Fermilab

IMAGING COSMIC AND RARE UNDERGROUND SIGNALS

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Improving ICARUS Track Reconstruction Algorithms

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HORIZON 2020

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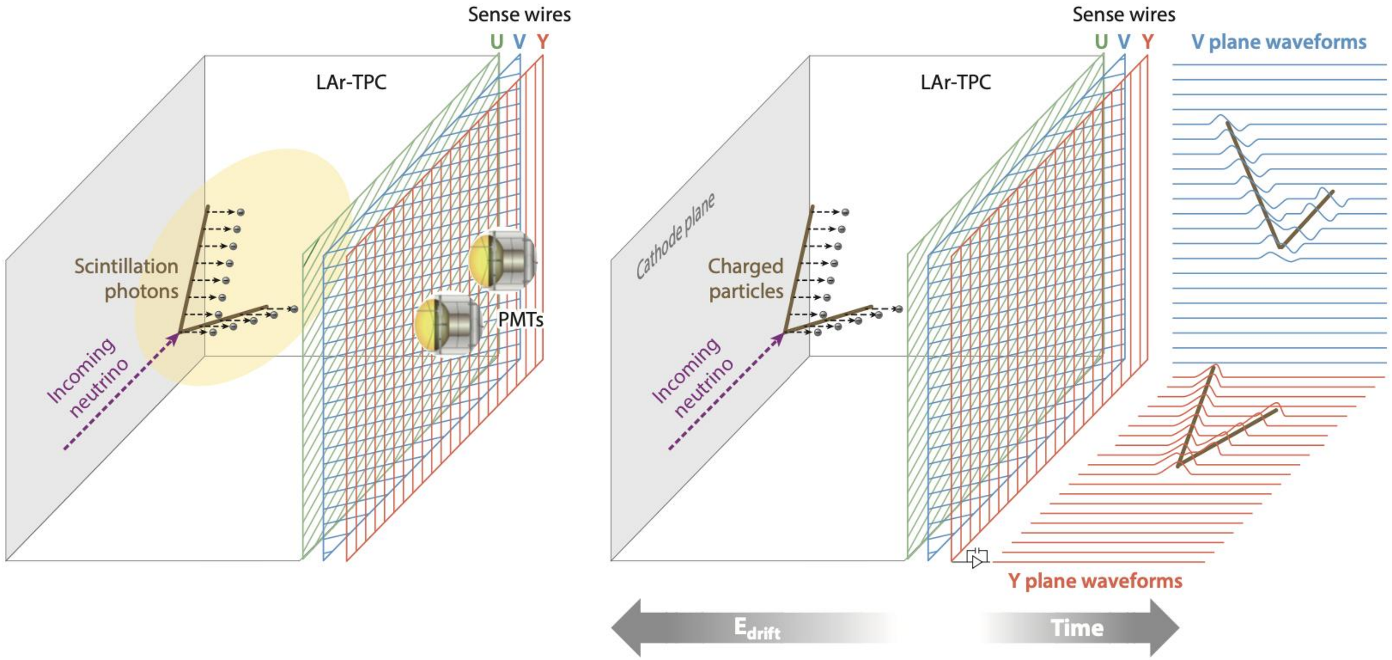
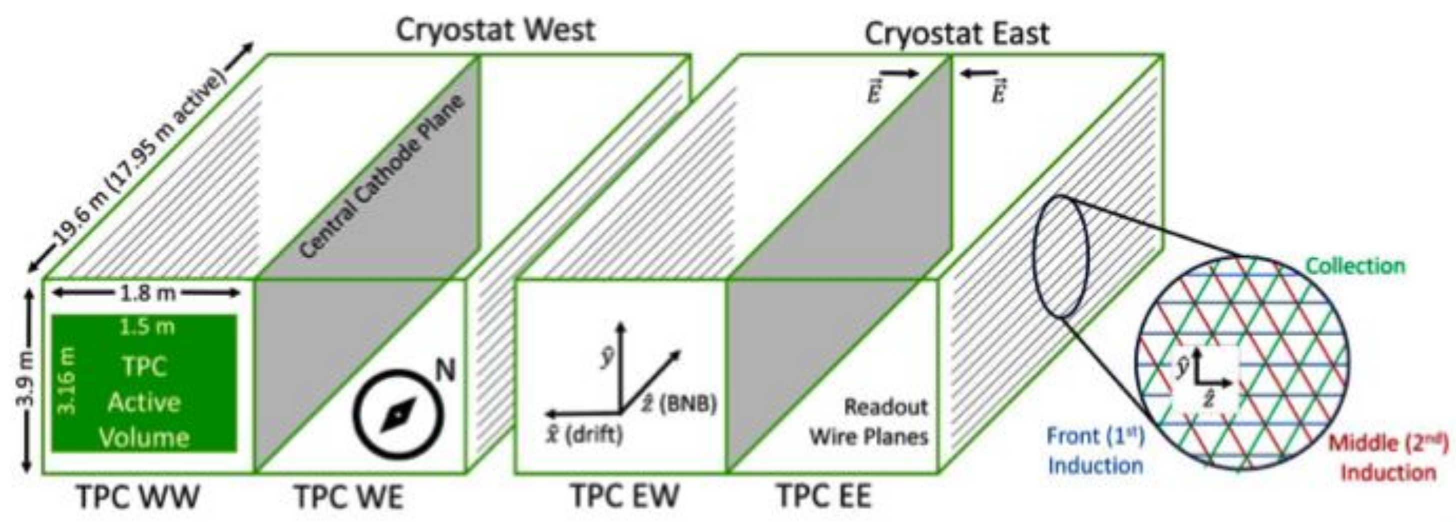
Liquid Argon Time Projection Chambers

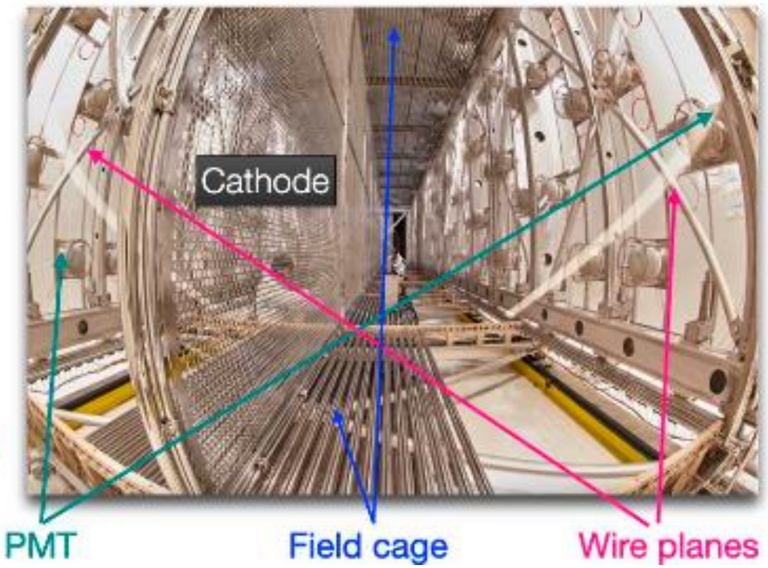
From an idea of Carlo Rubbia (1977), LArTPCs are ideal detectors for ν physics: they allow to have simultaneously an **energetic reconstruction** of the events and a **3D image** of ν interactions



- Charged particles generate excited argon molecules that **emit light**:
  - Fast component ($t < 2$ ns): identify time of neutrino interaction (**Trigger**).
  - Slow component ($t \sim 2 - 3$ μs): energy measurement.
- Charged particles **ionize argon**: 42000 e^-/MeV and the 500 V/cm Electric Field drifts the e^- (1.6 m/ms) towards the anode where wire planes are used to generate **2D images** of charged particle tracks.
- 2D images are combined into **3D trajectories** with mm resolution.

ICARUS at Fermilab

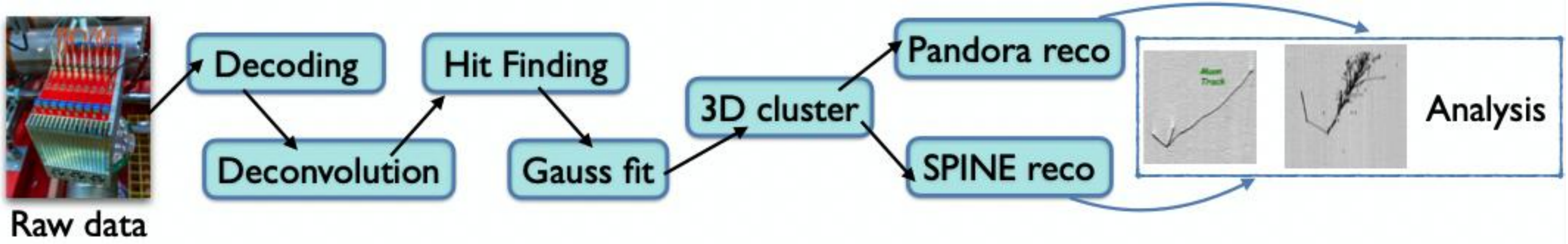




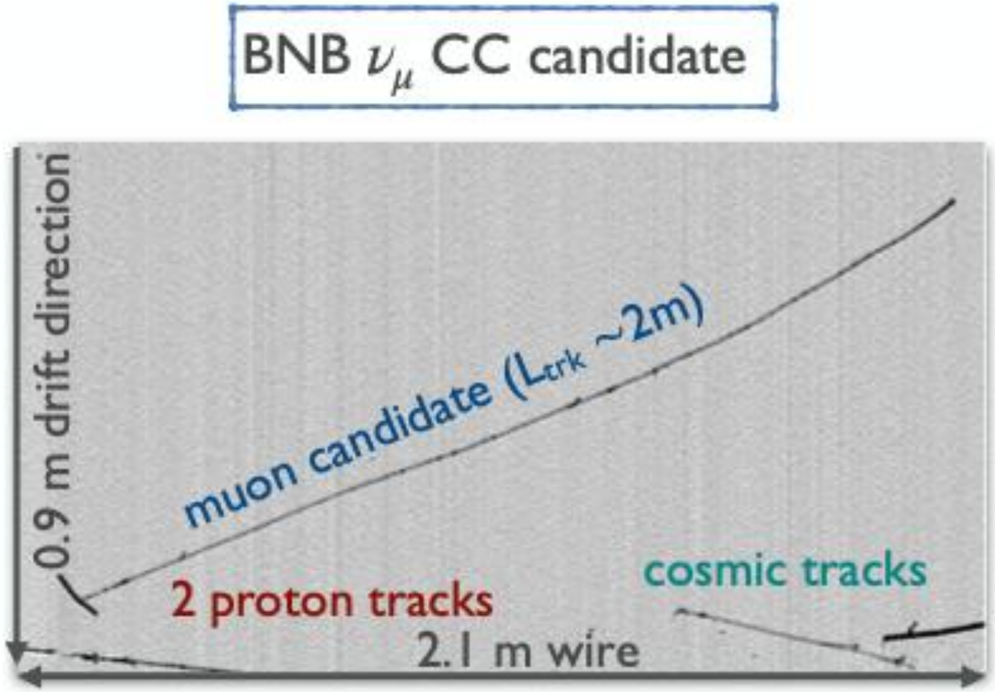
- **ICARUS T600:** the first large scale LArTPC ever built with 760 tons of pure LAr, **470 tons** active mass
- **2 cryostats** ($3.6 \times 3.9 \times 19.6\ m^3$) with 2 TPCs each and a central cathode (1.5 m drift, $\mathrm{E_D} = 500$ V/cm)
- **3 wire planes per TPC:** total of 54000 wires at $0^\circ, \pm 60^\circ$ with 3 mm pitch to measure ionization signal
- The ionization charge is fully collected by the Collection plane (0°)
- From the combination of three planes ($0^\circ, \pm 60^\circ$) it is possible to reconstruct the position of the particle in the space, providing an excellent 3D imaging and calorimetric reconstruction of any ionizing particle

See my talk "Latest Results from the ICARUS Experiment at the SBN Program" for further information.

Neutrino Candidate Reconstruction



- Two reconstruction frameworks to characterize ν events:
  - **Pandora**, pattern recognition software widely used in LArTPC
  - **SPINE**, entirely based on ML techniques
- Continuous effort to improve reconstruction and data/MC agreement
- Validation using **visual scanning:**
  - Interaction point (vertex) reconstruction.
  - Agreement between light and charge signal barycenters along longitudinal (beam) direction within 1 m.

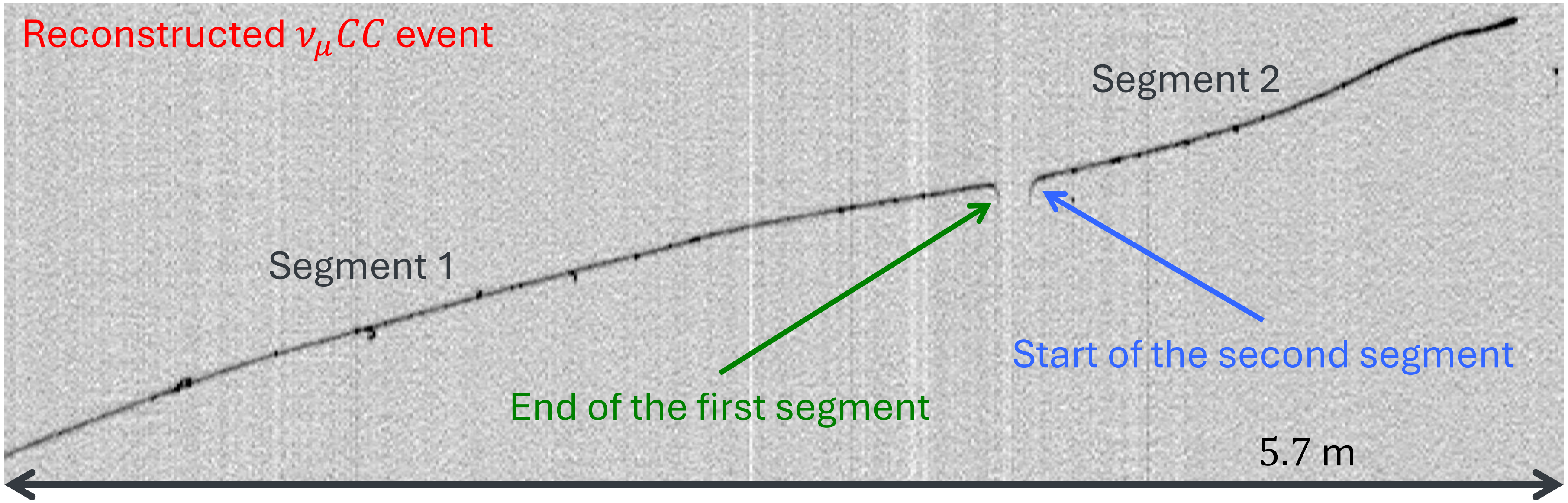


Tracks breaking in Pandora

- In some cases, related to inefficiencies in the hit detection, deflection of the particle trajectory or particles crossing the cathode or the wire support of Induction-1 (wires at 0°), Pandora breaks the particle's track into two or more smaller segments and considers each segment as an independent particle.

- The tracks broken by Pandora are sometimes poorly reconstructed; for example, the start and end points may be swapped with respect to the interaction vertex, or even the vertex may be placed between the two segments. In some cases, a segment of the track is associated to the wrong interaction.

- We estimated Pandora breaks about 6% of the muon tracks in a Monte Carlo sample of reconstructed $\nu_{\mu}CC$ events.

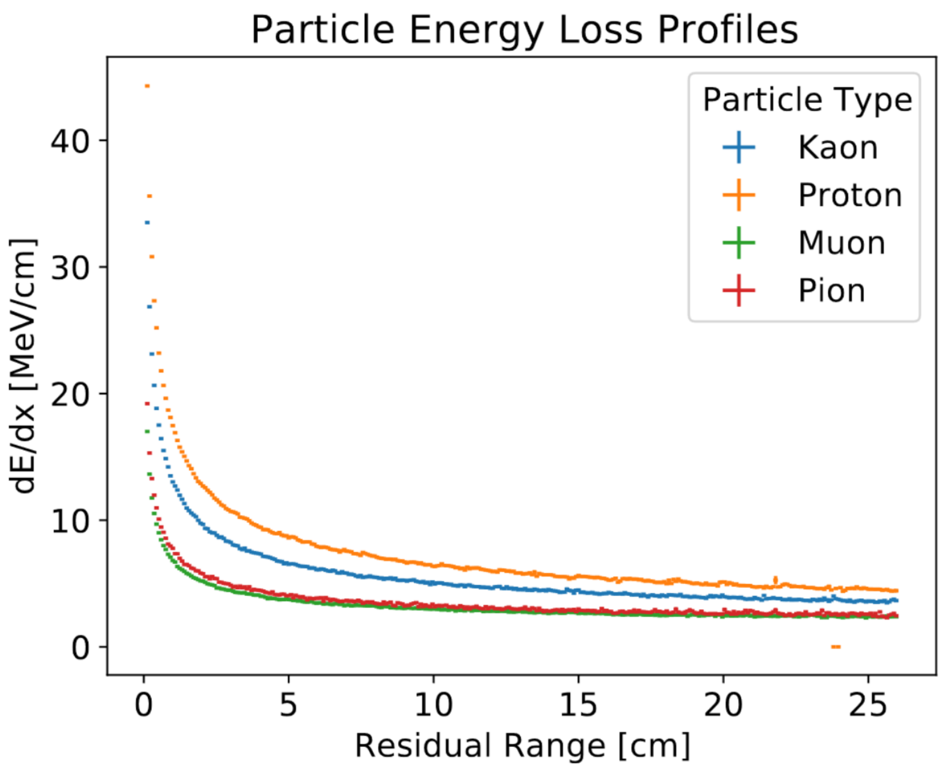


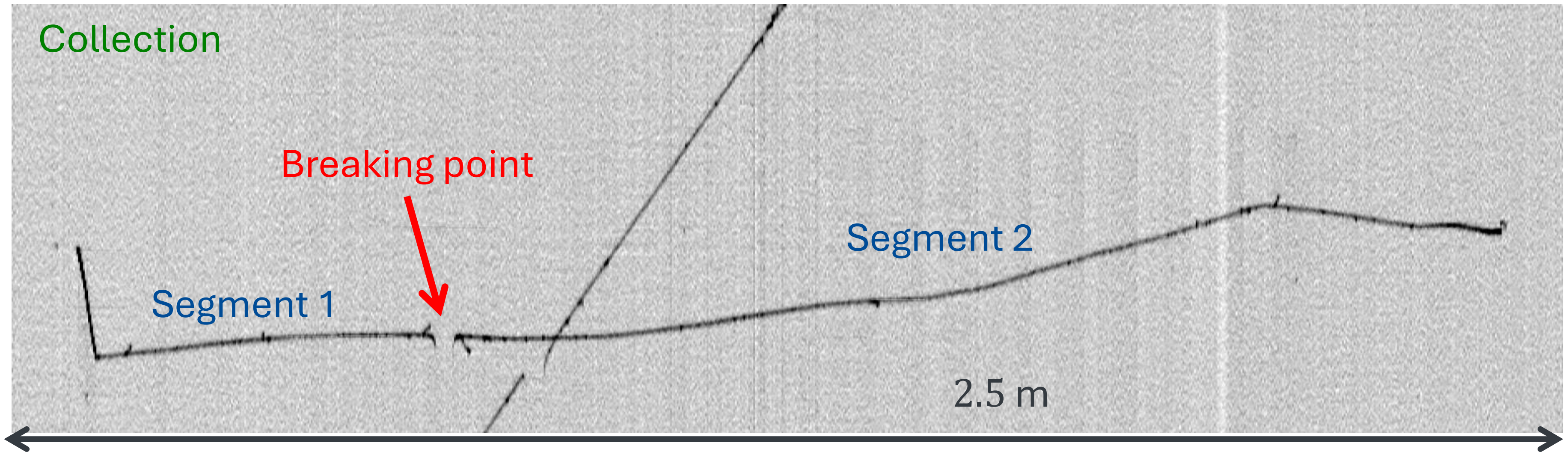
Tracks breaking in Pandora

- The track length is used to estimate the particle's energy: if the reconstructed μ length is 86 cm while the true μ length is 286 cm, this means that we are underestimating the muon energy of about 400 MeV.

- This brings to inaccurately estimate also the ν_μ energy.

- Moreover, if a track is broken in more segments, the particle identification (PID) based on the study of the $\frac{dE}{dx}$ vs Residual Range may fail.

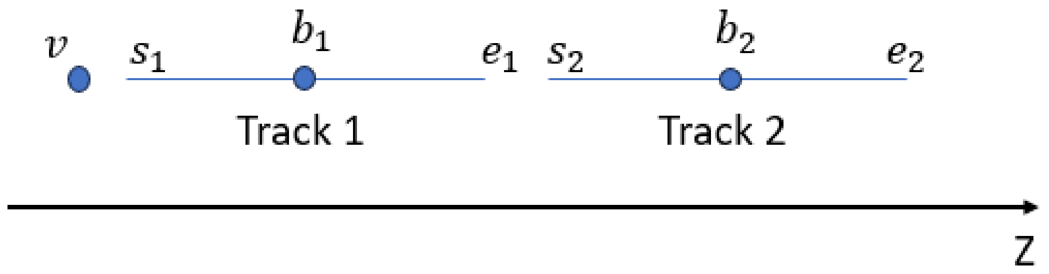




Stitching algorithm

- To mitigate this phenomenon, we designed an algorithm that detects and stitches the broken tracks.
- It evaluates two tracks simultaneously considering all possible pairs between the tracks in the event (hence also in different interactions!):

1. It aligns the interaction vertex and the barycenters of each track along the z-axis.



2. If the vertex is between the barycenters, it means the two tracks belong to different particles or Pandora wrongly determined the interaction point. In this case, the pair of tracks is rejected and considered non-repairable.

3. The track with the barycenter located centrally (Track 1) is closer to the interaction point. In this instance, the algorithm identifies the start and end points of both tracks based on the 3D distance from the interaction vertex ⇒ start and end point swap corrected!

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Stitching algorithm

4. When the tracks overlap along the z-axis, it verifies if the overlap is within the acceptable tolerance:

$$\text{If} \begin{cases} v = O(0) \text{ and } z_{e_1} > z_{s_2} \\ v = O(1) \text{ and } z_{e_1} < z_{s_2} \end{cases},$$

$$T_{ss} = \frac{|z_{s_2} - z_{e_1}|}{\min(D_{z,1}, D_{z,2})} < T_{0,1}, \quad D_{z,i} = |z_{e_i} - z_{s_i}|$$

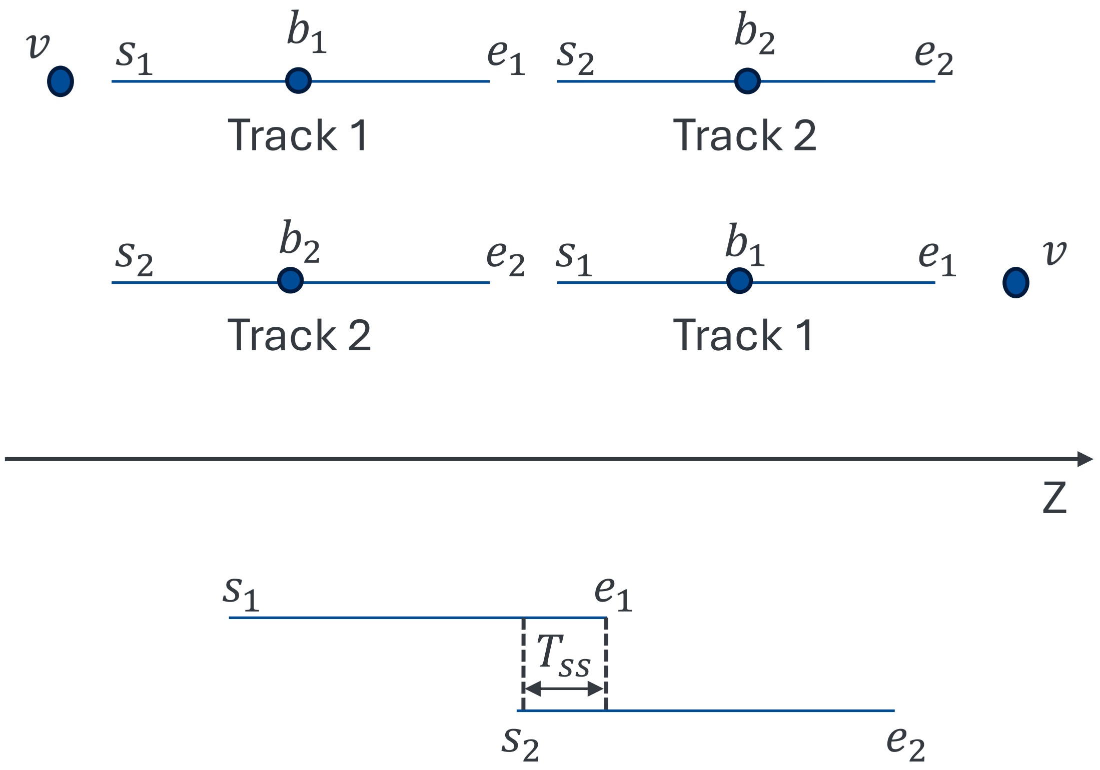
If the two tracks belong to the same interaction:

$$T_{ss} < T_0 = 0.7$$

If the two tracks belong to different interactions:

$$\mathrm{T_{ss}} < T_1 = 0.7$$

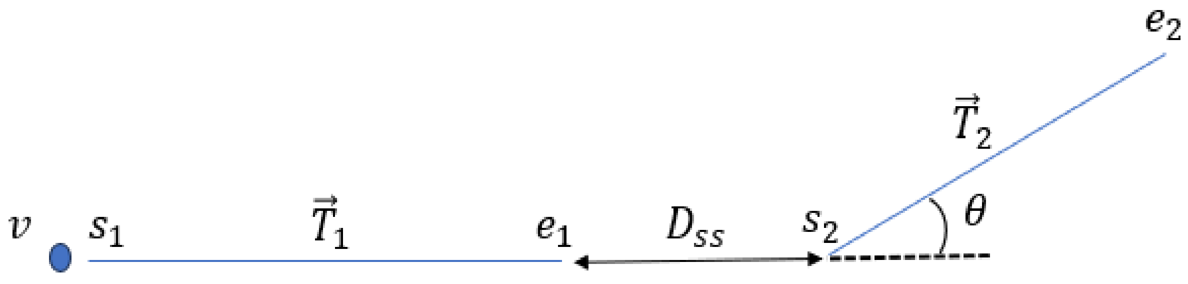
Ordering: $O = \{v, b_1, b_2\}$



Stitching algorithm

5. It checks the angle between the directions of the tracks:

$$\theta = \text{acos}\left(\frac{\vec{T}_1 \cdot \vec{T}_2}{|\vec{T}_1||\vec{T}_2|}\right) < \theta_{0,1}$$



6. It evaluates the 3D distance between the tracks:

$$D_{ss} = \frac{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}}{\min(D_{se,1}, D_{se,2})} < D_{0,1}, \qquad D_{se,i} = |\vec{T}_i| = |\vec{e}_i - \vec{s}_i|$$

If the two tracks belong to the same interaction:

$$\theta < \theta_0 = 35^\circ$$

If the two tracks belong to different interactions:

$$\theta < \theta_1 = 30^\circ$$

If the two tracks belong to the same interaction:

$$D_{ss} < D_0 = 0.7$$

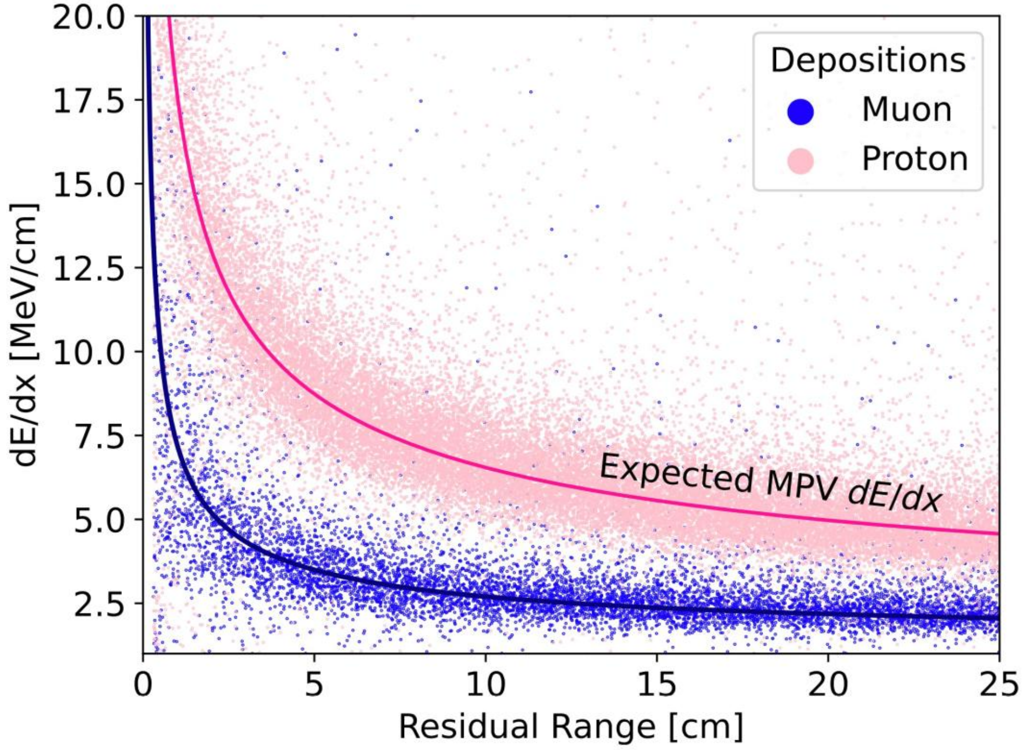
If the two tracks belong to different interactions:

$$D_{ss} < D_1 = 0.9$$

Selection criteria of the tracks

- We selected the tracks to which we applied the stitching algorithm in two different ways.

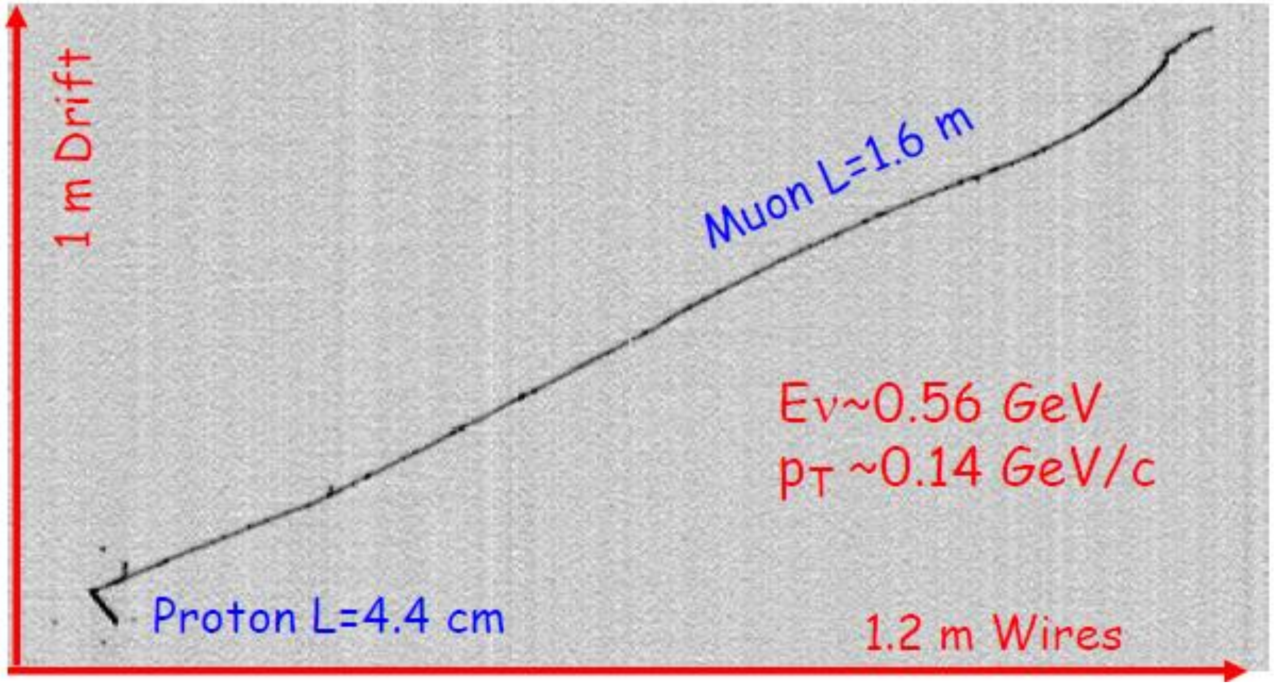
- The first selection is smoother and can be applied to different ICARUS analyses:
  1. the interaction vertex must be farther away than 25 cm from the edge of the active volume;
  2. the track must be contained within 5 cm from the edge of the active volume;
  3. the reconstructed track length $L_{trk,Reco} \geq 20$ cm (to exclude delta ray);
  4. the track must be associated with a particle and not a shower;
  5. identification of the track as a muon or a proton using $\frac{dE}{dx}$ vs residual range by fitting the curves with large thresholds.



$\frac{dE}{dx}$ vs Residual Range for μ and p used for PID

Selection criteria of the tracks

- A tighter selection is applied to pick **fully contained $\boldsymbol{\nu_\mu CC}$ events** with $1\mu + Np\ (N > 0)$ protons in the final state and is used for the ν_μ disappearance analysis:
  1. PMT light signal within 1.6 ms beam spill in coincidence with reconstructed TPC tracks, No CRT signal;
  2. A muon with $L_{trk} > 50$ cm;
  3. $\mathrm{N} \geq 1$ protons with $E_k > 50$ MeV ($L_{trk} > 2.3$ cm);
  4. No additional π or γ.



Algorithm Performance - Monte Carlo

- To evaluate the performance of the algorithm, we defined efficiency (E) and purity (P) on all μ tracks (broken and not broken) considered from the algorithm:

$$\mathrm{E} = \frac{n_{correctly\ stitched\ tracks}}{n_{reparable\ tracks}}, \qquad P = \frac{n_{correctly\ stitched\ tracks}}{n_{stitched\ tracks}}$$

- We evaluated the performance on 65573 μ primary daughters of $\nu_\mu CC$ interactions with a MC track length $L_{trk,MC} \geq 50$ cm to exclude the delta rays and very short segments that carry an irrelevant fraction of hit and energy.
- In MC, we define a μ split if it has two or more tracks sharing the same ID.

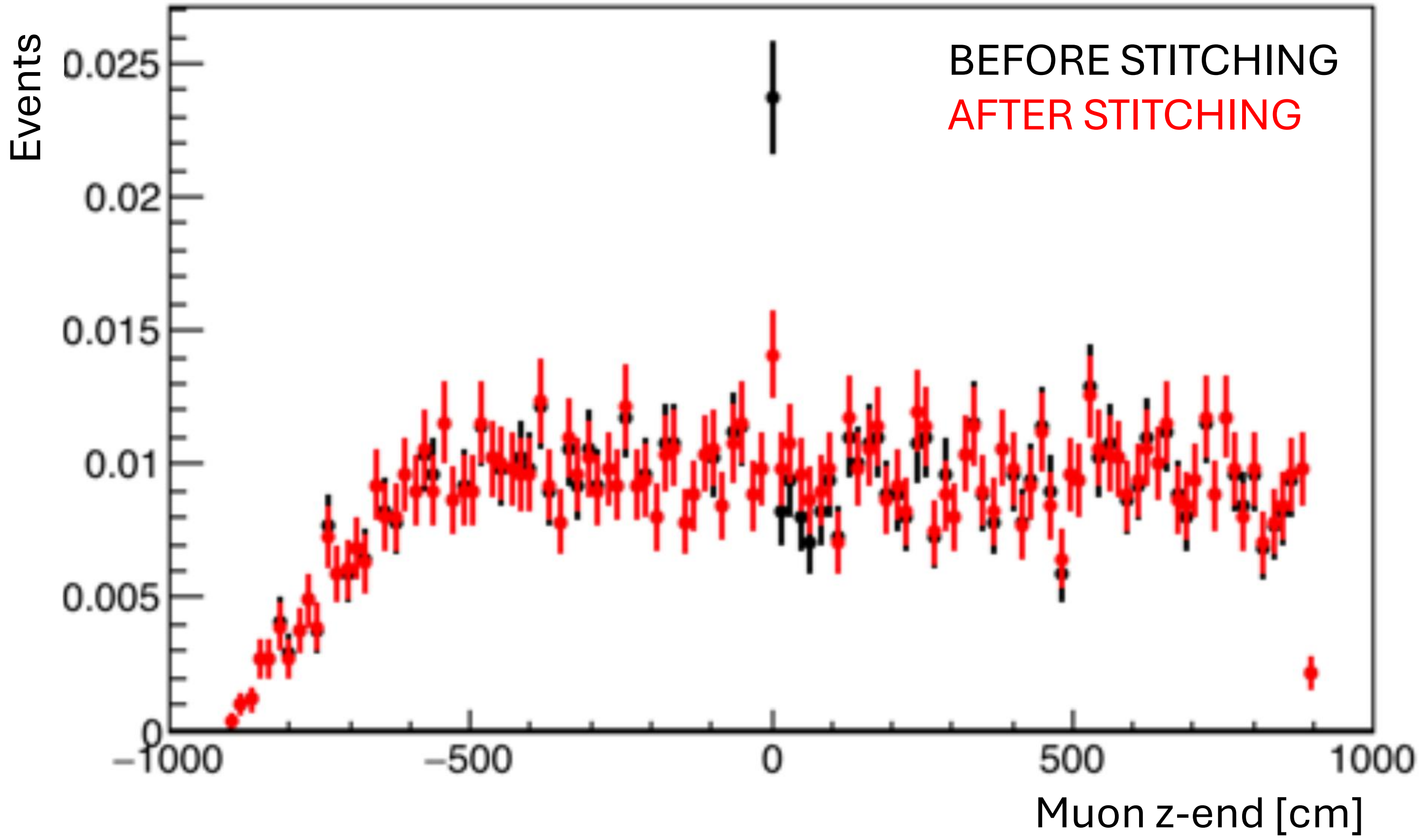
Cuts	Broken μ	Reparable μ[1]	Correctly stitched $\nu_\mu CC$ (E,P)	Wrong stitched $\nu_\mu CC$
Smooth selection	3755	2384	1727 (72.4%, 88.7%)	219
$1\mu Np$ selection	544	523	419 (80.1%, 96.8%)	17

1. Non-reparable μ: muons with the interaction vertex wrongly positioned between the barycenters of the segments. They are $\sim$37% of all broken muons.

Algorithm Performance - Real Data

- The stitching algorithm has been applied on the collected data with the $1\mu Np$ selection. It performs a stitch in $\sim 3.2\%$ of the selected events.

Excess of tracks stopping at z=0, where the wire support of Induction-1 is located. The number of broken tracks is significantly reduced from 2.4% to 1.4%.

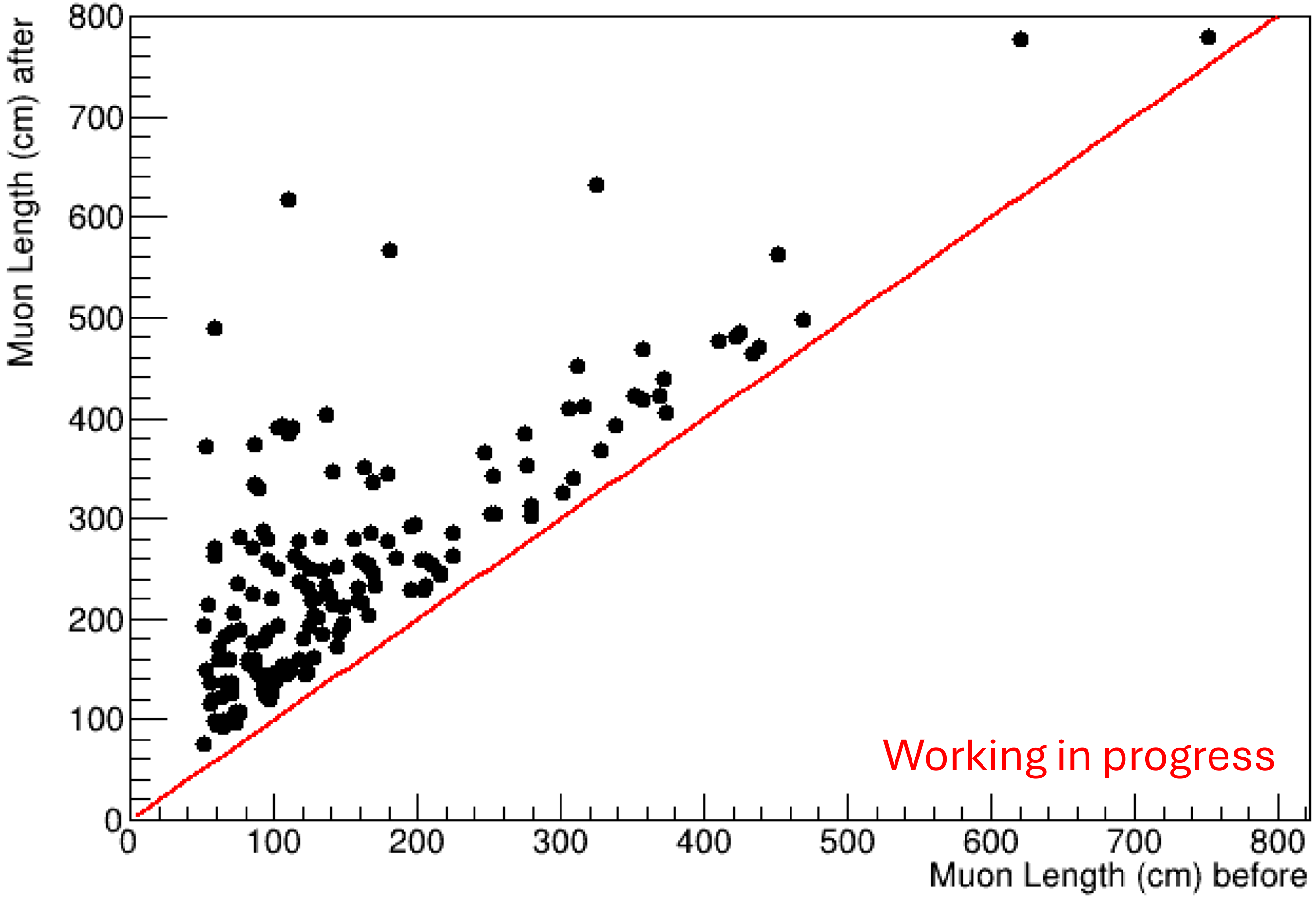


Algorithm Performance - Real Data

- The stitching algorithm has been applied on the collected data with the $1\mu Np$ selection. It performs a stitch in $\sim 3.2\%$ of the selected events.

Muon length after stitching versus muon length before stitching

$$\frac{dE}{dx} = 2 \text{ MeV/cm}$$



Conclusions

- The ICARUS experiment at Fermilab has been running smoothly in physics mode since June 2022.
- About 6% of $\nu_\mu CC$ tracks are incorrectly broken during the reconstruction process. This phenomenon brings to incorrect particle identifications and inaccurately estimation of the ν energy.
- The stitching algorithm detects and repairs tracks that have been incorrectly broken. It is capable of recognizing when an event results in a faulty reconstruction, making it preferable not to stitch in such cases.
- The algorithm has been validated through Monte Carlo simulations, demonstrating an efficiency of $\sim 73\%$ and a purity of $\sim 89\%$ with a smooth selection of the tracks and an efficiency of $\sim 80\%$ and a purity of $\sim 97\%$ with the $1\mu Np$ selection.
- The algorithm has been applied to a selected sample of reconstructed $\nu_\mu CC$ events in the real data. The algorithm performs a stitching process in $\sim 3.2\%$ of the events, significantly reducing the excess of broken tracks at $z = 0$, where the wire support of Induction-1 is located.
- It will be implemented at the end of the reconstruction process to reduce the number of tracks broken by Pandora and enhance the reconstruction of the ICARUS experiment.

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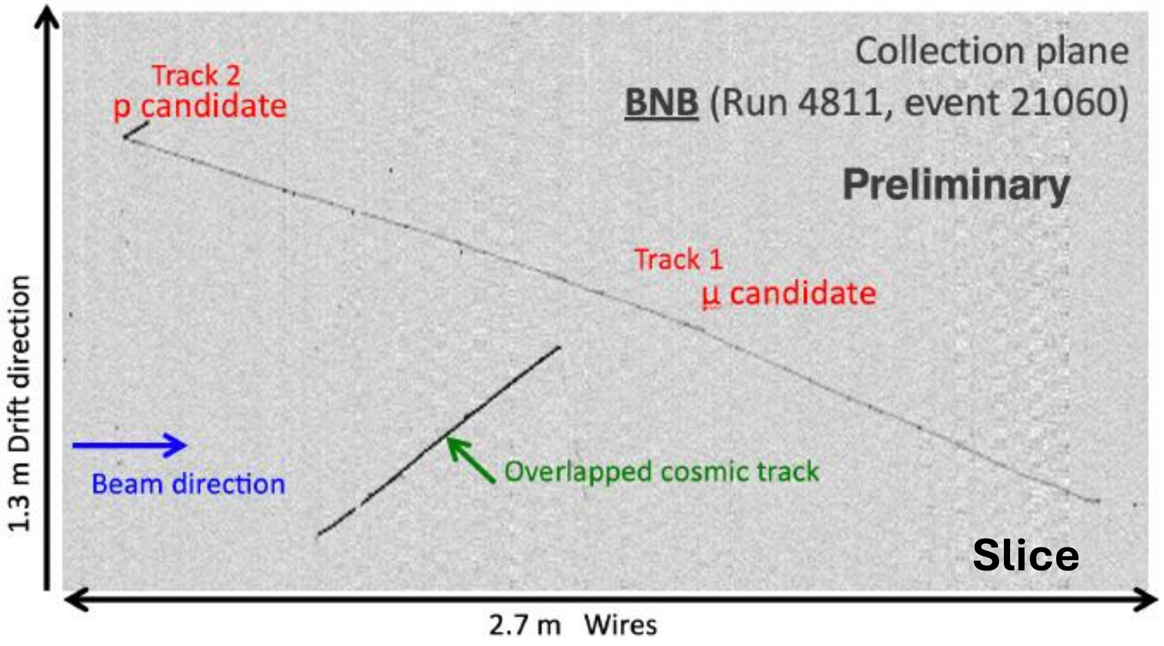
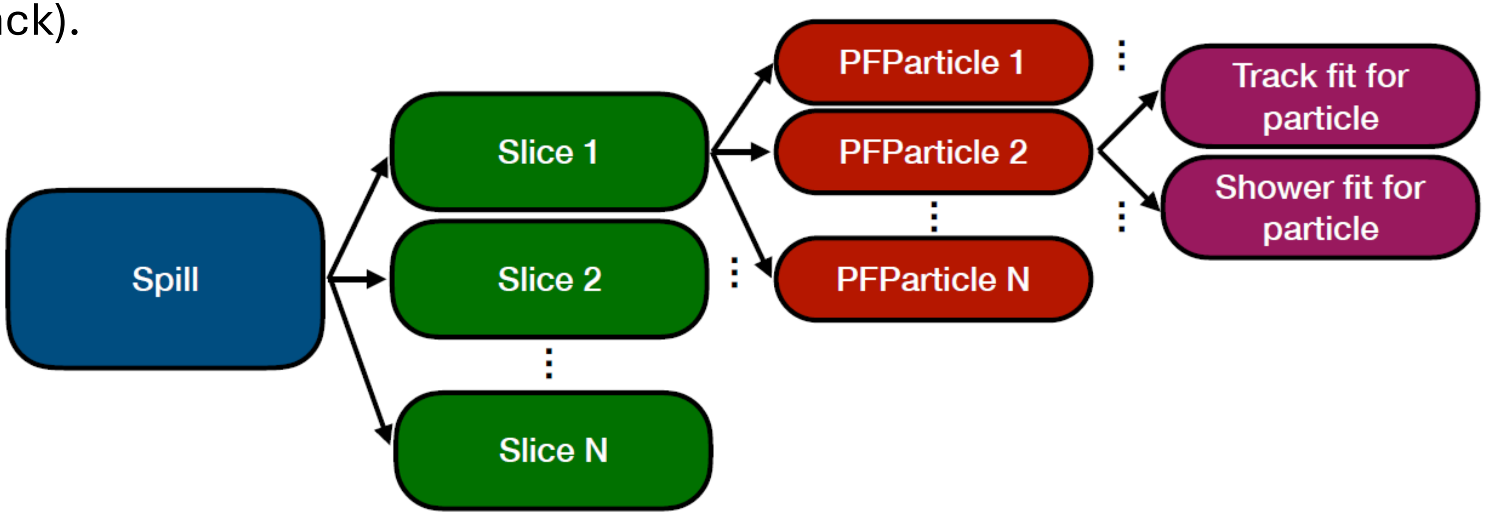
Backup

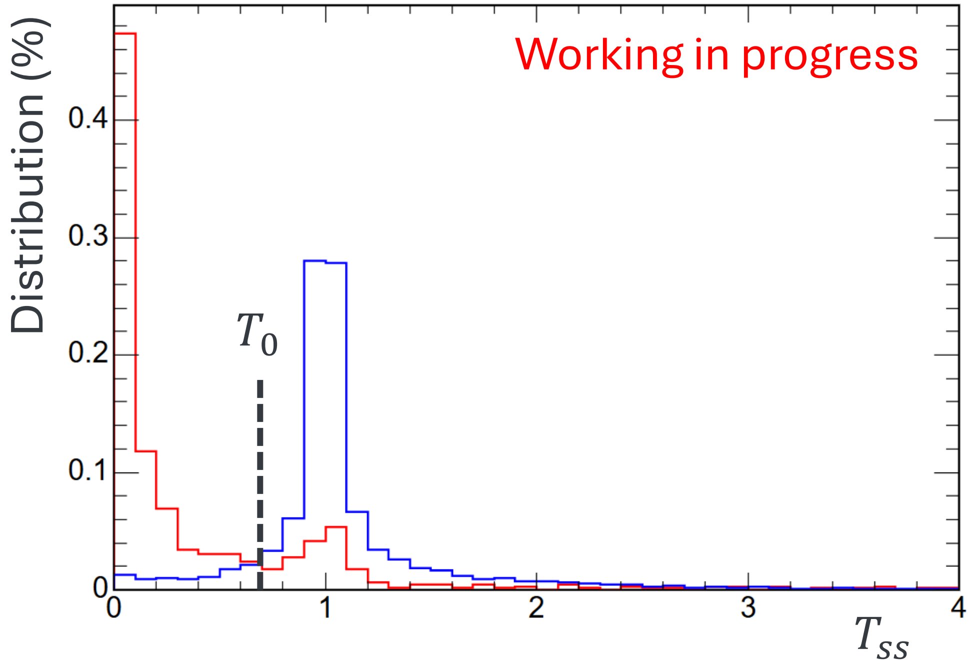
TPC Event Reconstruction

- Pandora reconstructs the interaction hierarchies (Slices) in each event (Spill).
- Within each reconstructed interaction there are one or more reconstructed particles (PFParticles), which can be tagged as primary or secondary.
- Those reconstructed particles are fit under the track and shower hypothesis and the related physical quantities are determined (for example the start and end points of the track).





Stitching Algorithm Calibration



- The algorithm has been calibrated on the tracks passing the smooth selection:
  - ➢ 🟥 = evaluation of two tracks belonging to the same $\nu_\mu CC$;
  - ➢ 🟦 = evaluation of a $\nu_\mu CC$ track with another of the background.
- $T_{ss}, D_{ss} > 1$ when $e_2 < e_1$.