Update on Kaon Reactive Cross Section

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Kaons in ProtoDUNE-SP

- Kaons are of interest for nucleon decay searches in the DUNE Far Detector.
  - Kaons could scatter off the argon preventing the detection of Bragg peak for PID.
- ProtoDUNE-SP has a small amount of high energy kaons to study the cross section of kaons on argon.
  - Result may be fed back into nucleon decay generator FSI modeling (Ex. *Physical Review D* **104**, 053006 (2021)).

		Momentum (GeV/c)			
		1	**2**	**3**	**6 - 7**
e	TOF (ns)	0, 105	0, 105	–	–
	XCET-L	1	1	1	1
	XCET-H	–	–	1	1
μ / π	TOF (ns)	0, 110	0, 103	–	–
	XCET-L	0	0	0	1
	XCET-H	–	–	1	1
K	TOF (ns)	–	–	–	–
	XCET-L	–	–	0	0
	XCET-H	–	–	0	1
p	TOF (ns)	110, 160	103, 160	–	–
	XCET-L	0	0	0	0
	XCET-H	–	–	0	0

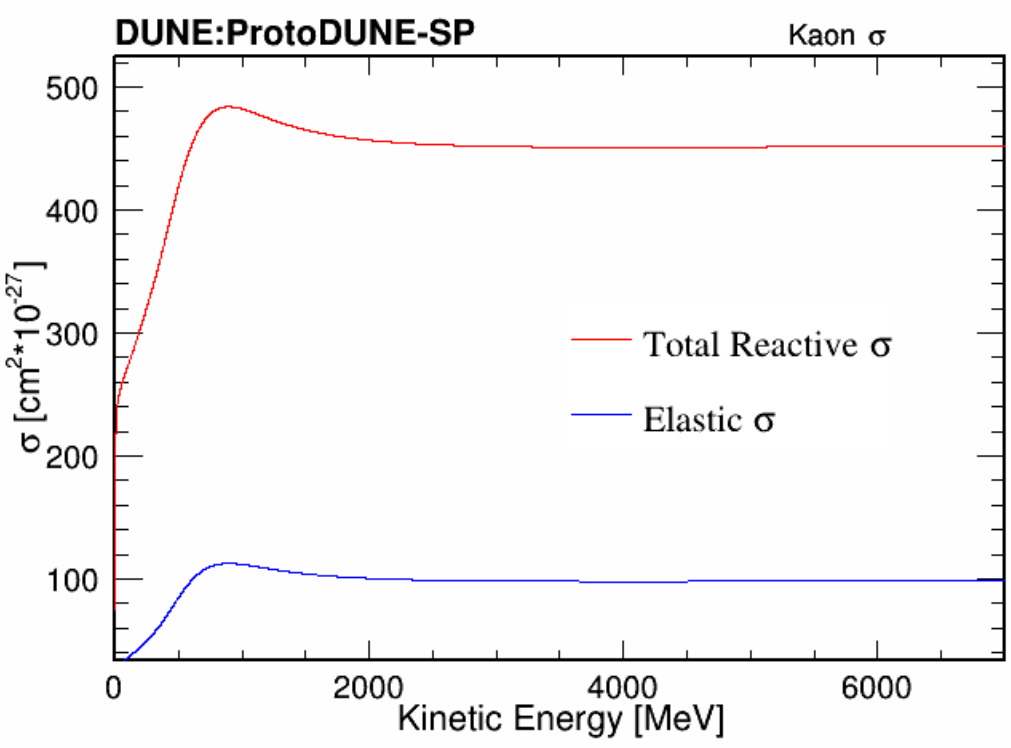
Beamline selection criteria based on information from the time-of-flight measurement and Cherenkov detectors (*JINST* **15** P12004).

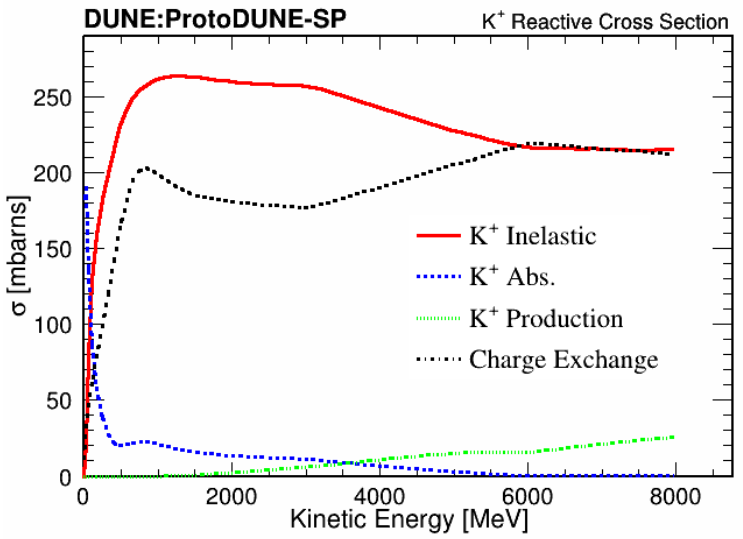
Momentum (GeV/c)	Pion-like (k)	Proton-like (k)	Electron-like (k)	Kaon-like (k)
0.3	0	0	242.5	0
0.5	1.5	1.5	296.3	0
1	381.8	420.8	262.7	0
2	333.0	128.1	173.5	5.4
3	284.1	107.5	113.2	15.6
6	394.5	70.1	197.0	27.9
7	343.7	58.4	112.9	28.2

Total run statistics by particle candidate from the beamline monitoring system with a rudimentary selection process.

Kaons in ProtoDUNE-SP

- Kaons at 6-7 GeV/c have a flat cross section according to Geant4.
- Analysis will look at total reactive cross section, also known as an inclusive inelastic cross section.
- Expectation: ~450 mbarns



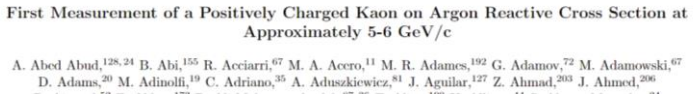


Total reactive cross section (left) and the exclusive cross sections (top) from Geant4. Plots produced using Geant4RW.

Analysis so Far

Feedback from Last Update:

- Add covariance matrix metrics to presentation.
- Start using statistical independent simulation samples for Asimov tests.


First Measurement of a Positively Charged Kaon on Argon Reactive Cross Section at Approximately 5-6 GeV/c

A. Abed Abud,[128,24] B. Abi,[155] R. Acciarri,[67] M. A. Acero,[11] M. R. Adames,[192] G. Adamov,[72] M. Adamowski,[67] D. Adams,[20] M. Adinolfi,[19] C. Adriano,[35] A. Aduszkiewicz,[81] J. Aguilar,[127] Z. Ahmad,[203] J. Ahmed,[206]

Progress made:

- Wrote five pages of PRD-like draft.
- Rebinning of whole analysis to ensure consistent results when choosing number of Bayesian-like unfolding iterations.
- Fit of the cross section results using TF1.
- Bug fix on covariance matrix in code allowing for quick access to full covariance matrix chi-squares.
- Broken tracks no longer considered “Fake” selections if they are kaon inelastic scatters.
  - Went back and forth on this but the fake penalties did not make sense and resolution plots show there is not a huge resolution advantage to throwing these events out of smearing matrix.
- Remade ntuple of almost the entire dataset of datadriven 6 GeV simulated events.
  - Production group is making an official ntuple so it goes through same auditing, samweb, and documentation practices as all other ntuples.

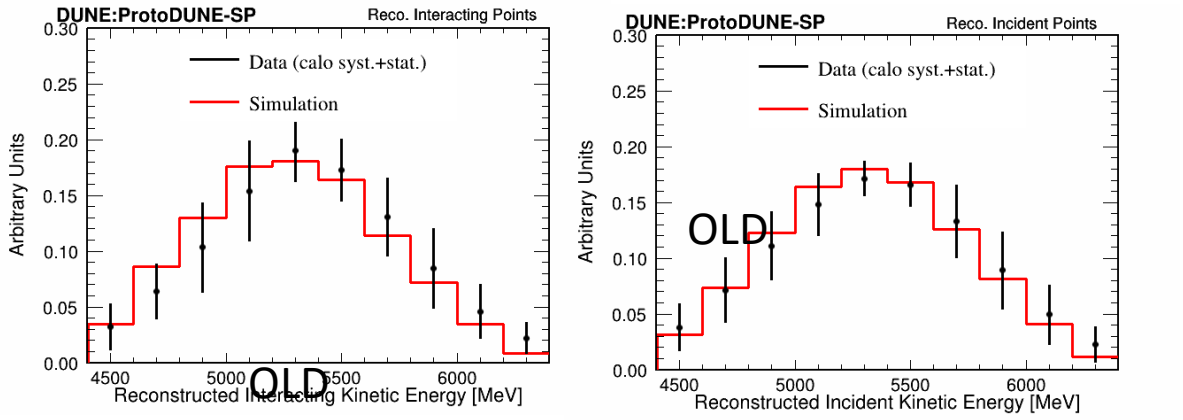
Binning Changes

What are the systematic uncertainties?

- 100 Gaussian throws assuming:
  - 2% uncertainty on dE/dx (see backup)
  - 3% uncertainty on beam momentum resolution (*Phys. Rev. Accel. Beams* **22**, 061003)

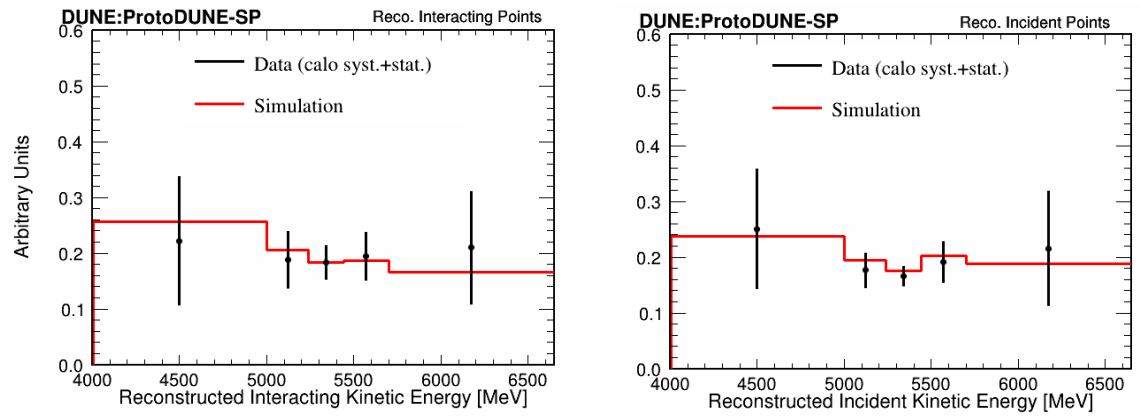
Uniform binning creates a Gaussian distribution that is susceptible to shifts.

Before:



Solution is to bin equally across the distribution using Run 5770 as a guide. Bin can be no smaller than 200 MeV as that is the energy resolution (3%*6 GeV/c=180 MeV from the beam alone!)

After:

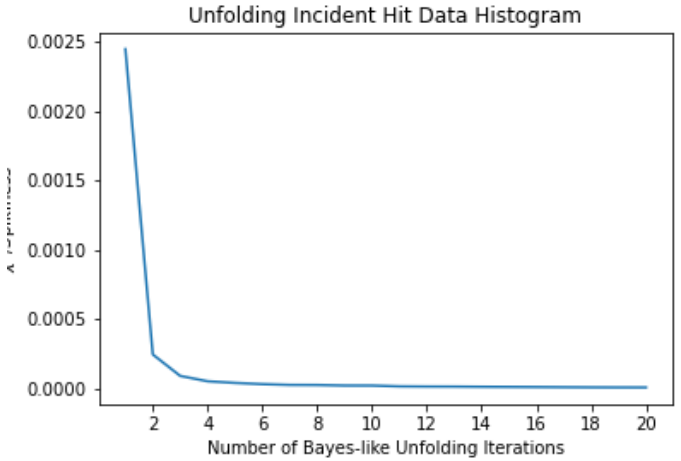


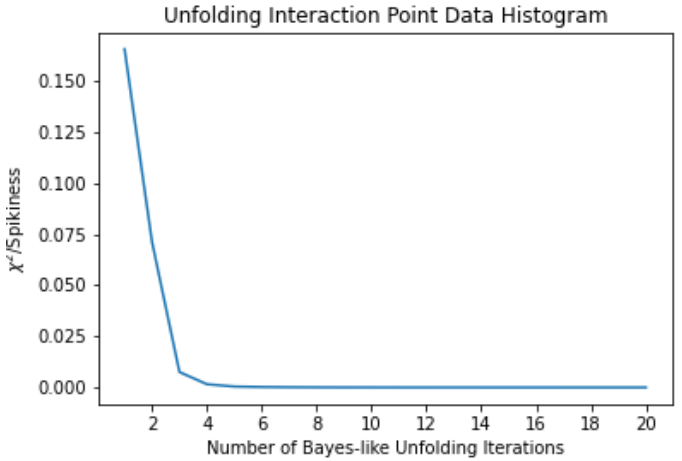
Optimal number of unfolding iterations

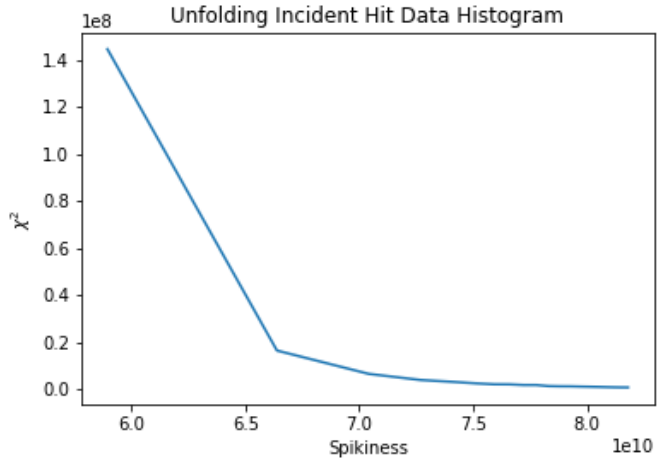
Slides from Stephen Dolan on optimizing iterations:
https://indico.cern.ch/event/735431/contributions/3268135/attachments/1784286/2904287/funfolding_phystatv2.pdf

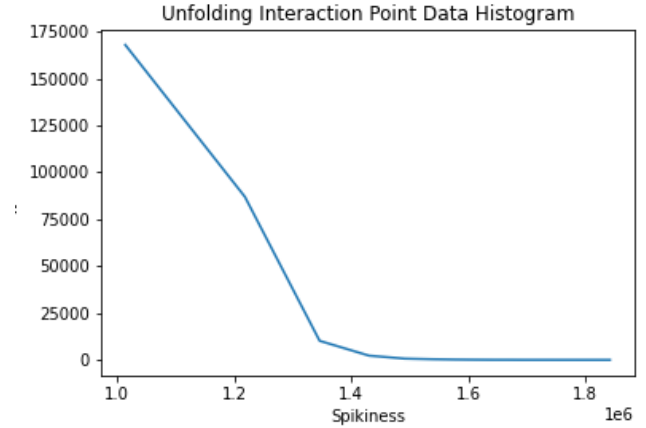
Spikiness: Difference bin to bin
Chi-square: Full 1k throw statistical covariance matrix chi-square with results with 1000 iterations.

With the old binning, the spikiness metric T2K uses ends up being meaningless as the unfolded incident and interacting distributions are spiky with/without unfolding. Ideal number of iterations is where neither diverge.







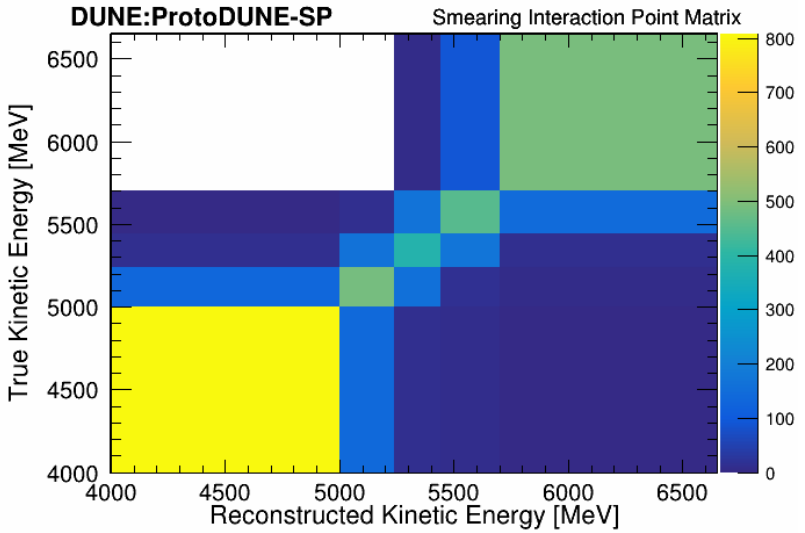


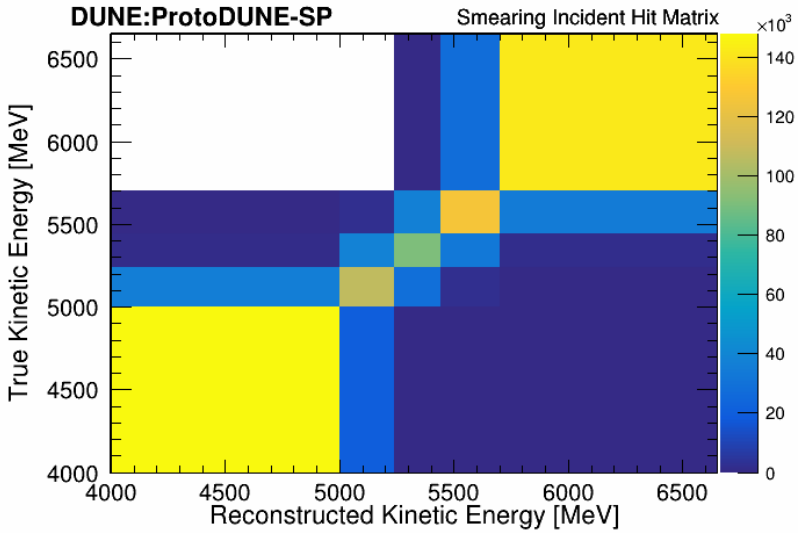
Spikiness and chi-square plot.

Ideal iterations curve (2-4 looks ideal)

Unfolding Methodology

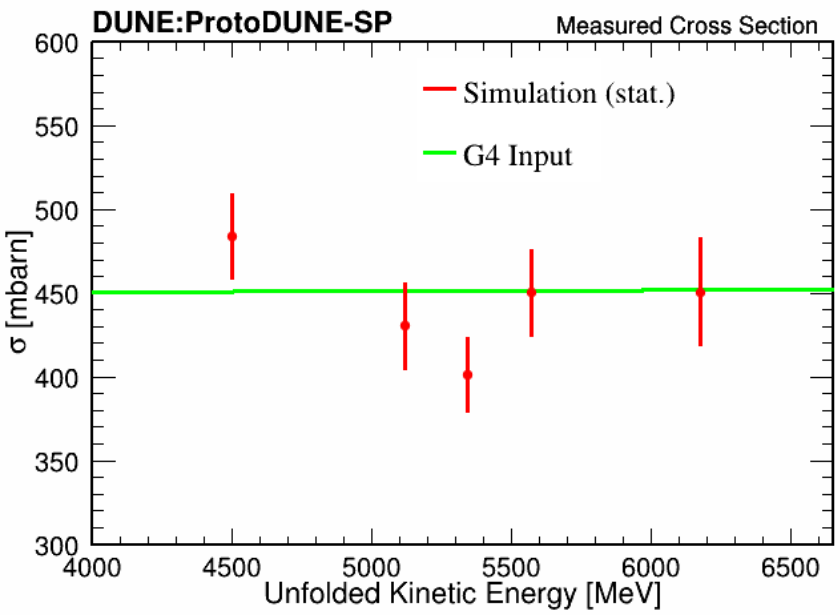
- Smearing matrix is filled with entire 6 GeV data-driven primary kaon dataset.
  - Because of low statistics, all events are used
    - Translation: No training sample.
- Fill matrix if:
  - Primary kaon was the track
- Miss if:
  - Unselected primary kaon
- Fake:
  - Selected particle was not the primary kaon or did not interact at the track endpoint.
- Use RooUnfold's Bayesian-like unfolding (by T. Adye)
  - 4 iterations (see Slide 6).



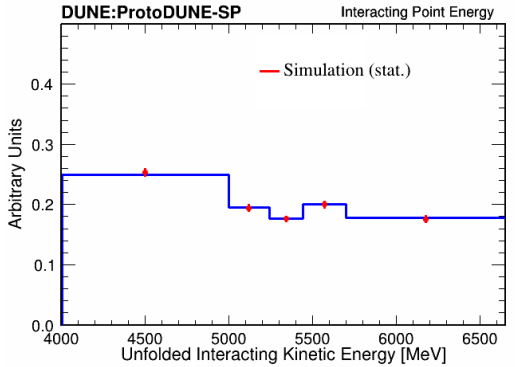


Unfolding Results in Simulation

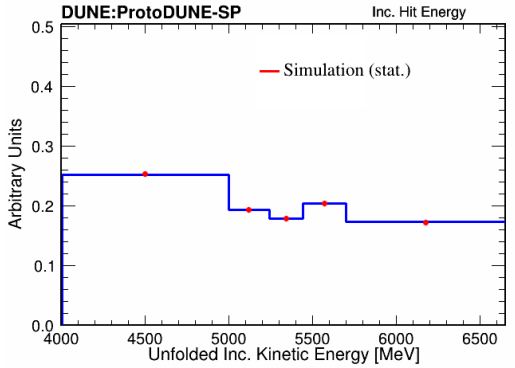
- 66% of sample used for training, 33% of events in sample used to test simulation (red)
- Simulation fits to a constant of 440+/-11 mbarns with a fit chi-squared ~6.5/5
- Full statistics covariance chi-square (1000 Poisson bin throws) to Geant4: 6.21/5.



Unfolded cross section (left) from unfolded distributions (right).

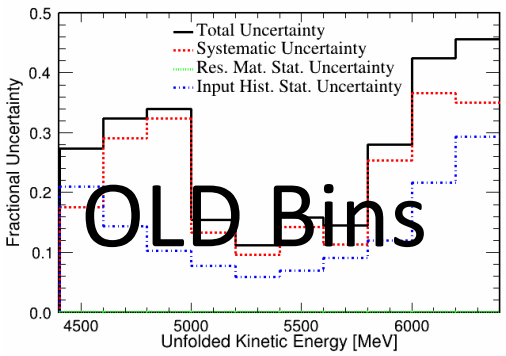


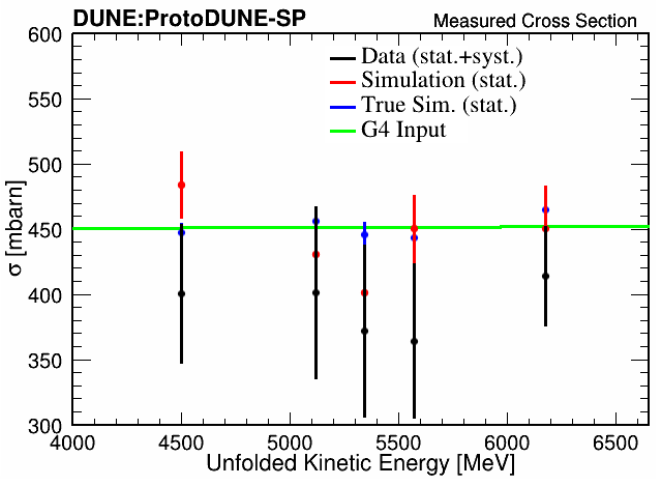
Unfolded interacting histogram (top) and incident histogram (bottom).

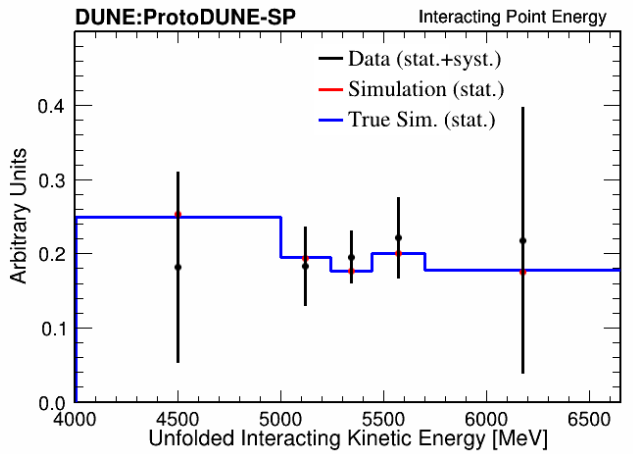


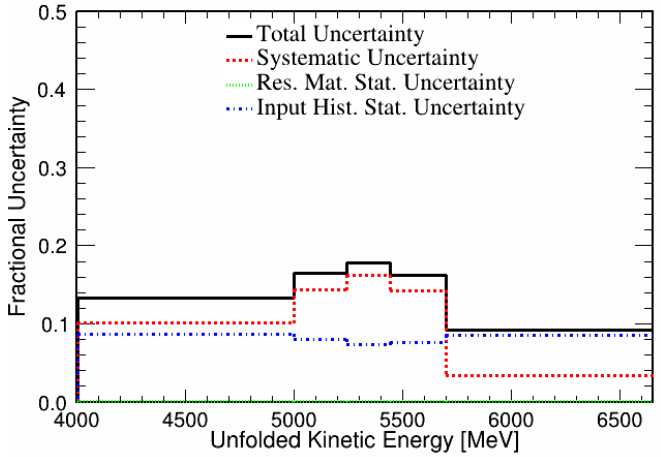
Unfolding Results with Run 5770

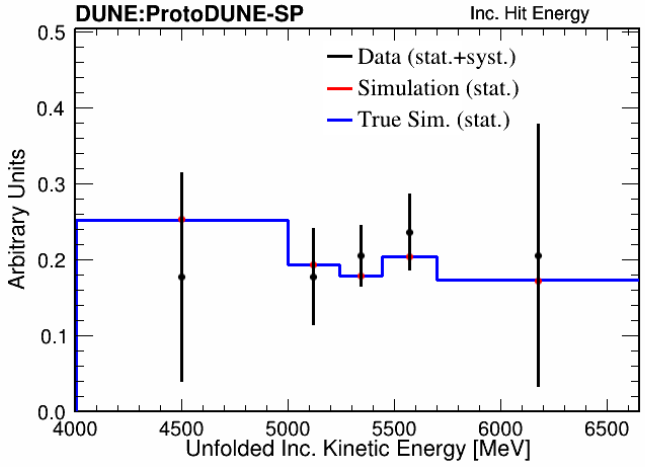
- Plots use 100 systematic uncertainty throws
  - 3% beam, 2% hit-by-hit calorimetric
  - No stat. response mat. uncertainty used here.
- Chi-squares to Geant4 (full covar.)
  - Data (stat.+syst.): 3.78/5 bins
  - Data (stat.): 27.4/5 bins
  - Sim. (stat.): 6.21/5 bins
- Linear fits:
  - Data: 396.3+/-23.7 mbarns
  - Sim: 440.0+/-11.5 mbarns







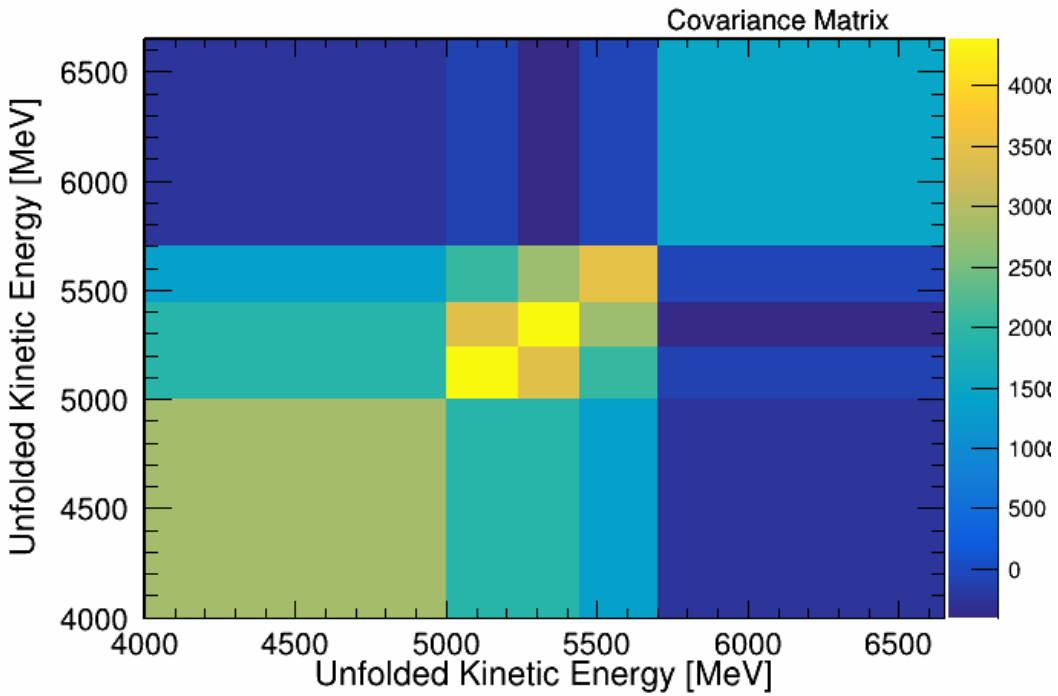


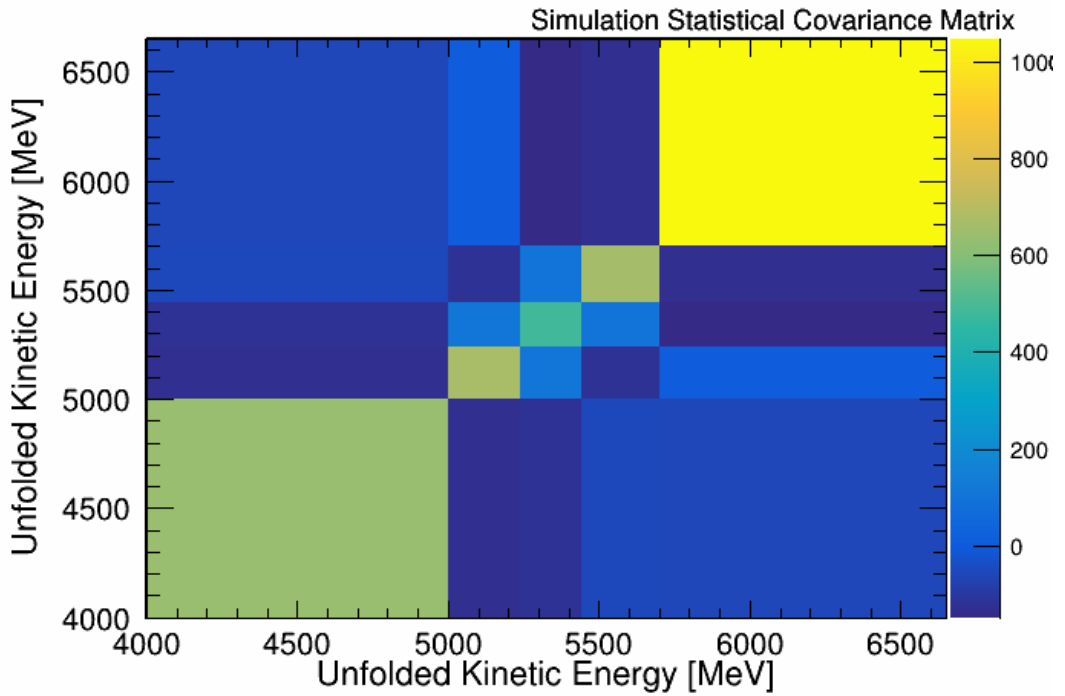


Note: Only the beam resolution and hit-by-hit calorimetry systematic uncertainties are used.

Covariance Matrixes

- Run 5770 (stat. and calo syst.) left.
- Simulation (stat. only) right.





Conclusion

- Remaining tasks:
  - Port everything over to the 7 GeV/c analysis.
  - Confirm e-slice method provides similar result.
  - Finalize selection based and Geant4 based systematics.
- Template fit results will be presented in next few meetings.
- No SCE simulation studies will also be shown soon.
- Binning has solved many statistical uncertainty issues and chi-squares confirm results within expectation.

Back-up Slides

Thin Slice Cross Section Formula

$$\sigma(\mathrm{KE}) = \frac{\mathrm{M_{Ar}}}{\mathrm{N_{avo.}}\,\mathrm{r_{wire\,pitch}}\,\rho_{\mathrm{Ar}}} \ln\left[\frac{\mathrm{N_{inc.}}(\mathrm{KE})}{\mathrm{N_{inc.}}(\mathrm{KE}) - \mathrm{N_{int.}}(\mathrm{KE})}\right]$$

LArIAT Formula (paper):

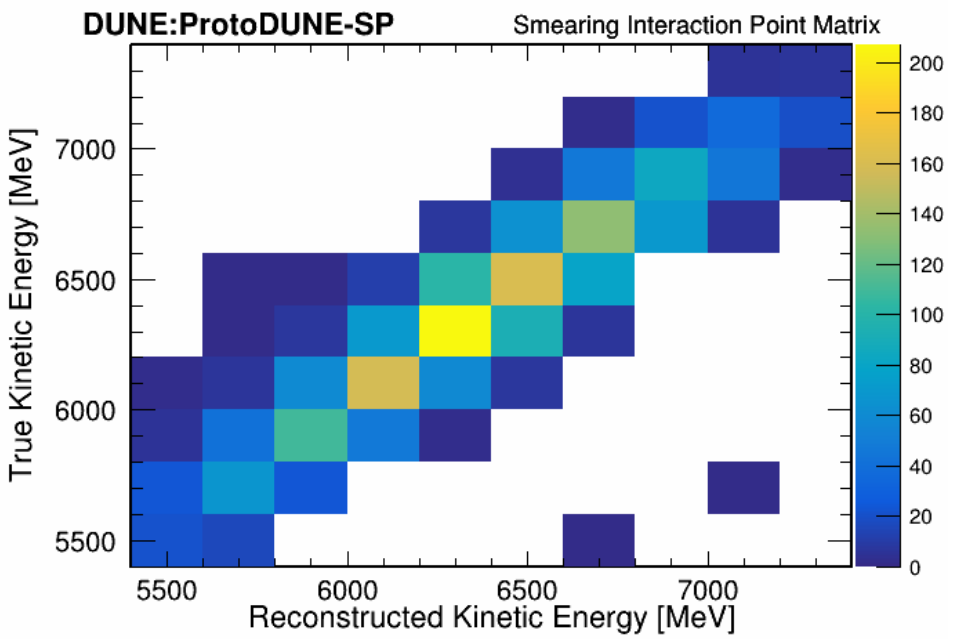
- N_int: Energy of the selected interaction points if the track ends before the first set of electron diverters.
- N_inc: All hits of selected events before the electron diverters.

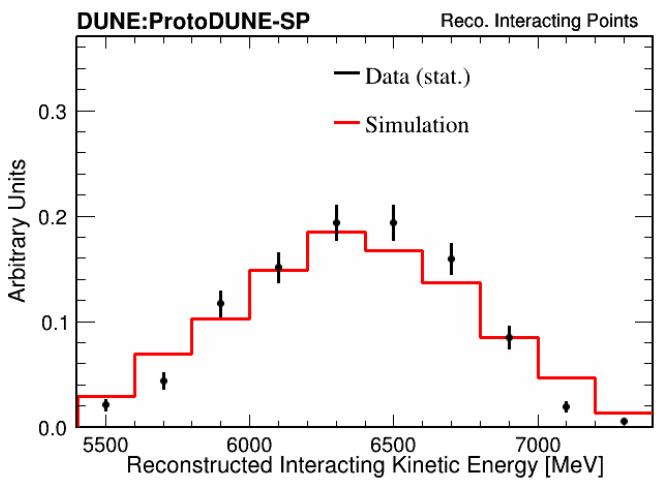
Currently working on:

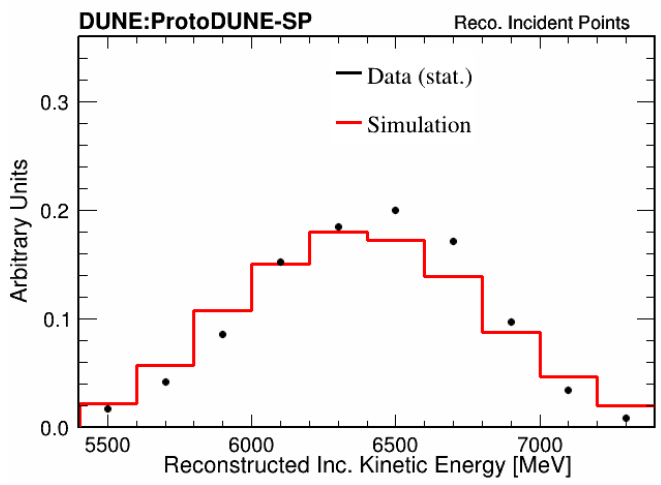
- Fit using likelihood metric (Jake Calcutt's fit)
- E-slice method (Although there are not enough statistics for it to be useful).

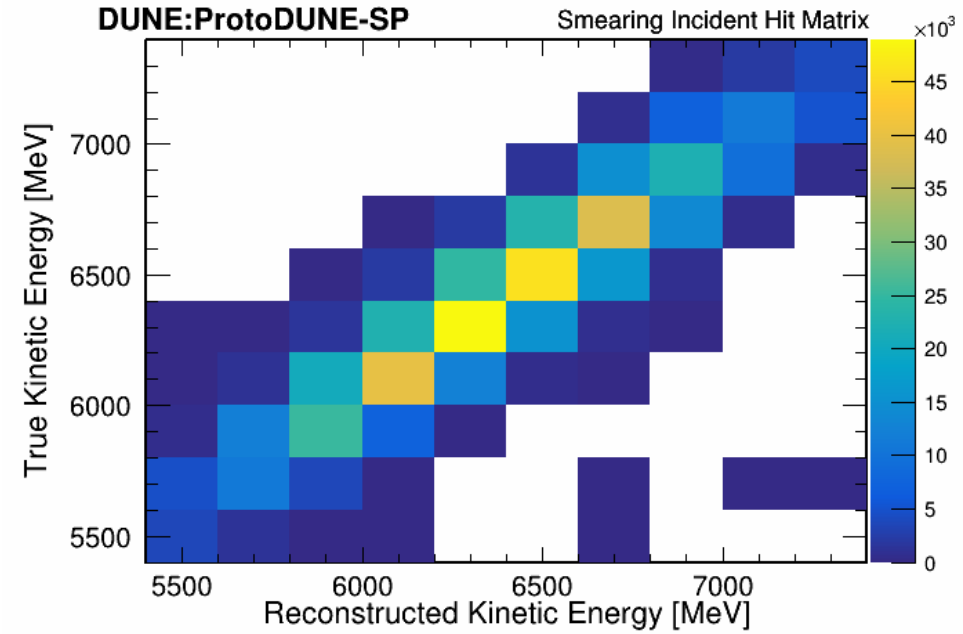
7 GeV Cross Section (Old Slide)

- Only the standard beam simulation is available.
  - That sample is both the training and fake data sample for this study.
- Event selection identical to the 6 GeV cross section analysis.
  - Preselection with beamline instrumentation also the same.
- Whole unblinded data sample and simulation are used
  - Both have low statistics
  - Use 6 GeV studies to inform the changes of the analysis.

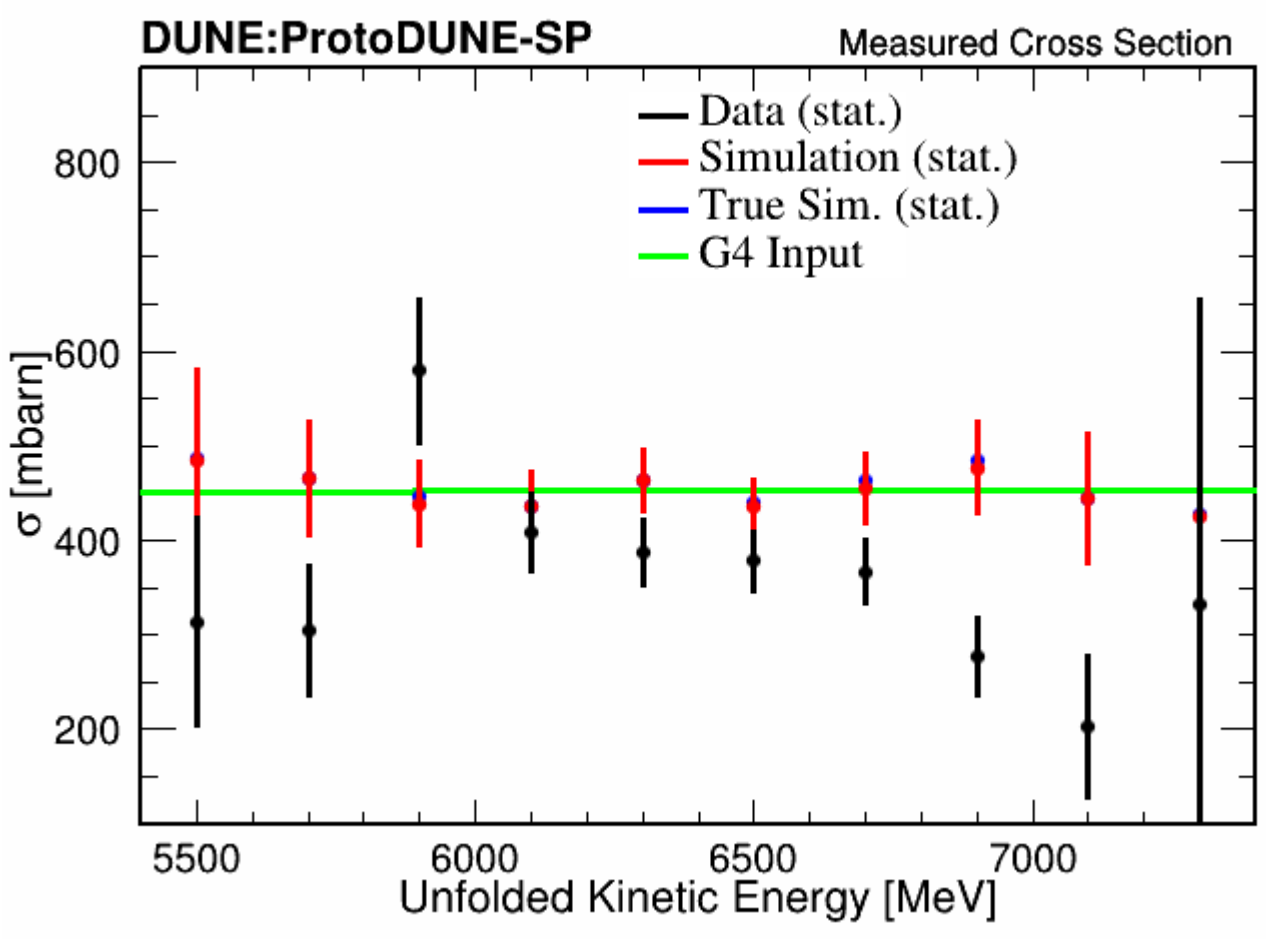








7 GeV Cross Section (Old Slide)

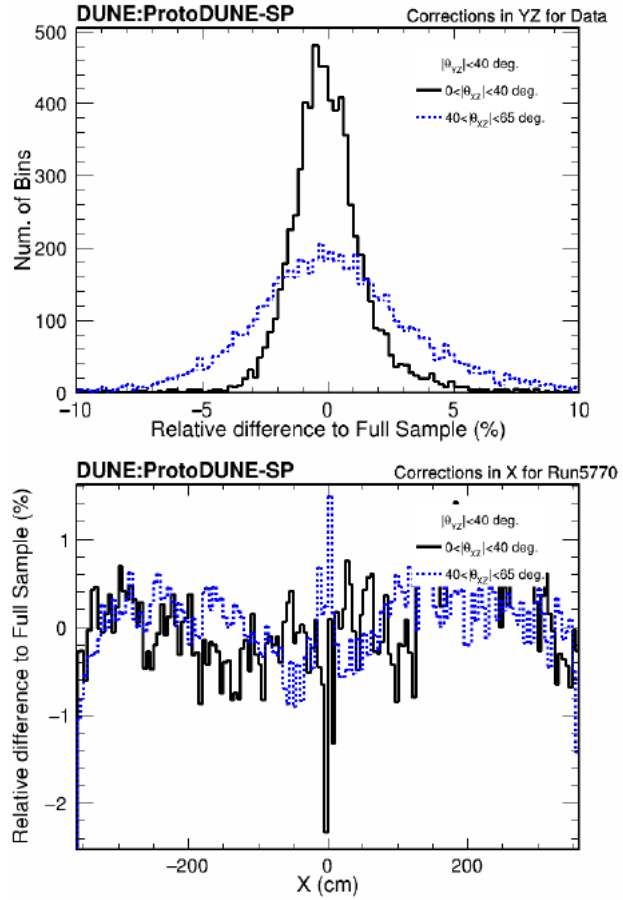


LArTPC Calorimetry Systematic Uncertainty

- Based uncertainty on cross-checks MicroBooNE did of their dQ/dx calibration (paper).
- This was redone with ProtoDUNE beam angles being taken into consideration.
- Data uncertainty set to conservative 2%. See my thesis for more information.

Data Set	σ_{YZ}	σ_{X}	$\sigma_{dE/dx}$
Simulation	0.72%	0.5%	0.97%
Data (Run 5770)	1.24%	1.00%	1.79%

Uncertainty of YZ and X calibration and the resulting dE/dx calibration from those uncertainties for data and simulation.



Plots used for YZ and X dQ/dx calibration to verify subsample deviations from the larger sample.

Analysis so Far at the Collaboration Meeting

- Thesis has preliminary analysis of 6 GeV kaons: My Thesis
- Continued working on it since November of 2021 in hopes of draft for DUNE approval near end of summer.
- Last update from ProtoDUNE internal meetings: Indico

Changes Implemented:

- Integrating the 6 GeV sample with the standard beam generator into analysis. Advantages of using that sample:
  - Almost 2x more statistics.
  - Every other ProtoDUNE-SP analysis uses the standard beam generator.
  - **Will be referred to as "Fake Data" for these slides and data-driven beam sample by Leigh and Jake is considered the "Simulation."**
- Analyzing the 7 GeV/c sample (see backup).
- Changing the "skip hit" feature that filled in hits with too high dE/dx from 5 MeV/cm to 20 MeV/cm
  - This part of the code would "fill in" large dE/dx hits with Bethe-Bloch expectation if the hit was not the last hit in the track.

Changes Being Working On:

- Testing analysis using Geant4RW fake data (with Tyler Stokes of LSU).
- Investigating the high dE/dx hits (encouraged by Jake Calcutt and Tom Junk).
- Verifying RooUnfold's "Overflow" feature.
- Systematic uncertainties related to MC/data mismodeling of background and broken reconstruction.

Many thanks and gratitude are owed to the first kaon-argon cross section measurement by Elena Gramellini (Thesis)

Event Selection

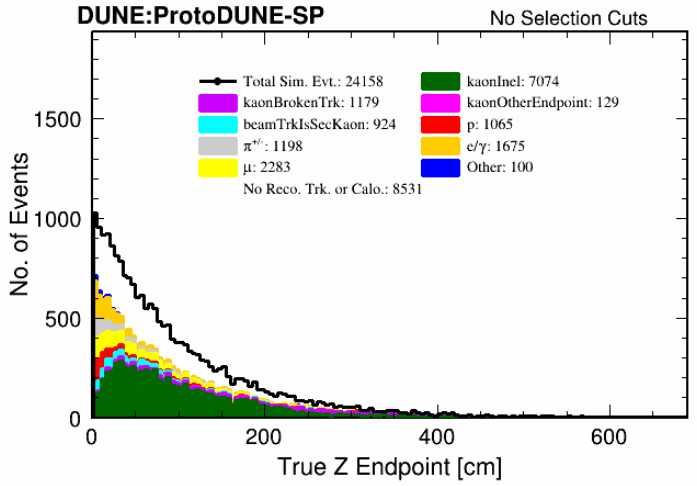
Process like other analyses at ProtoDUNE-SP.
Preselection: Beamline instrumentation reports Cherenkov detectors measured a kaon (see Slide 2) and the momentum is between 4 and 8 GeV/c.

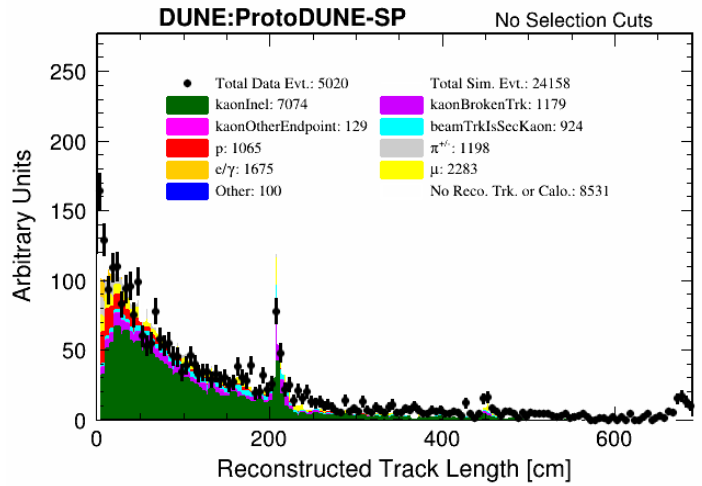
1. Pandora reports a TPC reconstructed beam track.
2. Beamline tracking and TPC reconstruction must agree within 3 standard deviations from the central-value for:
   - $\delta_{\text{xtpc-ybeam at face}}$
   - $\delta_{\text{ytpc-ybeam at face}}$
   - $\delta_{\text{ztpc-0}}$
   - $\cos(\theta_{\text{tpc dir.*beam dir.}})$
   - $\delta_{\text{xytpc-xybeam at face}}$

Tracks that pass these cuts have hits before the first set of electron diverters included in the incident hit histogram.

3. Track ends before 220 cm before the electron diverters (see spike on right).

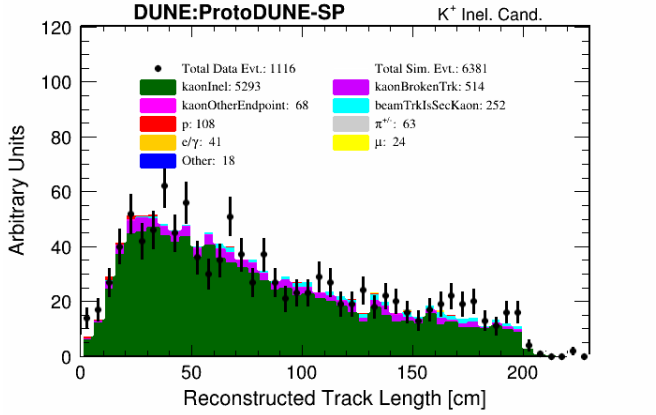
Tracks that pass all cuts are selected for the interaction point histogram.

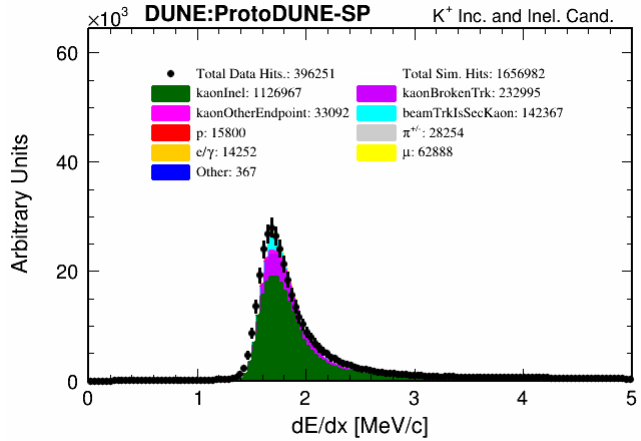


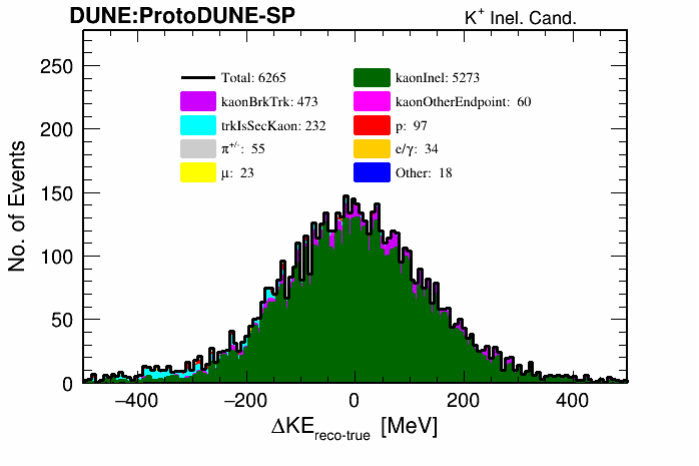


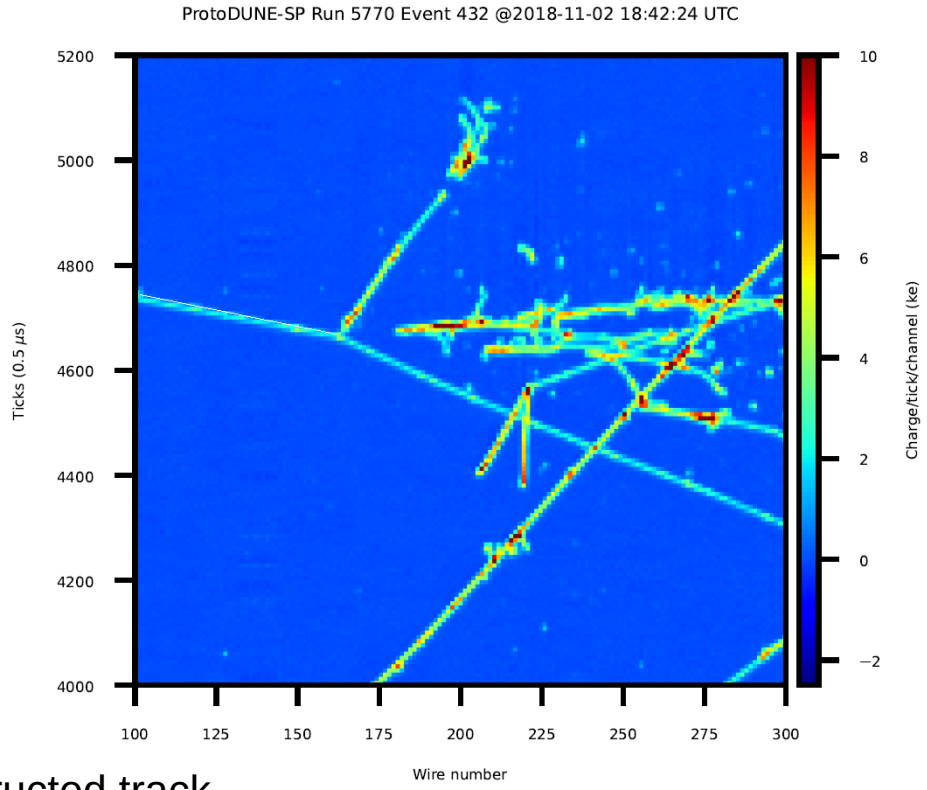
True track endpoint in simulation (top) and reconstructed track length (bottom) with data and simulation with only beamline Cherenkov detector and momentum measurement cuts.

Event Selection Validation Plots









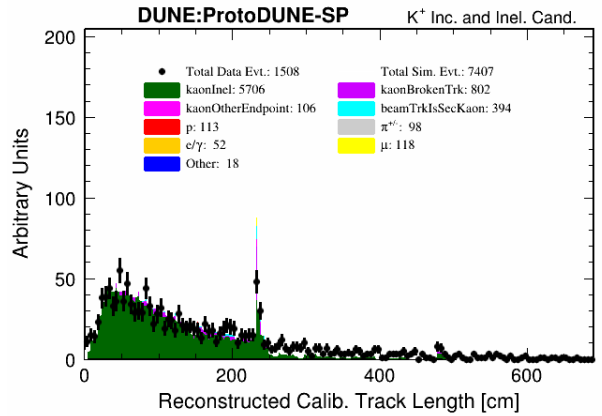
Reconstructed track length and dE/dx of data and simulation (top).

Energy resolution truth (bottom).

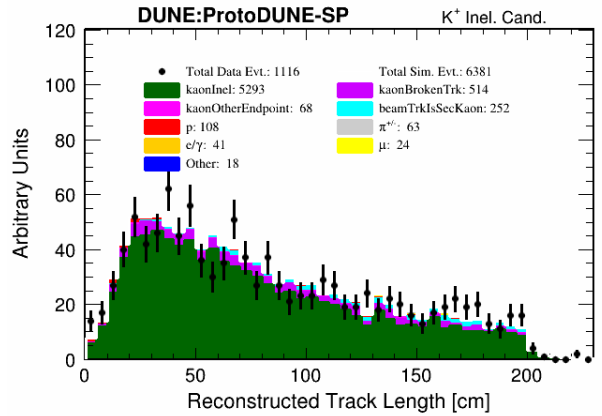
Kaon candidate event in data. Image taken from my thesis.

Event Selection

Sample	Preselected	Reco Trk. Cut	Selected Interacting and Incident Events	Selected Interacting Events
Data-driven MC	24,158	13,472	7,876	6,381
Standard MC (Fake Data)	40,620	22,336	10,474	8,421
Run 5770	5,020	2,899	1,508	1,116



Reconstructed track length for Run 5770 and simulation of selected events.



Reconstructed track length for Run 5770 and simulation of selected interacting events (same plot as the previous slide).