First Kaon-Argon Cross Section Measured at ProtoDUNE Single-Phase

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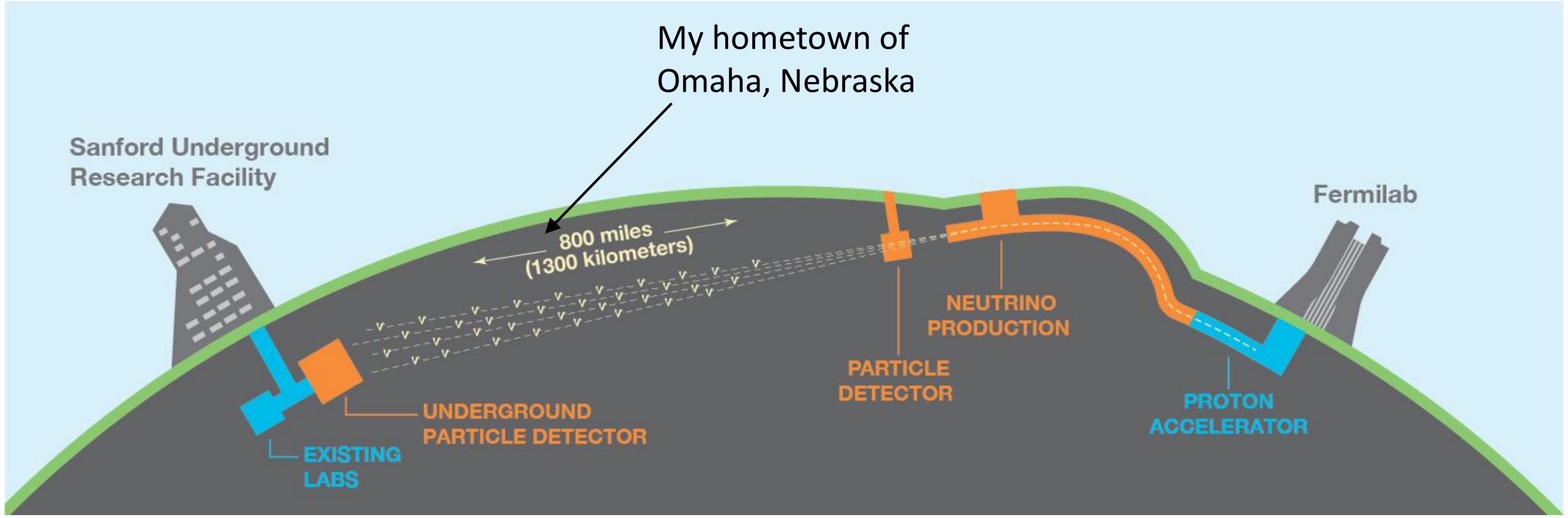
Presentation Based on 2408.00582 (Accepted by *PRD*)

Deep Underground Neutrino Experiment (DUNE)

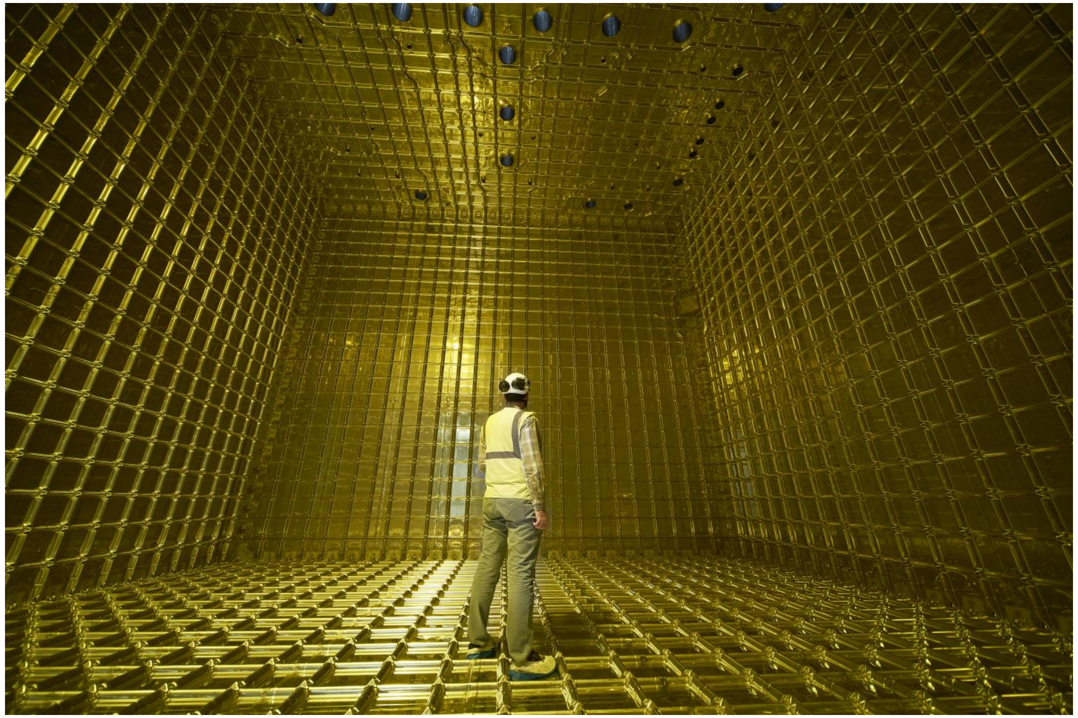
- A future long-baseline neutrino oscillation experiment to measure:
  - the mass hierarchy of neutrinos
  - the CP-violating phase in the leptonic sector.
- Will use a muon (anti)neutrino beam (1.2 MW, can be 2.1 MW) with GeV-scale neutrino energies.
  - Plans for four 17.5 kT liquid argon detectors at the Far Detector.
  - Multi-target (LAr, Iron, H) Near Detector at Fermilab.
- Additional physics measurements requiring advances in detector performance:
  - Atmospheric neutrinos
  - Solar and supernova neutrinos
  - Searches for proton decay
  - Searches for boosted dark matter
  - And much more!



DUNE at CERN

- Two cryostats constructed at Neutrino Platform 2 and Neutrino Platform 4.
  - ProtoDUNE Single-Phase (ProtoDUNE-SP) ran at Neutrino Platform 4.
  - ProtoDUNE Dual-Phase (ProtoDUNE-DP) ran at Neutrino Platform 2.
- ProtoDUNE Horizontal Drift, successor of ProtoDUNE-SP, is operating and took beam data in summer 2024.
- ProtoDUNE Vertical Drift, successor to ProtoDUNE-SP, will operate late 2024 and early 2025.

Inside of the ProtoDUNE Neutrino Platform 2 cryostat

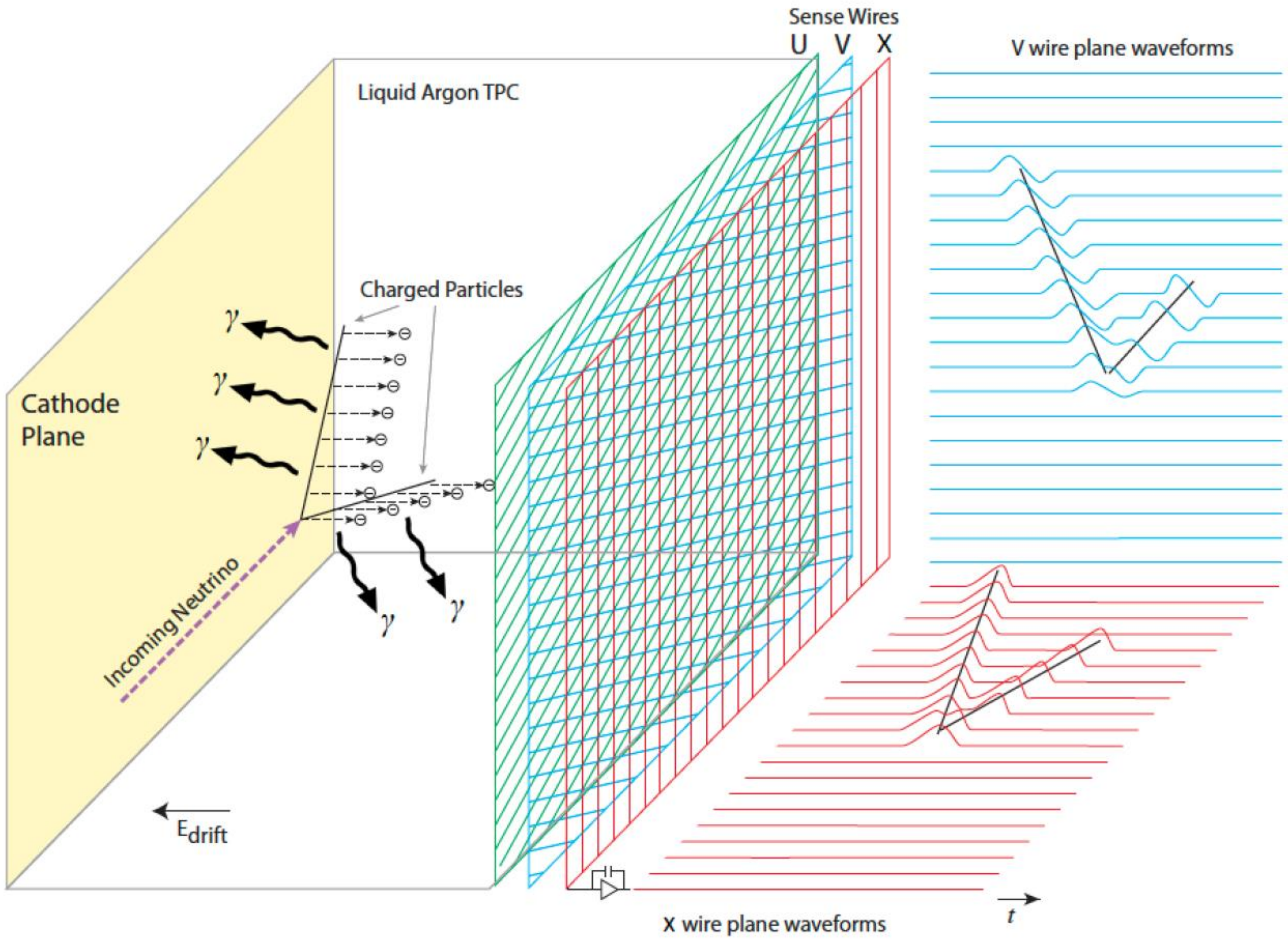


Liquid Argon Time Projection Chambers (TPCs)

- Detector Physics to Consider:
  - Purity of liquid argon
  - Uniformity of electric field
    - Surface-based detectors impacted by space charge on TPC walls.
  - Efficiency of light detection
  - Field response of the sensors
  - Electronics response

France is pioneering the Vertical Drift:

- an alteration of this technology with strips.



Example of a liquid argon detector with a wire-based readout (arXiv:2002.03005).

Detector Layout at ProtoDUNE

- Largest monolithic LArTPC (700 tons)
- ProtoDUNE-SP has two drift volumes:
    - 3.6 m long drift volumes
- Electrons drift horizontally in the x-direction, beam travels in a slight angle primarily in the z-direction.

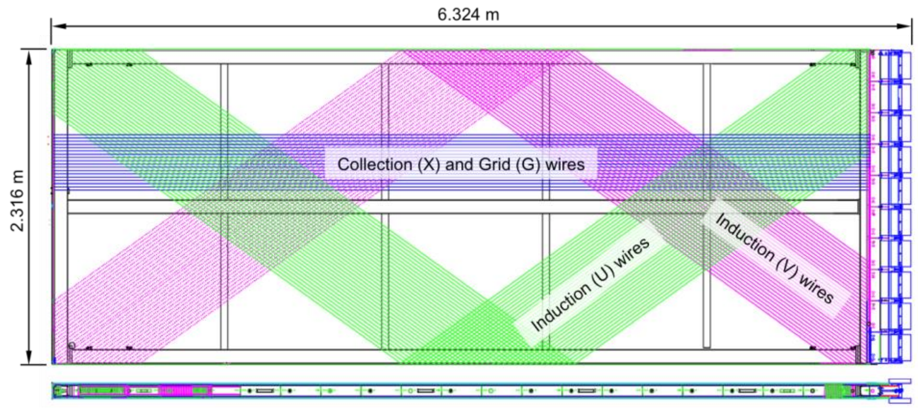
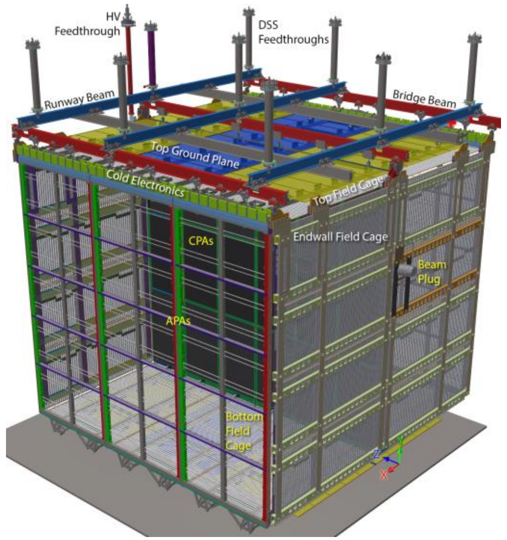


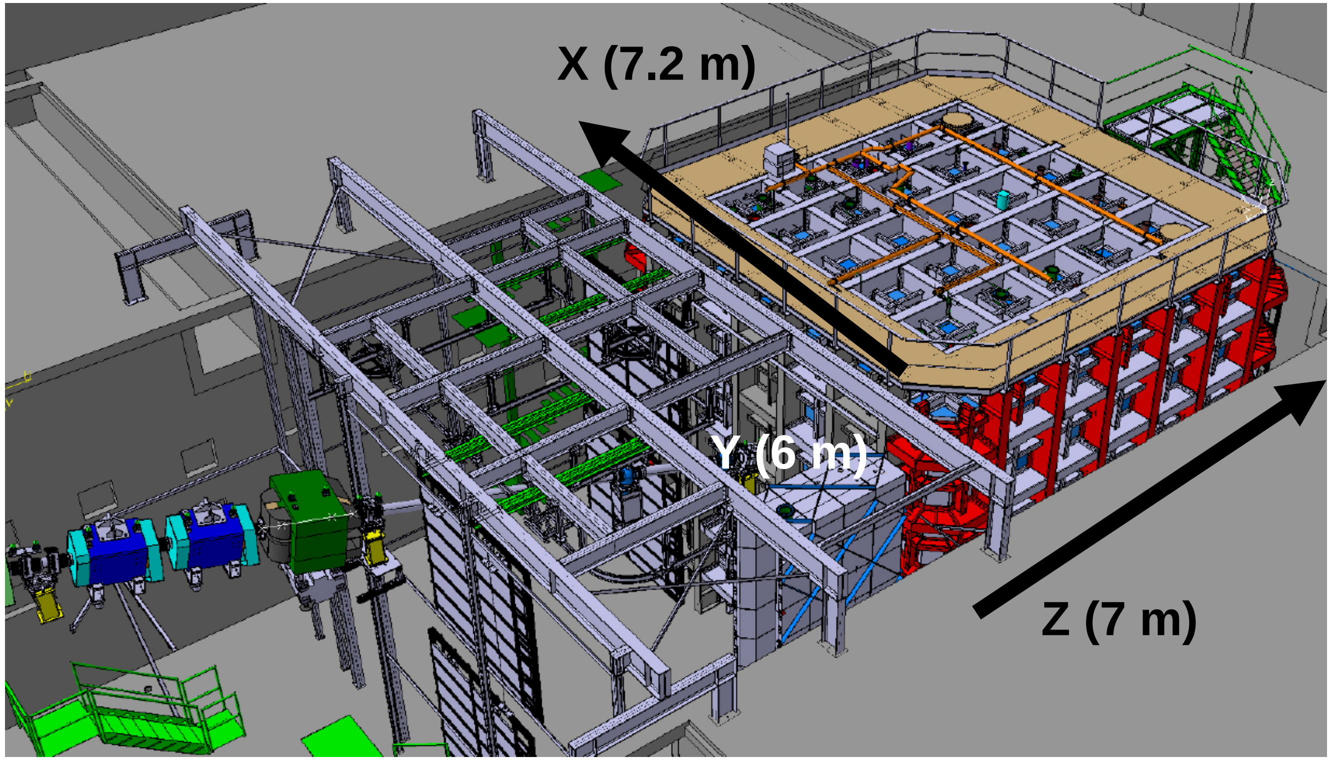
Diagram of APA wire planes used for readout. The diagram is rotated by 90 degrees clockwise from how it is installed to improve visualization.



Technical drawing of ProtoDUNE-SP. Three additional APAs are on the other side of the CPA.

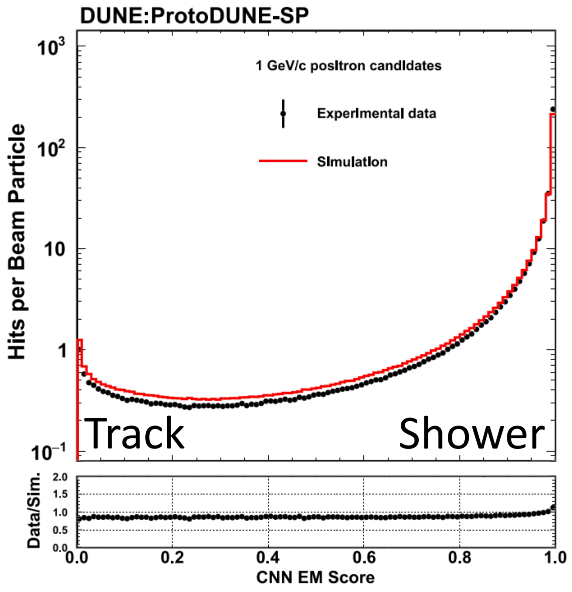
JINST **15** P12004

Image of CERN Neutrino Platform 4 with ProtoDUNE-SP. The beam comes in from left to right into the cryostat. The hanging scintillator in grey are the front Cosmic Ray Taggers.



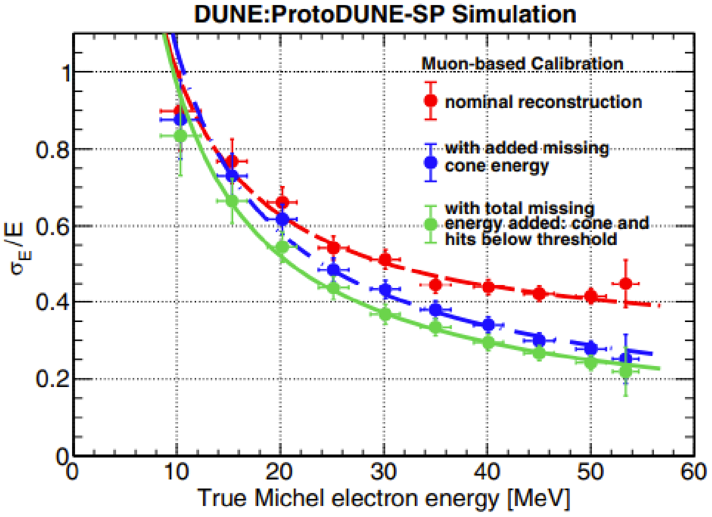
ProtoDUNE-SP Results

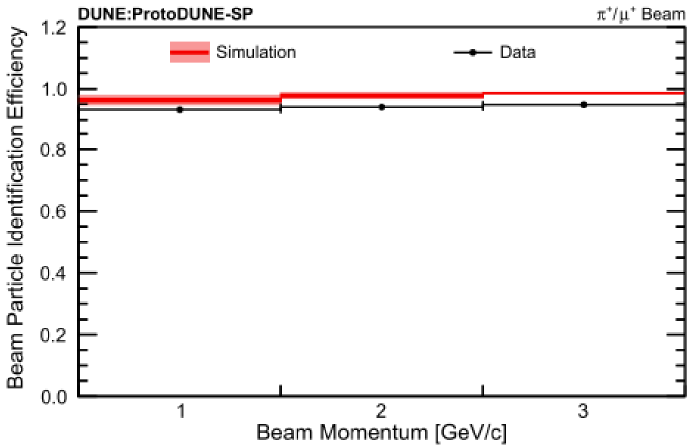
- ProtoDUNE-SP has published six papers on its performance:
  - Detector physics (*JINST* **15** P12004)
  - Design and operation (*JINST* **17** P01005)
  - Michel electron reconstruction (*Phys. Rev. D* **107**, 092012)
  - Reconstruction of cosmic/beam using Pandora (*EPJC* **83** 618)
  - Track/shower separation using a CNN (*EPJC* **82** 903)
  - Scintillation light detection with xenon-doping (*JINST* **19** P08005)



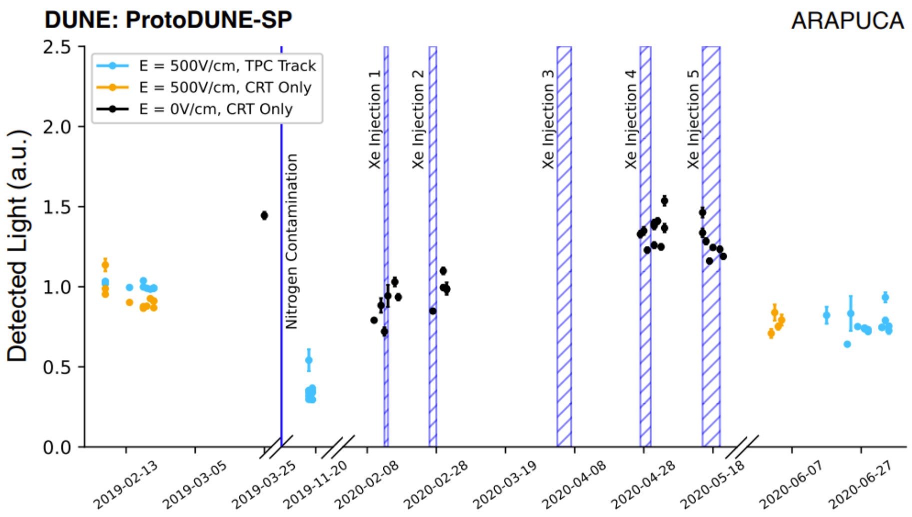
CNN score for positrons (*EPJC* **82** 903).

Resolution of reconstructing the energy of a Michel electron using various method with calibration taken from *JINST* **15** P12004 (*Phys. Rev. D* **107**, 092012)





Selection efficiency for muons and pions and beam momentum of particles in the TPC using Pandora (*EPJC* **83** 618).

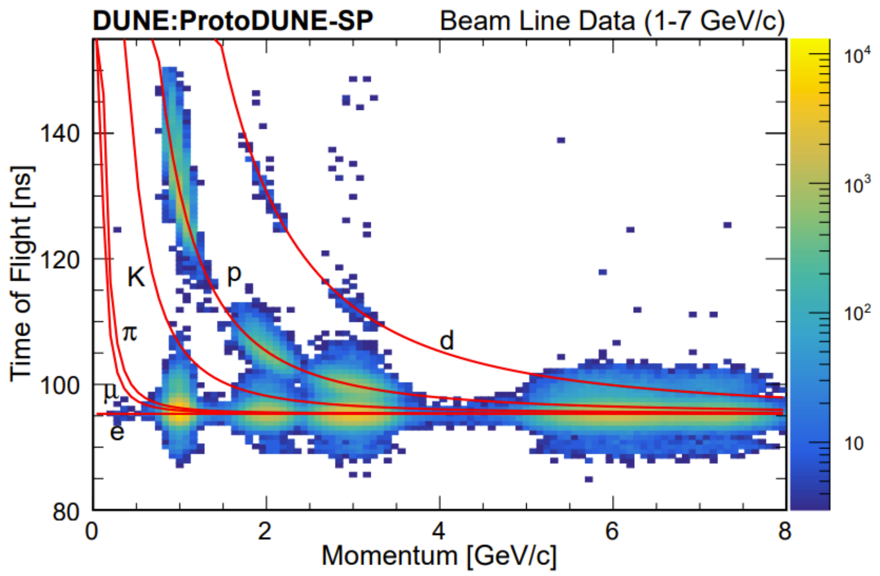


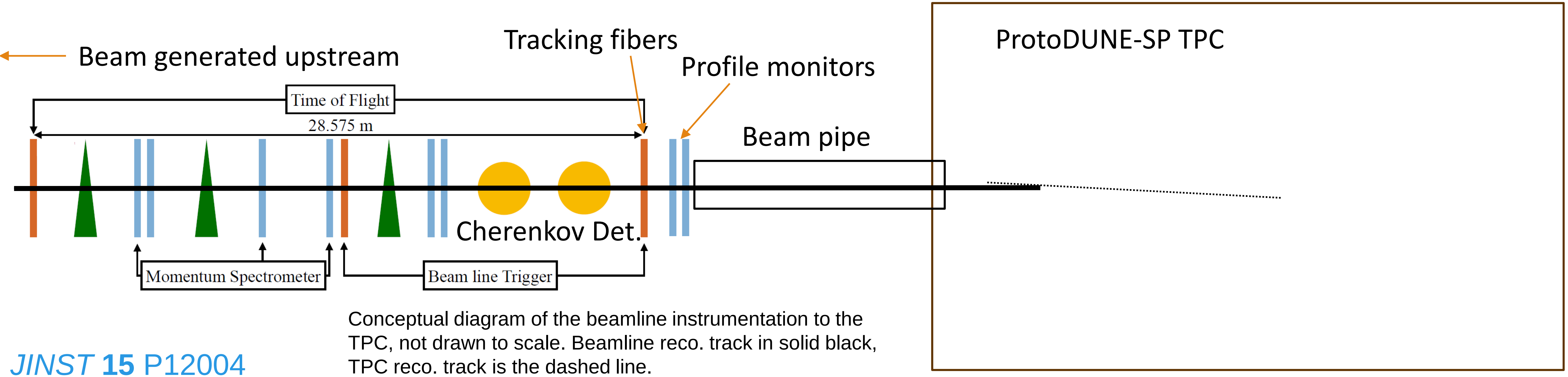
Light detection before and after xenon-doping (*JINST* **19** P08005).

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.

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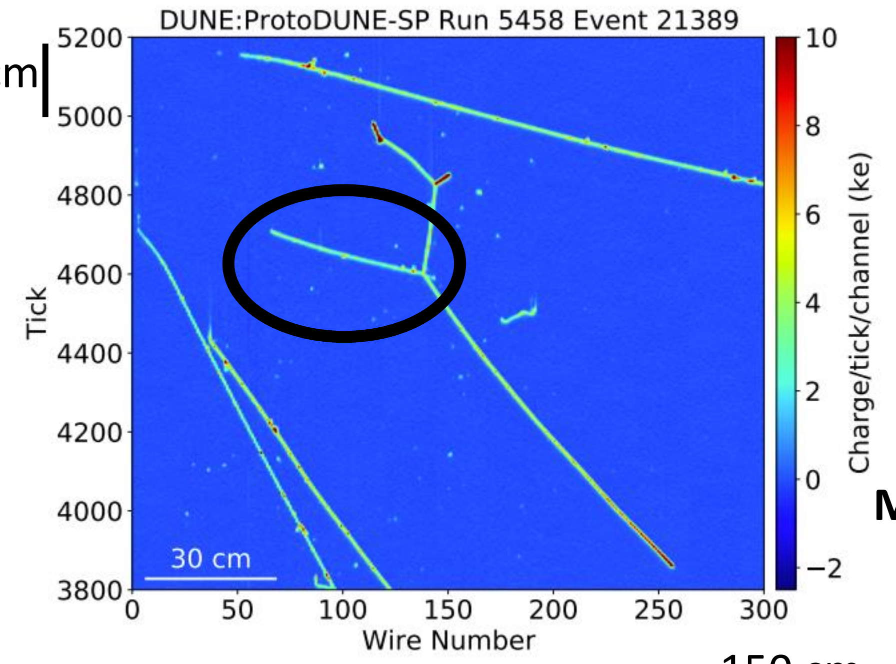
ProtoDUNE-SP Beam Event Displays

Highly ionizing

15 cm



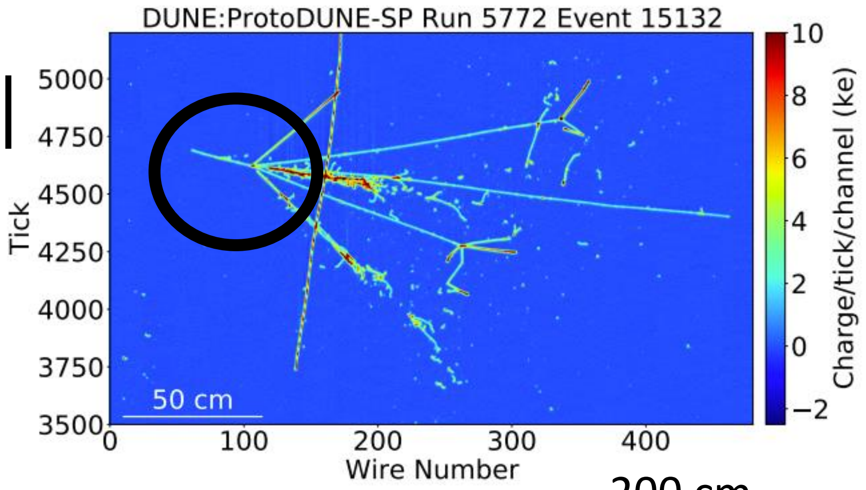
Minimal ionizing

150 cm

1 GeV/c pion candidate inelastic interaction

Highly ionizing

20 cm



Minimal ionizing

200 cm

2 GeV/c pion candidate interaction

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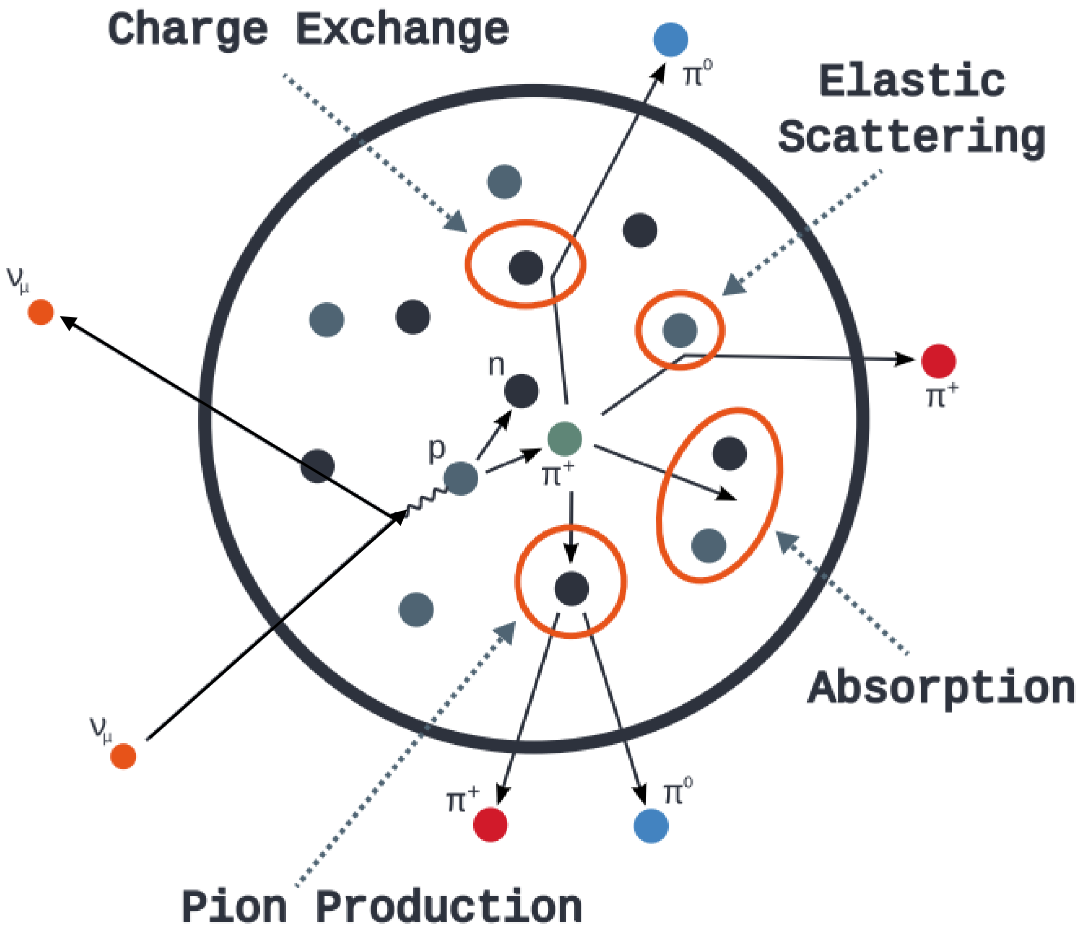
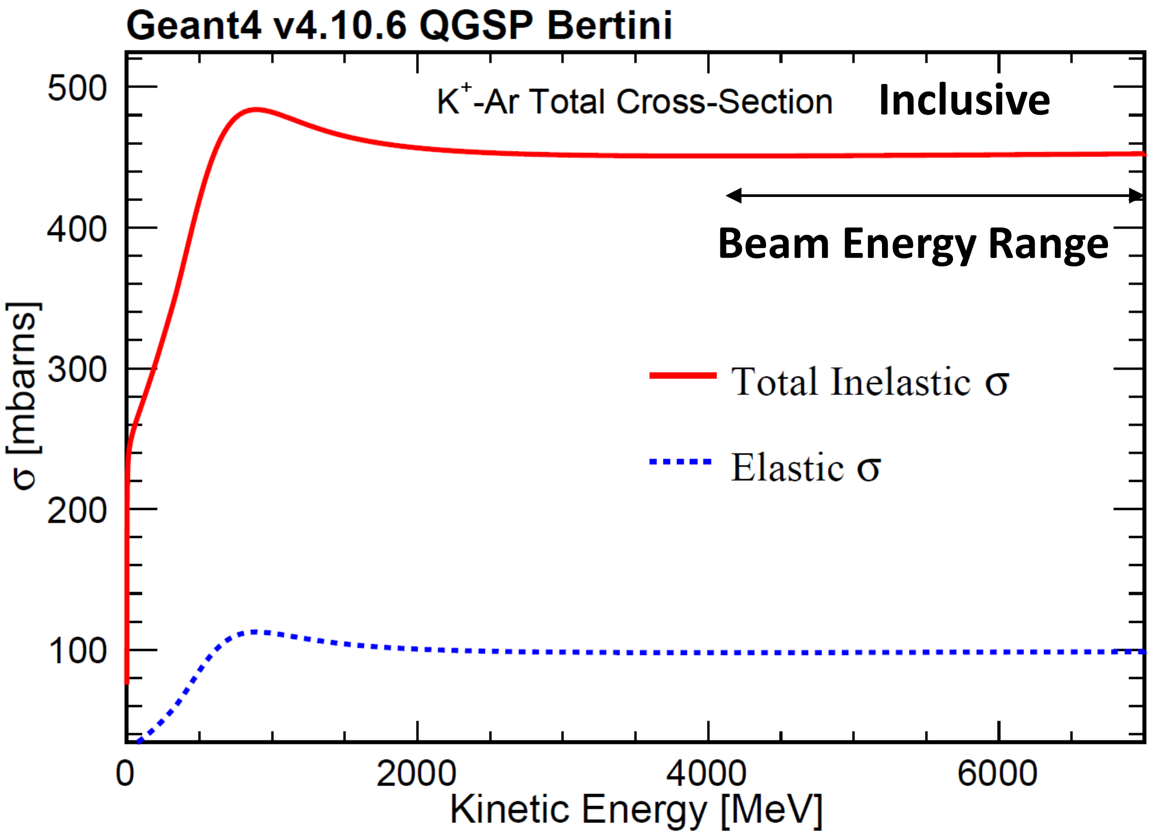
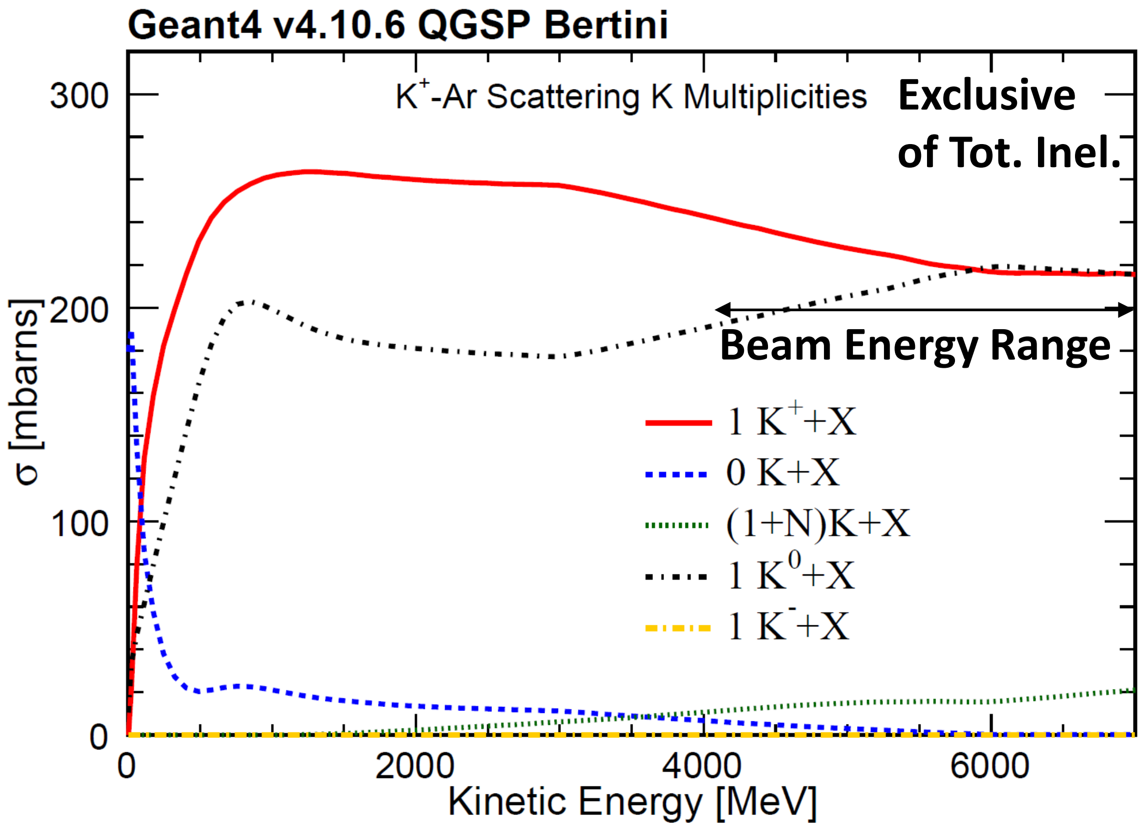
What is the point of a test beam?



Cartoon of the many fates of a NC1π interaction due to intranuclear scattering (T. Golan)

Kaon Cross Sections According to Geant4





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):

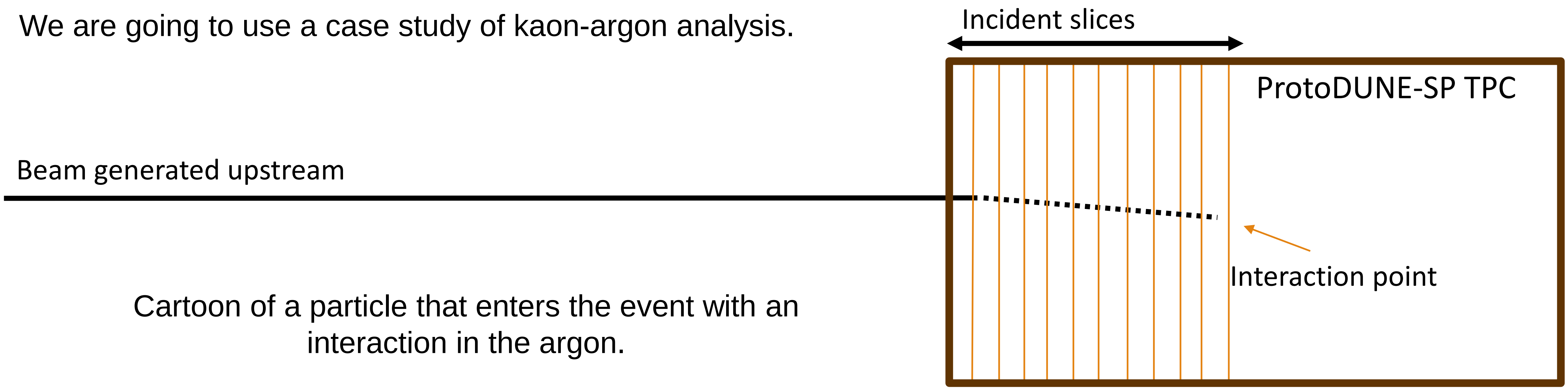
$$N_{inc.} - N_{int.} = N_{inc.} \exp\left(-\sigma r_{trk.pitch} n\right) = N_{inc.} \exp\left(-\frac{\sigma \rho_{Ar} r_{trk.pitch} N_{avo.}}{M_{Ar}}\right)$$

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

Constants used:

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

- We are going to use a case study of kaon-argon analysis.



Cartoon of a particle that enters the event with an interaction in the argon.

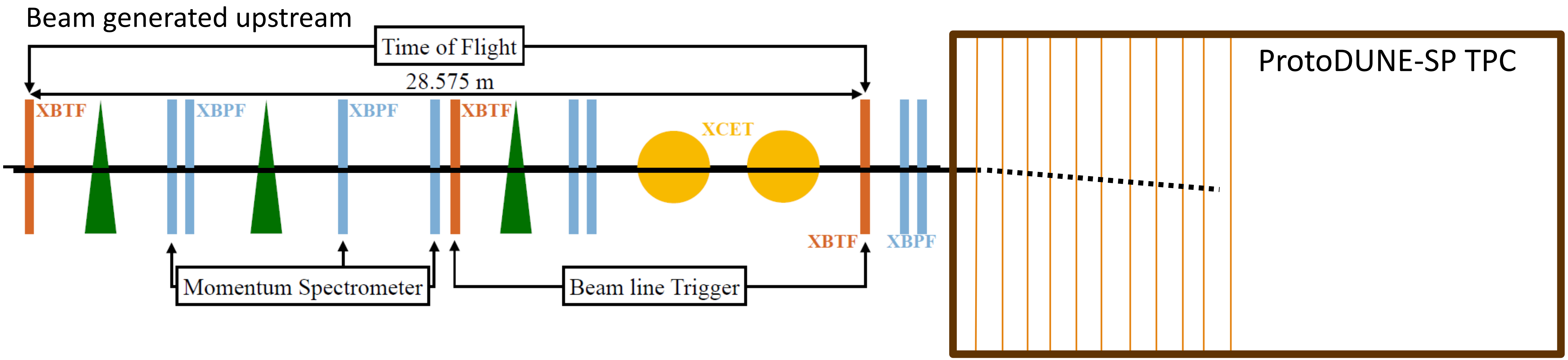
Measurement of a Kaon Cross-Section

Event Selection:

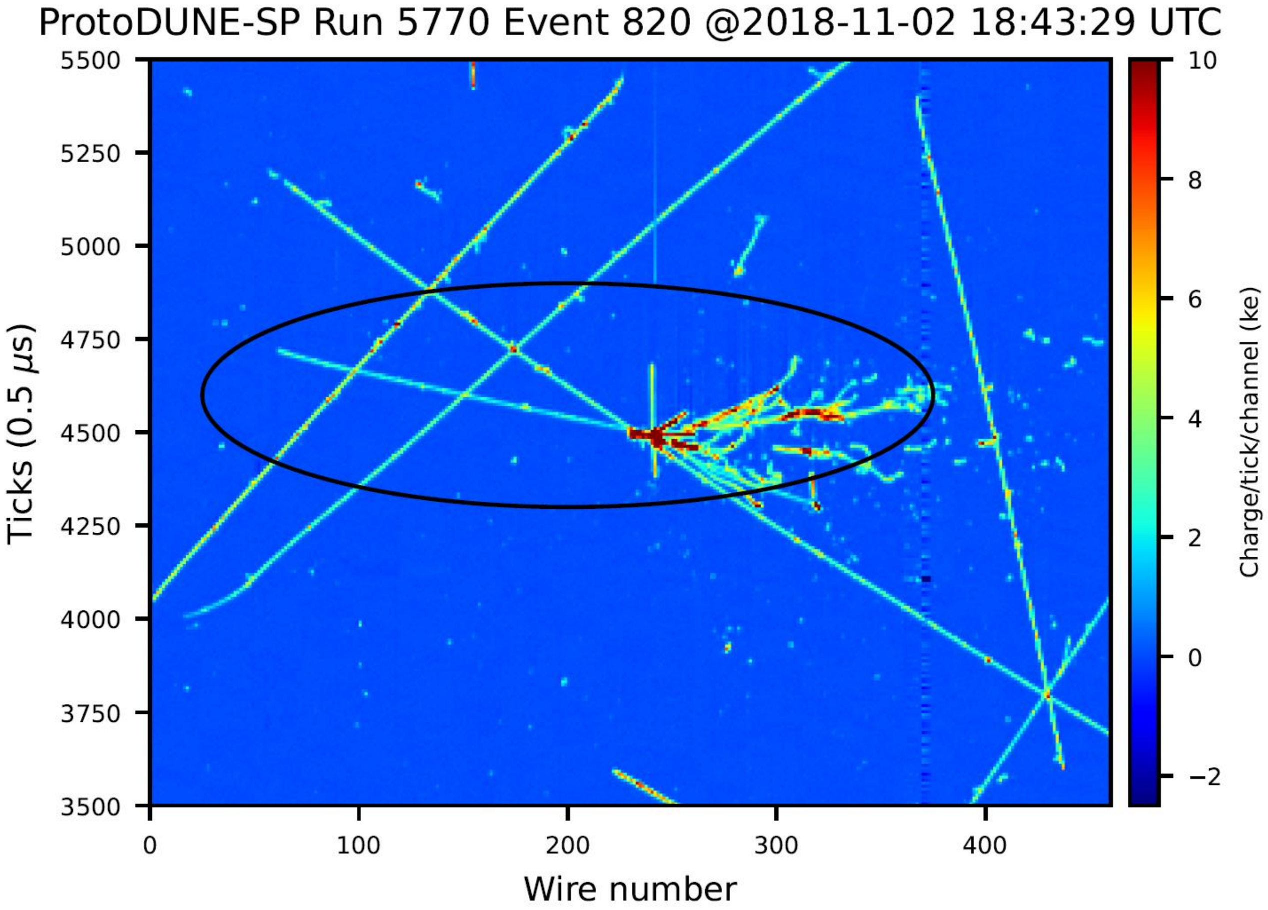
- Beamline instrumentation identifies kaon with Cherenkov detectors.
- Reconstruction (*EPJC* **83** 681) selects a TPC track.
- The TPC track must agree with beamline instrumentation tracking information.

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

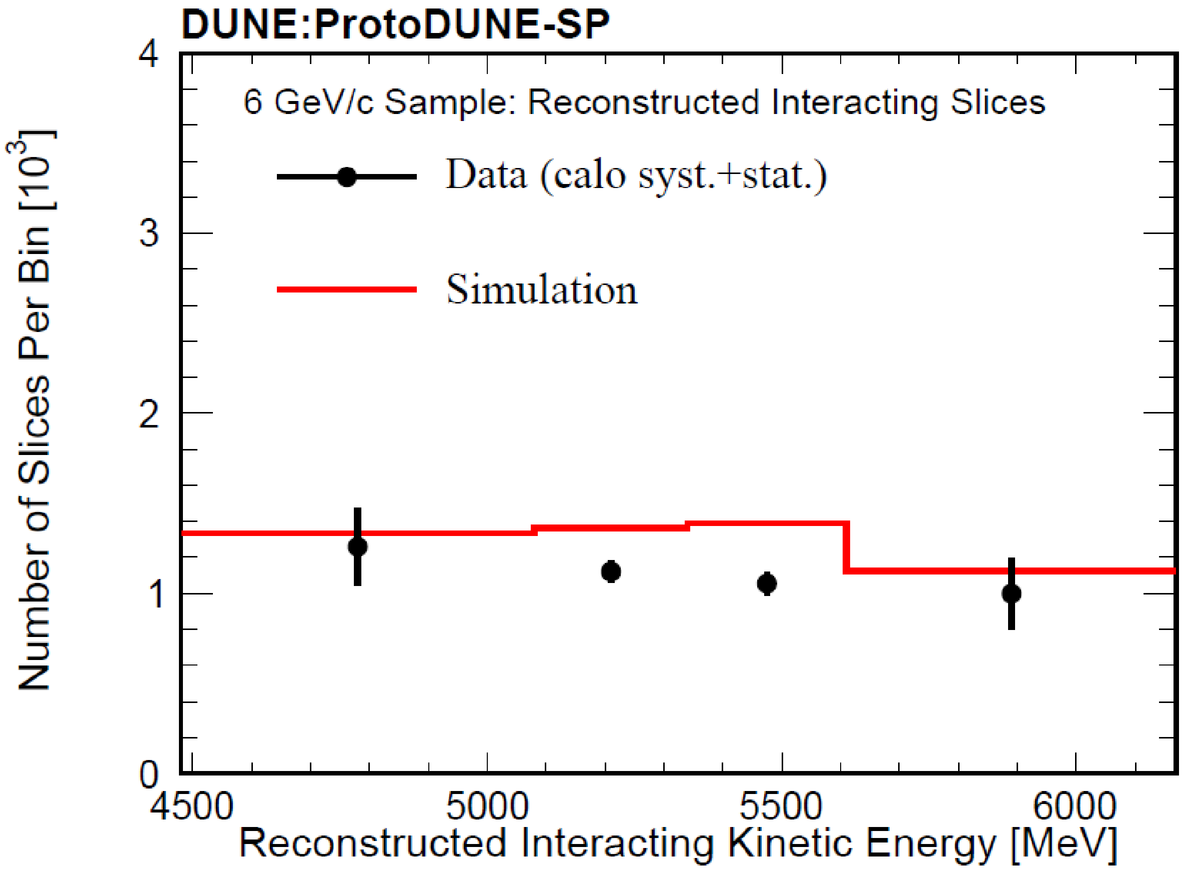
$$\sigma\left(\mathrm{KE}\right) = \frac{\mathrm{M_{Ar}}}{\mathrm{N_{avo.}} \mathrm{r} \rho} \ln\left[\frac{\mathrm{N_{inc.}}(\mathrm{KE})}{\mathrm{N_{inc.}}(\mathrm{KE}) - \mathrm{N_{int.}}(\mathrm{KE})}\right]$$

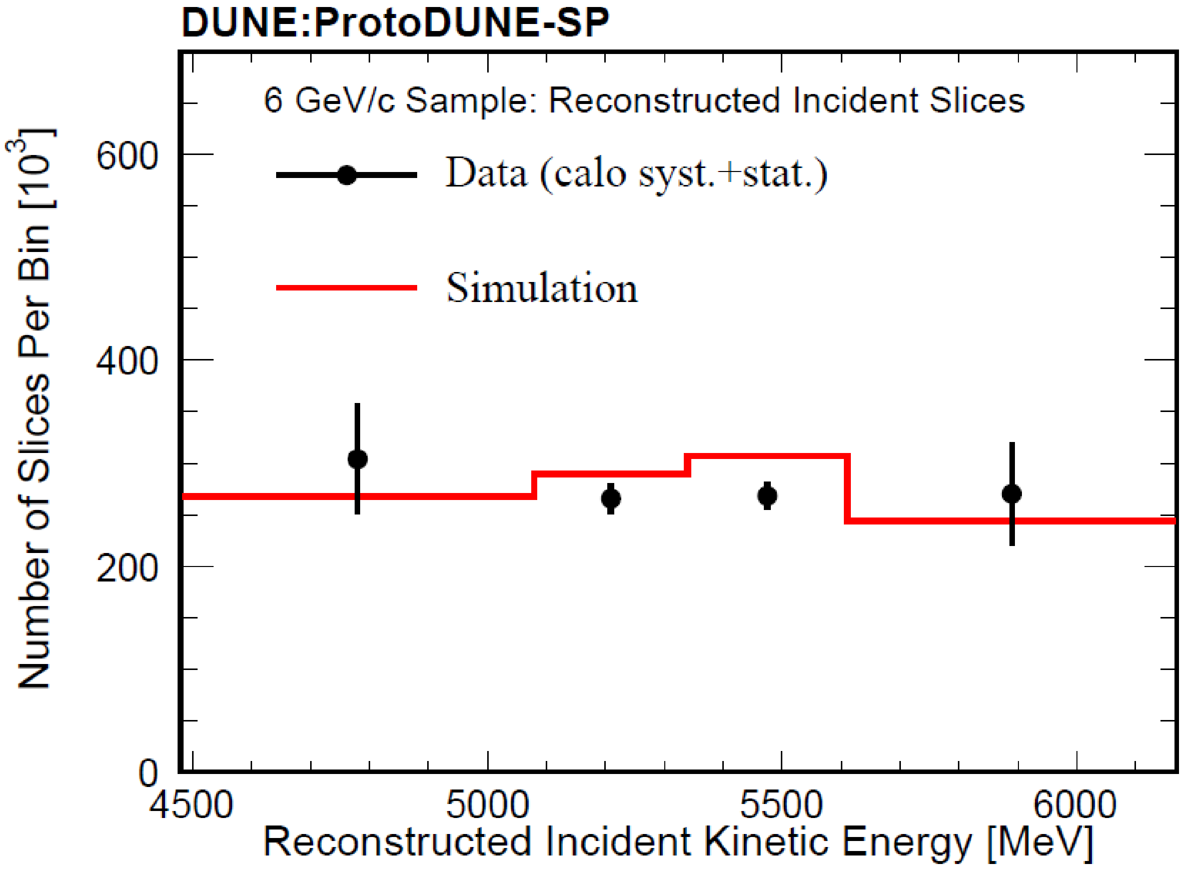


Event Display of Kaon-Argon Interactions

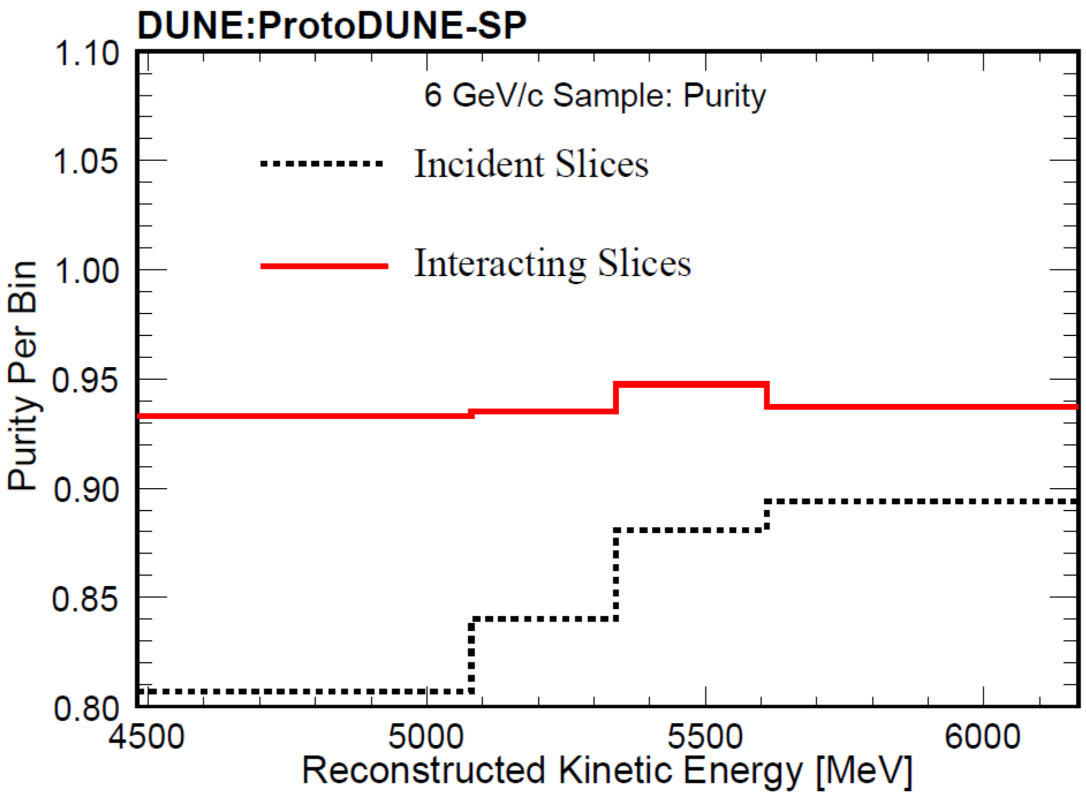


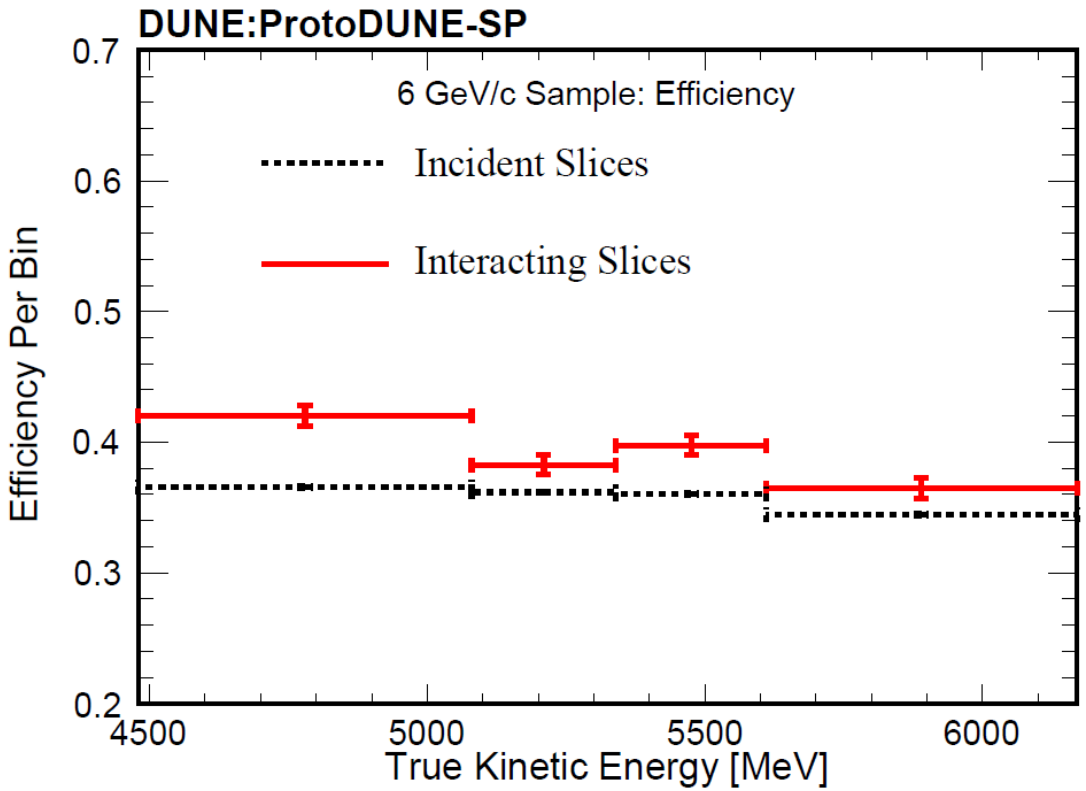
Reconstructed Distributions with Event Selection





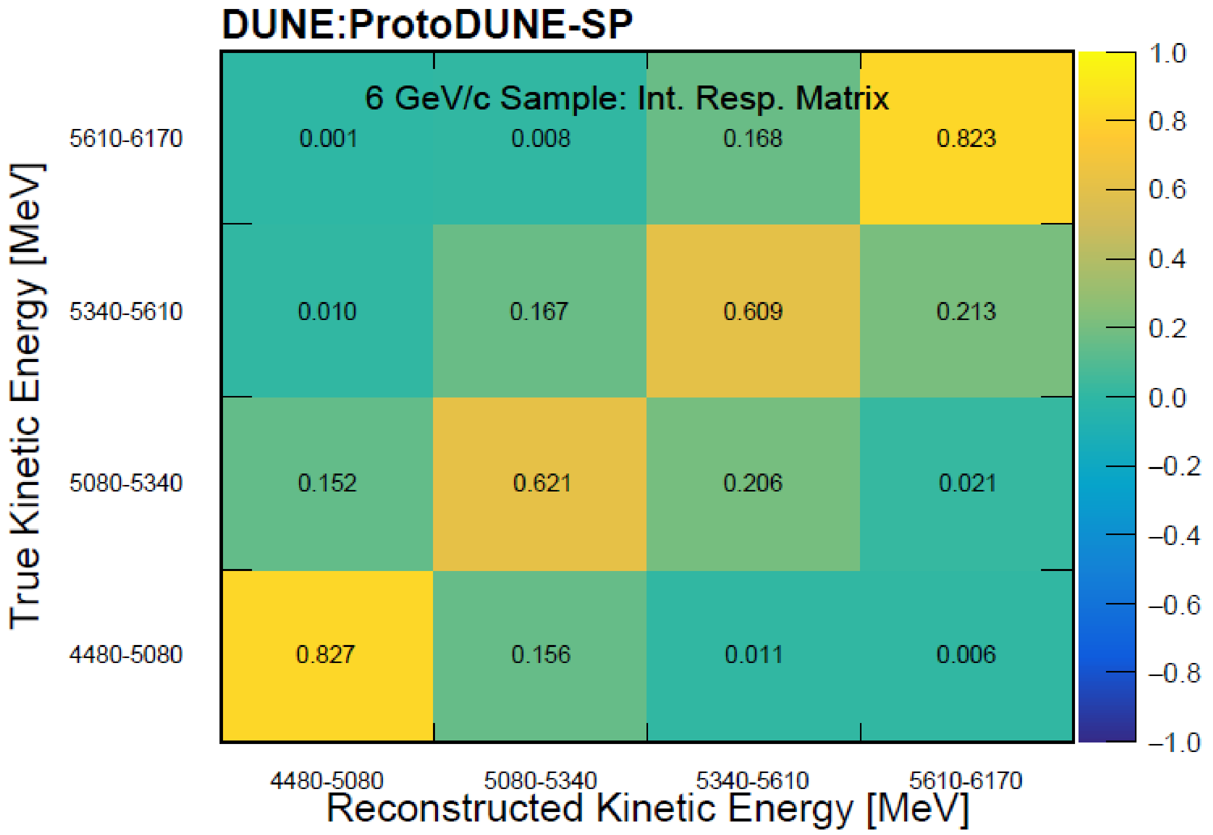
Purities and Efficiencies of the Event Selection

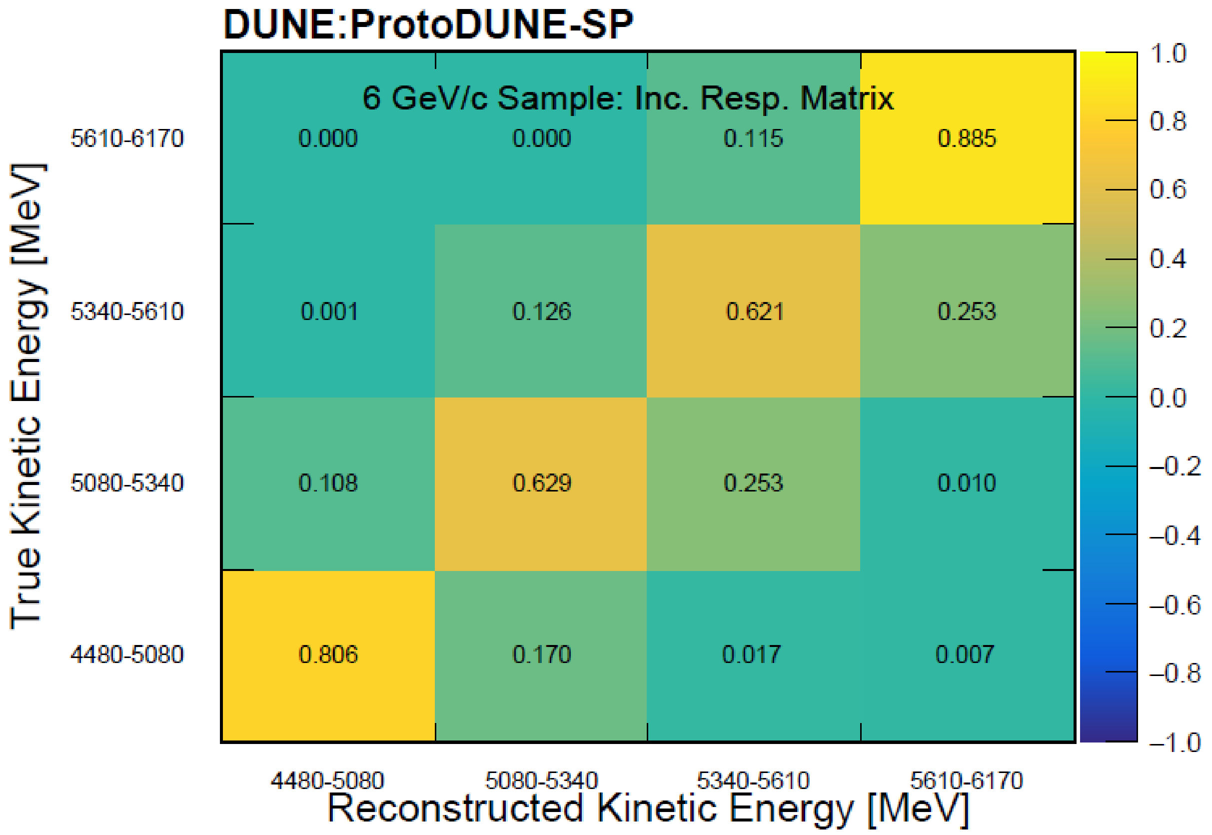




Response Matrices for the Measurement

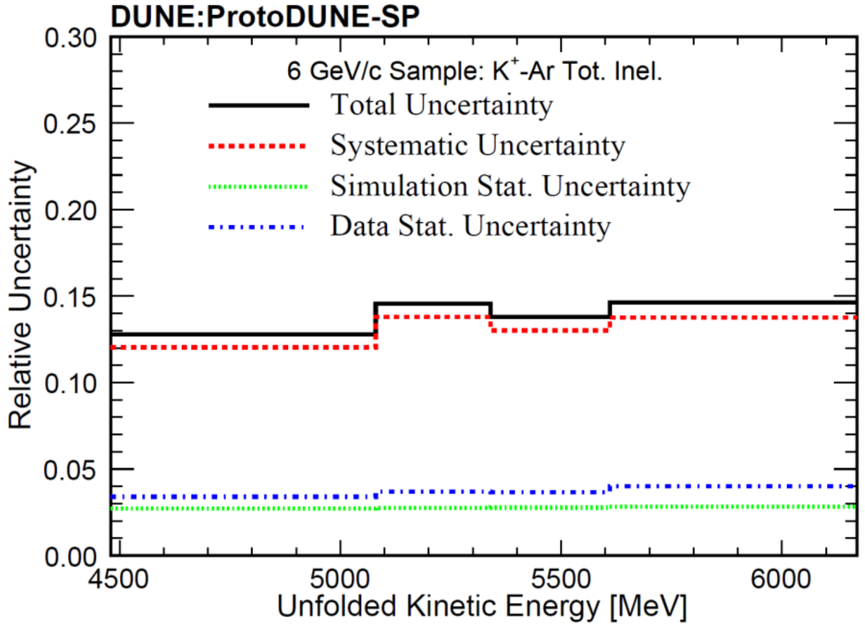
- Systematic uncertainties were developed to handle: mismodeling of the detector, calorimetry, beamline momentum resolution, and signal purity.
  - First usage of DUNE technologies for a full physics measurement.
- Unfold distributions using Bayes-like (Lucy-Richardson) unfolding with purity and eff. corrections (*NIMA* **362** 487)

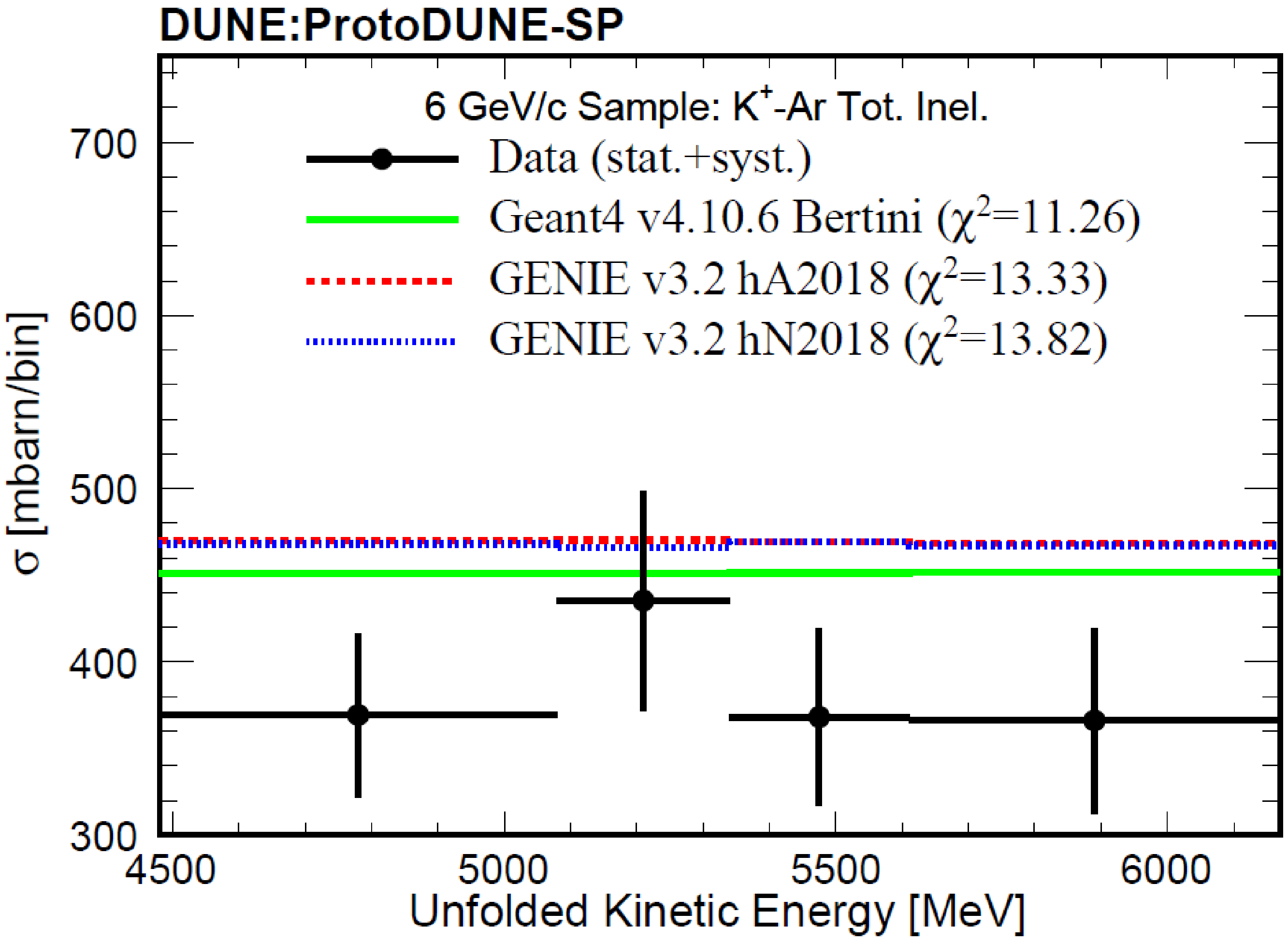




Conclusion: First DUNE Result

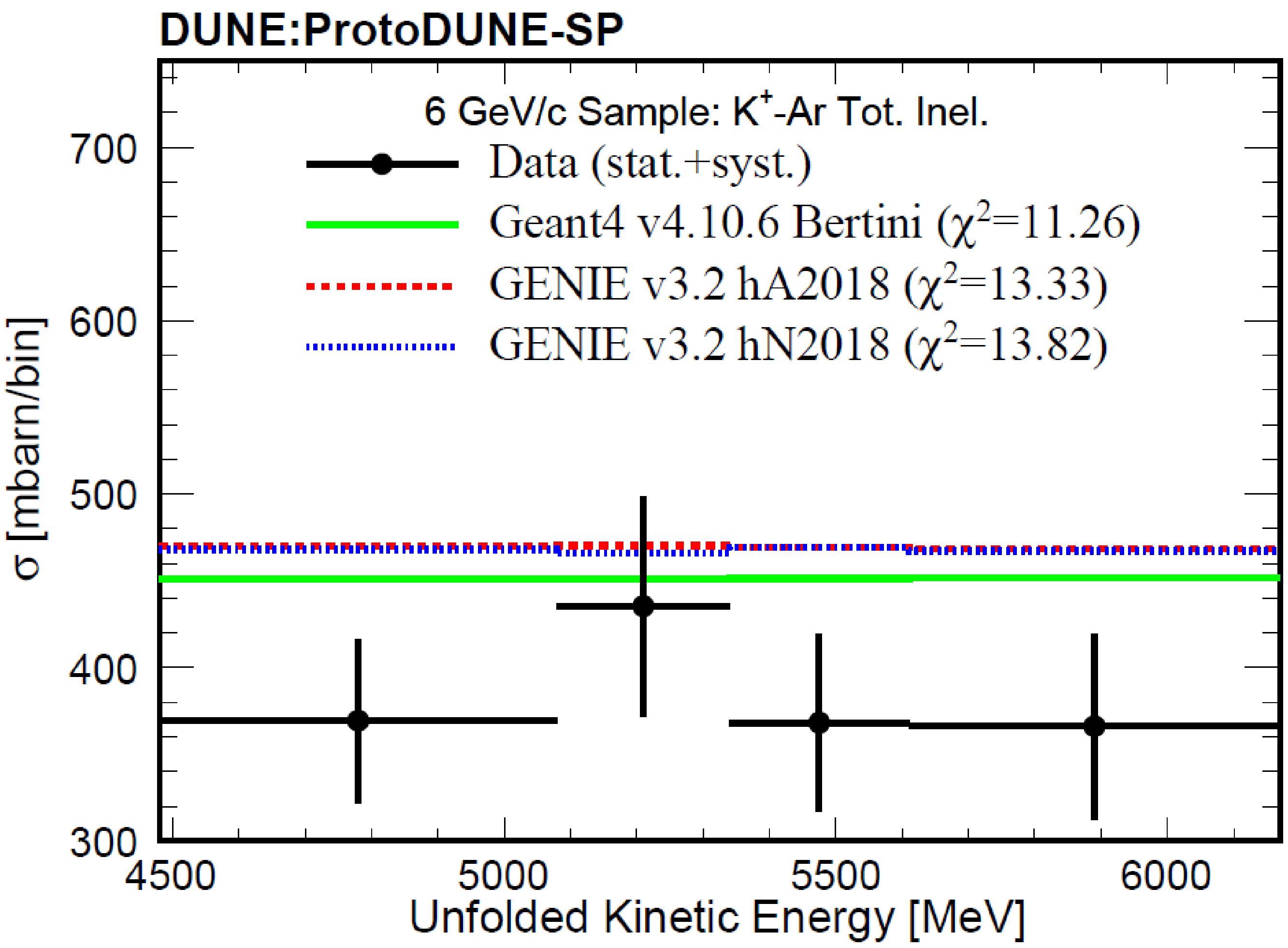
- Apply unfolded distributions to the *thin slice* equation to calculate cross section.
- Both GENIE and Geant4 overestimate the cross section by around 15%.





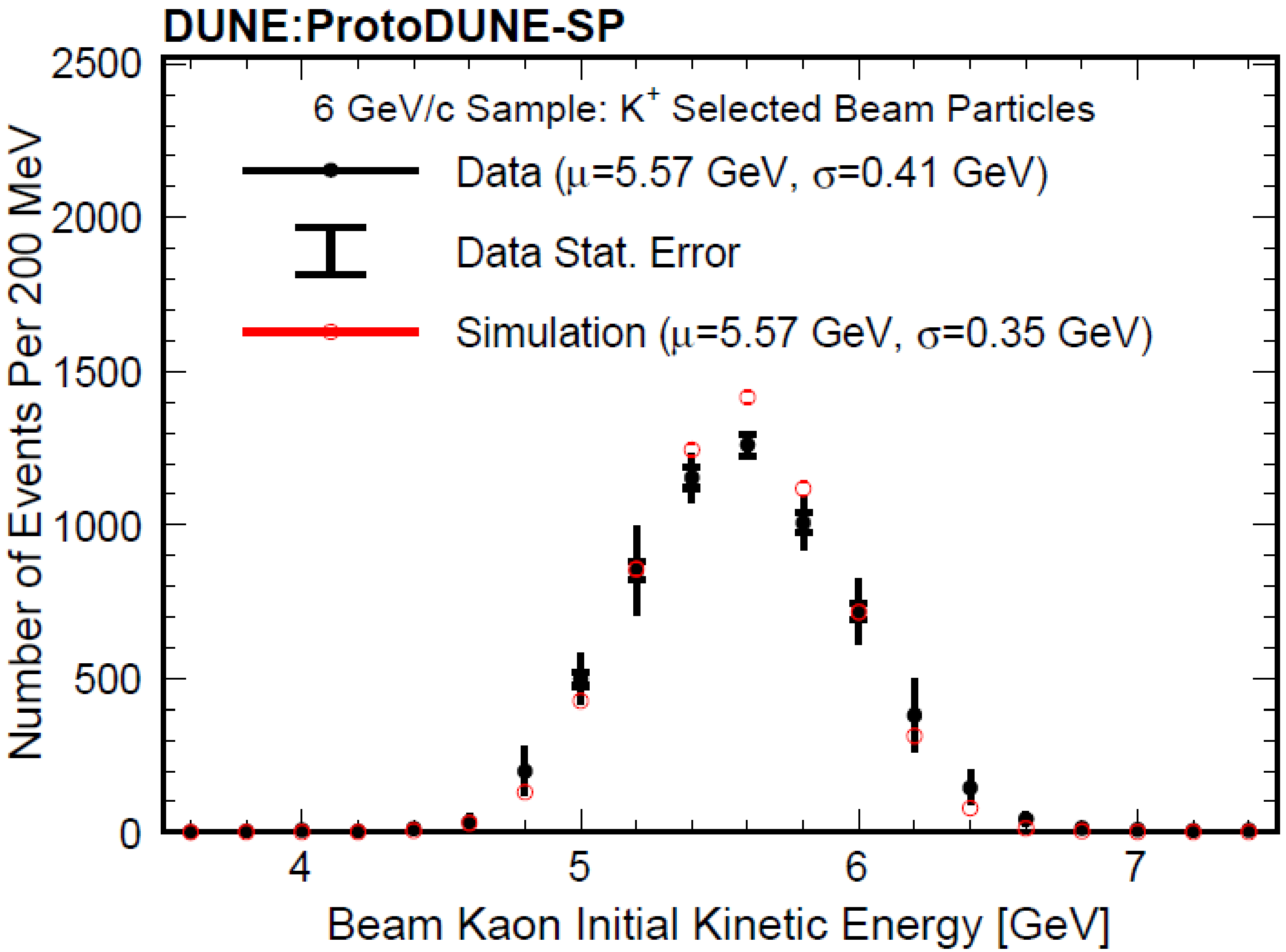
Conclusion: Future at ProtoDUNEs

- Pion and proton cross sections from PDSP.
- Preliminary results from ProtoDUNE-HD.
- ProtoDUNE-VD will take data soon later this year.
- All studies benefit neutrino physics and DUNE!
- Studies will:
  - Continue to evaluate technology performance.
  - Use new calibration techniques for argon.
  - Constrain hadron-nucleus uncertainties.
  - Inform sensitivities of future DUNE FD studies.

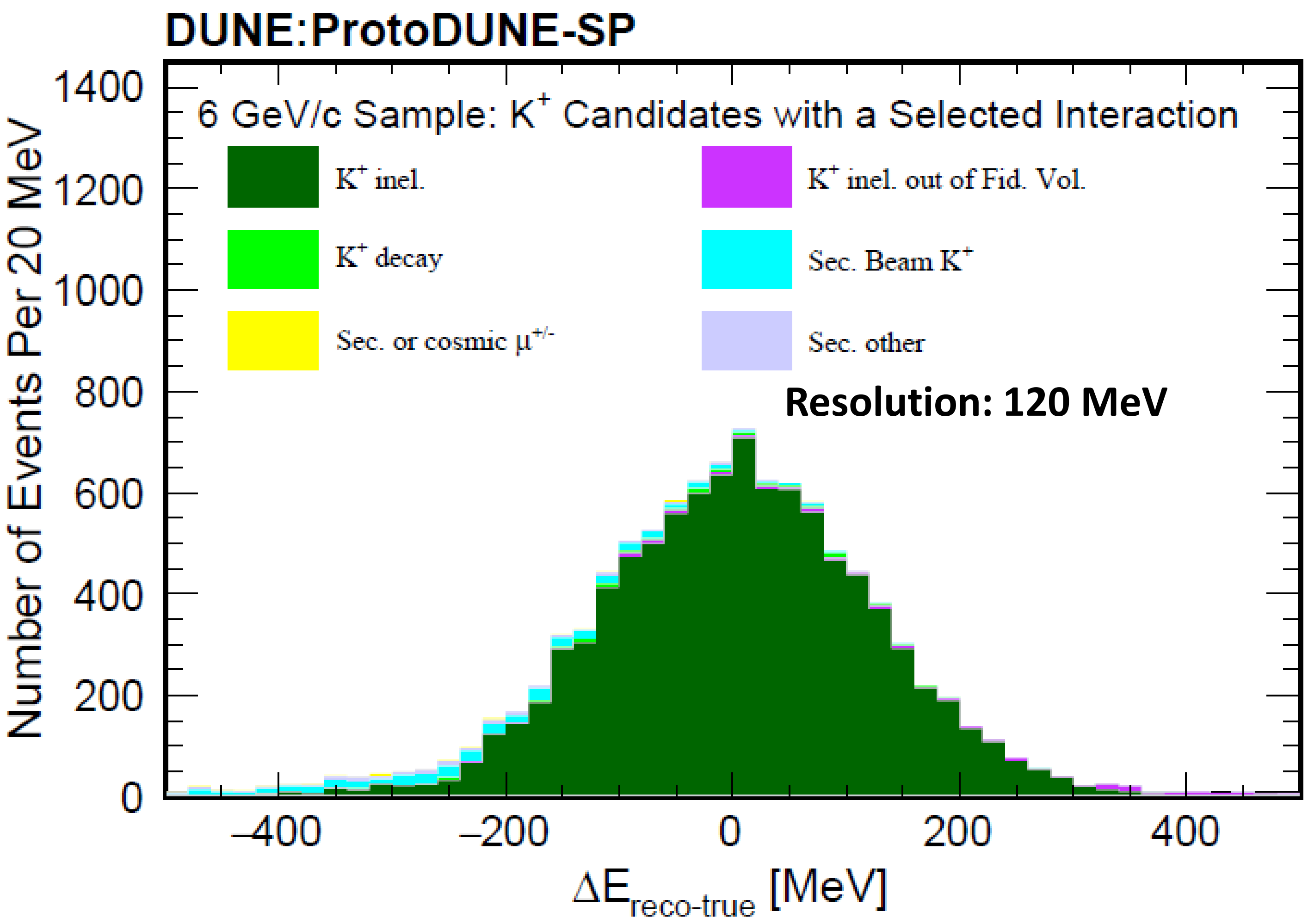


Backup Slides

Test Beam Kinetic Energy Distribution



Kinetic Energy Resolution



Systematic Uncertainties of Cross Section Study

Uncertainty Source ($^{+1\sigma}_{-1\sigma}$)	4480-5080 MeV (%)	5080-5340 MeV (%)	5340-5610 MeV (%)	5610-6170 MeV (%)
Beam modeling	−1.79 1.58	2.50 −3.89	−0.74 1.71	4.01 0.51
dE/dx calibration	0.94 1.59	−0.71 −0.76	−0.96 −1.69	1.92 1.66
Space charge effect	1.28 1.92	−1.18 0.76	−2.04 0.28	2.05 4.42
GEANT4 modeling	6.84 −4.60	3.72 −5.60	1.98 −5.16	4.32 −0.64
Electron diverter effect	6.54 −1.24	3.11 −2.68	1.64 −2.73	2.42 3.43
Vertex identification	8.55 −6.25	9.37 −10.57	7.93 −10.18	13.44 −8.28
Events without a track	1.61 1.22	−0.29 −1.40	−1.05 −1.83	2.70 1.27
Simulation statistics	−0.90 0.89	−1.81 2.12	−1.54 1.76	−2.27 2.48
Data statistics	2.65 −2.27	−4.80 −9.77	5.35 −0.06	6.58 −0.56
All Uncertainties	13.38 8.82	12.08 16.38	10.35 12.25	16.88 10.56

Summary of ProtoDUNE-SP Detector Physics

- DUNE is the future US-based neutrino oscillation experiment specializing in liquid argon.
- ProtoDUNE-SP was the first full-scale detector and showed that the technical specifications are accessible.
  - Cross section results are currently being finalized.

Detector parameter	*ProtoDUNE-SP performance*	*DUNE specification*
Average drift electric field	500 V/cm	250 V/cm (min) 500 V/cm (nominal)
LAr e-lifetime	> 20 ms	> 3 ms
TPC+CE Noise Signal-to-noise ⟨SNR⟩	 (C) 550 e, (I) 650 e ENC (raw) (C) 48.7, (I) 21.2 (w/CNR)	 < 1000 e ENC
CE dead channels	0.2%	< 1%
PDS light yield	1.9 photons/MeV (@ 3.3 m distance)	> 0.5 photons/MeV (@ cathode distance — 3.6 m)
PDS time resolution	14 ns	< 100 ns

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