Neutron to antineutron oscillation search with a Liquid Argon Time Projection Chamber

Yeon-jae Jwa, on behalf of the DUNE and MicroBooNE Collaborations
Columbia University

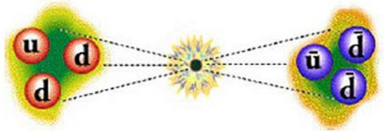
ICHEP 2020 Virtual Conference

Contents

- Theoretical motivation for neutron-antineutron oscillation ($n - \bar{n}$) and experimental searches
- Machine Learning (ML) based analysis method in Liquid Argon Time Projection Chambers (LArTPCs)
- Future bound neutron-antineutron oscillation search in DUNE
- Ongoing analysis validation in MicroBooNE

Theoretical motivation of baryon number violation processes

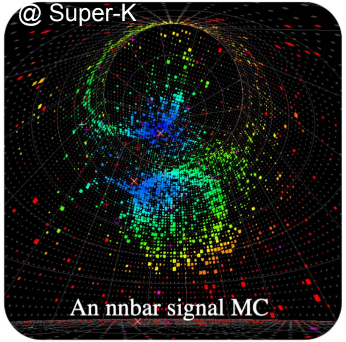
- $n - \bar{n}$ oscillation: n spontaneously converts itself to $\overline{\mathrm{n}}$



- Baryon number violation (BNV)
  - BNV is one of Sakharov's conditions, ***necessary*** for matter-antimatter asymmetry in the universe.
  - Baryon number (B) is not a fundamental quantum number of the Standard Model.
  - $n - \bar{n}$ oscillation violates baryon number by 2 units ($|\Delta B|=2$); this effectively makes neutron a Majorana particle (with a small Majorana component).
  - $n - \bar{n}$ oscillation is predicted by a number of beyond-Standard Model theories.

$n - \bar{n}$ searches with bound neutrons and free neutrons

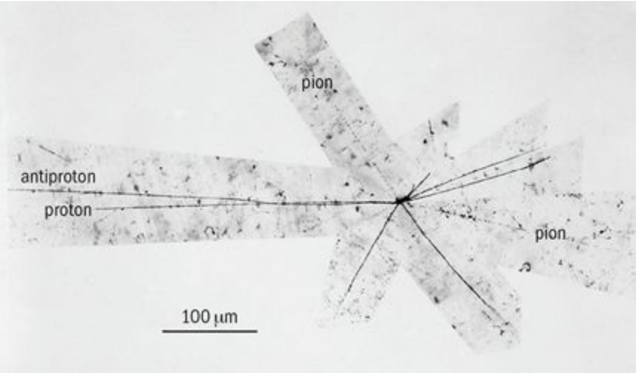
- **$n - \bar{n}$ search in free neutrons**
  - Current best $n - \bar{n}$ lifetime limit using free neutrons comes from ILL/Grenoble experiment: **8.6 × 10^7 s.**
  - Future project HIBEAM/NNBAR is planned at the European Spallation Source (ESS).
- **$n - \bar{n}$ search in bound neutrons (this talk!)**
  - Look for antineutron's annihilation signature in a nucleus.
  - The bound $n - \bar{n}$ lifetime ($T_{n-\bar{n}}$) is related to free $n - \bar{n}$ lifetime ($\tau_{n-\bar{n}}$) by intranuclear suppression factor *R*, as follows: $\tau^2_{n-\bar{n}} = \frac{T_{n-\bar{n}}}{R}$
  - Suppression factor for ^{40}Ar was recently calculated ($R = 5.6 \times 10^{22}\ s^{-1}$). [PRD.101.036008]
  - Super-K holds the current best $n - \bar{n}$ lifetime limit for oxygen-bound neutron: **3.6 × 10^{32} yrs**, equivalent to **4.7 × 10^8 s** for free $n - \bar{n}$ lifetime. [New result at Neutrino 2020]



$n-\bar{n}$ signature

- Multiple pion final state:
  - In ^{40}Ar, $n-\bar{n}$ oscillation is followed by the annihilation with a nearby nucleon (p or n).
  - ($\bar{n}$, n), ($\bar{n}$, p) annihilation generates multiple pions.
  - Momentum sum ~ 0, total energy release ~ 2 GeV
  - The topology of decay products has spherical symmetry with high pion multiplicity:

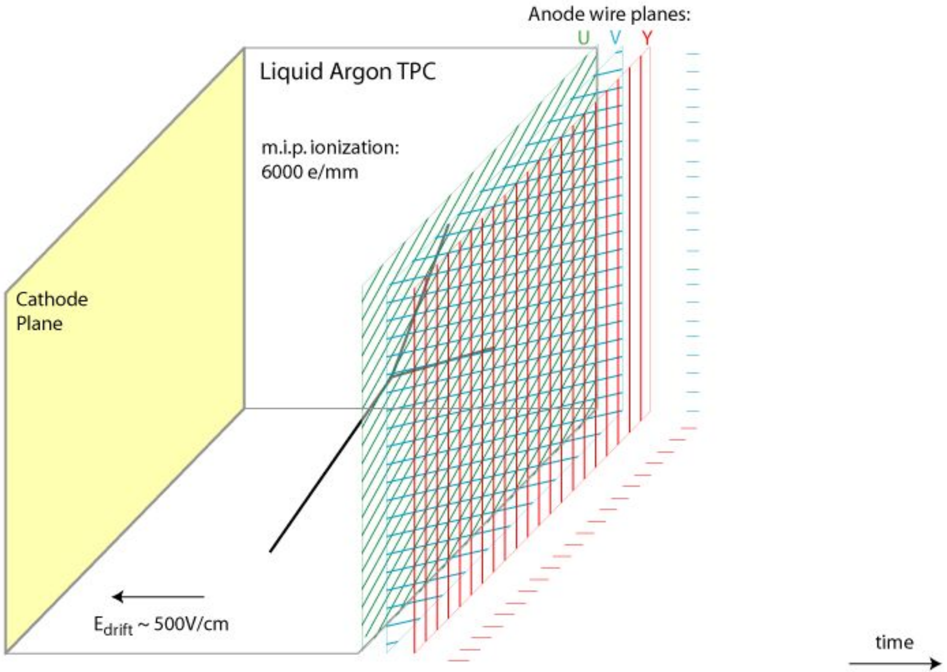
    $n-\bar{n}$ **'star-like'** signature topology.



Discovery of the antiproton, 1955
Photographic emulsion image at Bevatron.

$n - \bar{n}$ search in the DUNE or MicroBooNE LArTPCs

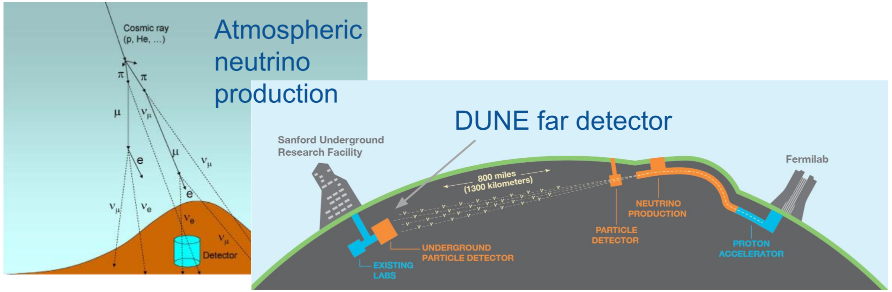
- **LArTPC technology** is shared by the MicroBooNE and DUNE experiments.
- LArTPCs, with ~mm wire resolution and good calorimetric (ionization dE/dx) resolution, are **well-suited** for capturing and identifying the signal topology.



$n-\bar{n}$ search in the DUNE or MicroBooNE LArTPCs

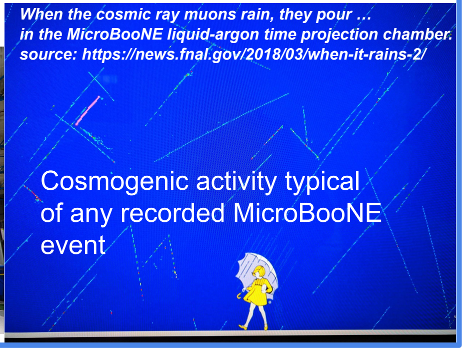
DUNE

- Deep underground, well-shielded from cosmogenic activity.
- Anticipated backgrounds: atmospheric neutrino interactions
- Very large detector mass and long exposure: 4 × 10 kt TPC volume, 10 yrs of exposure.
- Assumes self-triggering on rare events like proton-decay, $n-\bar{n}$, atmospheric neutrinos.

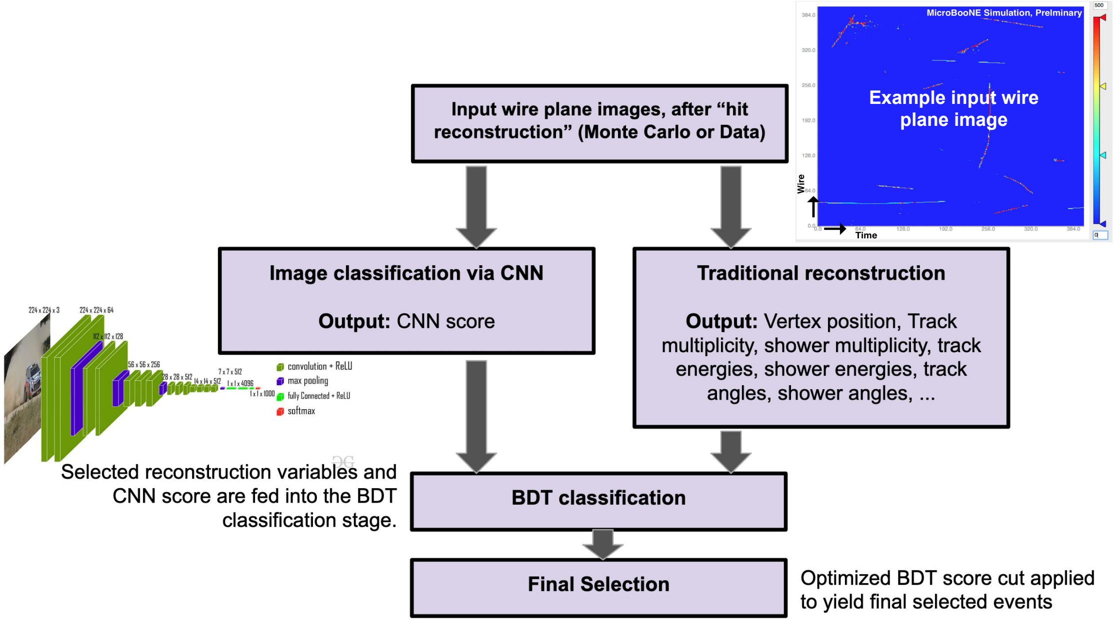


MicroBooNE

- On-surface operation
- Background-dominated: constant stream of cosmic ray muon tracks
- Very small detector mass (500x smaller than DUNE), and shorter exposure: 80 t TPC volume, ~hrs of exposure.
- Random trigger for off-beam readout.



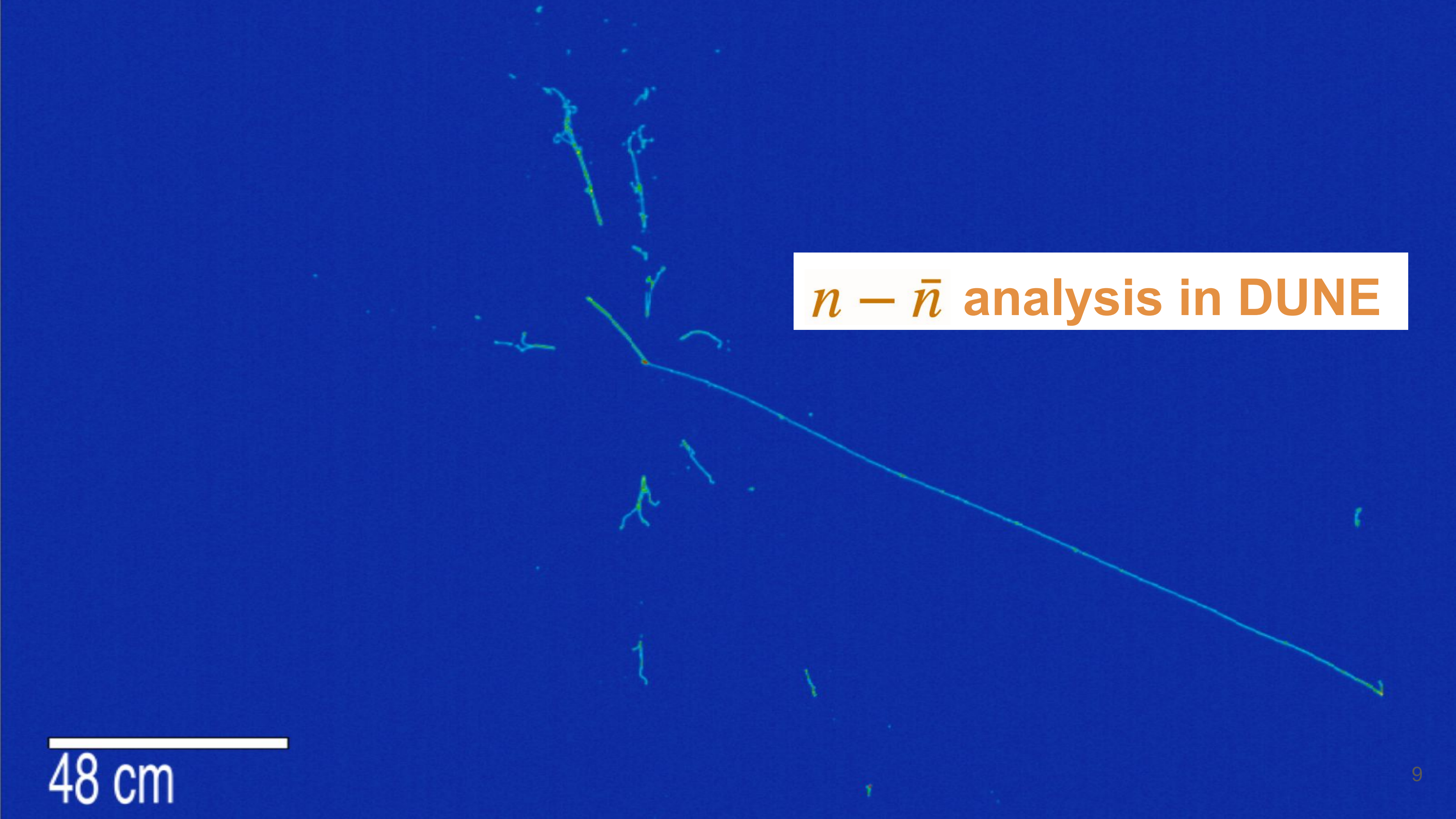
Analysis overview: ML based Method



- Analysis **combines traditional reconstruction with image classification**: A Boosted Decision Tree (BDT) combines:
  - traditionally reconstructed kinematic information, with
  - image classification score obtained from a Convolutional Neural Network (CNN)
- Alternatively:
  - CNN-only analysis
  - BDT-only analysis

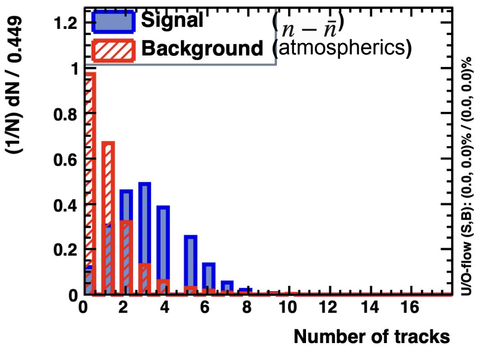
** This analysis scheme can be shared between DUNE and MicroBooNE which gives a unique opportunity of validation on MicroBooNE data.*

$n - \bar{n}$ analysis in DUNE

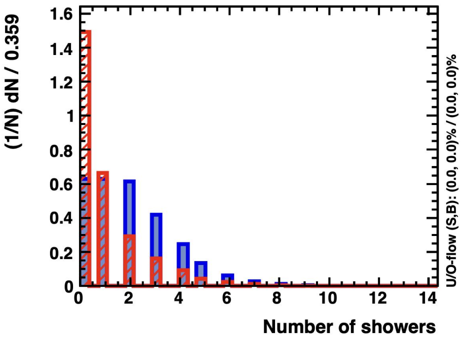


CNN+BDT combined analysis

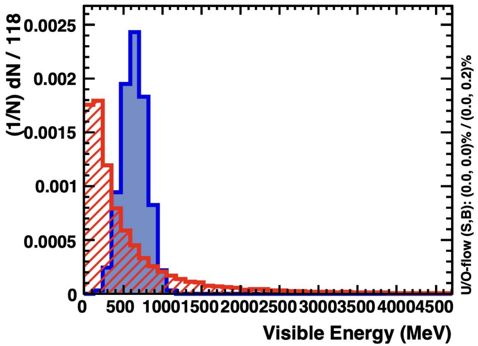
Input variable: Number of tracks



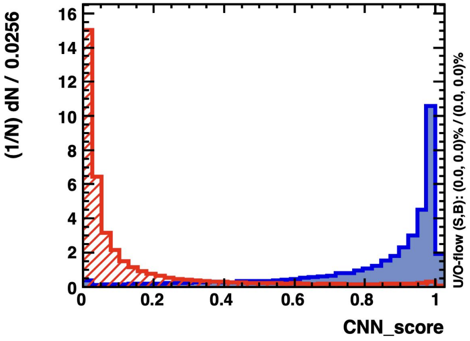
Input variable: Number of showers



Input variable: Visible Energy (MeV)



Input variable: CNN_score

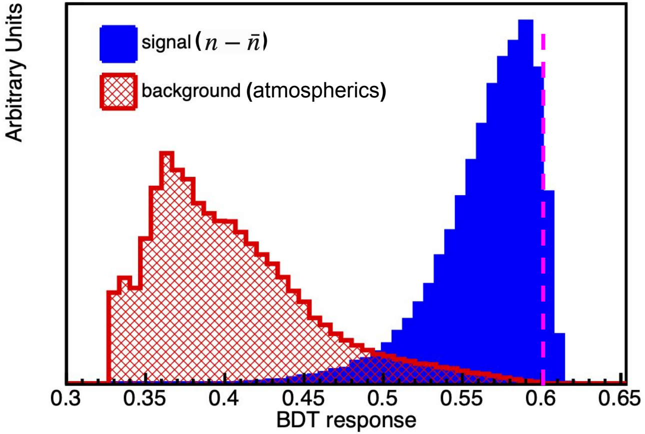


[DUNE Technical Design Report]

Input BDT variables include:

- **Number of tracks**
- **Number of showers**
- **Track-like visible Energy**
- EM-like visible Energy
- Visible energy
- Longest track PIDA
- Longest track Momentum
- EM-like visible Energy fraction
- Most energetic shower dE/dx
- **CNN score**

Selection cut and preliminary sensitivity in DUNE



[DUNE Technical Design Report]

- Using an optimized combined BDT cut, 8% signal efficiency with 0.02% background efficiency can be achieved.
- For 400 kt-years exposure,
  - ~20 background events are expected
  - ~30 signal events are expected, when $T_{n-\bar{n}}$ = 3.6 × 10^{32} yrs (current best limit at Super-K) is assumed.
- In calculating the 90% C.L. sensitivity,
  - Given exposure (E), signal efficiency (ϵ), background counts (b)
  - Poisson distribution in combination with Gaussian priors yields

$$P(\Gamma|n) = A\int\int\int \frac{e^{-(\Gamma\epsilon E+b)}(\Gamma\epsilon E+b)^n}{n!}P(\Gamma)P(E)P(\epsilon)P(b)dEd\epsilon db$$

$$90\% = \frac{\int_{\Gamma=0}^{\Gamma_{0.9}} P(\Gamma|n)d\Gamma}{\int_{\Gamma=0}^{\infty} P(\Gamma|n)d\Gamma}$$

$$T_{n-\bar{n}} = \frac{1}{\Gamma_{0.9}}$$

[MICROBOONE-NOTE-1093-PUB]

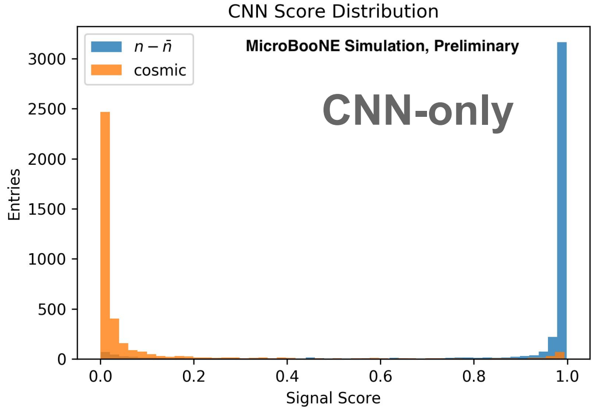
Selection cut and preliminary sensitivity in DUNE

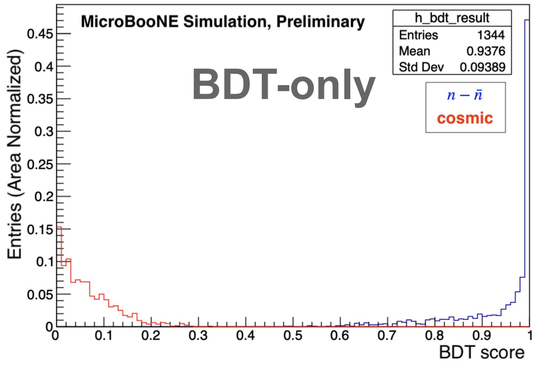
- The **90% C.L. sensitivity for argon-bound $n-\bar{n}$ lifetime corresponds to 6.45 × 10^{32} yrs**, for an exposure of 1.33 × 10^{35} neutron-years in DUNE.
  - This translates to a free $n-\bar{n}$ lifetime of 5.53 × 10^{8} s.
  - The result is comparable with the current best limit at Super-K (3.6 × 10^{32} yrs for bound, 4.7 × 10^{8} s for free $n-\bar{n}$ lifetime).
  - The effort on further improving the analysis and sensitivity continues.

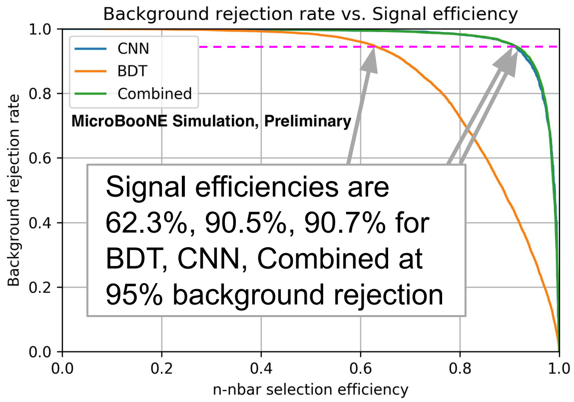
- A systematic error evaluation due to the choice of generators and intranuclear modeling is being established.

$n - \bar{n}$ analysis validation in MicroBooNE

CNN-only/BDT-only/Combined analysis using MicroBooNE Simulations



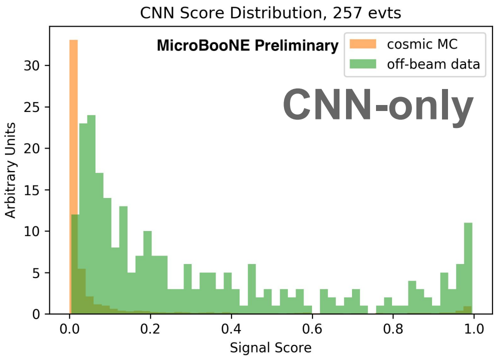


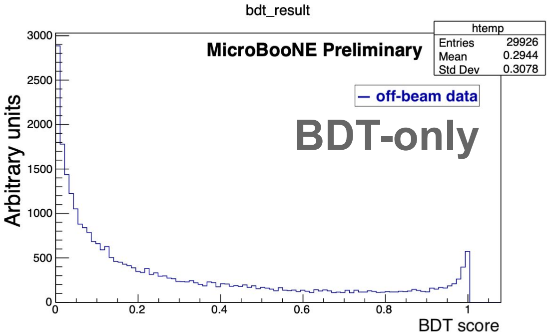


[MICROBOONE-NOTE-1093-PUB]

- The CNN-only, the BDT-only, the Combined methods have been demonstrated on MC events: cosmogenic background with signal overlays, and cosmogenic background only.

CNN-only/BDT-only method validation on MicroBooNE Off-beam Data





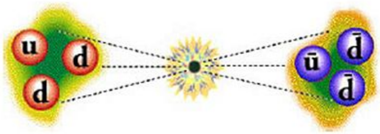
[MICROBOONE-NOTE-1093-PUB]

- A **small subset of MicroBooNE Run1 off-beam data** was used to validate the **CNN-only** and **BDT-only** methods.
  - The off-beam data is expected to follow the CNN/BDT responses of cosmic MC, since **negligible signal** is expected in the data given existing limit.
  - Data-MC disagreement is evident, understood to be due to **imperfect modeling** of cosmic flux and/or detector response.[1]
  - This illustrates the **challenge** in applying ML techniques trained only on simulation; improvement of the analysis targeting data-MC agreement is ongoing.

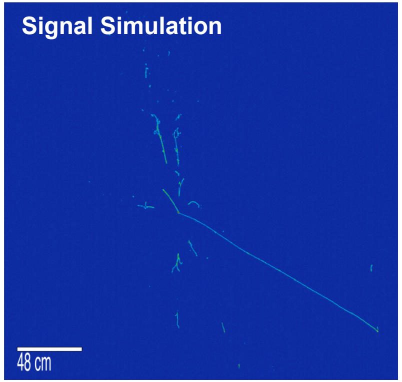
[1]Other MicroBooNE analyses currently make use of data overlays to emulate cosmogenic backgrounds and better approximate detector effects such as electronics noise.

Summary

- The future DUNE experiment is well positioned to provide
  - the world-leading sensitivity for neutron-antineutron oscillation.



- MicroBooNE, sharing the same technology as DUNE, is well positioned to provide
  - the stage for a proof-of-principle demonstration of ML based analysis methods,
  - the first LArTPC-based search for neutron-antineutron oscillation.
- Further improvement in data-MC agreement for the MicroBooNE analysis is ongoing.



Back Up

MicroBooNE performance

- Assuming 1.18×10^{27} neutron-years exposure from MicroBooNE Run1 off-beam data, 90% C.L. limit at 1.81×10^{25} years was achieved assuming 3%, 15%, 15% of uncertainties for the exposure (E), signal efficiency (ϵ), background rate (b).

$$\boxed{P(\Gamma|n) = A\int\int\int \frac{e^{-(\Gamma\epsilon E+b)}(\Gamma\epsilon E+b)^n}{n!}P(\Gamma)P(E)P(\epsilon)P(b)dEd\epsilon db}$$

$$\boxed{90\% = \frac{\int_{\Gamma=0}^{\Gamma_{0.9}} P(\Gamma|n)d\Gamma}{\int_{\Gamma=0}^{\infty} P(\Gamma|n)d\Gamma}} \quad \boxed{T_{n-\bar{n}} = \frac{1}{\Gamma_{0.9}}}$$

$(\bar{n}, n)$, $(\bar{n}, p)$ branching ratios in Genie v3.0.2.

$(\bar{n}, p)$		$(\bar{n}, n)$	
channel	branching ratio	channel	branching ratio
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$2\pi^+2\pi^-\omega^0$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

Table 1: *Effective branching ratios of $(\bar{n}, p)$ and $(\bar{n}, n)$ annihilations for Argon, excerpted from Table 5.3 of [6].*