# Meas. $K^+$-Ar Total Inelastic Cross Section at ProtoDUNE-SP

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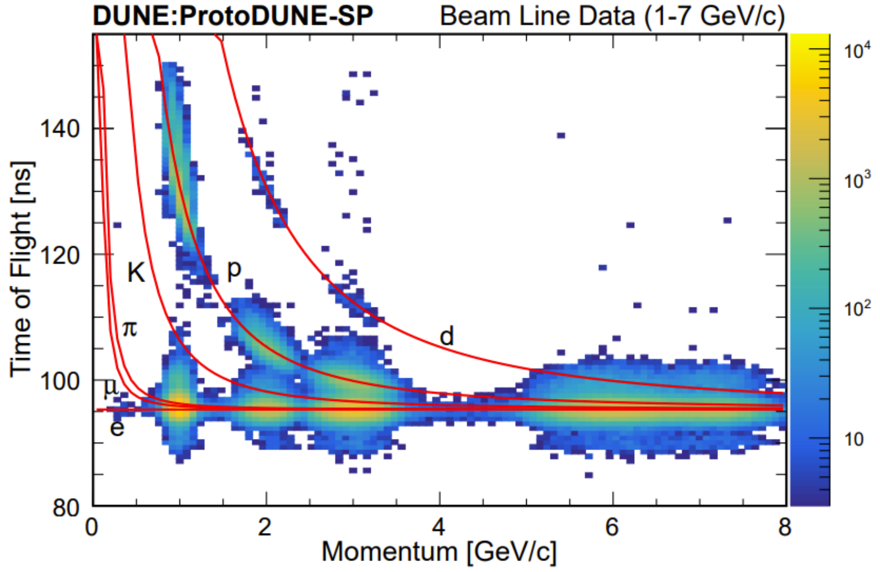
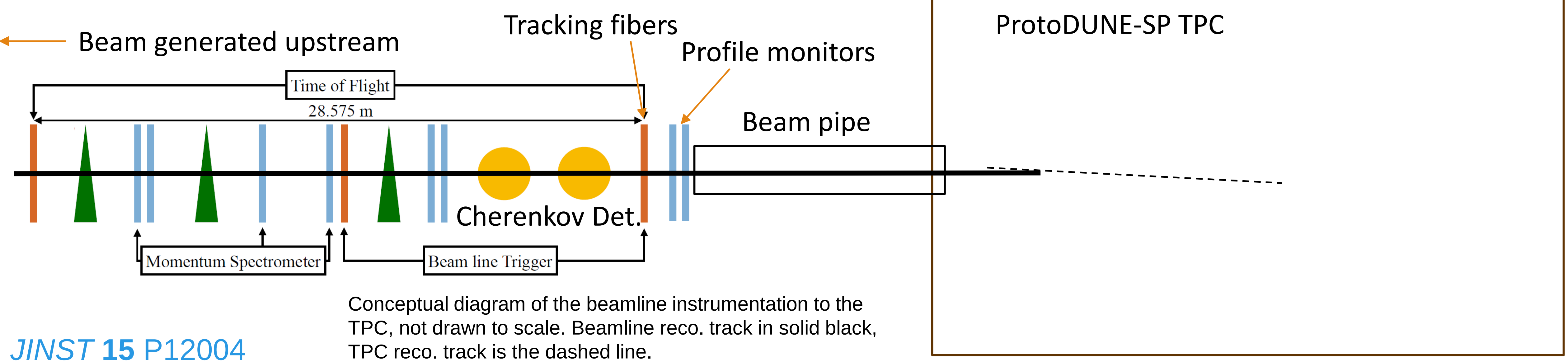
A Brief Introduction to ProtoDUNE-SP was Presented on Monday

# Hadron Beam Taken at ProtoDUNE-SP

- Uses a tertiary hadron beam from CERN SPS (*Phys. Rev. Accel. Beams* **22**, 061003).
- Beamline instrumentation provides tracking, PID, and momentum measurements (*JINST* **15** P12004).
- Beamline instrumentation tracking cross-checks tracking of Pandora-reconstructed beam candidate (*EPJC* **83** 618).

(Right) Time-of-flight information measured by the beamline information system. Cherenkov detectors used when TOF overlap.



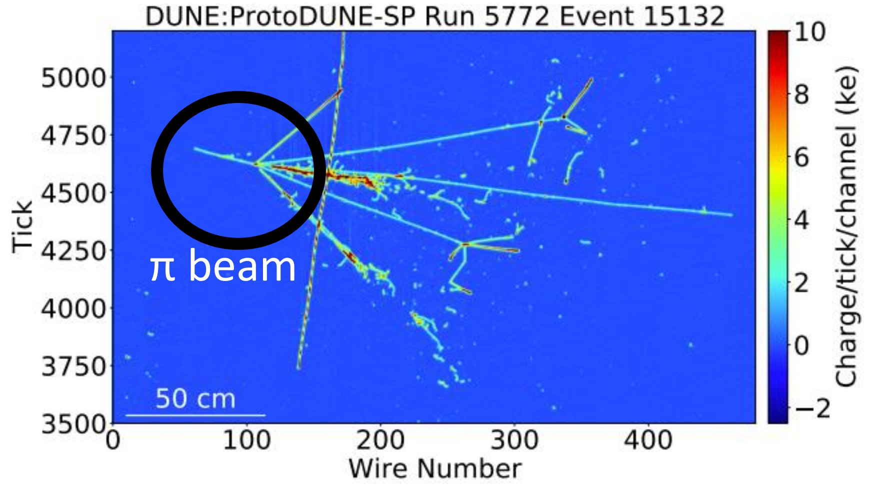




Conceptual diagram of the beamline instrumentation to the TPC, not drawn to scale. Beamline reco. track in solid black, TPC reco. track is the dashed line.

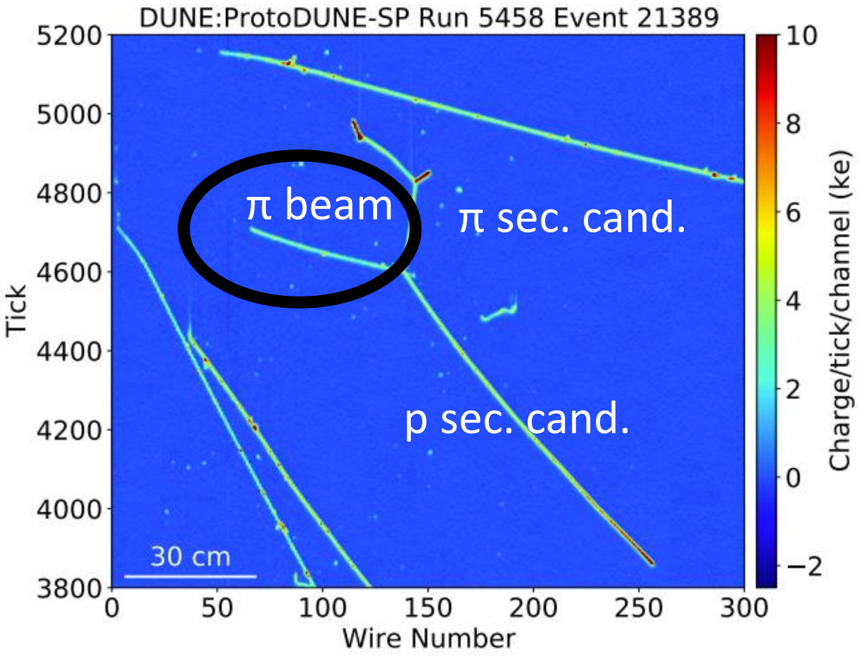
*JINST* **15** P12004

# Raw Data Event Displays from ProtoDUNE-SP

- LAr TPCs allow for event displays with near-continuous signals.
- Beamline provides particles one-at-a-time with a trigger, allowing for consistent identification of beamline hadrons.

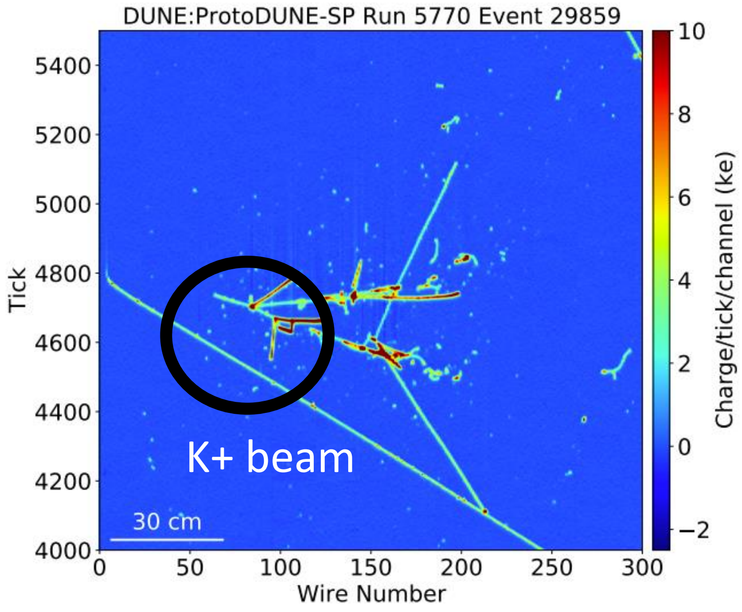


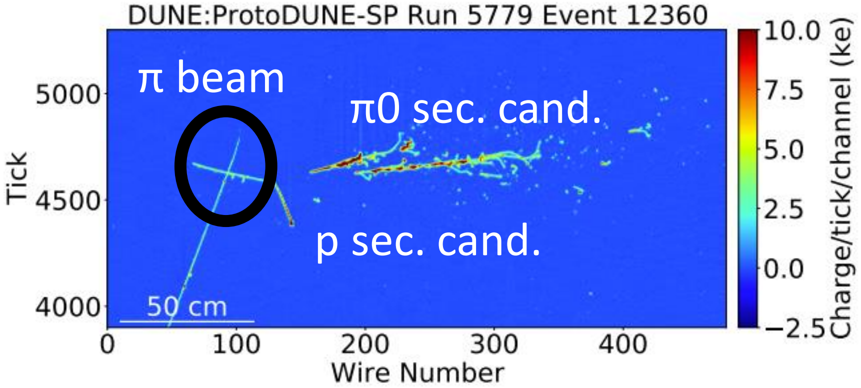

2 GeV/c positive pion candidate interaction




1 GeV/c positive pion candidate inelastic interaction

6 GeV/c kaon candidate interaction




2 GeV/c positive pion candidate charge exchange interaction

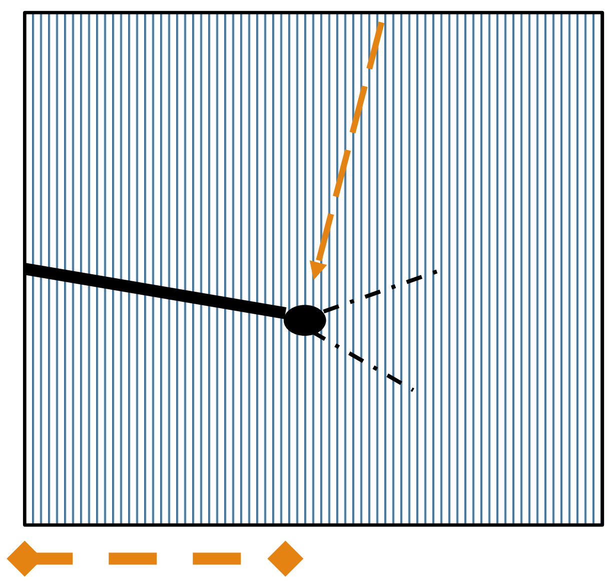
*JINST* **15** P12004

# ProtoDUNE-SP Hadron Cross Sections in a Time Projection Chamber

- All analyses use some version of the thin-slice equation pioneered by LArIAT (*Phys. Rev. D* **106**, 052009):

$$N_{inc.} - N_{int.} = N_{inc.}\exp\left(-\sigma r_{trk.pitch} n\right) = N_{inc.}\exp\left(-\frac{\sigma\rho_{Ar} r_{trk.pitch} N_{avo.}}{M_{Ar}}\right)$$

$$\sigma(KE) = \frac{M_{Ar}}{N_{avo.} r\rho}\ln\left[\frac{N_{inc.}(KE)}{N_{inc.}(KE) - N_{int.}(KE)}\right]$$




- Example:
    - A kaon travels from slice 0 to slice j at KE of $T_o$ and then interacts:

$$T(j) = T_o - \sum_{i=0}^{j}\frac{dE_i}{dx_i}\delta x_i = T_o - \sum_{i=0}^{j}\Delta E_i$$

    - Let's say we select N kaons that travels J slices and then interact:

$$N_{inc.}(KE) = \sum_{k=0}^{K}\sum_{i=0}^{j-1} N_{inc.}(KE) + \delta(KE - T_{ki})$$

$$N_{int.}(KE) = \sum_{k=0}^{K} N_{int.}(KE) + \delta(KE - T_{kj})$$

Constants used:

- n: number density
- $M_{Ar}$: mass of argon nucleus
- $N_{Avo.}$: Avogadro's number
- r: pitch between wires
- ρ: liquid argon density

# $K^+$-Ar Measurements Total Inel. Cross Section

- $K^+$ identified 6-7 GeV/c momenta settings.
- Presentation will focus on 7 GeV/c setting, but both settings are being analyzed.
- Event Selection:
  1. Beam must reach fiducial volume.
  2. Beamline information must “match” TPC-reconstructed track.

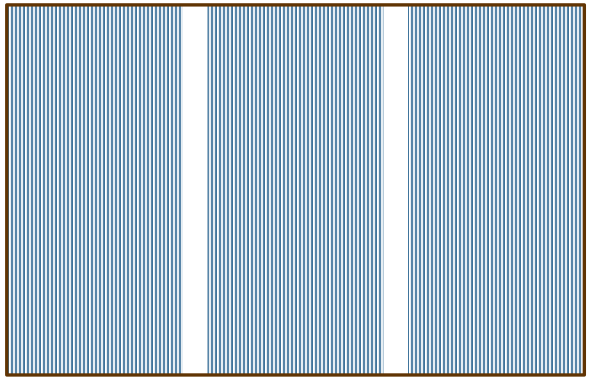
  For including a slice in the distributions:

  3. Slice only contributes to incident or interacting histogram if within the fiducial volume.

(Right) Number of beamline candidates identified as kaons reported by beamline monitoring system

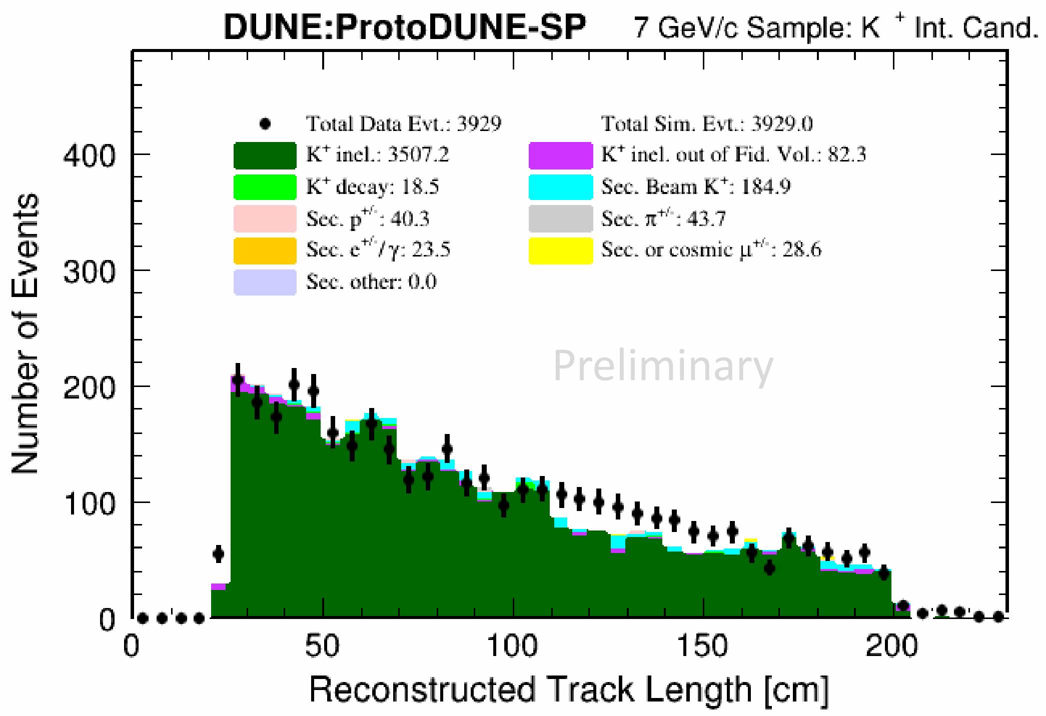
| Momentum (GeV/c) | Kaon-like (k) |
|---|---|
| 1 | 0 |
| 2 | 5.4 |
| 3 | 15.6 |
| 6 | 27.9 |
| 7 | 28.2 |

Detector height



Detector length

Cartoon of the wire readout plane (blue) layout in ProtoDUNE-SP. Separations between planes break tracks due to detector effects.




Track length distribution of selected kaon beam tracks for the 7 GeV/c sample with interactions in the fiducial volume.

# The "Simplest" Thing To Do

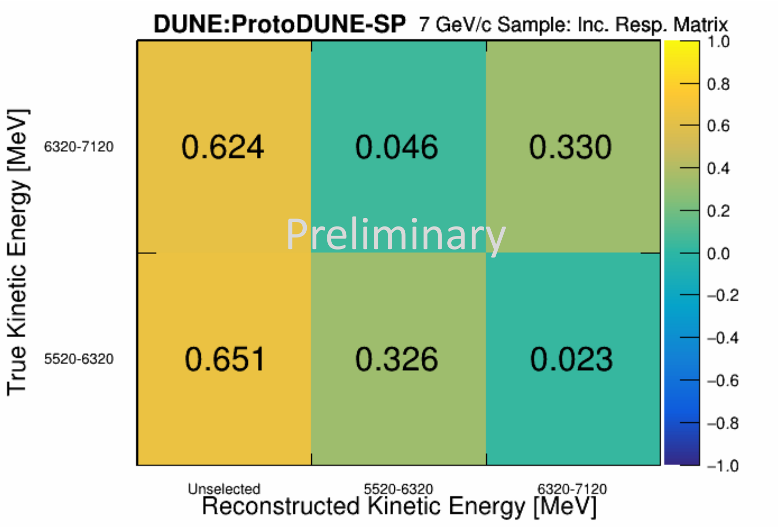
- Use Bayes-like unfolding to unfold the incident and interacting histograms separately using each wire as a "slice" of the detector.
  - Benefits:
    - Like the corrections-based method of LArIAT (*Phys. Rev. D* **106**, 052009)
    - Correct treatment of particles that pass the fiducial volume and only provide incident slices.
    - Eff. and pur. corrections come with unfolding.
  - Negatives:
    - Dependent on calorimetry for each wire slice.
    - Need to prove it is not model dependent

Reco.->Truth

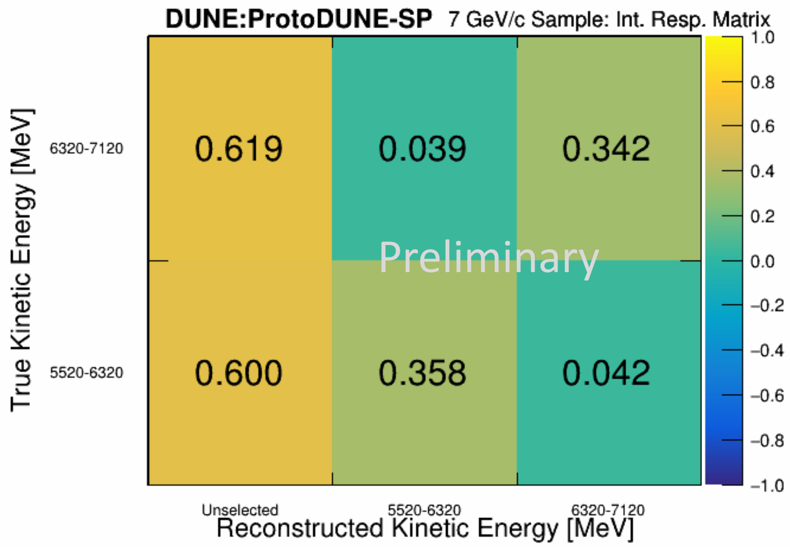
$$\sigma\,(\mathrm{KE}) = \frac{\mathrm{M_{Ar}}}{\mathrm{N_{avo.}} r \rho} \ln \left[ \frac{\mathrm{N_{inc.}}(\mathrm{KE})}{\mathrm{N_{inc.}}(\mathrm{KE}) - \mathrm{N_{int.}}(\mathrm{KE})} \right]$$

Reco.->Truth

Incident Resp.



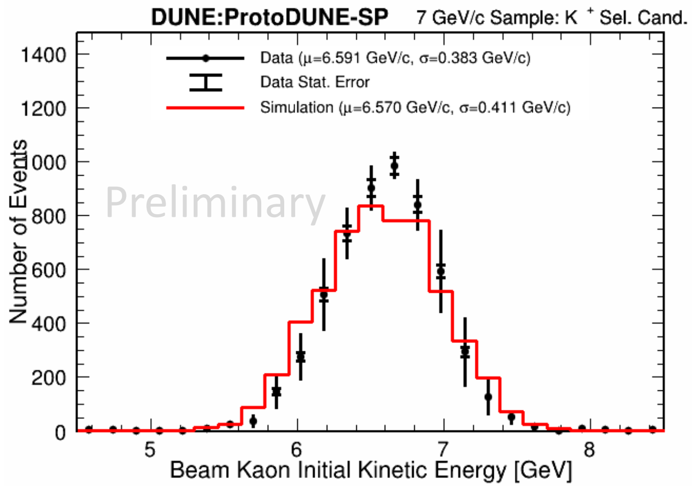

Interacting Resp.



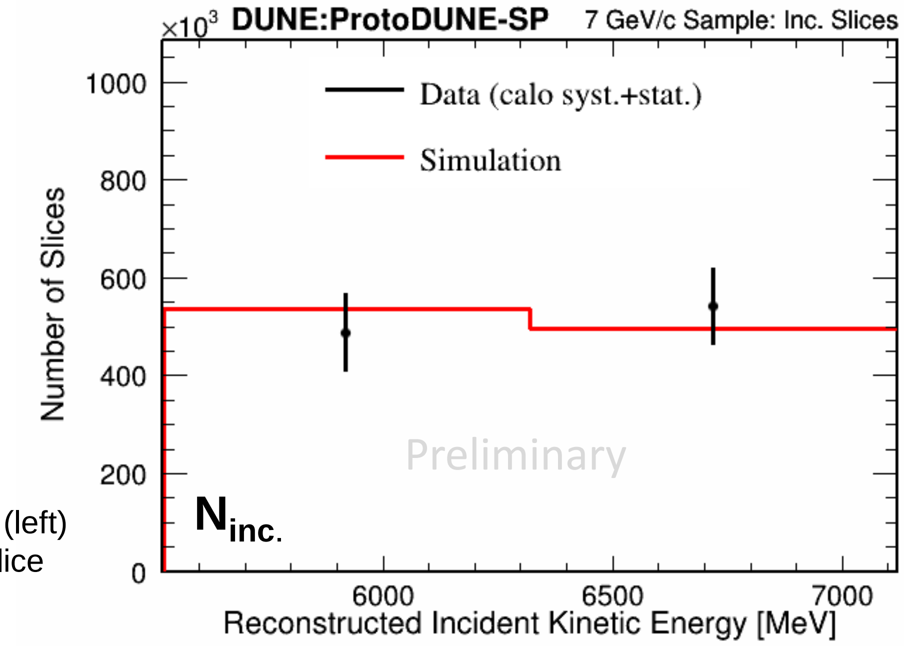

Response matrices normalized to 1 per row for the incident and interacting response matrices for the 7 GeV/c beam kaon candidates.

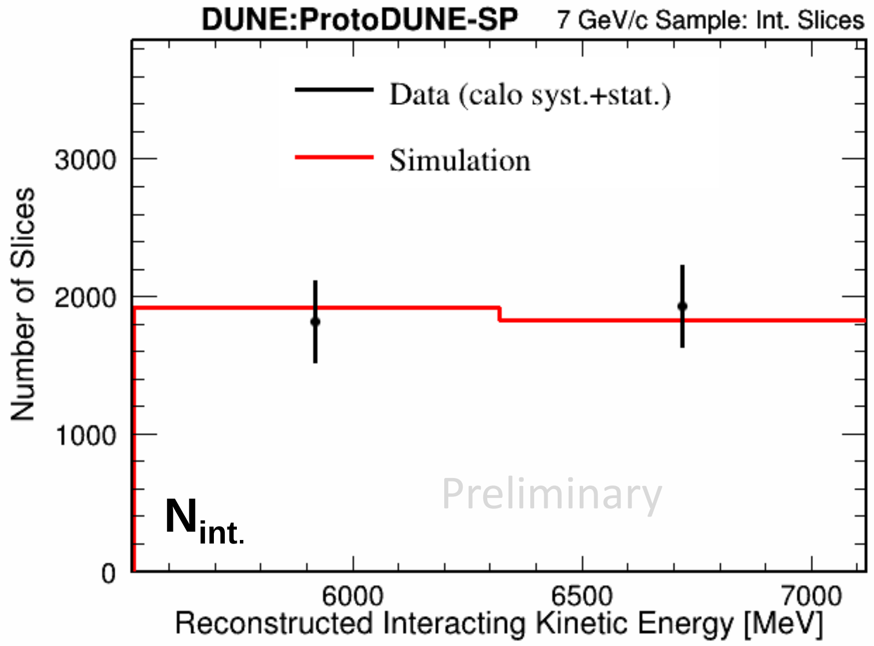
# Results in Reconstruction Space

- At high energies, CERN beam has wide width that is almost 200 MeV wide.
- Studies showed that calorimetry had:
  - A 3% calorimetry uncertainty on dE/dx in the TPC.
  - A 1.2% beam momentum modeling uncertainty.




Reconstructed beamline momentum as measured by the beamline instrumentation.



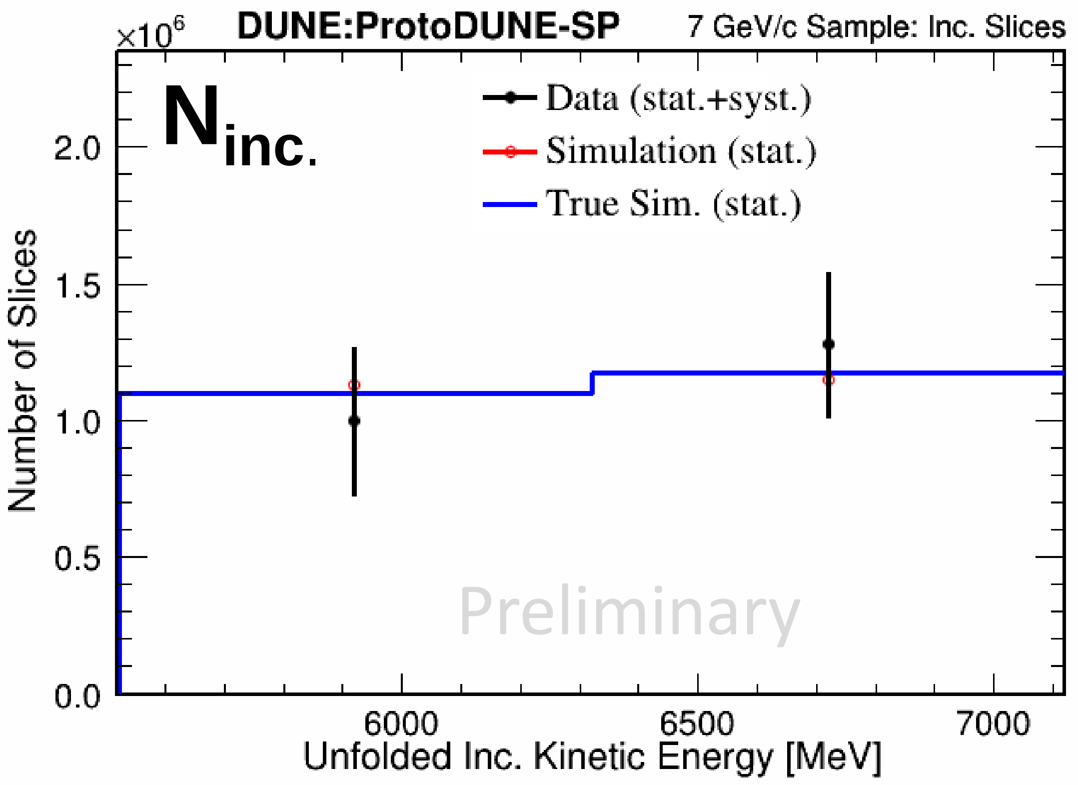

Reconstructed incident (left) and interacting (right) slice distributions with full uncertainties.

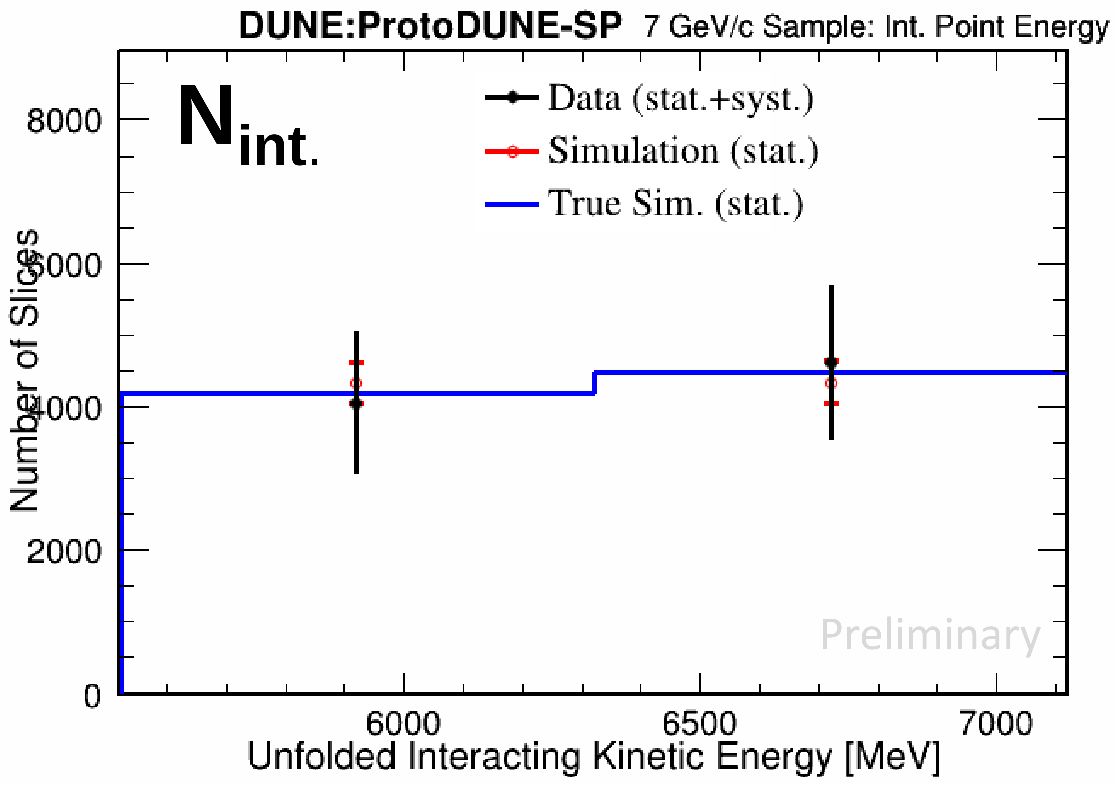
# Unfolded Distributions

- Cross section proportional to the division of $N_{inc.}$ divided by the difference between $N_{inc.}$–$N_{int.}$

$$N_{inc.} - N_{int.} = N_{inc.} \exp\left(-\sigma r_{trk.pitch} n\right) = N_{inc.} \exp\left(-\frac{\sigma \rho_{Ar} r_{trk.pitch} N_{avo.}}{M_{Ar}}\right)$$

$$\sigma\left(KE\right) = \frac{M_{Ar}}{N_{avo.} r \rho} \ln\left[\frac{N_{inc.}(KE)}{N_{inc.}(KE) - N_{int.}(KE)}\right]$$

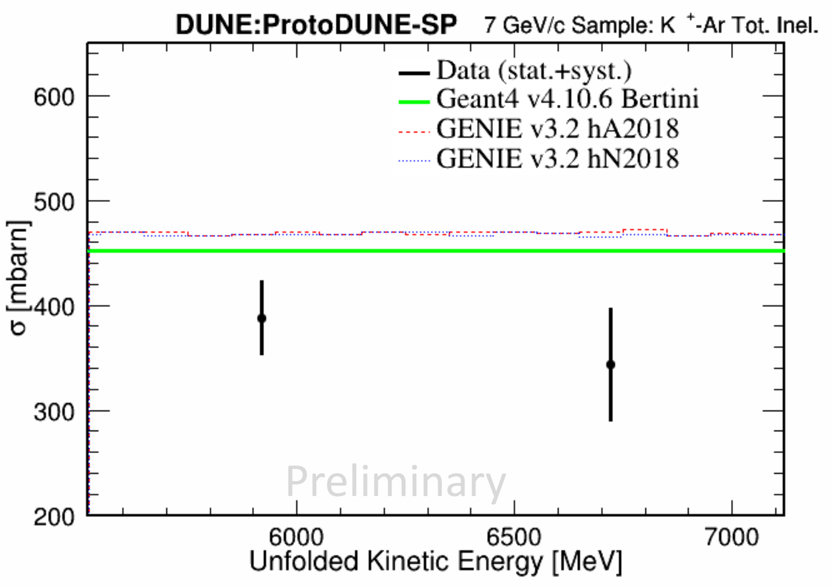


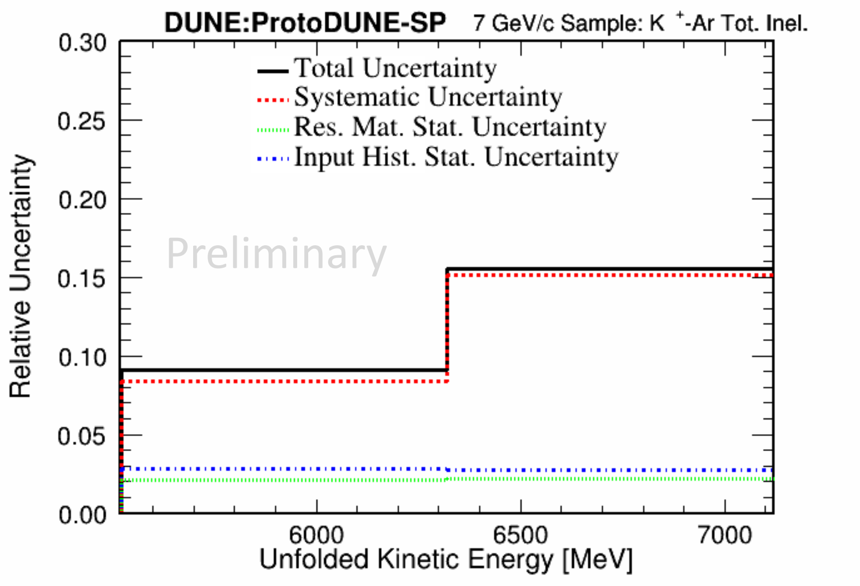



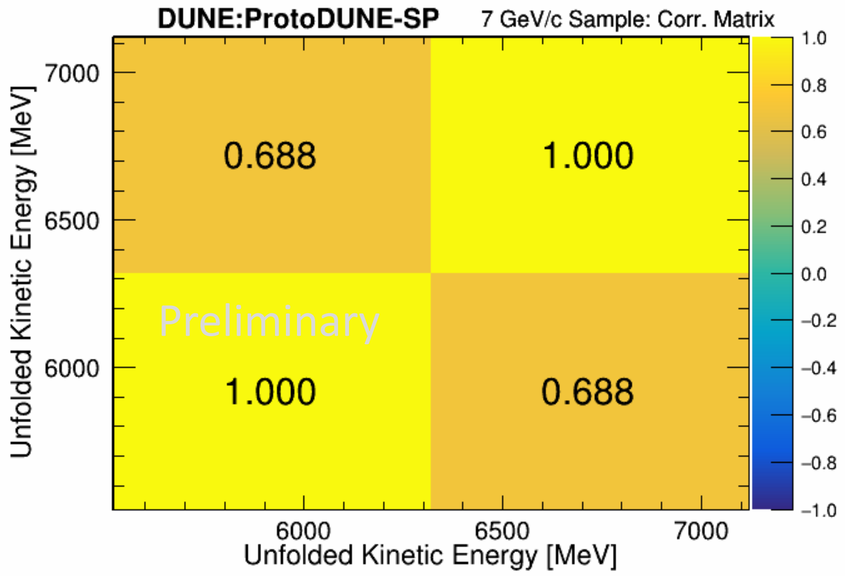

Unfolded incident (left) and interacting (right) slices for data and simulation compared to the truth-level distributions.

# Results

- Cross section has slight disagreement:
  - Chi-square:
    - Geant4: 4.47/2 bins
    - GENIE: 6.44/2 bins (v3.2 hA2018)



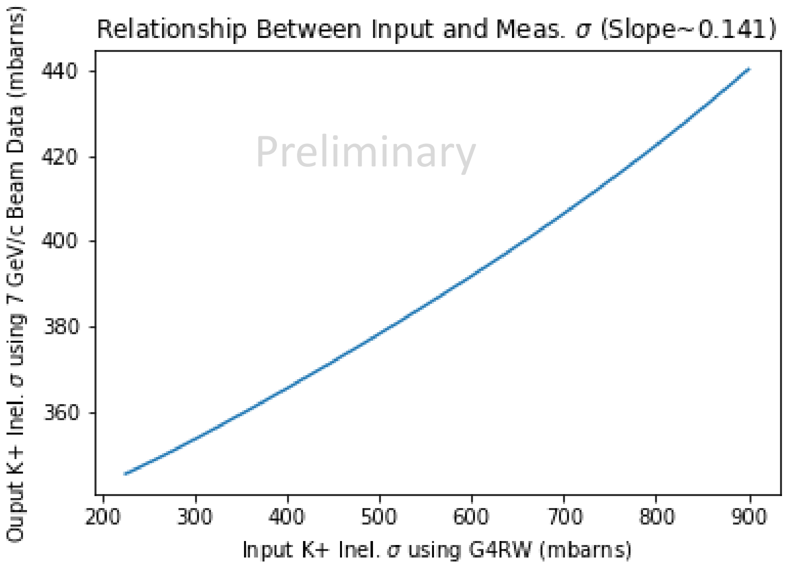




Extracted measurement (top left) with the relative uncertainty on the measurement (top right) and correlation matrix for all uncertainties (bottom)

# Conclusion

- $K^+$- Ar cross section being measured with the traditional thin-slice formula and "simple" and unfolding.
  - Conceptually, a direct development of the thin-slice equation.
  - Requires careful counting of every single slice.
  - Must be model-independent
- ProtoDUNE-SP can measure hadron-Ar cross sections to measure a cross section as a function of energy.
- Will provide $K^+$- Ar cross sections to help inform predictions for DUNE's physics program.




Measurement of the extracted cross section in data measured as a function of the true input cross section of the simulation using Geant4RW to alter the underlying simulation. Analysis used a 20% syst. uncertainty.