

Connecting the Dots: Using Multidetector Inputs in Machine Learning

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on behalf of the DUNE Collaboration

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About Me



IAIFI Postdoc Fellow at MIT & Tufts



Portrait of a Scientist



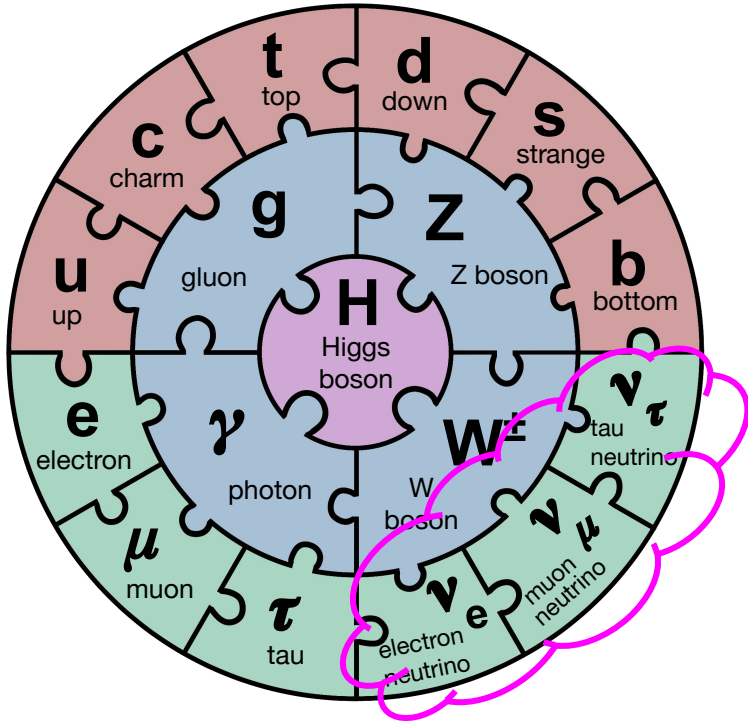
Fast Low Energy Reconstruction using CNNs



Fun facts: I do jiu jitsu & have a cat!

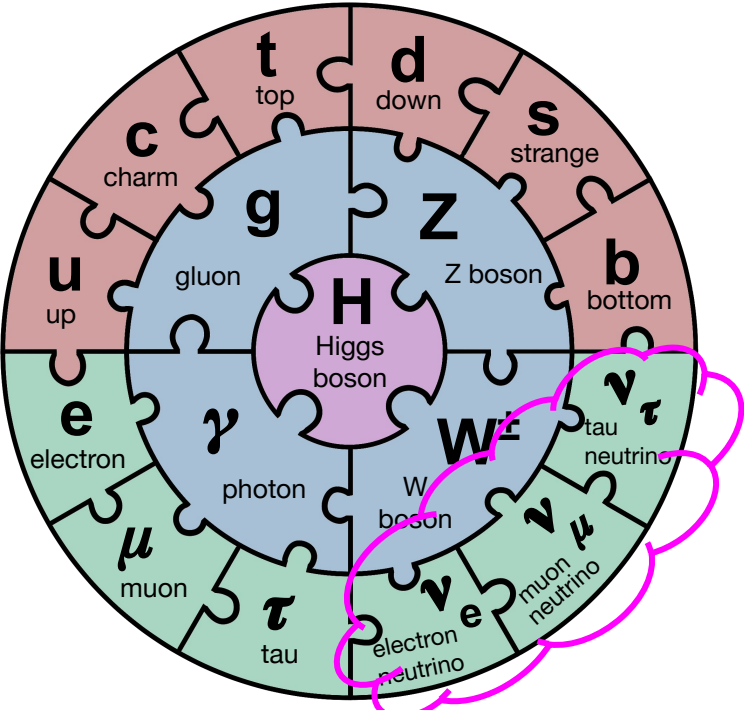


Standard Model: Neutrinos



[Why neutrinos matter - Silvia Bravo Gallart](#)

Standard Model: Neutrinos



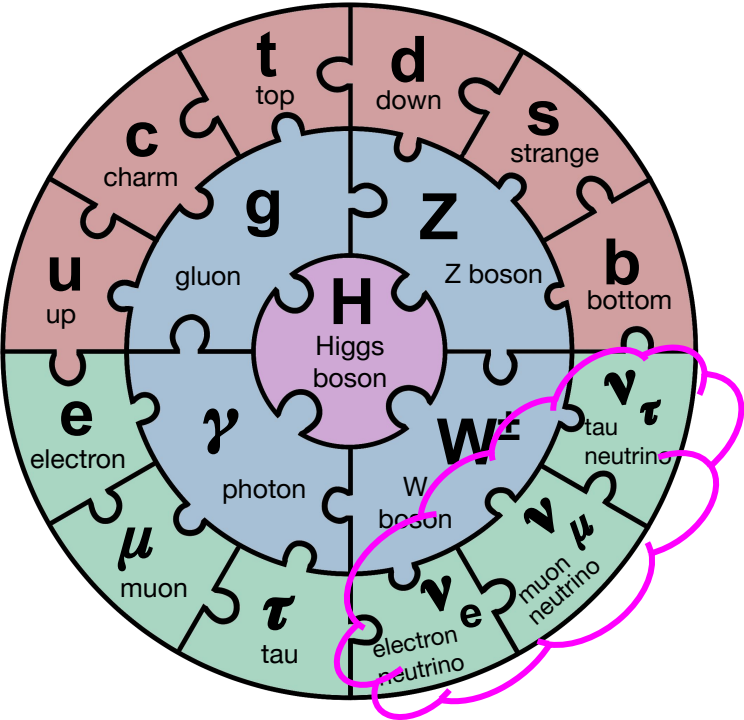
Oscillation: Produced & interact in flavor states \leftrightarrow propagates in mass states



[Why neutrinos matter - Silvia Bravo Gallart](#)

https://dchooz.titech.jp.hep.net/nu_oscillation.html

Standard Model: Neutrinos



Oscillation: Produced & interact in flavor states \leftrightarrow propagates in mass states



[Why neutrinos matter - Sílvia Bravo Gallart](#)

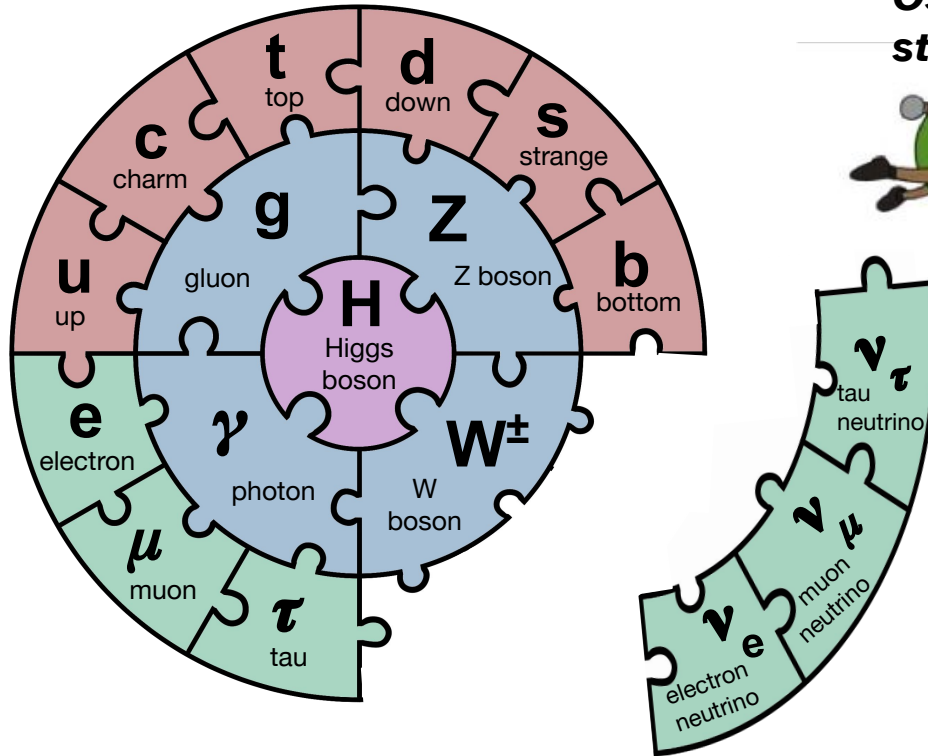
https://dchooz.titech.jp.hep.net/nu_oscillation.html

Neutrinos Defying Expectations

Oscillation: Produced & interact in flavor states \Leftrightarrow propagates in mass states



https://dchooz.titech.jp.hep.net/nu_oscillation.html



Neutrinos Defying Expectations

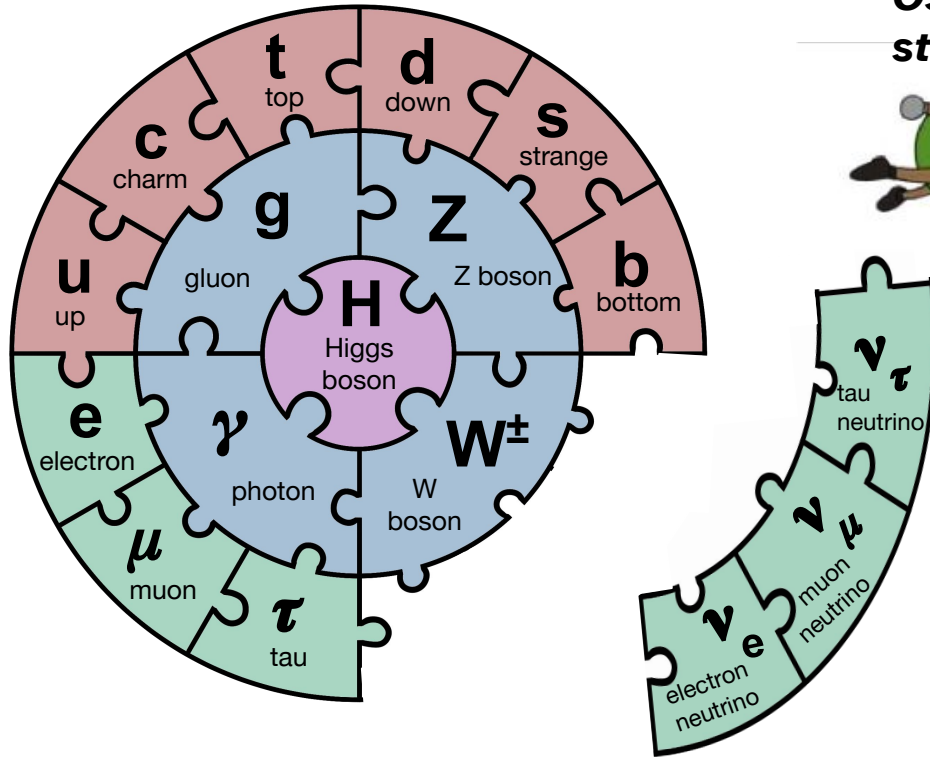
Oscillation: Produced & interact in flavor states \Leftrightarrow propagates in mass states



https://dchooz.titech.jp.hep.net/nu_oscillation.html

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} .$$

PMNS



Neutrinos Defying Expectations

Oscillation: Produced & interact in flavor states \Leftrightarrow propagates in mass states

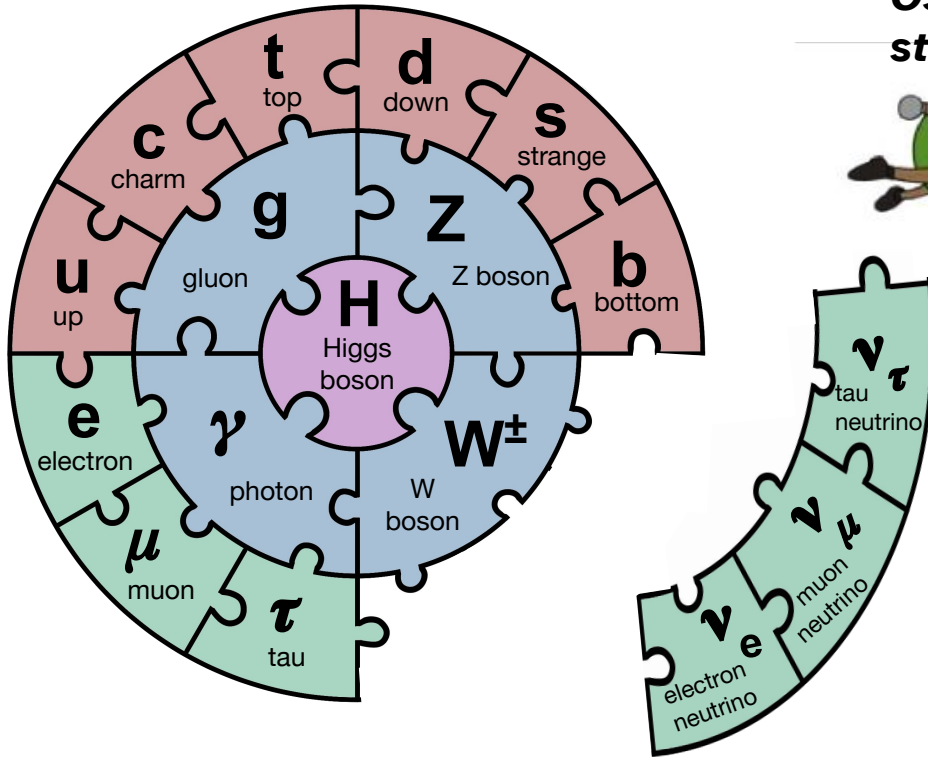


https://dchooz.titech.jp.hep.net/nu_oscillation.html

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

PMNS

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}.$$

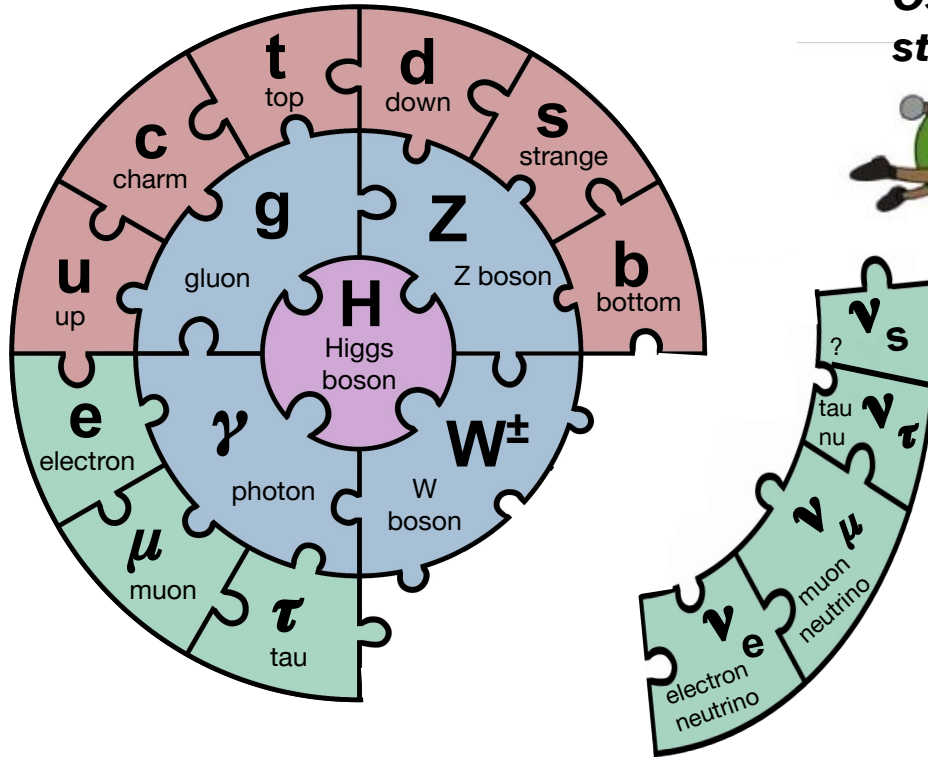


Neutrinos Defying Expectations

Oscillation: Produced & interact in flavor states \Leftrightarrow propagates in mass states



https://dchooz.titech.jp.hep.net/nu_oscillation.html

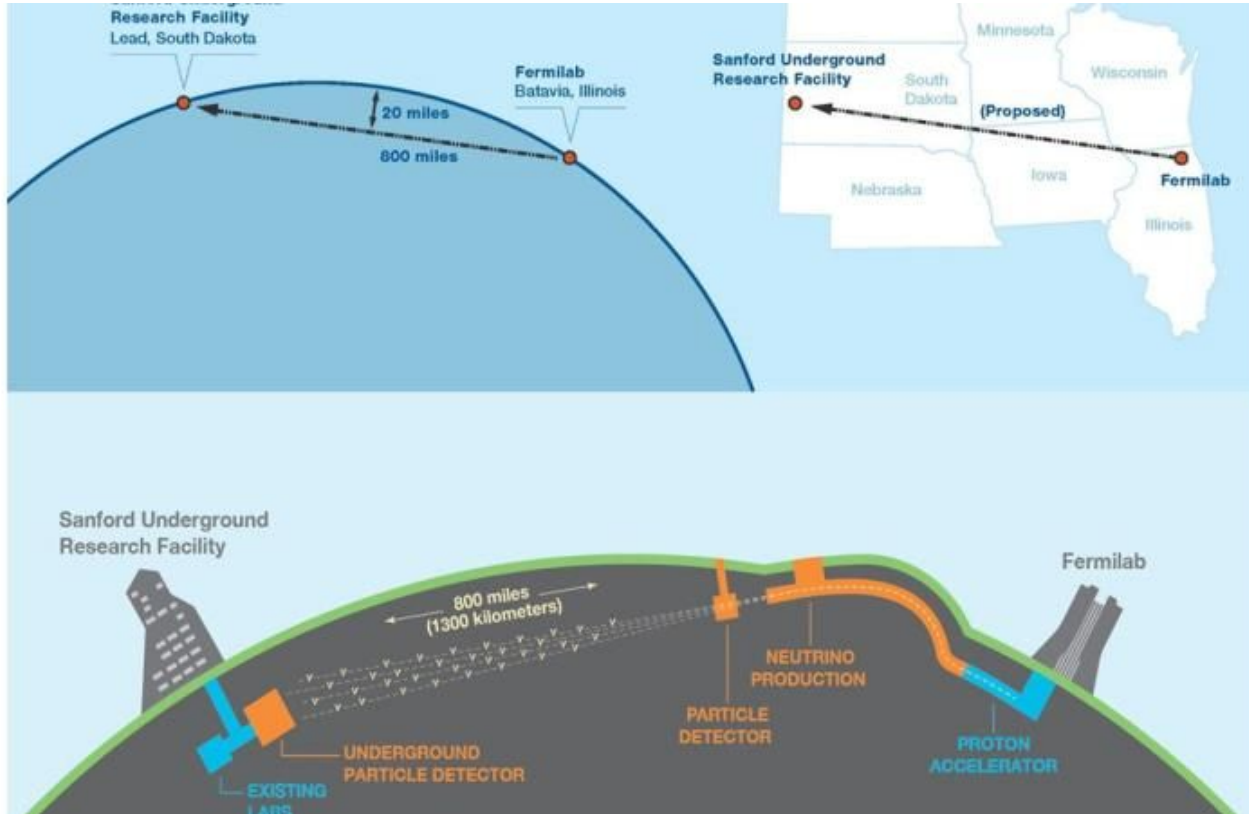


Neutrino mixing:

- Mass hierarchy?
- Symmetries in PMNS mixing matrix?
- Is PMNS matrix unitary?
- CP violation?

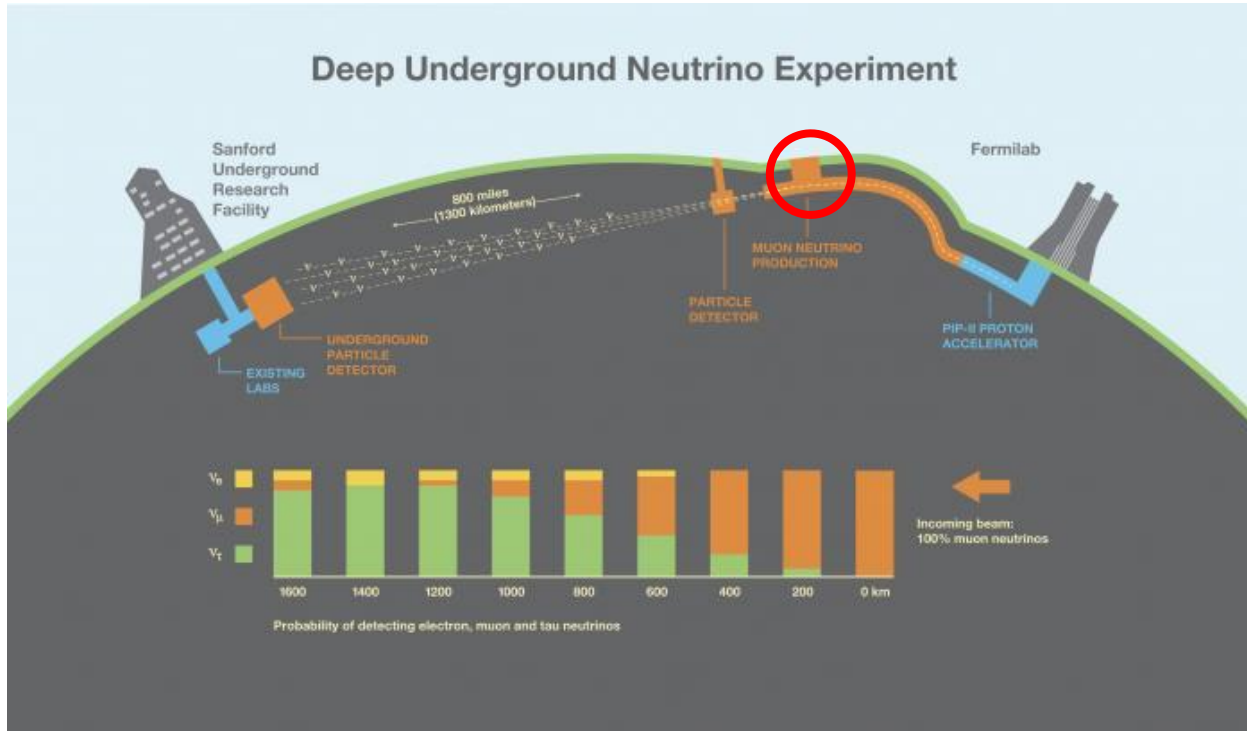
Beyond Standard Model behavior?

DUNE: Deep Underground Neutrino Experiment



<https://sciencebusiness.net/network-news/uk-pledges-ps65million-deep-underground-neutrino-experiment>

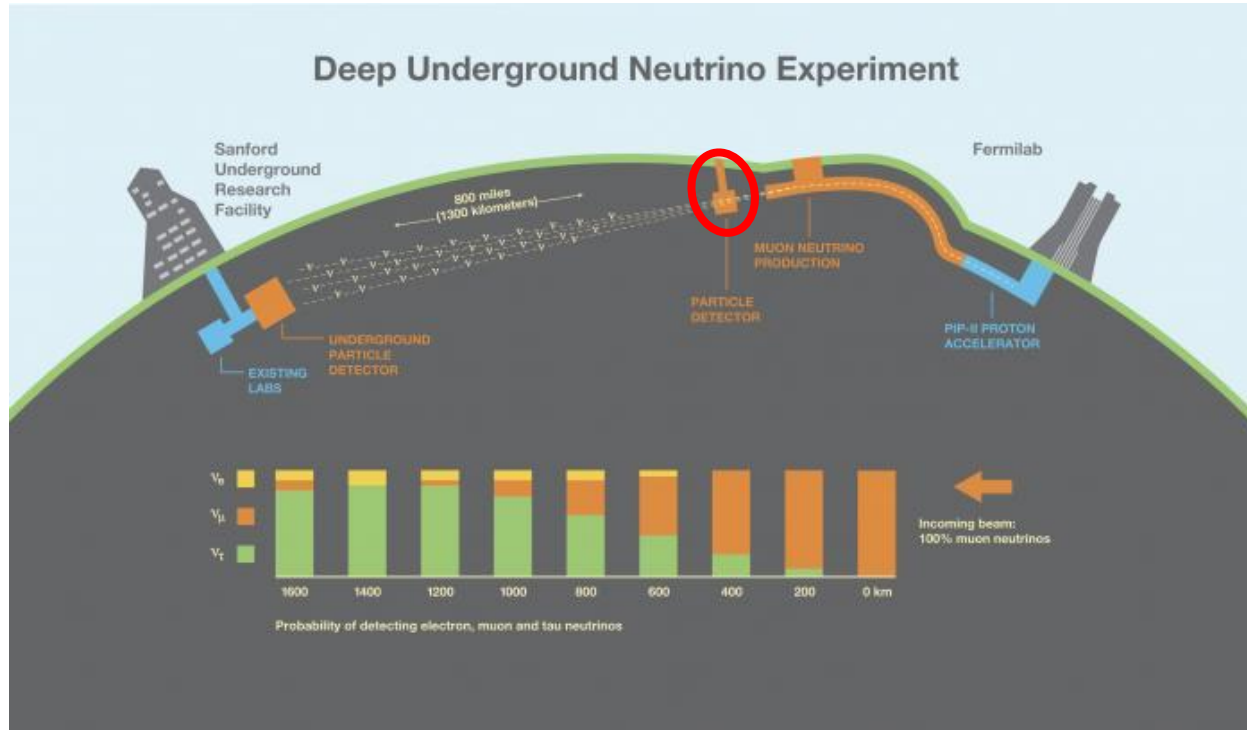
DUNE: Frontier Measurements of Neutrino Physics



- Well-known neutrino source

<https://www.fzu.cz/en/research/research-topics/deep-underground-neutrino-experiment-dune>

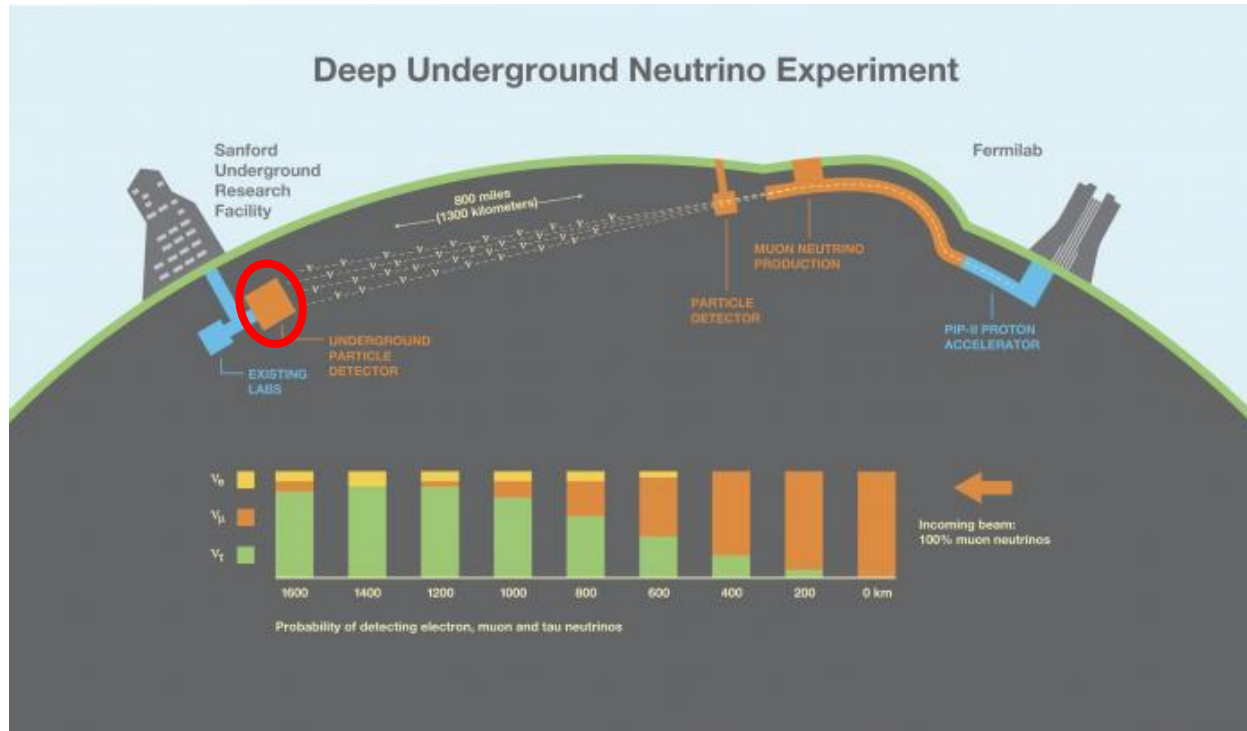
DUNE: Frontier Measurements of Neutrino Physics



- Well-known neutrino source
- Near detectors close to neutrino beam

<https://www.fzu.cz/en/research/research-topics/deep-underground-neutrino-experiment-dune>

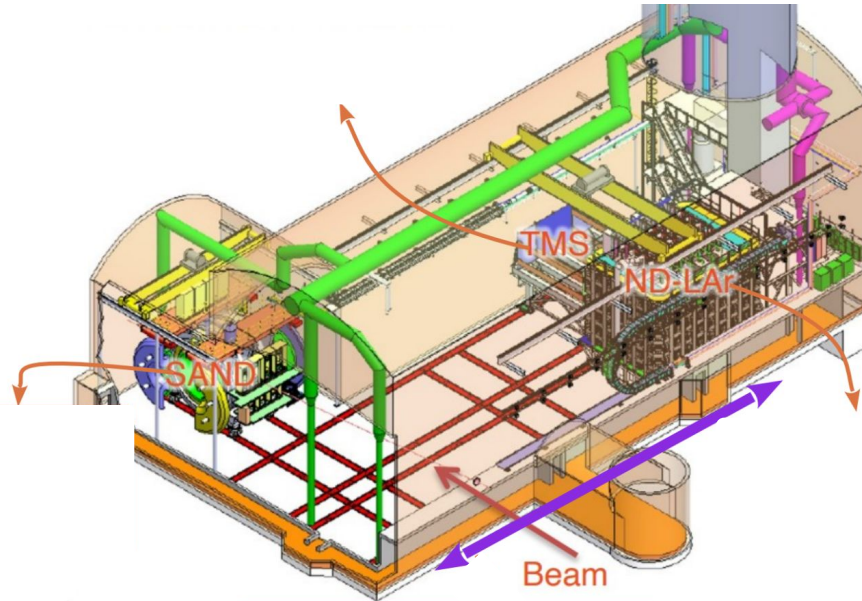
DUNE: Frontier Measurements of Neutrino Physics



- Well-known neutrino source
- Near detectors close to neutrino beam
- Measure neutrinos again after traveling

<https://www.fzu.cz/en/research/research-topics/deep-underground-neutrino-experiment-dune>

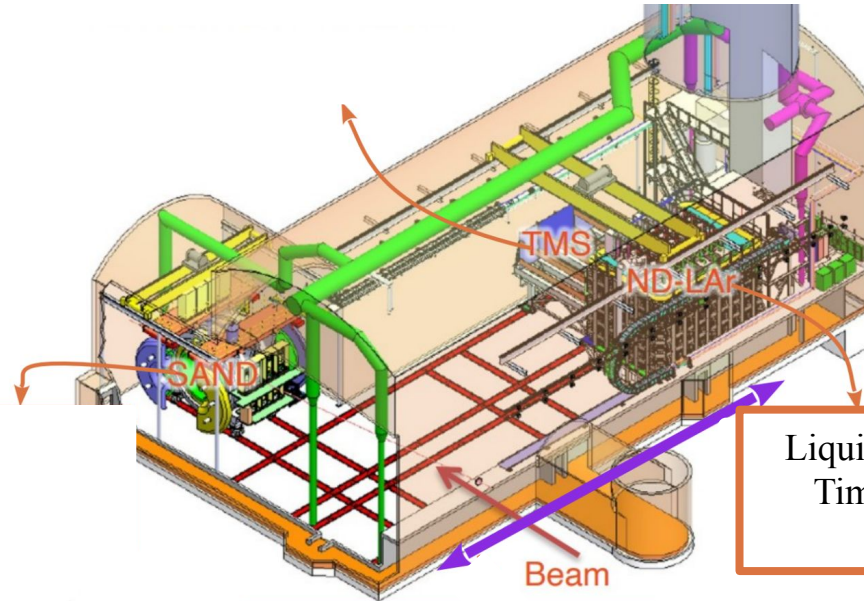
Near Detector Hall



Important to
measure ν ...

- Energy
- Cross section
- Flux

Near Detector Hall

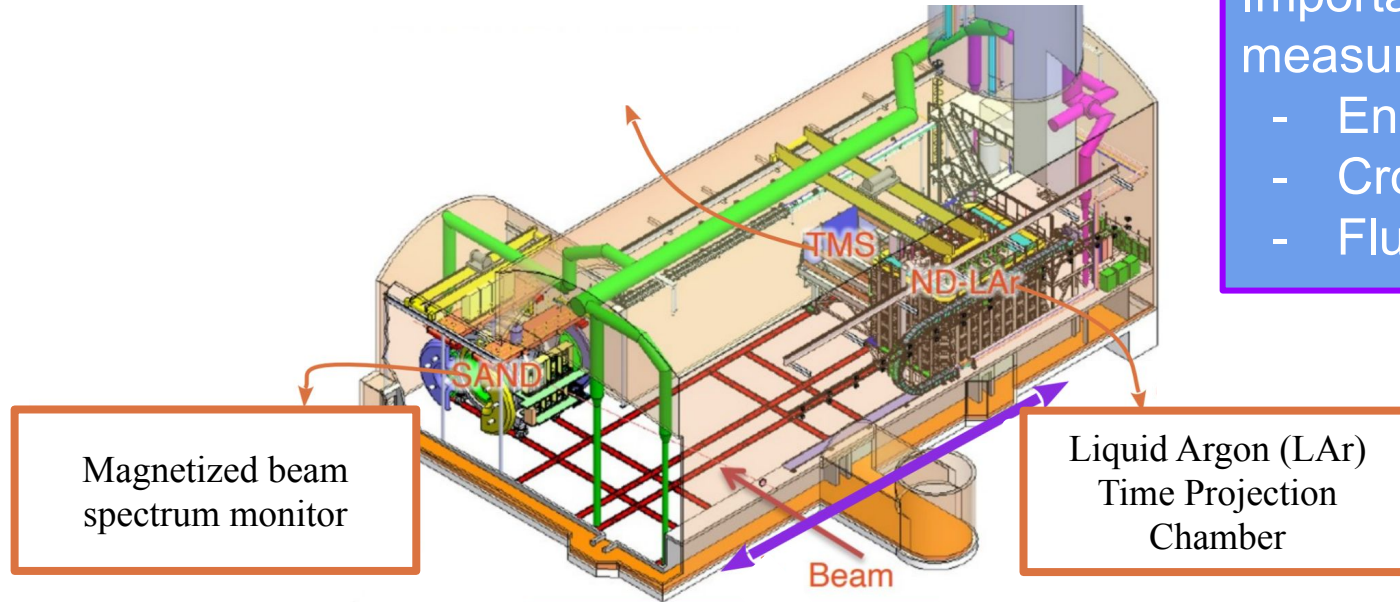


Important to
measure ν ...

- Energy
- Cross section
- Flux

Liquid Argon (LAr)
Time Projection
Chamber

Near Detector Hall



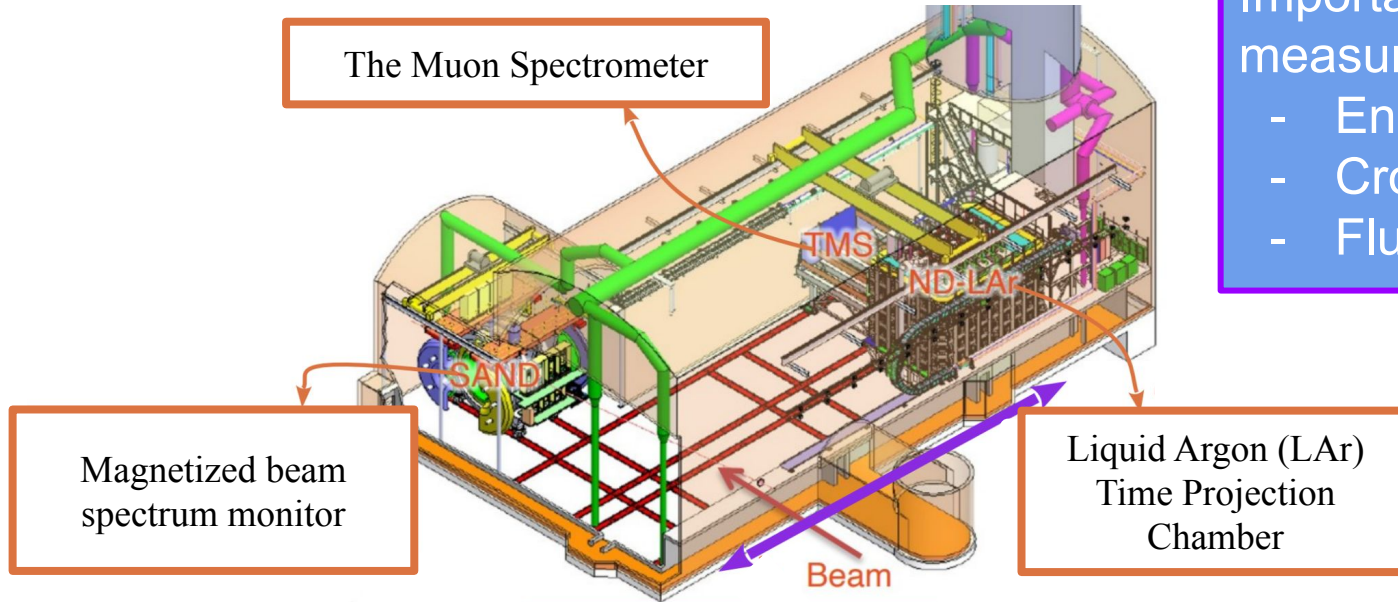
Magnetized beam
spectrum monitor

Liquid Argon (LAr)
Time Projection
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Near Detector Hall



Important to measure ν ...

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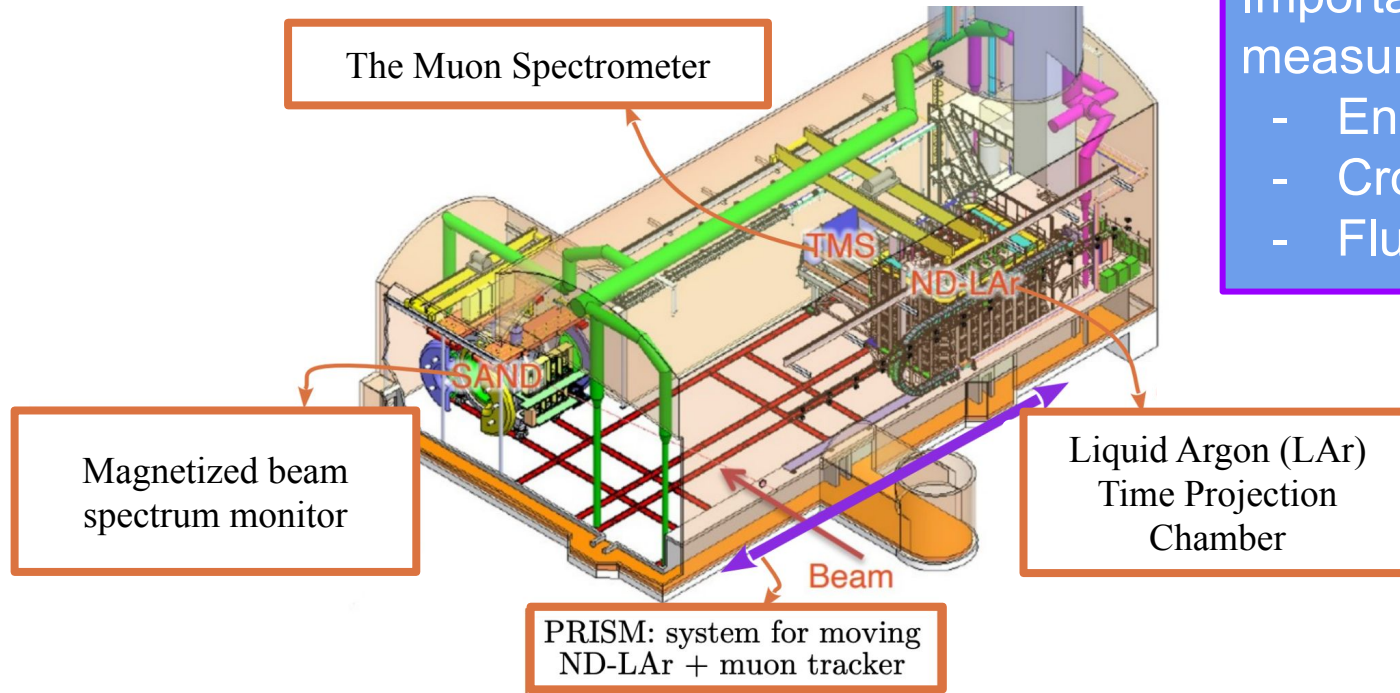
The Muon Spectrometer

Magnetized beam spectrum monitor

Liquid Argon (LAr)
Time Projection Chamber

Beam

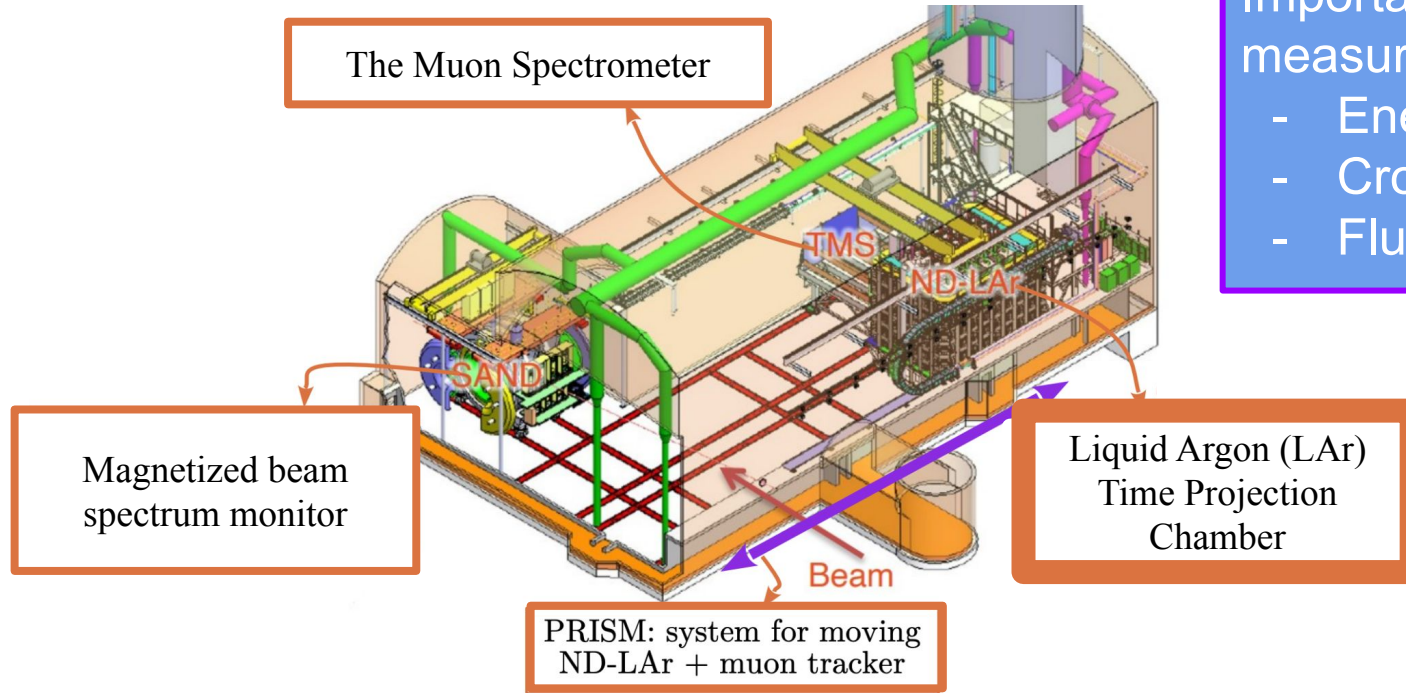
Near Detector Hall



Important to measure ν ...

- Energy
- Cross section
- Flux

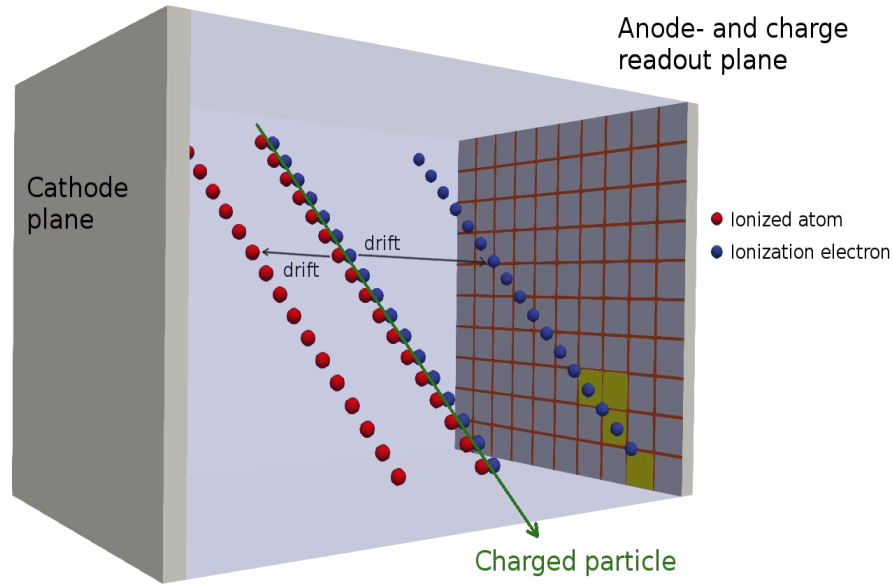
Near Detector Hall



Important to measure ν ...

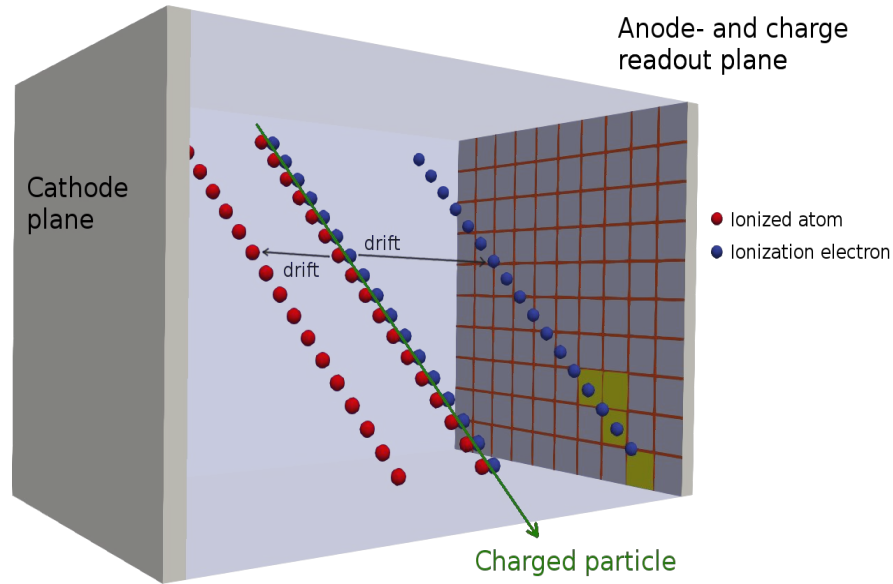
- Energy
- Cross section
- Flux

Liquid Argon (LAr) Time Projection Chamber (TPC)

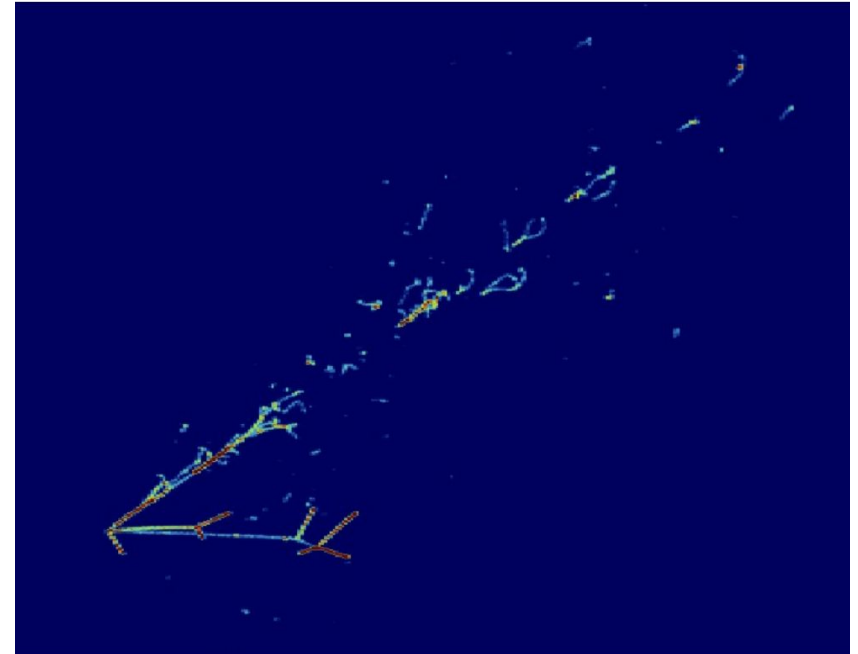


<https://argoncube.org/LArTPCs.html>

Liquid Argon (LAr) Time Projection Chamber (TPC)

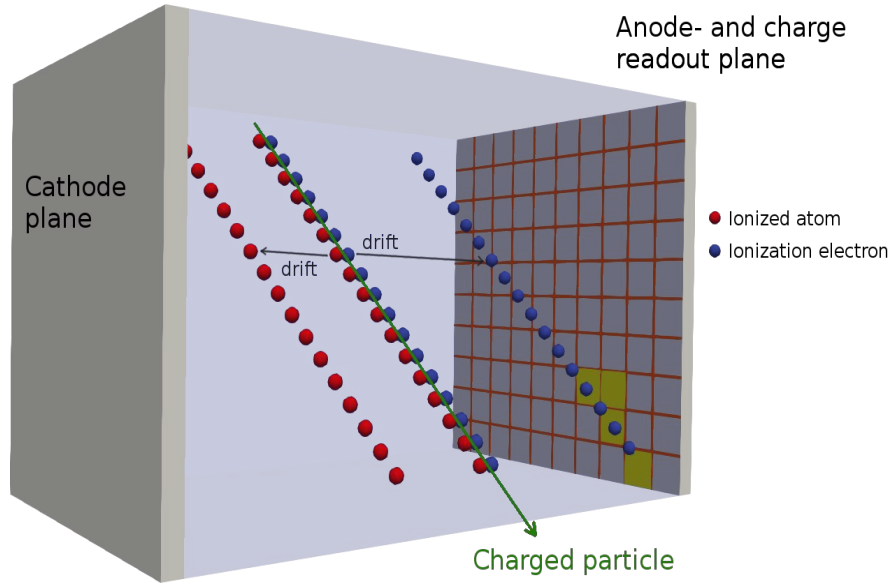


<https://argoncube.org/LArTPCs.html>

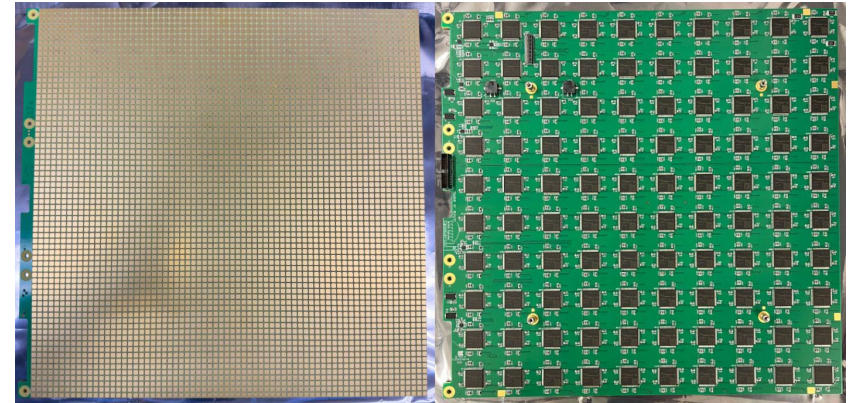


Color = charge deposition
Output: pion and two protons

Liquid Argon (LAr) Time Projection Chamber (TPC)



But we're using a 2D pixel plane readout! So we get a 3D image!



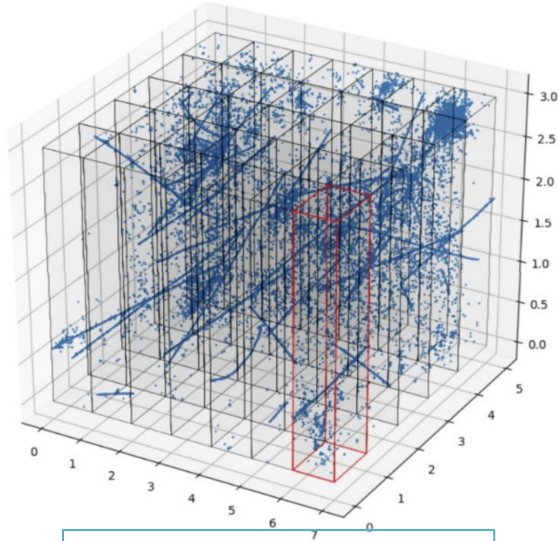
Both sides of a 1,000 square cm LArPix tile with 4900 pixels (left) and 100 LArPix ASICs (right). (Credit: Andrew Lambert)

<https://argoncube.org/LArTPCs.html>

<https://physicalsciences.lbl.gov/2023/06/22/larpix-berkeley-labs-new-3d-pixel-tile-detection-system-for-dune/>

DUNE: Near Detector LAr TPCs

- Expect ~ 20 ν interactions!

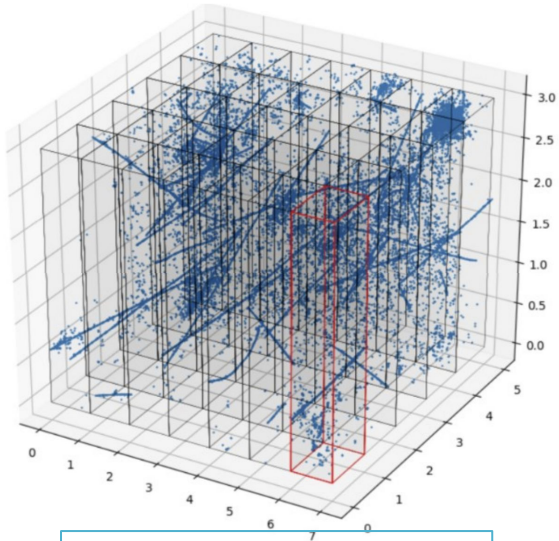


Simulation of ND LAr
beam spill ($10\mu s$)

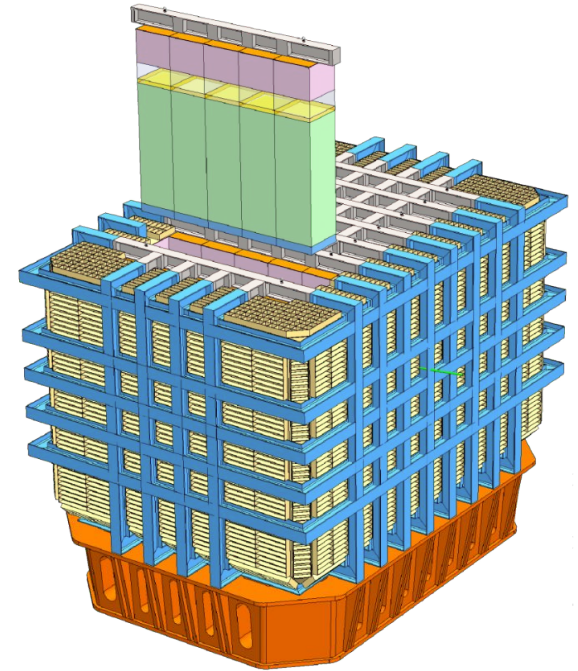
<https://argoncube.org/LArTPCs.html>

DUNE: Near Detector LAr TPCs

- Expect ~ 20 ν interactions!
- Need new technology:
 - Modularized detector



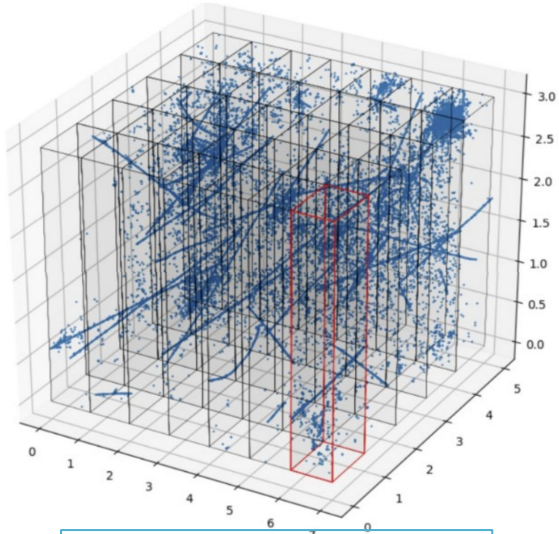
Simulation of ND LAr
beam spill ($10\mu s$)



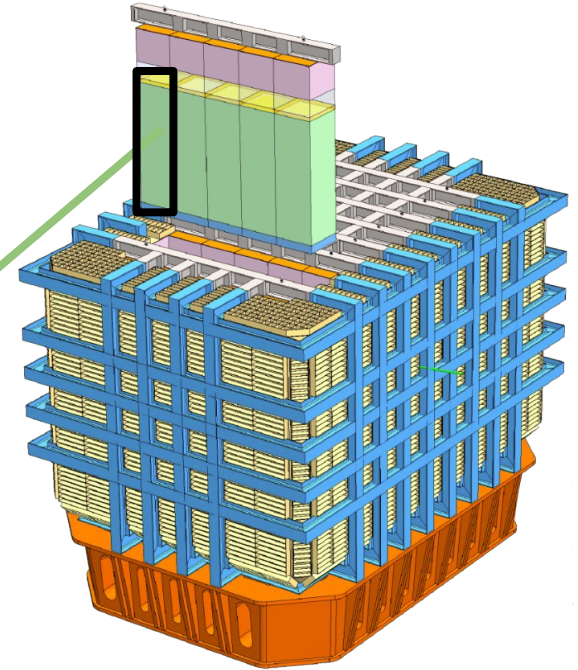
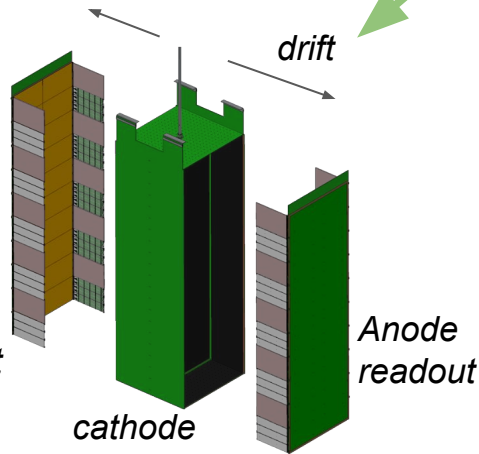
<https://argoncube.org/duneND.html>

DUNE: Near Detector LAr TPCs

- Expect ~ 20 ν interactions!
- Need new technology:
 - Modularized detector
- TPC with central cathode

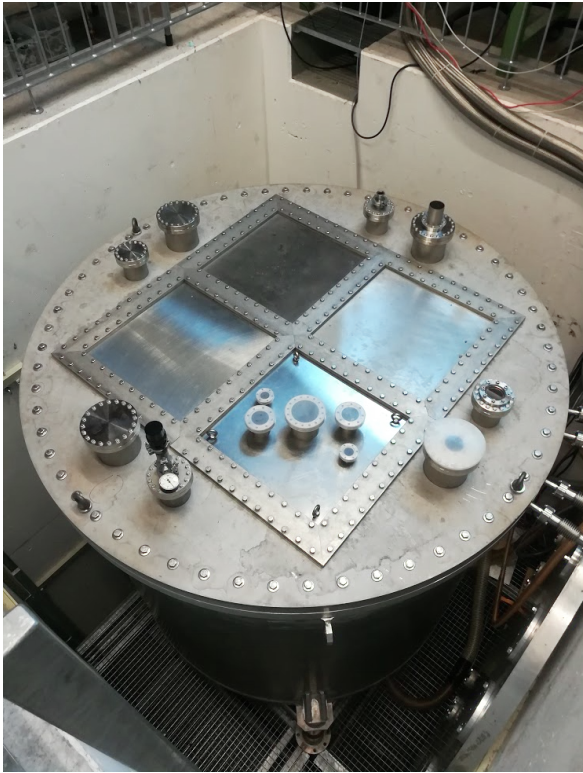


Simulation of ND LAr beam spill ($10\mu s$)



<https://argoncube.org/duneND.html>

2x2 Prototype Near Detector

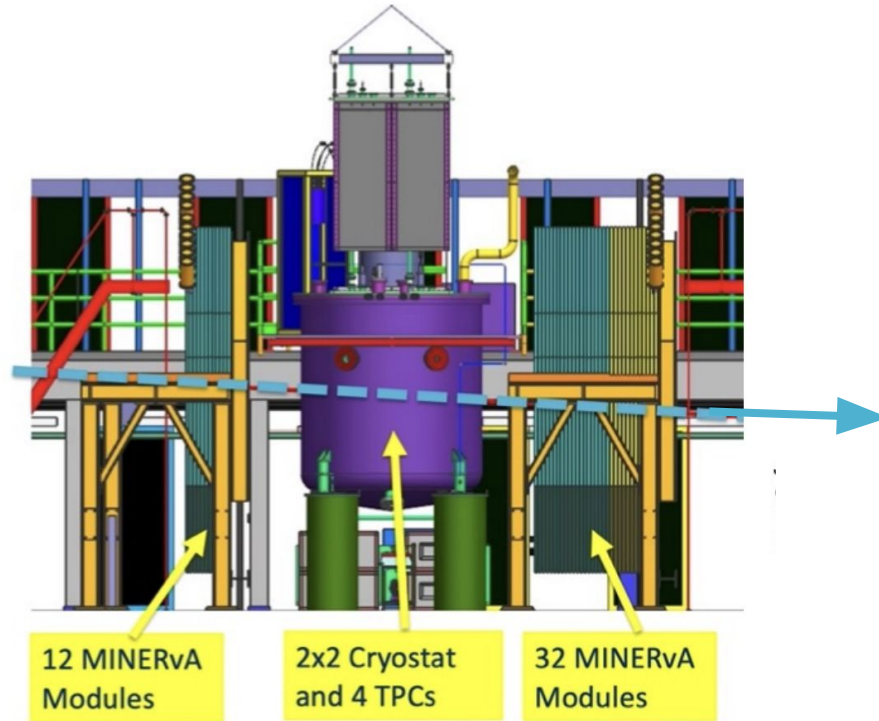


- Start with 4 ND-LAr modules (slightly smaller)
- Tested at University of Bern using cosmic rays
- Setup at Fermilab now to test in accelerator neutrino beam

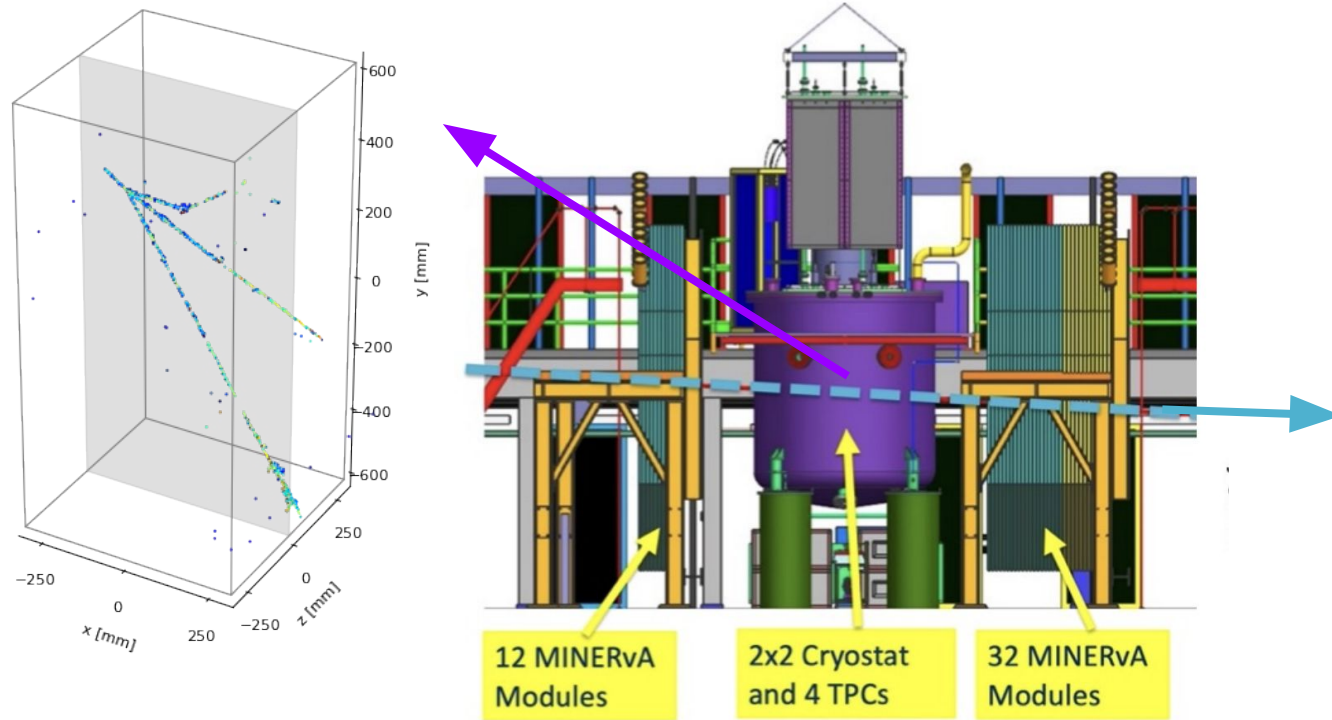
<https://argoncube.org/LArTPCs.html>

2x2 Prototype at Fermilab

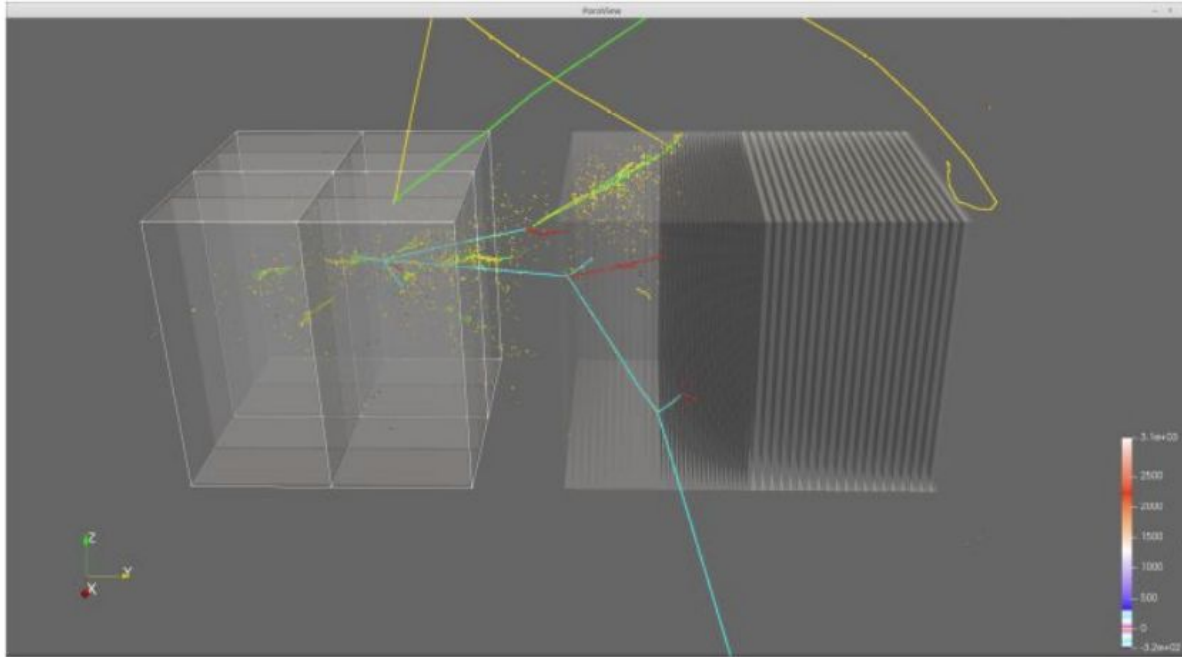
Neutrino beam
from Fermilab
(similar to future
beam for DUNE)



2x2 Prototype at Fermilab



2x2 Prototype + Additional Detector



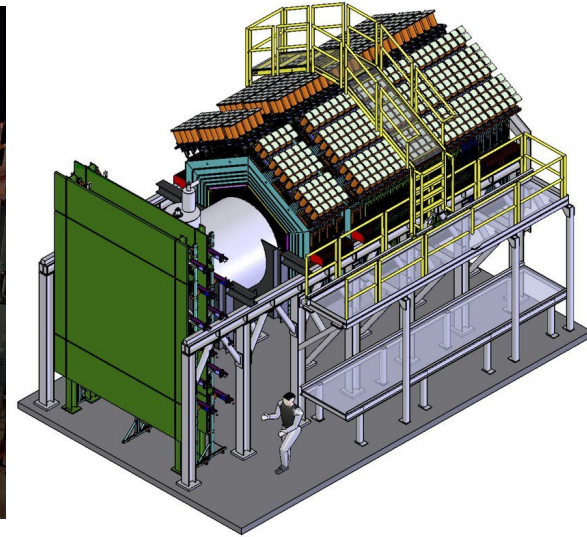
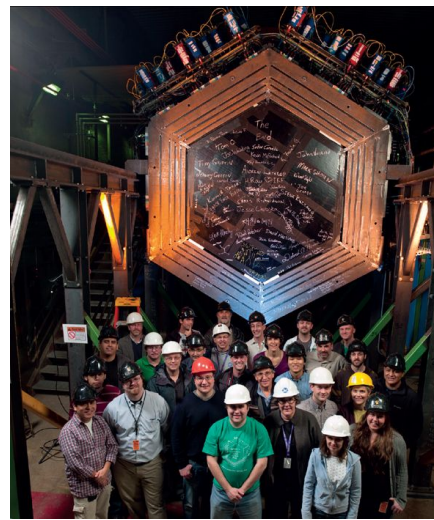
- Simulation
- Particles leave the 2x2 volume
- Additional detector can capture!

→ Let's repurpose an old detector!

<https://argoncube.org/duneND.html>

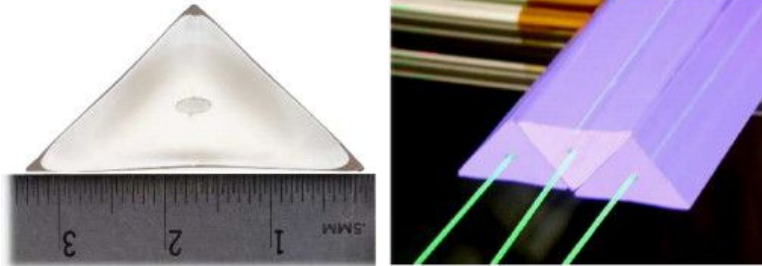
MINERvA

- Main Injector Neutrino Experiment to study ν -A interactions
- Studied ν reactions with 5 nuclei

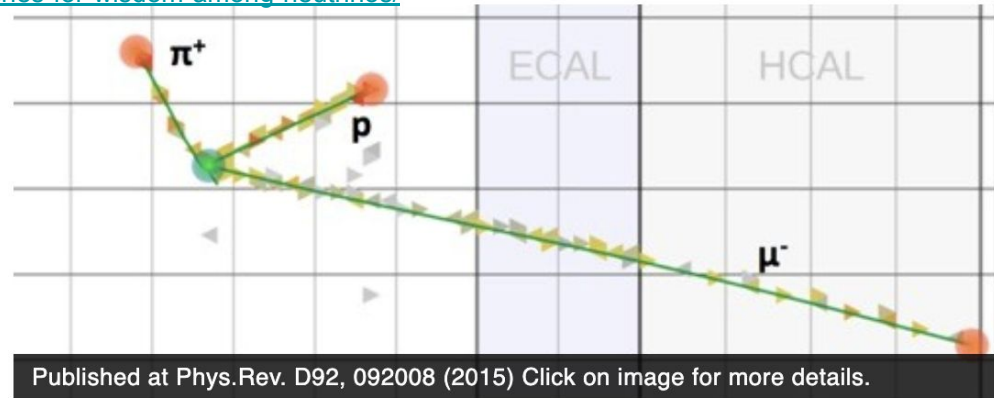


<https://cerncourier.com/a/minerva-searches-for-wisdom-among-neutrinos/>

DOI: [10.1109/IJCNN.2017.7966131](https://doi.org/10.1109/IJCNN.2017.7966131)



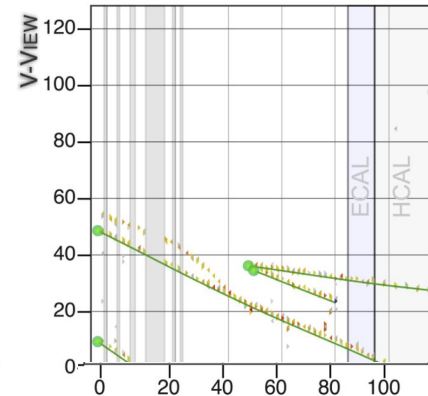
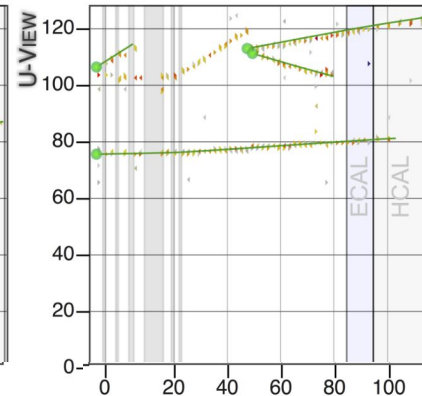
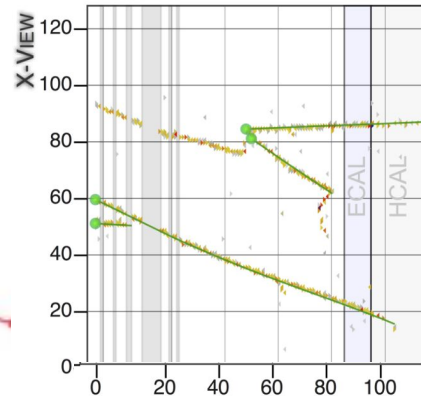
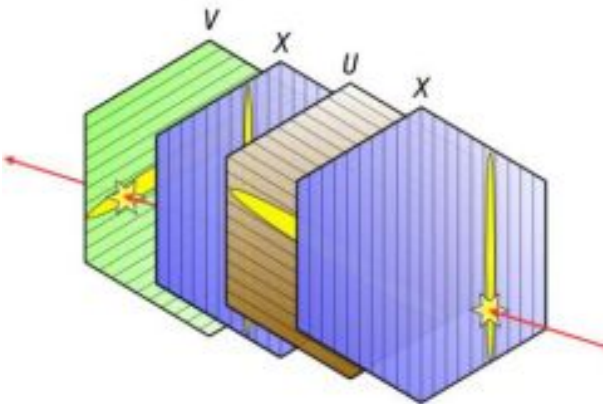
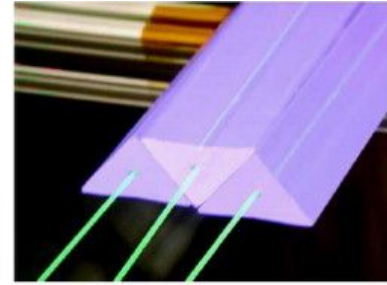
DOI: [10.1016/j.nima.2013.12.053](https://doi.org/10.1016/j.nima.2013.12.053)



MINERvA

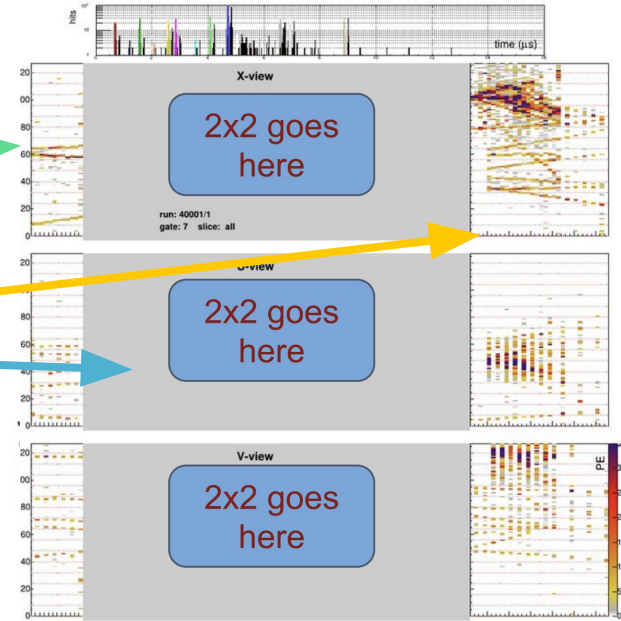
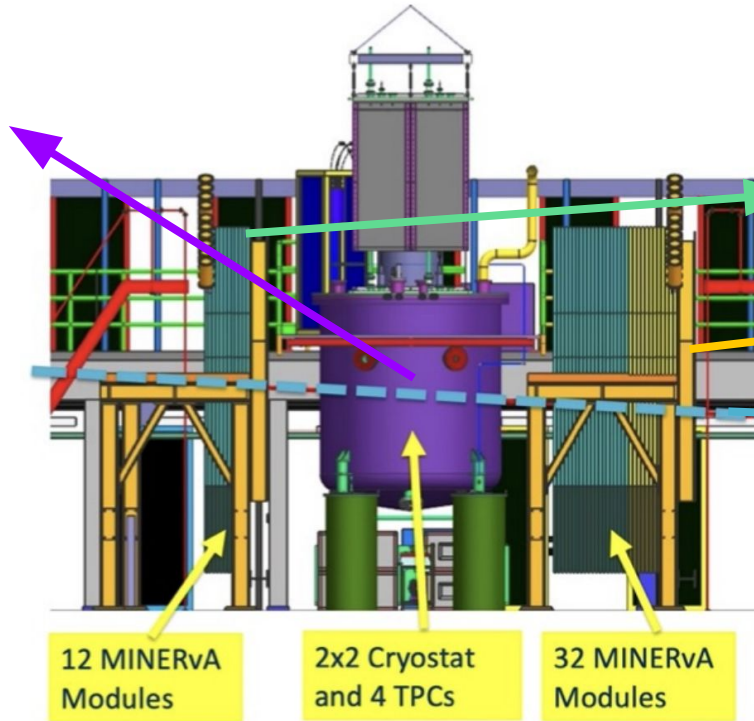
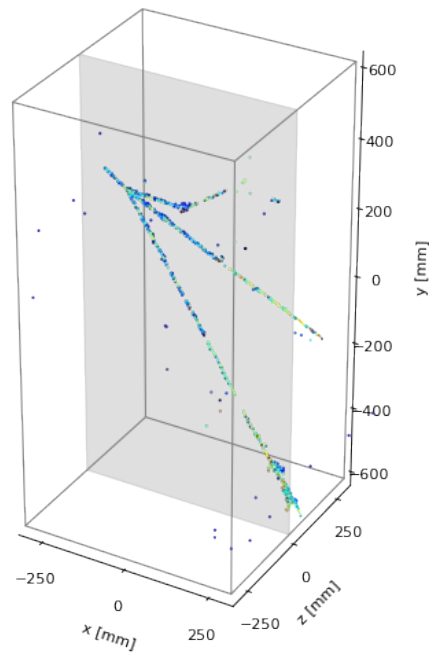


- Solid scintillation particle detector with 3 planes
- Detector split into upstream & downstream “sandwich” the 2x2



<https://arxiv.org/pdf/1111.5315.pdf>

Multi-Detector Network Training

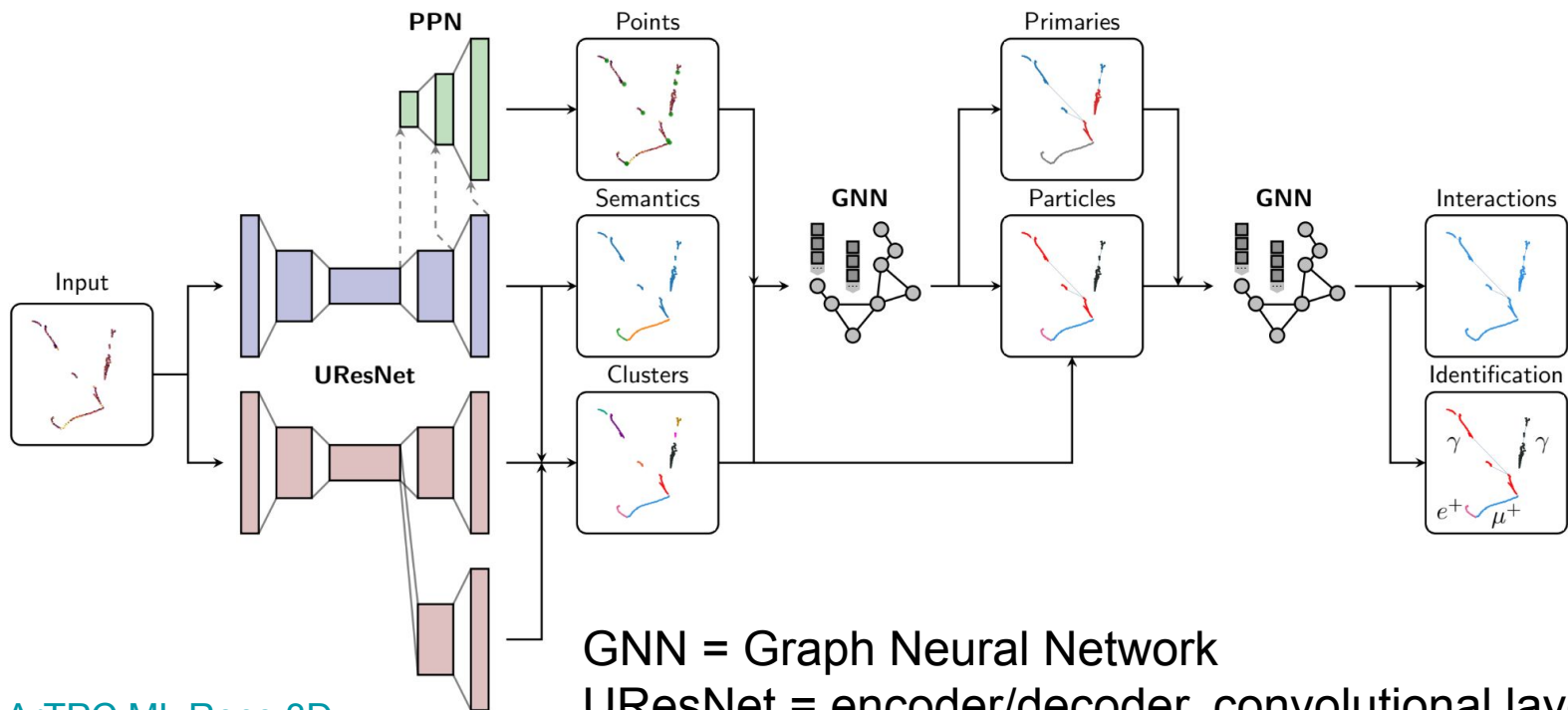


Preliminary
DUNE ND-LAr 2x2 MINERvA data

Let's talk ML!

→ Existing DUNE Tools

3D LAr TPC: ML Reco 3D



GNN = Graph Neural Network

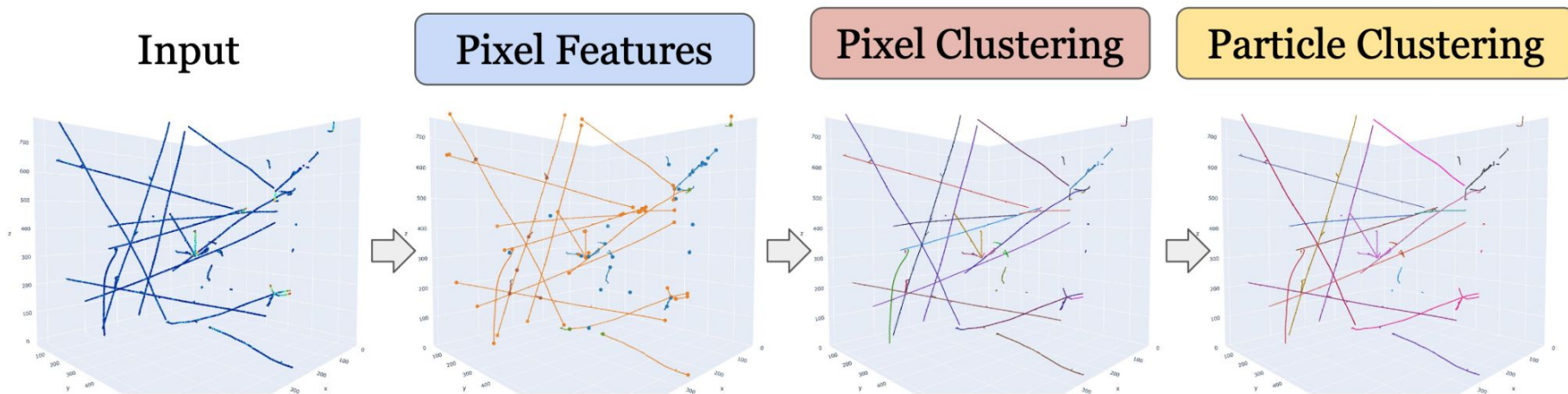
UResNet = encoder/decoder, convolutional layers

PPN = Point Proposal Network (convolutional)

[LArTPC ML Reco 3D](#)

3D LAr TPC: ML Reco 3D

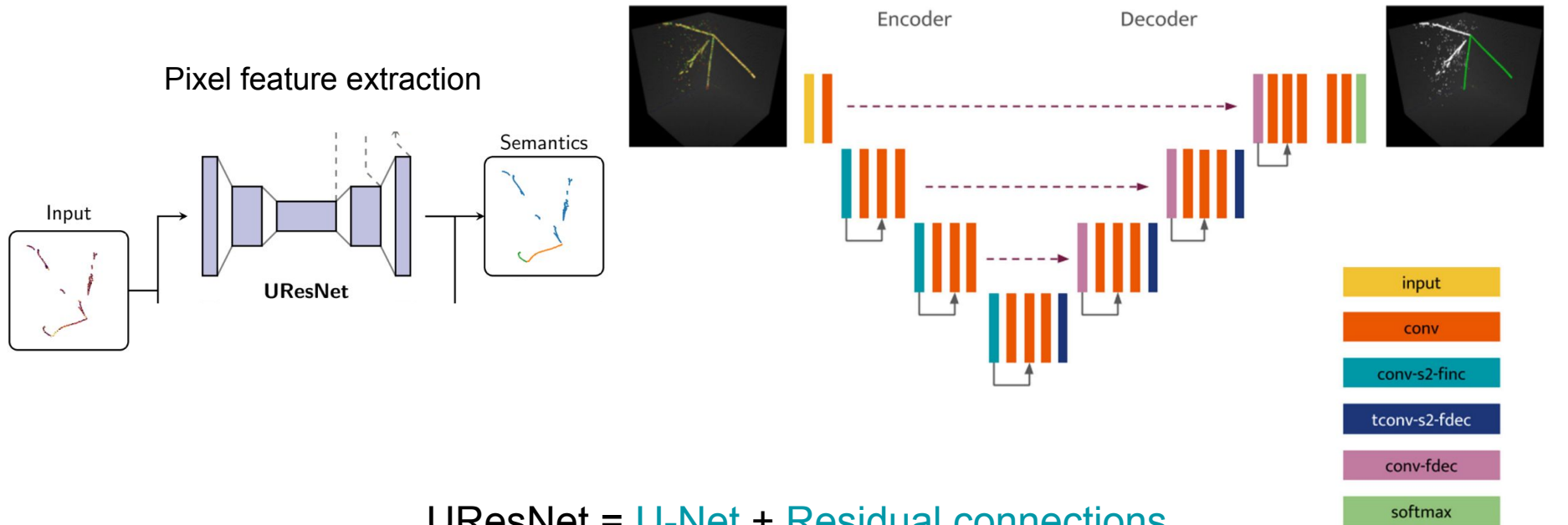
- Starts by labeling pixels & features
- End goal of chain: identifies particles in the input image



[LArTPC ML Reco 3D](#)

Graphic credit: Kazuhiro Terao

ML Reco 3D: Semantics



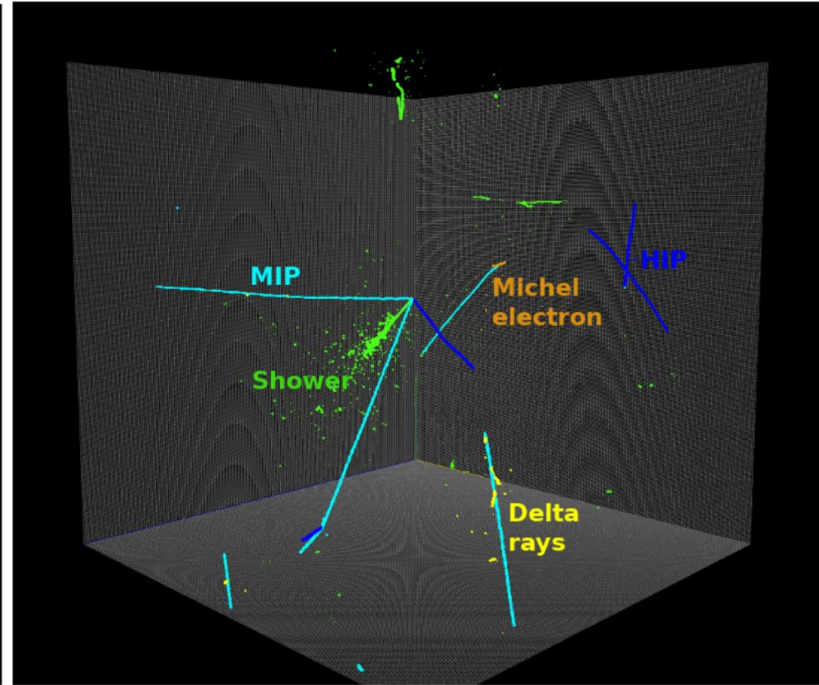
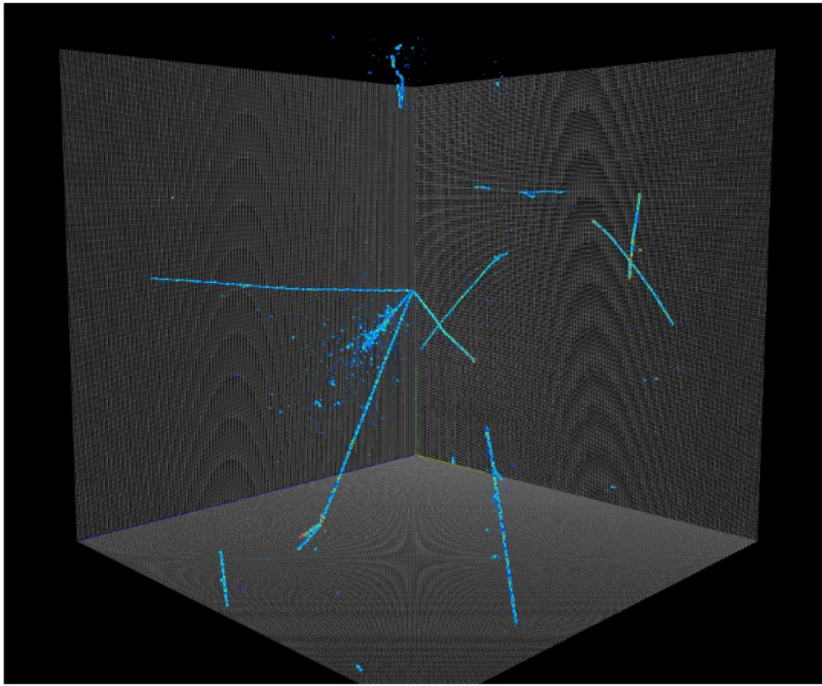
UResNet = U-Net + Residual connections

→ Uses autoencoder

→ Uses submanifold sparse convolutional layers

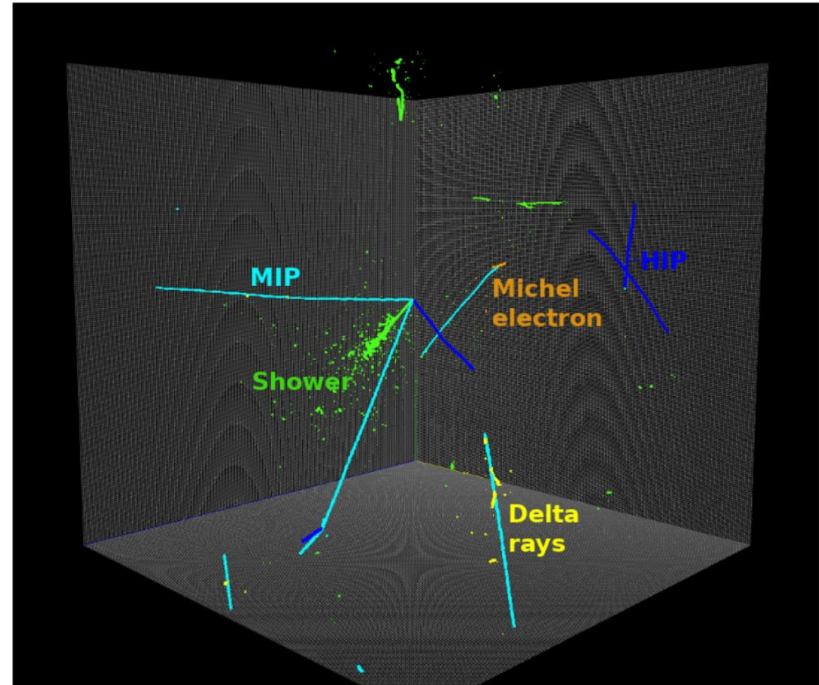
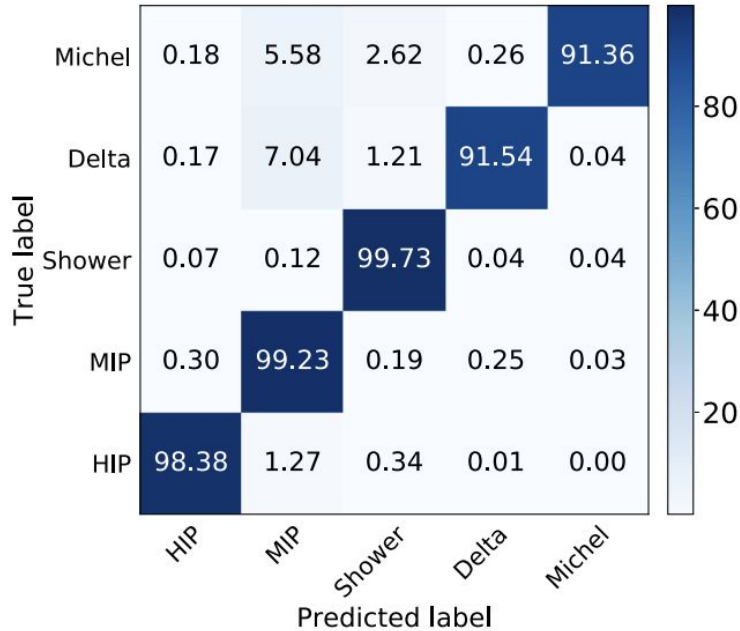
[LArTPC ML Reco 3D](#)
[Phys Rev D \(102\) 012005](#)

Assign Each Pixel To Label



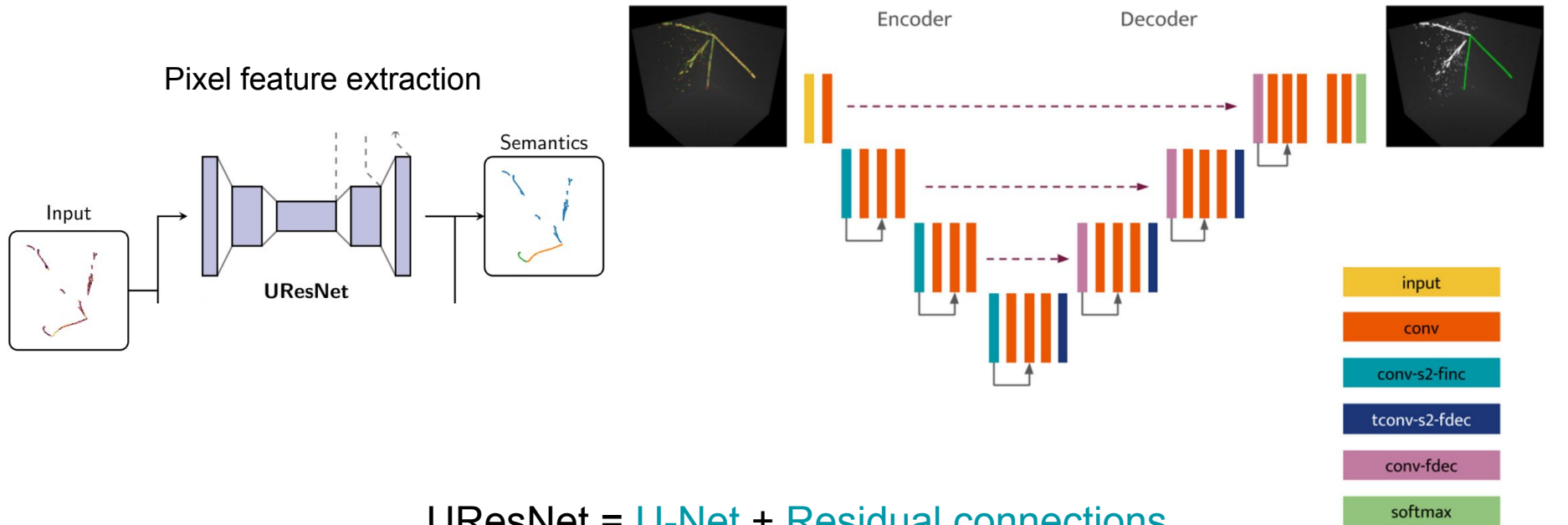
[Phys Rev D \(102\) 012005](#)

Assign Each Pixel To Label



[PhysRevD \(102\) 012005](#) & [PhysRevD \(104\) 032004](#)

ML Reco 3D: Semantics



UResNet = U-Net + Residual connections

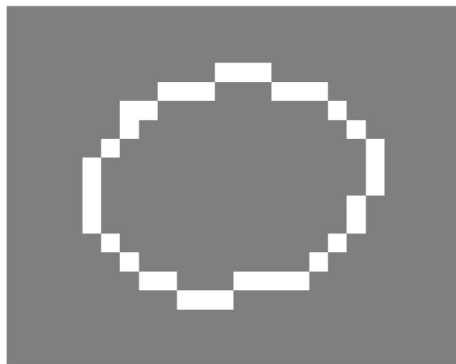
→ Uses autoencoder

→ Uses submanifold sparse convolutional layers

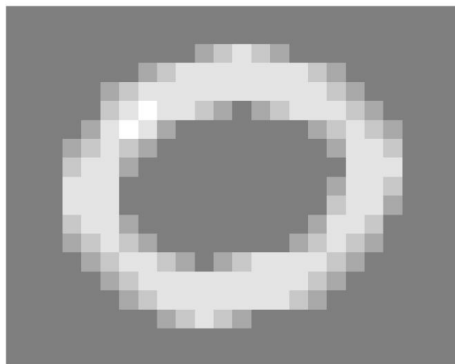
[LArTPC ML Reco 3D](#)
[Phys Rev D \(102\) 012005](#)

Submanifold Sparse Convolutions

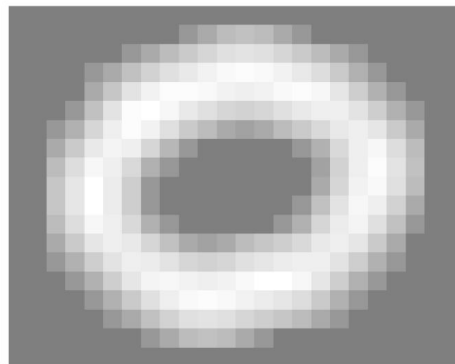
Original



3x3 Conv



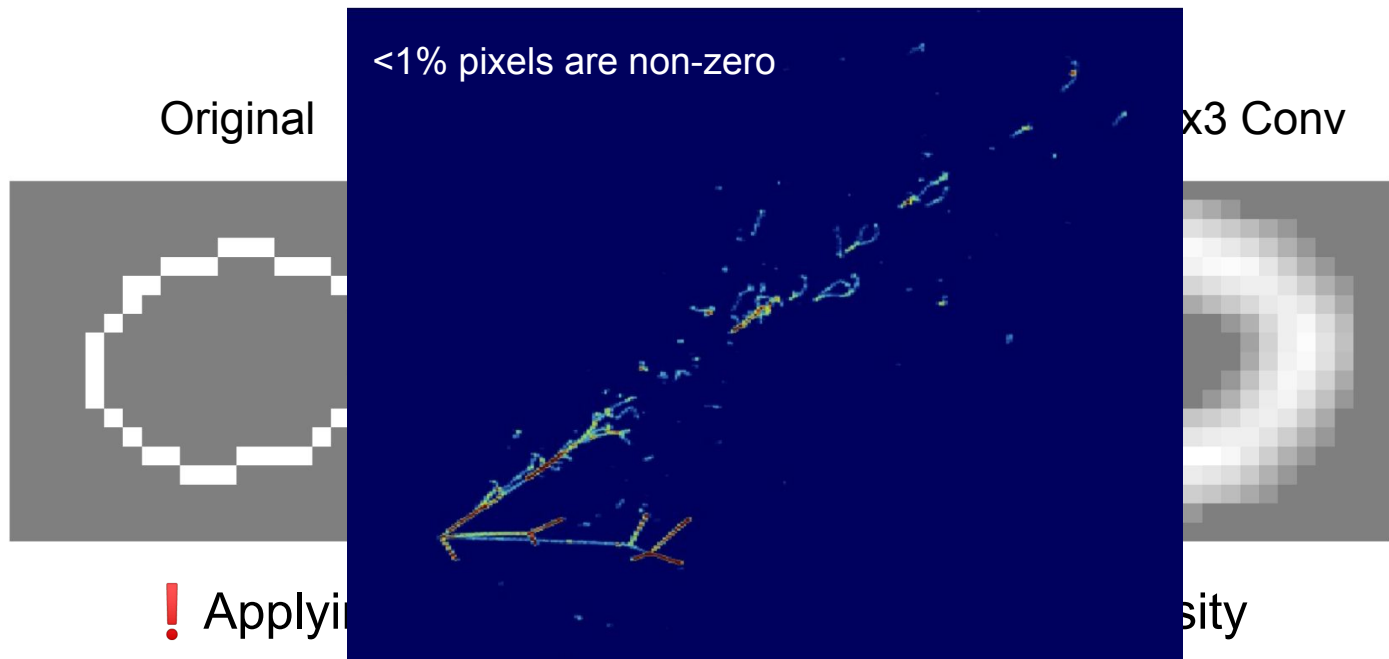
Another 3x3 Conv



! Applying regular convolutions reduces sparsity

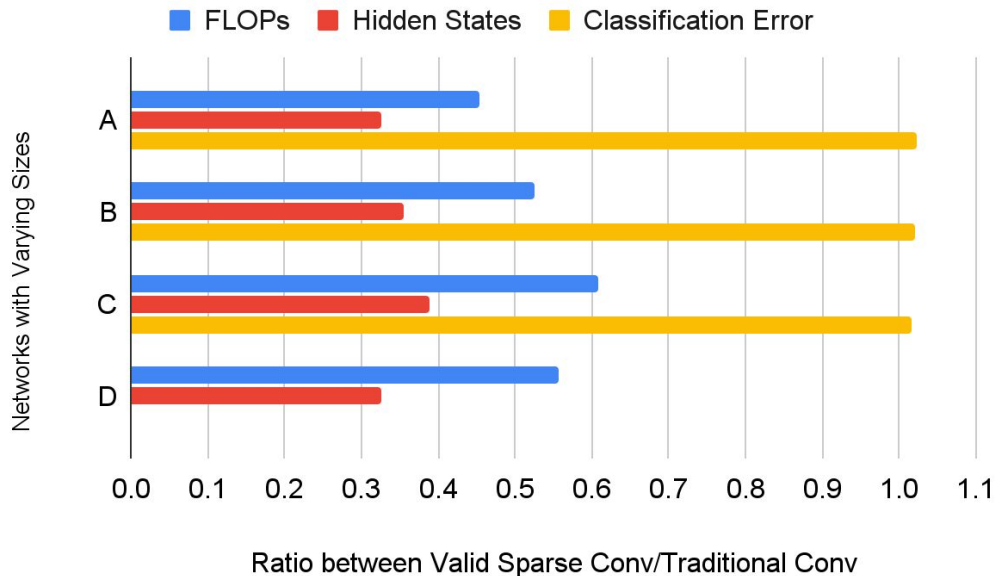
<https://arxiv.org/pdf/1706.01307.pdf>

Submanifold Sparse Convolutions



<https://arxiv.org/pdf/1706.01307.pdf>

Submanifold Sparse Convolutions



Advantage of sparse conv:

- ✓ Classification error ~equal
- ✓ Uses $\sim\frac{1}{2}$ FLOPs
- ✓ Uses $\sim\frac{1}{3}$ hidden states

Example Application:

*On MicroBooNE, gives capability to train on **entire** LArTPC image, instead of 64 crops (ref Ran's [Talk at NPML 2020](#))!*

<https://arxiv.org/pdf/1706.01307.pdf>

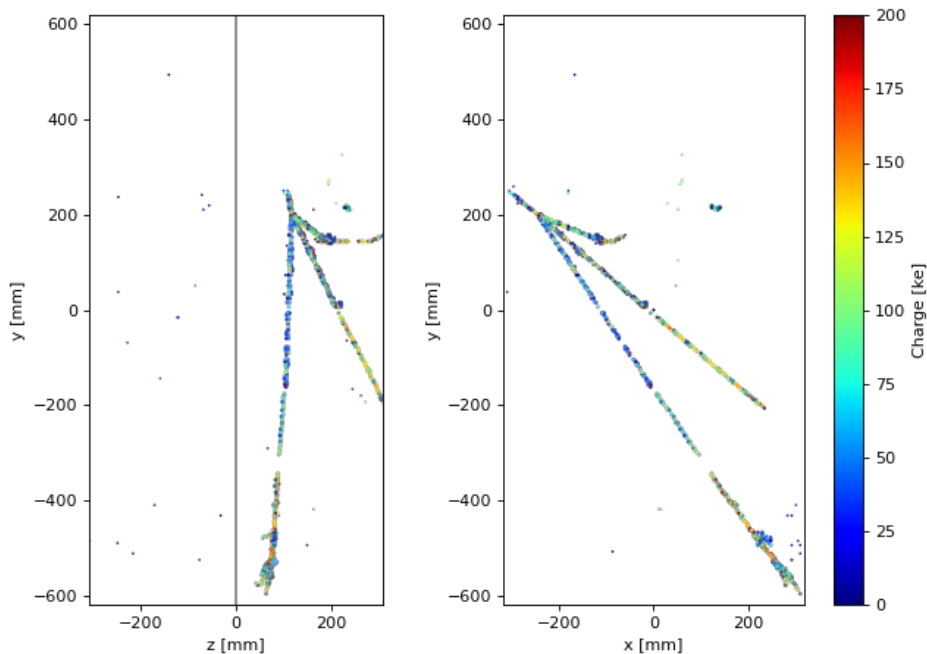
Wait! MINERvA has different detection resolution

→ *CNN would be affected by this*

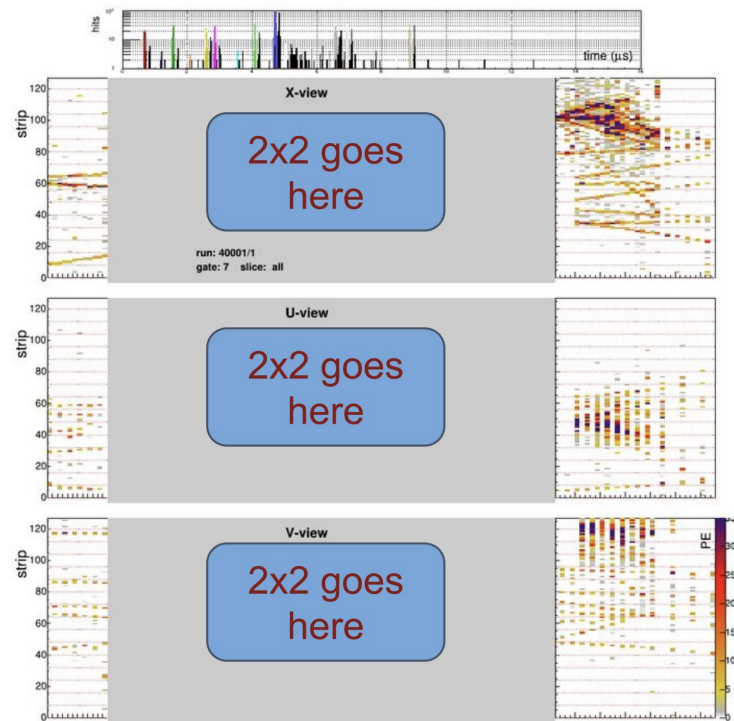
Wait! MINERvA has different detection resolution

→ *CNN would be affected by this*

2x2 in 2D projection simulation

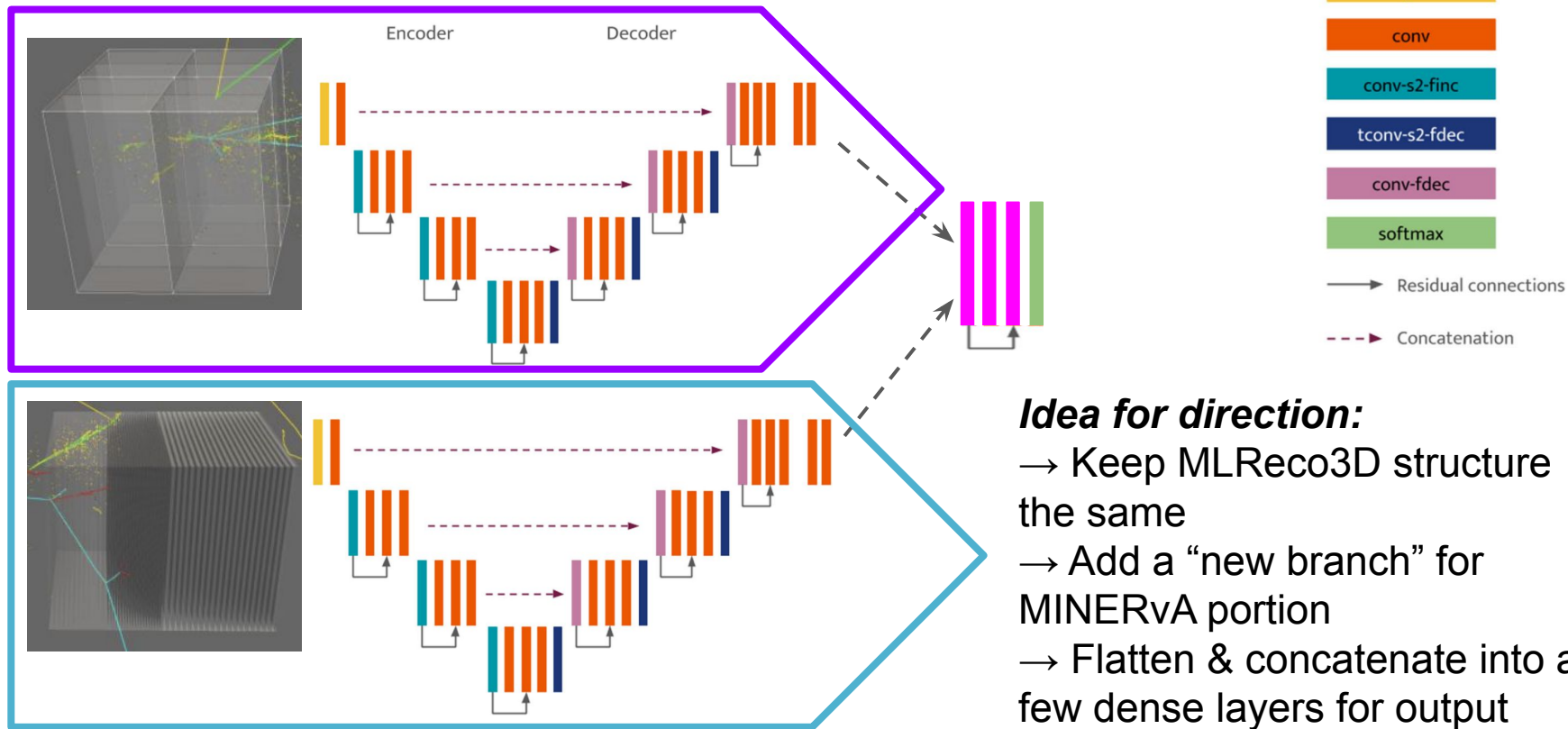


Preliminary DUNE ND-LAr 2x2 MINERvA data



Idea for ML Reco 3D: Adding MINERvA

ML Reco 3D: Adding MINERvA



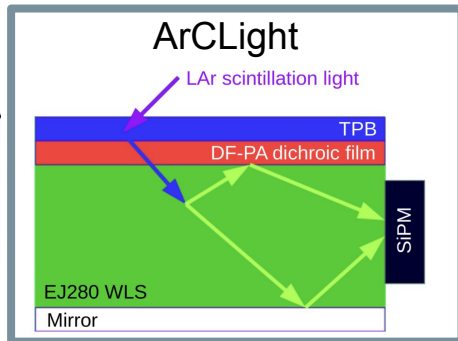
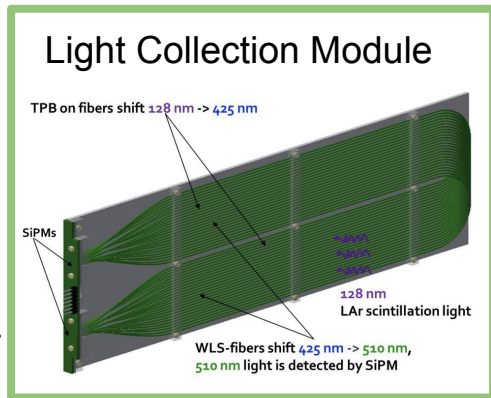
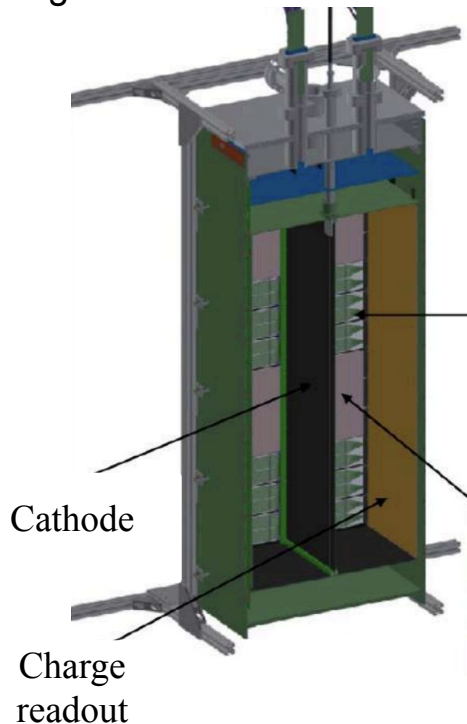
Idea for direction:

- Keep MLReco3D structure the same
- Add a “new branch” for MINERvA portion
- Flatten & concatenate into a few dense layers for output

Future Applications

- Integrating detection from multiple detectors into single network
 - Light & Charge

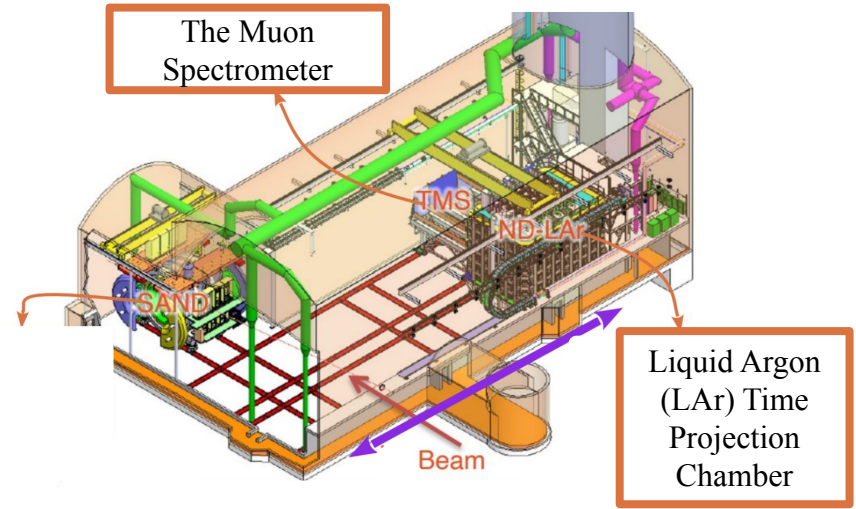
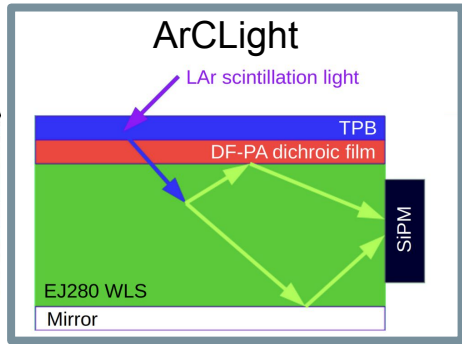
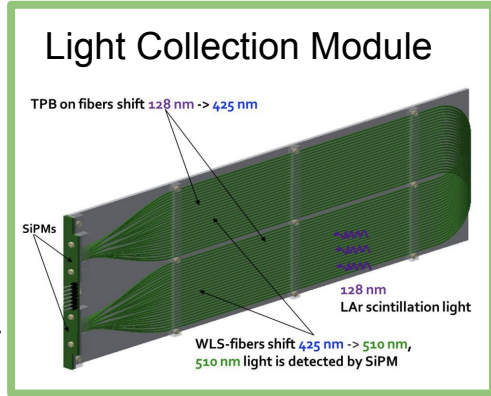
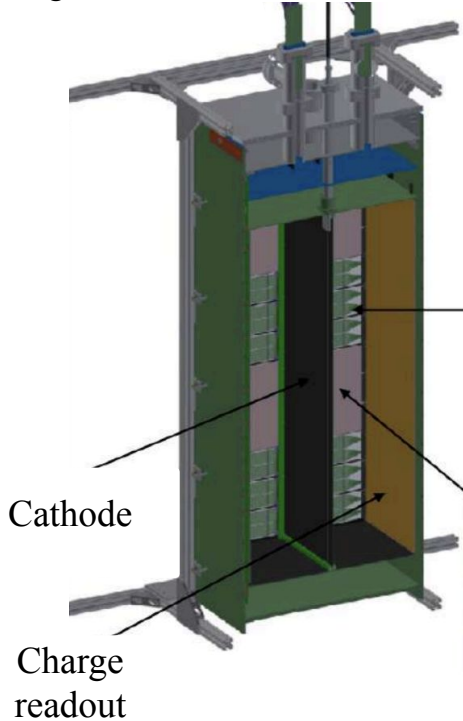
Single ND-LAr Module



Future Applications

- Integrating detection from multiple detectors into single network
 - Light & Charge
 - ND-LAr & TMS

Single ND-LAr Module



Thank you for your attention!



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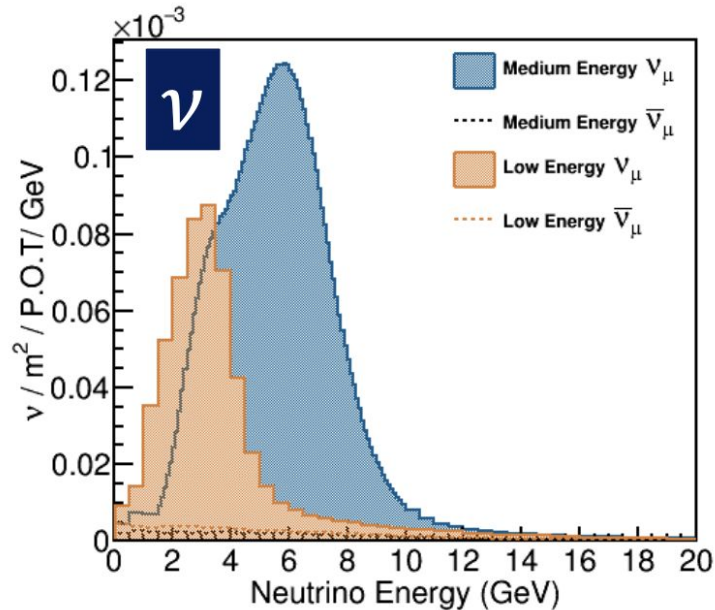


2x2 Analysis Workshop May 2023

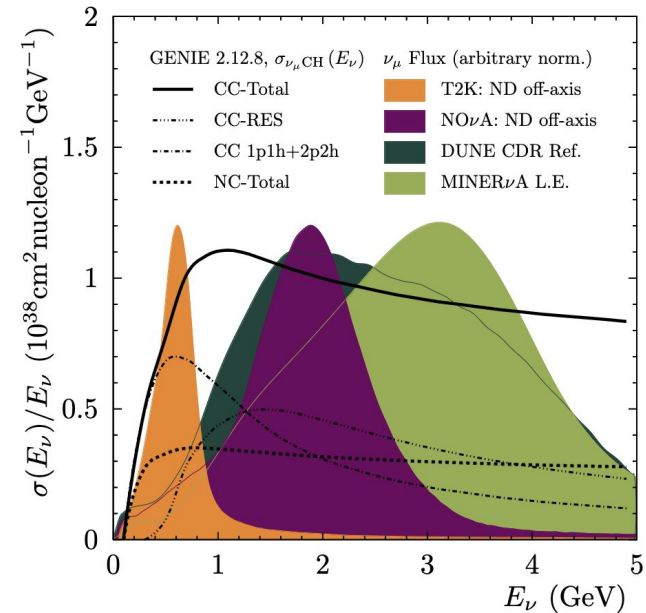
Backup

2x2 Prototype Beam vs DUNE Beam

NuMI



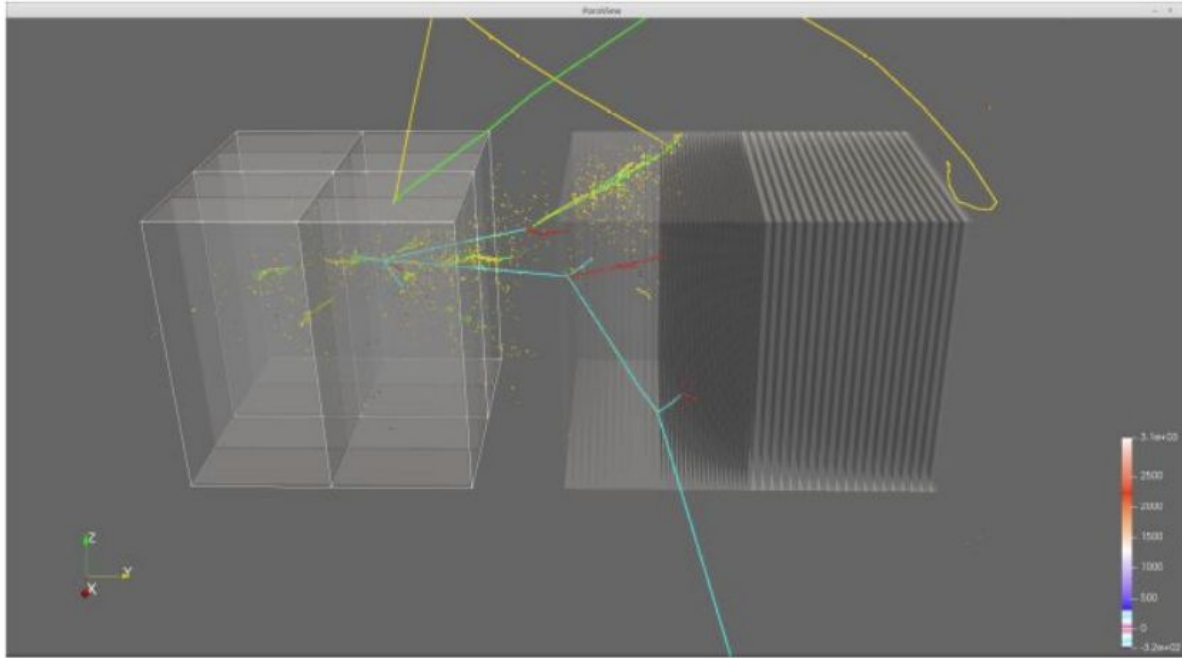
DUNE (green)



https://indico.cern.ch/event/881216/contributions/5048756/attachments/2534229/4361050/Klustova_MINERvAFlux_NuINT22.pdf

<https://arxiv.org/pdf/1803.08848.pdf>

Thinking About Multi-Detector Training



- Take 2D MINERvA output → 3D hits
- Choose voxel (“pixel”) resolution
 - Different than 2x2
- Extract target input features and training labels
 - Particle ID
 - Points of interest (stop & end points)
 - Parent particle

<https://argoncube.org/duneND.html>