

Convolution Neural Networks in Nucleon Decay Searches in Liquid Argon Time Projection Chambers

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Liquid Argon Time Projection Chambers (LArTPCs)

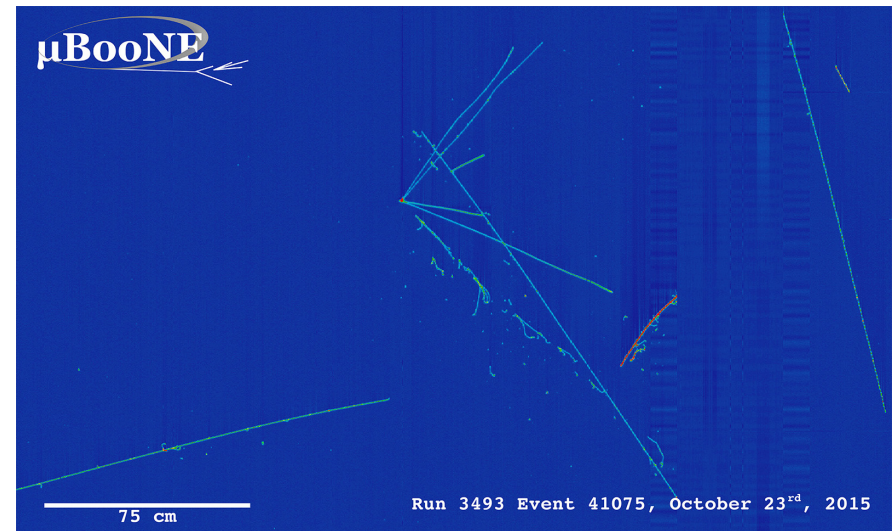
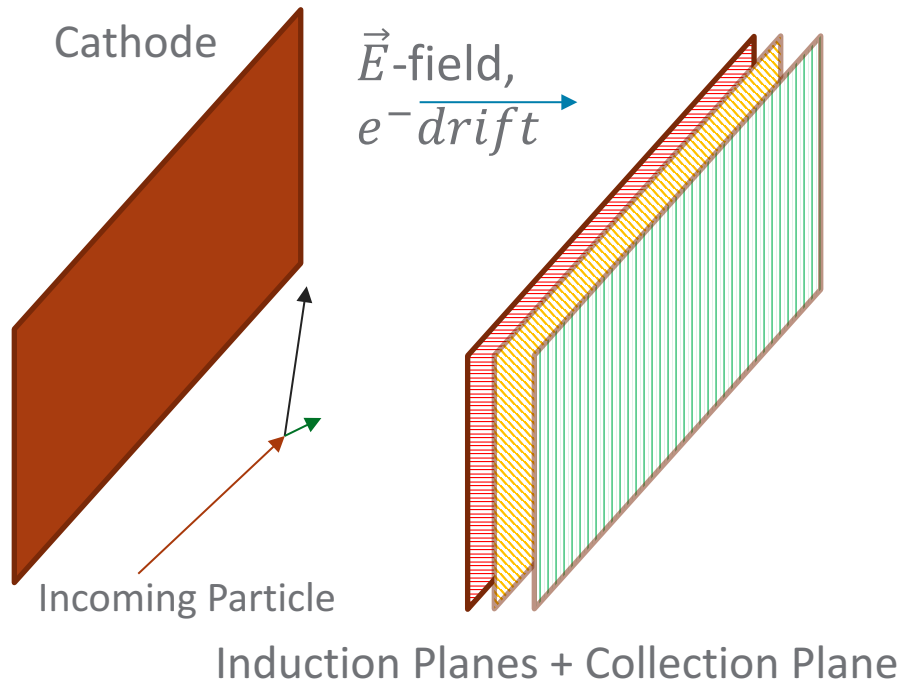
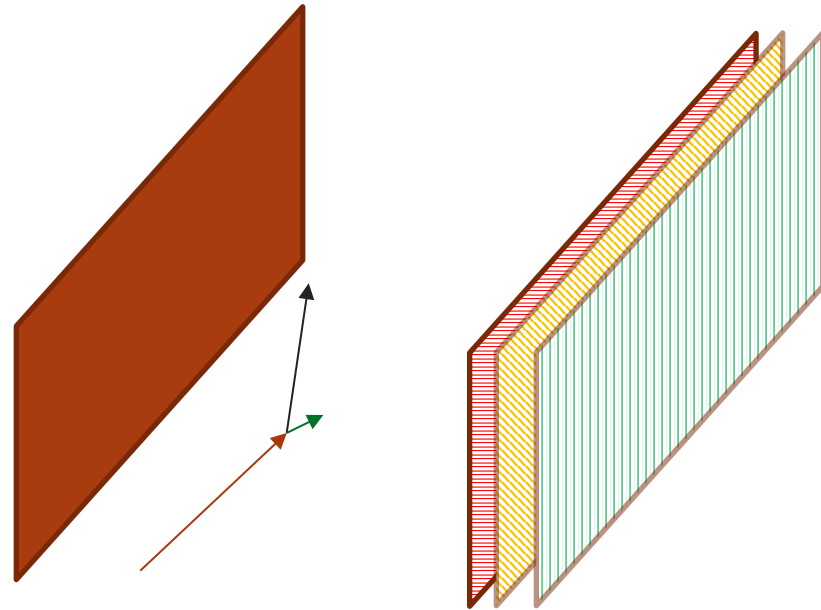


Image courtesy of MicroBooNE collaboration
<https://www-microboone.fnal.gov/>

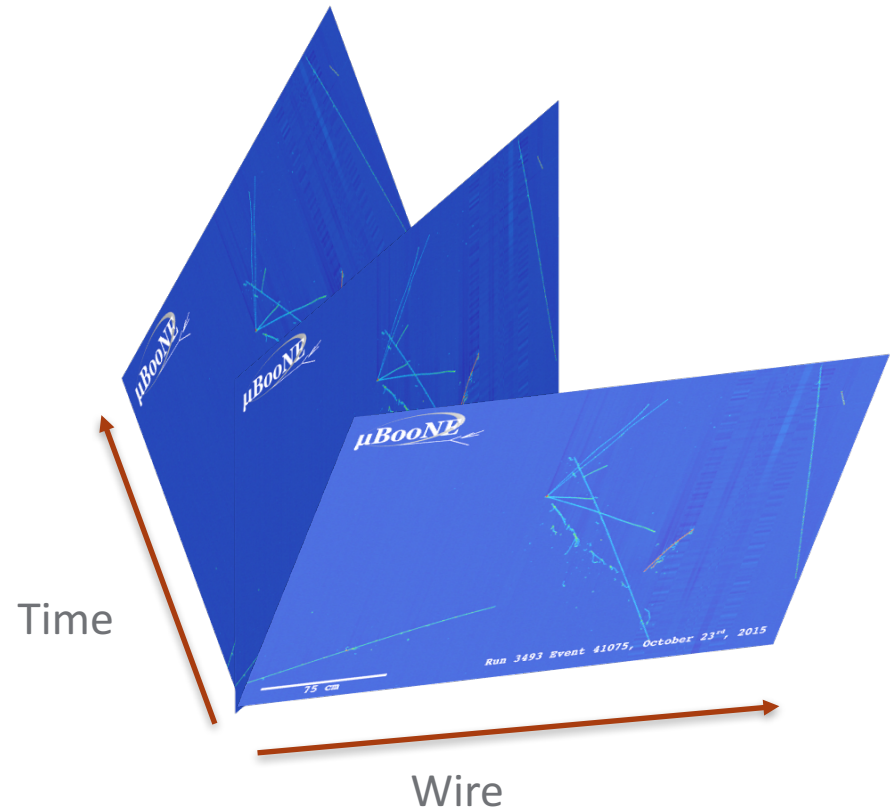


LArTPC Data From 3-Planes

Planes at an angle to each other



Particle tracks project onto wire planes





On Using 3 Planes

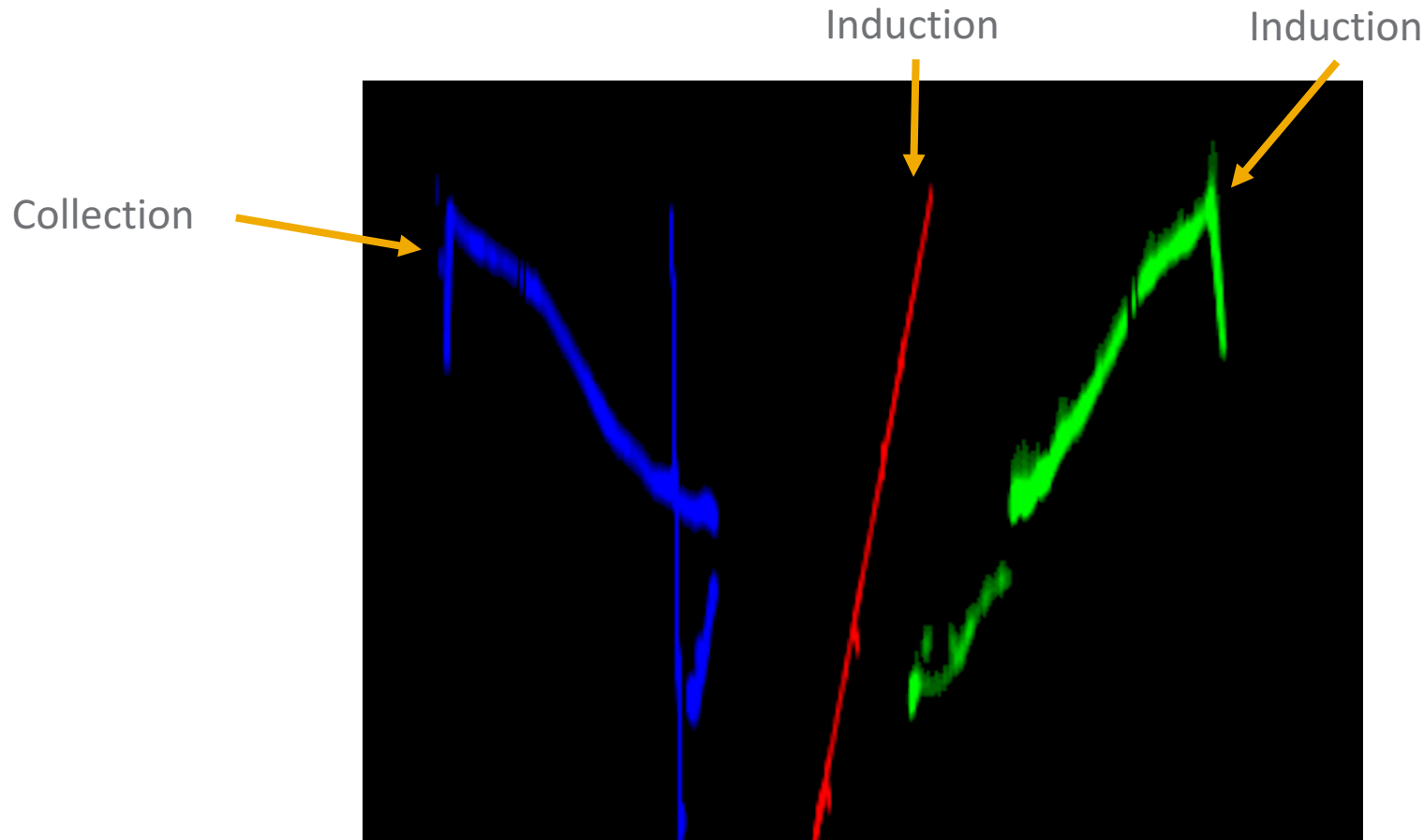
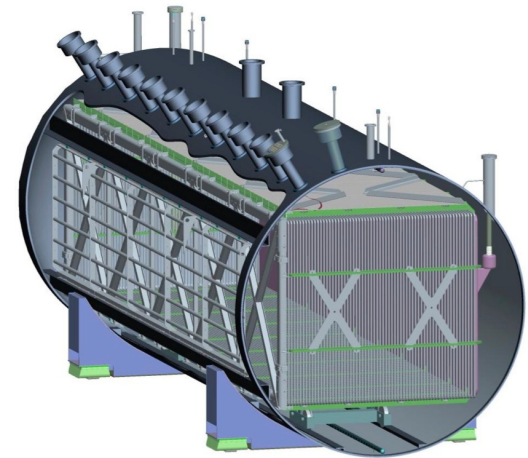


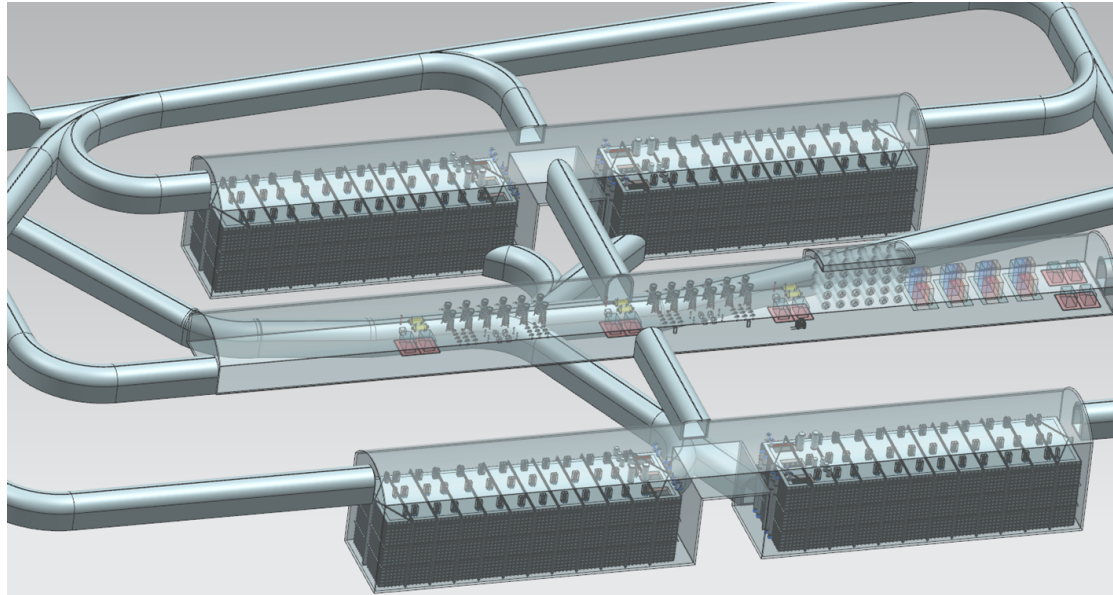
Image-like, but not quite. Image courtesy of LArSoft and Maze package.



MicroBooNE

- ▶ 170 Tonne LArTPC
 - Current generation scale TPC
 - Part of short baseline program
- ▶ 3 planes
 - 2 Induction planes @ 3256 wires
 - 1 Collection Plane @ 3600 wires
- ▶ Readout window
 - 9600 digitizations (or time ticks) total
 - 4.8 ms ($\sim 3\times$ drift length of TPC)
 - Additionally records optical data via PMTs for T0
- ▶ Image courtesy of: <https://www-microboone.fnal.gov/public/aboutdetector.html>

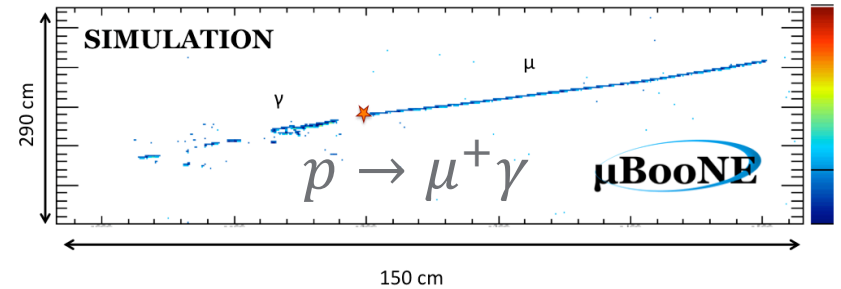
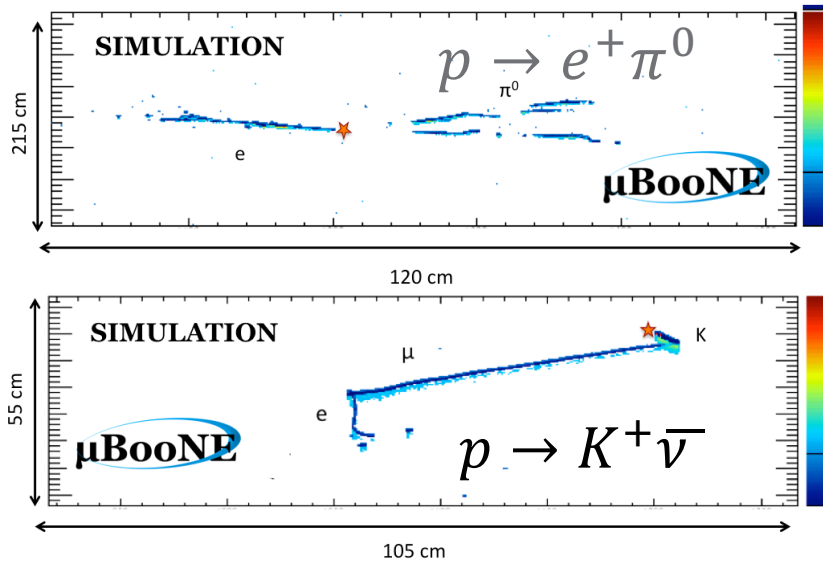




Dune Far detector

- 4x 17.1 kTonne LAr
- Single Phase design
 - 150 Anode Plane Assemblies (APAs)/module
 - 200 Cathode Plane Assemblies
 - 2560 Channels/APA, 1 collection, 2 induction
- Next generation long-baseline LArTPC
- Image courtesy of: <http://lbnf.fnal.gov/> .

Proton Decay



- Candidate decay processes from Bueno paper
 - (<https://doi.org/10.1088/1126-6708/2007/04/041>).
- PDK lifetime can limit GUT scale models.
 - SUSY favorite: $p \rightarrow K^+ \bar{\nu}$

Images courtesy of MicroBooNE collaboration and Elena Gremallini



NDK Measurement Goal

Our standard Bayesian analysis for rare decays:

Diagram illustrating the Bayesian analysis formula for rare decays, with annotations:

- Lifetime variable** (green text, arrow pointing to Γ)
- MC background rate** (red text, arrow pointing to b_{MC})
- Efficiency** (red text, arrow pointing to ϵ)
- Number of candidate events** (red text, arrow pointing to n)
- Background rate** (red text, arrow pointing to b)
- Luminosity** (red text, arrow pointing to \mathcal{L})
- Gaussian integrand terms** (red text, arrow pointing to the exponential term $e^{-\frac{b_{MC}^n (\Gamma \lambda \epsilon + b)}{b}}$)

$$CL \text{ (Set to 0.95)} = \int_0^{\Gamma_{lim}} d\Gamma \int_0^\infty db \int_0^\infty db_{MC} \int_0^\infty d\lambda \int_0^1 d\epsilon \frac{b_{MC}^n (\Gamma \lambda \epsilon + b)^n}{b} e^{-\frac{b_{MC}^n (\Gamma \lambda \epsilon + b)}{b}}$$

Formula courtesy of B. Viren, dissertation



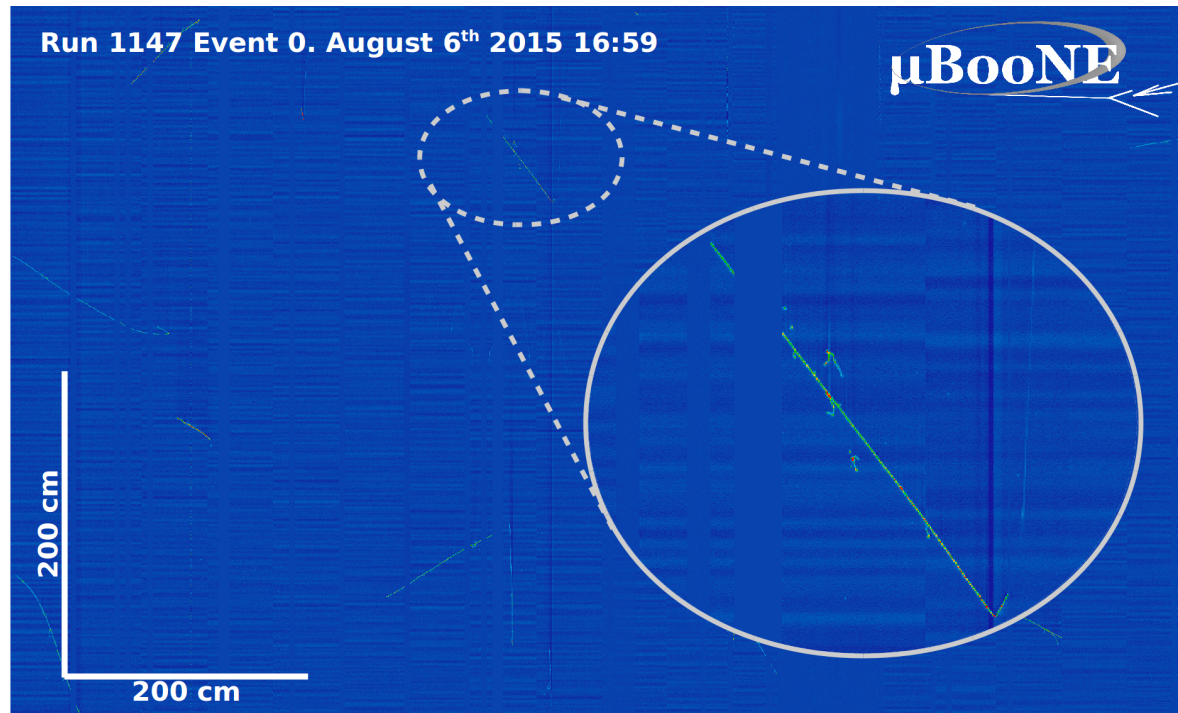
Backgrounds

▶ MicroBooNE

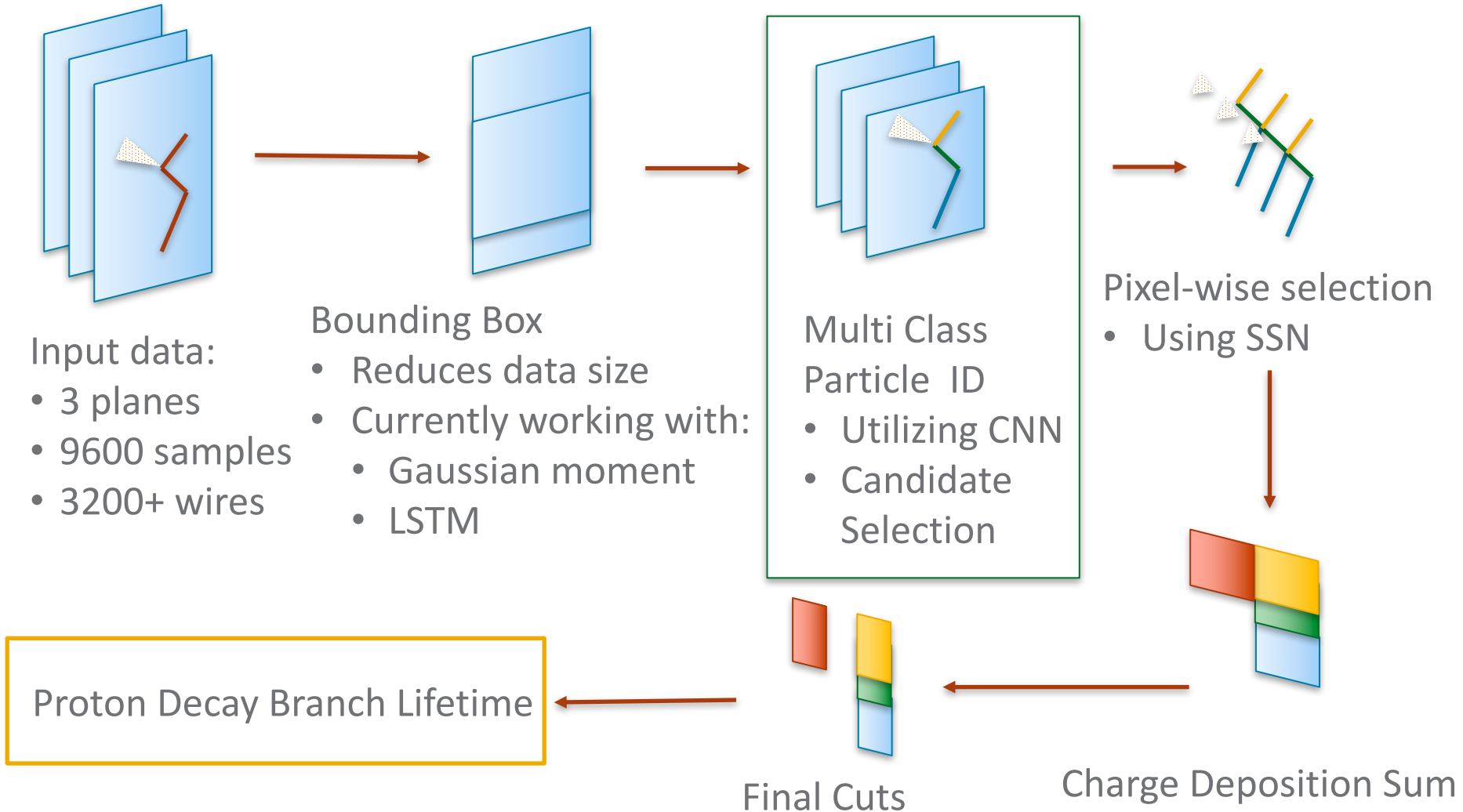
- Primary background: cosmics
- Roughly 11 cosmics per readout window

▶ DUNE

- Primary background: atmospheric ν 's
- 1 Background, $\text{Mt}^{-1} \text{y}^{-1}$



NDK Measurement Strategy using CNNs





Previous Work on CNNs in LArTPCs

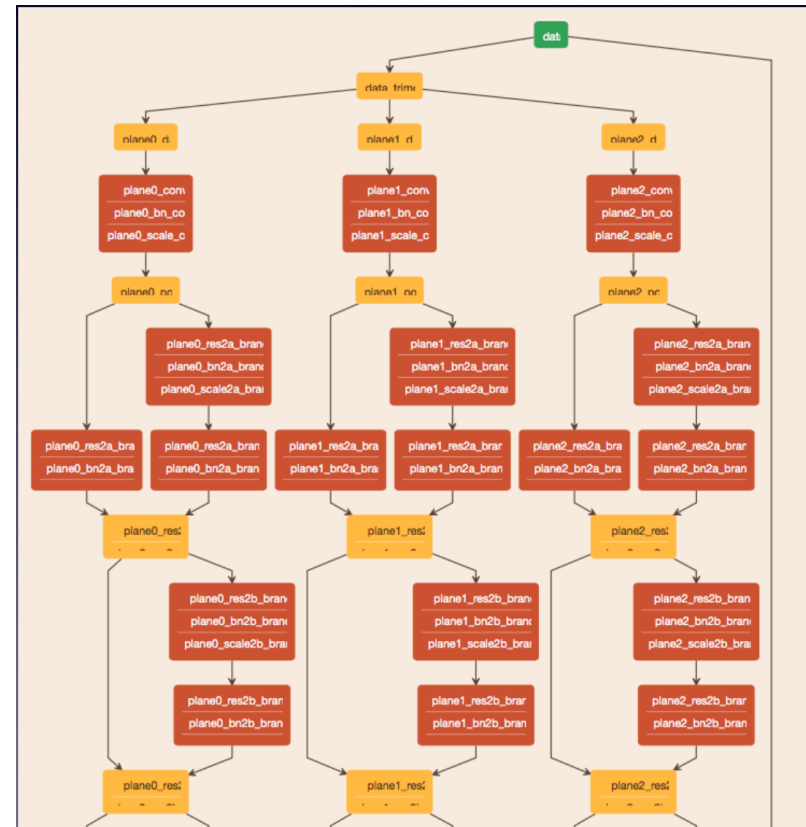
- ▶ DL work done by Nevis/MIT group for uBooNE
 - <https://arxiv.org/abs/1611.05531>
 - Aimed at the Neutrino LEE analysis
 - Provides:
 - Caffe-based framework
 - OpenCV based image pre-processing
 - 3-plane treatment
 - Single particle identification
 - Semantic segmentation





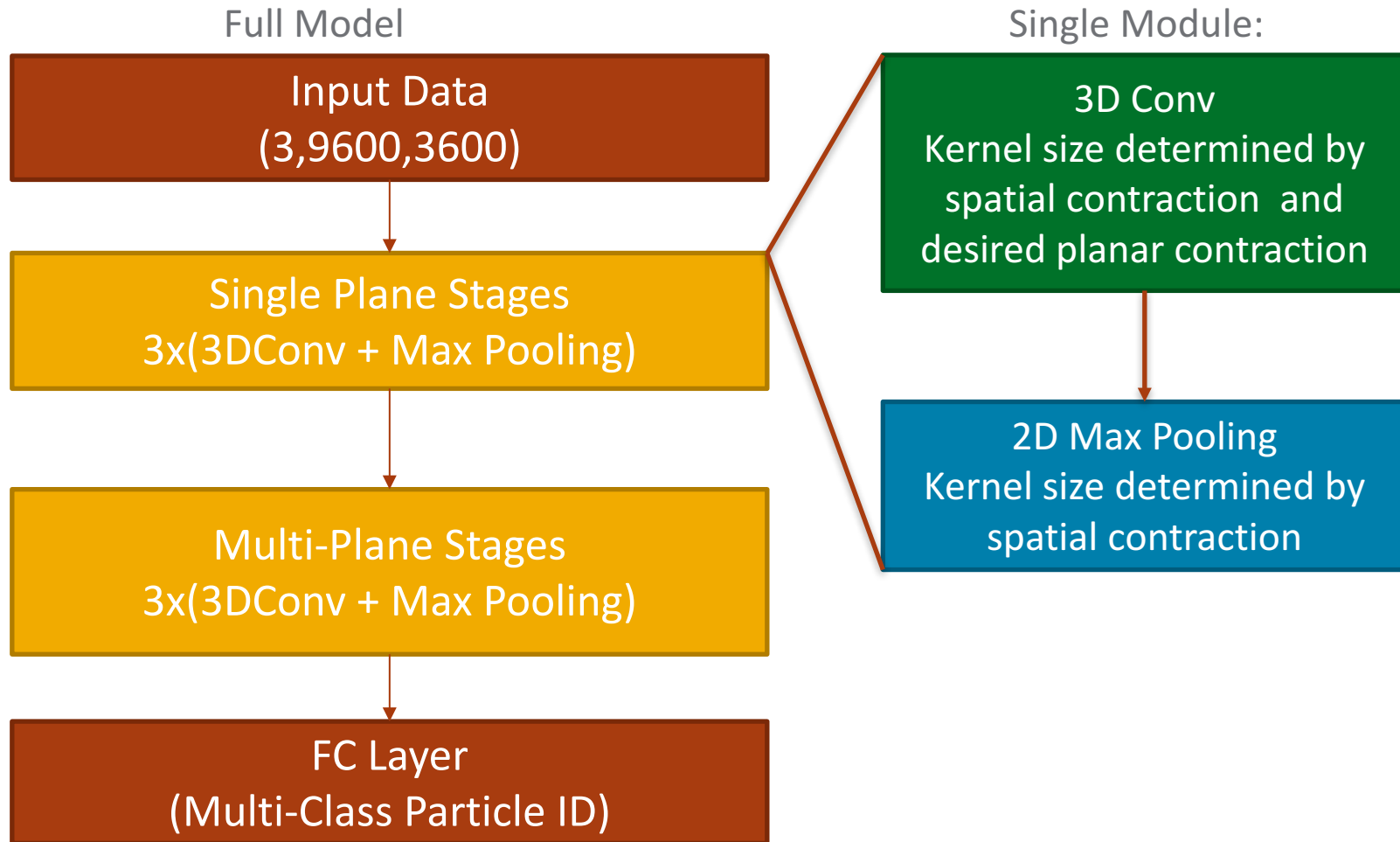
Siamese Towers

- ▶ Break 3 plane data into 3 sub-networks
- ▶ Concatenate output filters after several modules
- ▶ Perform more traditional analysis after concatenation
- ▶ Used in:
 - uBooNE LEE Analysis
 - NOVA
 - <https://arxiv.org/abs/1604.01444>



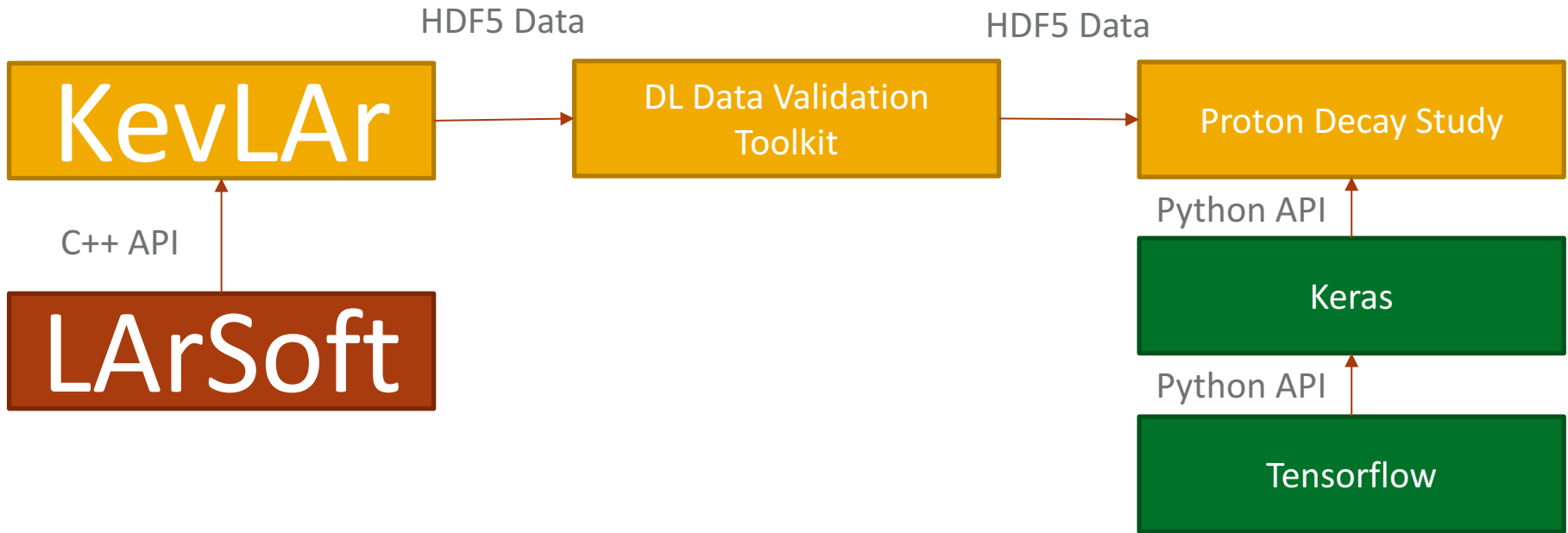


Network Architecture





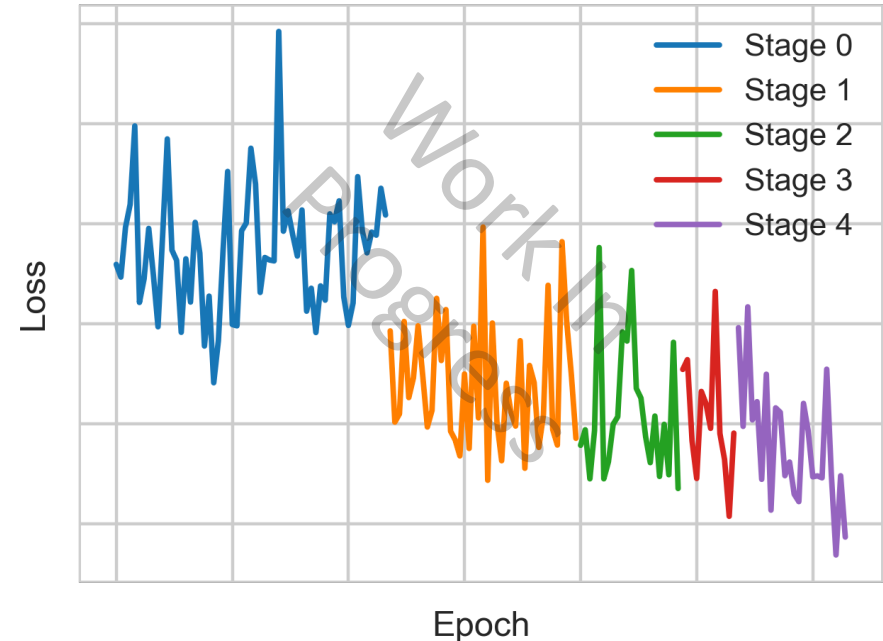
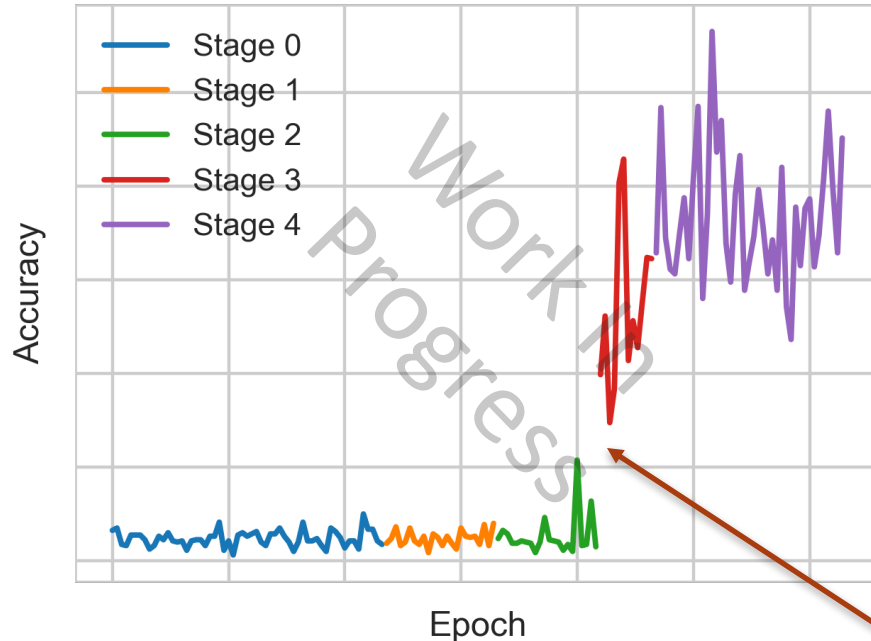
Software



- <http://larsoft.org/>
- <https://github.com/HEP-DL/kevlar>
- https://github.com/HEP-DL/dl_data_validation_toolset
- https://github.com/HEP-DL/proton_decay_study
- <https://keras.io/>
- <https://www.tensorflow.org/>



Work-In-Progress Results



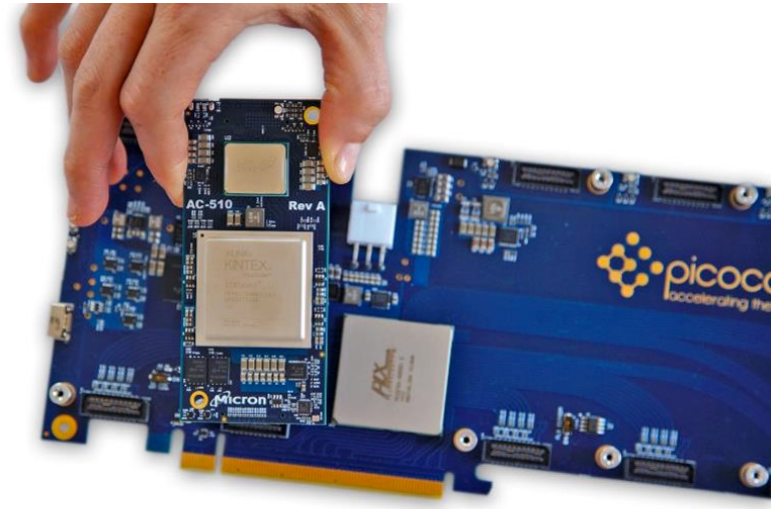
Stage where network goes from 1 plane to 3 planes

- Train by pre-training subsets of the network
- Stage 0 is the input, FC layer and 1st module
- Stage 1 is input, FC layer and 1st and 2nd modules, etc...



Inline/Neartime Analysis Work

- ▶ PNNL has a partnership with Micron
 - Working on developing architecture on FPGAs for inline triggering and analysis
 - Micron has provided Xilinx Vertex7 based FPGAs with hybrid memory cubes
 - Critical for identifying out-of-beamspill events using CotS components
 - Currently Work in Progress





Conclusion

- ▶ Working on identifying PDK in LArTPCs
 - 2 experiments
 - uBooNE
 - DUNE
- ▶ Creating methods common to both experiments
 - Both experiments have VERY LARGE datasets
 - Both experiments have backgrounds that motivate using CNNs
- ▶ Working on maximizing usage of multi-planar data using network architecture
 - Accuracy jump when moving to 3 planes shows that utilizing all planes is necessary
 - Requires architecture that supports all 3 planes
- ▶ Developing architecture on Micron FPGAs.
- ▶ More results to come!



Thanks to the other ML Groups!

► Working with other FNAL-based experiments and groups

■ uBooNE

- K. Terao, T. Wongjirad et al.

■ DUNE

- A. Radovic et al. (neutrino oscillations)
- J. Hewes, G. Karagiorgi (n-nbar oscillations)

■ NOVA

- F. Psihas and collaborators

And Many others!