Simulation Studies Toward the Search for Neutron—Antineutron Oscillation

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Appearance, Disappearance, and Baryogenesis

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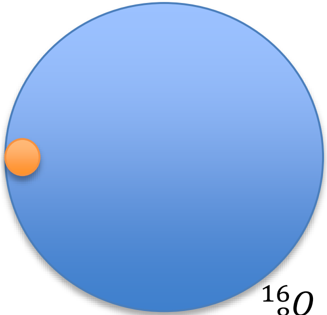
Experimental Overview

Part One

Phenomenology of $n \to \bar{n}$

- Can search for such oscillations in both free beam and bound nuclei experiments
  - **Free Oscillation**:

$$P_{free}\left[n(t_{exp}) = \bar{n}\right] \sim \left(\frac{t_{exp}}{\tau_{n\to\bar{n}}}\right)^2$$



$^{16}_{8}O$

  - The bound oscillation can be thought of as a *free oscillation* in a bag-type model
    - Here, the "experimental" time is of the order of $10^{-23}s$ rather than $\sim 1-10$ years
    - From this, we find that:

$$P_A\left[n(t_{exp}) = \bar{n}\right] \propto \Gamma = \frac{1}{\tau_A} = P_{free}\left[n(t_{exp} \cong 10^{-23}s) = \bar{n}\right] \cong \left(\frac{10^{-23}s}{\tau_{n\to\bar{n}}}\right)^2 \Longrightarrow \tau_A \cong R\tau_{n\to\bar{n}}^2$$

where

$$R \sim \frac{1}{10^{-23}s} \sim 10^{22}s^{-1}$$

    - Similarly, we can use the nuclear potential well's interaction difference between n and $\bar{n}$ to assess the same phenomena:

$$\tau_A = \frac{\Delta V_{n \text{ vs. } \bar{n}}}{\hbar}\tau_{n\to\bar{n}}^2 = R\tau_{n\to\bar{n}}^2$$

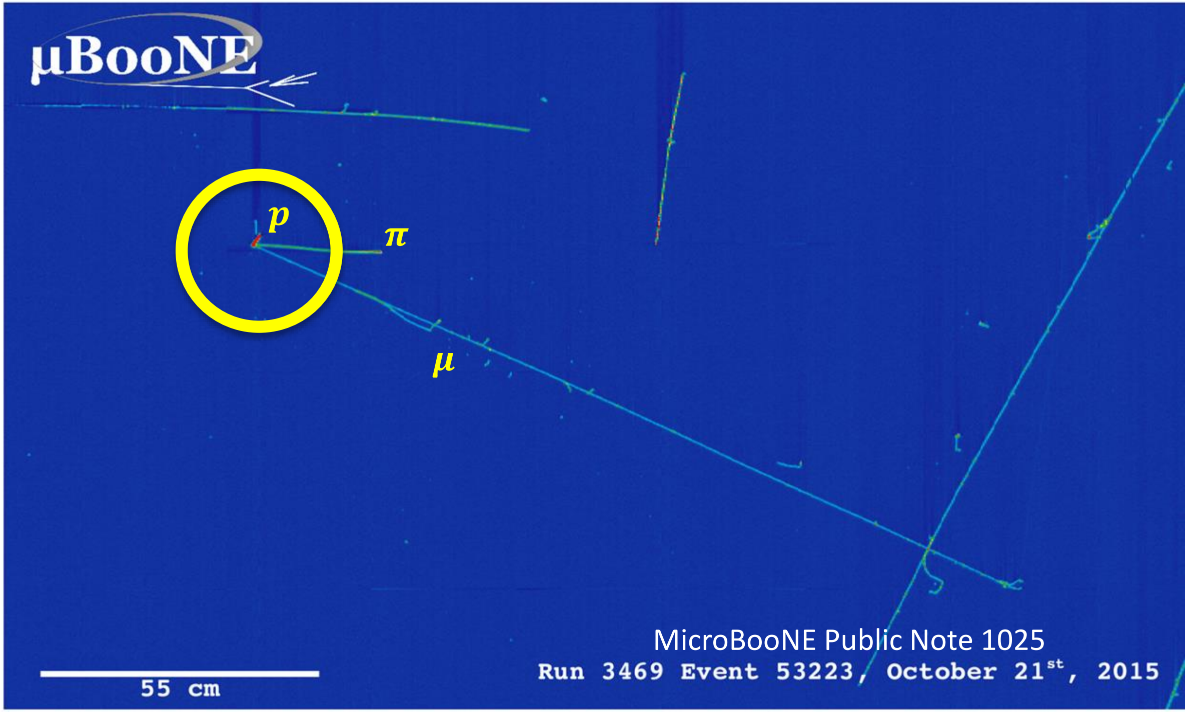
  - It has been shown that $R_O \sim 5 \cdot 10^{22}s^{-1}$ from an estimated $10-15\%$ uncertainty calculation by Friedman and Gal
  - Precisely, we find that this can be thought of as a nucleon decay-like experiment:

$$P_A\left[n(t_{exp}) = \bar{n}\right] = e^{-\frac{t_{exp}}{\tau_A}}$$

Excellence of LArTPCs—See MicroBooNE

An example charged current ν event in MicroBooNE

REAL DATA!



Proton reconstruction is an important step for DUNE in nucleon decay searches…

SK will soon add gadolinium to their WCD to tag neutrons!

<u>Neutron Detection in LAr???</u>

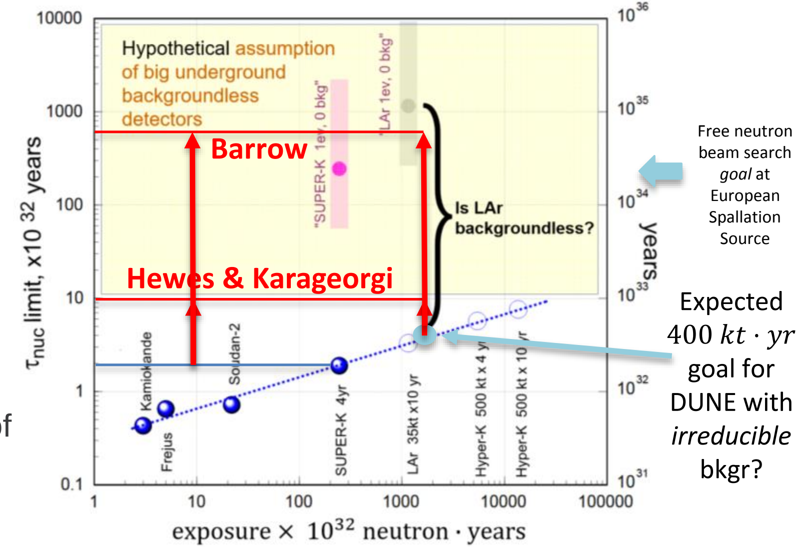
Atmospheric ν Backgrounds Impede $n \to \bar{n}$ Event Identification In Large Underground Experiments

Previous searches for $n \to \bar{n}$ suffered greatly from this!

- Super-Kamiokande: 24 candidate events
  - Expected $sig.eff: bkgrcount = \mathbf{12\%: 24.1}$
- DUNE?
  - **CNN**: $sig.eff: bkgrcount = \mathbf{14\%: 3}$
    - Fully oscillated sample!
    - Important ν_τ interactions
  - **Truth**: $sig.eff: bkgrcount = \mathbf{27\%: 0}$
    - Unoscillated sample! **DON'T BELIEVE!**

Theorists and computational physicists are working tirelessly to improve the accuracy of ν generators

- This is a requirement for understanding ν oscillation parameters precisely and atmospheric background properly
- GENIE is one of many used today
- GIBUU and NuWRO are supposedly getting great comparative results from MicroBooNE with their novel techniques
  - Plan to run events on these platforms for separability comparison in the future

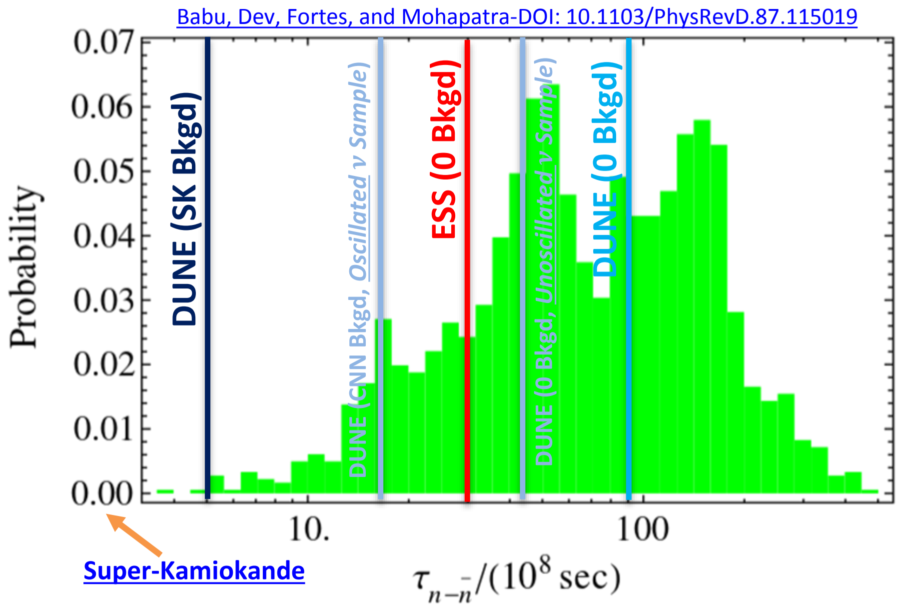


The bottom line…

- ***Atm. ν bkgr. increases faster than mass***
- Must counter this with more precise detectors
- Must ***understand underlying nuclear models***
- ***Test many simulations against one another*** for a full understanding of bkgr. topologies

Theoretically Important Probability Parameter Space of $\tau_{n\rightarrow\bar{n}}$

- A probability distribution from PSB can be seen as a function of predicted free oscillation time
  - Red line shows horizontal beamline oscillation time
    - ESS, 3 yr, ~500X ILL
  - Blue shows DUNE
    - 10 years, ~13,500X ILL
      - Assumes 100% efficiency!
      - Assumes no background!



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Simulation Analysis

Basic Overview with Some Simple Comparisons

Part Two

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DUNE and ESS *Truth-Level* Monte Carlo Analysis is Near Completion

Can looking purely at the kinematics give good results?

- Have studied MC generators for $n \rightarrow \bar{n}$ in…
  - ${}^{12}_{6}C$, with incident ***slow*** ($|\vec{p}| \cong 0 \frac{GeV}{c}$), free (beam), transformed $\bar{n}$ + cascade from annihilation
    - Original generator developed over 15+ years by Elena Golubeva of INR Moscow
    - Joint publication with full simulation discussion, along with with V&V forthcoming
  - ${}^{40}_{18}Ar$, with internal (bound) transformation + annihilation cascade
    - Original generator developed for GENIE over last ~2 years by Jeremy Hewes of DUNE for PhD work
    - Dissertation forthcoming
      - Hewes and Karageorgi's analysis revolves around CNN's rather than truth level discrimination between signal and background
  - Future generator being developed by E. Golubeva for ${}^{40}_{18}Ar$
    - Will use same cascade models
    - Will work to study neutrino FSI as well for complete comparison
- Study multiple generators with different assumptions to assess uncertainty in the models
  - Heavily dependent upon nuclear models

$n \rightarrow \bar{n}$ Generator Assumption Comparison

DUNE $^{40}_{18}Ar$—GENIE

- **Fermi Gas Model**
  - Bodek-Ritchie Distribution
  - ***No correlations included***
- $\sim$10 annihilation channels modeled
- Uses continuous analytical nuclear density function
  - How accurate for large nuclei?
- Probability of annihilation as a function of radius not modeled
  - Uses only density function

ESS $^{12}_{6}C$—E. Golubeva

- **Fermi Gas Model**
  - Personally Developed
  - ***No correlations included***
- $\sim$100 annihilation channels modeled
- Uses approximated ("stepped") discontinuous analytical nuclear density function
  - Accurate for small nucleus
  - Uses zones of constant nuclear density
- Probability of annihilation by radius known analytically

Nuclear Density Functions and the Radial $\bar{n}$-Annihilation Probability Density

GENIE

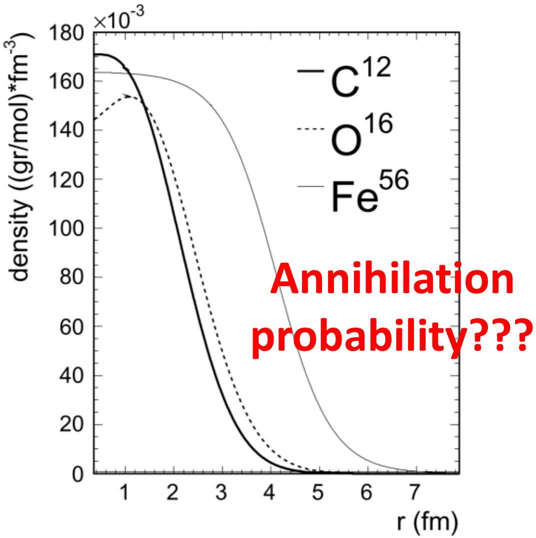
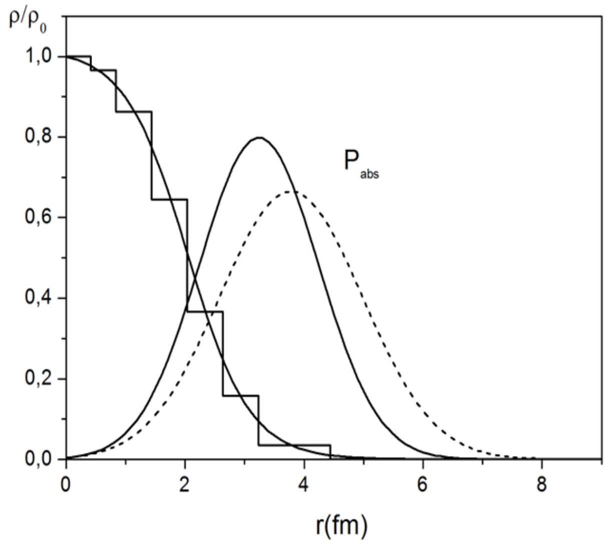


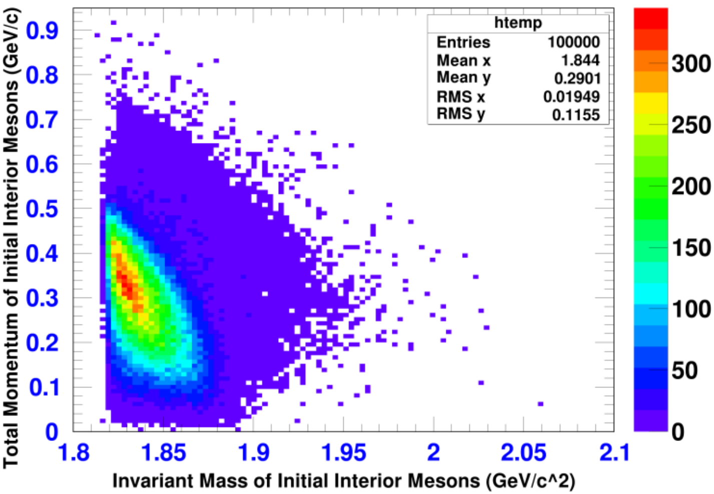
Figure 9.10: Nuclear density profiles for C^{12}, O^{16} and Fe^{56}.

ESS ${}^{12}_{6}C$—E. Golubeva

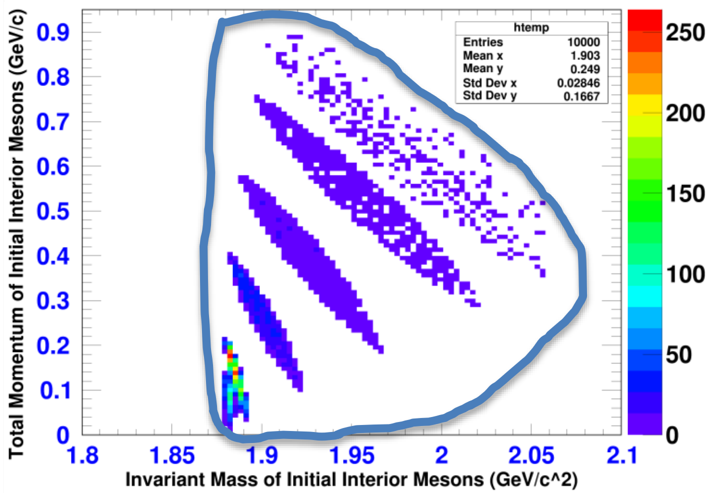


Initial Meson Production in $\bar{n}N$ Annihilation

DUNE $^{40}_{18}Ar$—GENIE

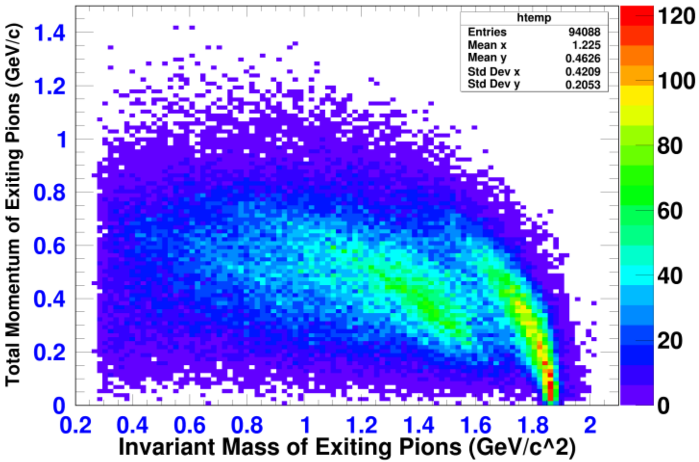


ESS $^{12}_{6}C$—E. Golubeva

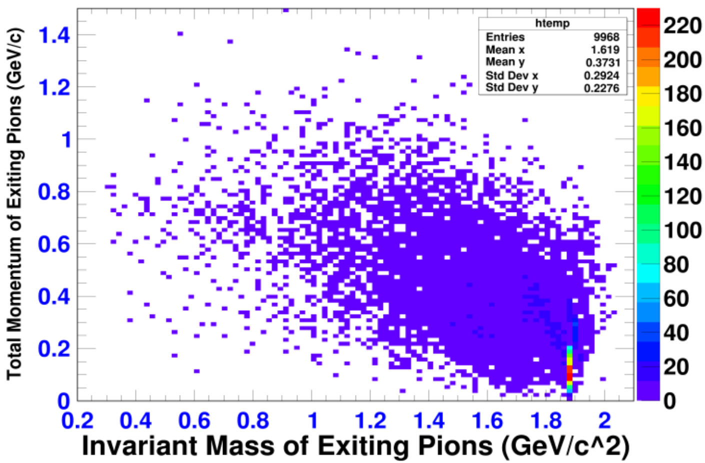


Final Exiting $\pi^{\pm,0}$ After Nuclear Transport

DUNE $^{40}_{18}Ar$—GENIE



ESS $^{12}_{6}C$—E. Golubeva

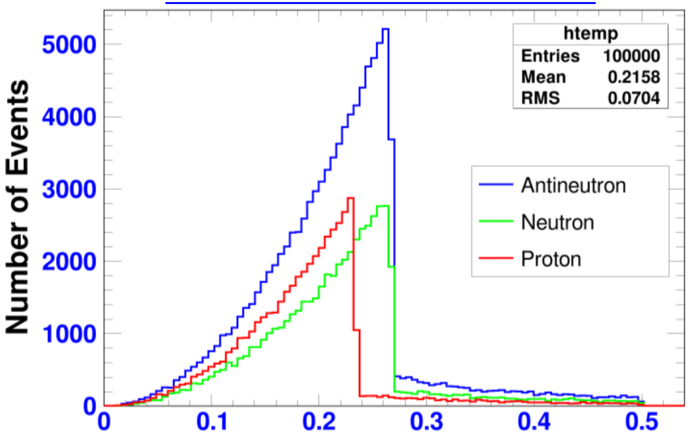


Annihilating Nucleon Momentum

Due to Fermi Motion

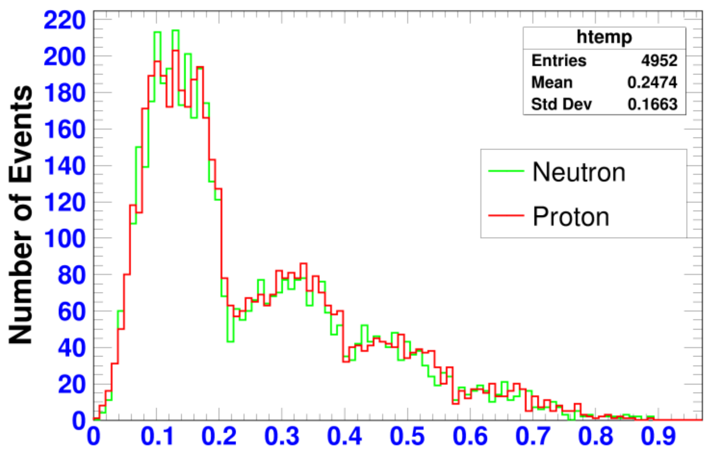
DUNE $^{40}_{18}Ar$—GENIE

Bodek-Ritchie Fermi Gas Distributions



Interior Nucleon Momentum (GeV/c)
(due to Fermi motion)

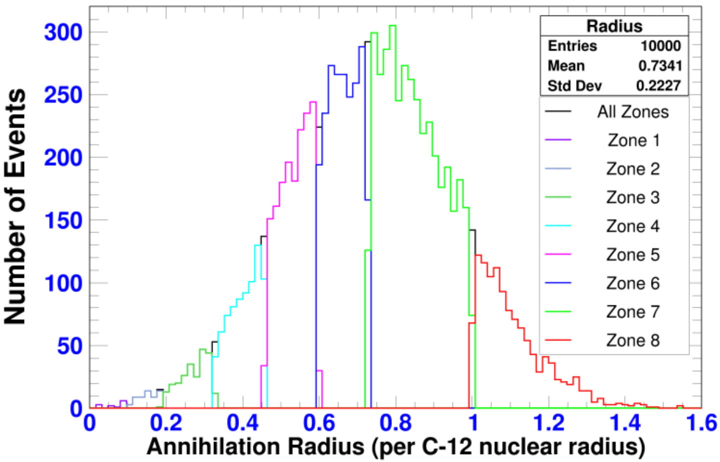
ESS $^{12}_{6}C$—E. Golubeva



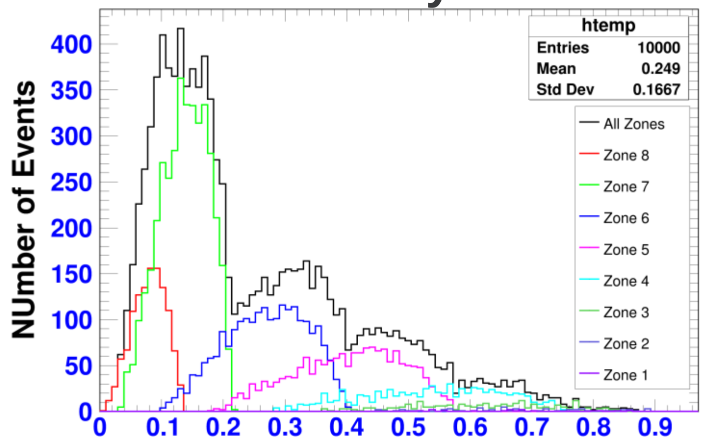
Interior Nucleon Momentum (GeV/c)
(due to Fermi motion)

More Results From $^{12}_{6}C$ MC Generator for ESS

Annihilation Radius by Zone



Annihilating Nucleon Momentum by Zone



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Potential Inaccuracies
in
Current Simulations
and a few
Proposed Directions
for
Future Progress

Part Three

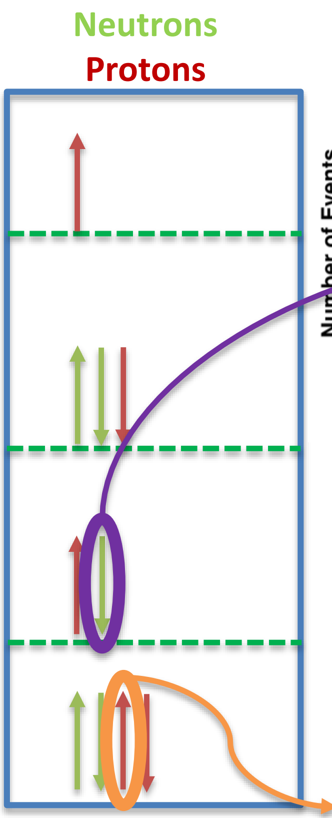
What to add to future generators for ${}^{40}_{18}Ar$?

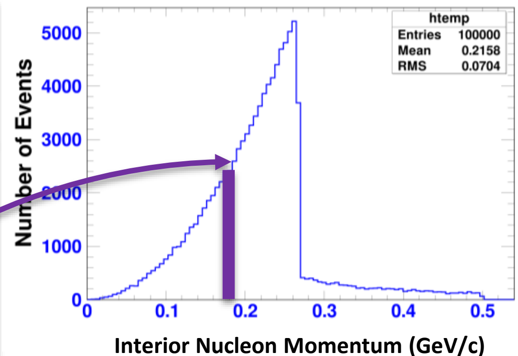
- **Resonances** (ρ, η, etc.)
- Infrequent reaction channels
  - Must be kinematically allowed—can change from nucleus to nucleus
- **Precise radial density functions**
  - Generally well known for light nuclei, but how well heavy?
- **Precise annihilation probability functions**
  - Matters in bound searches greatly, as the ***transformation is more likely to occur near or outside the nuclear envelope***
  - Completed analytically for $\bar{n}$ on ${}^{12}_{6}C$, but how to model this for $\bar{n}$ on ${}^{40}_{18}Ar$?
    - Can no longer model $\bar{n}$ as a plane wave!!
- **Two-body nucleon correlation functions**
  - $(\boldsymbol{n} \rightarrow \bar{\boldsymbol{n}})\boldsymbol{N}$ **is an inherently two-body system, unlike most $\boldsymbol{\nu}$ interactions**
  - What are the *real*, ***quantum mechanical*** nucleon momentum distributions for each annihilating nucleon in ${}^{40}_{18}Ar$?
  - ***Two body momentum distributions needed?***

An Interesting Forthcoming Investigation:

Nucleon Correlations

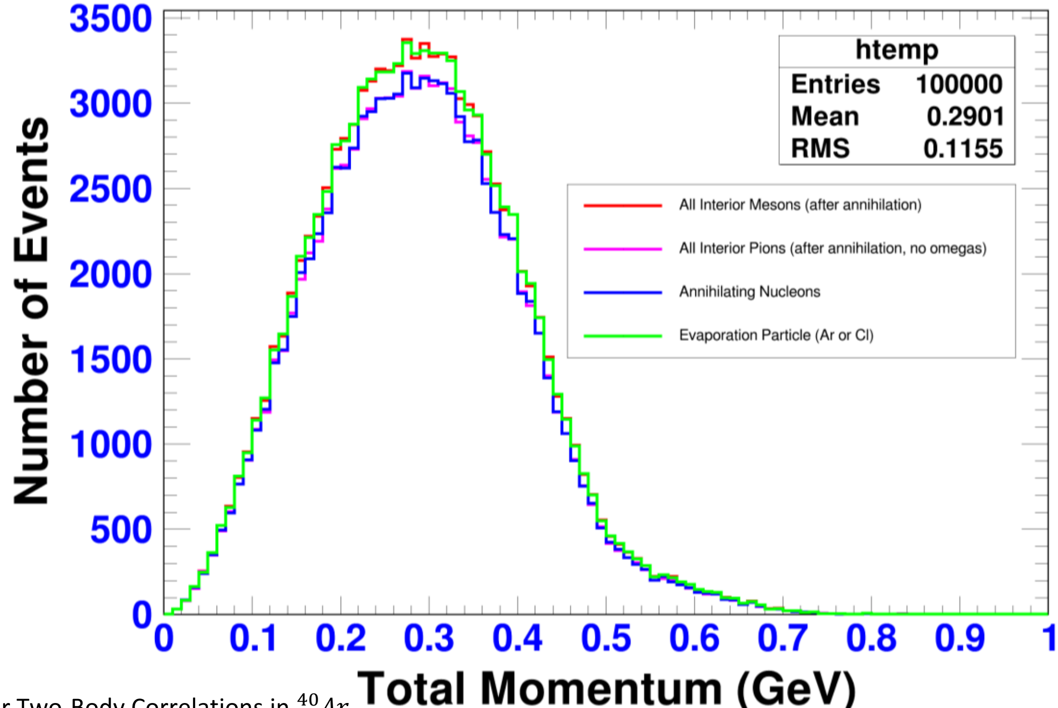
- There are QM problems with the assumptions made when throwing momenta for annihilating nucleons in $^{40}_{18}Ar$
  - By making a choice from a distribution of *all* nucleons, we have ***changed the remaining distribution***
- Furthermore, it has been found that ***nucleons are choosey*** ***about their neighbors***
  - **Neutrons spend more time around protons** in the nucleus
  - These pairs can have ***inextricably linked momenta***
  - Changes the weights of expected annihilation reactions
- **JLAB data** on LAr coming early next year?
- ***Can we simply use a two body momentum distribution instead of looking at individual nucleons?***





What do we use as the ***next*** distribution?

Use Inherently Two-Body Momentum Distributions?



JLAB Proposal for Two-Body Correlations in ${}^{40}_{18}Ar$

End Goals and To Do's

- Top priorities are…
  - Comparisons between multiple generators for uncertainty assessments
    - For $n \rightarrow \bar{n}$
    - For atmospheric ν
  - **Improving generators**
    - ***Add more physics*** to understand the precise nature of the topologies of $\bar{n}A$ annihilation
  - Analysis of generated events will continue
    - Partial and **full detector** simulations with reconstruction
    - **Proton and neutron detections** in LAr
  - Background rejection must be maximized
    - **Free or quasi-free**? Better separation techniques?
- Assess final feasibility of $\tau_{n \rightarrow \bar{n}}$ limit improvements
- Optimize experimental components (ESS)
- **Go and find the oscillation!**

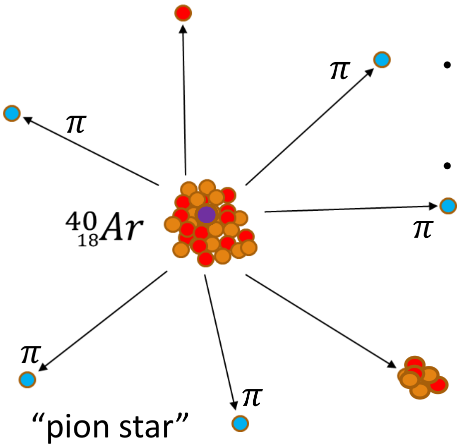
For the extra eager…

BACKUP SLIDES

Signal Comparison

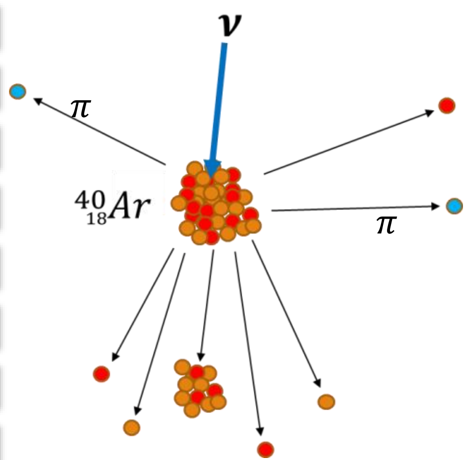
$n \rightarrow \bar{n}$ vs. Backgrounds (ex: Atmospheric Neutrino, ν)

$n \rightarrow \bar{n}$ Annihilation and Knockouts

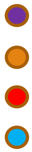


- Noncontinuous energy spectrum
- Generally a ~spherical topology
- Low momentum due only to Fermi motion

Neutral Current Atmospheric ν

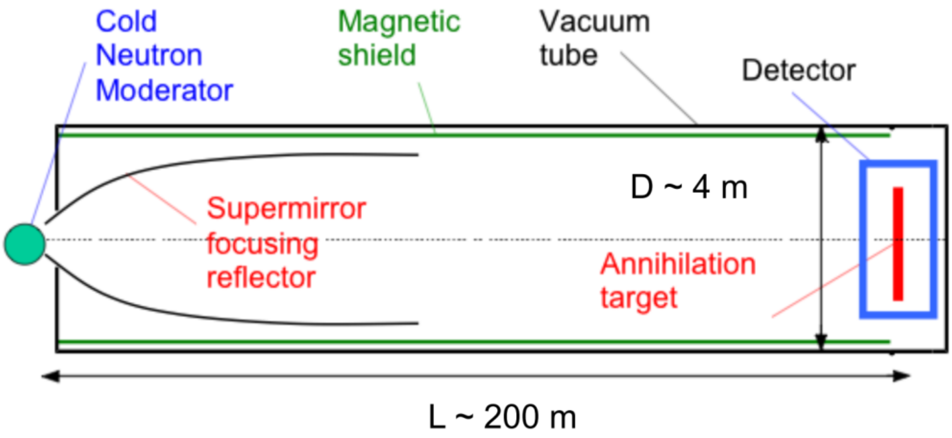


- Continuous energy spectrum
- Generally a ~correlated topology
- Large range of total momentum



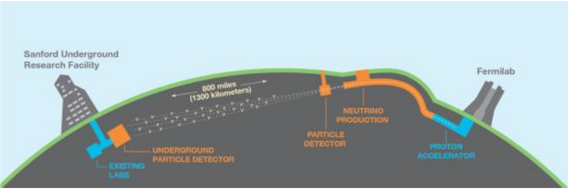
Free Neutron Beam Search at the European Spallation Source

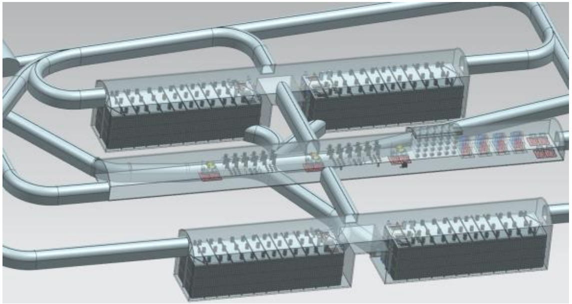
- Europe's answer to the SNS at ORNL
- Hopes to best Institute Laue-Langevin result with…
  - Longer beamline
  - Higher neutron reflectivity and more neutrons on target
  - Thinner carbon foil
  - General improvements in detector technology
- Benefits from ~guaranteed zero background!
  - Beam pulse timing
  - ν's aren't seen by foil
  - ILL saw $\frac{sig}{bkgr} = \frac{0}{0}$ for one year

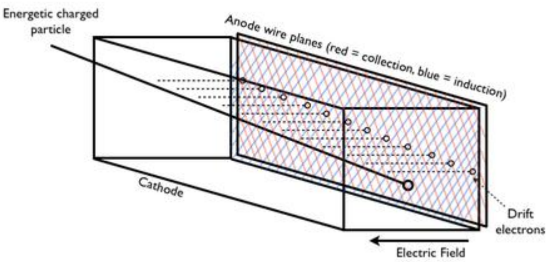


Bound Neutron Search at the Deep Underground Neutrino Experiment

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT







- **DUNE** international collaboration of 1000+
  - Partnership of Fermilab and LBNF
  - Will construct world's most intense ν beam
  - The far detector will utilize LArTPCs
  - **Fiducial volume** of ~40 kilotons
- LArTPC's superior tracking and PID capabilities enable background reduction
  - Is background-free/quasi-free $n \to \bar{n}$ search possible?
    - The ***real*** question we need to answer!!!

Why do we need to be accurate in our $n \to \bar{n}$ simulations?

1. For rare events, knowing precisely the expected topology and associated observables will always help
   - ***Accurate nuclear models are needed*** to understand the cascade of particles produced within the nucleus
   - Possibly aid in the separability between signal and background processes
2. Ability to ***compare simulations and assess their systematic uncertainties*** within them independently
   - Should be precise and **quantitative**
   - This is why we **need multiple types from multiple sources**
   - Wish to reliably understand whether the systematic uncertainties within these models lead to statistically irreducible background
   - ***Looking for consistency of results between simulations***
     - Did we get the physics right???
3. We learn more about interesting, underlying physics
4. Predict and analyze generated signals for hosts of other BSM processes