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)
- **Secondment at Fermilab: 7 Apr. - Now**

- 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)
- New Perspectives Conference 2023 (in person, talk)
  (26 Jun. – 27 Jun. 2023)

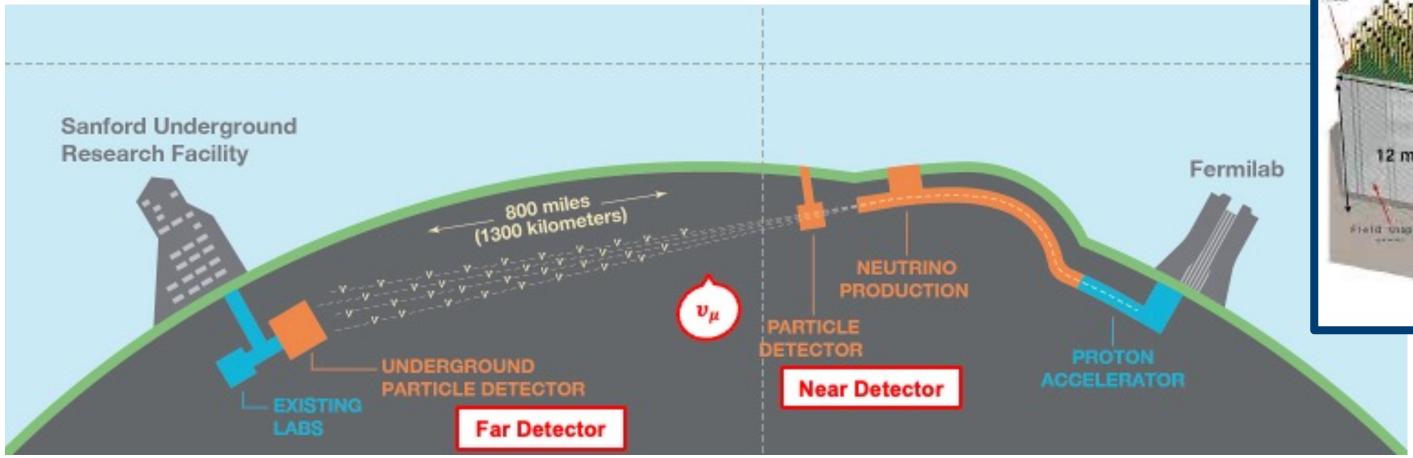
LArTPC Experiments: DUNE and MicroBooNE

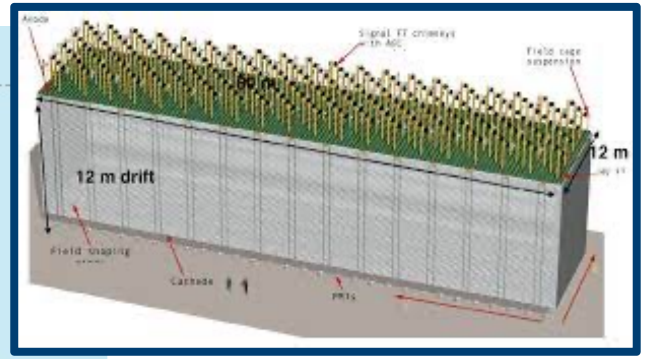
DUNE

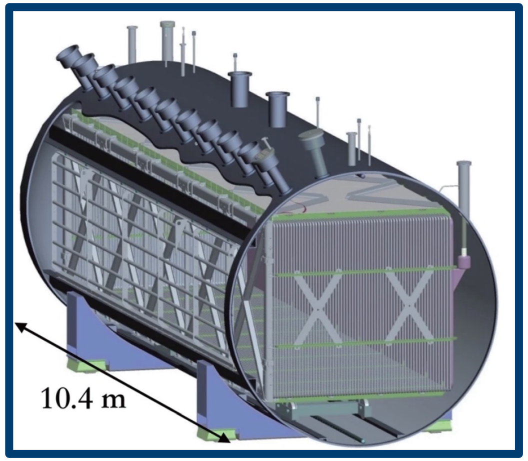
- Detector installation beginning in mid 20s
- Near and Far detectors located ~1300 km apart
  - Near detector: Complex of detectors for $\boldsymbol{\upsilon}$ properties
  - Far detector: 40 kton LArTPC with ~10^{35} of protons
- **Proton decay search: $p \rightarrow \bar{\nu} K^{+}$**

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 ~10^{24} POTs**





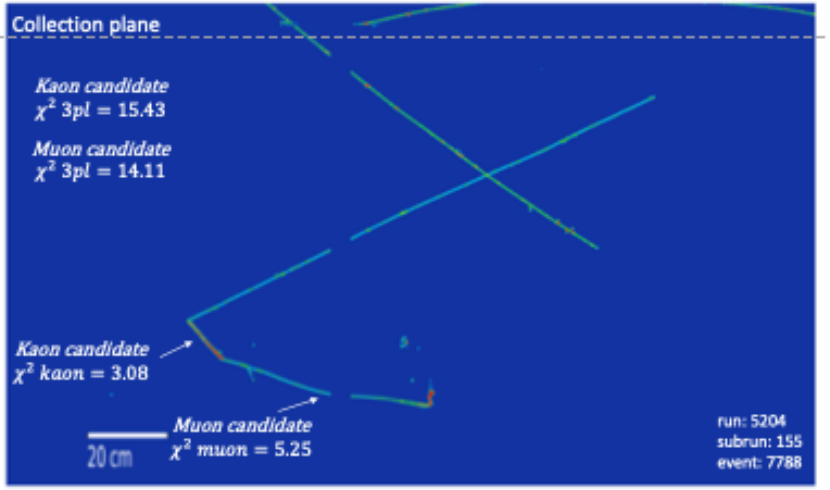


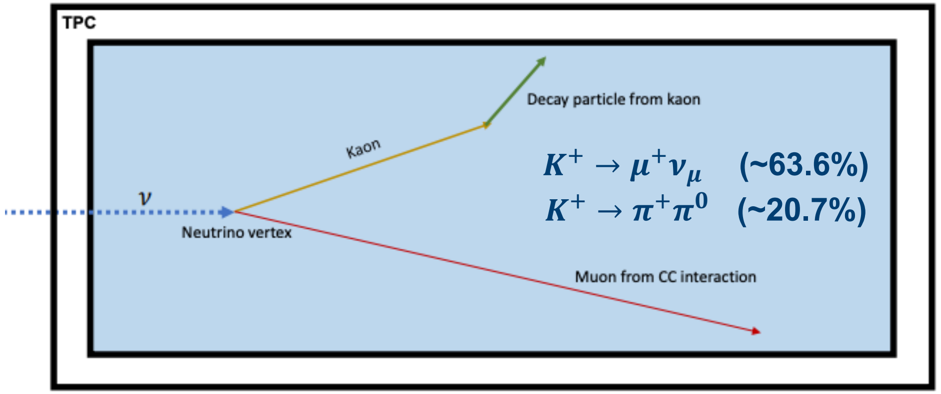
My Research: K^+ Production by CCNu Interactions in MicroBooNE

- **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. $\nu_\mu + p \to \mu^- + K^+ + \Sigma^+$
  - Single kaon production: ie. $\nu_\mu + p \to \mu^- + K^+ + p$

- **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

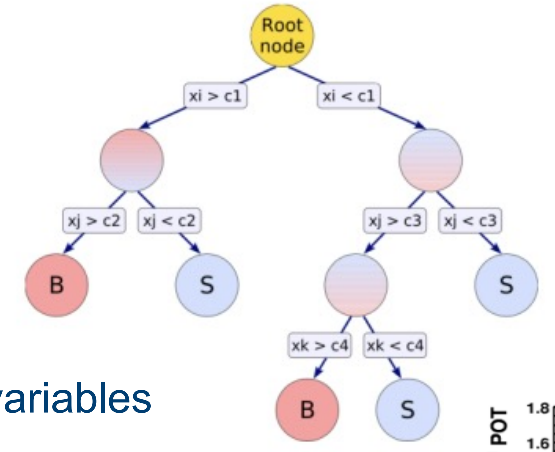




K^+ Event Features and Training by BDT

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

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

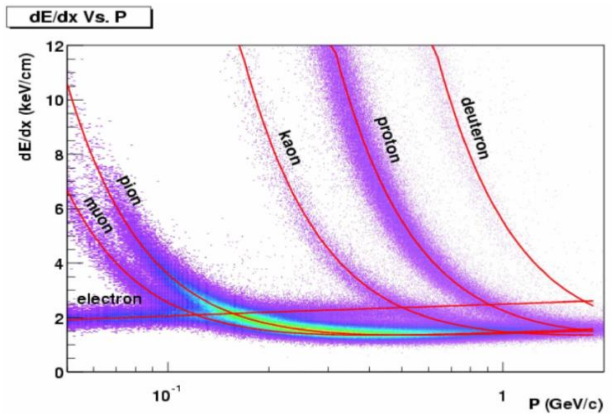


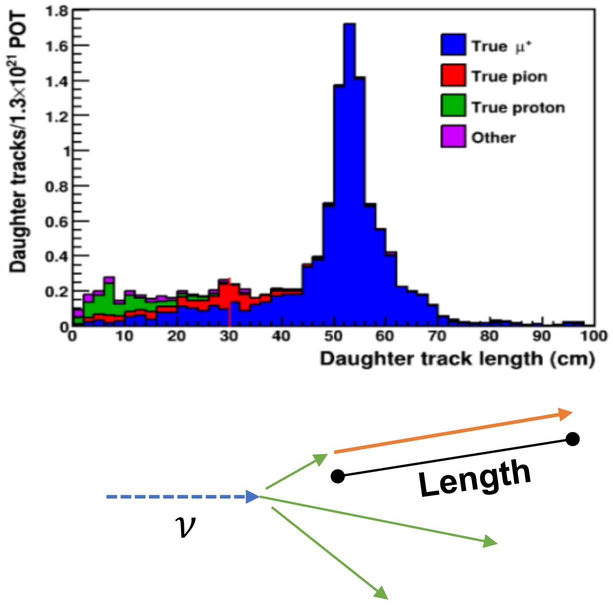
Separation with Boosted Descision Tree (BDT)

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

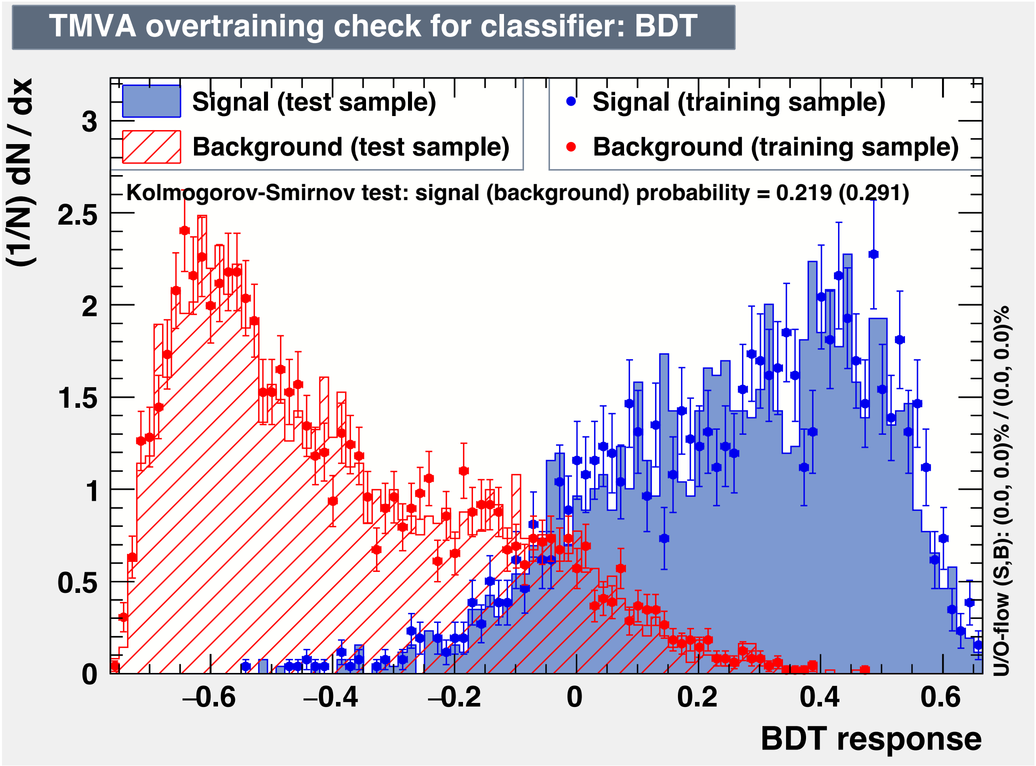
Training the BDT with MC events

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





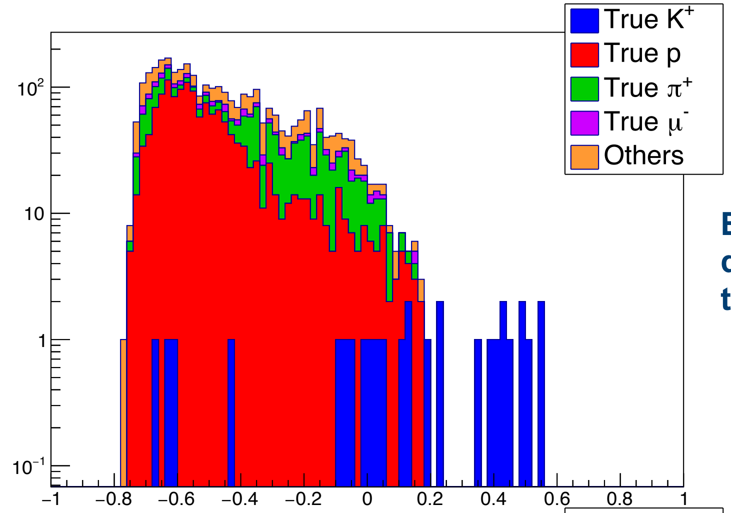
BDT Selection with MC Simulation



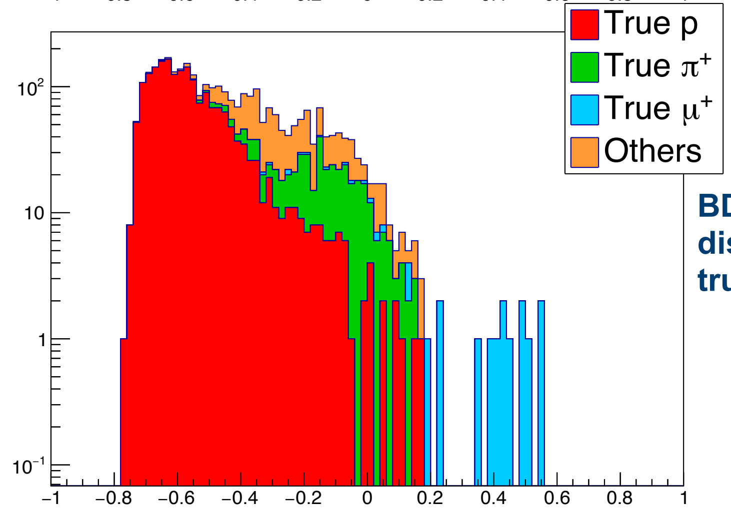
Signal: Reconstructed track has a true PDG = K^+
Reconstructed daughter has a true PDG = μ^+ or π^+

Background: !Signal

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



BDT score distribution for true track PDG

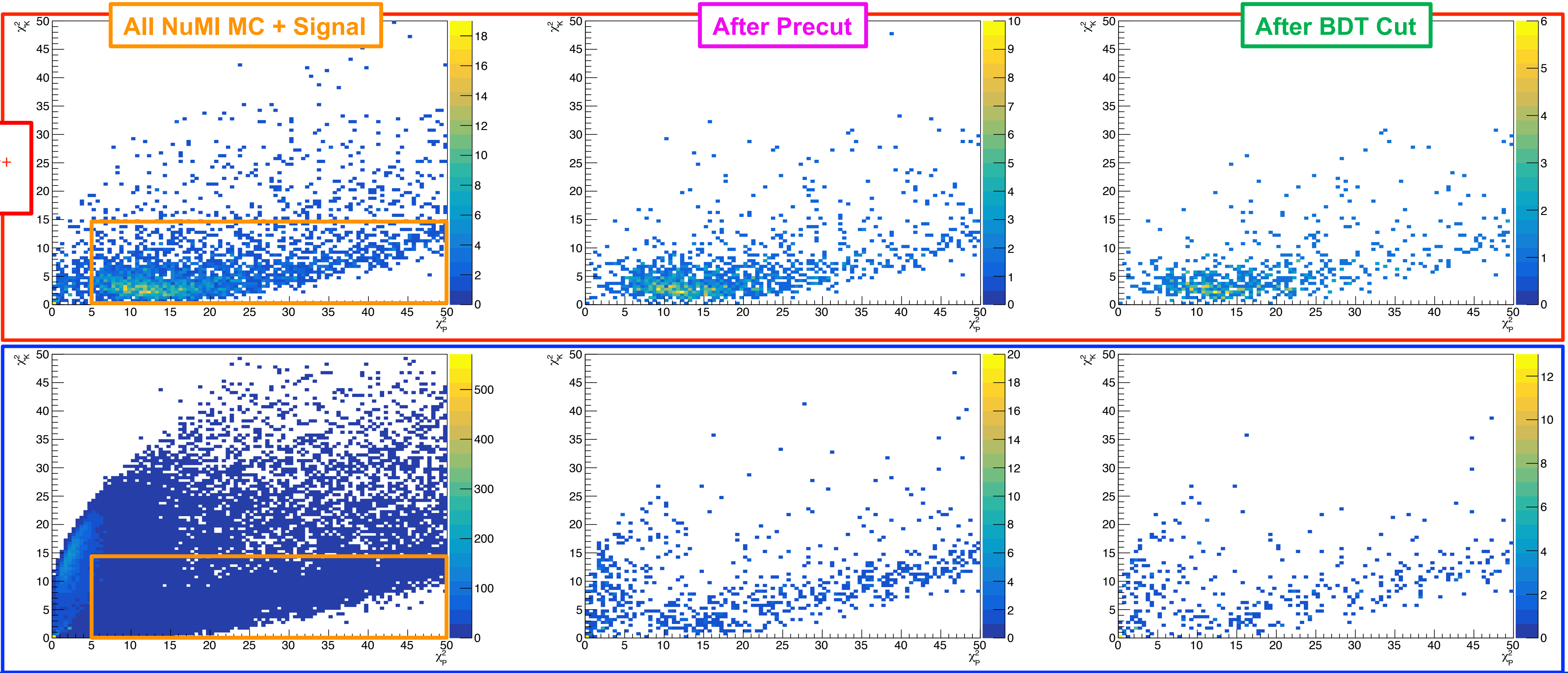


BDT score distribution for true daughter PDG

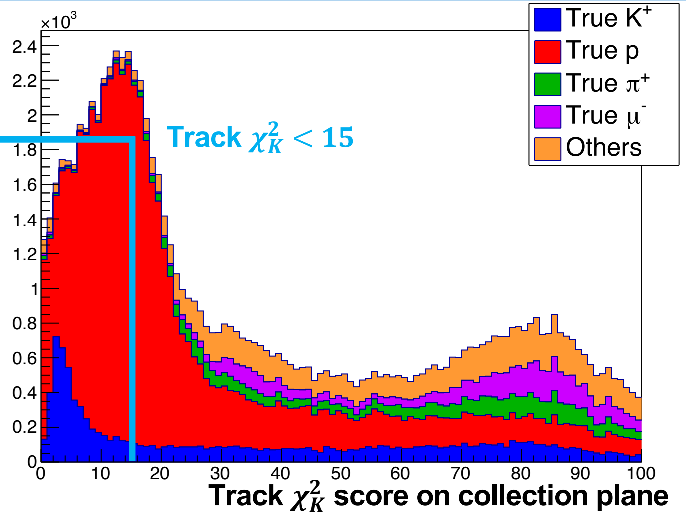
χ_p^2 vs χ_K^2 Track PID Score Plots of Collection Plane

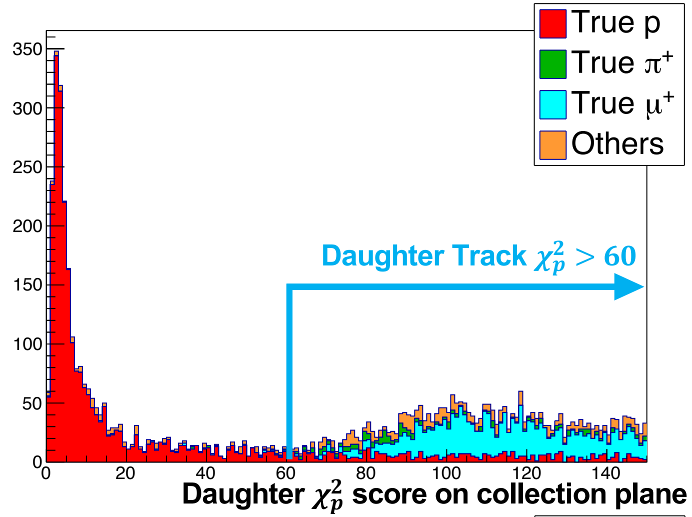
True $\nu_\mu CC K^+$ in FV

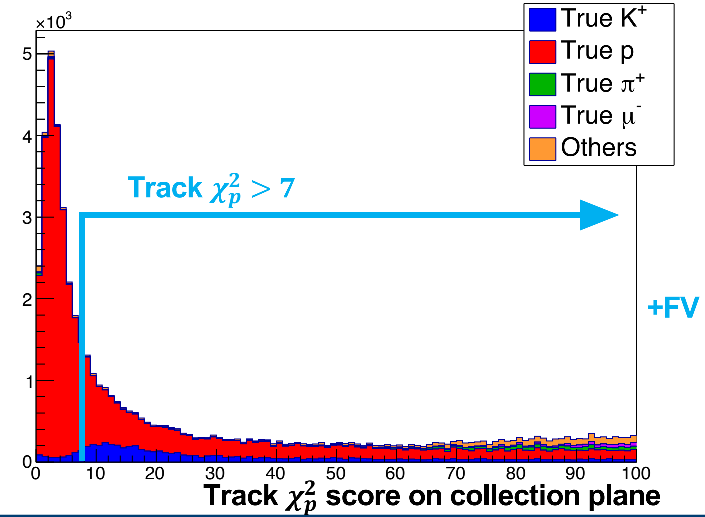
BG



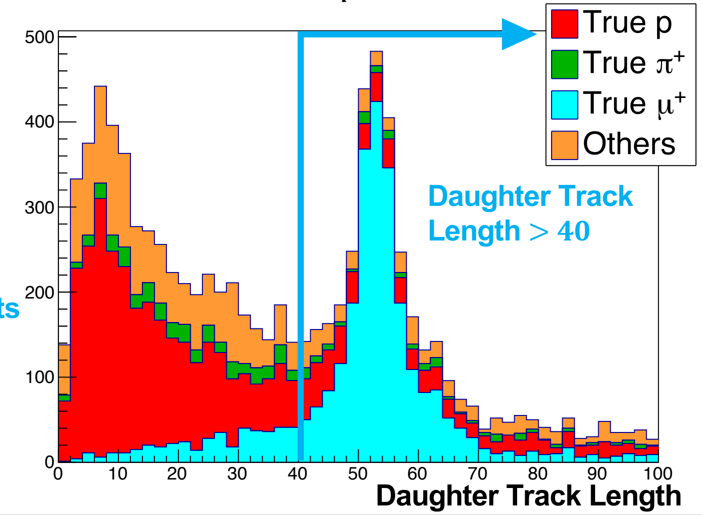
K^+ Event without BDT: χ^2 PID Scores and Daughter Track Length



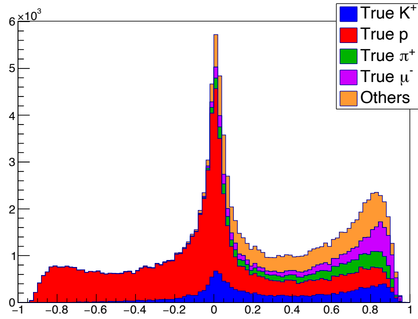




+FV Cuts

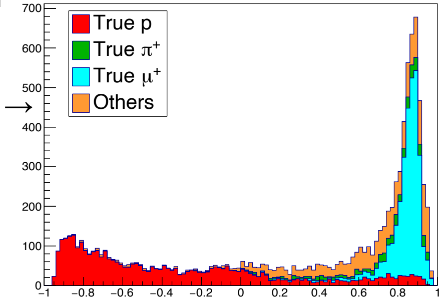


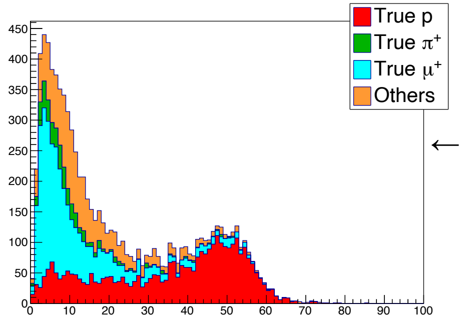
NOT USED



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

Daughter χ^2_μ score on collection plane: →
Worse separation than daughter χ^2_p score on pl2 or daughter track length





← **LLRPID for daughter track p/μ separation:**
Worse separation than daughter χ^2_p score on pl2 or daughter track length

Breakdown of BDT and χ^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

χ^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.

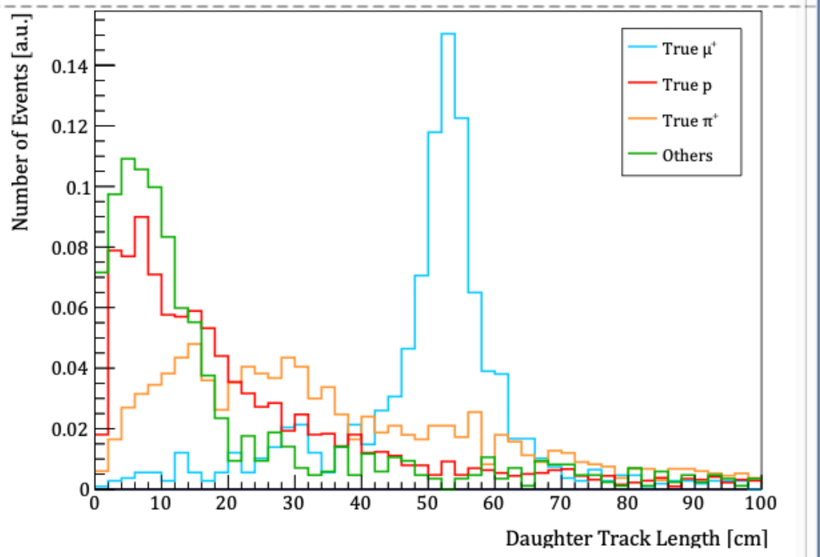
Better performance with BDT Selected Ever

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 ν_μ $Ar \rightarrow \mu^- \Sigma^0 K^+$	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 ν_μ $Ar \rightarrow \nu_\mu$	321	-13		Decay in flight

Length of daughter track

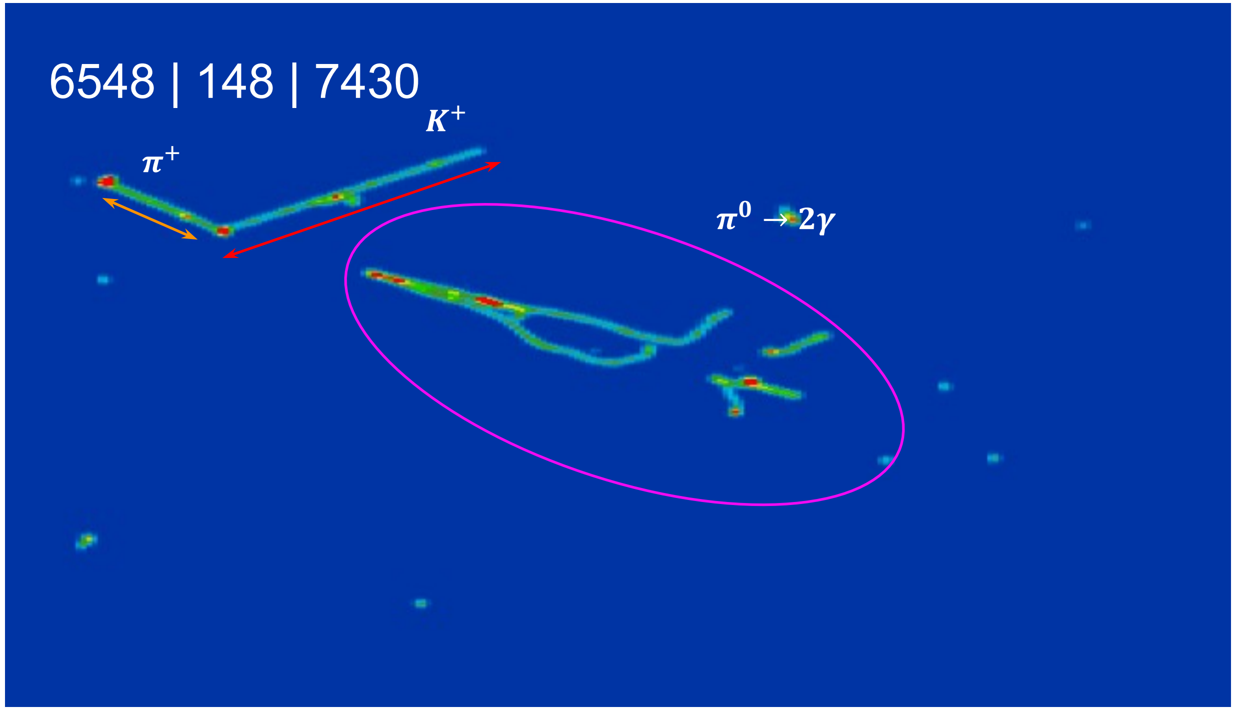
Effective for selection of μ^+ as K^+ daughter.

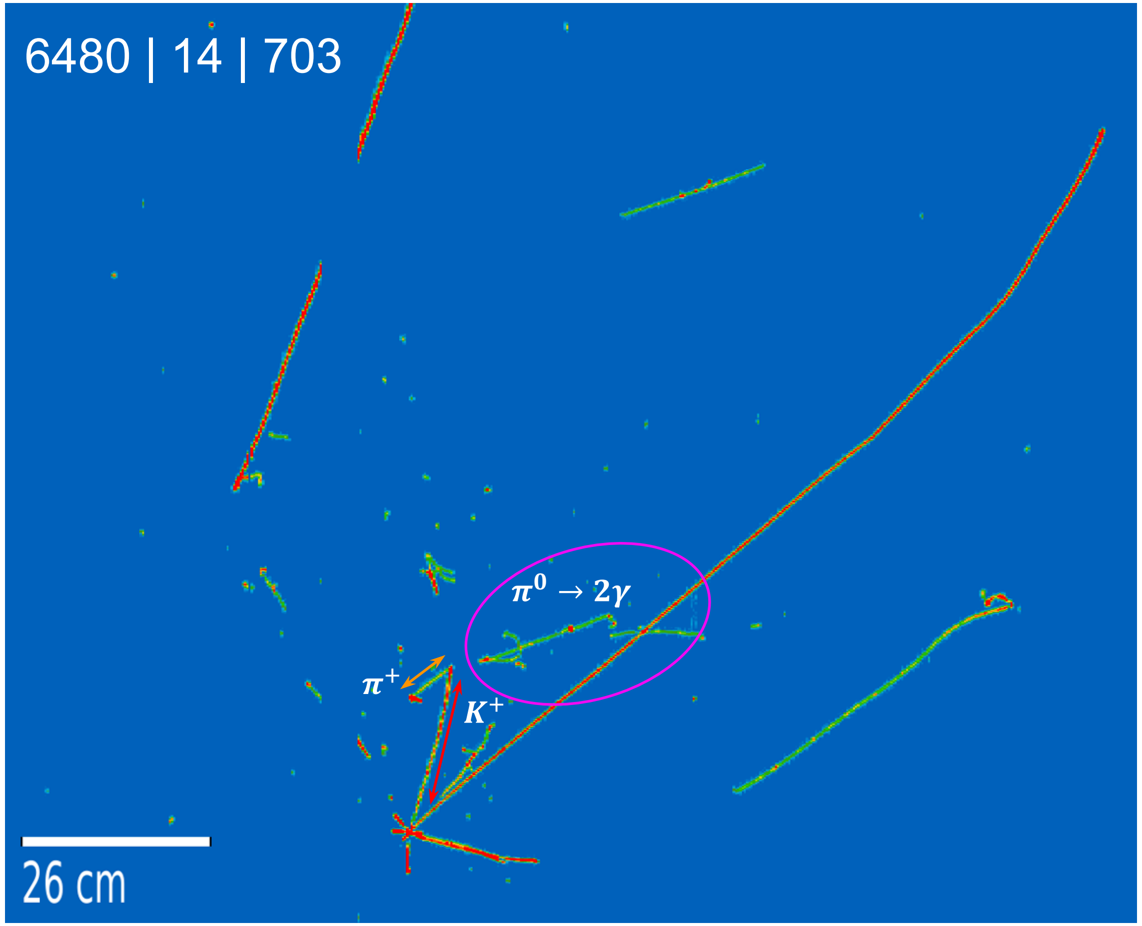


Eff: 5.4%
Pur: 71%
E*P: 0.038
BDT cut @0.19

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

Recap of two decay modes of K+

✓**Associated kaon production**:

Kaon accompanied by a hyperon in the final state

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

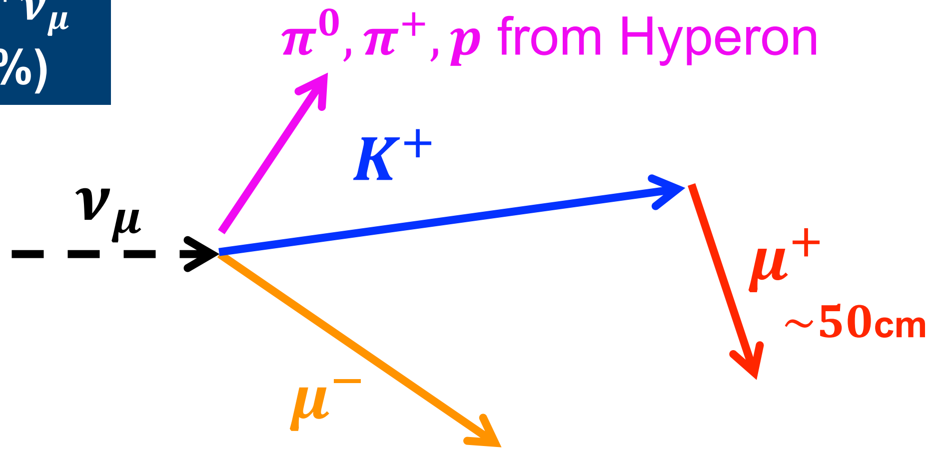
✓**Single kaon production**:

Single kaon produced in the final state

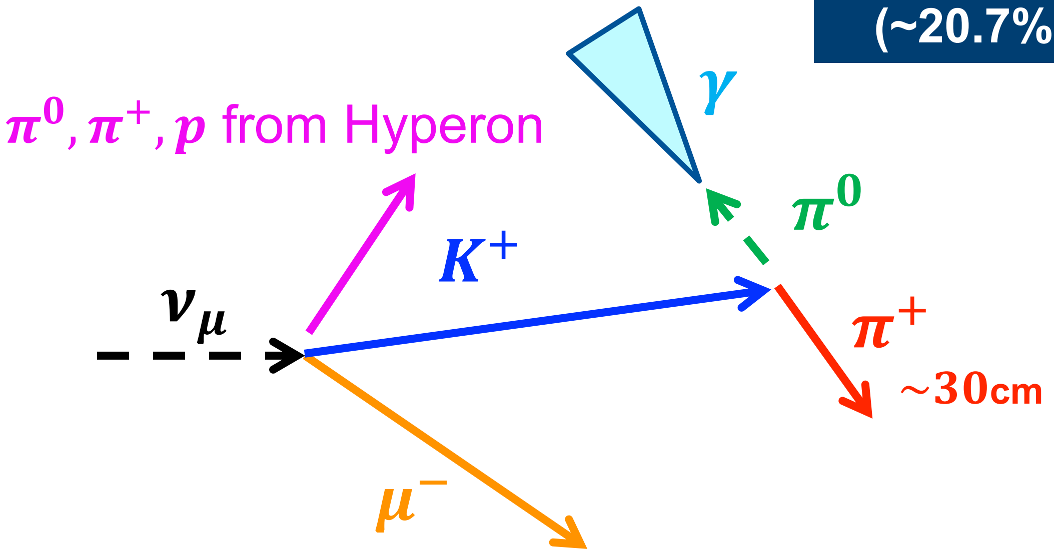
$$\nu_\mu + p \rightarrow \mu^- + K^+ + p$$

$K^+ \rightarrow \mu^+\nu_\mu$	(~63.6%)	$K^+ \rightarrow \pi^+\pi^+\pi^-$	(~5.6%)
$K^+ \rightarrow \pi^+\pi^0$	(~20.7%)	$K^+ \rightarrow \pi^0 e^+\nu_e$	(~5.0%)
		$K^+ \rightarrow \pi^+\pi^0\pi^0$	(~1.8%)

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

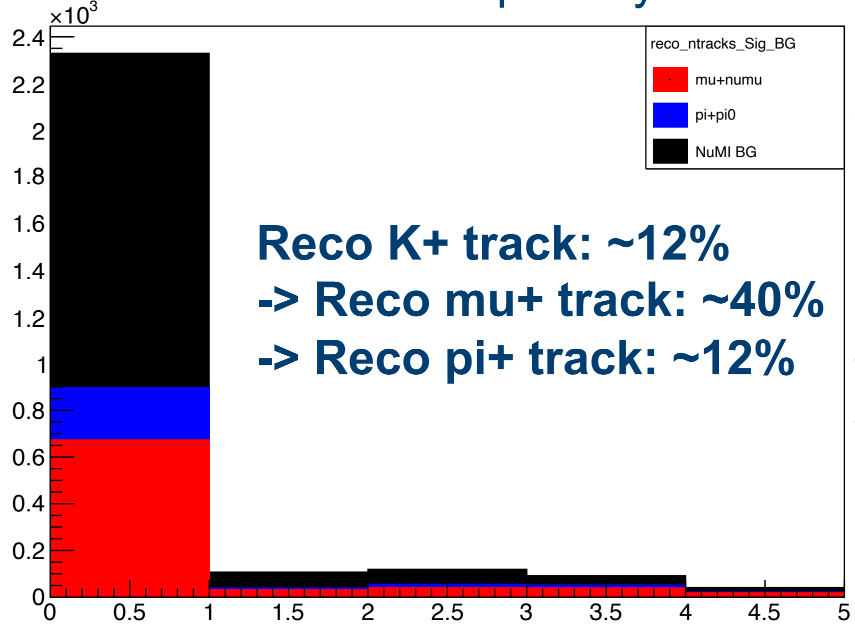


$K^+ \rightarrow \pi^+\pi^0$ (~20.7%)

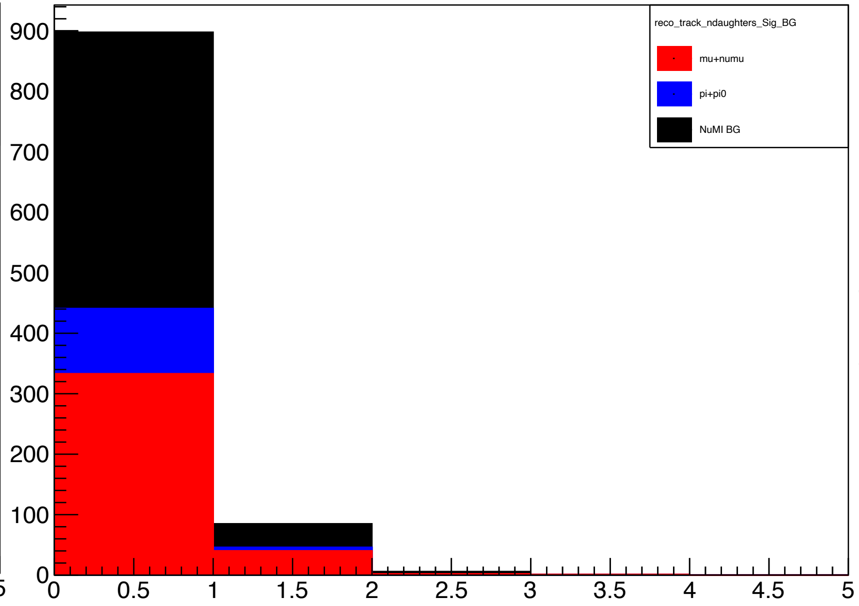


Mis-reconstruction in Asso K+ MC

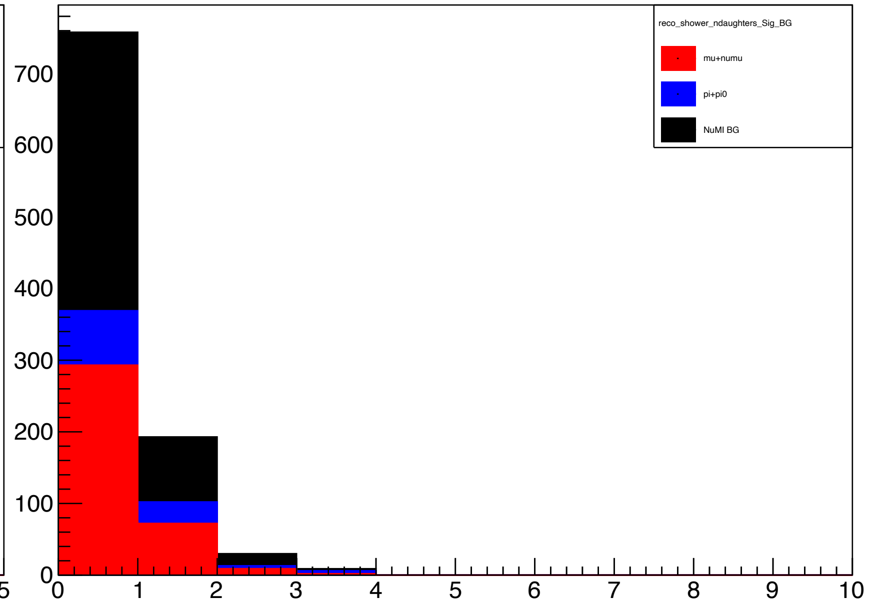
#Reconstructed primary track



#Reconstructed daughter track



#Reconstructed daughter shower



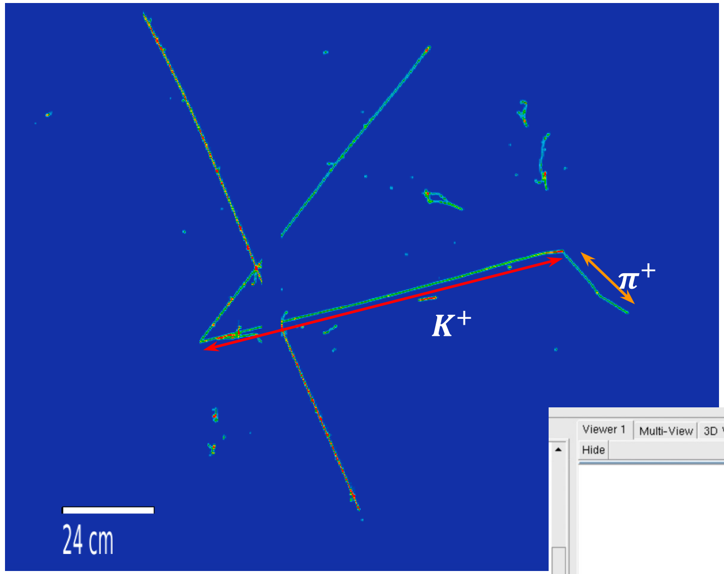
In True Associated K+ MC:

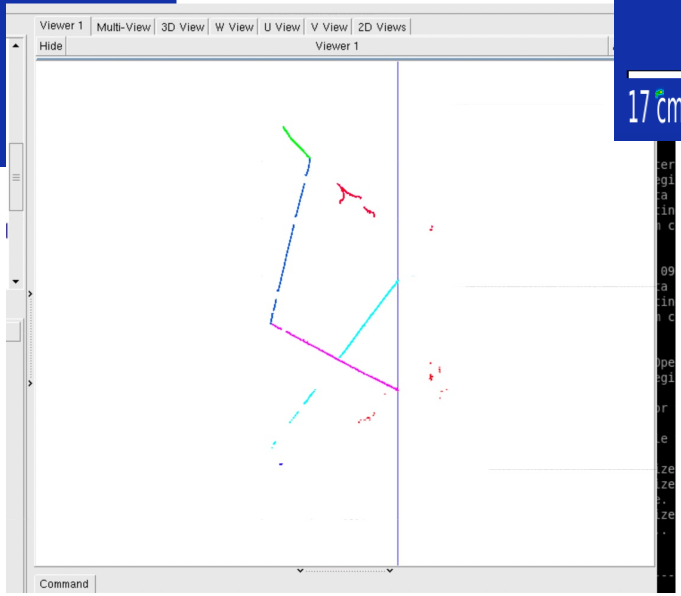
- 16% has reconstructed vtx
- 12% has reconstructed primary K+ track
- For K+ -> mu+, 5% has both reconstructed K+ and mu+ tracks
- **For K+ -> pi+, 1% has both reconstructed K+ and pi+ tracks**

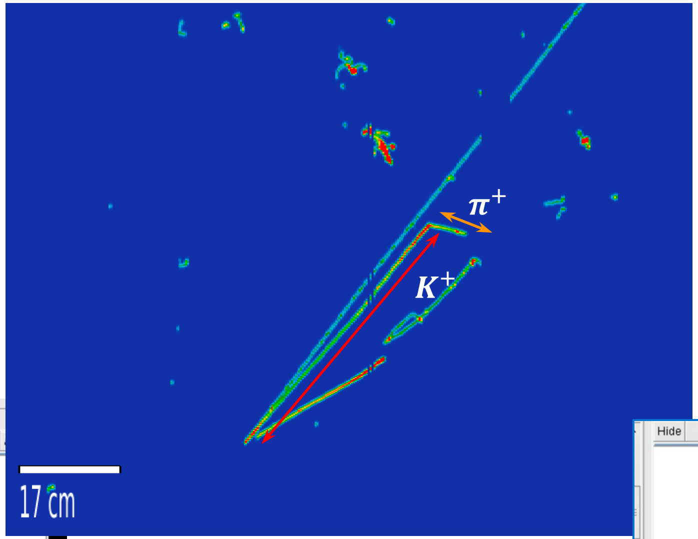
Daughter track def.: gap between end of mother track and its beginning is less than 10cm
Daughter shower def.: gap between end of mother track and its beginning is less than 15cm

***CC Mu- track is excluded from primary track**

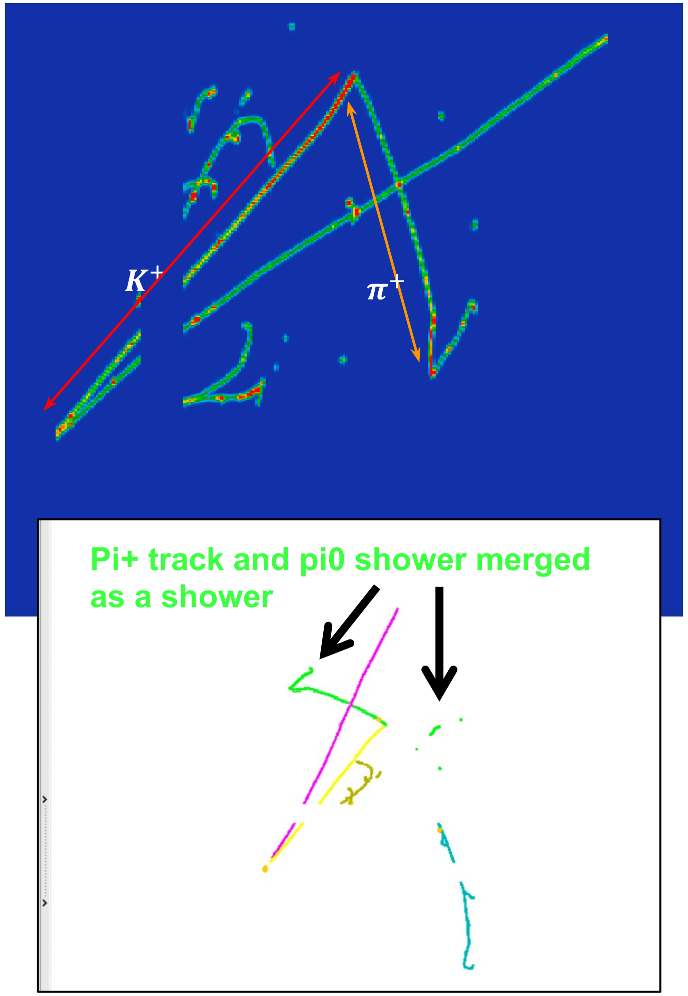
Reco K+ & Reco Pi+ (K+ Signal Sample MC)

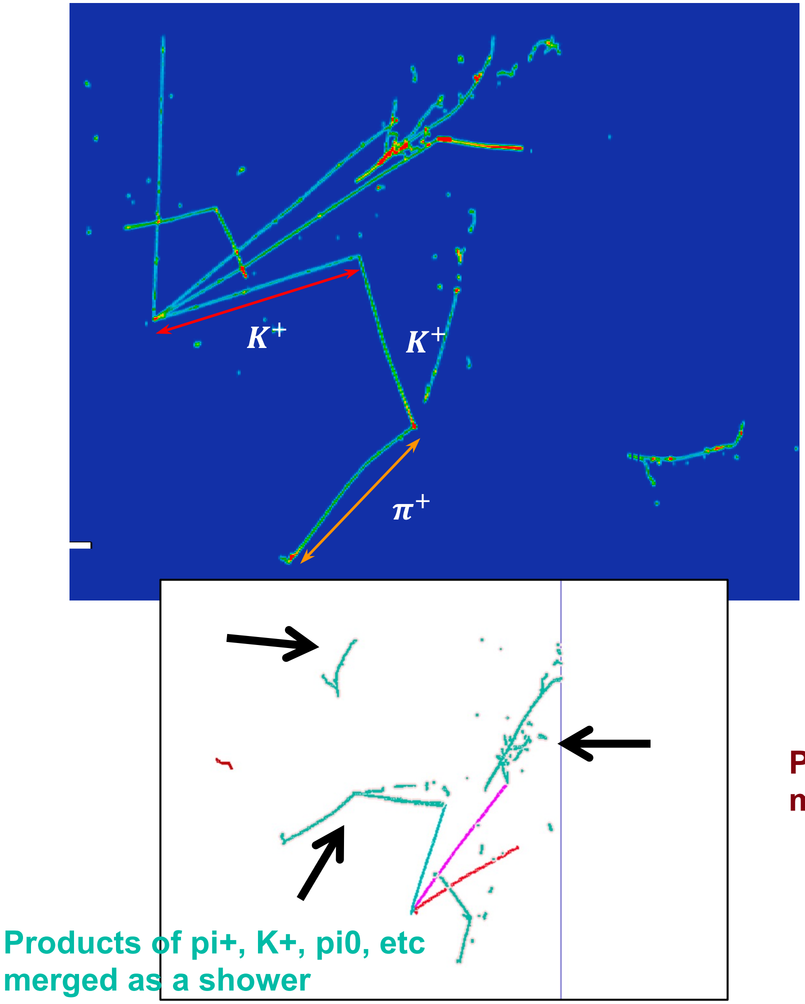


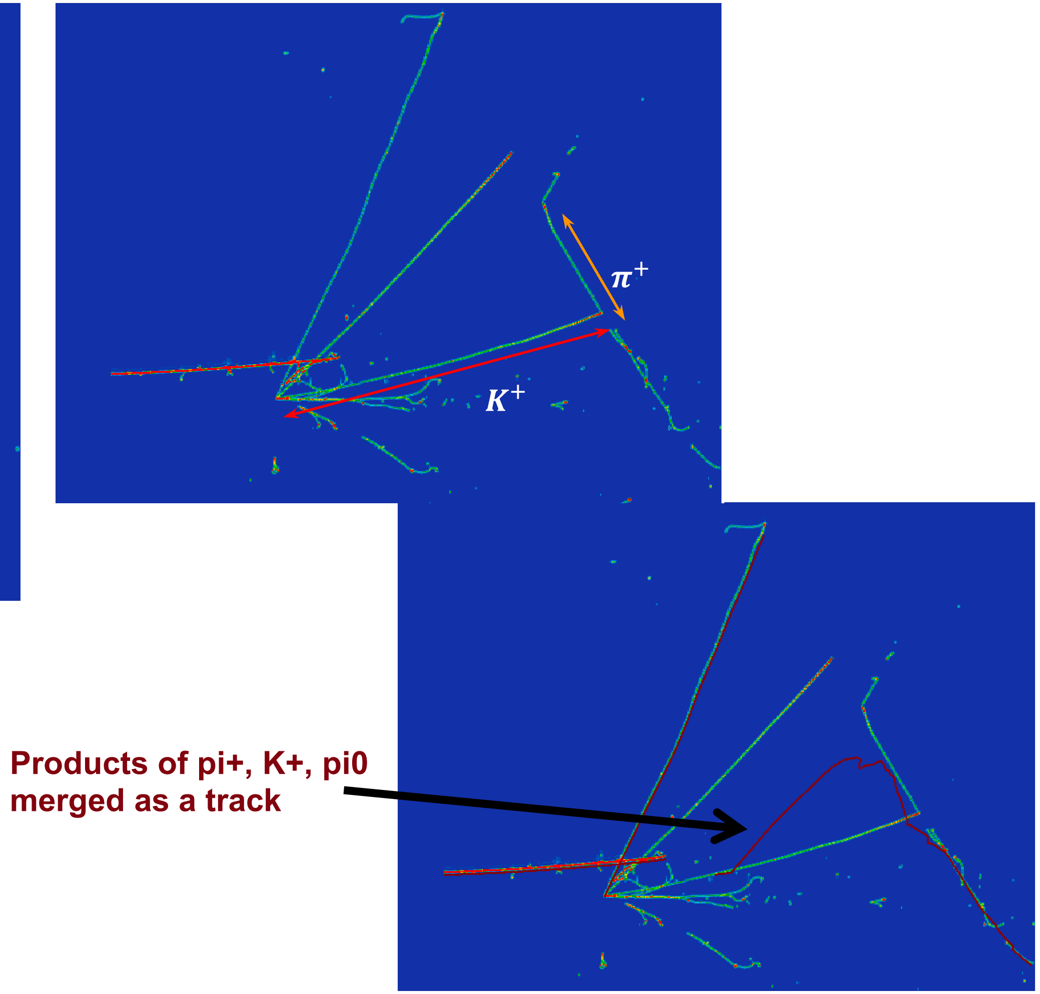




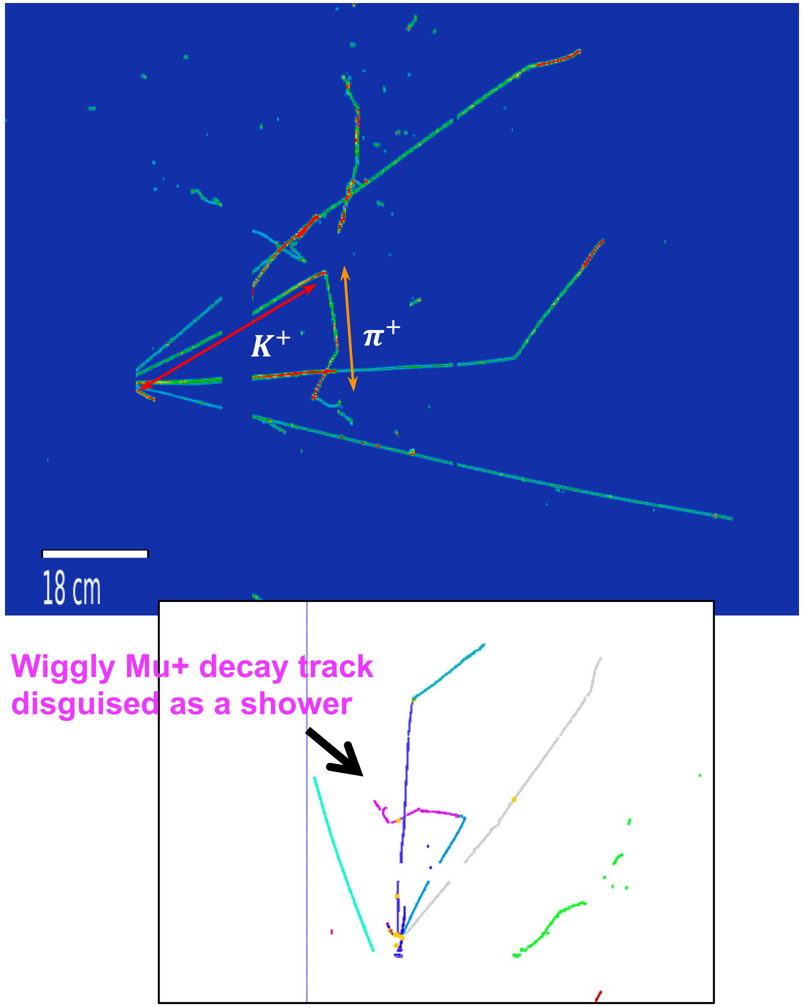
Mis-Reco Pi+: Merging into a shower/track



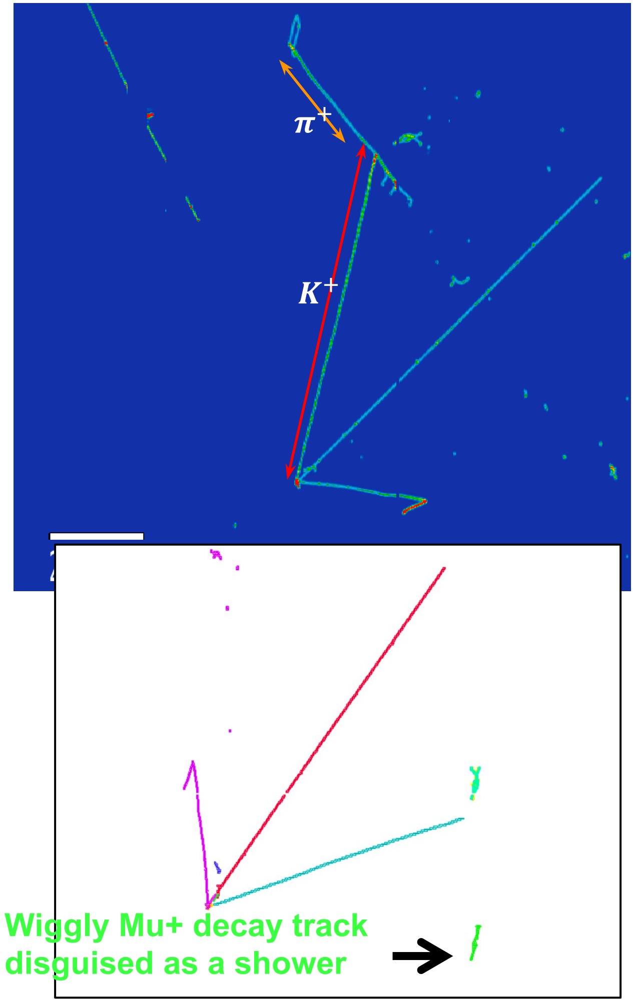




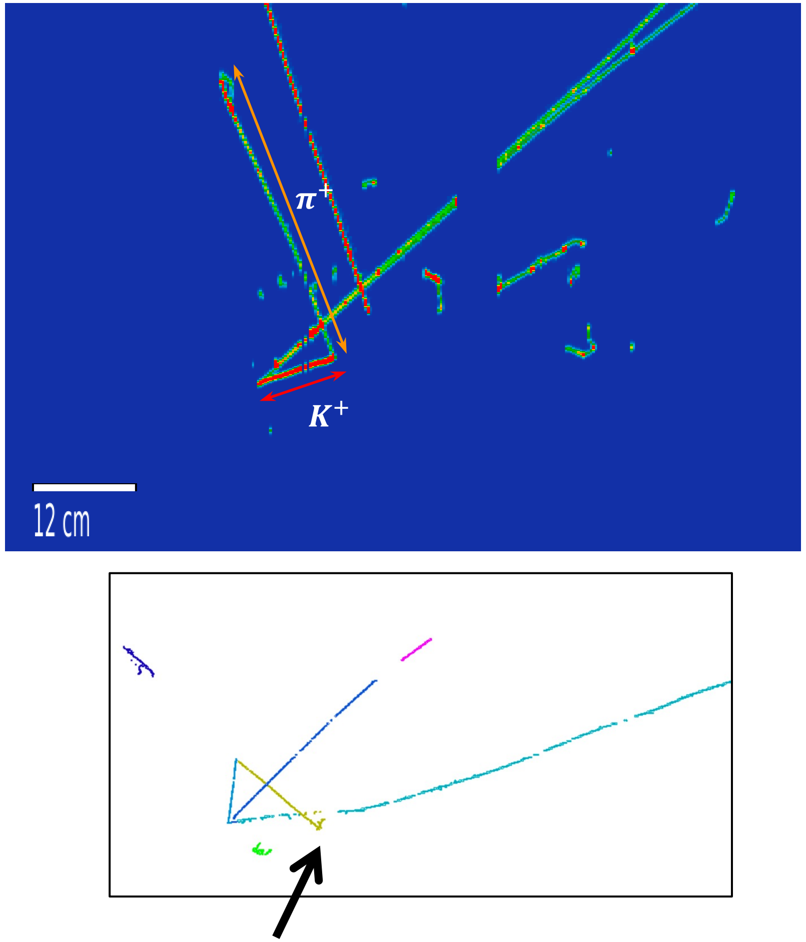
Mis-Reco Pi+: Reconstructed as a shower



Wiggly Mu+ decay track disguised as a shower

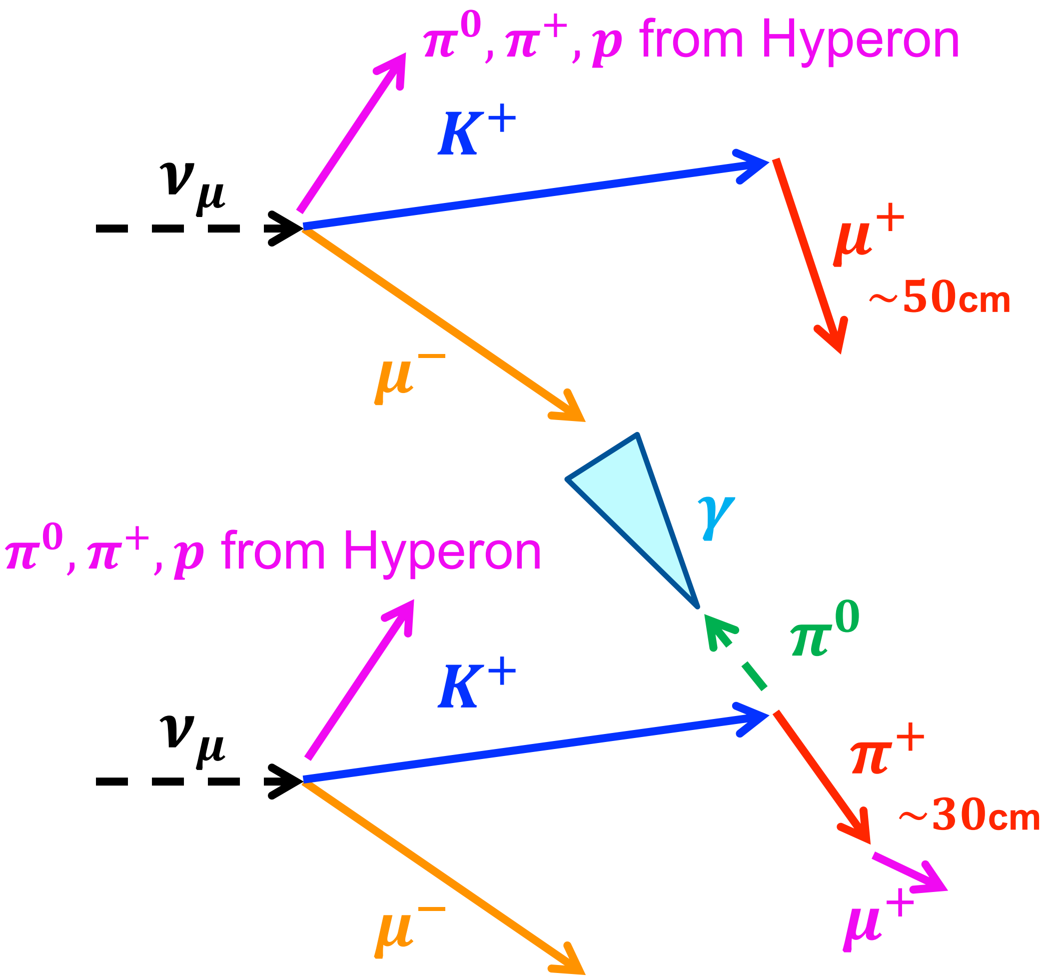


Wiggly Mu+ decay track disguised as a shower

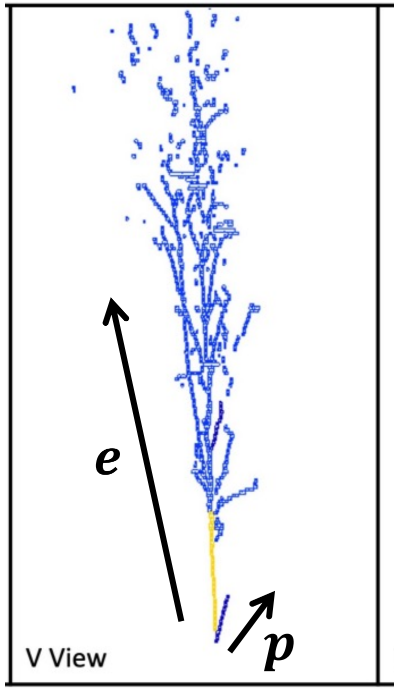


Wiggly Mu+ decay track disguised as a shower

Reconstruction Improvement Idea : Finding Connection Hits



Mu+ and pi+ are generated from K+, creating continuous hits from the end of K+ track



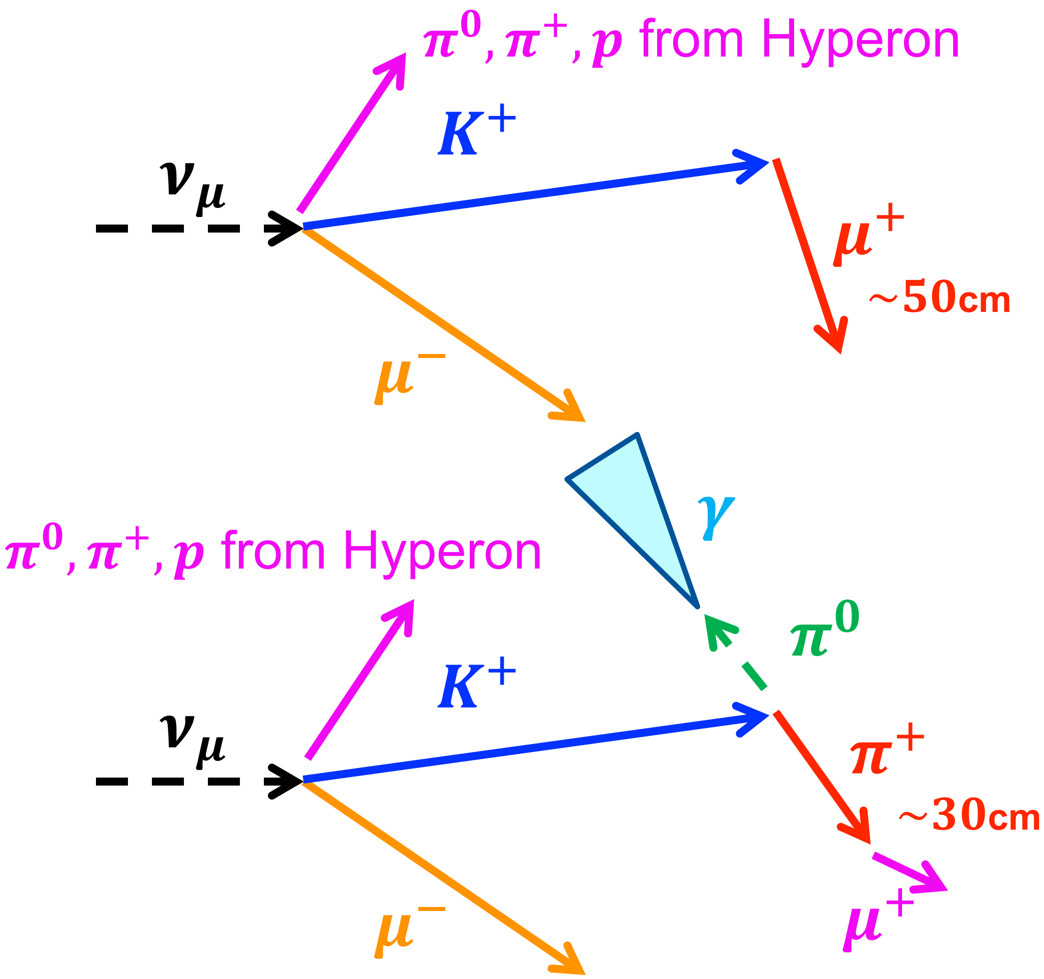
Isobel Mawby's PhD study at DUNE: Shower refinement algorithm for CCNuE

- Electron showers disconnected from initial track-like region
- Photon showers merge into e shower

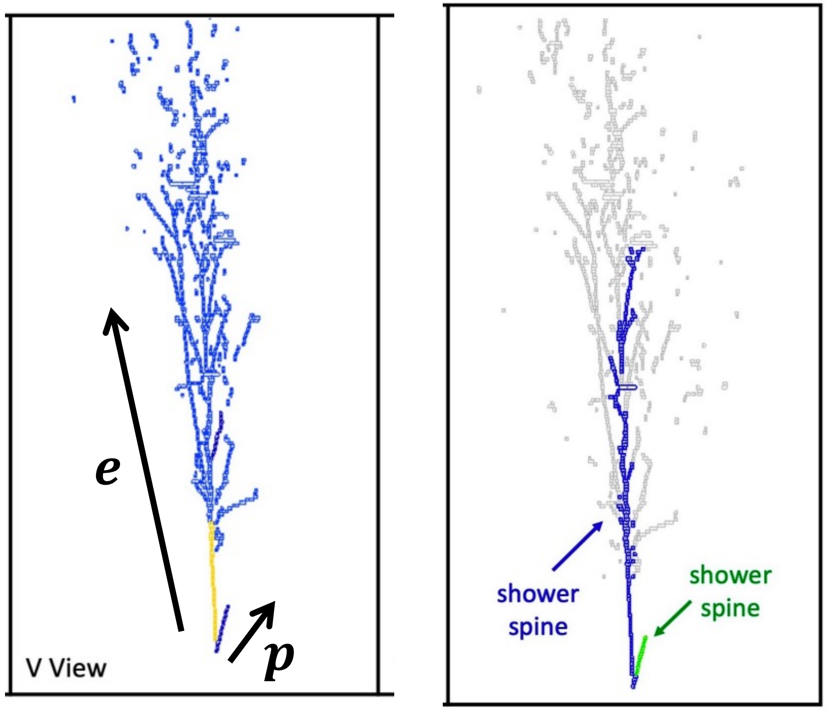
➢ Walk along the spine and find pathways look connected to the shower from nu vtx

➢ Select (remove) hits originated from e (photon)

Reconstruction Improvement Idea : Finding Connection Hits



Mu+ and pi+ are generated from K+, creating continuous hits from the end of K+ track



at DUNE:
t algorithm for CCNuE

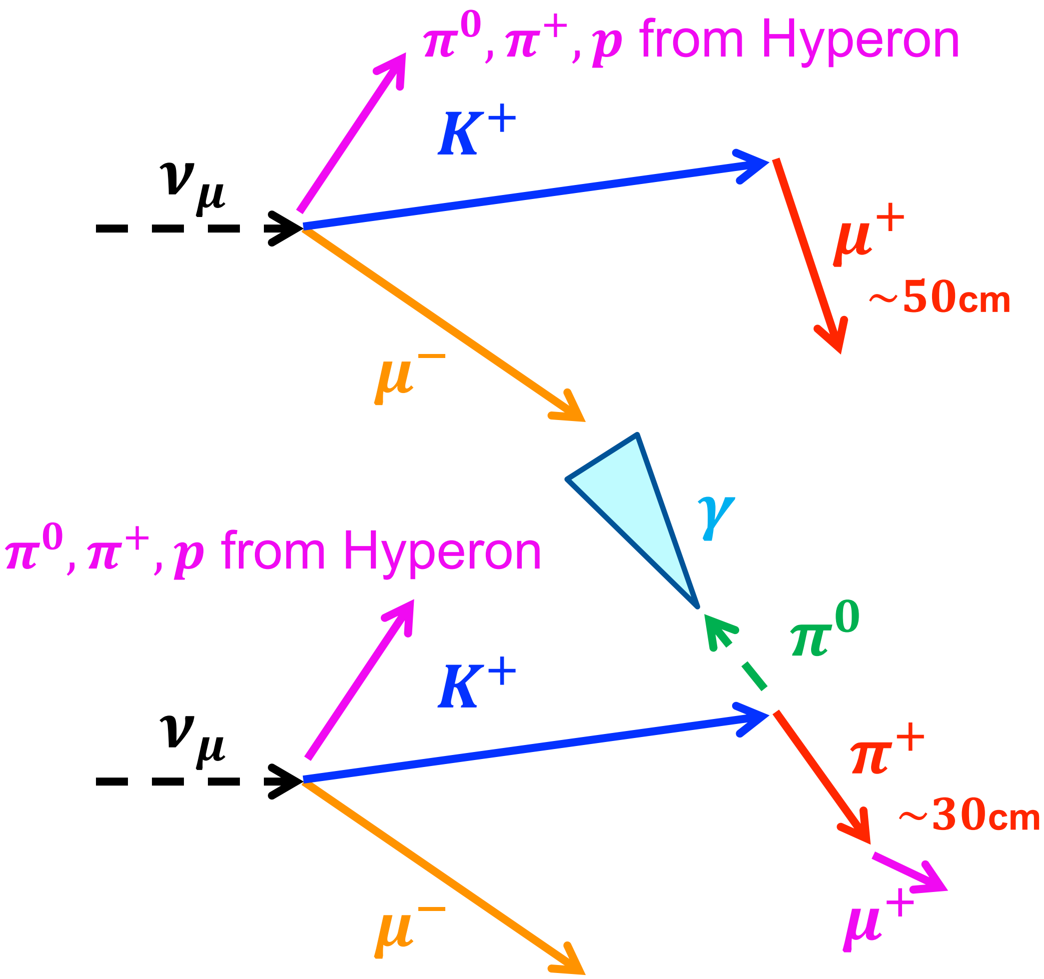
s disconnected from
region

merge into e shower

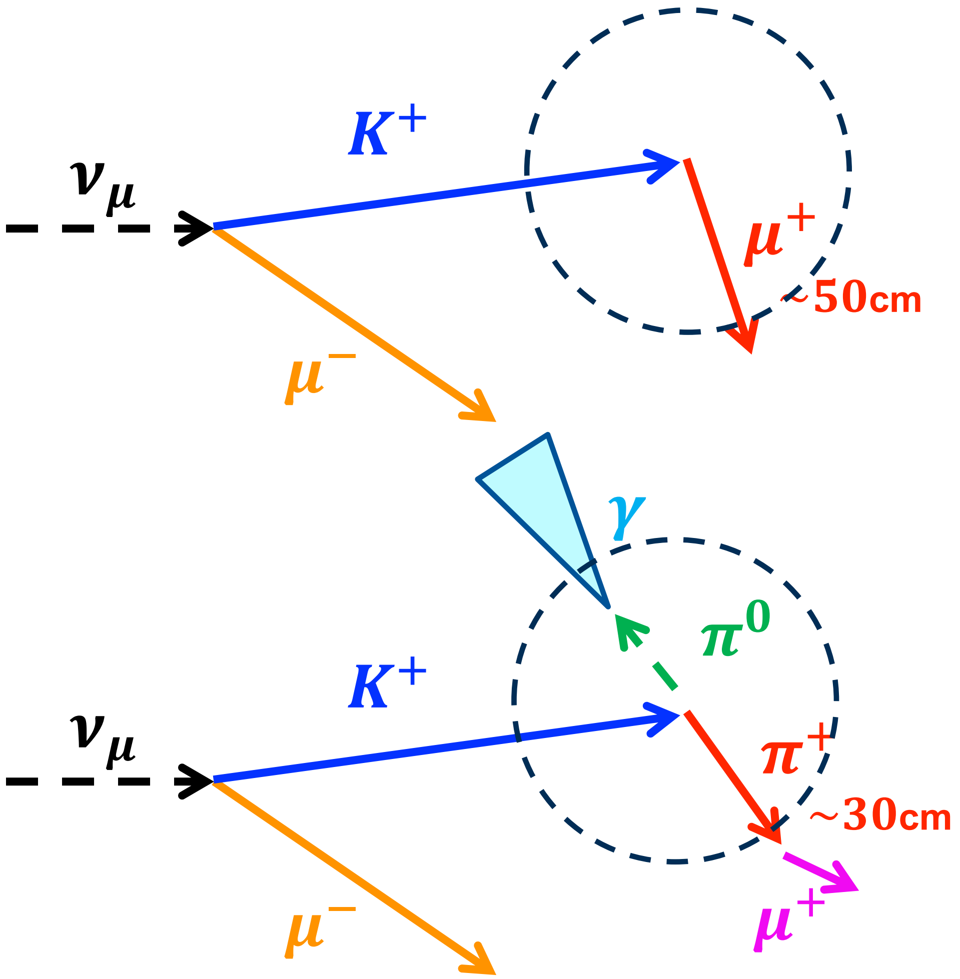
spine and find pathways
to the shower from nu

hits originated from e
(photon)

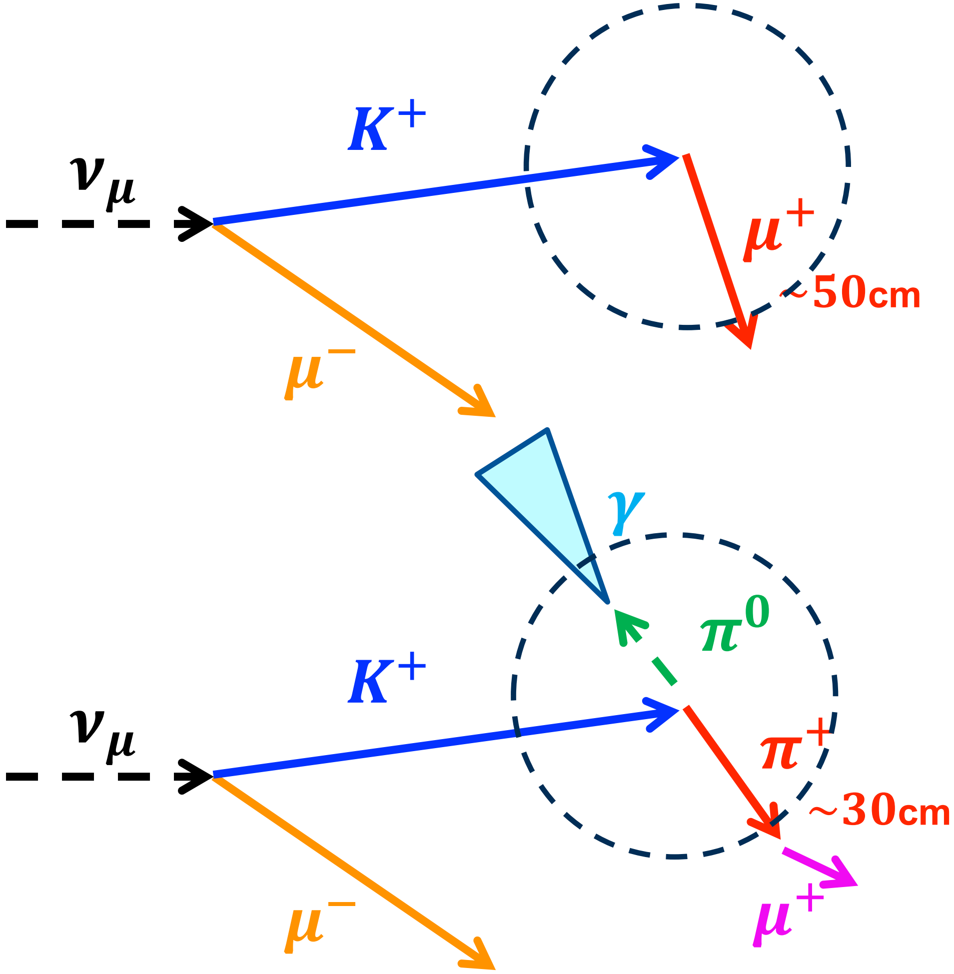
Idea of getting connected hits

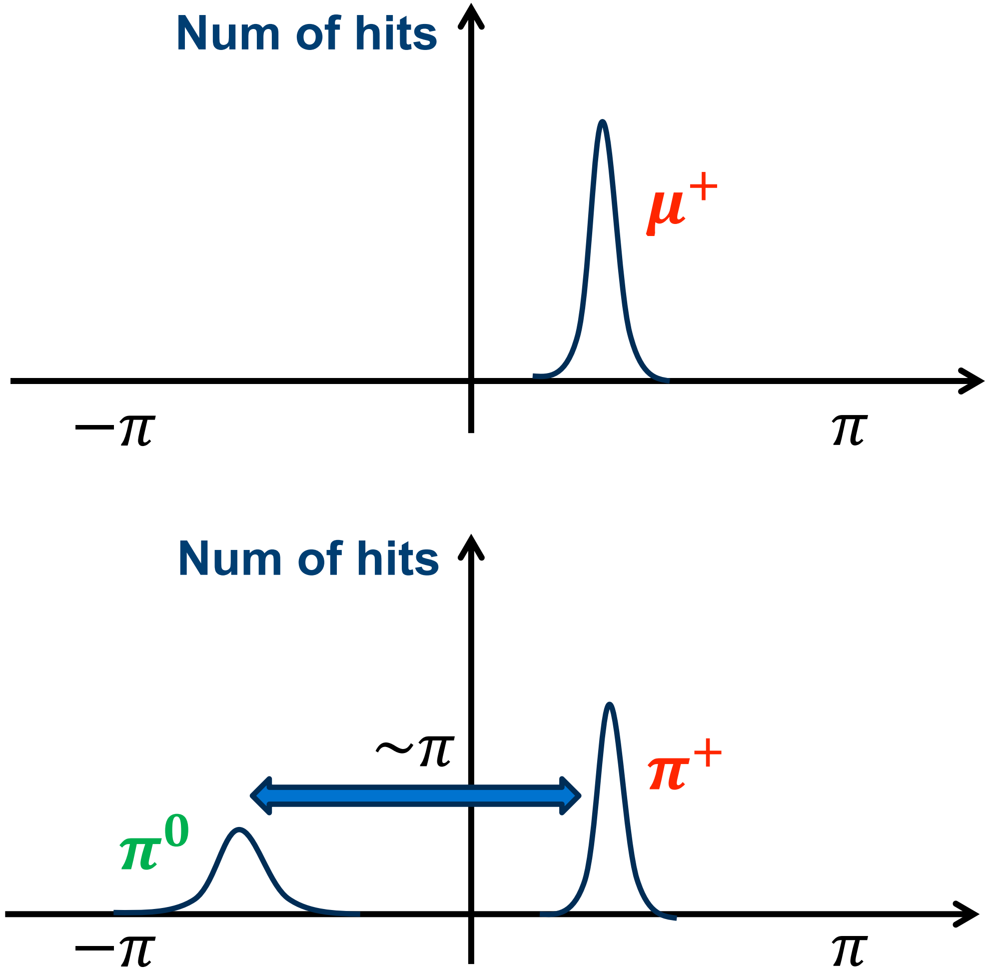


Define region of interest

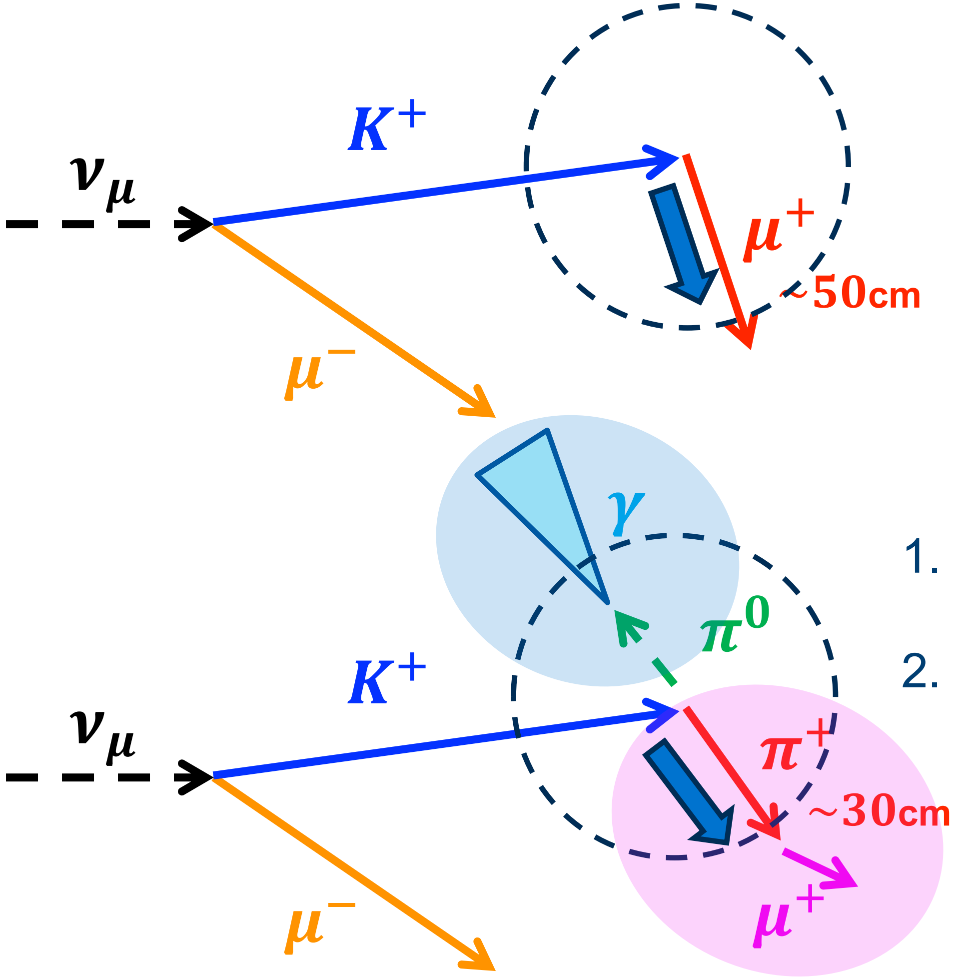


Get angular distribution of hits

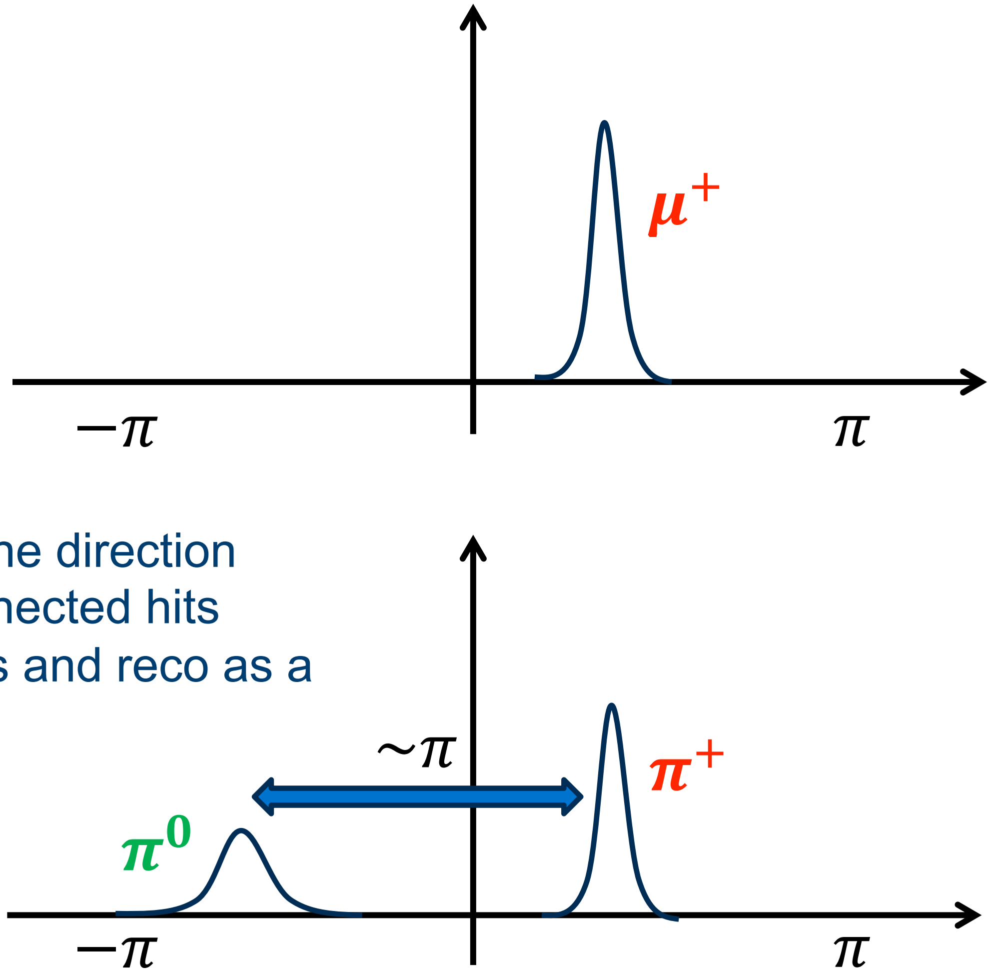




Get angular distribution of hits

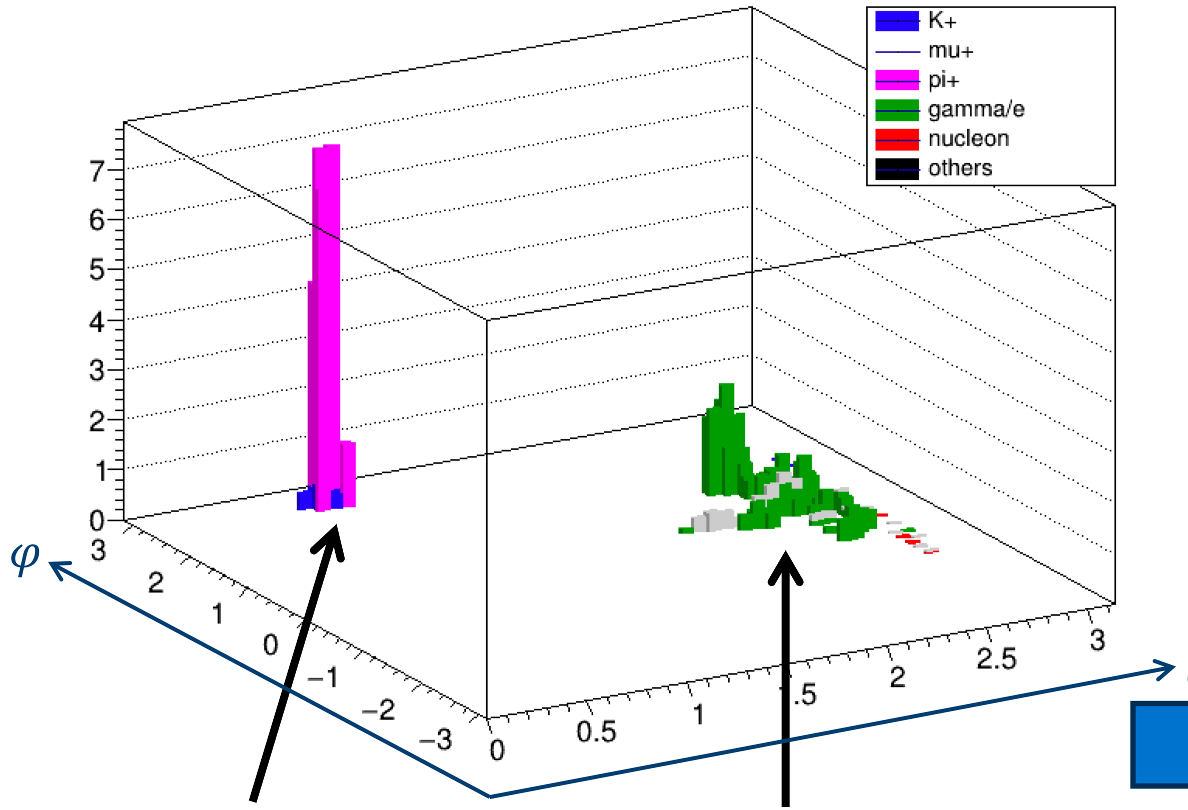


1. Walk along the direction and find connected hits
2. Separate hits and reco as a track/shower



Separating Hits for π^+/π^0 from $K^+ \rightarrow \pi^+\pi^0$

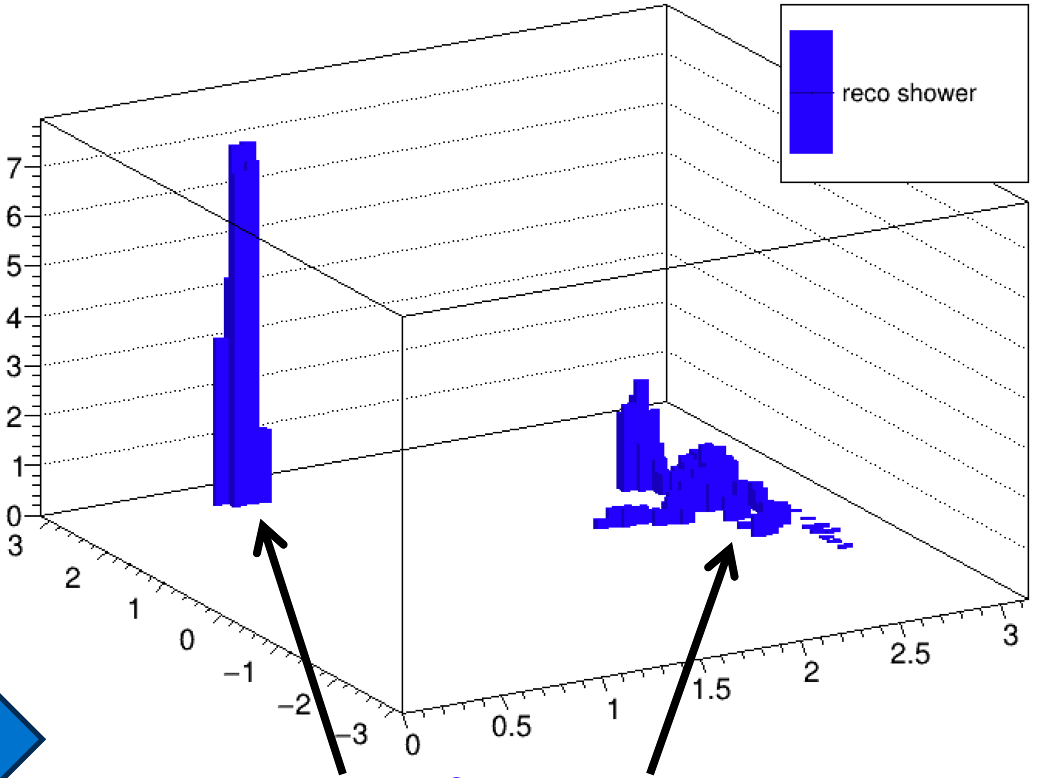
TRUE



Hits from π^+ track

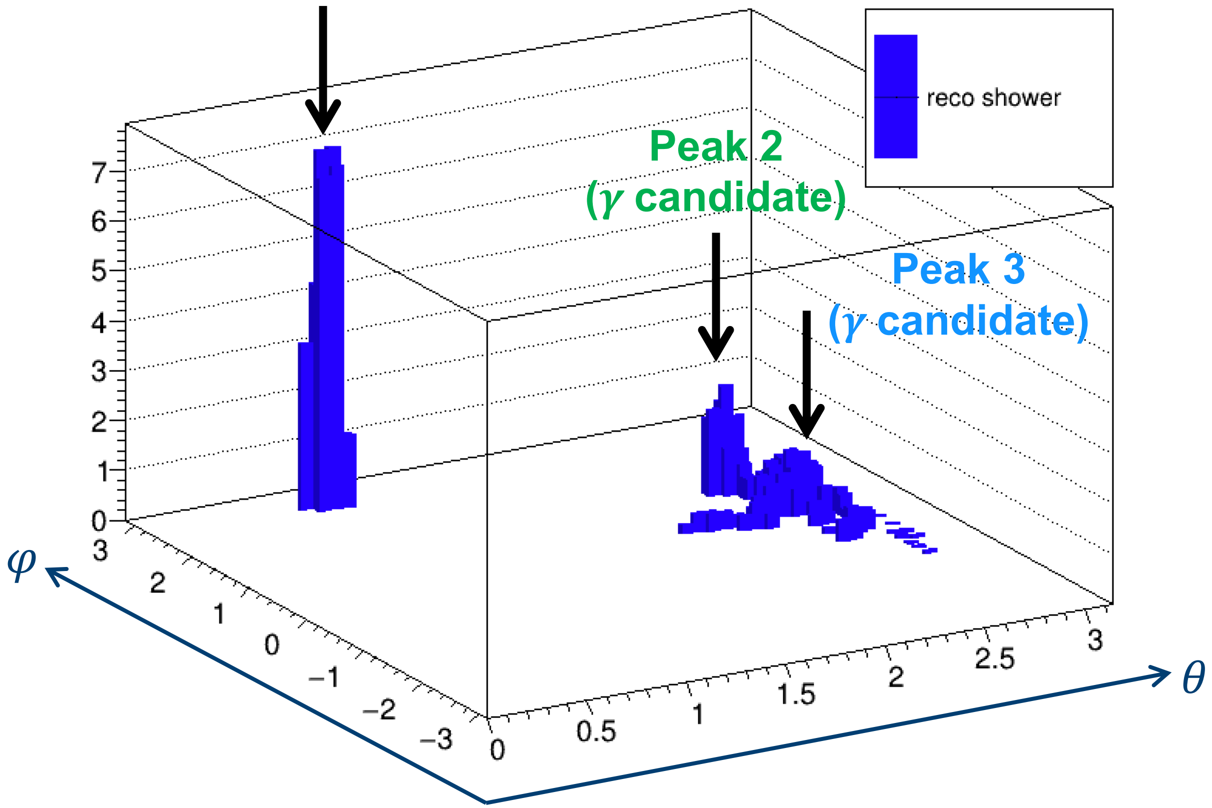
Hits from π^0 shower

RECONSTRUCTION



π^+ and π^0 are merged and reconstructed as a shower

Separating Hits for π^+/π^0 from $K^+ \rightarrow \pi^+\pi^0$



1. Make angular hit distribution as left plot
2. Find peaks as a pi+ track candidate and gamma shower candidate(s) from pi0 decay
3. Obtain directions for all candidates
4. Calculate the opening angle between pi+ and pi0 candidates
   $\rightarrow$ True $K^+ \rightarrow \pi^+\pi^0$ event should have large angle $\sim\pi$

This algorithm is under development

Summary and Future Plans

- ✓ K^+ production cross section measurement would be the key for future proton decay study at DUNE
- ✓ Event selection for $\nu_\mu CCK^+$ studied 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
- ✓ Causes of mis-reconstruction for pi+:
  - Merged into a shower/track with other particles
  - Reconstructed as a shower
- ✓ Exclusive selection for $K^+ \rightarrow \pi^+\pi^0$ is under development with shower information.
  - Get the angular distribution of hits from K+ track end to separate π^+/π^0
  - Apply BDT after this hit selection to select $K^+ \rightarrow \pi^+\pi^0$ events exclusively