K^+ Production Study with MicroBooNE for the Future Proton Decay Search at DUNE

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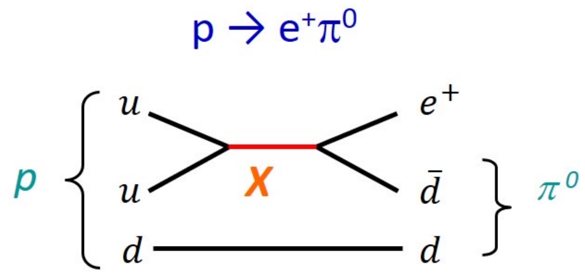
K^+ cross section measurement: Why Kaons?

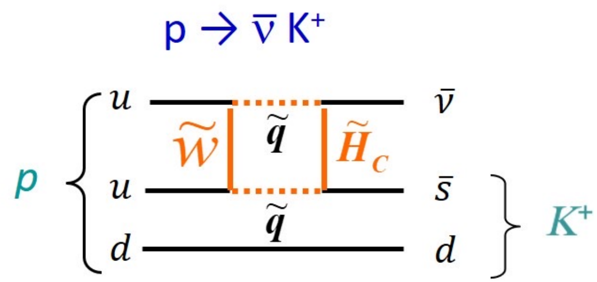
Importance of Kaon study:

- Many GUT models suggest major nucleon decay modes involving K^+ at final states (i.e: $p \rightarrow \bar{\nu}K^+, n \rightarrow e^- K^+$)
- Provide better understanding of backgrounds from atmospheric neutrinos in nucleon decay searches at future DUNE
- No kaon production measurements on Ar or other targets at 1 GeV neutrino energy region

✓ **Ongoing CCK^+ cross section study with BNB at MicroBooNE with very low statistics**

→ This study: CC K^+ production analysis with NuMI at MicroBooNE





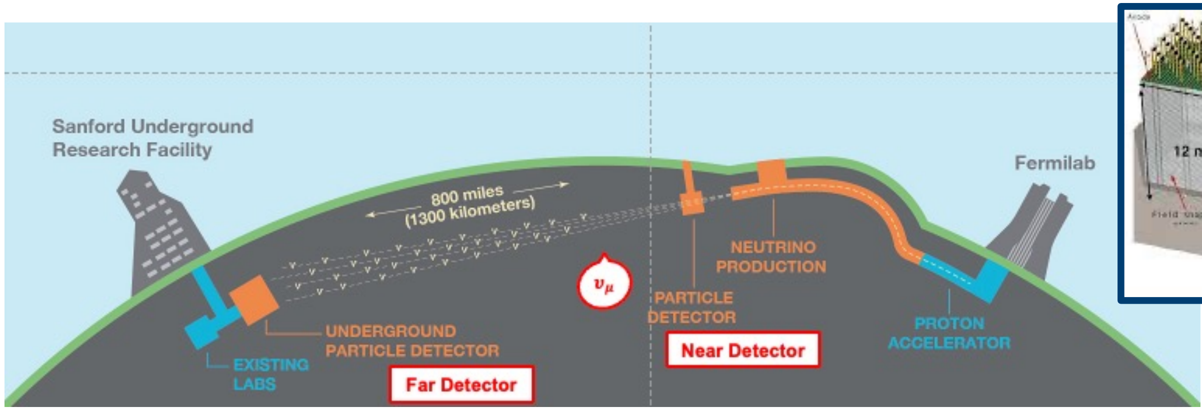
LArTPC Experiments: DUNE and MicroBooNE

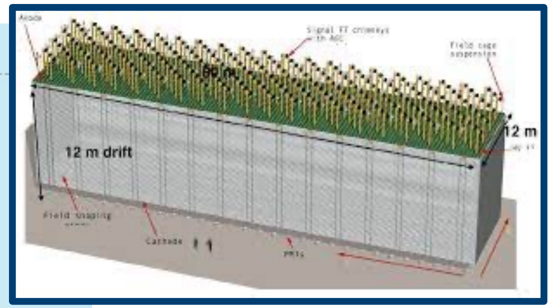
DUNE

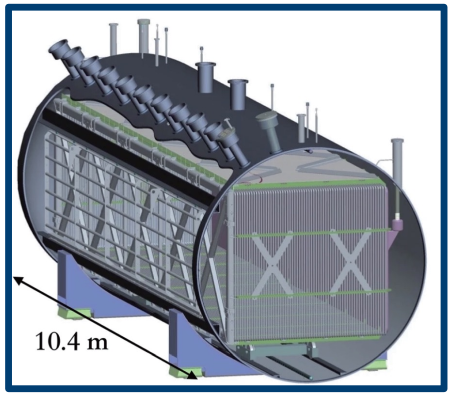
- ► Detector installation beginning in mid 20s
- ► Near and Far detectors located ~1300 km apart
  - Near detector: Complex of detectors for $\boldsymbol{\upsilon}$ properties
  - Far detector: 40 kton LArTPC with ~10^{35} of protons
- ► **Proton decay search: $\boldsymbol{p \rightarrow \bar{\nu} K^{+}}$**

MicroBooNE

- ► 85 ton LArTPC running 2015 - 2021
- ► 0.25-2 GeV υ beam from the Booster Neutrino Beam (BNB) and the Neutrino Main Injector (NuMI)
- ► **Available data of ~$\boldsymbol{10^{24}}$ POTs**







K^+ Production by neutrinos

3 modes to produce K^+ by CC neutrino interactions

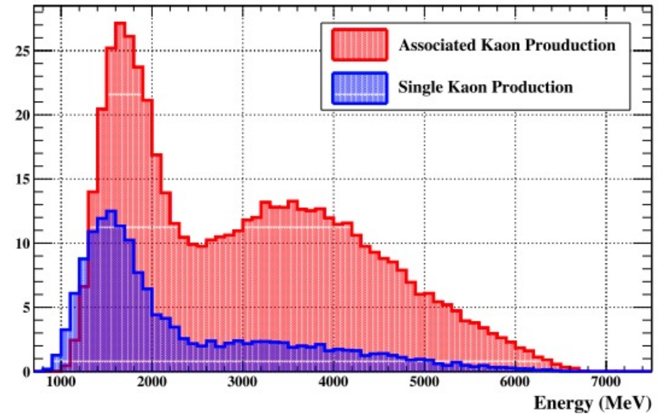
✓ **Associated kaon production**:
Kaon accompanied by a hyperon in the final state (E_{thres}: 1.1 GeV)

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

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

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

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



✓ **Coherent kaon production**:
Single kaon produced with target nucleus remaining intact. (RARE)

- Kaon decay:

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

$K^+ \rightarrow \pi^+ \pi^+ \pi^-$ (~5.6%)
$K^+ \rightarrow \pi^0 e^+ \nu_e$ (~5.0%)
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$ (~1.8%)

K^+ cross section measurement with MicroBooNE & MC

✓ **Very rare ν_μ-induced CCK^+ production process**

- Two candidates of ν_μ-induced CCK^+ production found in 6×10^{19} POT BNB data (DocDB 36161 by Jairo Rodoriguez Rondon)
- Selection performance of ~6.4% selection efficiency and ~75% purity with BNB MC

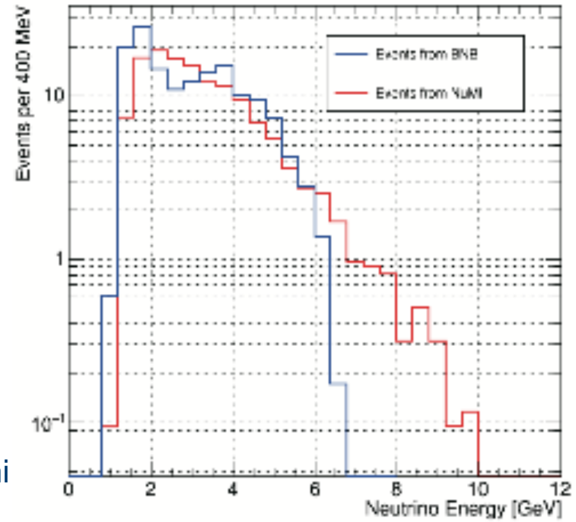
✓ **Why NuMI beam?**

- Comparable K^+ production estimated with NuMI

	Evt with at least one K^+	Evt with at least one K^-	Evt with K^+& K^-	Evt with $K^\pm$ & K0
NuMI	135	13	13	1
BNB	147	14	14	1

DocDB: 6975 by Elena Gramellini

Expected #ν-induced K events



$\sim 3.2\times10^{20}$ POT from BNB
$\sim 4.0\times10^{20}$ POT from NuMI

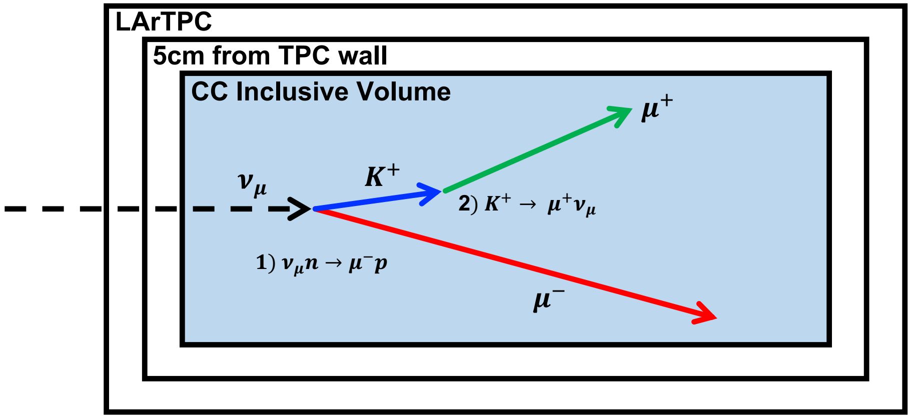
→ Study ν_μ-induced CC K^+ selection with NuMI MC for XSec measurement with BDT

→ Combine NuMI + BNB measurement and double in statistics

Preselection before BDT

Preselection Criteria (same as K+ BNB study DB36315):

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



True Signal definition:

- The event should have K^+ in final state produced via ν_μCC interaction
- FV cut same as preselection (ν vertex/End of K^+ track in CC inclusive volume, End of kaon daughter tracks within 5cm of TPC)
- True ν_μ-induced CC K^+ events in 1.1×10^{21} POT of FHC run1 NuMI MC: 186

  → 19 events remain after preselection (efficiency: 19/186 = 10.2%, purity: 19/3106 = 0.61%)

K^+ Event Features and Training BDT (1/2)

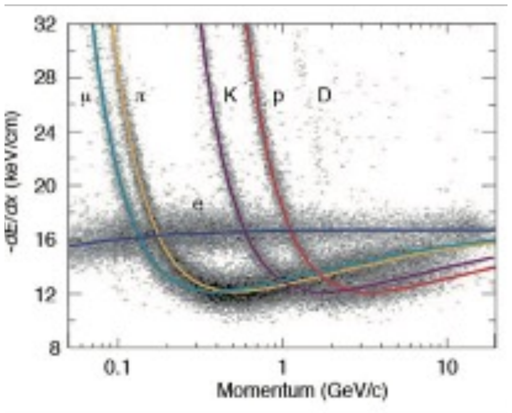
✓ NuMI MC + Generated ~20k samples in total for single/associated CC K^+ signals

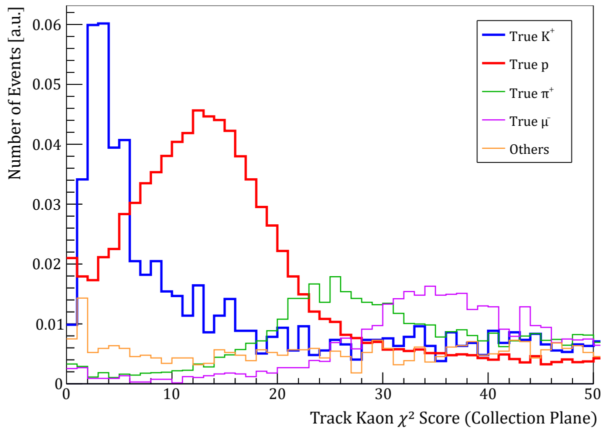
✓ Select variables well characterize true/BG events:

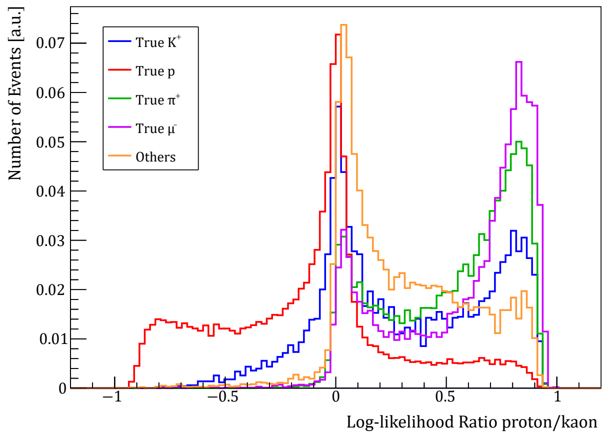
- **χ^2 hypothesis score for K, p, μ, π for 3 planes:**
  Calculated by the measured dE/dx and estimation from Bethe-Bloch formula.

$$\chi^2_{3pl} = \frac{\chi^2_{pl0} \times w_{pl0} + \chi^2_{pl1} \times w_{pl1 + \chi^2_{pl2} \times w_{pl2}}}{w_{pl0} + w_{pl1} + w_{pl2}}, \quad w_{plane} = \begin{cases} 1 \text{ if } \sin^2(\theta_{wire}) \geq 0.05, \\ 0 \text{ if } \sin^2(\theta_{wire}) < 0.05. \end{cases}$$

- **Log-likelihood ratio for K/p and μ/p separation:**
  PID score based on dE/dx PDF and wire pitch along the tracks.

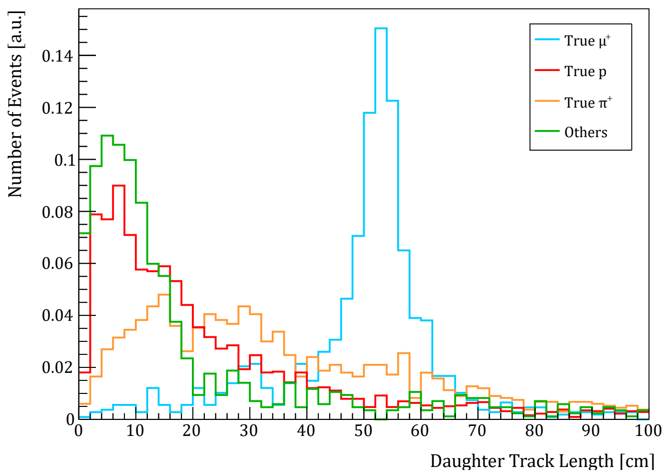




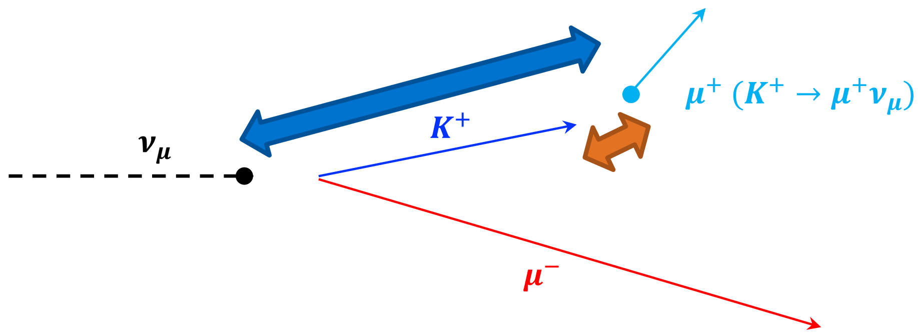


K^+ Event Features and Training BDT (2/2)

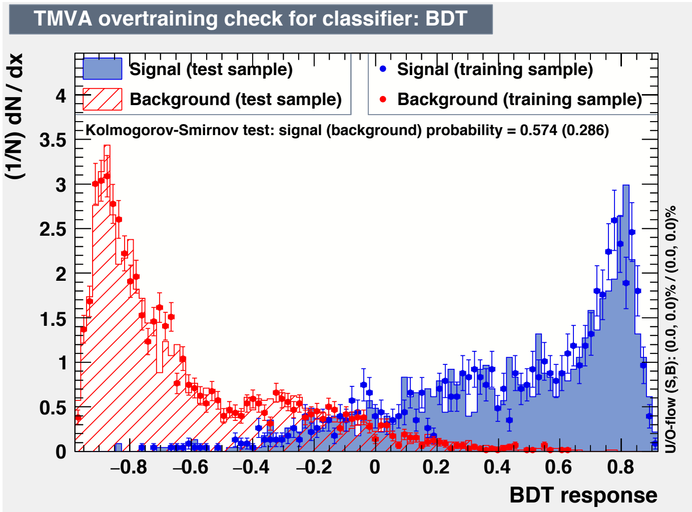
- **Length of daughter track**: Effective for μ^+ selection as K^+ daughter.

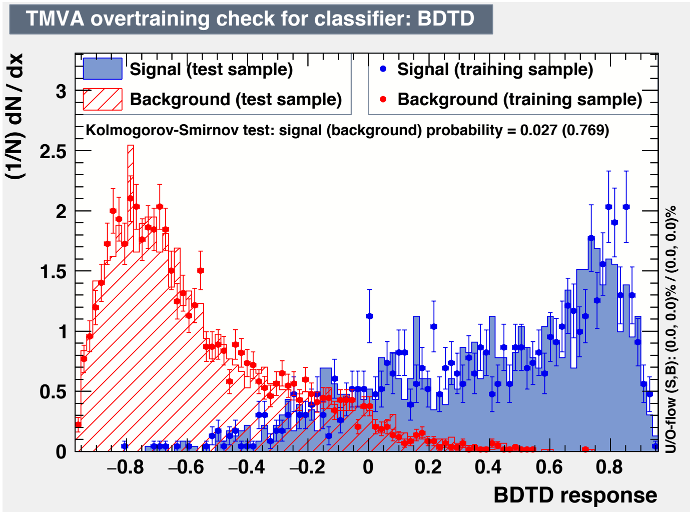


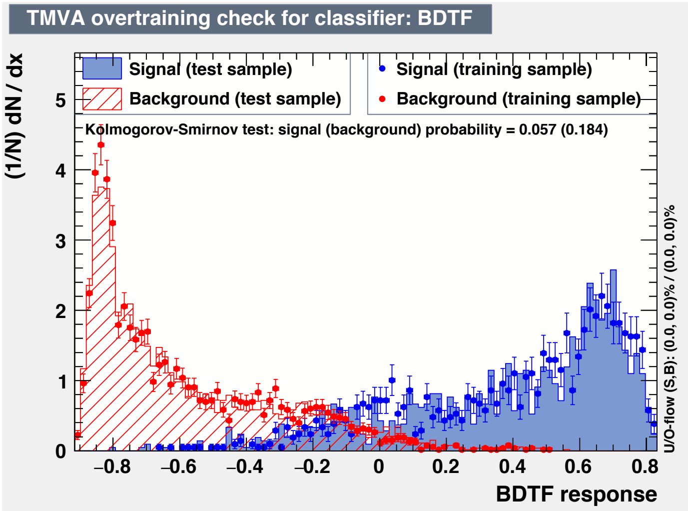
- **Length of track**
- **Length of daughter distance**
- **Length of daughter vertex distance**



BDT Training with Various Setups

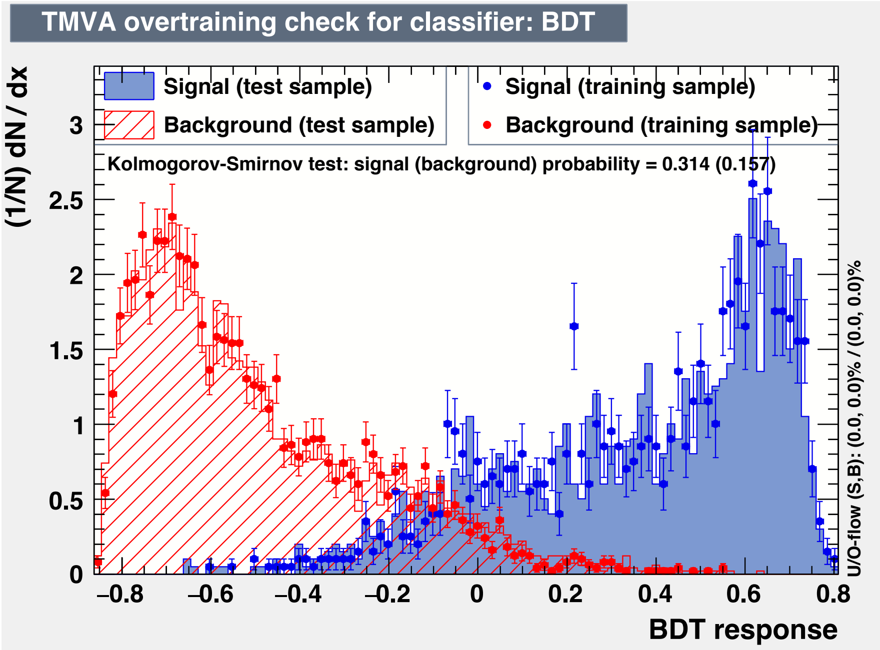






Find the best BDT by optimizing:
- -Input parameter sets
- -Information gain index for splitting
- -BDT algorithms

BDT Selection with MC Simulation

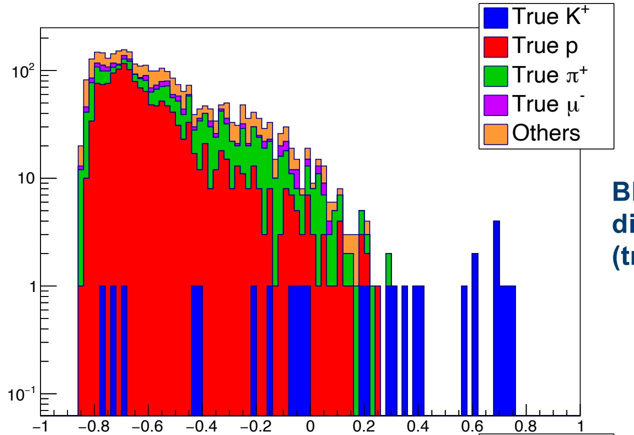


Signal: Reconstructed track has a true PDG = K^+

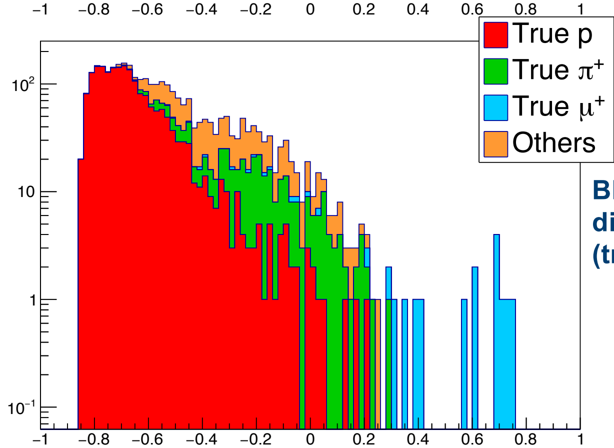
Reconstructed daughter has a true PDG = μ^+ or π^+

Background: !Signal

Apply trained BDT to 1.1e21 POT of FHC run1 NuMI MC



BDT score distribution (true track PDG)



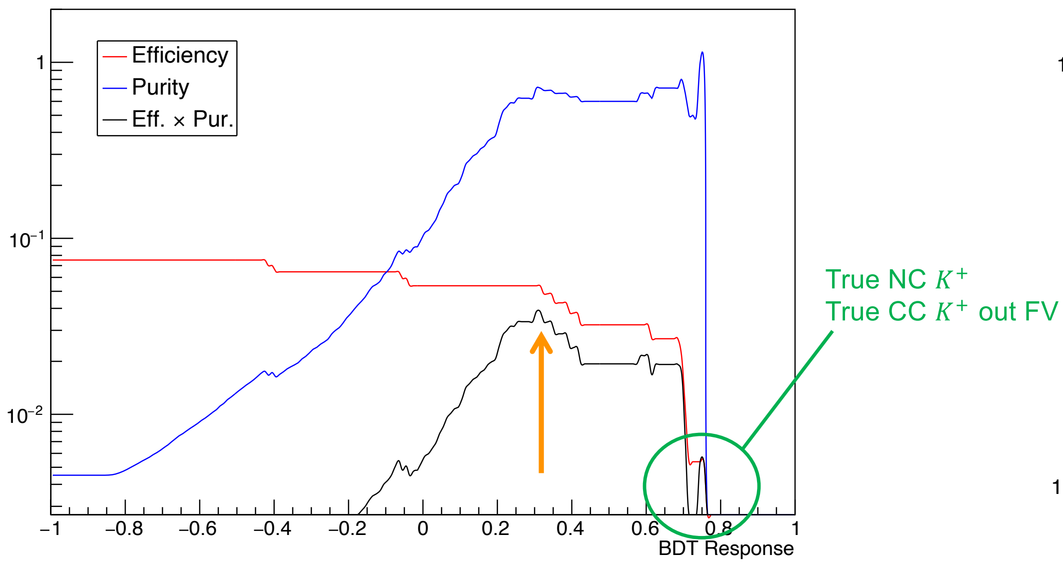
BDT score distribution (true daughter PDG)

Optimal BDT Cut

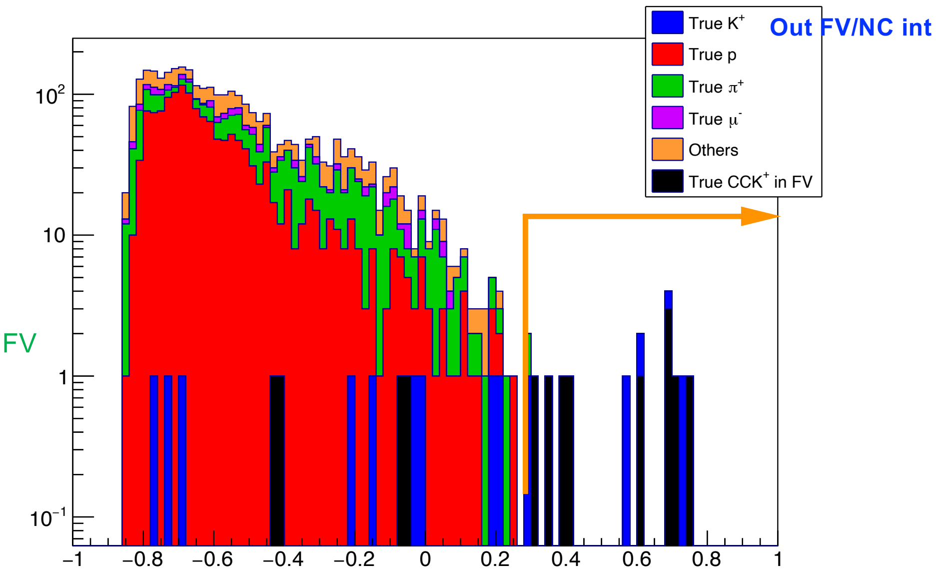
✓ **Optimal BDT cut assessed by the efficiency*purity distribution.**

$$\text{Efficiency} = \frac{\text{BDT-cut selected true } \nu_\mu \text{CC } K^+ \rightarrow \mu^+\nu_\mu/\pi^+\pi^0 \text{ events in FV}}{\text{Generated true } \nu_\mu \text{CC } K^+ \rightarrow \mu^+\nu_\mu/\pi^+\pi^0 \text{ events in FV}}$$

$$\text{Purity} = \frac{\text{BDT-cut selected true } \nu_\mu \text{CC } K^+ \rightarrow \mu^+\nu_\mu/\pi^+\pi^0 \text{ events in FV}}{\text{BDT-cut selected events}}$$



Efficiency: 5.38%, Purity: 71% at BDT cut 0.31



Number of generated true signals in NuMI MC 1.1e21 POT: 186 → True signals after BDT cut at 0.31: 10

Breakdown of BDT Selected Events

Run | Subrun | Event	True Interaction	K+ candidate true PDG	K+ daughter candidate true PDG	FV	K Process
6535 | 42 | 2101	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Sigma^0\ K^+$	321	-13	✓	Decay at rest
6549 | 20 | 1014	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ n\ p$	321	-13	✓	Decay at rest
6637 | 58 | 2914	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+$	321	-13	✓	Decay at rest
6605 | 85 | 4264	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ n\ 2p$	321	-13	✓	Inelastic
6689 | 43 | 2152	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+$	321	-13	✓	Decay at rest
6572 | 218 | 10949	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Sigma^+\ K^+\ \pi^+\ n$	321	-13	✓	Decay at rest
6599 | 30 | 1530	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+$	321	-13	✓	Inelastic
6572 | 226 | 11334	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+$	321	-13	✓	Decay at rest
6589 | 64 | 3207	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Sigma^+\ K^+\ 8p\ 3n\ \pi^+\ \pi^-\ \pi^0$	321	-13	✓	Decay at rest
7004 | 549 | 27485	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+$	321	-13	✓	Decay at rest
6605 | 10 | 526	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+$	321	-13		Decay at rest
6888 | 124 | 6632	NC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ \pi^0$	321	-13		Inelastic
6908 | 91 | 4597	NC DIS $\nu_\mu\ Ar \rightarrow \nu_\mu\ \Sigma^-\ K^+$	321	-13		Inelastic
6674 | 21 | 1095	NC DIS $\nu_\mu\ Ar \rightarrow \nu_\mu\ \Sigma^-\ K^+\ n$	321	-13		Decay in flight

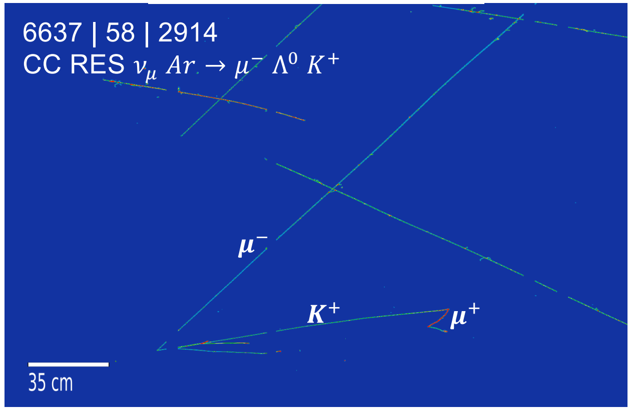
Breakdown of BDT Rejected True $\nu_\mu CC K^+$ Events in FV

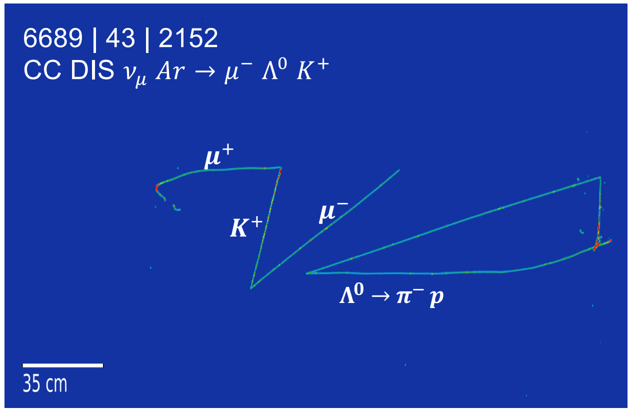
Run | Subrun | Event	True Interaction	K+ candidate true PDG	K+ daughter candidate true PDG	FV	K Process
6773 | 116 | 5814	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ K^+\ 3n\ 3p$	321	-13	✓	Inelastic
6789 | 118 | 5937	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+$	321	-13	✓	Inelastic
7008 | 1073 | 53670	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ \pi^0$	321	-13	✓	Inelastic
6752 | 100 | 5036	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ n$	2212	2212	✓	Inelastic
6776 | 206 | 10345	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ n\ \pi^0$	-211	-211	✓	Inelastic
6521 | 32 | 1610	CC DIS $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ 4n\ 5p\ \pi^+\pi^-$	-211	2212	✓	Decay at rest
6766 | 91 | 4591	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ n\ p$	2212	2212	✓	Decay at rest
7006 | 70 | 3528	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ n\ p$	2212	2212	✓	Decay at rest
7006 | 453 | 22669	CC RES $\nu_\mu\ Ar \rightarrow \mu^-\ \Lambda^0\ K^+\ n\ p$	-13	-11	✓	Decay at rest

- (orange) Rejected True $\nu_\mu CC K^+$ in FV with correct PID
- (yellow) Rejected True $\nu_\mu CC K^+$ in FV mis-PID track/daughter track
- (cyan) Rejected True $\nu_\mu CC K^+$ in FV with NO Reconstructed K+ track

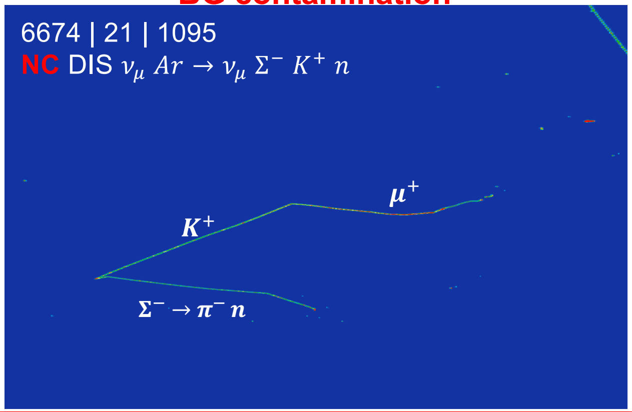
Typical Event Displays

Selected True Events

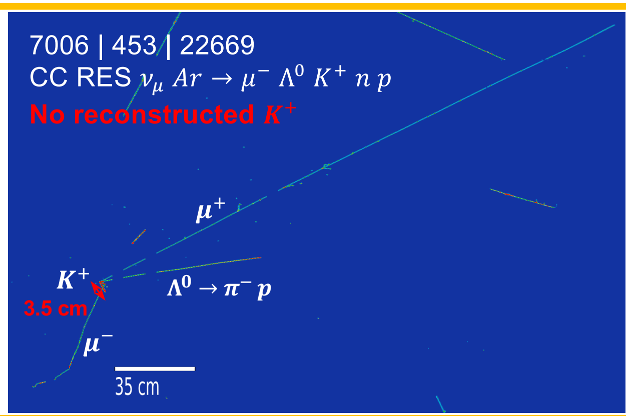


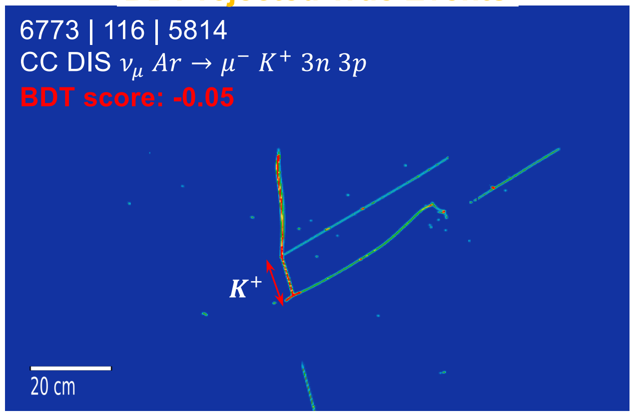


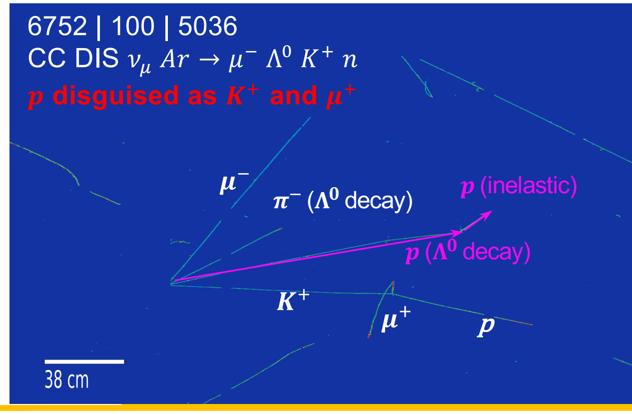
BG contamination



BDT rejected True Events







Summary and Future Plans

- ✓ K^+ production cross section measurement would be the key for future proton decay study at DUNE
- ✓ Since it is a very rare process, we will aim to double the statistics by using BNB and NuMI (this study) beams

- ✓ Event selection for ν_μCCK^+ studied by BDT method with NuMI + signal samples
  - ~5.4% efficiency and ~71% purity
  - Possibility of improvement by applying additional cut on kinetic energy or track length

- ✓ Systematic error estimation ongoing as preparations for real data analysis
- ✓ Aim to publish a paper as combined K+ cross section measurement with BNB+NuMI