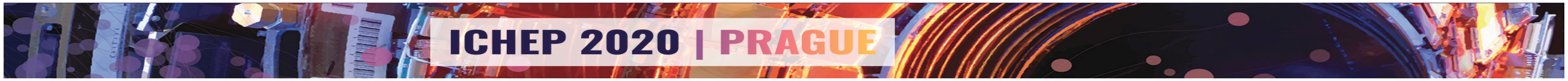
Hadron-argon Cross-section Measurements in ProtoDUNE-SP

- Outline
  - Final state interactions
  - ProtoDUNE-SP setup
  - Cross section methods used in ProtoDUNE-SP
  - Pion & proton interaction channels & event selections

Heng-Ye Liao, On behalf of the DUNE Collaboration
40th International Conference on High Energy Physics
July 29, 2020



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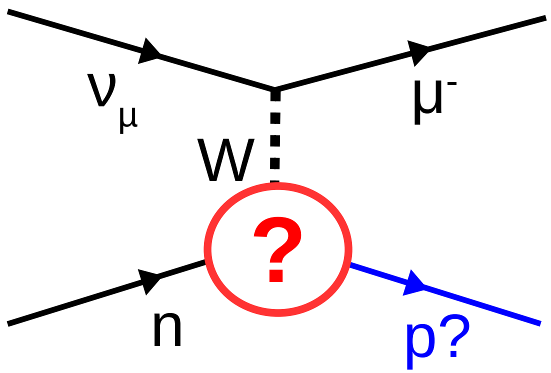
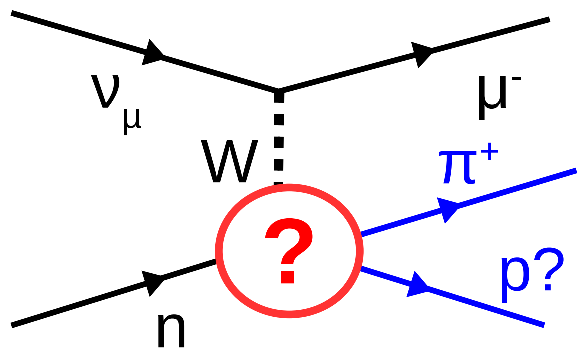
Introduction

- Modern neutrino experiments use complex nuclei as neutrino targets
- Final state interactions (FSI): Hadrons produced in a neutrino interaction can re-interact with the nuclear medium before leaving the nucleus
- FSI is an important process in neutrino interactions
  - FSI can change charge, multiplicity of outgoing hadrons, and altering their final state kinematics. → Misinterpret primary neutrino interactions



CCQE-like



CCRES-like

  - FSI is a key component in neutrino event generators
    Heavily rely on the nuclear models to unfold reconstructed neutrino energy to true neutrino energy

Reco. E_ν → Nuclear Model → E_ν shape (truth) → Oscillation Parameters

  - Validate FSI models by measurements

ProtoDUNE-SP at CERN Neutrino Platform

- Main physics goal of ProtoDUNE single phase (ProtoDUNE-SP):
  Measure hadron-argon cross sections
  - Results provide critical information on hadron scattering in the liquid argon and aid better understanding of FSI in neutrino-argon interactions
  - Improved FSI model can reduce systematic uncertainties on neutrino energy reconstruction & neutrino signal selection → Crucial to achieve DUNE physics goals

- ProtoDUNE-SP milestone
  https://arxiv.org/abs/2007.06722

arXiv.org > physics > arXiv:2007.06722

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Physics > Instrumentation and Detectors

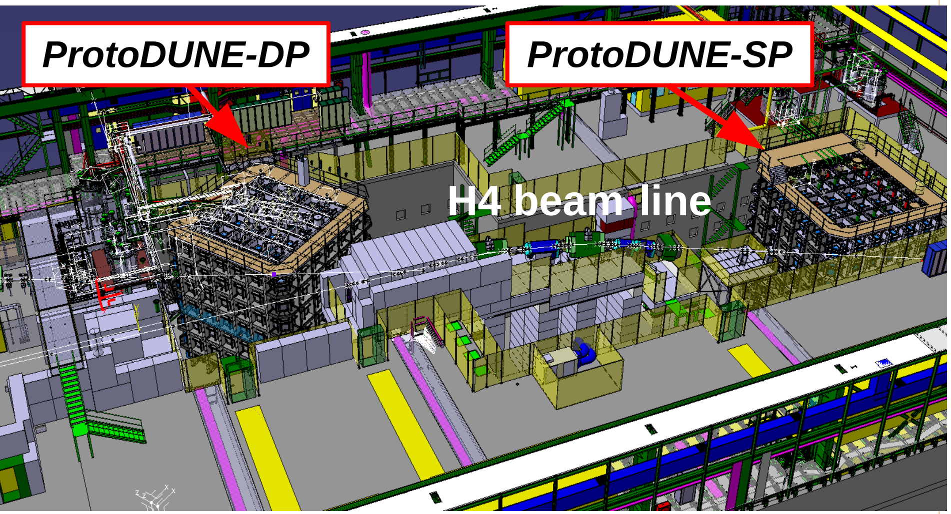
[Submitted on 13 Jul 2020 (v1), last revised 16 Jul 2020 (this version, v2)]

First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform

DUNE Collaboration: B. Abi, A. Abed Abud, R. Acciarri, M. A. Acero, G. Adamov, M. Adamowski, D. Adams, P. Adrien, M. Adinolfi, Z. Ahmad, J. Ahmed, T. Alion, S. Alonso Monsalve, C. Alt, J. Anderson, C. Andreopoulos, M. P. Andrews, F. Andrianala, S. Andringa, A. Ankowski, M. Antonova, S. Antusch, A. Aranda-Fernandez, A. Ariga, L. O. Arnold, M. A. Arroyave, J. Asaadi, A. Aurisano, V. Aushev, D. Autiero, F. Azfar, H. Back, J. J. Back, C. Backhouse, P. Baesso, L. Bagby, R. Bajou, S. Balasubramanian, P. Baldi, B. Bambah, F. Barao, G. Barenboim, G. J. Barker, W. Barkhouse, C. Barnes, G. Barr, J. Barranco Monarca, N. Barros, J. L. Barrow, A. Bashyal, V. Basque, F. Bay, J. L. Bazo Alba, J. F. Beacom, E. Bechetoille, B. Behera, L. Bellantoni, G. Bellettini, V. Bellini, O. Beltramello, D. Belver, N. Benekos, F. Bento Neves, J. Berger, S. Berkman, P. Bernardini, R. M. Berner, H. Berns, S. Bertolucci, M. Betancourt, Y. Bezawada, M. Bhattacharjee, B. Bhuyan, S. Biagi, J. Bian, M. Biassoni, K. Biery, B. Bilki, M. Bishai, A. Bitadze, A. Blake, B. Blanco Siffert, F. D. M. Blaszczyk, G. C. Blazey, E. Blucher, J. Boissevain, S. Bolognesi, T. Bolton, M. Bonesini, M. Bongrand, F. Bonini, A. Booth, C. Booth, S. Bordoni, A. Borkum, T. Boschi, N. Bostan, P. Bour, S. B. Boyd et al. (891 additional authors not shown)

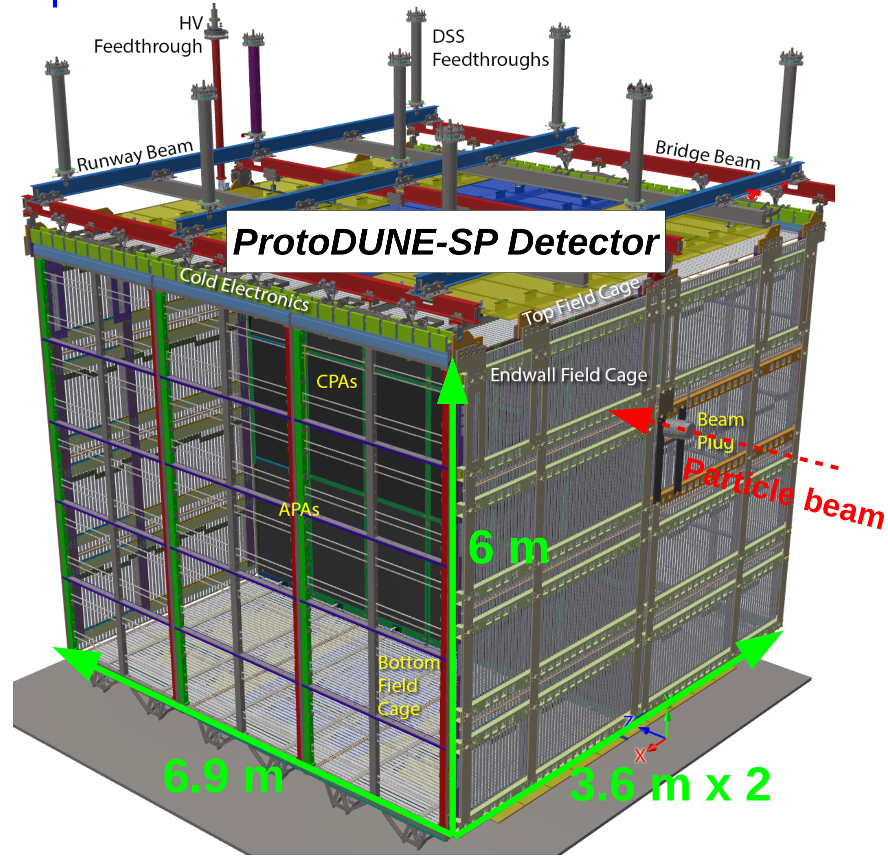
ProtoDUNE-SP: Experimental Setup

- **Controlled environment**
  CERN H4 beamline with known particle type (hadrons and electrons) & incident energies



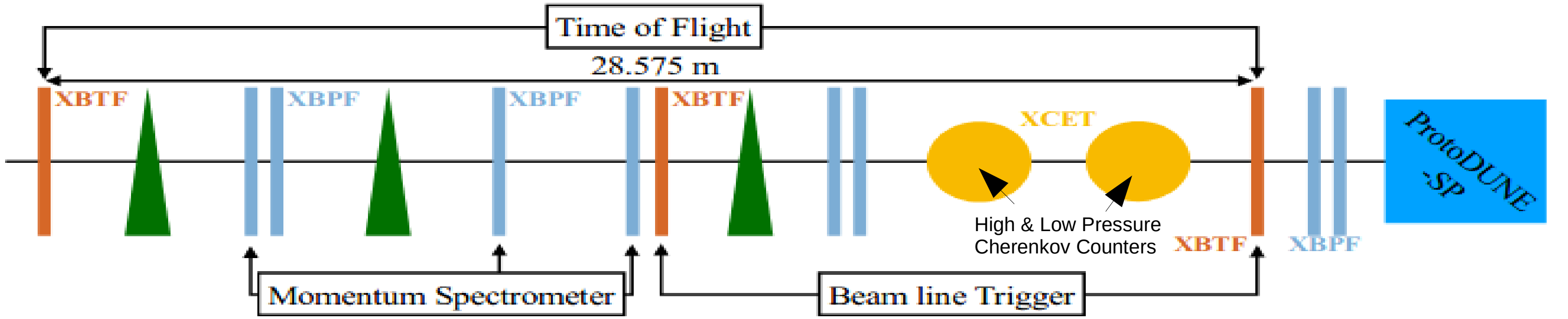
- **A variety of test-beam particles in broad range of momenta**
  0.5-7 GeV/c (**π^+/p/K^+/μ^+/e^-**)
- **Rich data to study hadron-Ar interactions**
  Over 4 million beam events collected (all momenta)

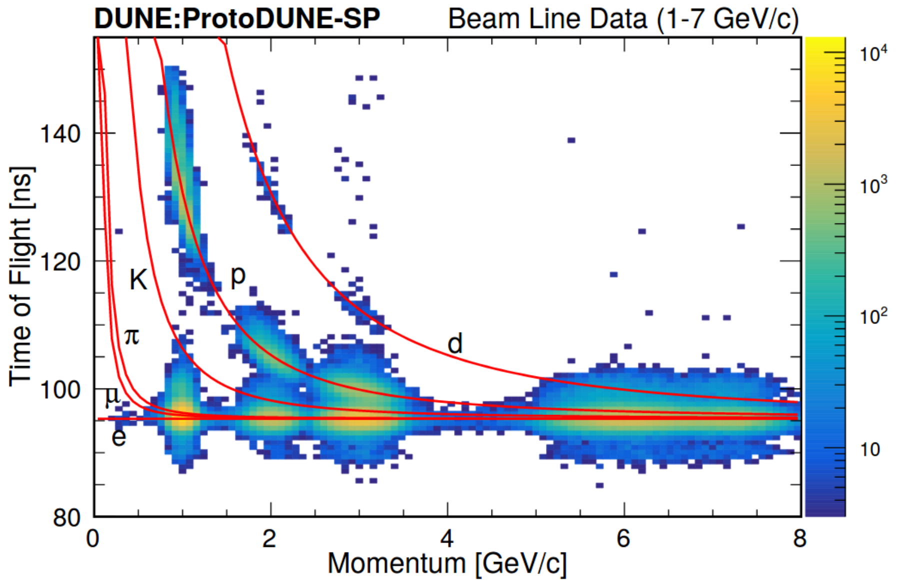
- **LArTPC** (main detector)
  Excellent tracking & calorimetric capabilities

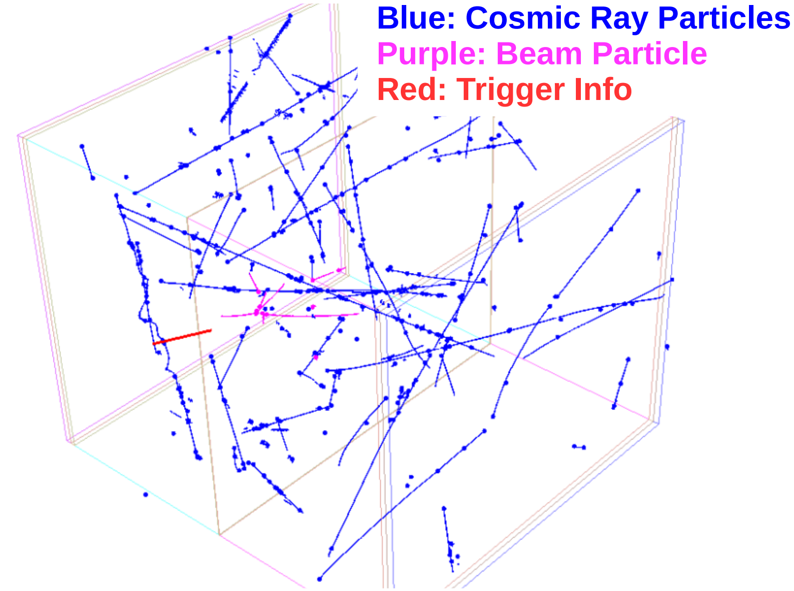


- One of the 2 prototypes for DUNE at CERN Neutrino Platform
- 7.2 x 6.0 x 6.9 m liquid largon time projection chamber (LArTPC) / ~740 tons of liquid argon

Particle Identification & Event Reconstruction







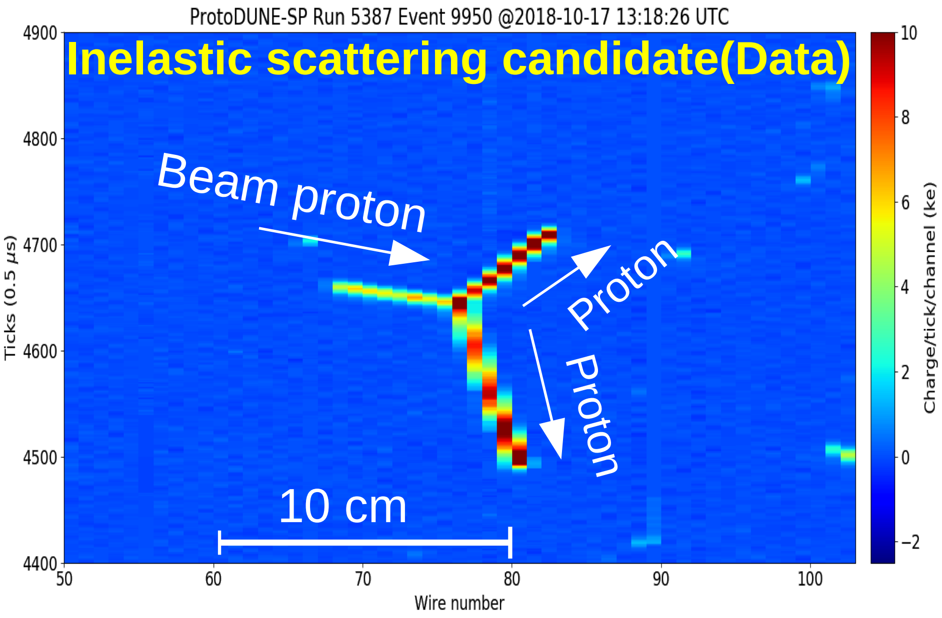
Pandora Event Display (Data)

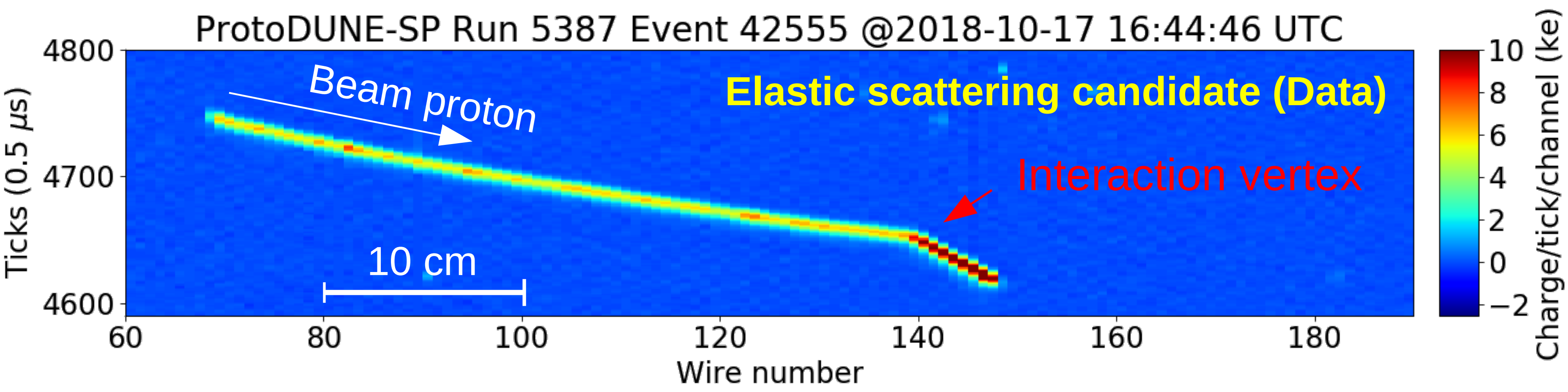
- Particle identification:
  → Use the info from TOF & Cherenkov counters*
- Event reconstruction:
  → Use Pandora** multiple algorithms to reconstruct tracks/showers

*Refer to page 19 for more details
**Pandora reconstruction algorithms: https://link.springer.com/article/10.1140/epjc/s10052-017-5481-6

Proton Cross Section Channels

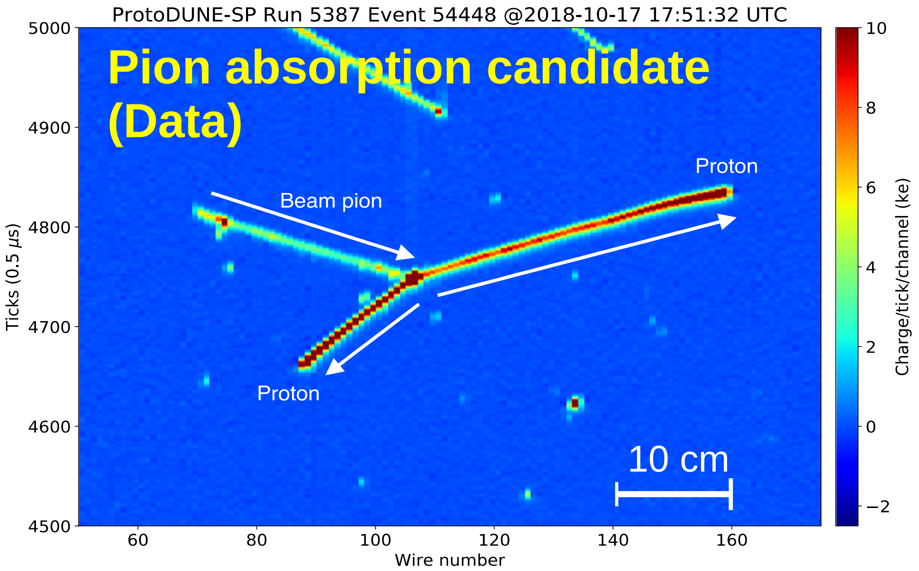
- **Inclusive**
  - **Elastic**
    Nucleus is left in ground state
  - **Inelastic**
    Nucleus is left in an excited state and/or one or more nucleons are knocked out

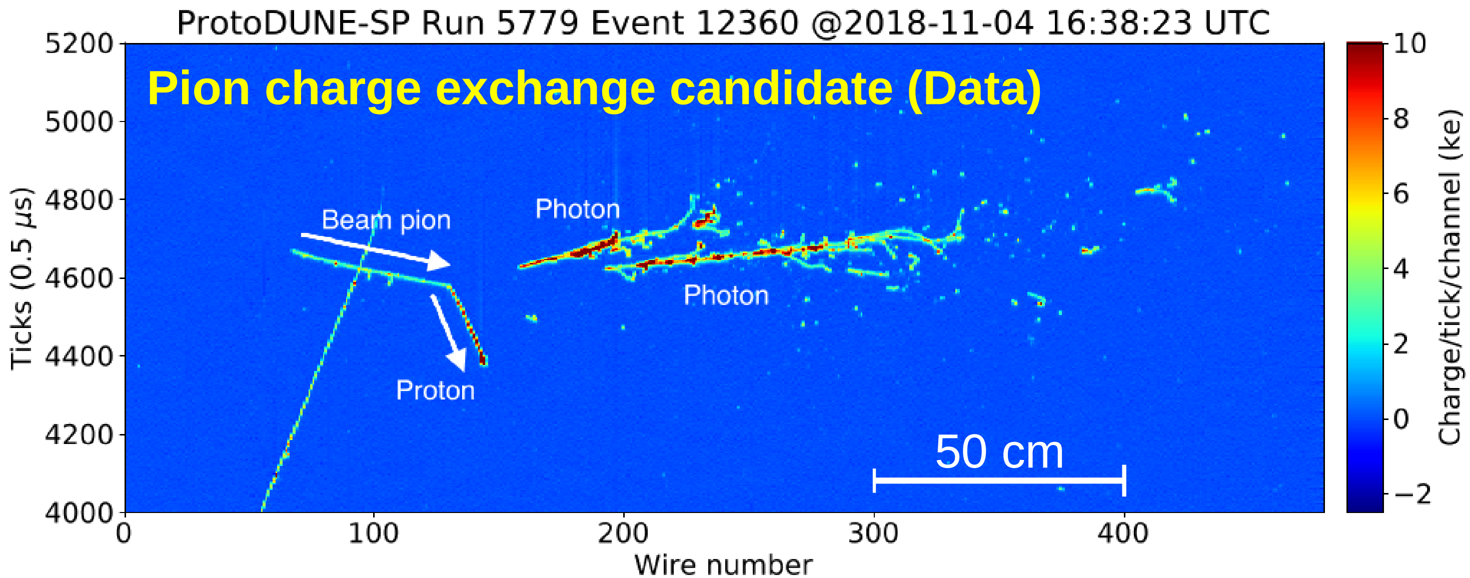




Pion Cross Section Channels

- **Inclusive**
  Elastic & Inelastic scattering
- **Exclusive**
  - **Charge Exchange (CEx)**
    Final state pion charge differs by one unit from the initial pion charge e.g. $\pi^+ \rightarrow \pi^0$
  - **Absorption (Abs)**
    No pion in the final state.



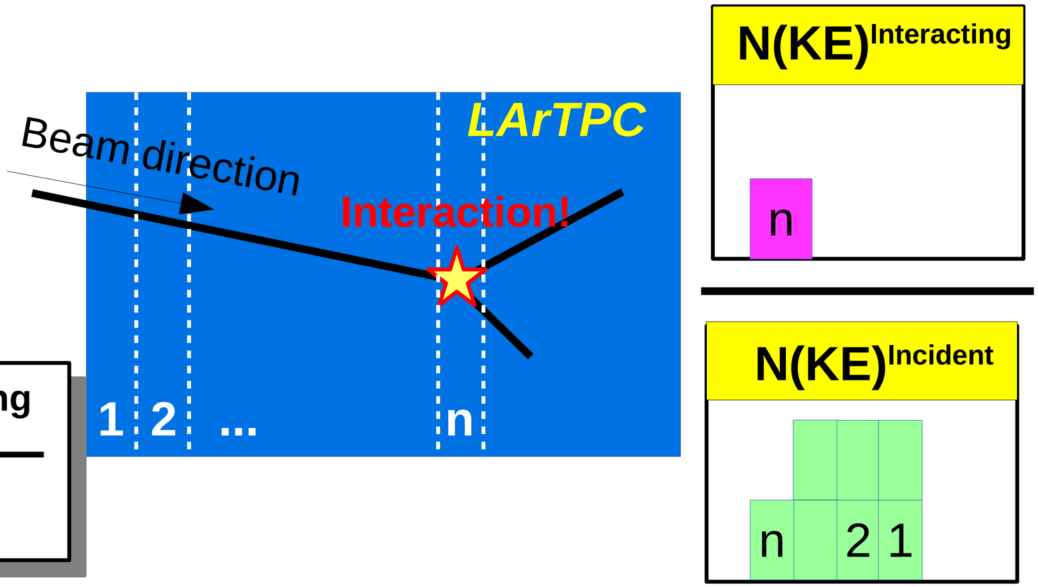


Cross Section Measurements: Methods

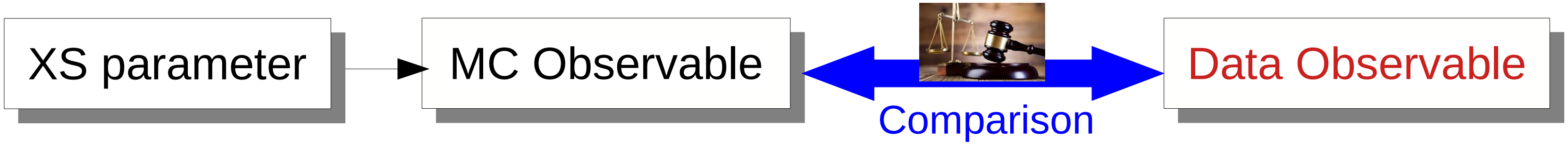
- Established a framework of cross section (XS) calculations
  - Thin slice method
    - Developed by LArIAT experiment*
    - Treat wire-to-wire spacing as a series of “thin-slab” targets
    - Each thin-slab is an independent measurement
    - XS formula:

$$XS(KE) = S_f \cdot \frac{N(KE)^{interacting}}{N(KE)^{incident}}$$

S_f ~100 barn for ProtoDUNE-SP



  - Reweighting method
    - Event-by-event weighted observables by changing XS parameters

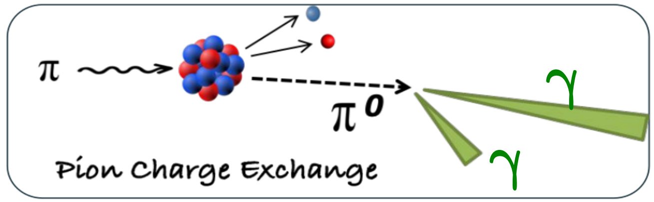


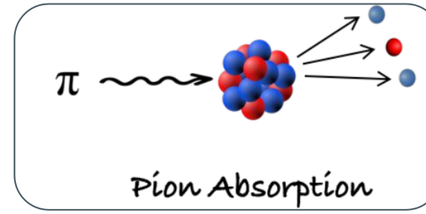
    - Used for XS systematics estimation & model-dependent XS calculation
    - Software package: Geant4Reweight (link)

*Reference: arXiv:1611.00821

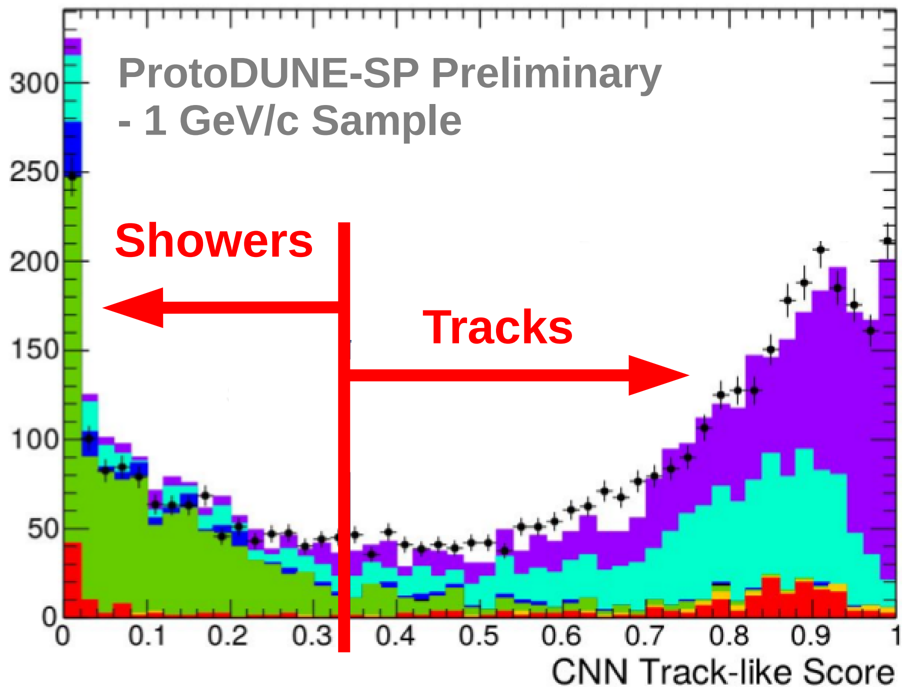
Pion Event Selection

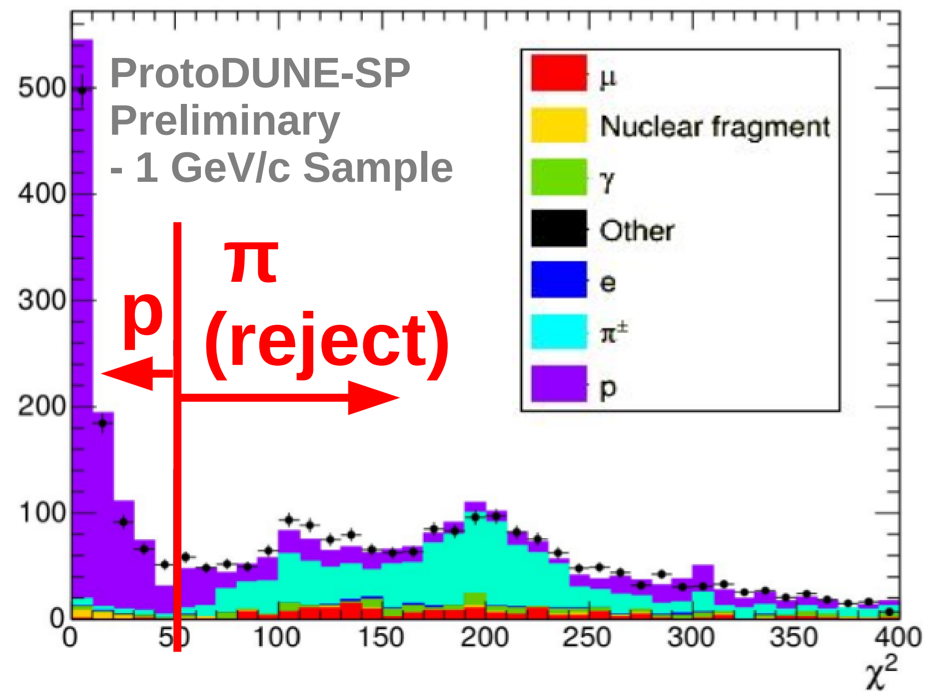
- Signature of CEx+Abs: No charged pions in final state





- Event Selection:
  - Daughter track/shower tagging using convolutional neural network (CNN)
  - Reject $\pi^{\pm}$ daughter tracks using χ^2-based PID

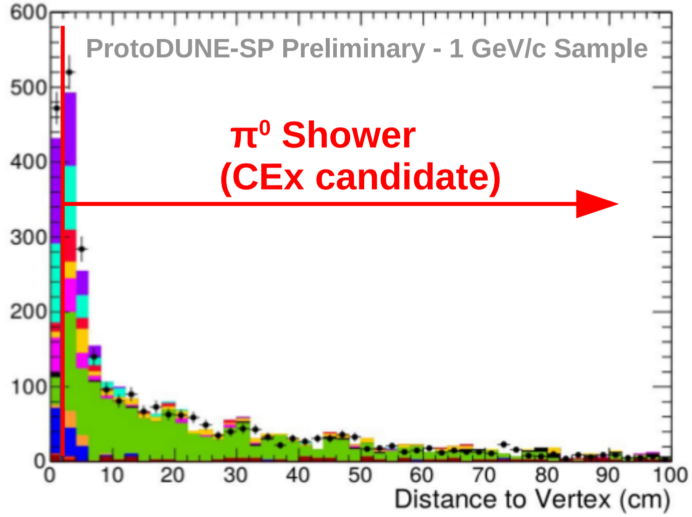


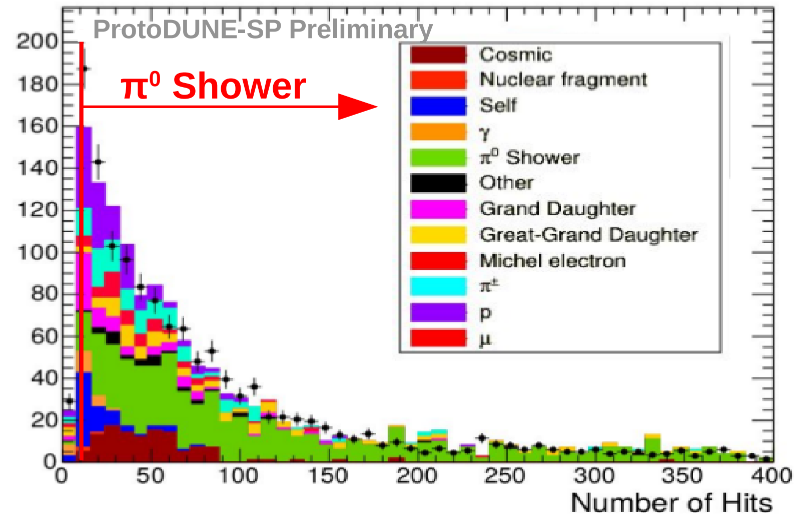


* χ^2 Definition:= $\frac{1}{n_{\mathrm{DoF}}} \sum_j \frac{\left[\frac{dE_j}{dx_j}(\ X\ ) - \frac{dE_j}{dx_j}(\text{MC Proton})\right]^2}{\sqrt{\delta^2 \frac{dE_j}{dx_j}(\ X\ ) + \delta^2 \frac{dE_j}{dx_j}(\text{MC Proton})}}$, where X: other MC particles

Pion Event Selection: Performance

- CEx & Abs separation: Look for π^0-like showers
  CEx: Showers from π^0 / Abs: No showers
  → Use (1)distance to vertex cut & (2)hit distribution cut



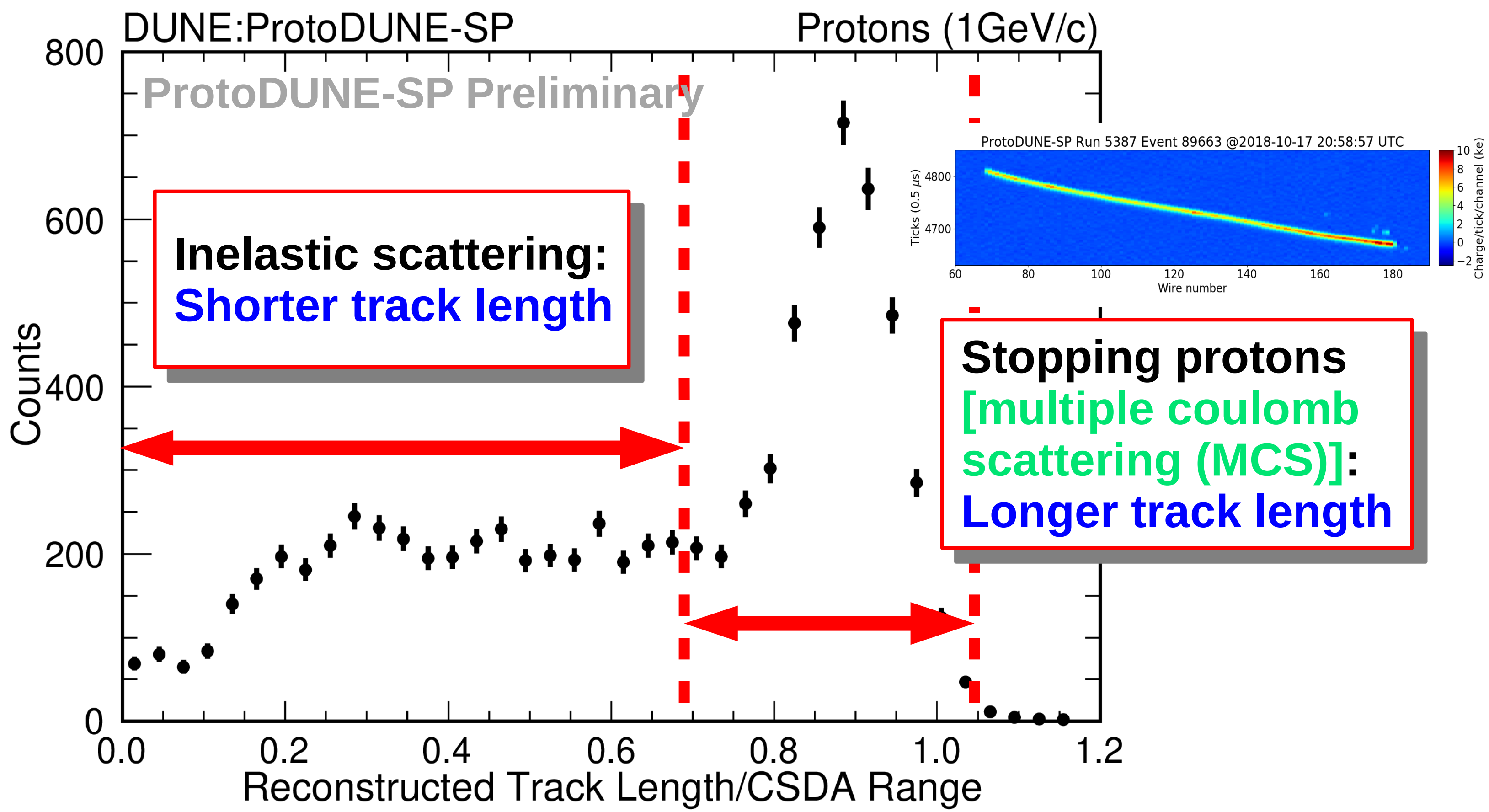


- Efficiency & Purity

	Efficiency	Purity
CEx + Abs	67 %	66 %
CEx	63 %	61 %
Abs	59 %	59 %

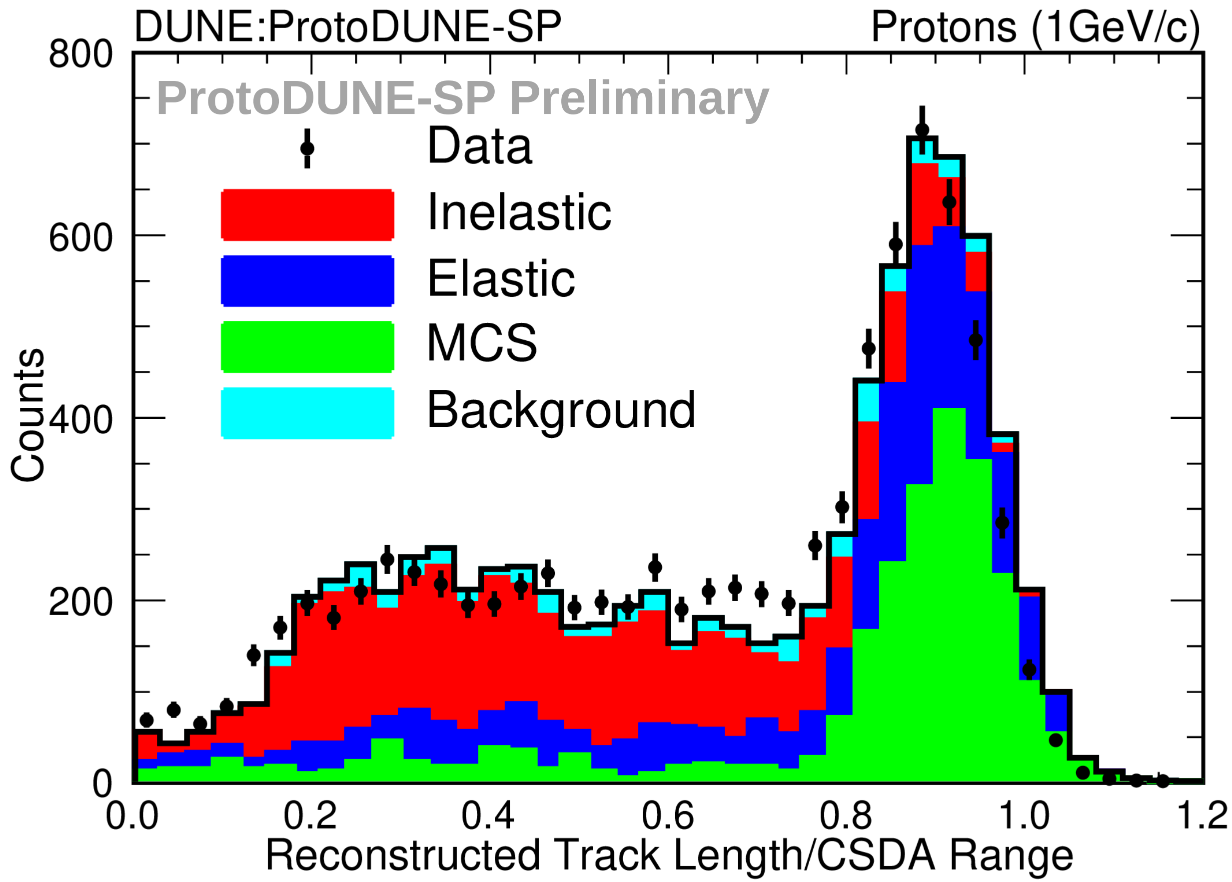
- Optimization of event selection in progress

Proton: Event Selection Observable



- Proton event selection using **normalized track length** cut
  - Normalized track length := primary track length/ CSDA range
  - Convert proton beam momentum to its CSDA range
    + CSDA range: Average track length of stopping protons

Proton: Data & MC



- Good Geant4 simulation to describe data observable
  - Elastic, inelastic, and MCS components are clearly seen
- Reasonable agreement between data & MC (χ^2/ndf:93.4/40)
- Normalized track length served as one observable for XS reweighting

Summary & Outlook

- FSI is crucial to neutrino interactions
- ProtoDUNE-SP measures hadron-argon cross sections
  - Provide valuable inputs for better understanding of FSI
  - Important results to achieve DUNE physics goals and beneficial to neutrino community
- Rapid progress in both the pion-Ar and proton-Ar cross section analyses
  - Established entire framework for hadron-Ar XS estimations
  - Preliminary results on pion & proton event selections
- ProtoDUNE-SP will deliver many more physics results. Stay tuned!

Stefania Bordoni
Construction, installation and operation of ProtoDUNE-SP
https://indico.cern.ch/event/868940/contributions/3813675/

Michael Mooney
Measurement of space charge effects in ProtoDUNE-SP
https://indico.cern.ch/event/868940/contributions/3813672/

Dante Totani
Performance of photon detectors in ProtoDUNE-SP
https://indico.cern.ch/event/868940/contributions/3813674/

Richard Diurba
Energy calibration of the ProtoDUNE-SP TPC
https://indico.cern.ch/event/868940/contributions/3813673/

Guillaume Eurin
ProtoDUNE Dual Phase: Design, Construction and First Results
https://indico.cern.ch/event/868940/contributions/3813836/

Richard Diurba
Purity monitoring for ProtoDUNE (Poster section)
https://indico.cern.ch/event/868940/contributions/3817045/

Backup

Impact of FSI on Oscillation Parameters

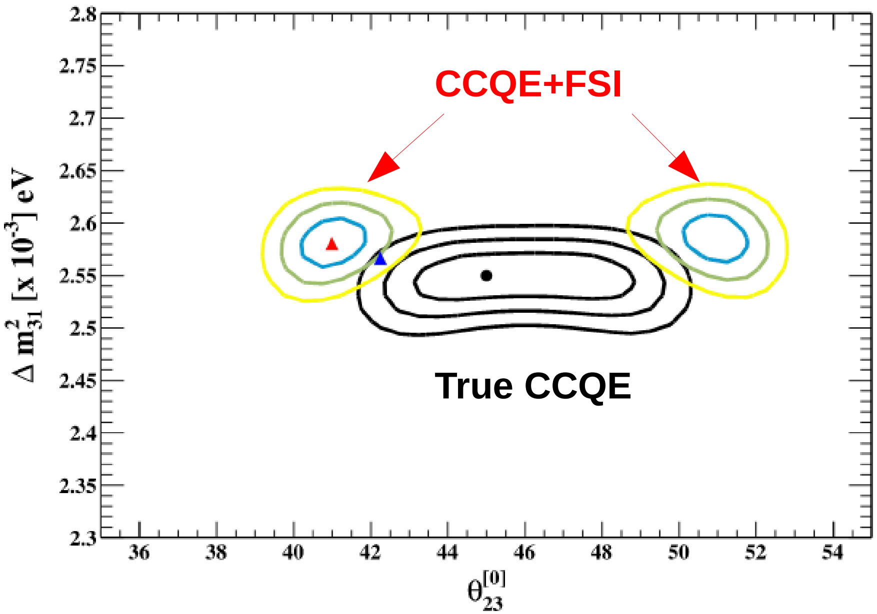


Fig. 6. Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure QE (black lines) and QE-like (color lines) in the absence of detector cuts. The red $(\alpha = 0)$ and blue $(\alpha = 0.5)$ triangles show the best fit points of oscillation parameters while circle $(\alpha = 1)$ shows the true values of the oscillation parameters.

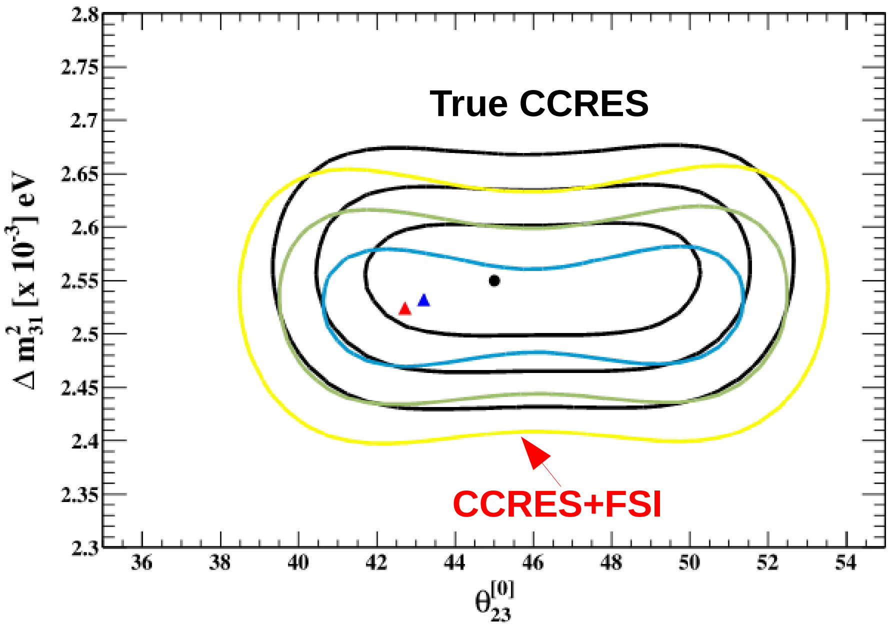


Fig. 7. Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure Res (black lines) and Res-like (color lines) in the absence of detector cuts. The red $(\alpha = 0)$ and blue $(\alpha = 0.3)$ triangles show the best fit points of oscillation parameters while circle $(\alpha = 1)$ shows the true values of the oscillation parameters.

- Simulation on DUNE: 5 yrs neutrino mode + 5 yrs anti-neutrino mode
- Neutrino generator: GiBUU
- No detector effect involved, only FSI

Reference:
"Effect of final state interactions on neutrino energy reconstruction at DUNE", Nuclear Physics B, Vol 933, Aug 2018, p40-52 (link)

Impact of FSI on Oscillation Parameters

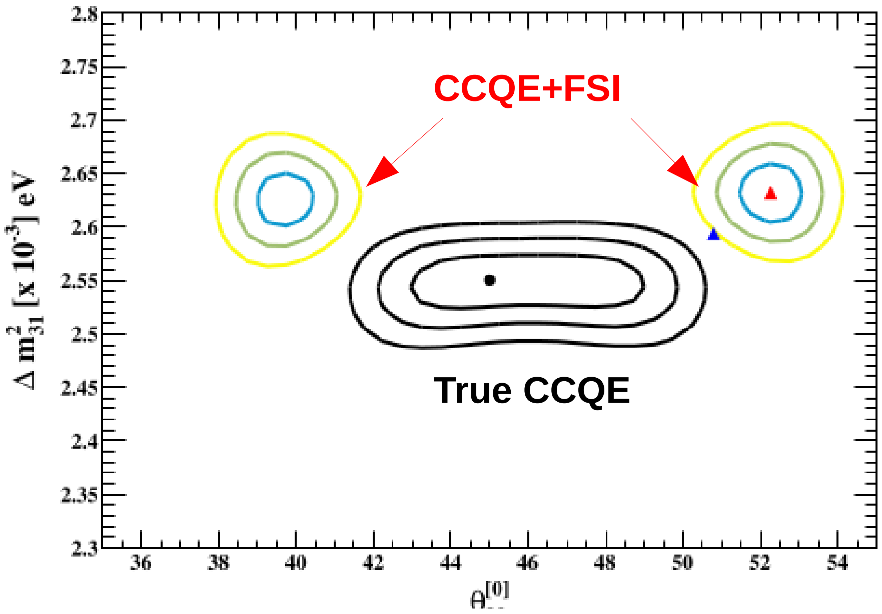


Fig. 8. Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure QE (black lines) and QE-like (color lines) in the presence of detector cuts. The red ($\alpha = 0$) and blue ($\alpha = 0.5$) triangles show the best fit points of oscillation parameters while circle ($\alpha = 1$) shows the true values of the oscillation parameters.

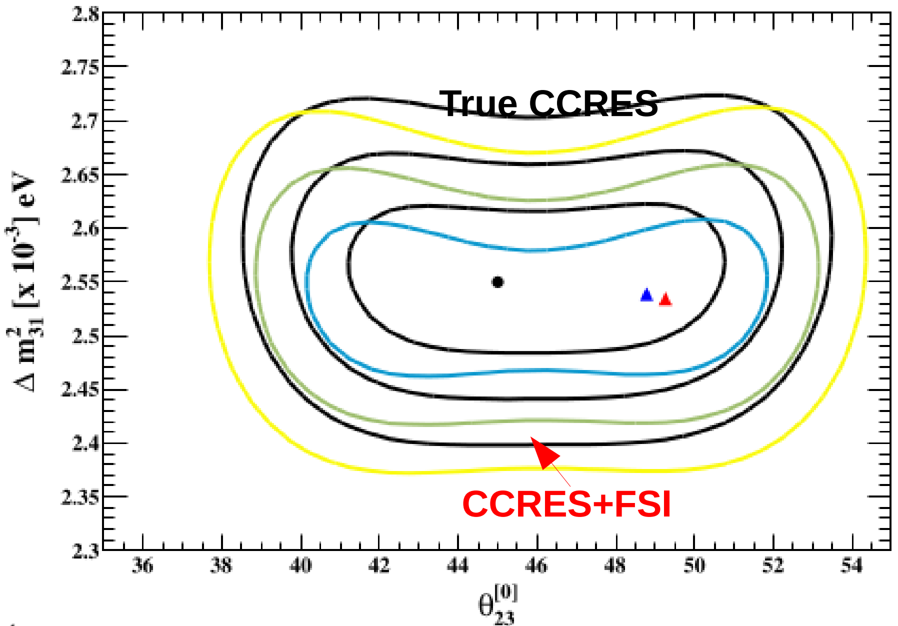


Fig. 9. Confidence regions in the $(\theta_{23}, \Delta m^2_{31})$ plane are obtained using the migration matrices pure Res (black lines) and Res-like (color lines) in the presence of detector cuts. The red ($\alpha = 0$) and blue ($\alpha = 0.3$) triangles show the best fit points of oscillation parameters while circle ($\alpha = 1$) shows the true values of the oscillation parameters.

- Detector effect involved + FSI
- Threshold kinetic energy cuts for particles.

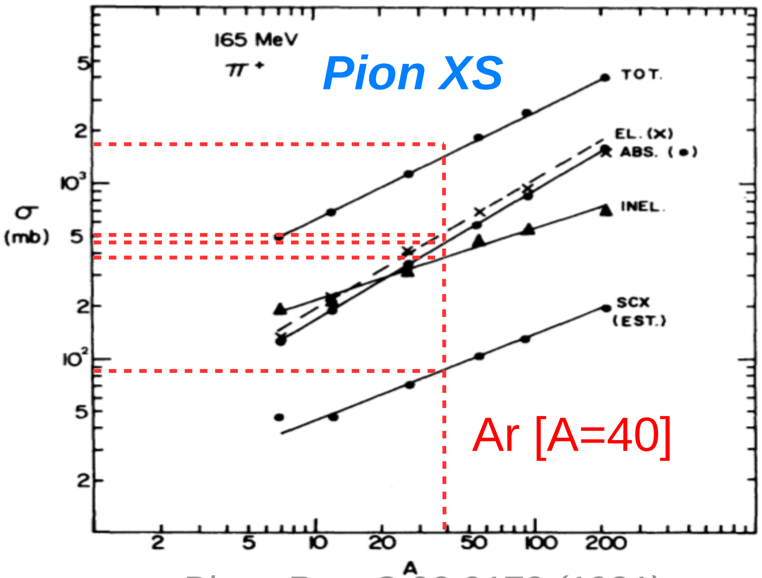
Particle type	p	n	π^+	π^-	π^0	μ
Threshold kinetic energy (GeV)	0.05	0.05	0.1	0.1	0.1	0.03

- Worse after including detector effect

$$N_i^{test}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE\text{-}like}$$
$$N_i^{test}(\alpha) = \alpha \times N_i^{Res} + (1-\alpha) \times N_i^{Res\text{-}like}$$

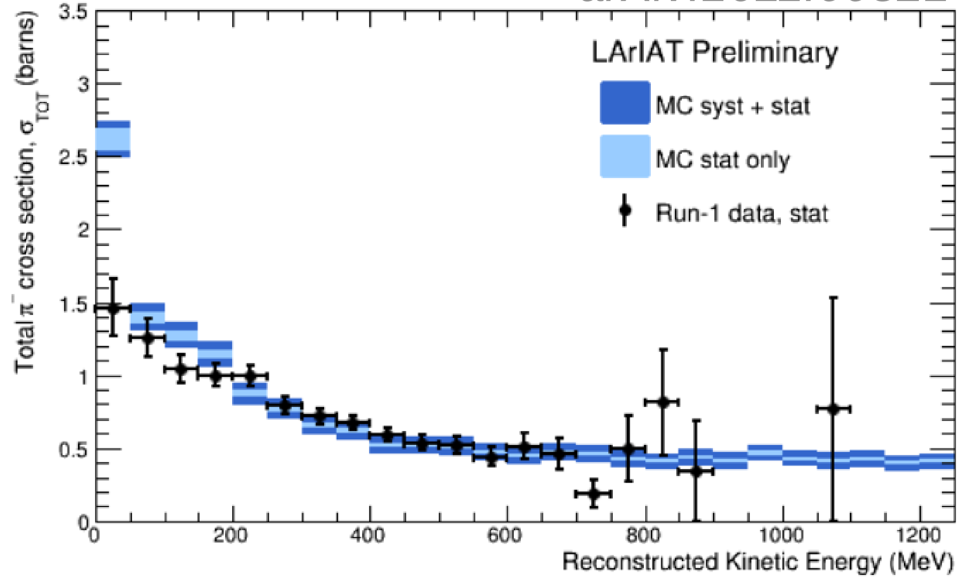
1. When $\alpha = 1$ (nuclear effects are completely disregarded).
2. When $\alpha = 0$ (nuclear effects are perfectly known).

Pion & Proton XS Measurements

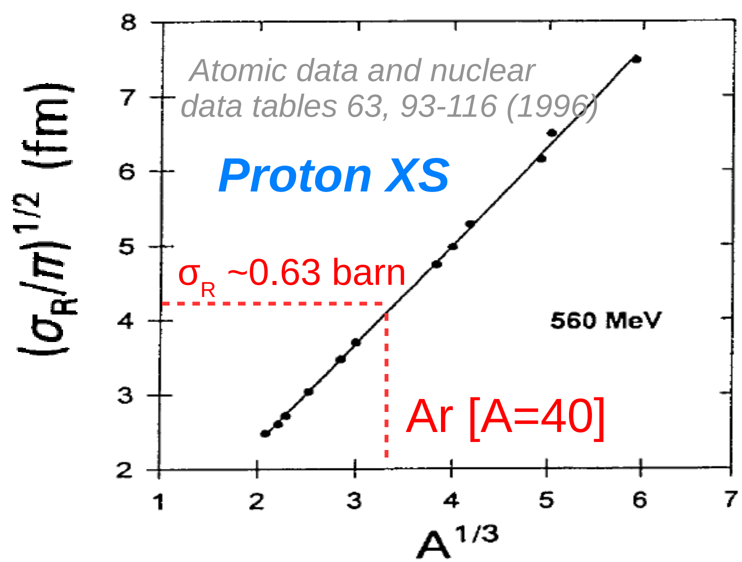


Phys. Rev. C 23 2173 (1981)

arXiv:1611.00821



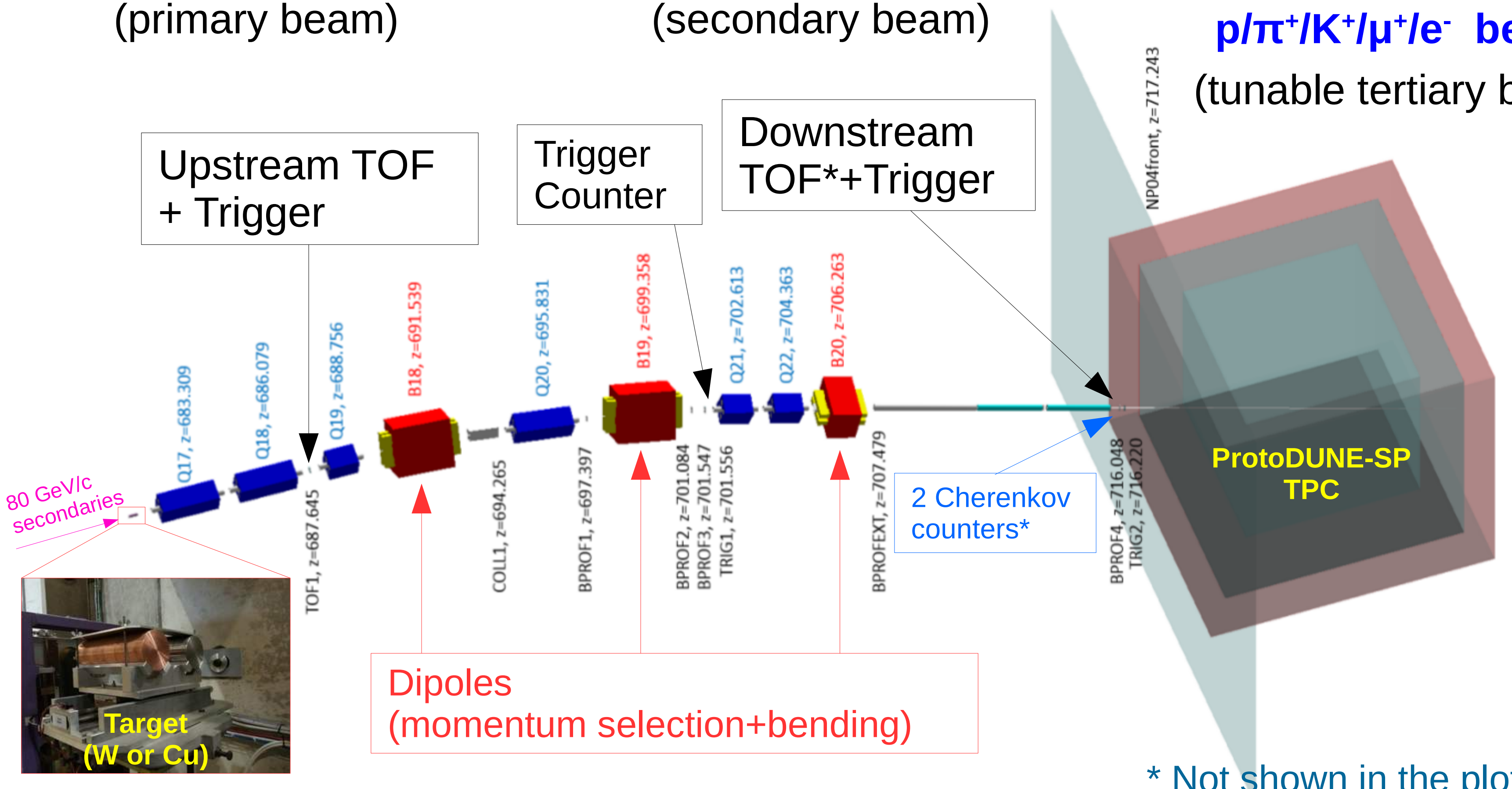
- Pion & proton XS predictions come from interpolation between heavier and lighter nuclei
- Only one π-Ar measurement from LarIAT experiment
- ProtoDUNE-SP measurements are important for LAr-based neutrino experiments



ProtoDUNE-SP: Beamline Instrumentation

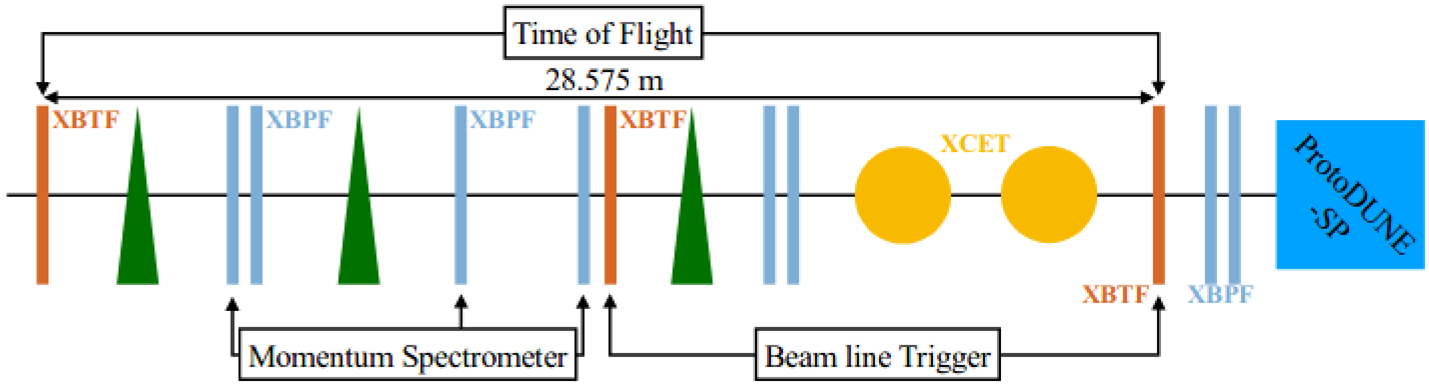
- CERN H4 beamline-extension & Beamline Instrumentation
  - Known particle type (hadrons and electrons) & incident energies

400 GeV/c protons → target → 80 GeV/c beam → target → **0.5 – 7 GeV/c $p/\pi^+/K^+/\mu^+/e^-$ beam**
(primary beam) (secondary beam) (tunable tertiary beam)



* Not shown in the plot

TOF & Cherenkov Info



		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

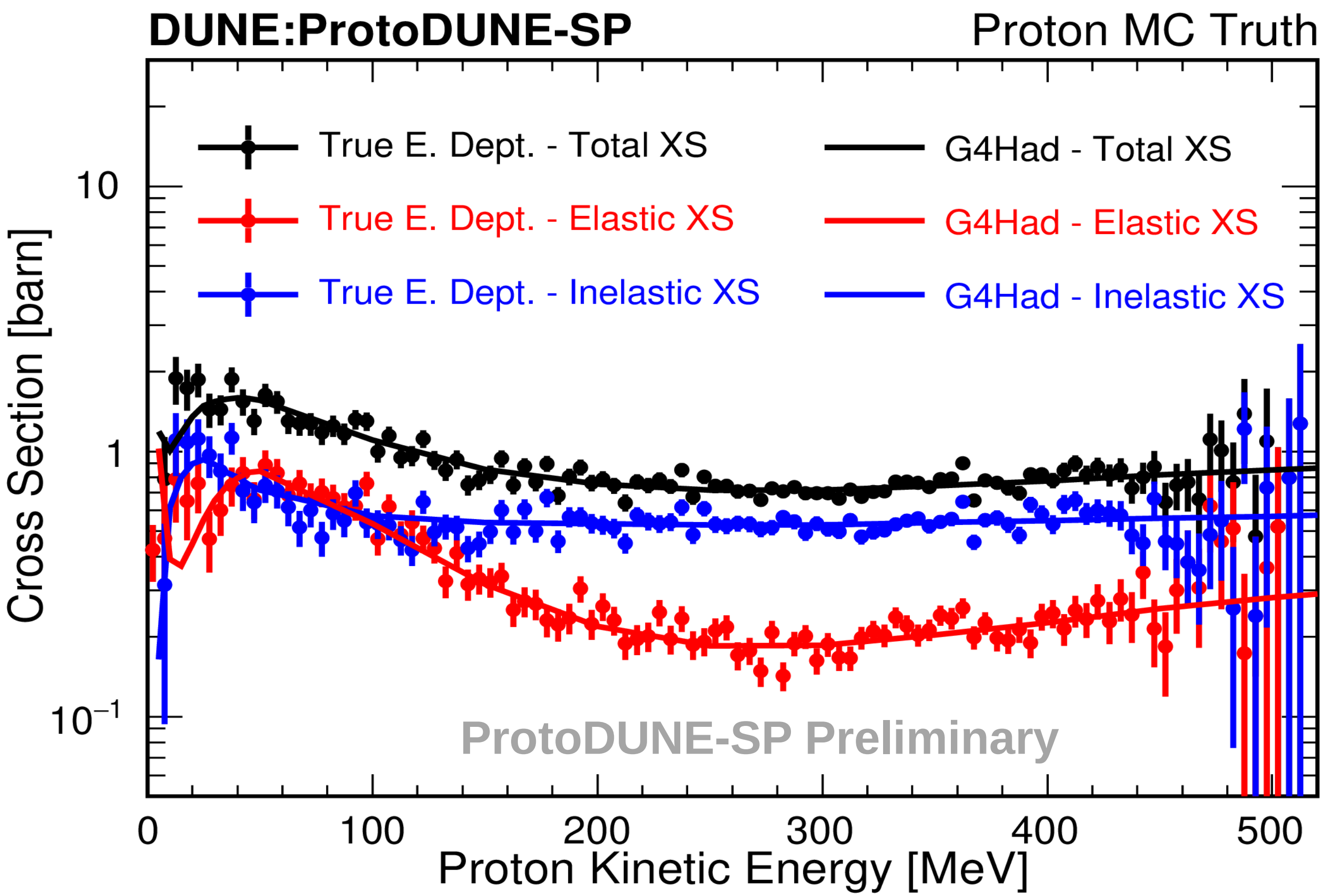
Rich Data to Study Hadron-Argon Interactions

- A variety of test-beam particles in broad range of momenta 0.5-7 GeV/c (**π^+/p/K^+/μ^+/e^-**)
- Over 4 million beam events (all momenta) collected
  Data taking: from 09/21/2019 to 11/12/2019 [~6 weeks beam run]
- Successful data collection as designed

	Data	Monte Carlo Simulation				
Momentum	Total Triggers	Total Triggers	Expected Pi Trigger	Expected Proton Trigger	Expected Electron Trigger	Expected Kaon Trigger
0.3 GeV/c	269K	242K	0	0	242K	0
0.5 GeV/c	340K	299K	1.5K	1.5K	296K	0
1 GeV/c	1089K	1064K	382K	420K	262K	0
2 GeV/c	728K	639K	333K	128K	173K	5K
3 GeV/c	568K	519K	284K	107K	113K	15K
6 GeV/c	702K	689K	394K	70K	197K	28K
7 GeV/c	477K	472K	299K	51K	98K	24K
All momenta	**4173K**	3924K	1694K	779K	1384K	73K

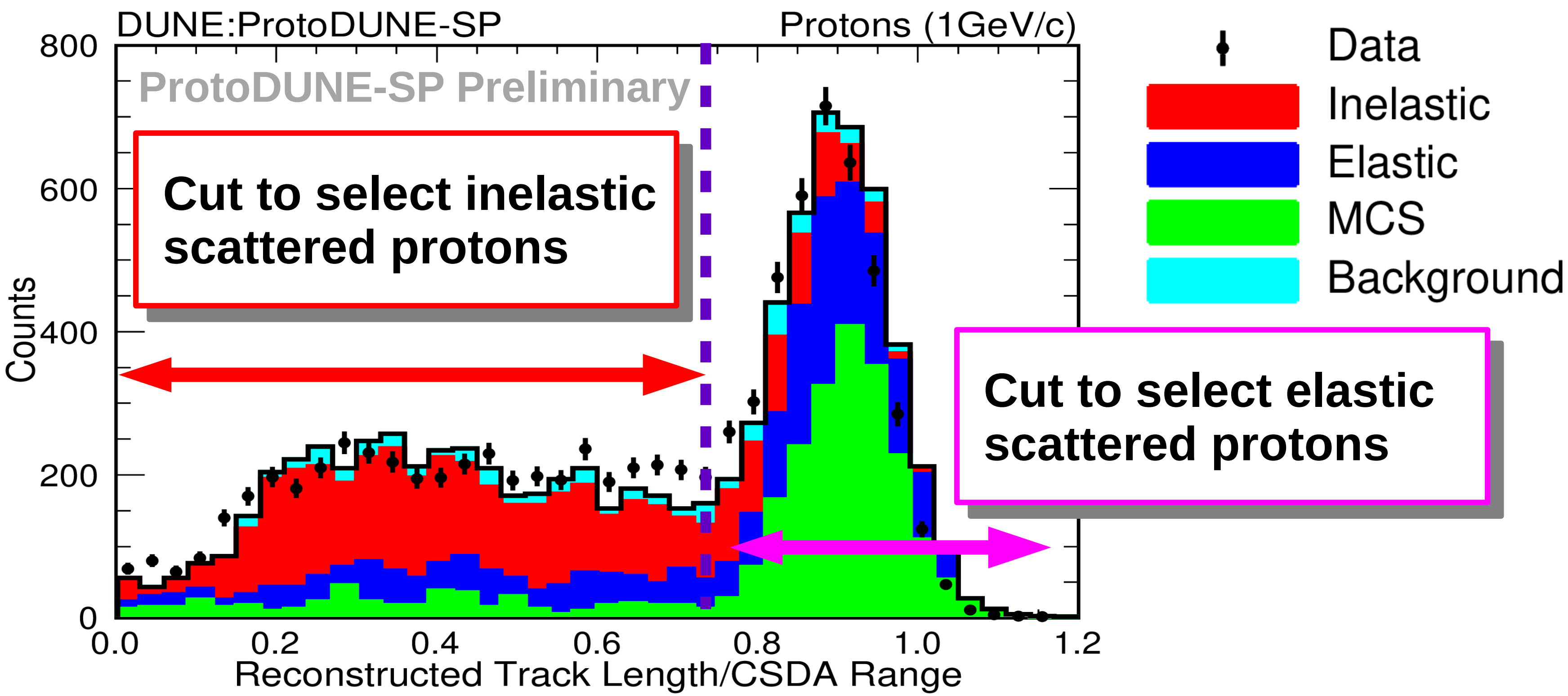
Thin Slice Method: Proof-of-Principle

- Verification of the thin slice method using stand-along Geant4 application (G4HadStudies*)



* Hans Wenzel's package: https://github.com/hanswenzel/G4HadStudies

Proton: Event Selection Performance

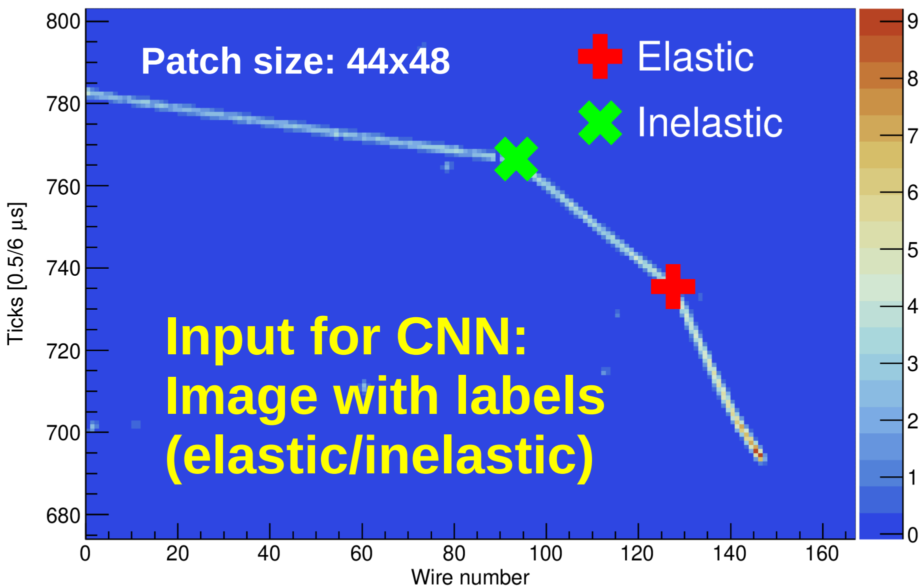


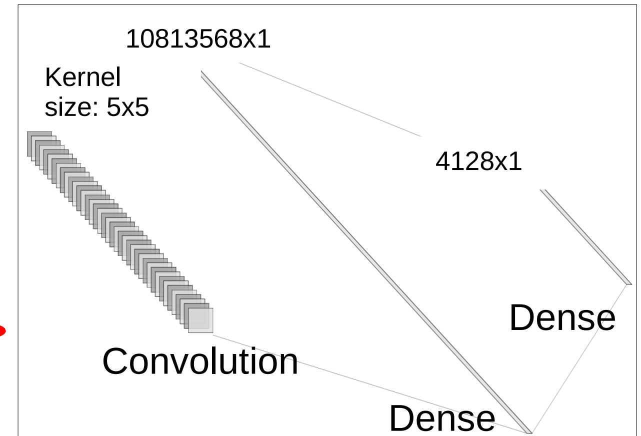
- Benchmark parameter: Efficiency*Purity

Inelastic	**81 %**
Elastic	**37 %**

Proton: Interaction Vertex Identification

- Vertex identification: Key to the success of XS measurement
- Vertex finding using CNN:





CNN Architecture

Output:
Elastic/Inelastic score
per pixel [0-1]

- Vertex identification efficiency

  Good reco.: Δr(truth-reco)≤5cm

  Inelastic 75 %

  Elastic 31 %

- Improvement on vertex-finding efficiency expected using sophisticated network structure