Incorporating Induction Hits Into $p \rightarrow \bar{\nu}K$ Event Selection

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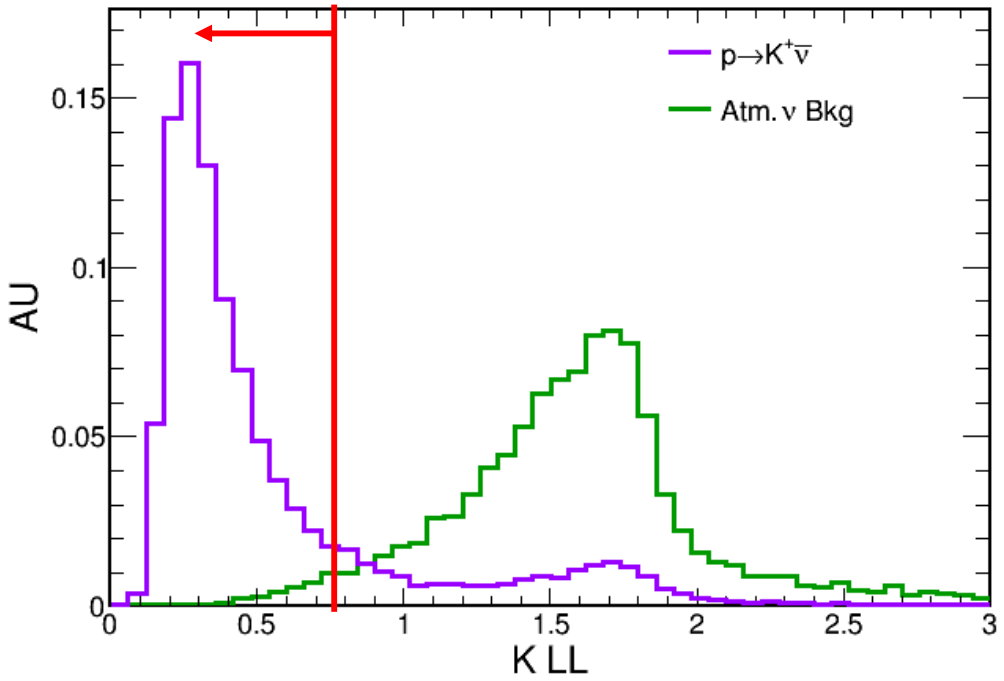
Overview

- The bulk of the talk is straightforward – apply the same reconstruction and selection strategy I've talked about previously to collection and induction hits
  - Mostly, I'm just recalculating the same selection variables, but with 3x as many hits
  - Expect decent improvements to the efficiency
    - Improved tracking efficiency due to projecting K+ track onto multiple planes
    - Better dE/dx discrimination from having multiple samples of the track – cancels electronic noise

- Also, added these selection variables to a MVA
  - Performance is comparable to cut-based selection, but need more MC to really test

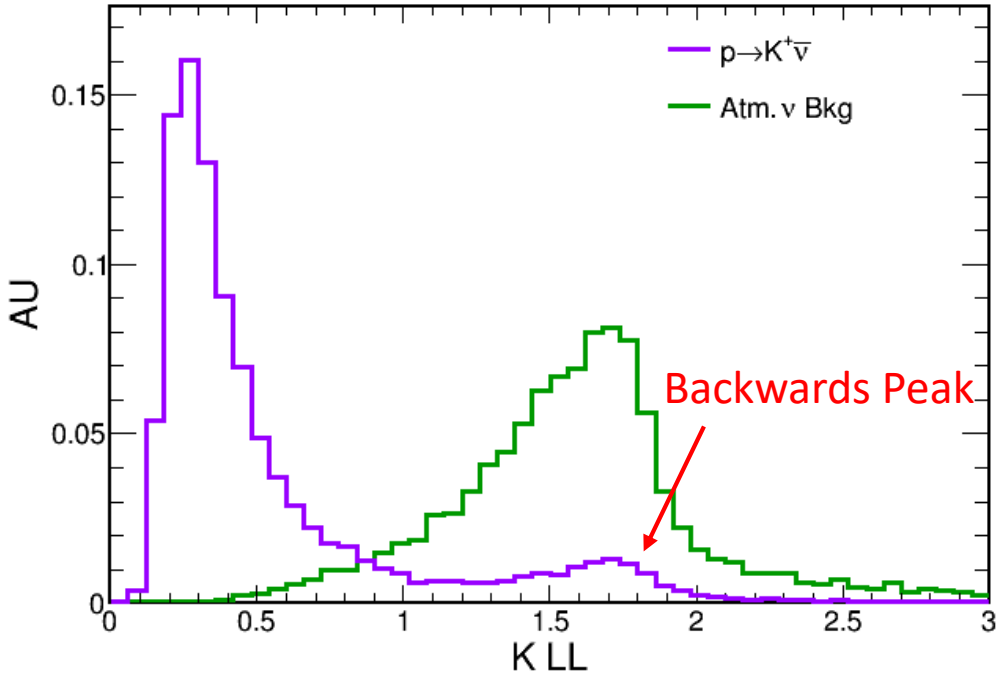
One Extra Variable

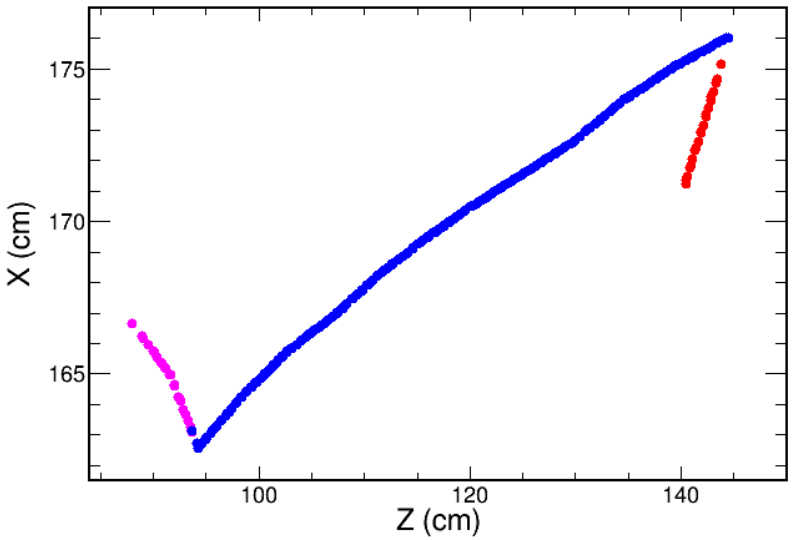
- In the past, I've always done a Bethe-Bloch fit to decide the K^+-ness of a track
  - Algorithm finds the best fit mass to that model, answer centers around m_K
- It turns out that a more traditional LL template variable is more powerful separating signal and bkg
- I do some clean-up of the template histogram
  - Including only K^+'s from $p \rightarrow K\nu$ events
  - Track length > 5 cm
  - At least 10 hits
  - | reco length – true length | < 2 cm
  - By truth, are going the right direction

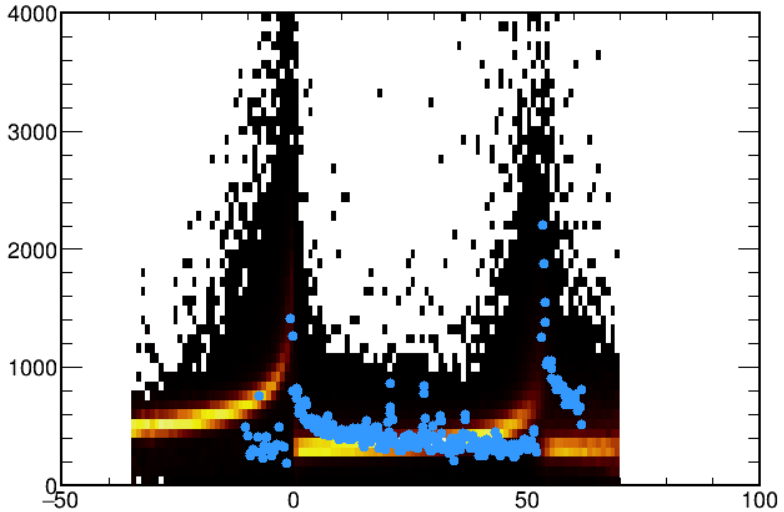


Small Opportunity for Efficiency Boost

- There's a little bump in the signal KLL distribution around 1.5-2
- These are backwards events
  - Have nice clean K→μ→e topology, but place the vertex between μ and e
  - K and e switch places, and all tracks are going the wrong direction
  - Potential to reclaim these events, but they aren't to common, ignoring for now

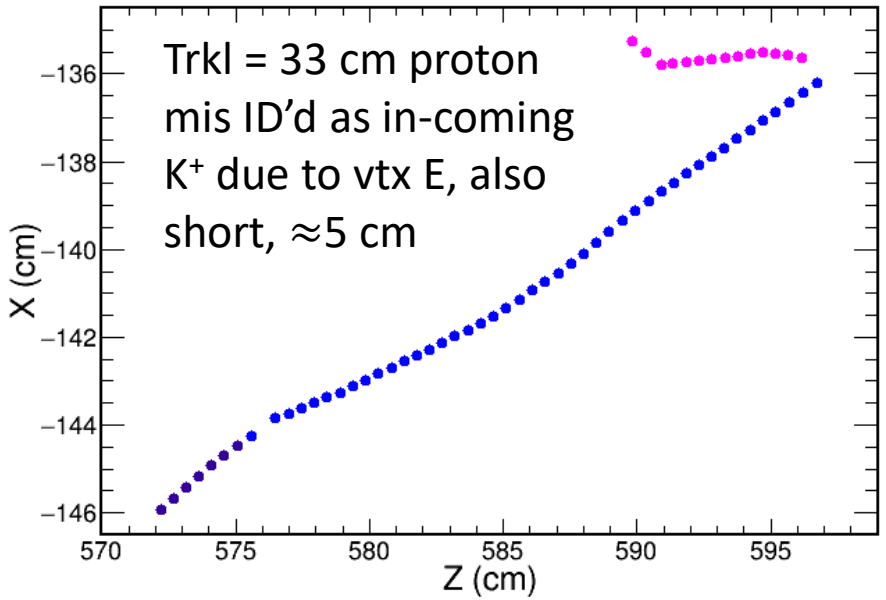


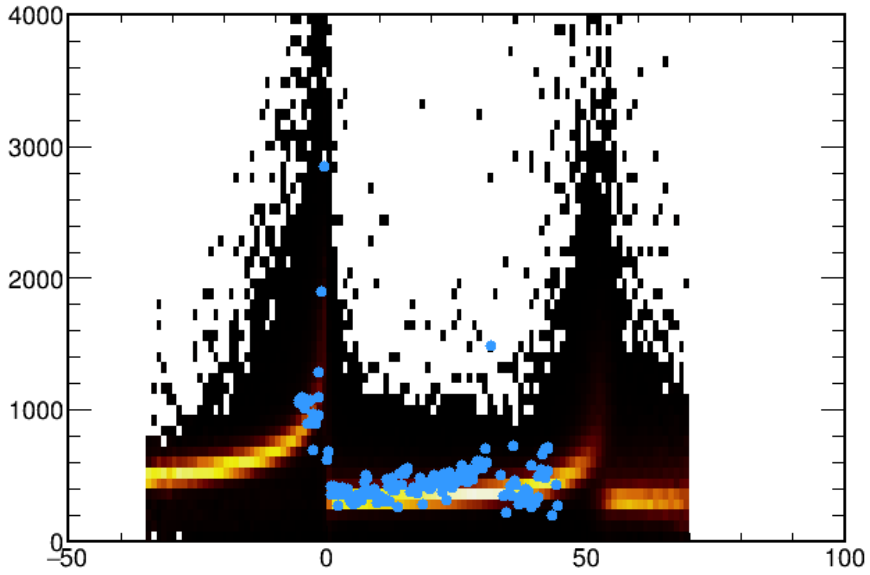




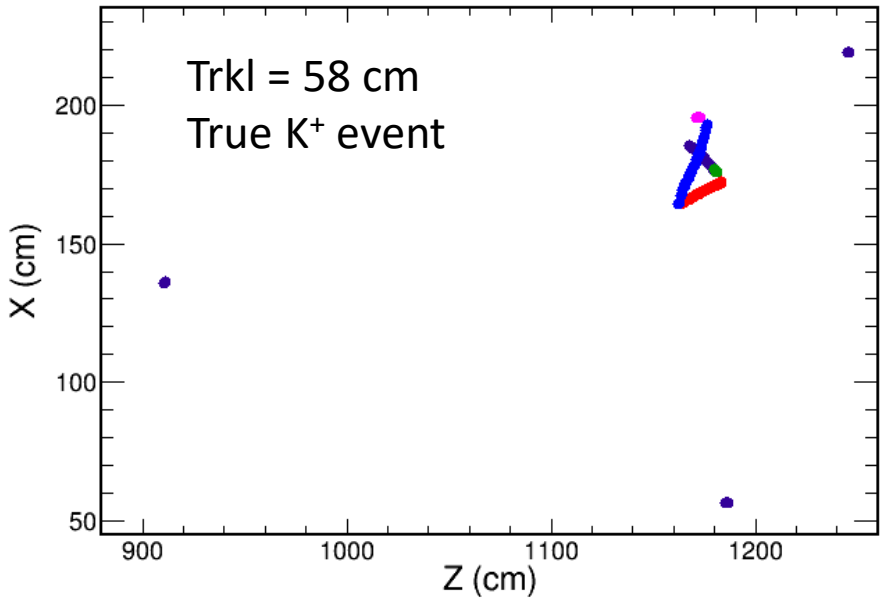
Selected Backgrounds

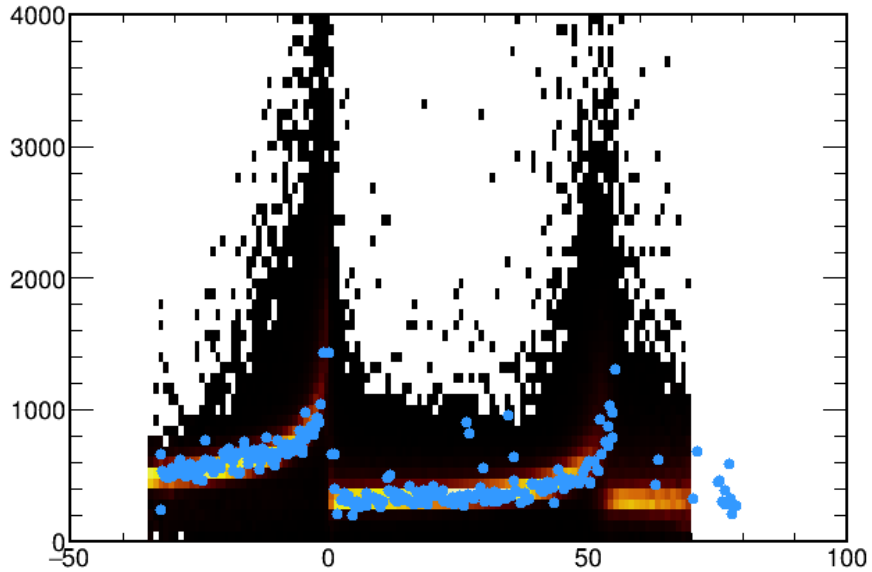
- Found three events – significantly more than previous iterations
  - Further track lengths were 33, 52, and 58 cm, overlapping with our signal region
    - A bit worrisome – selection sculpts bkg to overlap with the signal
- In a way though, bkgs are more re-assuring this time around, looking at dE/dx traces, they aren't obviously background, suggesting the reco is more robust

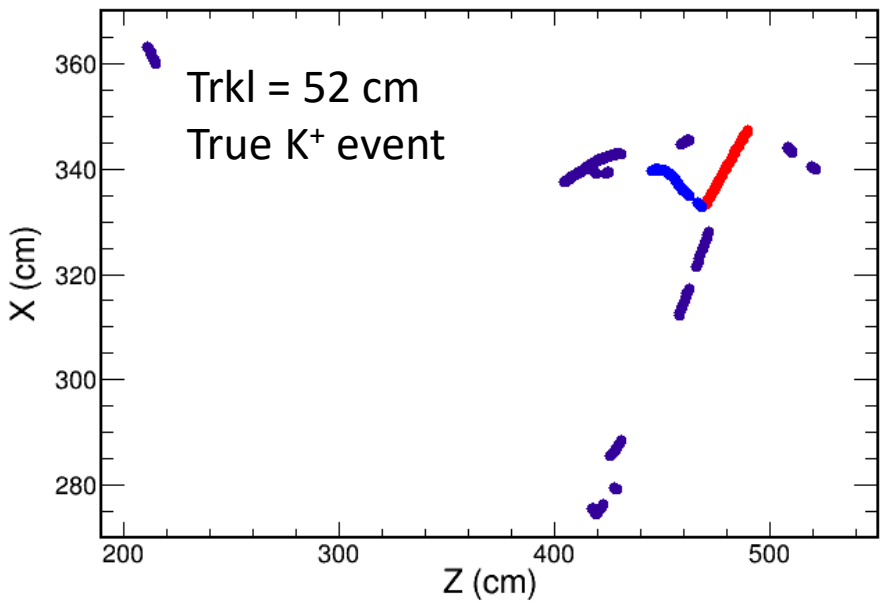


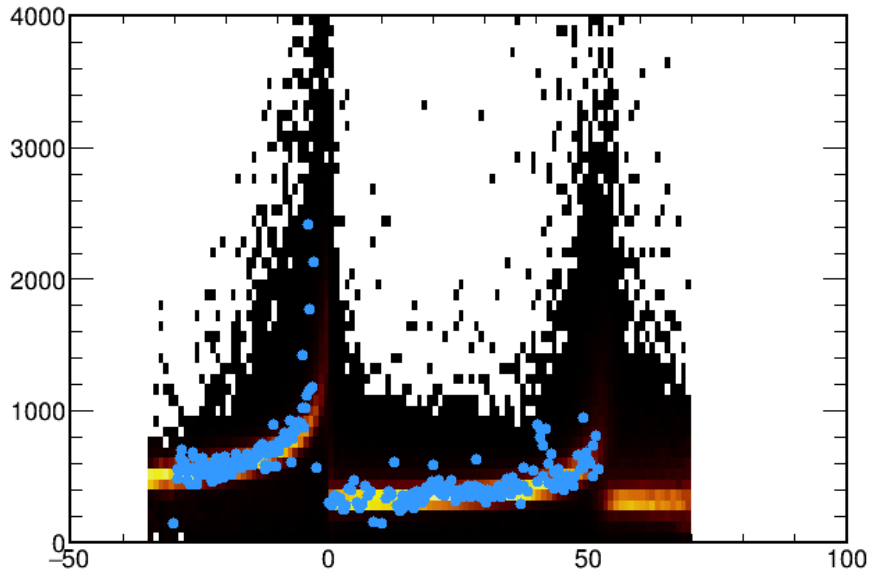


More Selected Backgrounds



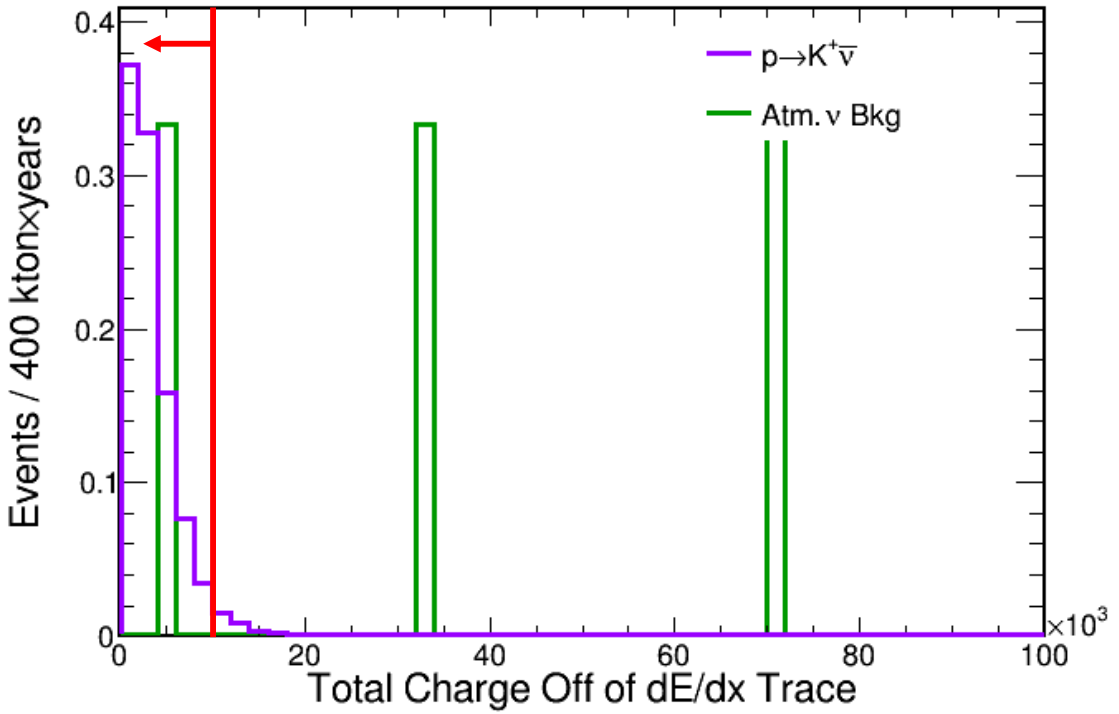






Vetoing Atm K^+ Events

- Can remove all K^+ neutrino events in our sample with a cut on energy off of the dE/dx trace
  - Require off energy < 10e3 (≈25 MeV)
  - Leaves just the selected event that didn't have a true K^+
  - Call this off-trace energy
  - Potentially more sensitive to systematics from knock-out nucleon model in GENIE

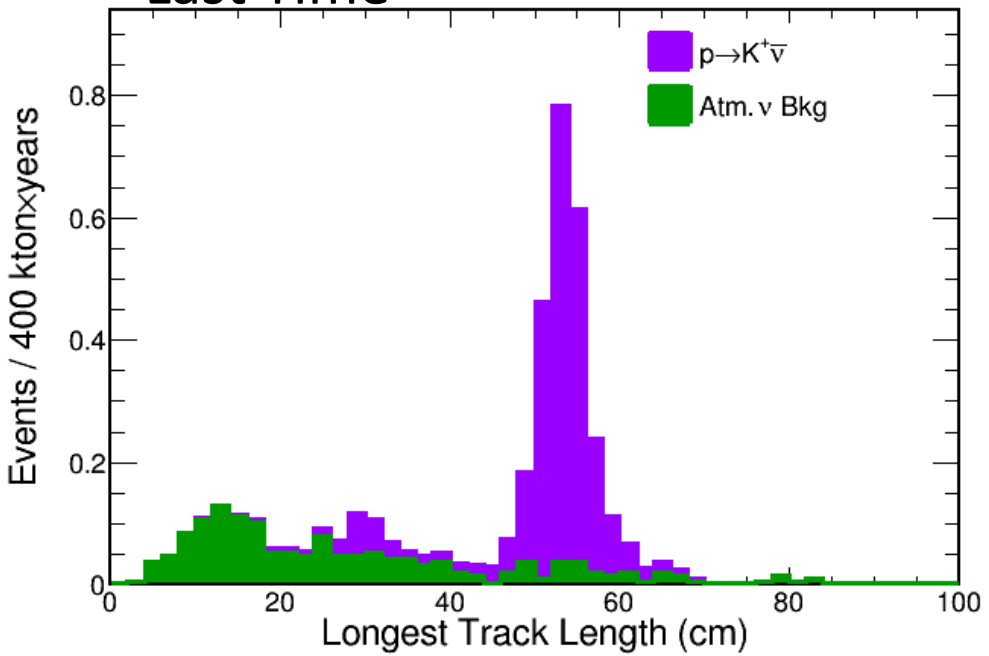


- As a consequence, I feel like this selection strategy is looking more robust, it finds a way to select out atm events with rare K^+ production
- Other selected event is hard to construct because of both vtx energy and a short proton – not super clear upon looking at the dE/dx trace that it is bkg
  - And, the track length is 33 cm – back to being able to estimate bkg in signal window using track length distribution at earlier levels of cuts

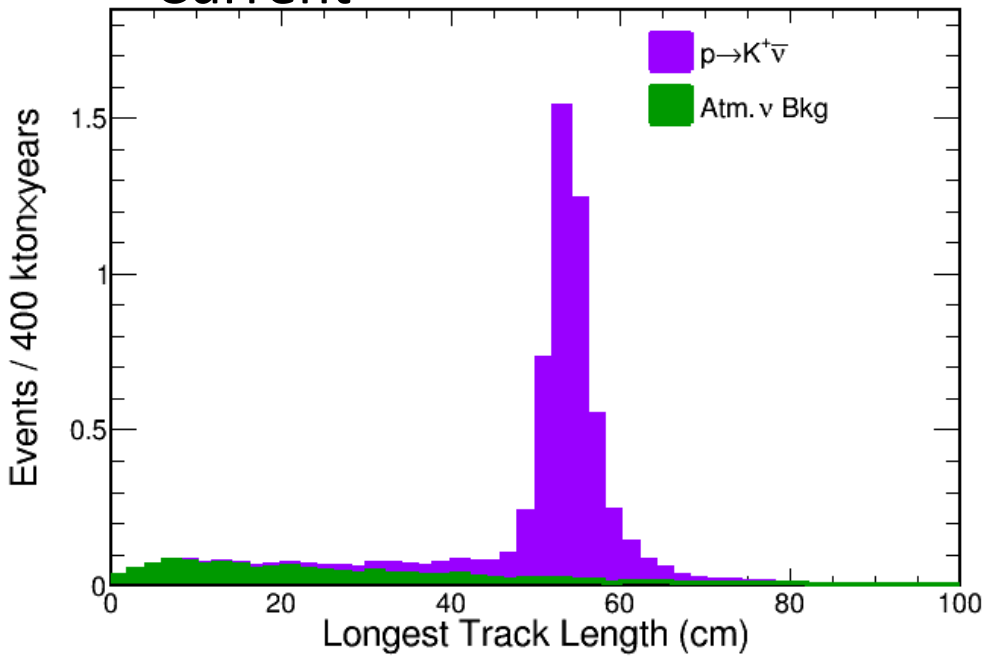
Results for K→μν

- Jump in efficiency is bigger than I was expected
  - Efficiency at 27.6%
  - Compare to 17.4% from last week, and 14% from the TDR, all having 0 bkg in signal region
- Adding in $K \to \pi^+\pi^0$ spectra from last iteration, this gives
  - $\tau_p/Br(p \to \bar{\nu}K) > 1.81e34$ years with 400 kton-years of data

Last Time



Current



Where Does Efficiency Gain Come From?

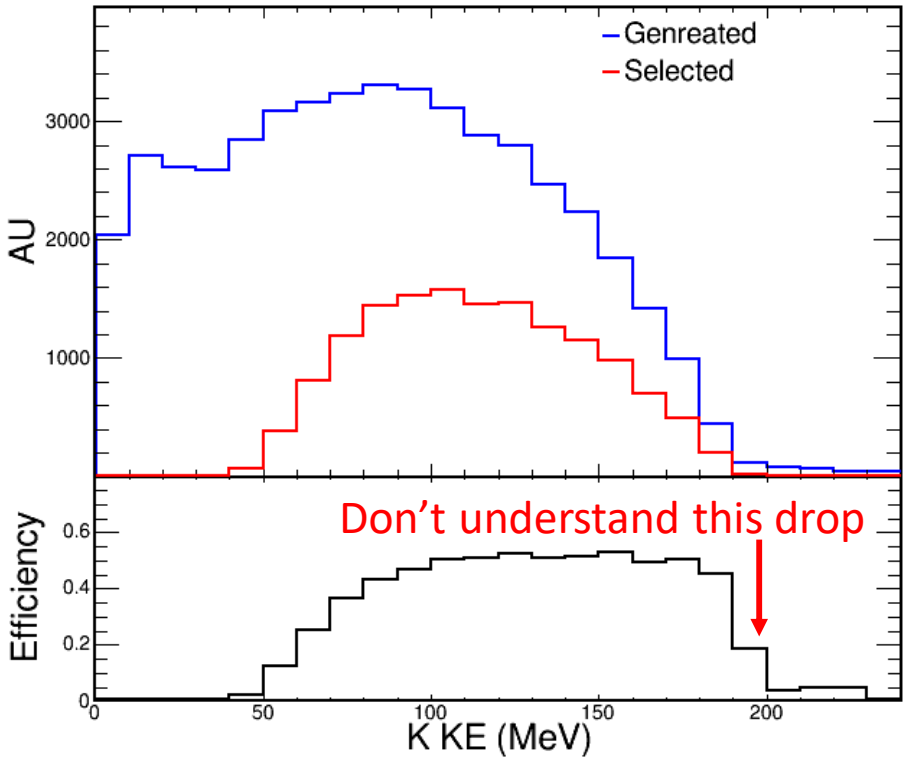
- Looks to come mostly from K^+ tracking improvements
  - Two-track requirement only goes from 0.50-0.61, but I'm actually requiring enough hits to run Bethe-Bloch fits
  - Preferentially gain back two-track events at high K^+ track length
  - 0.50x0.65 = 0.33 vs 0.83x0.78=0.65 (1.99x nominal) vs 0.61x0.85=0.52 (1.60x nominal)

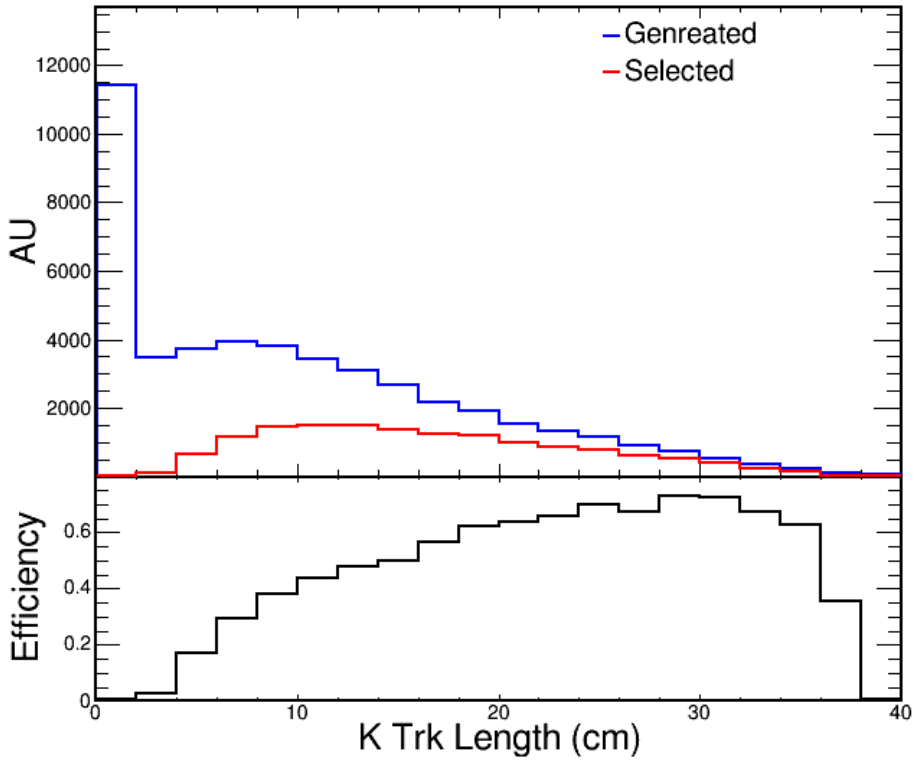
	Nominal	Optimistic	Current
Two Tracks	0.50	0.83	0.61
Muon length	0.83	0.90	0.77
K^+ length > 5 cm	0.65	0.78	0.85
dEdx, etc.	0.53	0.53	0.70
Total	0.14	0.31	0.28

- Also a notable increase in the dE/dx trace cuts compared to nominal
  - Makes sense that induction hits should increase efficiency here – gives you more samples to reduce statistical noise in our hit finding
- Don't understand why my efficiency for muon track length falling in signal window goes down

Efficiency vs Kinematics

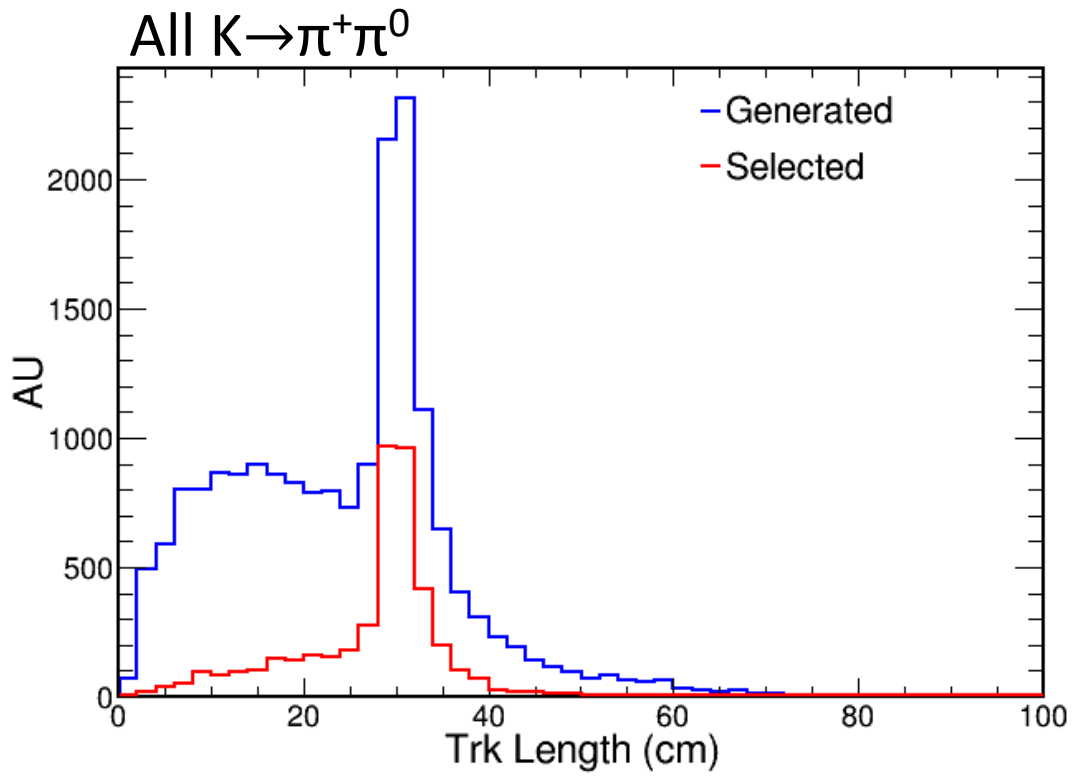
- Still have a threshold for our efficiency – consistent with Chris's reach studies
  - Pick up just a bit of efficiency for length < 5 cm, but KE < 50 MeV is invisible to us
  - Still need to worry about FSI systematic when quoting our signal efficiency





$K \to \pi^+\pi^0$ – a very different story

- Previously, the efficiency for the $K \to \pi^+\pi^0$ mode was 17.8%, similar to $K \to \mu\nu$
- Initially thought that adding in induction hits would give a similar boost to efficiency, but was much more modest: 17.8% -> 19.2%
- Looks like inefficiency is driven by lower-level reconstruction issues
  - Looks to be two populations, about 1/3 of events lie in trkl peak, rest are in a broad, falling distribution



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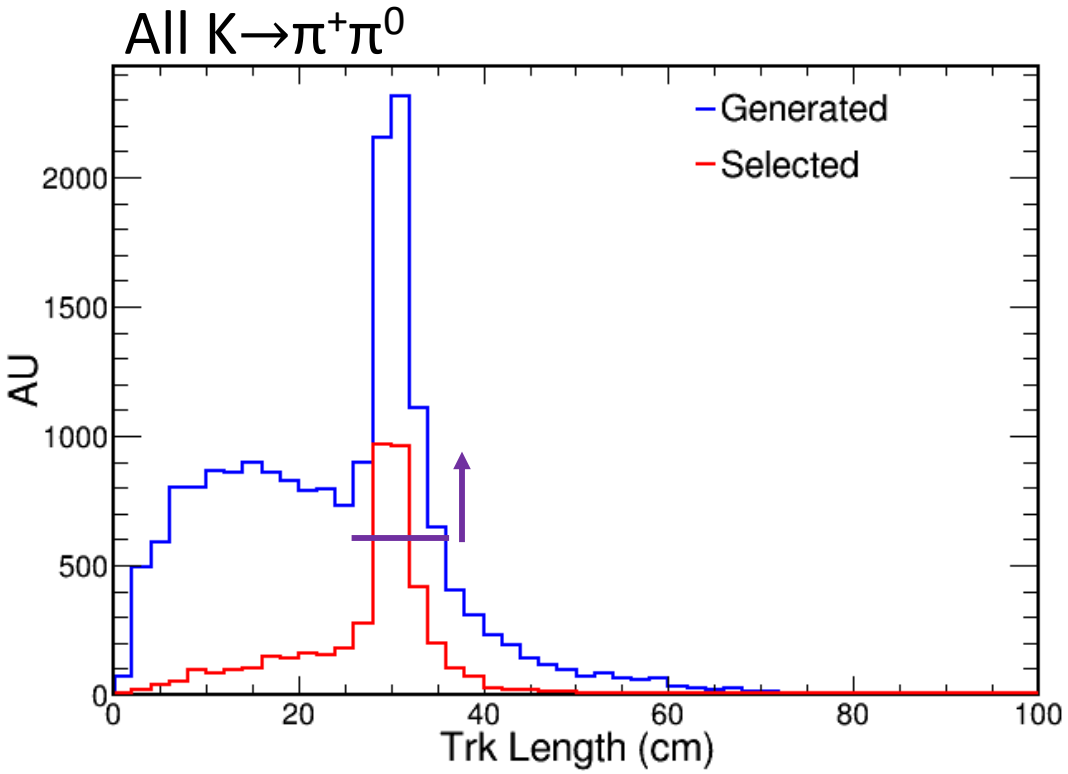
- Looks like inefficiency is driven by lower-level reconstruction issues
  - Looks to be two populations, about 1/3 of events lie in track length peak, rest are in a broad, falling distribution
- Trying to estimate efficiency for well-reco'd events
  - Take signal window = 26-36 cm
  - Take subtract off 600 evts/bin from generated histogram
  - Suggests ≈60% of well-reco'd events are selected



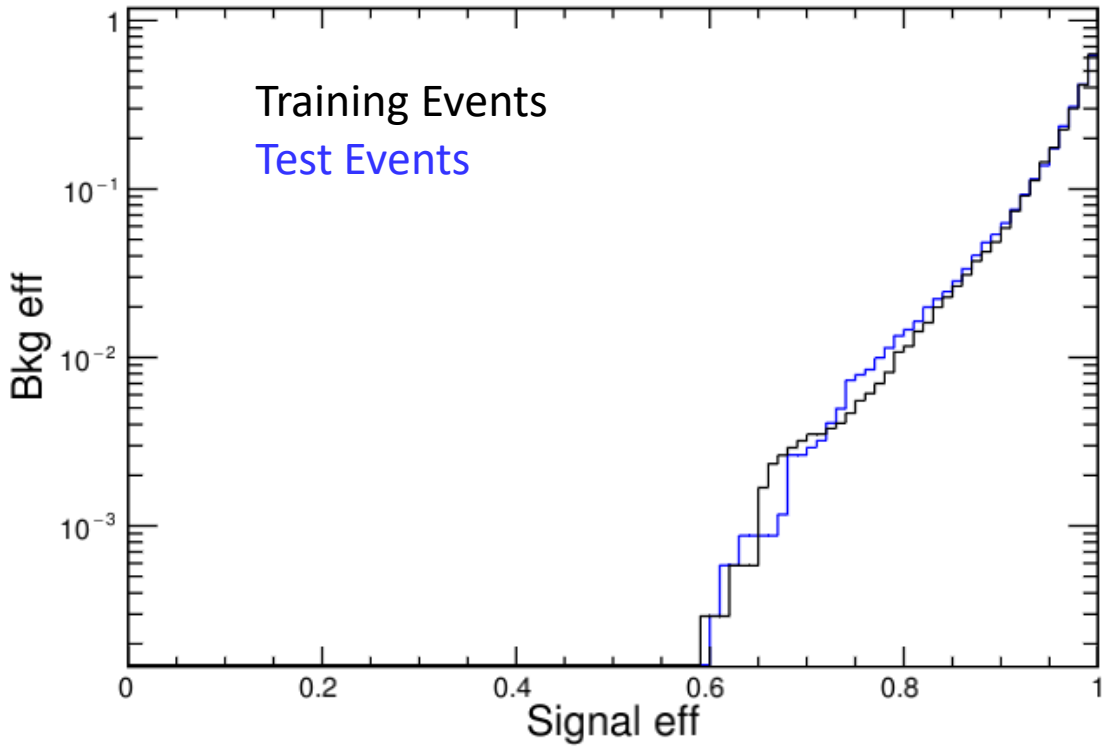
Moving to a BDT

- I have the hard part – coming up with a set of reco variables that do a good job of differentiating between signal and bkg, easy to train a TMVA on them
- Train the MVA based on six variables:
  - K^+ LL and directional $\Delta\chi^2$
  - μ LL and directional $\Delta\chi^2$
  - nhit reco'd for Michel (doesn't have to be > 0)
  - Longest track length
- A few MVA algorithms tested, BDT performed best
- Additionally, add in a preselection cut on the off-trace energy
  - Variable used to reject events with a true K^+
  - Didn't want MVA to make weird decisions about how to reject bkg based for these events which should look exactly the same as signal in the vars we pass the MVA
  - Total preselection efficiency = 55.4%

Overtraining Check

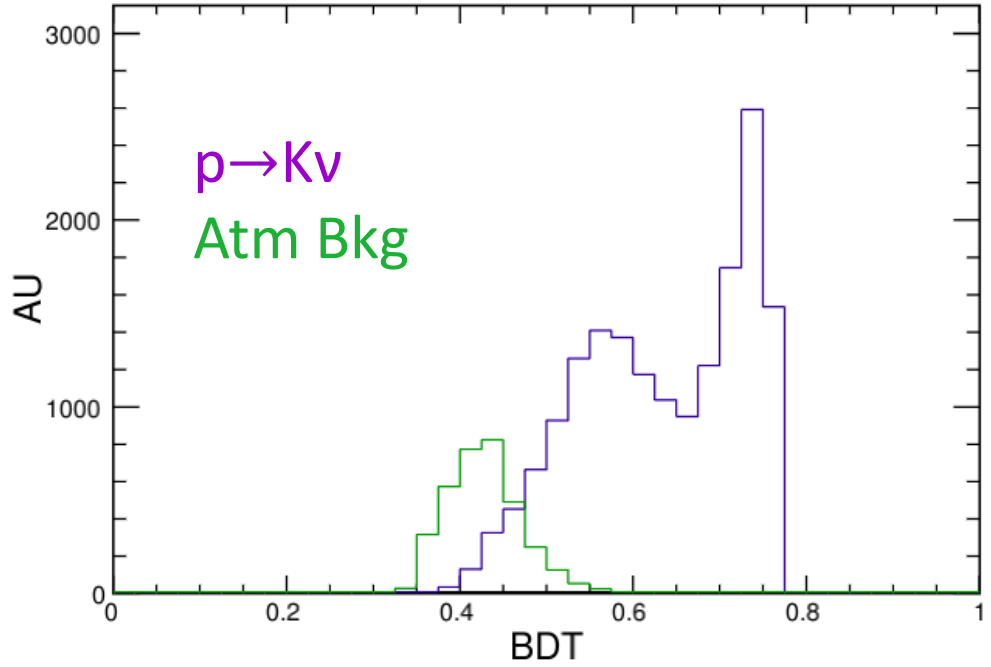
- Comparing the signal efficiency vs bkg rejection curve is a good way to test for overtraining of the MVA
  - Randomly split initial TTree of vars into test and training samples
  - If you do overtrain, high-MVA tail for background will be stretched to higher PID values

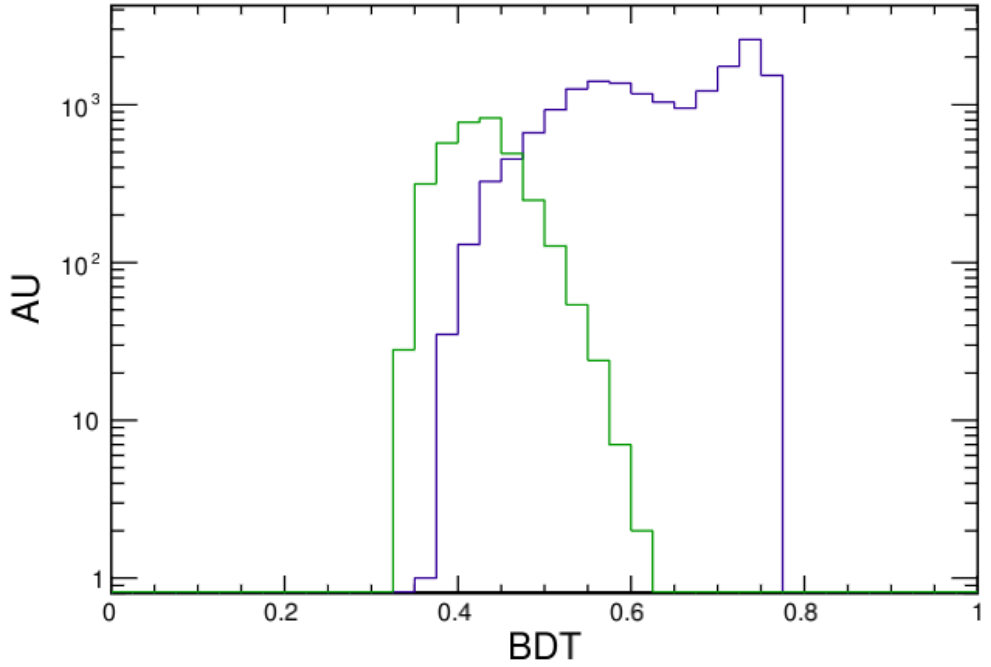
- Maybe some discrepancy when you've got 30ish bkg events remaining in your sample?
- But, at the highest PID values, the bkg tail looks like normal statistical jitter
- Signal efficiency here does not include 60.3% preselection from two tracks, nhit on K^+, and off-trace energy



BDT variable

- Highest BDT score for any bkg event in the test sample is 0.6053
- 60.9% of preselected K→μν signal have a BDT score greater than this
  - Folding in preselection efficiency, total 33.7% efficiency for selecting K→μν events
- Bkg exposure in test sample is 200 kton-years -> expect 5 bkg / Mton-years



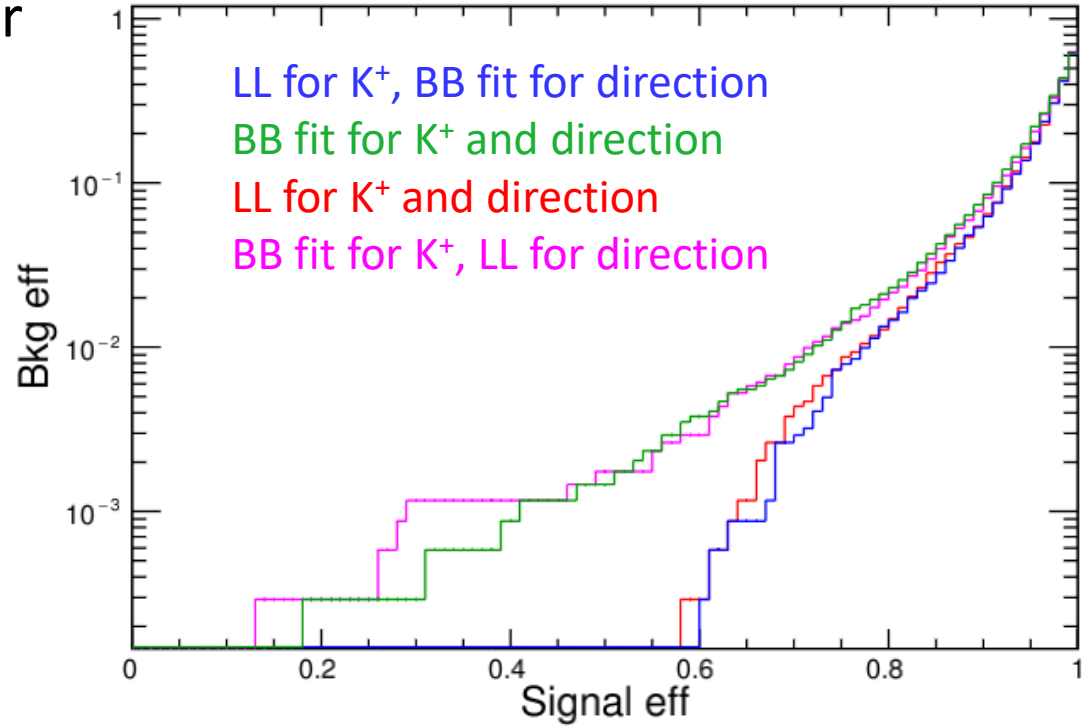


Aside: Justification for μ/K dE/dx Variables

- An apparent FOM is the signal efficiency in the test sample at point where 1 bkg event is selected

- Try out all possible combinations of using the template LL vs Bethe-Bloch fit for reconstructing K^+-ness and direction
  - Huge improvement for switching to LL K^+-ness compared to BB fit, but cuts actually do better than green / magenta curves
  - The BB fit, however, does slightly better deciding whether a particle was going forward or backward

- Same relation holds for muon variables, but these variables matter less, all FOM's where between 0.55 and 0.60



Summary

- There's valuable information in the induction planes
- Efficiency for tagging $K \rightarrow \mu\nu$ increases from 17.4 → 27.6%
  - Comes from mixture of improved tracking and improved bkg rejection from dE/dx, both can attribute to sampling the event from different yz projections
  - Pushes lifetime sensitivity up to around 1.8e34 years at 400 kton-years
    - Without any systematics
- Gains are very slim for the $K \rightarrow \pi^+\pi^0$ mode
  - Most efficiency improvement come from tracking K^+ in $K \rightarrow \mu\nu$, but the K^+ is detected by the $\pi^+\pi^0$ decay products, so this makes sense
- BDT analysis looks promising, efficiency improves to 33.7%, but you loose half the bkg to training so its estimate is even more uncertain than usual