

# Nucleon decay search with DUNE

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for the DUNE collaboration

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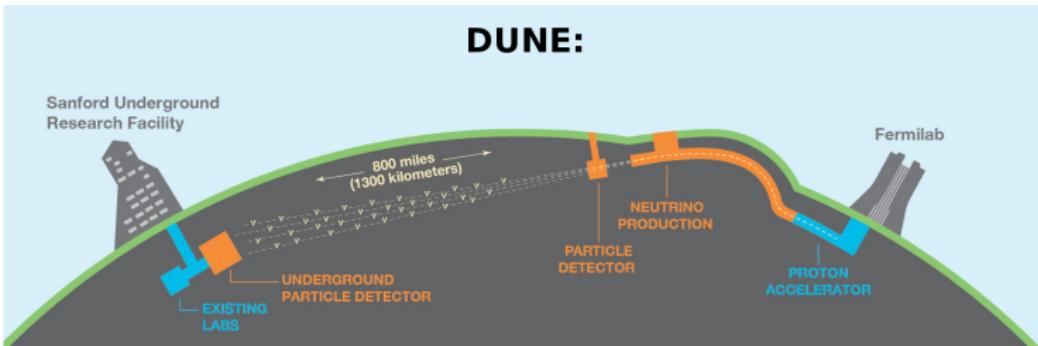
Note: underlined text throughout presentation contains links to references

# **1. Motivation**

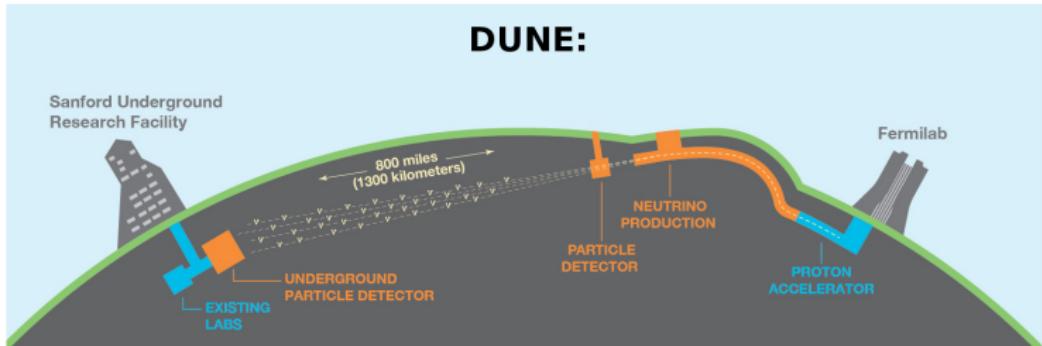
- Observation: dominance of matter over antimatter in today's universe
- 1967: **Baryogenesis under Sakharov conditions**, requires baryon number  $B$  violating process: nucleon decay?
- 1970's: **Grand Unified Theories (GUT)** predict  $p \rightarrow e^+ \pi^0$  (and other decay modes)
- nucleon decay most promising test
- 1970's: **Supersymmetry (SUSY)**: higher proton lifetimes, new decay modes:  $p \rightarrow \bar{\nu} K^+$  with  $\tau \approx 10^{34-35}$  years
- **focus of this talk**
- World's best limits by Super-Kamiokande are:  
$$\tau(p \rightarrow e^+ \pi^0) > 2.4 \times 10^{34} \text{ years}$$
$$\tau(p \rightarrow K^+ \bar{\nu}) > 8.2 \times 10^{33} \text{ years}$$

## 2. The Deep Underground Neutrino Experiment (DUNE)

# DUNE:



Physics program: accelerator  $\nu$ 's ( $\delta_{CP}$  & mass hierarchy),  
nucleon decay, supernova  $\nu$ 's,  $n\bar{n}$  oscillations, ...

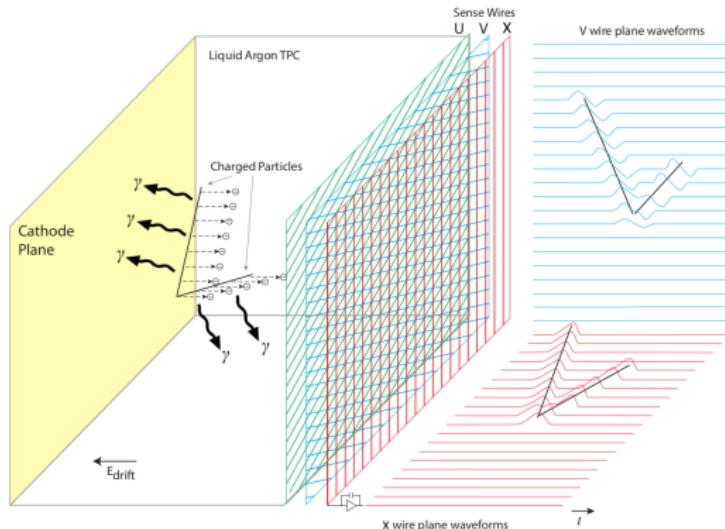


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### DUNE far detector:

- Four single and dual phase LAr TPC modules, each with:  
 $m_{\text{total}} = 17 \text{ kt}$ ,  $m_{\text{active}} = 14 \text{ kt}$  &  $m_{\text{fiducial}} = 10 \text{ kt}$
- Spatial resolution:  $\sim 5 \text{ mm}$
- 1500 m underground
- R&D program: 35t,  $3 \times 1 \times 1 \text{ m}^3$ , protoDUNEs (0.8 kt)

# Single Phase LAr TPC (used in this study)

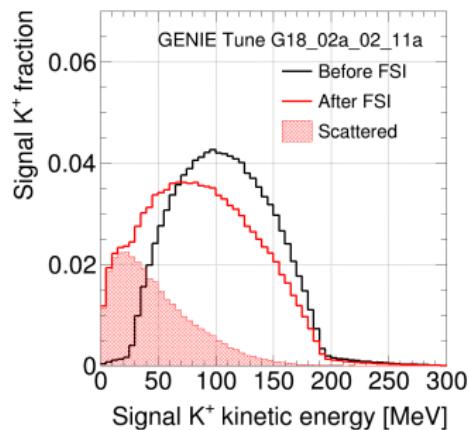


- Ionization charge and scintillation light recorded in liquid
- 3 readout planes, 3.6 m maximum drift, 150 TPCs per module
- Dual phase LAr TPC: charge amplification in argon gas  
→ Nucleon decay sensitivity study in progress

### **3. Simulation and reconstruction**

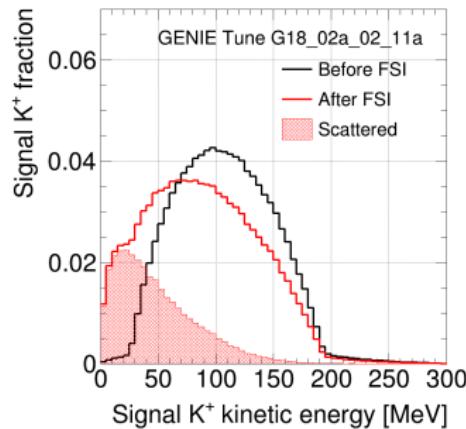
# Signal

- Focus on  $p \rightarrow \bar{\nu}K^+$ 
  - Nucleon density:  
Woods-Saxon distribution
  - Fermi motion: Bodek-Ritchie global Fermi gas
  - Final state interactions (FSI): hA2018



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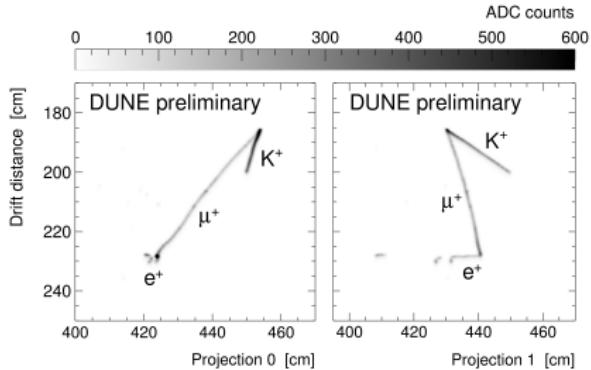
## Background

- Atmospheric neutrinos
- Bartol flux + GENIE  
x-sections & nuclear model  
 $\rightarrow \mu, e, \pi, p, n, \gamma, K, \Sigma, \dots$
- Most events below 1 GeV
- no single kaons!

Expected interactions:

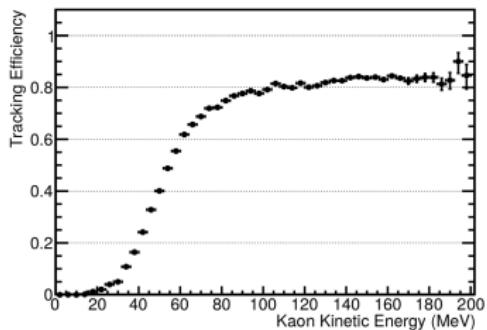
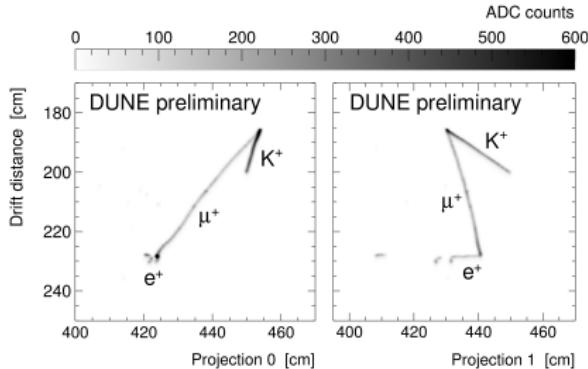
10 kt · year	CC	NC	Total
$\nu_\mu$	1038	398	1436
$\bar{\nu}_\mu$	280	169	449
$\nu_e$	597	206	803
$\bar{\nu}_e$	126	72	198
Total	2041	845	2886

- Validated LAr TPC simulation and reconstruction in LArSoft  
(\*below is a dual phase LAr TPC event display for  $p \rightarrow \bar{\nu} K^+$ , the principle is the same for single phase LAr TPCs)



- Reconstruction:
  1. Hit finding
  2. 2D pattern recognition
  3. 3D track and shower reconstruction

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- Reconstruction:

1. Hit finding
2. 2D pattern recognition
3. 3D track and shower reconstruction

- 30 MeV  $K^+$ : 1 cm in LAr
- 90 MeV  $K^+$ : 10 cm in LAr
- Eye scans: overall signal  $K^+$  tracking efficiency can be improved to 80 %

## **4. Analysis and results**

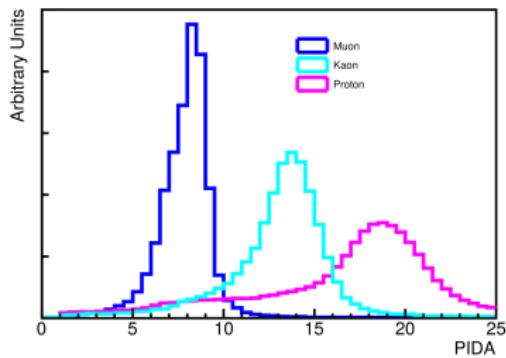
- Goal: lower limit on  $\tau(p \rightarrow \bar{\nu}K^+)$  at  $\sim 0$  background
- Strategy: identify 3D tracks of  $K^+$  and decay products

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## Particle identification

- Particle ID variable:

$$\text{PIDA} = \left\langle \left( \frac{dE}{ds} \right)_{\text{Hit}} \cdot R_{\text{Hit}}^{0.42} \right\rangle$$



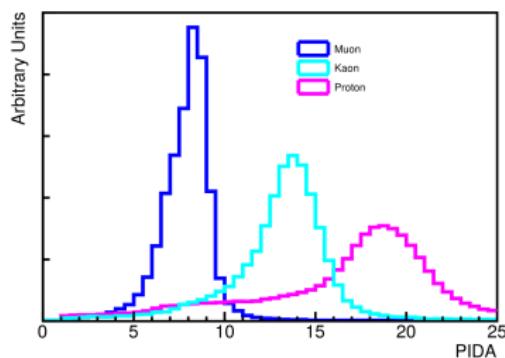
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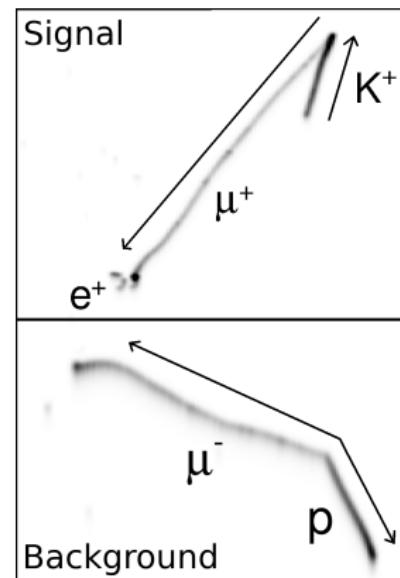
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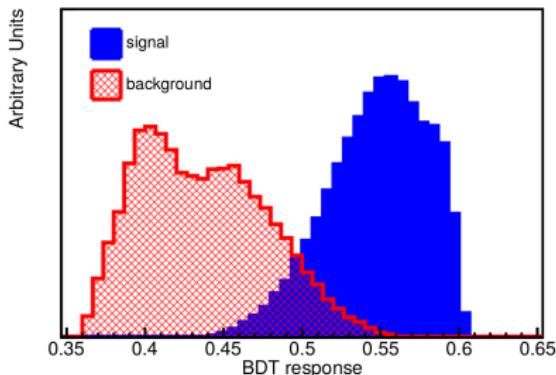
$$\rightarrow \mathcal{L}_{p-K^+} = \mathcal{L}_{\text{forw}} + \mathcal{L}_{\text{backw}}$$

## Event classification

1. Preselection:  $\geq 2$  reco tracks and longest reco track  $< 100$  cm
2. Boosted Decision Tree (BDT): PIDA,  $\mathcal{L}_{p-K^+}$ ,  $E_{\text{vis}}$ , event display convolutional neural network score,  $N_{\text{Tracks}}$ , ...

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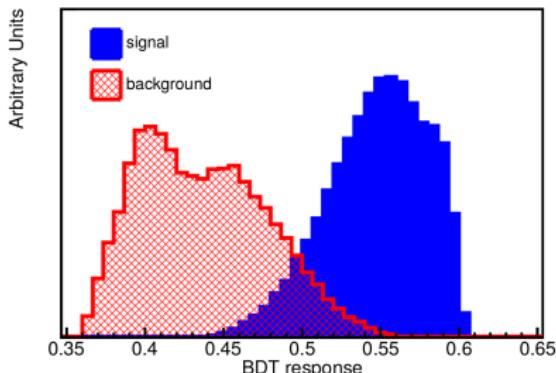
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- $\epsilon = 15\%$  & 1 background event (BE) in  $1 \text{ mt} \cdot \text{yrs}$
- $\epsilon = 30\%$  with improved reco
- $\tau(p \rightarrow \bar{\nu} K^+) > 1.3 \times 10^{34} \text{ yrs}$   
@ 90 % CL after  $400 \text{ kt} \cdot \text{yrs}$

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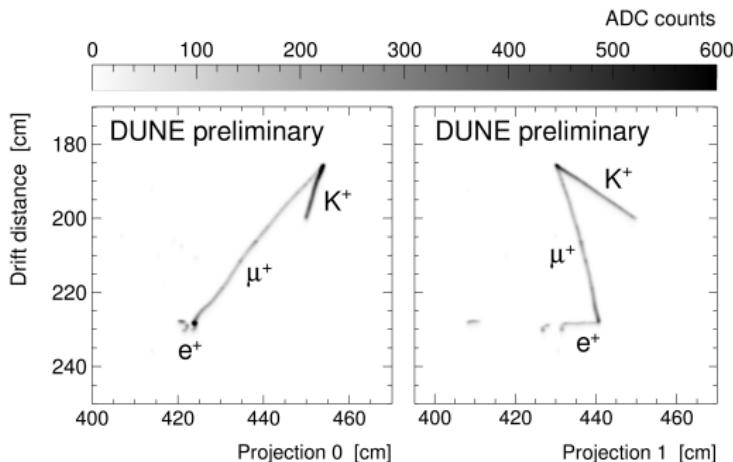
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## Other decay modes

- $\bullet n \rightarrow e^- K^+$ :  $\epsilon = 47\%$  &  
15 BE in  $1 \text{ mt} \cdot \text{yrs}$   
 $\rightarrow \tau > 1.1 \times 10^{34} \text{ yrs}$   
 $\text{@ 90\% CL after }$   
 $400 \text{ kt} \cdot \text{yrs}$
- $\bullet p \rightarrow e^+ \pi^0$   
 $\rightarrow$  Monte Carlo truth study,  
energy smeared  
 $\rightarrow \tau > (0.9 - 1.1) \times 10^{34} \text{ yrs}$   
 $\text{@ 90\% CL after }$   
 $400 \text{ kt} \cdot \text{yrs}$

# Summary

- Nucleon decay searches can test Grand Unified Theories, Supersymmetry and Baryogenesis
- DUNE will be competitive for favored SUSY decay channel:  $\tau(p \rightarrow \bar{\nu} K^+) > 1.3 \times 10^{34}$  yrs @ 90 % CL after 400 kt · yrs
- DUNE complements searches by Super- & Hyper-Kamiokande and JUNO, offers unique high-resolution imaging capabilities:



**Thank you!**