Backgrounds to nucleon decay in DUNE

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1. DUNE experiment

DUNE (Deep Underground Neutrino Experiment) is a next-generation neutrino experiment. The far detector (FD) will be located 4850 ft below ground and be comprised of four 10 kton modules. The modules will be either of single or two phase liquid argon time projection chambers (LArTPCs), shown in figures 1 and 2 respectively. The first module will be a single phase detector which will be completed in 2024. DUNE will also have a high precision near detector. The beam line will be the PIP-II upgrade at Fermilab which will have a peak energy at 2.5 GeV and an initial flux of 1.2 MW rising to 2.1 MW. There is a rich physics program planned including measuring δ_{CP}, θ_{13}, θ_{23} and determining the neutrino mass hierarchy in addition to looking for nucleon decay and supernova neutrinos.

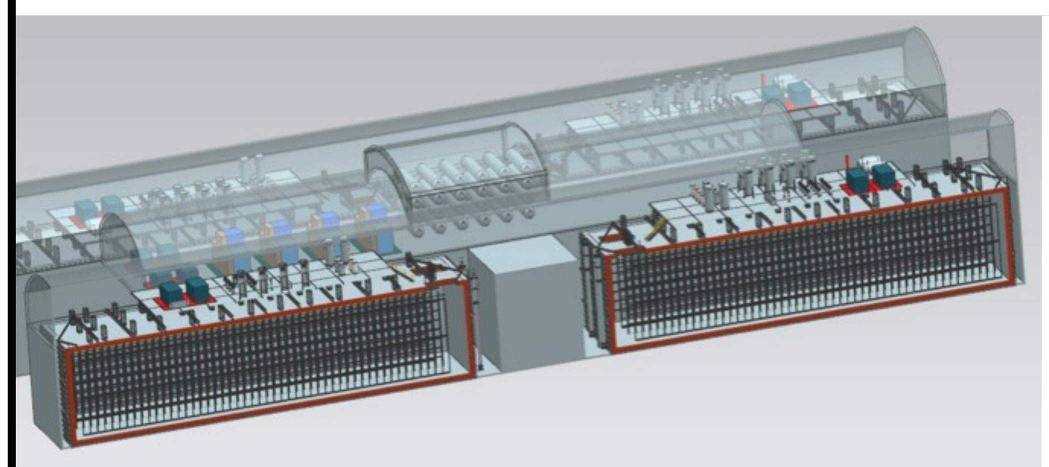

Figure 1.
A schematic view of the four 10 kt modules when constructed and installed at SURF. The modules shown here are the single phase reference design [1].

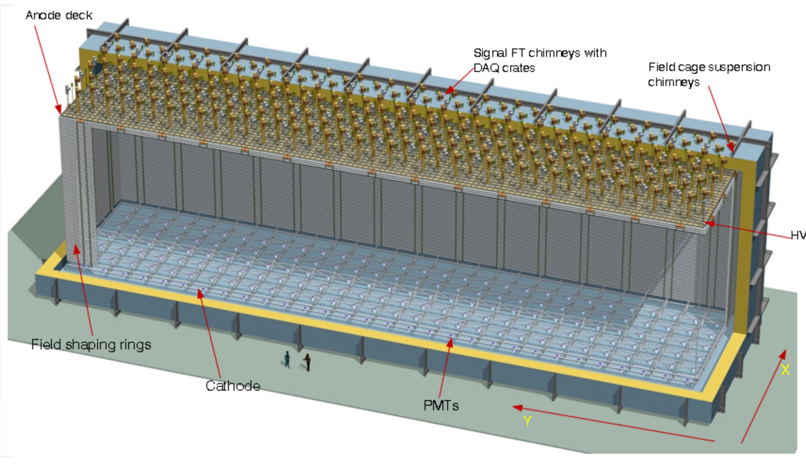

Figure 2.
A schematic view of the two phase far detector design [1].

2. Observing nucleon decay in DUNE and sensitivities

LArTPCs have very good spatial resolution meaning that decay channels resulting in a kaon final state can be clearly identified. This is a major advantage over water Cherenkov detectors where the reconstruction efficiency is typically low. A comparison of DUNE sensitivities to other experiments for some favoured decay modes is shown in figure 3, exposures are 400 kt yr and 5600 kt yr for DUNE and Hyper-Kamiokande respectively. Figure 4 shows a kaon interaction in ICARUS.

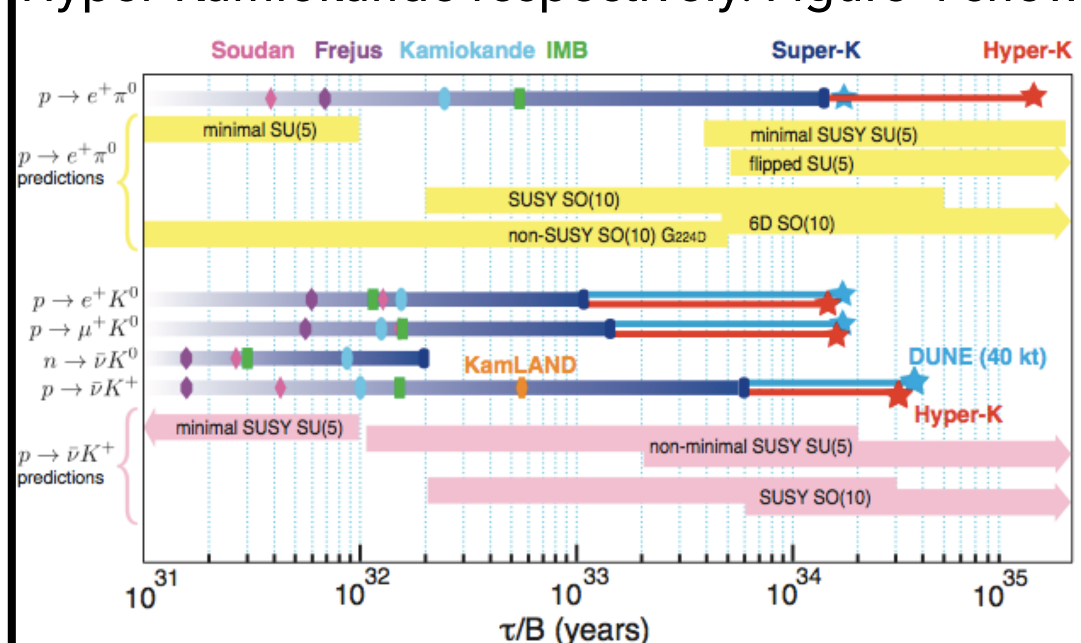

Figure 3.
The proton lifetimes which DUNE will reach in some popular decay channels compared with sensitivities in other experiments [1].

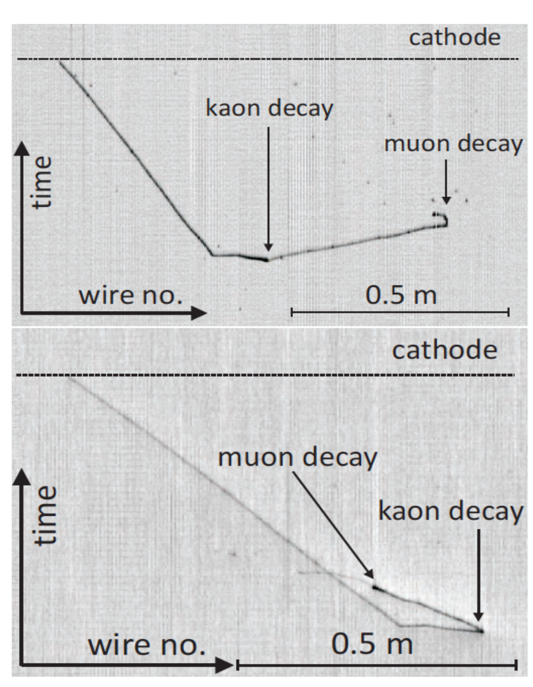

Figure 4.
A kaon interaction seen during the ICARUS T600 experiment [2].

3. Backgrounds to nucleon decay in DUNE

Rare processes such as proton decay require extremely low background environments. Two of the most common sources of background events in nucleon decay searches are atmospheric neutrinos and cosmogenic muons. The collaboration is actively studying both sources of background. Background events and cuts for the $p \to K^+ \bar{\nu}$ channel are discussed below.

- **Atmospheric neutrinos**
  - NC interactions can produce K^+ and no other charged particles.
  - CC interactions can produce K^0, which can produce K^+ via charge exchange.
  - They are unaffected by detector depth and so cuts are required on dE/dx, range and on the number of leptons in the final state.
- **Cosmogenic backgrounds**
  - Muons can produce neutral particles which interact in the detector leading to a K^+. An example of this is shown in figure 5 where a K^0 produced by a muon enters the detector and leads to a K^+.
  - Depth greatly reduces the background rate.
  - Fiducial cuts and cuts on the sums of energy depositions (E_{dep}) from the primary decay particle, its decay products and particles not related to the decay can further reduce background.

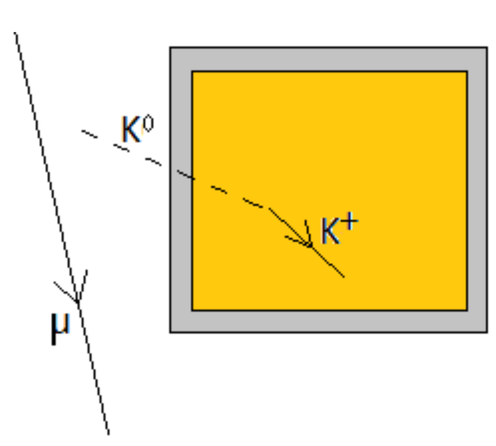

Figure 5.
An example of a muon induced K^+ background event.

4. Simulating the cosmogenic background in DUNE

Muons are generated in LArSoft (a common software package shared by LAr experiments based at Fermilab) using the MUon Simulations UNderground (MUSUN) generator which takes the output of MUon SImulation Code (MUSIC) as input [3, 4]. Both packages have been tuned for the proposed DUNE FD site, as shown in figure 6. Muons are generated on the surface of a box around a single 10 kt module surrounded by 7 m of rock with density 2.7 g cm^{-3}. Thus far 10^8 muons have been simulated, this represents 20.08 years worth of detector live time. To reduce simulation time and disk usage events with a muon track longer than 1 m or with no energy depositions in the LAr are discarded.

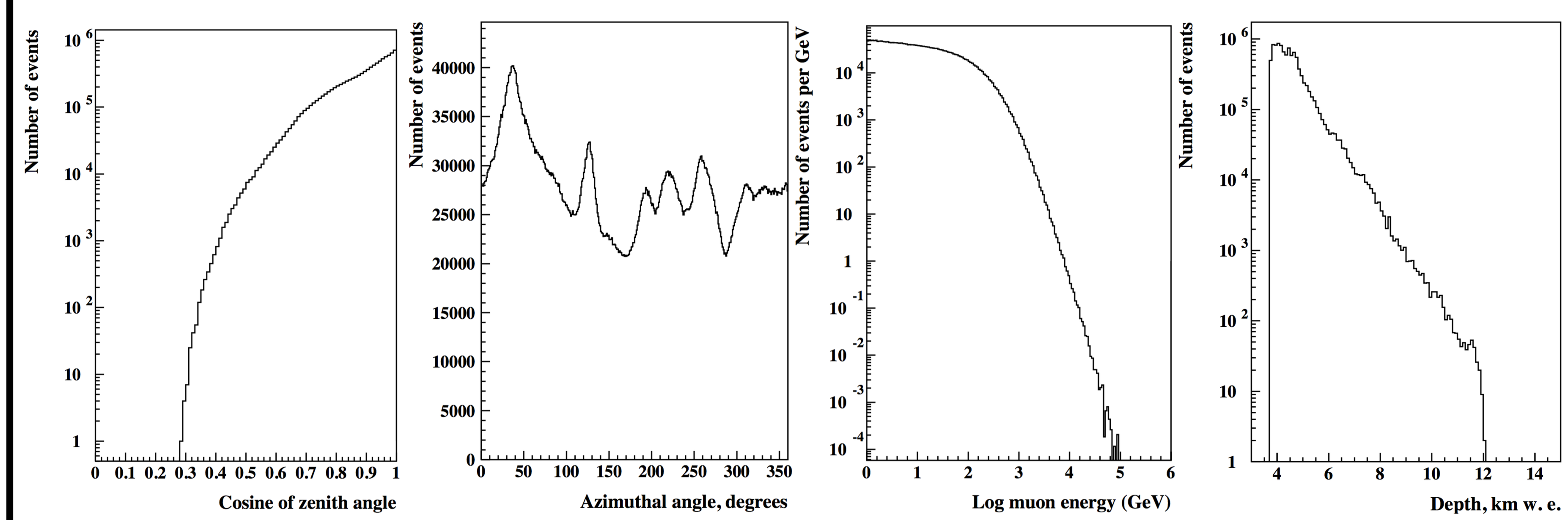

Figure 6.
Beginning on the left the zenith, azimuthal, energy and slant depth distributions of a 10^7 muon sample generated by MUSUN for the far detector site at SURF [5]. The azimuthal angle is counted from East to North.

5. Results of background simulations

Initial simulations have focused on the $p \to K^+ \bar{\nu}$ channel using truth information. This means that a reconstruction efficiency of 100% is assumed. The neutrino was also assumed to not interact in the detector. A series of sequential cuts are applied to the generated muon sample to calculate a background rate [6, 7]:

- Only events with a single charged kaon are considered.
- All events with a muon track longer than 20 cm are rejected.
- All events with E_{dep} within 2 cm of edge of active volume are rejected.
- E_{dep} from kaon excluding decay products < 250 MeV.
- E_{dep} from kaon including decay products < 1 GeV.
- E_{dep} from particles not related to the decay < 50 MeV.

No events in this sample pass all of these cuts.

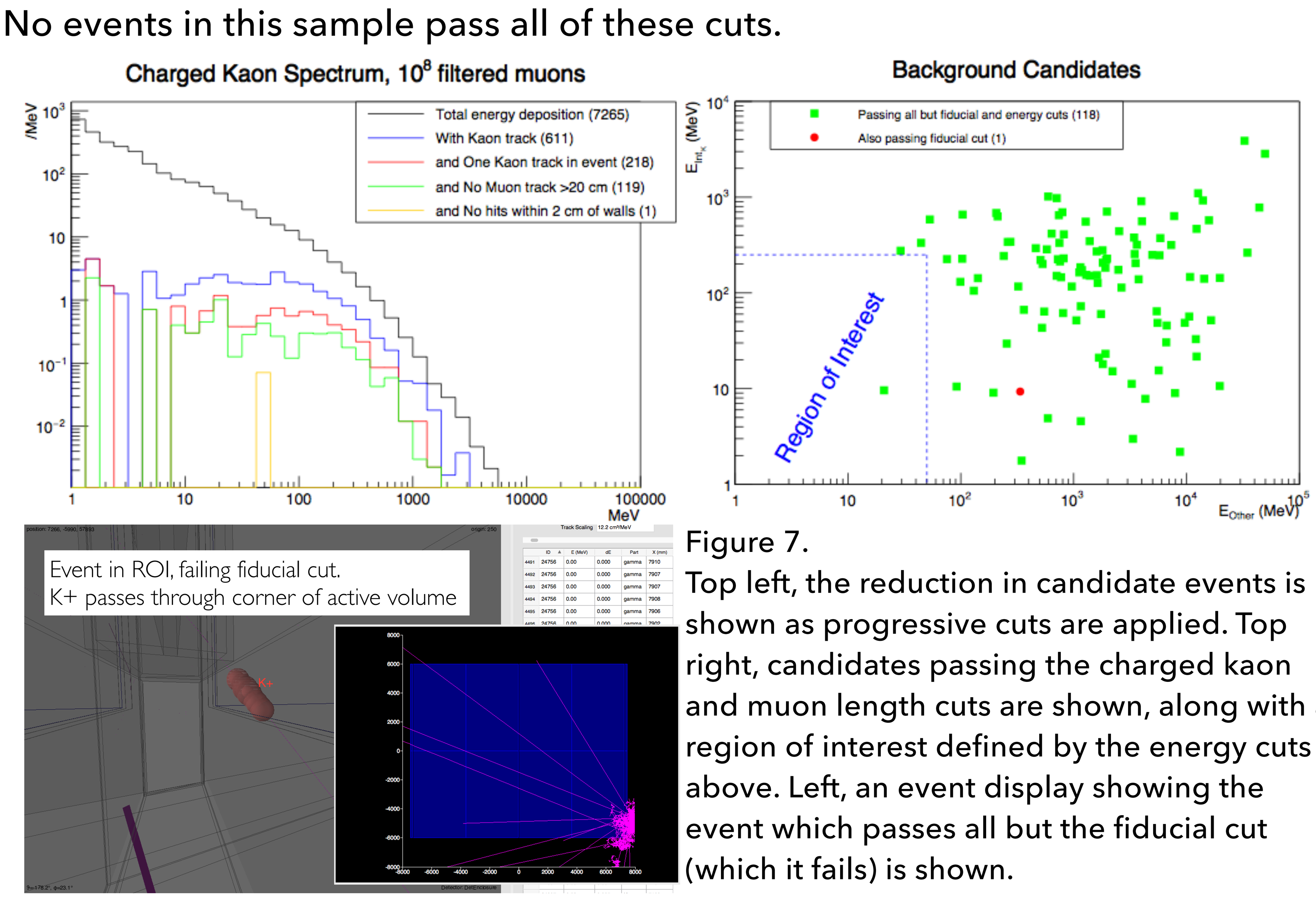

Figure 7.
Top left, the reduction in candidate events is shown as progressive cuts are applied. Top right, candidates passing the charged kaon and muon length cuts are shown, along with a region of interest defined by the energy cuts above. Left, an event display showing the event which passes all but the fiducial cut (which it fails) is shown.

6. Summary and future plans

Using a sample of 10^8 muons, representing an exposure of 20.08 years, an upper limit for the muon induced background at 90% confidence level for the $p \to K^+ \bar{\nu}$ channel is found to be 0.0122 events/kt/yr. This study will be extended to include other channels, the full reconstruction chain and 10^9 muons.

7. References

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