Bound n-nbar signatures and searches in DUNE

Georgia Karagiorgi*, on behalf of the DUNE Collaboration
*Columbia University and The University of Manchester

INT Workshop INT-17-69W
Neutron-Antineutron Oscillations: Appearance, Disappearance, and Baryogenesis

Oct. 23, 2017

Outline

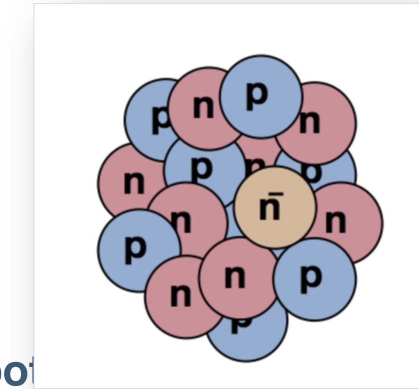
1. **Bound neutron-antineutron oscillation**:
   Review, and past experimental searches
2. **DUNE**:
   Detector specifications and liquid argon time projection chamber operating principle
3. **Searches for neutron-antineutron oscillations in DUNE**:
   Approach and projected sensitivity
4. **Argon-bound neutron-antineutron oscillations**:
   A rudimentary signal simulation utilizing the GENIE event generator

Bound neutron-antineutron oscillation

- **Nucleus-bound neutrons abound!**

E.g. 40 g of argon: N_A x 22 = **1.3E25 neutrons**

40 kilotons of argon: **1.3E34 neutrons**



- **Drawback: transition is heavily suppressed due to nuclear pot**

$$\tau_A = T_R \, \tau^2_{n \to \bar{n}}$$

nuclear disappearance lifetime

free neutron oscillation lifetime

nuclear suppression factor

- theoretically calculated
- varies for different nuclei

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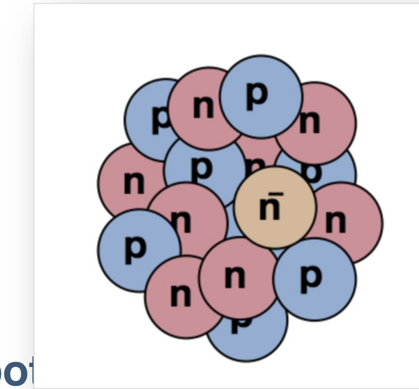


- **Drawback: transition is heavily suppressed due to nuclear pot**

$$\tau_A = T_R \, \tau^2_{n\rightarrow\bar{n}}$$

nuclear disappearance lifetime (τ_A)

free neutron oscillation lifetime ($\tau_{n\rightarrow\bar{n}}$)

For in-depth calculations of **nuclear suppression factors** (^{16}O, ^{56}Fe), see [Friedman & Gal, 2008].

Note: for **argon** (DUNE), T_R has not explicitly been calculated.

Assumption (this talk): same as for ^{56}Fe

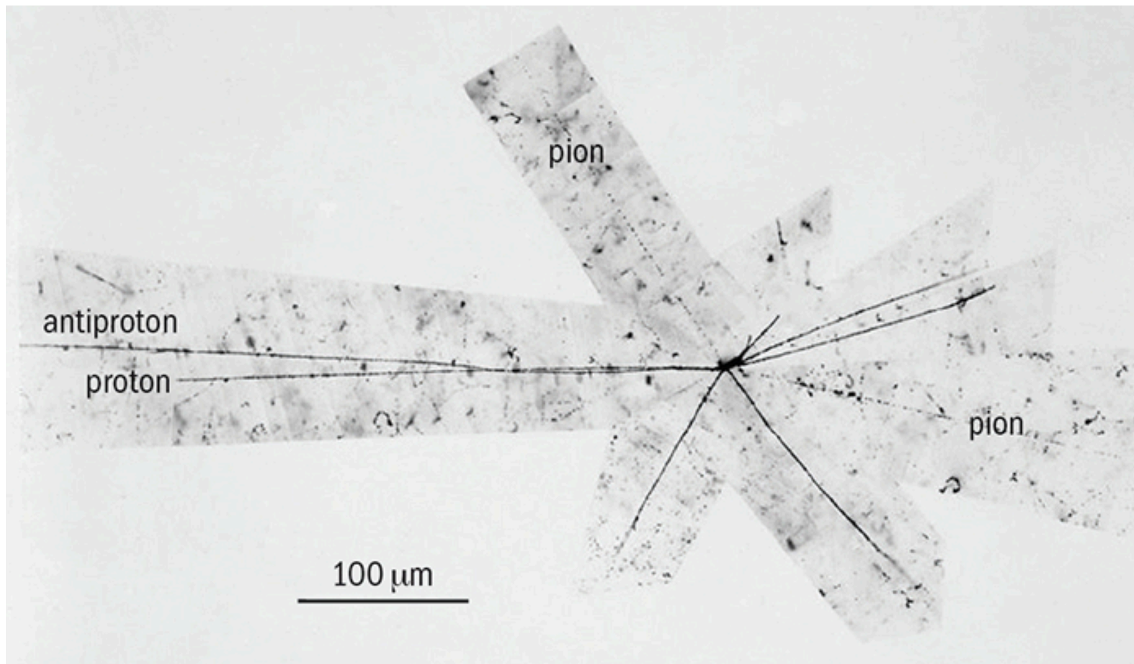
Element	T_R	Uncertainty
^{16}O	0.517-0.543E23s^{-1}	10-15%
^{56}Fe	0.666E23 s^{-1}	10-15%
^{40}Ar	~0.666E23 s^{-1}	~20-40%

Bound neutron-antineutron oscillation

- **Signature:**

  Annihilation with nearby nucleon (p or n) inside parent nucleus
  → multi-pion final state

Discovery of the antiproton, 1955



Observation of Antiprotons*

Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis

Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received October 24, 1955)

PRL, 1955

Annihilation "star event"

$\Sigma E \sim 2\, m_n \sim 2$ GeV

$\Sigma p \sim 0$ GeV

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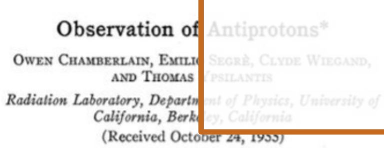
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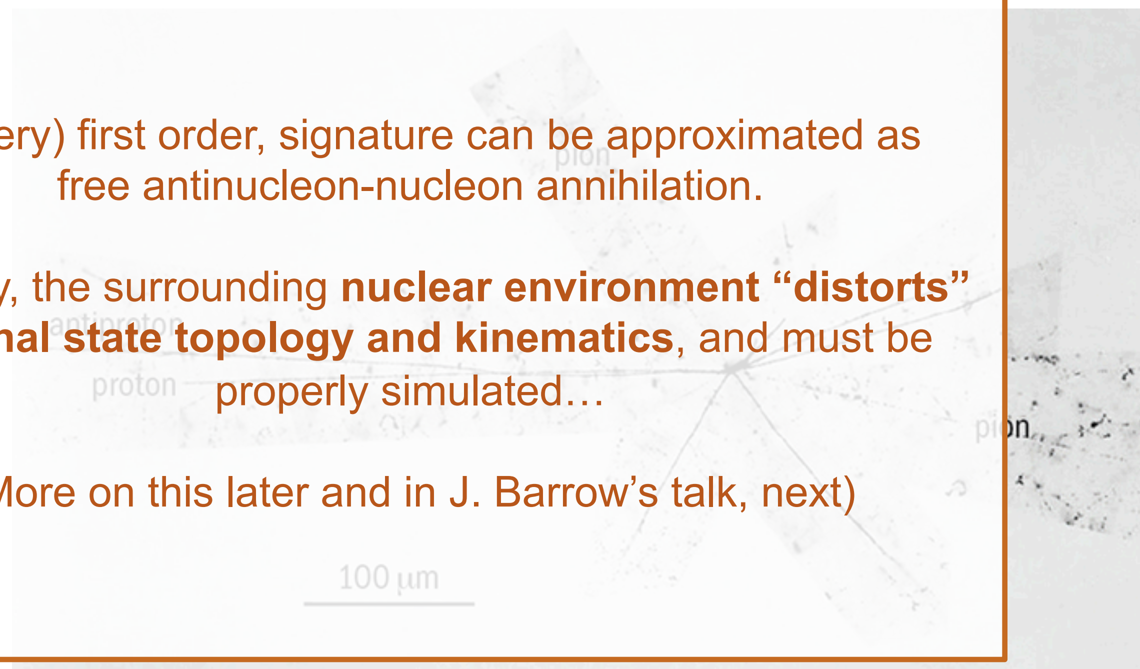


To (very) first order, signature can be approximated as free antinucleon-nucleon annihilation.

In reality, the surrounding **nuclear environment "distorts" the final state topology and kinematics**, and must be properly simulated…

(More on this later and in J. Barrow's talk, next)

Annihilation "star event"

$\Sigma E \sim 2\ m_n \sim 2$ GeV
$\Sigma p \sim 0$ GeV

Bound neutron-antineutron oscillation

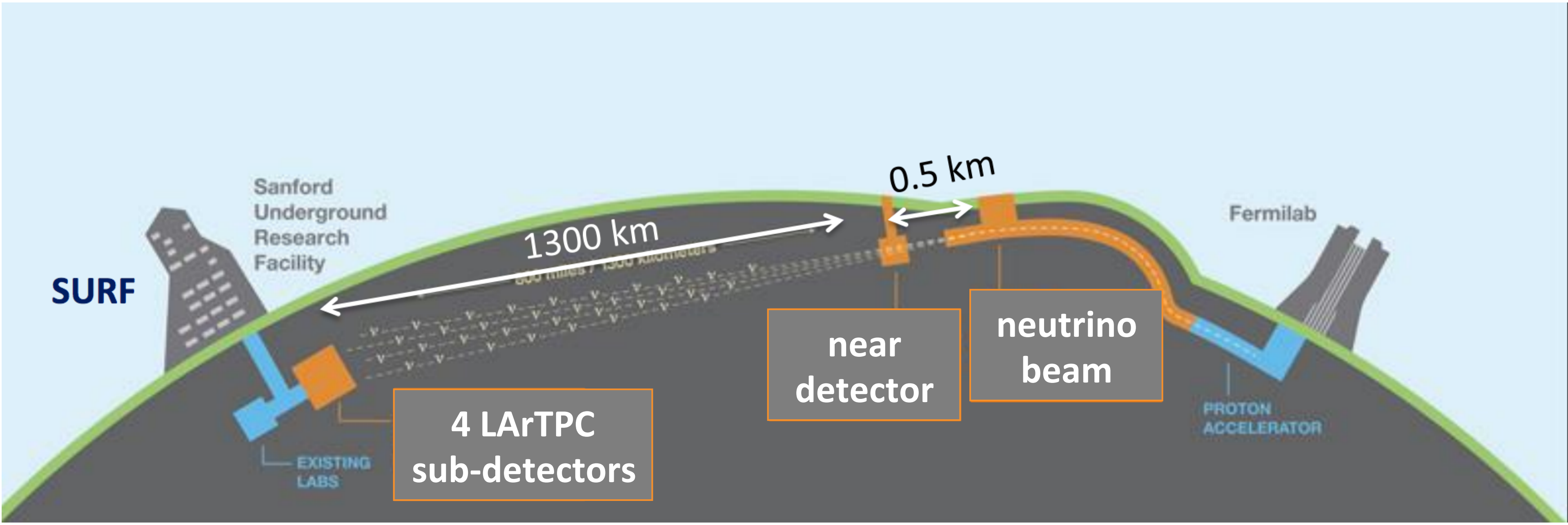
Current best limits on free neutron lifetime:

- **Super-K oxygen-bound** neutron search: $\tau > 2.7 \times 10^8$ s (90%CL) [arXiv:1109.4227]
- **SNO deuterium-bound** neutron search: $\tau > 1.23 \times 10^8$ s (90%CL) [arXiv:1705.00696]

- For reference:
  Free neutron beam search at **ILL**: $\tau > 0.86 \times 10^8$ s (90%CL) [Z. Phys. C. v63, 409-416]

Deep Underground Neutrino Experiment

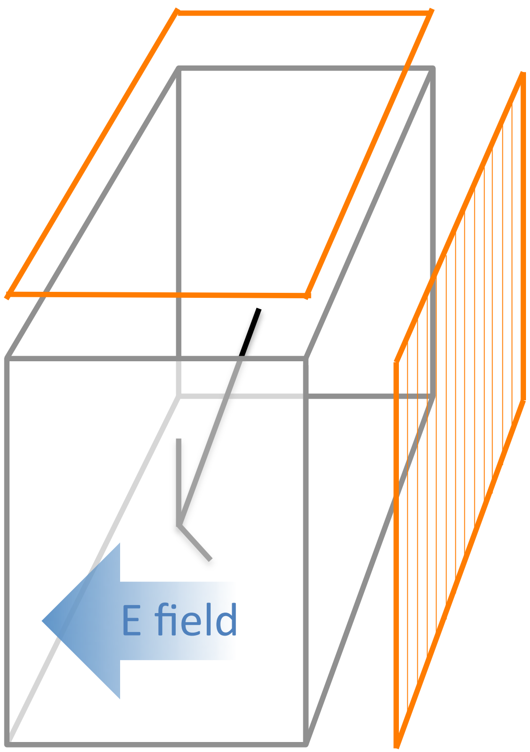
DUNE will employ a **large-mass** liquid argon time projection chamber (LArTPC) detector, **deep underground** in a low cosmogenic background environment —
ideal for rare physics searches!



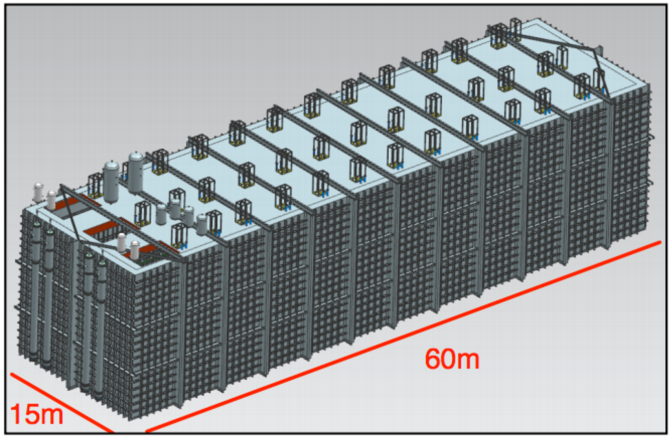
Each LArTPC sub-detector: 10kton fiducial mass; 4850ft (1.5km) underground.
Staged detector construction: first sub-detector operational in 2024; subsequent ones 1/year.

DUNE: An ionization 3D imaging device

DUNE "single-phase" design: Each 10kton sub-detector consists of 300 LArTPC "cells":



(*This talk assumes all four sub-detectors are single-phase.)



DUNE 10kt sub-detector

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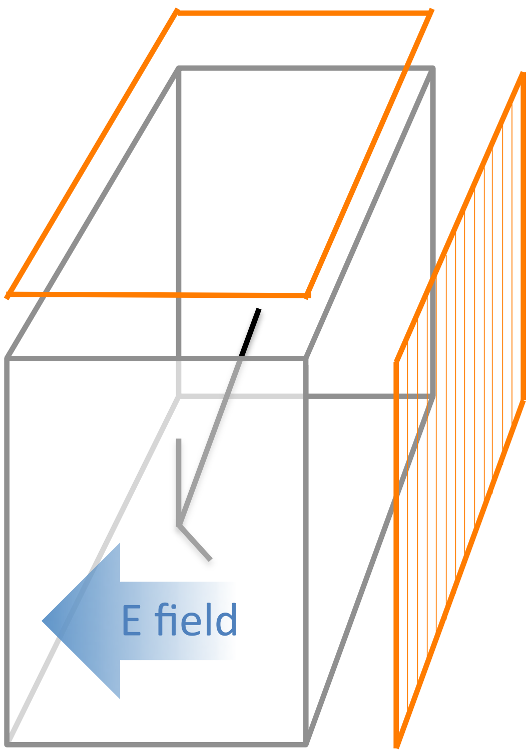

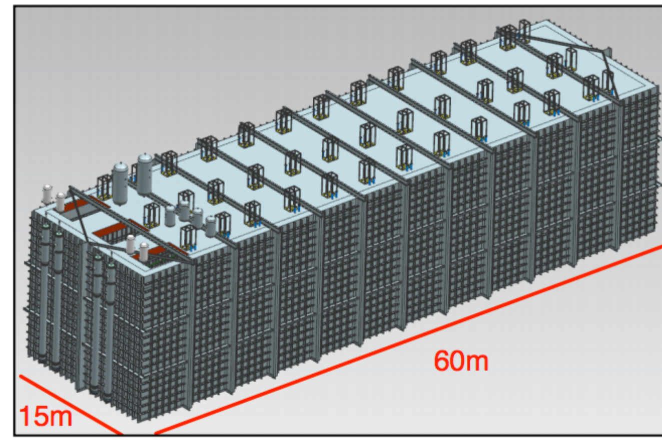

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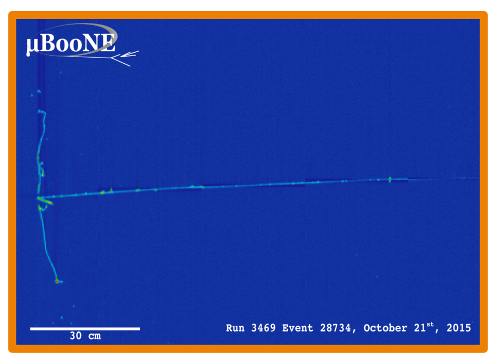

Local ionization dE/dx recorded with sub-mm spatial resolution; can resolve minimum-ionizing particles (MIPs) to few overlapping protons based on local ionization energy deposition.

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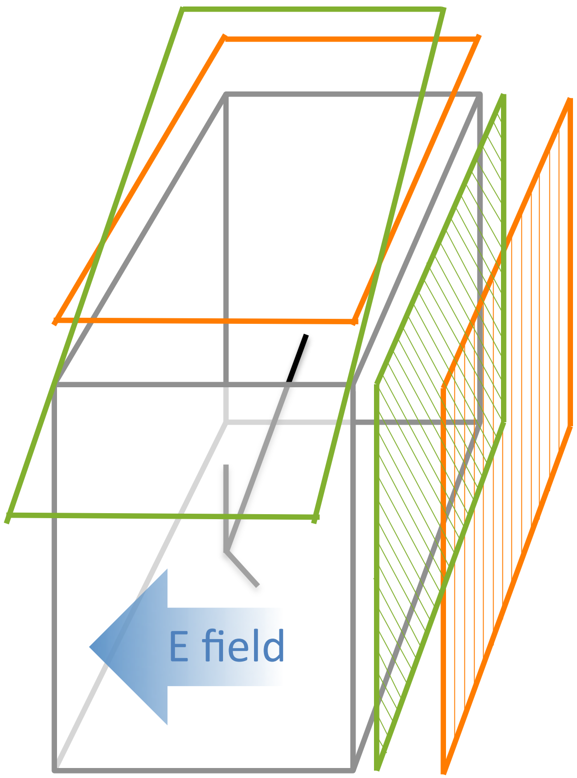

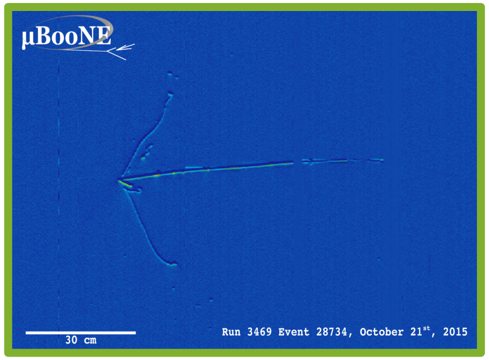

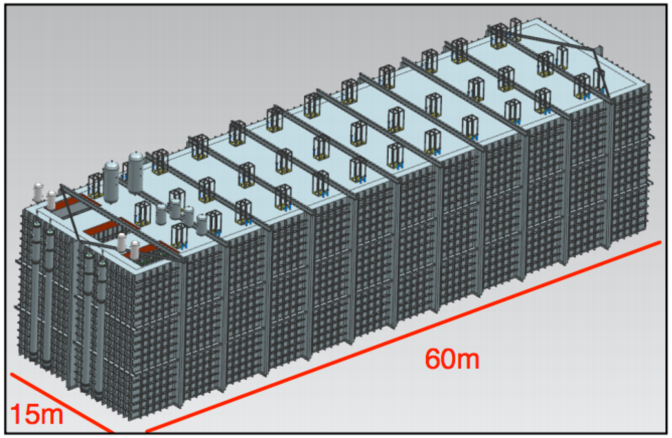

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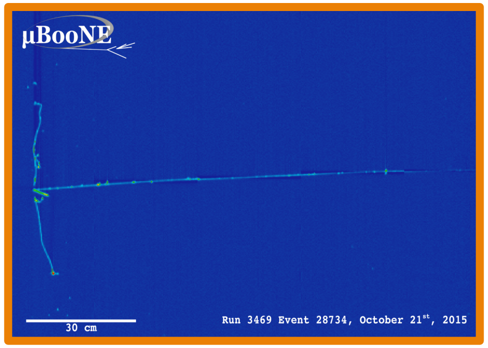

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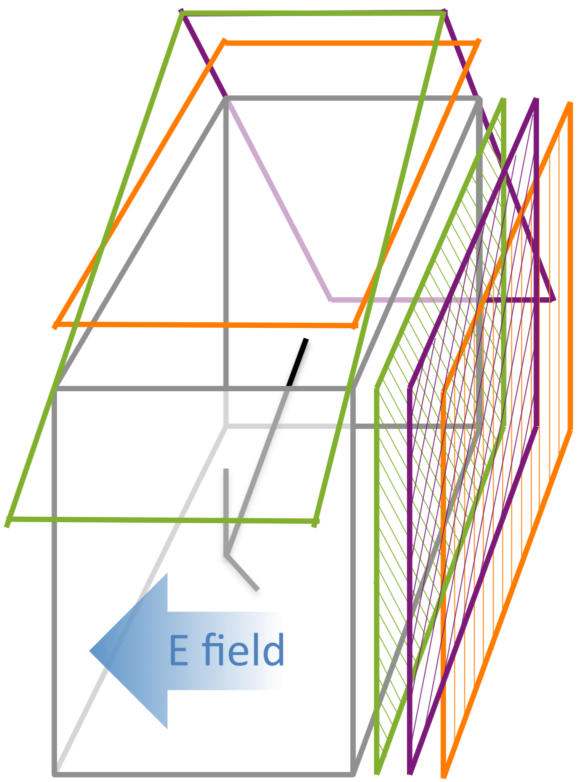

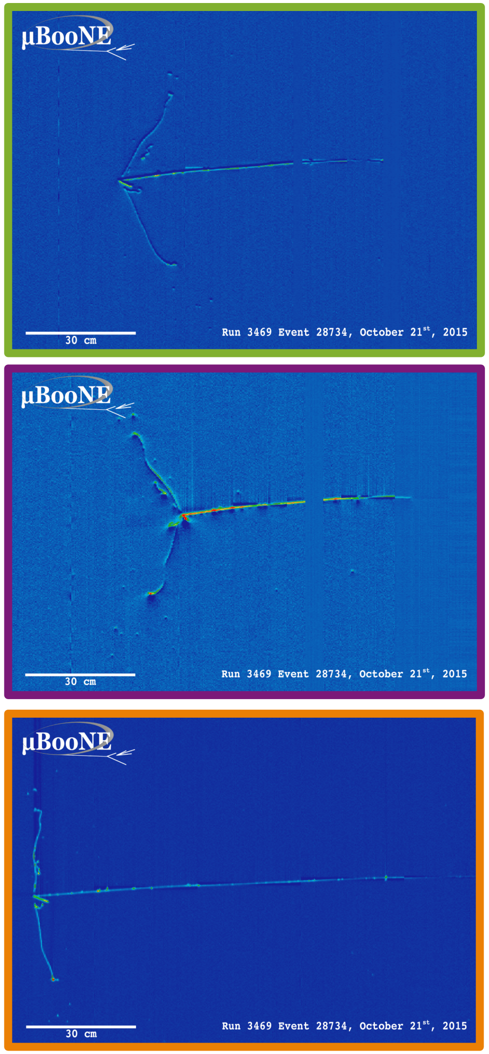

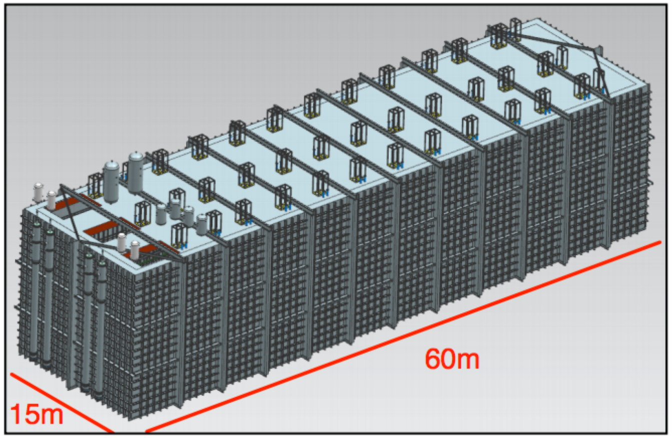

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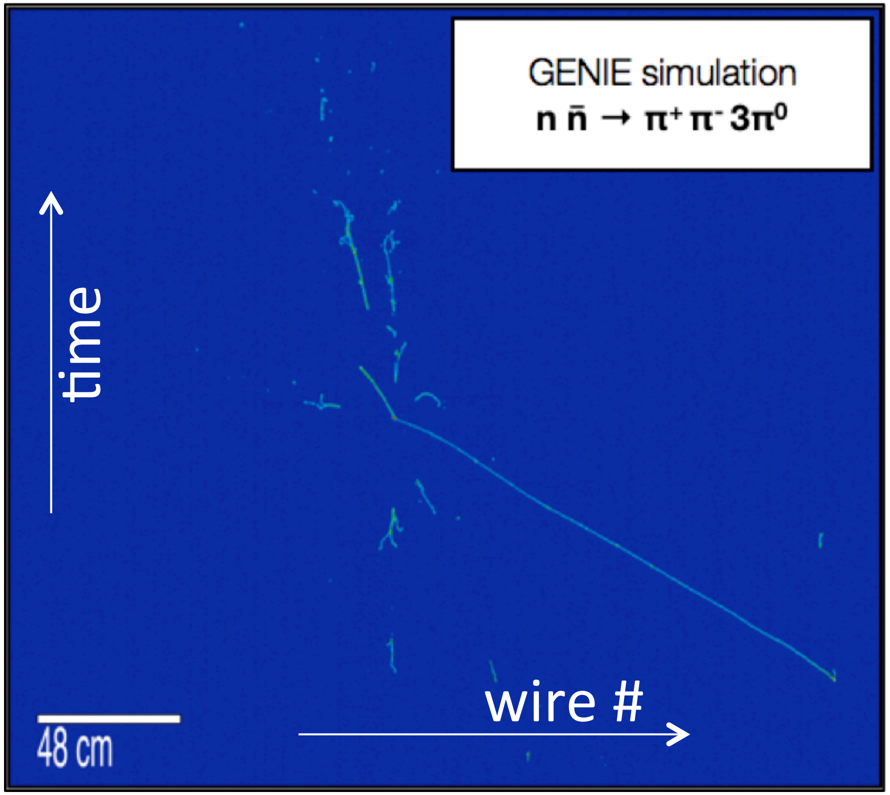
n-nbar event signature in a LArTPC



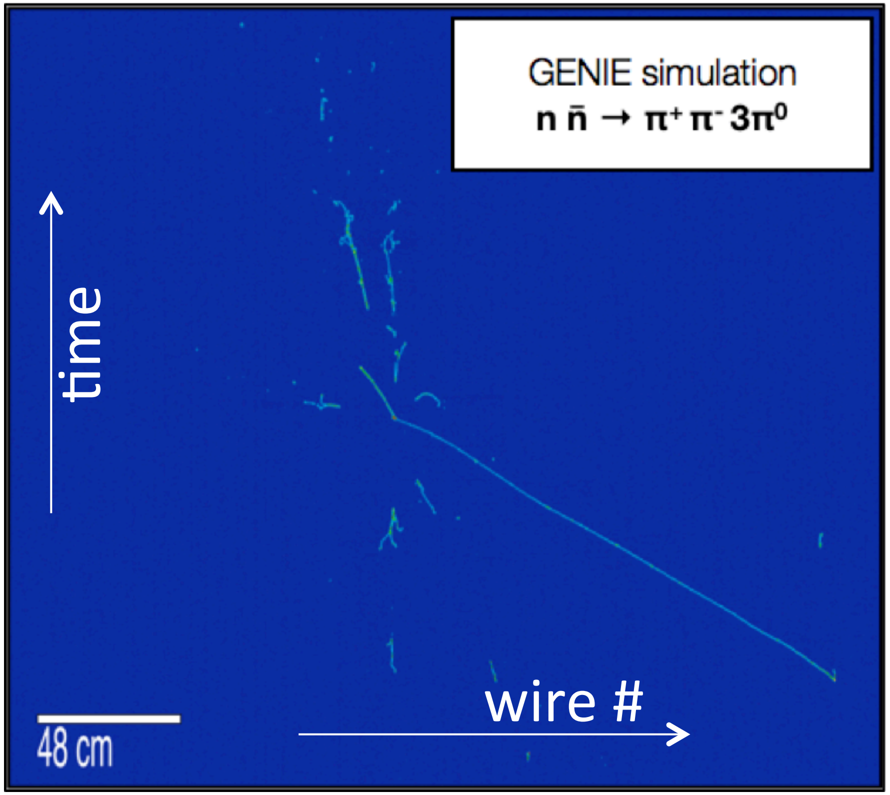
Simulated neutron-antineutron ($n - \bar{n}$) oscillation event in liquid argon, using the GENIE 2.12 $n - \bar{n}$ event generator. The 6 showers from the decays of 3 π^0's are clearly seen, as well as two tracks from the two charged pions. The distinctive spherical topology makes these events easily identifiable by eye, and work is underway to develop event selection criteria using DUNE reconstruction and particle ID algorithms.

"Star"-event topology simulated in a LArTPC

$\pi^{+/-}$: MIP-like tracks
$\pi^0 \rightarrow \gamma\gamma$: showers from $\gamma \rightarrow e^+e^-$ conversion

One such image per wire plane (3 total).

n-nbar event signature in a LArTPC



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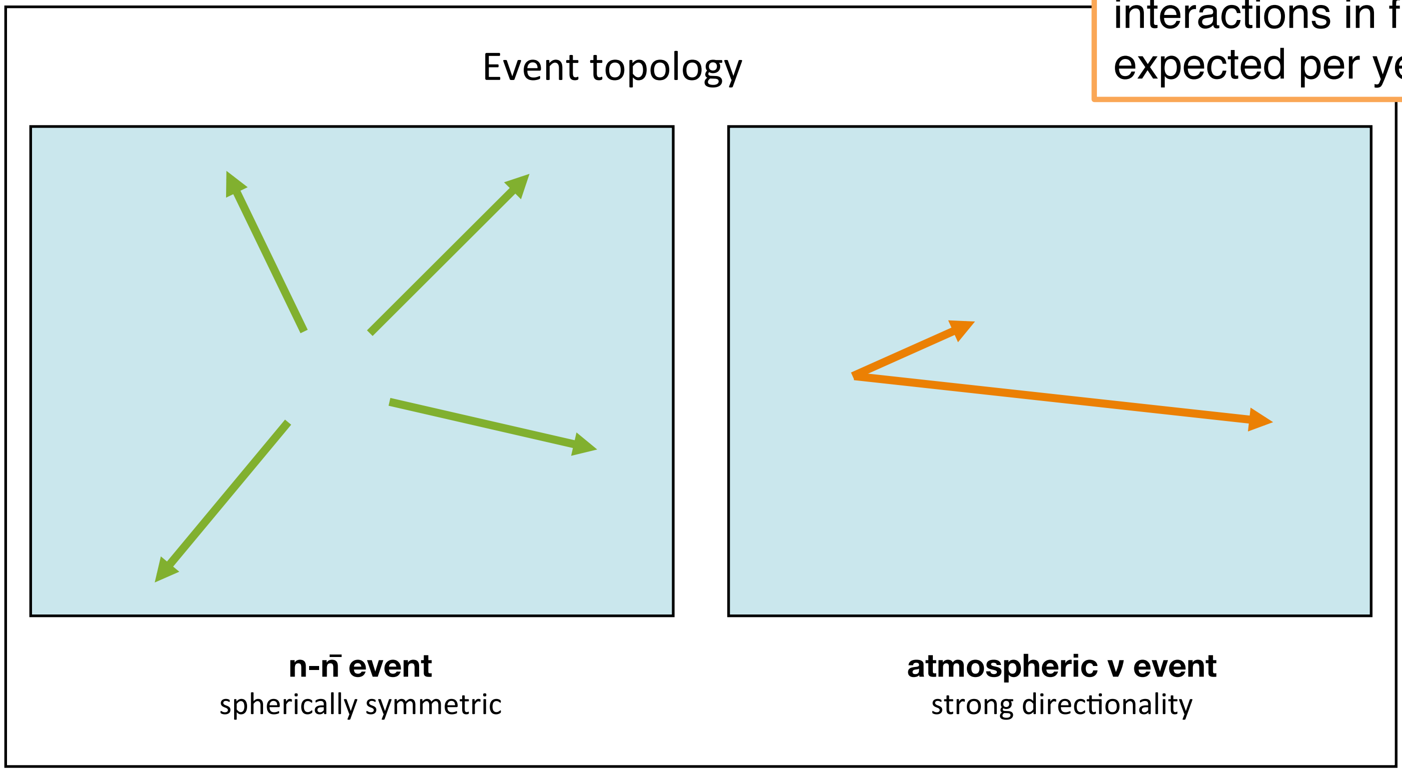
Traditional reconstruction:

- (wire,time) “hits” clustered into 2D tracks and 2D showers.
- 2D track/shower wire plane projections reconstructed into 3D objects.
- Calorimetry and particle identification.
- Full event reconstruction, event identification.

DUNE search for neutron-antineutron oscillation

11,000 atmospheric neutrino interactions in full 40kton detector expected per year



Dominant background expected to be from atmospheric neutrino interactions.

Mitigation with traditional reconstruction exploits topology (spherical symmetry/net momentum) and calorimetric energy reconstruction.

DUNE search for neutron-antineutron oscillation

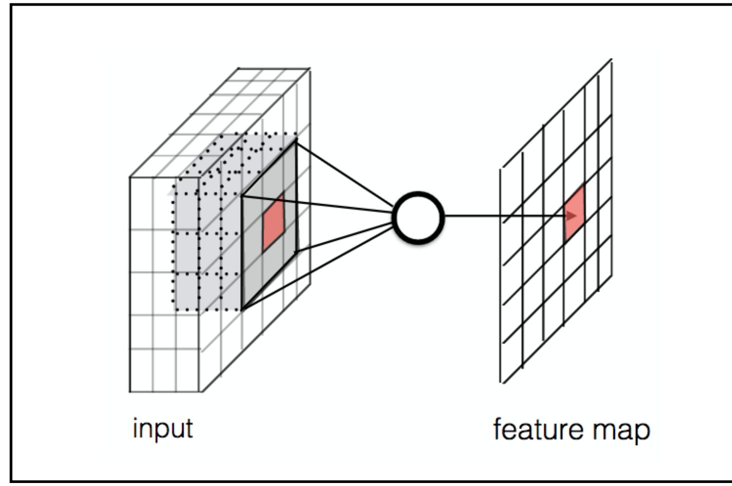
- This analysis: Non-traditional search approach, using **deep-learning-based reconstruction**
- **Convolutional Neural Networks:**
  a revolutionary image analysis technique → Well suited for LArTPC's!

  Successful in identification and differentiation among different particle types.
  [JINST 12, P03011 (2017)]

- **Sensitivity analysis approach:**
  - Train network to differentiate between n-nbar signal and background events
  - Benchmark efficiencies
  - Estimate sensitivity

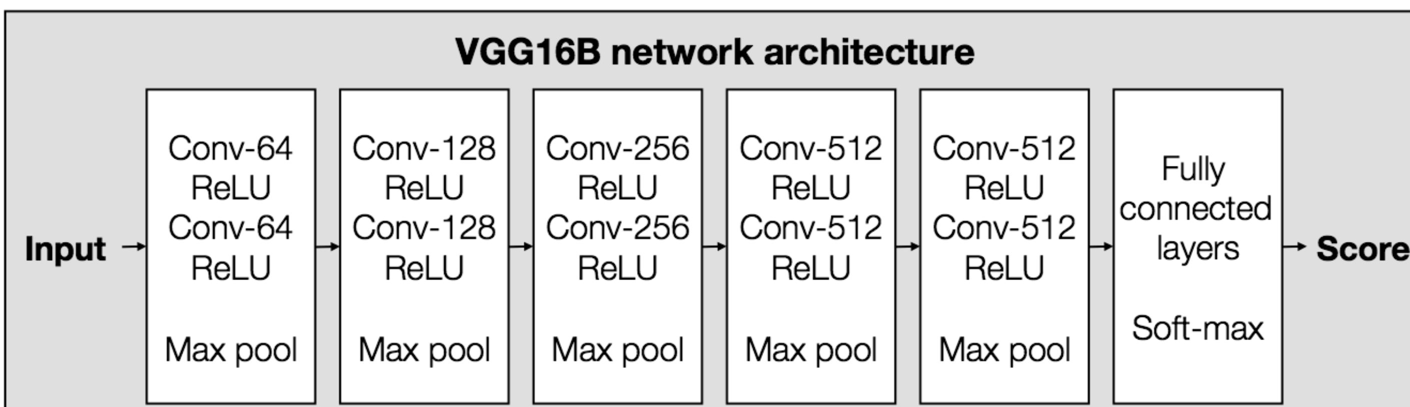
DUNE search for neutron-antineutron oscillation

- **CNN:** A class of deep, feed-forward artificial neural network, typically applied in image analysis.



Network performs convolutions on input images to pick out complex features, and learns to associate these features with the event type.

- **Example:** VGG16B network architecture



DUNE search for neutron-antineutron oscillation

High-resolution image of a (strikingly unique) "star-event" topology

+

powerful technique for image-based classification

=

promising high-sensitivity to this rare signature!

DUNE search for neutron-antineutron oscillation

DUNE n-nbar analysis details (*assumes "single-phase" detector):

EVENT GENERATION

Signal and background samples generated in GENIE.

Atmospheric flux: Honda @ Homestake (oscillated).

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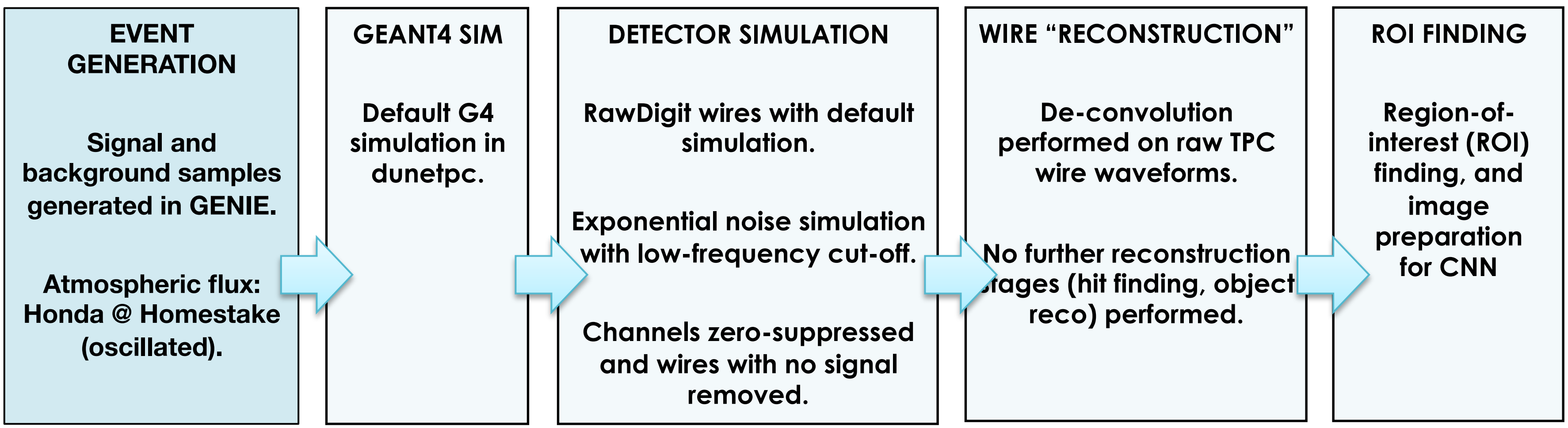
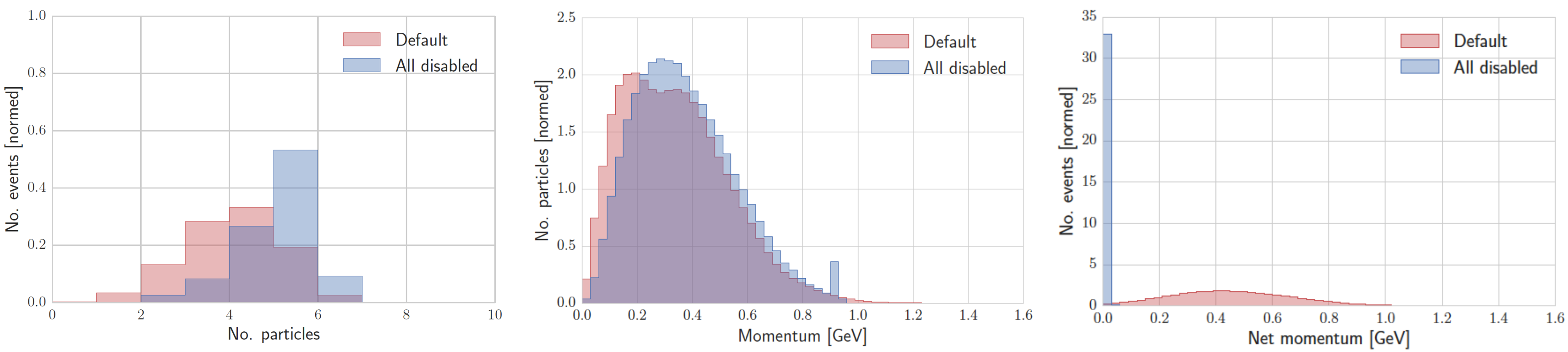


Argon-bound neutron-antineutron oscillation

Signal generator for argon-bound neutron-antineutron oscillation:

- New module written in GENIE event generator for neutron-antineutron oscillation, based on GENIE's nucleon decay module.
- Accounts for **Fermi motion, argon nucleus binding energy, final state interactions**
- Currently available as part of official GENIE release (as of v2.12)
- Works for any atomic nucleus!

No nuclear effects
With nuclear effects



Argon-bound neutron-antineutron oscillation

Signal generator:

- Initial state: ^{40}Ar nucleus.

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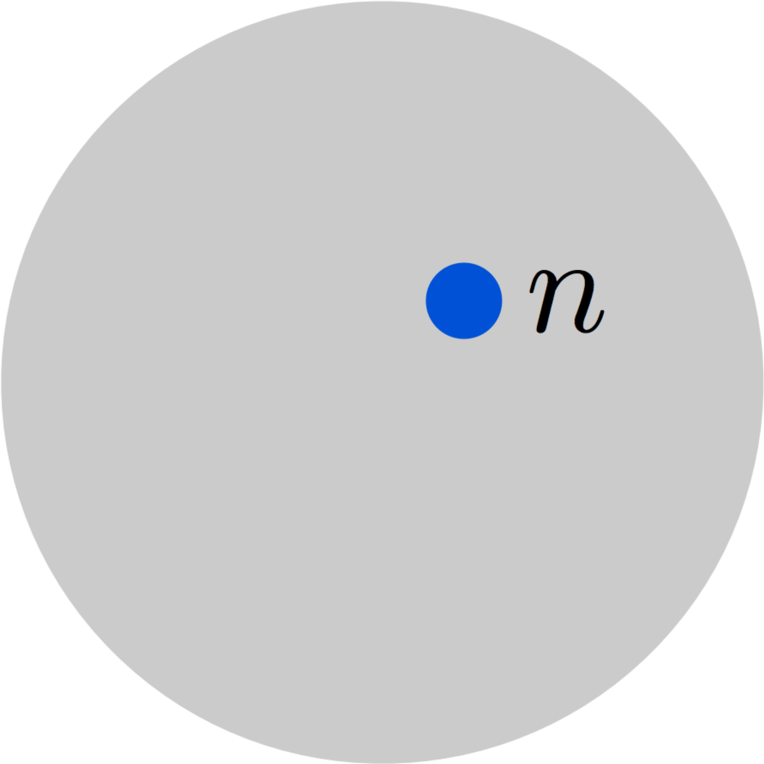
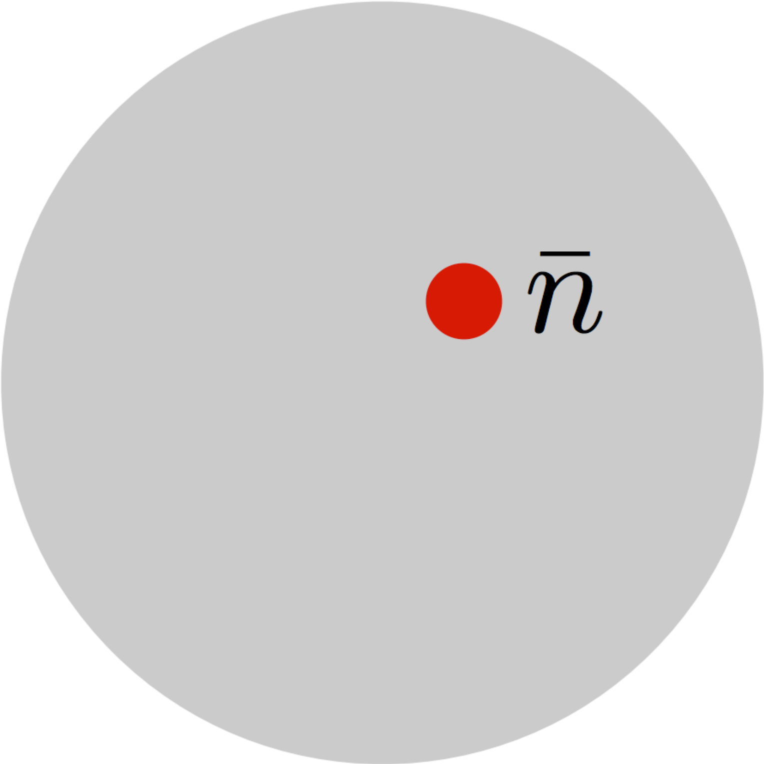


Argon-bound neutron-antineutron oscillation

Signal generator:

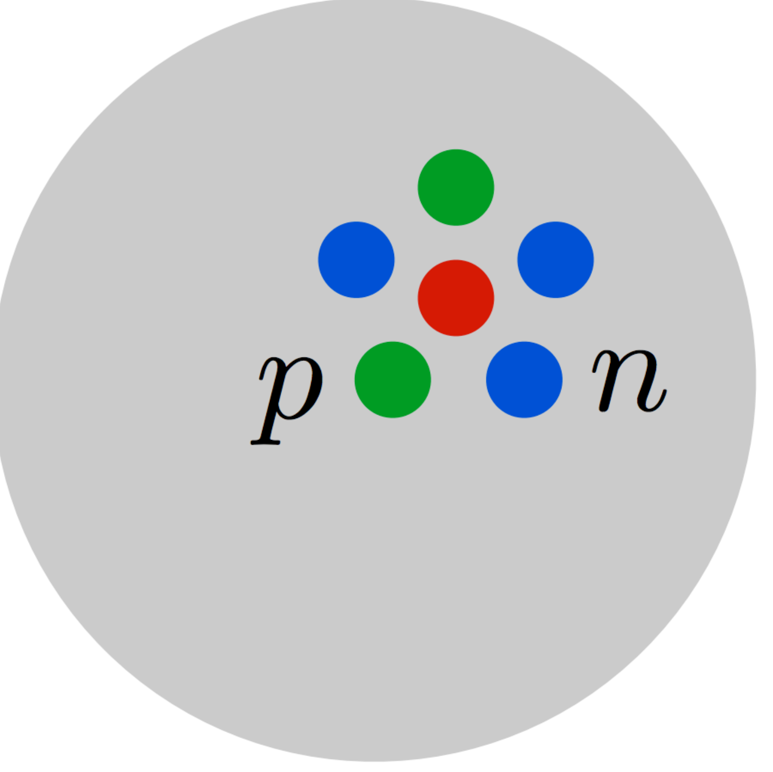
- Initial state: ^{40}Ar nucleus.
- Neutron oscillates into antineutron.



Argon-bound neutron-antineutron oscillation

Signal generator:

- Initial state: ^{40}Ar nucleus.
- Neutron oscillates into antineutron.
- Antineutron annihilates with proton or neutron.

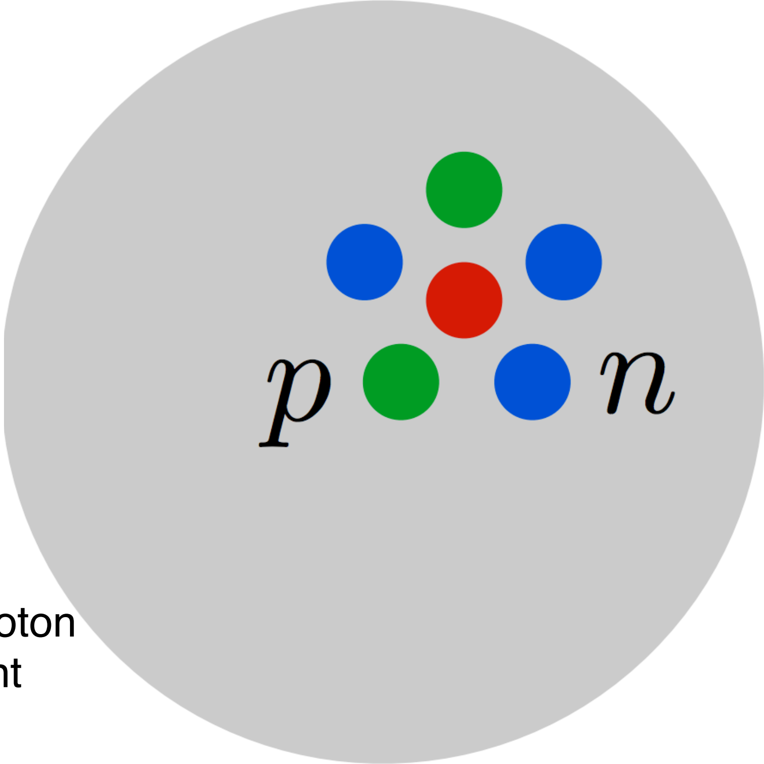


Argon-bound neutron-antineutron oscillation

Signal generator:

- Initial state: ^{40}Ar nucleus.
- Neutron oscillates into antineutron.
- Antineutron annihilates with proton or neutron.
  - 21 neutrons, 18 protons.
  - Randomly select annihilation mode according to branching ratios.

sourced from past antiproton annihilation measurement experiments



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Effective BR for Argon, in GENIE (adapted from Super-K)

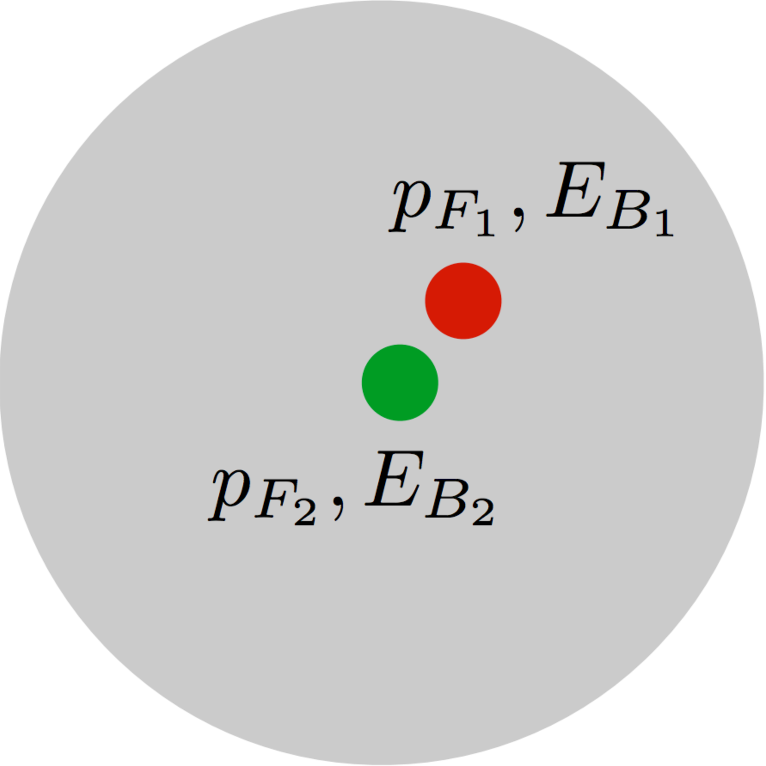
$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1.2%	$\pi^+\pi^-$	2.0%
$\pi^+2\pi^0$	9.5%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	11.9%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	26.2%	$\pi^+\pi^-2\pi^0$	11.0%
$2\pi^+\pi^-2\pi^0$	42.8%	$\pi^+\pi^-3\pi^0$	28.0%
$2\pi^+\pi^-2\omega$	0.003%	$2\pi^+2\pi^-$	7.1%
$3\pi^+2\pi^-\pi^0$	8.4%	$2\pi^+2\pi^-\pi^0$	24.0%
		$\pi^+\pi^-\omega$	10.0%
		$2\pi^+2\pi^-2\pi^0$	10.0%

sourced from past antiproton annihilation measurement experiments

Argon-bound neutron-antineutron oscillation

Signal generator:

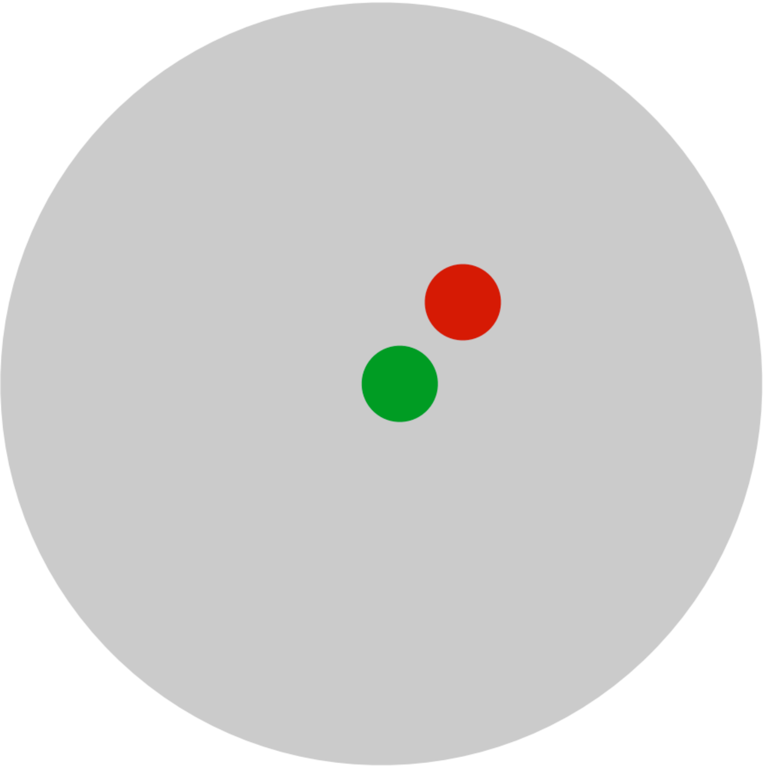
- Initial state: ^{40}Ar nucleus.
- Neutron oscillates into antineutron.
- Antineutron annihilates with proton or neutron.
    - 21 neutrons, 18 protons.
    - Randomly select annihilation mode according to branching ratios.
- Assign Fermi momentum & binding energy to antineutron & nucleon.



Argon-bound neutron-antineutron oscillation

Signal generator:

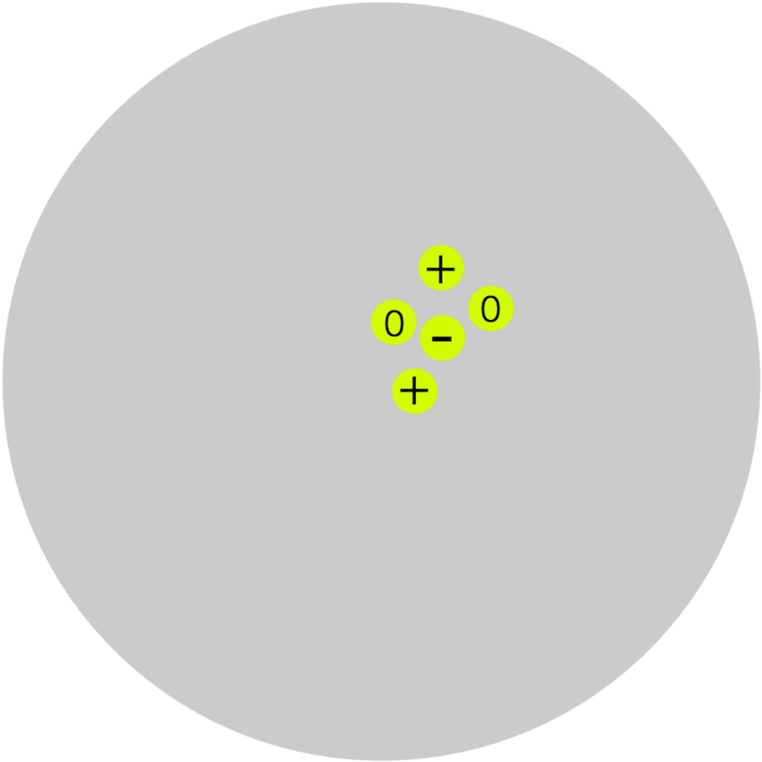
- Lorentz boost into CM frame of two-nucleon system.



Argon-bound neutron-antineutron oscillation

Signal generator:

- Lorentz boost into CM frame of two-nucleon system.
- Generate decay products.



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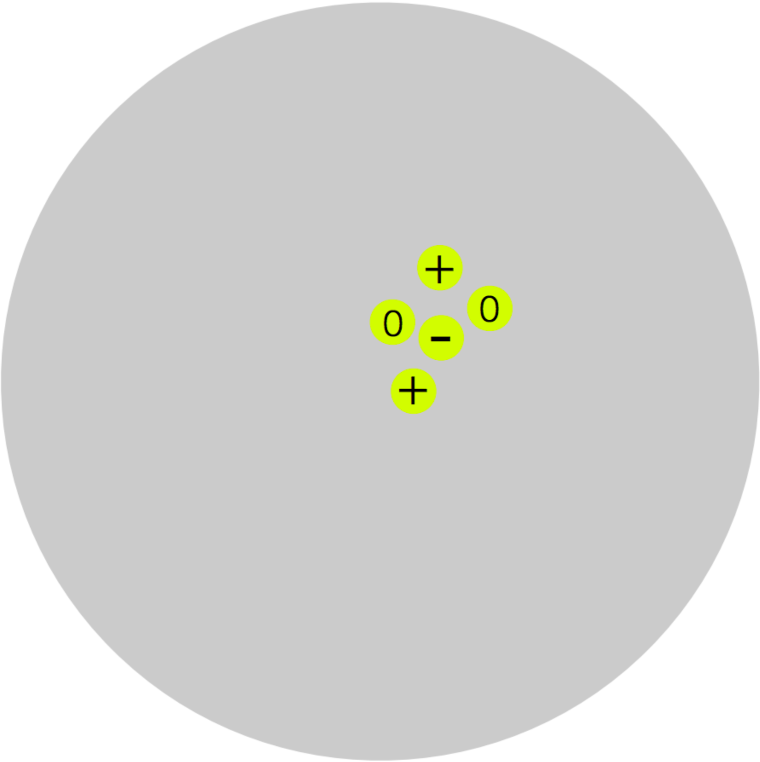
Signal generator:

- Lorentz boost into CM frame of two-nucleon system.
- Generate decay products.
- Assign momentum & energy using phase-space decay.
- Lorentz boost back into original frame.



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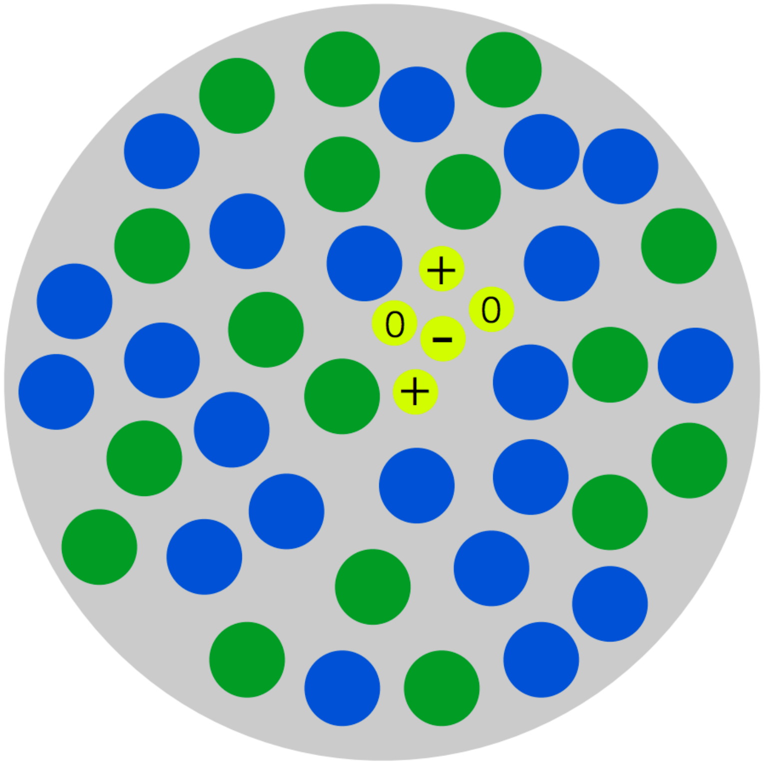
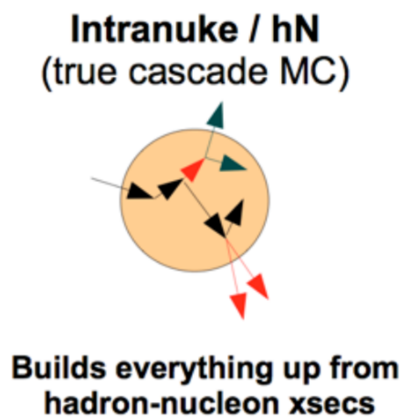
- Propagate final state particles through nucleus.

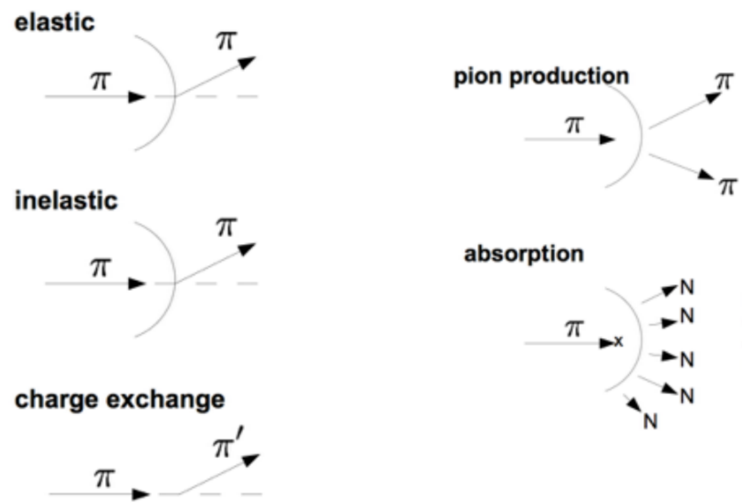


Argon-bound neutron-antineutron oscillation

Signal generator:

Final state particle propagation through nucleus uses INTRANUKE hA, an **effective, data-driven model** (less computational than hN).





- GENIE's hadron transport package.
- Full cascade model, propagates hadrons through the nucleus.
- Cross-generator comparisons of pion multiplicities on a later slide.

DUNE search for neutron-antineutron oscillation

DUNE n-nbar analysis details (*assumes "single-phase" detector):

EVENT GENERATION

Signal and background samples generated in GENIE.

Atmospheric flux: Honda @ Homestake (oscillated).

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GEANT4 SIM

Default G4 simulation in dunetpc.

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DETECTOR SIMULATION

RawDigit wires with default simulation.

Exponential noise simulation with low-frequency cut-off.

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WIRE "RECONSTRUCTION"

De-convolution performed on raw TPC wire waveforms.

No further reconstruction stages (hit finding, object reco) performed.

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ROI FINDING

Region-of-interest (ROI) finding, and image preparation for CNN

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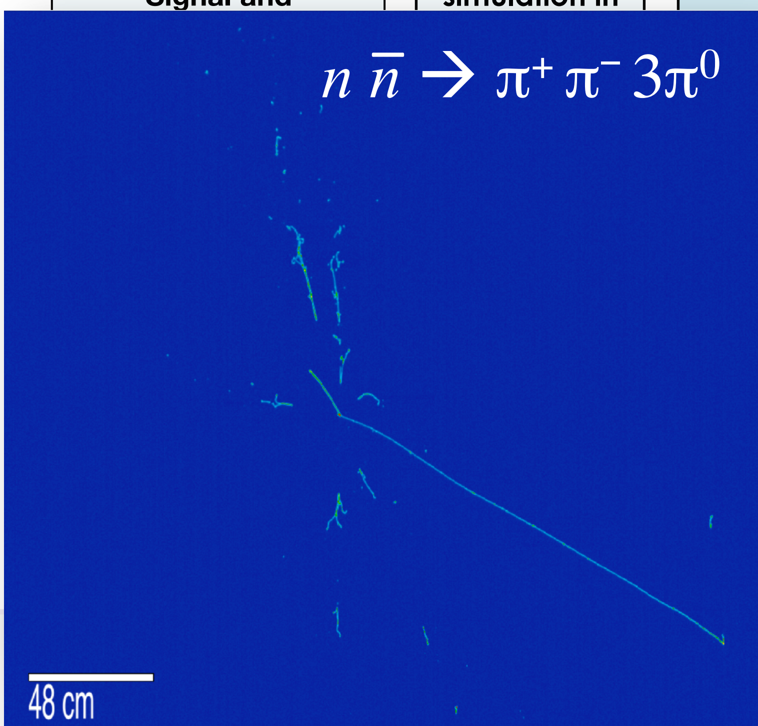

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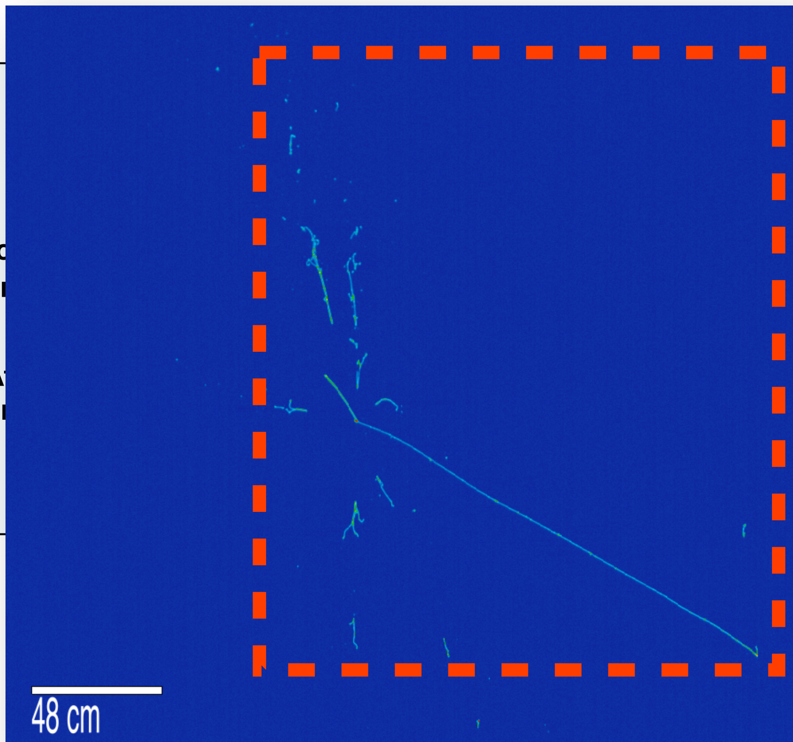
WIRE “RECONSTRUCTION”

De-convolution performed on raw TPC wire waveforms.

No further reconstruction stages (hit finding, object reco) performed.

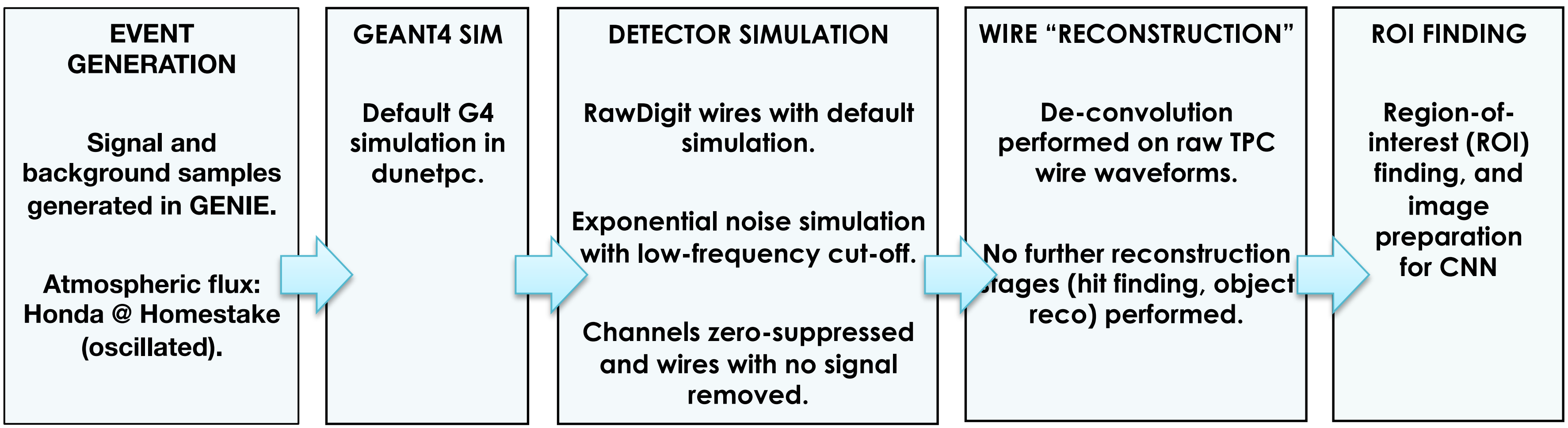
ROI FINDING

Region-of-interest (ROI) finding, and image preparation for CNN



DUNE search for neutron-antineutron oscillation

DUNE n-nbar analysis details (*assumes "single-phase" detector):

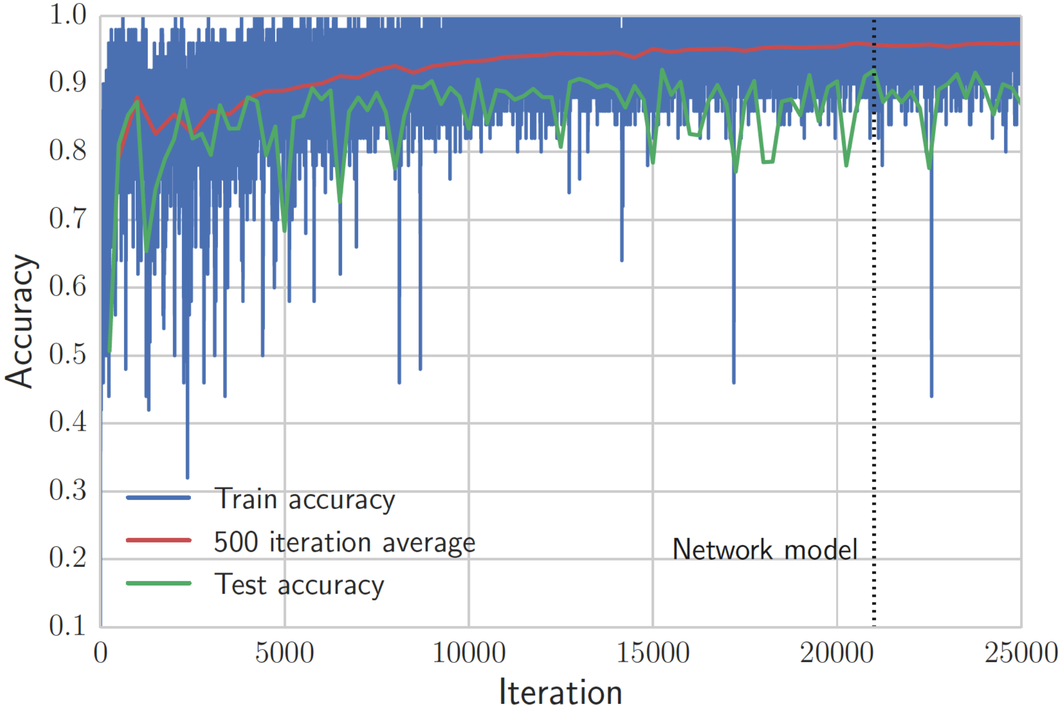


Using version of Caffe CNN framework [arXiv:1408.5093] modified to interface with LArTPC data files [arXiv:1611.05531].

VGG16 network architecture [arXiv:1409.1556] trained with 50,000 signal and 50,000 background events; and tested with 200,000 events each.

DUNE search for neutron-antineutron oscillation

- During training, network learns by minimizing a **loss function**, derived from network weights, which abstracts how many **classification mistakes** the network made.
- Network also monitors **accuracy** — the proportion of images **classified correctly**.
- Accuracy improves over more iterations.

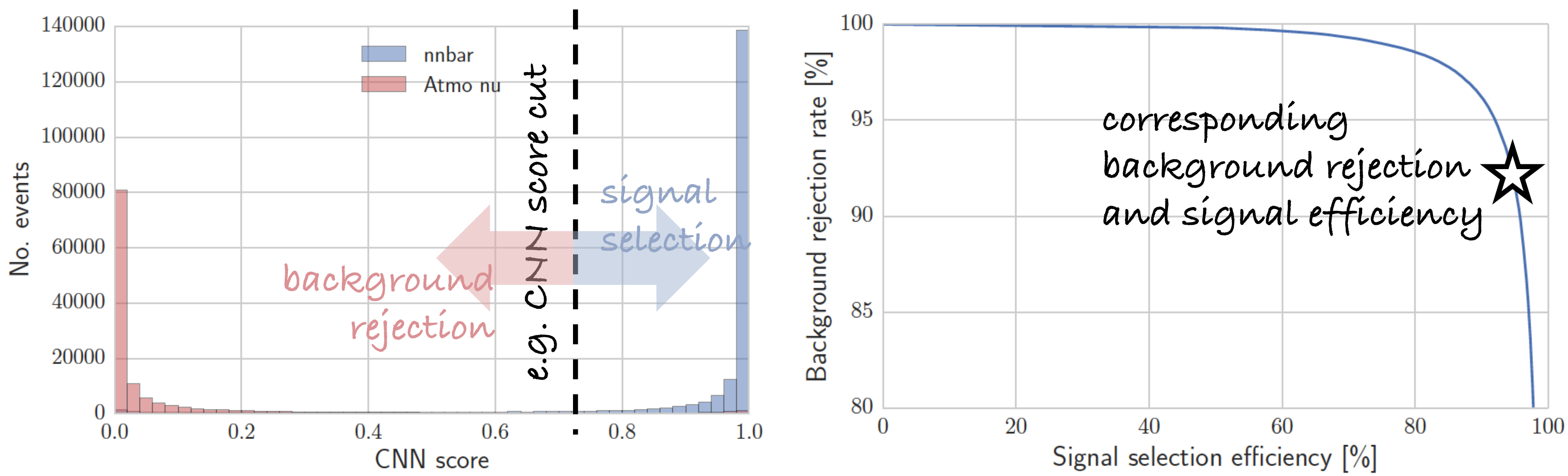


Training sample shown in blue and red.

Statistically independent test sample shown in green.

DUNE search for neutron-antineutron oscillation

- Benchmarking CNN performance on simulated signal and background event test samples:

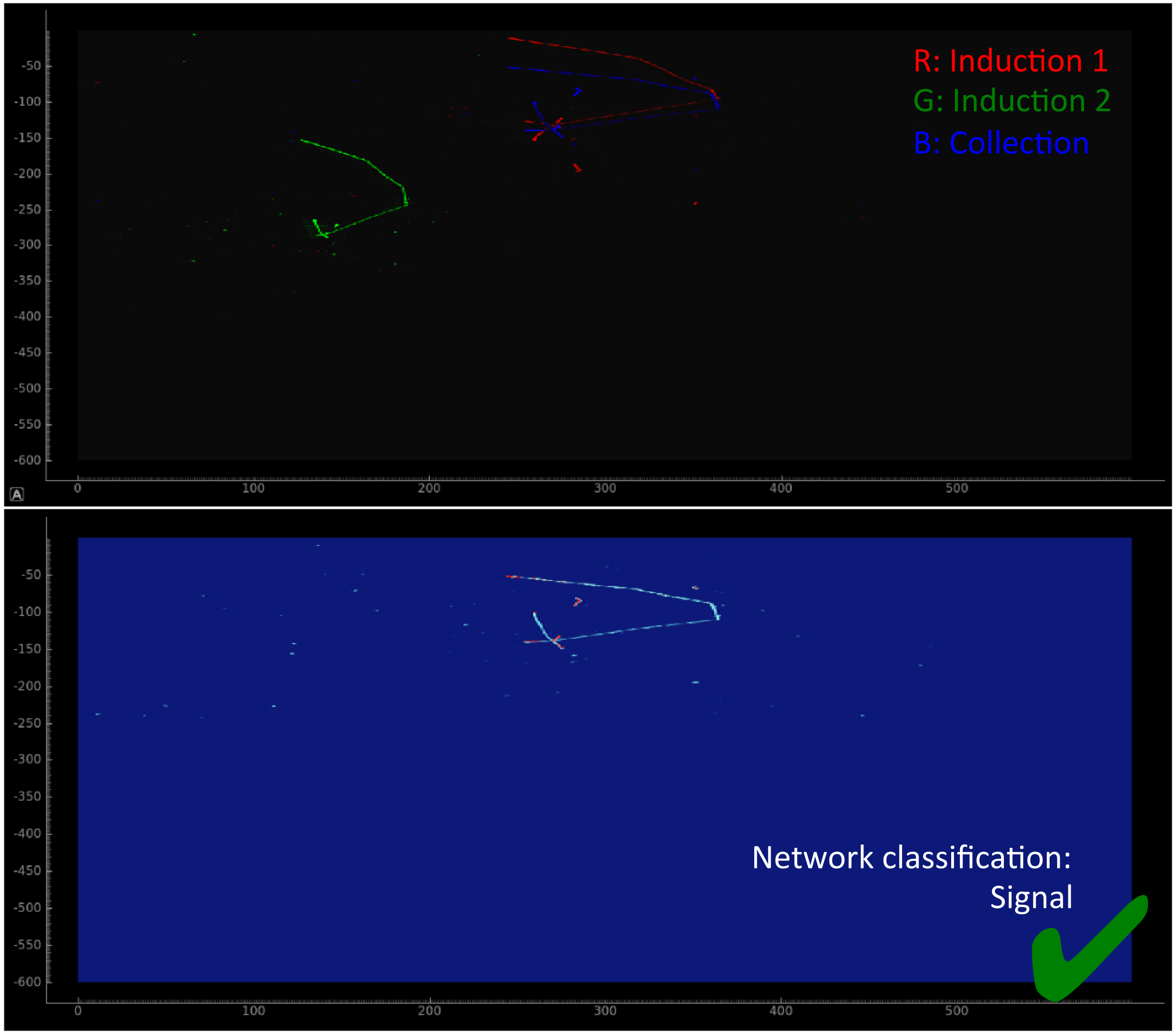


- In this analysis:
An optimized cut on CNN score of 0.99995 provides a signal selection efficiency of 14% and an atmospheric ν background rejection rate of 99.997%.

DUNE search for neutron-antineutron oscillation

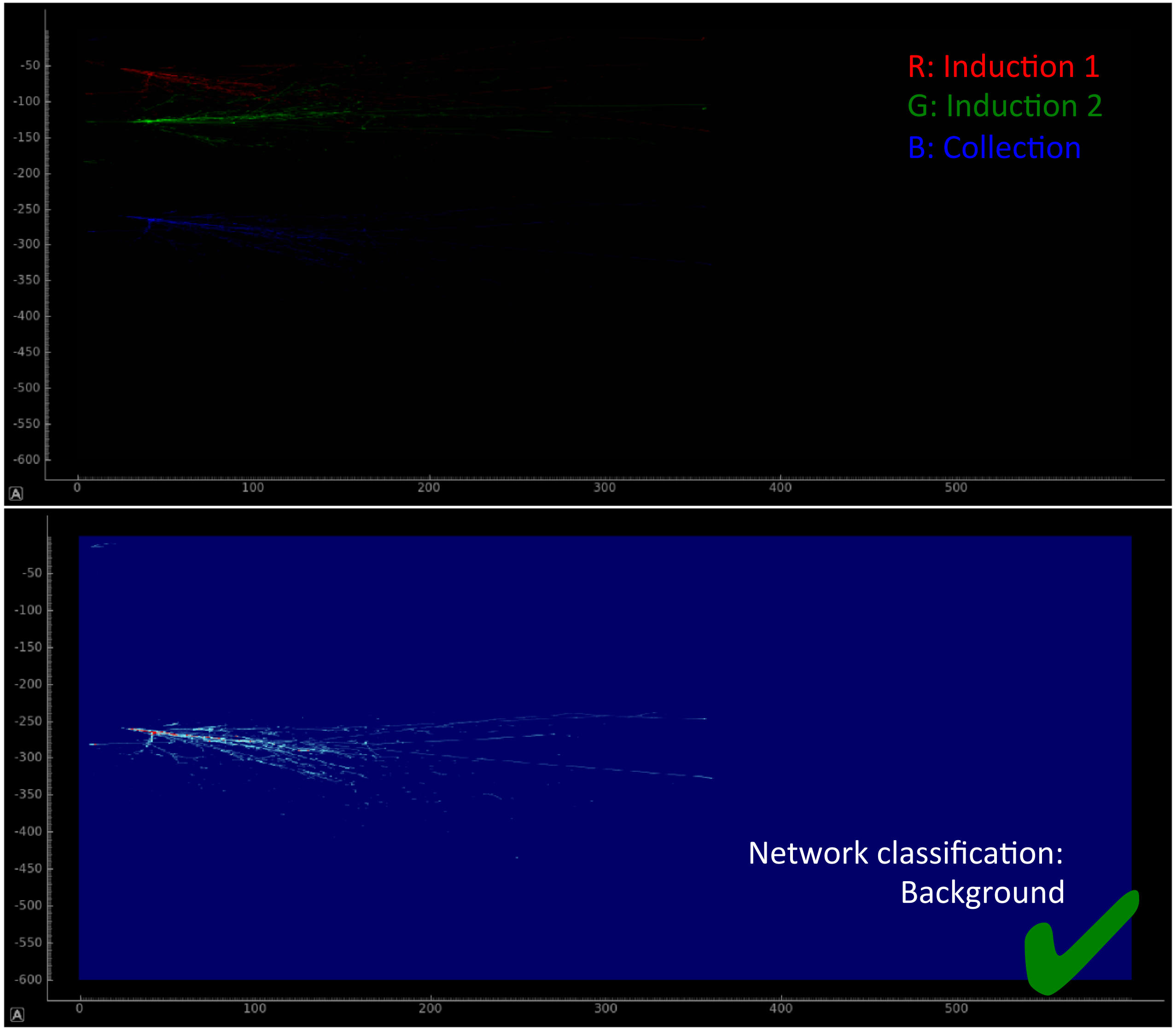
- **Image classification:**
- **Could be done in all 3 planes; only focusing on single plane**

Truth=Signal



DUNE search for neutron-antineutron oscillation

- **Image classification:**
- **Could be done in all 3 planes; only focusing on single plane**

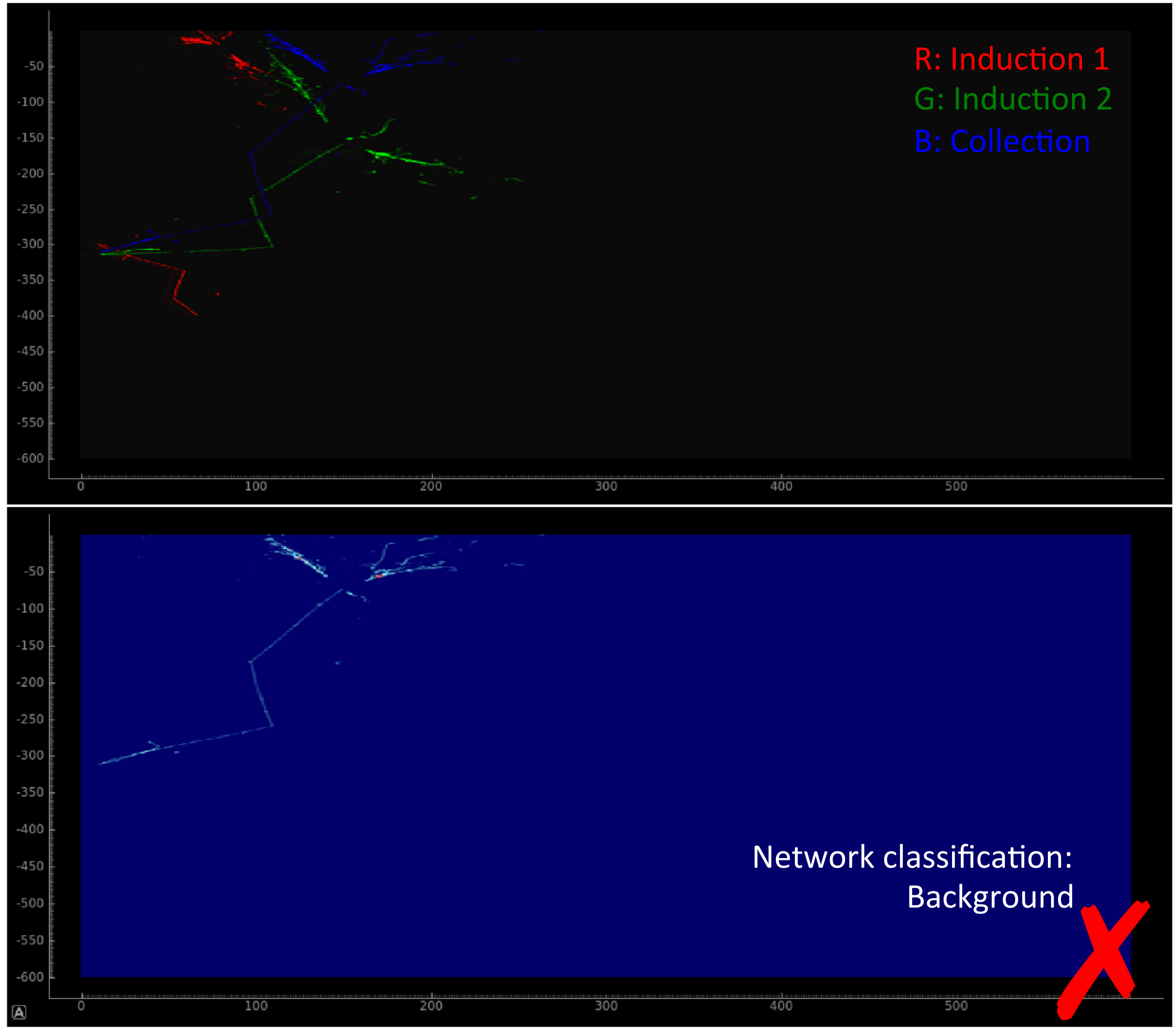


Truth=Background

DUNE search for neutron-antineutron oscillation

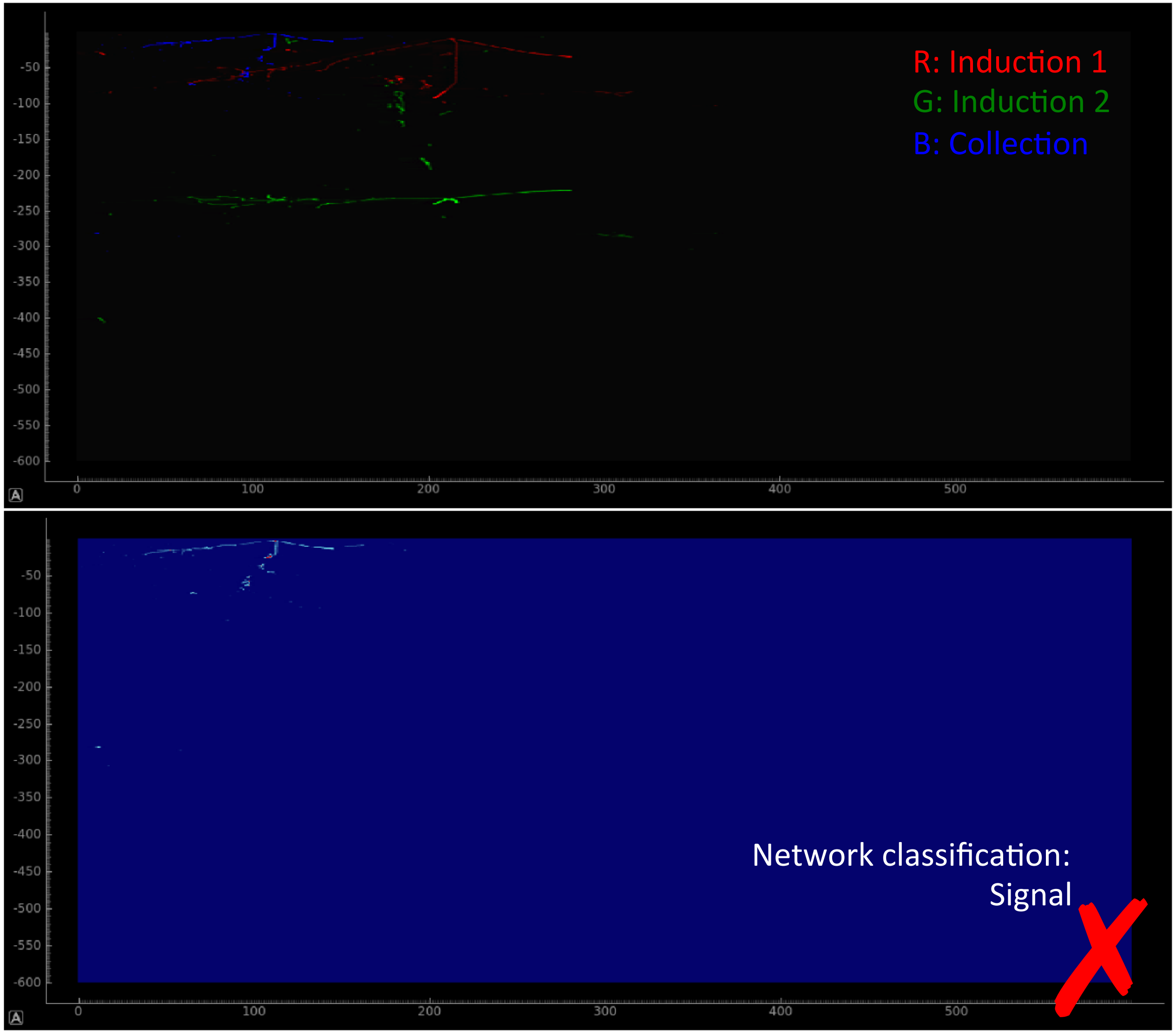
- **Image classification:**
- **Could be done in all 3 planes; only focusing on single plane**

Truth=Signal



DUNE search for neutron-antineutron oscillation

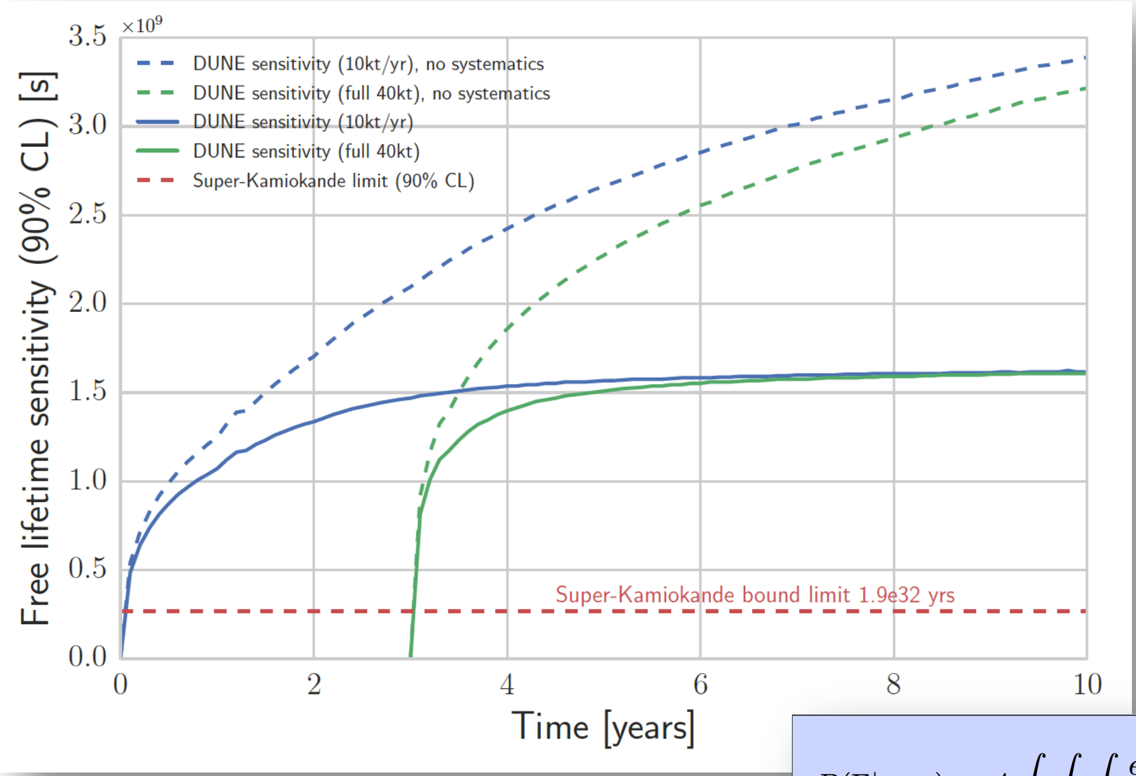
- **Image classification:**
- **Could be done in all 3 planes; only focusing on single plane**



Truth=Background

Sensitivity prospects for DUNE

- **DUNE's sensitivity to neutron oscillation lifetime:**



Free neutron lifetime sensitivity >1.6E9 s (90% CL) after 4 years of exposure (staged approach).

Sensitivity calculation inputs:
CNN score cut: 0.99995
Signal selection efficiency: 14%
Background rejection rate: 99.997%
Exposure: Varied

Using $T_R = 0.666E23\ s^{-1}$

Variable	Systematic uncertainty
Exposure	3 %
Signal selection efficiency	25 %
Background rate	25 %

$$P(\Gamma|n_{obs}) = A\int\int\int \frac{e^{-(\Gamma\lambda\epsilon+b)}(\Gamma\lambda\epsilon+b)^{n_{obs}}}{n_{obs}!}P(\lambda)P(\epsilon)P(b)d\lambda d\epsilon db$$

$$\int_0^{\Gamma_{90\%}} P(\Gamma|n_{obs})d\Gamma = 0.9$$

Γ = Oscillation width
n_{obs} = No. events observed
A = Normalisation constant
λ = Exposure
ε = Selection efficiency
b = Background rate

Summary

- DUNE will be a very large, deep underground detector with excellent prospects for rare event searches.
- There are good qualitative arguments for its ability to improve on current lifetime limits for neutron-antineutron oscillation.
- A simple nucleus-bound neutron-antineutron oscillation event generator has been implemented in GENIE, leveraging existing nuclear effects simulations within GENIE, and has been used to benchmark DUNE's sensitivity.
- Convolutional neural networks (CNNs) are able to very efficiently separate signal from background (in DUNE Monte Carlo studies).
- At optimum CNN performance, DUNE's sensitivity to the free neutron oscillation lifetime has been estimated as 1.6E9 seconds at 90% CL (for 10 years of running).
  - This presents a x5 improvement over the current (best) limit from Super-K.
- Better systematics treatment is necessary moving forward.

Thank you!

DUNE timeline

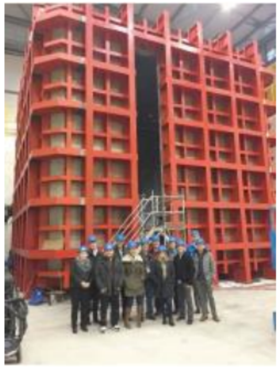
2017: Far Site Construction Begins

2018: protoDUNEs at CERN

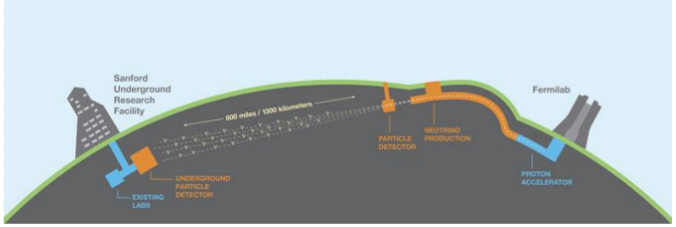
2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available



DUNE groundbreaking at SURF, 21st July 2017



Past searches: Summary

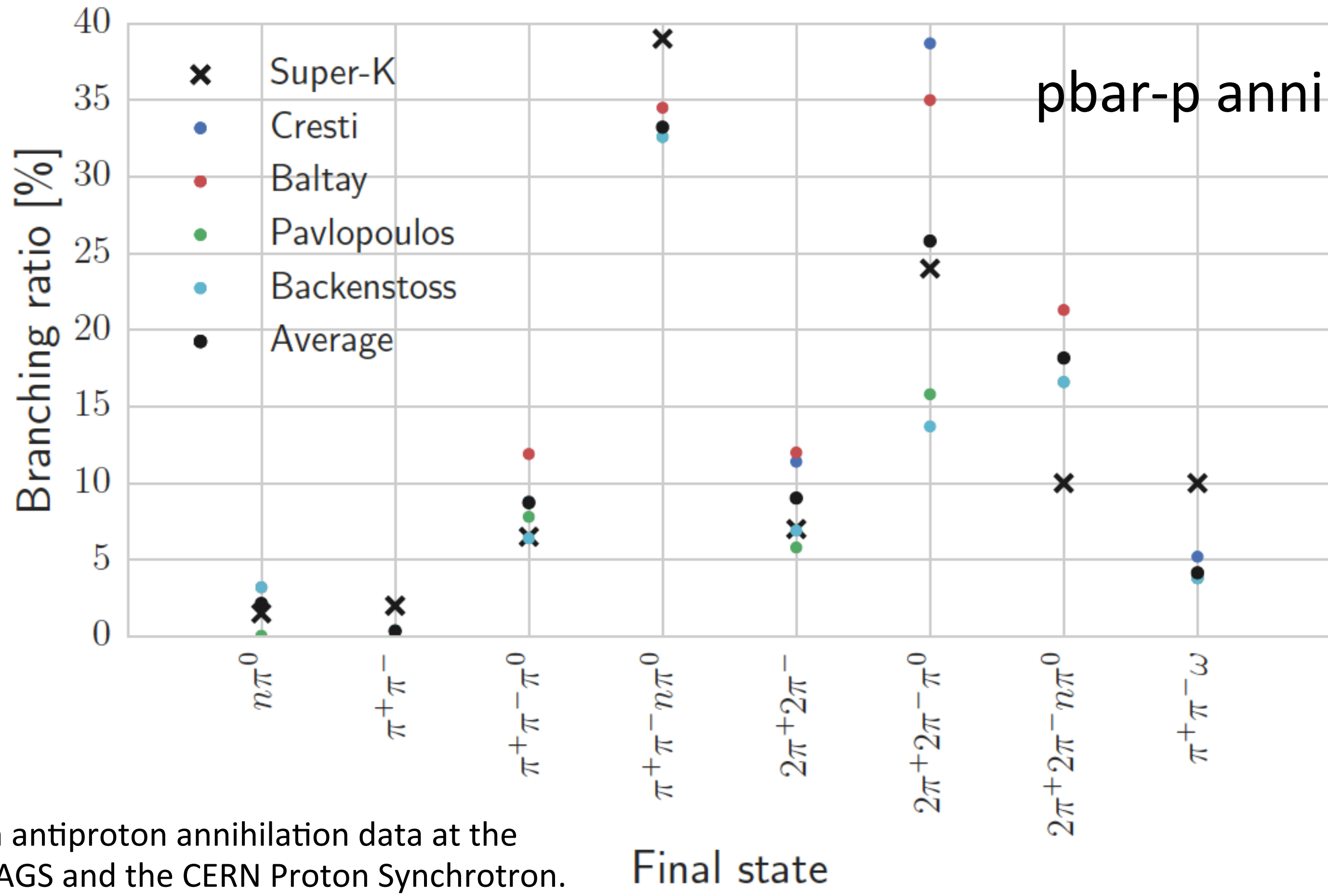
Experiment	Year	Type	τ_{free} limit [s]
Homestake	1983	Bound	2×10^7
IMB	1984	Bound	1.1×10^8
ILL	1985	Free	10^6
Kamiokande	1986	Bound	1.2×10^8
Triga Mk. II	1989	Free	4.9×10^5
Frèjus	1990	Bound	1.2×10^8
ILL	1994	Free	8.6×10^7
Soudan 2	2002	Bound	1.3×10^8
Super-Kamiokande	2015	Bound	2.7×10^8
SNO	2017	Bound	1.23×10^8

Annihilation branching ratios

	$\bar{n}p$		$\bar{n}n$
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%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

As used in Super-K

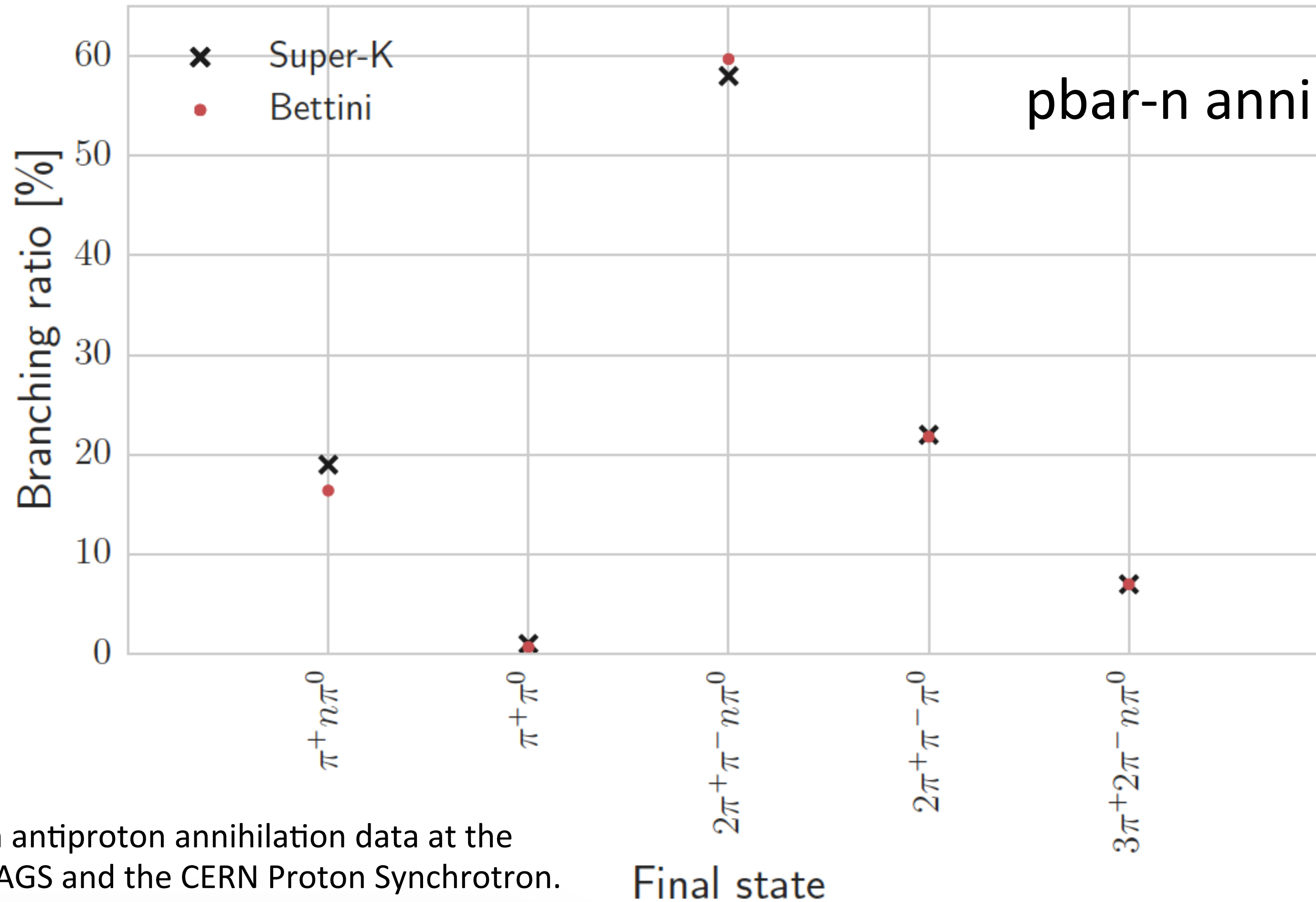
Annihilation branching ratios



pbar-p annihilation

Derived from antiproton annihilation data at the Brookhaven AGS and the CERN Proton Synchrotron. [A more recent, detailed analysis utilizes data from Crystal Barrel Spectrometer and ASTERIX at LEAR.]

Annihilation branching ratios



pbar-n annihilation

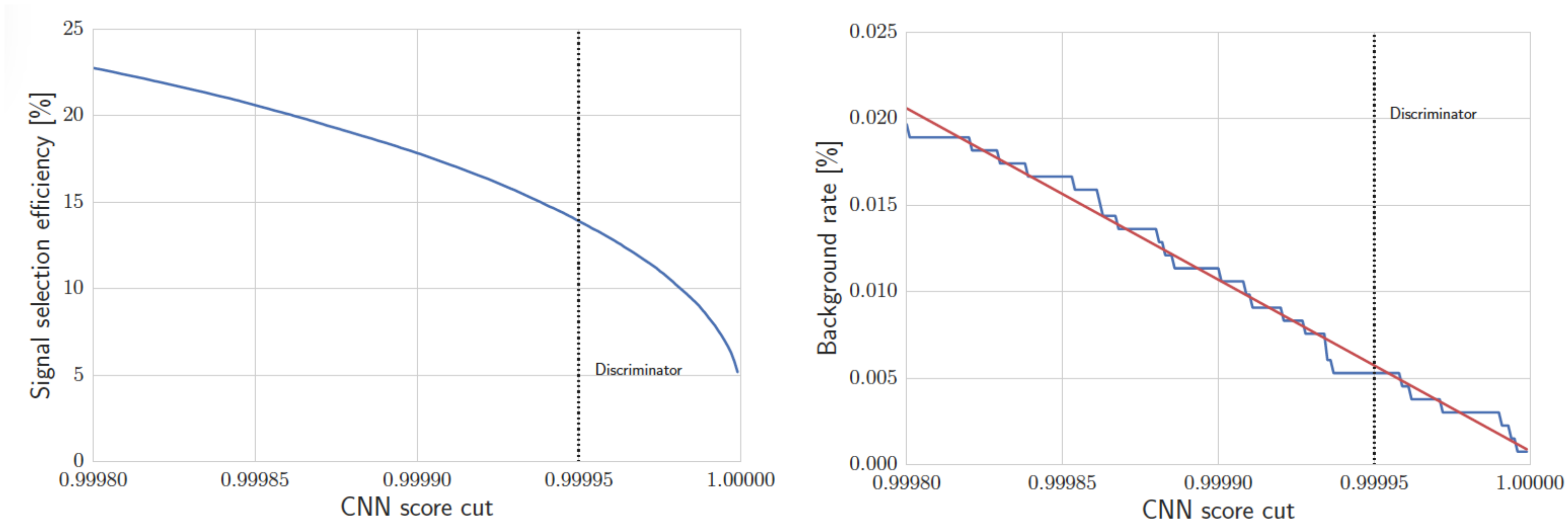
Derived from antiproton annihilation data at the Brookhaven AGS and the CERN Proton Synchrotron. [A more recent, detailed analysis utilizes data from Crystal Barrel Spectrometer and ASTERIX at LEAR.]

Annihilation branching ratios

	$\bar{n}p$		$\bar{n}n$
Channel	Branching ratio	Channel	Branching ratio
$2\pi^0$	0.06%	$\pi^+\pi^0$	0.1%
$3\pi^0$	0.8%	$\pi^+2\pi^0$	0.7%
$4\pi^0$	0.3%	$\pi^+3\pi^0$	14.8%
$5\pi^0$	1.0%	$\pi^+4\pi^0$	1.4%
$6\pi^0$	0.01%	$2\pi^+\pi^-$	2.0%
$7\pi^0$	0.1%	$2\pi^+\pi^-\pi^0$	17.0%
$\pi^+\pi^-$	0.3%	$2\pi^+\pi^-2\pi^0$	10.8%
$\pi^+\pi^-\pi^0$	1.6%	$2\pi^+\pi^-3\pi^0$	30.1%
$\pi^+\pi^-2\pi^0$	13.0%	$3\pi^+2\pi^-$	5.5%
$\pi^+\pi^-3\pi^0$	11.2%	$3\pi^+2\pi^-\pi^0$	2.3%
$\pi^+\pi^-4\pi^0$	3.3%		
$\pi^+\pi^-5\pi^0$	1.4%		
$2\pi^+2\pi^-$	6.0%		
$2\pi^+2\pi^-\pi^0$	13.5%		
$2\pi^+2\pi^-2\pi^0$	16.6%		
$2\pi^+2\pi^-3\pi^0$	0.6%		
$3\pi^+3\pi^-$	2.2%		
$3\pi^+3\pi^-\pi^0$	2.0%		

Derived from antiproton annihilation data at the Brookhaven AGS and the CERN Proton Synchrotron. [A more recent, detailed analysis utilizes data from Crystal Barrel Spectrometer and ASTERIX at LEAR.]

Benchmarking signal efficiency, background rejection



Signal selection efficiency (left) and background mis-ID rate (right) as a function of CNN score discriminator, with linear fit performed (right) to smooth statistical fluctuations

GENIE event generator

	Super-K.	GENIE (^{16}O)	GENIE (^{40}Ar)
π multiplicity	3.5	2.37	2.94
$\pi^{\pm}$ multiplicity	2.2	1.57	1.96
$\pi^{\pm}$ mean mom. [MeV]	310	372	344
$\pi^{\pm}$ RMS mom. [MeV]	190	190	190

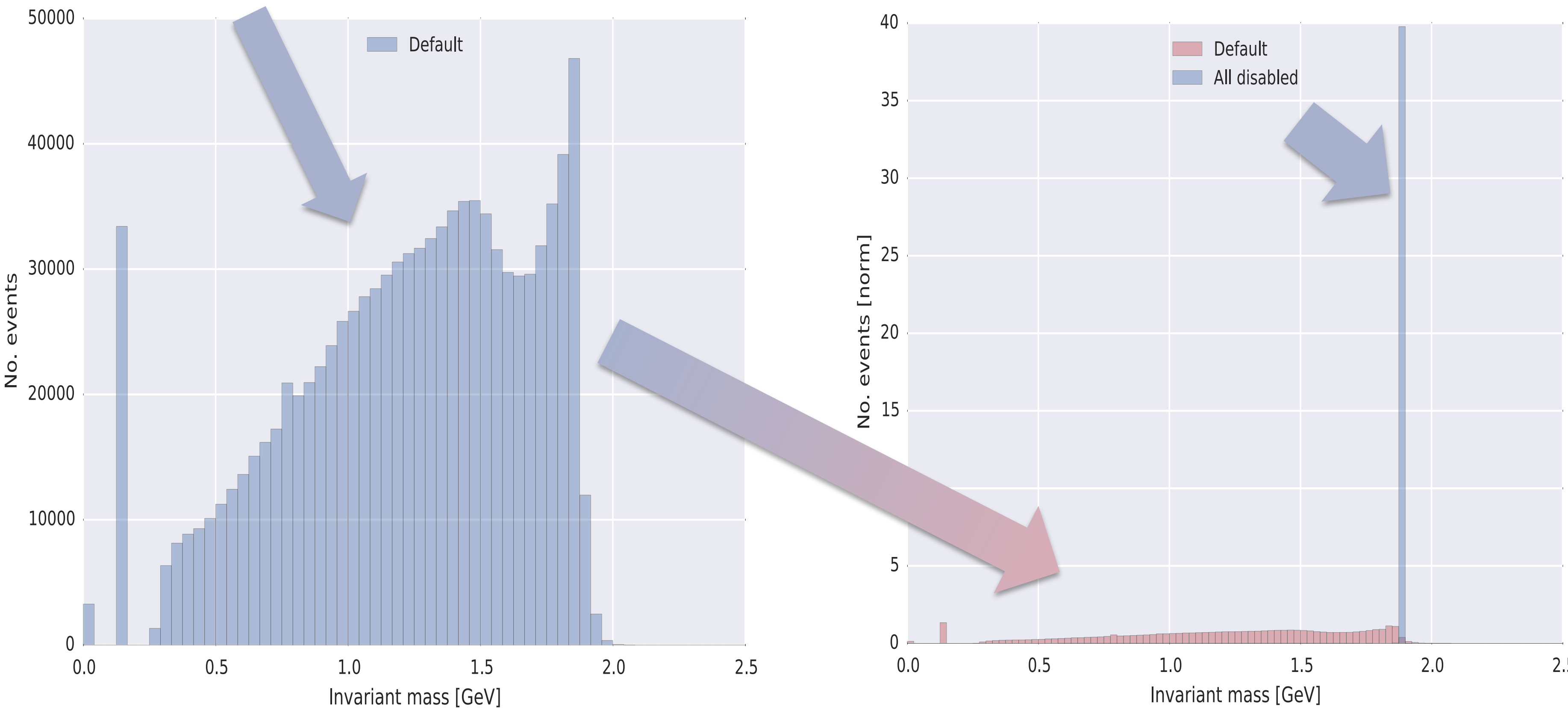
	Super-K.	GENIE (^{16}O)	GENIE (^{40}Ar)
No FSI	49%	34.0%	15.6%
Absorption	24%	18.8%	24.0%
Nucleon interaction	3%	4.2%	5.3%
Scattering	24%	43.1%	55.1%

nnbar event generator in GENIE

Demonstrating nuclear effects at event generator level:

All nuclear effects enabled in GENIE: Fermi motion, binding E, and FSI (hA model)

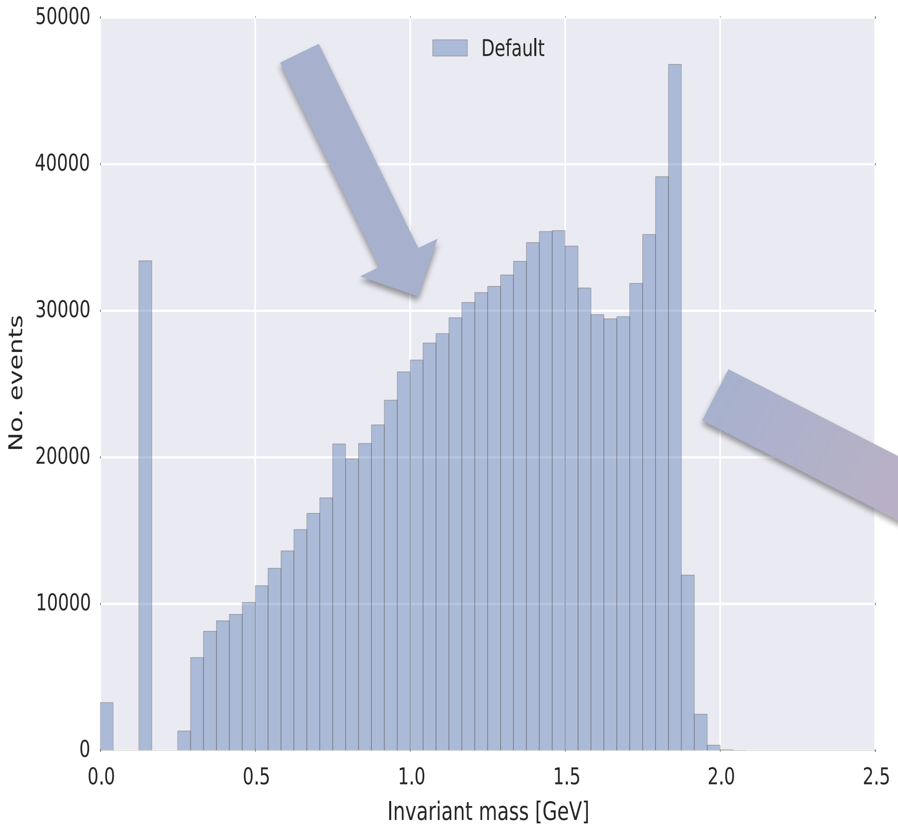
All nuclear effects turned off (delta function at $2m_n$)



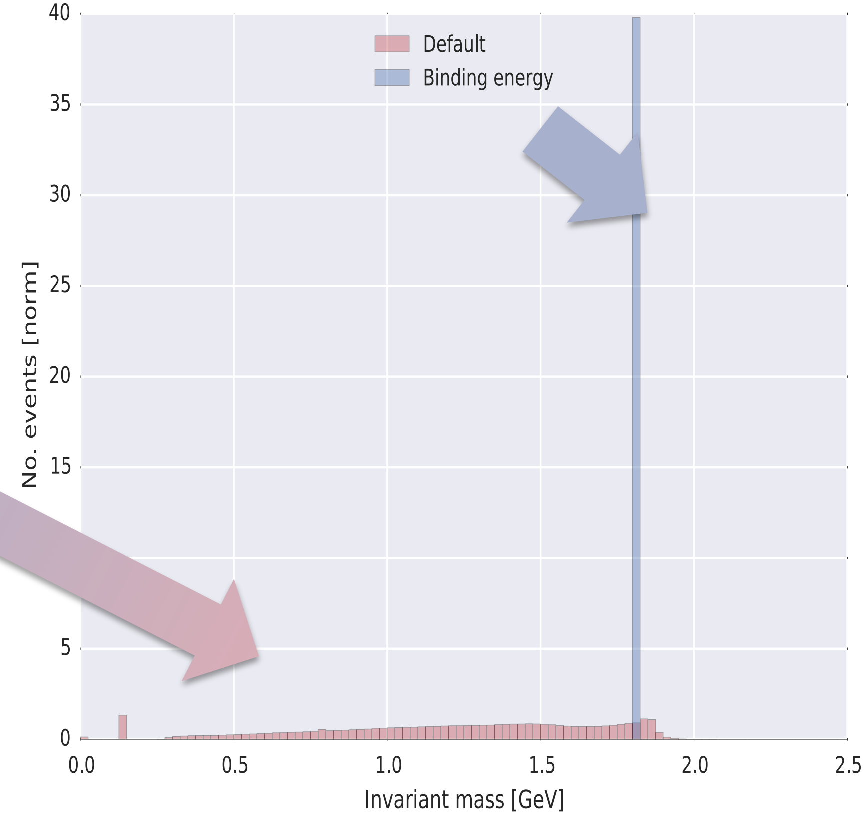
nnbar event generator in GENIE

Demonstrating nuclear effects at event generator level:

All nuclear effects enabled in GENIE:
Fermi motion, binding E, and FSI (hA model)



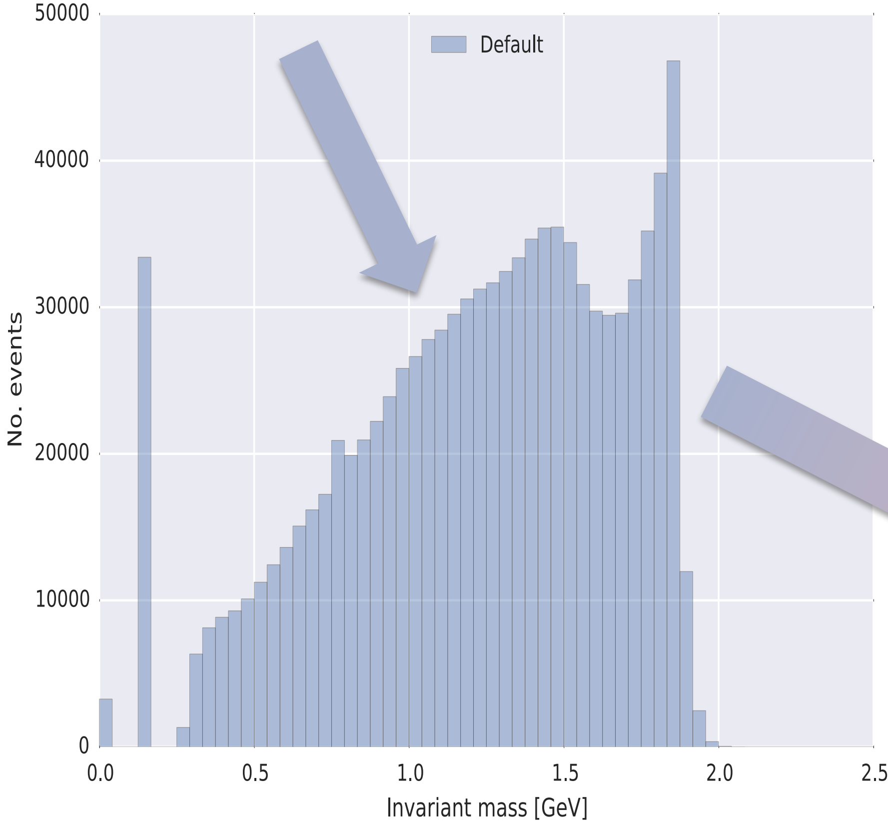
Only binding E turned on



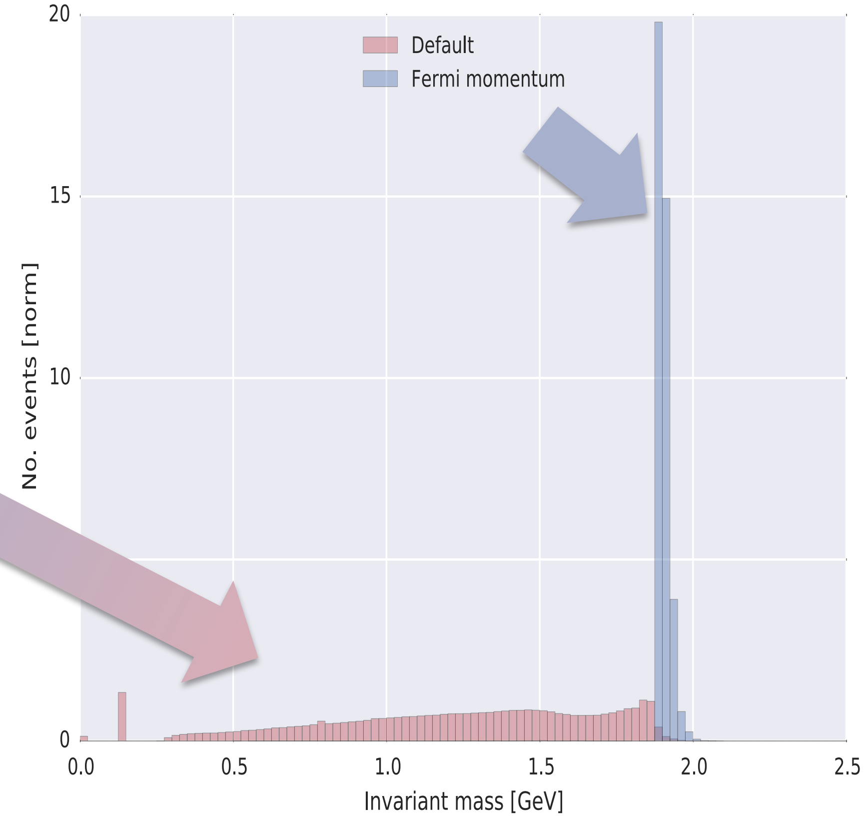
nnbar event generator in GENIE

Demonstrating nuclear effects at event generator level:

All nuclear effects enabled in GENIE:
Fermi motion, binding E, and FSI (hA model)



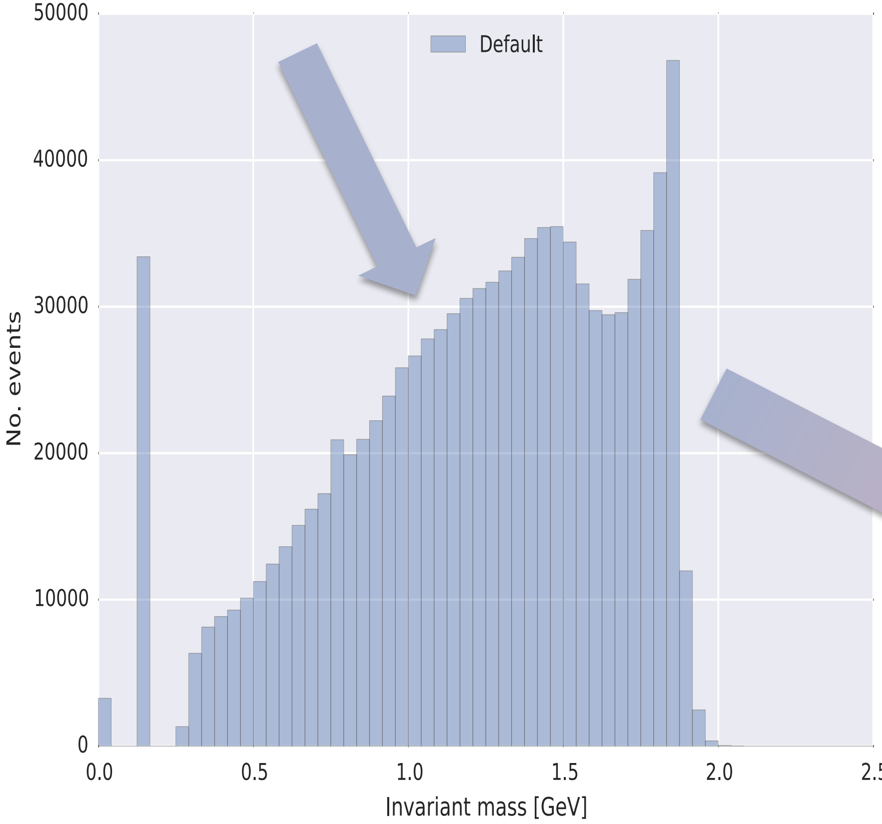
Only Fermi momentum turned on



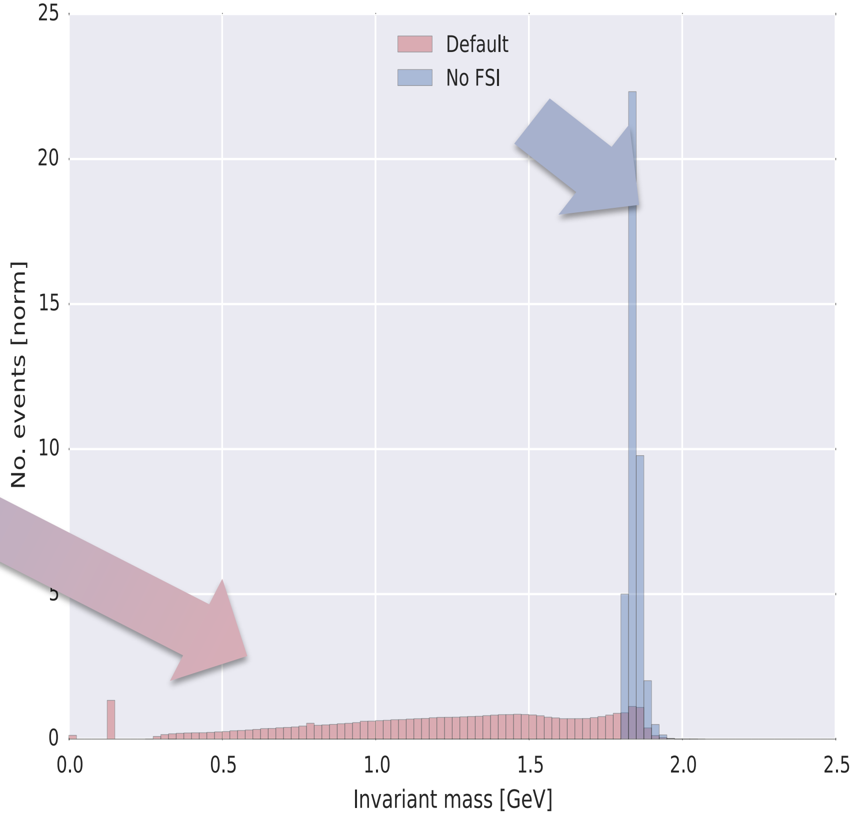
nnbar event generator in GENIE

Demonstrating nuclear effects at event generator level:

All nuclear effects enabled in GENIE: Fermi motion, binding E, and FSI (hA model)



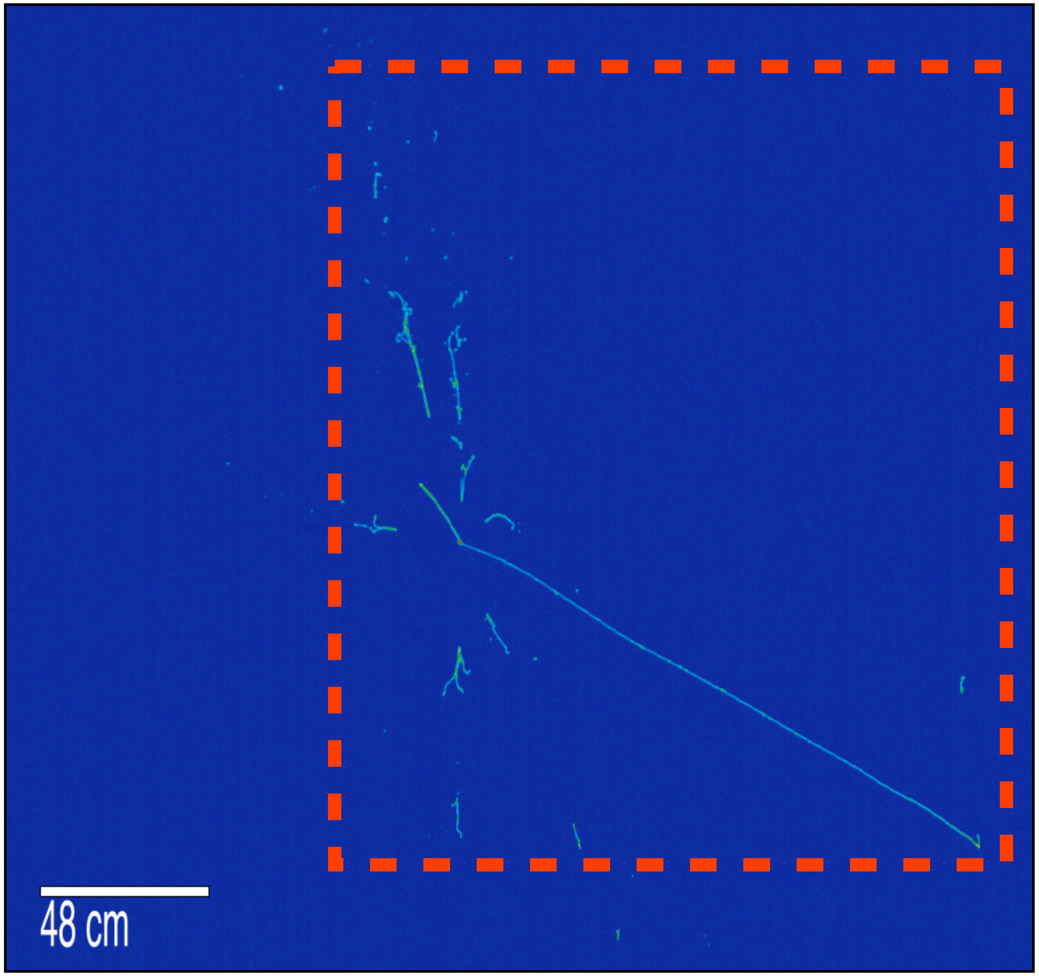
Only Fermi momentum and binding E turned on (no FSI)



DUNE

2. CNN input preparation

- Events must be converted into images in order to be processed by CNN.



Rectangular region of interest found, by identifying first & last wire & time tick above 20 ADC threshold.

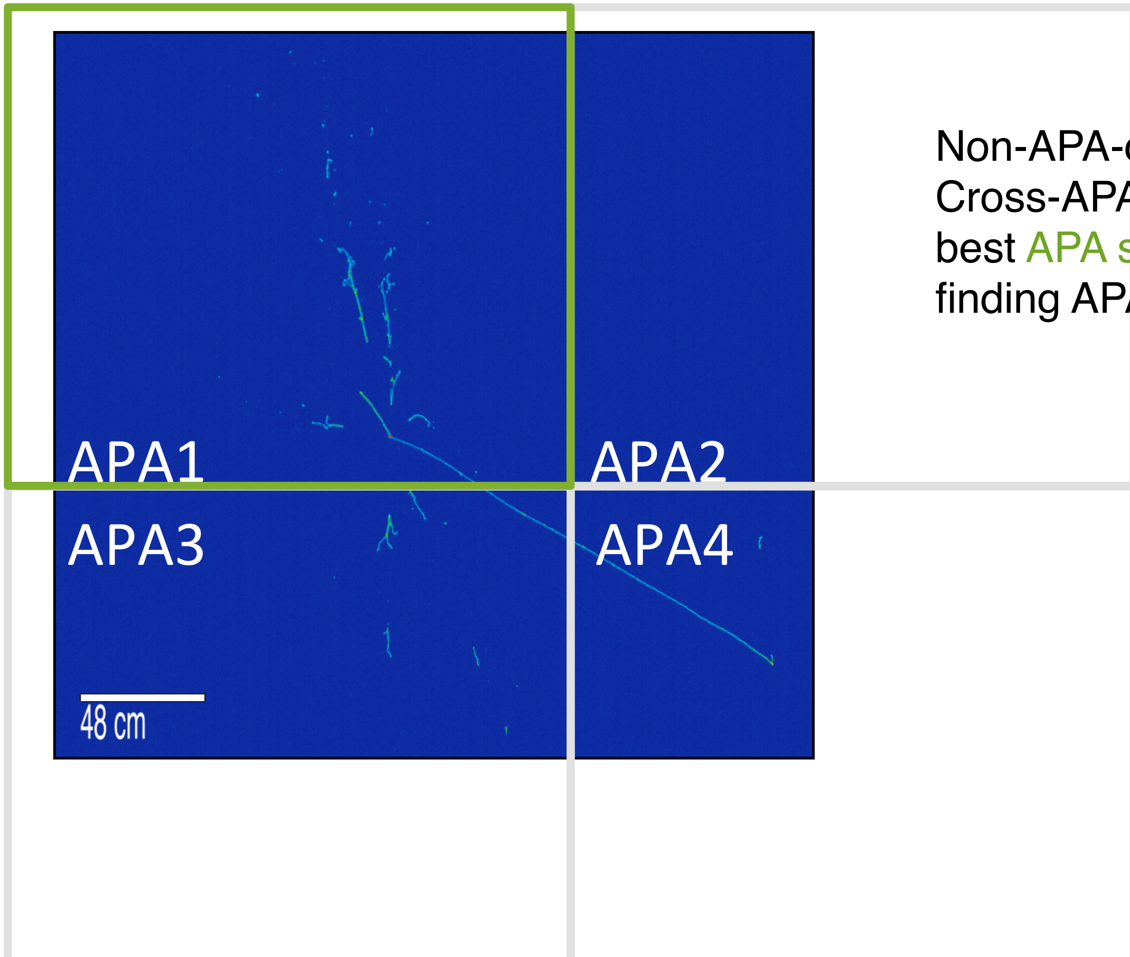
Size of APA is ~1000 wires x ~4000 time ticks. Average every 4 time ticks to downsample by factor 4.

ROI downsampled again until smaller than 600x600 pixels.

Image embedded inside empty 600x600 px image.

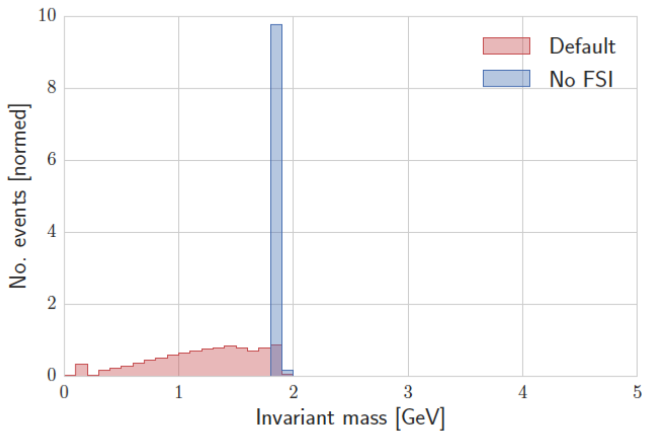
2. CNN input preparation

- Events must be converted into images in order to be processed by CNN.

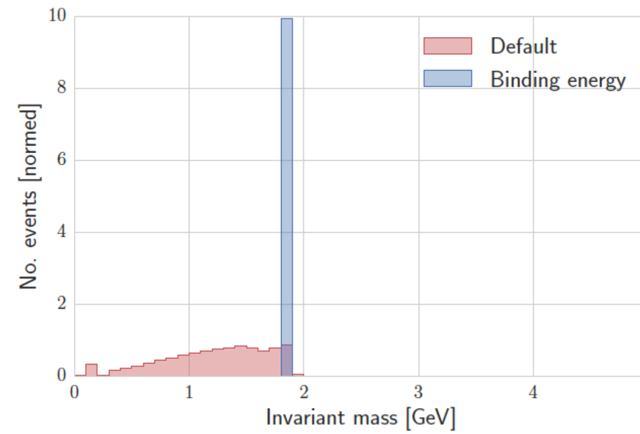


Non-APA-contained events:
Cross-APA stitching non-trivial — for now, best APA selected for image generation by finding APA with largest total ADC sum.

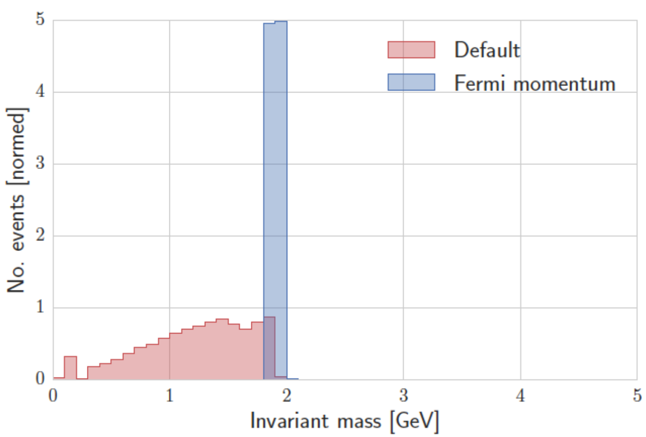
GENIE nuclear effects



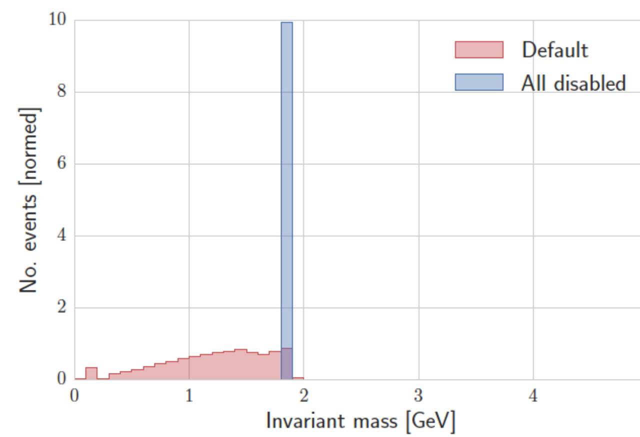
(a) Binding energy and Fermi momentum enabled, FSI disabled.



(b) Binding energy enabled, Fermi momentum and FSI disabled.

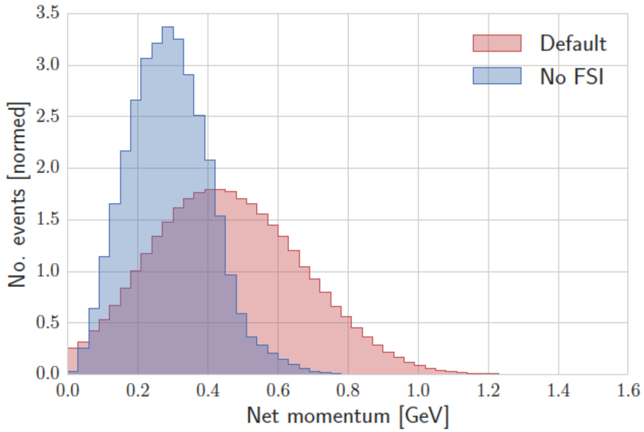


(c) Fermi momentum enabled, binding energy and FSI disabled.

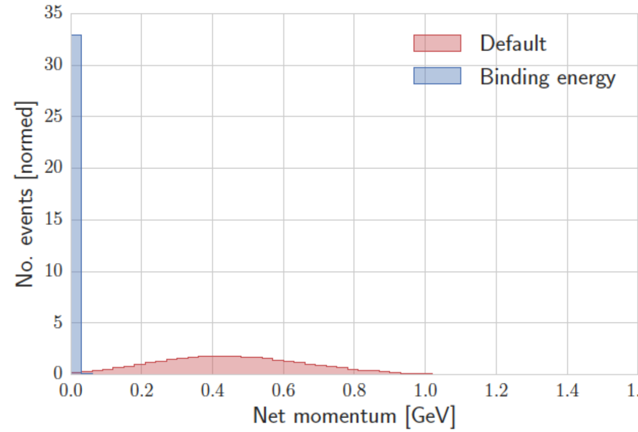


(d) Binding energy, Fermi momentum and FSI disabled.

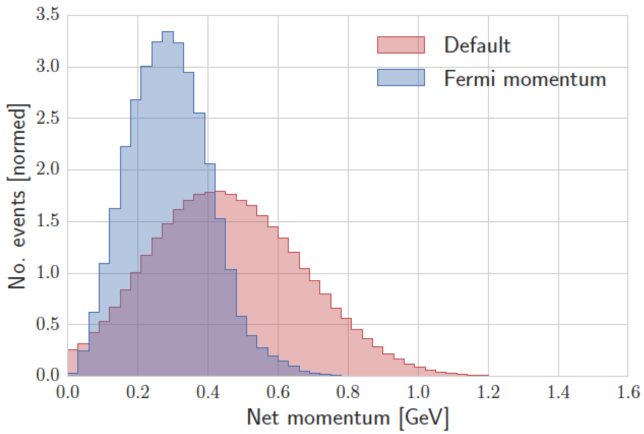
GENIE nuclear effects



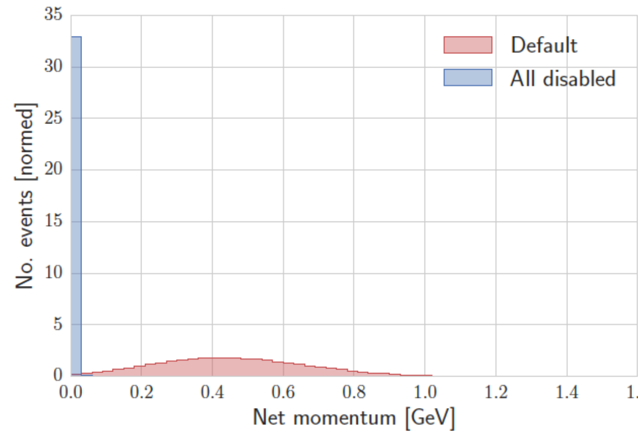
(a) Binding energy and Fermi momentum enabled, FSI disabled.



(b) Binding energy enabled, Fermi momentum and FSI disabled.

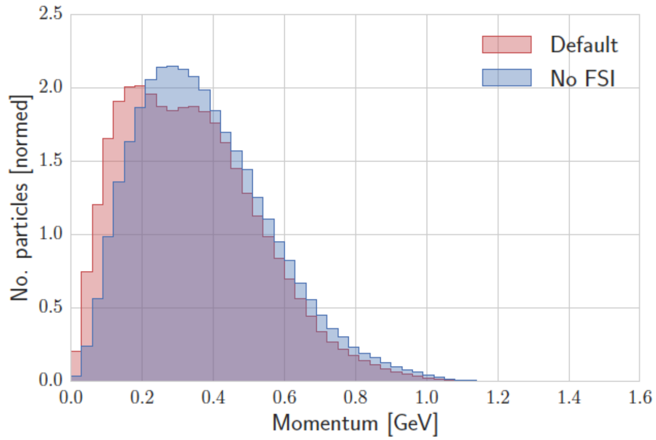


(c) Fermi momentum enabled, binding energy and FSI disabled.

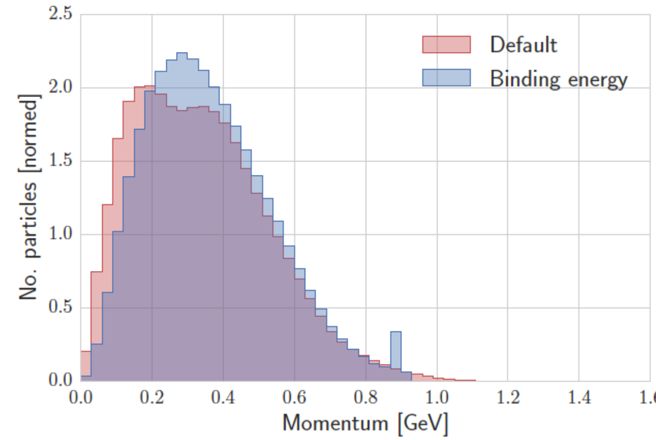


(d) Binding energy, Fermi momentum and FSI disabled.

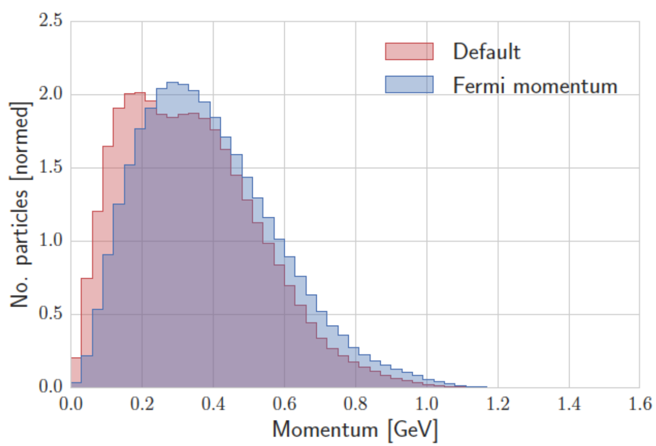
GENIE nuclear effects



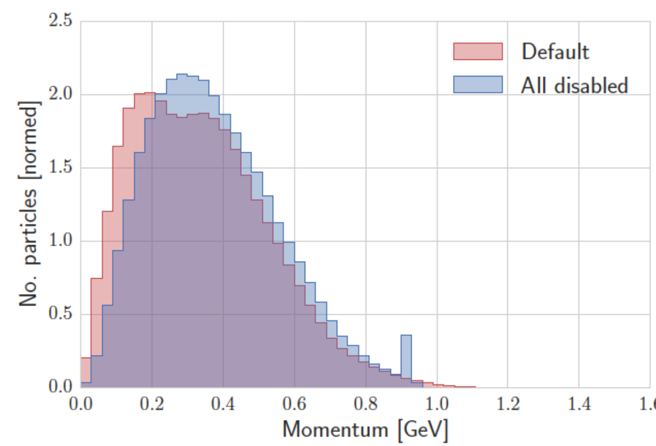
(a) Binding energy and Fermi momentum enabled, FSI disabled.



(b) Binding energy enabled, Fermi momentum and FSI disabled.

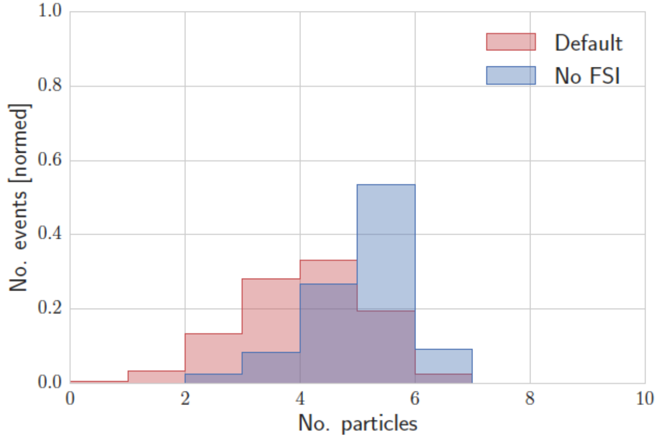


(c) Fermi momentum enabled, binding energy and FSI disabled.

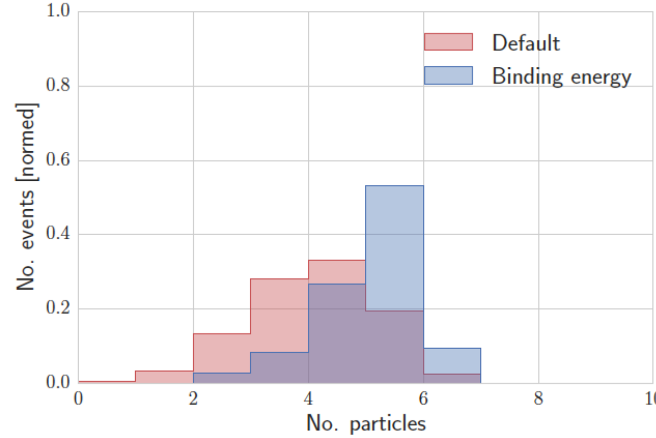


(d) Binding energy, Fermi momentum and FSI disabled.

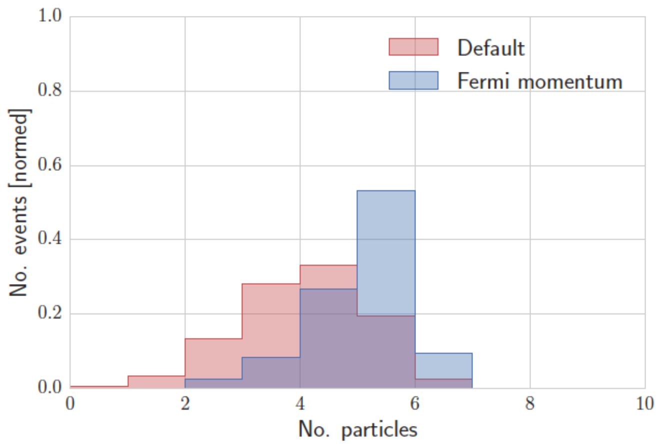
GENIE nuclear effects



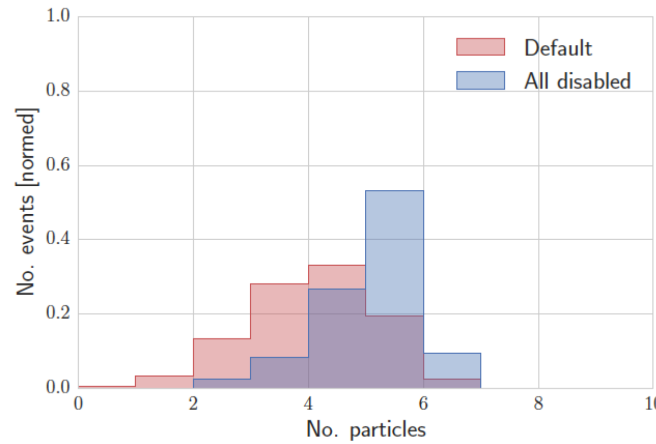
(a) Binding energy and Fermi momentum enabled, FSI disabled.



(b) Binding energy enabled, Fermi momentum and FSI disabled.



(c) Fermi momentum enabled, binding energy and FSI disabled.



(d) Binding energy, Fermi momentum and FSI disabled.