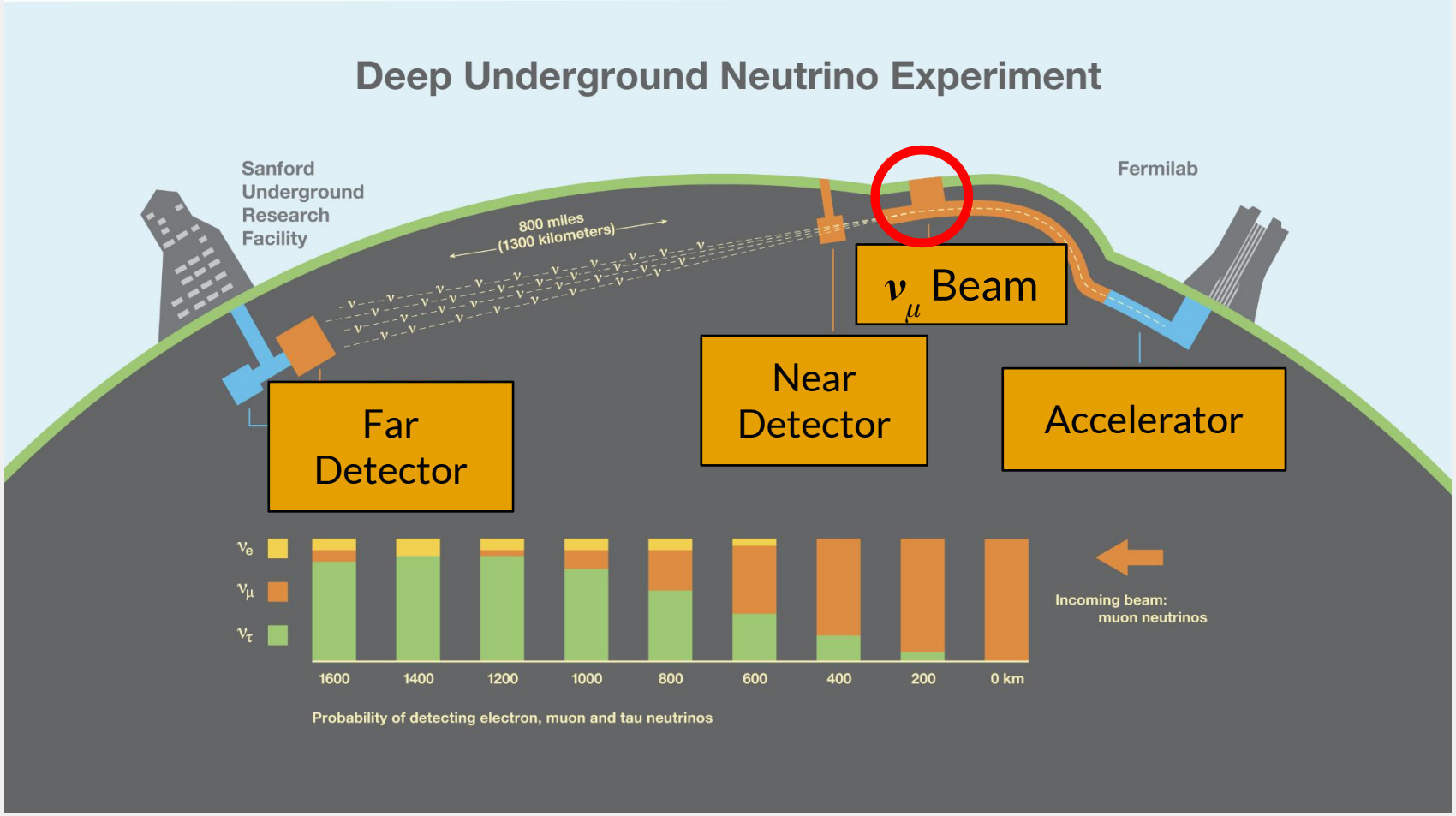
Track Matching during Reconstruction using Graph Neural Networks Across DUNE's Near Detectors

Jessie Micallef on behalf of the DUNE Collaboration

Neutrino Physics and Machine Learning Workshop

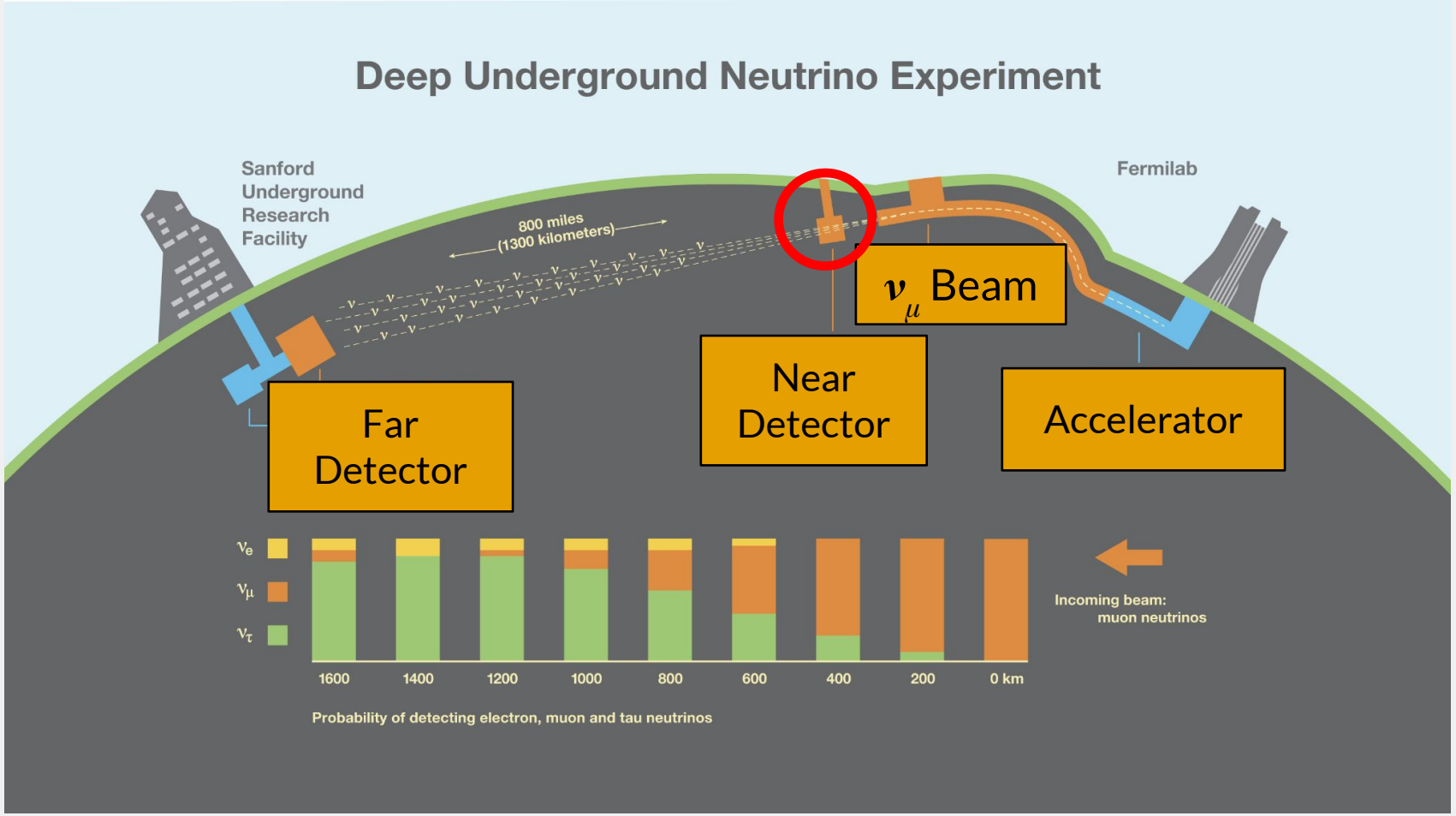
15 June 2026

DUNE: Deep Underground Neutrino Experiment



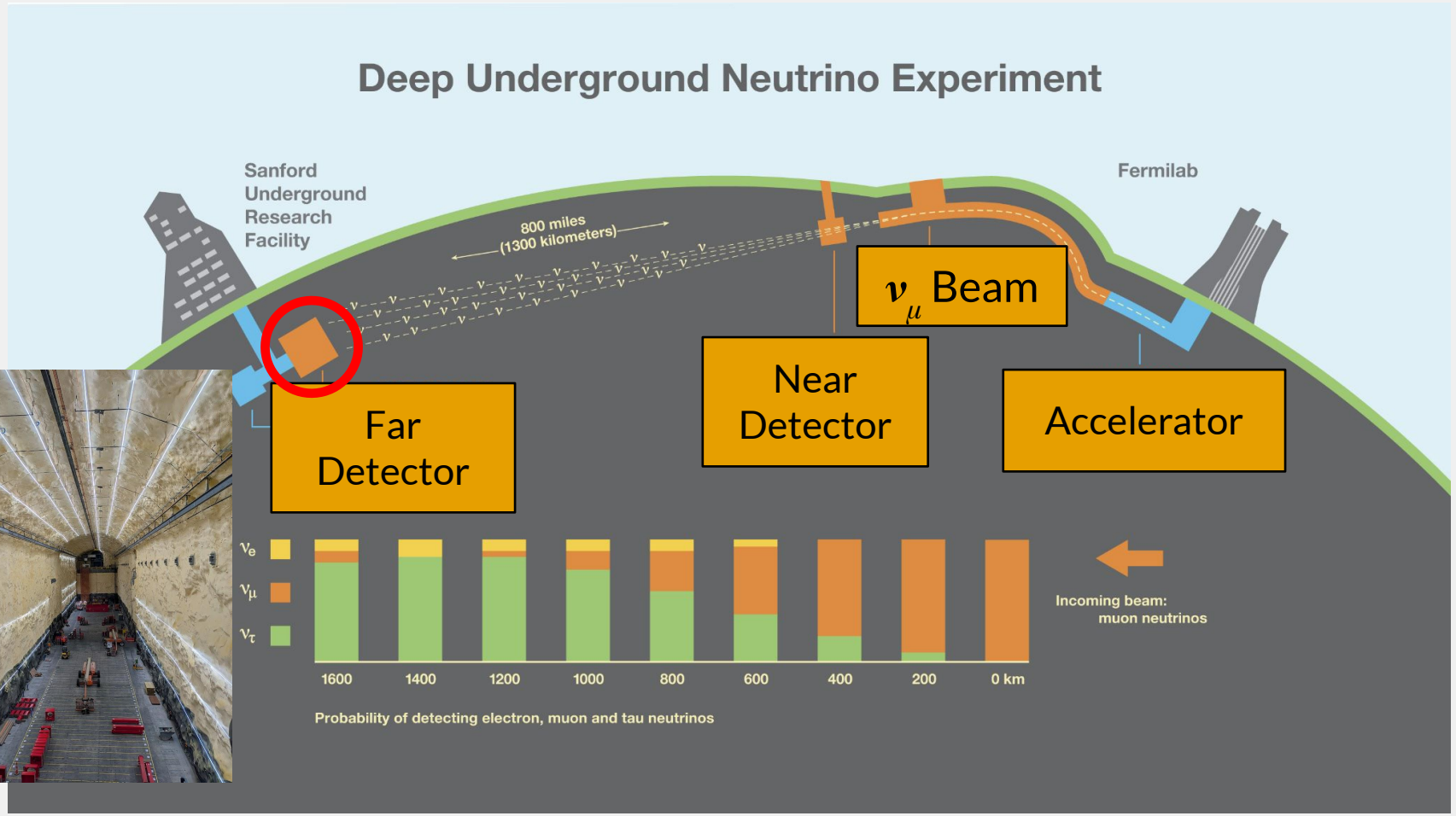
- Upgrade will lead to world's most intense neutrino beam

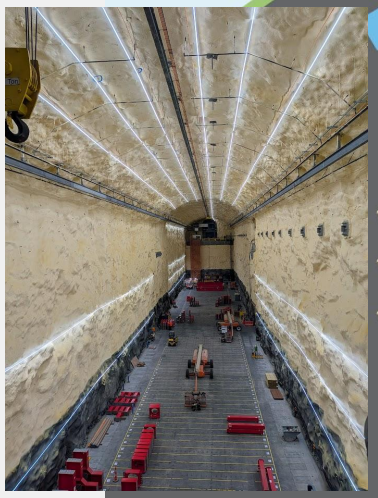
DUNE: Deep Underground Neutrino Experiment



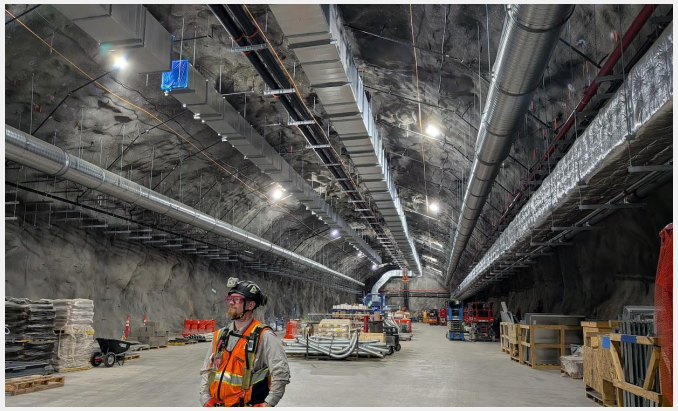
- Upgrade will lead to world's most intense neutrino beam
- Near detectors at Fermilab (Illinois, USA)

DUNE: Deep Underground Neutrino Experiment

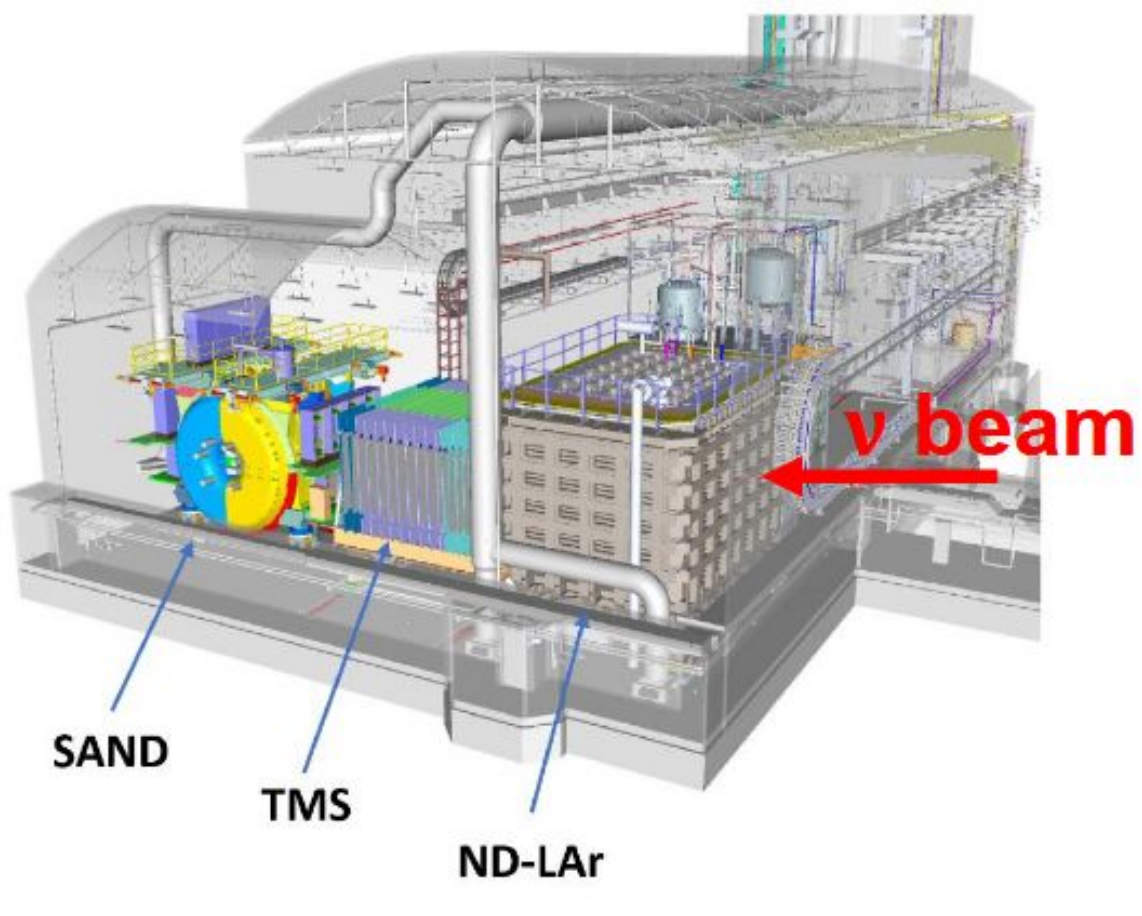




- Upgrade will lead to world's most intense neutrino beam
- Near detectors at Fermilab (Illinois, USA)
- Far detector at Sanford Underground Research Facility (South Dakota, USA)



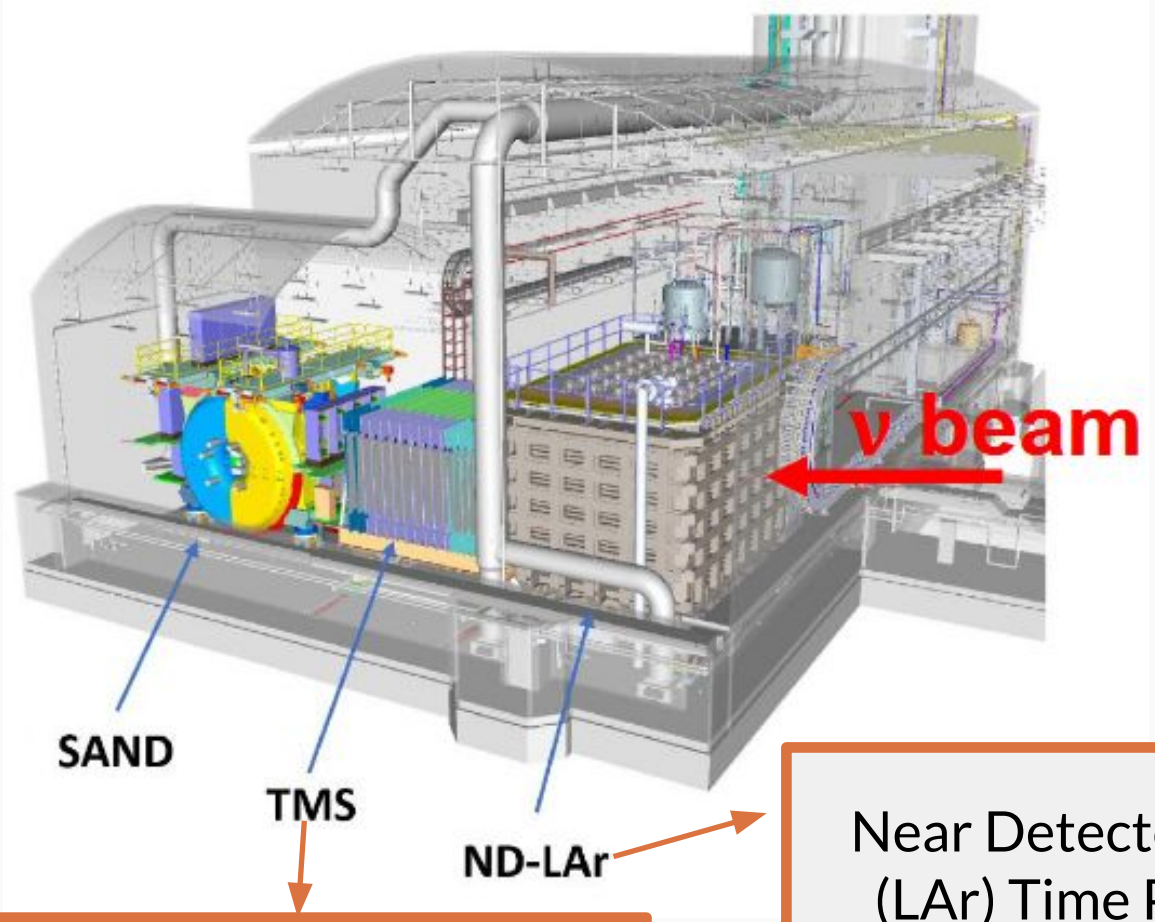
Near Detector (ND) Liquid Argon (LAr)



Important to constrain ν
- Flux (enter)
- Cross section (interact)
- Detector systematics (detected)

with ND that has same target (LAr) as Far detector

Near Detector (ND) Liquid Argon (LAr)



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- Flux (enter)
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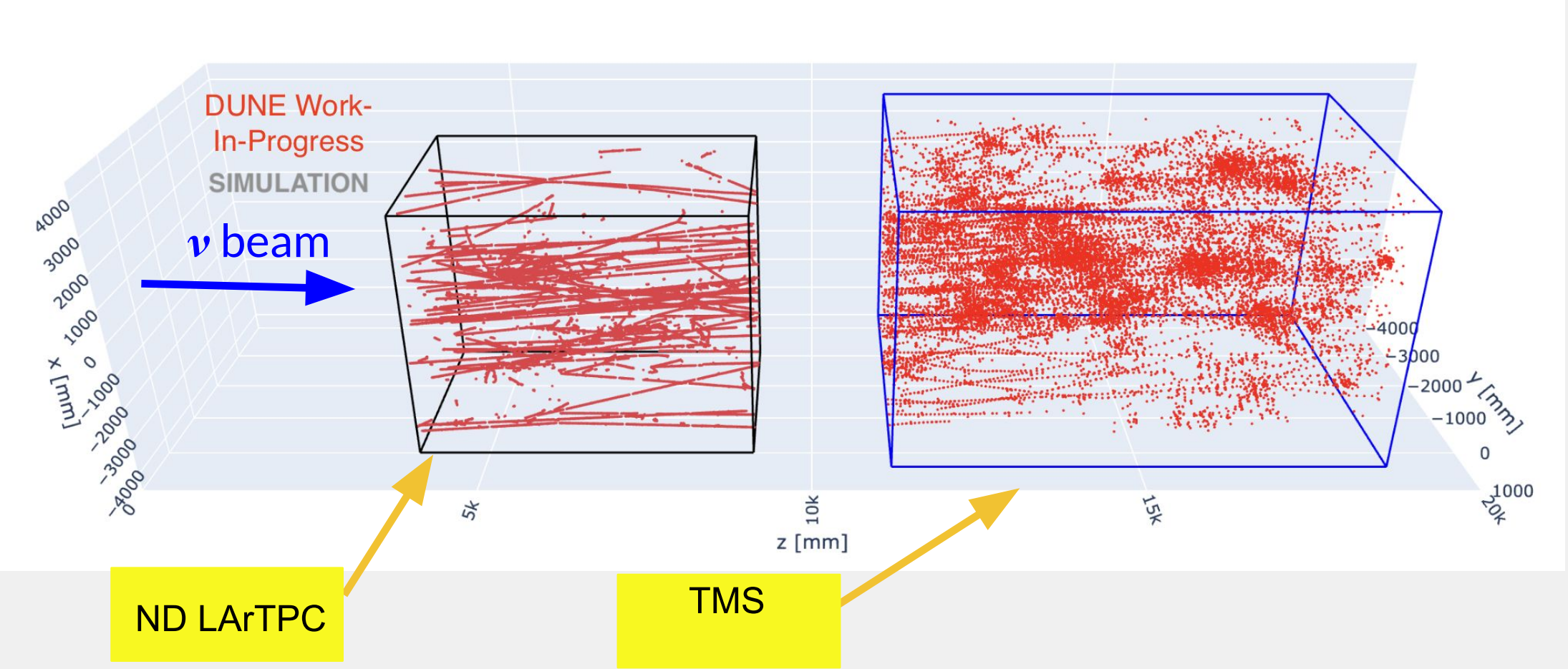
Near Detector (ND) Liquid Argon (LAr) Time Projection Chamber

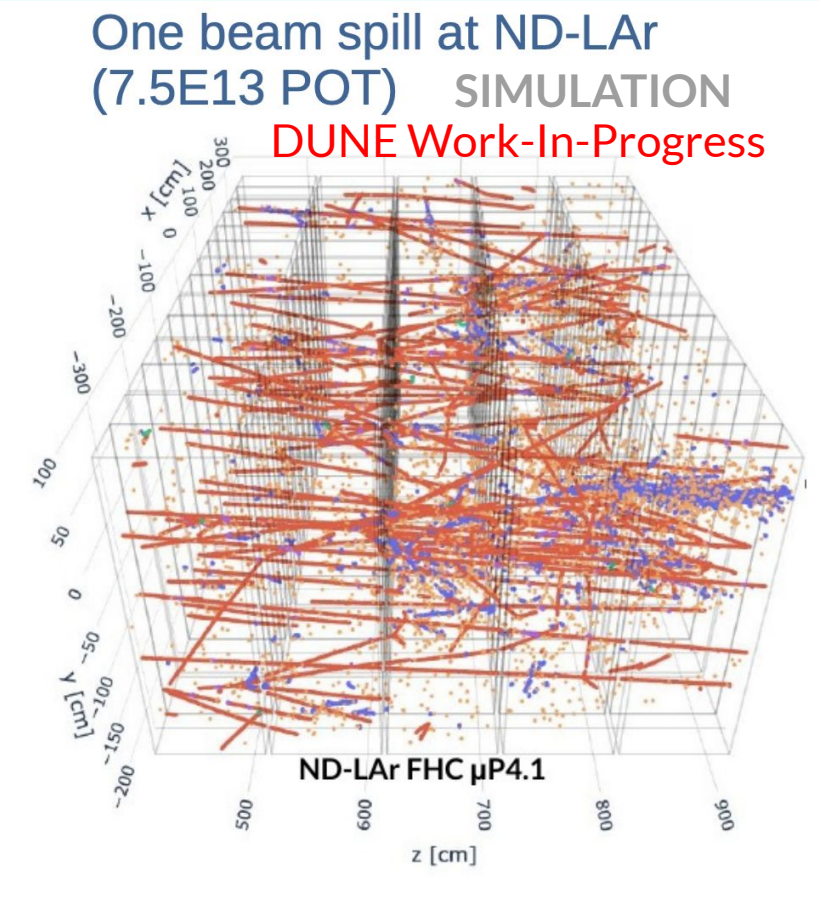
The Muon Spectrometer

The Muon Spectrometer: Valuable for PID and Removing Background Muons



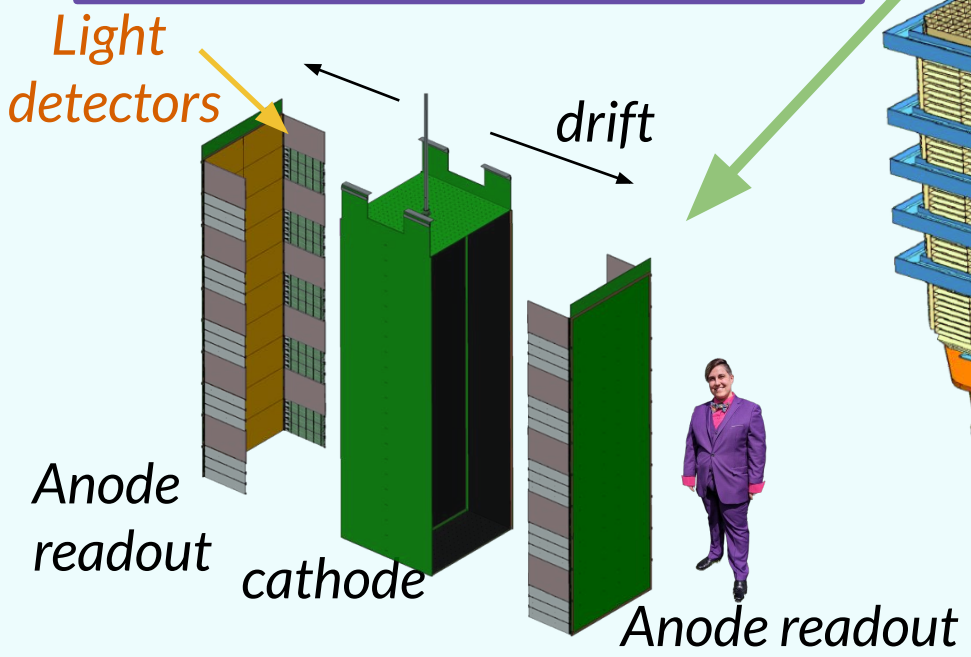
Handling Beam Intensity in Near Detector LAr

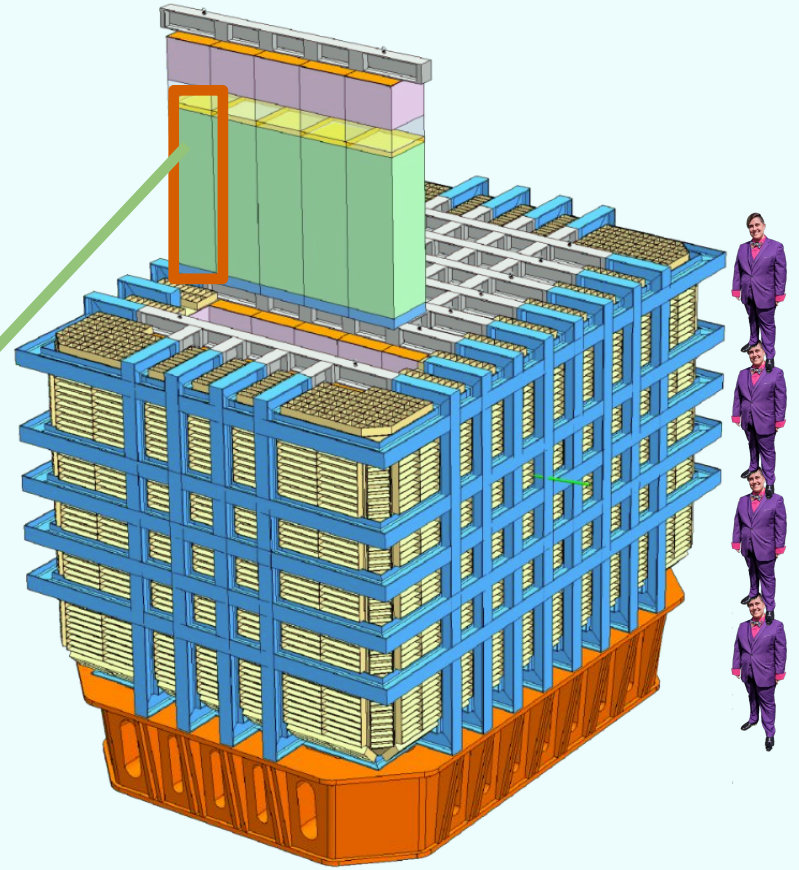
Expect ~100 ν interactions!



Advanced detector tech:

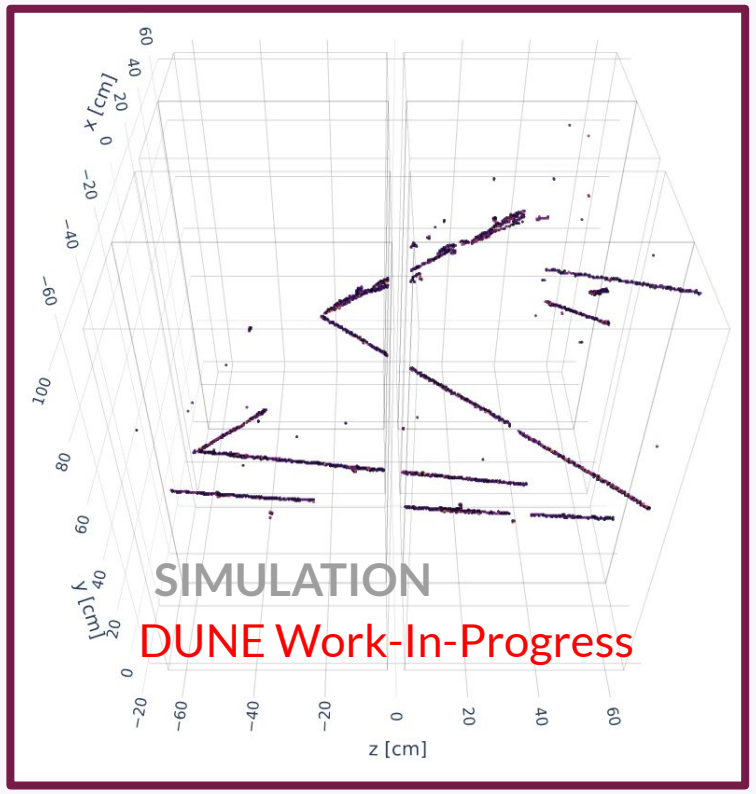
- ✅ LArTPC detectors
- ✅ Native 3D detection
- ✅ Separated modules

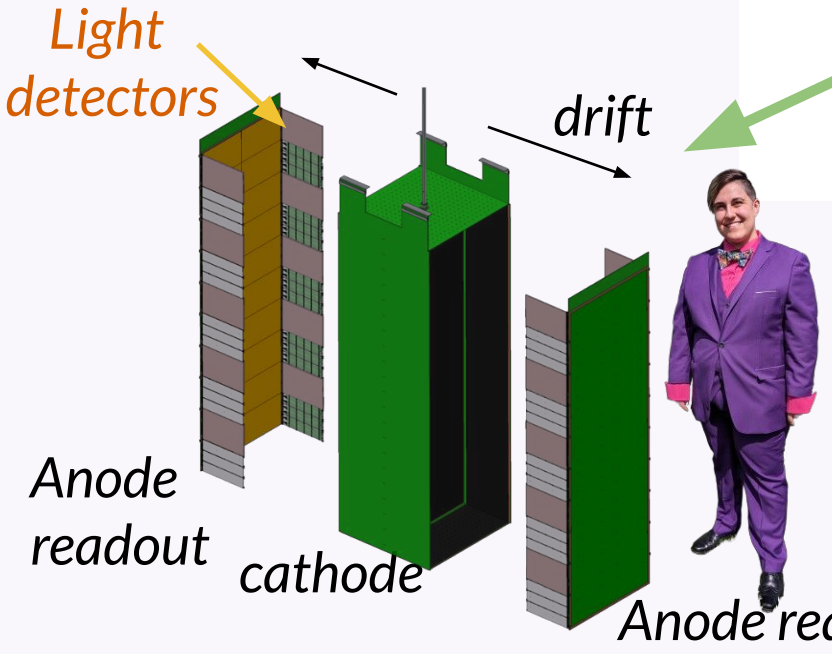


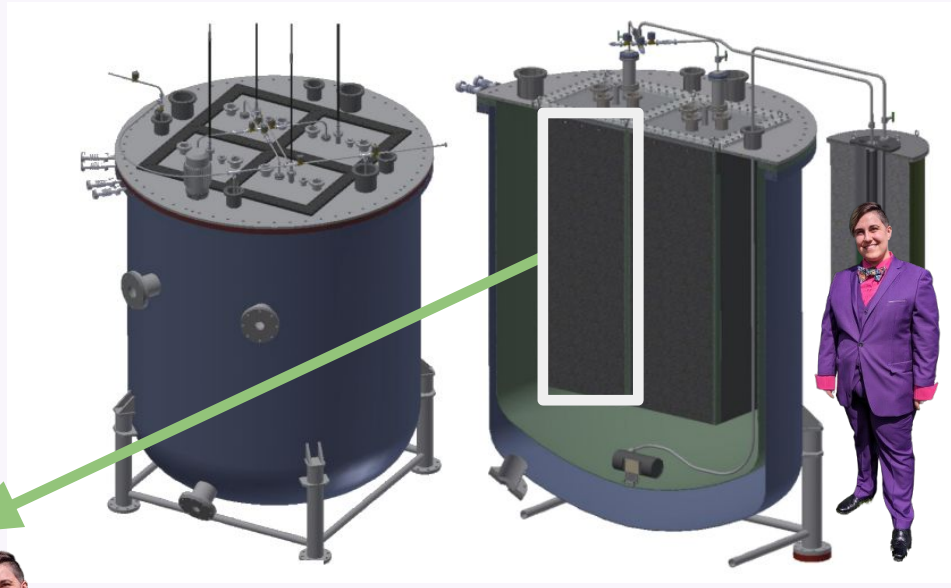


5x7 Modules

2x2 Demonstrator Prototype Near Detector





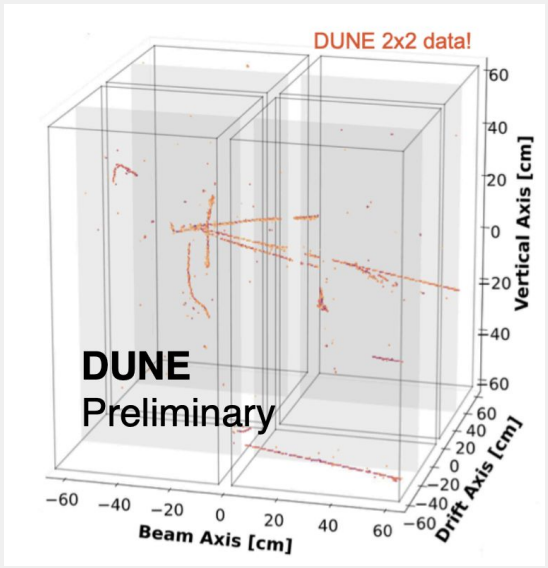


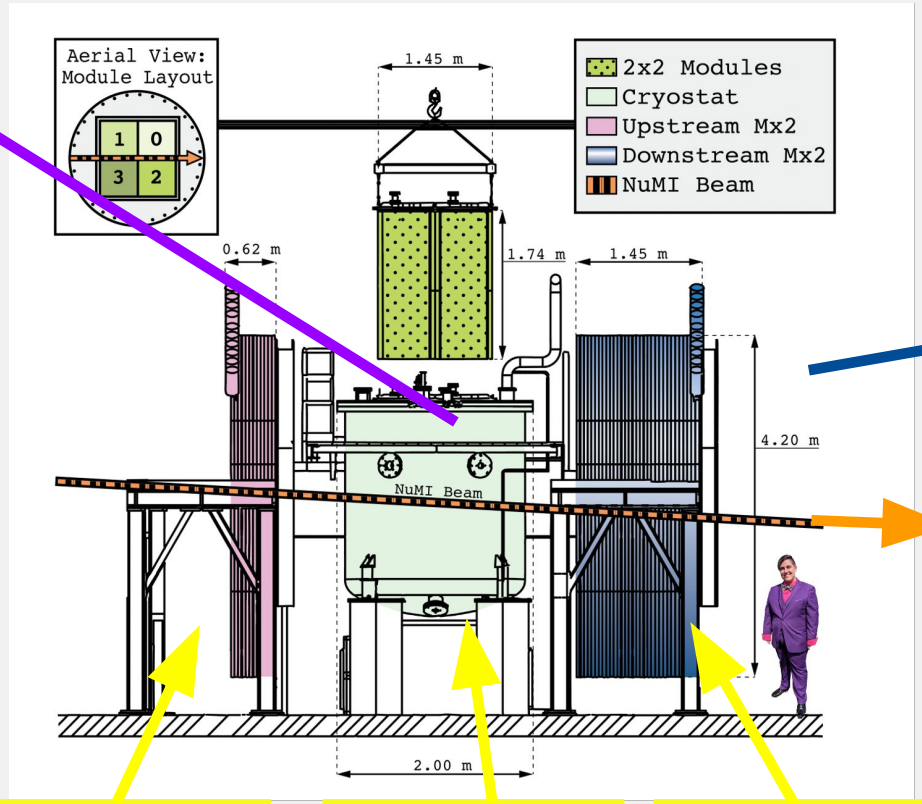
2x2 Modules

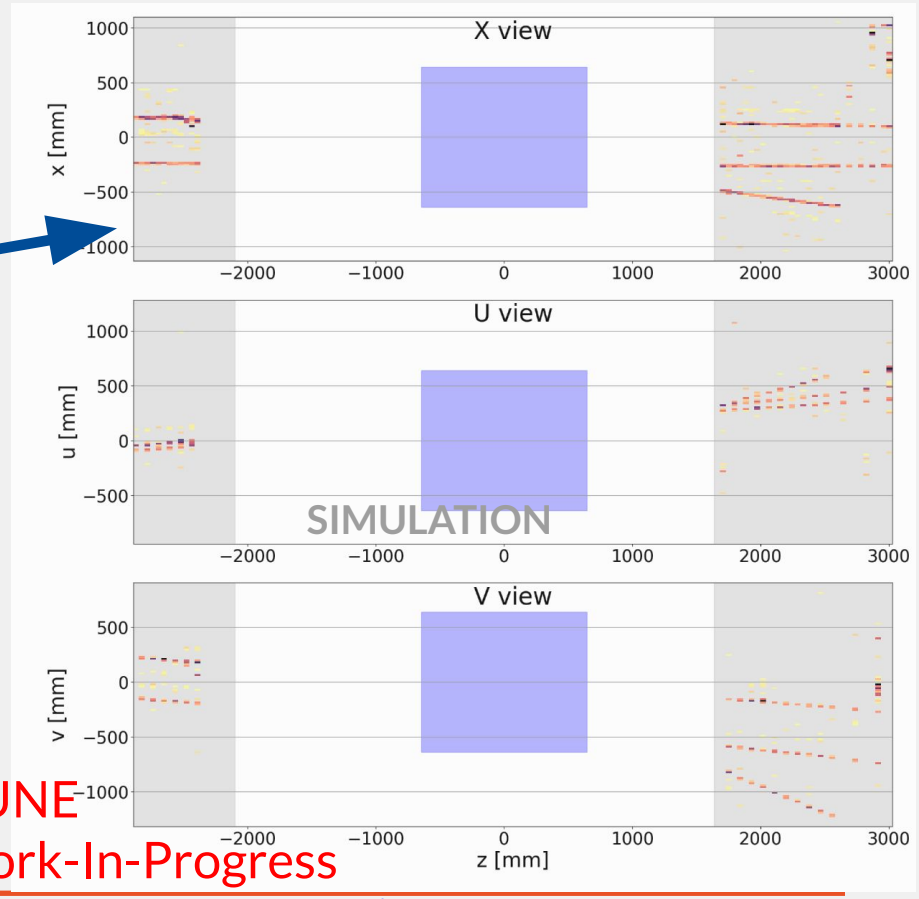
3D LAr vs 2D Muon Tagger

Inherently a 3D pixel readout

MINERvA & TMS: inherently a 2D output!







Upstream MINERvA

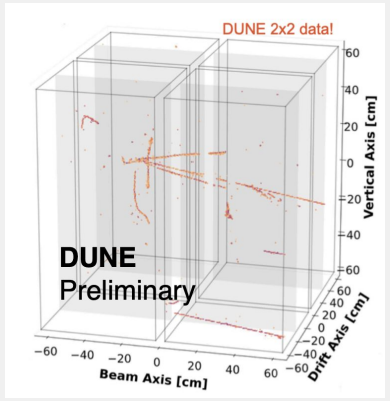
2x2 LArTPC

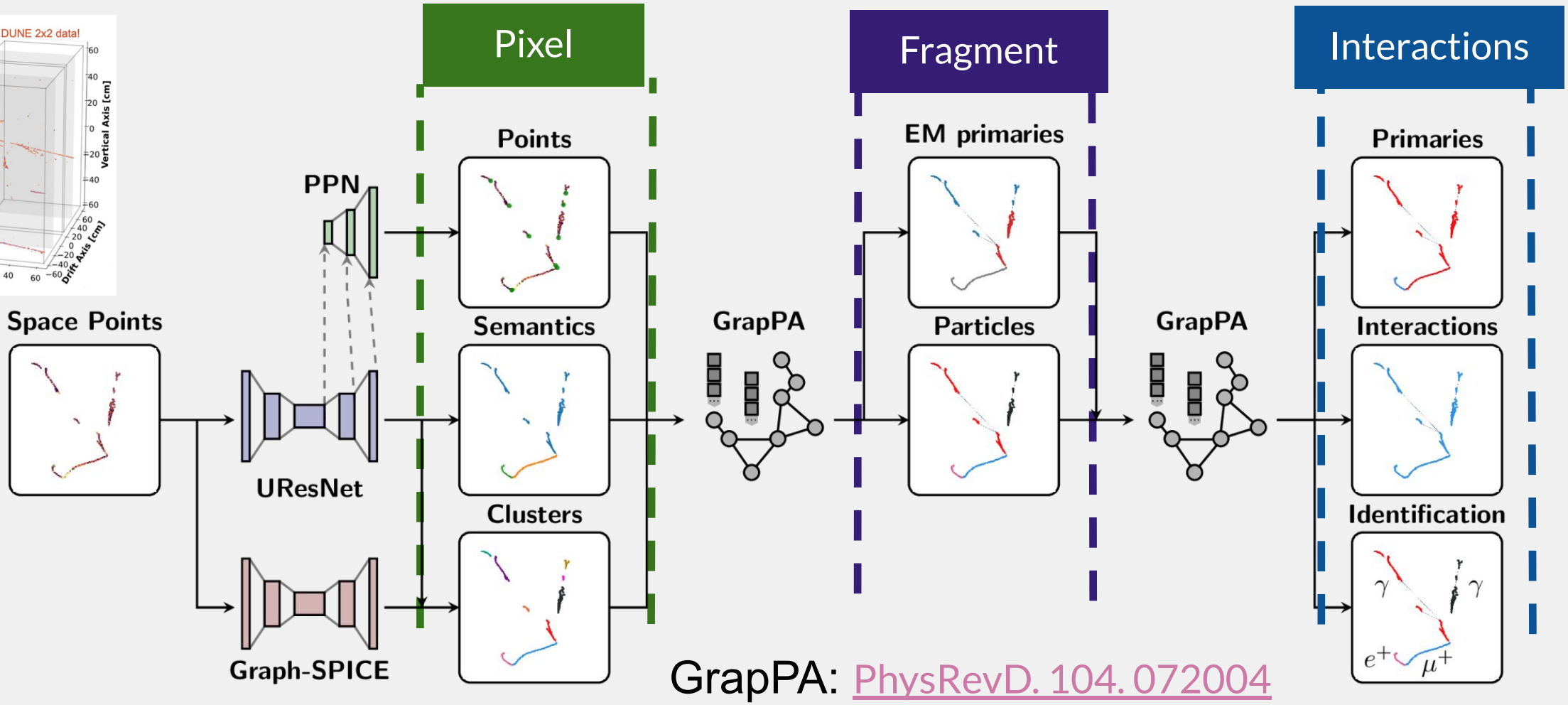
Downstream MINERvA

DUNE Work-In-Progress

MINERvA Operations

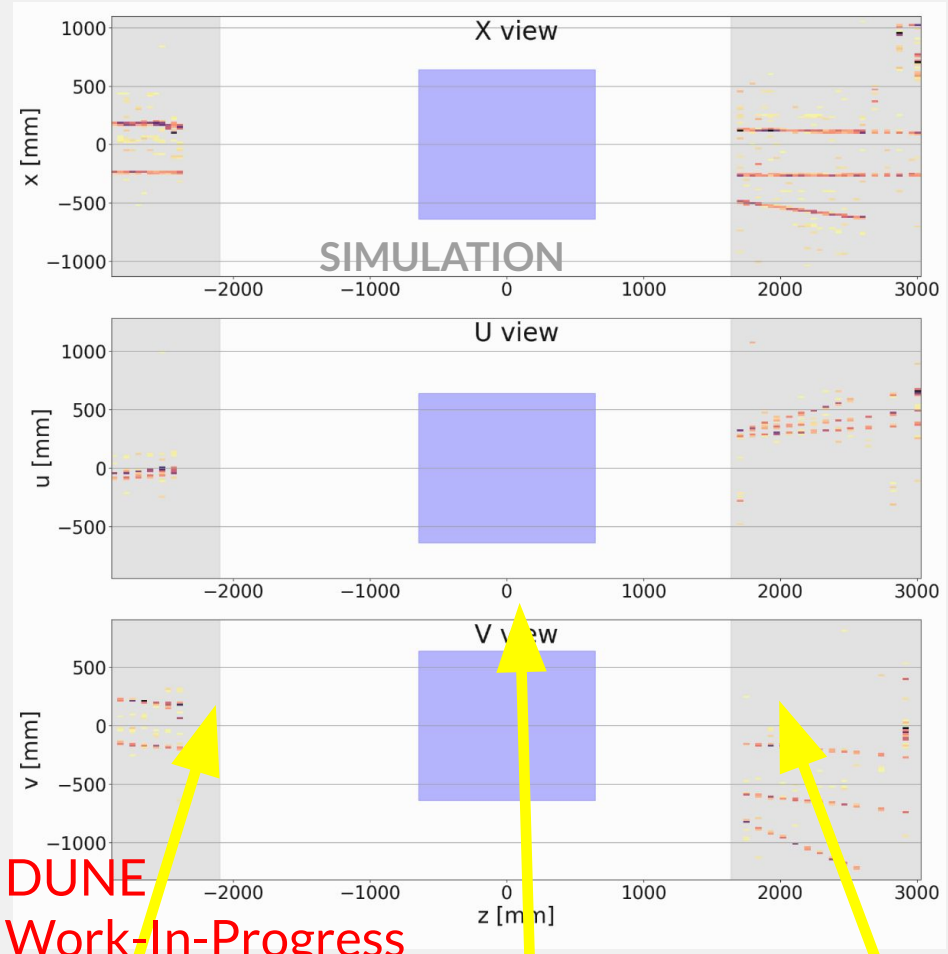
SPINE: Input is 3D Charge Deposition





GrapPA: PhysRevD. 104. 072004

MINERvA Track Segments (TMS also has own 3D Reco)



DUNE Work-In-Progress

Upstream MINERvA

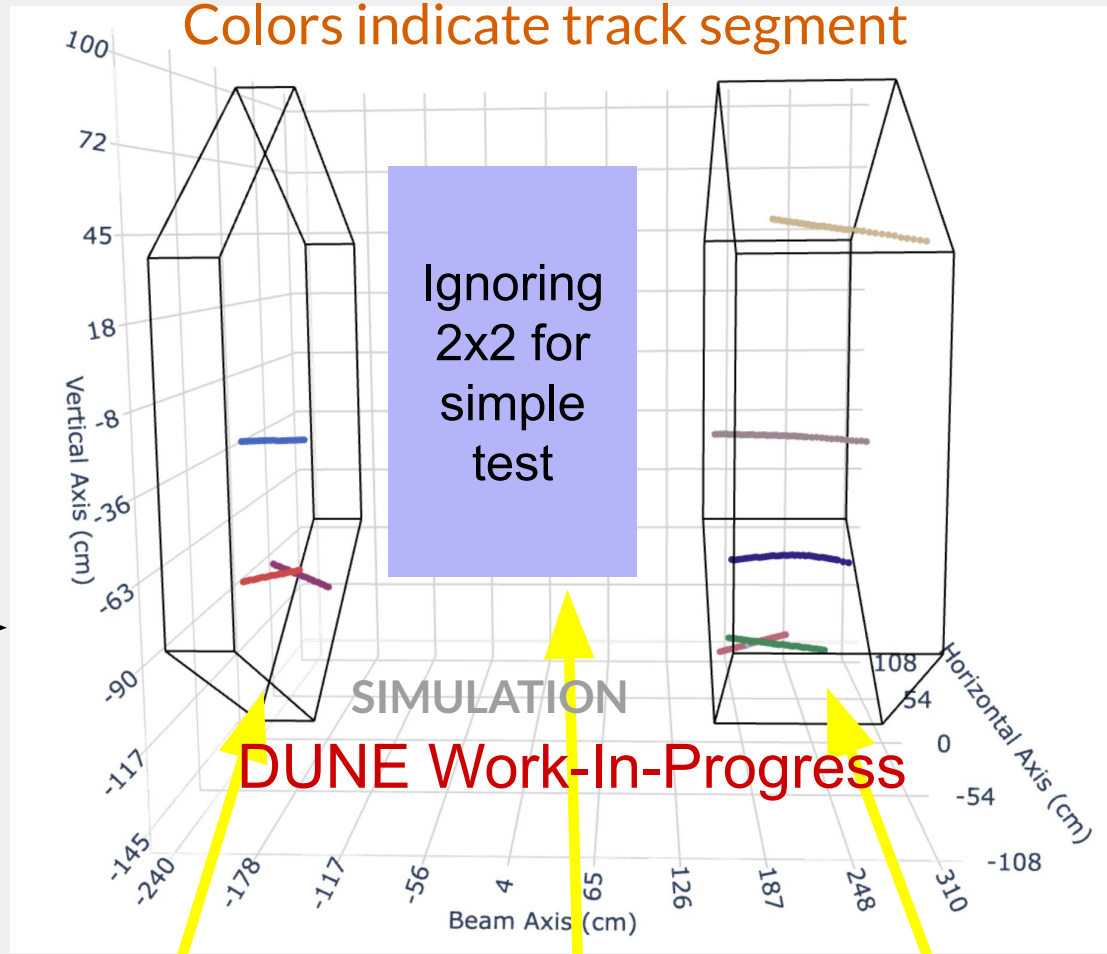
2x2 LAr with 4 TPCs

Downstream MINERvA

Traditional Track Reconstruction

Note: left & right are not the same particles

Colors indicate track segment



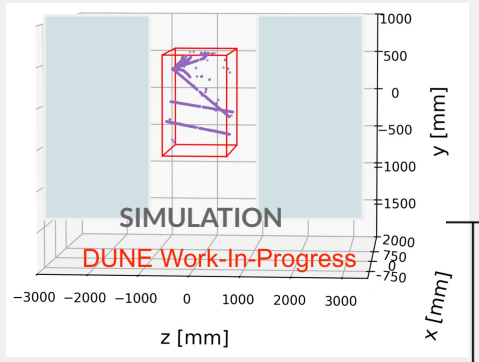
Upstream MINERvA

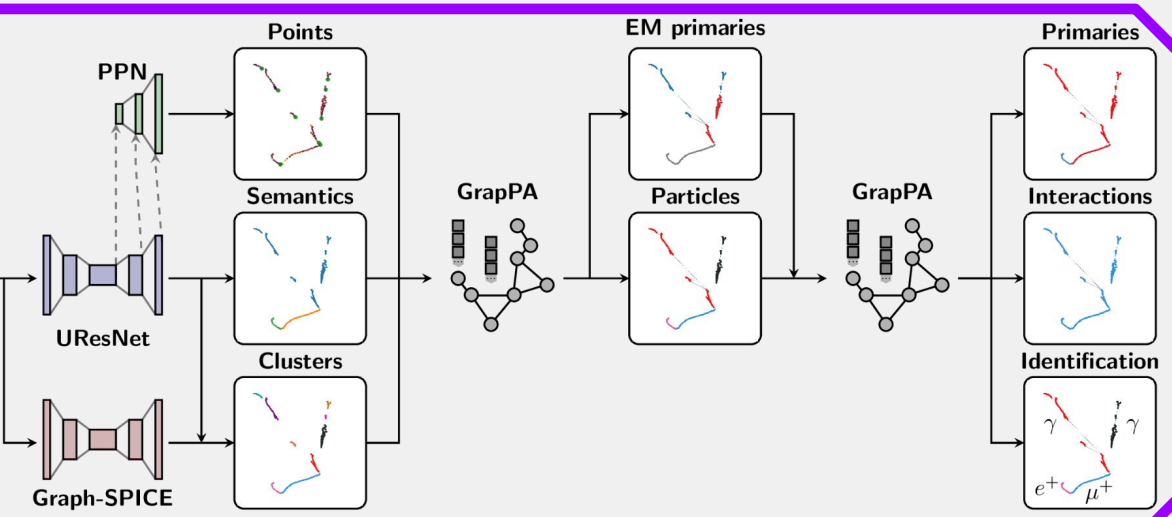
2x2 LAr TPC

Downstream MINERvA

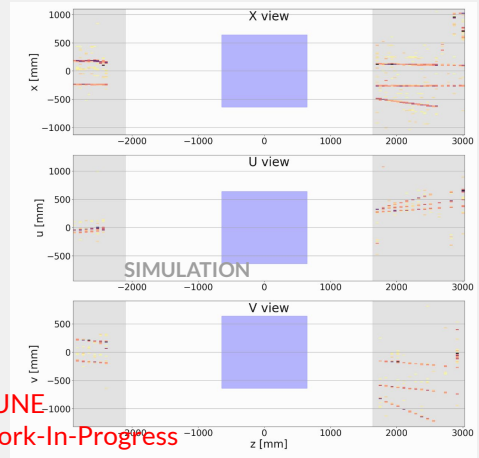
Inserting Mx2

2x2





Mx2



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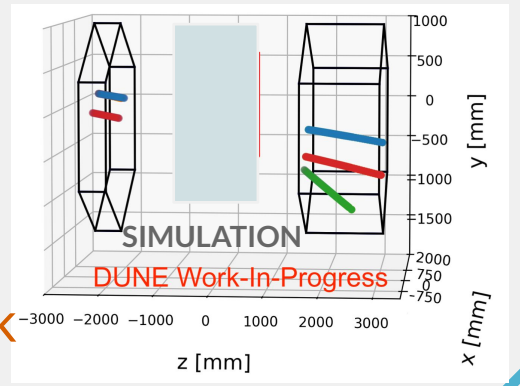
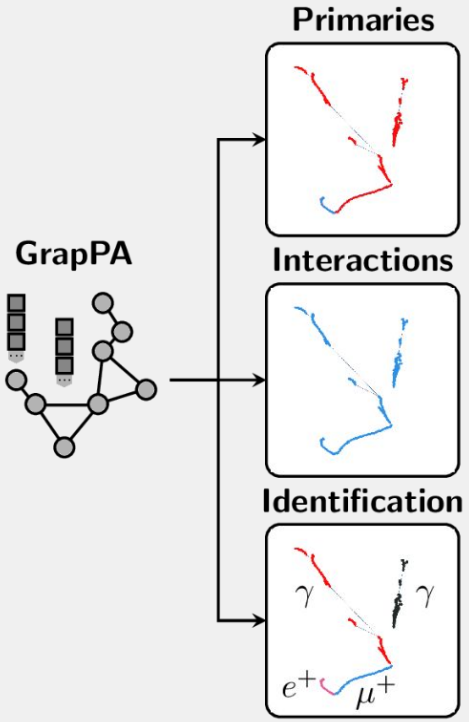


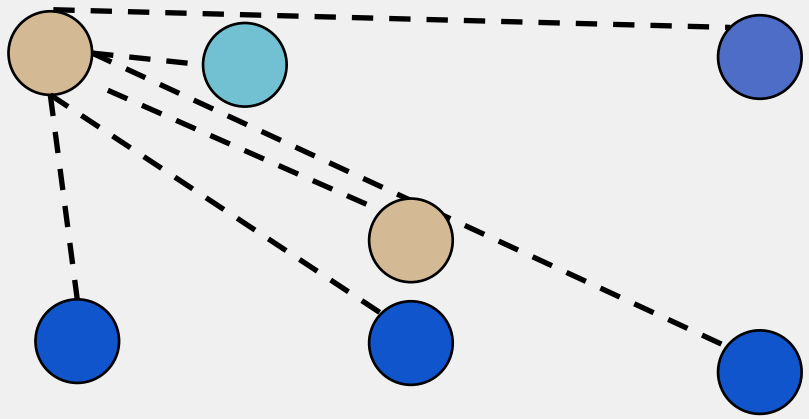


GrapPA: PhysRevD. 104. 072004

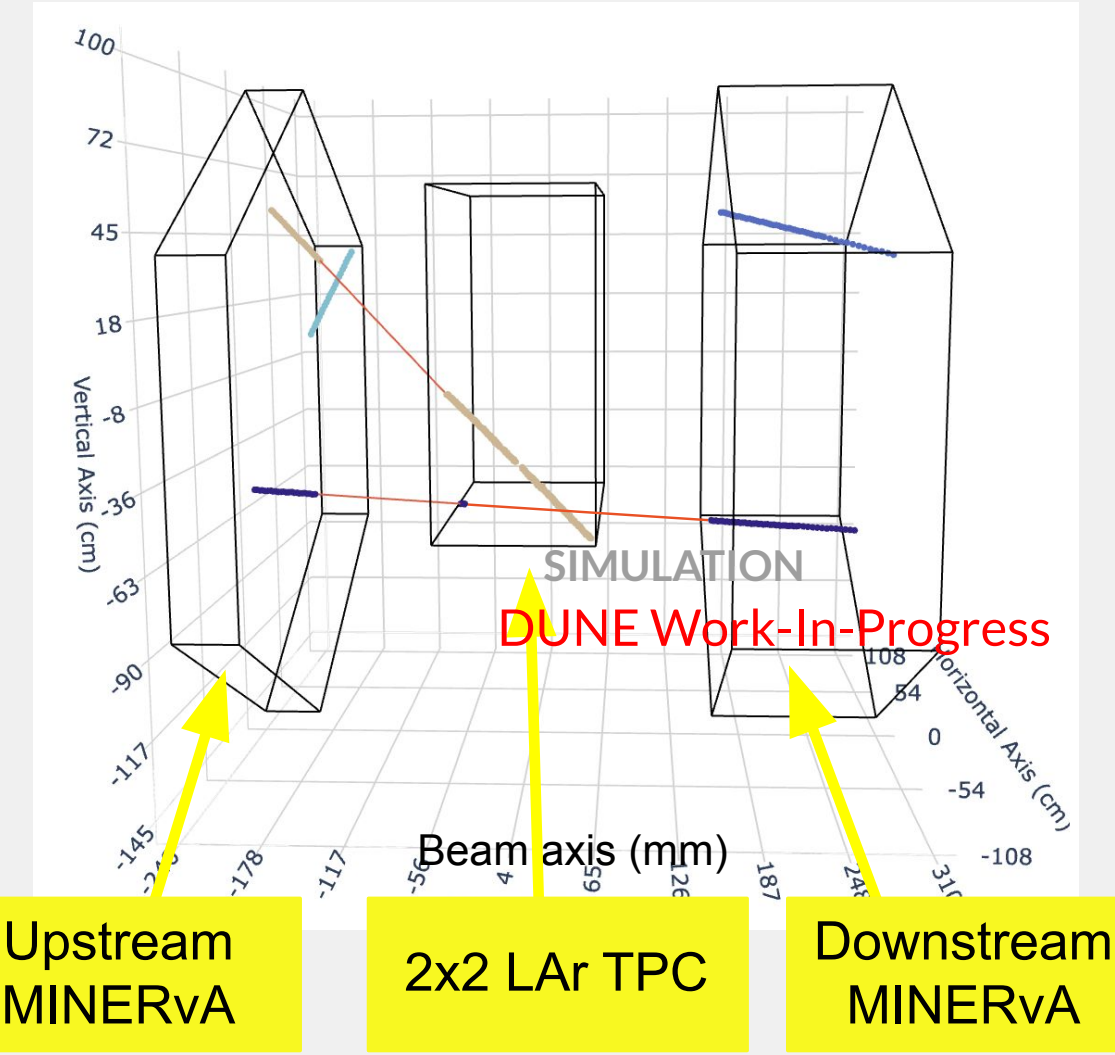
Graph Representation

Node = summary info for each track segment

Network determines which nodes should be connected



Example shows ONE node's potential connections



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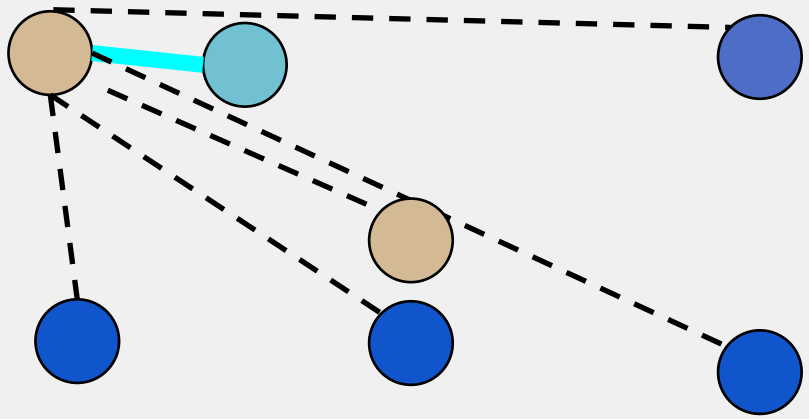

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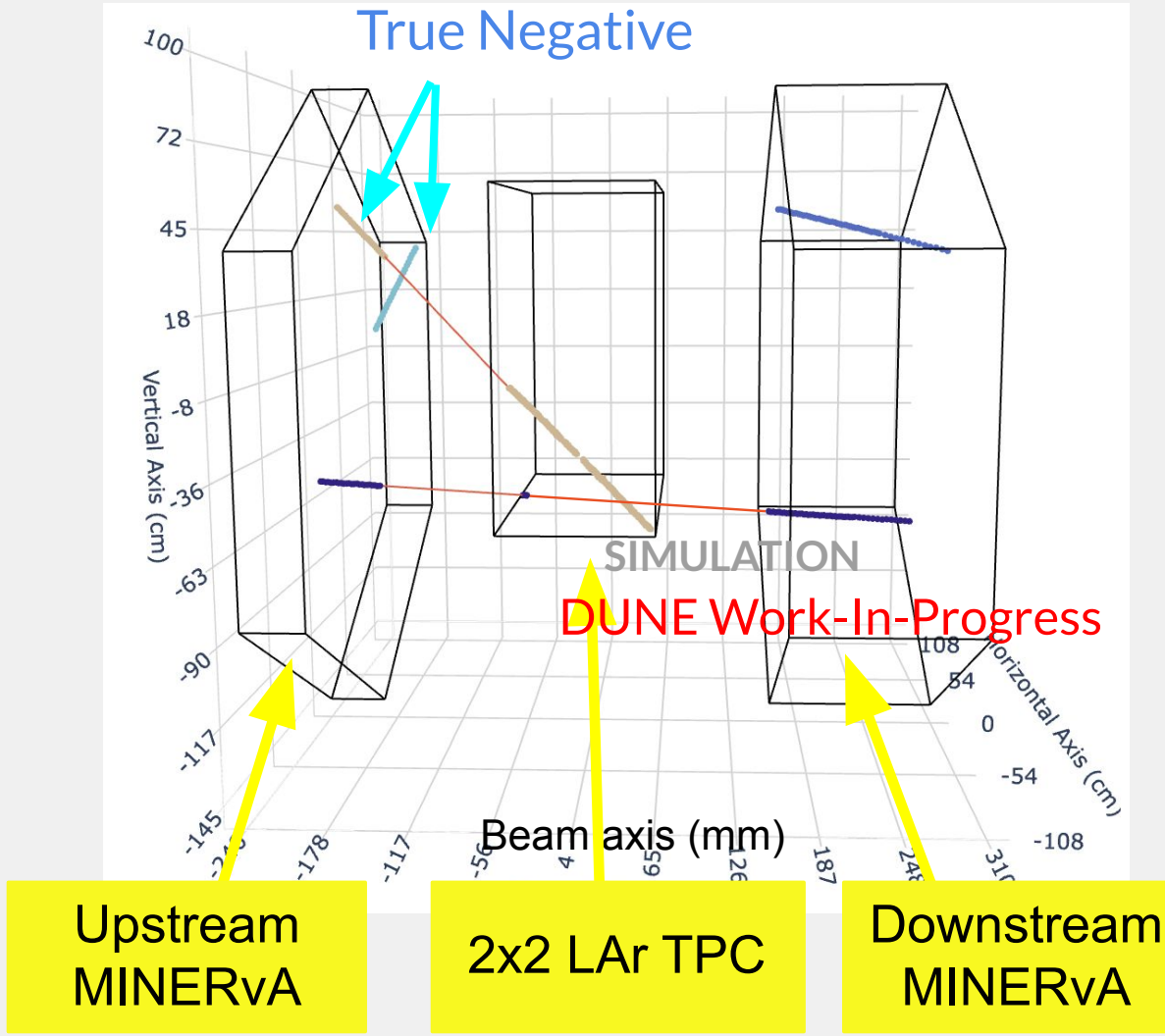

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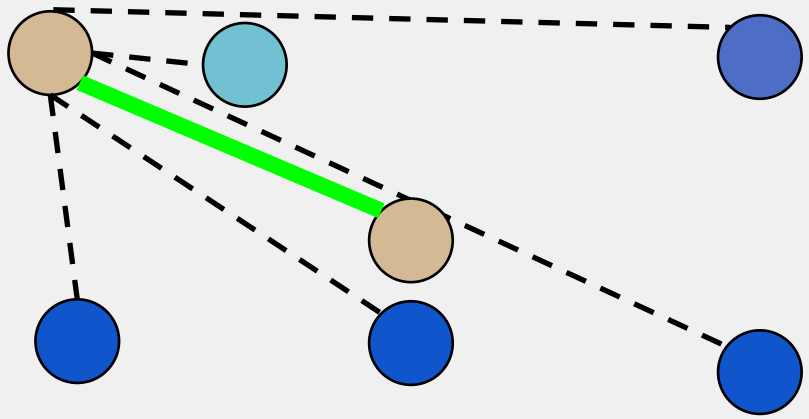

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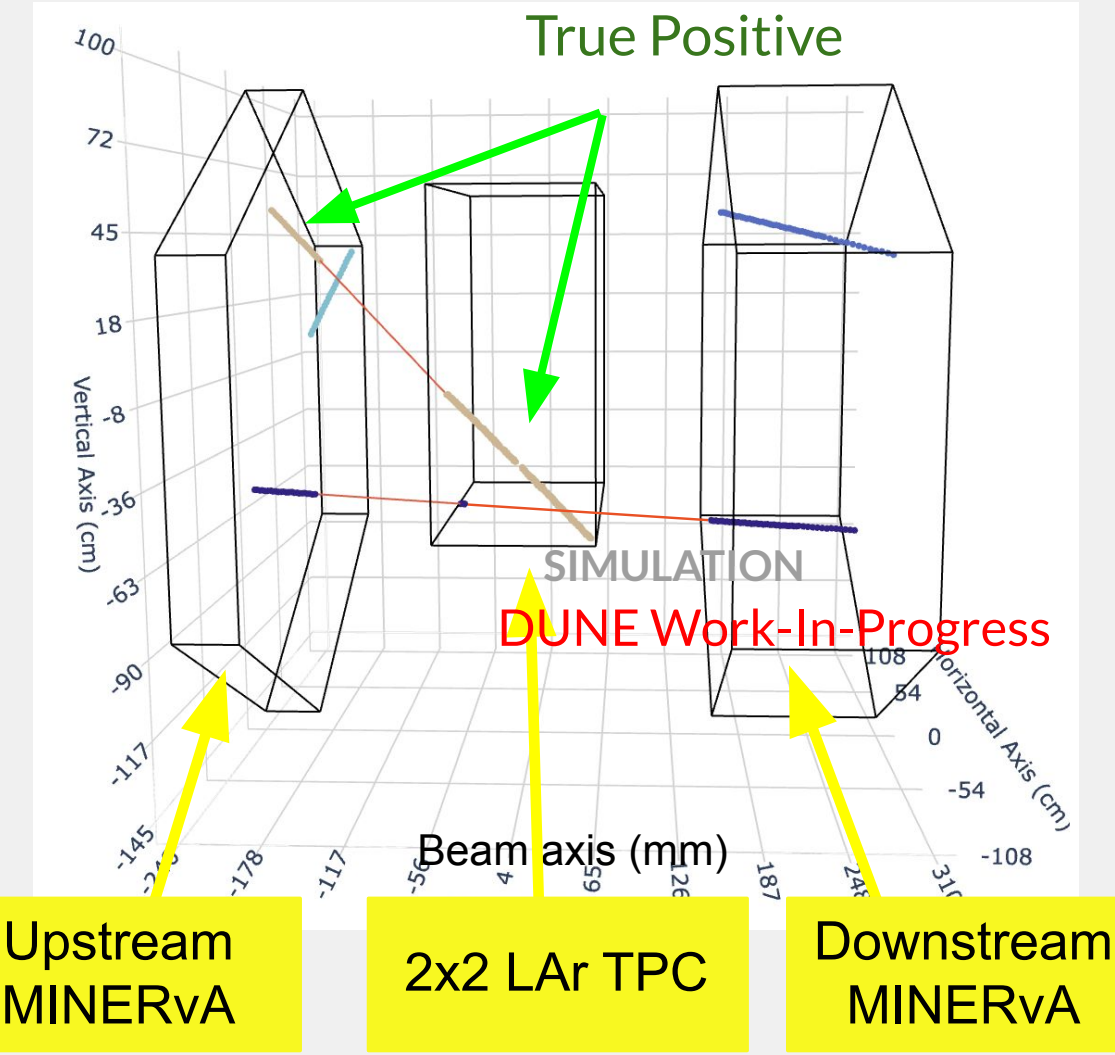
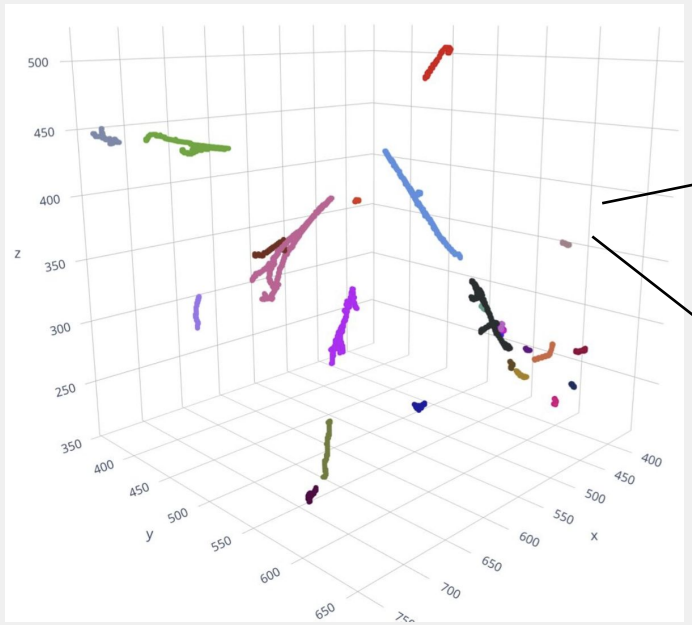
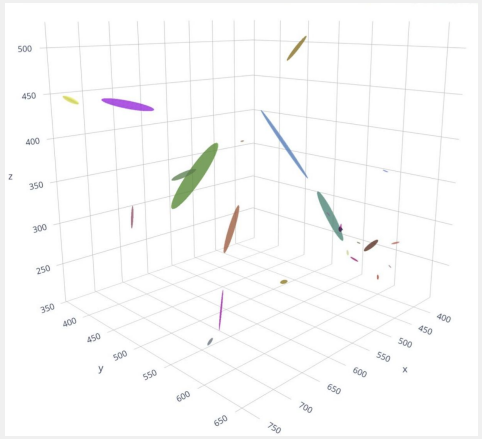
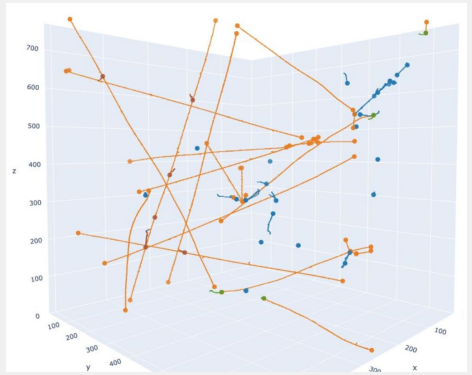


Cluster Clustering: Inputs

Input: Encode Fragments into set of node features



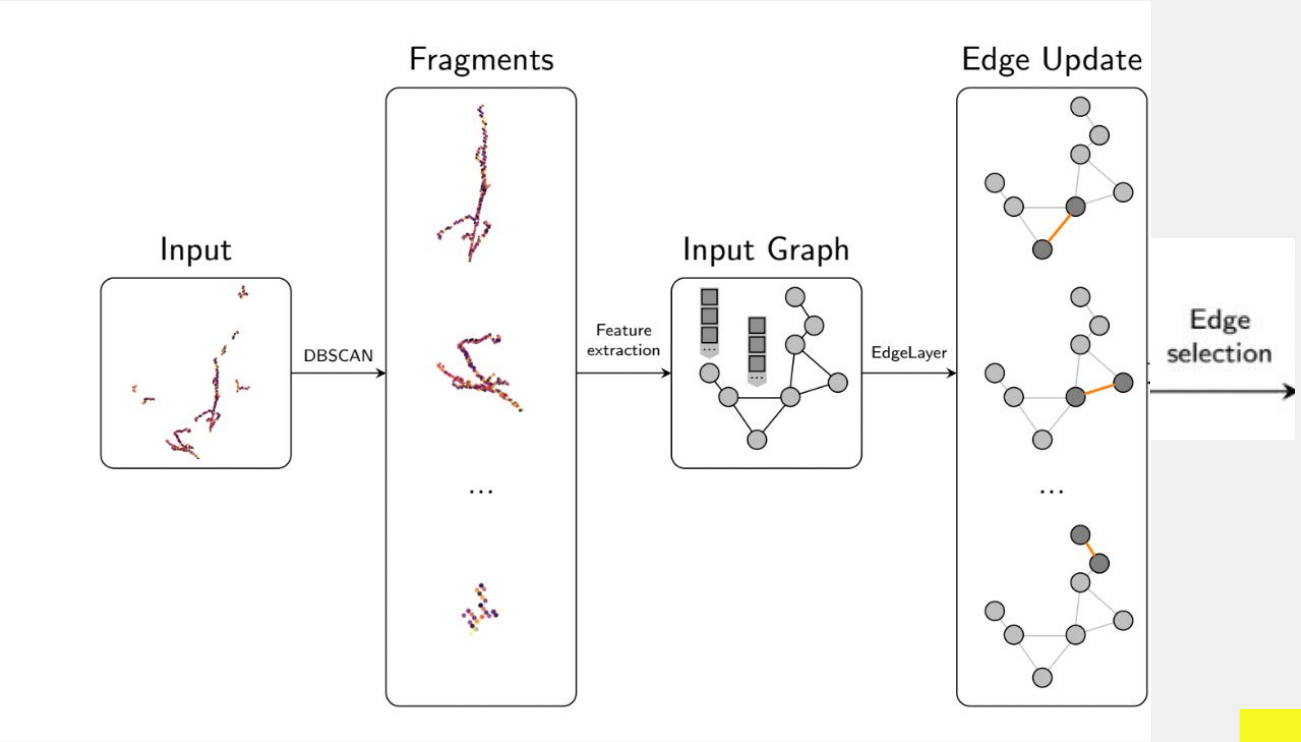




Fragment Summary	# Features
Number of voxels	1
Initial Point	3
Normalized initial direction	3
Normalized covariance matrix	9
Normalized principal axis	3
Centroid	3

GrapPA in SPINE

Use Edge Update only currently



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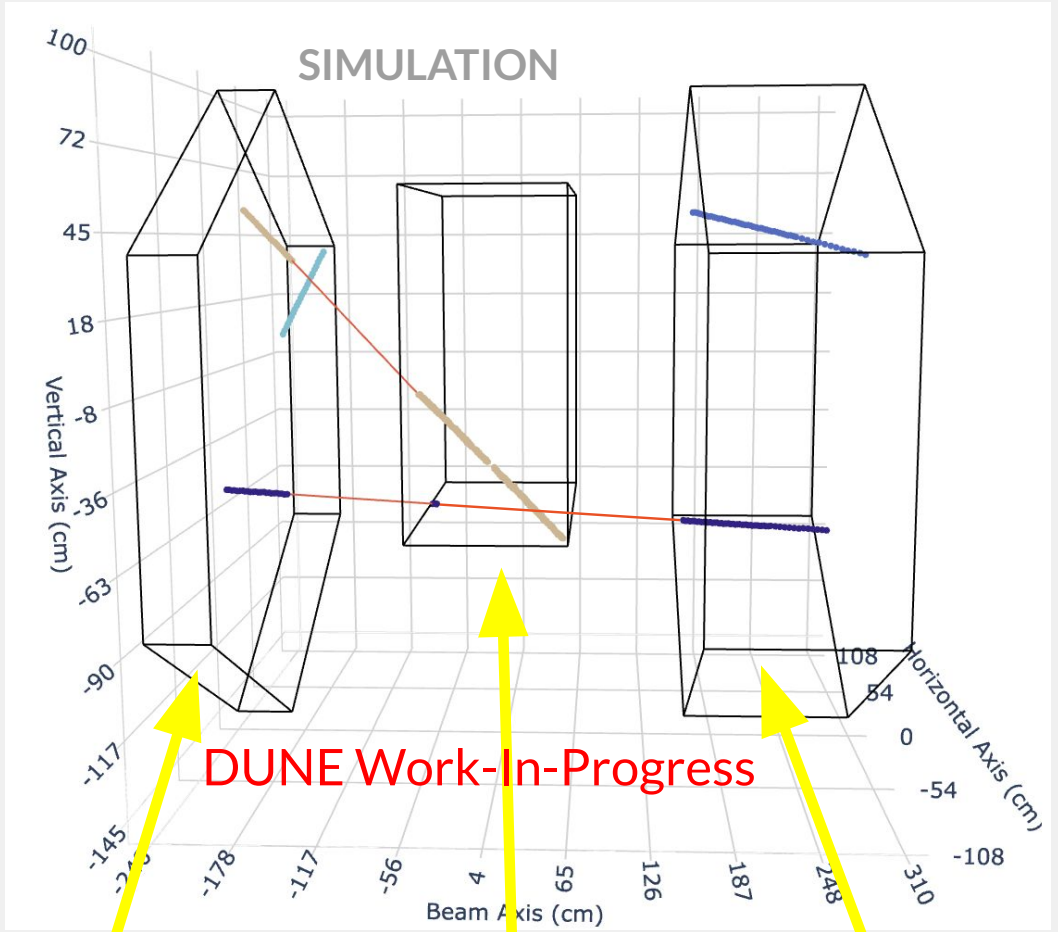
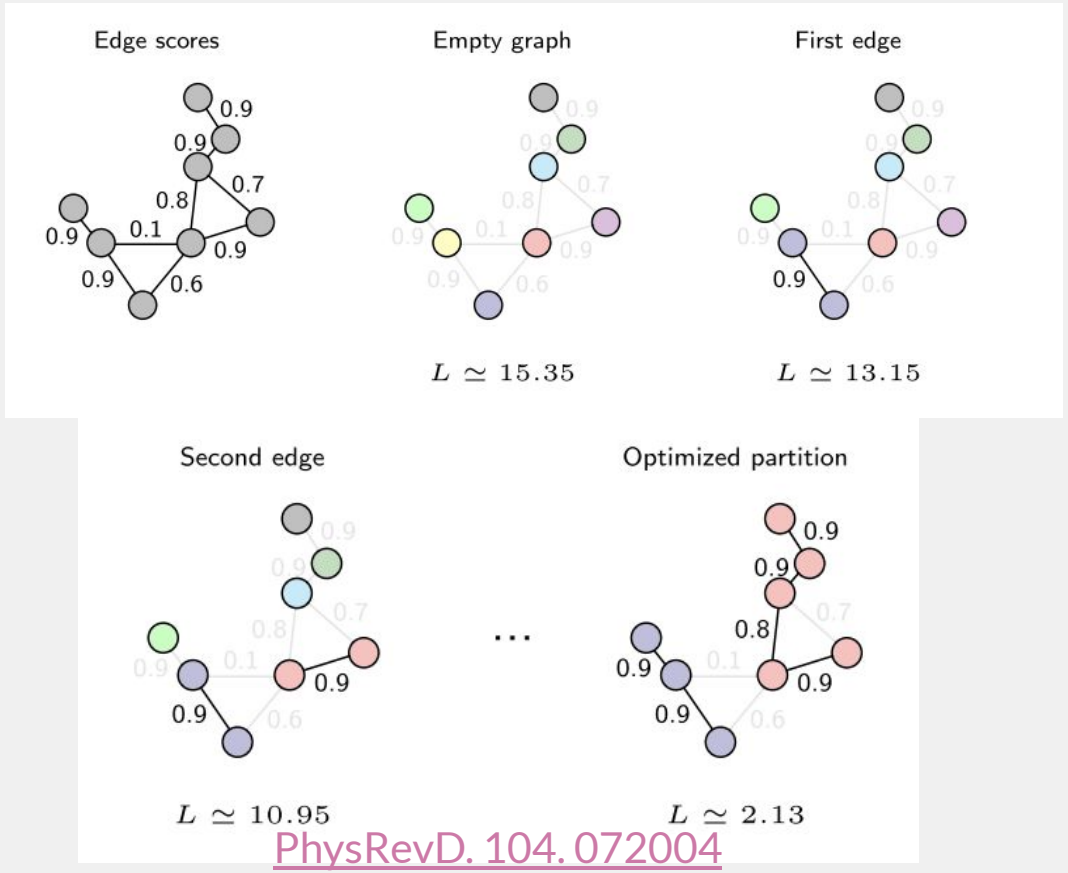
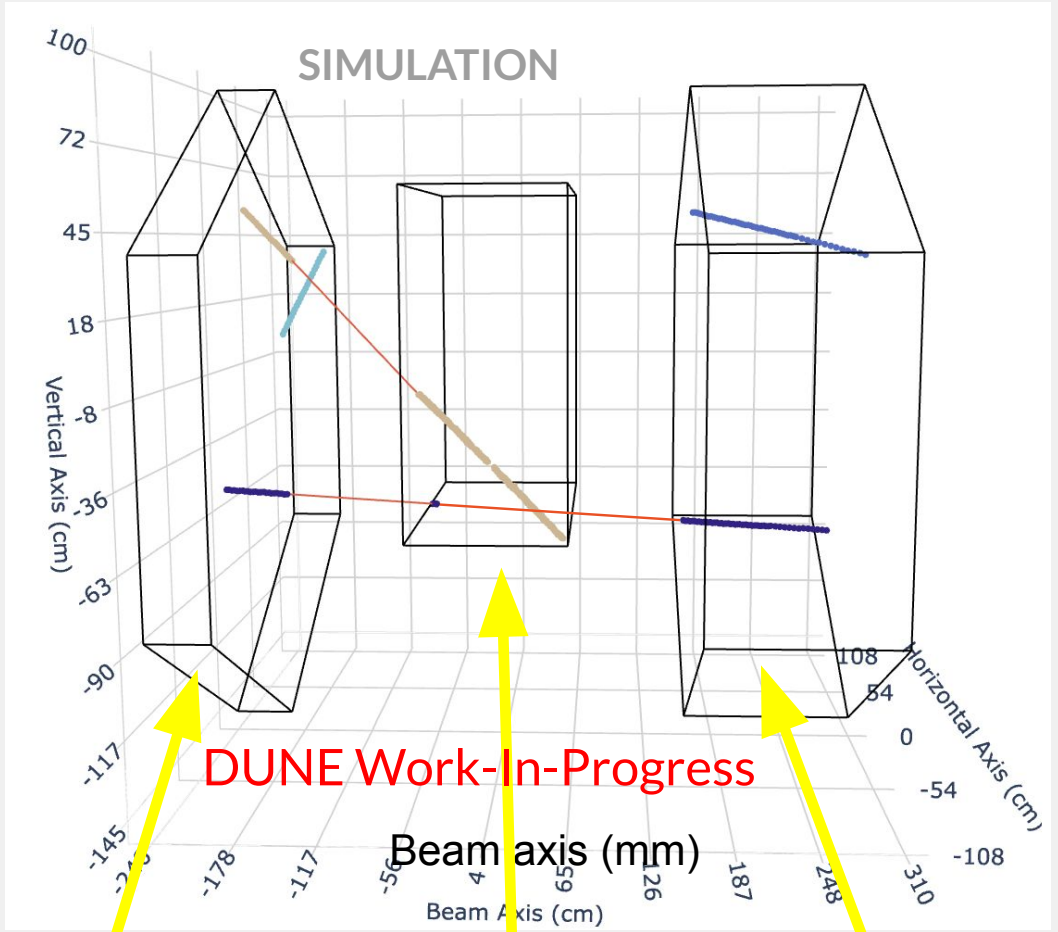


GrapPA in SPINE

Finds best edge configuration for whole entry



Edge selection



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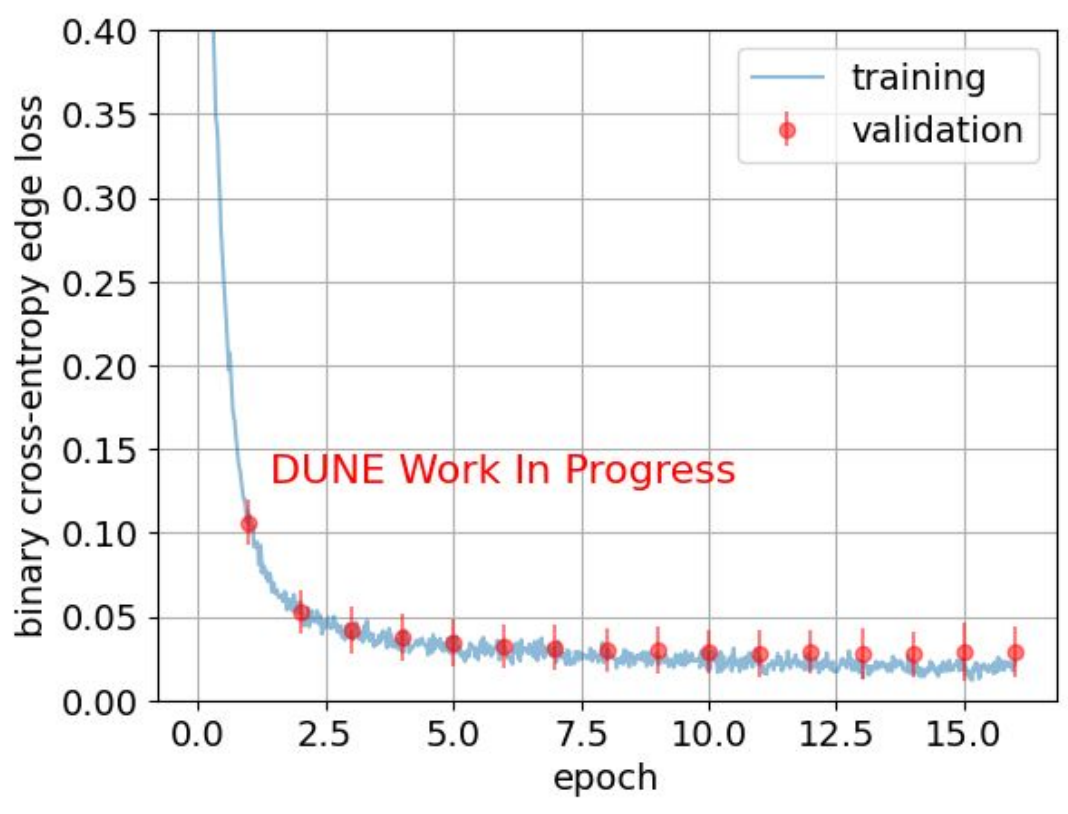
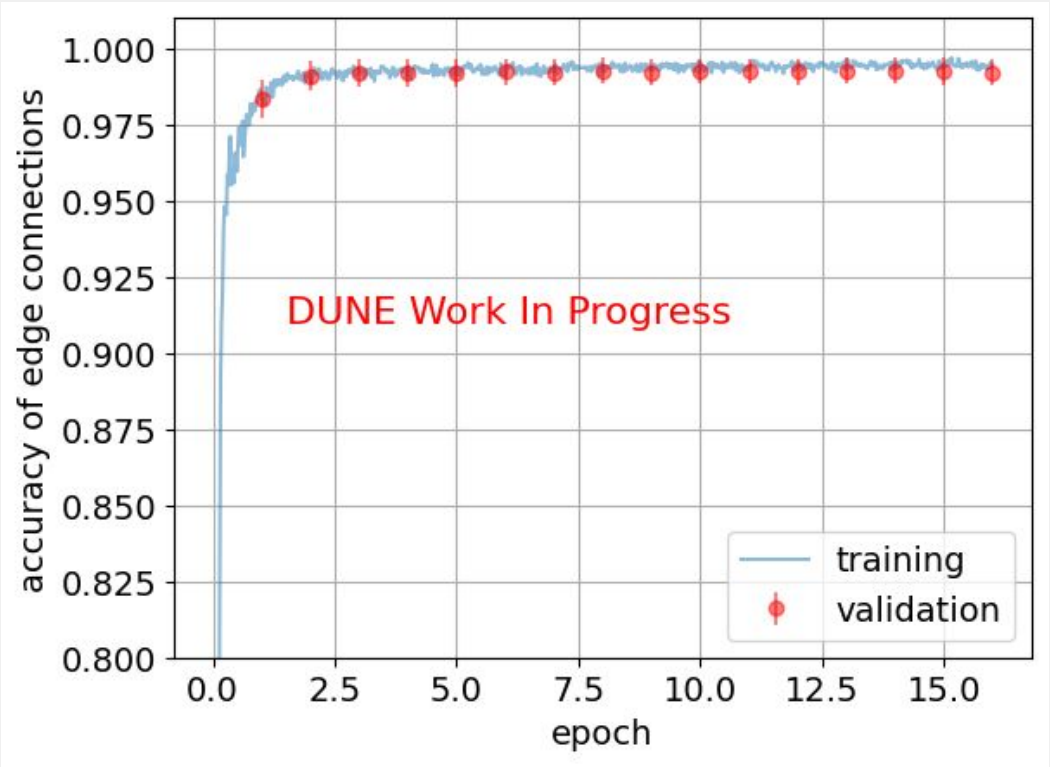
Training on SPINE Reconstructed Fragments

- Most MINERvA Up + Downstream already connected via MINERvA reco
- Most 2x2 fragments are connected within 2x2 (SPINE missed some)





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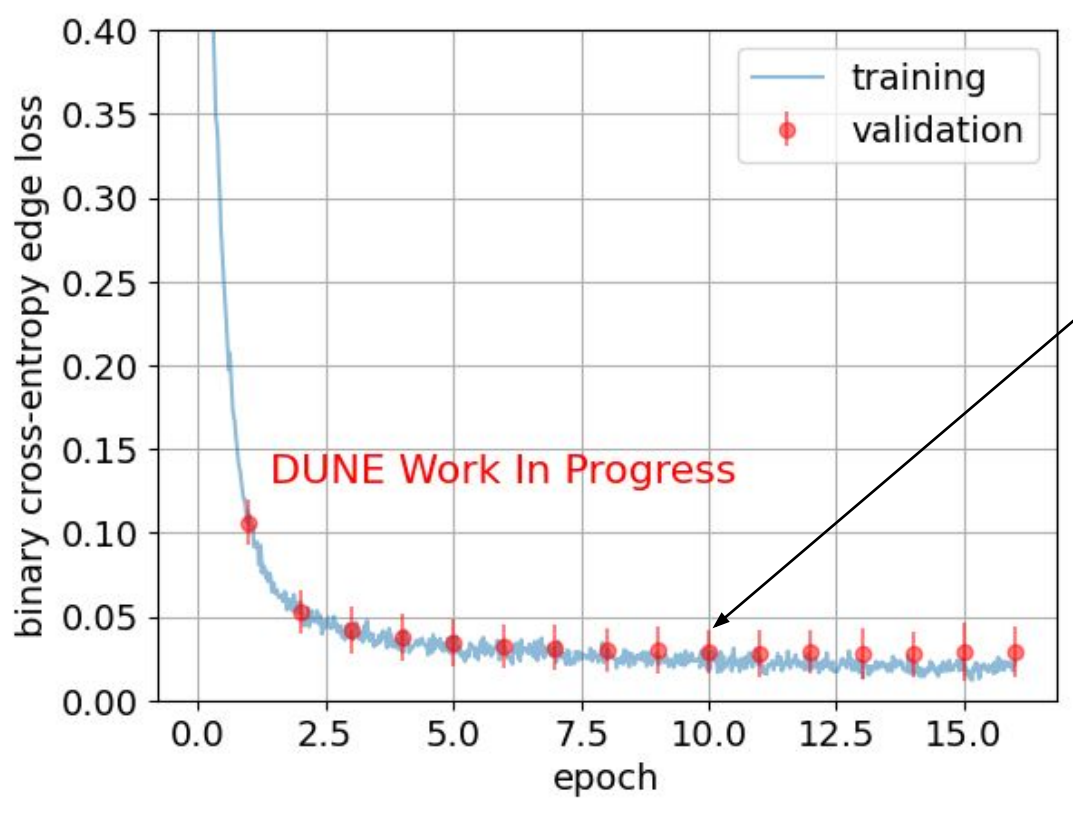
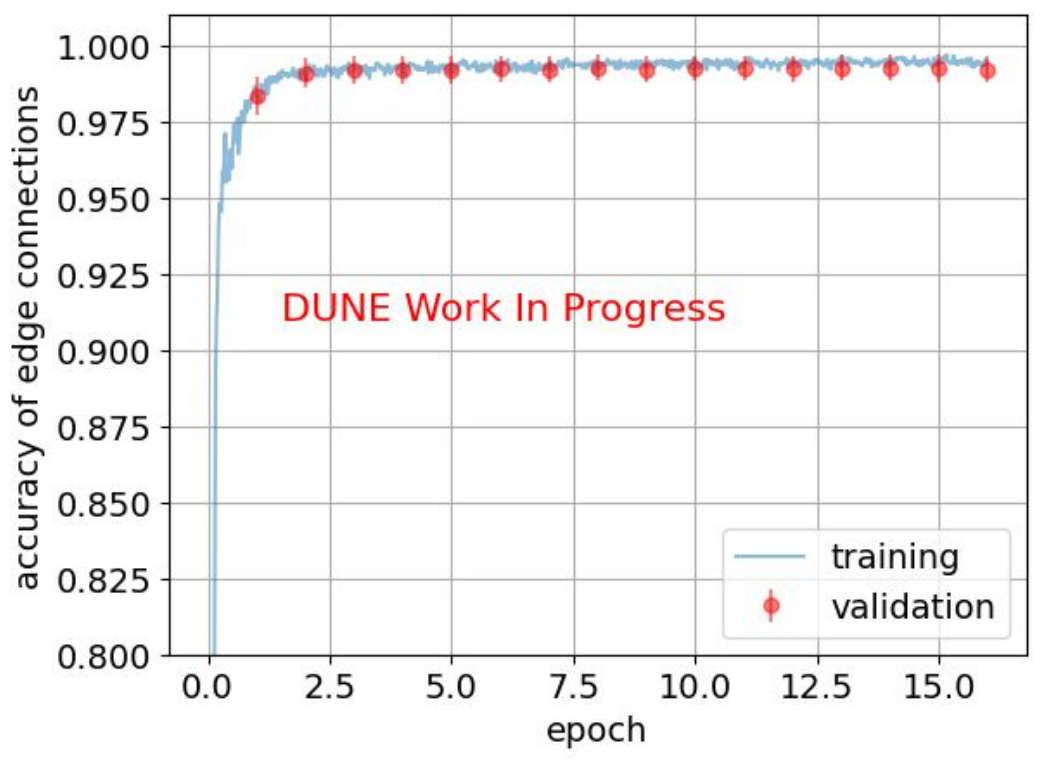
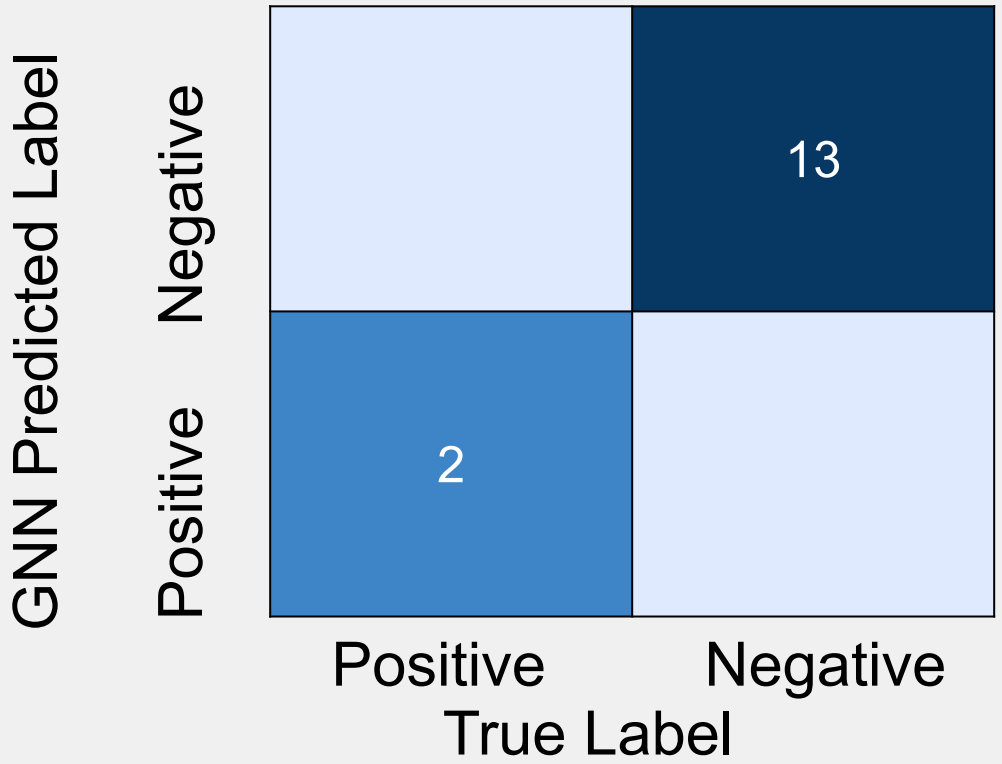


Using epoch 10 before over-training

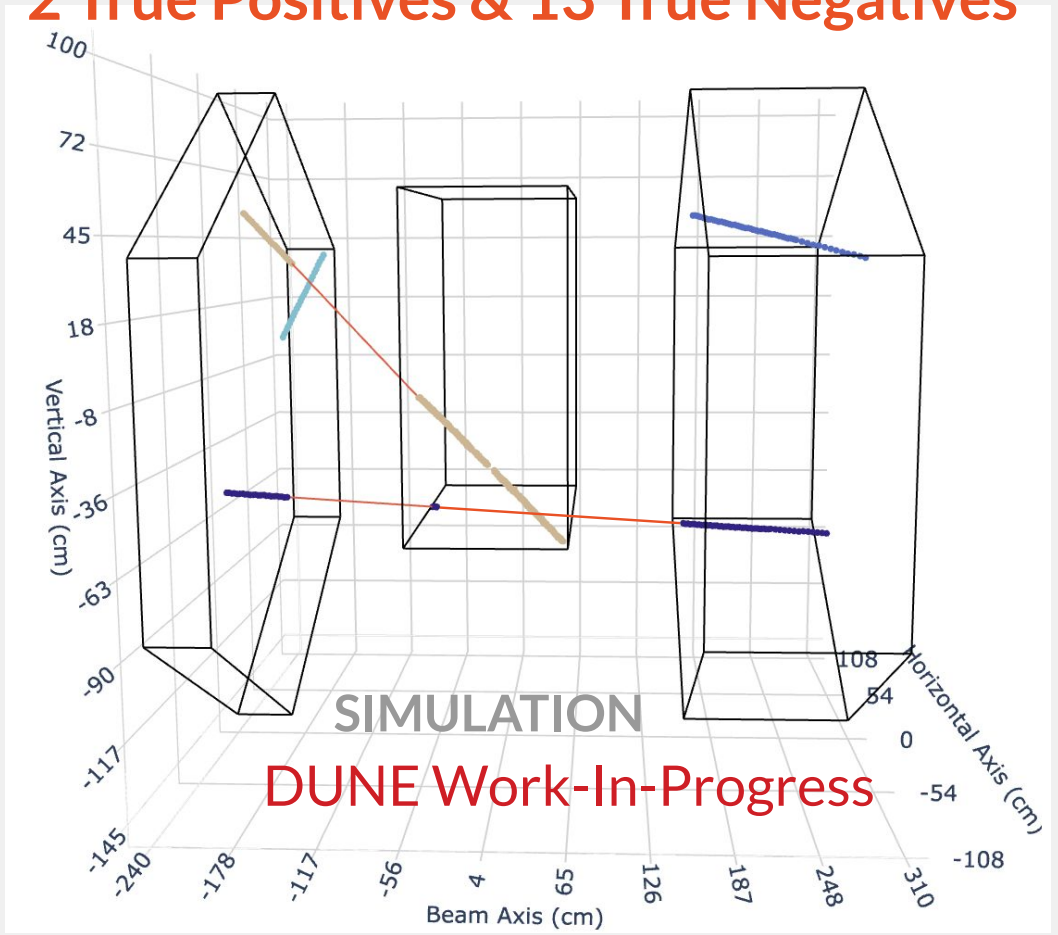


Negatives >> Positives

Training & testing sample dominated by negative cases → inherently biased sample



2 True Positives & 13 True Negatives



Color code is TRUTH
Red line is GNN connected

Bidirectional Graph

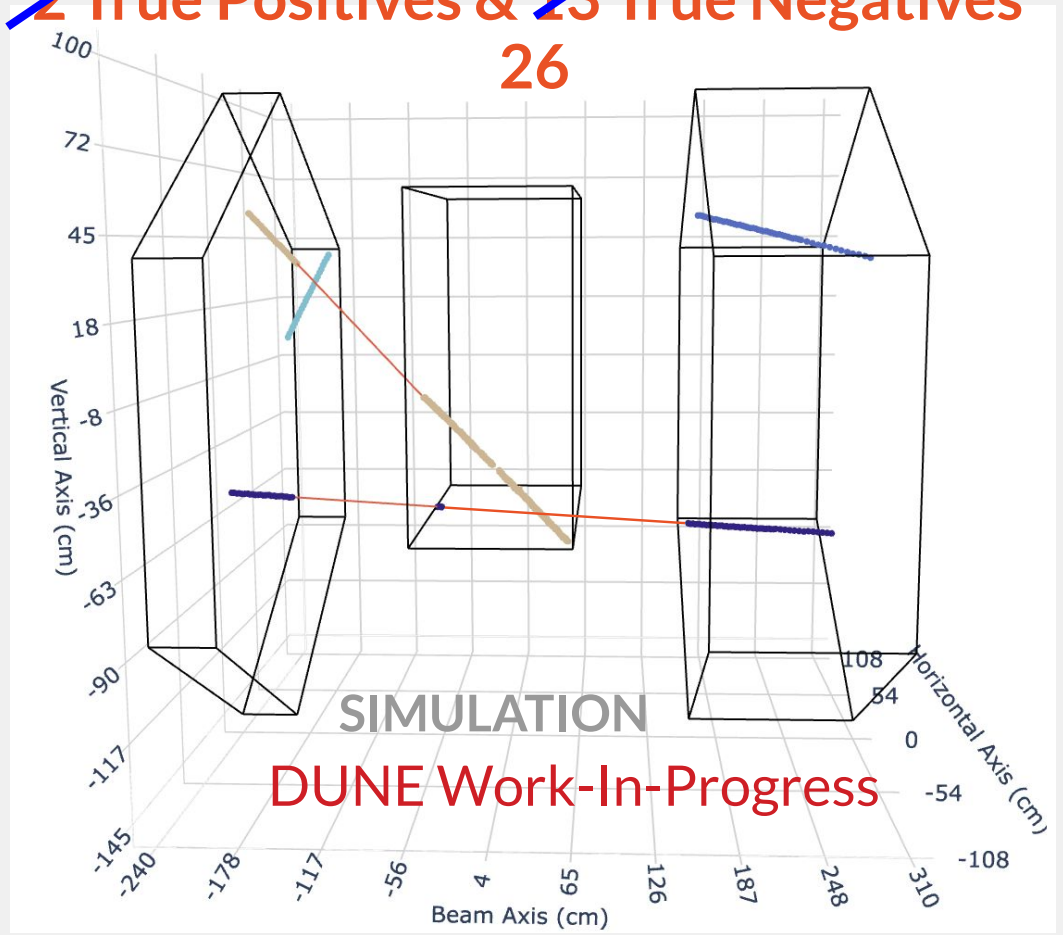
SPINE has GNN setup as bi-directional:
Cluster 1 → Cluster 2 AND Cluster 2 → Cluster 1

GNN allowed to predict single or bi-directional

Keep for higher efficiency

Require for higher purity

~~4~~ ~~2~~ True Positives & ~~13~~ True Negatives
26



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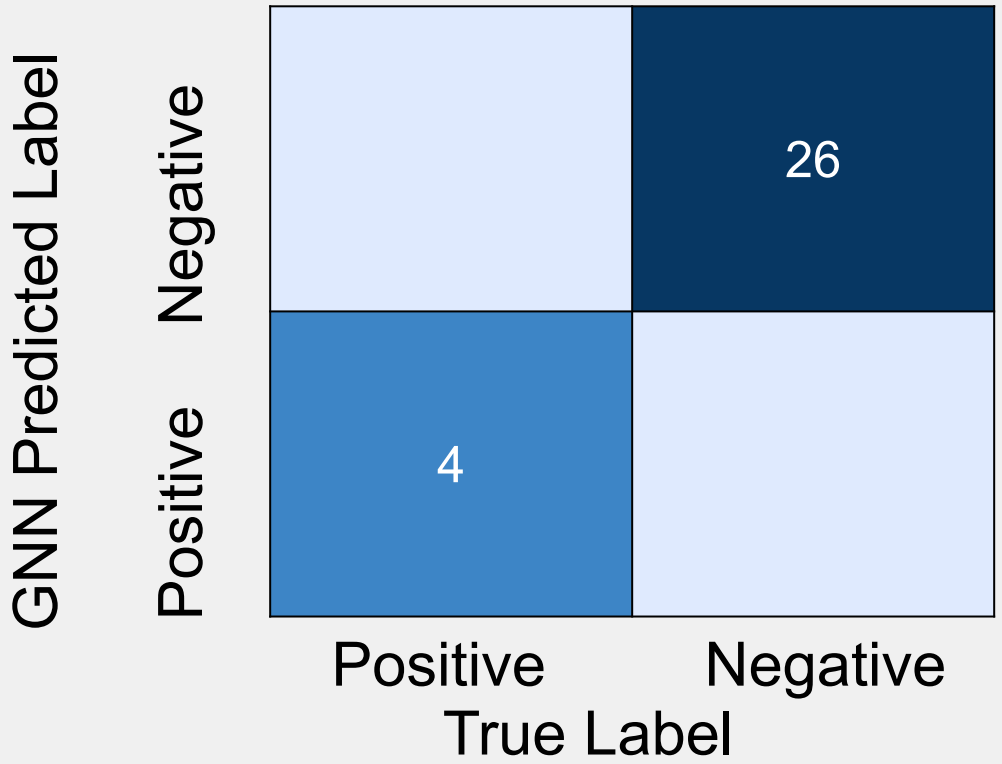
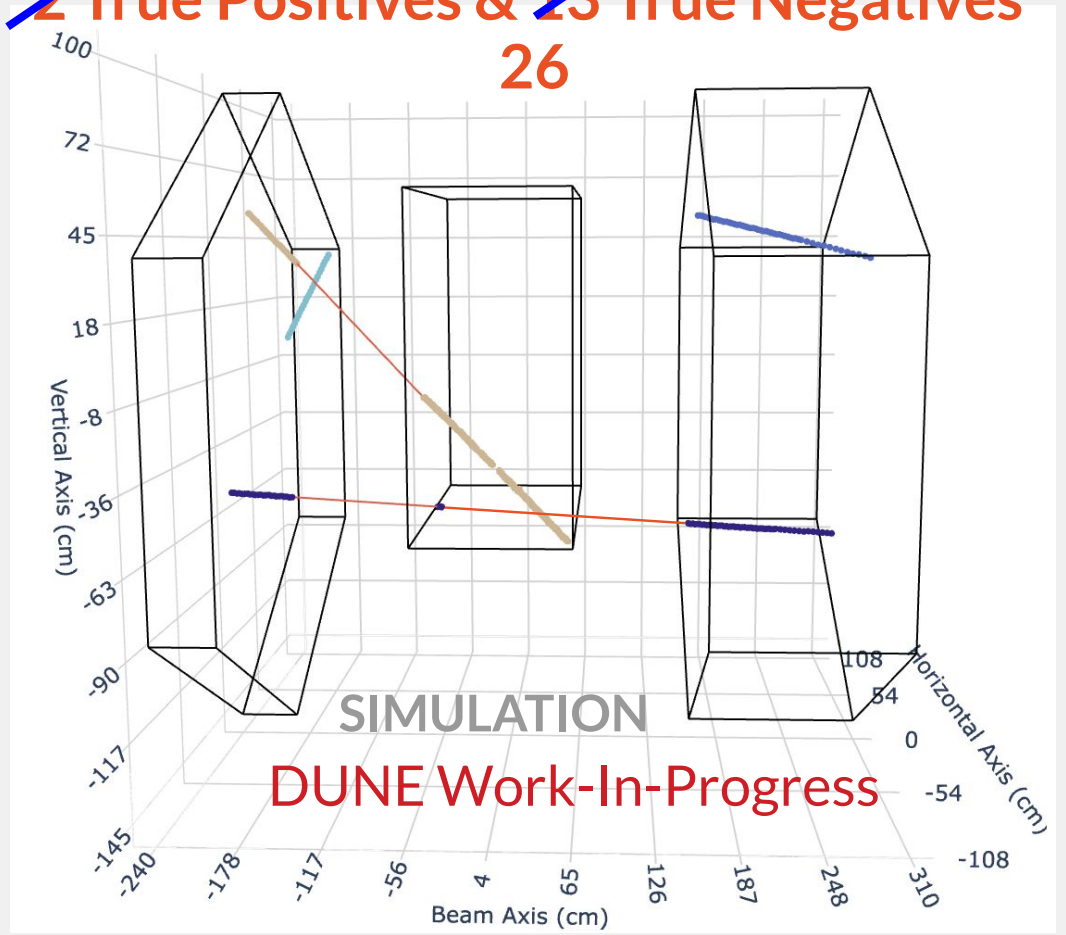


4 ~~2~~ True Positives & ~~13~~ 26 True Negatives



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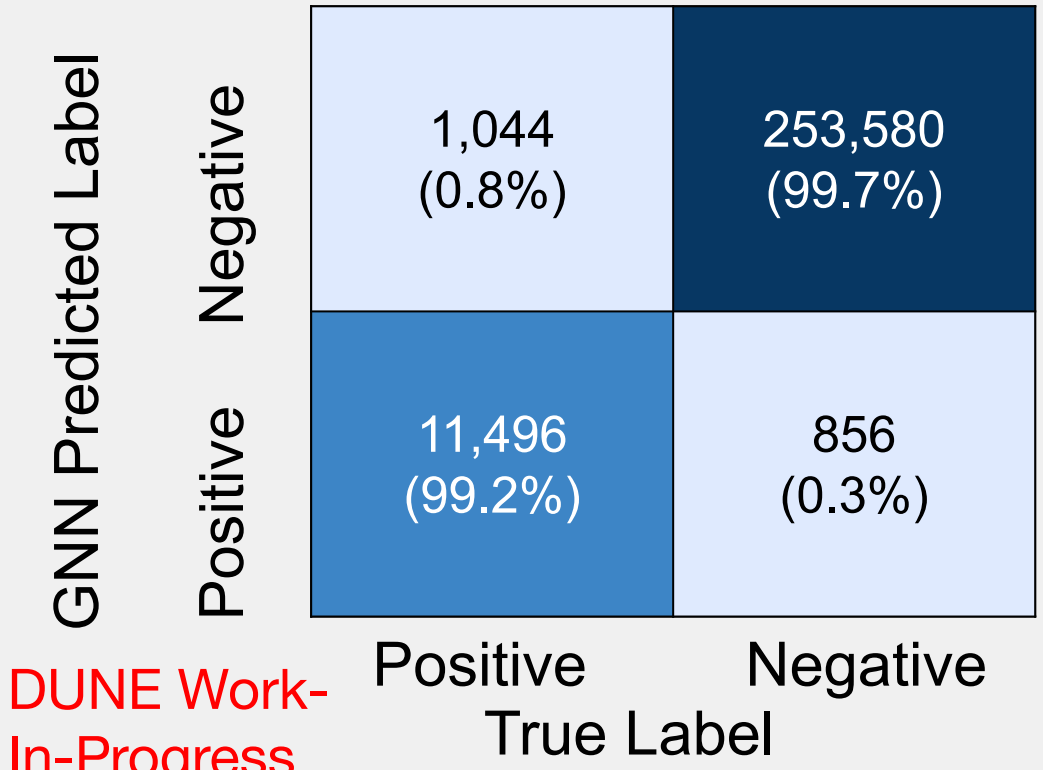
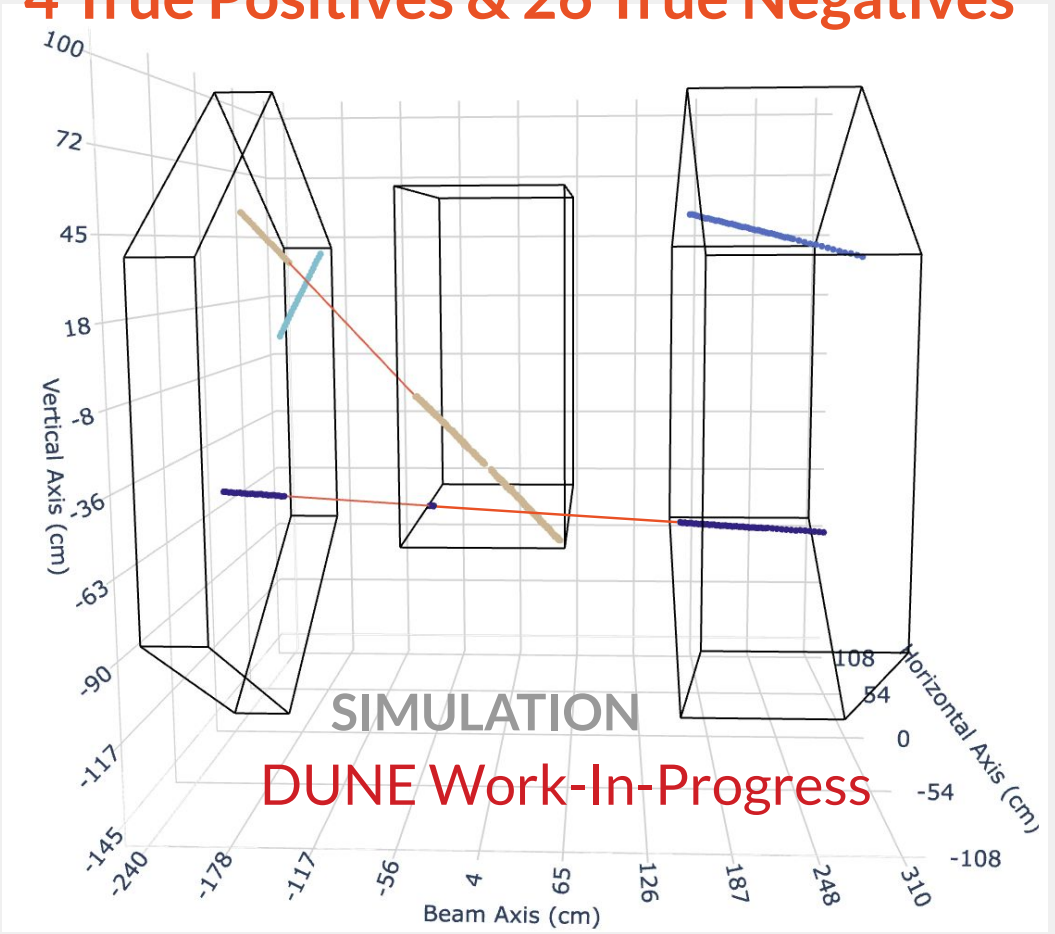
Confusion Matrix Result

- About 7,000 spills tested
- Each connection (single direction)



DUNE Work-In-Progress

4 True Positives & 26 True Negatives



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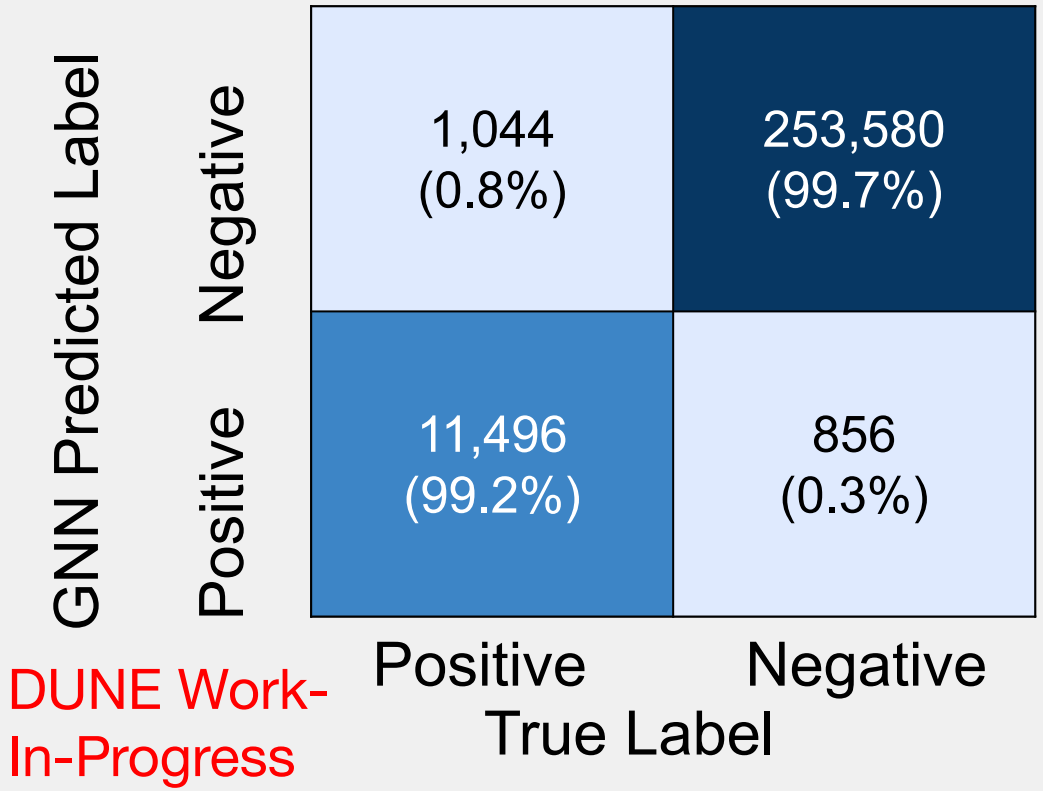
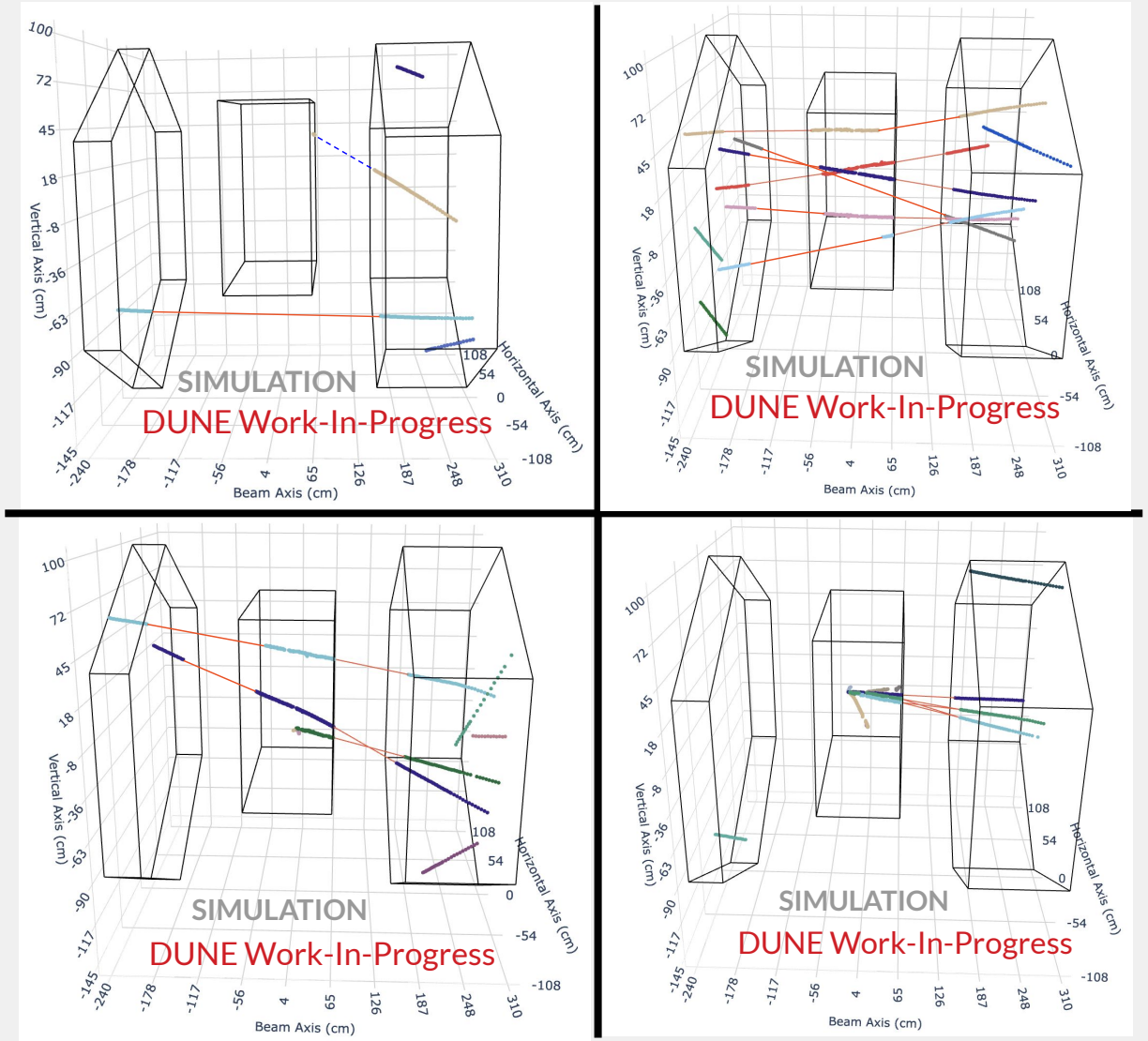
Confusion Matrix Result

GNN identifies positives without bias!



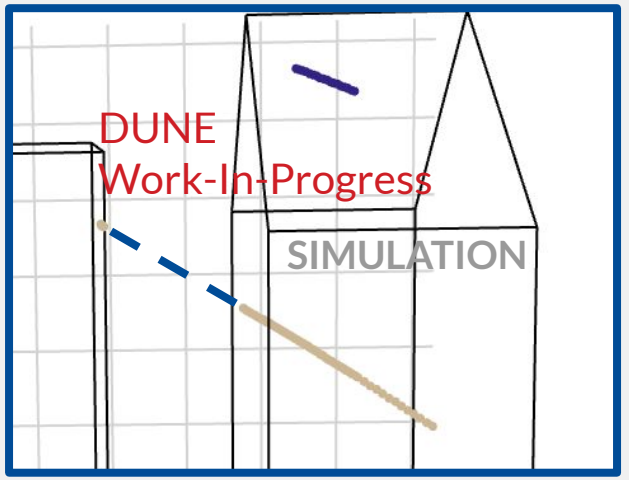


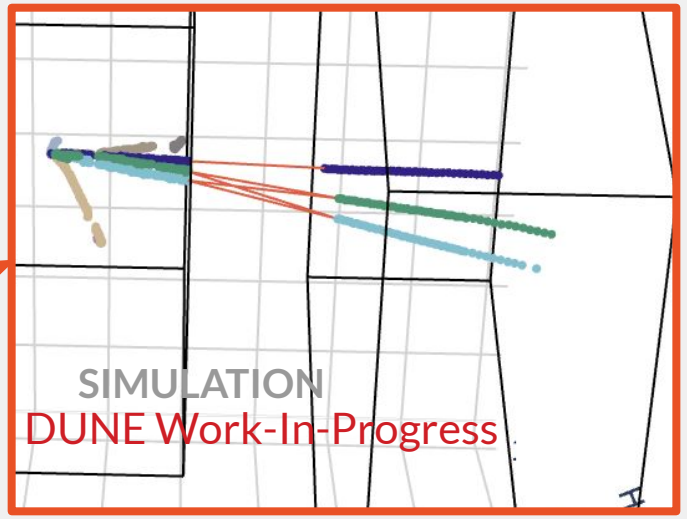
Cases: 2x2 to MINERvA (Mx2)

*Require bidirectional connection

Main Target

Connection	Colloquial	Mx2 to 2x2
True Positive	Got it 🎉	5,569
False Negative	**Missed it**	237
False Positive	**Faked it**	340





Cases: 2x2 to MINERvA (Mx2), 2x2 to 2x2

Main Target

Found some that SPINE missed!

Connection	Colloquial	Mx2 to 2x2	2x2 to 2x2
True Positive	Got it 🎉	5,569	88
False Negative	Missed it	237	138
False Positive	Faked it	340	28

Cases: 2x2 to MINERvA (Mx2), 2x2 to 2x2

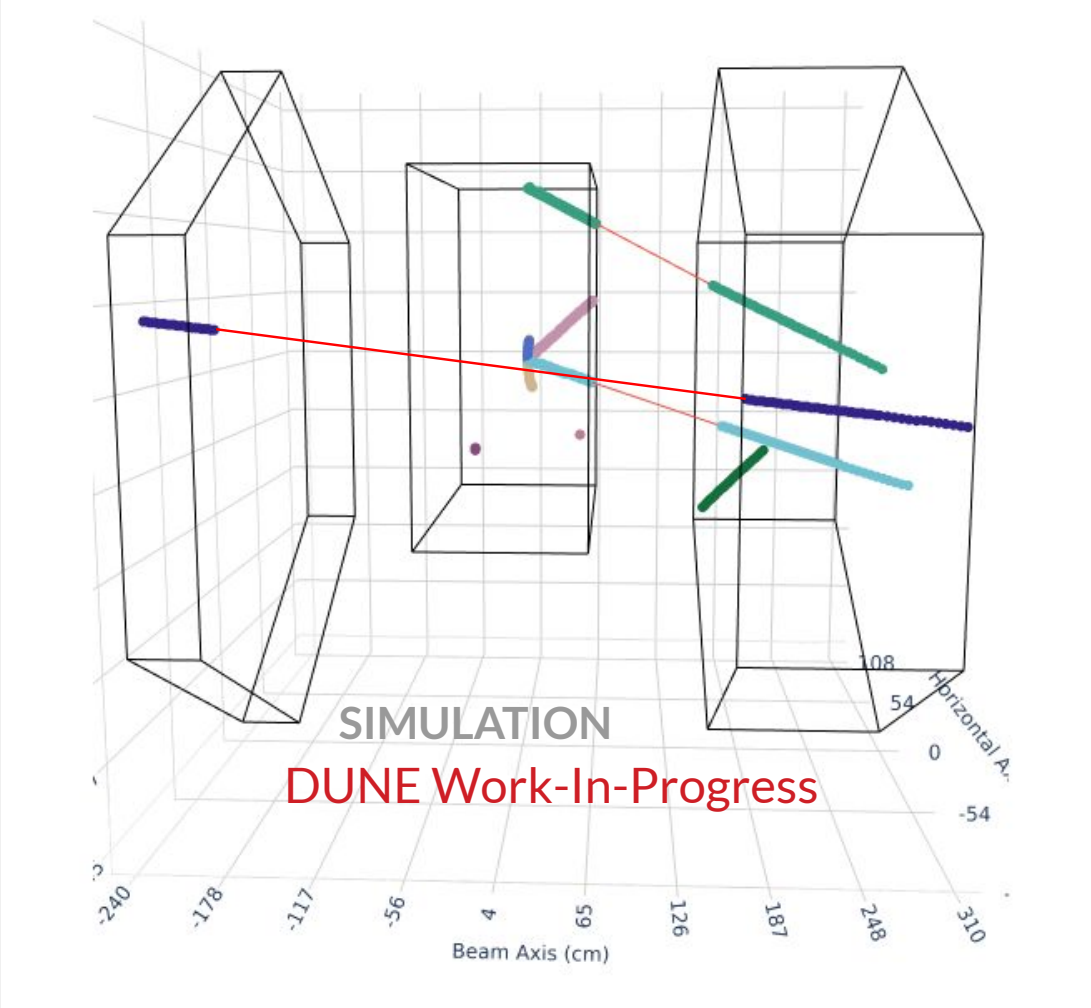
Main Target

Found some that SPINE missed!

Connection	Colloquial	Mx2 to 2x2	2x2 to 2x2
True Positive	Got it 🎉	5,569	88
False Negative	Missed it	237	138
False Positive	Faked it	340	28

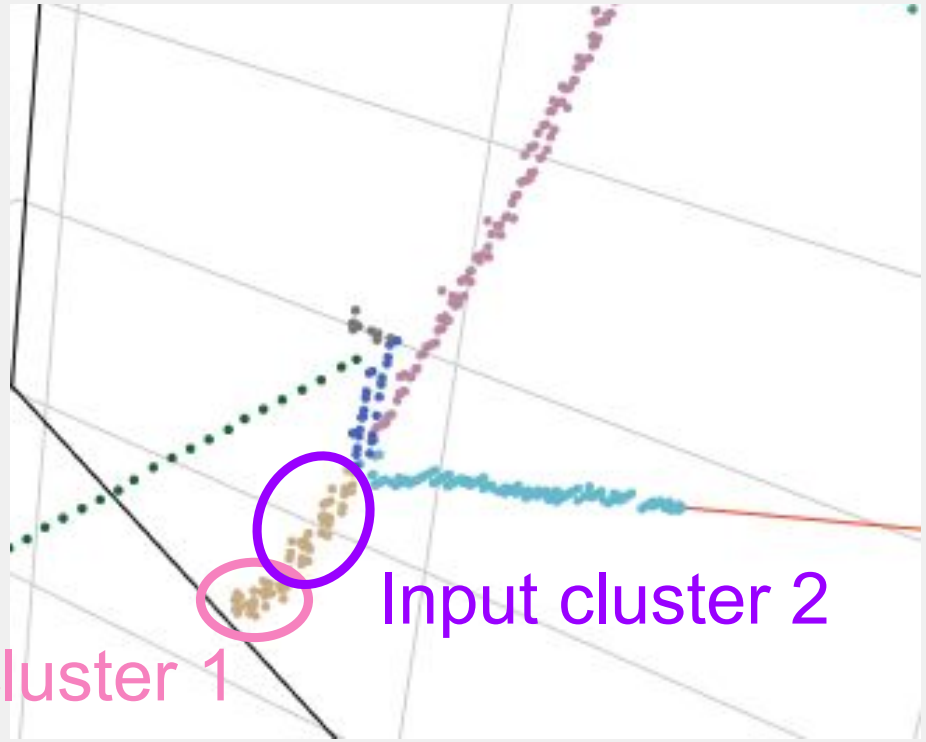
What do these look like?

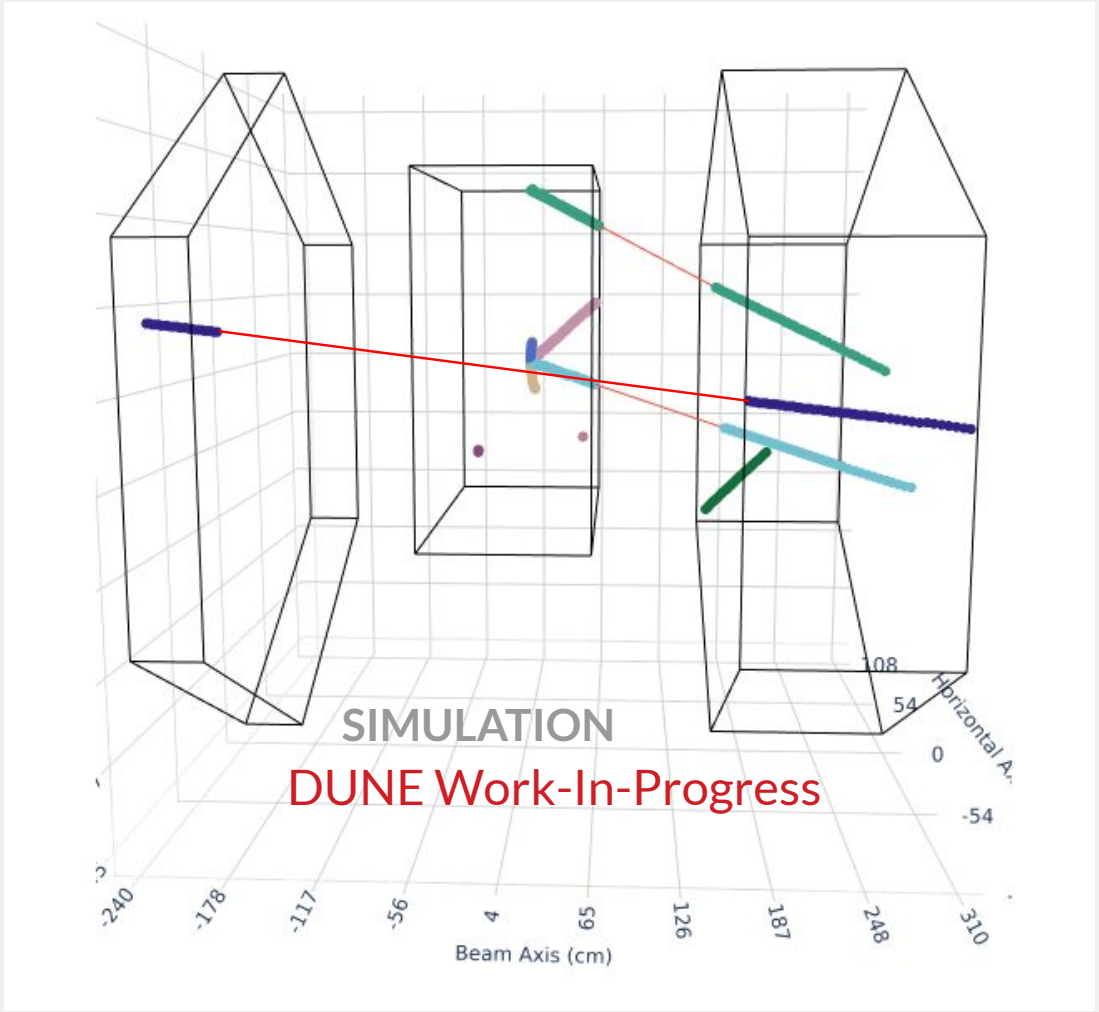
False Negative inside 2x2



False Negative inside 2x2

- 1st run of SPINE did not connect
- GNN Track match also does not





Cases: 2x2 to Mx2, 2x2 to 2x2, Mx2 to Mx2

Main Target

Found some that SPINE missed!

Found some that MINERvA reco missed!

Connection	Colloquial	**Mx2 to 2x2**	2x2 to 2x2	Mx2 to Mx2
True Positive	Got it 🎉	5,569	88	43
False Negative	Missed it	237	138	195
False Positive	Faked it	340	28	11

Cases: 2x2 to Mx2, 2x2 to 2x2, Mx2 to Mx2

Main Target

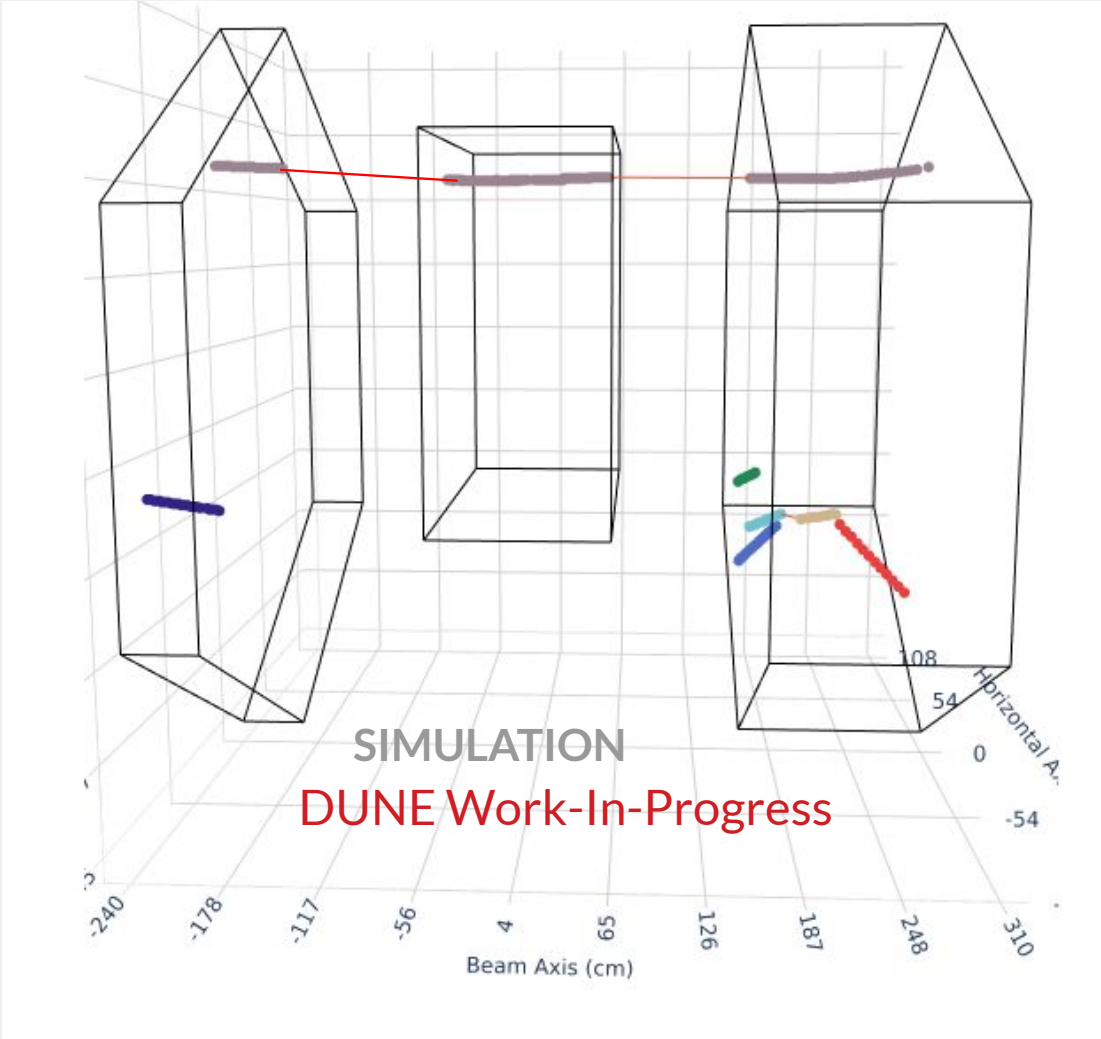
Found some that SPINE missed!

Found some that MINERvA reco missed!

Connection	Colloquial	Mx2 to 2x2	2x2 to 2x2	Mx2 to Mx2
True Positive	Got it 🎉	5,569	88	43
False Negative	Missed it	237	138	195
False Positive	Faked it	340	28	11

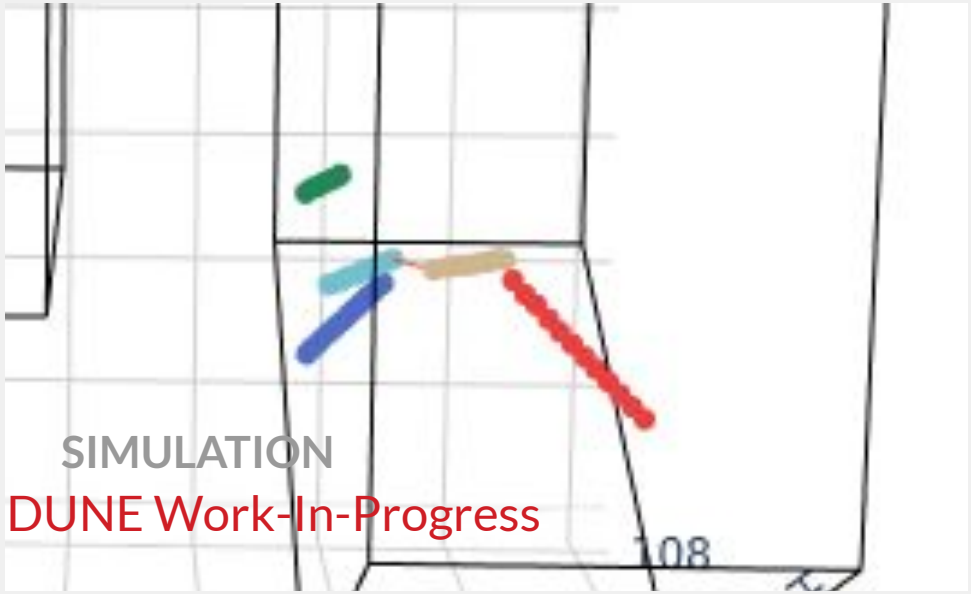
What do these look like?

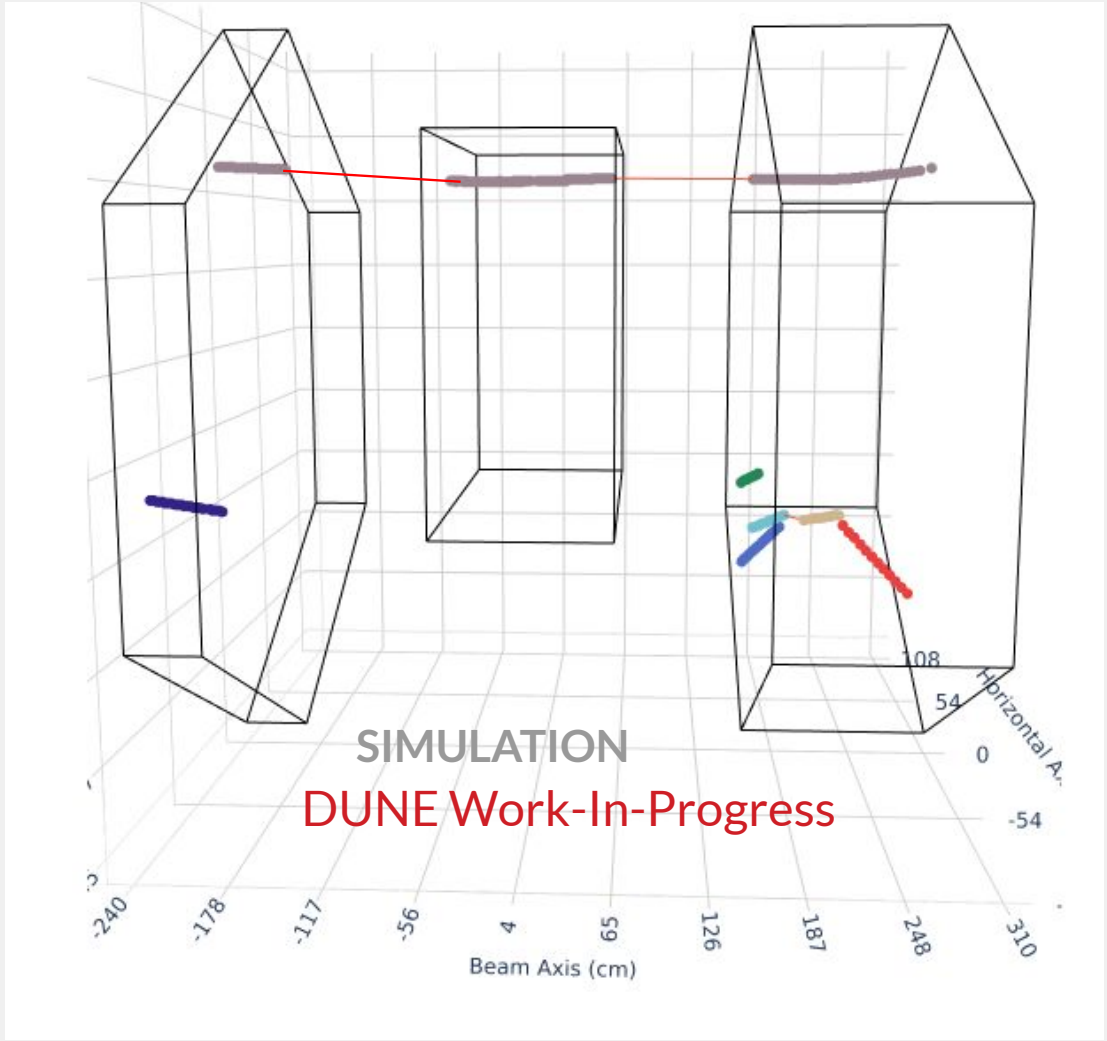
Extra Connection inside MINERvA



Extra Connection inside MINERvA

- GNN tries to connect two internal MINERvA tracks
- Low rate of False Positives though





Cases: 2x2 to Mx2, 2x2 to 2x2, Mx2 to Mx2

Main Target

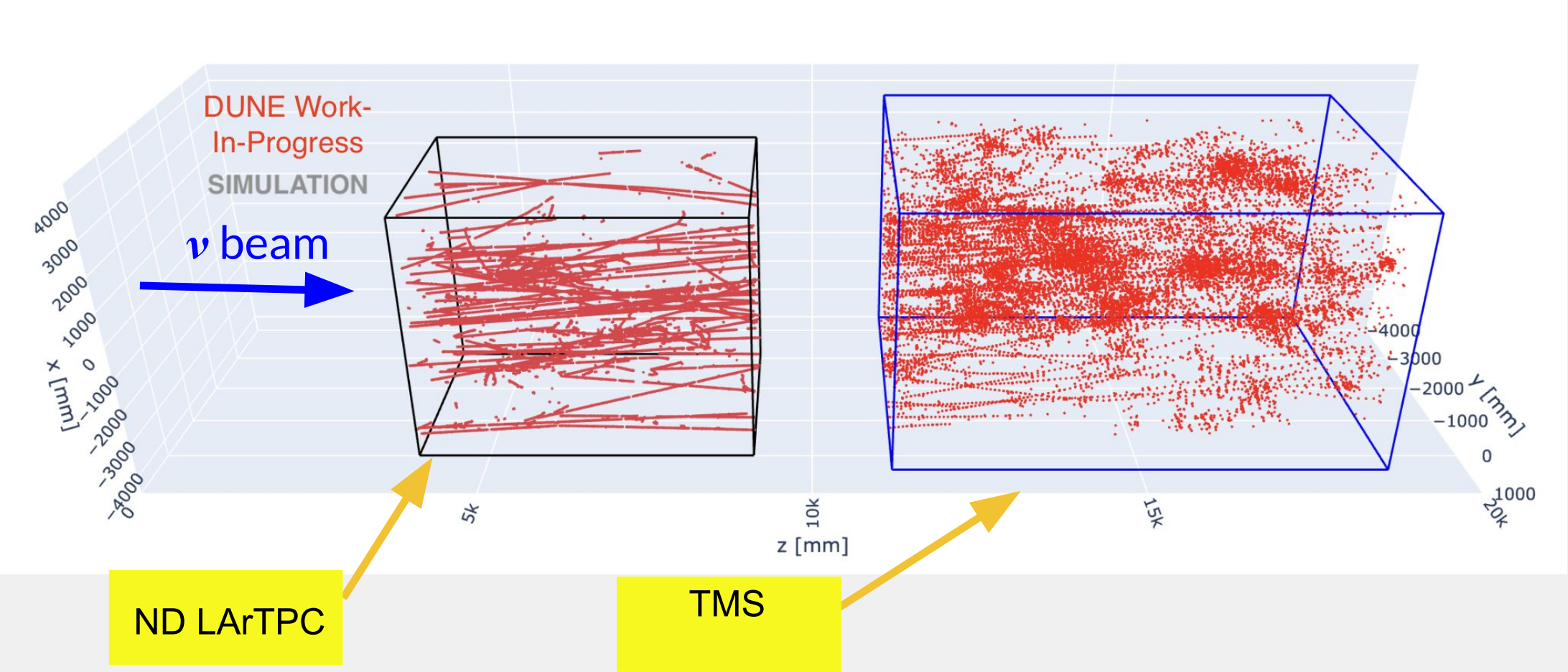
Found 88 that SPINE missed!

Found 43 that MINERvA reco missed!

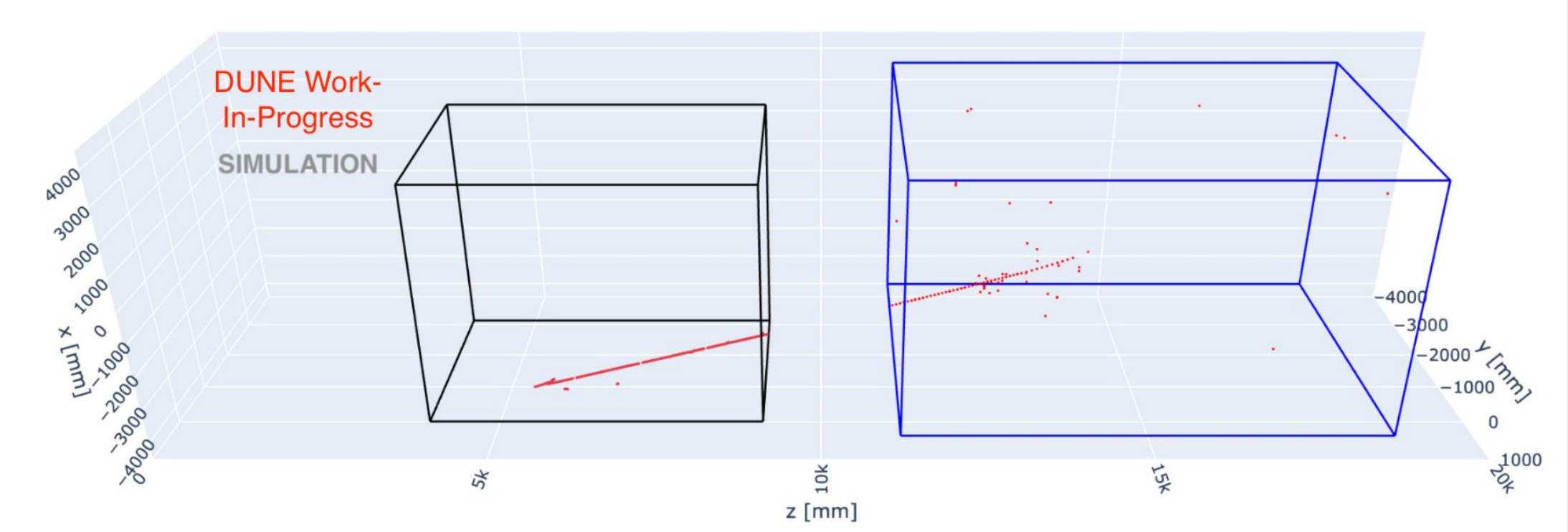
Connection	Colloquial	**Mx2 to 2x2**	2x2 to 2x2	Mx2 to Mx2
True Positive	Got it 🎉	**5,569**	88	43
False Negative	Missed it	**237**	138	195
False Positive	Faked it	**340**	28	11

Low False Positive Rates!

Progress on porting to ND-LAr + TMS

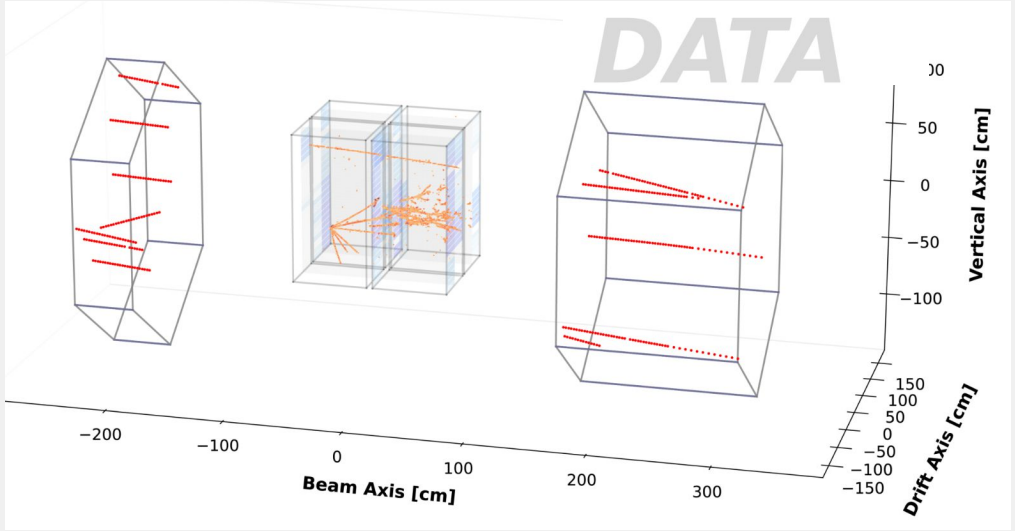


Matching track by track per spill in truth



- Have ~100 interactions
- Need to sort through parent + secondaries to match

Next Steps



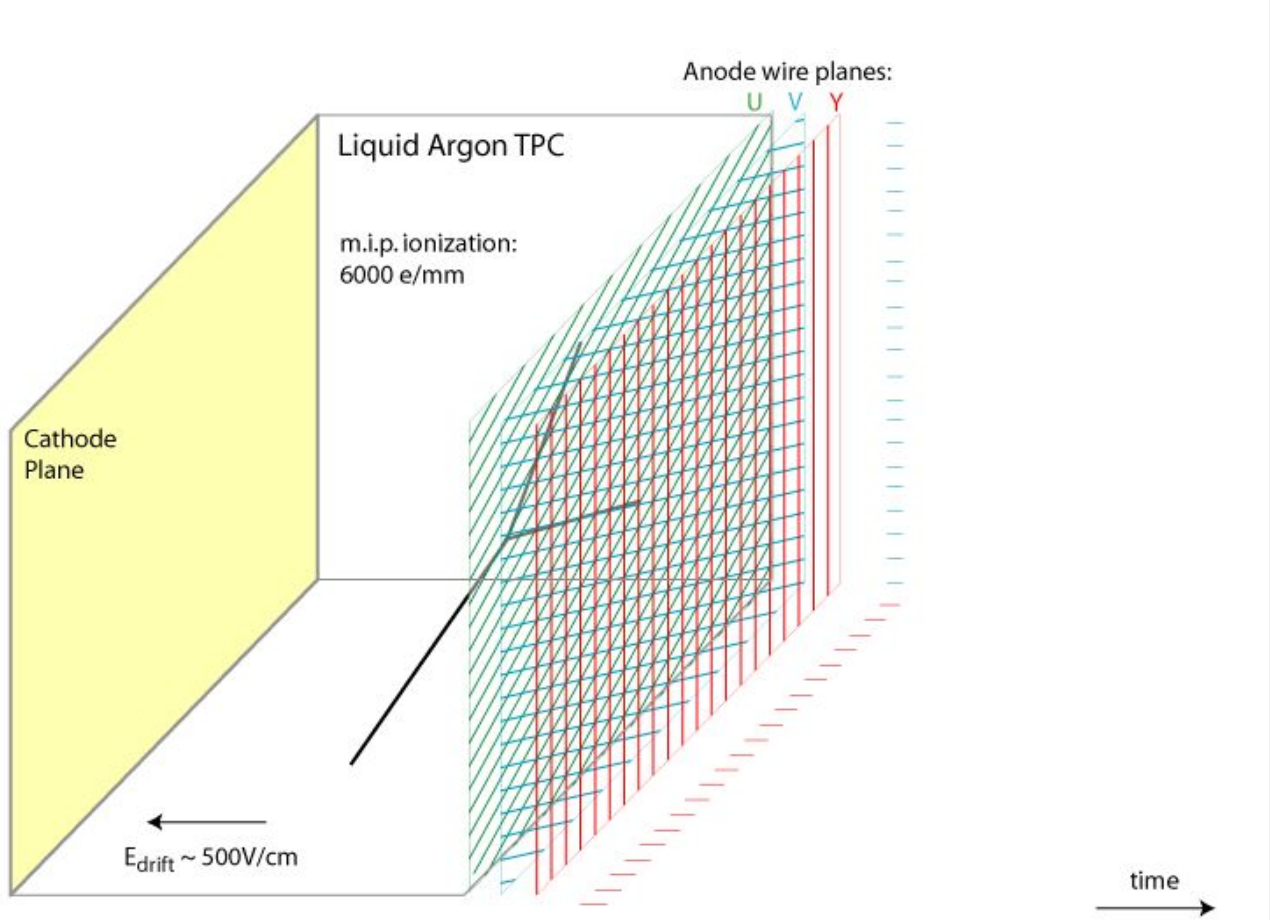
- 2x2 Prototype is great testing ground!
  - Has 5 days of data
  - Can test GNN on real, handscanned events
- Full scale ND LAr + TMS will have…
  - Some of the same challenges
  - Additional challenges due to the intensity
- So far, traditional SPINE has handled the scale up well
  - Stay tuned to see if track matching will also!

Thank you


SANFORD
UNDERGROUND
RESEARCH
FACILITY
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

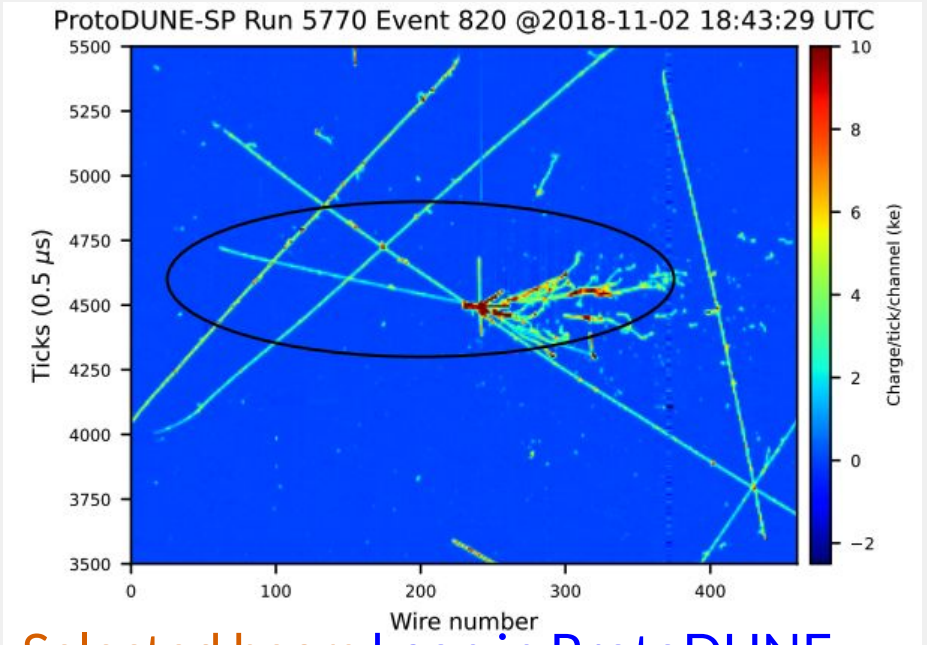
Backup

Liquid Argon Time Projection Chamber (LArTPC)



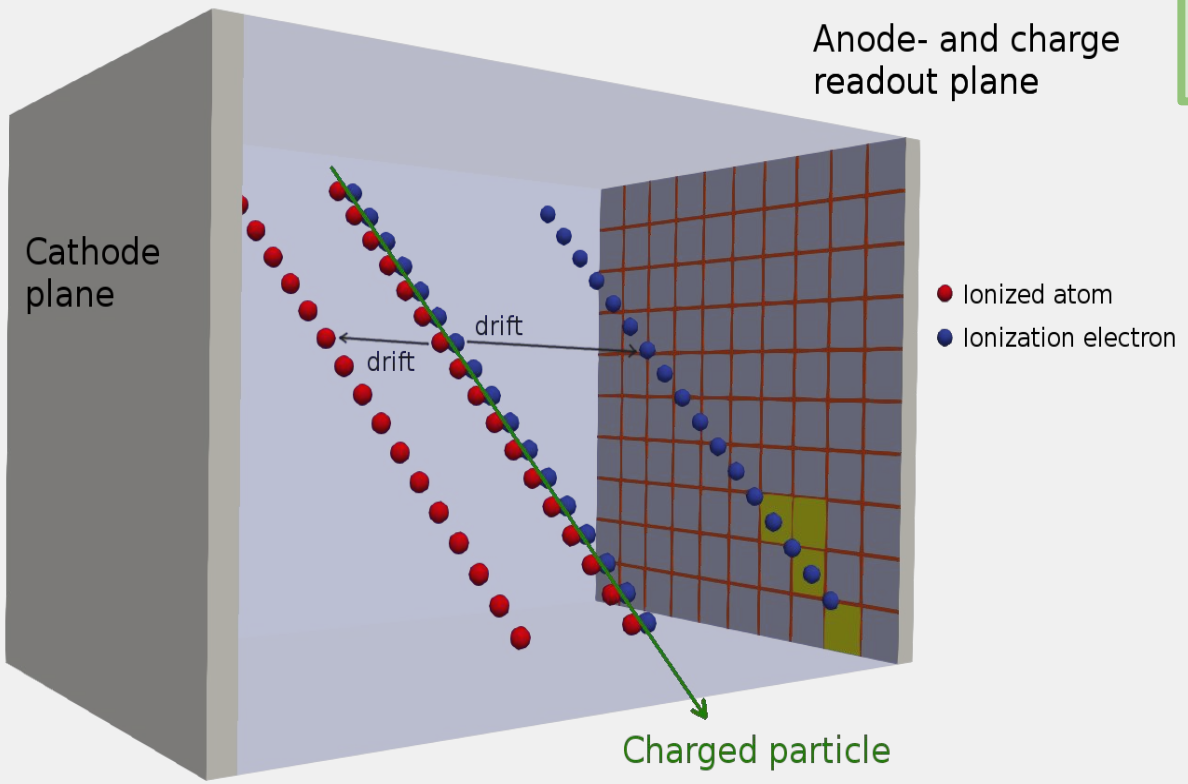
https://lar.bnl.gov/wire-cell/

LArTPC wire plane detectors used for 3 neutrino experiments taking data at Fermilab & DUNE Far Detector

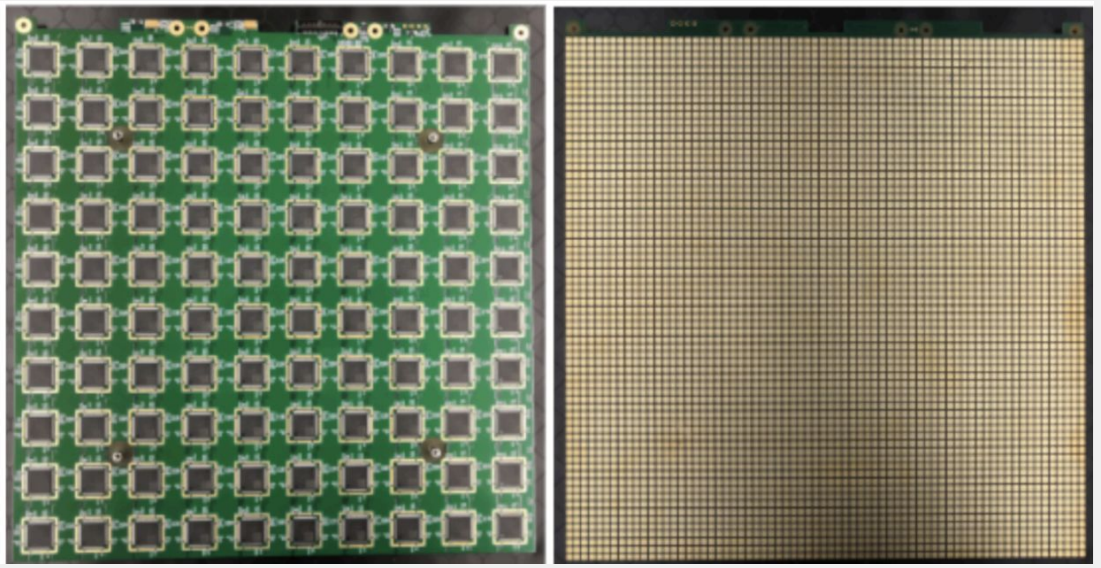


Selected beam kaon in ProtoDUNE (PhysRevD.110.092011)

LArTPC with Pixel Readout

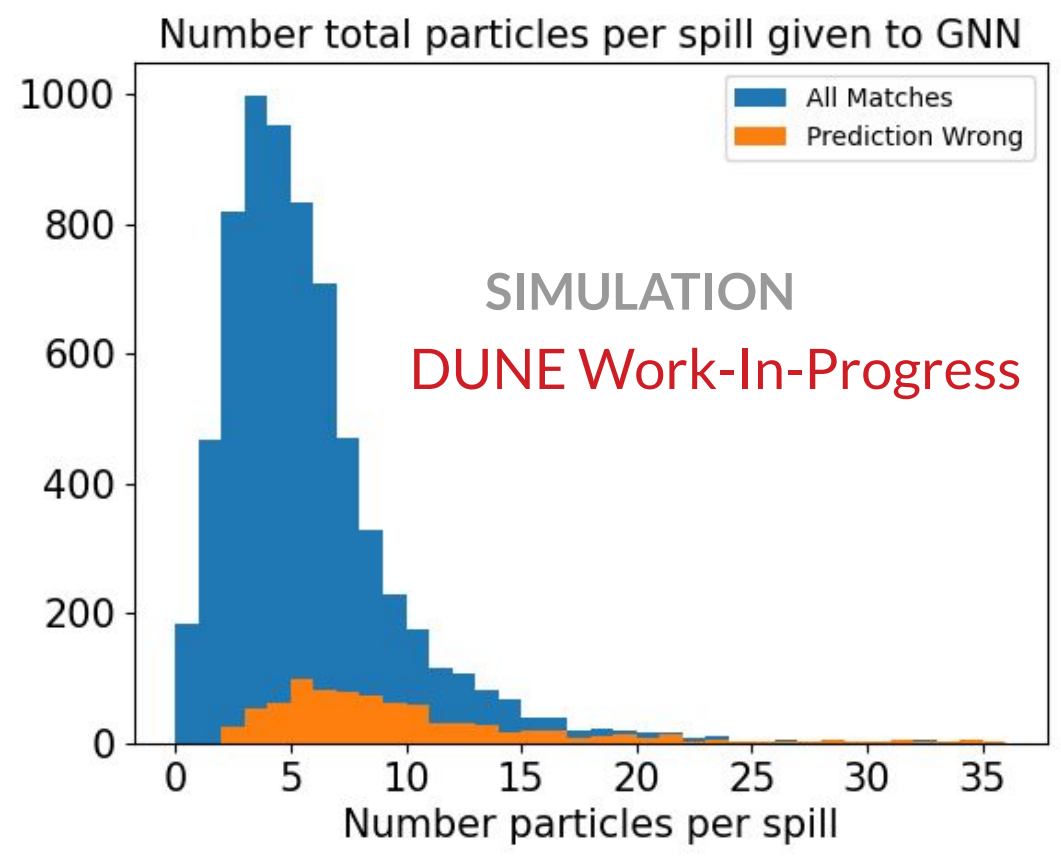


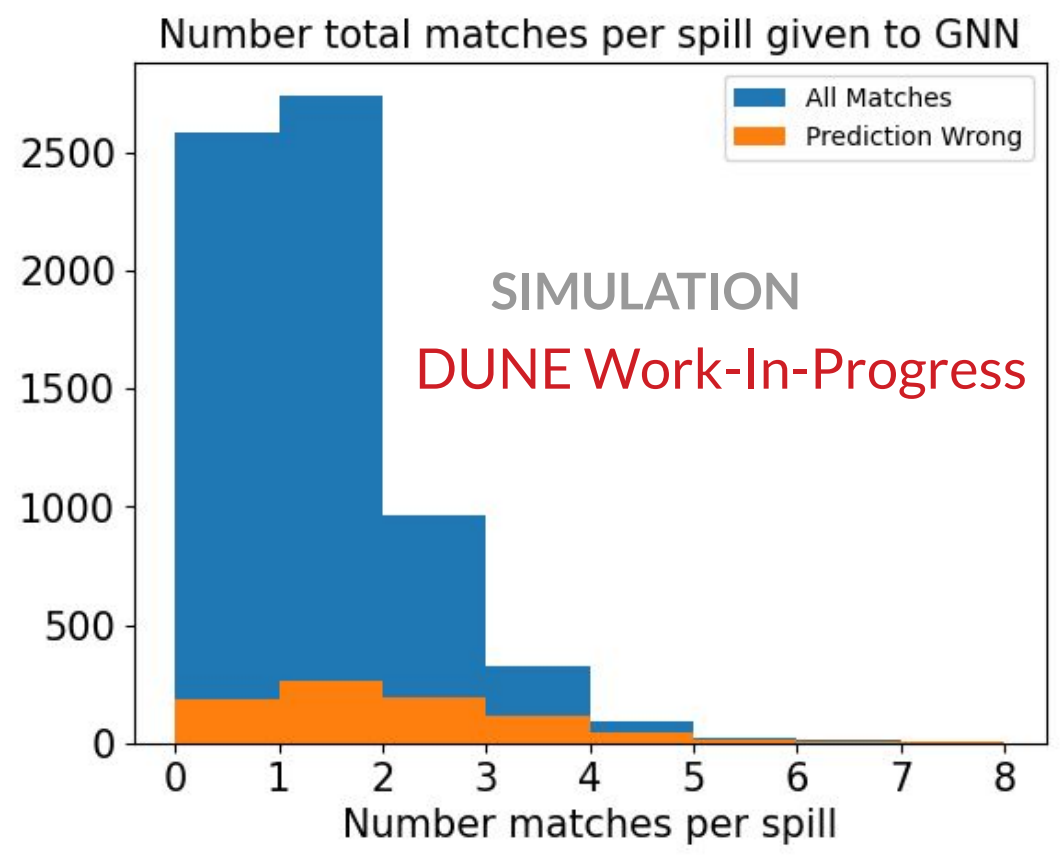
DUNE ND-LAr uses 2D **pixel plane** readout instead of wires → **native** 3D image!



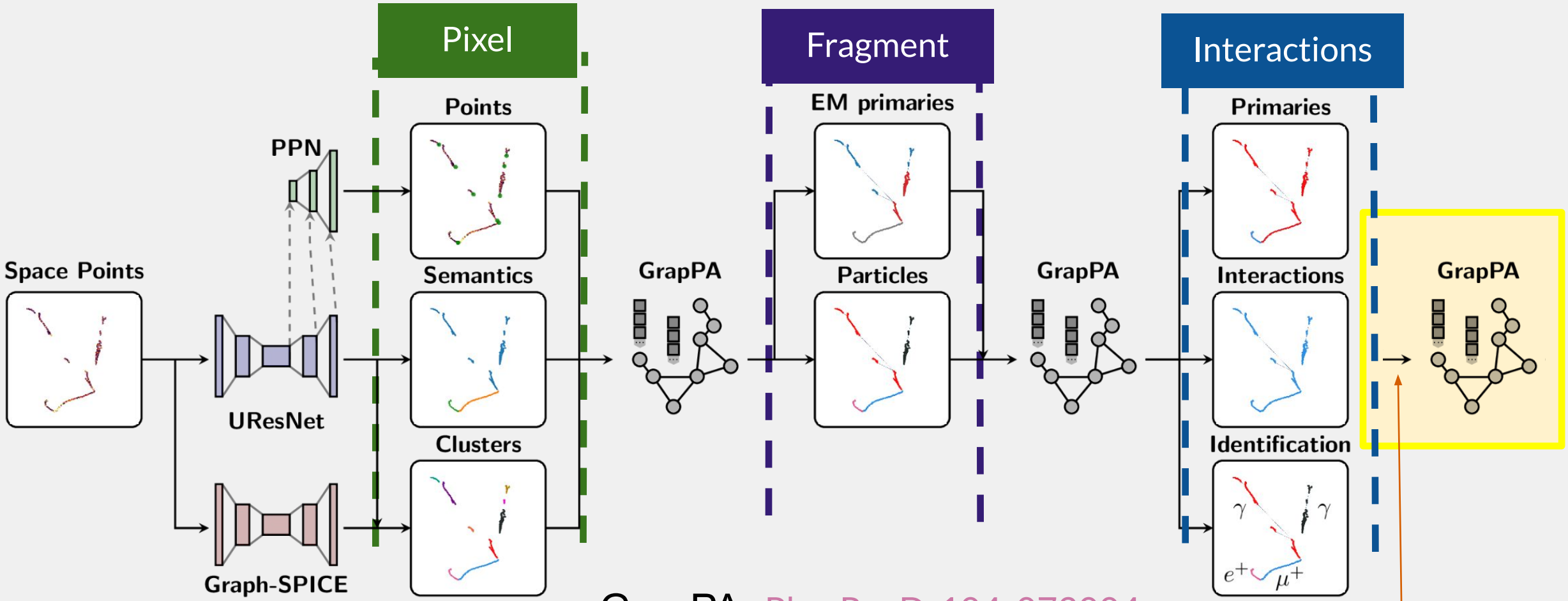
Back of plane with LArPix ASICs (left) & TPC-facing side of pixel plane with pixel pitch ~4mm (right)
LArPix Paper

Mx2 Training Sample





SPINE: Inserting Another GNN Layer



GrapPA: PhysRevD. 104. 072004

Muon Tagger 3D Reco Information