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Proton Decay Search with MicroBooNE and DUNE Experiments

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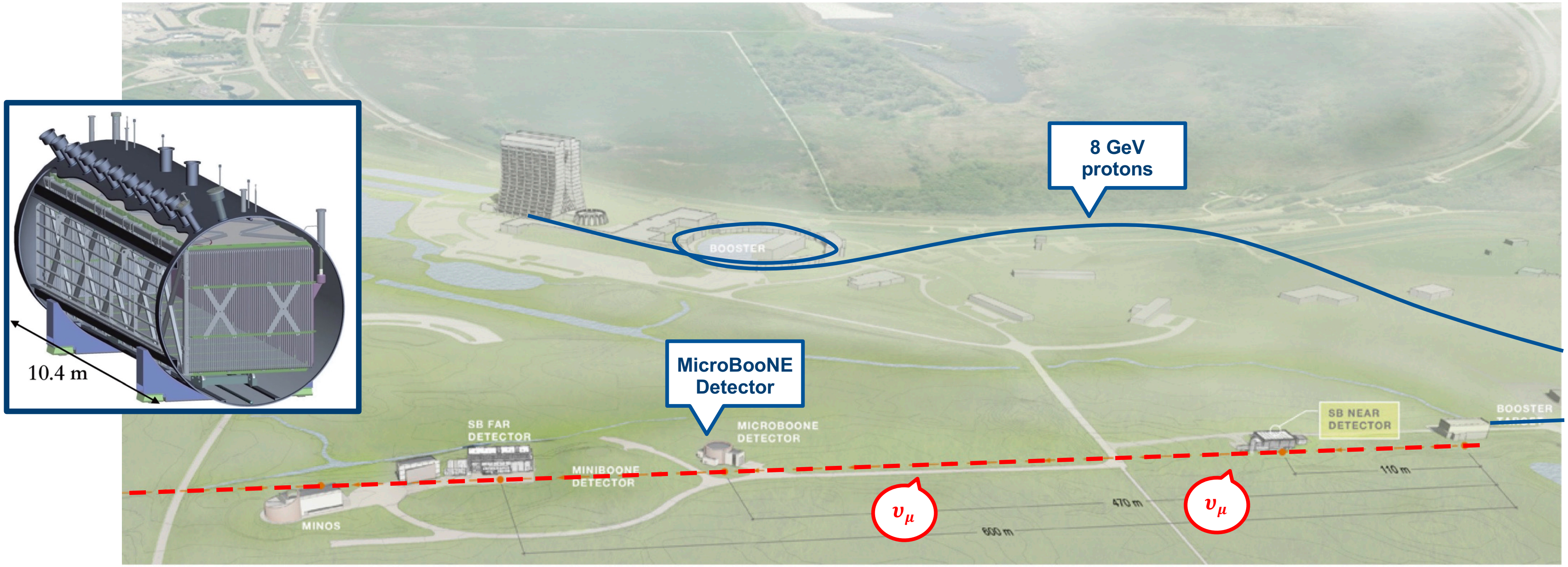
Natsumi Taniuchi — 03/02/2022 Annual ESR Meeting

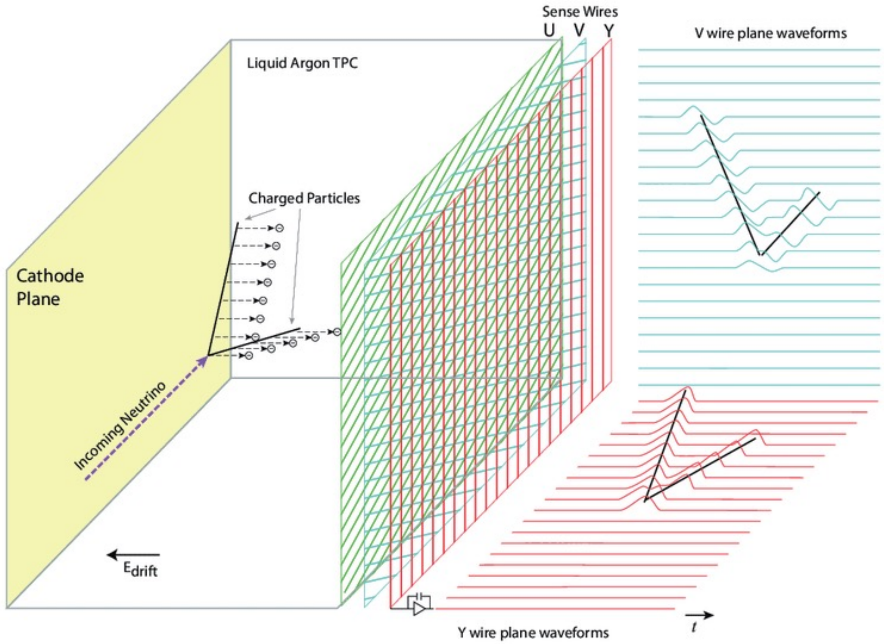
MicroBooNE: Micro Booster Neutrino Experiment

- 85 ton LArTPC running from 2015
- 0.25-2 GeV υ beam from the Booster Neutrino Beam (BNB) and the Neutrino Main Injector (NuMI)



LArTPC: Liquid Argon Time Projection Chamber

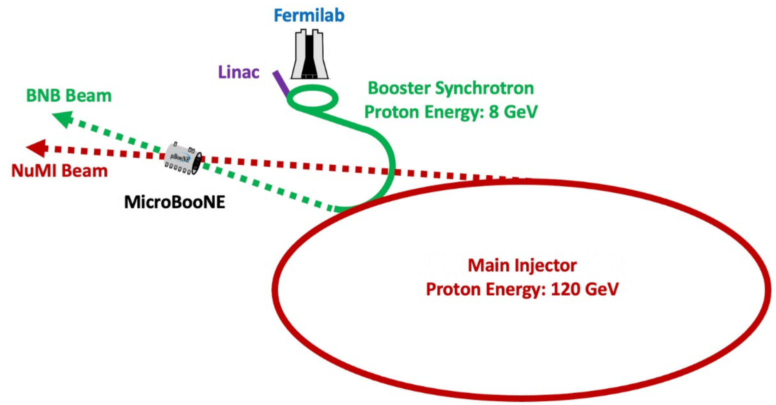
- Charged particles traversing the medium ionizes atoms to generate electrons along the path
- Deliver precise 3D tracking image with fine-grained wire readouts for various particles including Kaon



2 neutrino beams in MicroBooNE

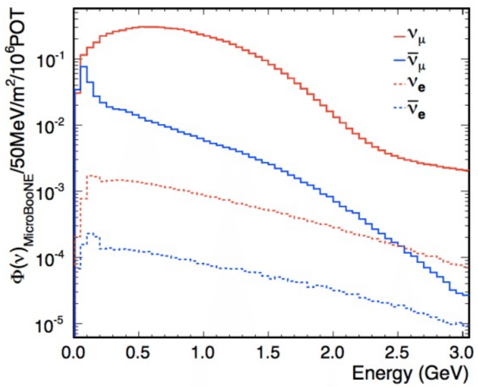
Booster Neutrino Beam (BNB)

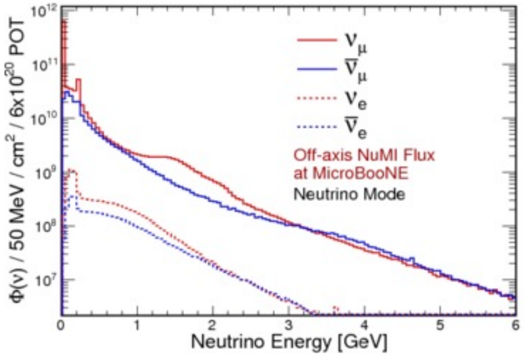
- Dominant flux component: ν_μ
- On-axis beam mainly used for low E excess



Neutrino Main Injector (NuMI)

- Both rich in ν_μ & ν_e with higher energy than BNB
- Off-axis beam suited for cross section measurement of neutrino interactions



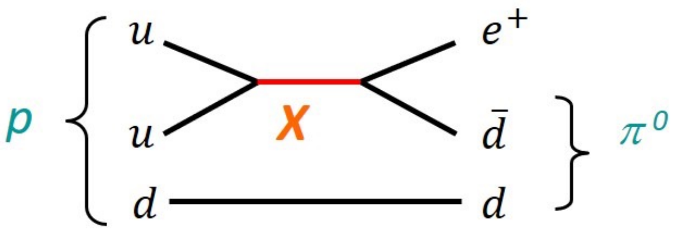


Proton Decay Phenomenon expected by GUTs

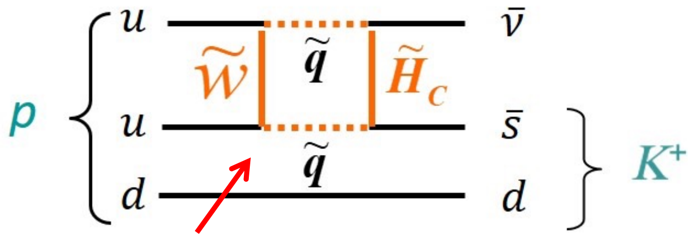
GUTs predict protons to decay into lighter particles.

- ✓ Low decay probability & long lifetime: $10^{30}\sim10^{40}$ years.
- ✓ Various decay modes: with/without SUSY
    1. lepton + non-strange meson (e.g.: $p \to e^+\pi^0$)
    2. lepton + strange meson: (e.g.: $p \to \bar{\nu}K^+$) → Assume Supersymmetry (SUSY)
       A conjectured symmetry between fermions and bosons.
       Particles will have supersymmetric partner.

$p \to e^+\pi^0$



$p \to \bar{\nu} K^+$



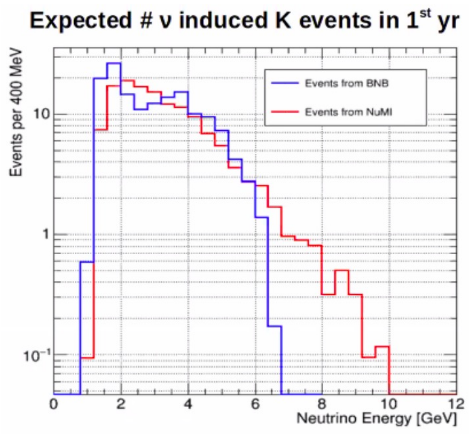
Supersymmetric partners

My study plan: K^+ cross section measurement with MicroBooNE

Importance of Kaon study:

- Many GUT models suggest major proton decay modes involving K^+ at final states
- Provide better understanding of backgrounds from atmospheric neutrinos in proton decay searches
- No kaon production measurements on Ar or other targets at 1 GeV neutrino energy region

  → previous analysis: K^+ cross section study with BNB neutrino beam data by MicroBooNE



My research plan:

- K^+ cross section study with NuMI neutrino beam data by MicroBooNE
- Doubles in statistics

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K^+ Production by neutrinos

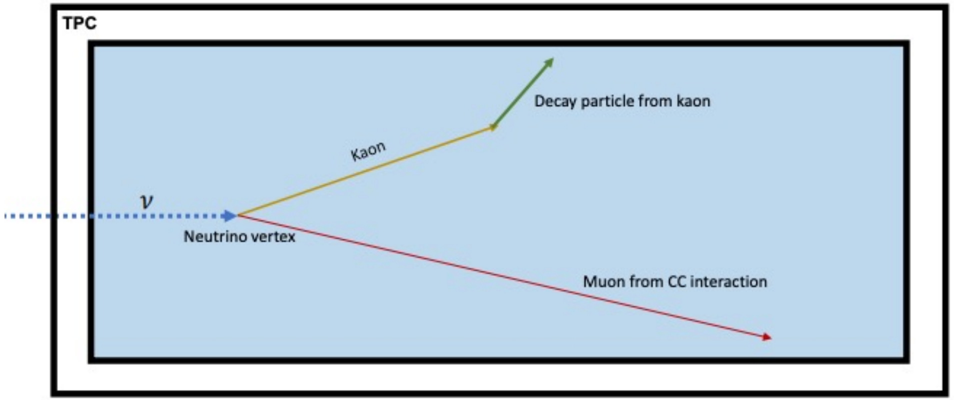
2 modes to produce K^+ by neutrino interactions

✓ **Associated kaon production**:
Kaon accompanied by a hyperon in the final state (E_{thres}: 1.1 GeV)

$$\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0 \qquad \nu_\mu + p \rightarrow \nu_\mu + K^+ + \Lambda^0$$
$$\nu_\mu + p \rightarrow \mu^- + K^+ + \Sigma^+ \qquad \nu_\mu + n \rightarrow \nu_\mu + K^+ + \Sigma^-$$
$$\nu_\mu + n \rightarrow \mu^- + K^+ + \Sigma^0$$

✓ **Single kaon production**:
Single kaon produced in the final state (E_{thres}: 0.8 GeV)

$$\nu_\mu + p \rightarrow \mu^- + K^+ + p$$
$$\nu_\mu + n \rightarrow \mu^- + K^+ + n$$



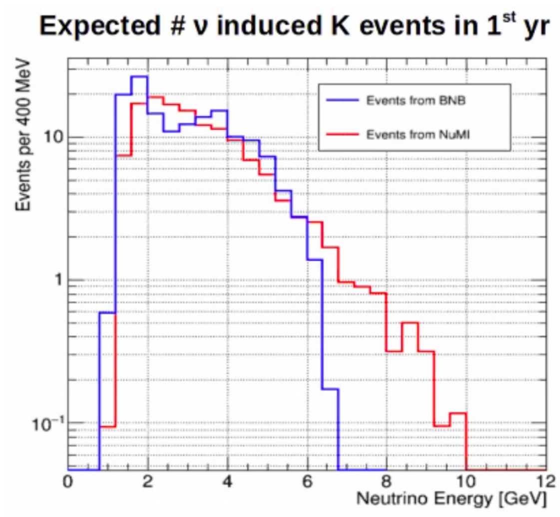
- CC neutrino interaction: $\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + K^+ + n/(\mathrm{Hyperons})$
- Kaon decay: $K^+ \rightarrow \mu^+ \nu_\mu$ (~64%), $K^+ \rightarrow \pi^+ \pi^0$ (~21%)

Detectable as tracks

Definition of Kaon Signal

✓ **Definition**

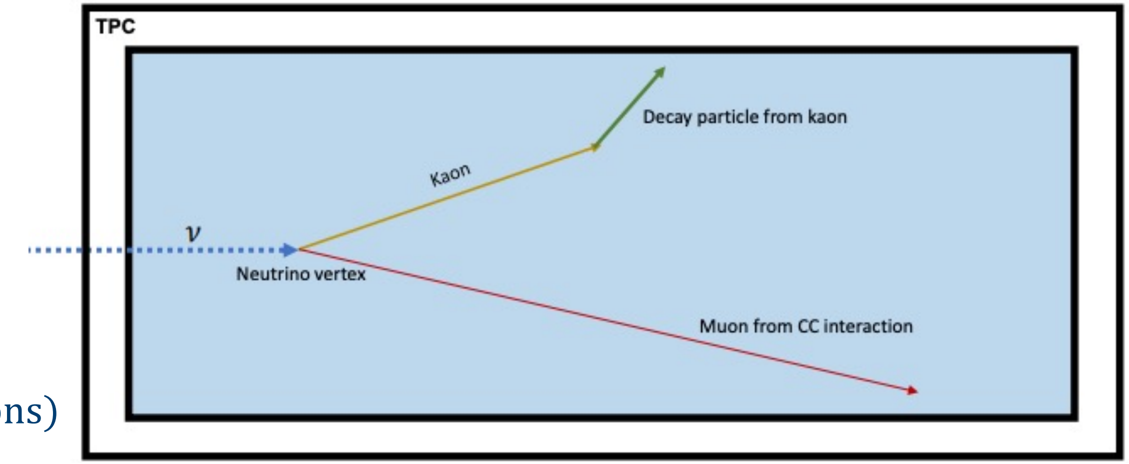
- Events with K+ in final state via ν_μCC interaction
- Neutrino vertex in the CC inclusive volume
- K+ would decay into: $K^+ \rightarrow \mu^+\nu_\mu$, $K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \pi^+\pi^+\pi^-$, $K^+ \rightarrow \pi^0 e^+\nu_e$, $K^+ \rightarrow \pi^+\pi^0\pi^0$
  - 70 events found in NuMI FHC 4.8e+20 POT MC sample



✓ **FV cuts in addition**

- Kaon track end in the CC inclusive volume
- End of kaon daughter tracks within 5cm of TPC
  - 43 events from NuMI 4.8e+20 POT FHC

Preselection for BDT



CC nu interaction

$\nu_\mu + \mathrm{Ar}$
$\rightarrow \mu^- + K^+ + n/(\mathrm{Hyperons})$

Daughter particle from K+

$K^+ \rightarrow \mu^+ \nu_\mu$ (~63.6%)
$K^+ \rightarrow \pi^+ \pi^0$ (~20.7%)

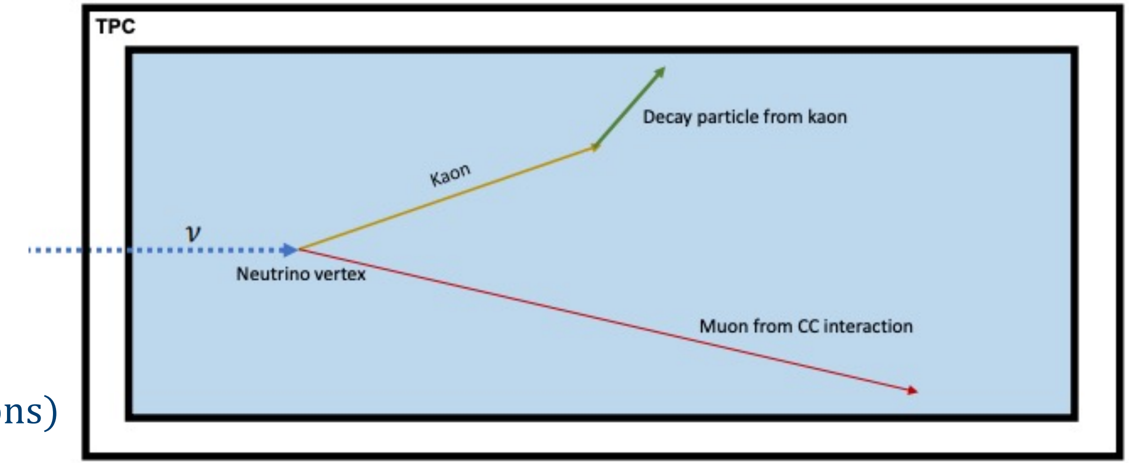
Preselection for BDT

Preselection defined in BNB kaon analysis (the same definition as the previous BNB analysis)

1. Neutrino events accepted by neutrino CC inclusive filter
2. Neutrino vertex in CC inclusive volume
3. End of tracks from neutrino interaction in CC inclusive volume
4. One daughter track
5. End of daughter tracks within 5cm of TPC

CC nu interaction

$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + K^+ + n/(\mathrm{Hyperons})$



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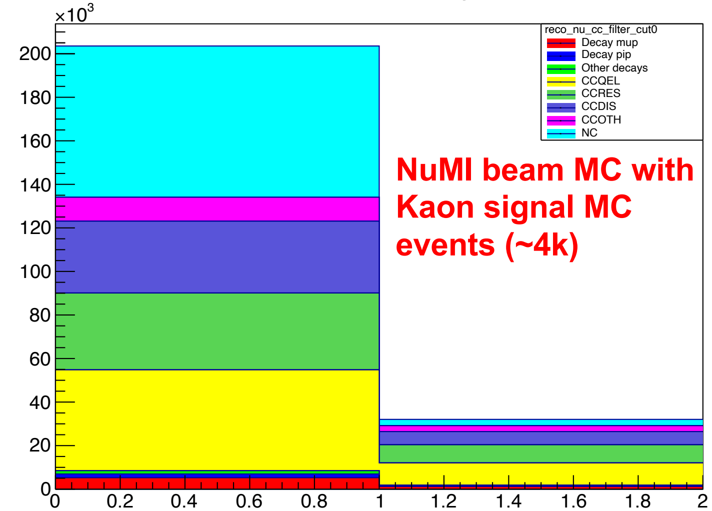
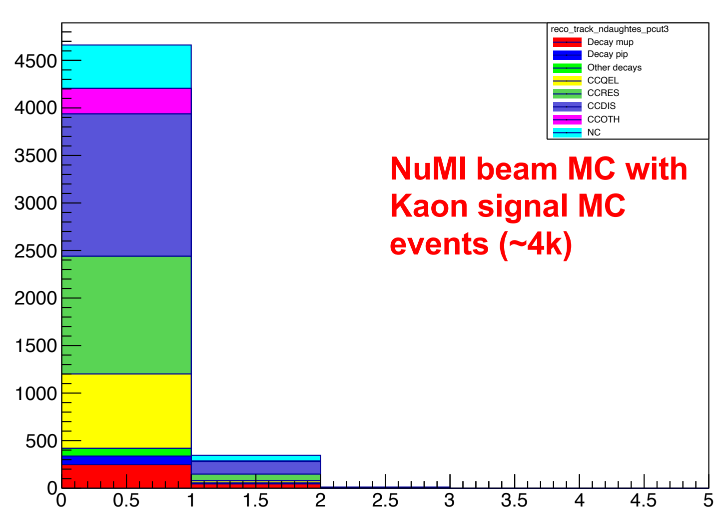
reco_nu_cc_filter_pcut0



reco_track_ndaughters_pcut3



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CUT	Num of events	Efficiency	Purity
w/o cuts	235600 (FHC samples)	3926 (true signals)	3926/235600 = 1.67%
1	32042	1668/3926 = 42.5%	1668/32042 = 5.20%
2	32042	1668/3926 = 42.5%	1668/32042 = 5.20%
3	23694	1545/3926 = 34.3%	1545/23694 = 6.5%
4	2463	413/3926 = 10.5%	413/2463 = 16.8%
5	2249	364/3926 = 9.3%	364/2249 = 16.2%

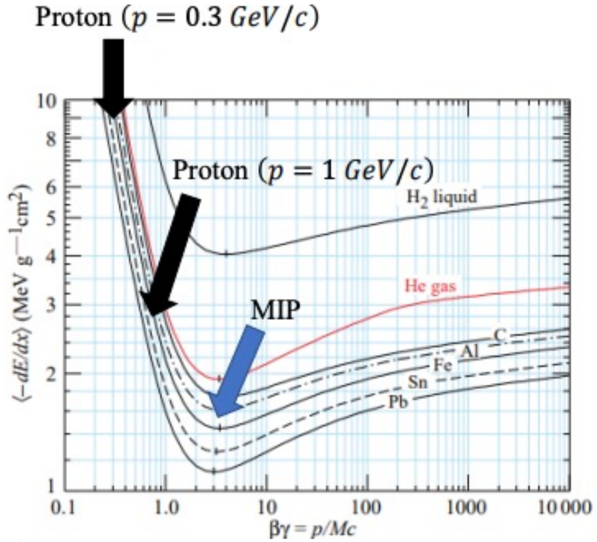
NuMI beam MC with Kaon signal MC events (~4k)

Improving precut selection with MIP information

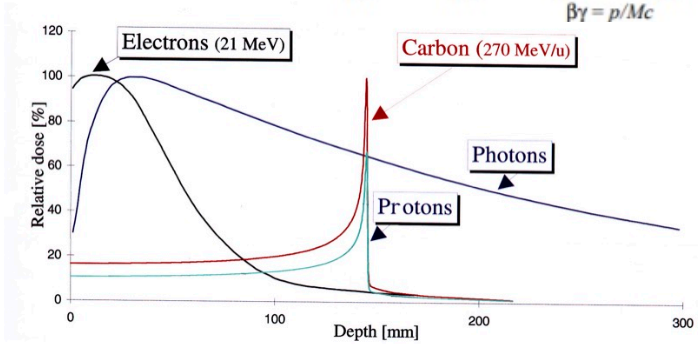
✓ **Particle Identification in TPCs**

- MIP (Minimum Ionizing Particle): stopping power decreases with $\sim 1/\beta^2$, increases by ln(γ^2) term, and reaches its minimum at $\beta\gamma \sim 3$
  Ex. cosmic muons

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$



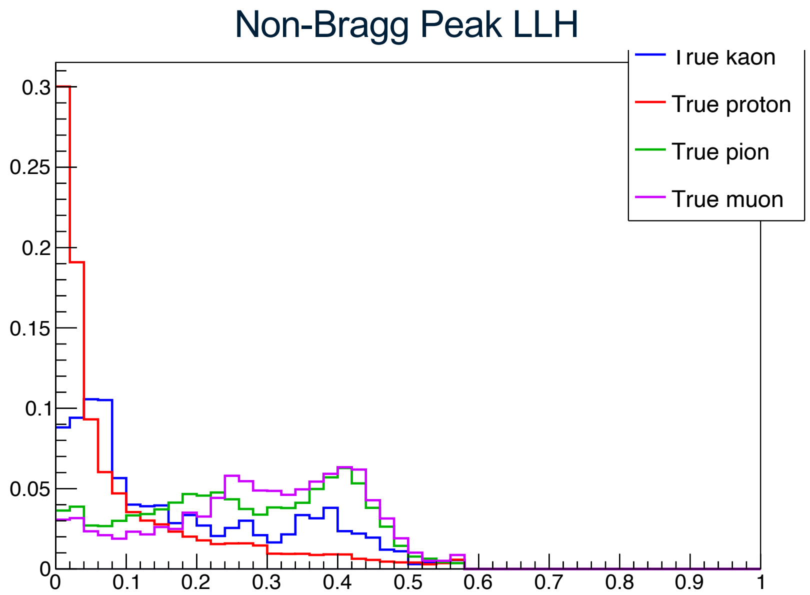
- Bragg Peak: The energy loss of a heavy charged particle reaches its maximum before stopping.
  Ex. Protons

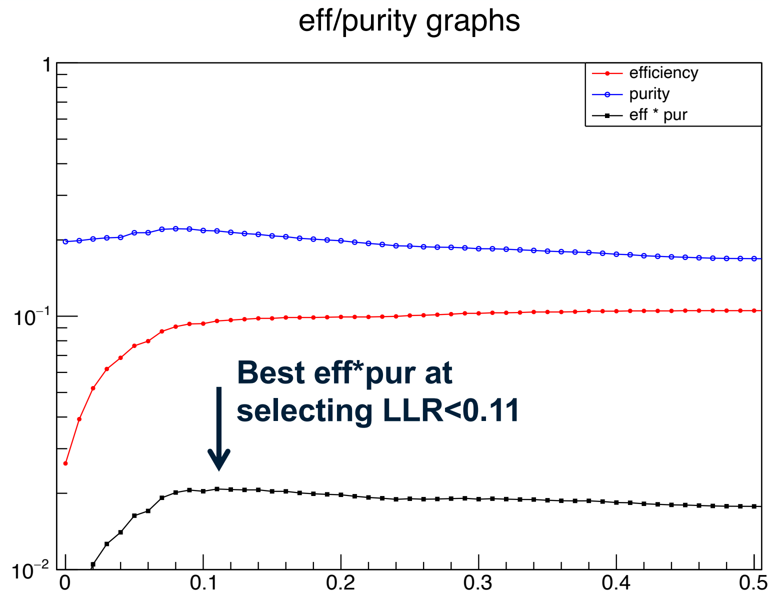


✓ **Charged Current Neutrino Interaction we want to see**

- Primary track from K+: Track of a Non-MIP particle
- Preselection on tracks by using Bragg Peak Likelihood

Selecting a non-MIP track by non-Bragg Peak LLH





Preselection	Efficiency	Purity	Efficiency*purity
previous	9.3%	16.2%	1.50%
Non-MIP (this study)	8.4%	20.8%	1.75%

NuMI beam MC with Kaon signal MC events (~5k)

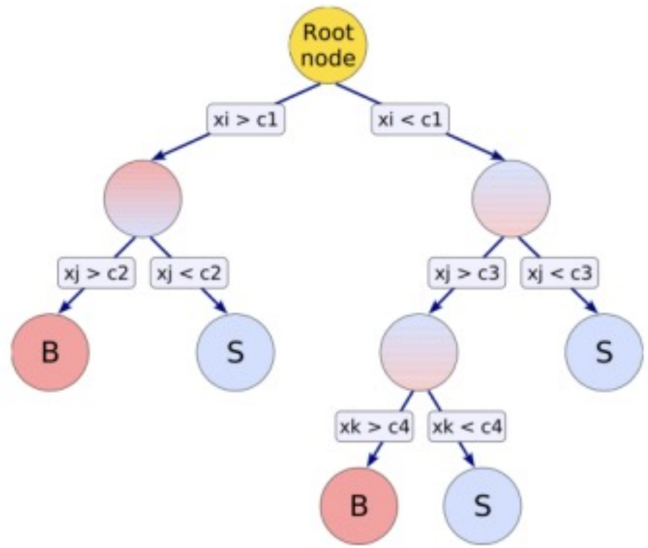
Next step – BDT selection

✓ True signal: $\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + K^+ + \mathrm{nucleons/Hyperon}$

✓ Possible BG events: $\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + \pi^- + \mathrm{nucleons}$

Classify signal/BG events with BDT

- Structured like binary tree: sort events by yes/no decisions upon training variables
  - Keep splitting until all the events are classified as signal or background
  - "Boosted": Add weights for mis-identified events
- Select variables and values for splitting conditions with best separation



Schematic of decision tree: leaf nodes at bottom are labeled "signal" and "background" after binary splits are made; these labels depend on the majority of events that end up in nodes

https://indico.fnal.gov/event/17409/contributions/42949/attachments/26558/32939/Conley_2018June20_SNBMeeting.pdf

Characteristics of K+ Signals: PID and Daughter Track Length

Possible training variables for BDT

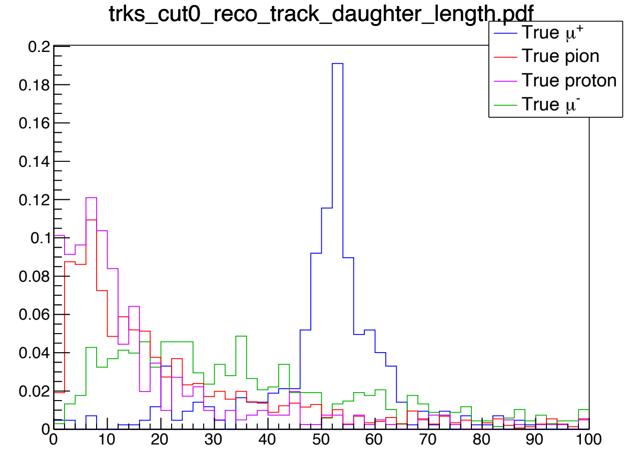
✓ Daughter track length

- majority of K^+ decay into μ^+ (~64%)

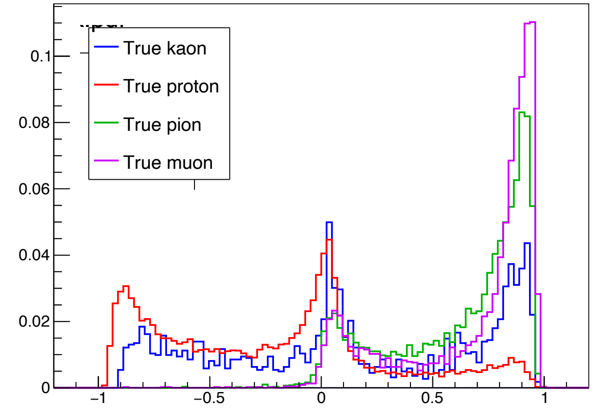
✓ Log-likelihood PID for tracks

- muon/proton separation
- kaon/proton separation

Track length of daughter particles of true K+



Log-likelihood PID for tracks



Summary and Outlooks

- Kaon detection is crucial for proton decay searches

- Kaon production study with NuMI beam
    - Generated single kaon MCs to decide preselection cuts
    - Improve the preselection criteria by using non-MIP information:
      Better efficiency*purity by ~15% compared to the previous criteria in BNB study
    - Next step is selection by BDT