SAND Sim/Reco Updates

M. Tenti

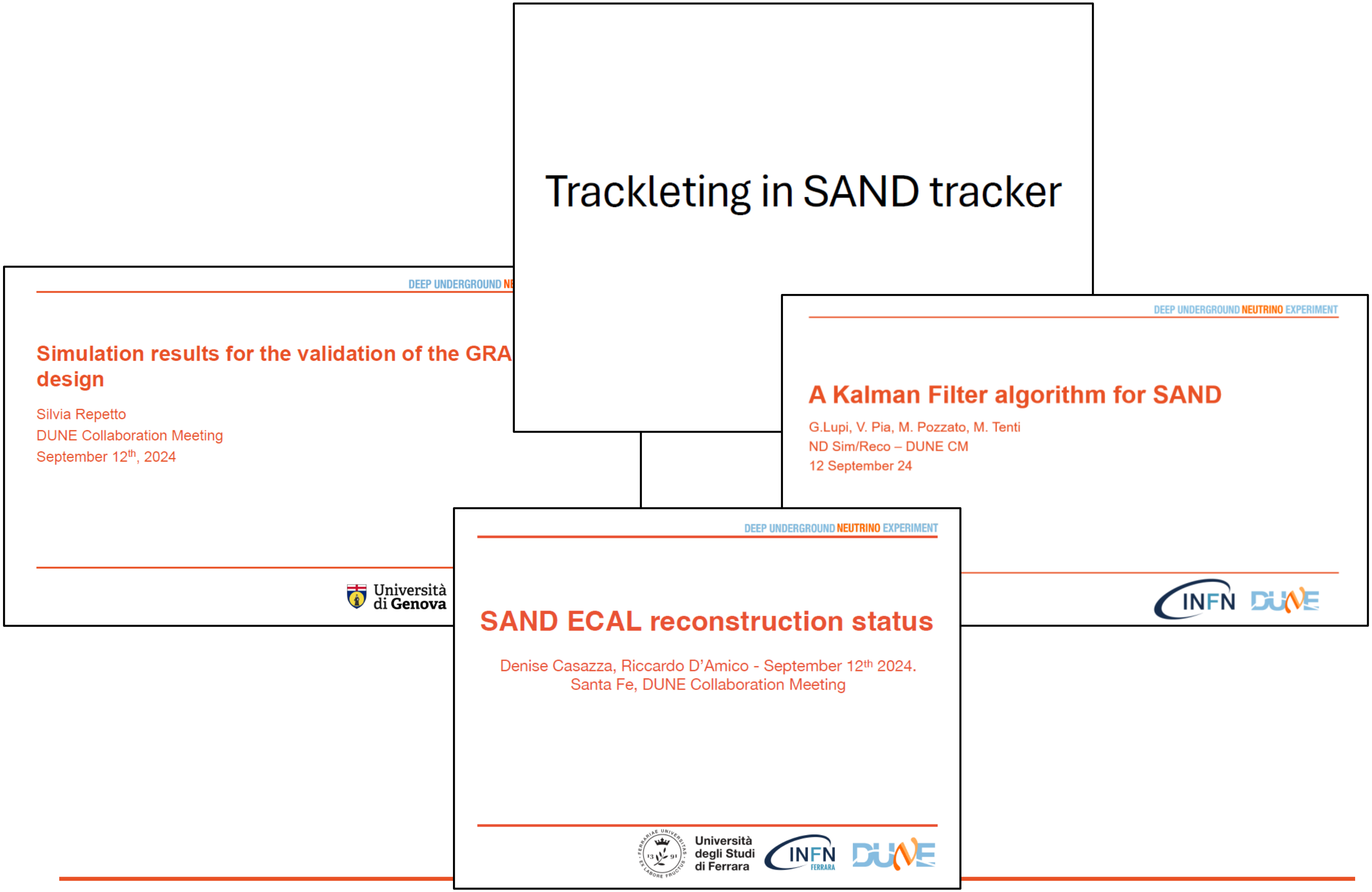
ND sim/reco – DUNE CM

11/09/2024

SAND Physics Software WG

- Mailing lists:
  - DUNE-ND-SAND-PHYSICS@FNAL.GOV
  - DUNE-ND-SAND-SOFTWARE@FNAL.GOV
- Meetings: Tuesday at 15.00 CEST (08:00 CT) [Weekly]
- Here the notes
- Aims:
  - Delevop reconstruction tools
  - Perform physics analyses
  - Alignment/Integration w/ DUNE

Content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DUNE Collaboration Meeting
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Università di Genova
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A Kalman Filter algorithm for SAND

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Trajectory parametrization

- **Trajectory state vector (a_k)**

$$\begin{pmatrix} x \\ y \\ q/R \\ \tan\lambda \\ \phi \end{pmatrix}$$

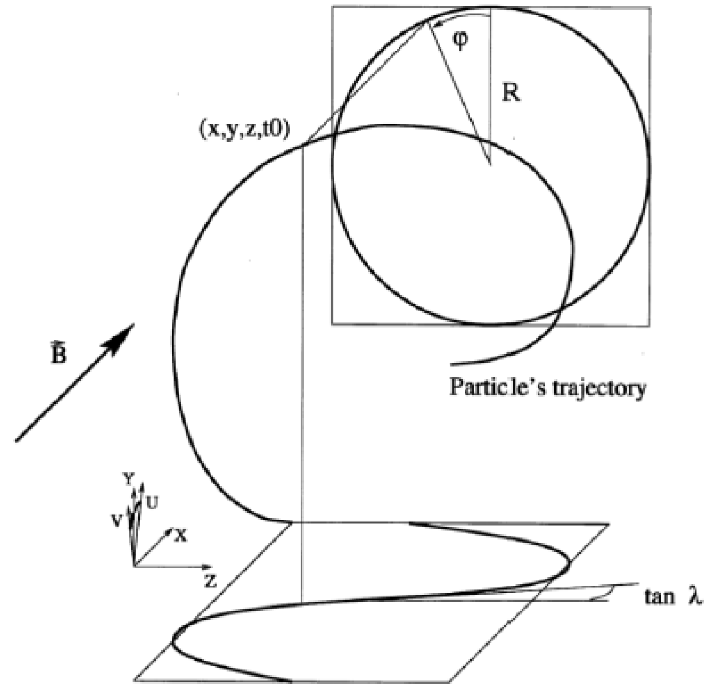
- x → x coordinate
- y → y coordinate
- q/R → signed inverse radius
- $\tan\lambda$ → tangent of dip angle
- ϕ → rotation angle

- **Measurement vector (m_k)**

$$m_x = \begin{pmatrix} x \\ \theta_{xz} \end{pmatrix}$$ Angle in the horizontal plane wrt z-axis

$$m_y = \begin{pmatrix} y \\ \theta_{yz} \end{pmatrix}$$ Angle in the vertical plane wrt z-axis

- KF propagation from downstream to upstream



- Magnetic field along x-axis
  - Circlular trajectory in the yz-plane (vertical plane)
  - Straight line in the xz-plane (horizontal plane)

- STT passive targets
  - Energy loss between subsequent STT planes
  - Multiple Coulomb Scattering

↓

Trajectory parametrized as an **helix of variable radius**

ΔE and MCS

Energy loss from layer *k-1* to layer *k* computed as:

$$\Delta E_k = \left.\frac{dE}{dx}\right|_{Bethe-Bloch} \times \Delta Z_k \,[g \cdot cm^{-2}]$$

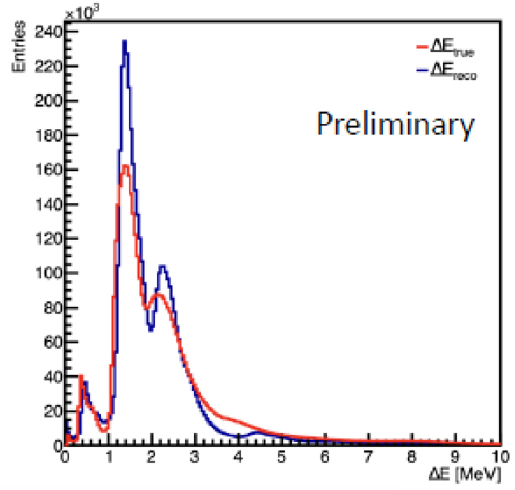
$$\Delta Z_k = \rho \cdot L \left[\frac{g}{cm^2}\right]$$

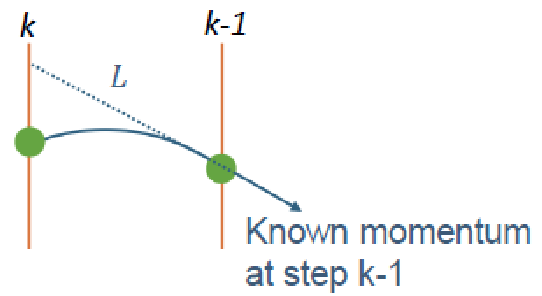
MCS angle computed as:

$$\theta_k = \frac{13.6\ \mathrm{MeV}}{\beta c p} \cdot q \cdot \sqrt{\Delta Z_k / X_0}\,[1 + 0.038 \ln(\Delta Z_k / X_0)]$$

Where:

- materials information taken from geometry file
- L computed as a straight line from measurement layer *k-1* to *k*
- direction taken from trajectory state of previous step

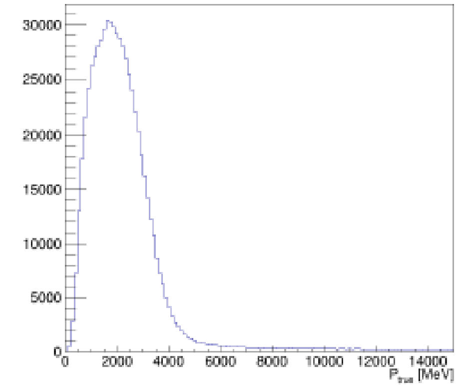




Simulation chain

SAND Geometry
- GDML file as seen earlier

Neutrino Flux
- LBNF beam flux (same as for DUNE TDR)

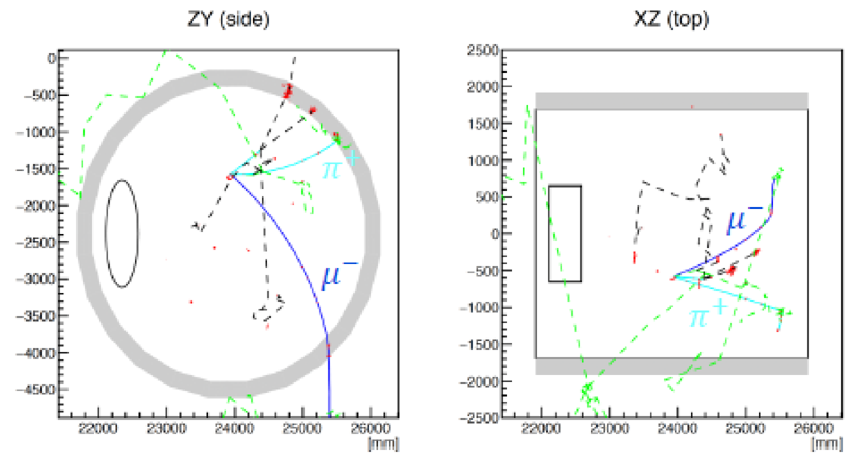


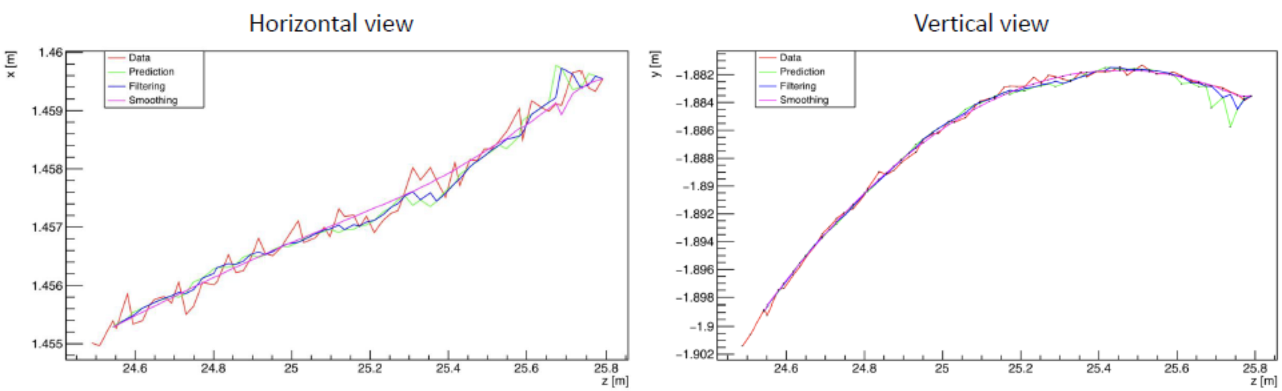
Genie Production
- ν_μ CC in SAND tracker

Particle propagation
- EDepSim

Track selection
- μ^-, π^+, p produced at vertex
- 10 points in the STT

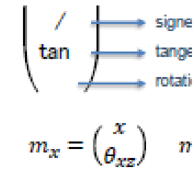
Digitization
- Fast simulation

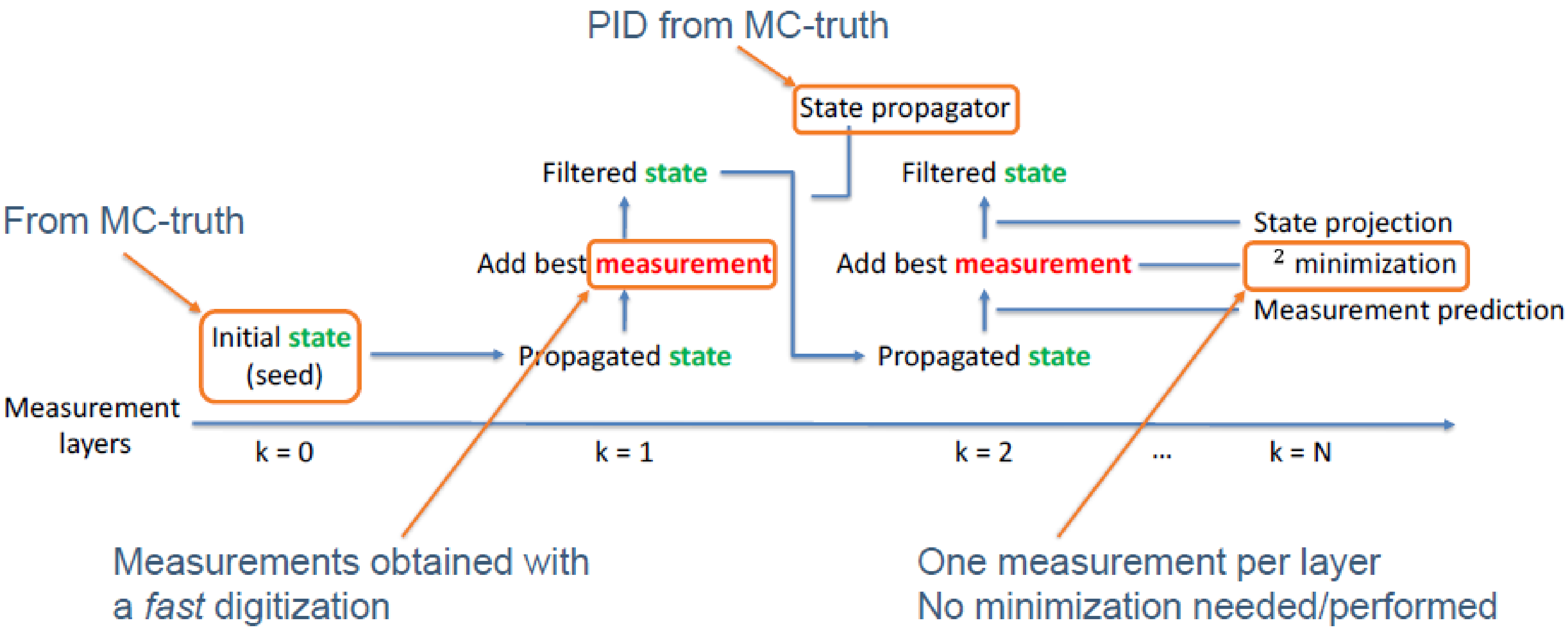




Caveats

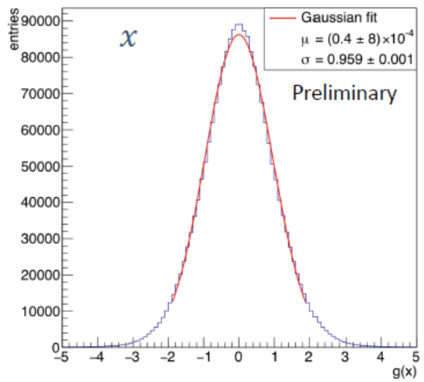
$$\Delta(1/R) = -\frac{(1/R)^2}{0.3\cdot B}\cdot\sqrt{1+\tan^2\lambda}\cdot\sqrt{1+\frac{m^2(1/R)^2}{(0.3\cdot B)^2}(1+\tan^2\lambda)}\cdot\Delta E$$

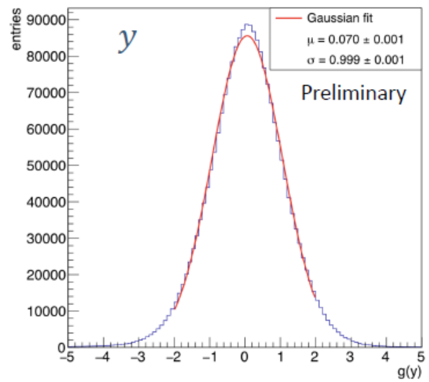




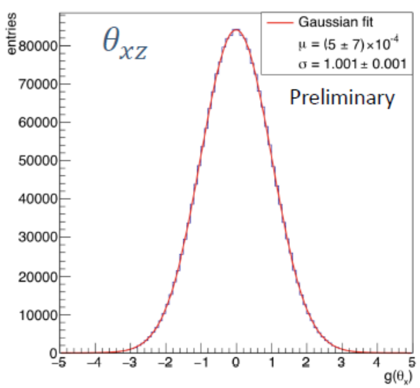
KF Standard consistency checks

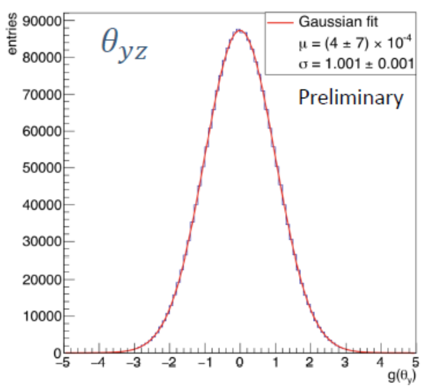
$$g(pos)_k = \frac{r(pos)_k}{\sqrt{C(pos)_k}} \rightarrow \text{standard gaussian distribution } (\mu = 0,\ \sigma = 1)$$





$$g(\theta)_k = \frac{r(\theta)_k}{\sqrt{C(\theta)_k}}$$

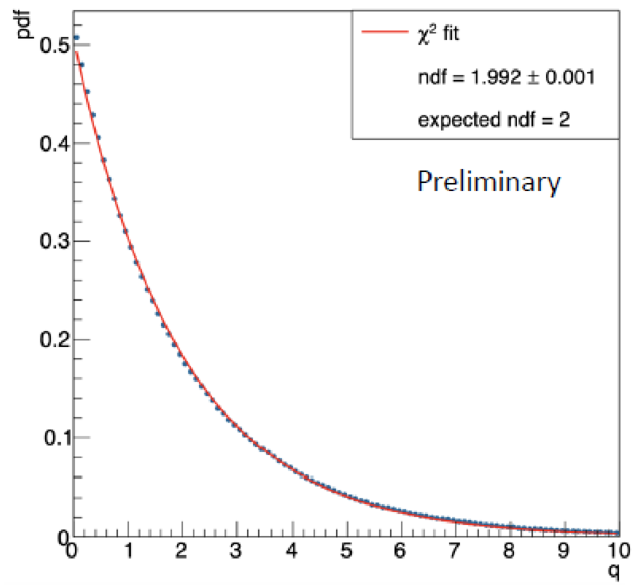




$r_k^i = m_k^{pred} - m_k^{true}$

$C_k^i =$ measurement covariance matrix

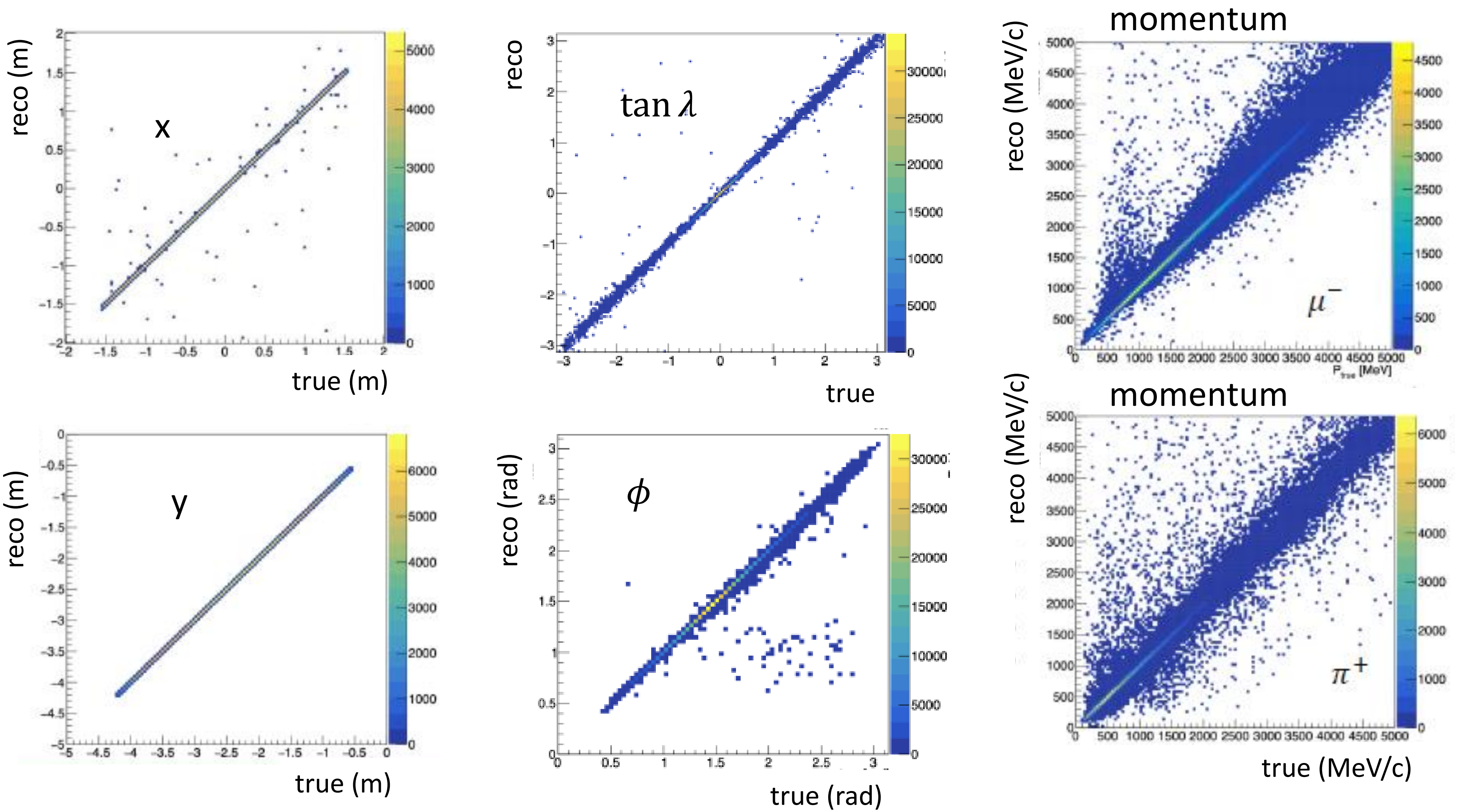
$$q_k = r_k^T C_k^{-1} r_k$$



χ^2 with 2 ndf

Track reconstruction

preliminary

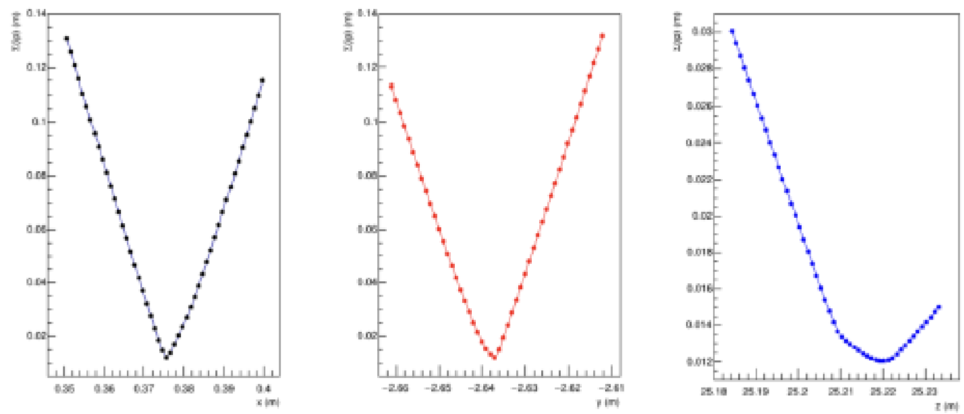


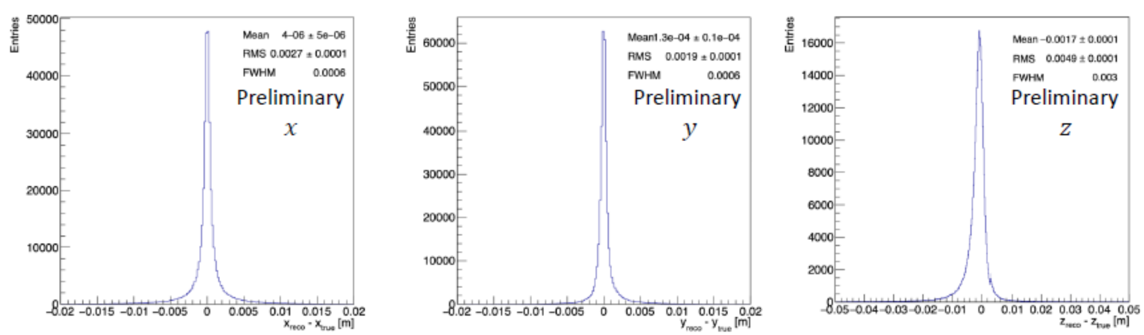
Vertex reconstruction

- Tracks are modeled as **straight lines** in this step

- Reconstructed tracks linked into 2-prong vertices if:
  - The **impact parameter** (perpendicular distance from the tracks to the vertex) is **< 5 cm**.
  - The **longitudinal distance** (distance along the beam axis) between the upstream position of the track and the point of closest approach **< 10 cm**

- **2-prong vertices within a 5 cm radius** are clustered and merged into a single vertex
  - multi-prong coordinates as mean of the individual 2-prong vertices
    - minimization of the impact parameters of all the tracks associated with the vertex





Conclusions

- KF algorithm applied on muons, pions an protons
- Consistency checks applied to the KF
  - Few open questions on the position prediction
- Trajectory and vertices reconstructions are promising
  - Some tracks at low momentum still need investigation

Outlooks

- Integrate the complete STT digitization
- Integrate a realistic seeding

Trackleting in SAND tracker

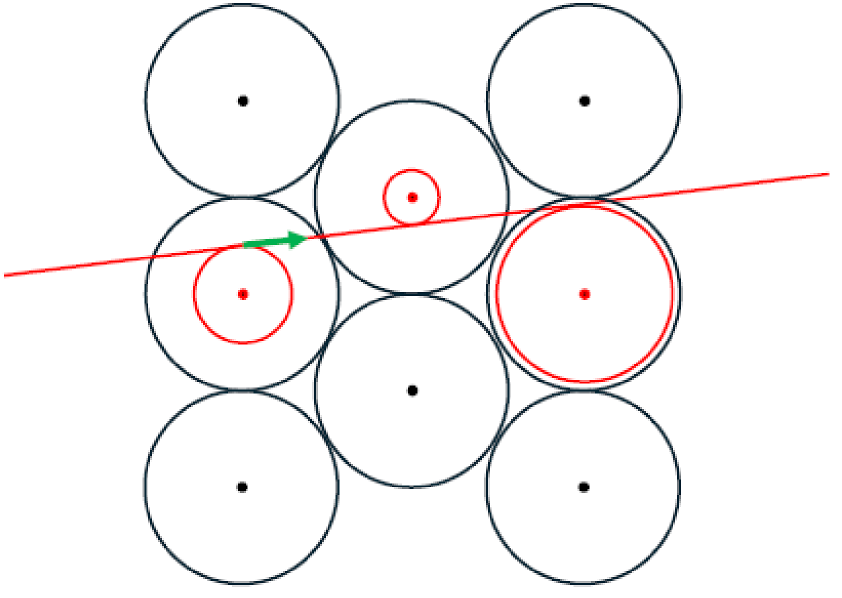
Goal

- Obtain a tracklet on each tracker layer from the recorded signal on the wires

- Tracklet defined as:
  - 3D position
  - 3D direction

- The algorithm should work for every configuration of the tracker

The algorithm



Input:

- info of fired wires (direction, position)
- distance of track from each wire (radius)
- guess of the track direction

Method:

- minimization of

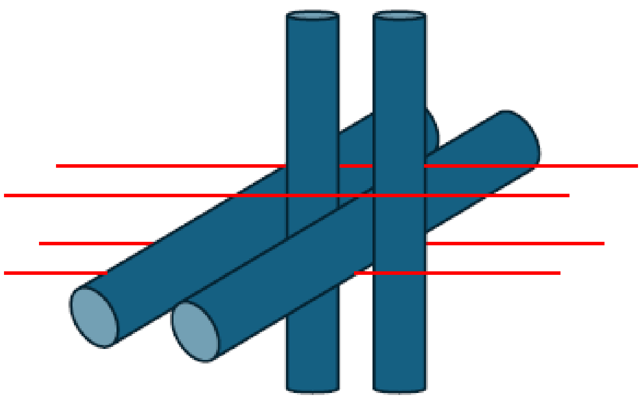
$$D = \sum_i (d_i - r_i)^2$$

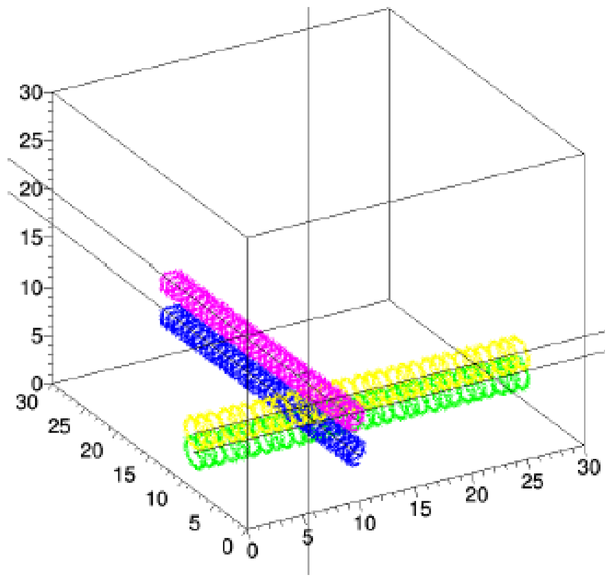
d_i is the distance between the i-th fired wire and the track candidate
r_i is the reconstructed radius

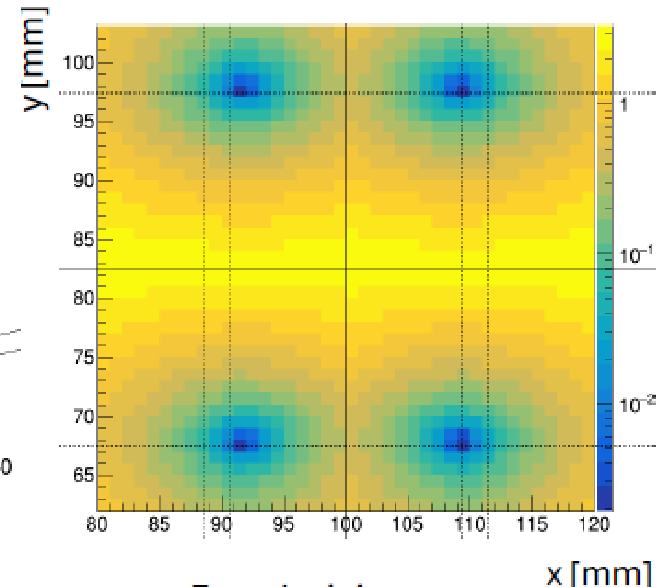
Output:

- position and direction of track candidates in correspondence of the first fired layer

Example with smearing







Simulated trajectory:
- (x, y, z) = (11, 9.7, 20)
- (ax, ay, az) = (0, 0, 1)
- 1 mm smear to the radius of each cylinder

Found minima

x	y	ax	ay	az
9.13	6.74	-0.06	0.002	0.998
9.13	9.74	-0.06	-0.002	0.998
10.87	6.74	0.06	0.002	0.998
10.87	9.74	0.06	-0.002	0.998

Summary and prospectives

- Porting of code into SandReco repo
- Adding support for STT and Drift trackers
- Uptade digitization to handle both tracker options
- Update KF code to work with the latest SandReco version
- Reproduce KF results by using realistic measurements (from tracklets)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

SAND ECAL reconstruction status

Denise Casazza, Riccardo D'Amico - September 12th 2024.
Santa Fe, DUNE Collaboration Meeting

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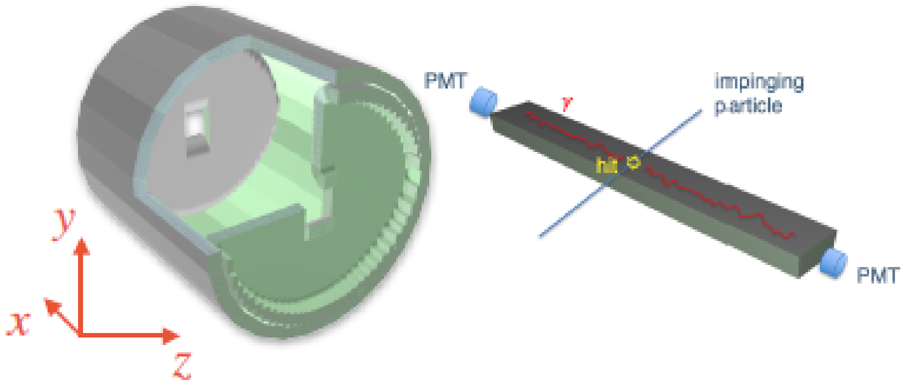
ECAL reconstruction workflow

Reconstruction of the signal position and time



The coordinate along the barrel (endcap) module length x(y) is derived by time difference between two ends while z(x) and y(z) are given by the geometrical center of the fired cell.

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

Each module cell is read out by two photosensors, one per side (A,B) which collects the scintillation light, guided by the optical fibers.

edep-sim simulation of energy deposited hits.

ECAL digitization

Conversion into **DAQ detector digits** stored in a ROOT TTree.

- Photoelectrons generating the photo signals (hits time and index).
- Photo signals (side A,B) with ADC, TDC.
- Cells with photo signals.

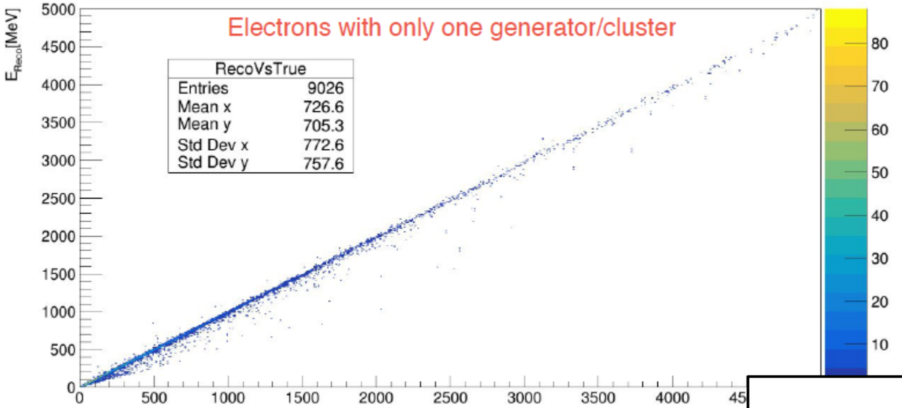
Clustering

ROOT TTree with **cluster** of cells with photo signals.

- Cluster information.
- Cells composing the cluster.

Clustering validation: energy

Sample: 30k ν_e with beam energy spectrum, interacting in STT volume, all the interactions are selected, no overlays.



Only deposited energy due to scintillation!

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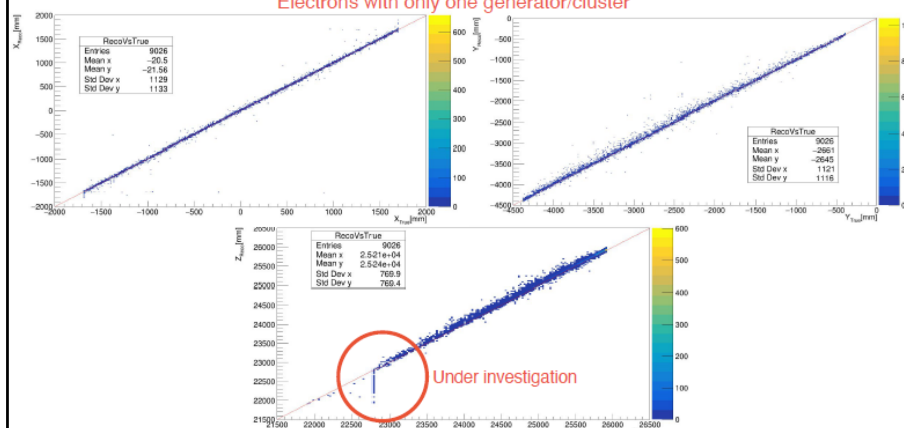
Clustering validation: position

Sample: 30k ν_e with beam energy spectrum, interacting in STT volume, all the interactions are selected, no overlays.



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

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Single particle discrimination: e/π

Sample: 30k ν_e with beam energy spectrum, interacting in STT volume, all the interactions are selected, no overlays.

Selection applied

- Only one generator/cluster.
- Generator particles $e^{\pm}$, $\pi^{\pm}$ + condition on Track ID of the (ν_e) *parent* = -1.
- *ECAL* variables (**reconstructed**) from clustering algorithm.
  - Cluster energy, Ncells, layer energy, …
- *Tracker* variable (**MC+smearing**) of the generator + smearing.
  - Generator initial momentum with 4% smearing.

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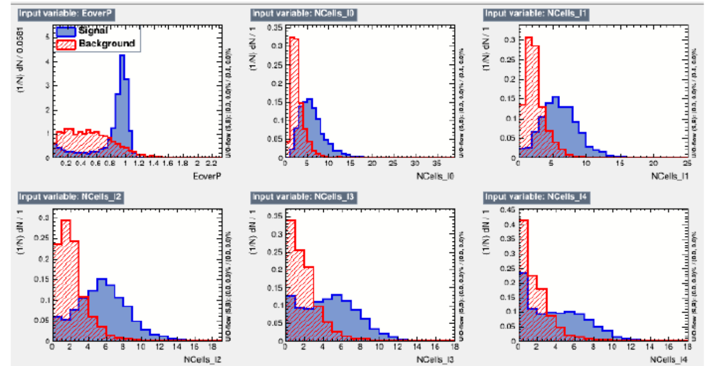
Single particle discrimination: e/π

Input variables (& more)



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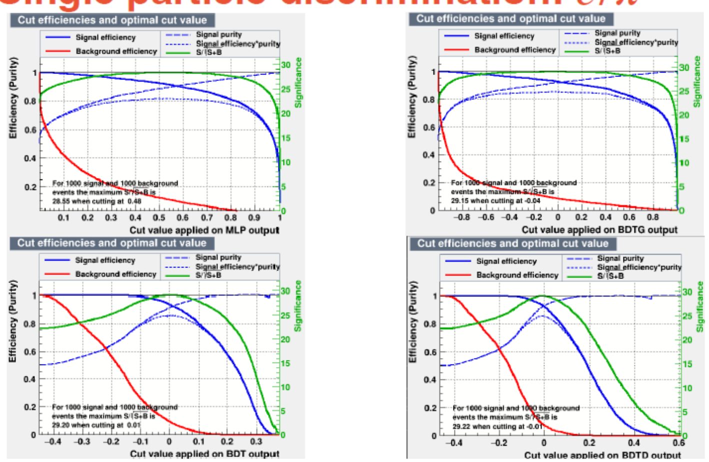
Single particle discrimination: e/π



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Conclusions & next steps

- ECAL **simulation** chain (edep-sim + digitization) ready and available on GitHub sandreco.
- MC - cluster association tool ready and used to:
  1. Reconstruction **algorithm** evaluation.
     - ECAL **clustering** validated with energy and position variables. Almost ready for integration on GitHub after code clean up.
  2. **Analyses**.
     - Single particle discrimination ongoing for e/π ECAL separation power with ML.

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Simulation results for the validation of the GRAIN ASIC design

Silvia Repetto

DUNE Collaboration Meeting

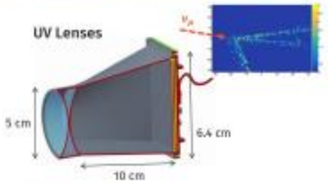
September 12th, 2024

Introduction – GRAIN

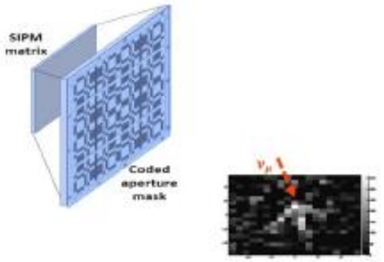
- **GRAIN** = **GR**anular **A**rgon for **I**nteractions of **N**eutrinos
  - It's a **passive** target to study for ν-Ar interactions with downstream tracker/calorimeter
  - It's an **active** target, instrumented with sensors for collecting UV scintillation light with arrays of SiPMs and for performing imaging of the event

- Two possibilities for the optical system:

- Lens-based optical detector



- Coded mask-based optical detector



- **Similar** SiPM **32x32 matrices**:
  - 2x2 mm^2 for lenses or SiPM 3x3 mm^2 for masks
  - A **unique ASIC** specifically designed for GRAIN

Introduction – ASIC design

Physics Requirements

- Distinguish **multiple events in the same spill**
- **Distinguish separate pulses,** providing an **amplitude information** for each of them
- Determine the **total number of photons in a pulse** with an error lower than 5%

ASIC Requirements

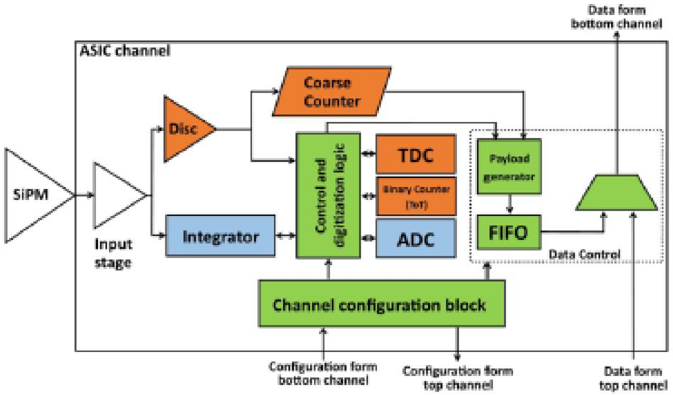
1024 channels

Must operate at **cryogenic and room** temperature

Measure **deposited charge and time**

Timing resolution better than **100 ps**

Power consumption **< 5 mW/ch**



GRAIN ASIC Pixel Scheme

Credits: Torino's INFN group

Starting point: ALCOR (**A** **L**ow-power **C**hip for **O**ptical sensors **R**eadout)

- Developed by INFN Section of Torino
- **32** channels
- **Single-photon time tagging** mode or **time and charge measurement**

Final configuration:

- **1024** channels
- **Energy** branch: **charge integrators** + ADC
- **Time** branch: **Time-to-Amplitude Converters** + ADC

Samples under study – Genova's group

The goal of this analysis is to validate the ASIC architecture. To do this, we select four samples, considering three different regions each (most significative or critical regions)

Selected samples		Electronics validation
1. Channels that need a high number of integration windows	→	1. For validating the architecture with 2 ADCs and a conversion time of 40-50 ns
2. Channels with the highest number of photons within an integration window	→	2. For optimizing/validating the dynamic range
3. Channels with the highest number of photons within 20 ns from the true interaction time*	→	3. Is the electronics capable of detecting such a high number of photons in a small time window?
4. Channels with the lowest time between the interaction time* and the previous detected photon	→	4. Which amount of channels per interactions have not the right t_0, due to previous photons

Calorimetric reconstruction (items 1–3)

Event identification (item 4)

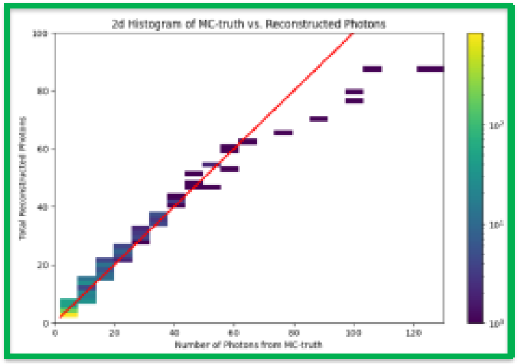
* The interaction time is given by true information from MonteCarlo, if a peak of at least 3 photons is detected in the channel

Results – Genova's group

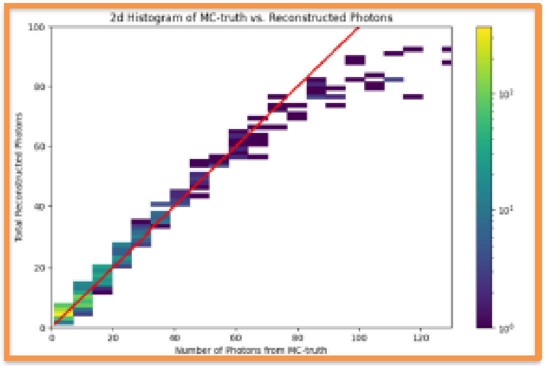
PRELIMINARY

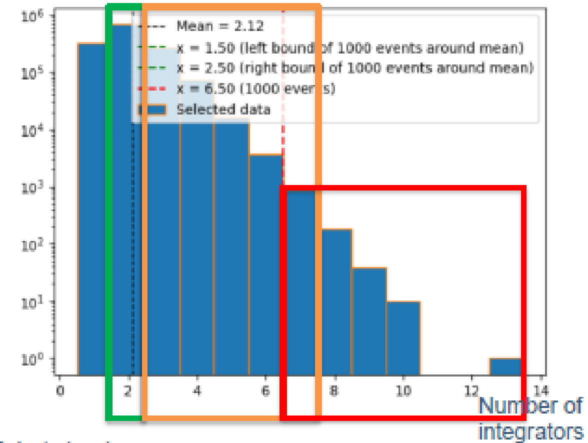
- The results shown concern simulations in Xenon-doped liquid Argon, totalling 720 spills

N° of integrators = 2

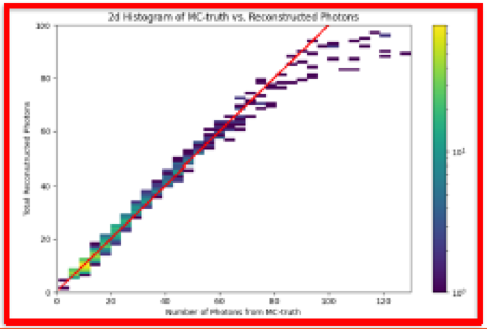


3 < N° of integrators < 7





N° of integrators > 7



The reconstruction is **good until 70 photons.**

Selected regions:

1. Very good reconstruction of the number of photons from the integrated charge for the channels that require 2 integration windows
2. Good reconstruction of the number of photons from the integrated charge for the channels that require between 3 and 7 integration windows
3. We also select the worst and pathological cases (i.e. the channels that require at least 7 integration windows) but we don't ask for a good reconstruction of the number of photons

Results
Genova's group

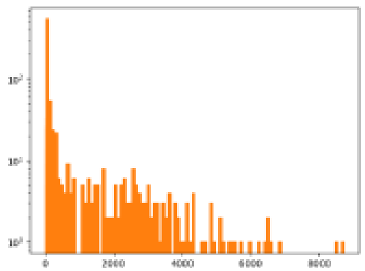
- For each channel:
  - Search for the interaction: at least 3 photons within 50+10 (10 takes into account the time of flight of photons to the sensor) ns from the t_0 of the interaction
  - Save the detected time of the interaction t_{int}
  - Calculate $dt = t_{int} - (t_{lastphoton}$ before the interaction)

Pure liquid Argon

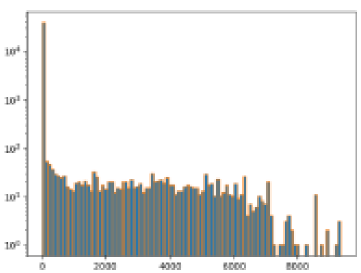
- **120 spill**

dt distribution in pure liquid Ar

t_{slow} = 1600 ns



Channels which detect more than 1 interaction = 833
551 have dt = 0 (66%)
124 have dt<500 ns (14%)



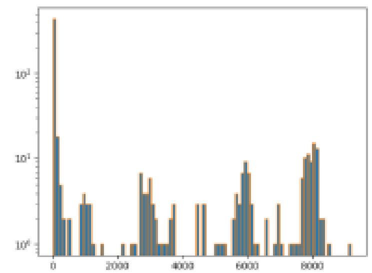
Channels which detect only 1 interaction = 40193
38835 have dt = 0 (96%)
243 have dt<500 ns (0.6%)

Xenon-doped Argon

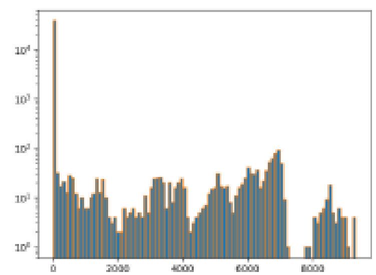
- **120 spill**

dt distribution in Xenon-doped Ar

t_{slow} = 160 ns



Channels which detect more than 1 interaction = 646
438 have dt = 0 (67%)
17 have dt<500 ns (2%)



Channels which detect only 1 interaction = 39136
37714 have dt = 0 (96%)
148 have dt<500 ns (0.4%)

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Preliminary studies for masks – Bologna's group

ASIC performance was tested varying independently different parameters:

- SiPM **quenching resistance R_q**
- Trigger **hold-on** value after signal goes below the discriminator threshold
- ADC **clock period**

Each simulation comprises **120 spills with 60k channels in GRAIN.**

Discriminator **threshold** was set to **0,5 pe.**

We looked for:

- The amount of **charge lost per channel**
- The number of channels in which the ADC was **saturated**

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Preliminary studies for masks – Bologna's group

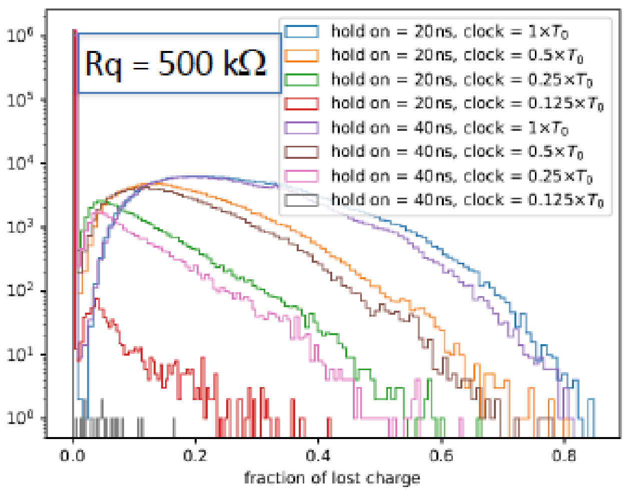
To have a general overview of the ASIC behaviour we can define two quantities:

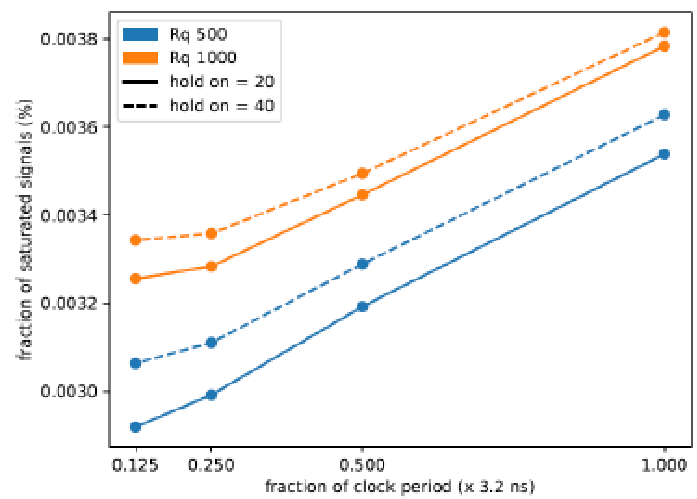
Lost charge

The charge lost per channel decreases (as expected) decreasing the clock period.

Saturated fraction: fraction of events in which the ADC saturated

$$\frac{\text{Number of saturated events (ch==2^9)}}{\text{total number of events}}$$





10 12-09-2024 S. Repetto | Simulation results for the validation of the GRAIN ASIC design

UniGe INFN DUNE

Conclusion

- The samples has been analysed as a function of the clock period. Since the speed of the DACs can be increased up to 4/8 times, we conclude that we need at least clock period of ¼
- Unfortunately, Genova's group has found that in no case it's possible to obtain a good reconstruction for a number of photons greater that 60/70. In the near future, we will make further checks on the various parameters to see if we can achieve better results
- Everything presented will alse be verified for simulations in pure liquid Argon
- Front-End structure is currently under study in collaboration with the INFN Section of Torino
- The preliminary ASIC design works as expected
- The amount of charge lost or saturated can be minimized choosing the parameters properly
- Further and more detailed studies are being performed

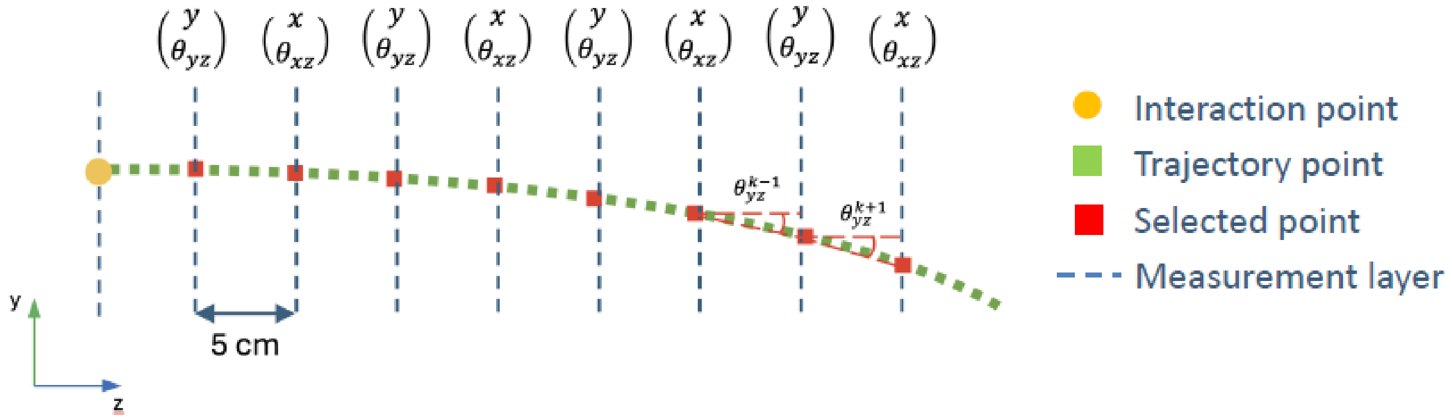
In addition

- Reconstruction:
  - Comparison of straw- vs drift-based tracker
  - Full event reconstruction studies
- Anaysis:
  - Study of $\bar{\nu}_\mu + H \rightarrow \mu^+ + n$ channel
  - Study of ν_μ CCQE on Ar (w/ parametrized reco in GRAIN)
- Integration w/ DUNE:
  - ND simulation and reconstruction workflow
  - CAF
  - Software distribution

Thank you

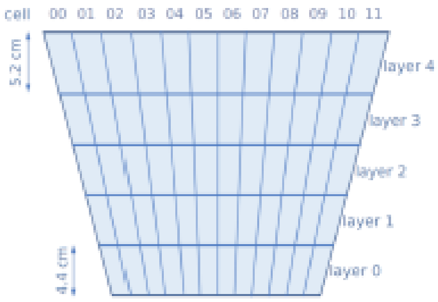
Fast digitization

- Fine sampling of MC-points (position and momentum of trajectory)
- MC-points selected every **5 cm** from the interaction point
- Measurement position as *x (y)* coordinate smeared with **200 μm** gaus smear
- Measurement angle as mean value of angles between previous/next points with **0.2 rad** gaus smear
- **Horizontal and vertical measurements alternating each 5 cm**



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

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

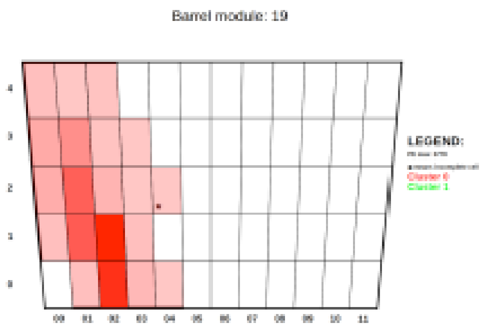
- Arrival time [ns].
$t_{pe} = t_{cross} + t_{decay} + t_{prop} + Gauss(1ns)$
- ADC counts $S_i^{B,A} = N_{pe} \cdot peADC$.
- TDC: 2 options constant fraction or fixed threshold.

Digit structure:

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

ECAL reconstruction: clustering

Pre-clustering



Spatially neighbour cells are added together

Pre-cluster variables: energy, position, time (as the energy weighted mean of the reconstructed time of the cluster cells), collection of reco cells.

Splitting

Cluster overlapping are checked evaluating the pre-cluster spread in **time**.

If criteria are satisfied pre-clusters are divided into time quadrants

Merging

Check for pre-clusters that have been split incorrectly and others that can have cells which are not spatially adjacent.

Position and **time** are evaluated.

Cluster output structure

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