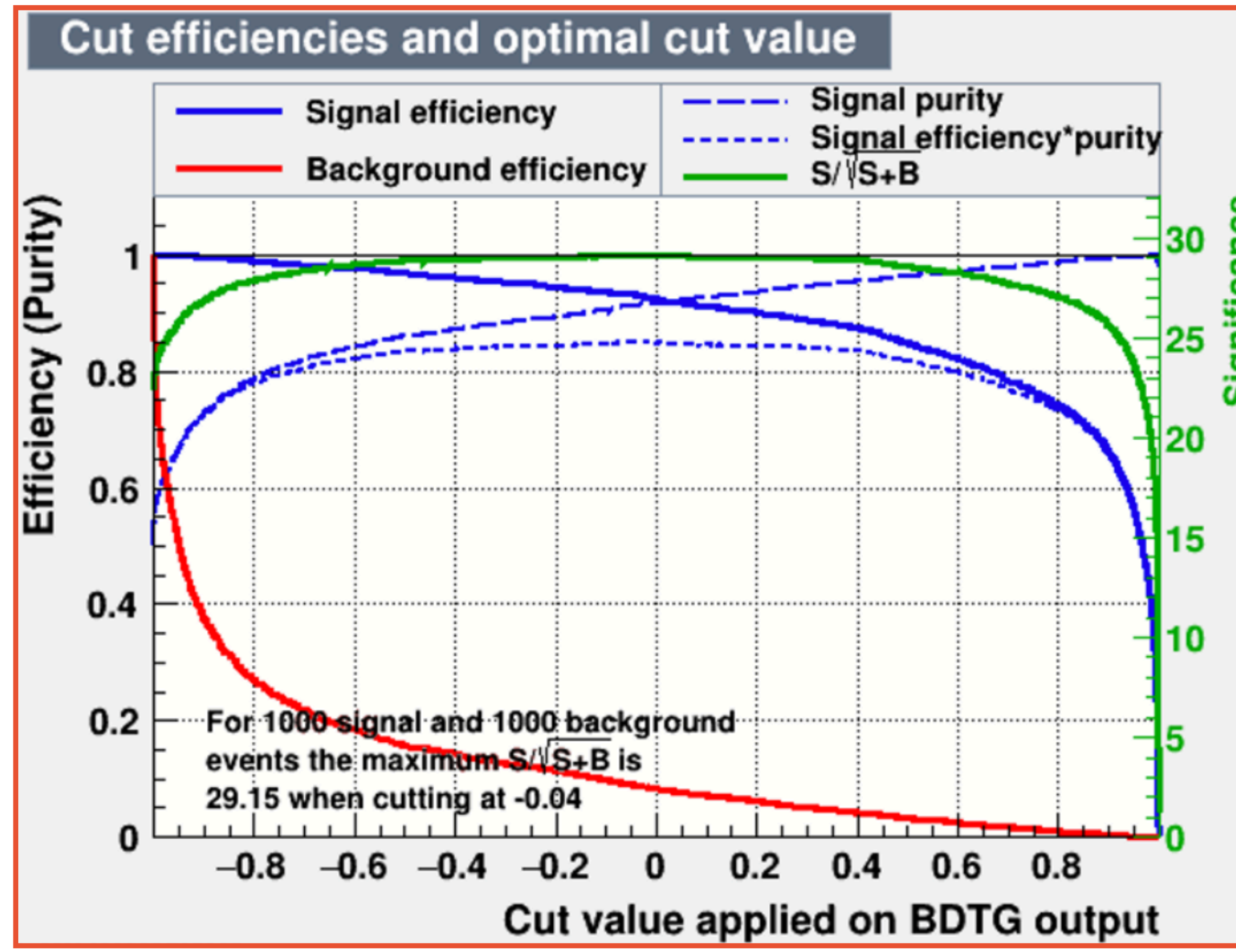




Ecal reconstruction for physics-driven analysis: PID

Preliminary results extracted testing some ML algorithms





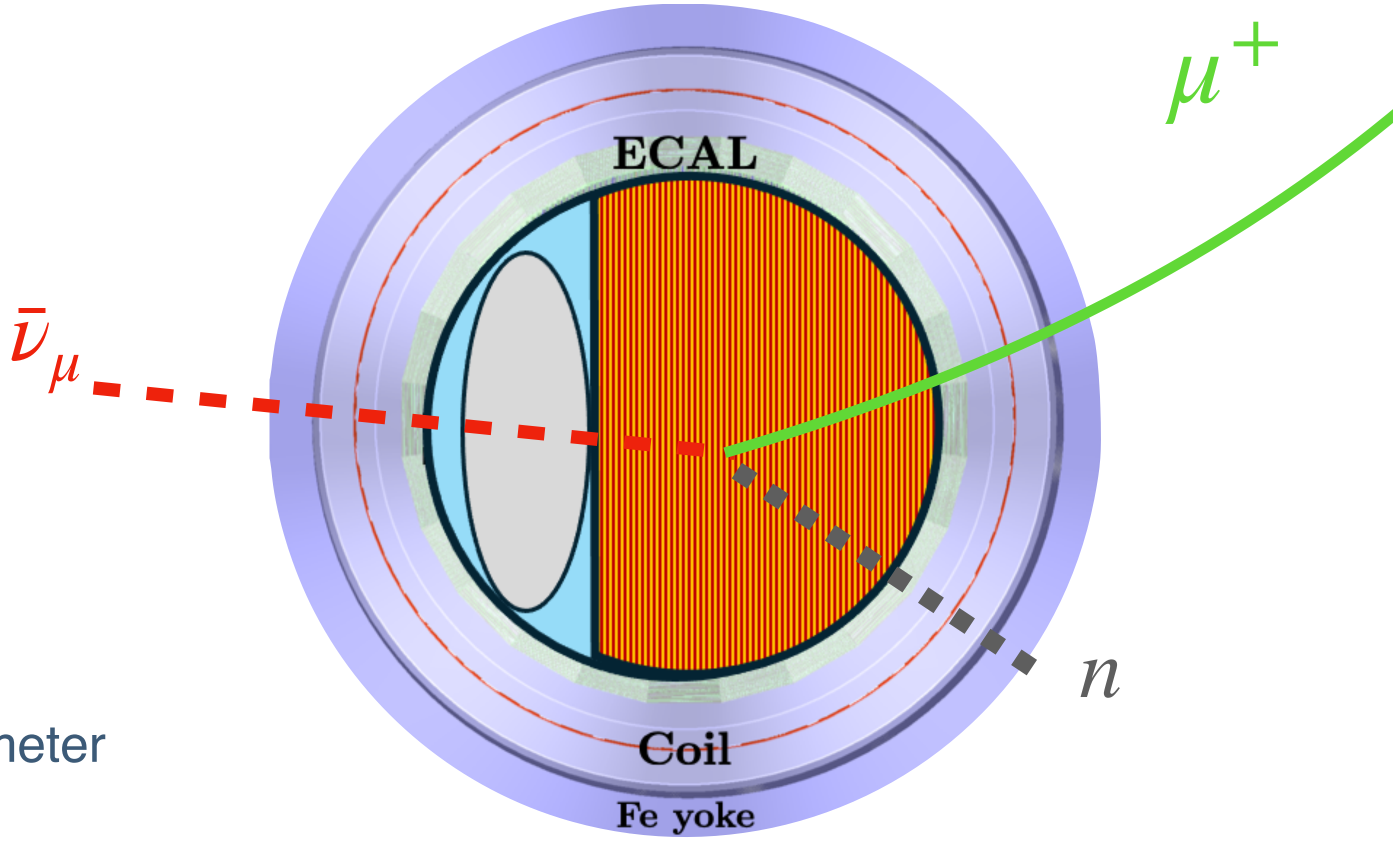
Ecal reconstruction for physics-driven analyses
Flux measurement w/ CCQE interactions

- Use CCQE interactions on H to extract **flux measurements** [1]
  $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  as $\bar{\nu}_\mu$ interactions are expected to be **perfectly balanced** on the transverse plane

- Once μ^+ **is fully reconstructed** (vertex, $\vec{\mathrm{p}}$, E)
  neutron energy can be derived from

$$\mathrm{E}_{\bar{\nu}}^{\mathrm{reco}} = \frac{\mathrm{M}_\mathrm{n}^2 - \mathrm{m}_\mu^2 - \mathrm{M}_\mathrm{p}^2 + 2\mathrm{M}_\mathrm{p}\mathrm{E}_\mu^{\mathrm{reco}}}{2\left(\mathrm{M}_\mathrm{p} - \mathrm{E}_\mu^{\mathrm{reco}} + \mathrm{p}_\mu^{\mathrm{reco}} \cos\theta_\mu{}^{\mathrm{reco}}\right)}$$

as $\mathrm{E}_\mathrm{n}^{\mathrm{pred}} = \mathrm{E}_{\bar{\nu}}^{\mathrm{reco}} + \mathrm{M}_\mathrm{n} - \mathrm{E}_\mu^{\mathrm{reco}} \rightarrow \beta_\mathrm{n}^{\mathrm{pred}} = \frac{\mathrm{p}_\mathrm{n}^{\mathrm{pred}}}{\mathrm{E}_\mathrm{n}^{\mathrm{pred}}}$



and neutron is tagged from its **ToF** to the Ecal calorimeter

$\mathrm{t} = \frac{\mathrm{s}}{\mathrm{v}_\mathrm{n}^{\mathrm{pred}}}$ where we assume a the trajectory is a **straight line** vtx - first point with $\mathrm{E_{dep}}$ in Ecal (no int in tracker)

[1] $N_{ND}^{\nu_\mu}(\mathrm{p}_{reco}) = \sum_i \boxed{\Phi_{\nu_\mu}(E_{true})} \cdot \sigma_{\nu_\mu}^i(\mathrm{p}_{true}) \cdot \epsilon_{\nu_\mu}(\mathrm{p}_{true}) \cdot R_i(\mathrm{p}_{true}; \mathrm{p}_{reco})$

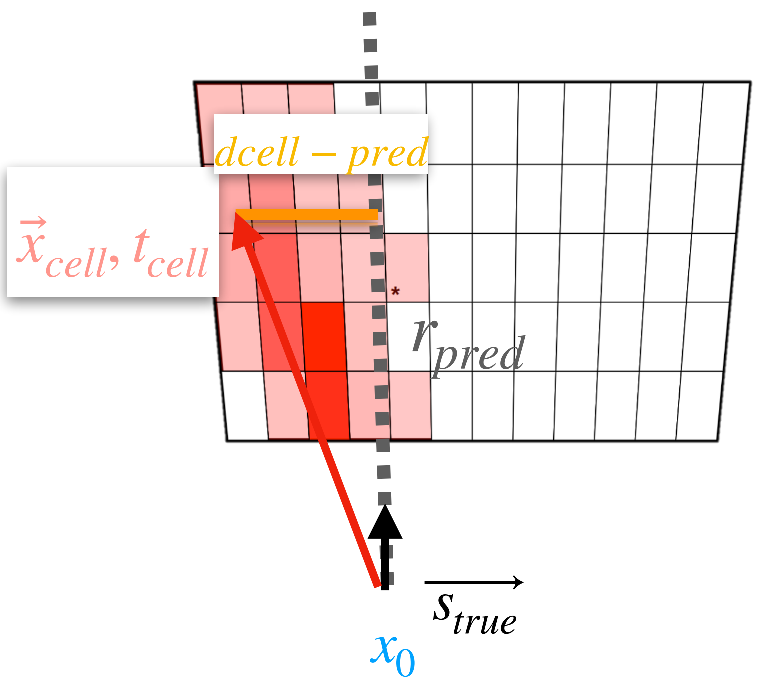
DUNE

Ecal reconstruction for physics-driven analyses
Evaluation of neutron detection efficiency - *work in progress*

- First step towards the analysis: evaluation of visible neutron tagging efficiency with Ecal and kinematic considerations on signal/background
  - Sample of $3 \cdot 10^4\ \bar{\nu}_\mu$ interactions in SAND tracker volume (1.43×10^{20} PoT) with a single neutron to select interactions on Hydrogen

Efficiency w/o energy threshold and fiber attenuation as $\epsilon^{\mathrm{ECal}}_{\mathrm{n},\geq 1\mathrm{hit}} = \dfrac{\mathrm{N_n}\left(\geq 1\mathrm{hit}\right)}{\mathrm{N_n}\left(\mathrm{produced}\right)}$

Efficiency w/ 0.08 MeV ($\equiv$ 2.5 pe) threshold given by $\epsilon^{\mathrm{ECal}}_{\mathrm{n,cluster}} = \dfrac{\mathrm{N_n}\left(\geq 1\ \text{hit, clu}\right)}{\mathrm{N_n}\left(\geq E_{\text{min, clu}}\right)}$



- Idea: select CCQE only where μ is properly reco (thus neutron) and the cluster w/ primary neutron as generator, extract the space/time distance between reco cell and predicted hit position: any deviation from a straight line is potentially a means to discriminate between signal and background (e.g. neutron interacting before reaching the calorimeter, not on Hydrogen) Optimising cut in Δr, Δt to maximize bkg rejection

Ecal reconstruction: ongoing/next steps

- Software for the Ecal-based event reconstruction w/ MC info for PID is now part of sand reco legacy: PR approved, further tests post-PR-merge are necessary

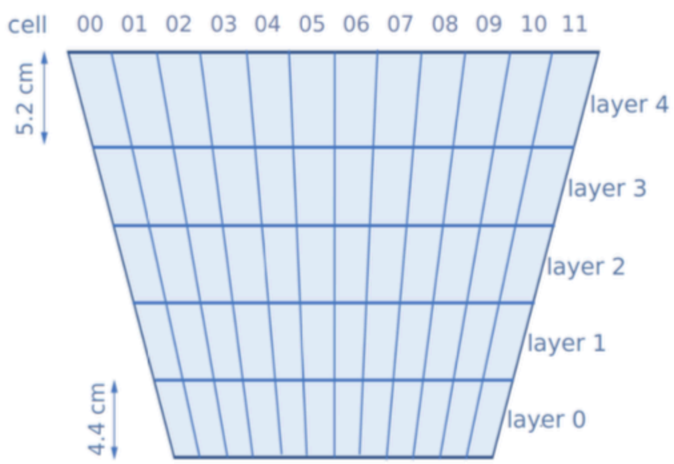
- Current analyses lead by D. Casazza and R. D'Amico (see earlier presentation) based on Ecal and ongoing within the sim/reco and calibration working groups rely on the original code that was later included in sand reco - tests & validation checks are foreseen when sandreco legacy software will be frozen

- CAF files: Pull Request merge is in progress as part of the continuous effort to integrate SAND sim/reco software in ND shared software infrastructure

Back-up slides

ECAL reconstruction: digitization

Module segmentation



Segmentation of the modules in 5 layers and cells of $4.4 \cdot 4.4(5.2)cm^2$ granularity.

Cell id: 20 1 11

Module barrel/endcap
00-23/30&40

Layer 0-4

Cell barrel/endcap
0-11/0-89

Digit formation in cells

- N_{pe} number of photoelectron produced by an hit is extracted by Poisson distribution with

$$\mu_{pe} = dE \cdot E_{pe} \cdot A_l$$

- Arrival time [ns].
$t_{pe} = t_{cross} + t_{decay} + t_{prop} + Gauss(1ns)$

- ADC counts $S_i^{B,A} = N_{pe} \cdot peADC$.

- TDC: 2 options constant fraction or fixed threshold.

Digit structure:

- Cell information.
- Photo-signals$_{A,B}$:
  - ADC, TDC.
  - Collection of pe:
    - Hit index.
    - Time.