Nucleon Decay in DUNE

Jen Raaf, FNAL

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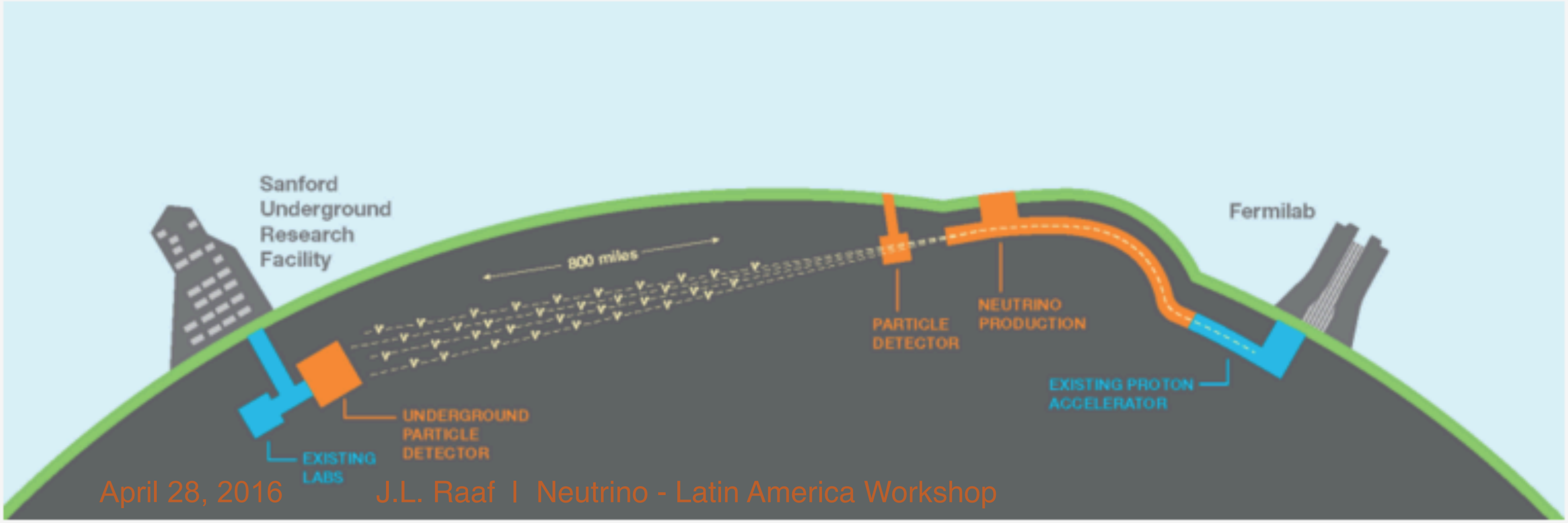
Aiming for transformative discoveries about the universe

The DUNE experiment is designed to achieve discoveries that could transform our understanding of the origins and evolution of the universe:

- Do neutrinos exhibit matter-antimatter asymmetries? Answering this question will help unravel the mystery of why matter generation dominated that of antimatter in the early universe.
- DUNE's observation of thousands of neutrinos from a core-collapse supernova in the Milky Way would allow us to peer inside a newly-formed neutron star and potentially witness the birth of a black hole.
- With the world's largest cryogenic particle detector deep underground, DUNE will be able to observe proton decay, if it should occur, and seek a relation between the stability of matter and the Grand Unification of forces.



Why search for proton decay?

Testing fundamental symmetries is our job!

- Conservation of baryon number is observed in Nature, but no compelling reason for it
- Matter-antimatter asymmetry requires baryon number violation (Sakharov conditions)

There are well-motivated models that suggest proton decay may exist and be observable

- Grand Unified Theories make specific predictions for decay modes, lifetimes, branching ratios
  - Observation of proton decay is “smoking gun” evidence
- Also, connections with cosmology, inflation, baryon asymmetry of the universe…

Beyond the Standard Model

Grand Unification

- Unifies strong, weak, and EM forces into a single underlying force at high energies
  - Standard Model's SU(3) x SU(2) x U(1) is embedded within a larger gauge group
  - Fundamental forces are low-E manifestations of unified force
- Can neatly explain many of the puzzling things observed in Nature but not explained by SM
  - Quantization of electric charge
  - Co-existence of quarks and leptons
  - Quantum numbers of quarks and leptons
  - …

First Grand Unified Theory (GUT)

VOLUME 32, NUMBER 8 — PHYSICAL REVIEW LETTERS — 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

It makes just one easily testable prediction, $\sin^2\theta_w = \frac{3}{8}$. It also predicts that the proton decays—but with an unknown and adjustable rate.

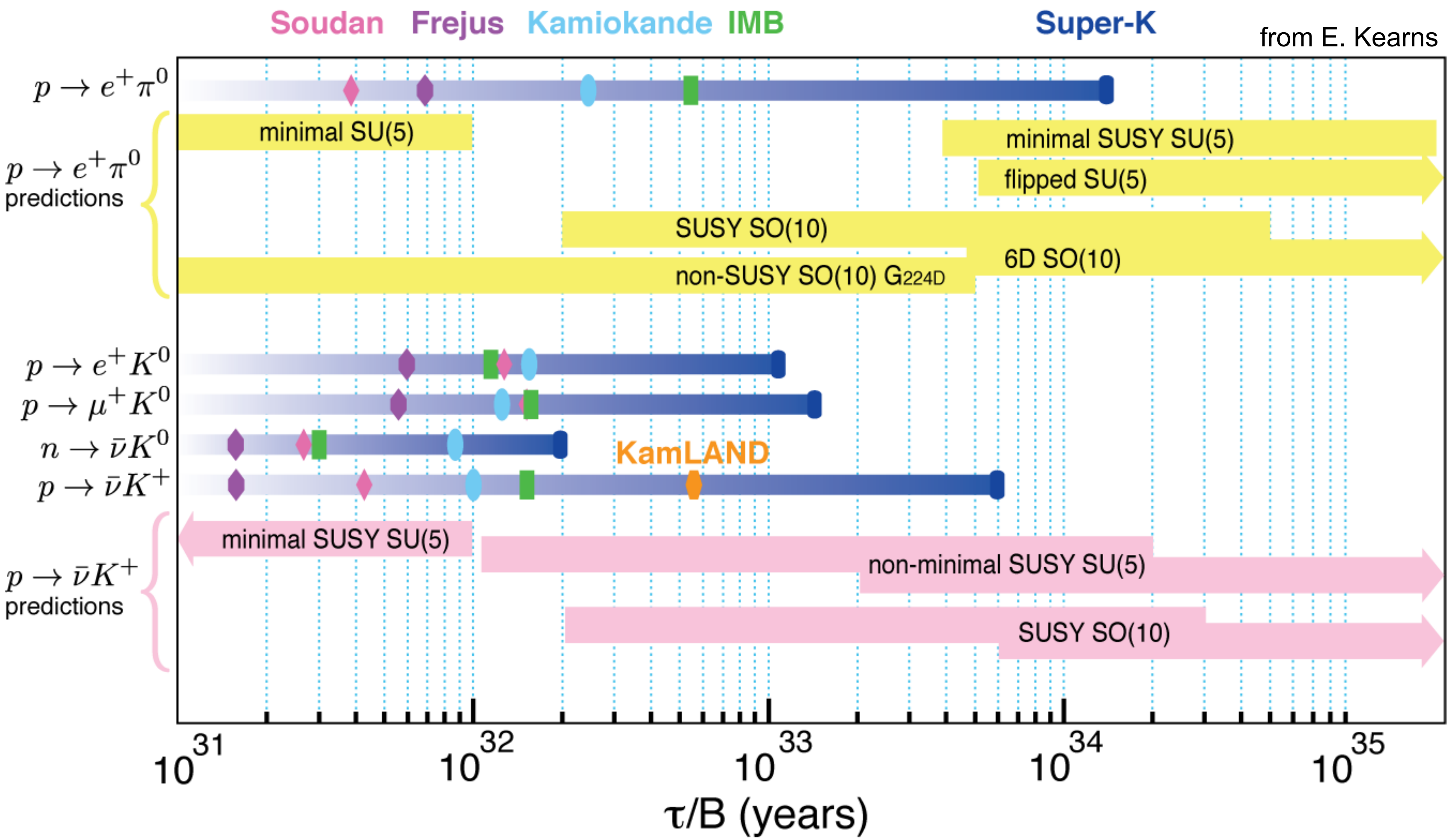
Had some nice consequences (charge quantization, unified coupling,…) but clearly didn't get everything right (value of weak mixing angle, also predicted monopoles and massless neutrinos).

An Experimentalist's View of Theory

- **Various types of models exist**
- **Lifetime predictions within those models are not precise**
  - (~2-3 orders of magnitude uncertainty)
- **Typically two decay modes used as "benchmarks" for models:**
  - $p \rightarrow e^+\pi^0$ (gauge mediated)
  - $p \rightarrow \nu K^+$ (SUSY D=5)
- **BUT, many other modes also allowed, and since we don't know which model (if any) is correct, it's important to search for as many as possible**
  - Beyond $e^+\pi^0$ and νK^+
    - Conserve B-L (p → antilepton + meson)
    - Conserve B+L ($p \rightarrow \mu^- \pi^+ K^+$ and many others)
    - $\Delta B=2$ ($n \rightarrow$ anti-n, $pp \rightarrow K^+K^+$)
    - 3-body decays ($p \rightarrow e^+\nu\nu$)
    - Invisible decays ($n \rightarrow \nu\nu\nu$)
    - …
  - Even if no signal seen, limits constrain the theories

Plenty to look for!

Experiment Confronts Theory



How to achieve good sensitivity in experiment?

$$\frac{\tau}{B} = \frac{N_0\ \Delta t\ \epsilon}{n_{obs} - n_{bg}}$$

Low Background Rate

- Cosmogenically-induced
  - Entering neutral kaons and neutrons
- Atmospheric neutrinos

High Efficiency

- Reconstruction, energy resolution
- Proton decay signal selection

Large Exposure (Detector Mass x Time)

Ongoing tasks within NDK (together with Atmospheric & Cosmogenic groups):

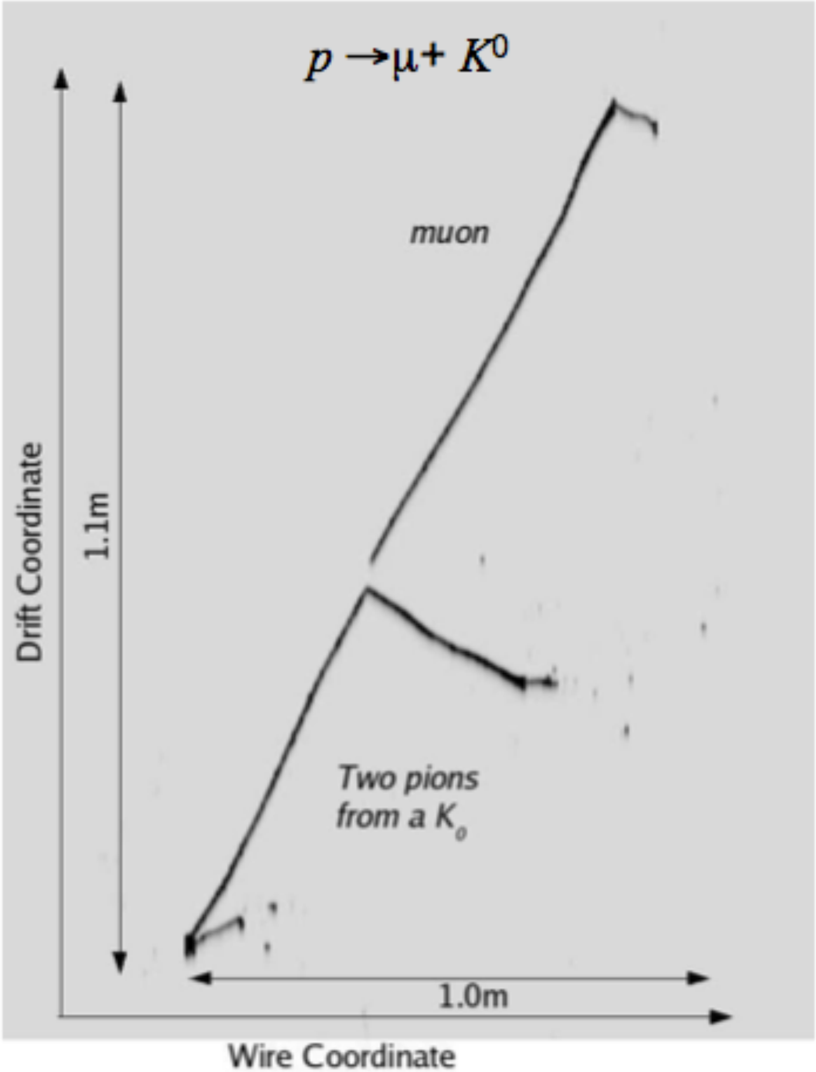
Simulate and reconstruct backgrounds and signal to understand impact on sensitivity and identify areas for improvement

Modes in which a LArTPC should do well

- Modes with kaon in final state
- Modes with displaced vertices
- Modes with multiple prongs

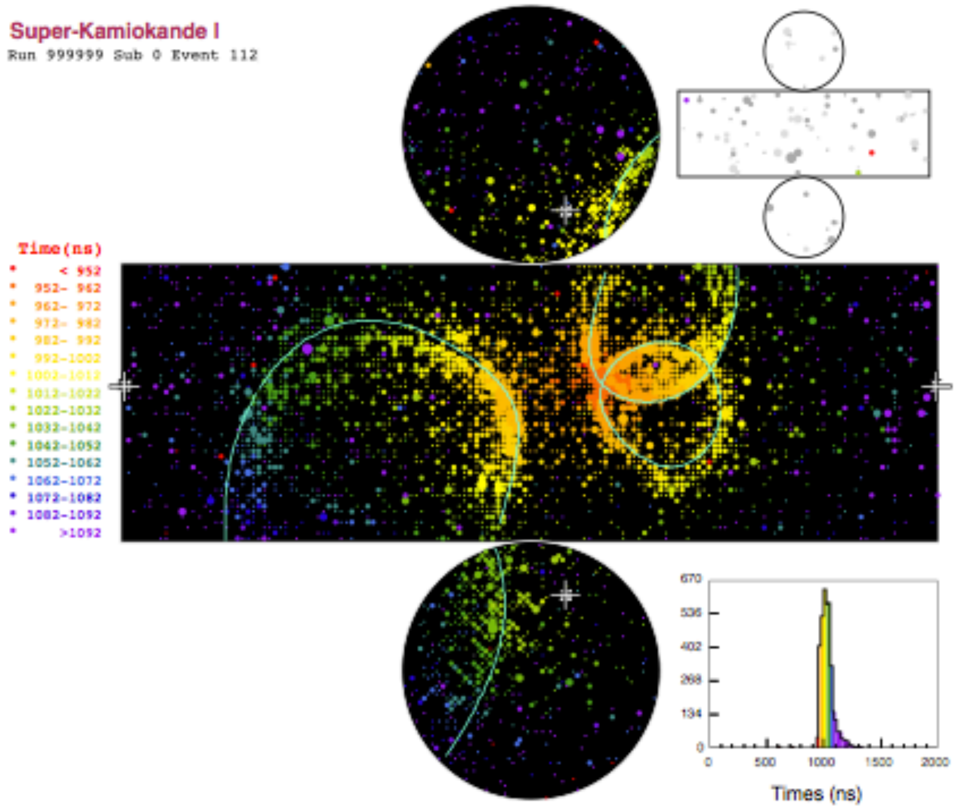
Ongoing tasks within NDK working group:

Simulate promising decay modes to assess reconstruction and selection efficiencies using full DUNE detector geometry

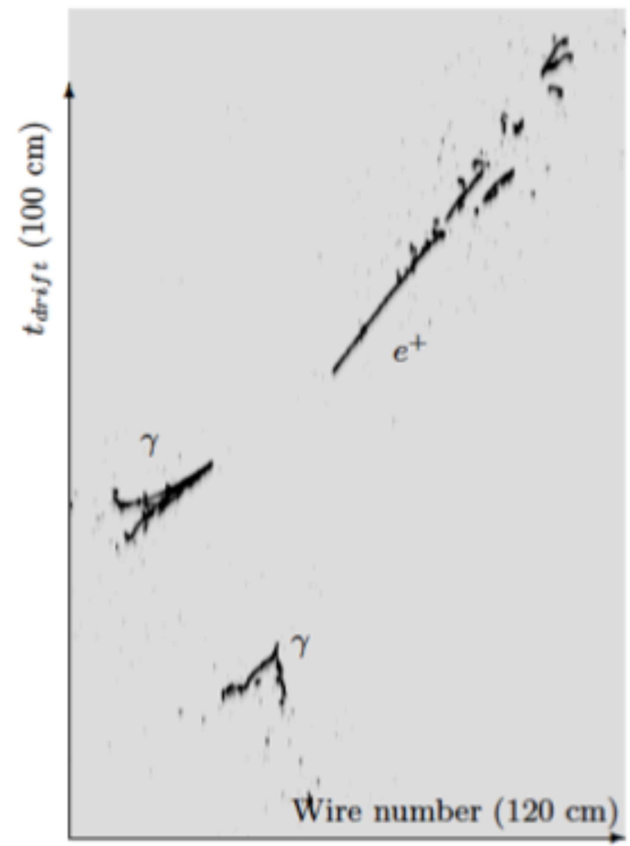


From E. Kearns

$p \rightarrow e^{+}\pi^{0}$



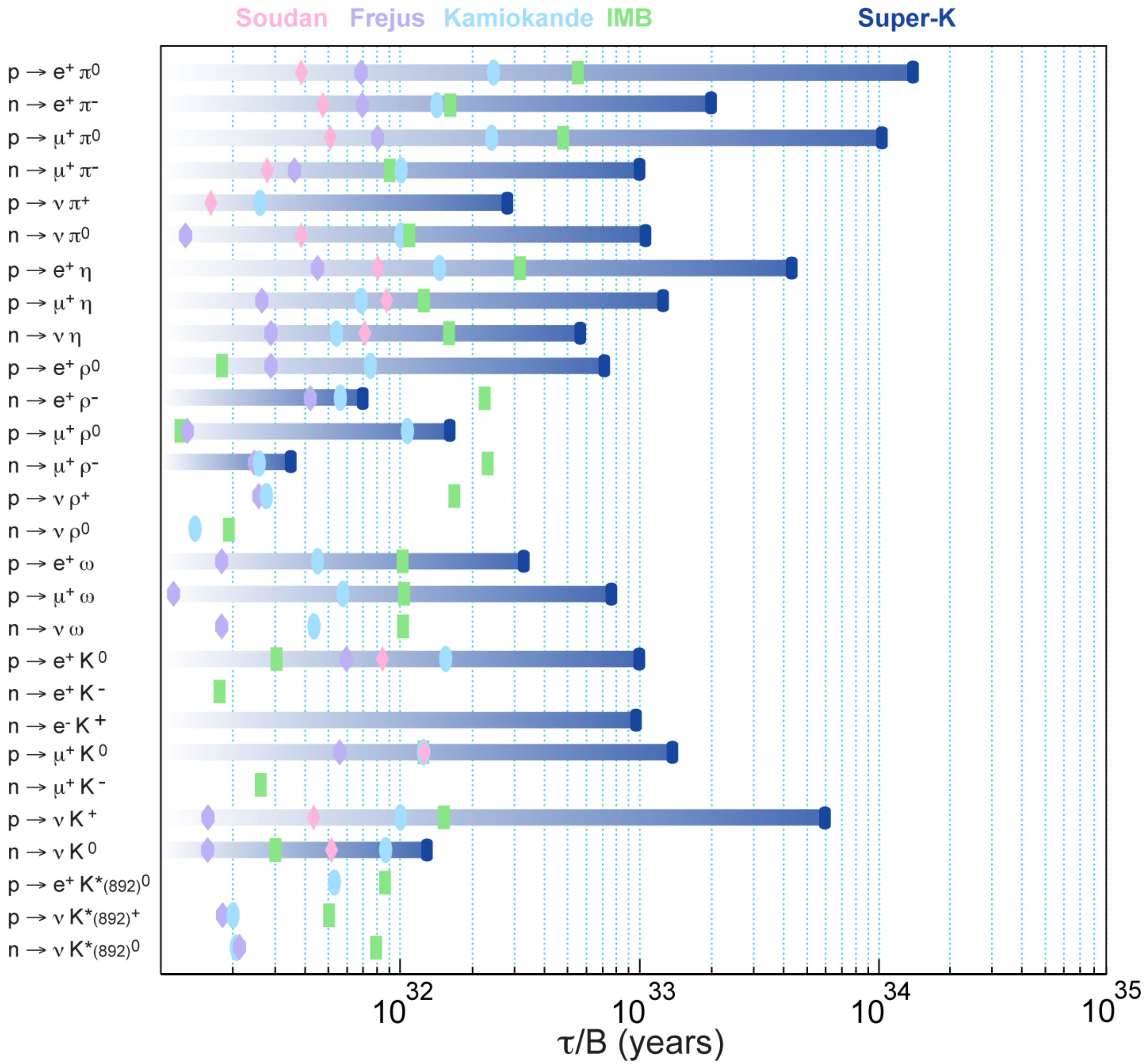
A. Bueno et al. hep-ph/0701101



Lepton + light meson modes will be "ok but not great" in LAr

- Nuclear effects are the major efficiency-killer (and worse in LAr than water)

Antilepton + Meson, 2-body decay modes (B-L conserving)



Summary

Observation of proton (or bound neutron) decay would be a smoking gun signature of Grand Unification

- Probes energy scale higher than achievable with accelerators
- Can only do this with a large detector placed deep underground

***Non*-observation of proton decay places strong constraints on GUT models. Model-builders must evade limits!**

- Some of the simpler models have already been excluded by experimental limits, but many channels left to investigate…

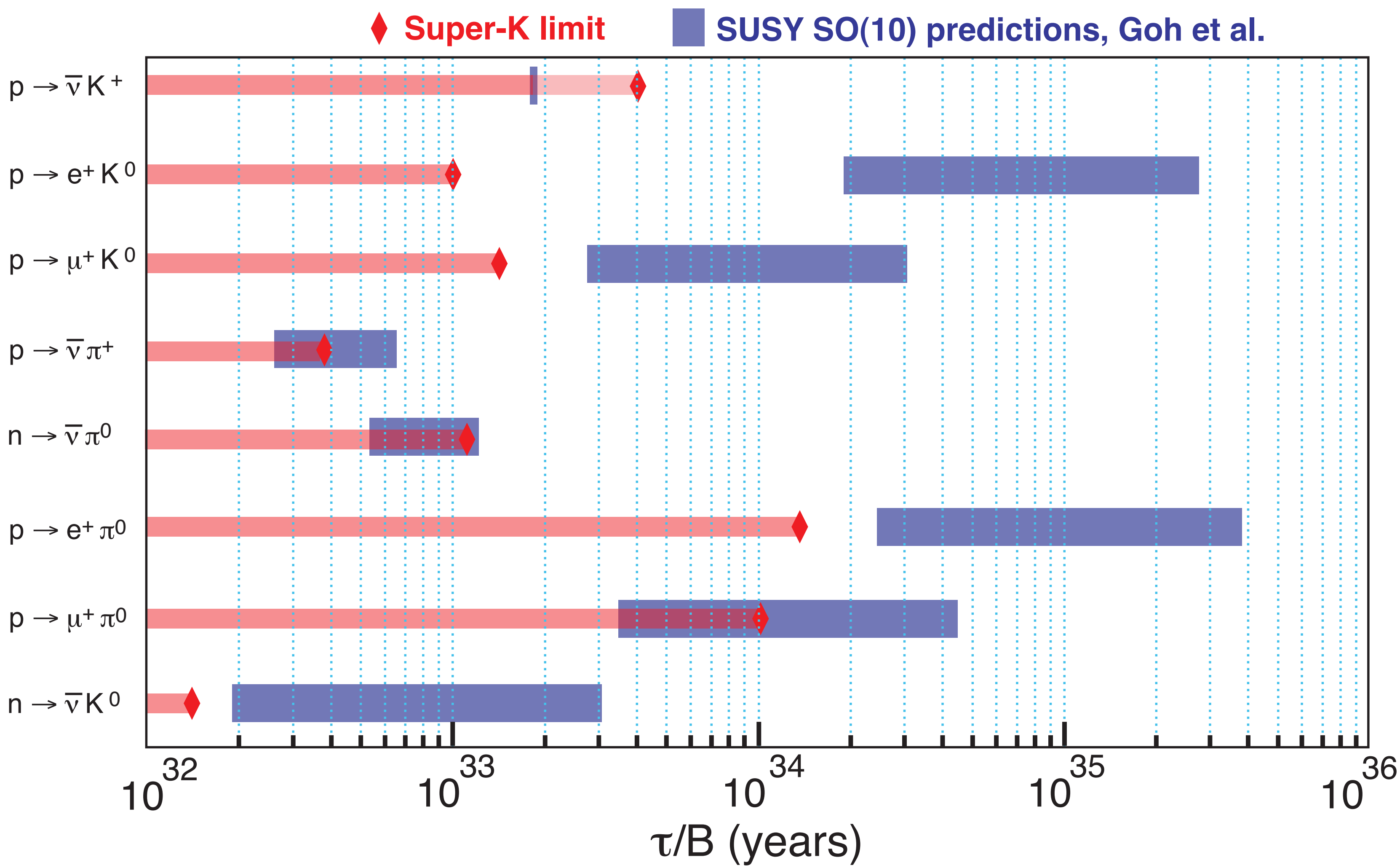
Once it is observed in multiple channels, relative branching ratios give additional information to possibly distinguish among models

Many opportunities/projects within the DUNE NDK working group for students and other interested people!

Extras

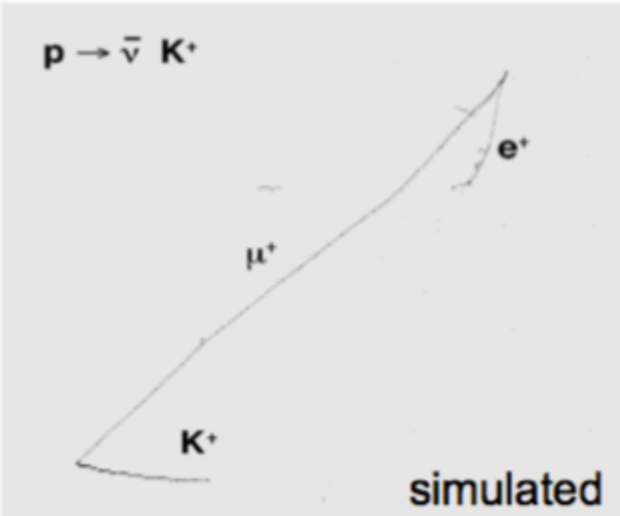
Example: SUSY SO(10)-motivated search

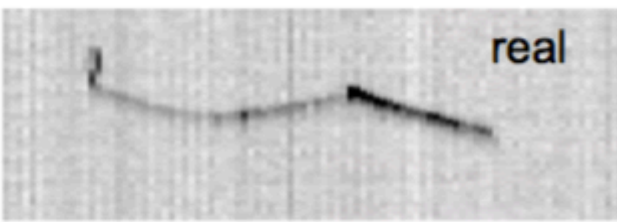
H.S. Goh, R.N. Mohapatra, S. Nasri, S-P. Ng, Phys Lett B587:105-116 (2004)

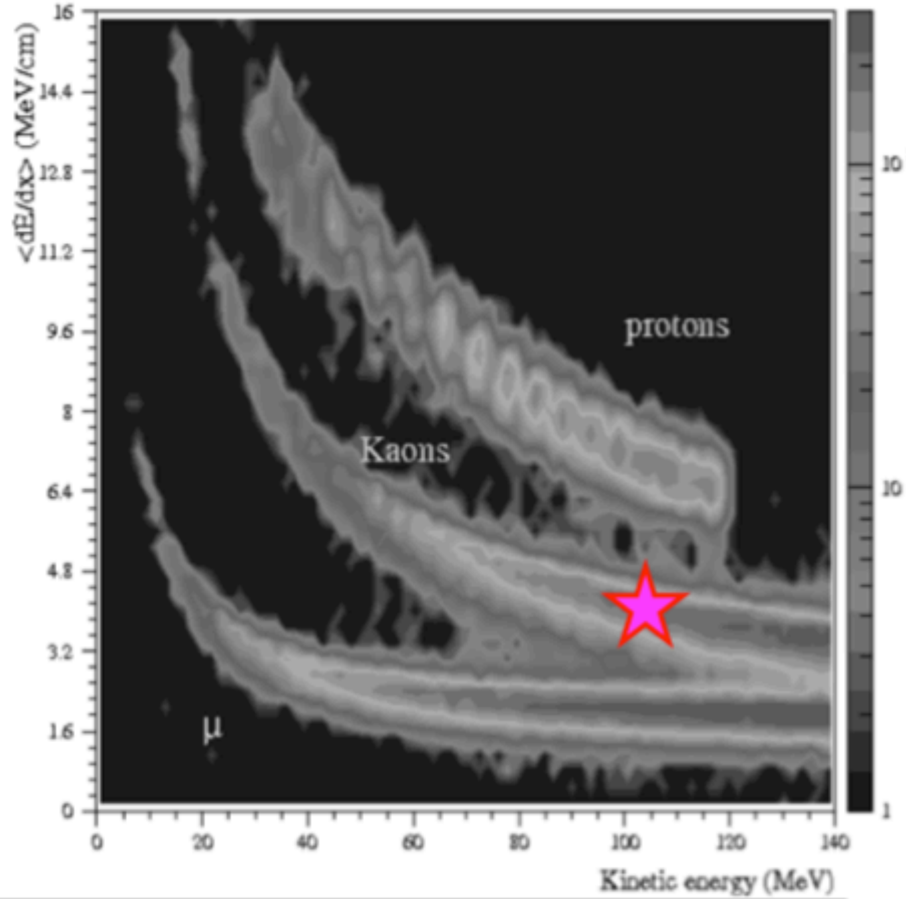


From E. Kearns

νK^+ in LAr







Cuts	(p3) $p \to K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One kaon	96.8%	308	36	871	146	282	77
No other charged tracks, no π^0	96.8%	0	0	0	0	57	9
$E_{vis} < 0.8$ GeV	96.8%	0	0	0	0	1	0

Bueno et al.