Neutrino events reconstruction with the Time Projection Chamber detector in the ICARUS experiment

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Italian Summer Student Program @ FNAL - Midterm reviews 2022

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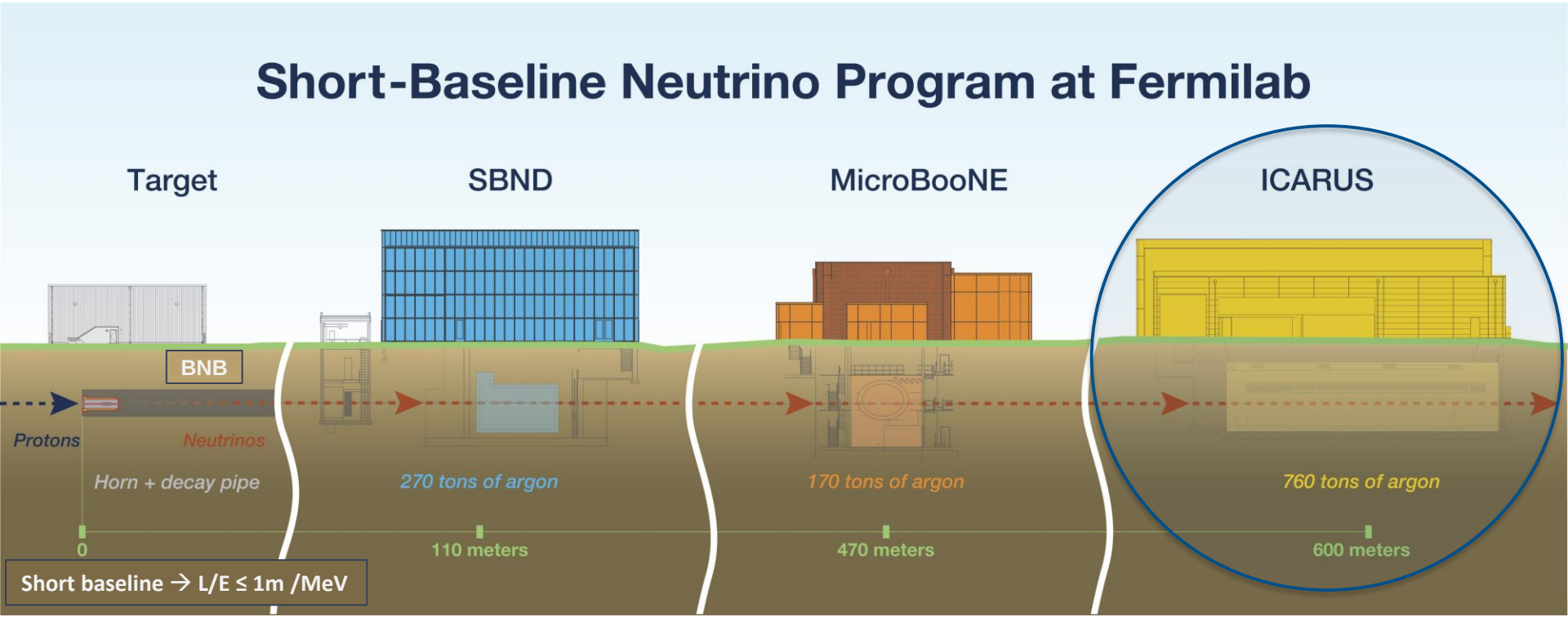
ICARUS: Imaging Cosmic and Rare Underground Signal



ICARUS is the **Far Detector** in the Short Baseline Neutrino Program (**SBN**) at FNAL.

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Neutrino Oscillations

Neutrinos can oscillate and change their flavor. The oscillation depends on L/E ratio and $\Delta m^2_{ij} = m^2_i - m^2_j$

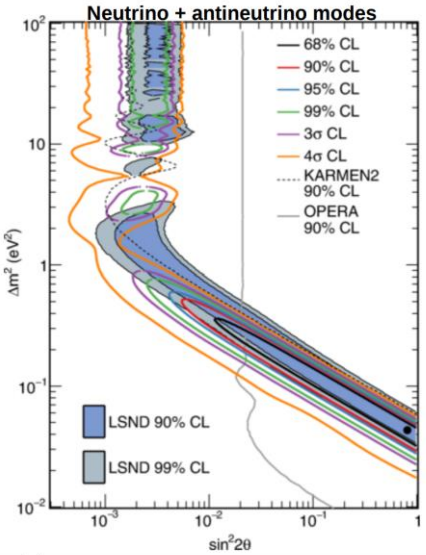
Short baseline → L/E ≤ 1m /MeV

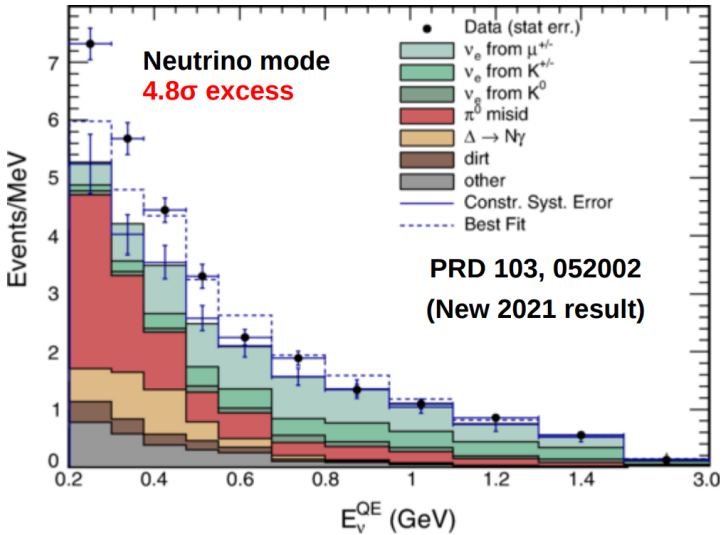
$$\Delta m^2_{21} = 7.5 * 10^{-5}\ \text{eV}^2$$
$$|\Delta m^2_{31}| = 2.5 * 10^{-3}\ \text{eV}^2$$

Anomalies!

Several SBN experiments have observed **anomalies:**

- **LSND** and **MiniBooNE: excesses of electromagnetic-like events**
- there are accelerator experiments, reactors and radioactive sources experiments explained with the presence of additional sterile neutrinos with $\Delta m^2 \sim 1\ \text{eV}^2$ (neutrino-4)





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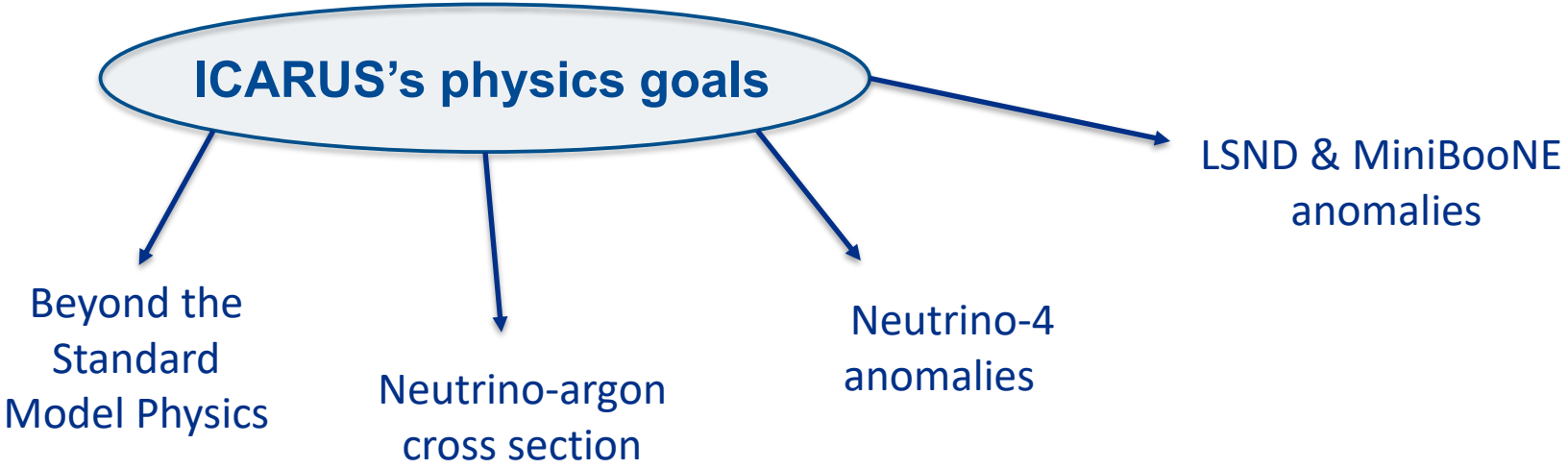
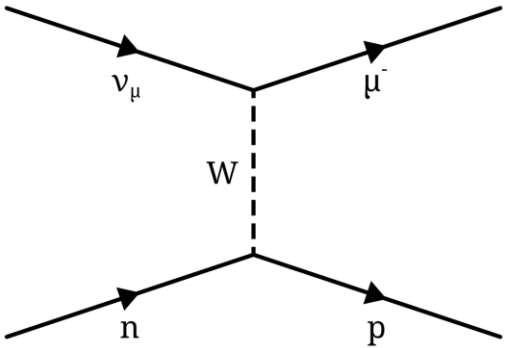


CCQE: Charge Current Quasi-Elastic

- $\nu\mu$ **disappearance** channel from BNB focusing on QE contained $\nu\mu$CC;
- νe **appearance** channel in the NuMI beam, selecting QE contained νeCC.

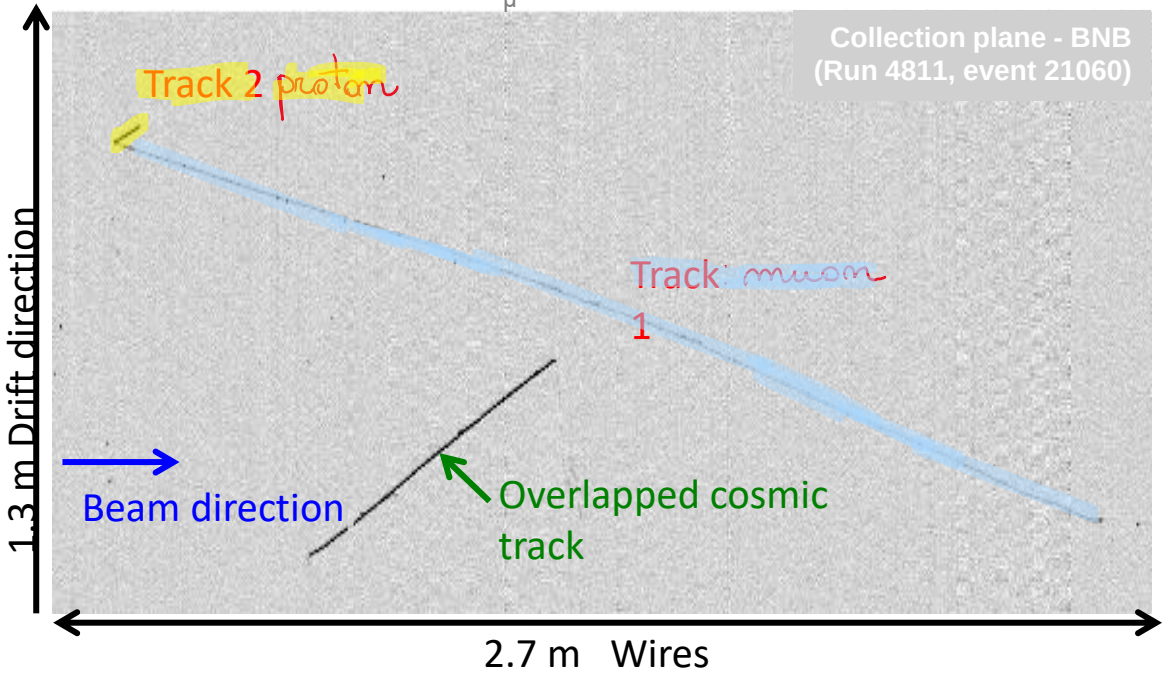
CCQE



- CCQE are the simplest kind of event that we can look at

- We can't see the neutrino but it's interaction products (**muon** and **proton**)

One of the first candidate ν_μ interactions found in BNB.



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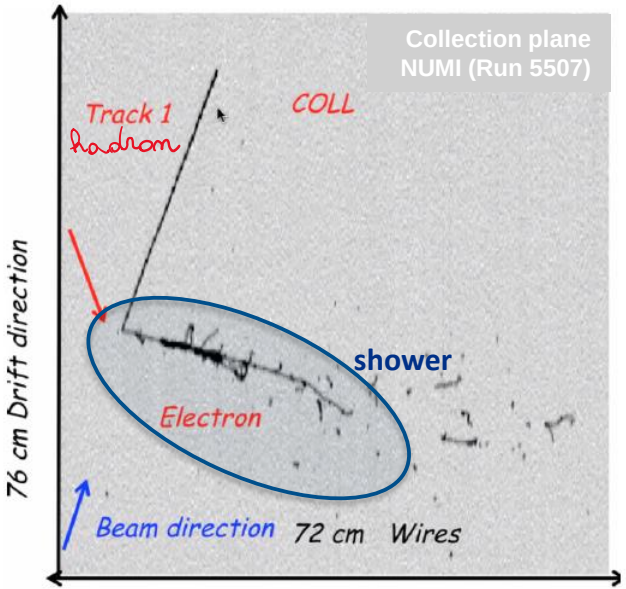
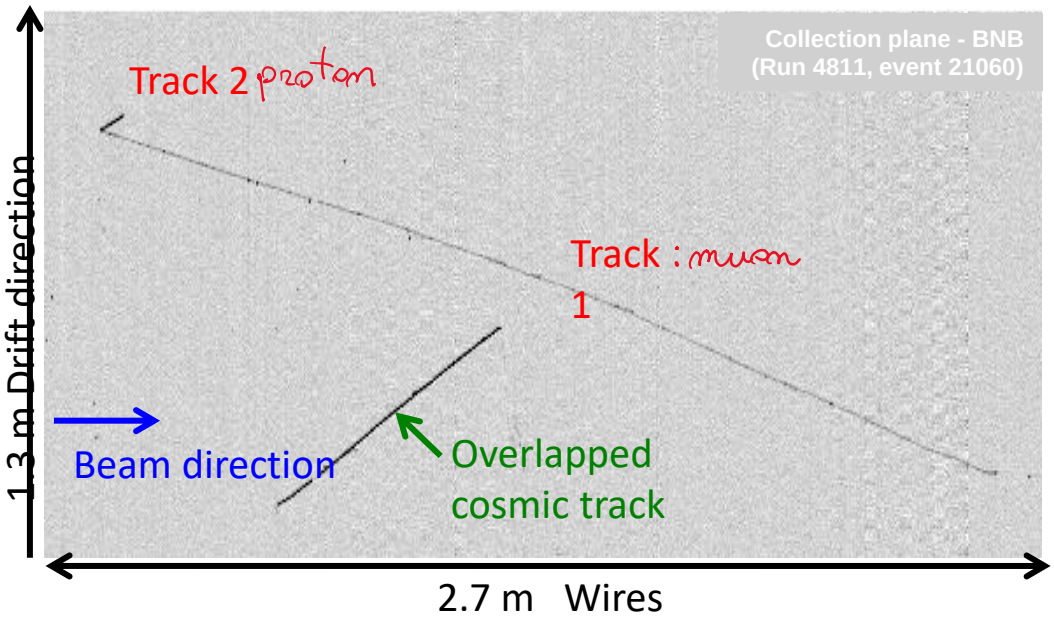
Candidate ν_e CCQE vs ν_μ CCQE



Candidate ν_e interaction from NuMI



One of the first candidate ν_μ interactions found in BNB.

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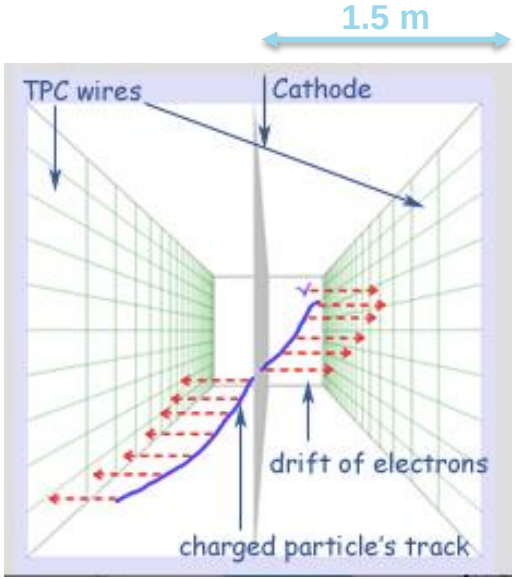
LAr TPC (Liquid Argon Time Projection Chamber)



TPCs are born as a fusion between:

- High resolution bubble chambers
- Electron detectors (large interactive mass)

760 tons of LAr! (476 active mass)

ICARUS' TPC

- two identical cryostat (3.6x3.0x19.6 m^3 each)
- Resolution ~mm^3
- 360 PMTs coated TPB (scintillation light)

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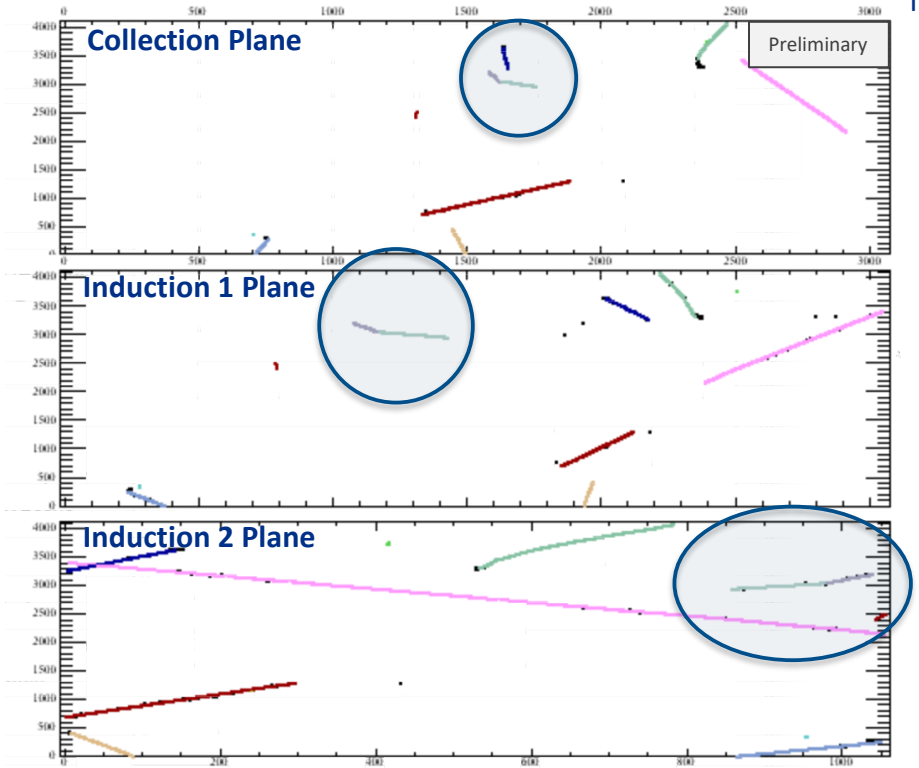
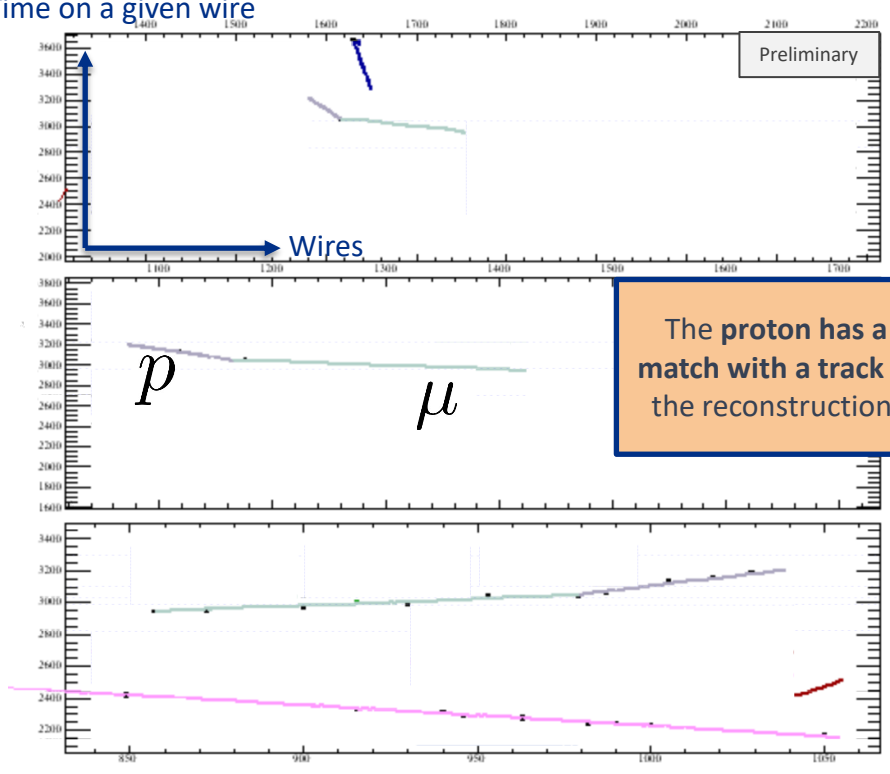
A well reconstructed $\nu\mu$ CCQE event on the event display – MC simulated data



Each color is a different track

Time on a given wire



Zoom in

The **proton has a match with a track** in the reconstruction.

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But not always everything goes smoothly

Sometimes it's **not easy** to **distinguish tracks** and **showers**

*In particular, my job is to help investigating the reconstruction of CCQE events where the **proton** is **reconstructed as a shower***

But how do we discriminate a track from a shower?

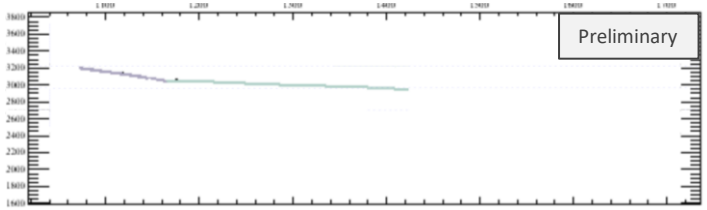
Using a **BDT** (Boosted decision trees) **algorithm!**

BDTs are like the Sorting Hat

Look at some feature

How **brave** is he?
How **loyal**?
Strong, **ambitious**,…
etc

BDTs are like the Sorting Hat



BDTs

Look at some feature

Reconstructed **length**,
Some **Linear Fit Charge**, **PCA** eigenvalue, … etc

Shower

Track

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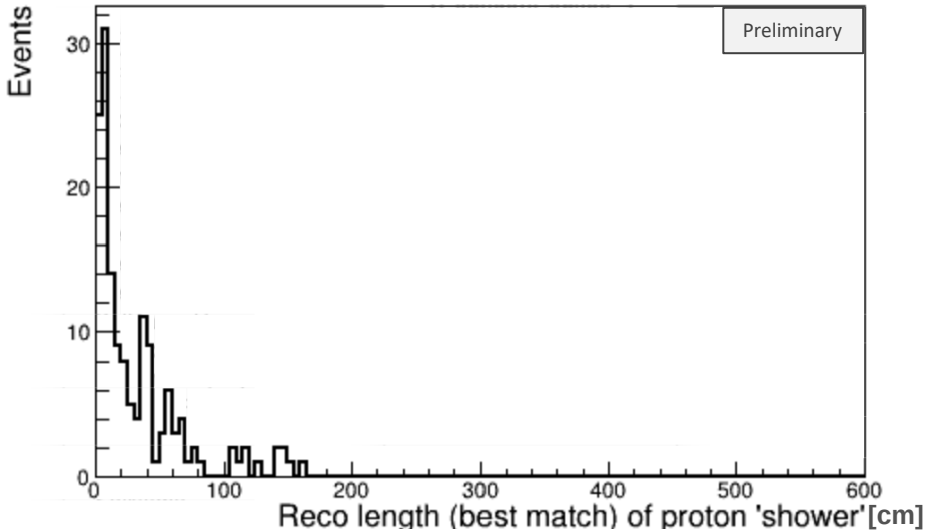
Proton: topology of cut

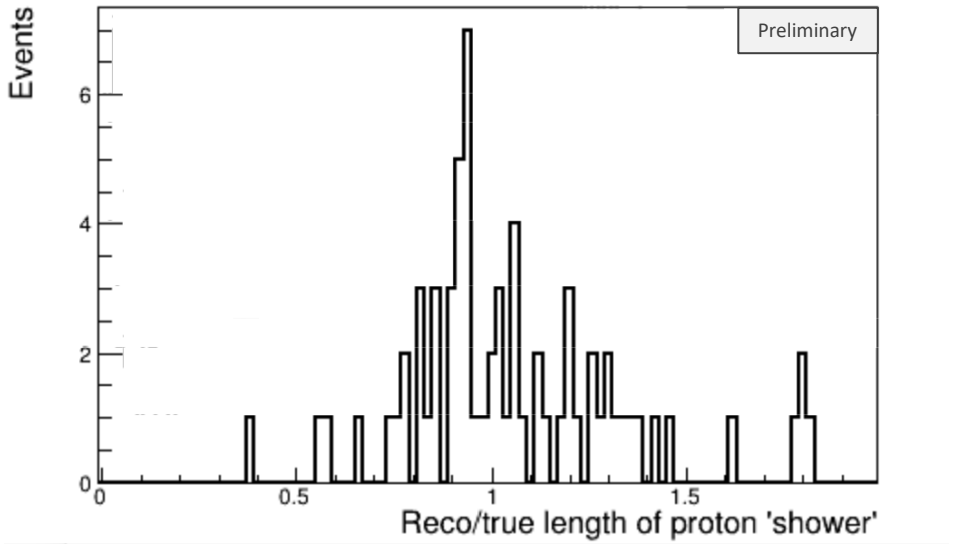
In order to investigate why the BDT particle identification fails, I'm looking at protons dividing reconstructed events in different categories. If there is more than on proton, I look at the most energetic one

Type of Protons Events	Number	Percentage
Found only in the reconstructed tracks	2885	80,0%
Found only in the reconstructed showers	149	4,1%
Found both in reconstructed tracks and showers*	448*	12,4%
Not reconstructed at all	127	3,5%
Total	**3609**	****

*of which **212 have most of their energy reconstructed as a shower**, meaning their best match is a shower

Example of Cut: only match is a shower – MC simulated data





Testing an alternative to BDT

Alternative algorithm **based on simple variables cut** to discriminate if the particle is more likely a track or a shower. It considers variables such as:

- the length of the track reconstructed from a linear fit
- the transverse width of the particle

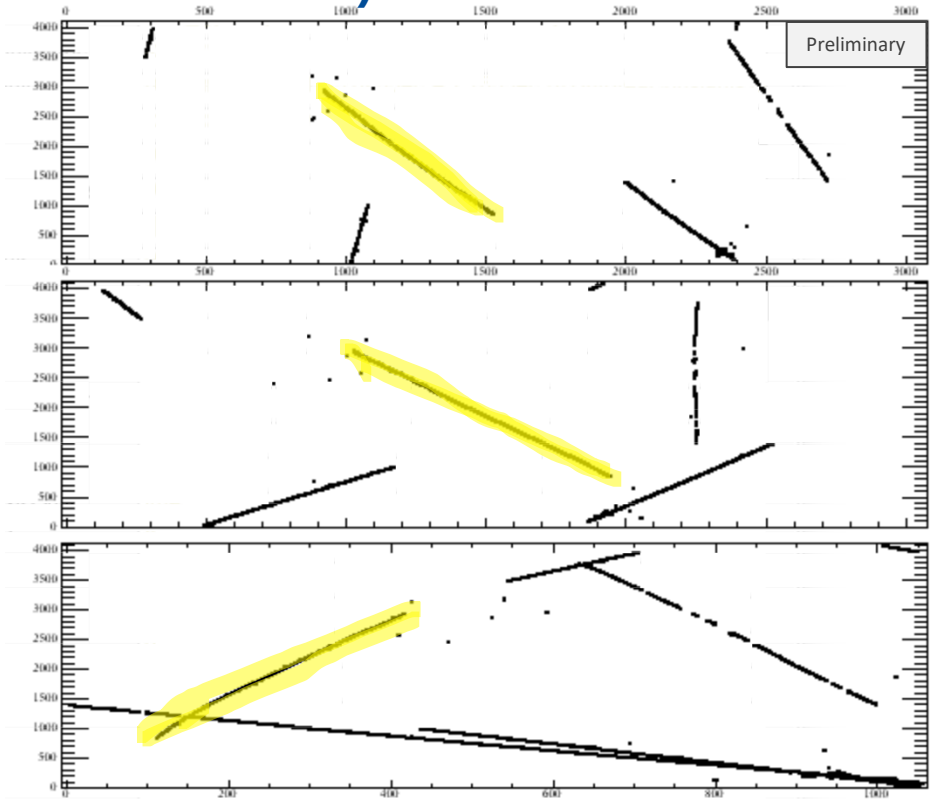
The idea is to **compare the particle identification** with the **two alternatives** in order to understand which of the BDT parameters drives the choice to tag protons as showers

Run 11 SubRun 18 Event 8 (best match is a shower) - MC simulated data

PROTON
xStart **228.152** xEnd 226.29
yStart **-57.5873** yEnd -56.7188
zStart **-631.652** zEnd -632.641
length 2.28083
Reco length (as a Shower) 2.81928
Egen 0.987579
Edep 0.0493066
EMatchBest 0.0417645

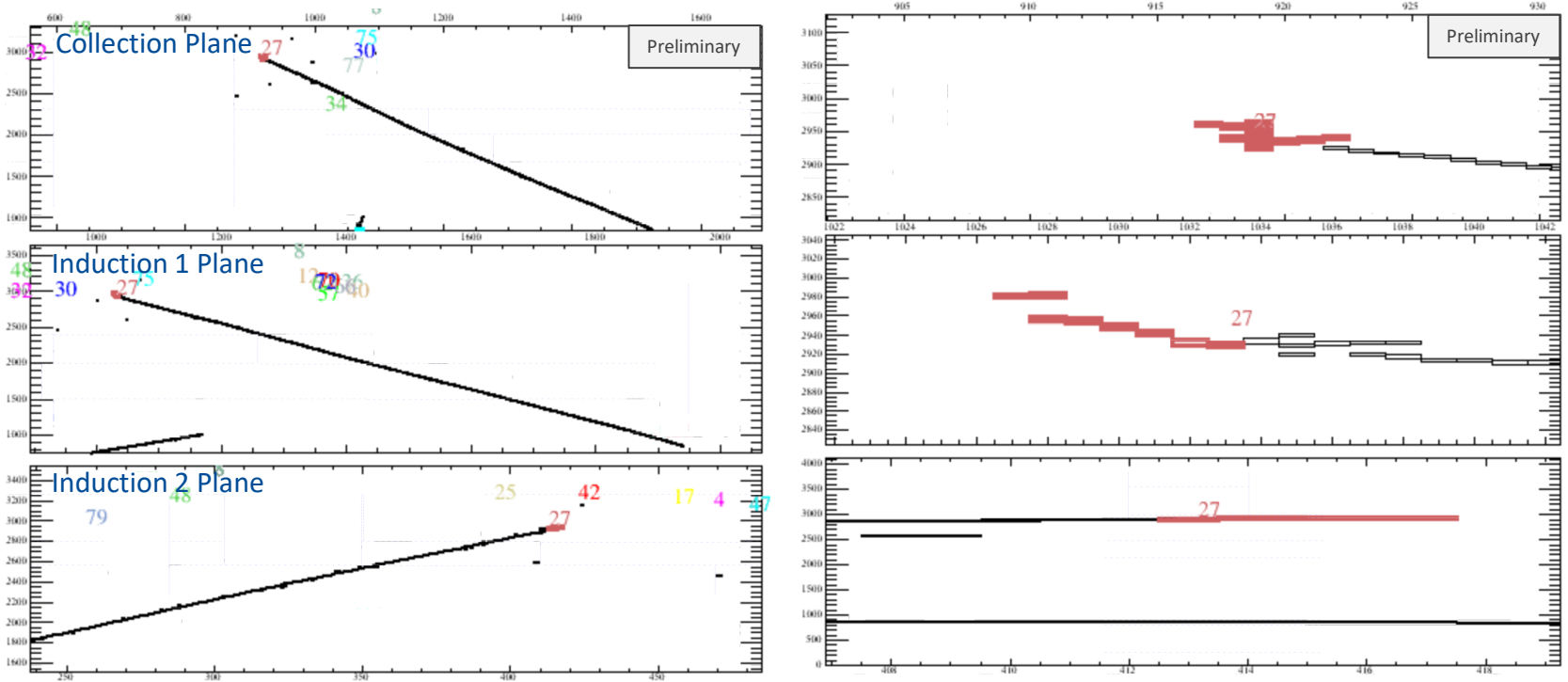
MUON
xStart **228.152** xEnd 358.49
yStart **-57.5873** yEnd -148.399
zStart **-631.652** zEnd -370.186
length 306.284
reco_length_Best 304.793
Egen 1.28524
Edep 0.667817
EMatchBest 0.535782

VERTEX POSITION



Angle between muon and proton: 2.55302 radians

Run 11 SubRun 18 Event 8 (best match is a shower) - MC simulated data



The red particle is the proton reconstructed as a shower

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Reconstructed length

Real		BDT		Alternative to the BDT	
MUON		**(Reconstructed as a Track)**		**(Reconstructed as a Track)**	
Length	**306.284 cm**	Reco Length Best Match	**304.793 cm**	Length: on view U	**300.9 cm**
				on view V	**222,0 cm**
PROTON		**(Reconstructed as a Shower)**		**(Reconstructed as a Shower)**	
Length	**2.281 cm**	Reco Length as a Shower	**2.819 cm**	Length: on view U	**2.100 cm**
		Reco Length as a Track	**No match as a track**	on view V	**2.401 cm**
				on view W	**2.104 cm**

In this case the proton is considered to be a shower in both of the methods

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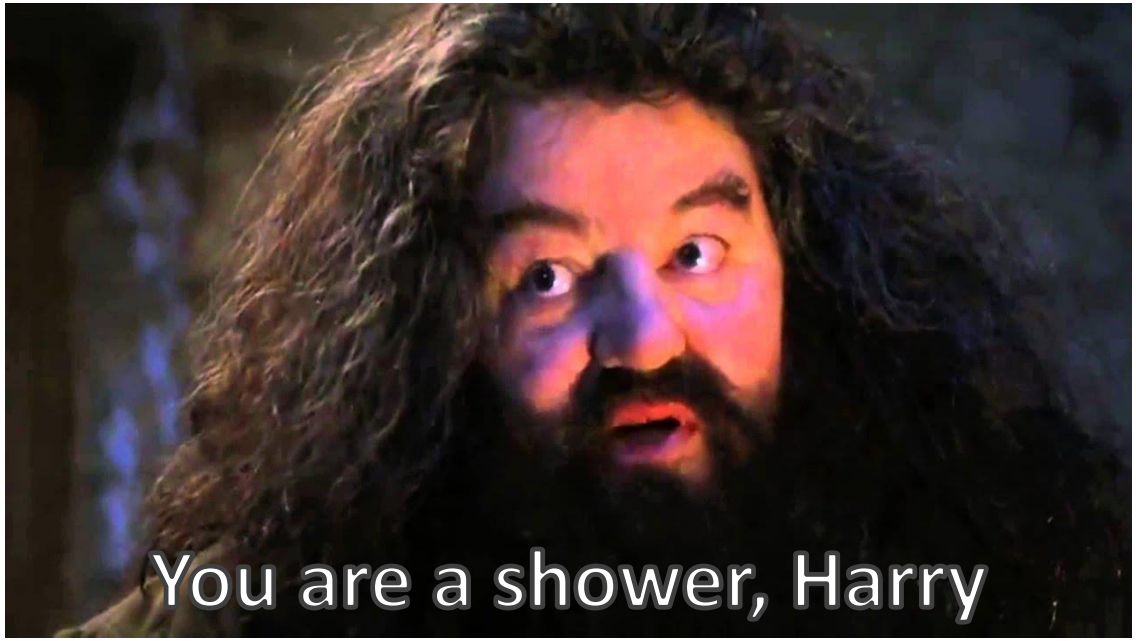
The next steps

- Expanding the sample looking at more events
- Look at the BDT variables to understand the situation and compare to the alternative method
- We have a set of files where the same proton is fit with both tracks and showers so we can look at the track fit
- Looking at the real data



Thanks for your attention

References

[1] Chrisitan Farnese || 20 July 2022 || Neutrino Search with the Icarus Detector

[2] José I. Crespo-Anadón || 20 July 2022 ||The MicroBooNE Experiment

[3] B. Howard || 20 April 2022 || Neutrino hunting with ICARUS at Fermilab B

[4] B. Howard || 25 April 2022 || Brief update on track vs shower BDT scores

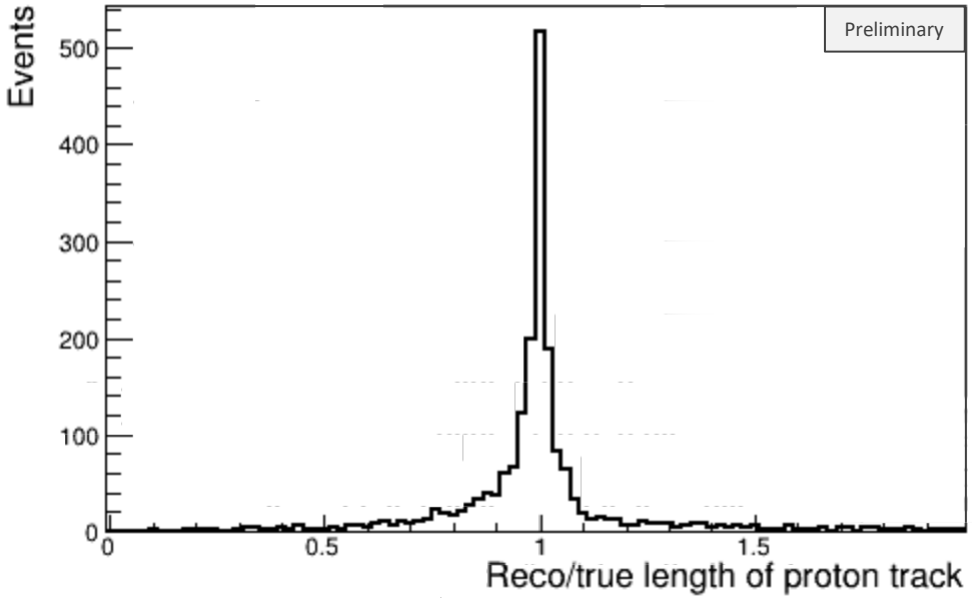
[5] P. Machado, O. Palmara, D. Schmitz || Annu. Rev. Nucl. Part. Sci. (1019). Doi: 10.1146

[6] A.P. Serebrov, R.M. Samoilov, M.E. Chaikovskii || Doi:10.48550

[7] F. Poppi || FNAL 55° Annual Users Meeting|| ICARUS spreads its wings

Backup

Example of Cut: only match is a track – MC simulated data



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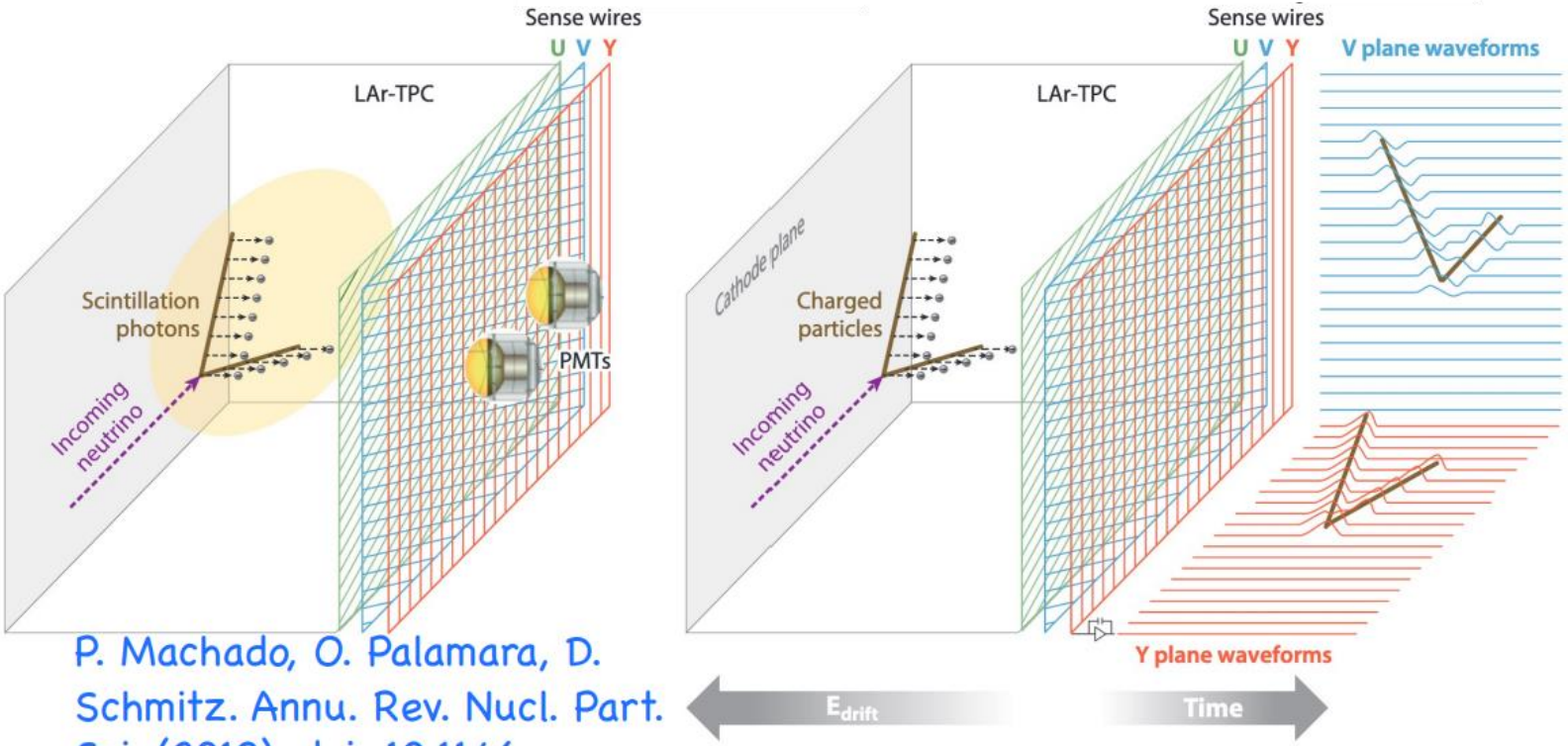

P. Machado, O. Palamara, D. Schmitz. Annu. Rev. Nucl. Part. Sci. (2019). doi: 10.1146

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Track Score BDT

- The BDT uses 10 input variables:
  - Length — estimate of length of the reco particle
  - Sliding Linear Fit: *Estimate of difference with respect to a straight line (/ length)*
  - Sliding Linear Fit: *Estimate of largest gap on the 3 planes (/ length)*
  - Sliding Linear Fit: *Estimate of RMS w.r.t. the fit (/ length)*
  - Vertex distance: *Distance from interaction vertex (reco) to start of reco particle*
  - Difference in “opening” angle & “closing” angle (from 2 points at beginning & end of particle)
  - Principal Component Analysis: *secondary eigenvalue / primary* (estimate of how linear)
  - Principal Component Analysis: *tertiary eigenvalue / primary* (estimate of how linear)
  - Charge: *fractional spread* (using spread in values and mean value)
  - Charge: *fraction near the end of particle* (using charge near end and total)

Bruce Howard (FNAL) - 25 April 2022- Brief update on track vs shower BDT scores

Muon

[PfoCharacterisationBaseAlgorithm] This is particle (pfo) with id: 11 and mass 0.105658 [GeV], energy 0 [GeV], charge -1, momentum module 0 [GeV], momentum p = (px, py, pz) 0 0 0 , with N = 1 vertices.
This is a vertex with position: **228.494 -57.937 -630.507**

[PfoCharacterisationBaseAlgorithm::IsClearTrack3X2D()] **This is the cluster on view U**
This particle is immediately identified as a track because of the length of the linear fit.
This is the length 300.9 [cm]
To be compared with max shower length cut which is 80
For this particle dT/dL min is -0.154221
For this particle dT/dL max is 0.185963
For this particle dT/dL avg is 0.000640003
dT/dL(max-min)/L = 0.00113056
From the current cluster it appears as a track

$$\frac{dT}{dL} = \frac{transverse\ fit\ gradient}{straight\ line\ length}$$

[PfoCharacterisationBaseAlgorithm::IsClearTrack3X2D()] **This is the cluster on view V**
This particle is immediately identified as a track because of the length of the linear fit.
This is the length 222 [cm]
To be compared with max shower length cut which is 80
For this particle dT/dL min is -0.109879
For this particle dT/dL max is 0.11415
For this particle dT/dL avg is -0.00276616
dT/dL(max-min)/L = 0.00100914
From the current cluster it appears as a trackTwo clusters --> views indicate this is a track.

Done everything for this particle.

Proton – more information

Done everything for this particle. [PfoCharacterisationBaseAlgorithm] This is particle (pfo) with id: 11 and mass 0.105658 [GeV], energy 0 [GeV], charge -1, momentum module 0 [GeV], momentum p = (px, py, pz) 0 0 0, with N = 1 vertices.
This is a vertex with position: **228.501 -57.75 -631.679**

[PfoCharacterisationBaseAlgorithm::IsClearTrack3X2D()] This is the cluster on view U.
This particle is saved as a shower because **(dT/dL max-dT/dL min)/L is above the max ratio.**
Reporting all the values:
dT/dL min = -0.102459 dT/dL max = 0.0680074d
T/dL avg = 0.00587218 **dT/dL(max-min)/L = 0.0811737,** to be compared with max ratio **cut 0.03**
From the current cluster it appears as a shower

$$\frac{dT}{dL} = \frac{transverse\ fit\ gradient}{straight\ line\ length}$$

[PfoCharacterisationBaseAlgorithm::IsClearTrack3X2D()] This is the cluster on view V
This particle is saved as a shower because (dT/dL max-dT/dL min)/L is above the max ratio.
Reporting all the values:
dT/dL min = -0.220746 dT/dL max = 0.236978
dT/dL avg = -0.0238366 **dT/dL(max-min)/L = 0.190603**, to be compared with max ratio cut **0.03**
From the current cluster it appears as a shower

[PfoCharacterisationBaseAlgorithm::IsClearTrack3X2D()] This is the cluster on view W
This particle is saved as a shower because (dT/dL max-dT/dL min)/L is above the max ratio.
Reporting all the values:
dT/dL min = -0.449894 dT/dL max = 0.142601
dT/dL avg = -0.0487548 **dT/dL(max-min)/L = 0.281558**, to be compared with max ratio cut **0.03**
From the current cluster it appears as a shower

This is a shower. Done everything for this particle.