Sensitivity study for $p \to K^+\bar{\nu}$ in DUNE dual phase

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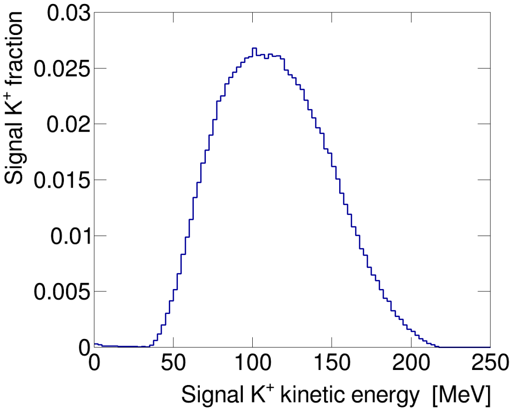
Outline

1. Signal simulation
2. Atmospheric neutrino background simulation
3. Detector simulation
4. Reconstruction
5. Kaon ID
6. Event selection
7. Proton decay sensitivity

Signal simulation

- Decay: $p \rightarrow K^{+}\bar{\nu}$, $\quad K^{+} \rightarrow \mu^{+}\nu_{\mu}$ (BR: 64 %)
- Proton momentum: Fermi Box model
- NEUT v5.4.0: K^{+} placed inside argon nucleus to simulate FSI
  $\sim$0.07 % of K^{+} charge-exchange into K^{0}
  $\sim$0.1 % of K^{+} scatter inelastically (tail on the left)



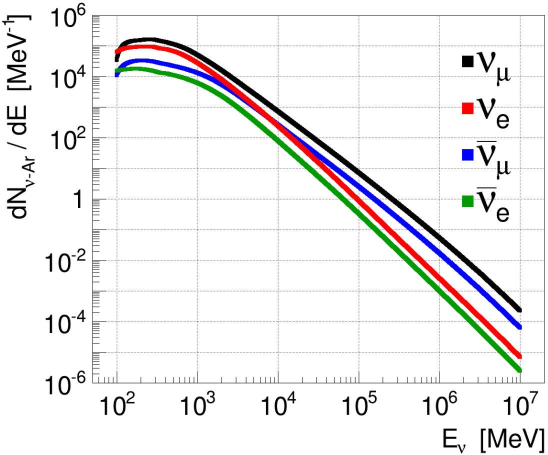
Atmospheric neutrino background simulation

- Flux: Honda flux tables for SURF as a function of energy and θ (zenith angle) at solar maximum. Flat in ϕ.
- Cross-sections and FSI: NEUT v5.4.0 in standard configuration, all interaction modes included
- Normalizing to 1 Mton x years gives 299 728 events in total:

Flavor	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	total
Interactions	84 319	18 145	156 744	40 520	299 728
CC	63 212	12 648	107 070	24 949	207 879
NC	21 107	5 497	49 674	15 571	91 849
CC res K^+	22	0	33	4	59
NC res K^+	2	1	4	1	8
DIS $K^\pm$	15	2	64	9	90

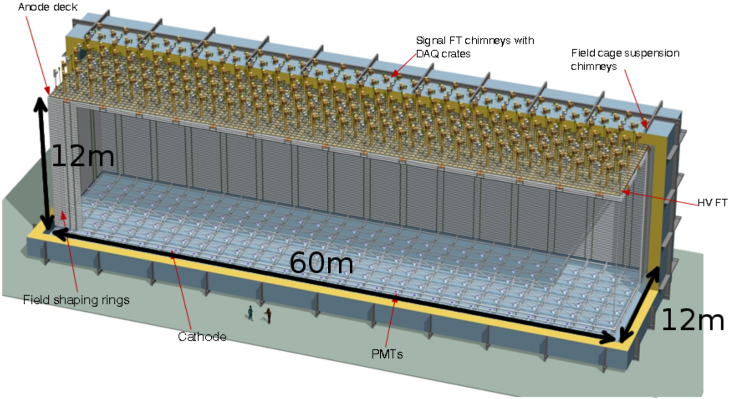
- $K^\pm$ always produced with at least one additional FSP

Differential neutrino-argon interaction spectrum as function of neutrino energy:



- Integrating over energy results in 299 728 events (sum of all 4 flavors)

Detector simulation: DUNE dual phase far detector



- "Workspace" geometry used for this study:
- 12 meter drift (design value)
- Nine 3x3 m^2 charge readout planes (CRP) $\rightarrow$ 9x9 m^2 charge readout area
- 3 mm channel pitch, 1 cm gap between CRPs (design values)

Detector simulation (signal and ANB)

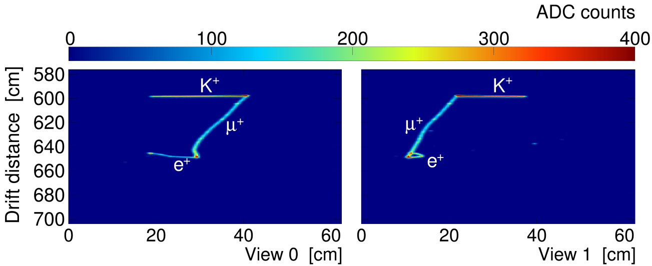
1. FSP from NEUT read into LArSoft and placed 6 meter below center of 9x9 m^2 charge readout
2. G4 simulation

$\rightarrow$ $\sim 7\%$ of K^+ decay in-flight

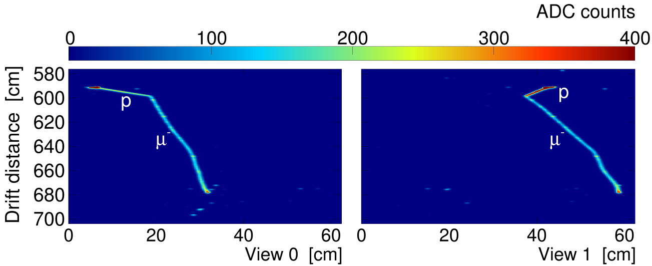
3. Birk's model for ionization
4. Diffusion: $D_T = 1.62\ mm^2/ms$ and $D_L = 0.6\ mm^2/ms$ (standard LArSoft values)
5. No attenuation, no noise and total gain $= 20$
6. Preamp shaping according to 3x1x1 prototype measurements

- Differences w.r.t. single phase simulation:
  - Longer drift $\rightarrow$ more diffusion
  - Gain in charge readout
  - Two perpendicular collection readout views share charge equally

Signal event display:



ANB ν_μ CC event display:



Reconstruction

- **In LArSoft**:

1. Hit finder: DPRawHitFinder (no deconvolution of waveforms)
2. Pattern recognition: match each hit to truth particle with highest charge contribution

- **Write hit collection to ROOT file and continue with very simple track reconstruction outside of LArSoft:**

3. For each particle, match first and last hit in both views to get 3D end points (require two hits in each view)
4. Define particle 3D track as straight line between two 3D end points
4. With 3D track, calculate dQ/ds for each hit and, through Birk's law, dE/ds
5. Identify starting and stopping point of particle by splitting track in half and comparing charge in both halves

Kaon ID

- Consider all reconstructed tracks
- Goal: identify signal K^+ with high efficiency and little background
- Strategy: Preselection + neural network classification

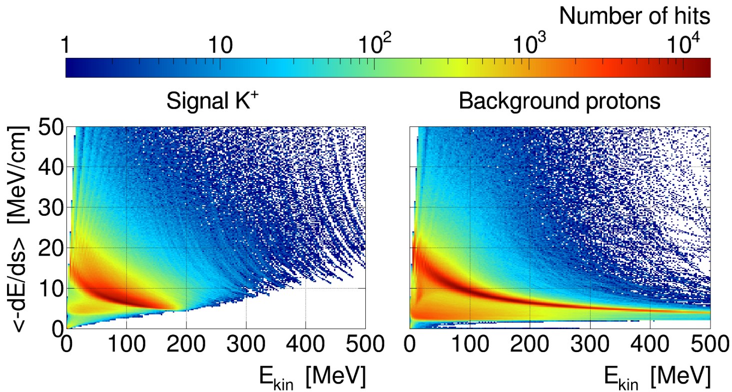
- Track preselection cuts:

1. $L_{\text{Reco}} \geq 4\,\text{cm}$
2. $Q_{\text{Reco}} \geq 50\,\text{fC}$
3. $p_S \leq 0.1$
   p_S: fraction of empty channels between starting and stopping point (low for tracks and high for showers)

$\rightarrow$ Signal K^+ preselection efficiency: 0.91

Kaon ID

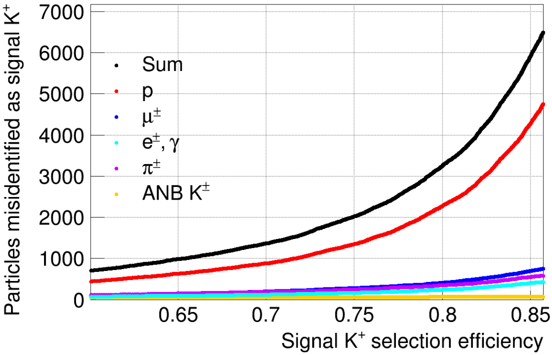
- Neural network based on $\langle -dE/ds \rangle$ vs. E_{kin} track profiles:



- For each track, a histogram with 20x20 bins in the ranges $0 \leq \langle -dE/ds \rangle \leq 20\,\mathrm{MeV/cm}$ and $0 \leq E_{\text{kin}} \leq 20\,\mathrm{MeV}$ is filled
- Bin contents input to train a neural network (Tensorflow/Keras) for signal K^+ vs. all other particles

Kaon ID

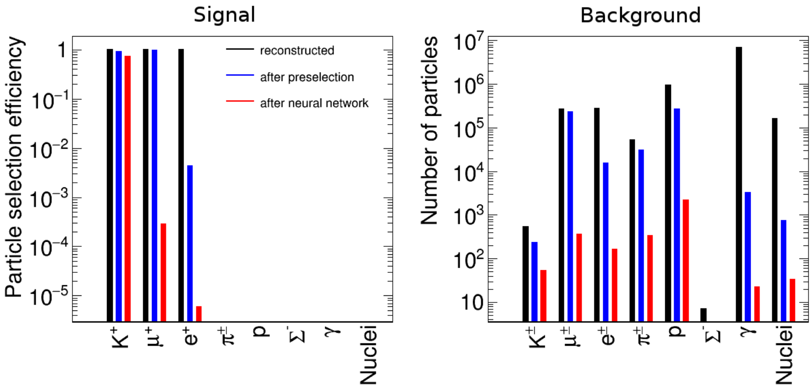
- Neural network trained with dedicated data set
- Continue analysis with independent signal (∼175 k events) and ANB (2 Mton x years ≈ 600 k events) datasets
- Signal K^+ selection efficiency vs. misidentified particles



- Choose neural network signal K^+ selection efficiency $= 0.8$

→ 3224 particles misidentified as signal K^+

Summary kaon ID



- Signal K^+ selection efficiency $= 0.91 \cdot 0.8 = 0.73$
- Background sample normalized to 2 Mton x years
- Out of 3224 particles misidentified as signal K^+, 2175 are protons

Event selection

Cut 1: One signal K^+-like particle

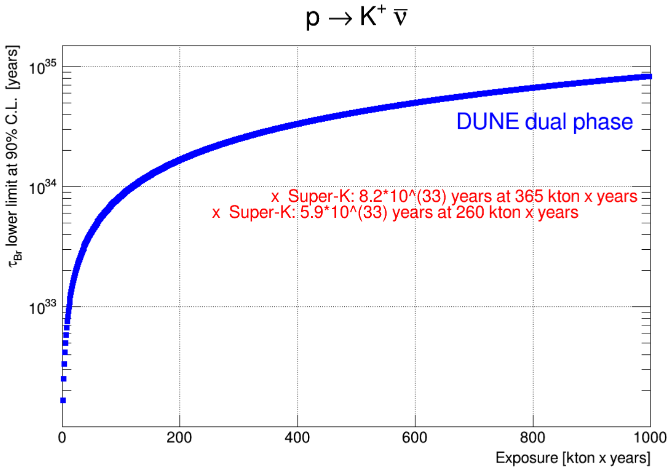
Cut 2: One particle with $40\,\mathrm{cm} \leq L_{\mathrm{Reco}} \leq 60\,\mathrm{cm}$ and starting point within 15 cm from signal K^+-like particle stopping point

Cut 3: Three reconstructed particles with ≥ 5 Hits in at least one readout view

Cut 4: $500\,\mathrm{fC} \leq Q_{\mathrm{Event}} \leq 2000\,\mathrm{fC}$

Cut	Signal efficiency (ϵ)	Background events (B)
/	1	599 456
1	0.728	3224
2	0.679	95
3	0.677	1
4	0.677	0

Sensitivity at 90% C.L. vs. exposure



- DUNE dual phase calculated with $\epsilon = 0.677$ and $B = 0$
- Current Super-K limit can be reached with $\sim$ 100 kton x years

Summary

- Sensitivity study for $p \to K^+\bar{\nu}$ in DUNE dual phase
- Full simulation and reconstruction with aided pattern recognition
- Only looked at $K^+ \to \mu^+\nu_\mu$, similar performance for other K^+ decay channels very likely
- $\tau_{\mathrm{Br}} > 8 \cdot 10^{34}$ years with 1 Mton x years exposure in LAr TPC

Outlook

- NEUT includes resonant and DIS K^+ production in ANB
- I think GENIE includes coherent K^+ production
- FSI in NEUT and GENIE may be different

$\rightarrow$ Look at a ANB sample generated with GENIE

Extra slides

Proton decay sensitivity

- "sensitivity": which lower limit on the proton decay lifetime can be measured if no proton decay is observed?
- This limit depends on
  1. the exposure
  2. the proton decay signal selection efficiency
  3. the expected number of background events for the given exposure and selection, represented by $\frac{1}{S}$

τ_{Br} = Exposure x Signal selection efficiency x $\frac{1}{S}$

• $\sum_{n=0}^{B} P(n, B+S) = 0.1 \cdot \sum_{n=0}^{B} P(n, B)$, 0.1: 90% C.L.

• $P(n, B)$: Poisson likelihood to measure n events when expecting B background events: $P(n, B) = \frac{e^{-B} B^n}{n!}$

• $\sum_{n=0}^{B} P(n, B)$: likelihood to measure B or less events when expecting B background events

Proton decay sensitivity

Number of expected background events: B=0

$$\sum_{n=0}^{B} P(n, B+S) = 0.1 \cdot \sum_{n=0}^{B} P(n, B)$$

$$\Leftrightarrow P(0, S) = 0.1 \cdot P(0, 0)$$

$$\Leftrightarrow e^{-S} = 0.1$$

$$\Leftrightarrow S = -ln(0.1) = 2.3$$