Kaon Production Study with MicroBooNE and DUNE

ESR Monthly Update
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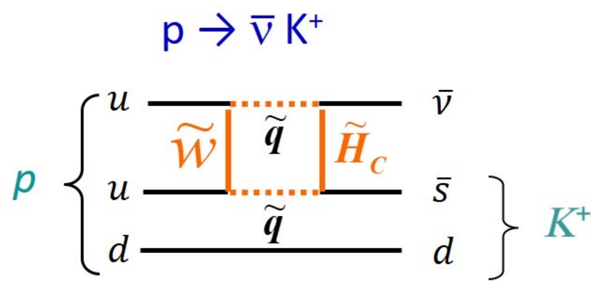
K^+ cross section measurement: Why Kaons?

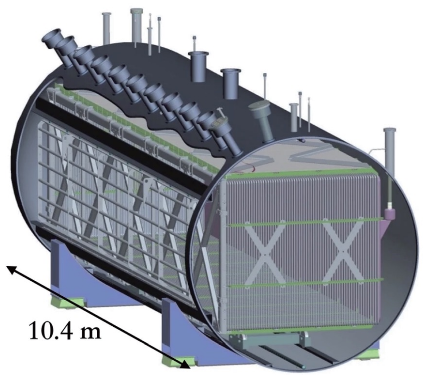
Importance of K^+ study:

- Nucleon decay modes involving K^+ at final states
- Provide better understanding of K^+ inside LArTPC
- No K^+ xsec on Ar or other targets at 1 GeV ν energy region



MicroBooNE Experiment

- 85 ton LArTPC running 2015 - 2021
- 0.25-2 GeV ν beam from the Booster Neutrino Beam (BNB) and the Neutrino Main Injector (NuMI)
- My Analysis: CC K^+ production analysis with NuMI
  - K^+ selection by BDT
  - Reconstruction Algorithm exclusive for K^+ daughters



MicroBooNE detector

Overview of K^+ Production

✓**Associated kaon production**:

Kaon accompanied by a hyperon in the final state

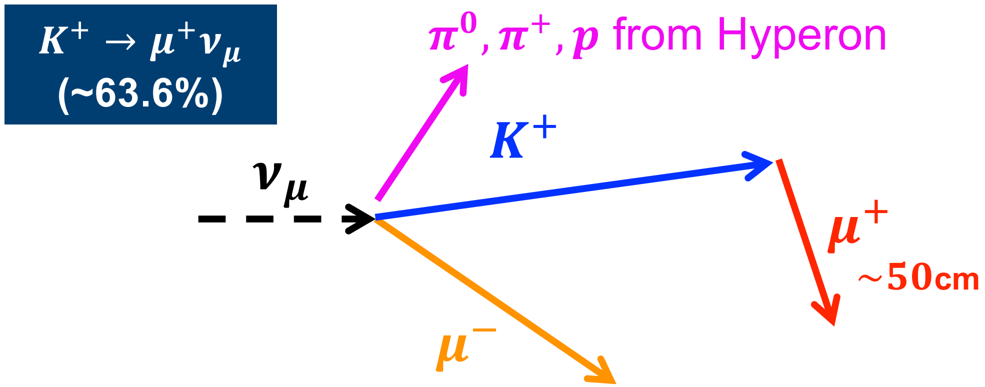
$\nu_\mu + n \rightarrow \mu^- + K^+ + \Lambda^0$ (E_{thres}: 1.1 GeV)

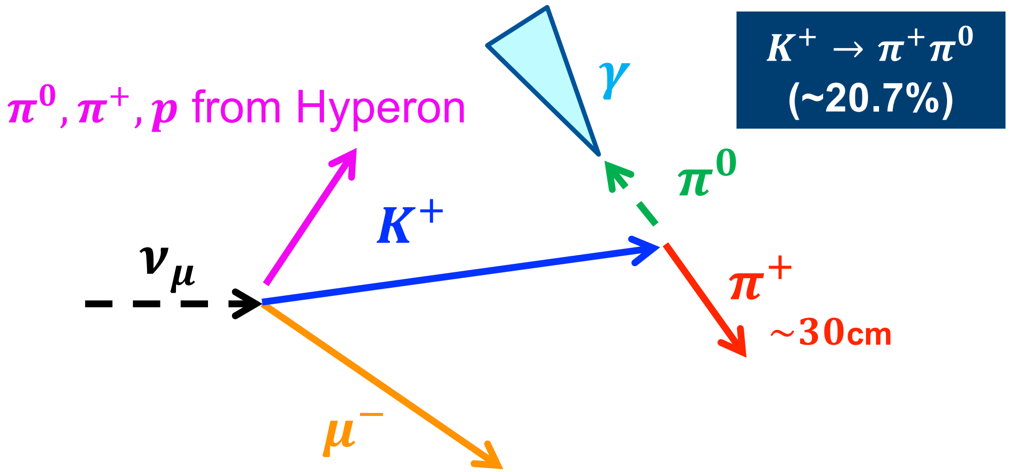
✓**Single kaon production**:

Single kaon produced in the final state

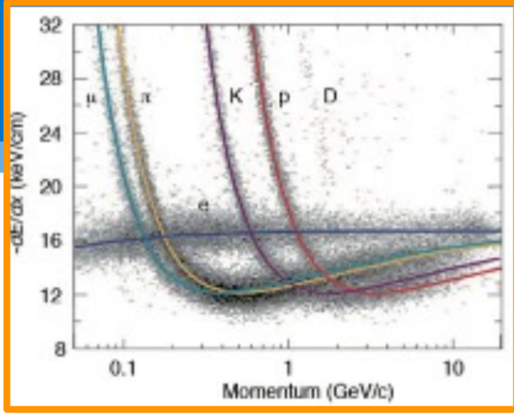
$\nu_\mu + p \rightarrow \mu^- + K^+ + p$ (E_{thres}: 0.8 GeV)

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





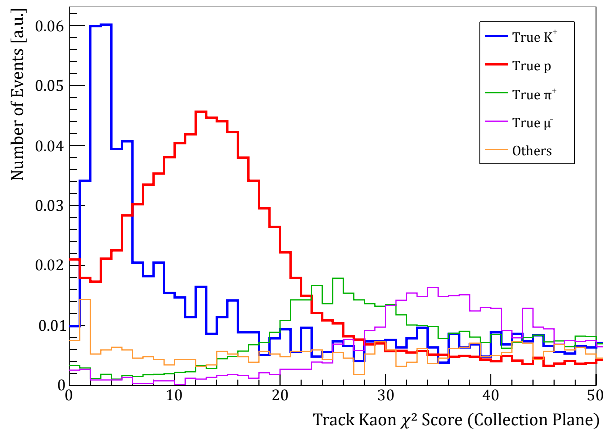
K^+ Event Features and Training BDT

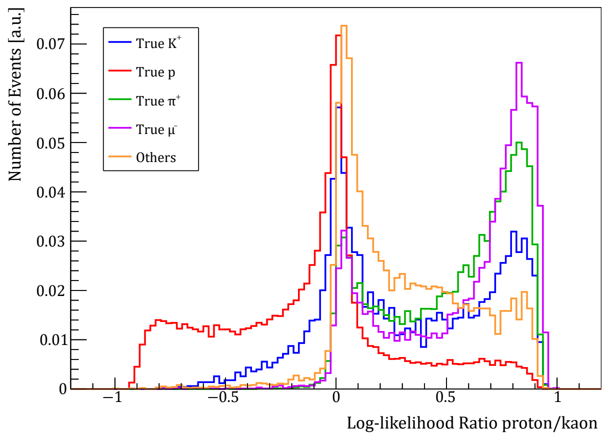


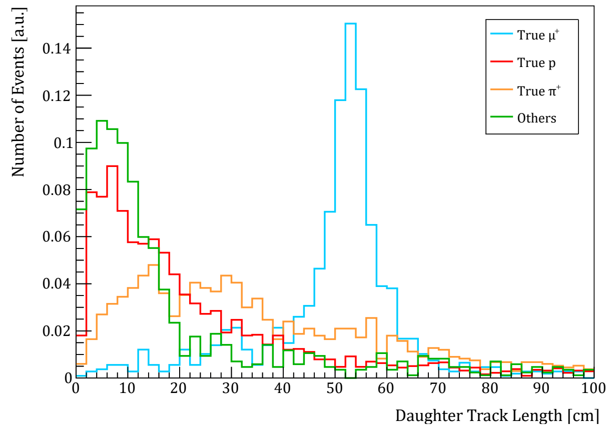
- ✓ NuMI MC + Generated ~20k samples in total for single/associated CC K^+ signals
- ✓ Select variables well characterize true/BG events for BDT training:

$$\chi^2_{3pl} = \frac{\chi^2_{pl0} \times w_{pl0} + \chi^2_{pl1} \times w_{pl1+\chi^2_{pl2} \times w_{pl2}}}{w_{pl0} + w_{pl1} + w_{pl2}},$$

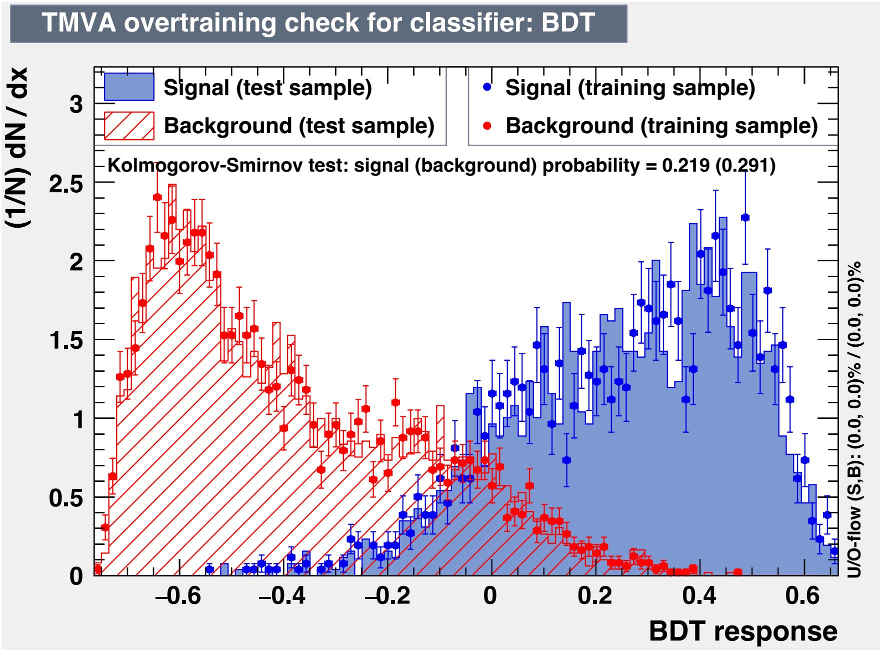
3-plane χ^2 hypothesis score for K, p, μ, π	LLR for K/p and μ/p separation	Length of daughter track
Calculated by the measured dE/dx and estimation from Bethe-Bloch formula.	PID score based on dE/dx PDF and wire pitch along the tracks.	Effective for selection of μ^+ as K^+ daughter.







BDT Selection with MC Simulation

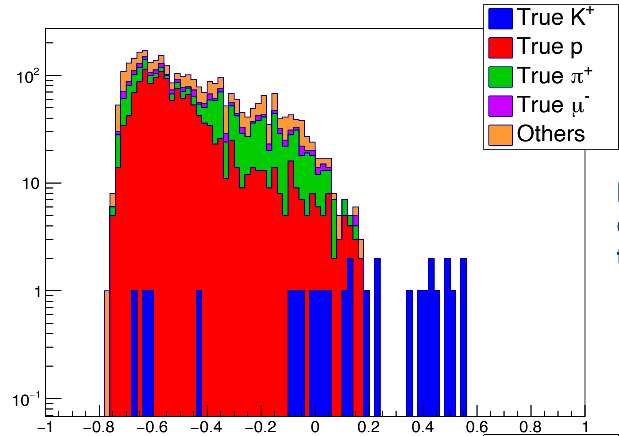


Signal: Reconstructed track has a true PDG = K^+

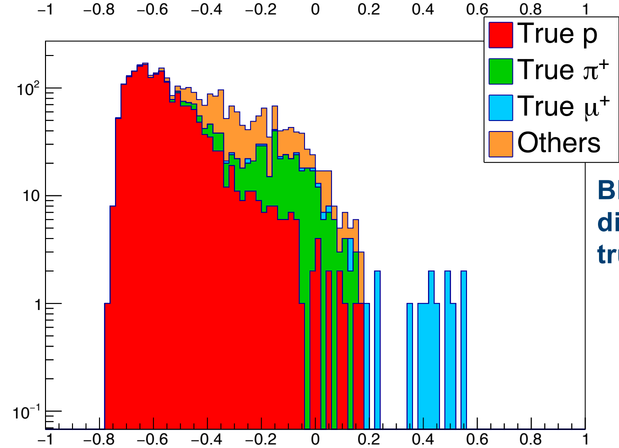
Reconstructed daughter has a true PDG = μ^+ or π^+

Background: !Signal

Apply trained BDT to 9.3e20 POT of FHC run1 NuMI MC



BDT score distribution for true track PDG



BDT score distribution for true daughter PDG

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 Events

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

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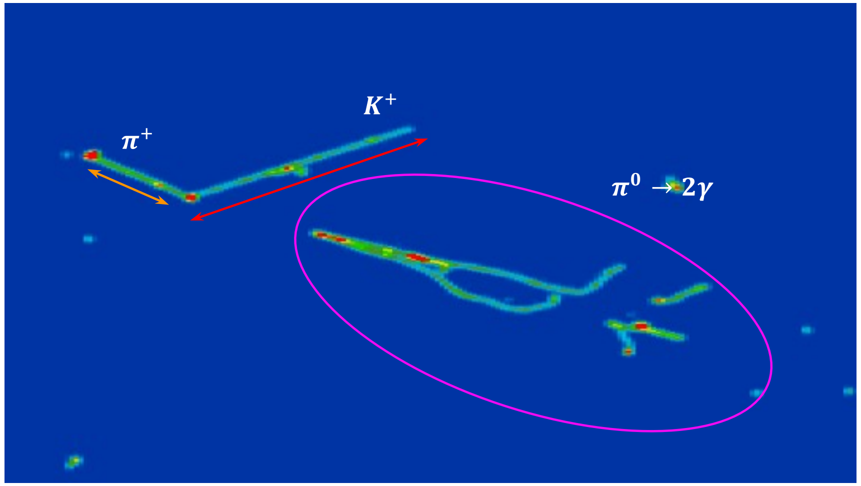
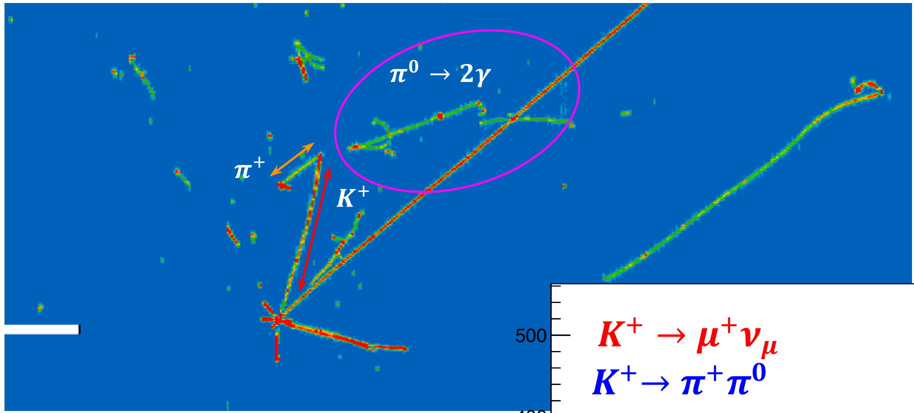
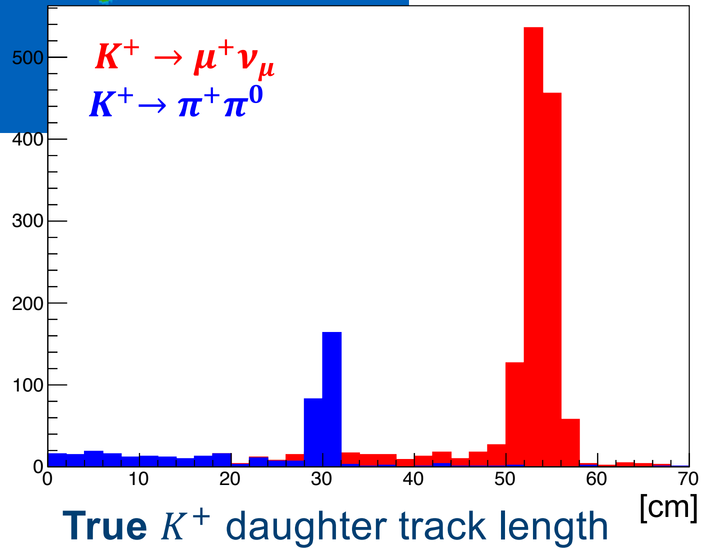
Same breakdown as BDT w track length.

Event displays for $\pi^+ \pi^0$ signal

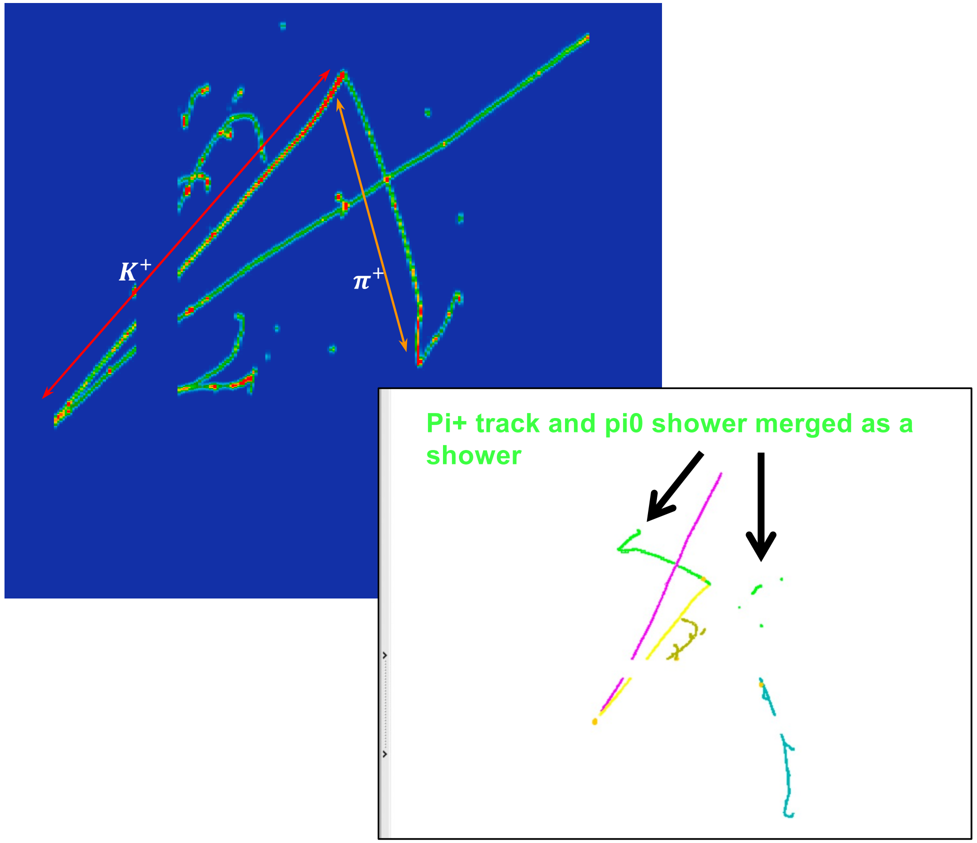


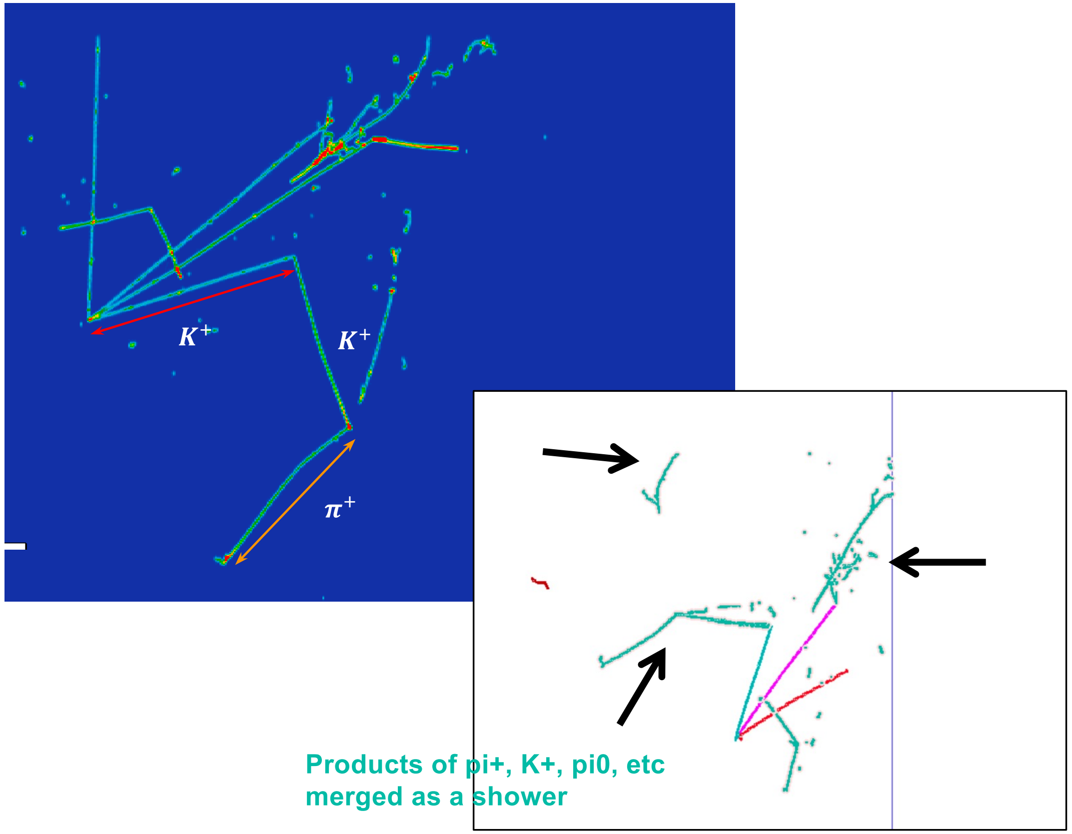




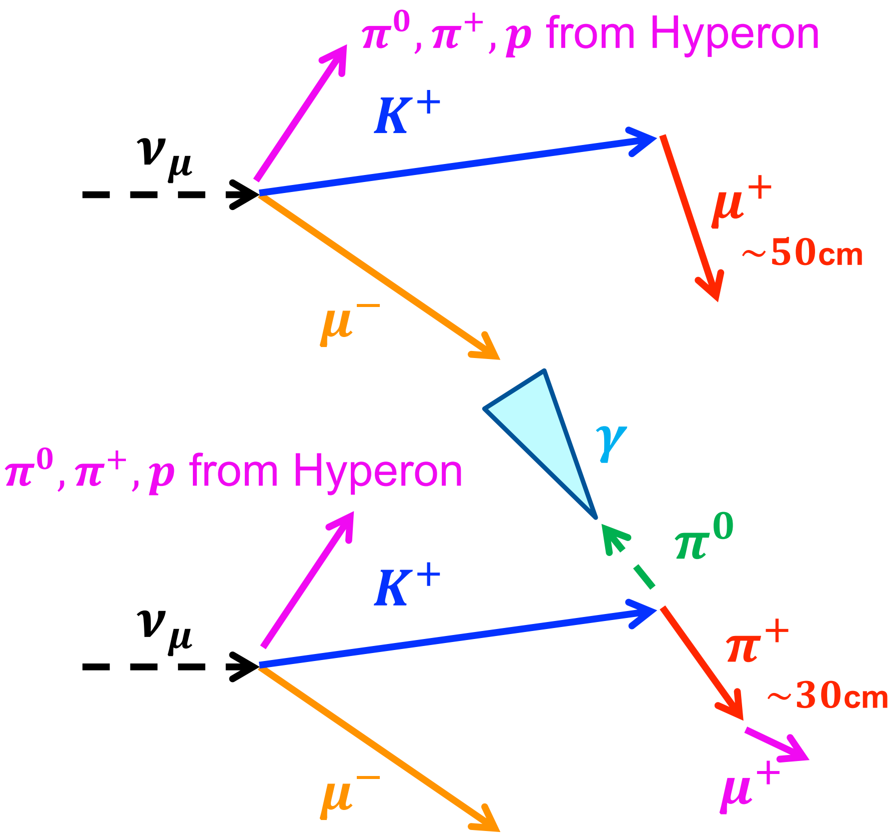
- ✓ Most (~90%) $K+$ decay at rest
- ✓ π^0 will decay into 2γ
- ✓ π^+ has distinct and long track length of 30cm

Pandora Reconstruction Failure: π^+ Merging into a shower / track





Reconstruction Improvement Idea: Separating Hits of π^+ and π^0



π^+ tracks are rarely reconstructed as π^+ hits get merged into showers from π^0.

→ Can we separate π^+/π^0 hits?

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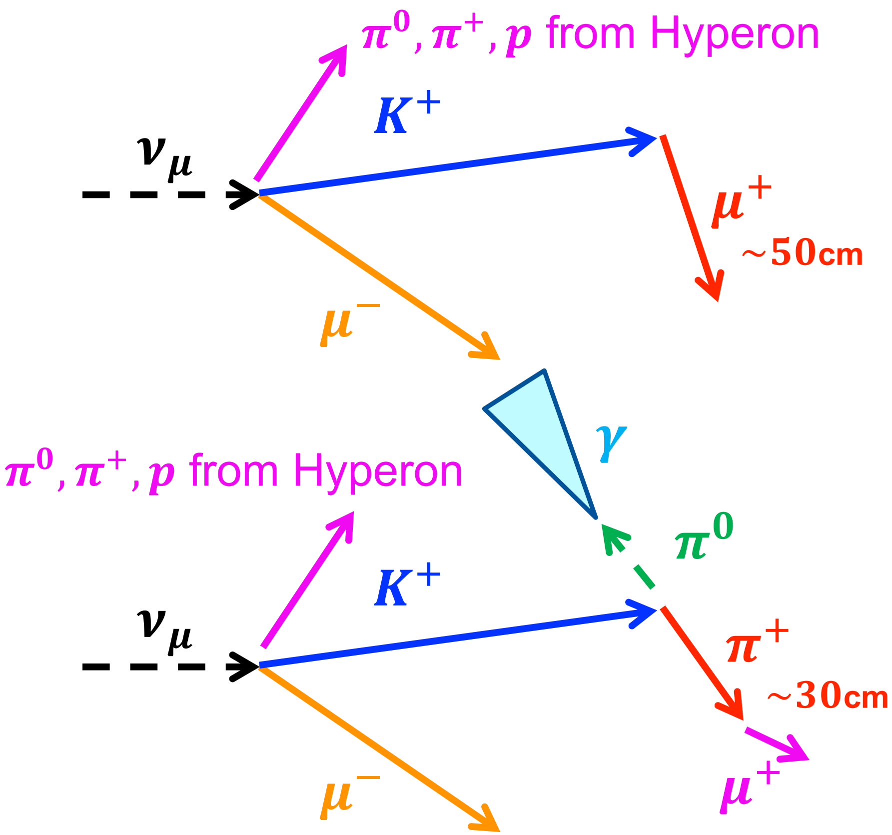

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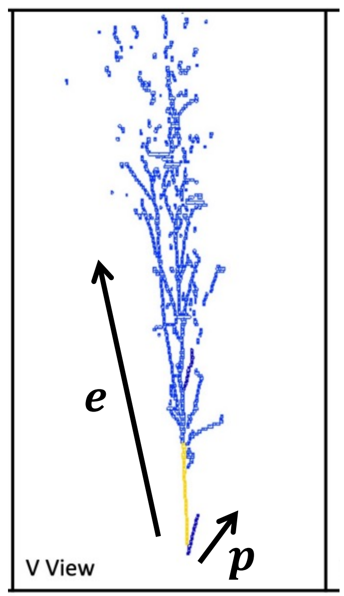


Isobel Mawby's PhD study at DUNE: Shower refinement algorithm for CCν_e

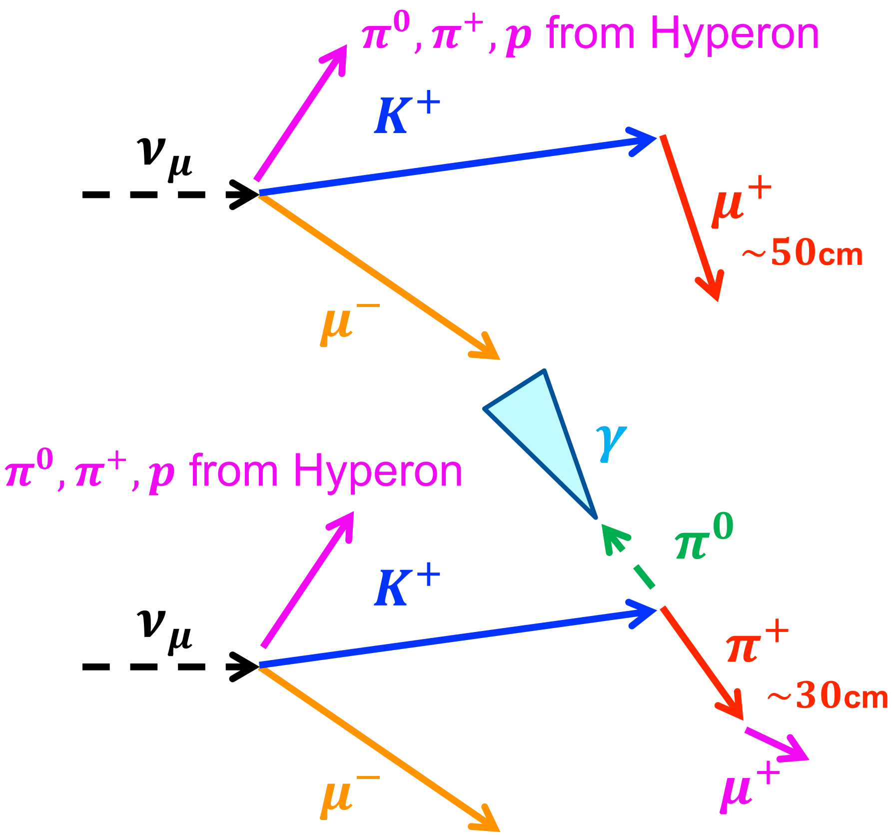
- e showers disconnected from initial track-like region
- γ showers merge into e shower

➢ Find continuous hits from the shower spine of e

➢ Remove contamination hits of γ

From Isobel Mawby's PhD Thesis

Reconstruction Improvement Idea: Separating Hits of π^+ and π^0



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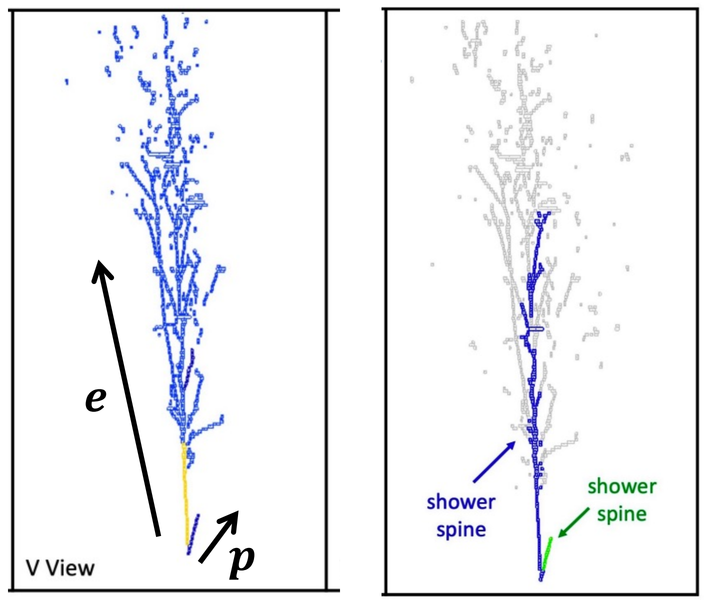


ıD study at DUNE:

ıt algorithm for CCν_e

ɔnnected from initial

ı

ɟe into e shower

; hits from the shower

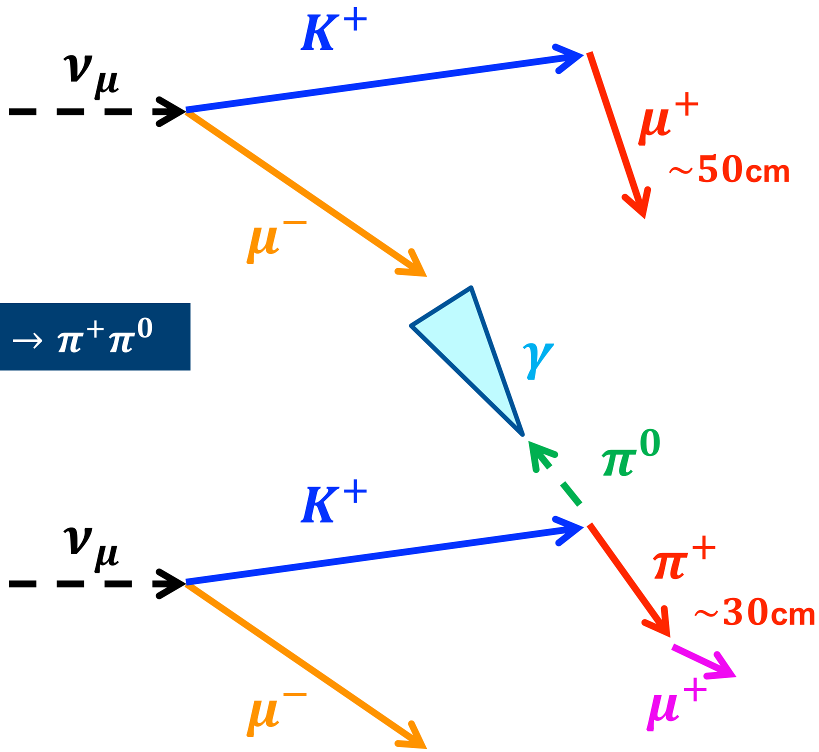
nination hits of γ

From Isobel Mawby's PhD Thesis

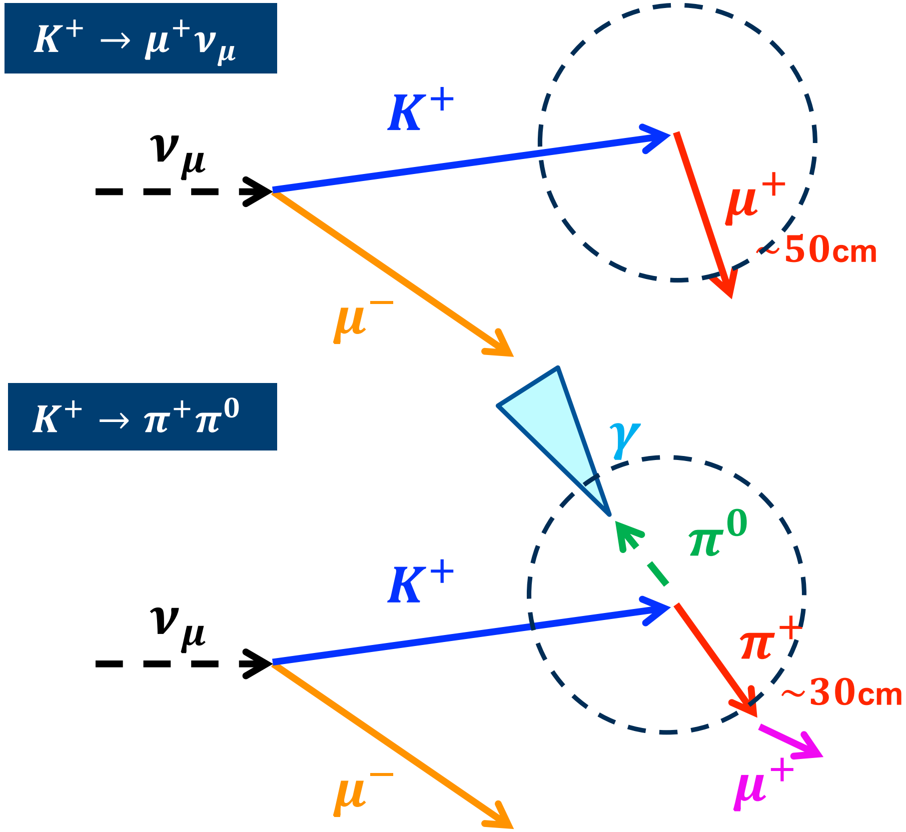
How HitSplitAlgorithm works

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

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



1. Define Region of Interest

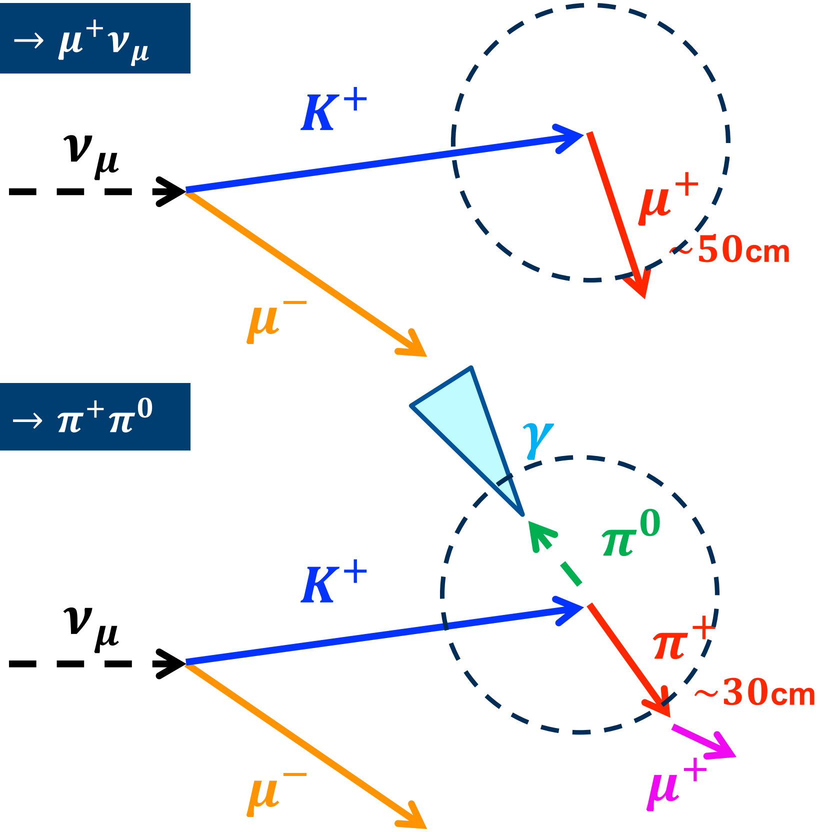


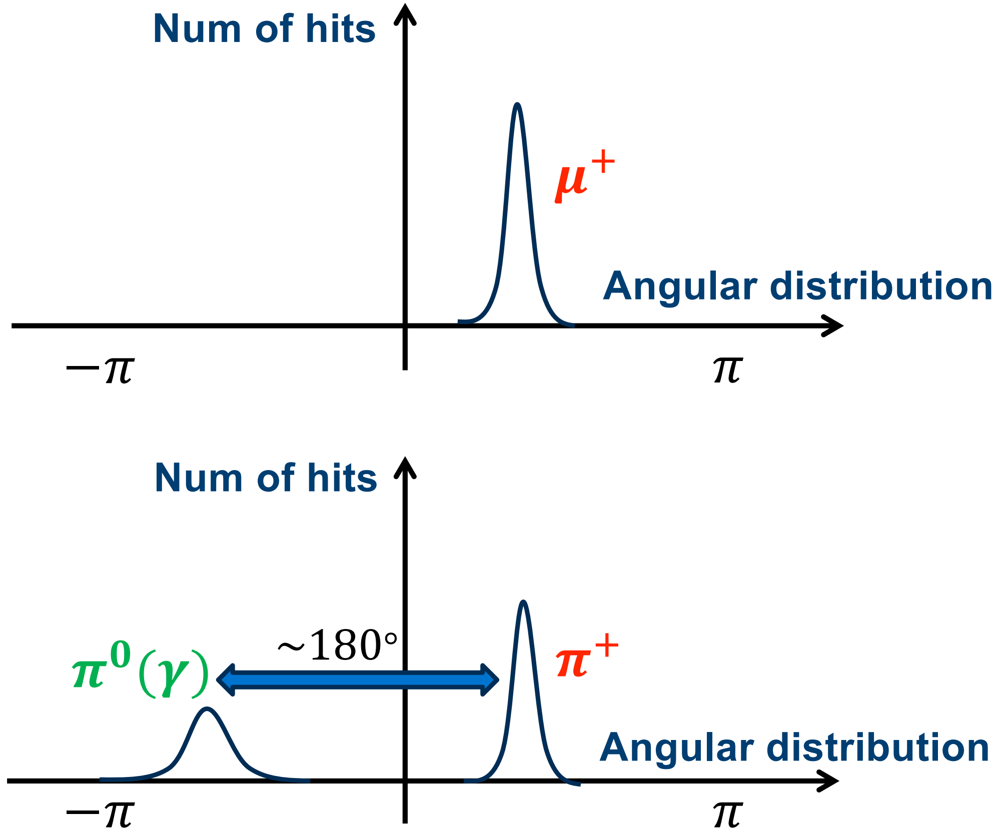
- ✓ Define Region of Interest (RoI): 3D sphere centered at end of K+ track
- ✓ Collect hits from reconstructed daughter track/shower inside RoI

2. Get Angular Distribution of Hits

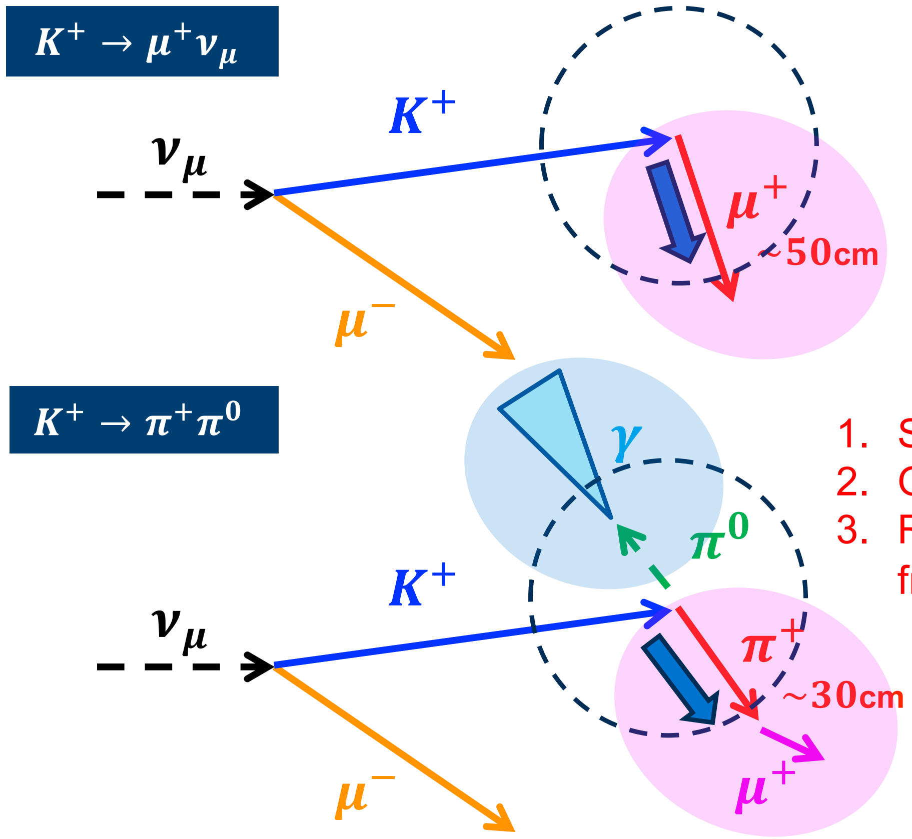
$K^+ \to \mu^+ \nu_\mu$

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

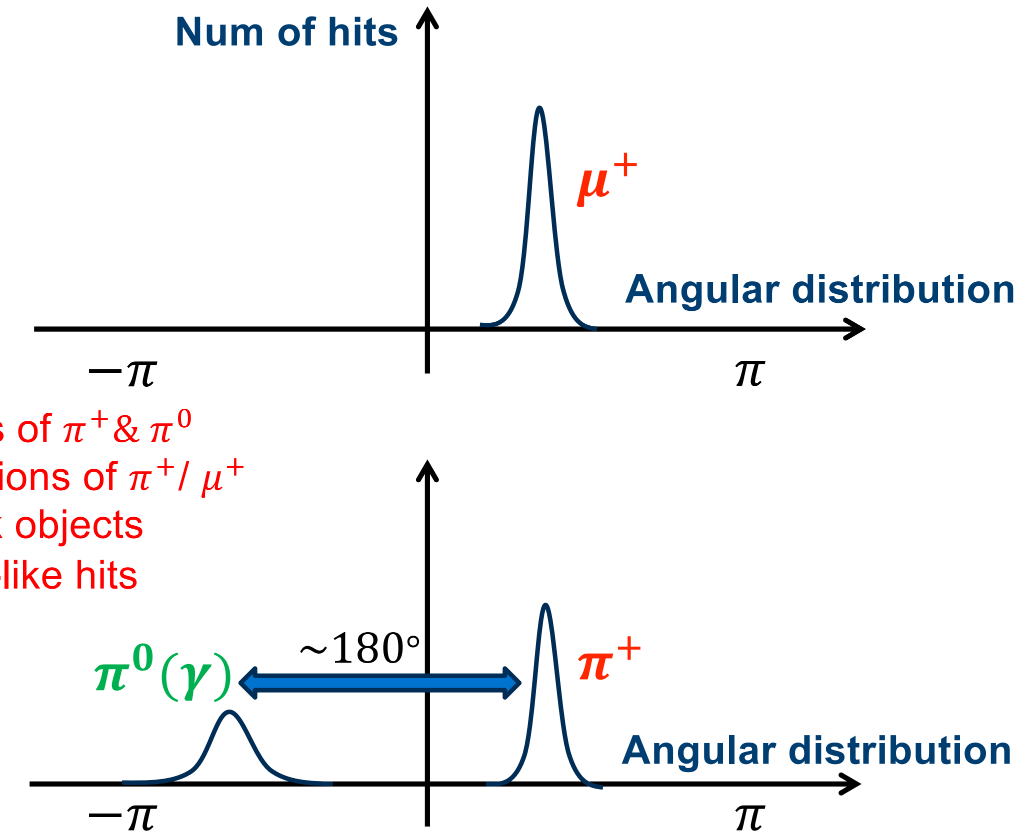




3. Obtain Directions of Daughter μ^+/π^+ Tracks

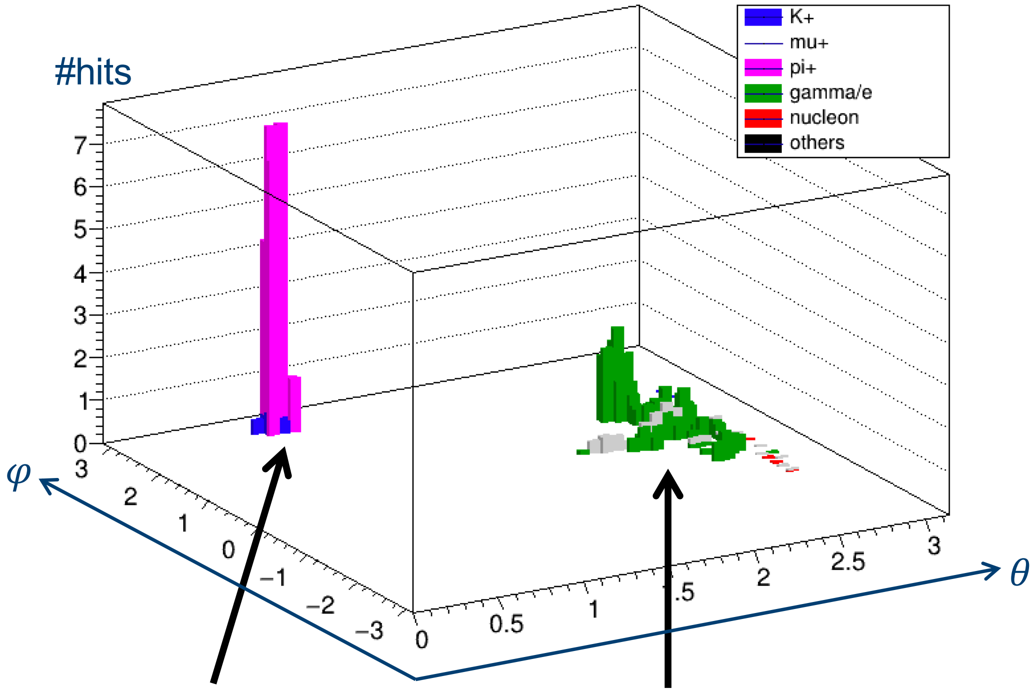


1. Separate hits of π^+& π^0
2. Obtain directions of $\pi^+/\ \mu^+$
3. Rebuild track objects from $\pi^+/\ \mu^+$ -like hits



Separating π^+/π^0 Hits in $K^+ \rightarrow \pi^+\pi^0$ Event

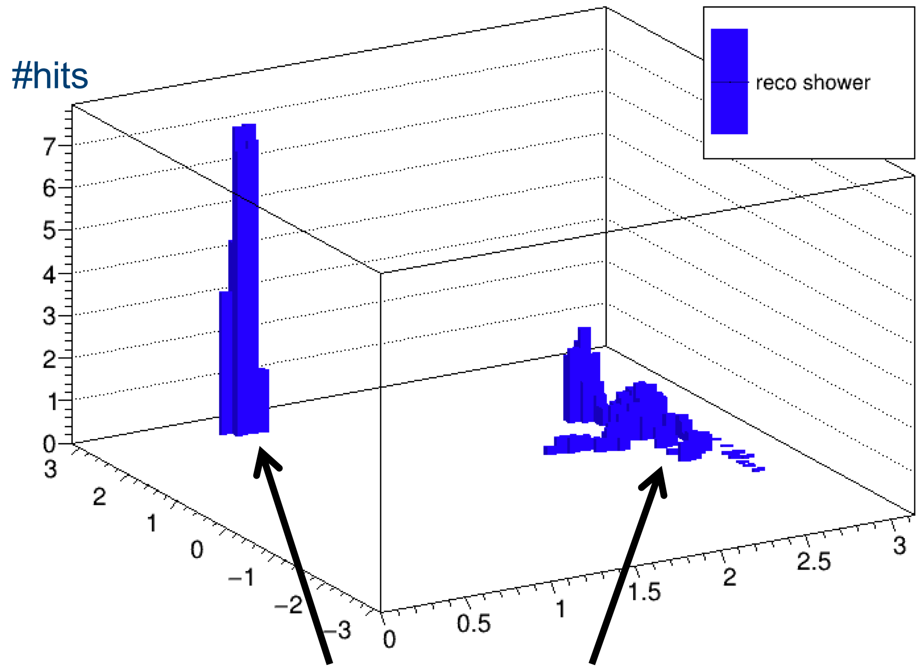
TRUE INFO



Hits from π^+ track

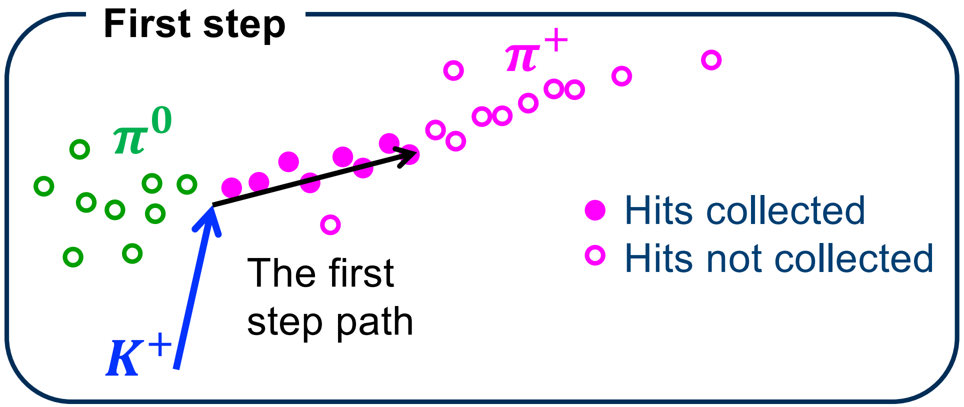
Hits from π^0 shower

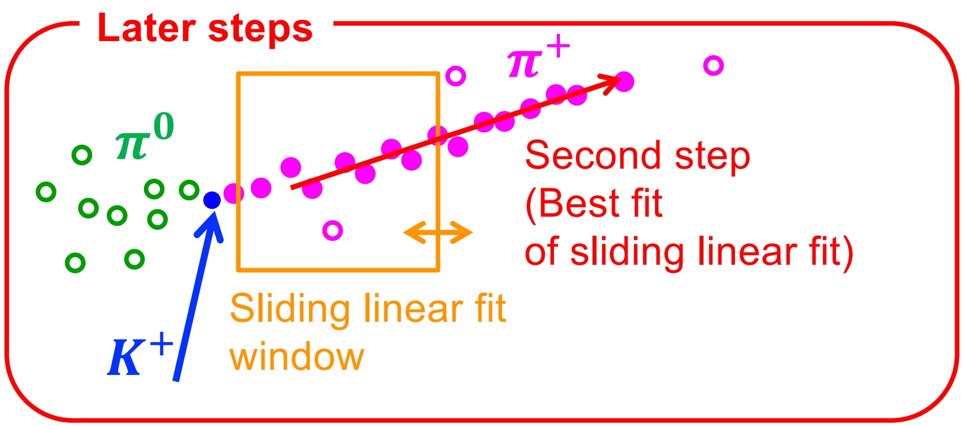
RECONSTRUCTION



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

4. Collect π^+/ μ^+-like Hits from Sliding Linear Fit





To collect π^+/μ^+ like hits, step paths are defined by a start position, direction and length.

- ✓ First step: direction of $\pi^+/\mu^+$and K^+ track end
- ✓ Later steps: by sliding linear fit with collected hits

Hits are collected if:

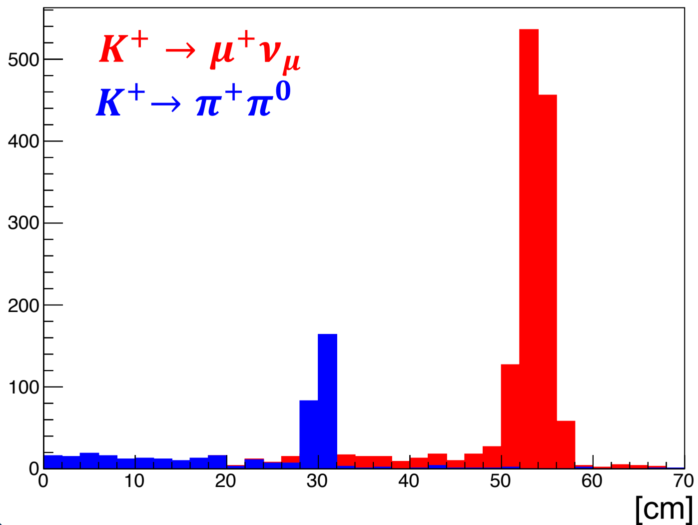
1. their projection onto the step's path lies between the step's start and end points.
2. their transverse distance from the step path is less than 1cm.

- ✓ Repeat until no additional hits are collected.
- ✓ Rebuild reco:track by LArPandoraTrackCreation

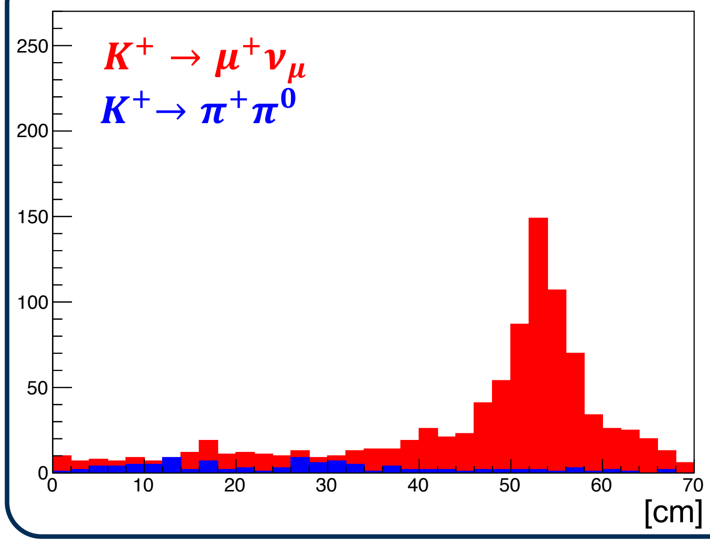
Before and After Introducing HitSplitAlgorithm

Event filter: True Associated Production K^+ event with reconstructed primary track with true K^+ PDG

True K^+ daughter track length



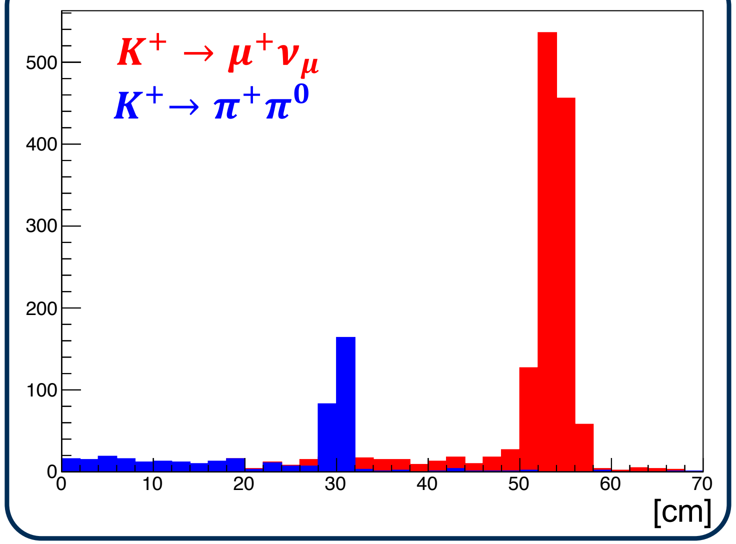
Reconstructed K^+ daughter track length



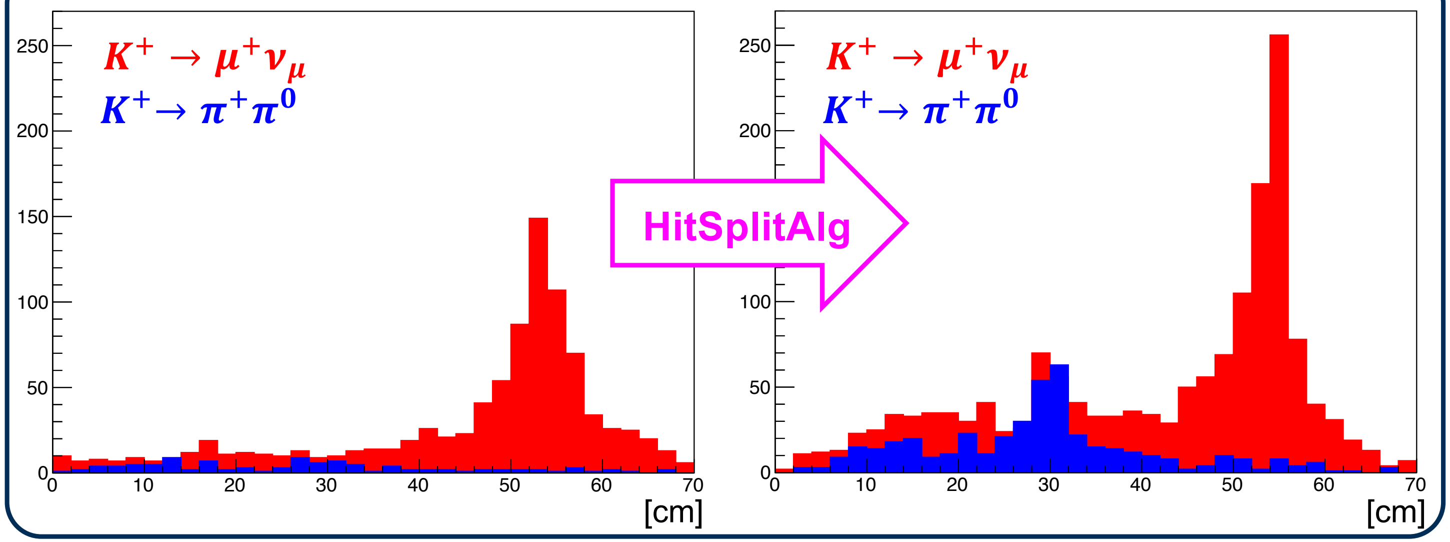
Before and After Introducing HitSplitAlgorithm

Event filter: True Associated Production K^+ event with reconstructed primary track with true K^+ PDG

True K^+ daughter track length



Reconstructed K^+ daughter track length



Reconstruction efficiency daughter track with correct ($\pm 10\%$) track length

μ^+: 2.7% → **μ^+: 3.3%**

π^+: 0.6% → **π^+: 2.4%**

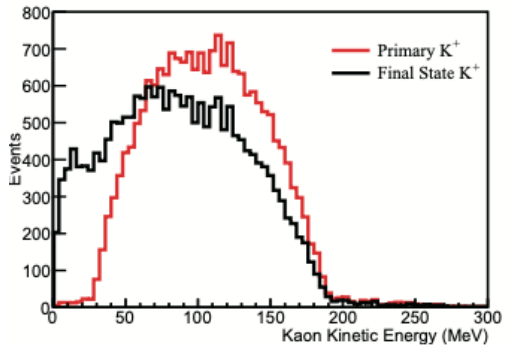
How This Could Help DUNE

✓ **CC K^+ Production study with NuMI at MicroBooNE**

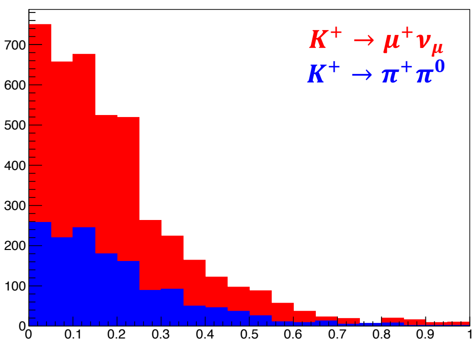
- Algorithm is under development and needs further tuning and testing with signal/BG MC
- With reconstruction algorithm:
  - $K^+ \rightarrow \mu^+\nu_\mu$: μ^+ track reco eff. improvement by ~20%
  - $K^+ \rightarrow \pi^+\pi^0$: π^+ track reco eff. improvement by ~400%, comparable to $K^+ \rightarrow \mu^+\nu_\mu$

✓ **Application to DUNE**

- PDK search
  - Improvement of μ^+ track reconstruction
  - Possibility for $p \rightarrow \bar{\nu}K^+$, $K^+ \rightarrow \pi^+\pi^0$ observation
- K^+ production
  - Larger statistics with higher ν energy and larger detector volume
  - First CC $K^+ \rightarrow \pi^+\pi^0$ measurement ever



From DUNE TDR



True E of CC K^+ [GeV/c]

Summary and Outlooks

✓ **Neutrino induced K+ production study at MicroBooNE**

- Developed pandora reconstruction algorithm exclusive for K+
- Checking the performance of this algorithm with signal and BG MCs
- Currently building a new BDT for signal/BG selection and systematic error estimations undergoing

✓ Proton decay search at DUNE

- Importing the reconstruction algorithm for K+ from MicroBooNE to DUNE
- Estimate the reconstruction improvement of K+ daughter particles on DUNE proton decay samples
- Aim to enhance the sensitivity of future $p \rightarrow \bar{\nu}K^+, K^+ \rightarrow \mu^+\nu_\mu$ and seek the possibility of new proton decay search channel: $p \rightarrow \bar{\nu}K^+,\ K^+ \rightarrow \pi^+\pi^0$