Track vs shower discrimination in the event reconstruction of the ICARUS experiment

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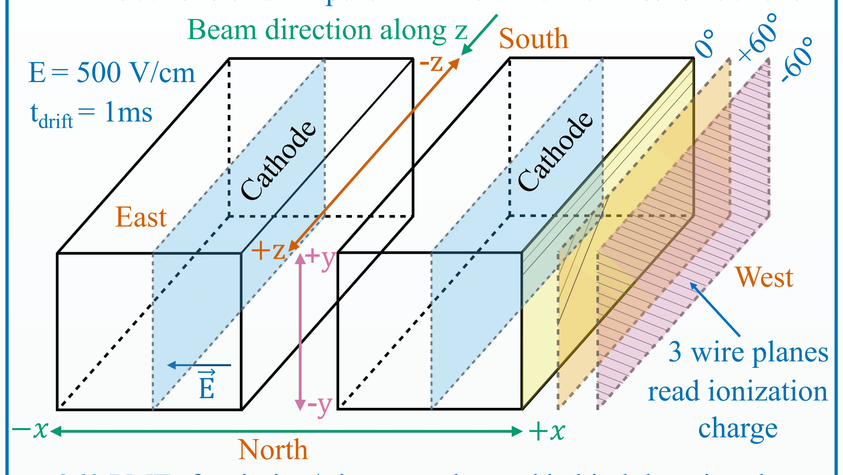
1 The ICARUS experiment in a nutshell

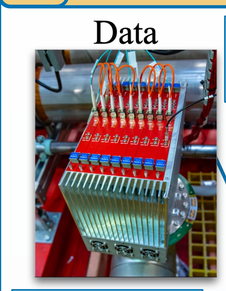
- Liquid Argon Time Projection Chambers (LAr-TPCs)[1]: detectors with 3D imaging and calorimetric reconstruction capabilities - ideal for ν interaction studies in a wide E range
- ICARUS-T600[2] is the first large scale LAr-TPC: two identical cryostats (3.6 x 3.9 x 19.6 m^3) housing two TPCs each, filled with 760 tons of ultra-pure LAr - total active mass is 470 tons



360 PMTs for timing/trigger are located behind the wire planes

- Initial operations at LNGS[3] (Italy), taking data at FNAL (US) since June 2022 - far detector of the SBN[4] program
- Rich physics program: search for 1eV mass-scale sterile ν, measurements of ν-Ar cross sections, beyond SM searches

2 The ICARUS TPC event reconstruction chain



Remove $\vec{E}$ distortions and electronics shaping effects

Threshold-based algorithm to find signal *hits*

Deconvolution

ROI Finding

Decoding

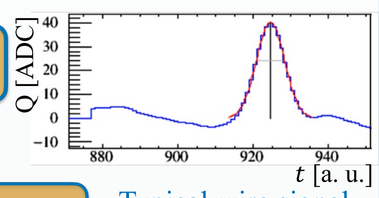
Unpack the data and turn it into a raw waveform

Gauss fit hits

Area of the hits as a proxy of the total charge

Keep only hits consistent with 3D points

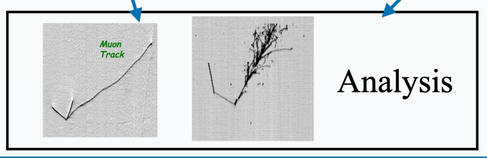
Cluster 3D



Typical wire signal (charge vs time)

Pandora

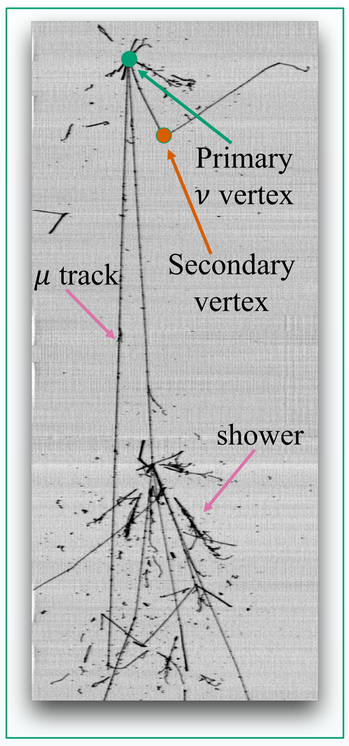
Machine Learning



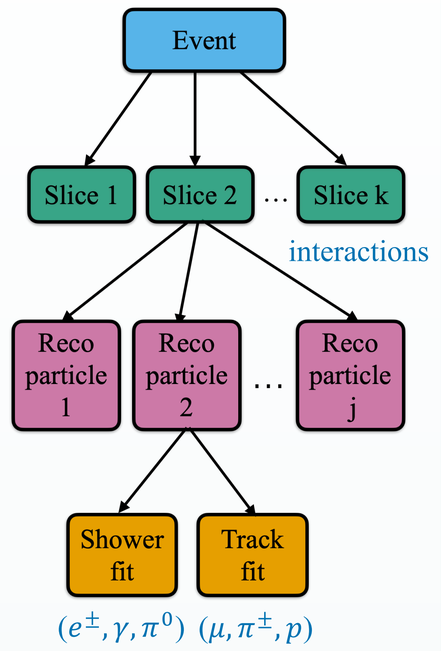
Full chain based on Machine Learning

3 The Pandora event reconstruction framework

- Multi-algorithm pattern-recognition software[5] PandoraPFA
- Ultimate goal is to reconstruct particle interaction hierarchies



- Common in LAr detectors

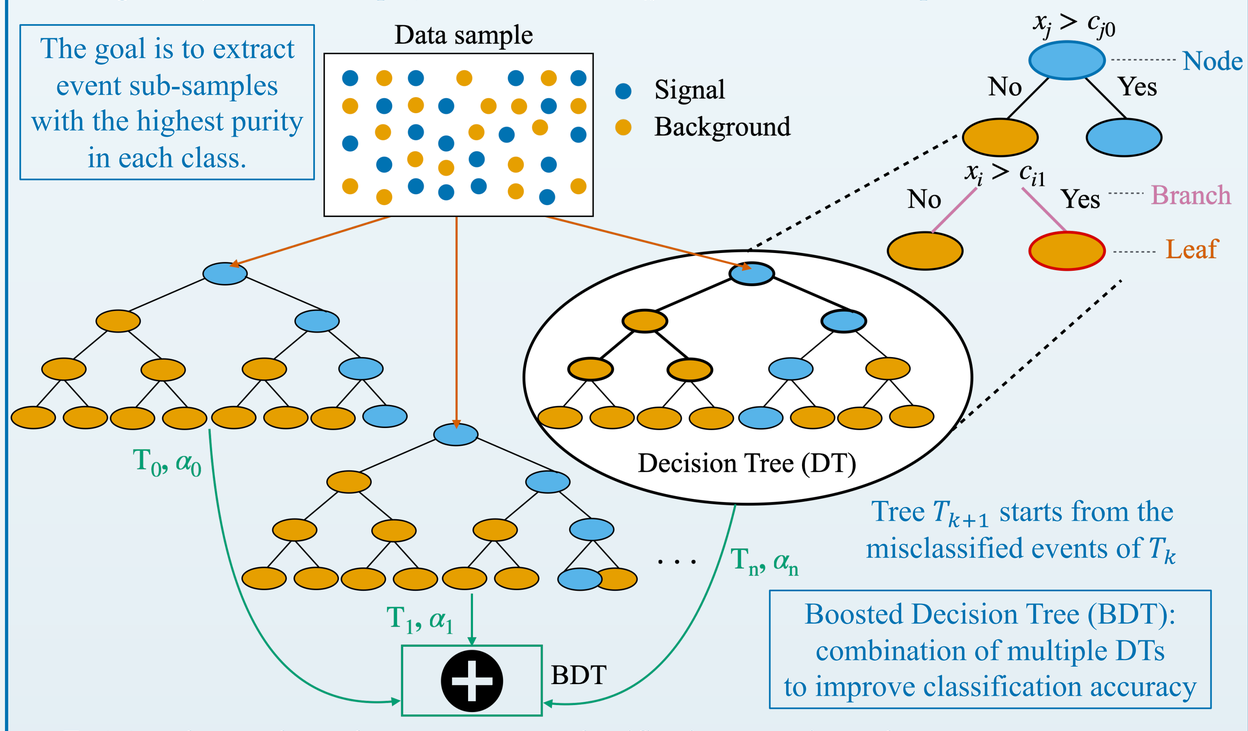


- Boosted Decision Trees used to separate ν/cosmics, find primary vertex, separate tracks/showers

4 Boosted Decision Trees (BDTs)

- Machine learning algorithm used for event classification: given n event classes (e.g. signal and background) in a data sample, a set of features x_k and cuts is used to separate them

The goal is to extract event sub-samples with the highest purity in each class.



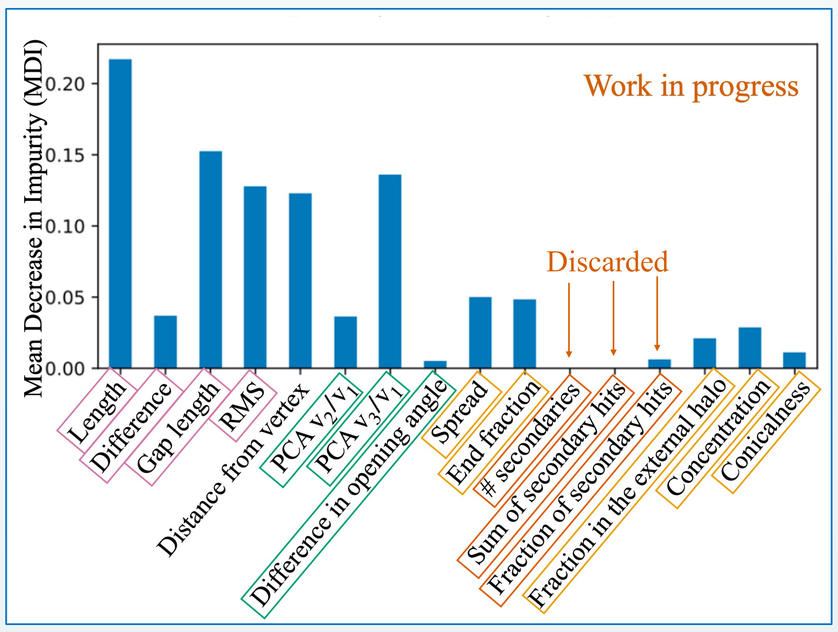
Tree T_{k+1} starts from the misclassified events of T_k

Boosted Decision Tree (BDT): combination of multiple DTs to improve classification accuracy

- *Training* phase to learn the correct events classification on an input dataset
- *Testing* phase to classify events from a different sample using the outcome of the previous step

5 The BDT to discriminate tracks and showers in ICARUS

- BDT to separate *track-like* $(\mu, \pi^{\pm}, p)$ and *shower-like* $(e^{\mp}, \gamma, \pi^0)$ particles relies on geometrical and calorimetrical features (charge as energy proxy) of the reconstructed particle hits
- The output is a *track-score*: parameter in [0,0.5) for showers and [0.5,1] for track-like particles
- Previous training on SBND Monte Carlo (MC) sample with outdated simulation/reconstruction



- New BDT training with adaptive boosting based on Python library Scikit learn
- 6 new features tested,
- Final set includes 13 BDT variables with the highest relative importance

Variable type	#	Selected
Linear fit	4	✓
Distance from interaction vertex	1	✓
Principal Component Analysis (PCA)	3	✓
Charge (old)	2	✓
Hierarchy (new)	3	✗
Conical charge (new)	3	✓

- Different training/testing sample compositions and combinations tested with $\mathcal{O}(10^4\text{-}10^5)$ MC events from the BNB ν beam – cross validation to mitigate *overtraining* and optimize parameters

6 New BDT training: results and validation tests

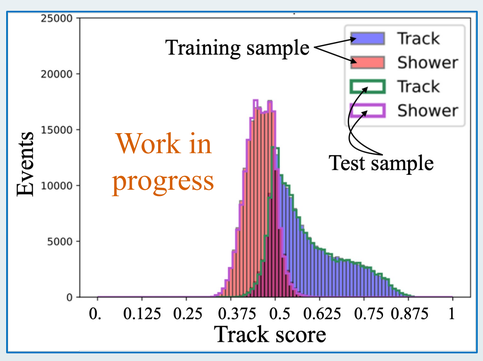
BNB beam MC samples

Test sample

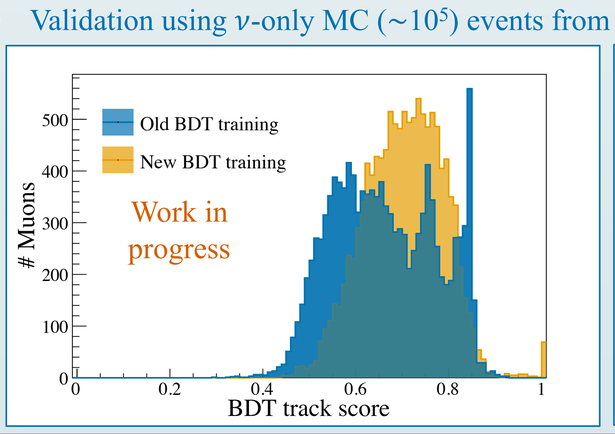
Training sample \ $\epsilon_{classification}$	v-only	v + cosmics
v-only	81.8%	81.4%
v + cosmics	81.5%	82.0%
old training	72.0%	71.8%

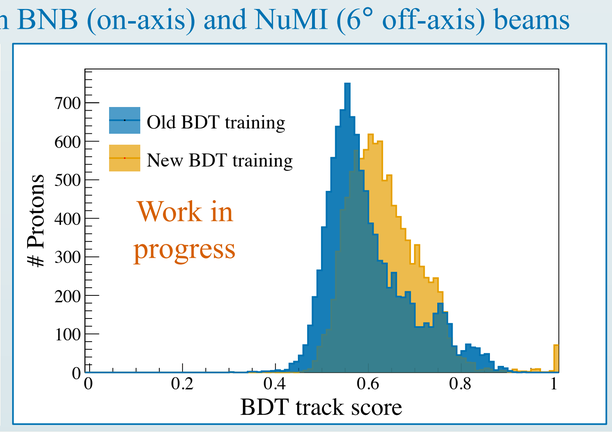
Work in progress

~10% improvement in all explored cases

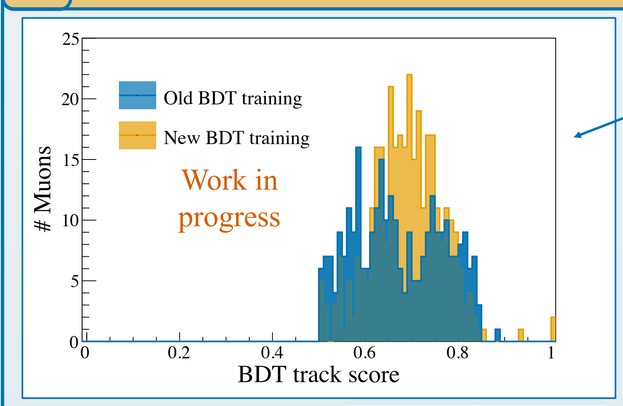


- Validation using ν-only MC (~10^5) events from BNB (on-axis) and NuMI (6° off-axis) beams

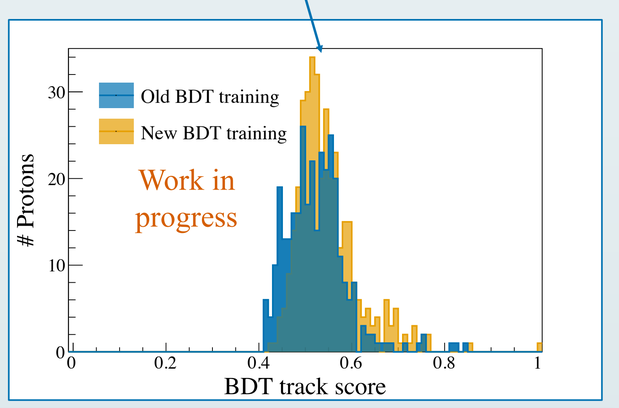




7 New training: results and validation tests



Additional validation on data from run 9435 with the standard $1\mu Np$ selection used for oscillation analyses, including a 0.5 (0.4) track score cut on the muon (proton)



MC samples Validation results

$\epsilon_{classification}$	Old training	New training
BNB v-only	72.3%	80.3%
NuMI v-only	66.7%	79.2%

Work in progress

8 Conclusions and perspectives

- Repeat the BDT training on new MC samples to include recent upgrades of the signal processing
- Test different event samples for the training, including a generator-model-agnostic input sample also used within the Machine-Learning-based processing chain

References

[1] C. Rubbia, *CERN-EP*, **77-08**, (1977)

[2] P. Abratenko *et al.* (ICARUS Collaboration), *Eur. Phys. J. C* ***83***, 467 (2023)

[3] M. Antonello *et al.* (ICARUS Collaboration), *Eur. Phys. J.* C **73**, 2599 (2013)

[4] P. A. N. Machado, O. Palamara, and D.W. Schmitz, *Annual Review of Nuclear and Particle Science*, **69**, 367–387 (2019)

[5] R. Acciarri et al. (MicroBooNE Collaboration), Eur. Phys. J. C 78 (2018)