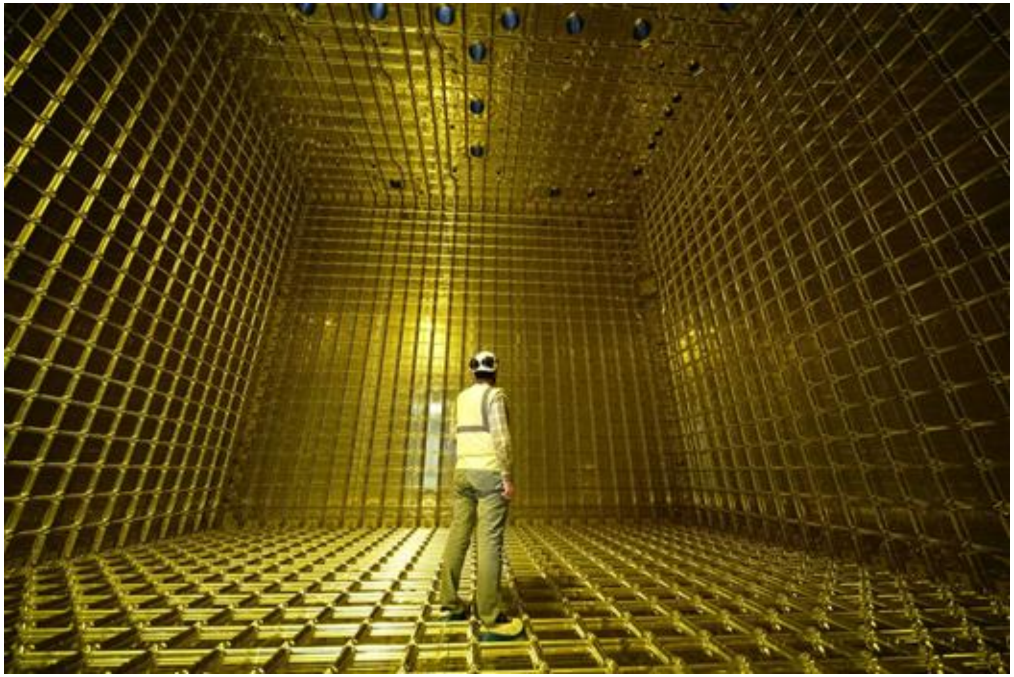
Learning pairwise associations for event slicing in ProtoDUNE-SP

FutureData4EU
Training Future Big Data Experts for Europe



Credit: CERN

Christina Karagianni
University of Ferrara, INFN Ferrara
ML4Jets 2026, Vienna, Austria
Sept 15th, 2026

Co-funded by the European Union

"FutureData4Eu (Grant. Agreement n. 101126733) Co- Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or REA. Neither the European Union nor the granting authority can be held responsible for them."

OUTLINE

- **Physics & Detectors**
- Pandora & Event Slicing
- Learning Pairwise Associations
- Preliminary Results
- Summary

Neutrino physics questions
Beyond the Standard Model physics

Credit: Pandey, INSS 2025

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Neutrino oscillations ($L/E \simeq 1/\Delta m^2$) $\rightarrow$ non-zero mass

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Flavor eigenstates Mass eigenstates

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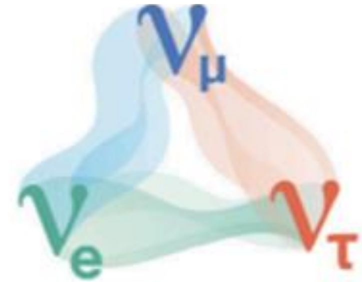

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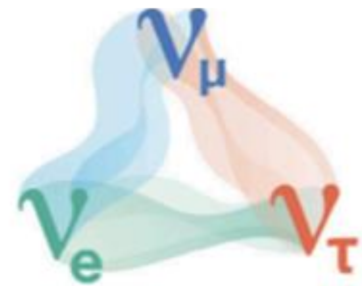

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Neutrino oscillations (L/E ≃ 1/Δm²) → non-zero mass

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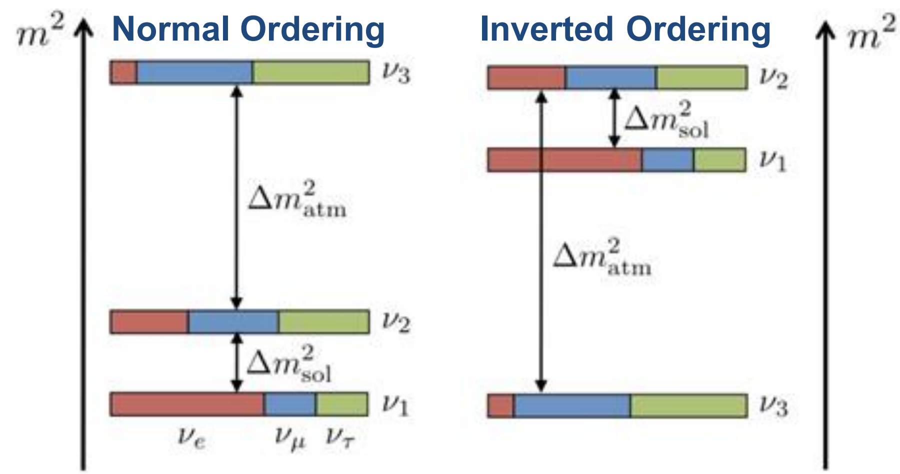

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Neutrino physics questions
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Neutrino oscillations (L/E ≃ 1/Δm^2) → non-zero mass

- CP violation
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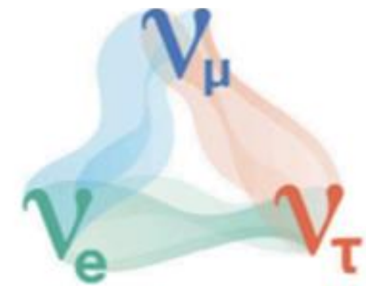
➡ better understand neutrino nature



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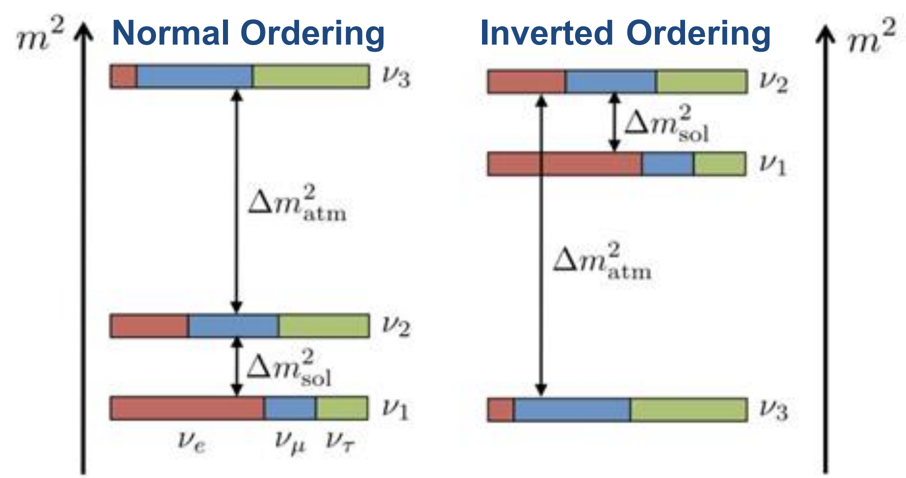

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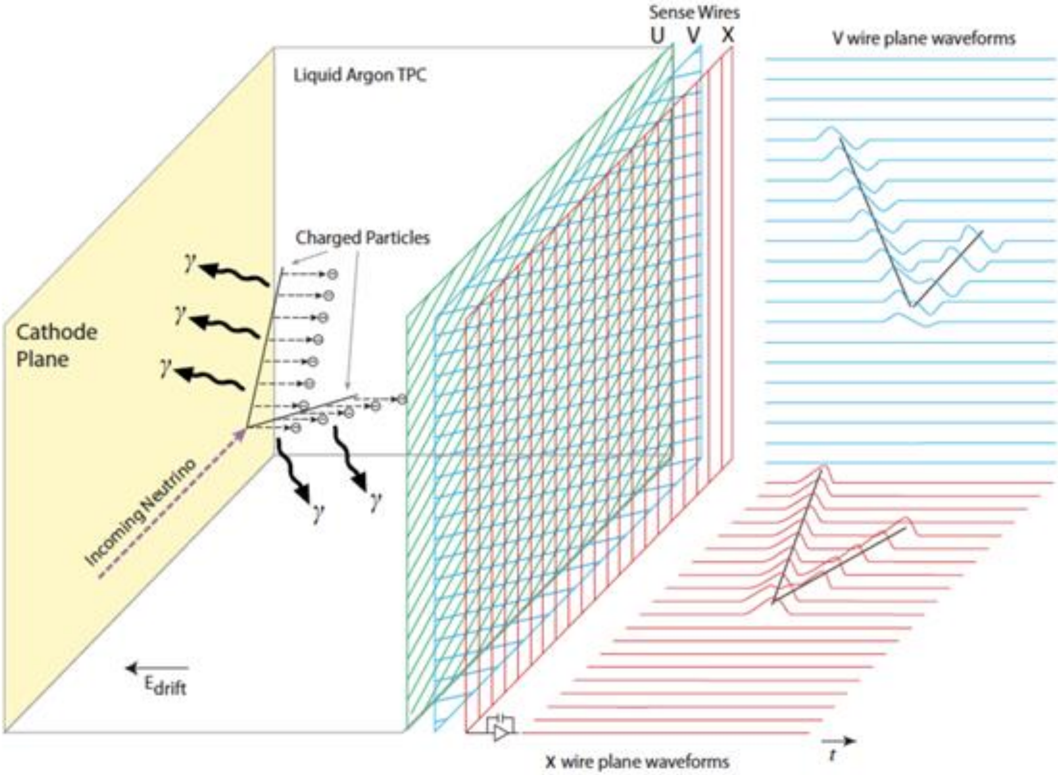
LArTPC operating principle

High resolution imaging detector (≈ 1mm)



Source: Abi et al. 2020, JINST 15 T08008

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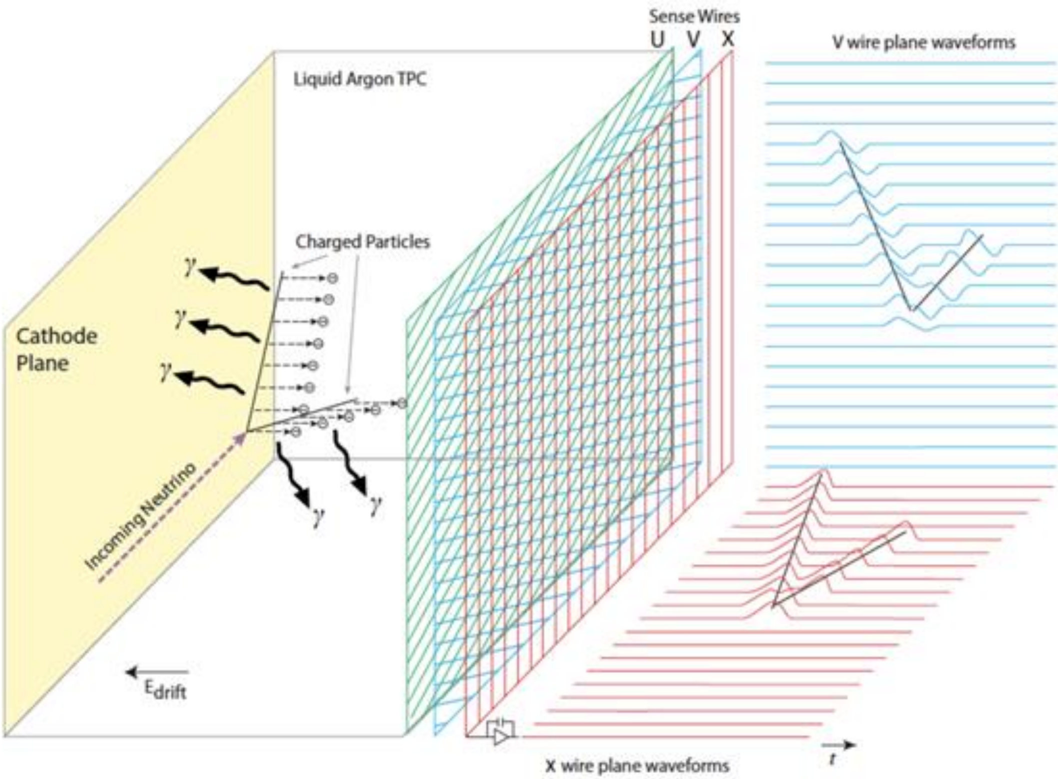

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- Dense, homogeneous volume of LAr

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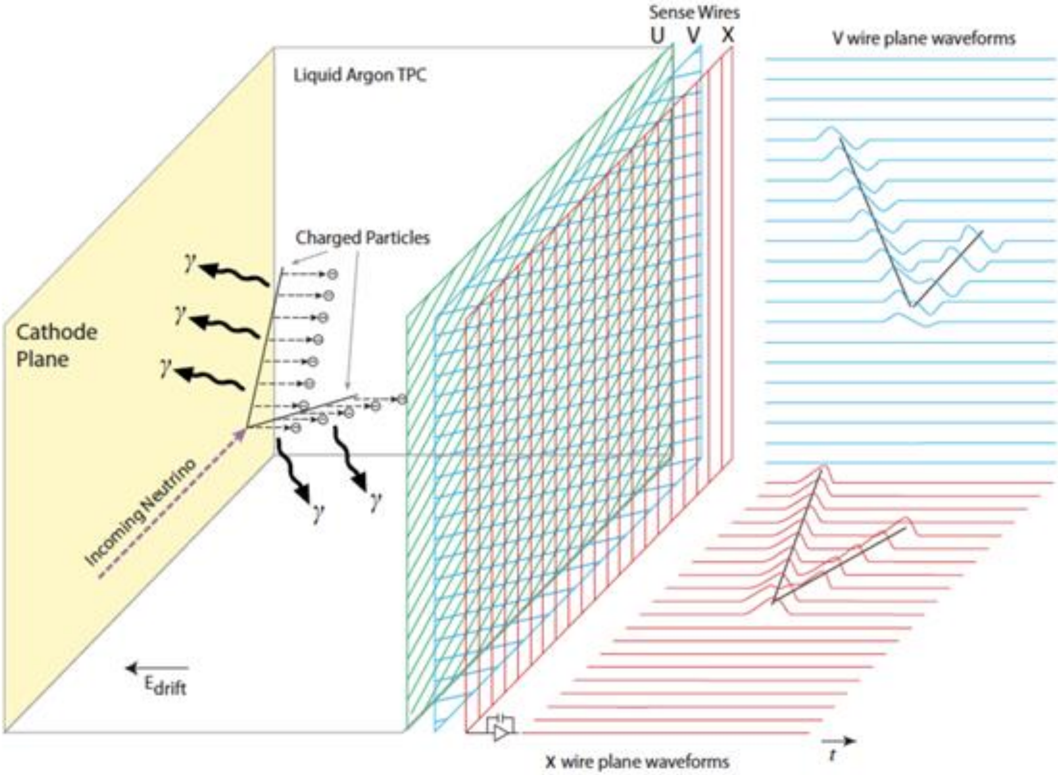

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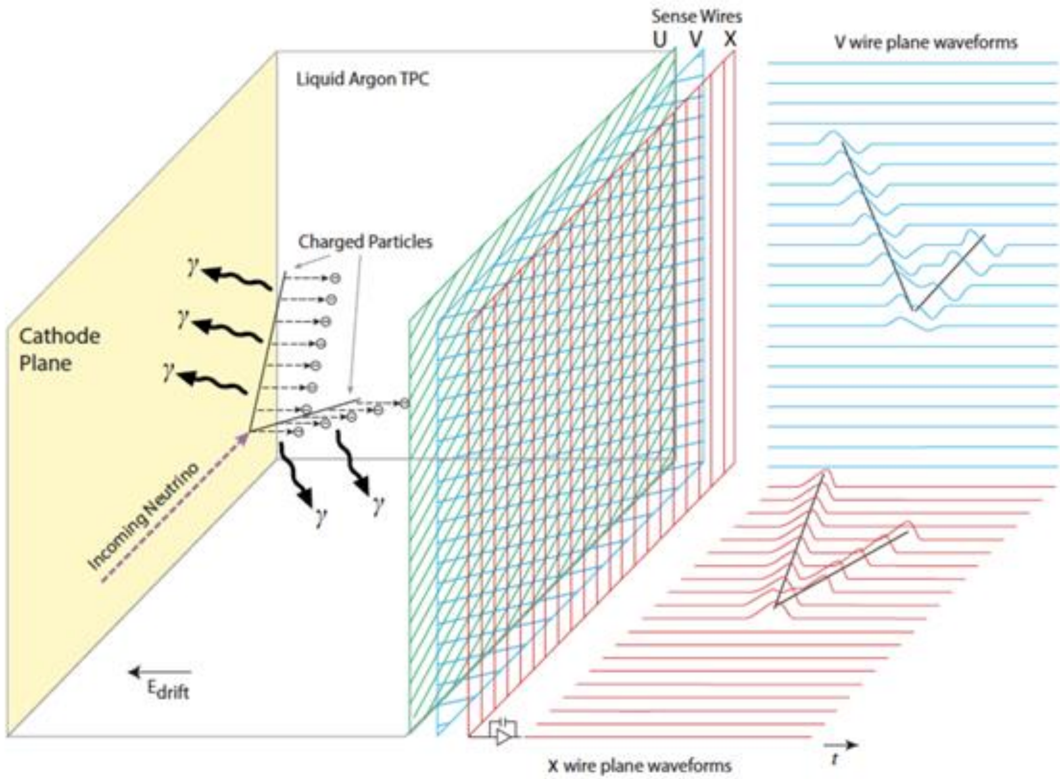

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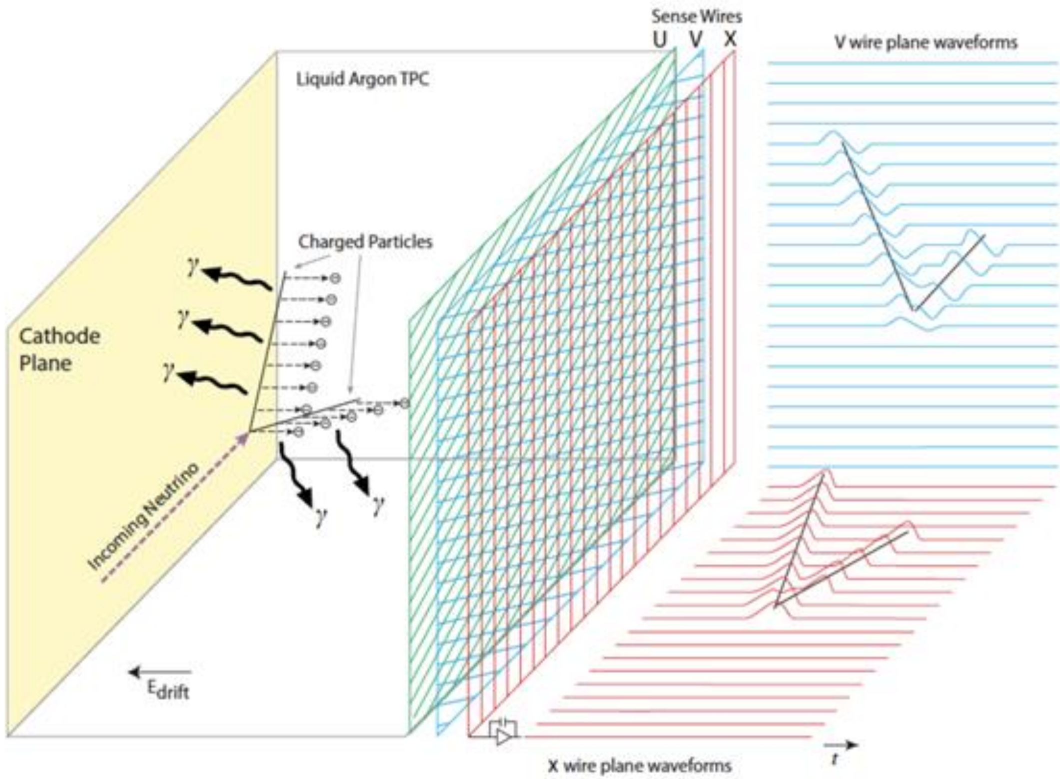

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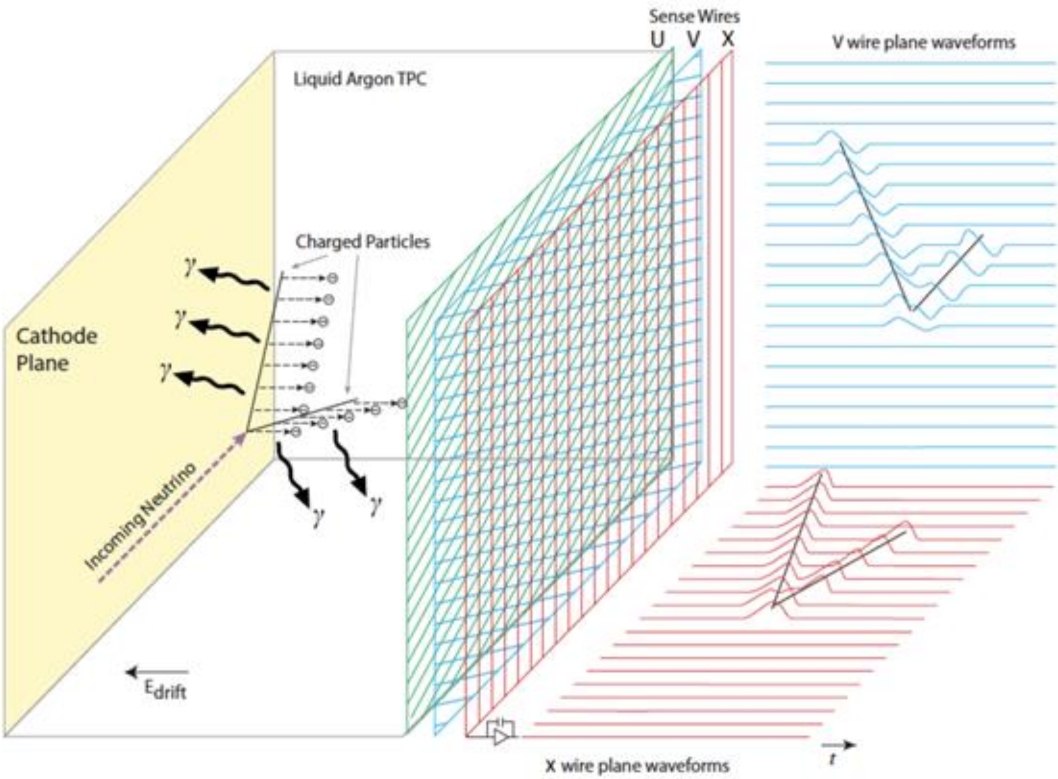

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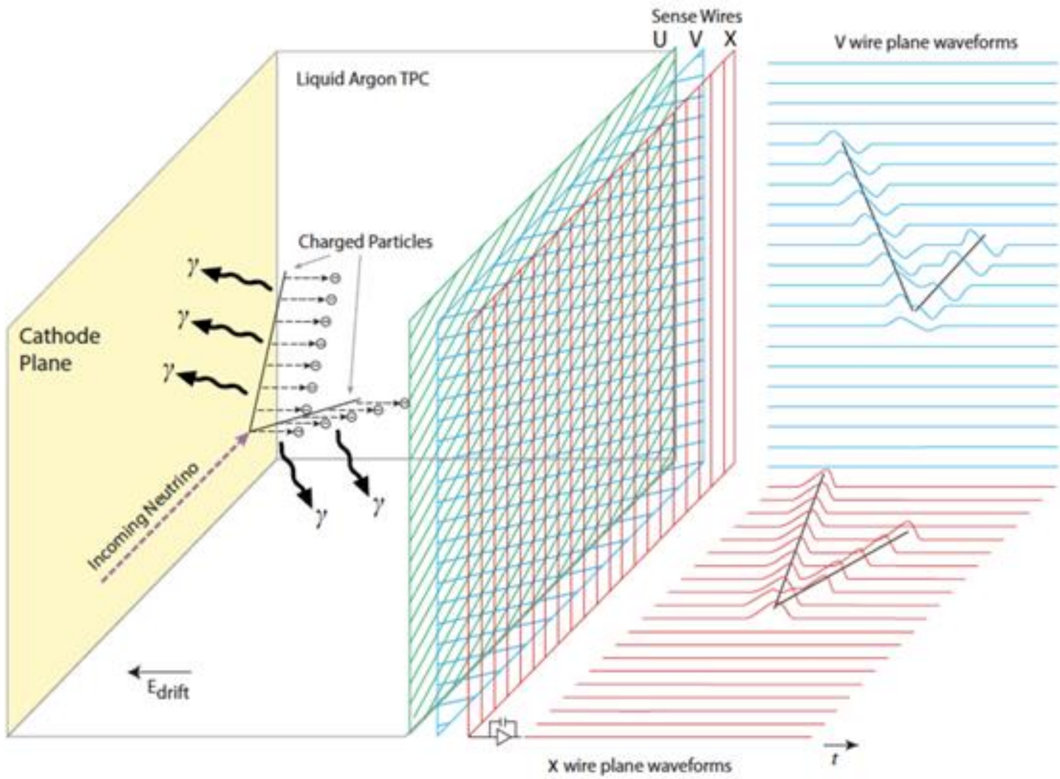

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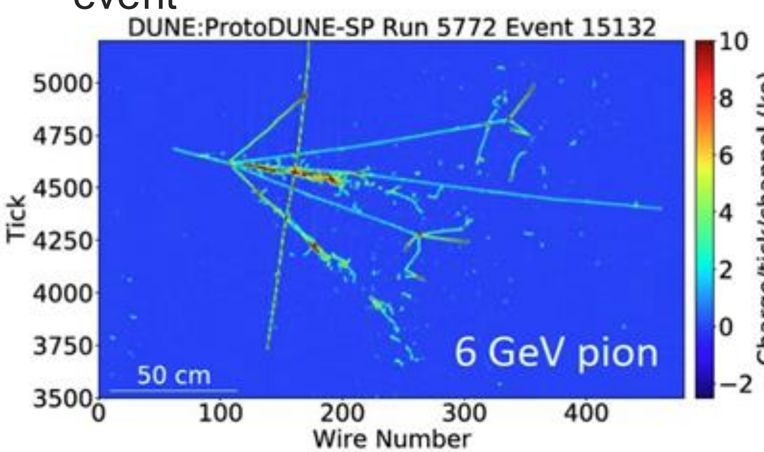

Source: Abi et al. 2020, JINST 15 P12004

ProtoDUNE-SP

A prototype for the DUNE far detector

- Constructed and operated (2018-2020) on the CERN Neutrino Platform
- Largest LArTPC constructed to date
- Exposed to a charged particle test beam

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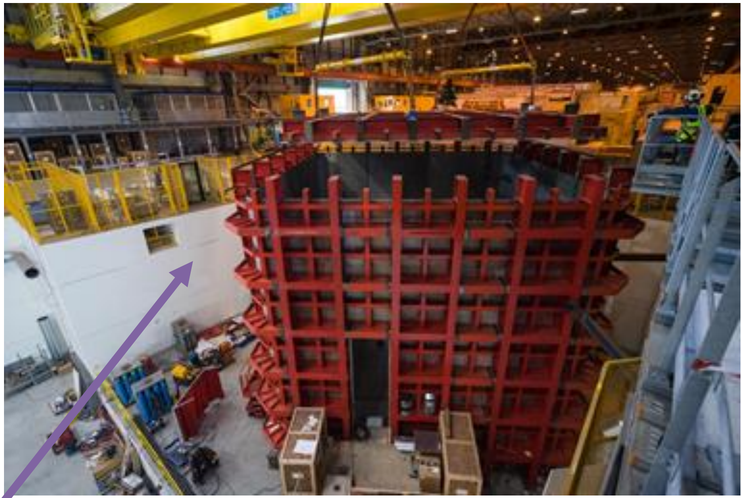

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- **Pandora & Event Slicing**
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Pandora Software Development Kit

A multi-algorithm approach

over 100 decoupled algorithms

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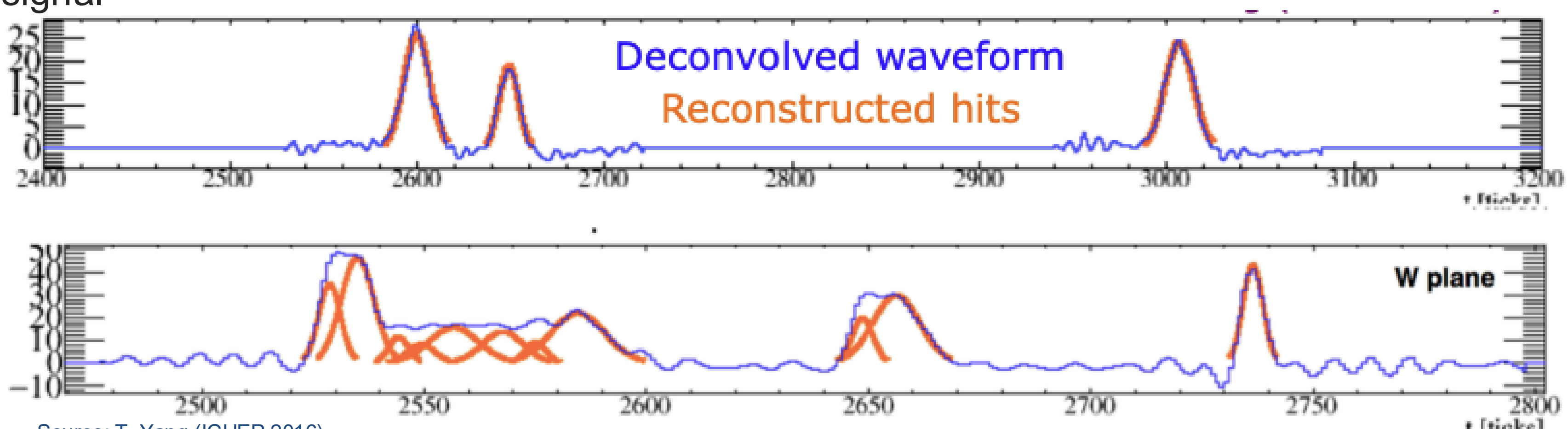
over 100 decoupled algorithms

input hits

Gaussian fitted peaks in the cleaned-up wire signal



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A multi-algorithm approach

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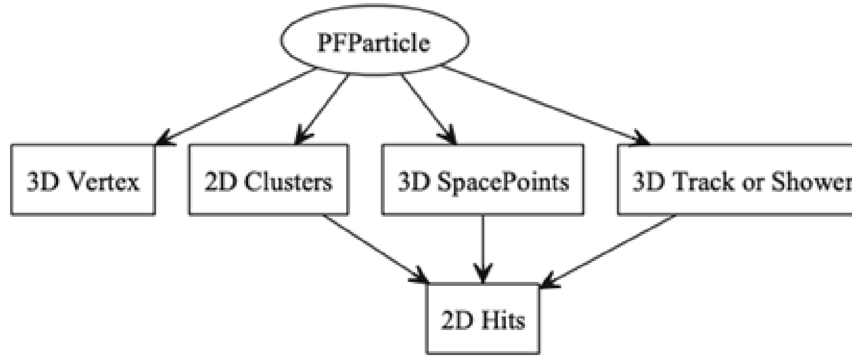
input hits → hierarchy of reco 3D particles



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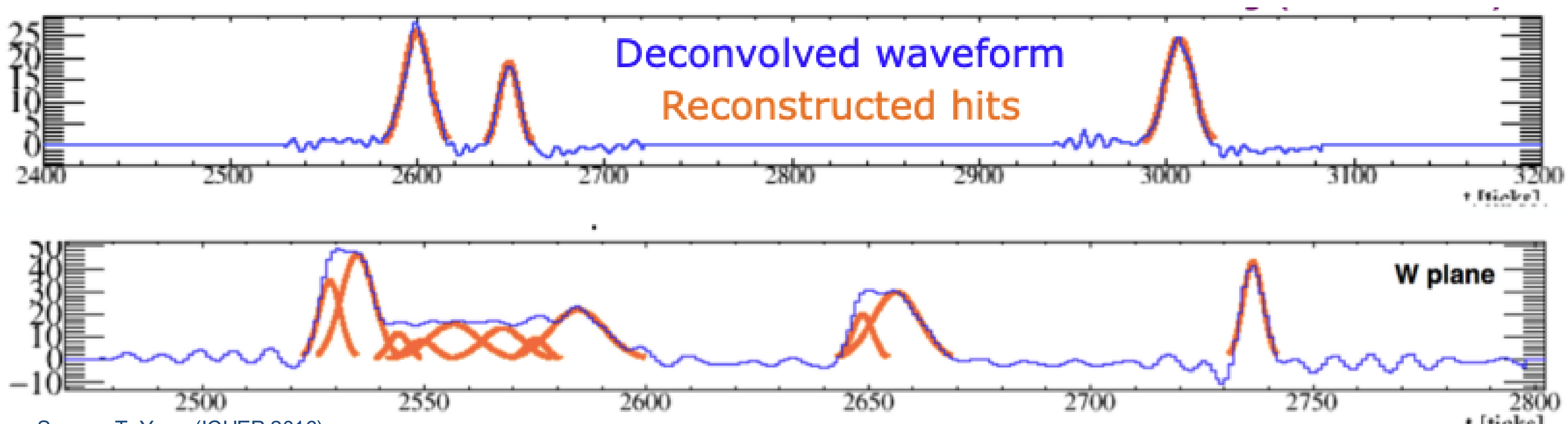

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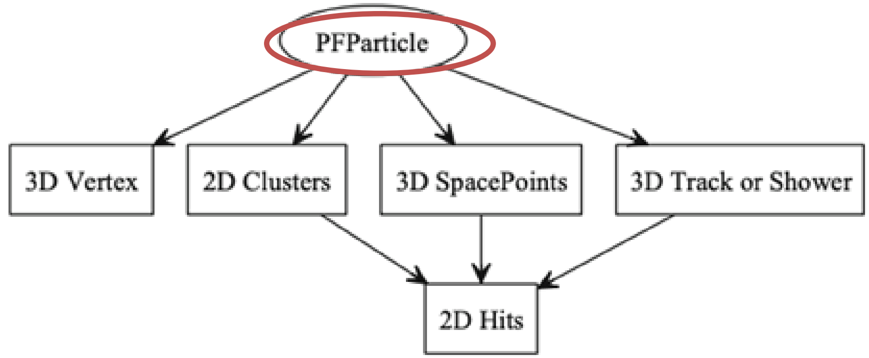

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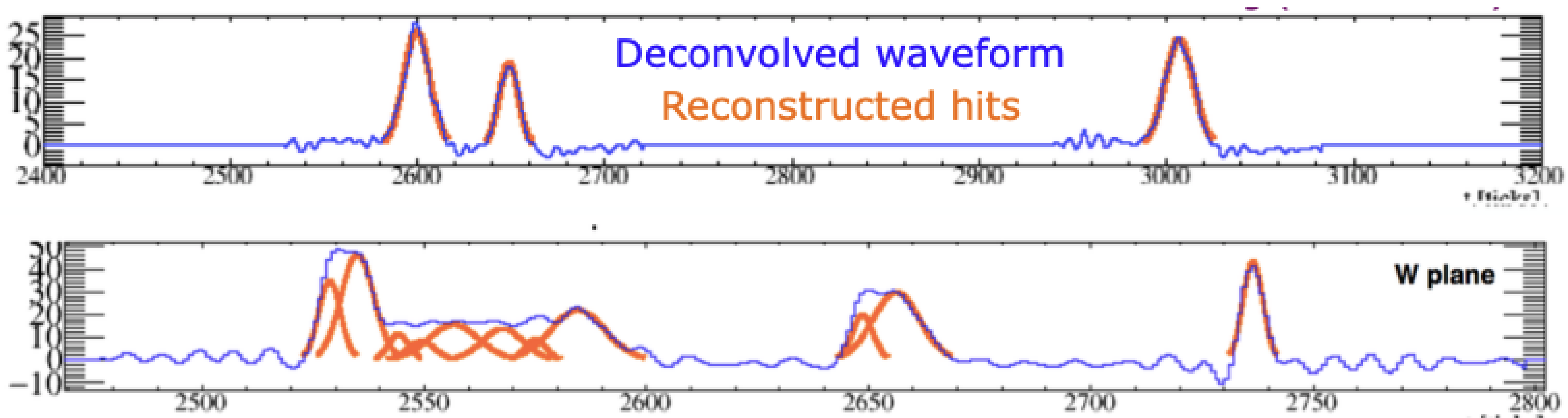

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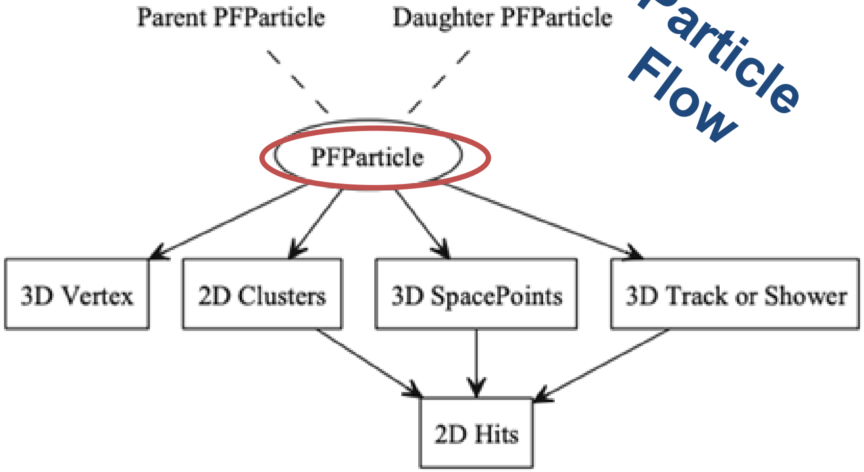

Particle Flow

over 100 decoupled algorithms

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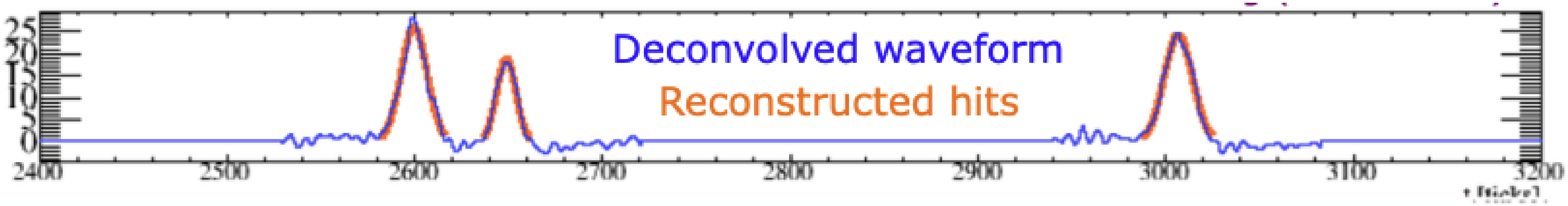

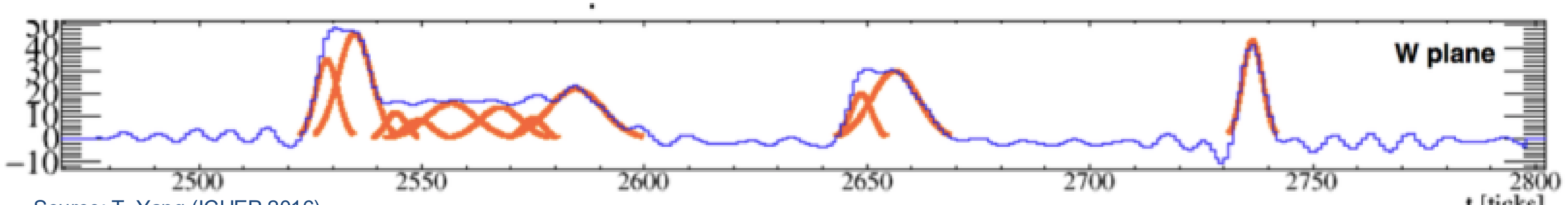

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Università degli Studi di Ferrara

INFN FERRARA

FutureData4EU

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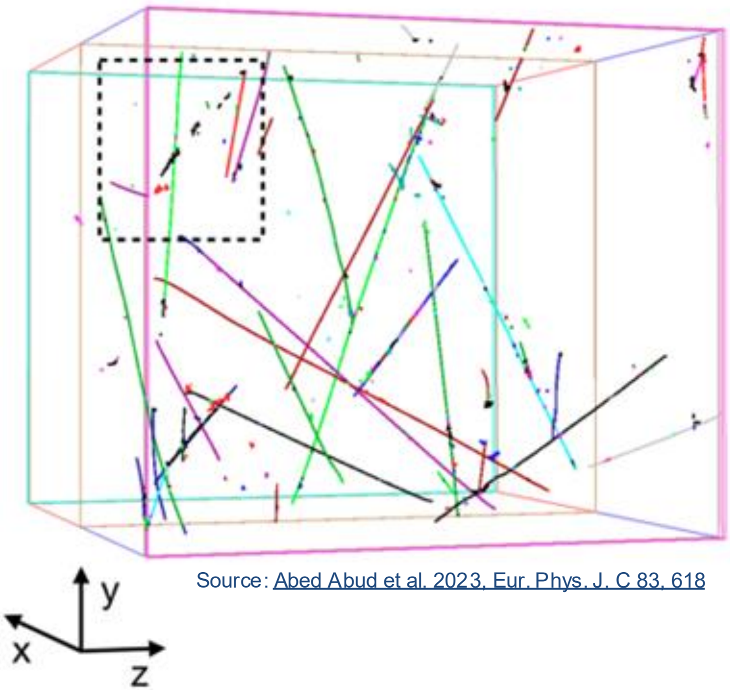
Pandora consolidated reconstruction
A multi-algorithm approach

- Exposed to O(50) cosmic rays per readout (with one beam hierarchy hidden)

ProtoDUNE-SP data run 5387



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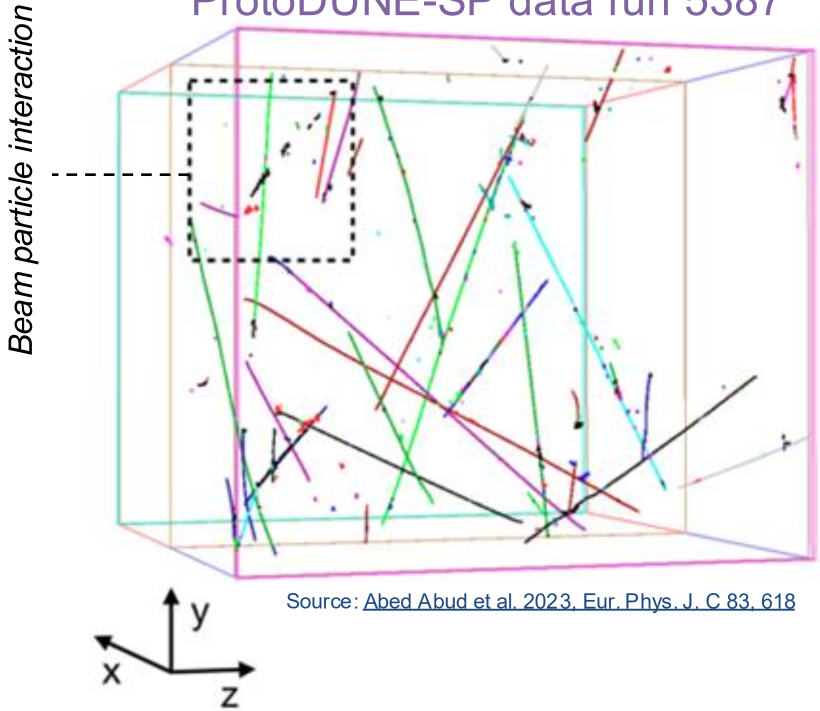

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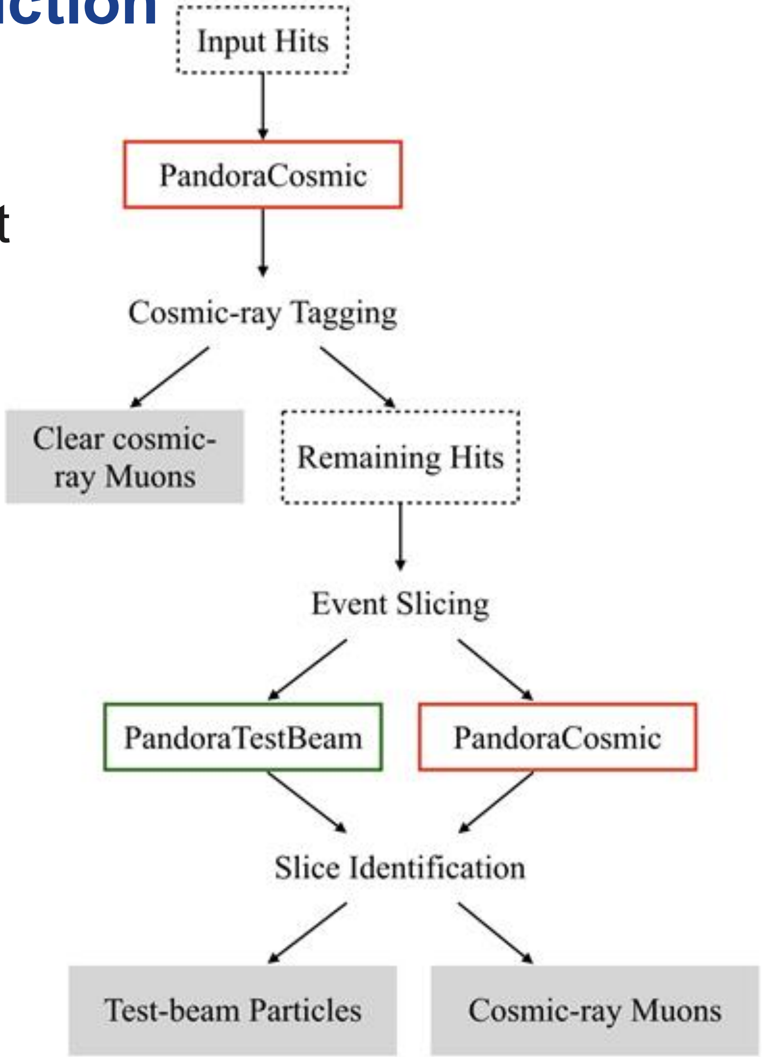

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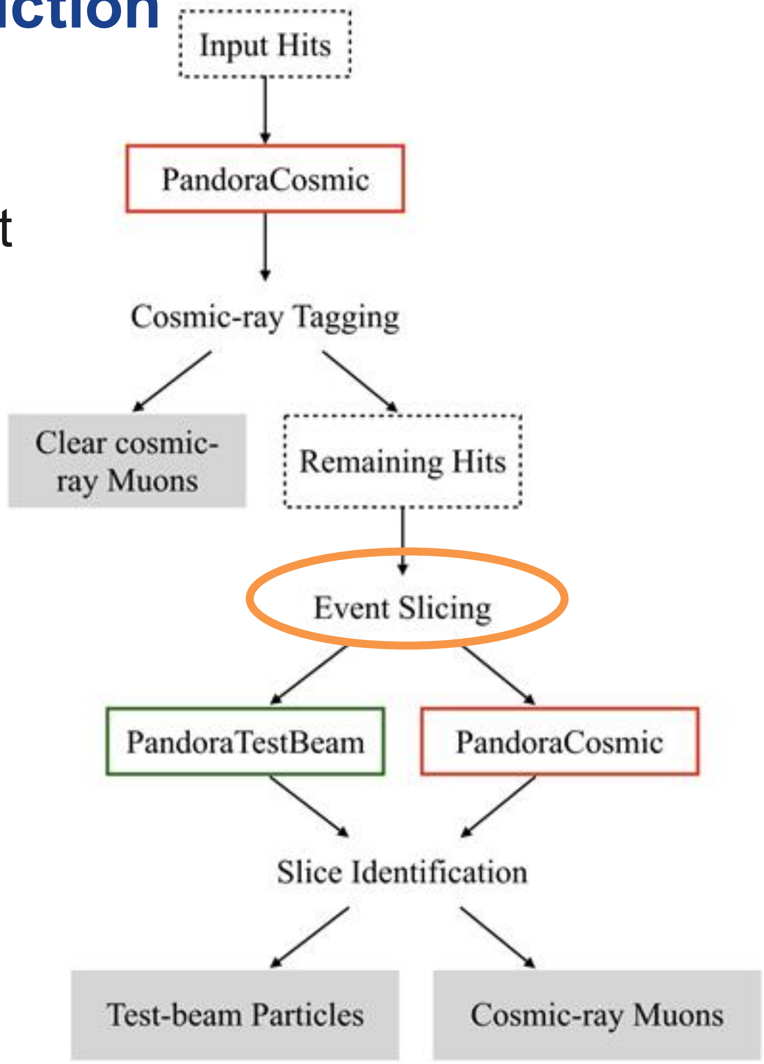
- Event slicing → hierarchies



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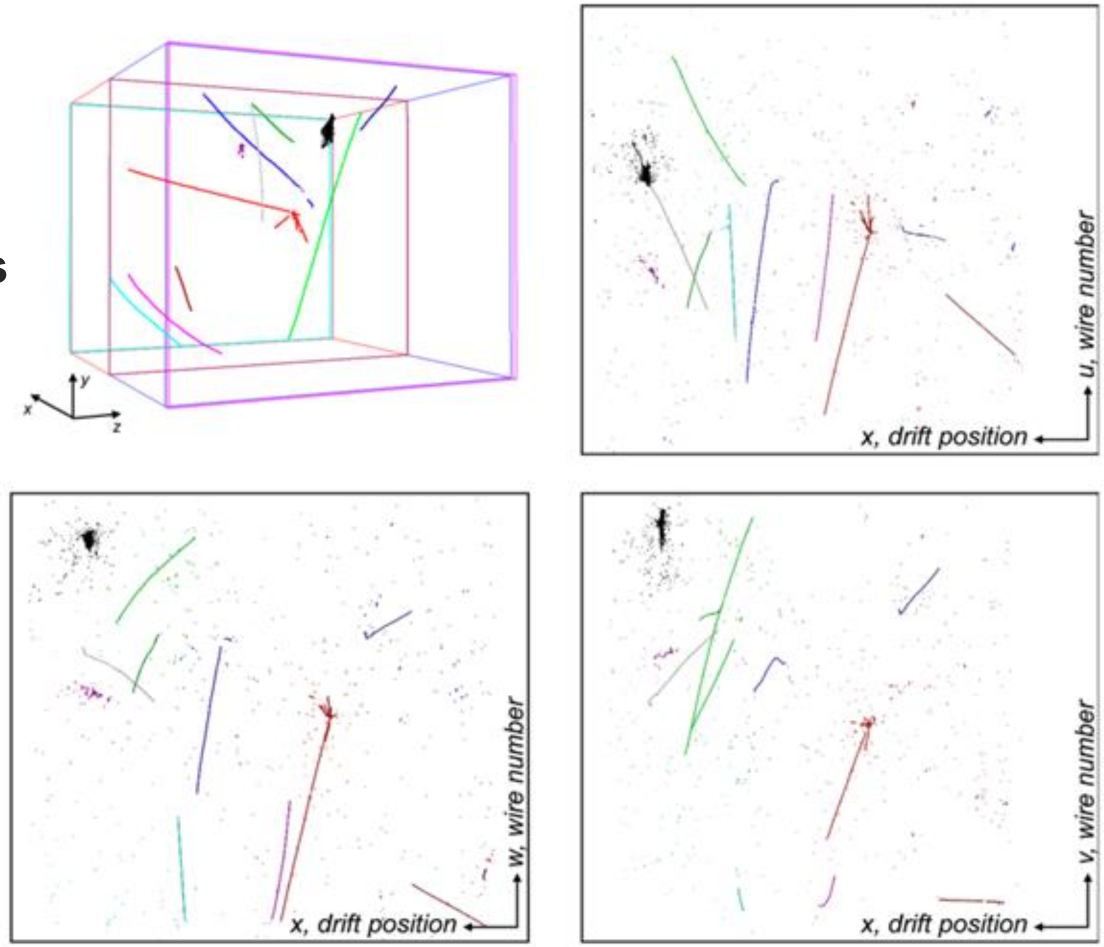
Pandora Event Slicing

Divide up the detector activity into distinct particle hierarchies

3D clusters are divided into slices based on hand-engineered association rules

1. spatial proximity
2. pointing
3. shower cone



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- **Learning Pairwise Associations**
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Learning Pairwise Associations

ProtoDUNE-SP MC data
4 beam energies (0.5, 1, 2, 6 GeV/c)

Energy	# Events	# Pandora slices	# PFPs
0.5 GeV	3,099	269,052	1,607,255
1 GeV	1,500	136,393	760,663
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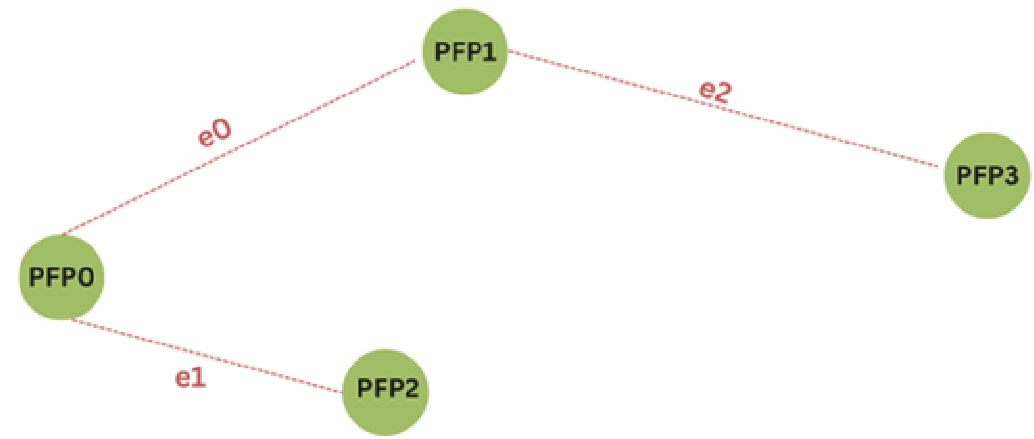
- node = reconstructed PFP
- edge = candidate PFP pair
- edge label = same_true_hierachy (0 or 1)

4 PFPs -> 4 nodes, 3 candidate pairs -> 3 edges



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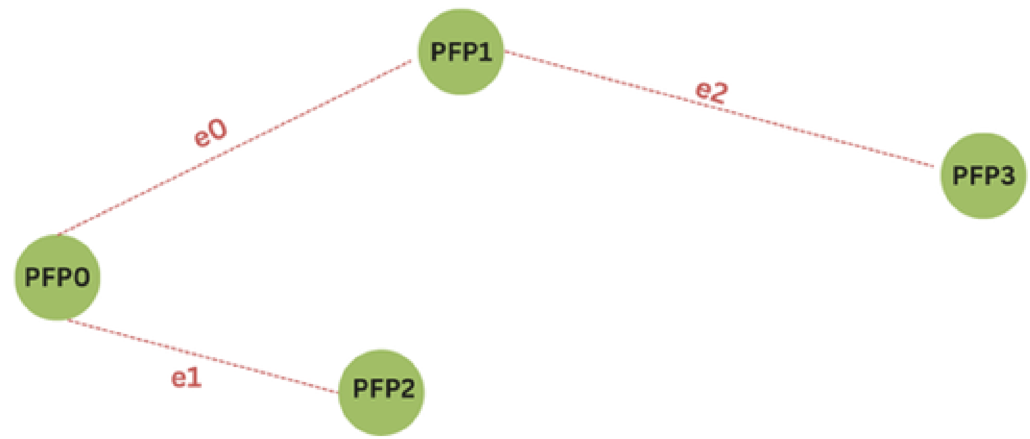

Output: the per-edge probability that the two PFPs belong to the same true hierarchy

Learning Pairwise Associations
Node and edge features

N PFPs and M candidate pairs

node_x
[N, 6]
PFP features

edge_attr
[M, 16]
Pair features

y
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Target

edge_index
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Connectivity

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- PFP length
- Number of 3D space points
- Is-primary flag
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16 pairwise features

- Centroid distance (1)
- Direction cosine (1)
- Length, A and B (2)
- Length ratio (1)
- Spacepoint count, A and B (2)
- Spacepoint-count ratio (1)
- Primary flags, A and B (2)
- Track-like flags, A and B (2)
- Shower-like flags, A and B (2)
- Hit counts, A and B (2)

Learning Pairwise Associations
Training details

- 60-20-20% train/val/test event-level splits
- 100 epochs
- trained with class-weighted binary cross-entropy

$$L_{\text{BCE}} = -\frac{1}{N}\sum_{i=1}^{N}\left[y_i \ln(\hat{y}_i) + (1 - y_i)\ln(1 - \hat{y}_i)\right]$$

- High-confidence edges (≥0.90) → Slices connected component clustering
- 1× GPU on CINECA Leonardo, 100 GB RAM, 1.7h wall-clock training time

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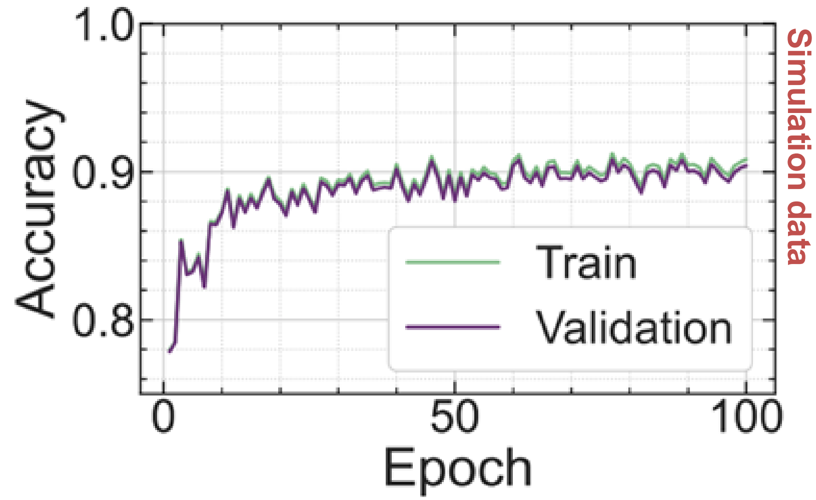

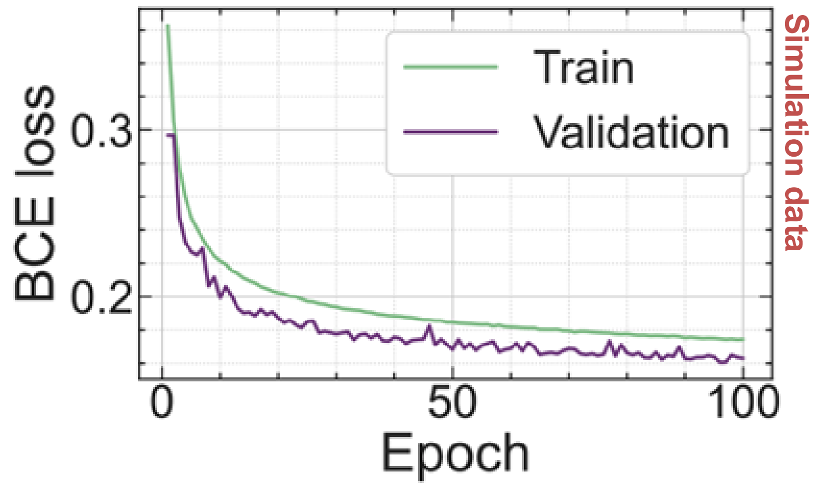

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Preliminary Results

Purity: Does each slice mostly contain hits from one true hierarchy?

Fraction of hits in a reco slice that comes from its dominant true hierarchy

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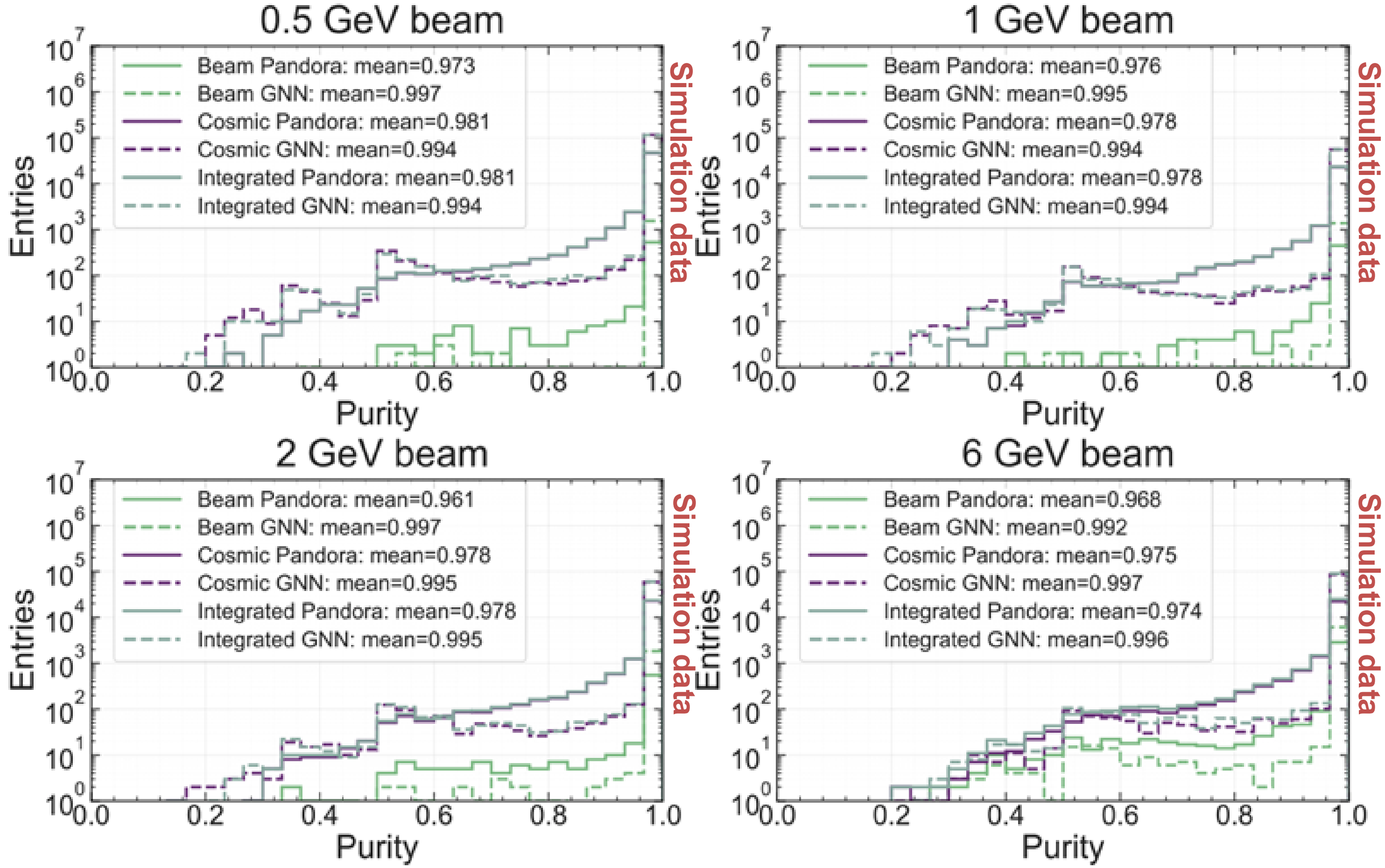

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Completeness: Is each true hierarchy kept together in one slice?

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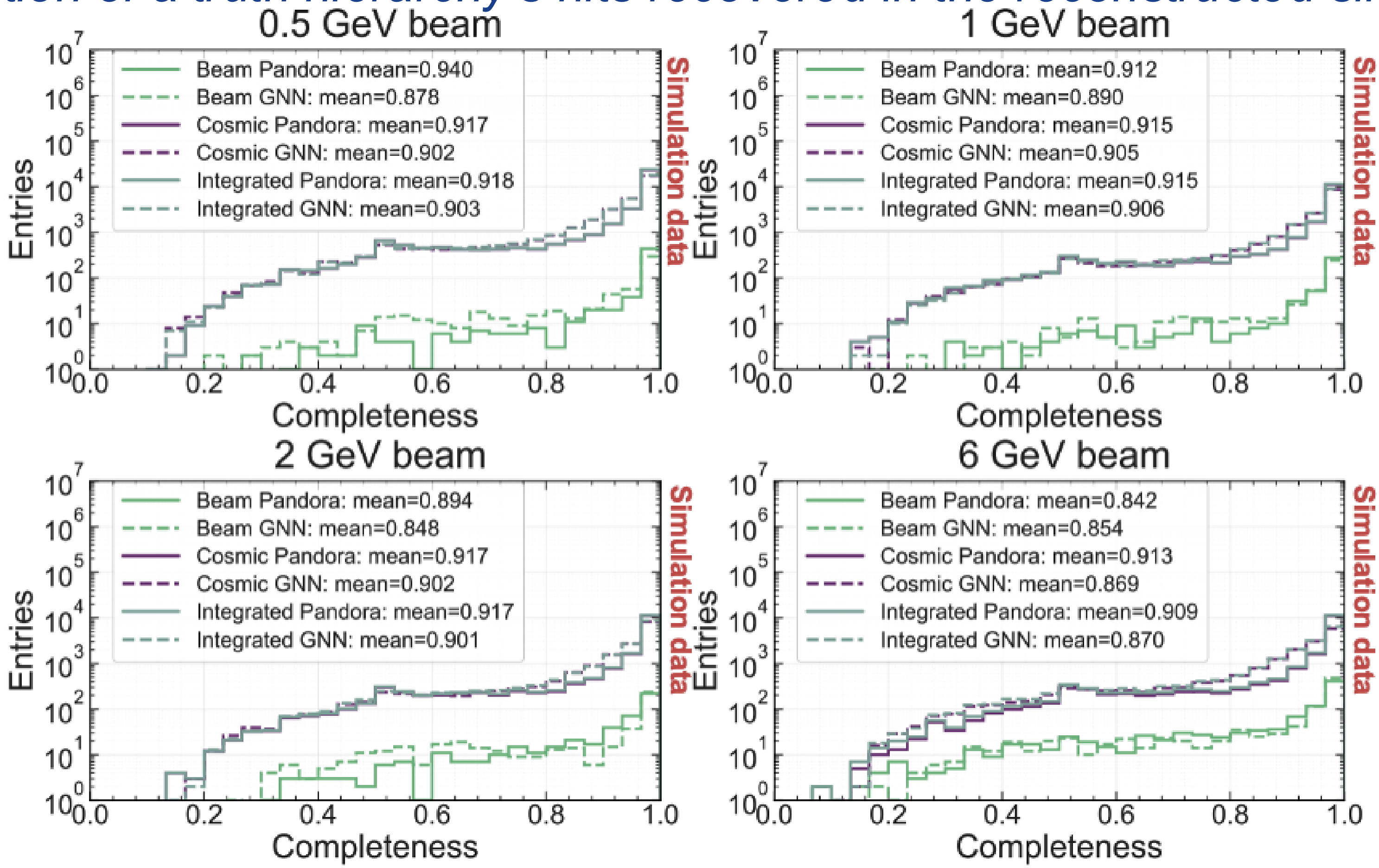
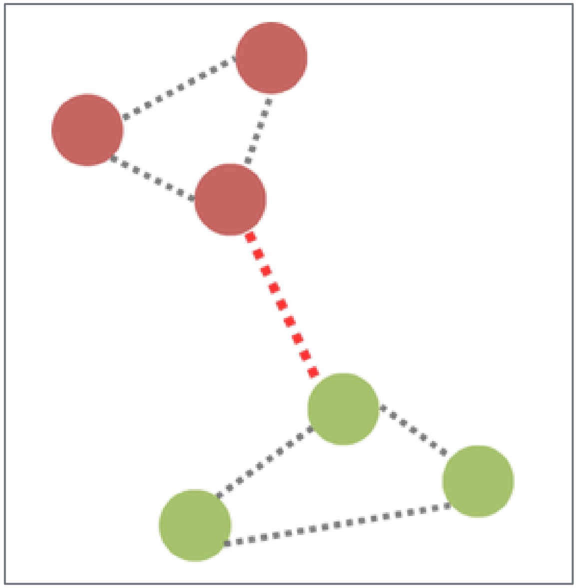


Preliminary Results
Two failure modes

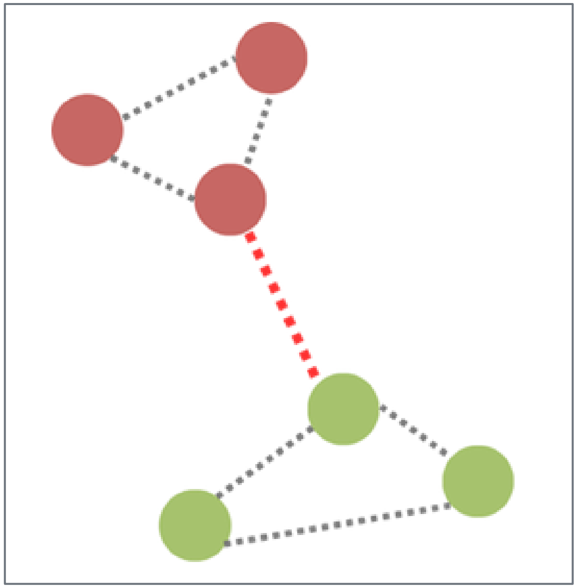
Merging
2 truth hierarchies → 1 predicted slice



false positive rate
two unrelated PFPs are connected

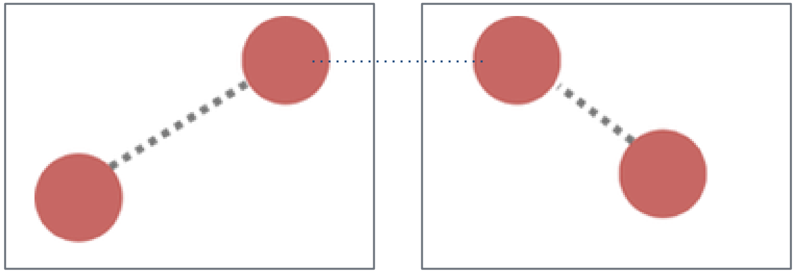
Preliminary Results
Two failure modes

Merging
2 truth hierarchies → 1 predicted slice



false positive rate
two unrelated PFPs are connected

Fragmentation
1 truth hierarchy → 2 predicted slices



false negative rate
two related PFPs are not connected

Preliminary Results

Efficiency: Fraction of reco truth hierarchies matched to a slice

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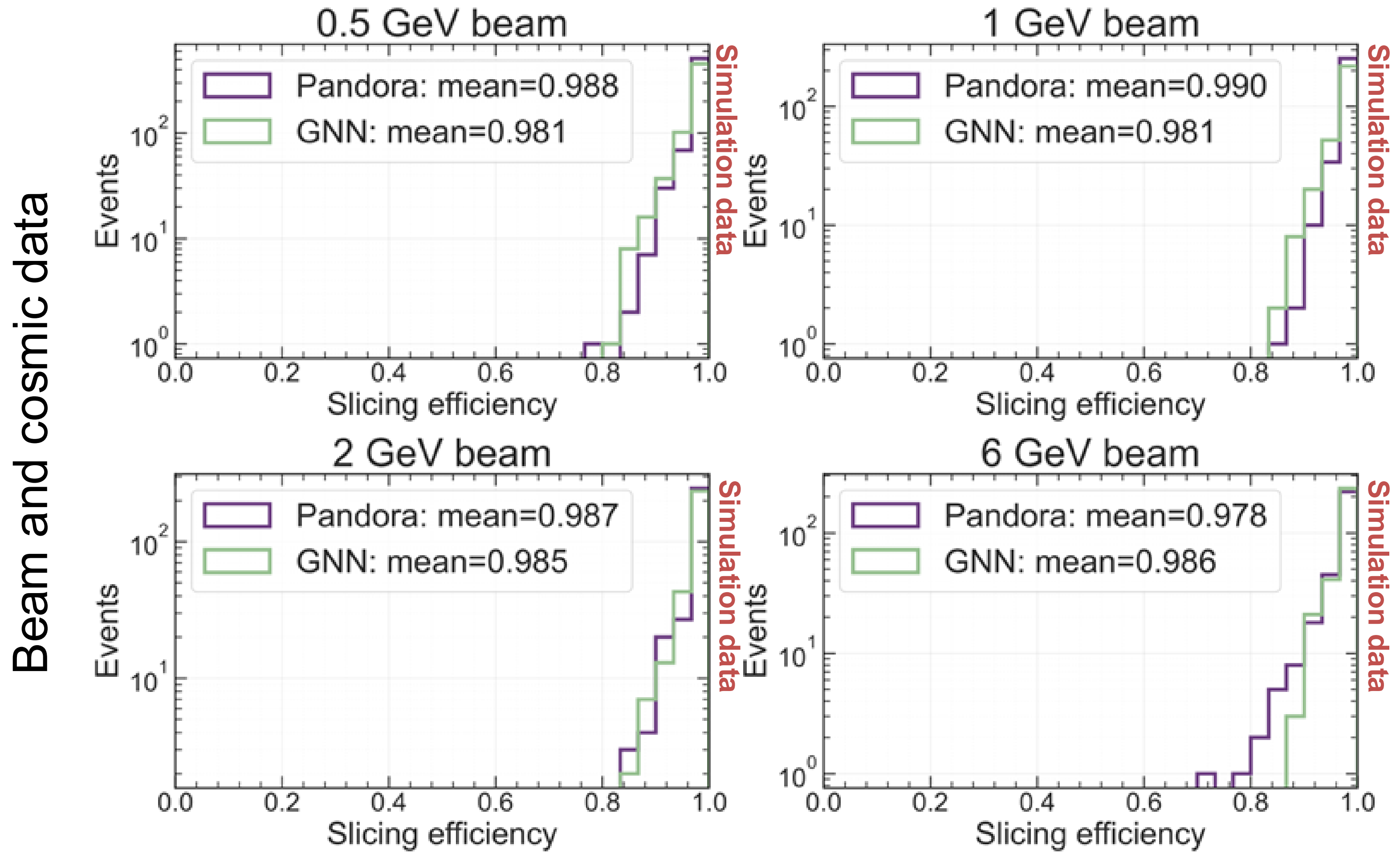

Preliminary Results

Adjusted Rand Index (ARI): Agreement between the predicted slice and the true hierarchy grouping

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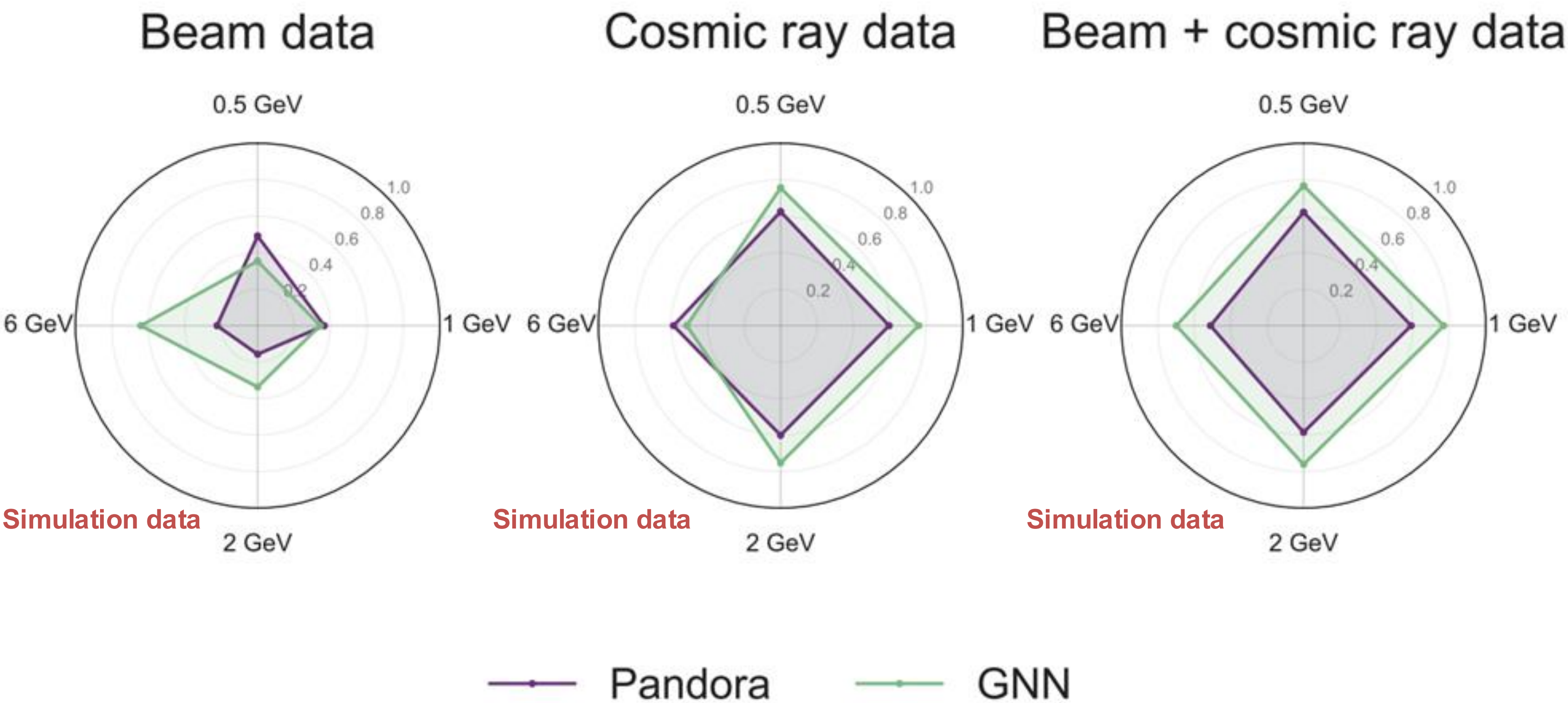
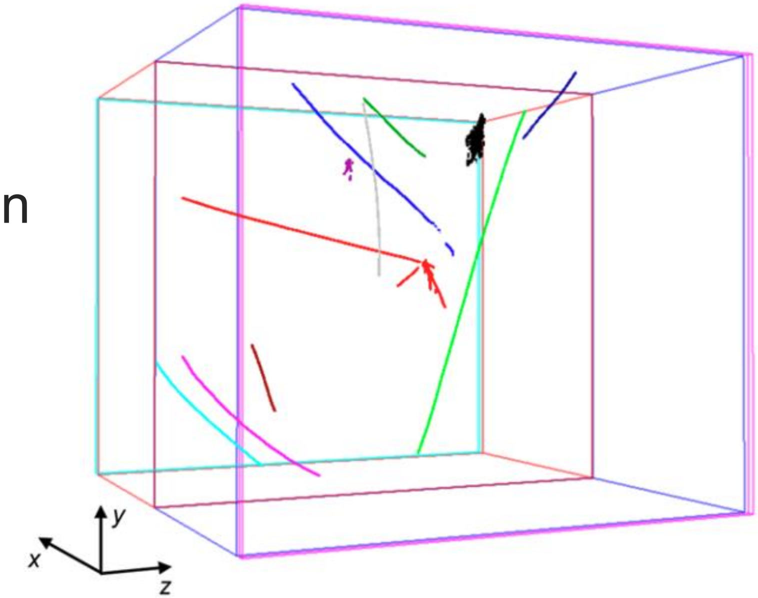


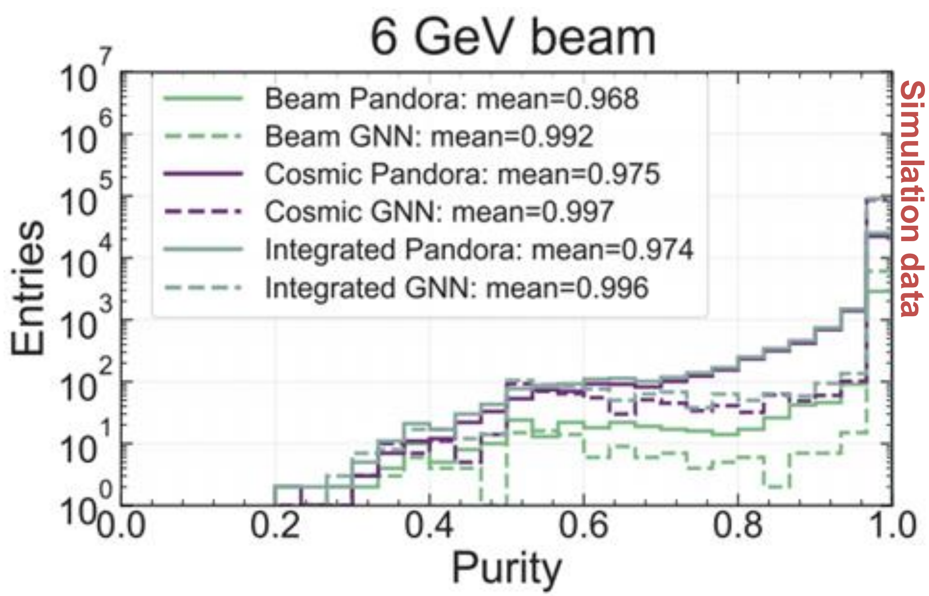
OUTLINE

- Physics & Detectors
- Pandora & Event Slicing
- Learning Pairwise Associations
- Preliminary Results
- **Summary**

Closing remarks

- Event slicing reframed as edge classification
- Pandora favors completeness over purity
- GNN favors purity over completeness
- A proof of principle: learned pairwise association is a viable alternative to hand-engineered slicing rules





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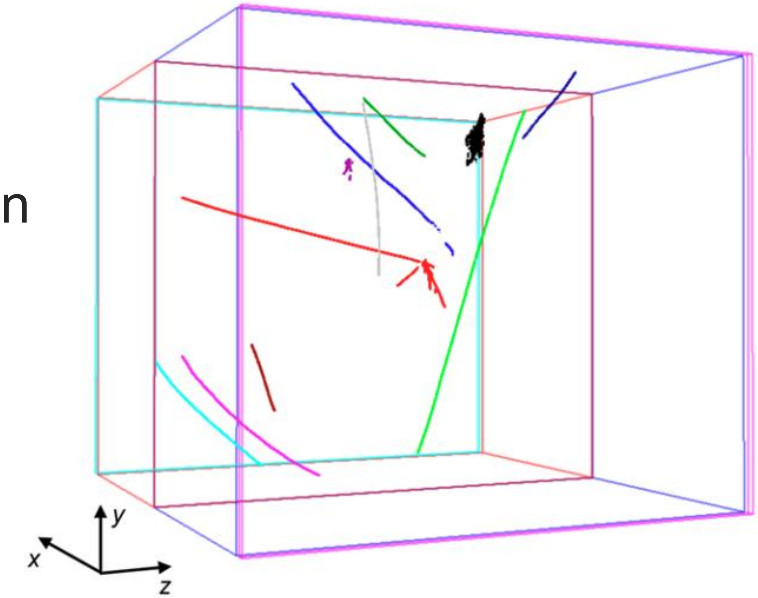
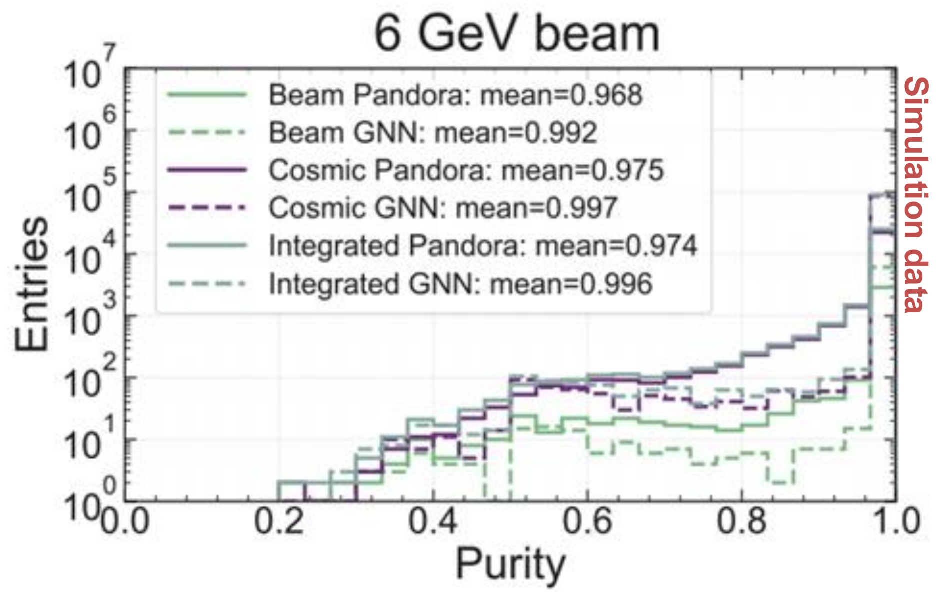


Thank You!

… and thanks to Leigh Whitehead[1], Dominic Brailsford[2], and Andy Chappell[3]

[1] University of Cambridge,
[2] Lancaster University,
[3] University of Warwick



FutureData4EU

Training Future Big Data Experts for Europe

Funding

COESIONE ITALIA 21-27 EMILIA-ROMAGNA

Co-funded by the European Union

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Università degli Studi di Ferrara

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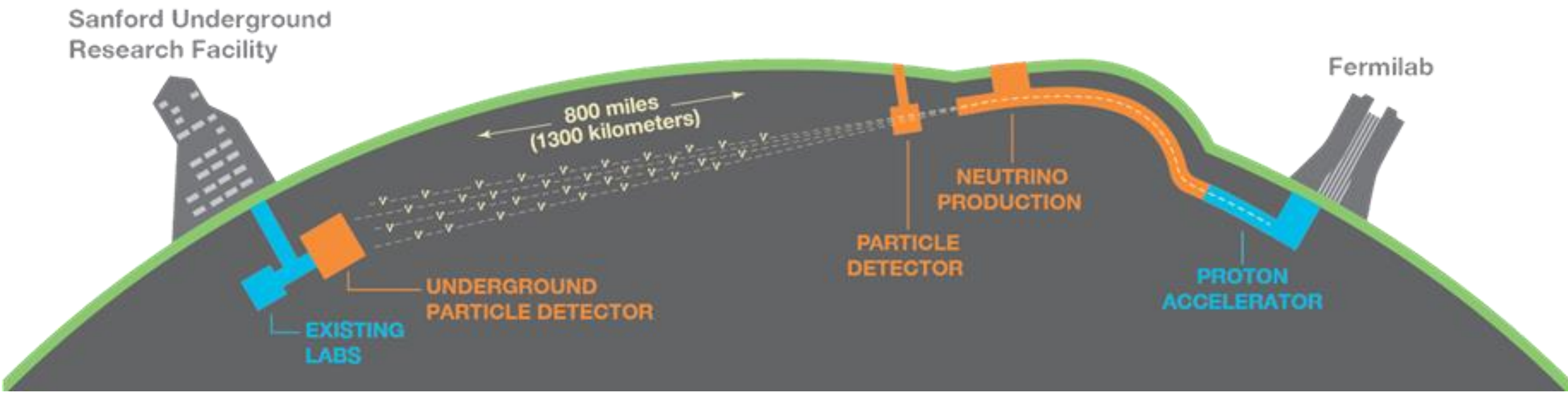
UNIVERSITÀ DI PARMA

POLITECNICO MILANO 1863

Backup slides

The Deep Underground Neutrino Experiment

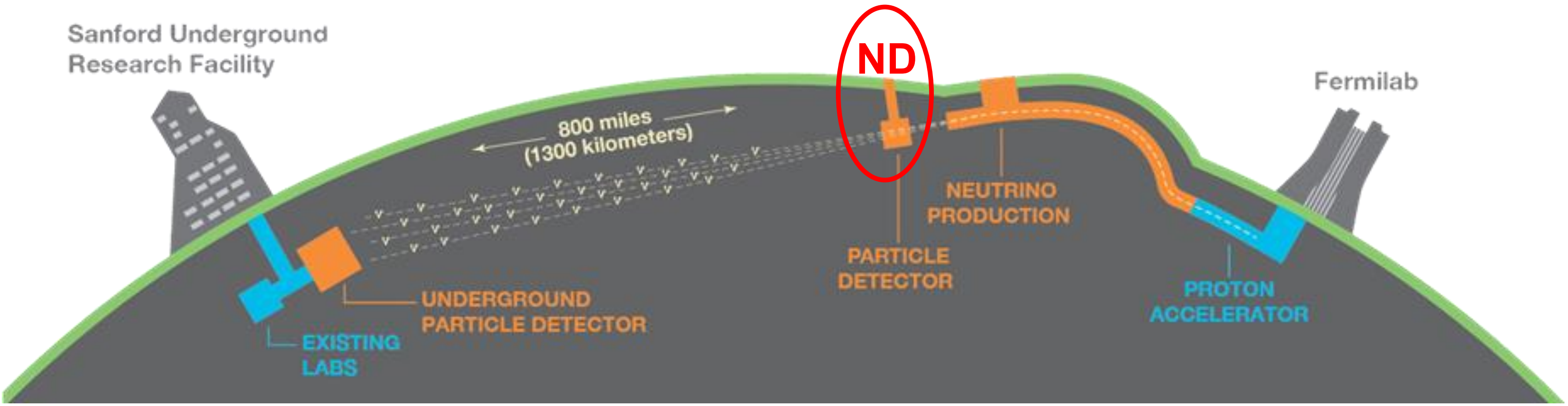


Source: Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I: Introduction to DUNE (2020).

<u>Long-baseline neutrino oscillation experiment</u>

- High-power proton beam of 1.2MW upgradable to 2.4MW.
- High-power, wide-range neutrino beam (~GeV energy range)
- Near detector (ND) (575m from the ν source)
- Far detector (FD) in South Dakota (~1300km) and 1.5km deep underground

The Deep Underground Neutrino Experiment



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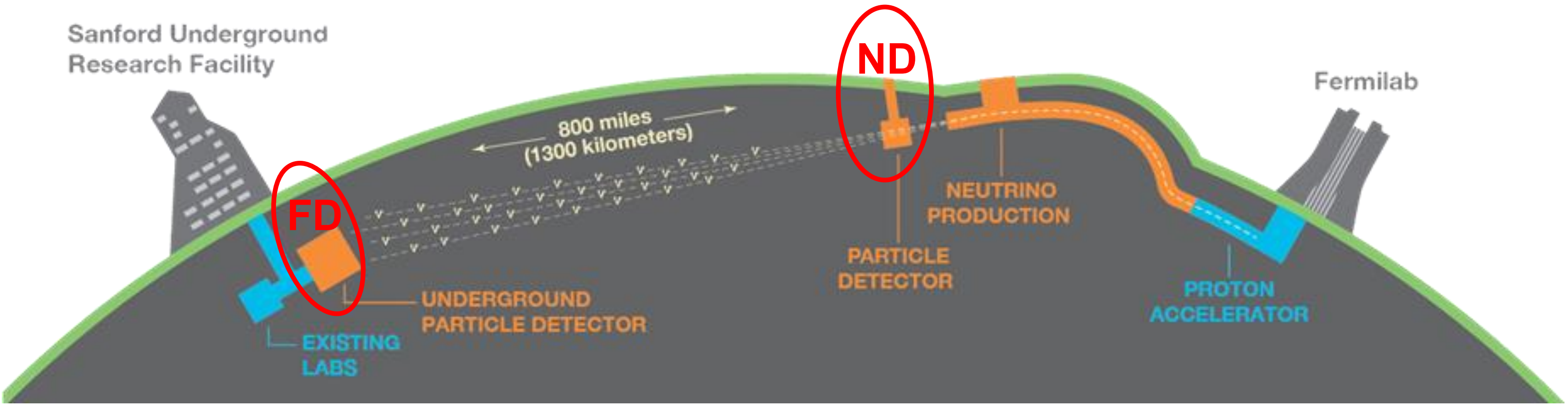

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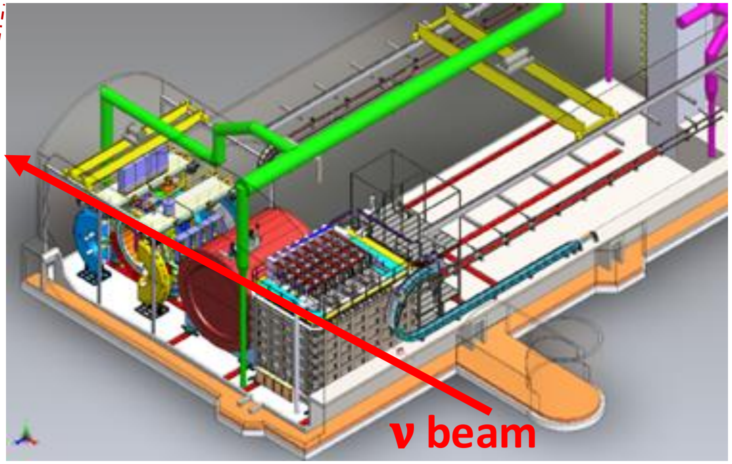
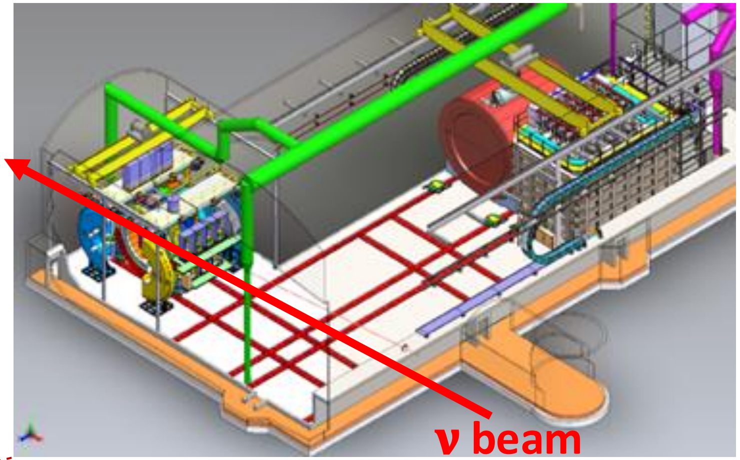
DUNE-PRISM ND Complex

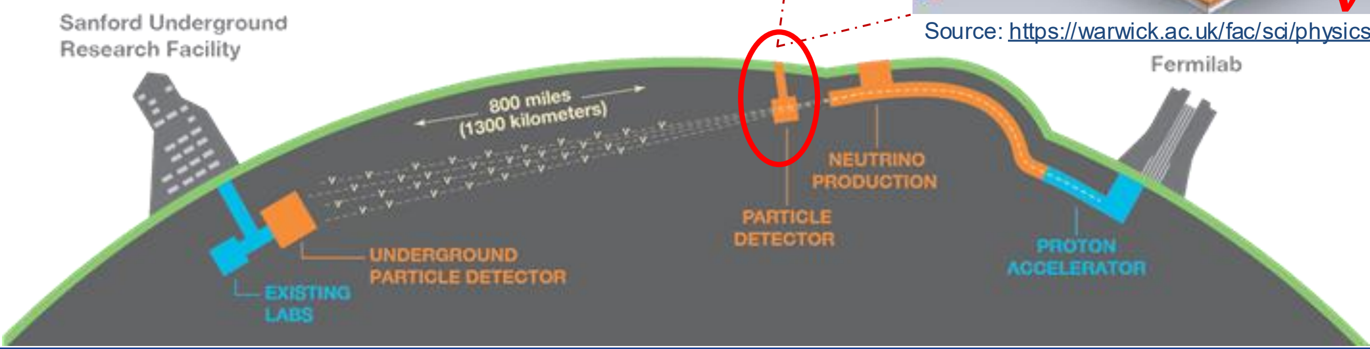
Off-axis beam measurement

- Constrain systematic uncertainties
- Beam monitoring
- Initial neutrino flux measurement before any oscillations





Source: https://warwick.ac.uk/fac/sci/physics/research/epp/exp/dune/



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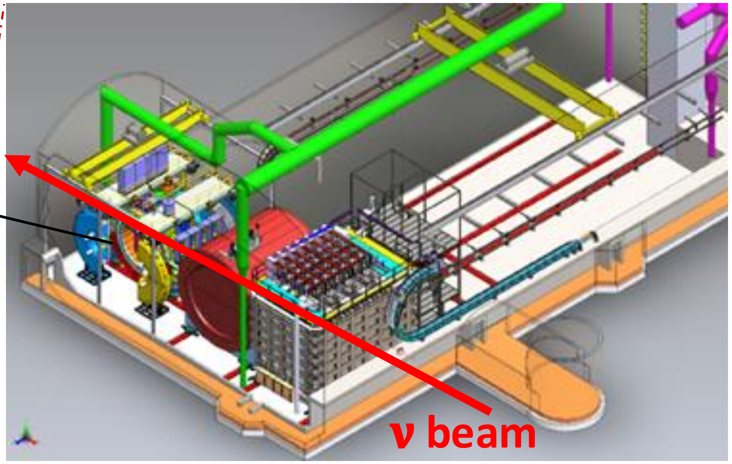

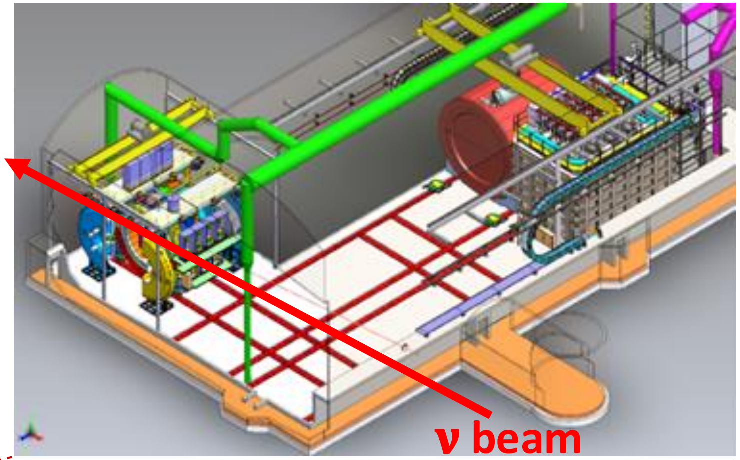

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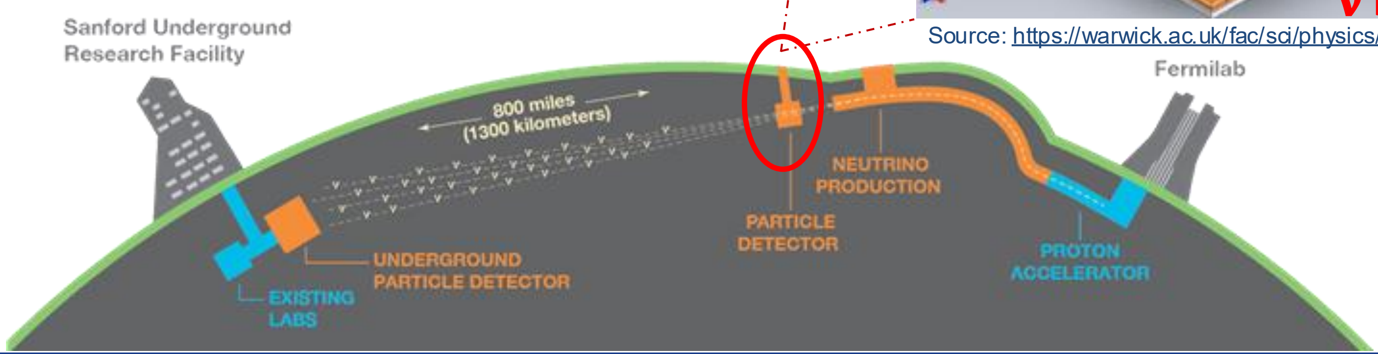
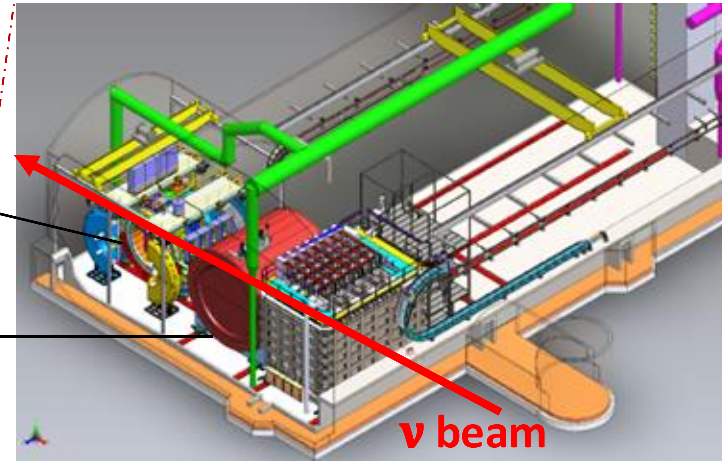
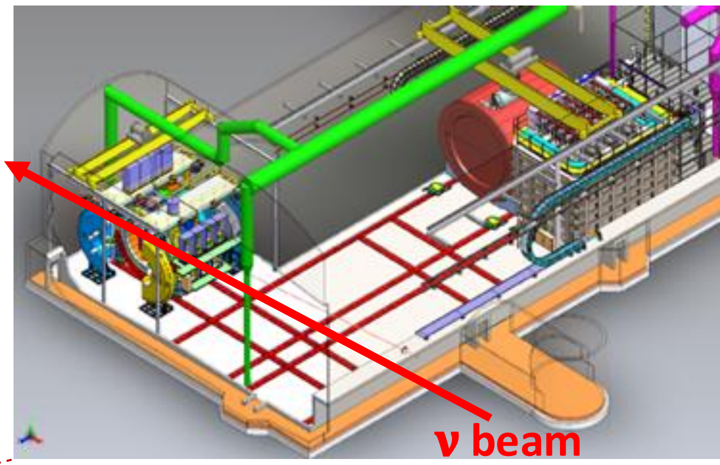


DUNE-PRISM ND Complex
Off-axis beam measurement

SAND

TMS -> ND-GAr





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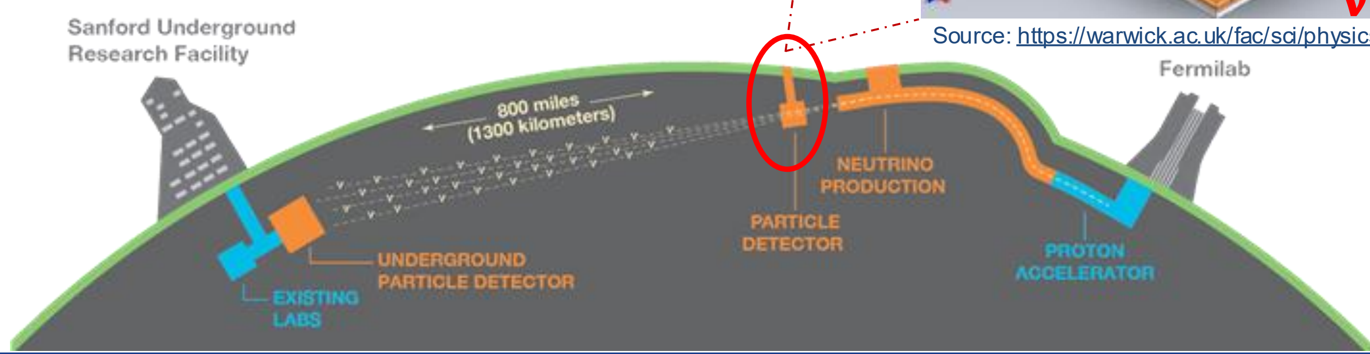

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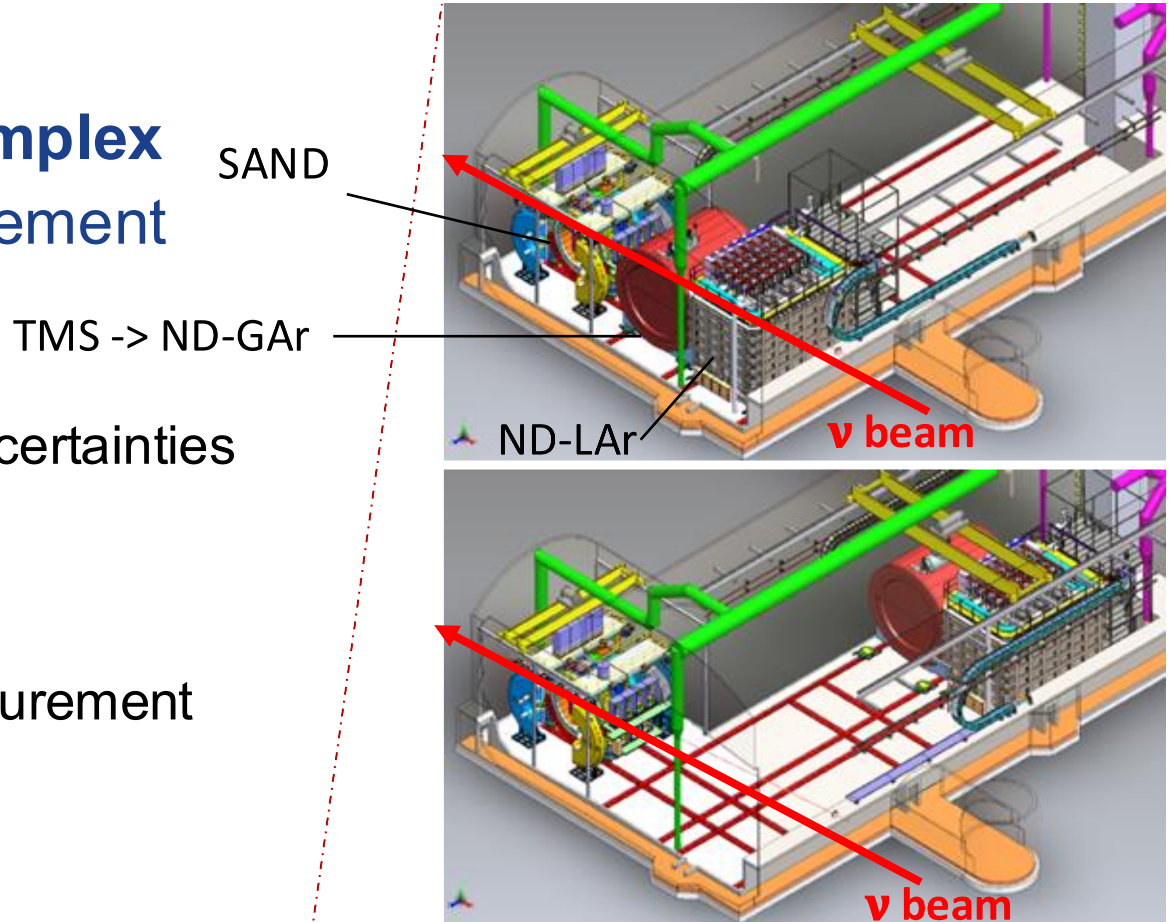

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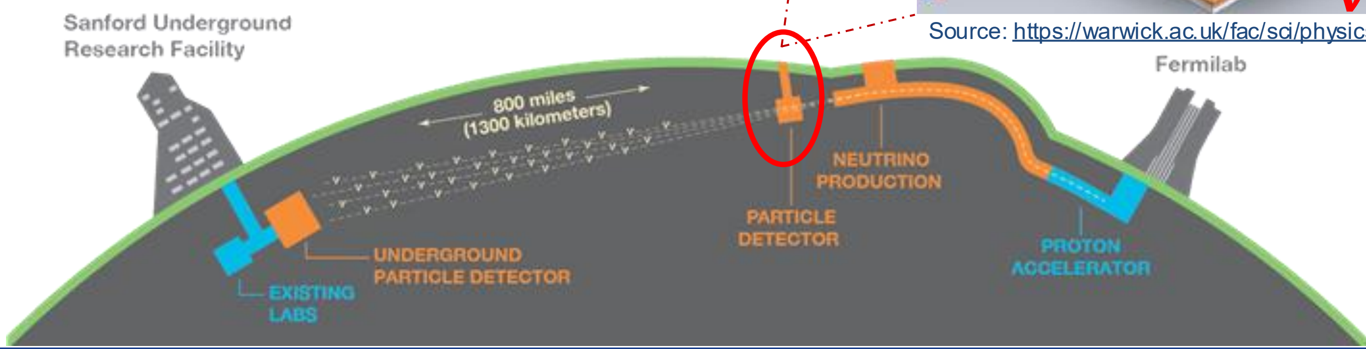

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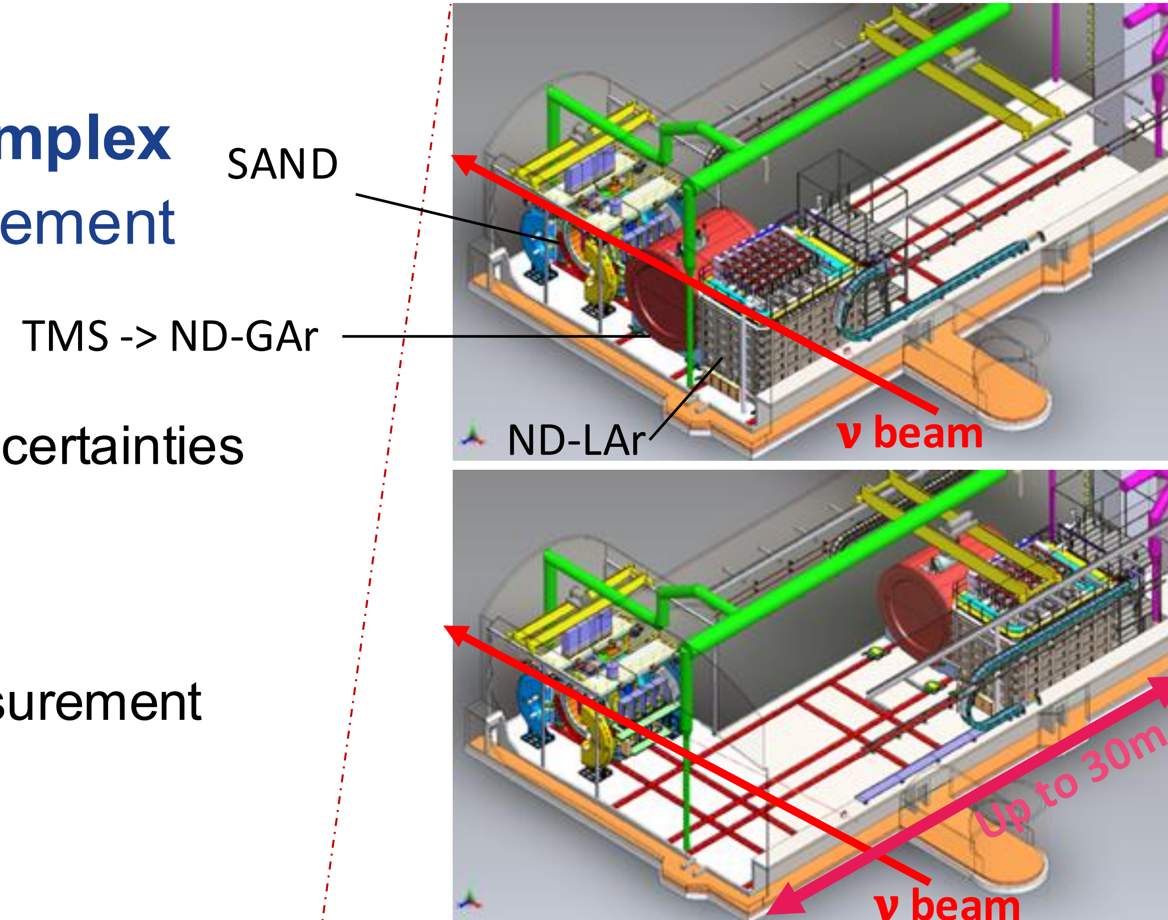

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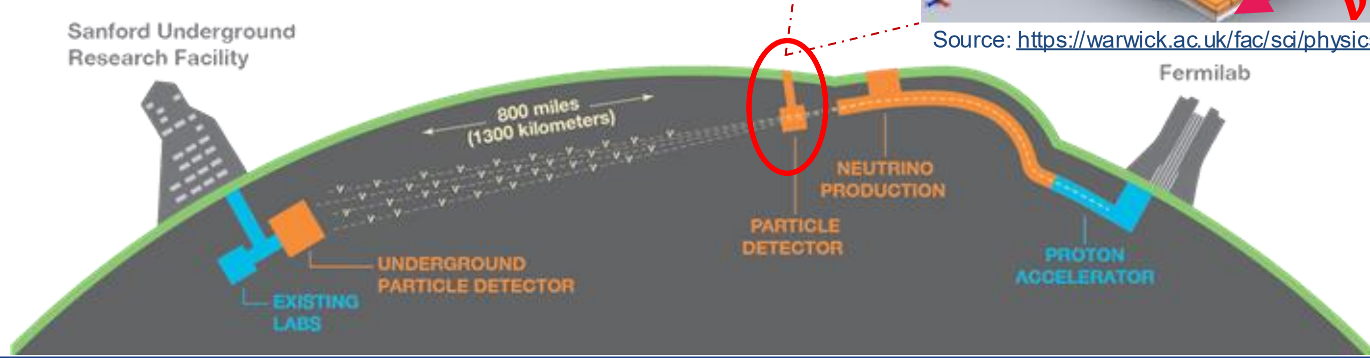
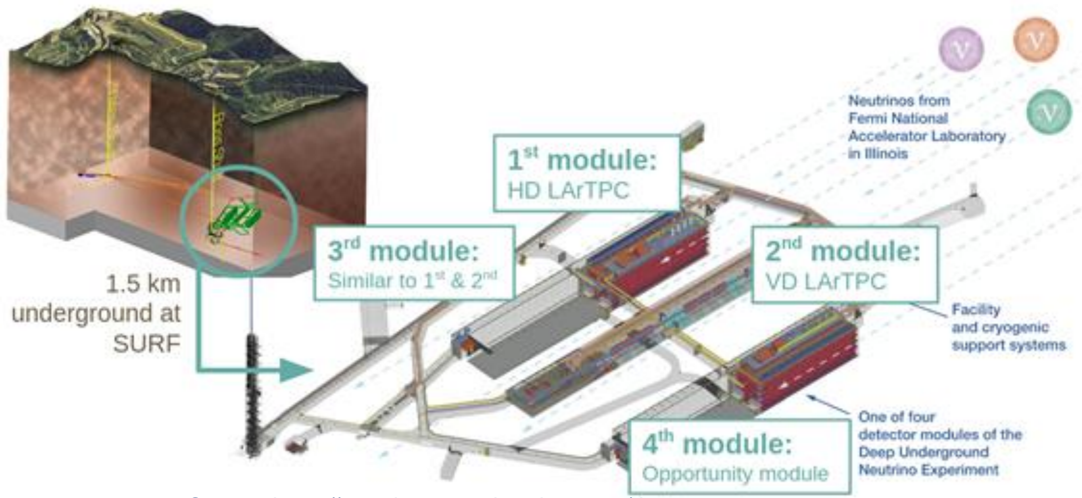


DUNE: The FD Complex



Source: https://neutrinos.portales.ciemat.es/dune-en

- 2→4 modules
- Fiducial (sensitive) mass of 40kt of liquid argon (LAr)
- Measure flavor-tagged neutrino interaction and compare the results with the ND prediction