Nucleon decay search with DUNE

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for the DUNE collaboration

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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 $p \to e^+\pi^0$ (and other decay modes)

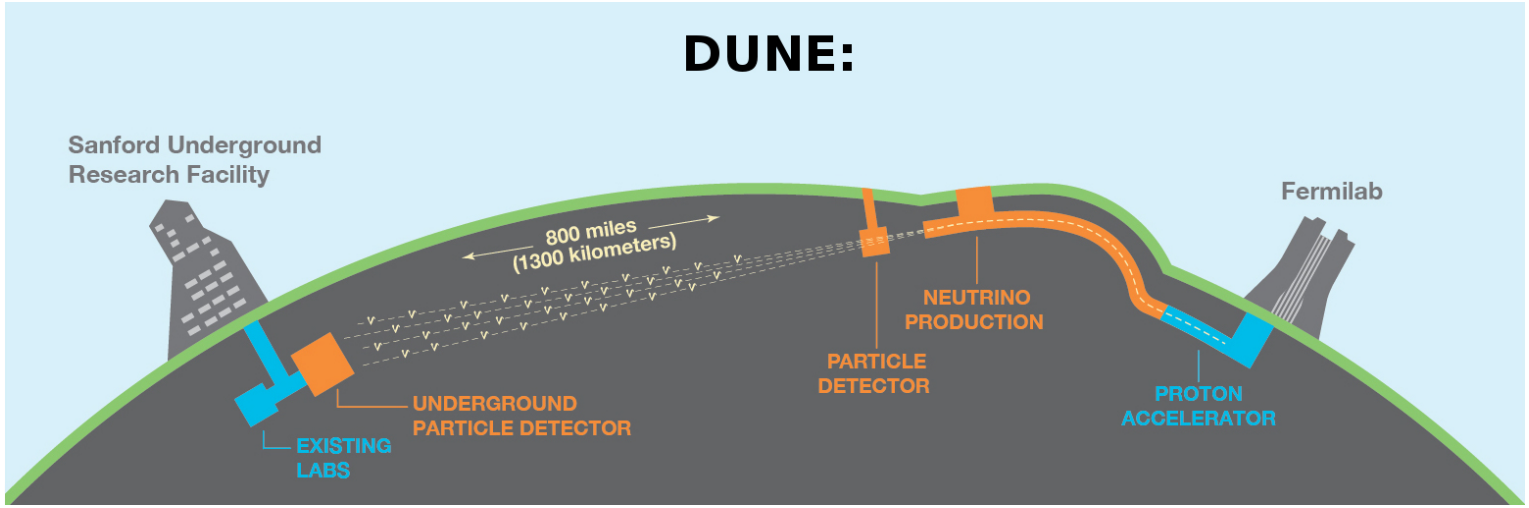
→ nucleon decay most promising test

- 1970's: **Supersymmetry (SUSY)**: higher proton lifetimes, new decay modes: $p \to \bar{\nu}K^+$ with $\tau \approx 10^{34-35}\,\mathrm{years}$

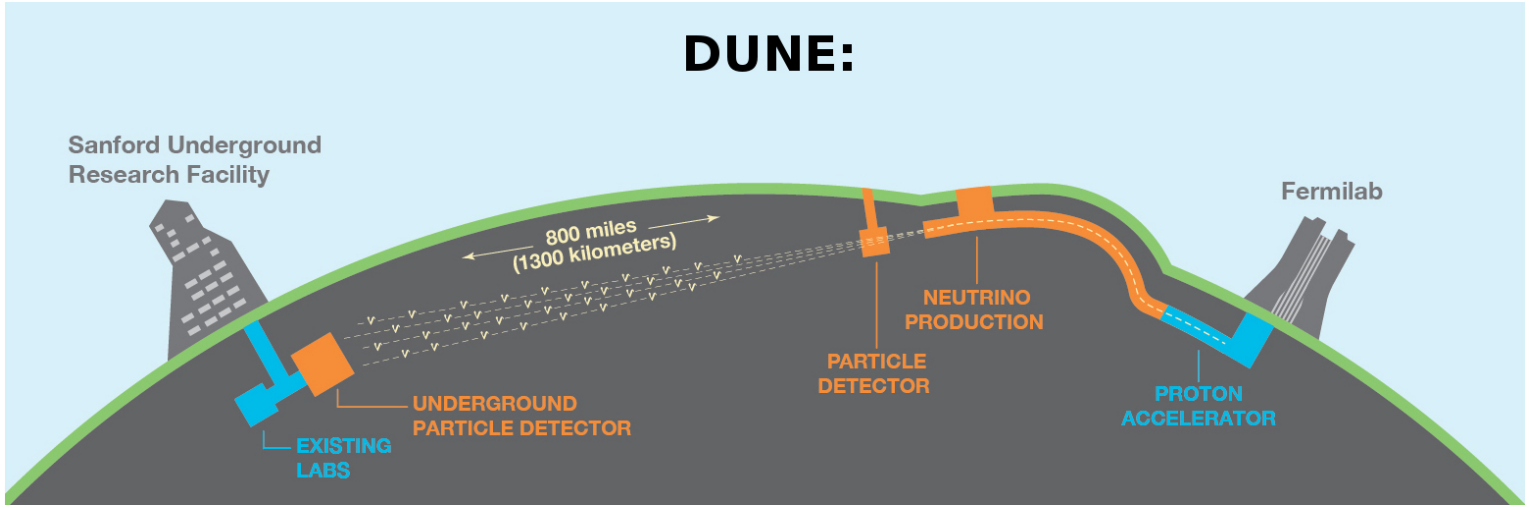
- Best limits by SK are below predictions of GUT & SUSY:

$\tau/Br\,(p \to e^+\pi^0) > 2.0 \cdot 10^{34}\,\mathrm{years}$
$\tau/Br\,(p \to K^+\bar{\nu}) > 8.2 \cdot 10^{33}\,\mathrm{years}$

2. The Deep Underground Neutrino Experiment (DUNE)



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



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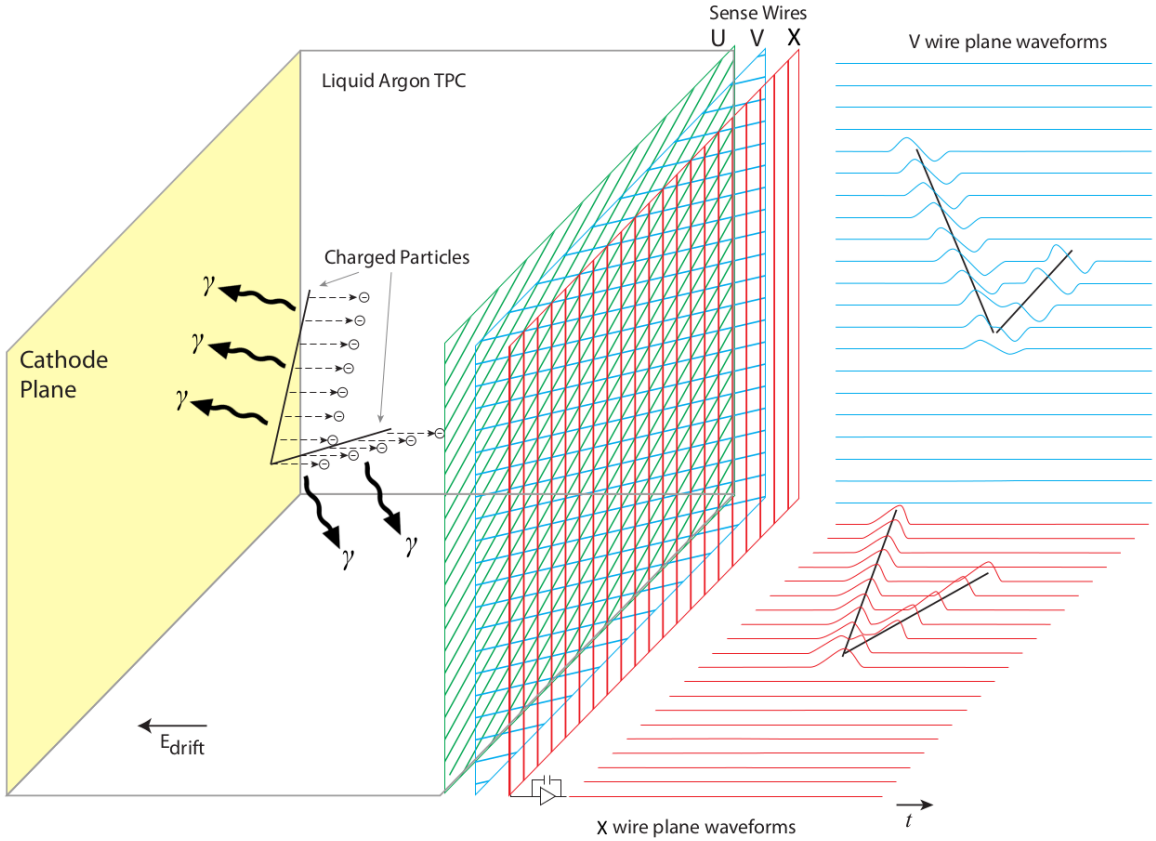
DUNE far detector:

- Four independent single and dual phase LAr TPC's, each with $m_{\text{tot}} = 17\,\text{kton}$
- Spatial resolution: $\sim$5 mm
- 1500 m underground
- R&D program: 35T, 3x1x1 m^3, protoDUNEs (0.8 kton)

Single Phase LAr TPC



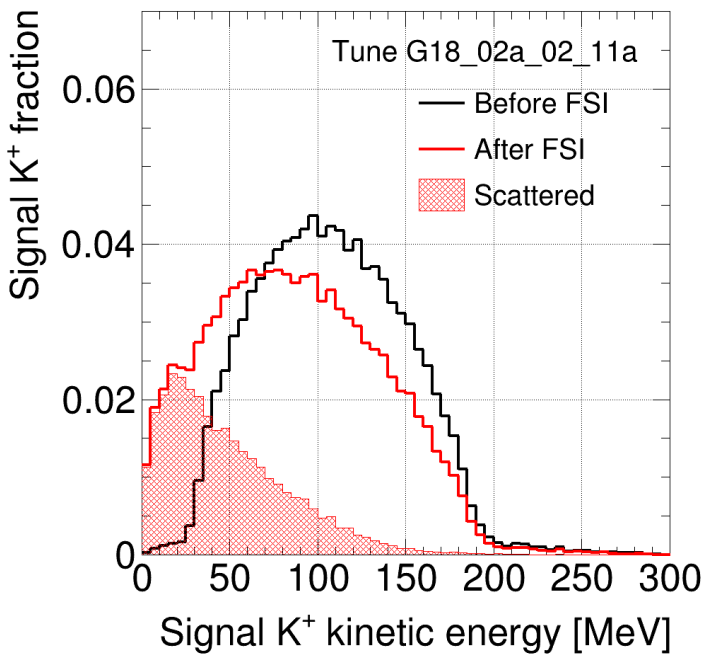
- Ionization charge and scintillation light recorded in liquid
- 3 readout planes
- 3.6 m maximum drift

3. Simulation and reconstruction

Signal

- Focus on $p \to \bar{\nu} K^+$
- Nuclear model for argon:
  - Nucleon density
  - Fermi motion
  - Final state interactions

$\to$ simulated in GENIE



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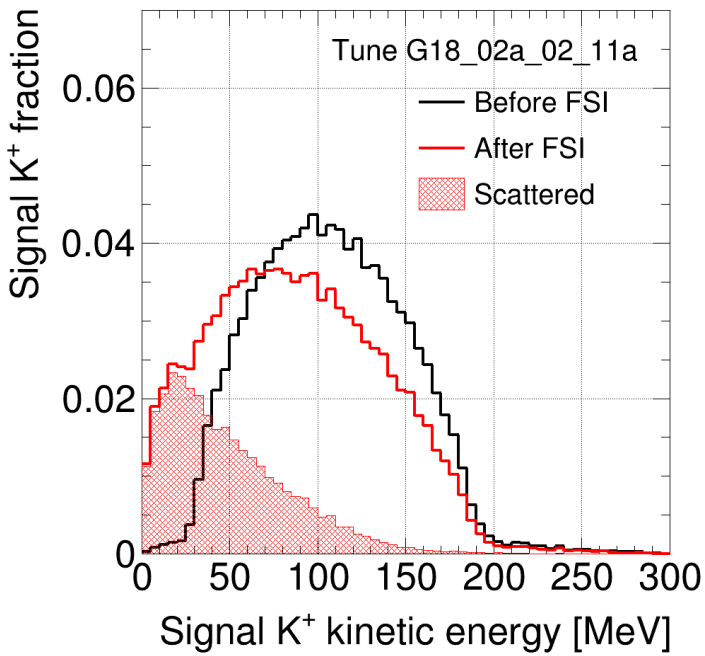


Background

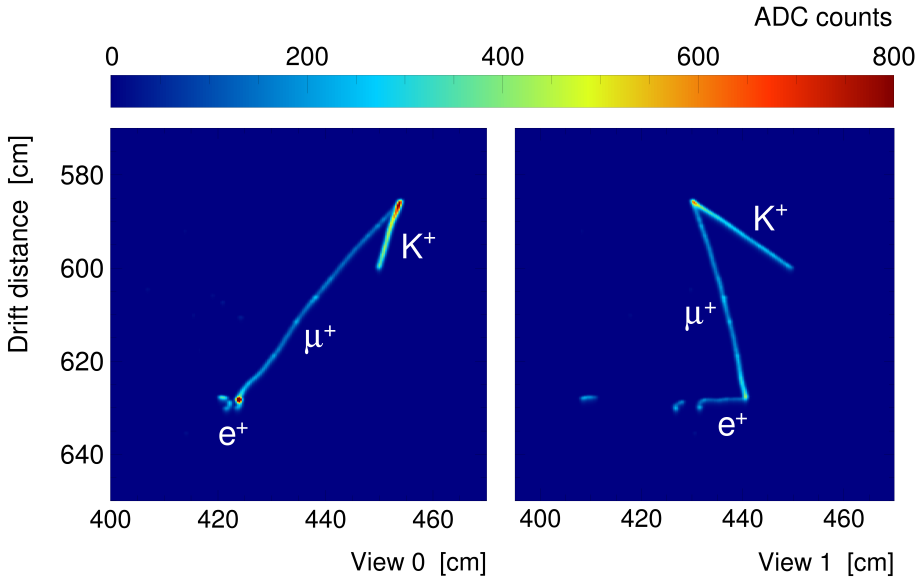
- Atmospheric neutrinos
- Bartol flux + GENIE x-sections & nuclear model

$\to$ μ, e, π, p, n, γ, K, Σ, ...

- Most events below 1 GeV
- no single kaons!

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

- Validated LAr TPC detector simulation in LArSoft



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

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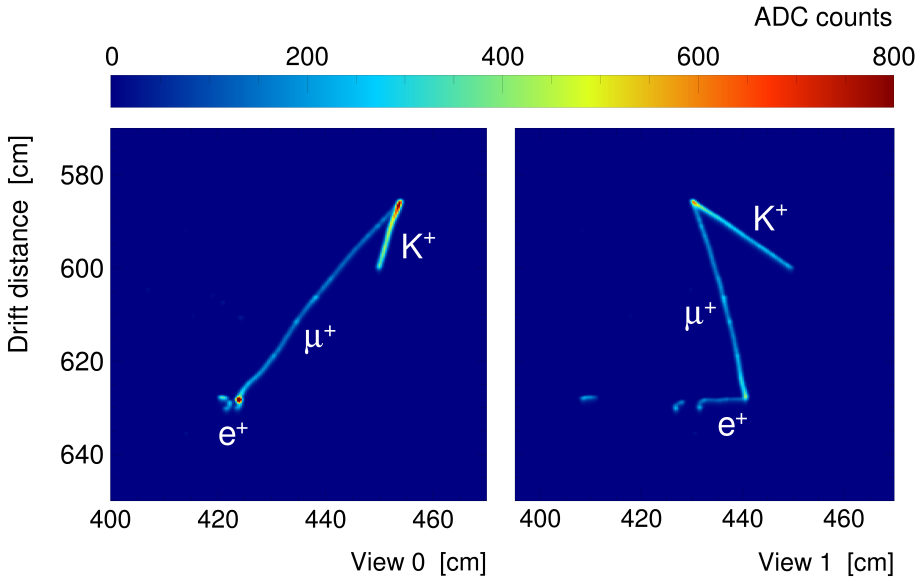

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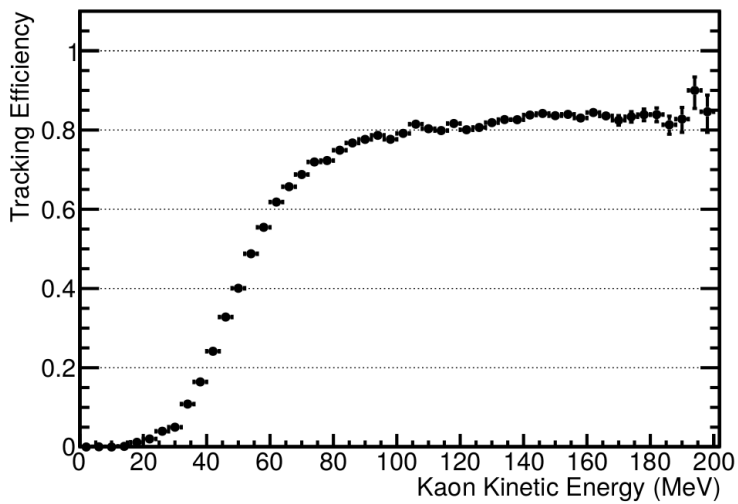
- Low signal K^+ tracking efficiency for low-energy $K^+ \rightarrow$ can be improved
- 30 MeV K^+: 1 cm in LAr
- 90 MeV K^+: 10 cm in LAr



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4. Analysis and results

- Goal: lower limit on $\tau\,(p \to \bar{\nu} K^+)$ at $\sim$0 background

$\to$ Strategy: identify 3D tracks of K^+ and decay products

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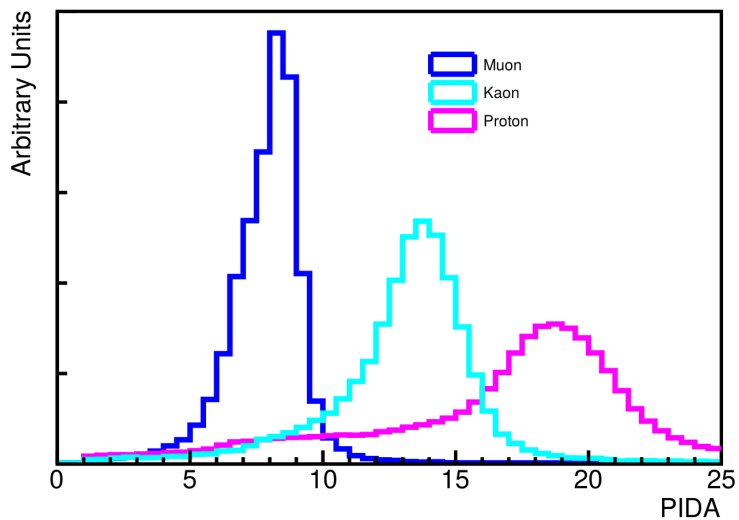
Particle identification

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



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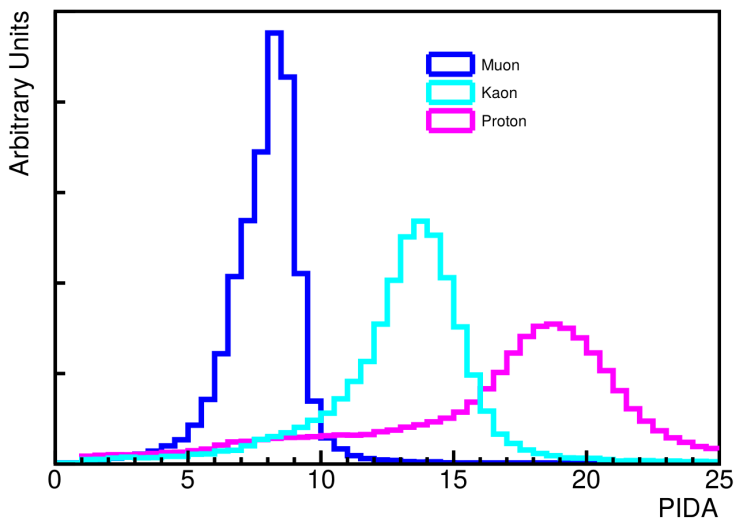
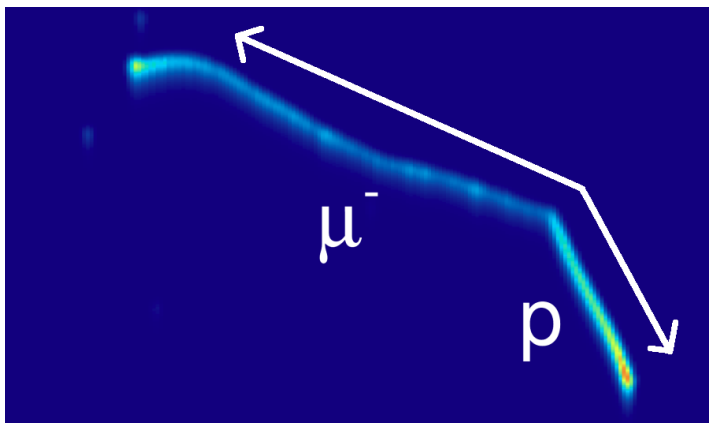


- Proton-kaon confusion, e.g. in ν_μ CC:



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

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Event classification

- Preselection: ≥ 2 reco tracks and longest reco track $< 100\,\mathrm{cm}$
- BDT input: PIDA, $\mathcal{L}_{p-K^+}$, E_{vis}, event display CNN score, N_{tracks}, N_{showers}, N_{vertices}, L_{tracks}, p_{tracks}, ...

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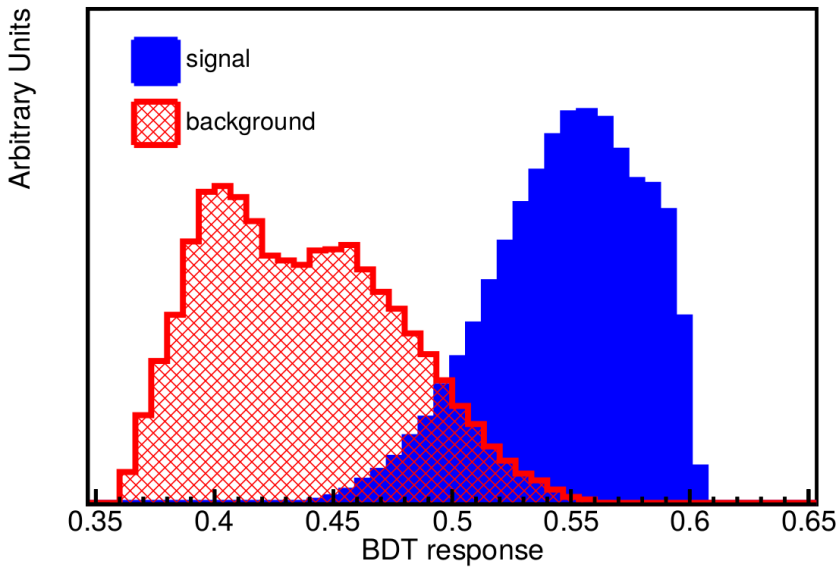

- $\epsilon = 15\,\%$, 1 BE in $1\,\mathrm{MT}\cdot\mathrm{yrs}$
- $\epsilon = 30\,\%$ with improved reco

$\rightarrow$ $\tau\,(p \rightarrow \bar{\nu}K^+) > 1.3 \cdot 10^{34}\,\mathrm{yrs}$
@ 90 % CL after $400\,\mathrm{KT}\cdot\mathrm{yrs}$

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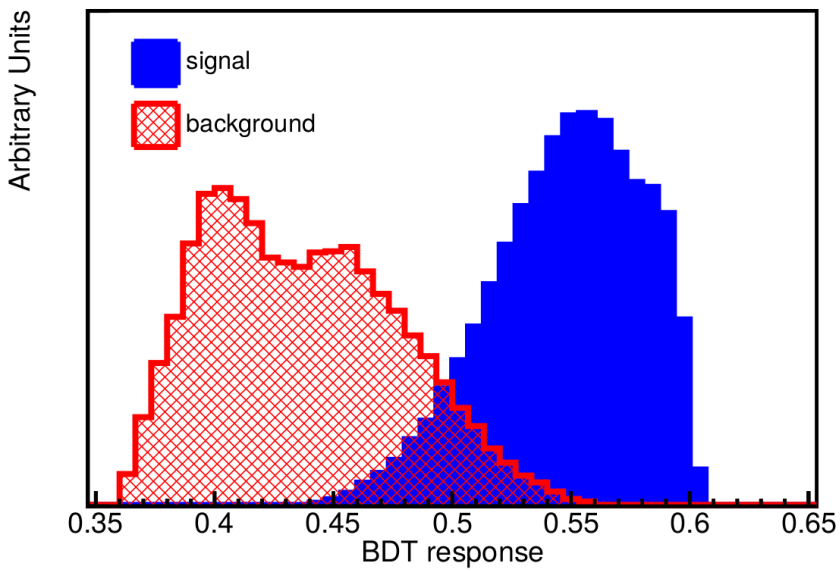

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Other decay modes

- $n \rightarrow e^- K^+$

$\rightarrow$ $\tau > 1.1 \cdot 10^{34}\,\mathrm{yrs}$ @ 90 % CL after $400\,\mathrm{KT}\cdot\mathrm{yrs}$

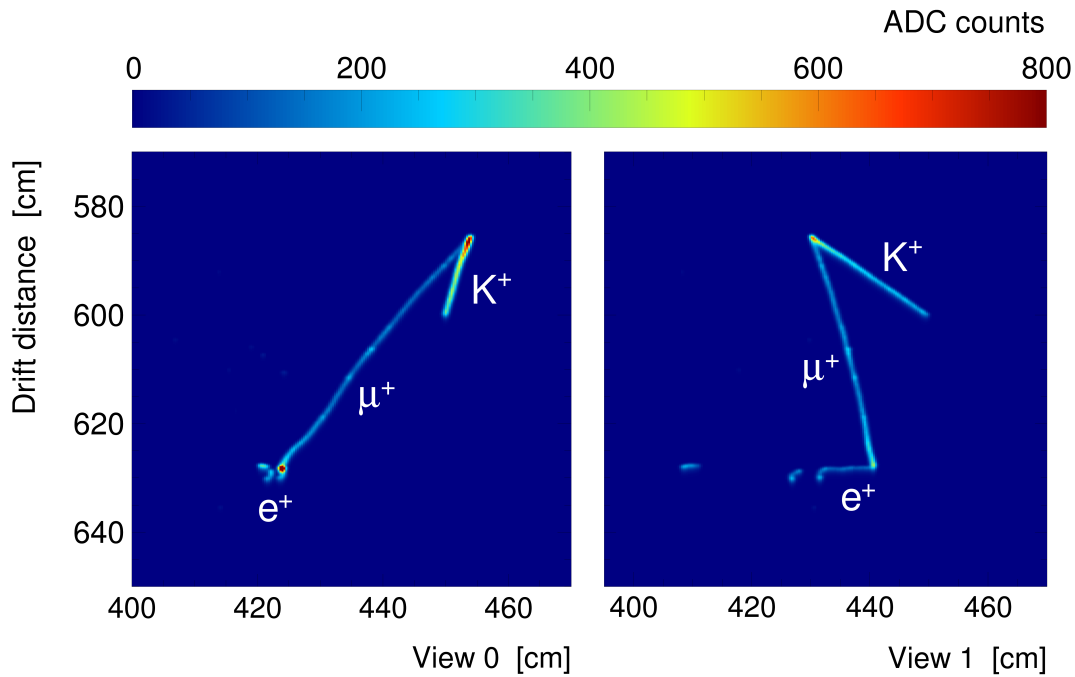
- $p \rightarrow e^+ \pi^0$

$\rightarrow$ MC truth study, E smeared

$\rightarrow$ $\tau > 0.9 - 1.1 \cdot 10^{34}\,\mathrm{yrs}$ @ 90 % CL after $400\,\mathrm{KT}\cdot\mathrm{yrs}$

Summary

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



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Thank you!