# Kaon production Study with Liquid Argon TPC of MicroBooNE for DUNE

**Midterm Review Meeting- INTENSE**
**24 June 2022**

**Natsumi Taniuchi – University of Cambridge**
ntaniuchi@hep.phy.cam.ac.uk

**Supervisor: Dr Melissa Uchida**
mauchida@hep.phy.cam.ac.uk

H2020 MSCA ITN
G.A. 858199

# Attended Courses, Conferences, and Workshops

- Lecture for modern particle physics
  (Oct. 2021 – Mar 2022)
- Machine learning course
  (Oct. 2021 – Mar 2022)
- First-year report/exam (Jul. - Aug. 2022)
- LArSoft Workshop
  (1 Nov. – 3. Nov 2021)
- MicroBooNE Analysis Retreat Workshop
  (9 May – 13 May 2021)
- Annual Intense Workshop
  (2 Feb. - 4 Feb. 2022)
- Cavendish Graduate Conference, poster presentation
  (25 Nov. 2021)
- MicroBooNE Collaboration Meeting
  (2 May. – 6 May. 2022)
- DUNE Collaboration Meeting
  (16 May. – 20 May. 2022)
- MicroBooNE Collaboration Meeting (in person, talk)
  (17 Jan. – 20 Jan. 2023)
- IOP HEPP Annual Conference (in person, poster)
  (3 Apr. – 5. Apr. 2023)

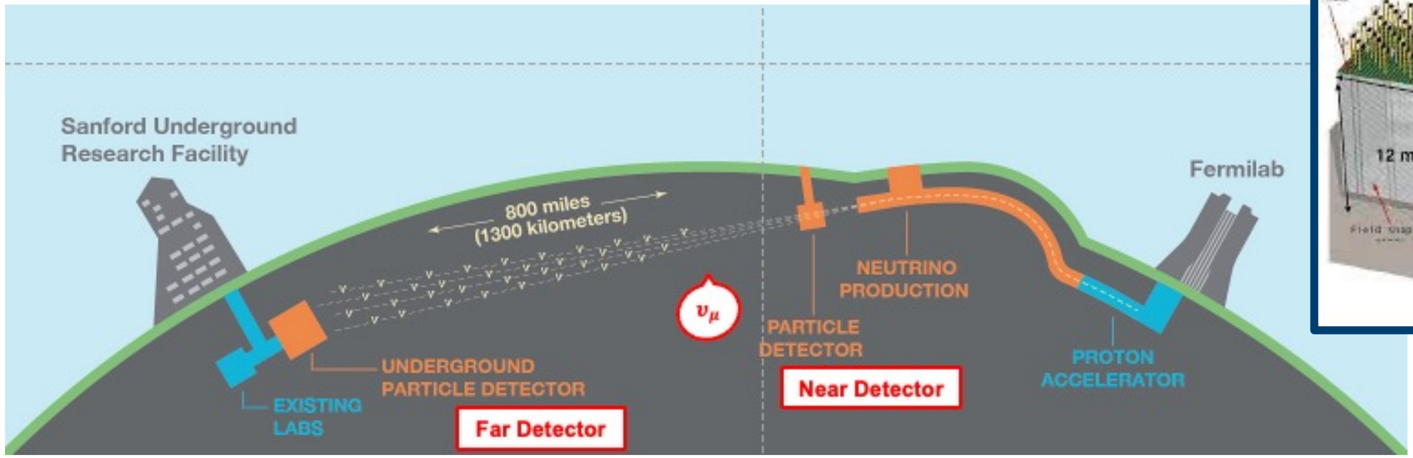
# LArTPC Experiments: DUNE and MicroBooNE

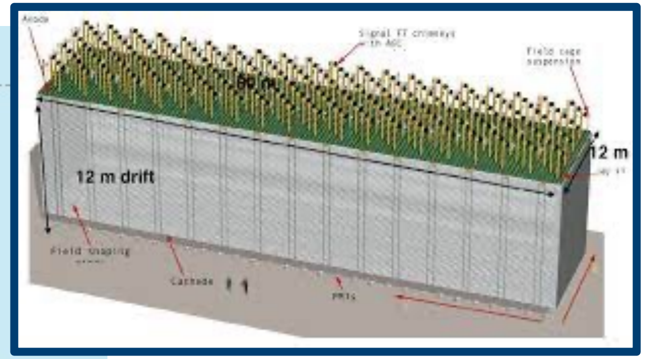
## DUNE

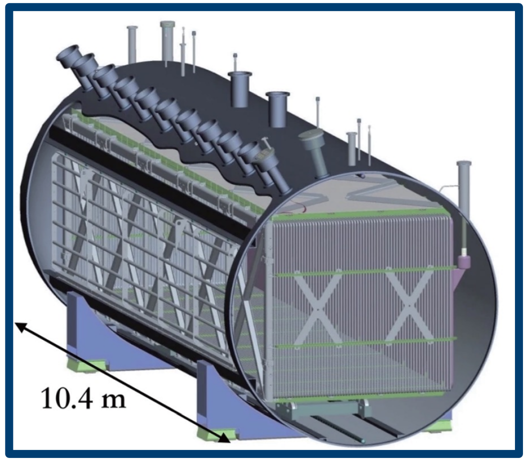
- Detector installation beginning in mid 20s
- Near and Far detectors located ~1300 km apart
  - Near detector: Complex of detectors for $\boldsymbol{\upsilon}$ properties
  - Far detector: 40 kton LArTPC with $\sim 10^{35}$ of protons
- **Proton decay search: $p \rightarrow \bar{\nu} K^{+}$**

## MicroBooNE

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



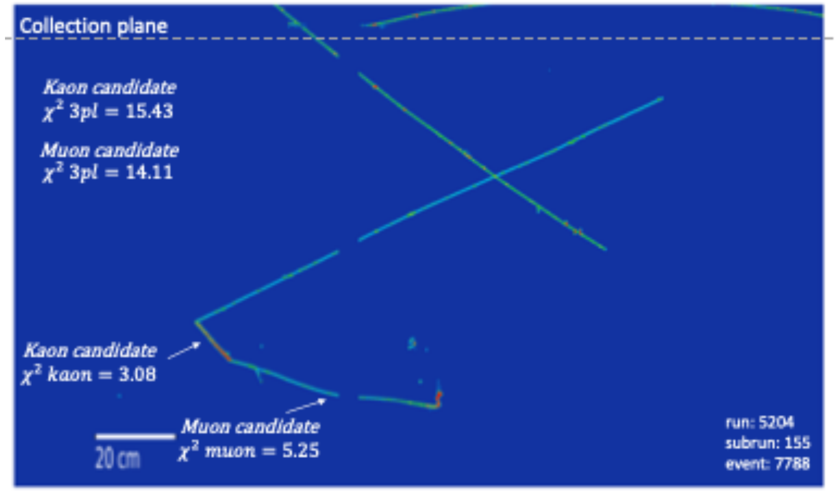



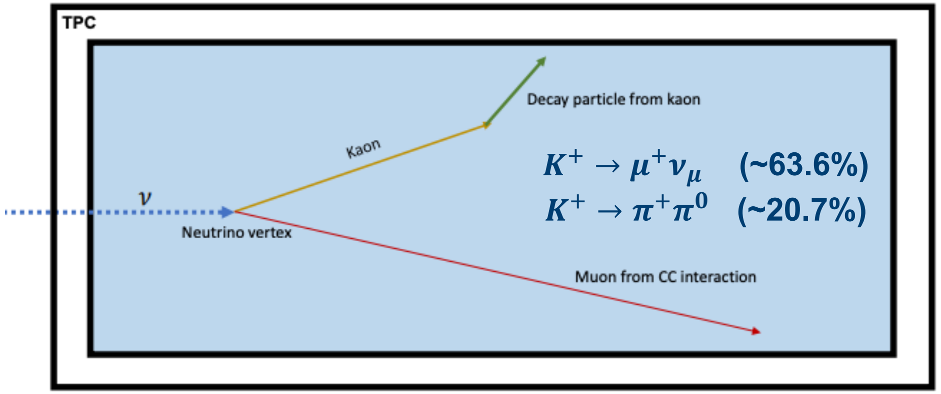
# My Research: $K^+$ Production by CCNu Interactions in MicroBooNE

- ✓ **Why K+ study is important?**
  - Better understanding of K+ backgrounds from atmospheric neutrinos for future proton decay research at DUNE
  - No measurements on Ar at 1 GeV neutrino energy region

- ✓ **2 modes to produce $K^+$ by neutrino interactions in Ar**
  - Associated kaon production: ie. $\nu_\mu + p \rightarrow \mu^- + K^+ + \Sigma^+$
  - Single kaon production: ie. $\nu_\mu + p \rightarrow \mu^- + K^+ + p$

- ✓ **Search $K^+$ events with NuMI beam by Machine Learning**
  - Measure cross section of $K^+$ and install for future DUNE simulation
  - Develop better Kaon-proton PID separation

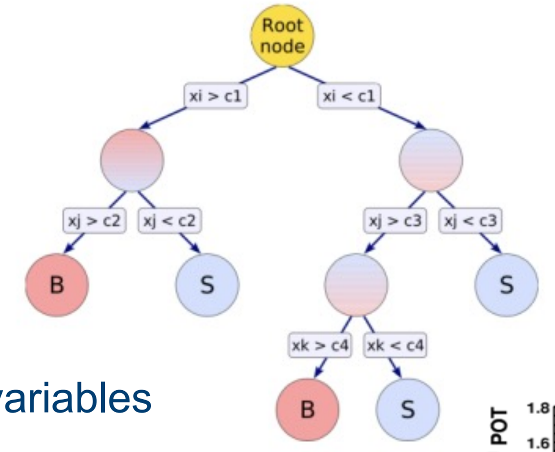


# $K^+$ Event Features and Training by BDT

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

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

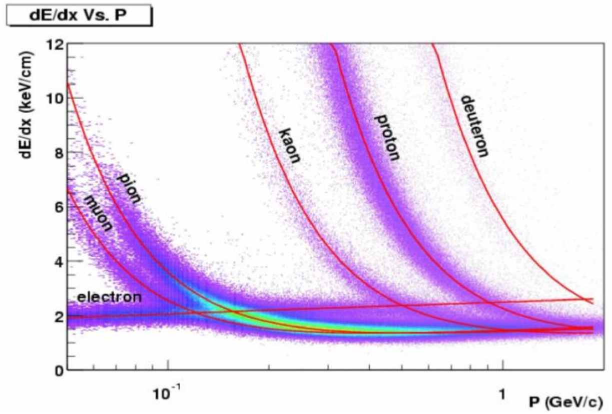


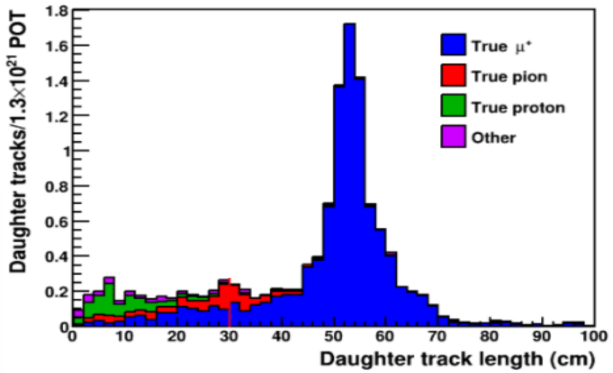

## Separation with Boosted Descision Tree (BDT)

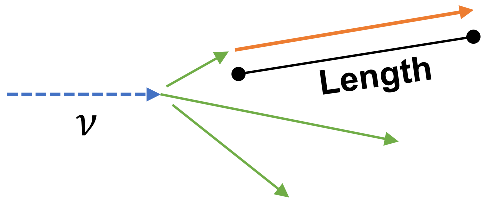
- Binary tree structure: sort events by yes/no decisions on training variables
- Select variables and values for splitting conditions with best separation

## Training the BDT with MC events

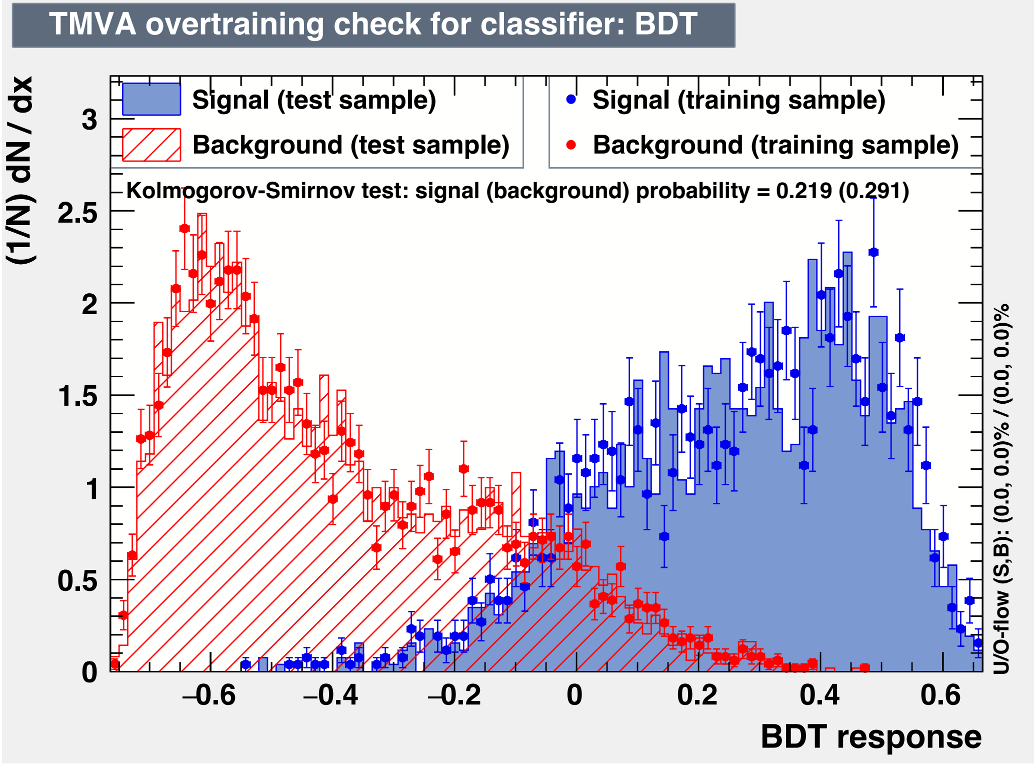
- Select variables well characterize true/BG events:
  - PID score based on dE/dx for kaon/proton separation
  - Lengths of tracks: effective for muon selections



# BDT Selection with MC Simulation

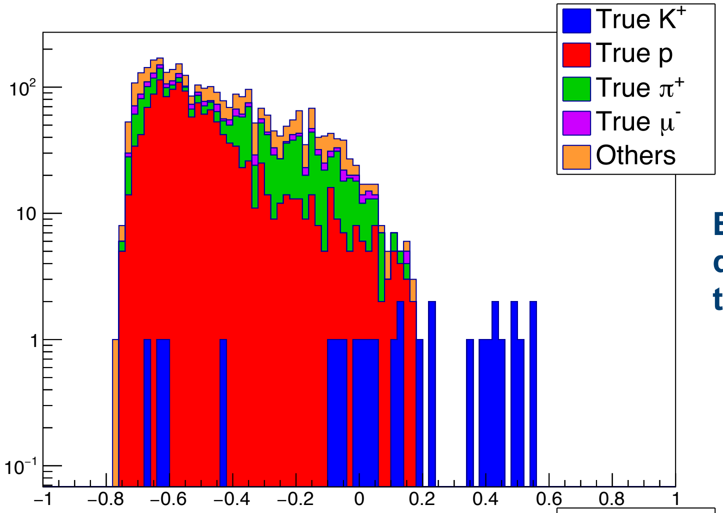



**Signal:** Reconstructed track has a true PDG = $K^+$

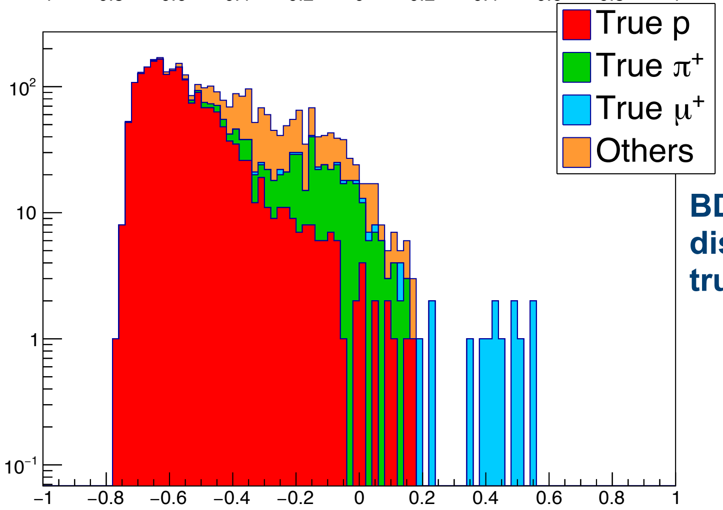
Reconstructed daughter has a true PDG = $\mu^+$ or $\pi^+$

**Background: !Signal**

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

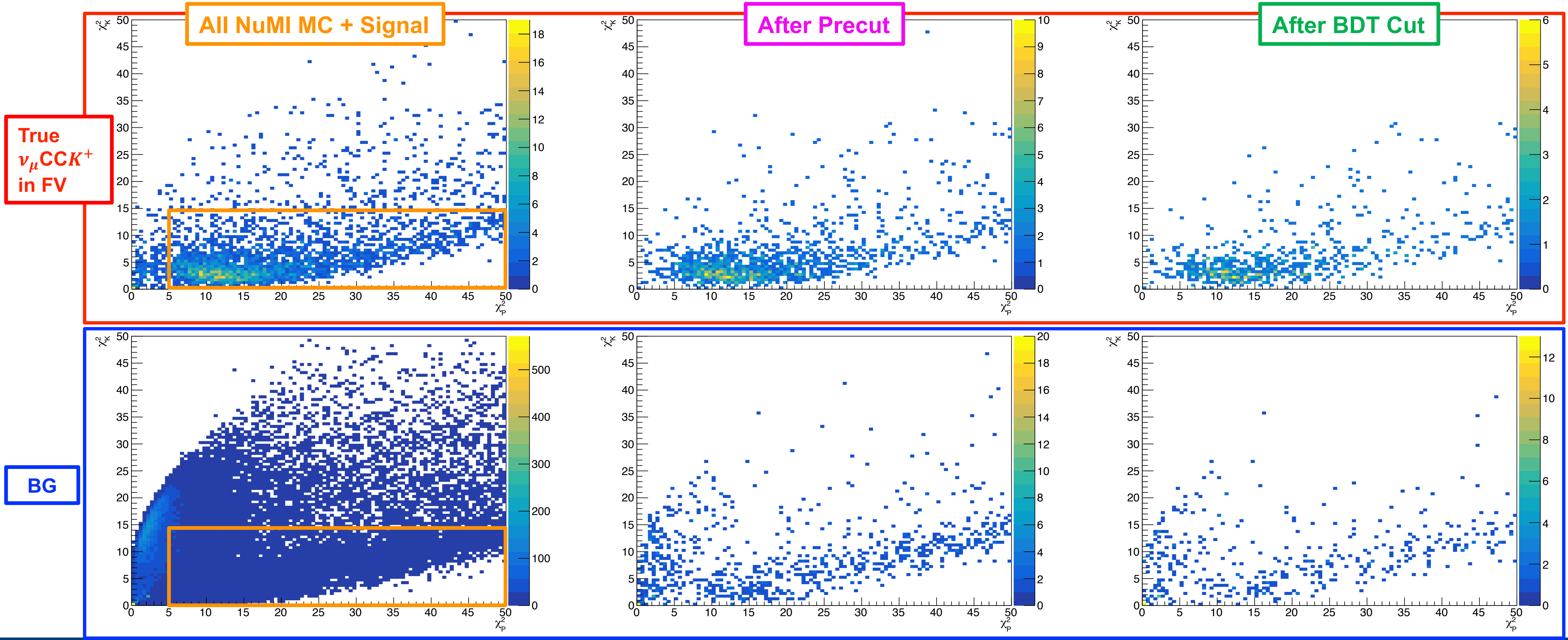



**BDT score distribution for true track PDG**

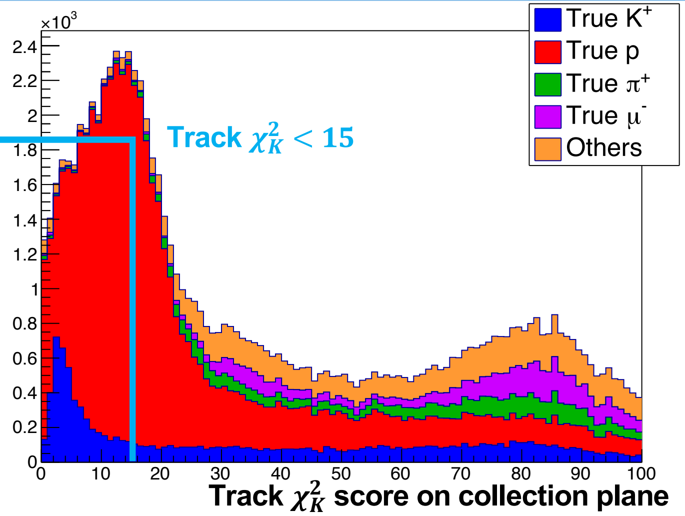


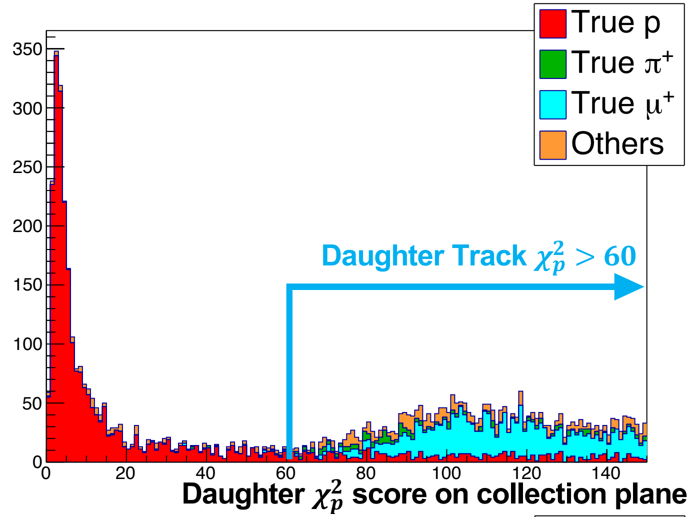

**BDT score distribution for true daughter PDG**

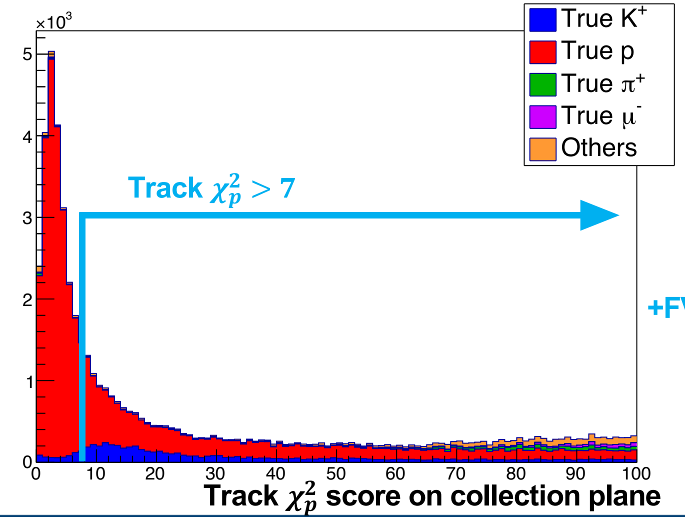
# $\chi_p^2$ vs $\chi_K^2$ Track PID Score Plots of Collection Plane



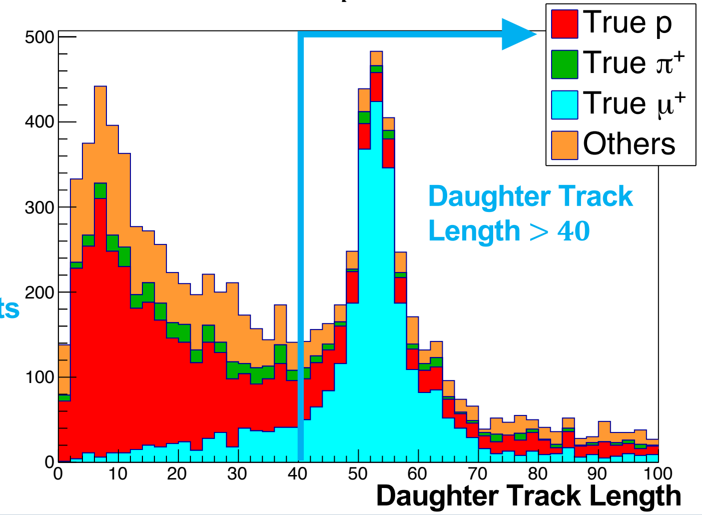
# $K^+$ Event without BDT: $\chi^2$ PID Scores and Daughter Track Length



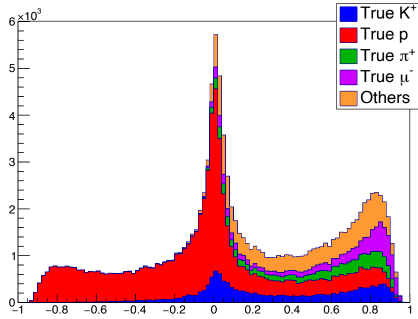




+FV Cuts

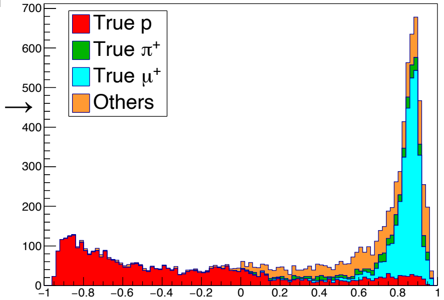


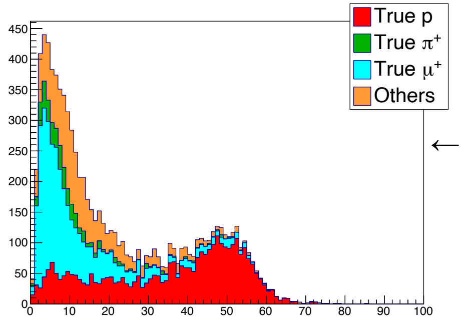

NOT USED




← **LLRPID for track $K^+/p$ separation:**
Too many proton contamination

**Daughter $\chi^2_\mu$ score on collection plane:** →
Worse separation than daughter $\chi^2_p$ score on pl2 or daughter track length




← **LLRPID for daughter track $p/\mu$ separation:**
Worse separation than daughter $\chi^2_p$ score on pl2 or daughter track length

# Breakdown of BDT and $\chi^2$-cut Selected Events

## BDT selected

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

**Efficiency: 5.4%, Purity: 71%, E*P: 0.038**

## $\chi^2$-cut selected

| Run \| Subrun \| Event | True Interaction | Track PDG | Daughter PDG | FV |
|---|---|---|---|---|
| 6535 \| 42 \| 2101 | CC RES $\nu_\mu\, Ar \rightarrow \mu^-\, \Sigma^0\, K^+$ | 321 | -13 | ✓ |
| 6637 \| 58 \| 2914 | CC RES $\nu_\mu\, Ar \rightarrow \mu^-\, \Lambda^0\, K^+$ | 321 | -13 | ✓ |
| 6605 \| 85 \| 4264 | CC RES $\nu_\mu\, Ar \rightarrow \mu^-\, \Lambda^0\, K^+\, n\, 2p$ | 321 | -13 | ✓ |
| 6689 \| 43 \| 2152 | CC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, \Lambda^0\, K^+$ | 321 | -13 | ✓ |
| 6572 \| 218 \| 10949 | CC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, \Sigma^+\, K^+\, \pi^+\, n$ | 321 | -13 | ✓ |
| 6572 \| 226 \| 11334 | CC RES $\nu_\mu\, Ar \rightarrow \mu^-\, \Lambda^0\, K^+$ | 321 | -13 | ✓ |
| 6589 \| 64 \| 3207 | CC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, \Sigma^+\, K^+\, 8p\, 3n\, \pi^+\, \pi^-\, \pi^0$ | 321 | -13 | ✓ |
| 7004 \| 549 \| 27485 | CC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, \Lambda^0\, K^+$ | 321 | -13 | ✓ |
| 6605 \| 10 \| 526 | CC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, \Lambda^0\, K^+$ | 321 | -13 | |
| 6888 \| 124 \| 6632 | NC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, \Lambda^0\, K^+\, \pi^0$ | 321 | -13 | |
| 6908 \| 91 \| 4597 | NC DIS $\nu_\mu\, Ar \rightarrow \nu_\mu\, \Sigma^-\, K^+$ | 321 | -13 | |
| 6827 \| 220 \| 11018 | CC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, 3p\, 3n\, \pi^+$ | 2212 | 221 | |
| 6766 \| 41 \| 2054 | CC QE $\nu_\mu\, Ar \rightarrow \mu^-\, 4p\, n$ | 2212 | 2212 | |
| 6959 \| 115 \| 5757 | CC DIS $\nu_\mu\, Ar \rightarrow \mu^-\, 2p\, 2n\, \pi^+\, \pi^-$ | 2212 | 13 | |

**Efficiency: 4.3%, Purity: 57%, E*P: 0.025**

# Better performance with 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 |

**Eff: 5.4%**
**Pur: 71%**
**E*P: 0.038**
**BDT cut @0.19**

**Same breakdown as BDT w track length.**

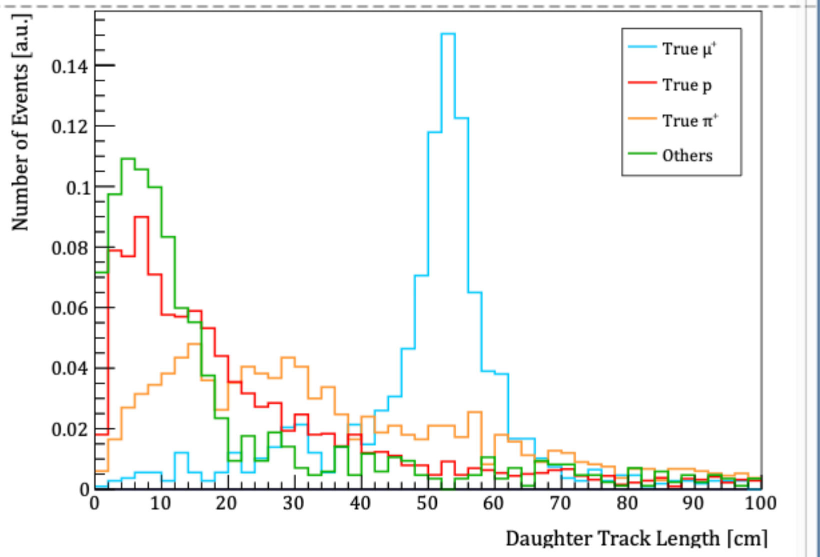
# Better performance with BDT Selected Ever

**100 % comes from $K^+ \rightarrow \mu^+\nu_\mu$ (~63.6%)**
**Can be missing a few events from**
**$K^+ \rightarrow \pi^+\pi^0$ (~20.7%)**

| 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 |
| 6 | | 321 | -13 | ✓ | Decay at rest |
| 6 | | 321 | -13 | ✓ | Decay at rest |
| 6 | | 321 | -13 | ✓ | Inelastic |
| 6 | | 321 | -13 | ✓ | Decay at rest |
| 65 | | 321 | -13 | ✓ | Decay at rest |
| 6 | | 321 | -13 | ✓ | Inelastic |
| 65 | | 321 | -13 | ✓ | Decay at rest |
| 6 | $^- \pi^0$ | 321 | -13 | ✓ | Decay at rest |
| 70 | | 321 | -13 | ✓ | Decay at rest |
| 6 | | 321 | -13 | | Decay at rest |
| 68 | | 321 | -13 | | Inelastic |
| 6 | | 321 | -13 | | Inelastic |
| 6674 \| 21 \| 1095 | NC DIS $\nu_\mu$ $Ar \rightarrow \nu_\mu \Sigma$ $K$ $\pi$ | 321 | -13 | | Decay in flight |

**Length of daughter track**

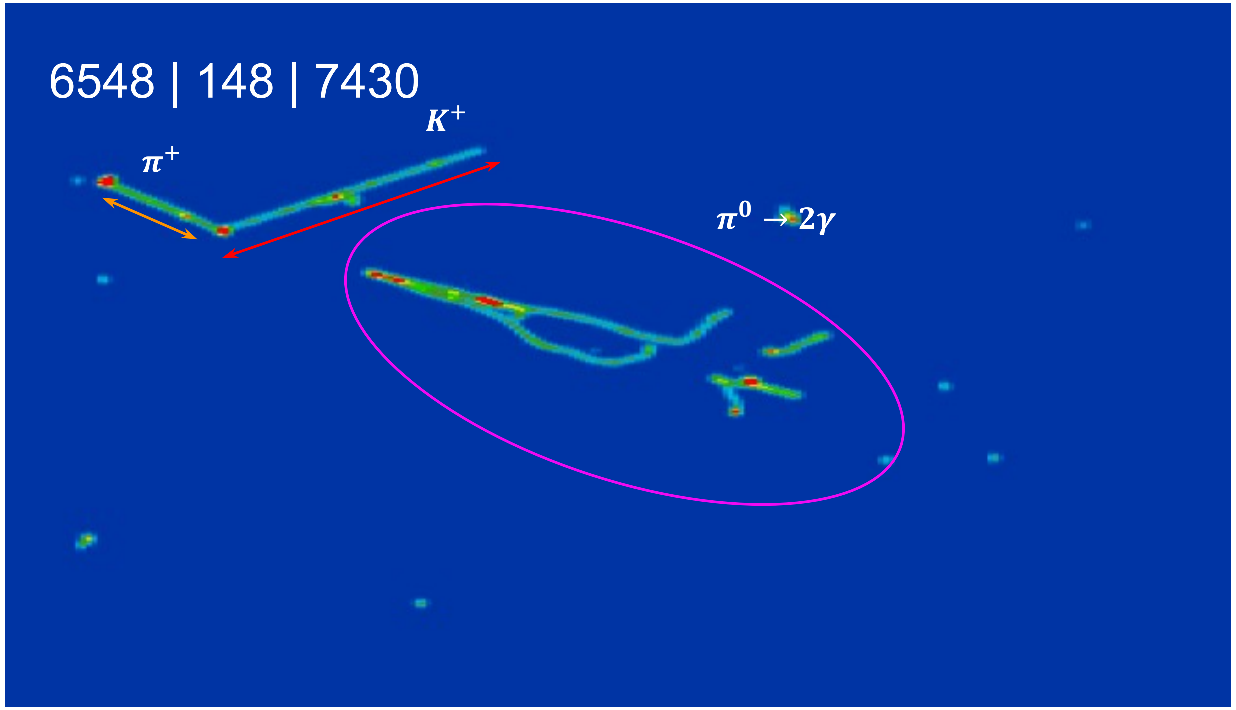
Effective for selection of $\mu^+$ as $K^+$ daughter.

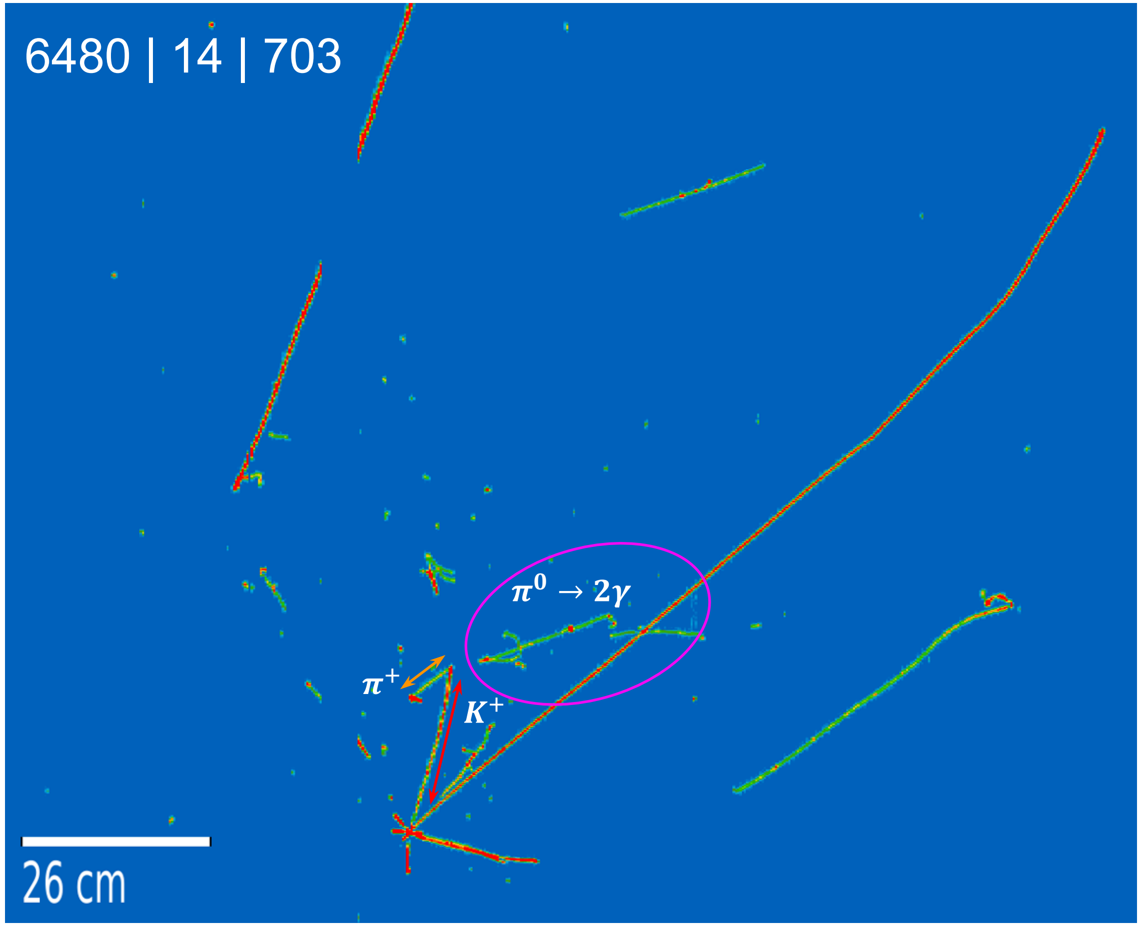



**Eff: 5.4%**
**Pur: 71%**
**E*P: 0.038**
**BDT cut @0.19**

**Same breakdown as BDT w track length.**

# Event displays for pi+pi0 signal




- ✓ Most (~90%) K+ decay at rest
- ✓ Pi0 will decay into two gammas

# Strategy for selecting pi+pi0 events

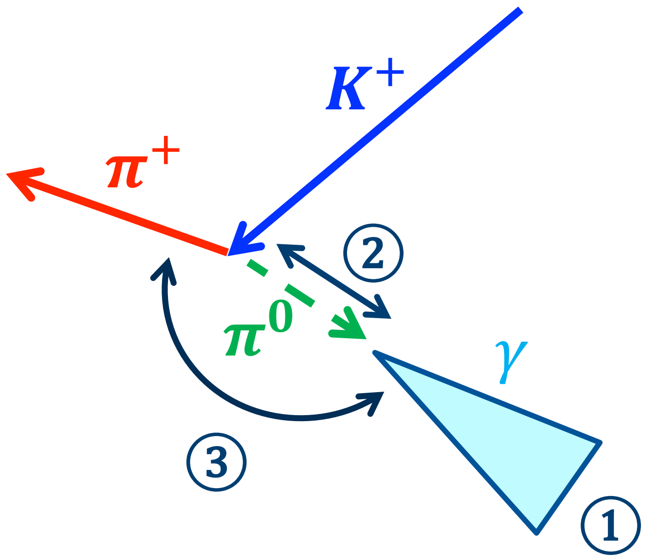
**$K^+ \rightarrow \pi^+\pi^0$ Selection:**

✓ $\pi^0 \rightarrow 2\gamma$ decay:

1. The event should have at least one shower.
2. Gap between end of $K^+$ track and beginning of a shower.

✓ Most $K^+$ decay at rest:

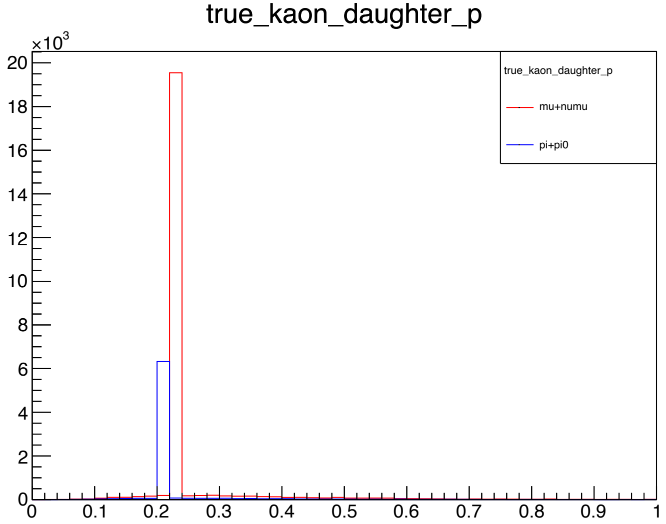
3. Large opening angle between $\pi^+$ track and a shower.




**$K^+ \rightarrow \pi^+\pi^0$ Reconstruction:**

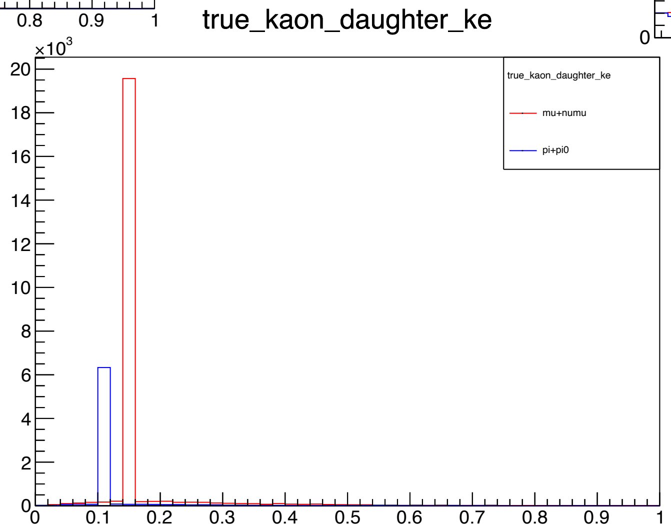
- 50% of true $\pi^+\pi^0$ have more than one shower
- Mis-reconstruction of $\pi^+$: ~99% fails to have reco $\pi^+$ track
  - (# $K^+ \rightarrow \mu^+\nu_\mu / K^+ \rightarrow \pi^+\pi^0$ ): 23090/7497
    - with reconstructed $K^+$ track: 2838/742
      - **with reconstructed daughter track ($\mu^+$/ $\pi^+$): 1125/99**

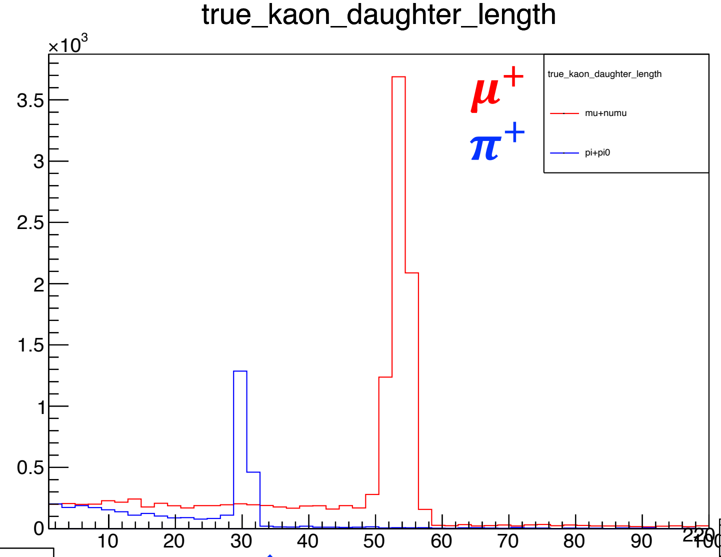
# $K^+ \to \mu^+\nu_\mu / K^+ \to \pi^+\pi^0$ true plots




$K^+ \to \mu^+\nu_\mu$

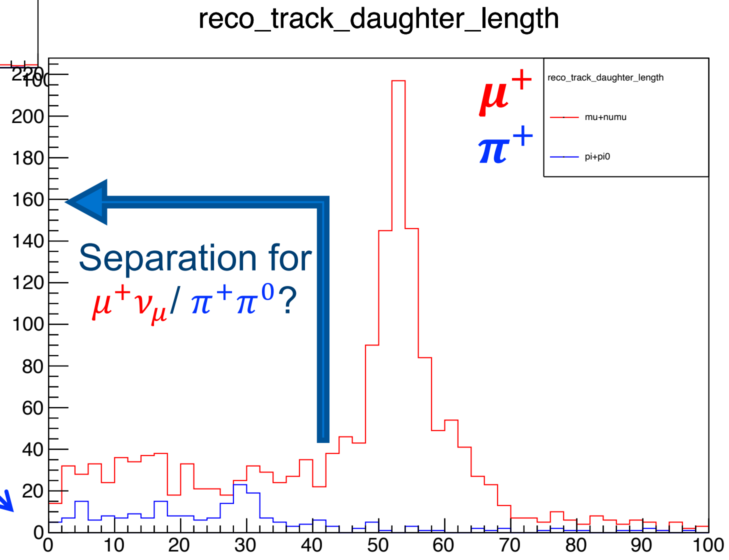
$K^+ \to \pi^+\pi^0$



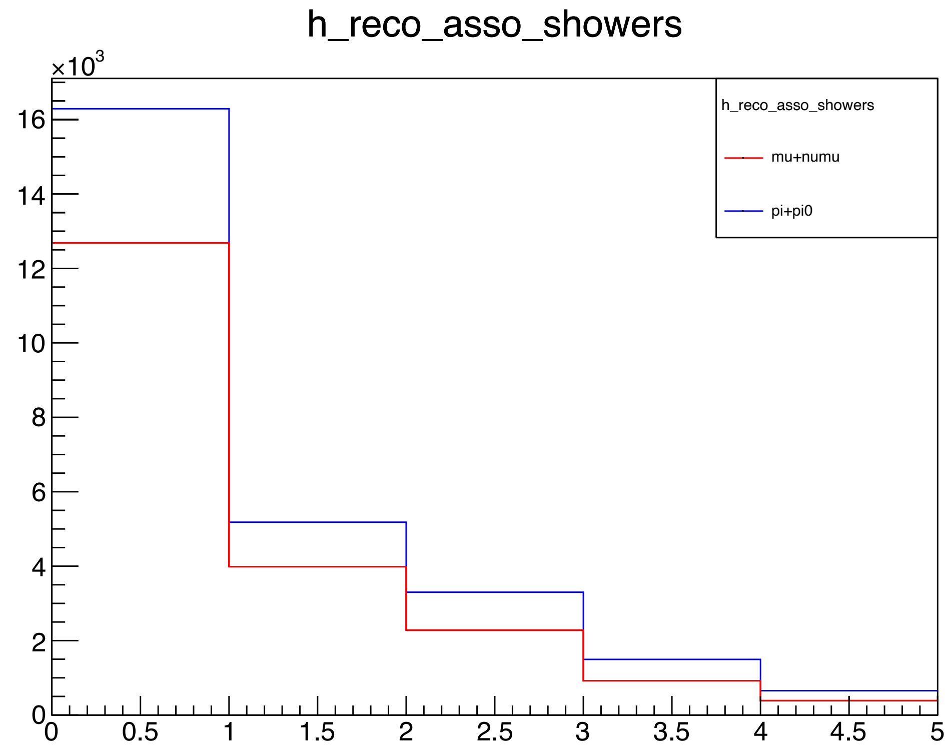




← True $K^+$ daughter track length

↓ Reco $K^+$ daughter track length



# 1). Number of reconstructed shower




- ✓ #Event with shower(s) / #All Event:
  $K^+ \to \mu^+\nu_\mu$: 38%, $K^+ \to \pi^+\pi^0$: 47%, BG: 19%

$\pi^0 \to 2\gamma$ is dominant shower source for both modes and BG

- ✓ #Event with reconstructed $\gamma$ shower / #Event with shower(s):
  $K^+ \to \mu^+\nu_\mu$: 56%, $K^+ \to \pi^+\pi^0$: **79%**, BG: 55%

- ✓ Other origins of shower:
  $K^+ \to \mu^+\nu_\mu$: $\mu^+$ from $K^+$ decay (11% of n_shw>0 events)
  $K^+ \to \pi^+\pi^0$: $\pi^+$ from $K^+$ decay (10% of n_shw>0 events)
  Others: $e^+$ from $\mu^+$ decay

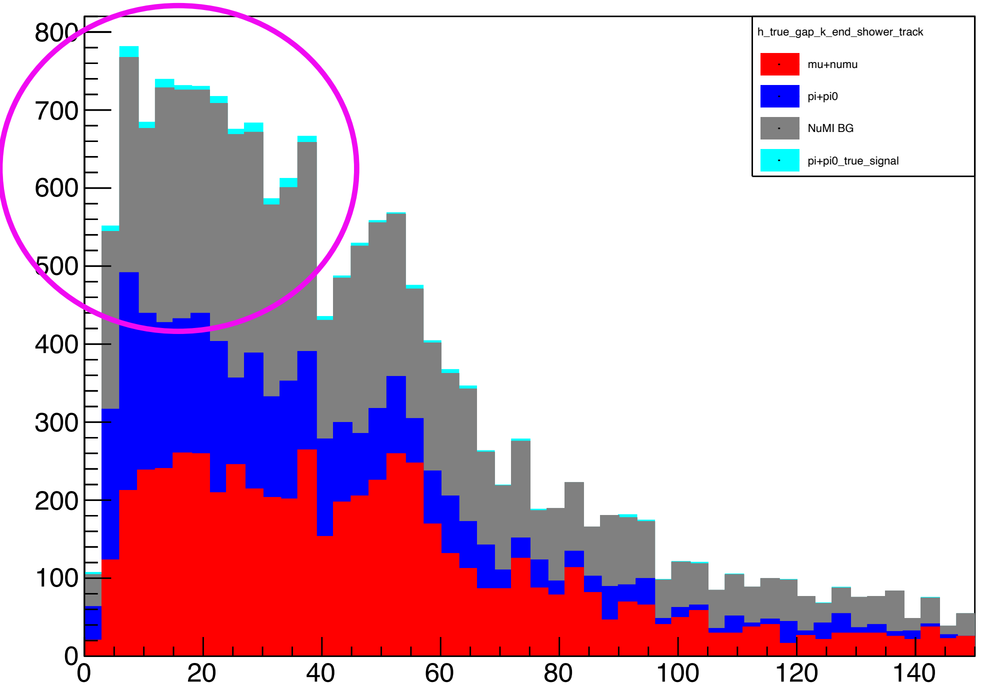
# 2). Gap between K+ end and shower

**Numi BG with shower**

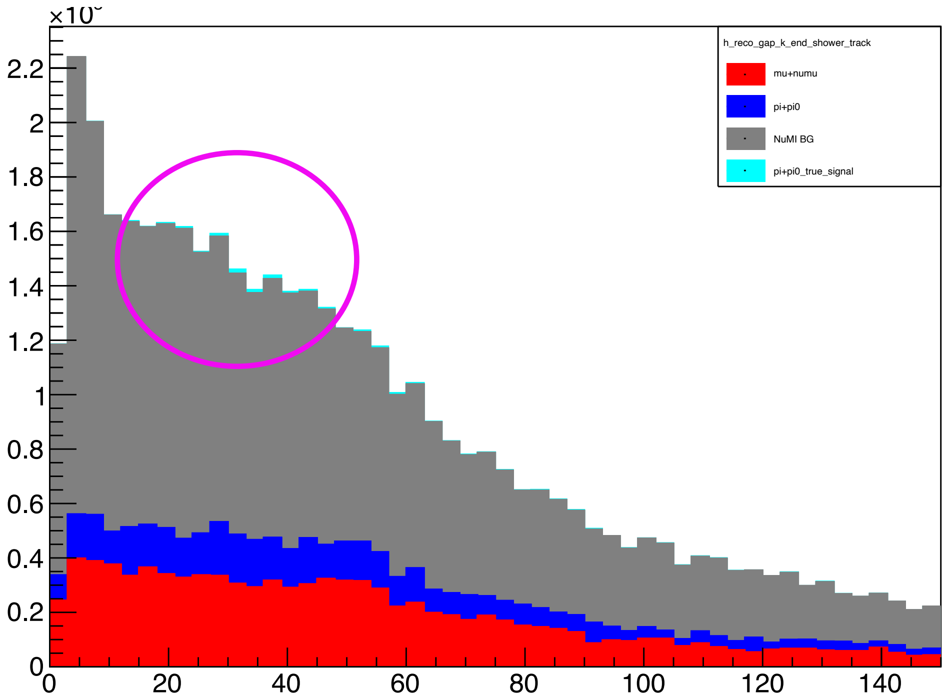
$K^+ \rightarrow \mu^+\nu_\mu$ $K^+ \rightarrow \pi^+\pi^0$

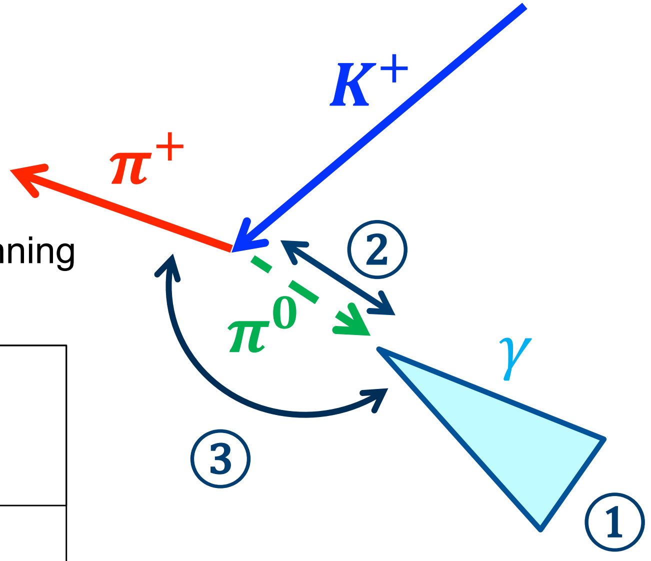
$K^+ \rightarrow \pi^+\pi^0$ with reconstructed $\pi^+$ and $\gamma$ from $\pi^0$ (unknown $\pi^0$ parent)

True gap between end of $K^+$ and beginning of a shower




Reco gap between end of $K^+$-like track and beginning of a shower



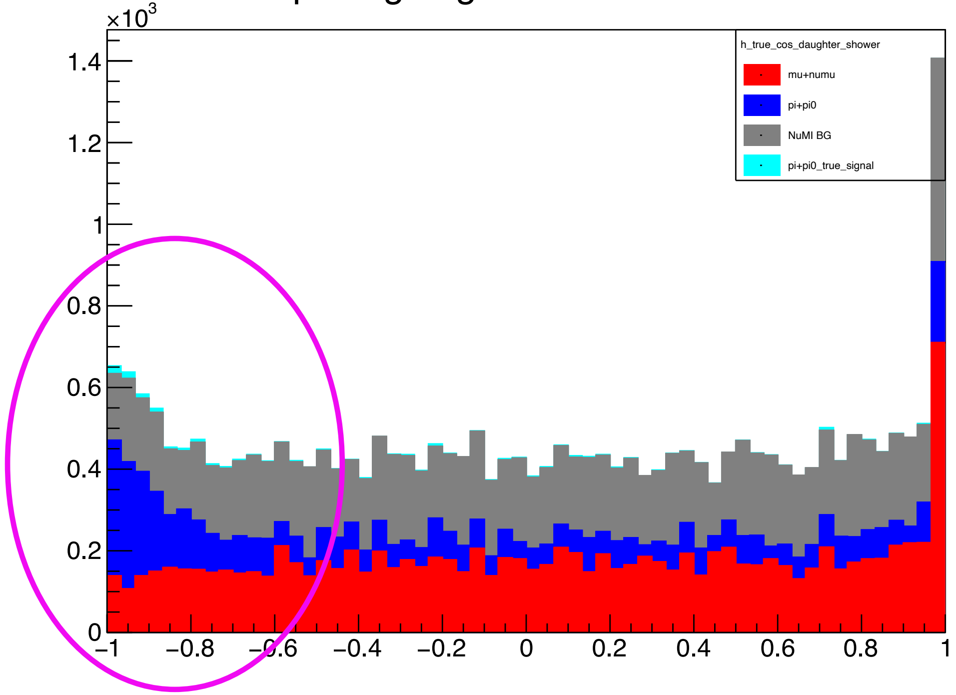
# 3). Opening angle

**Numi BG with shower**

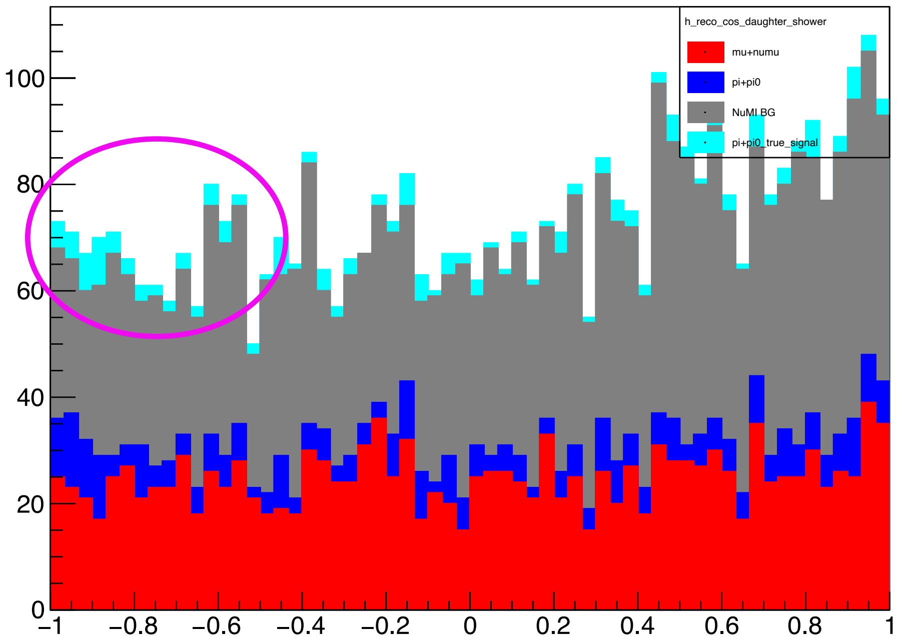
$K^+ \to \mu^+\nu_\mu$ $K^+ \to \pi^+\pi^0$

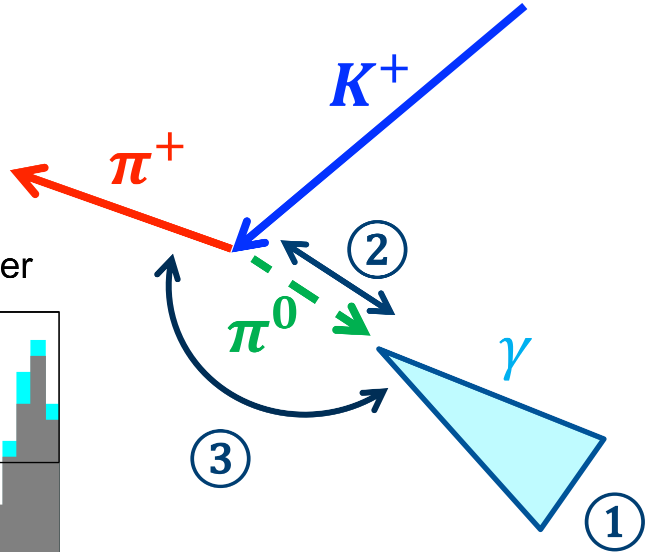
$K^+ \to \pi^+\pi^0$ with reconstructed $\pi^+$ and $\gamma$ from $\pi^0$ (unknown $\pi^0$ parent)

True opening angle of $\pi^+$ and a shower




Reco opening angle of $\pi^+$ -like track and a shower



# 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 $\nu_\mu CCK^+$ studied by 1.) BDT (page 5-6) and 2.) linear cuts (page 7-8) with MC samples
  - Better performance with BDT method: ~5.4% efficiency and ~71% purity

- ✓ BDT only selected $K^+ \rightarrow \mu^+\nu_\mu$ (BR ~64%) where $K^+ \rightarrow \pi^+\pi^0$ (BR ~21%) where all missed
  - Exclusive selection for $K^+ \rightarrow \pi^+\pi^0$ is under development with shower information.
  - Looking into details of reconstruction process to seek the cause of mis-reco $\pi^+$ events.

- ✓ Systematic error estimation ongoing as preparations for real data analysis. This estimation has been taking a long time to generate sufficient MC samples for this rare process.