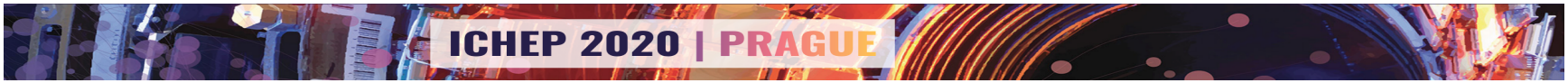
Hadron-argon Cross-section Measurements in ProtoDUNE-SP

Heng-Ye Liao, On behalf of the DUNE Collaboration

40th International Conference on High Energy Physics

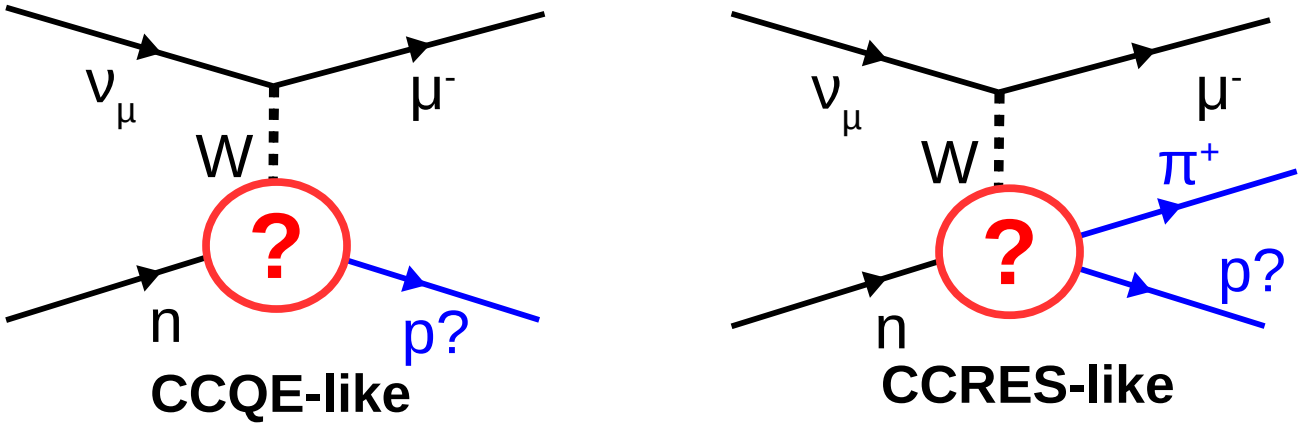
July 29, 2020



KANSAS STATE UNIVERSITY
Fermilab
Neutrino PLATFORM
DUNE

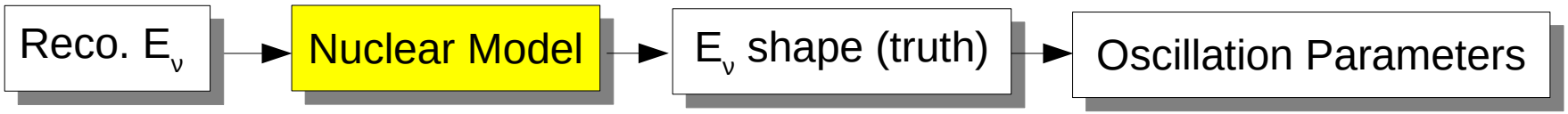
Introduction

- 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



  - FSI is a key component in neutrino event generators

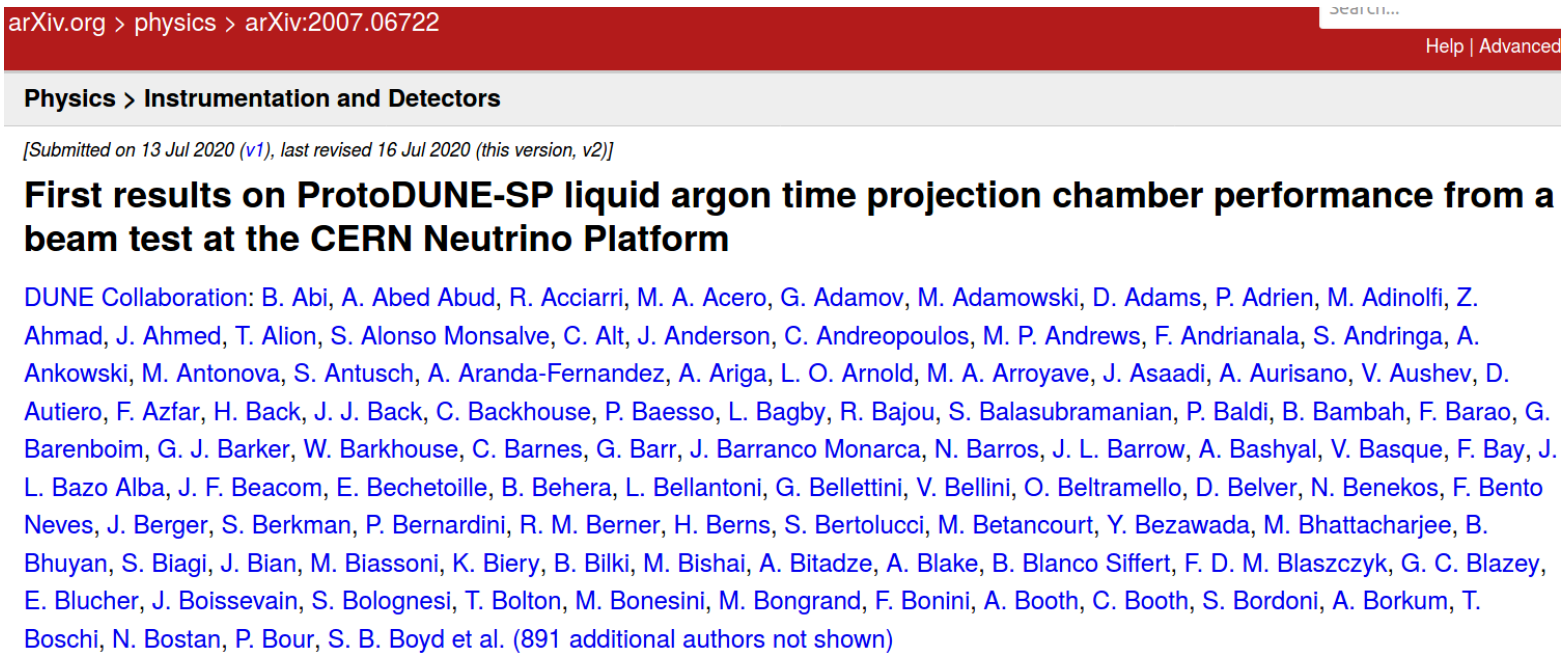
    Heavily rely on the nuclear models to unfold reconstructed neutrino energy to true neutrino energy



  - Limited measurement in argon, FSI has yet to be understood

ProtoDUNE-SP at CERN Neutrino Plateform

- Main physics goal of ProtoDUNE single phase (ProtoDUNE-SP):
  Measure hadron-argon cross sections
  - Results provide critical information to 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

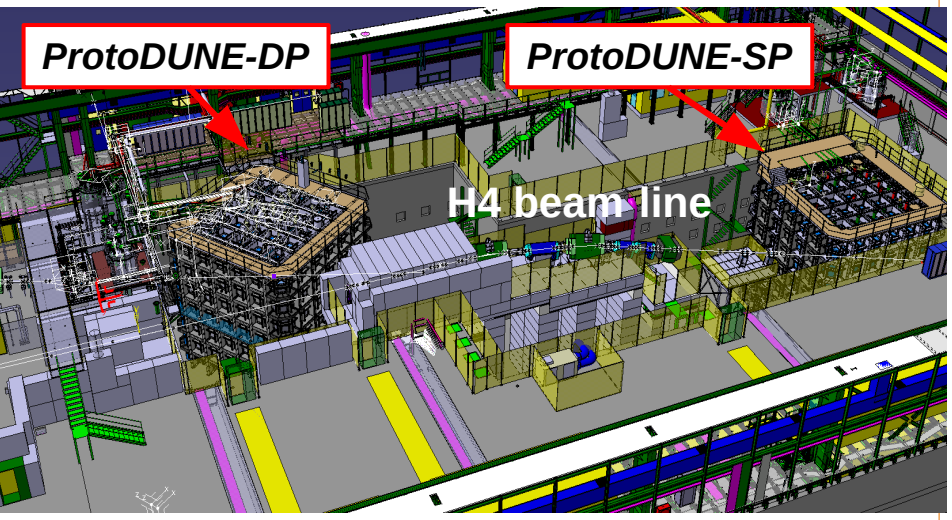
[Submitted on 13 Jul 2020 (v1), last revised 16 Jul 2020 (this version, v2)]

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)

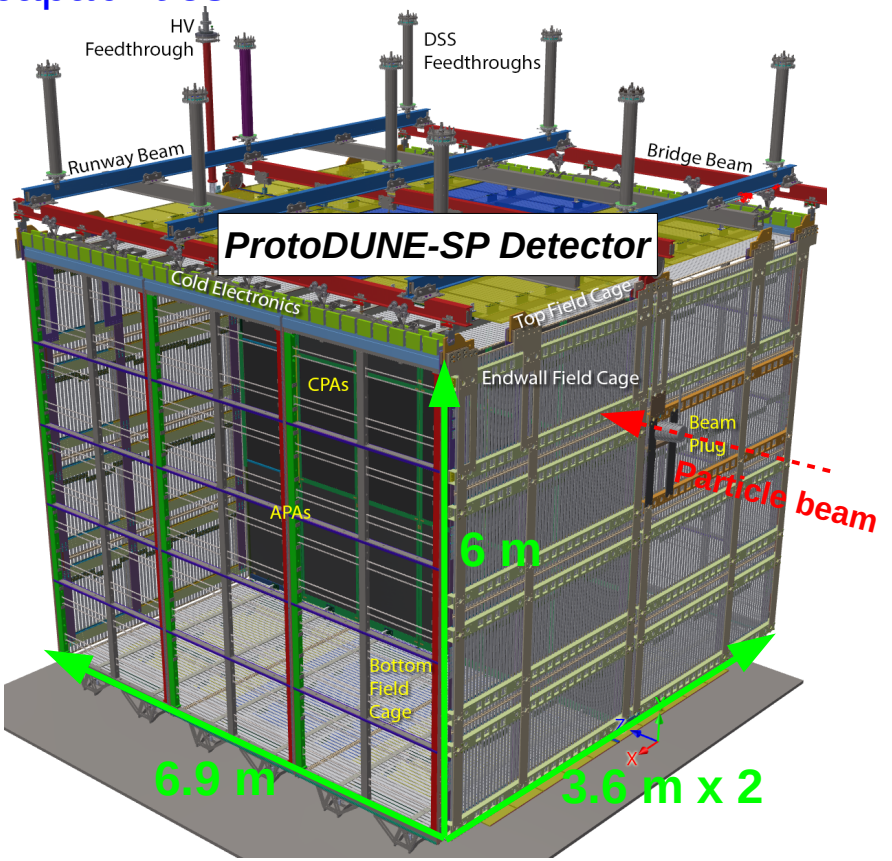
ProtoDUNE-SP: Experimental Setup

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



  - Tunable particle beam:
    0.5 – 7 GeV/c $p/\pi^+/K^+/\mu^+/e^-$

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



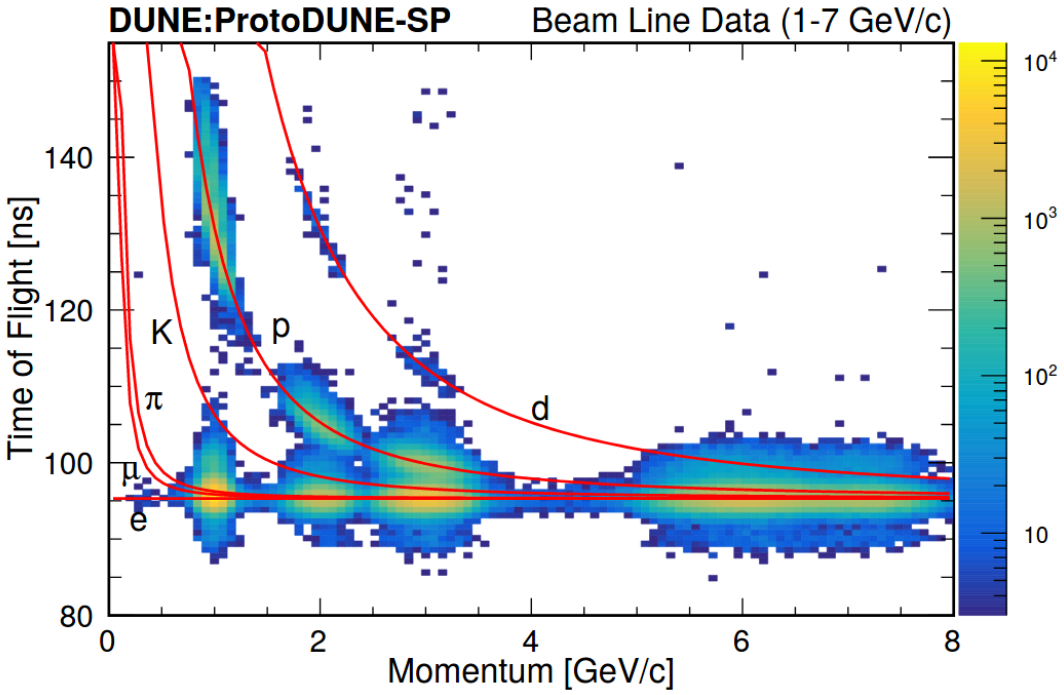
  - One of the 2 prototypes for DUNE at CERN Neutrino Platform
  - 7.2 x 6.0 x 6.9 m liquid largon time projection chamber (LArTPC) / ~740 tons of liquid argon

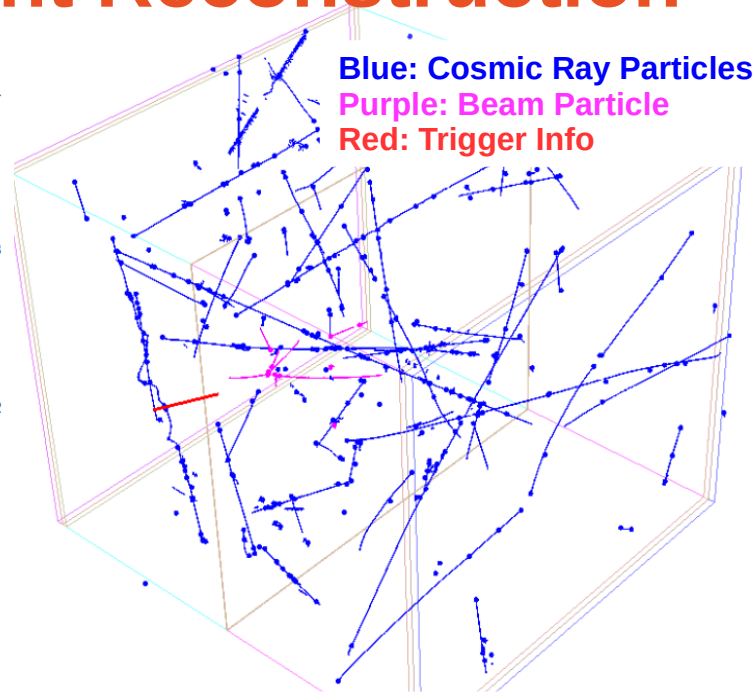
Rich Data to Study Hadron-Argon Interactions

- 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

Particle Identification & Event Reconstruction





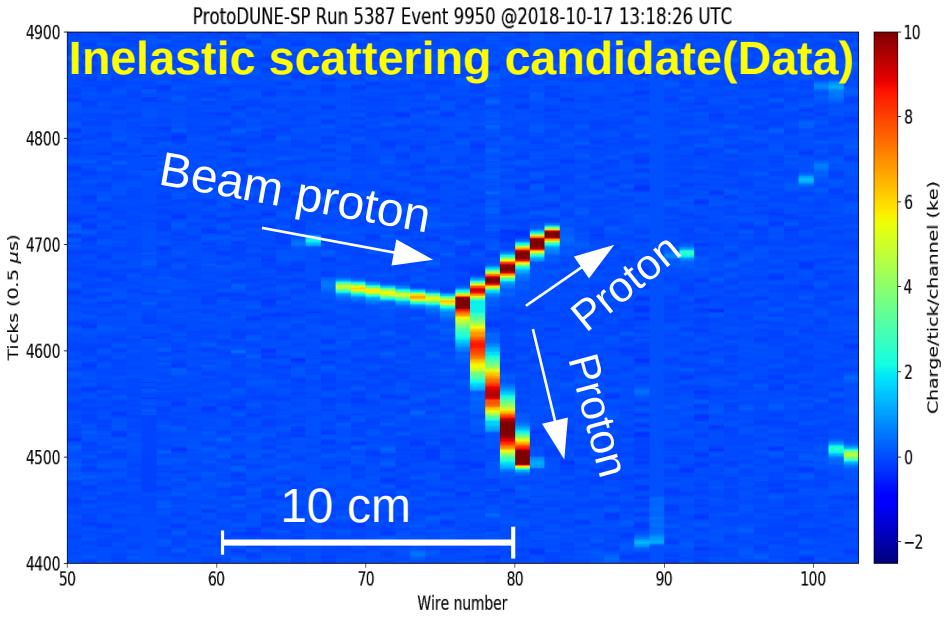
Pandora Event Display (Data)

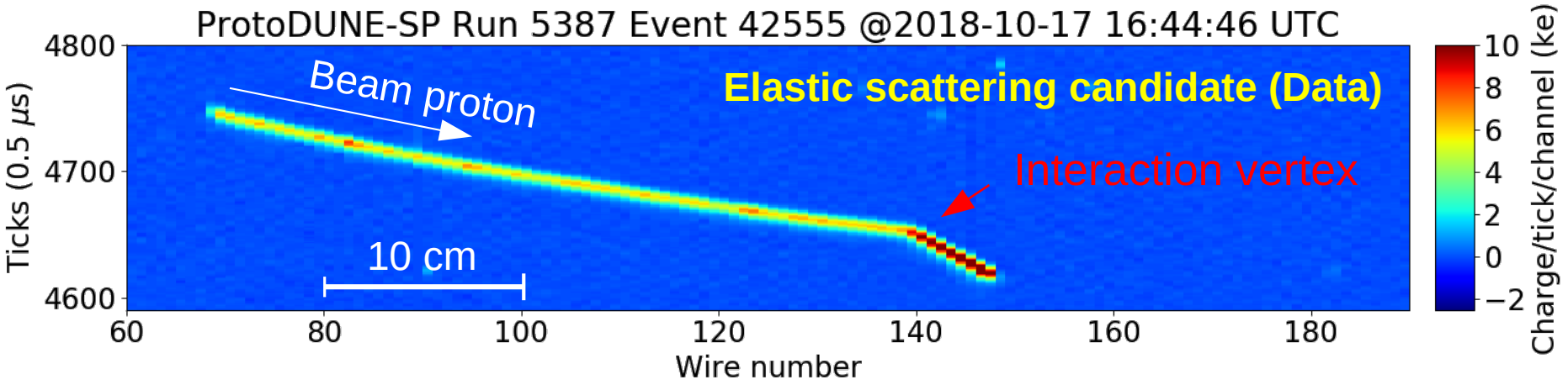
- Particle identification:
  → Use the info from TOF & Cherenkov counters
- Event reconstruction:
  → Use Pandora* multiple algorithms to reconstruct tracks/showers

*Pandora reconstruction algorithms: https://link.springer.com/article/10.1140/epjc/s10052-017-5481-6

Proton Cross Section Channels

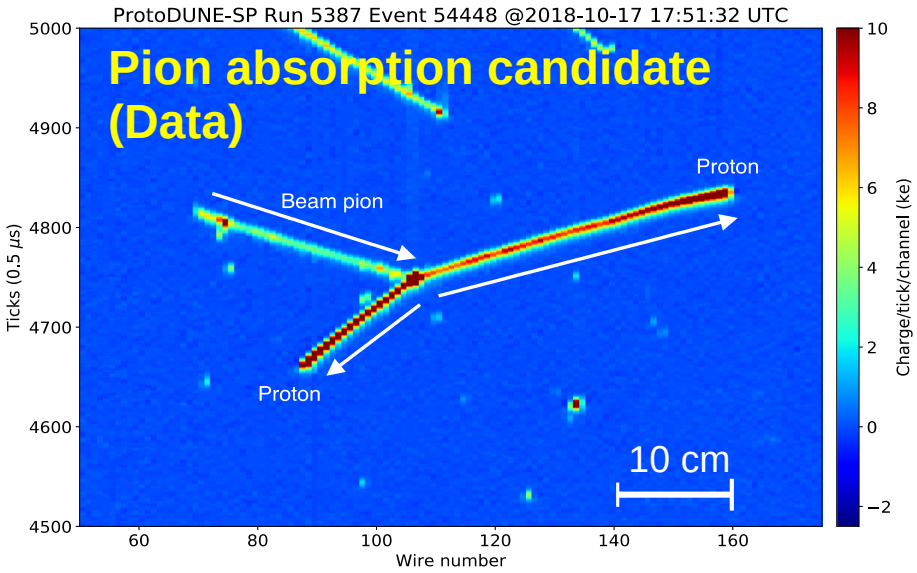
- **Inclusive**
  - **Elastic**
    Nucleus is left in ground state
  - **Inelastic**
    Nucleus is left in an excited state and/or one or more nucleons are knocked out

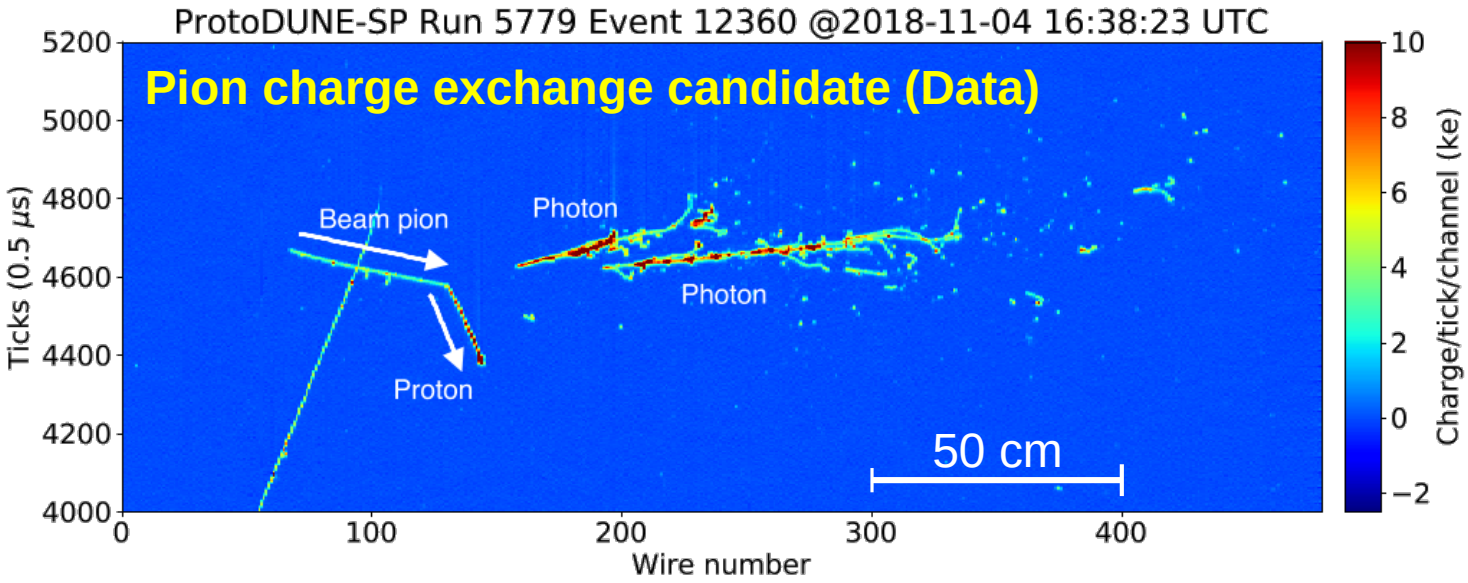




Pion Cross Section Channels

- **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.



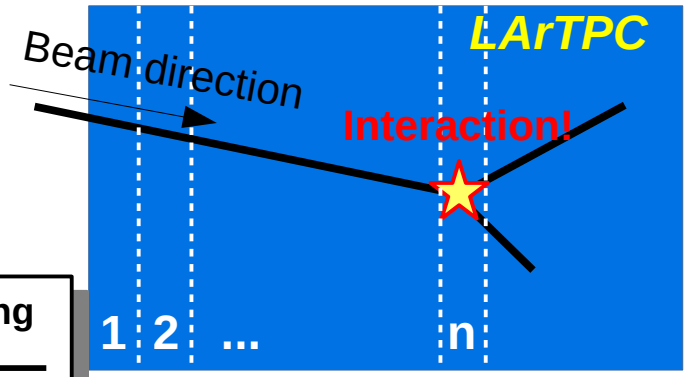


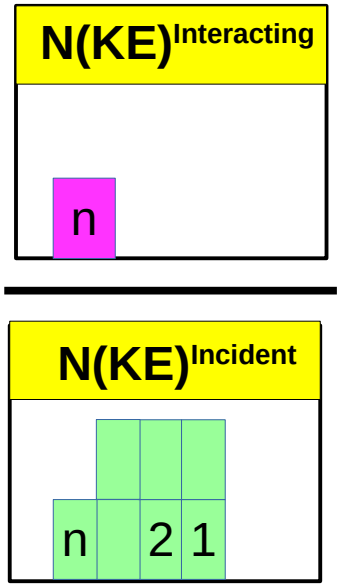
Cross Section Measurements: Methods

- 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:

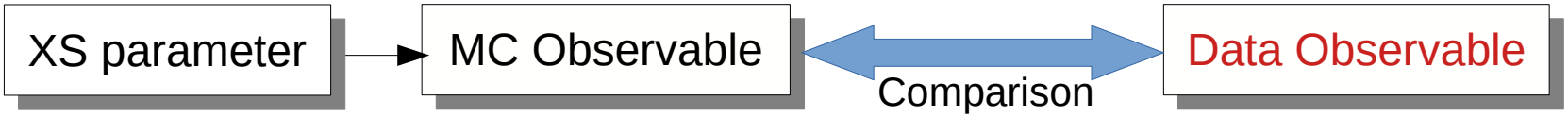
$$XS(KE) = S_f \cdot \frac{N(KE)^{interacting}}{N(KE)^{incident}}$$

S_f ~100 barn for ProtoDUNE-SP





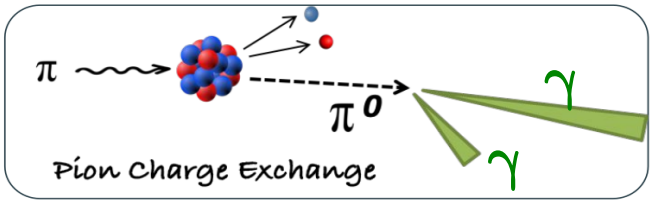
  - Reweighting method
    - Event-by-event weighted observables by changing XS parameters

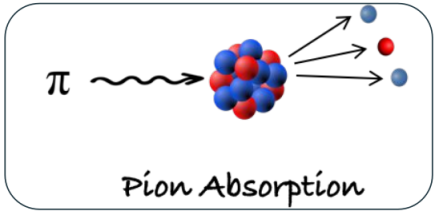


    - Geant4Reweight software package (link)
    - Use for XS systematics estimation & model-dependent XS calculation

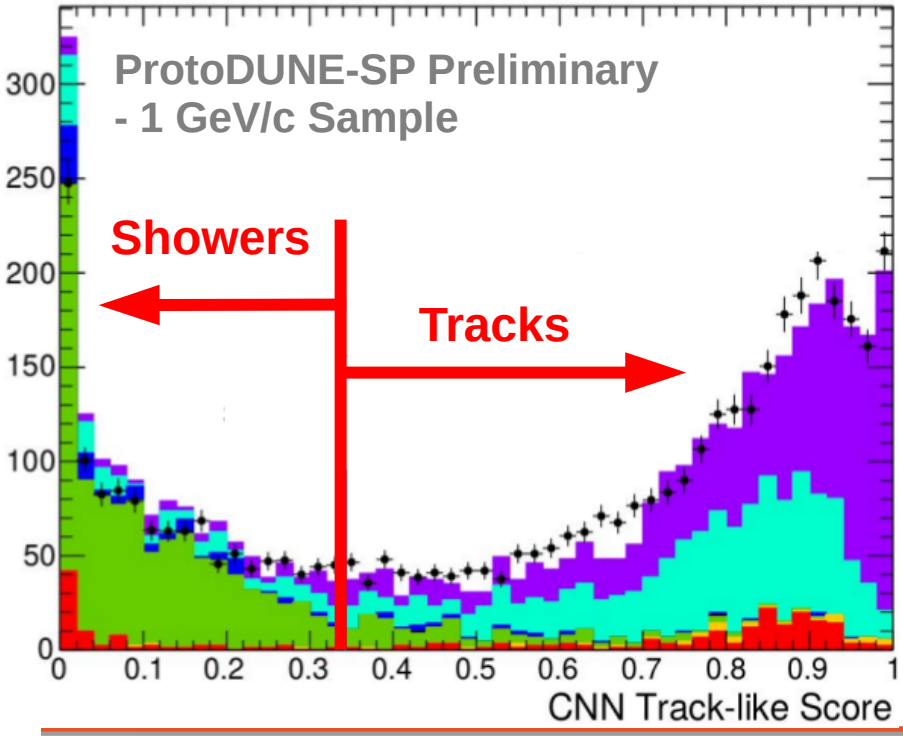
Pion Event Selection

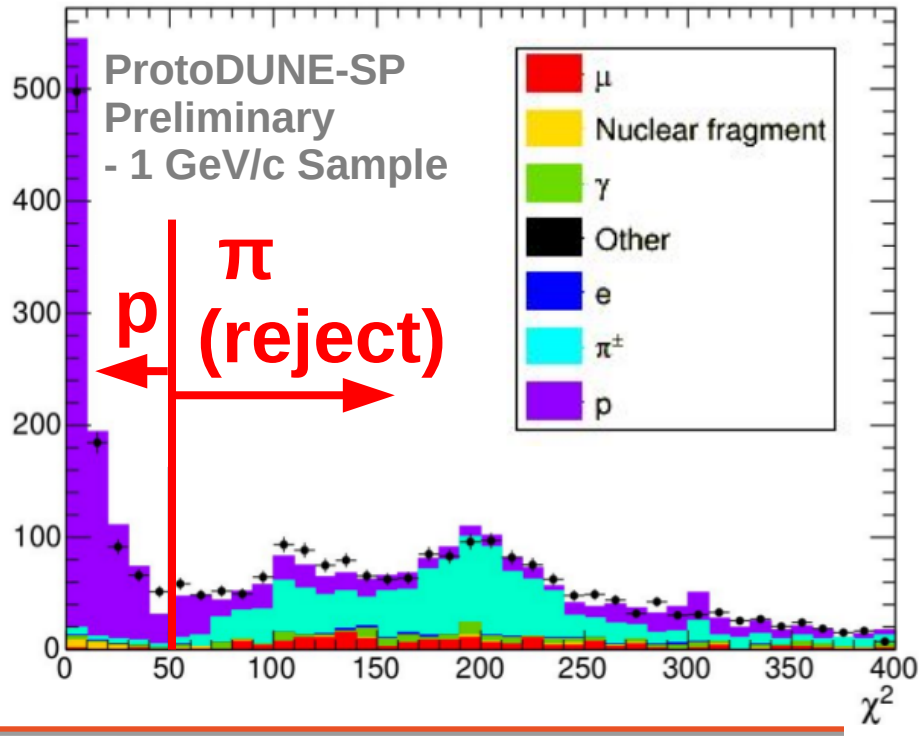
- Signature of CEx+Abs: No charged pions in final state





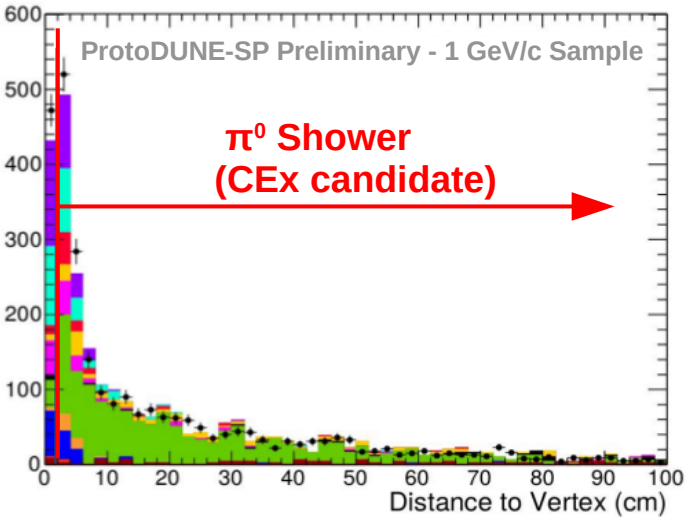
- Event Selection:
  - Daughter track/shower tagging using CNN
  - Reject $\pi^{\pm}$ daughter tracks using χ^2-based PID

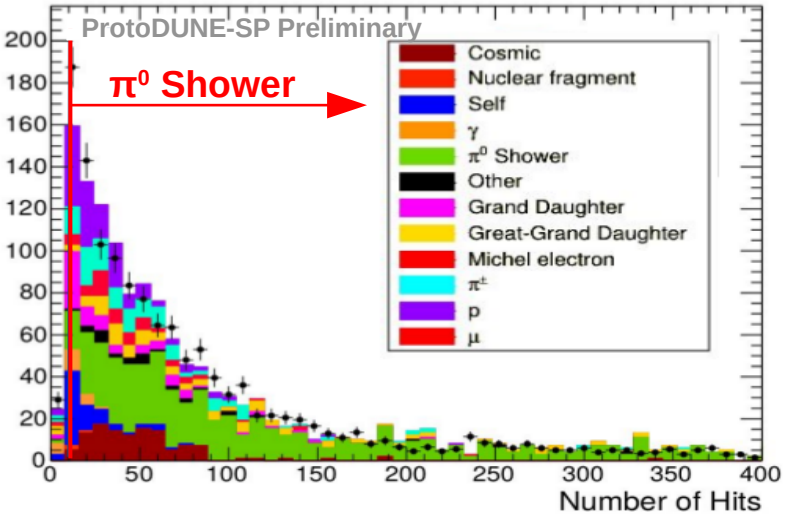




Pion Event Selection: Performance

- 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



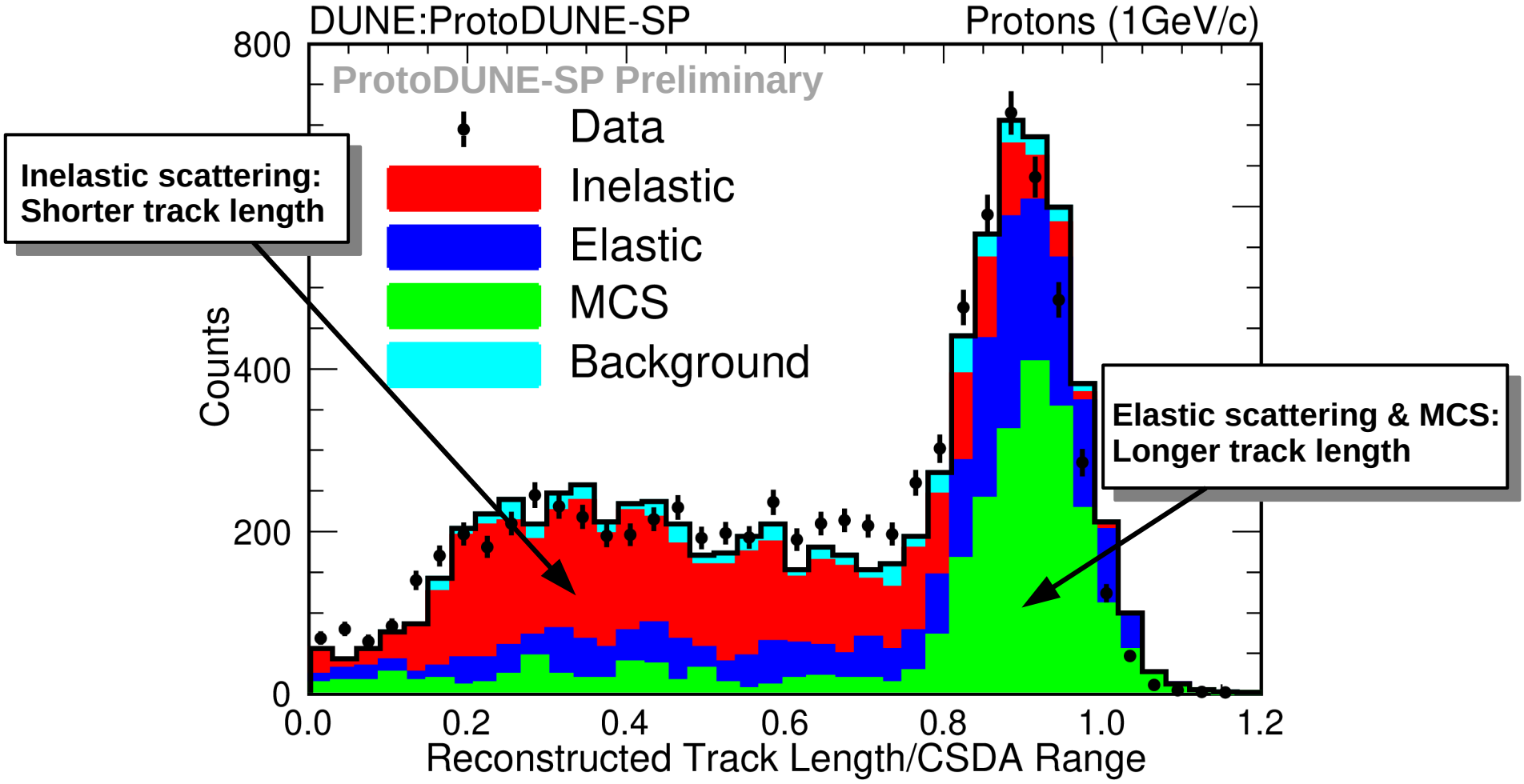


- Efficiency & Purity

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

- Optimization of event selection in progress

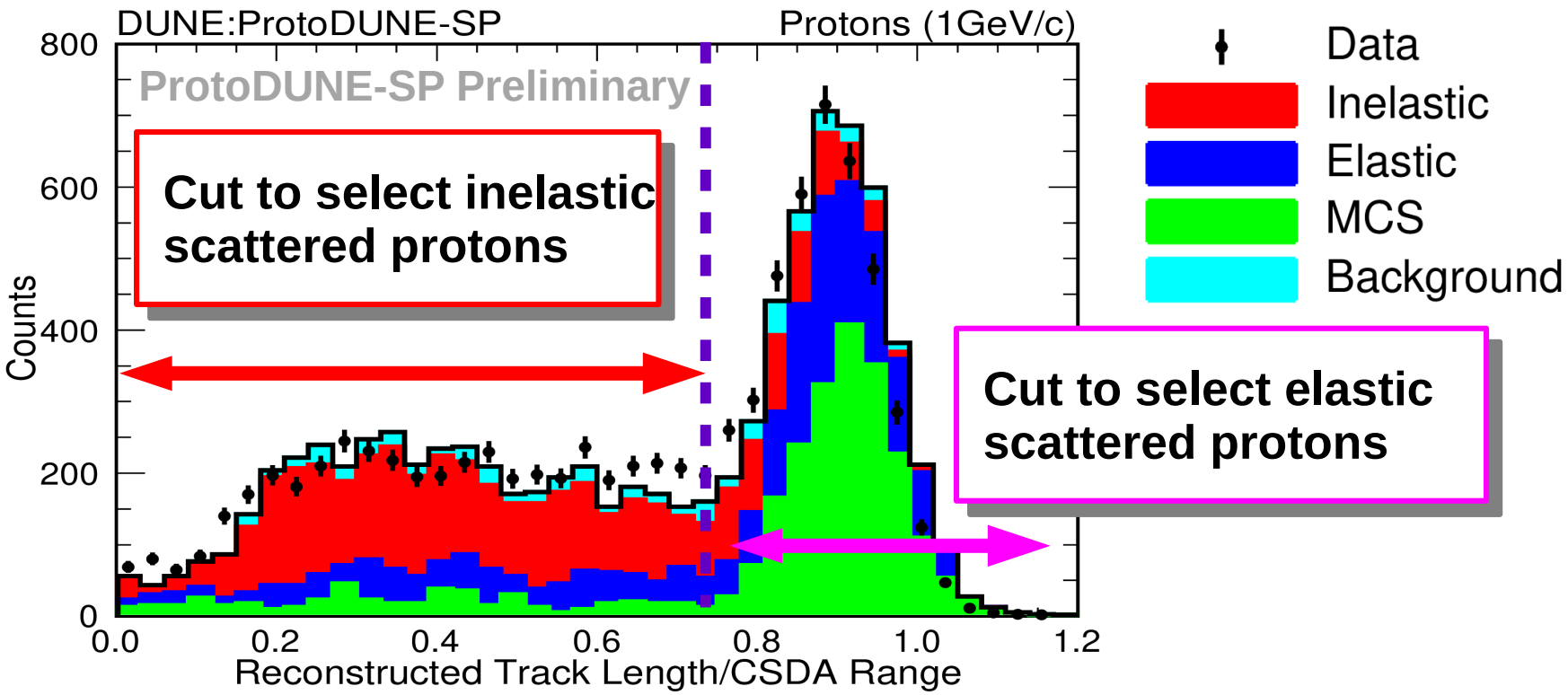
Proton: Elastic/Inelastic Event Selection



- Data & MC in good agreement (χ^2/ndf: 93.4/40)
- Good simulation that we can see elastic & inelastic components clearly

*CSDA range: Average track length of stopping protons

Proton: Event Selection Performance

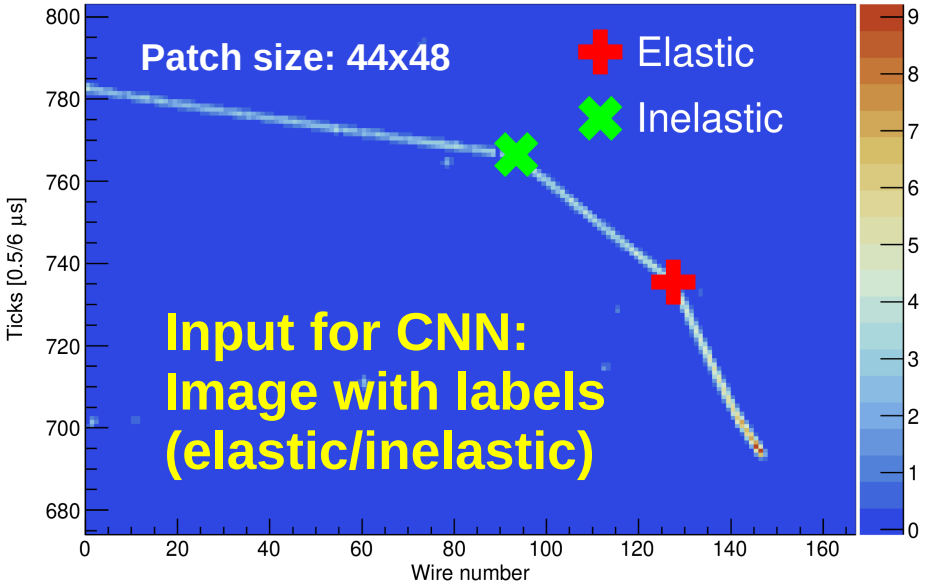


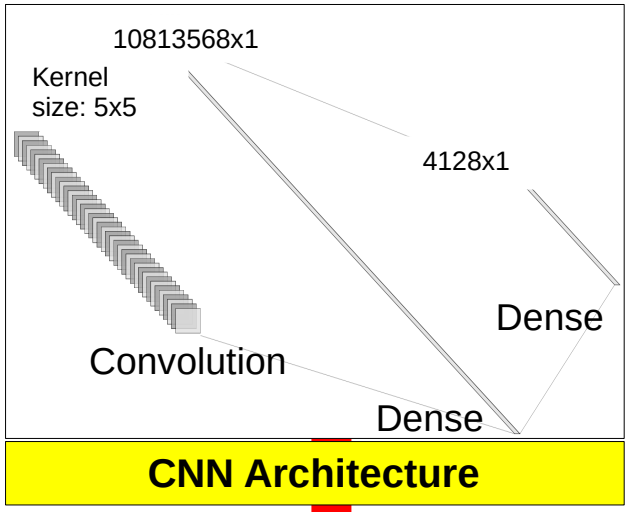
- Benchmark parameter: Efficiency*Purity

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

Proton: Interaction Vertex Identification

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





- Vertex identification efficiency

  Good reco.: Δr(truth-reco)≤5cm

  Inelastic 75 %

  Elastic 31 %

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

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

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
- ProtoDUNE-SP first result on detector performance has published
- Rapid progress in both the pion-Ar and proton-Ar cross section analyses
- 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/

Richie Diurba
Purity monitoring for ProtoDUNE
https://indico.cern.ch/event/868940/contributions/3817045/

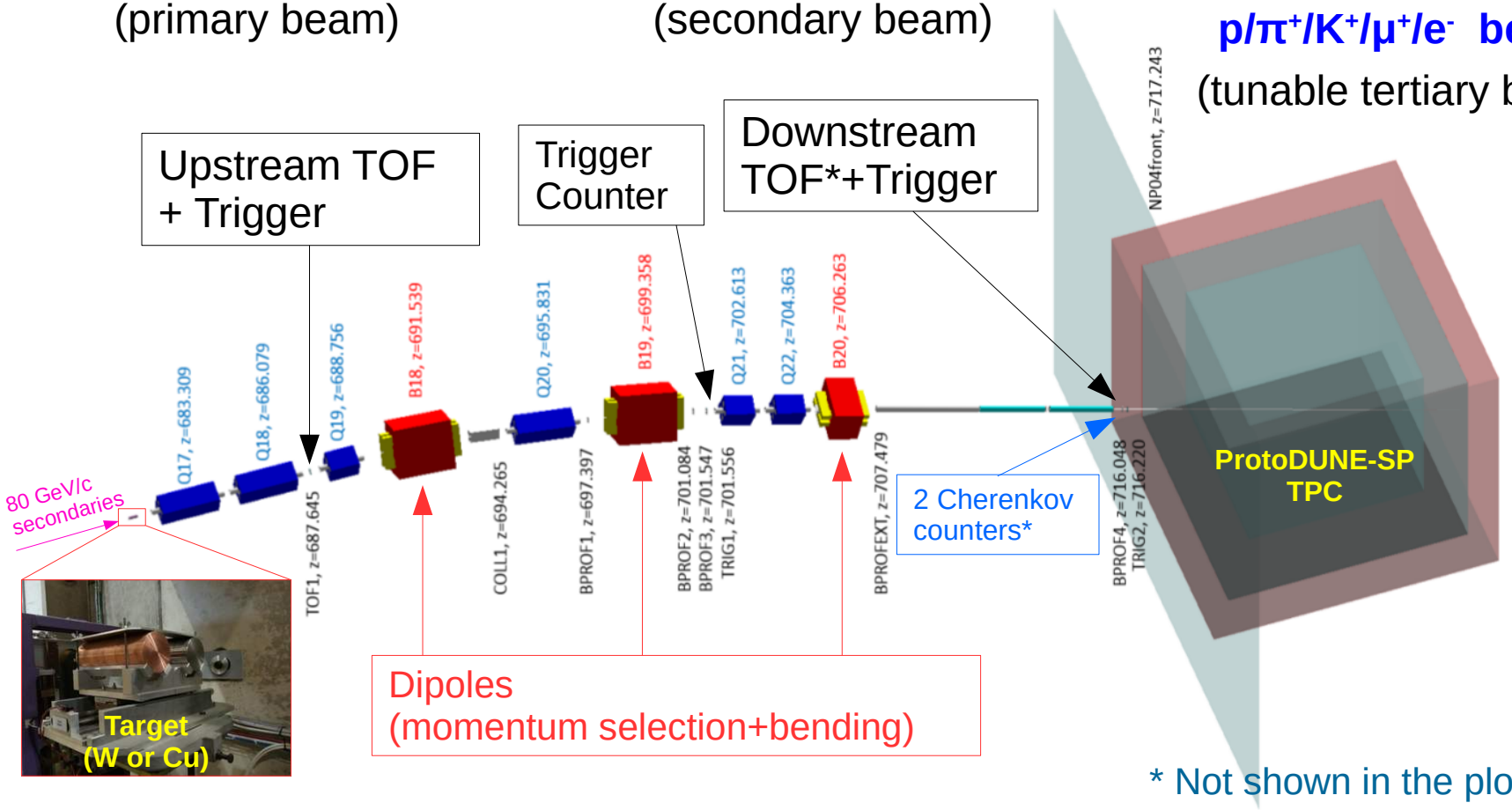
Guillaume Eurin
ProtoDUNE Dual Phase: Design, Construction and First Results
https://indico.cern.ch/event/868940/contributions/3813836/

Backup

ProtoDUNE-SP: Beamline Instrumentation

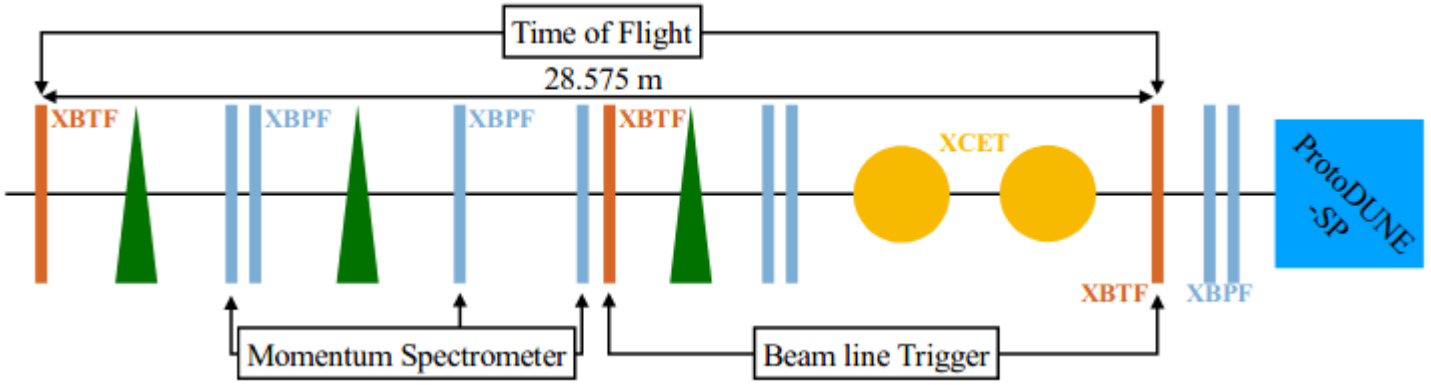
- CERN H4 beamline-extension & Beamline Instrumentation
  - Known particle type (hadrons and electrons) & incident energies

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



* Not shown in the plot

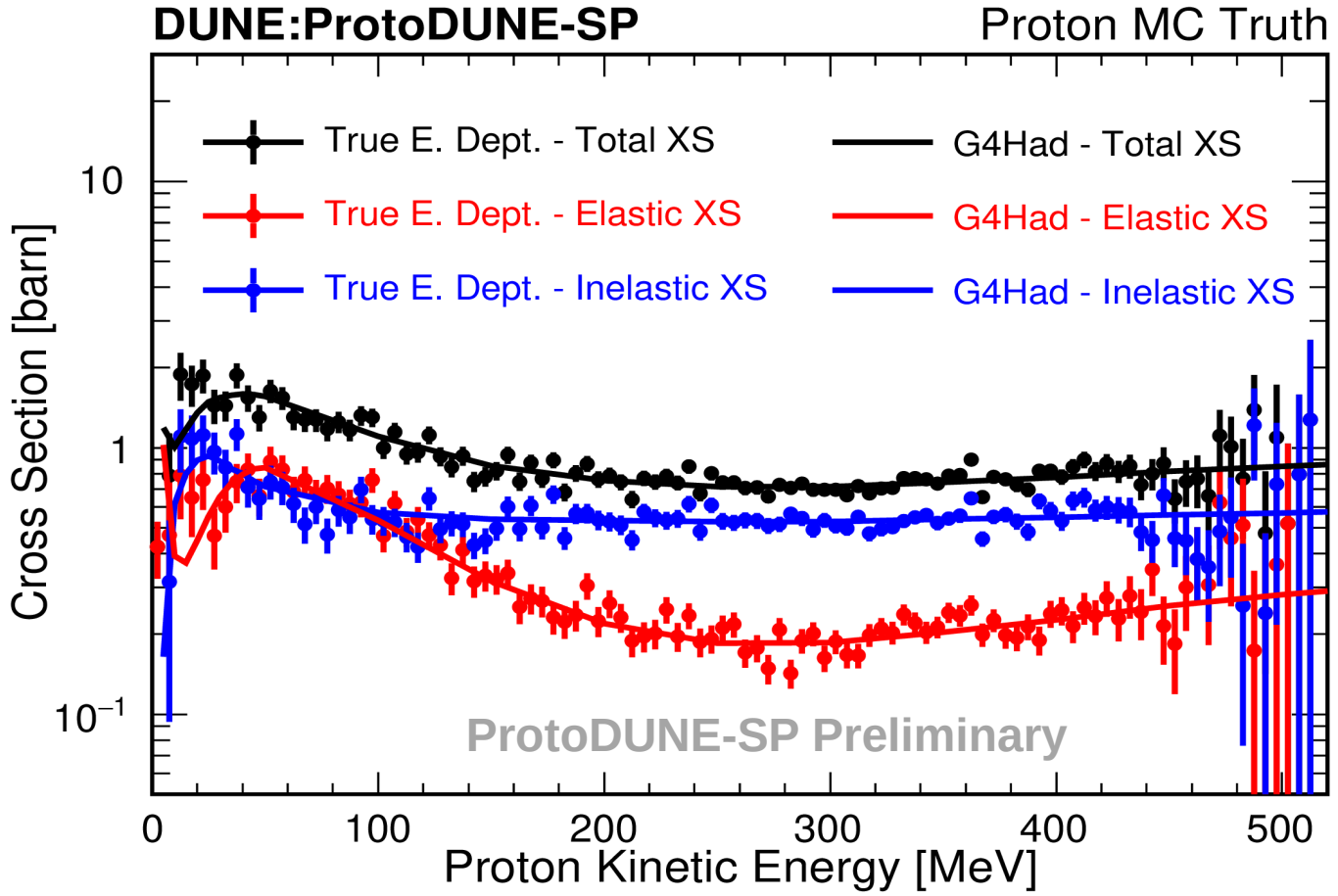
TOF & Cherenkov Info



		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

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