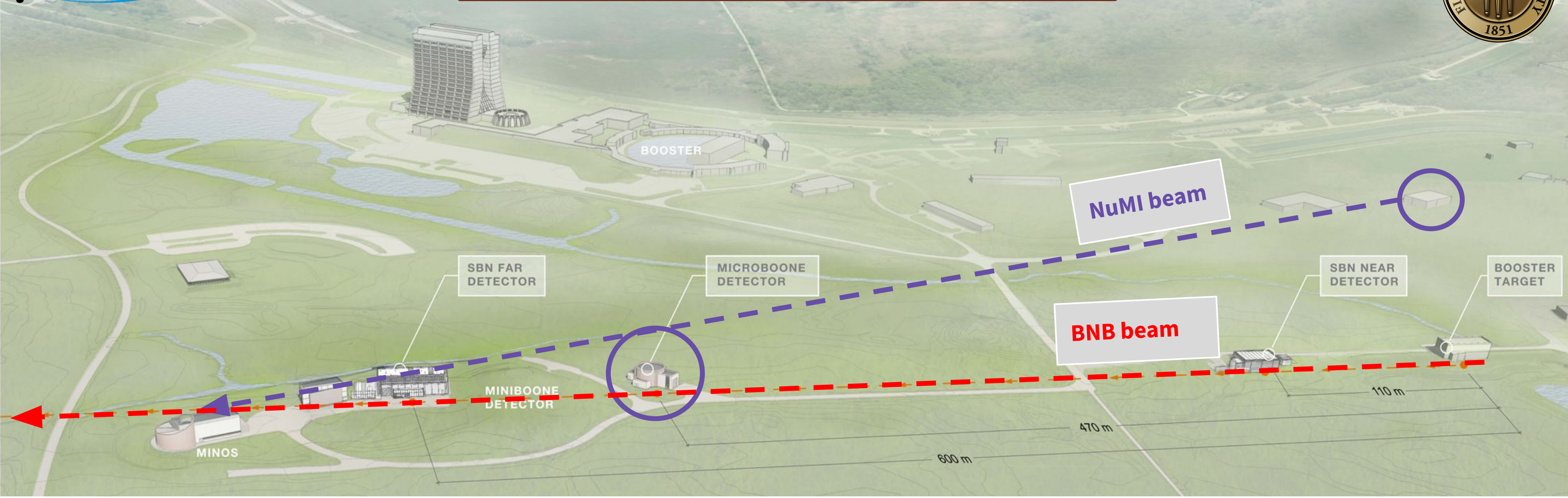
Searching for Dark Tridents with Convolutional Neural Networks

Luis Mora-Lepin on behalf of the MicroBooNE collaboration
Neutrino Physics and Machine Learning Conference, ETH Zürich
25/06/2024

Outline

- The MicroBooNE detector and NuMI
- Overview of dark trident search
- A CNN for signal and background classification
- Results

MicroBooNE at Fermilab



MicroBooNE:

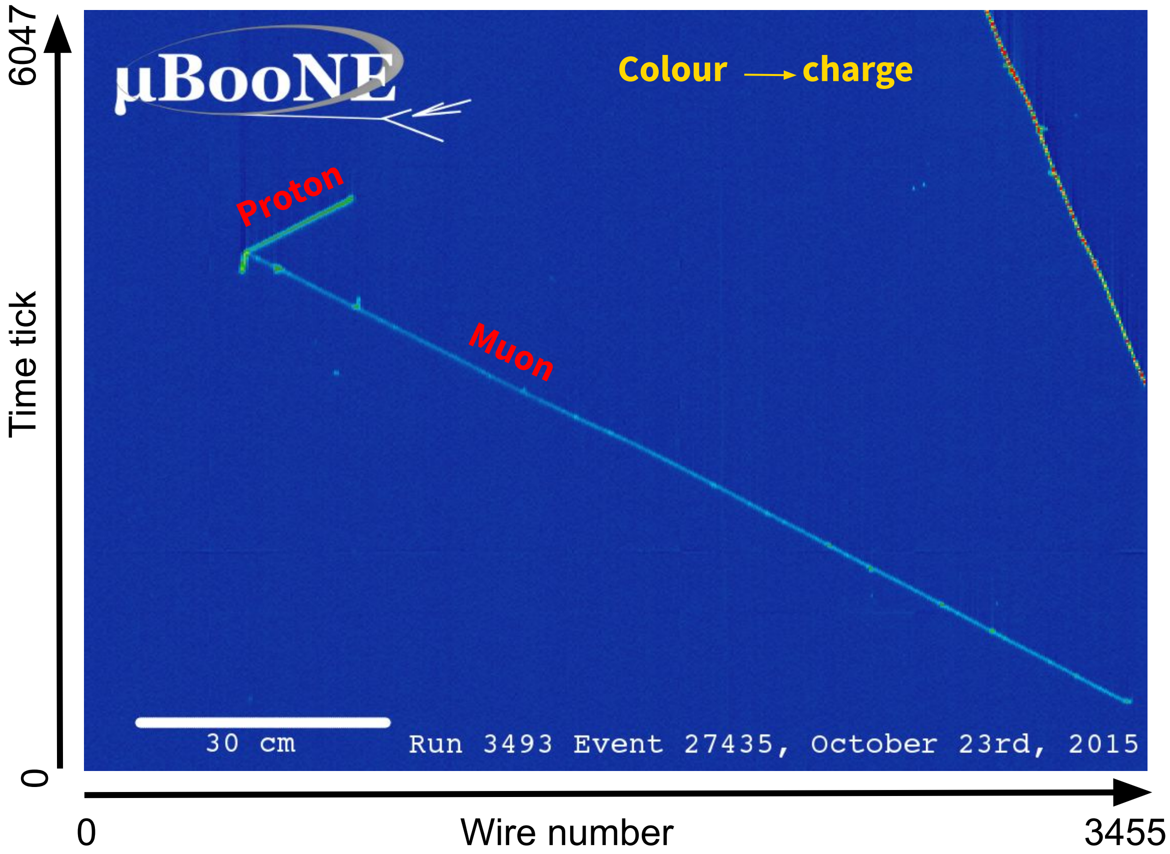
- Liquid argon time projection chamber (LArTPC)
- Active mass 85 tonnes
- Dimensions: 10.36 x 2.56 x 2.32 m^3
- **At surface level**

Rich physics program:

- Neutrino physics (Oscillations, cross section)
- BSM physics (This talk)
- LArTPC R&D

MicroBooNE Data

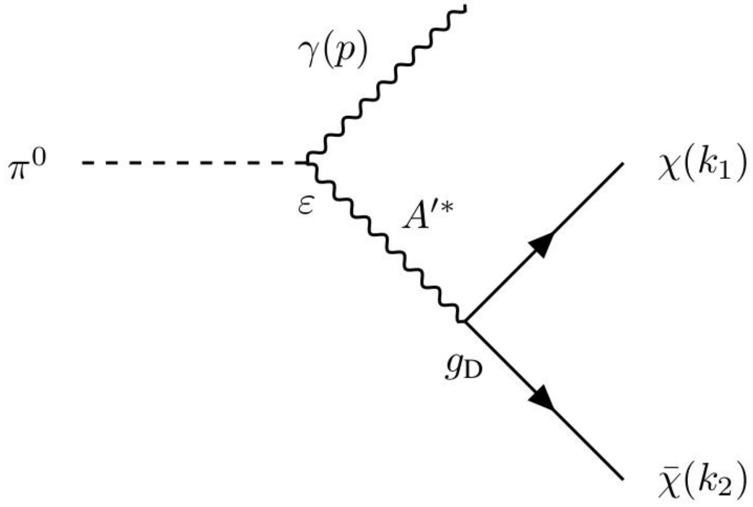
- MicroBooNE has three wire planes. Each plane produces a 2D view of the charged particles interacting with the detector volume
- Spatial resolution of 3 mm per pixel
- Good calorimetric capacity
- The image shown here corresponds to the collection plane



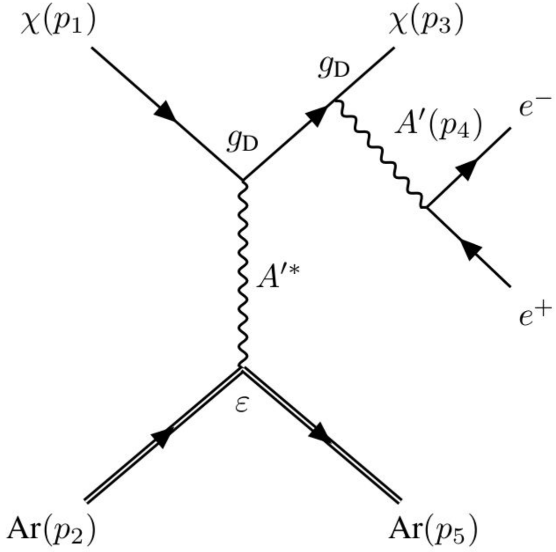
Dark Tridents: A Dark Sector Portal

- DM candidate can be produced at fixed-target facilities through neutral meson decays
- Off-axis search of DM scattering has been proposed in: **arXiv:1809.06388**
- Interaction channel: DM scattering with the emission of an on-shell dark photon

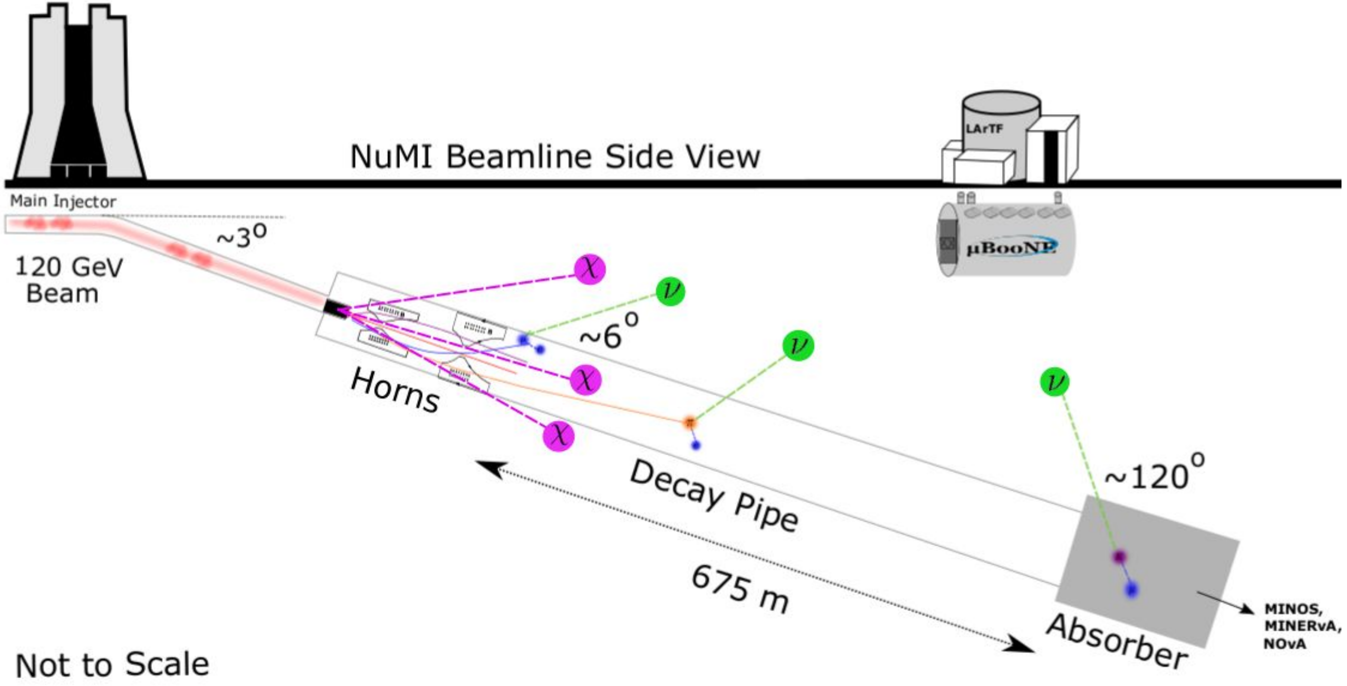
Production



Scattering with Ar



Search Strategy



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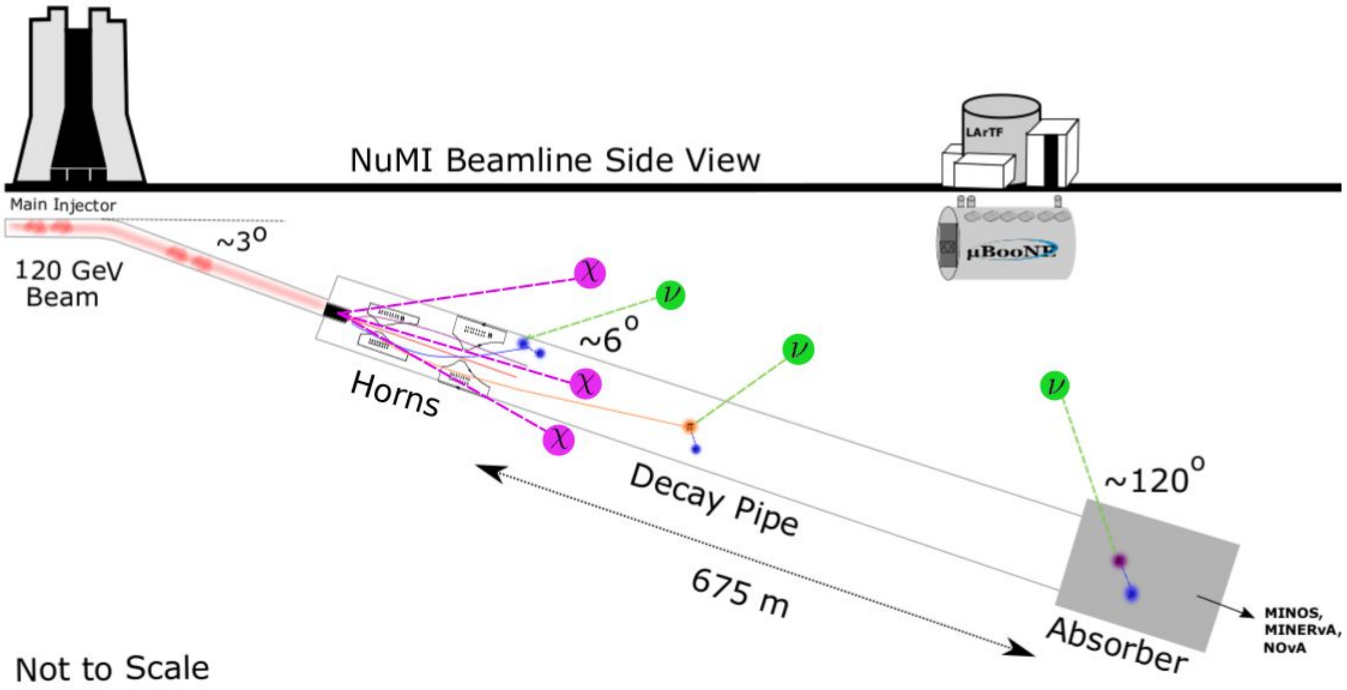

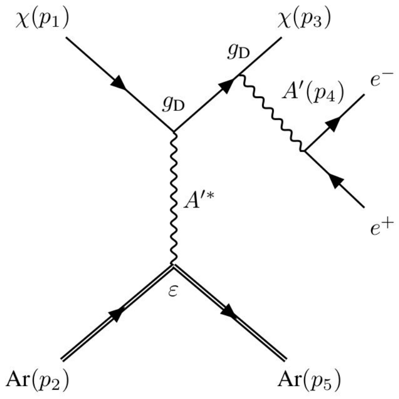

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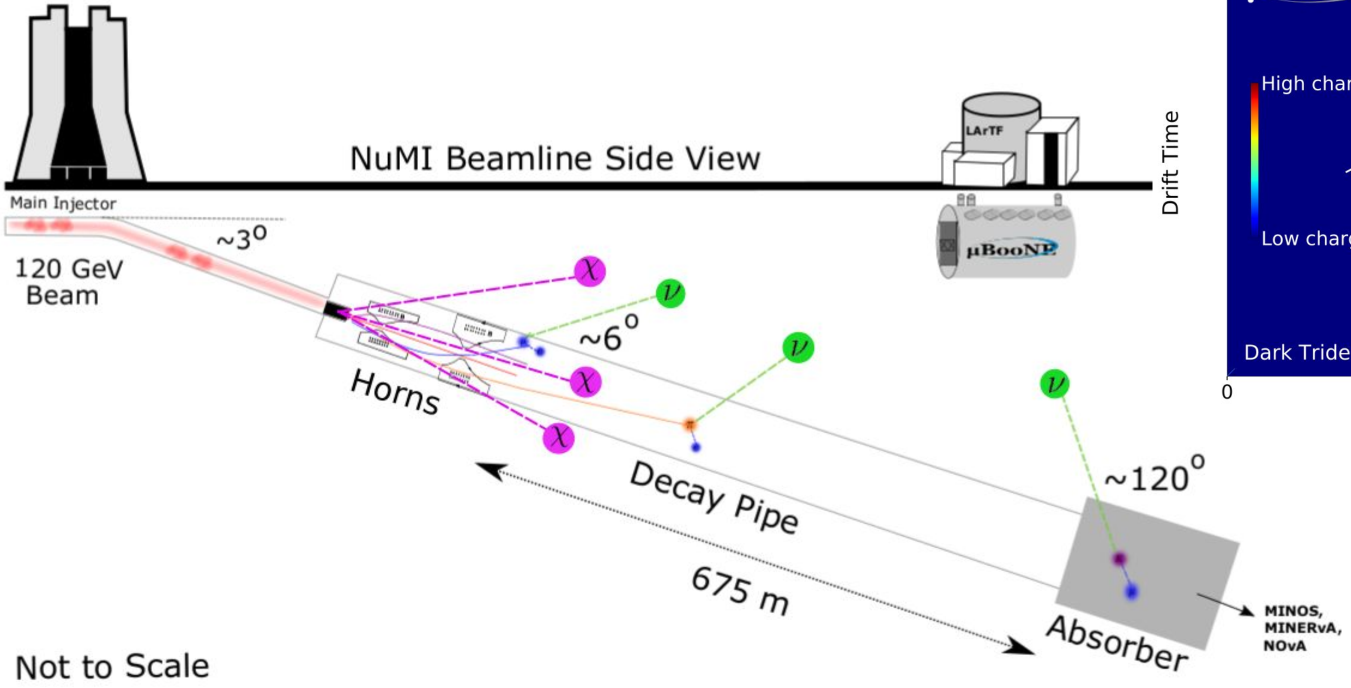

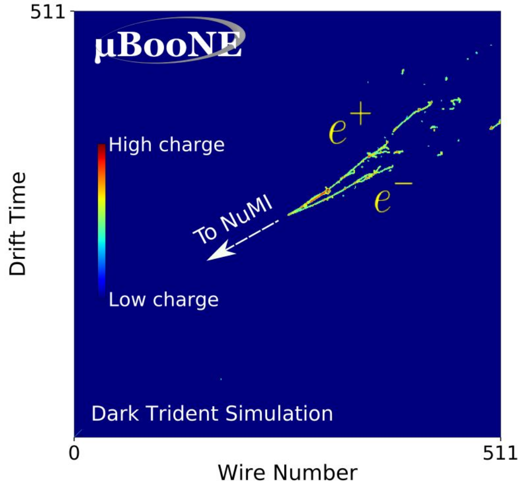

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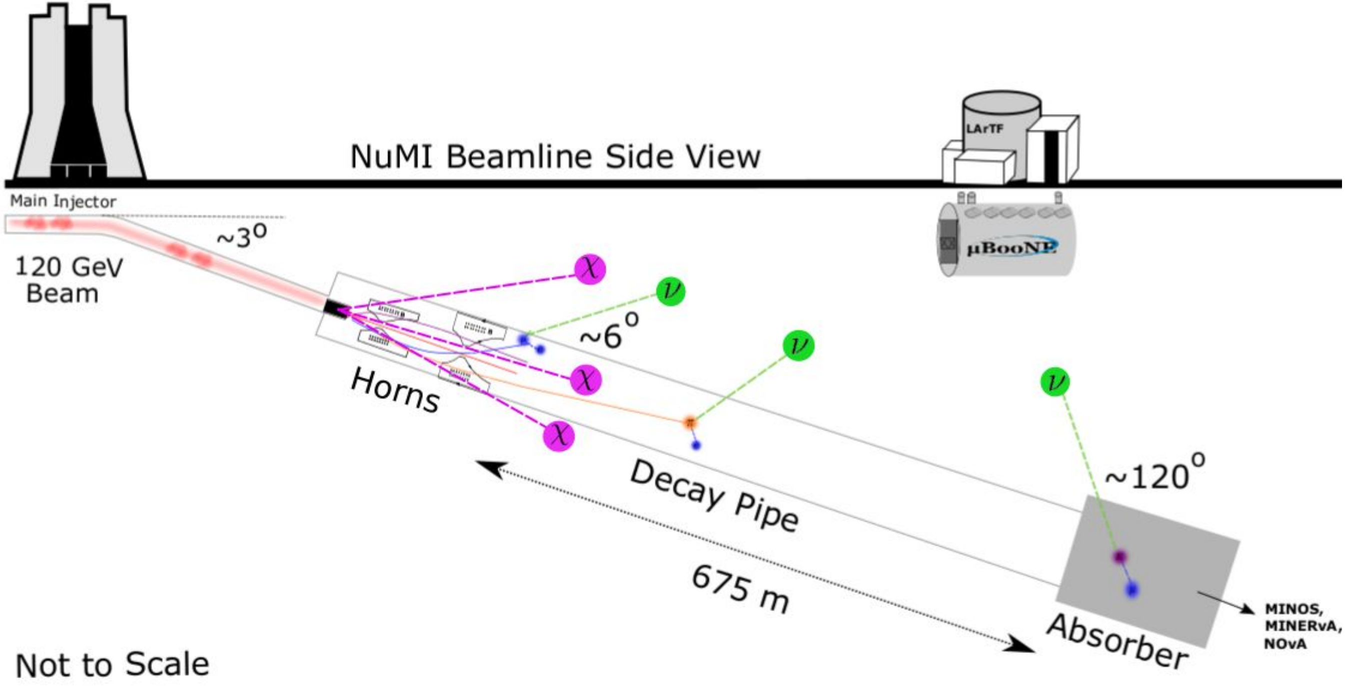
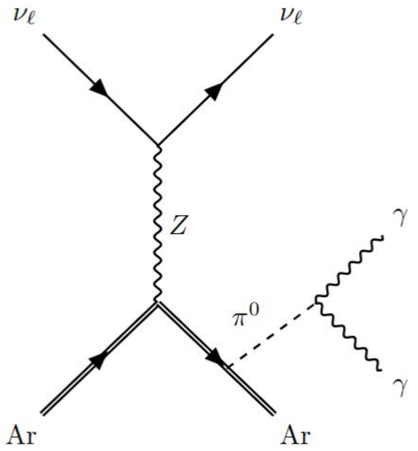
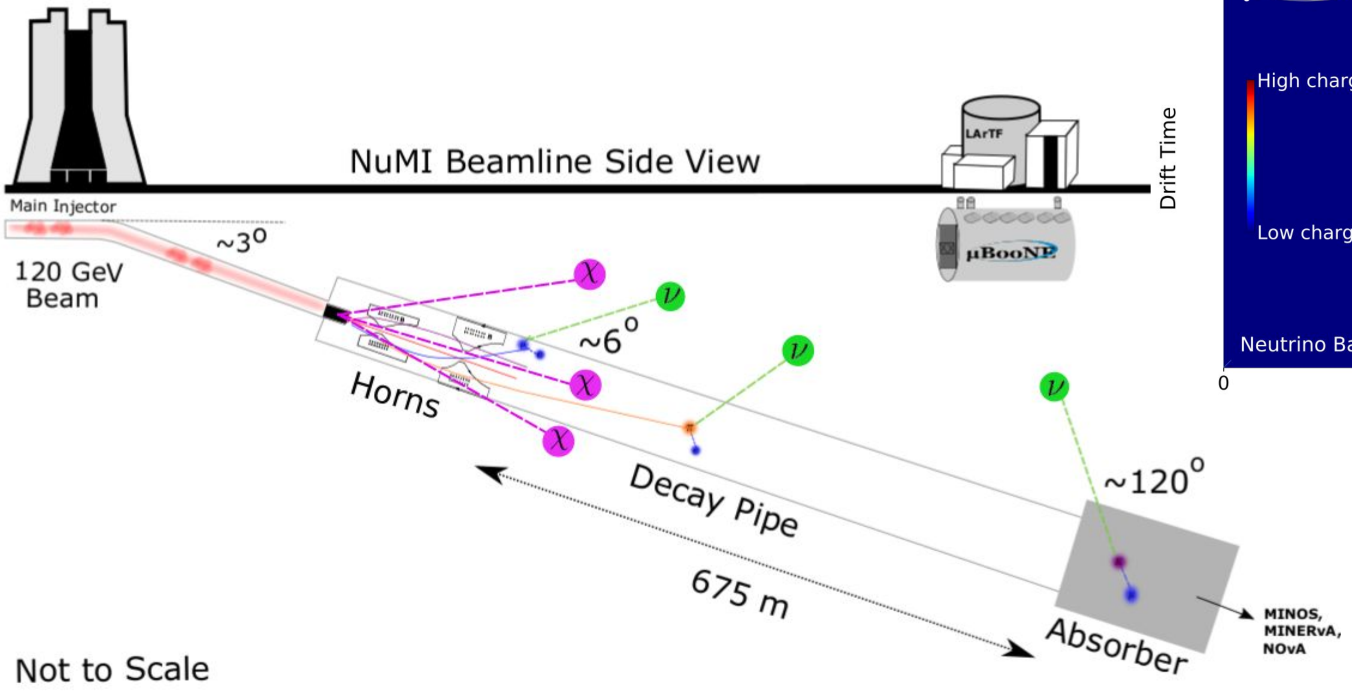
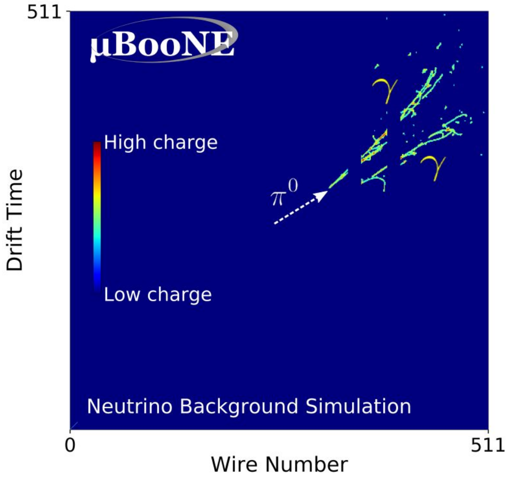




One of the most problematic backgrounds are nu-Ar interactions producing neutral mesons or single photons

Search Strategy





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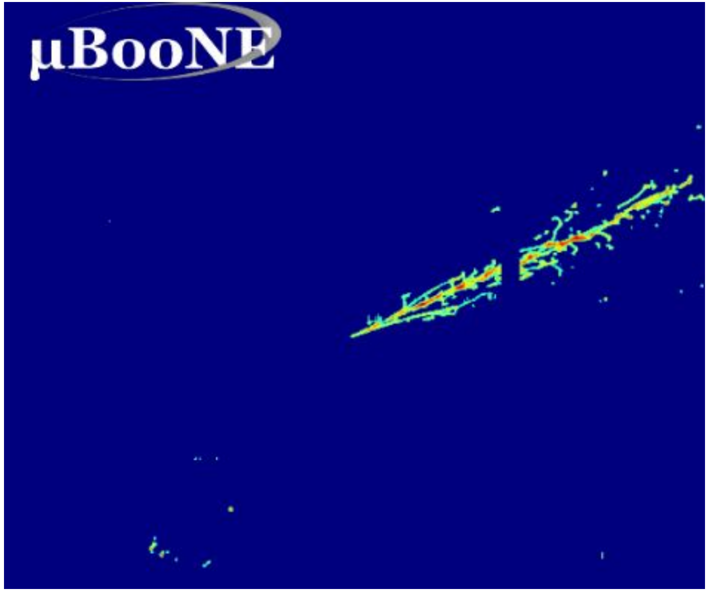
A Possible Deep Learning Problem!



Signal or background?

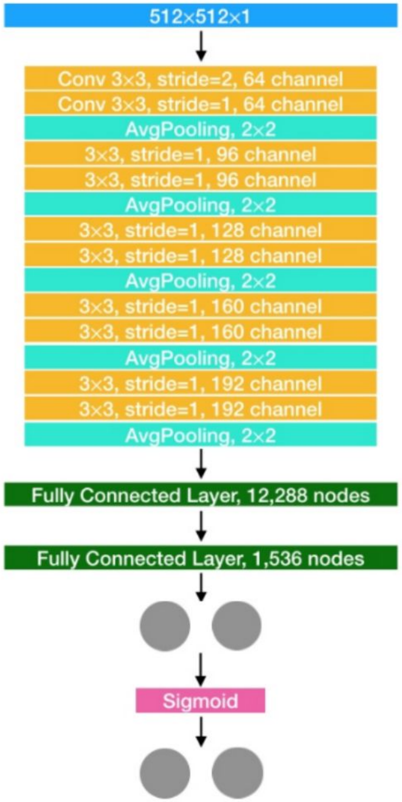
A CNN for Background Rejection

- For this analysis we took advantage of the existing architecture developed for the Multi-Particle Identification Network (MPID)

- The CNN input are 512x512 MicroBooNE images cropped around the interaction vertex

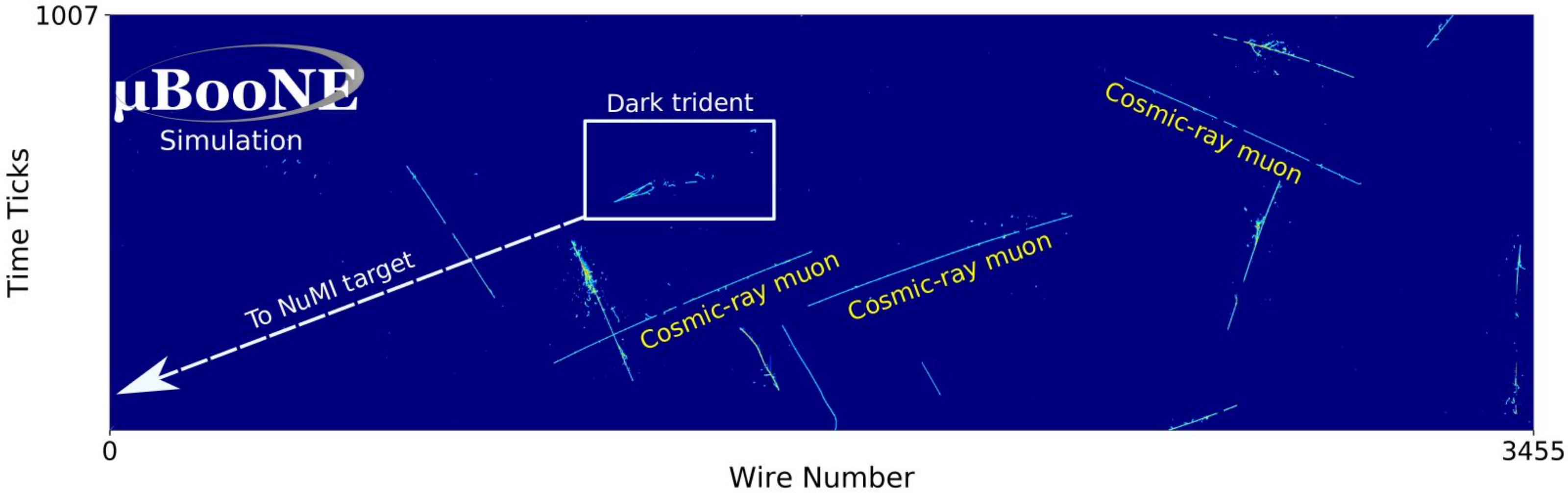
- MPID's has filters with a size comparable to the activity expected on showers and tracks

- The final layer has been configured to output the probability of having either dark trident signal or background interactions



MPID details: Phys. Rev. D 103, 092003

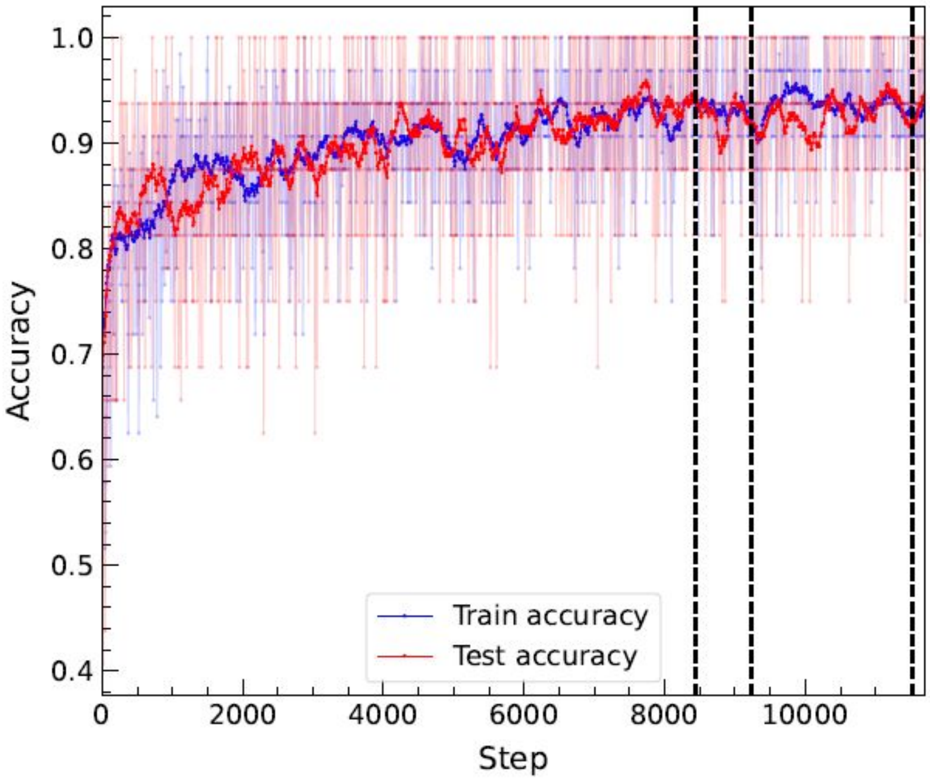
Training Set Preparation



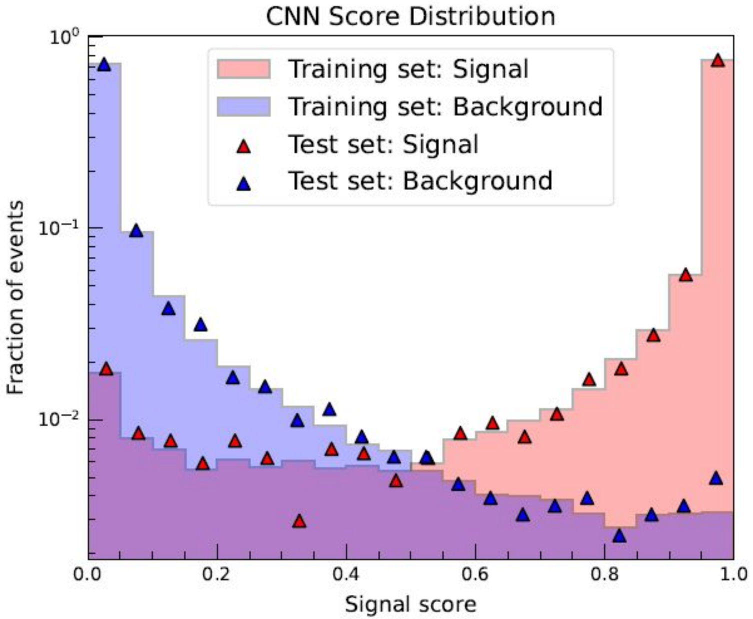
- Images are compressed by a factor of 6 on the time tick axis
- Cropping around of the interaction vertex obtaining an image of 512x512 pixels
- For training true vertex is used. In contrast for the actual analysis we use reco vertex (provided by pandora)
- The images are stored in a user-friendly format using the LArCV package
- A dedicated training/test set containing a benchmark signal sample and neutrino NCpi0 interactions was created. Cosmic rays tracks were also included

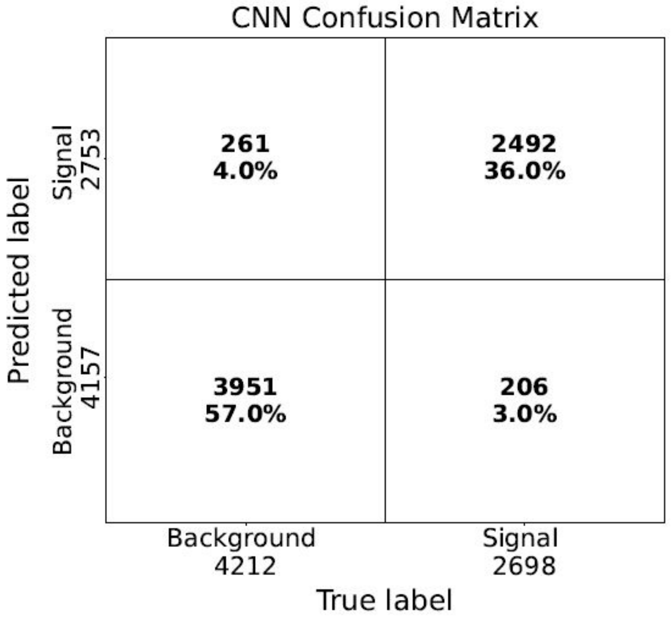
Network Training

- Training set size: 62879
- Hardware: NVIDIA V100
- Iterations: 11786 (~5 epochs)
- Time: ~4 hours
- Batch size: 32
- Learning rate: 0.001
- Adam optimizer
- Dropout layers and L2 regularization were implemented to control the overfitting
- Binary cross entropy loss and accuracy were used to monitor the training



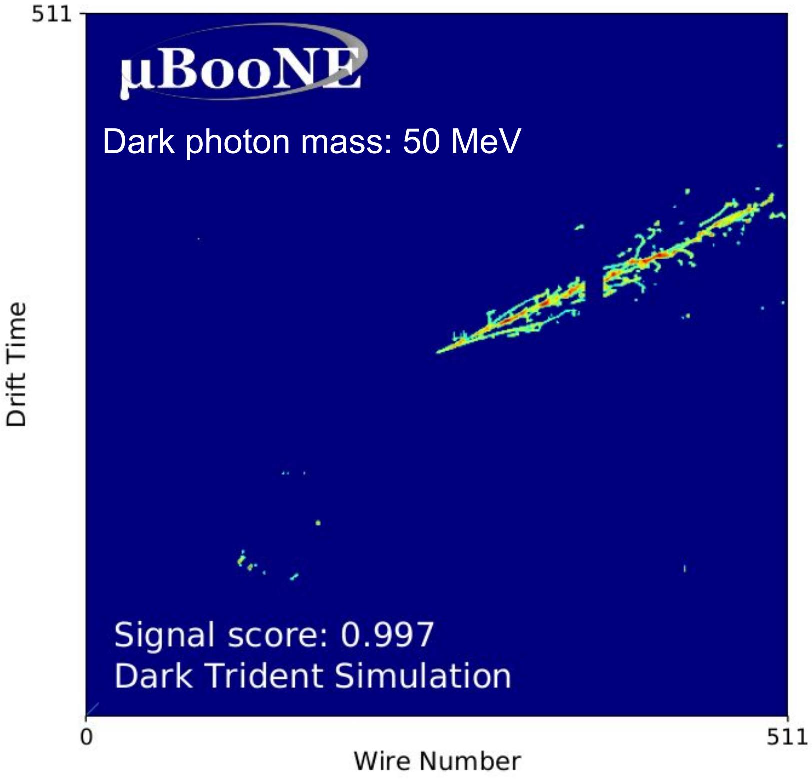
Training Results

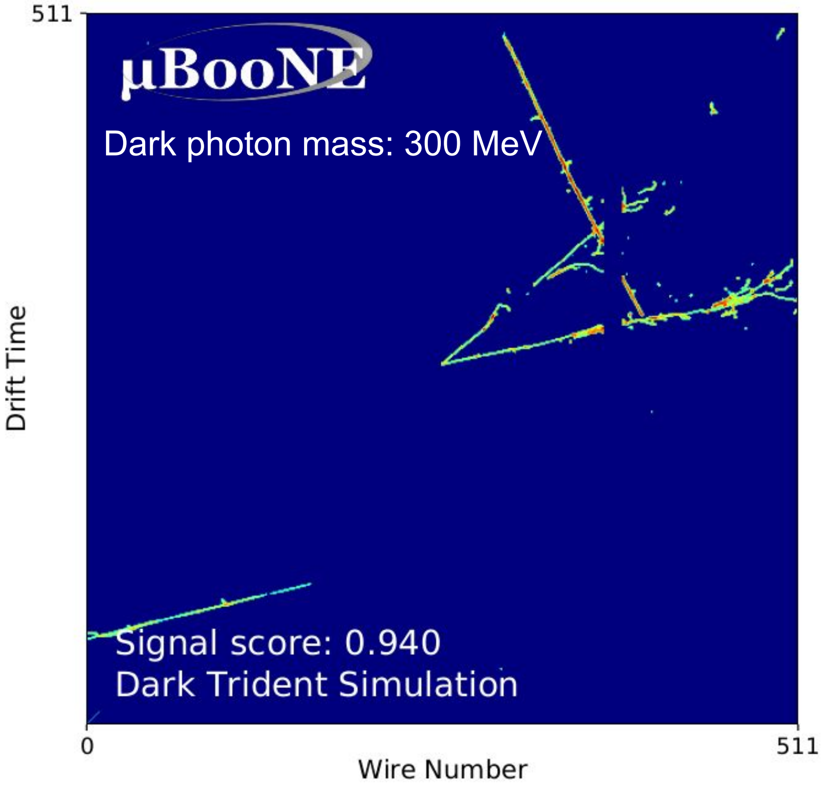




- The CNN achieves good separation of signal and background
- It reaches ~93% of accuracy
- Good generalization to signal samples simulated with different masses
- No signs of overfitting

Training Results



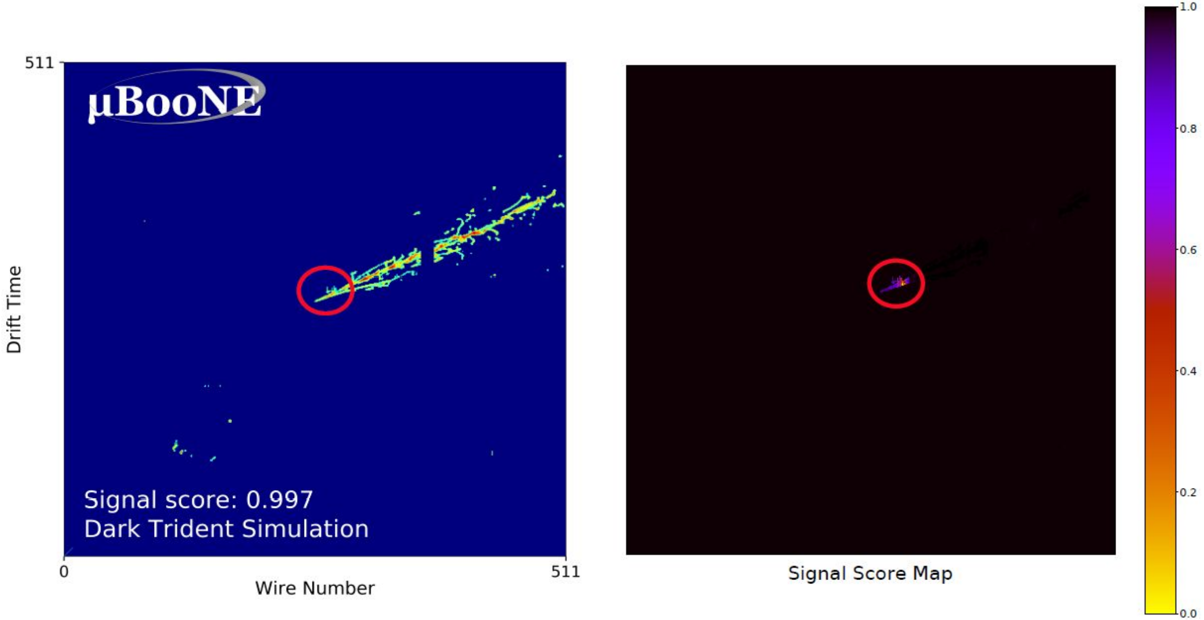


Occlusion analysis

- In this test a zone of nxn pixels in the image is ‘hidden’ before passing it to the CNN

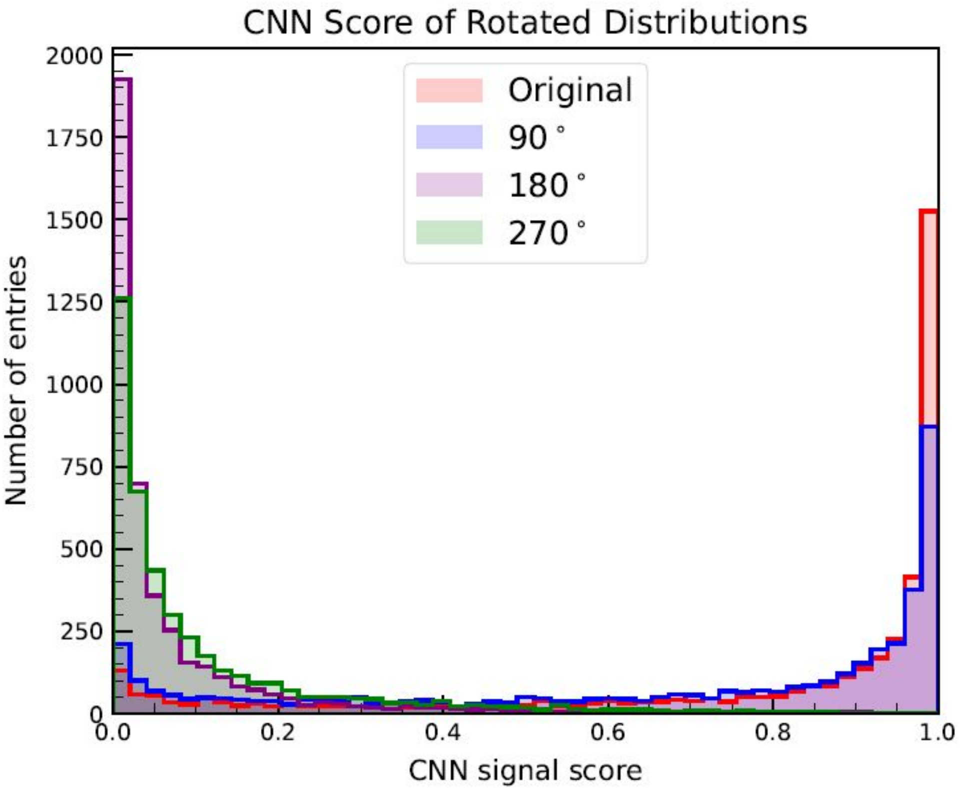
- The CNN score will vary if important pixels of the image are occluded

- Pixels at the beginning of the showers contribute with important features



Angular Dependance

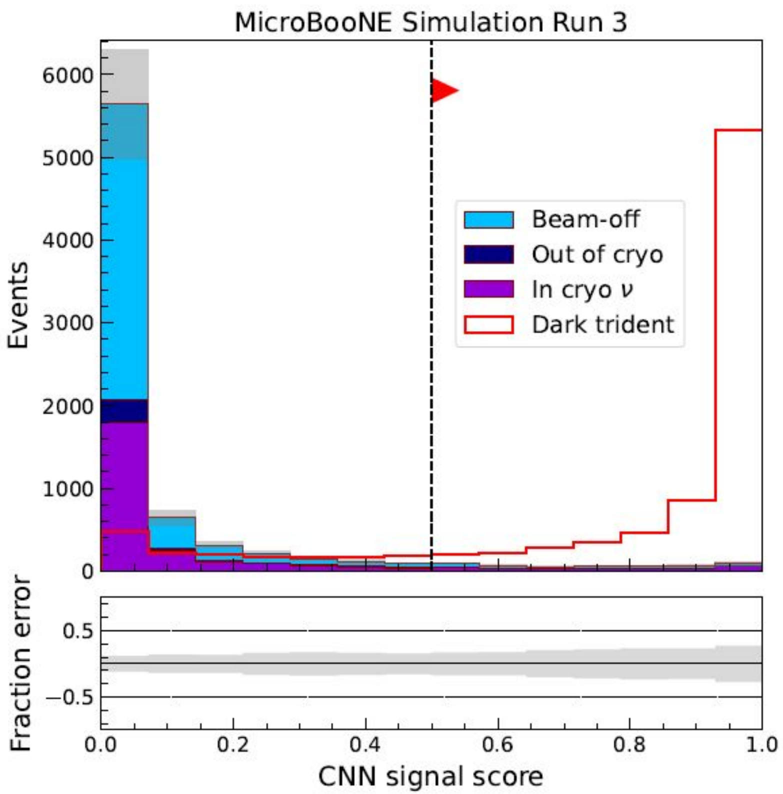
- The electron-positron shower direction typically point back to the NuMI target
- On the other hand, less neutrinos are expected from this direction as a result of the focusing horns
- We study if the CNN is able to infer the typical dark trident direction respect to NuMI
- Note: The MPID network was trained with isotropic angular distributions



Inference Over Analysis Datasets

- The background prediction is composed of cosmic-ray (beam-off) interactions, and neutrino interactions produced inside and outside the cryostat

- The CNN also generalizes to events coming from these three background samples



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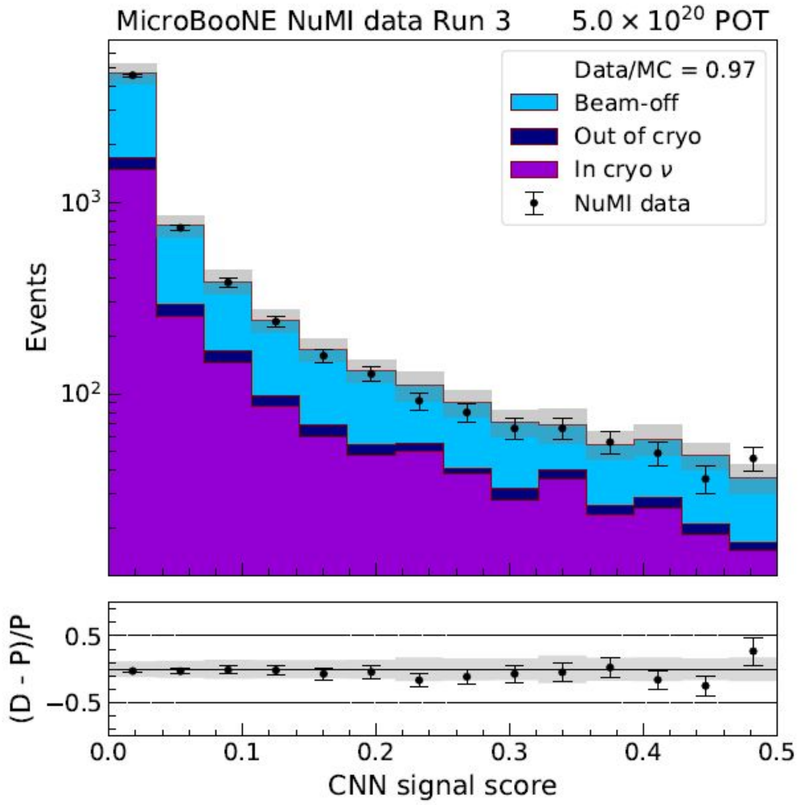
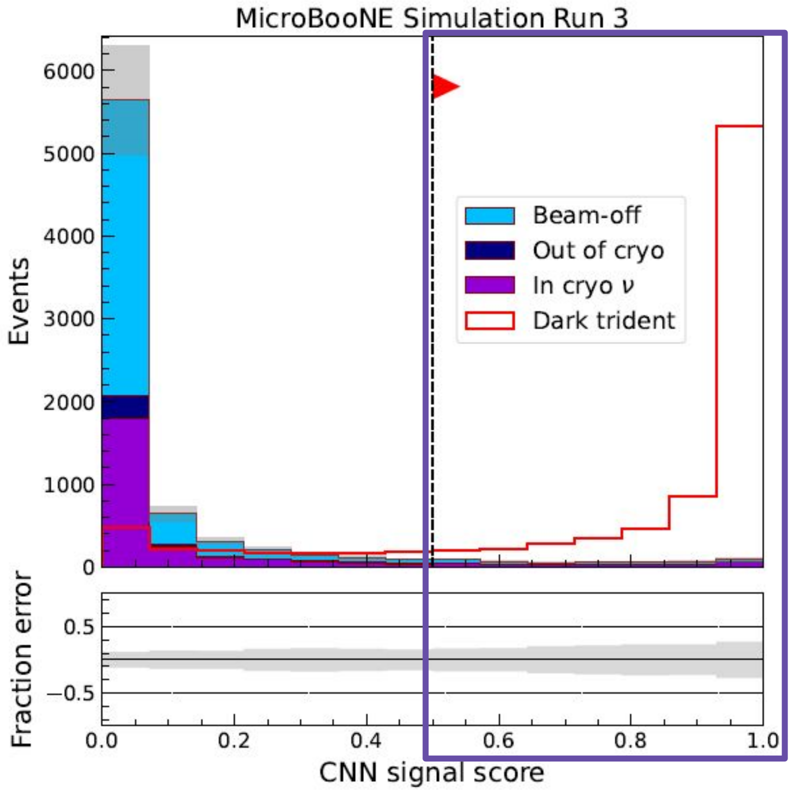
- We also checked the performance over data collected using the NuMI beam over a control region (CNN score < 0.5)



Results

- The CNN score region above 0.5 is used to probe the dark trident hypothesis

- The scores are passed through a logit transformation which maps the interval (0.5,1.0) to (0, infinity)



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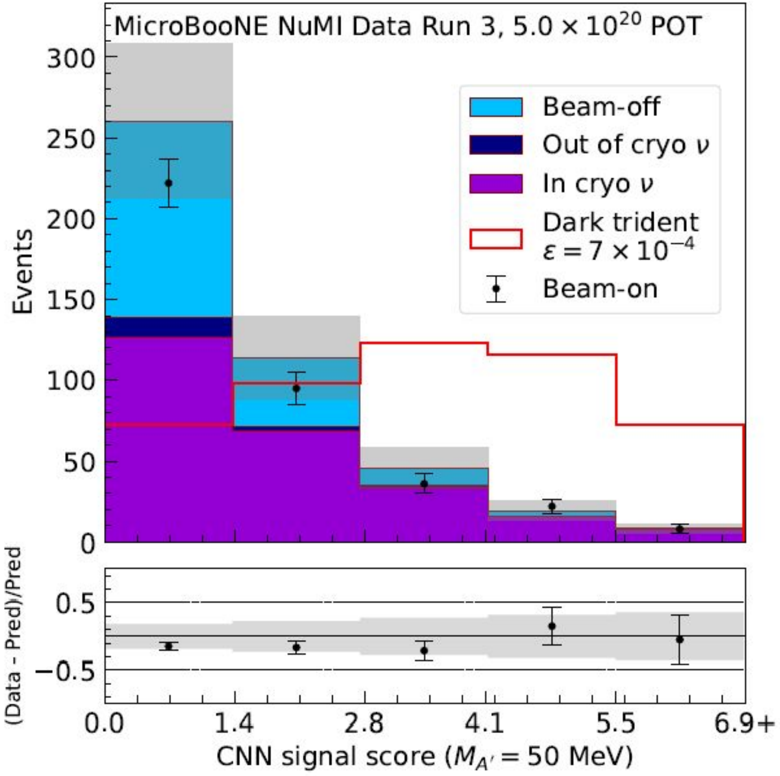
- The number of candidates found in the NuMI data is consistent with the background expectation



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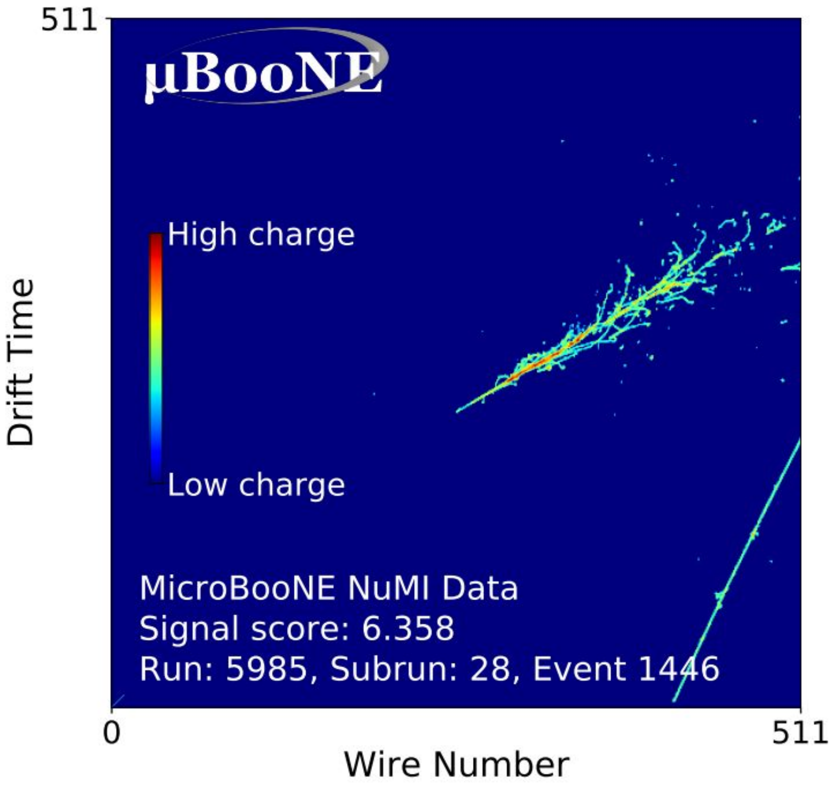
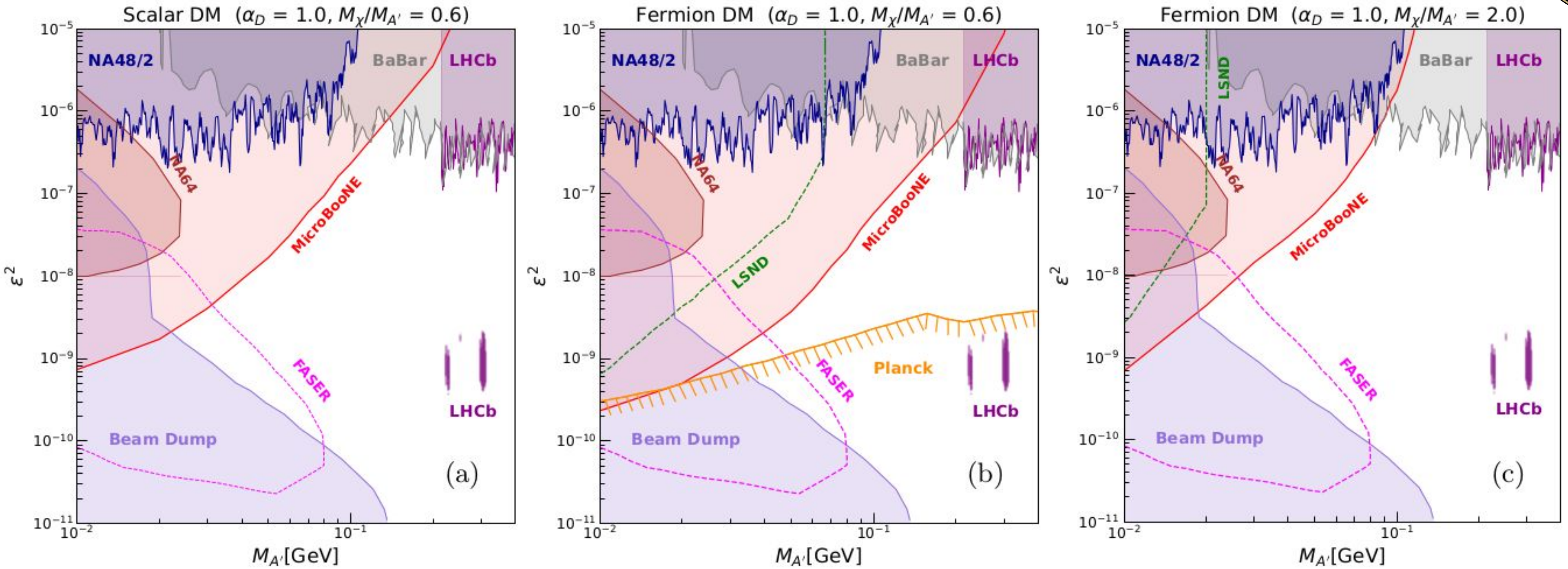


MicroBooNE Limits



- The results obtained were used to set constraints to different combinations of the parameter space using the CLs method
- The limits obtained by MicroBooNE are the most stringent ones for dark photon masses below 100 MeV

Conclusions

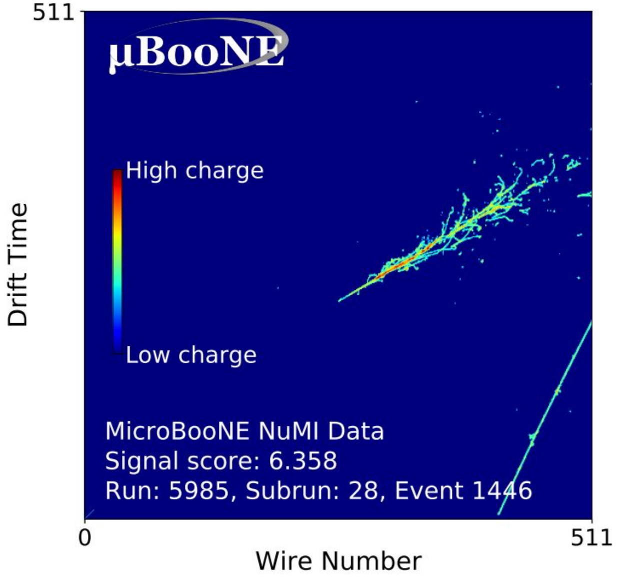
- We have successfully implemented a CNN to discriminate dark trident interactions from neutrino interactions and cosmic rays

- The CNN was used to search for dark trident candidates in dataset collected using the NuMI beam

- A few candidates were found but the number is consistent with background expectation. New constraints on the model parameter space were obtained

- This technique can be generalized to other BSM models and LArTPC experiments

- Results published by PRL: *Phys.Rev.Lett.* 132 (2024) 24, 241801

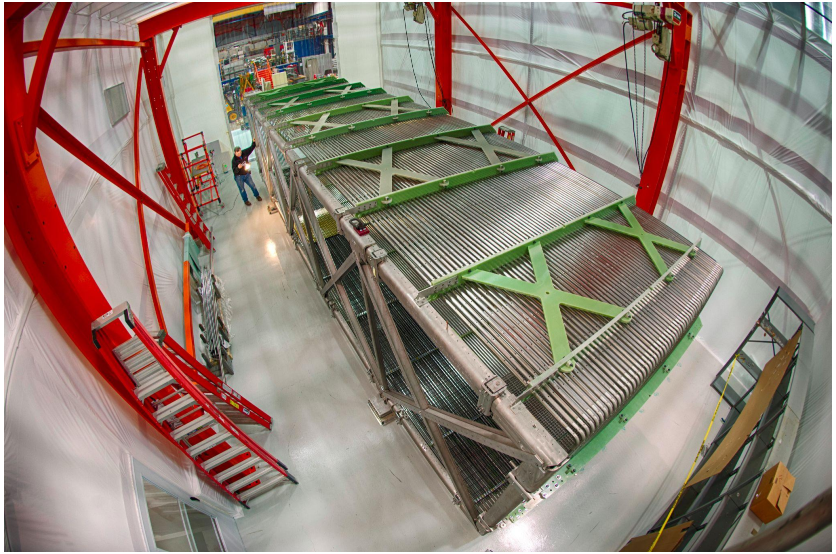


Backup

Training and Test Set

Type of event	Number of events in training set	Number of events in test set
Dark trident	12601	1399
Dark trident + Cosmic rays	11776	1299
NCπ^0	12601	1399
NCπ^0 + Cosmic rays	12601	1415
Cosmic rays only	13300	1399

The MicroBooNE Detector



MicroBooNE Dataset