Bound neutron to antineutron oscillation search with a Liquid Argon Time Projection Chamber

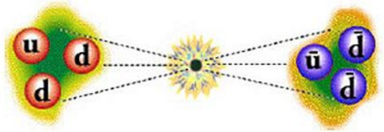
Yeon-jae Jwa, on behalf of the DUNE and MicroBooNE Collaborations
Columbia University

Nevis Laboratories
Columbia University

Contents

- Theoretical motivation for neutron-antineutron oscillation & experimental methods
- Machine Learning-based analysis method in LArTPCs
- Bound neutron-antineutron oscillation search in DUNE
- Analysis validation in MicroBooNE

Theoretical motivation of baryon number violation processes



- n-nbar oscillation: n spontaneously converts itself to nbar
- 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-nbar oscillation violates baryon number by 2 units ($|\Delta B|=2$), this effectively makes neutron a Majorana particle (with a small Majorana component).
  - n-nbar oscillation is predicted by a number of Grand Unification Theories (GUTs).

n-nbar searches with bound neutrons and free neutrons

- n-nbar search in free neutrons
  - Neutron beam is propagated on the target at a distance, look for interaction between propagated antineutron and the target nucleus.
  - Current best nnbar lifetime limit using free neutrons comes from ILL/Grenoble experiment: **8.6e7 s**.
  - Future project HIBEAM/NNBAR is planed @ European Spallation Source (ESS)
- n-nbar search in bound neutrons
  - Look for antineutron's annihilation signature in a nucleus.
  - The bound n-nbar lifetime ($T_{n-\bar{n}}$) is related to free n-nbar lifetime ($\tau^2_{n-\bar{n}}$) by intranuclear suppression factor R, by the conversion formula ($\tau^2_{n-\bar{n}} = \frac{T_{n-\bar{n}}}{R}$).
  - Recently, the suppression factor for ^{40}Ar is calculated. arxiv:1906.02833
  - Super-K holds the current best nnbar lifetime limit in bound neutron: **1.9e32 yrs**, which translates to **2.7e8 s** for free neutron lifetime.

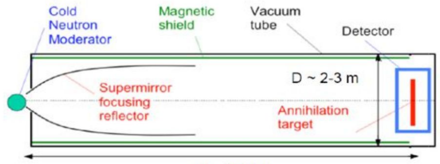
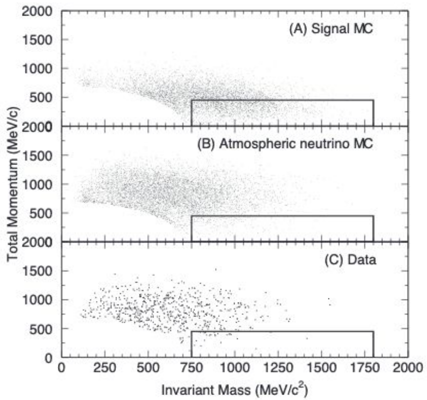


Figure 3: Schematic outline of experiment for neutron-antineutron oscillations at the NNBAR experiment. NNBAR @ ESS

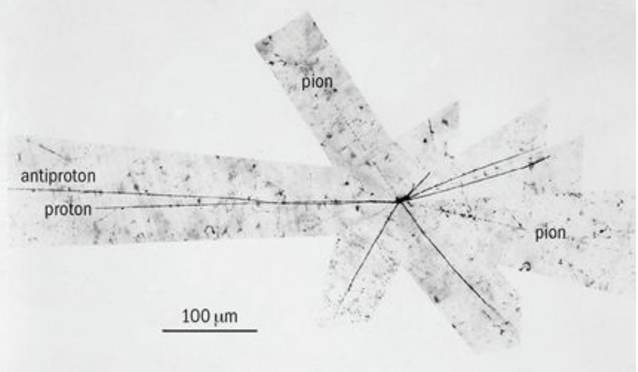


SK nnbar paper

n-nbar signature

- Multiple pion final state:
  - In ^{40}Ar, n-nbar oscillation is followed by the annihilation with a nearby nucleon (p or n).
  - $(\bar{n}, n)$, $(\bar{n}, p)$ mainly generate multiple pions.
  - The outgoing particles' momentum sum should be close to 0, the topology of decay products has spherical symmetry with high pion multiplicity:

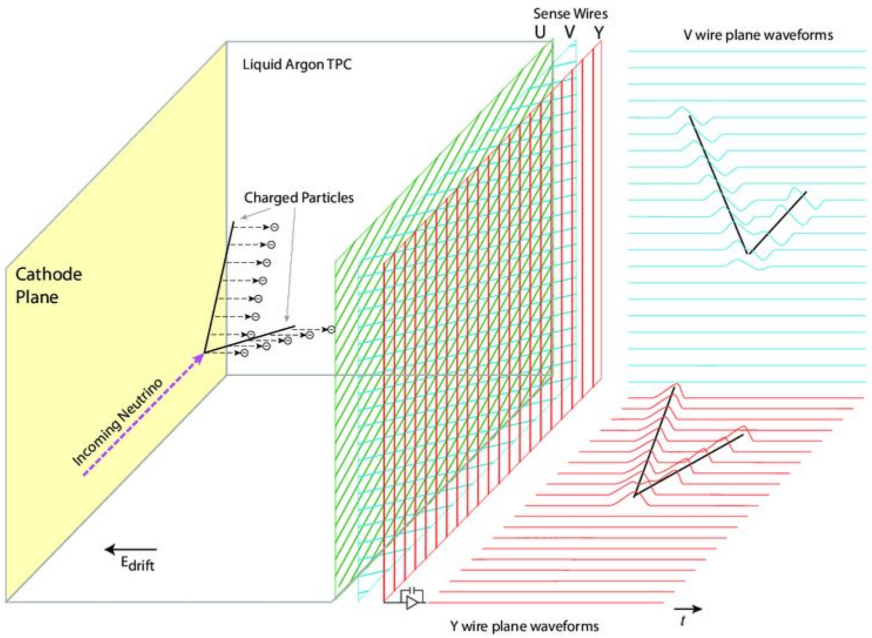
    n-nbar **'star-like'** signature topology.



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

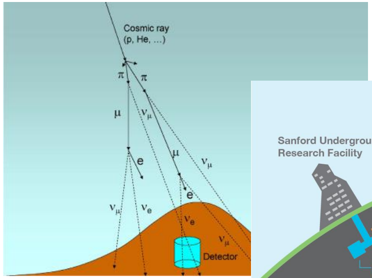
n-nbar search in the DUNE or MicroBooNE LArTPCs

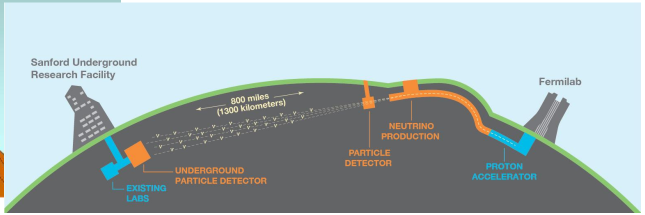
- Liquid Argon Time Projection Chamber (LArTPC) technology is shared with MicroBooNE and DUNE, (*DUNE will be ~ x 500 larger than MicroBooNE*).
- LArTPCs with ~mm wire resolution and good calorimetric (dE/dx) resolution are well-suited to capture the signal topology.



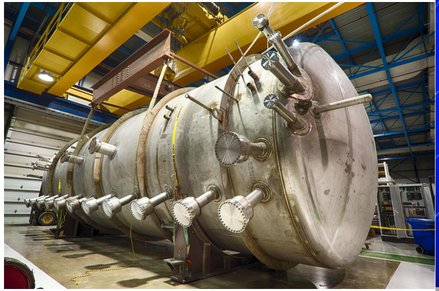
n-nbar search in the DUNE or MicroBooNE LArTPCs

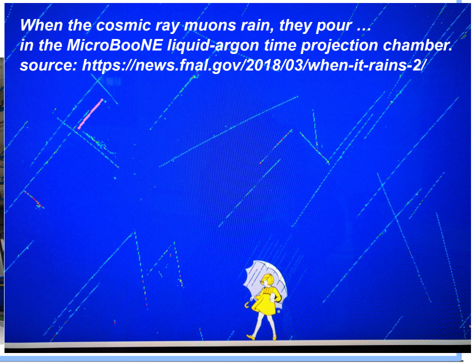
- Background event: high-energy atmospheric neutrino interactions
- Background rate: Integrated atmospheric flux on the DUNE far detector
- 4 x 10kT TPC volume, 10 yrs of exposure.
- Assumes self-triggering on high energy events like proton-decay, n-nbar, atmospheric neutrinos.





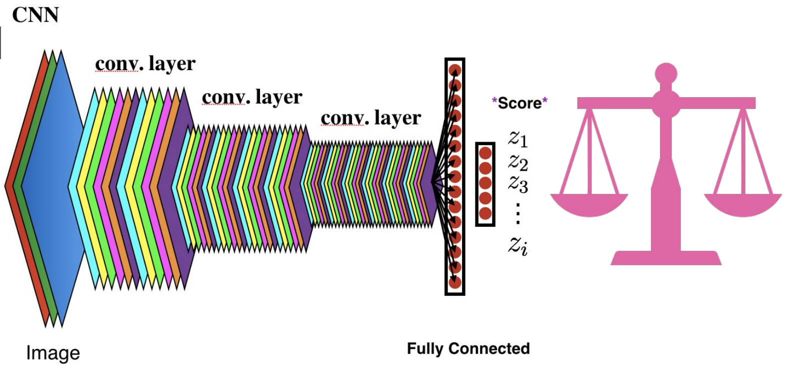
- Background event: constant stream of cosmic ray muon tracks
- Background rate: exposure* event acquisition frequency.
- 80T TPC volume, ~hrs of exposure.
- Random trigger on off-beam readout.



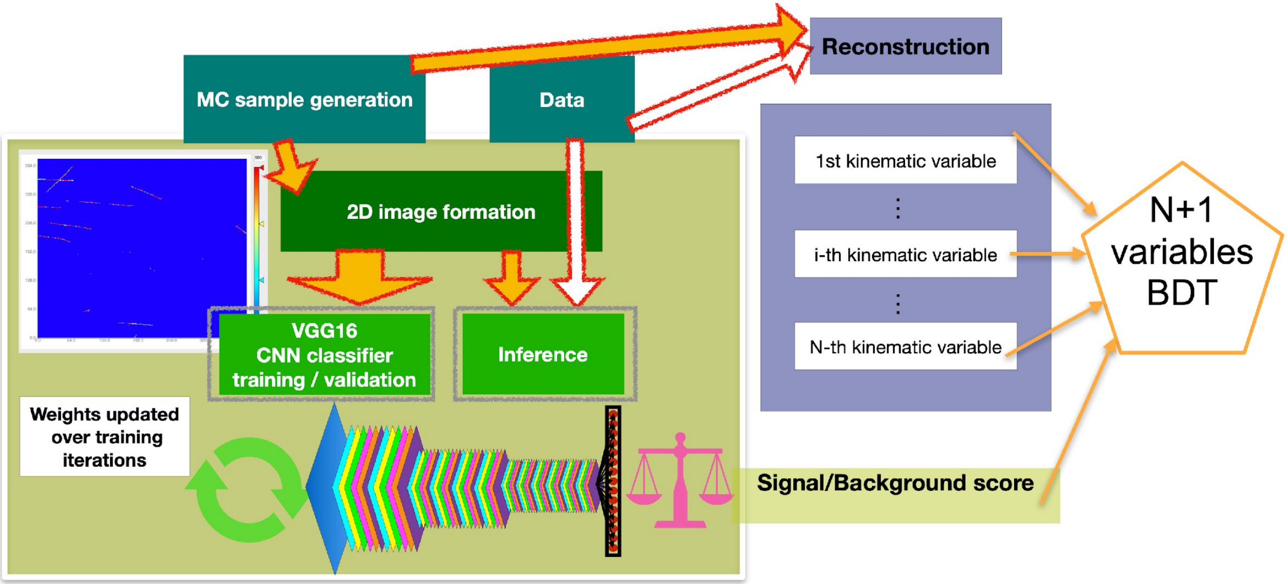


Analysis overview: ML based Method

- Image classification using convolutional neural network (CNN) is used to classify n-nbar signal vs. background out of TPC images.
- Boosted decision tree (BDT) classification takes kinematic variables plus CNN score as inputs to make a decision for signal vs. background events.
- Analysis makes use of rich topological and calorimetric information through
  - Image analysis (CNN)
  - Calorimetric reconstruction (BDT)



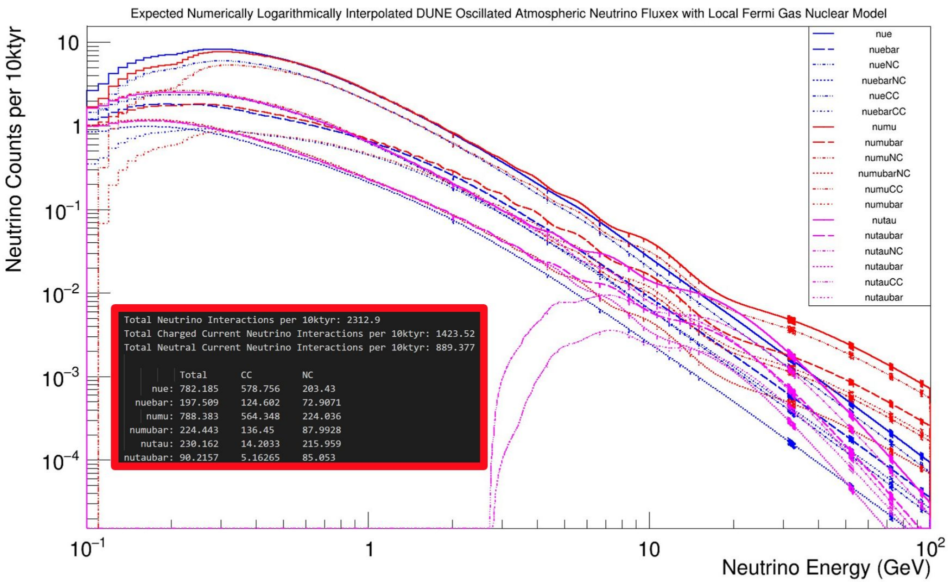
Analysis overview: CNN+BDT Analysis Flow



- This analysis scheme can be shared for MicroBooNE & DUNE analysis, offering a unique opportunity for validation with existing MicroBooNE data.

Progress in n-nbar search in DUNE

Atmospheric neutrino simulation for DUNE

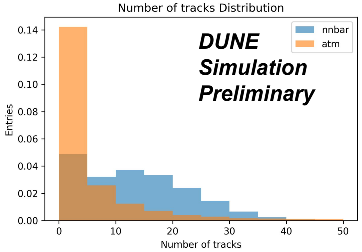


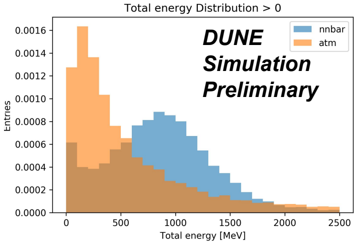
By J. Barrow in collaboration with Martinez-Soler.

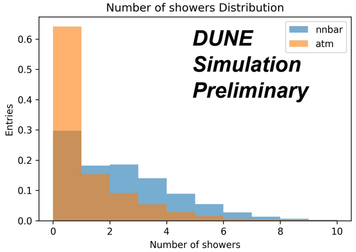
- Honda atmospheric neutrino flux has been oscillated and the rotation to the DUNE far detector has been established, to yield the expected atmospheric neutrinos at DUNE far detector.
- 231.29 / kT-yr atmospheric neutrino interactions are expected, which corresponds to ~92k total atmospheric events during a 10-year run with 40 kton DUNE far detector.

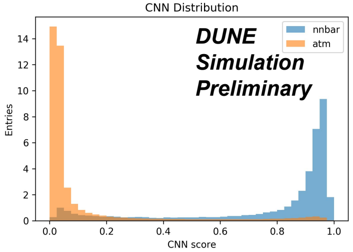
CNN+BDT combined analysis

Arbitrarily normalized distributions:





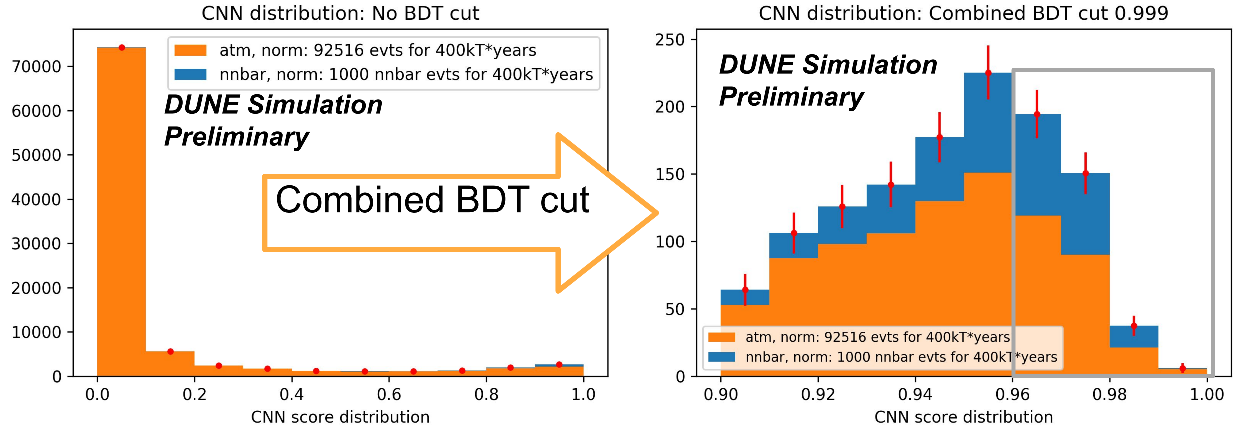




Input BDT variables

- **Number of tracks**
- **Number of showers**
- **Total energy**
- Shower energy
- Track energy
- Longest track PID
- Longest track momentum
- leading shower dEdx
- Shower energy fraction to total energy
- **CNN score**

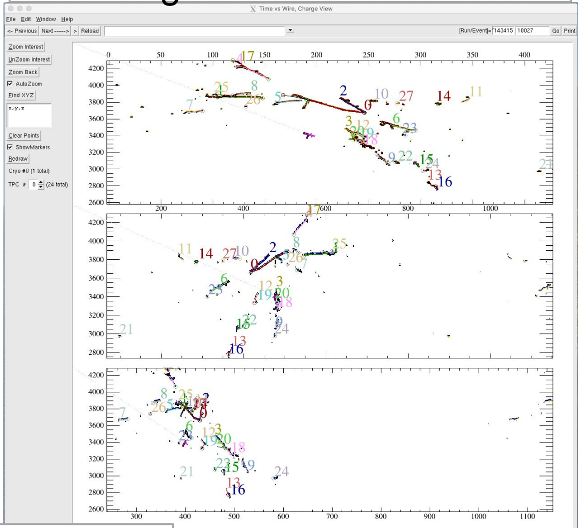
Selection cut and preliminary sensitivity in DUNE



- Final selection makes use of combined BDT cut plus additional CNN score cut.
- Final selection efficiencies for signal and background after Combined BDT cut (>0.999) + additional CNN cut (>0.97):
    - ~5% for signal
    - 0.063% for background

Example nnbar and background events passing final selection

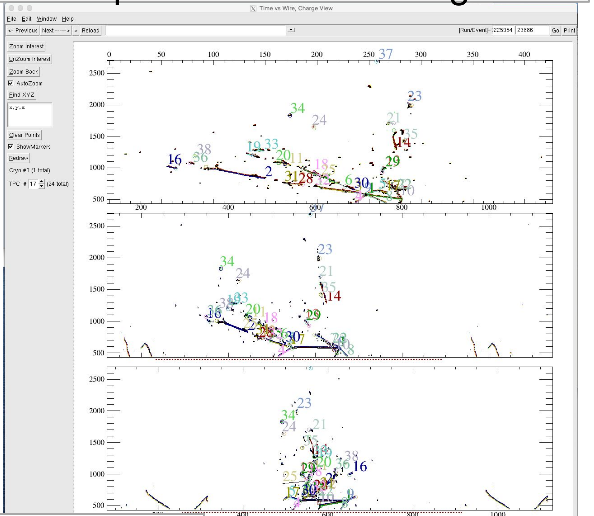
nnbar signal



2 protons, 2 neutrons,
1 pi+, 3 pi0

MCTruth	Ptcl	trackID	PDG	P	T	Moth	Process
0	0	0	^{40}Ar	0	0	-1	primary
0	9	9	#pi^{0}	394	281	4	primary
0	10	10	p	564	156	4	primary
0	11	11	#pi^{+}	348	235	5	primary
0	12	12	p	467	110	5	primary
0	13	13	#pi^{0}	324	216	6	primary
0	14	14	n	174	16	6	primary
0	15	15	#pi^{0}	131	53	7	primary
0	16	16	n	345	61	7	primary
0	17	17	#pi^{0}	110	39	8	primary

Atmospheric neutrino background



1 muon,
1 proton,
1 neutron,
2 pi+, 1pi-

MCTruth	Ptcl	trackID	PDG	P	T	Moth	Process
0	0	0	#nu_{#mu}	2418	2418	-1	primary
0	1	1	^{40}Ar	0	0	-1	primary
0	4	4	#mu	355	265	0	primary
0	10	10	p	779	281	6	primary
0	11	11	#pi^{+}	218	119	7	primary
0	12	12	n	461	107	7	primary
0	13	13	#pi^{+}	946	816	8	primary
0	14	14	#pi^{-}	419	302	9	primary

Note: Momentum, P, and kinetic energy, T, in MeV/c

- Visual similarity in the event displays
- Shared truth-level profiles
- Including more BDT input variables (net momentum, invariant mass) is underway

Preliminary sensitivity for DUNE

- A preliminary 90% C.L. sensitivity for nnbar lifetime can be achieved at 2.01E+32 years, with the selection, under the assumption of 3% of uncertainty for the exposure, and 25% of uncertainty for the signal & background selections.
- With the nuclear suppression factor for Argon R = 5.60E+22, this result corresponds to a free neutron lifetime 3.4e8 s, using the conversion formula. ($\tau^2_{n-\bar{n}} = \frac{T_{n-\bar{n}}}{R}$)
- The result is comparable with the current best limit at SK (2.7 e8 s), and 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-nbar search in MicroBooNE

CNN-only analysis in MicroBooNE

BDT-only analysis in MicroBooNE

CNN+BDT combined analysis in MicroBooNE

Summary

The future DUNE experiment is well positioned to provide world-leading limits to baryon number violation process of neutron-antineutron oscillation.

MicroBooNE, sharing the same technology as DUNE, with a total accumulated exposure of xxxx seconds of unbiased data, is well positioned to provide a first proof-of-principle demonstration of this search, and the first LArTPC-based search for neutron-antineutron oscillations.

Back Up

Atmospherics passing this selection

$(\bar{n}, p)$		$(\bar{n}, n)$	
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].*