Hadron-argon cross-section measurements at ProtoDUNE and their implications for DUNE

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University of Chicago

Aug. 14, 2025 @ SLAC FPD Seminar

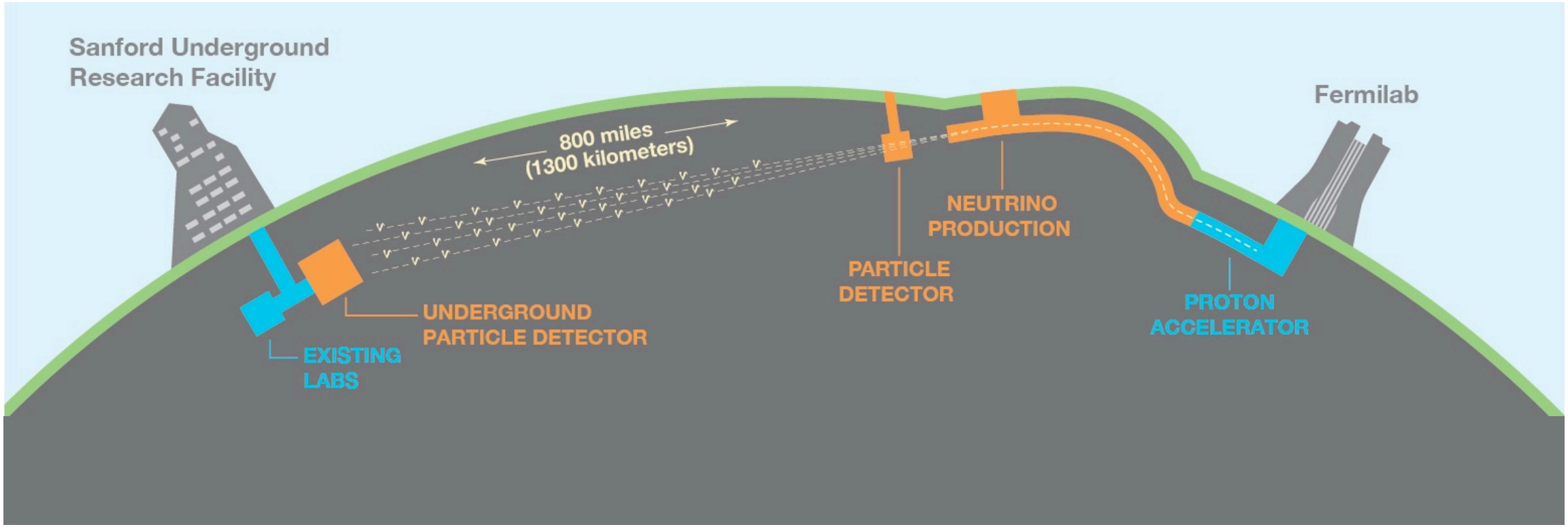
DEEP UNDERGROUND NEUTRINO EXPERIMENT

NATIONAL ACCELERATOR LABORATORY

Deep Underground Neutrino Experiment (DUNE)

JINST 15 (2020) 08, T08008

- DUNE is a flagship neutrino experiment for the next decade and beyond.



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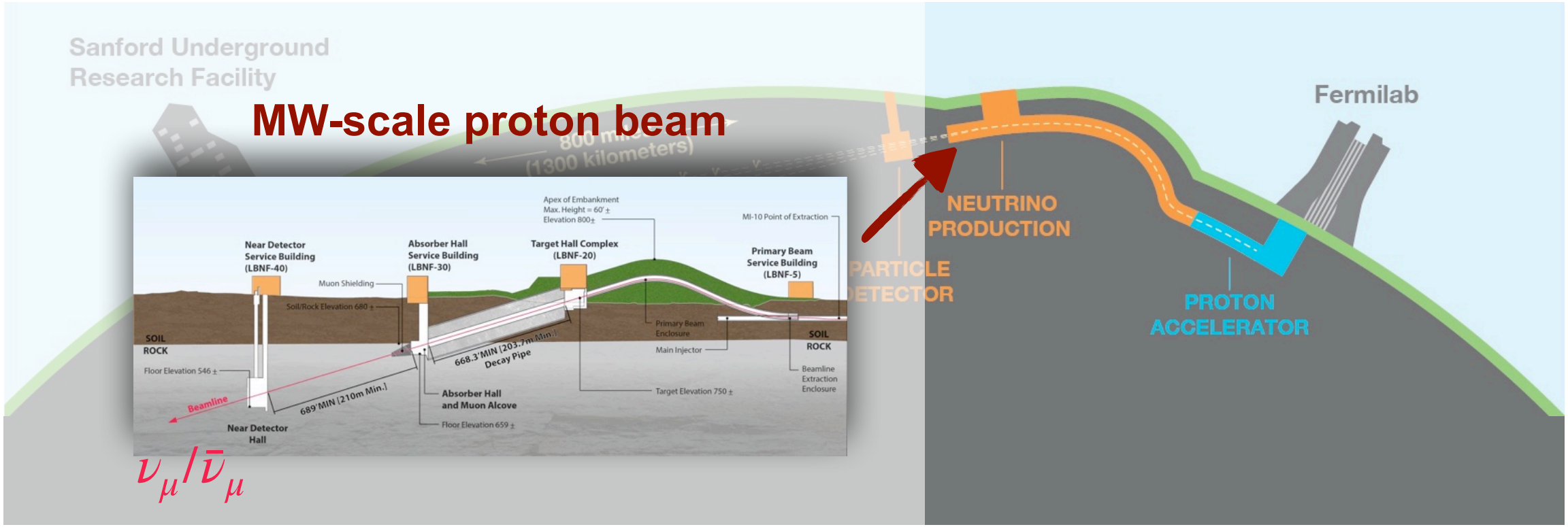

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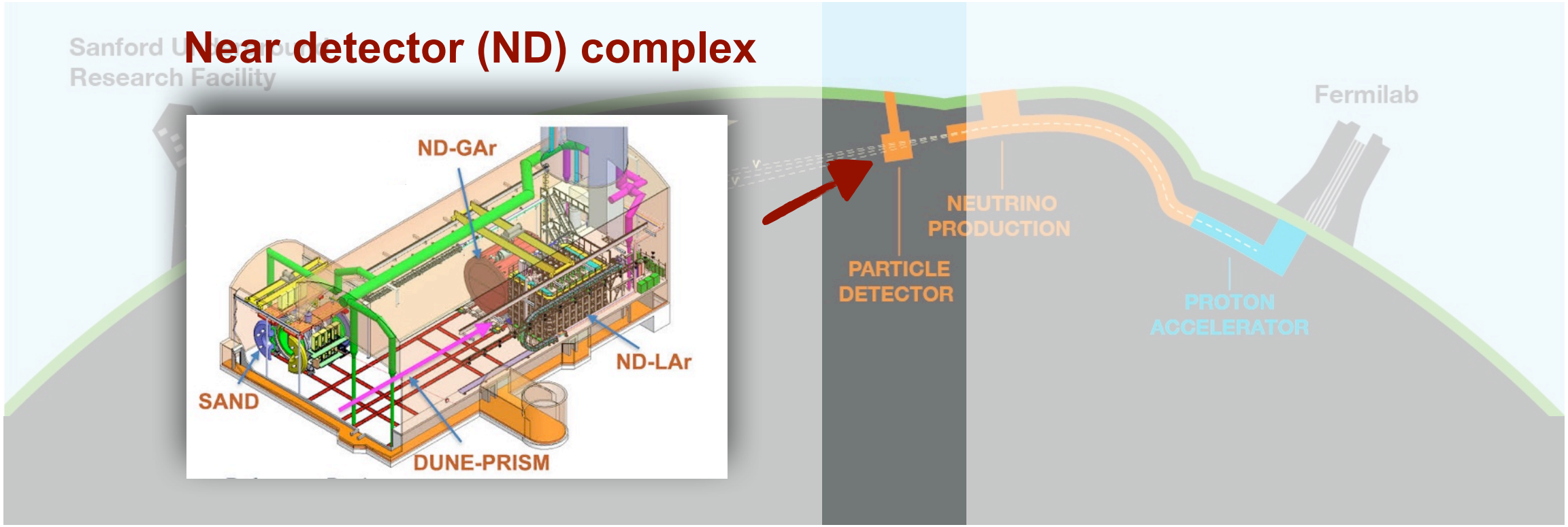

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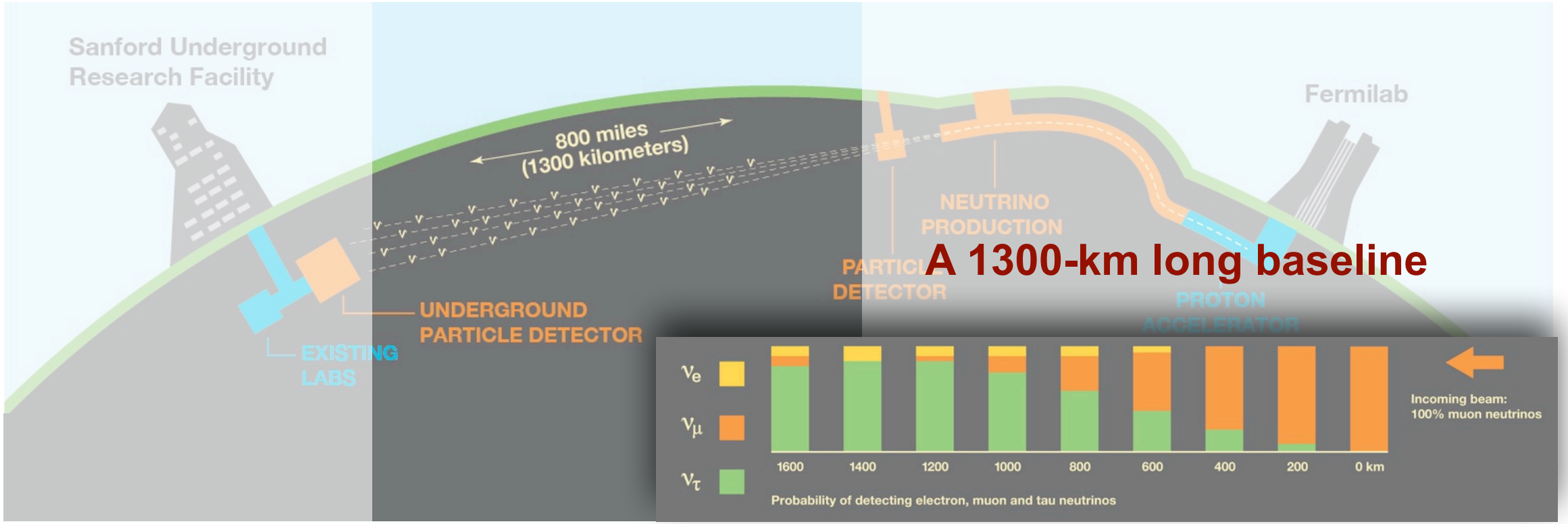

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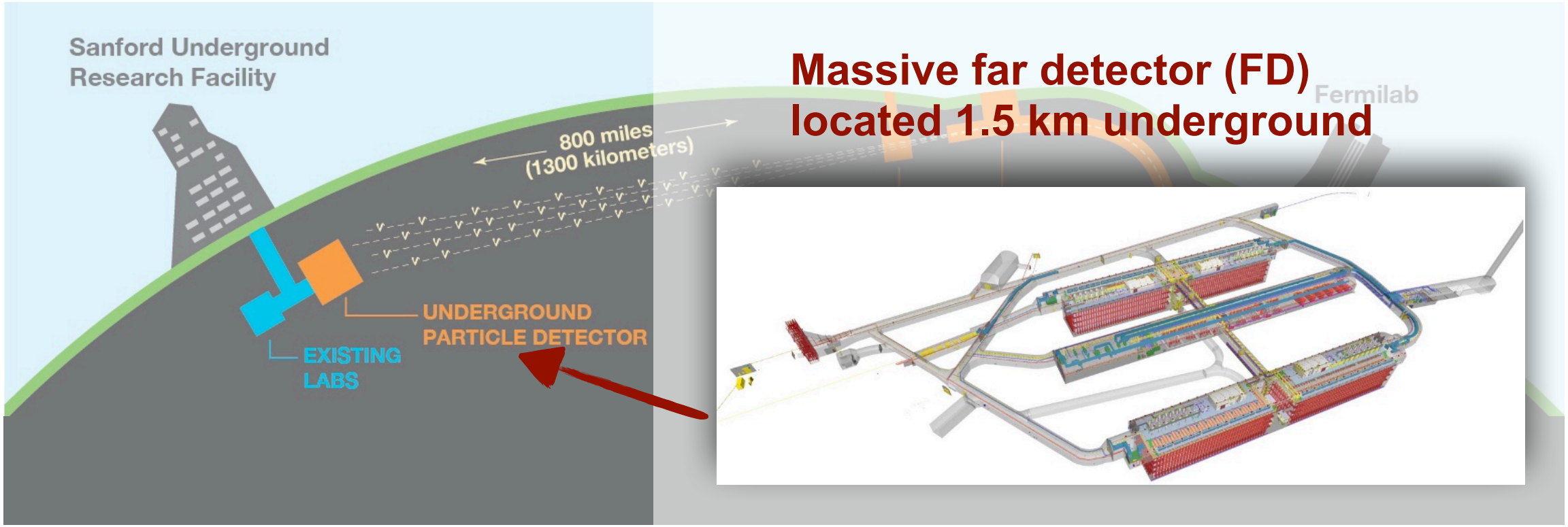

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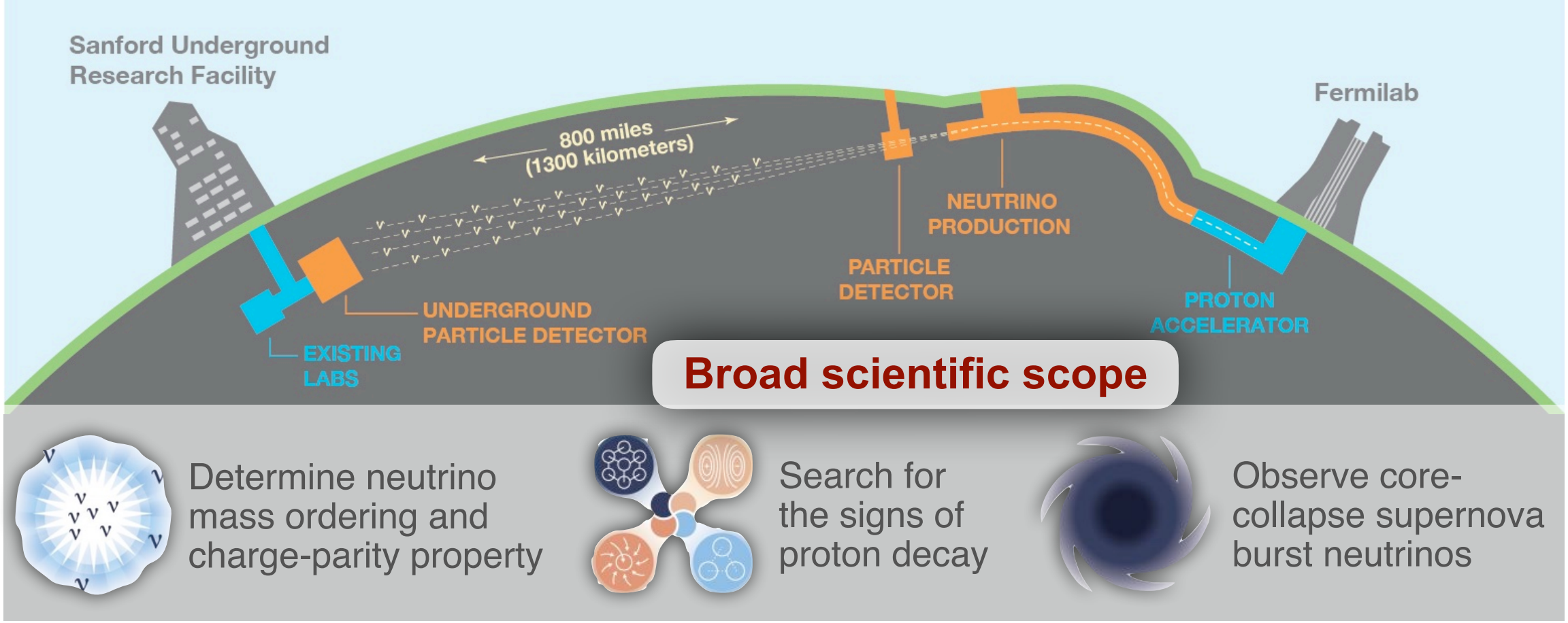
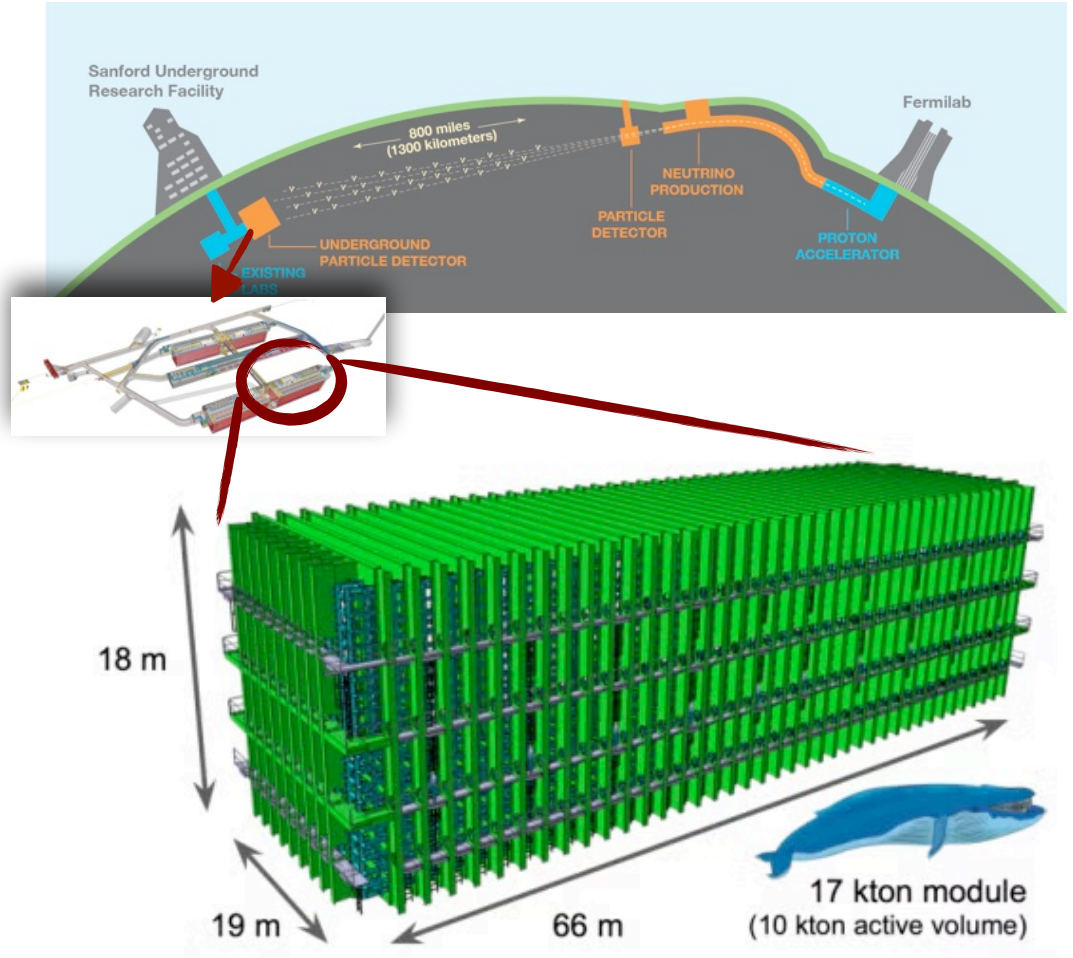
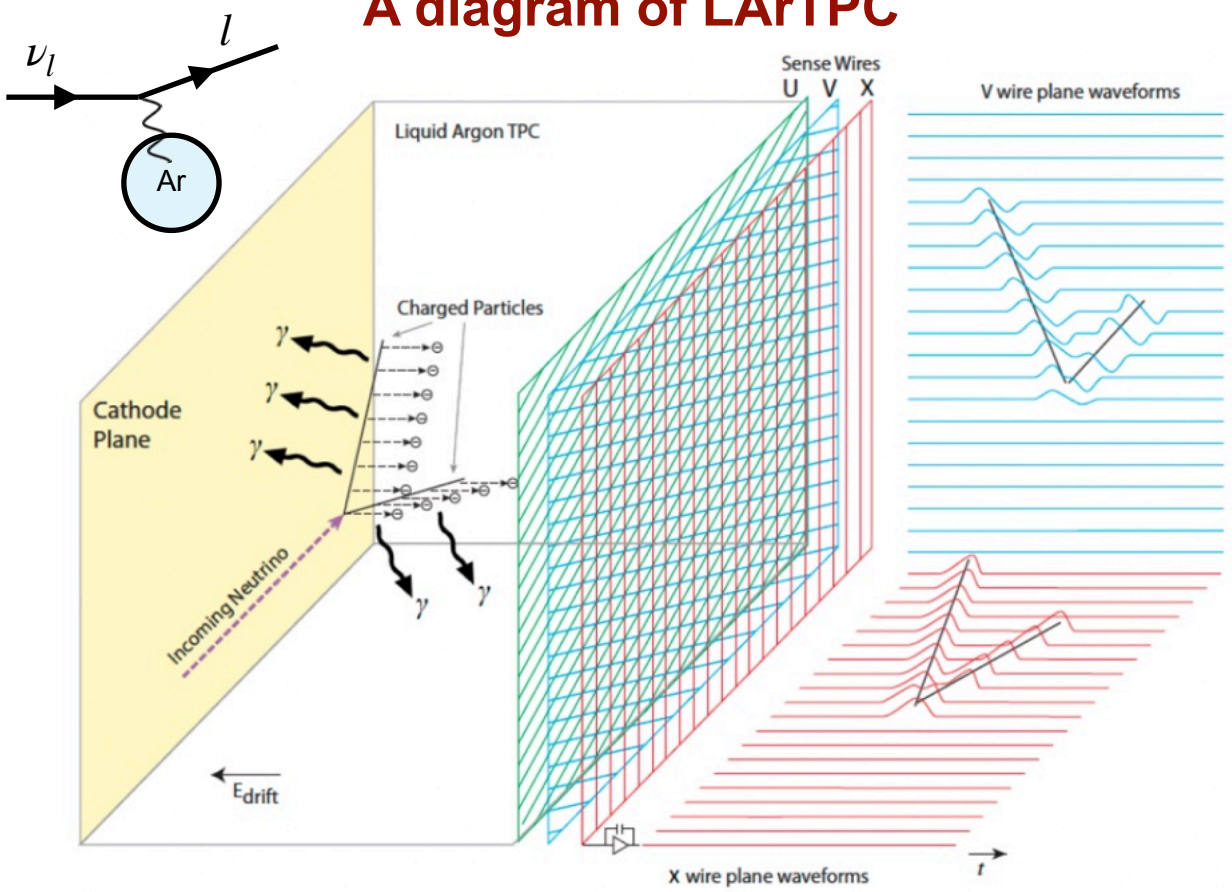


Liquid argon time projection chamber (LArTPC)

- DUNE FD employs ten-kiloton-scale LArTPCs to detect neutrinos.



A diagram of LArTPC



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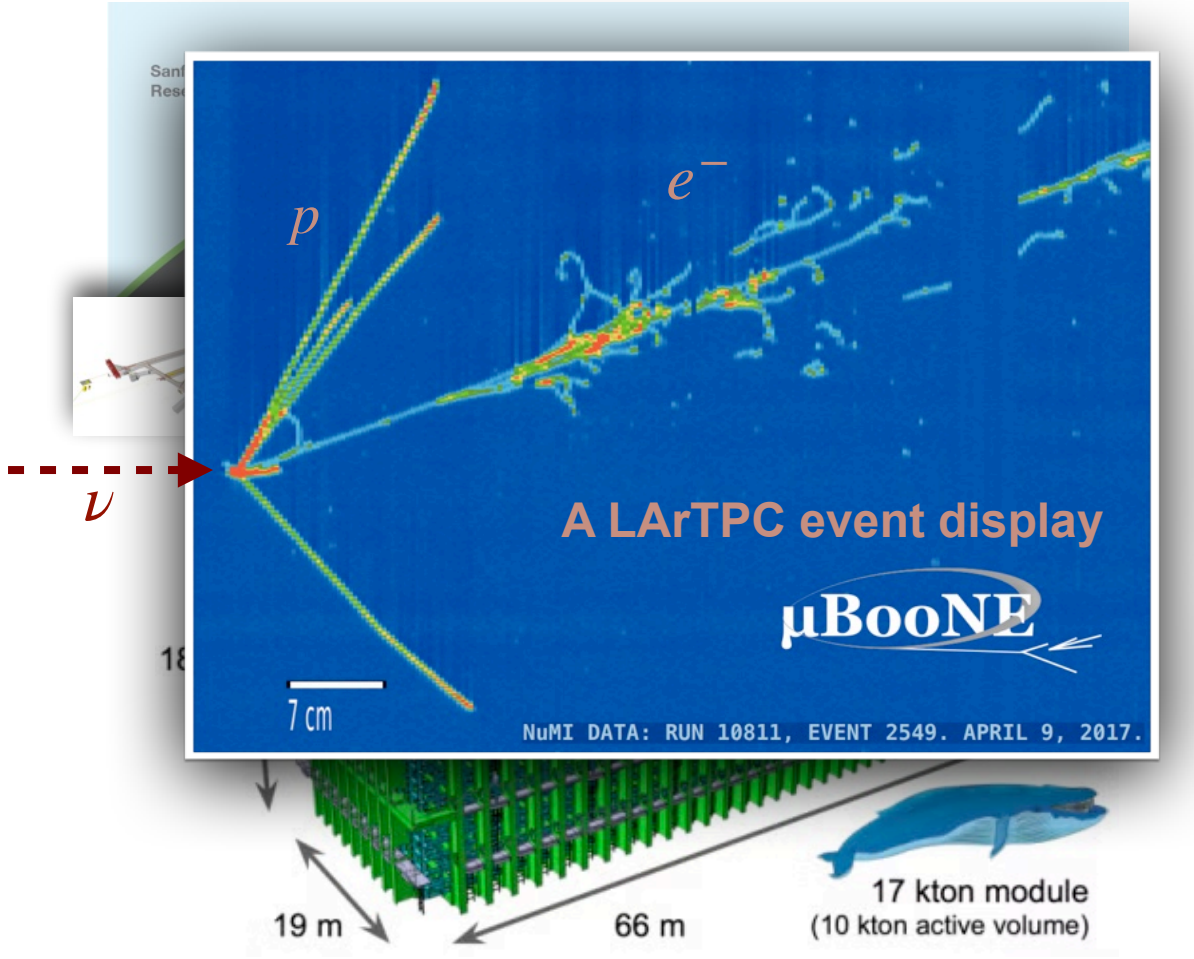

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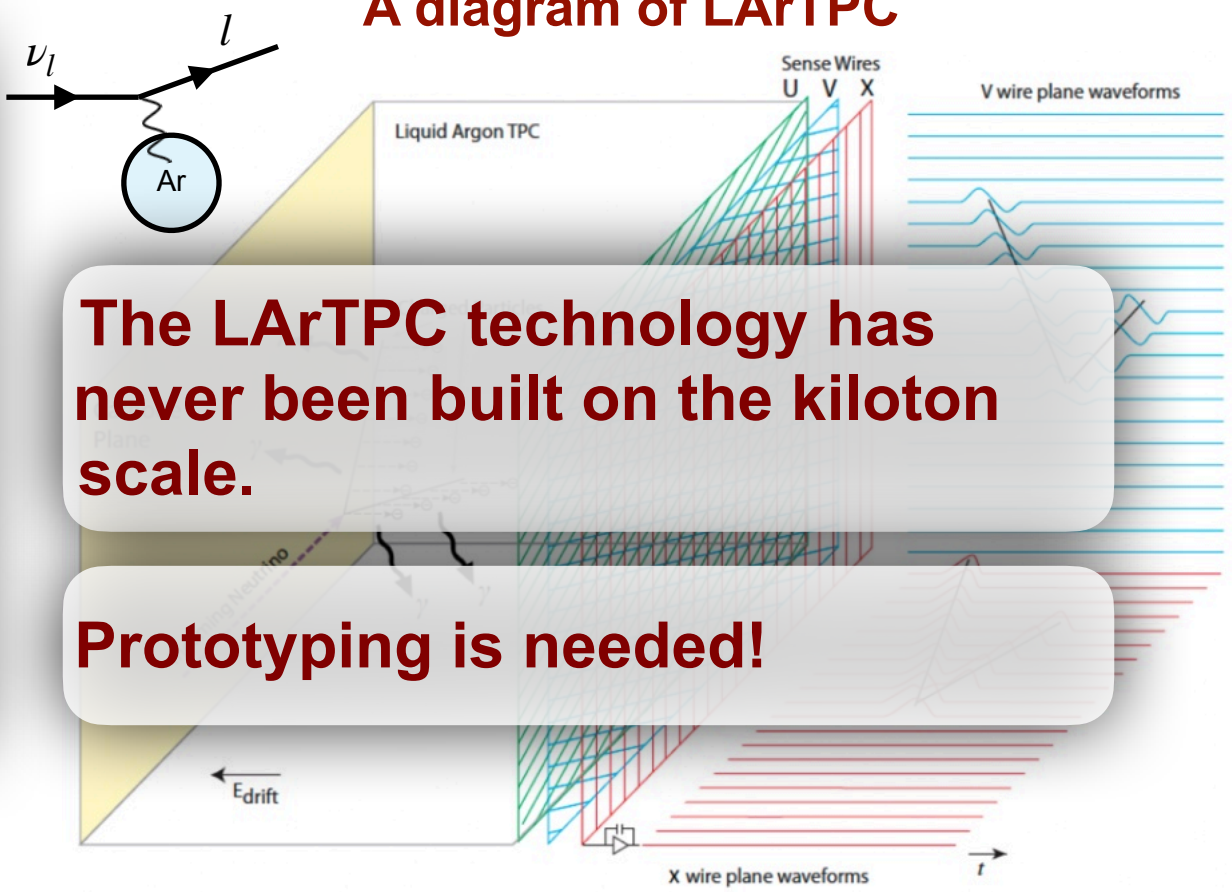


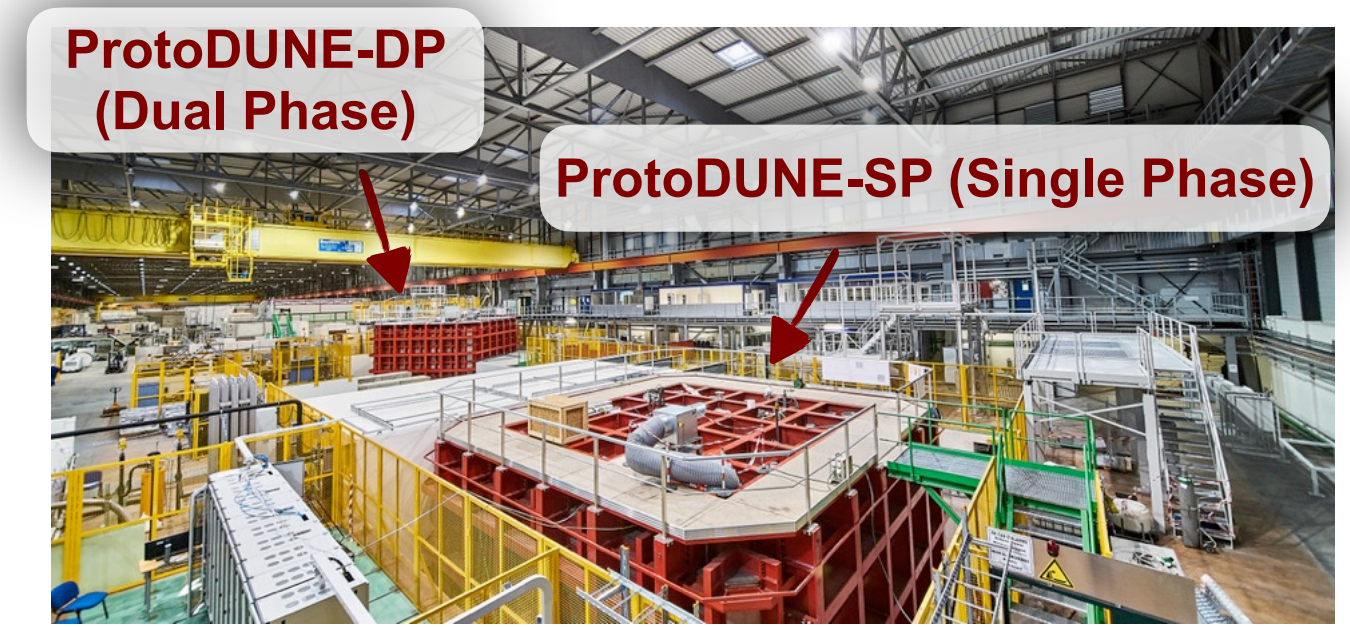
The LArTPC technology has never been built on the kiloton scale.

Prototyping is needed!

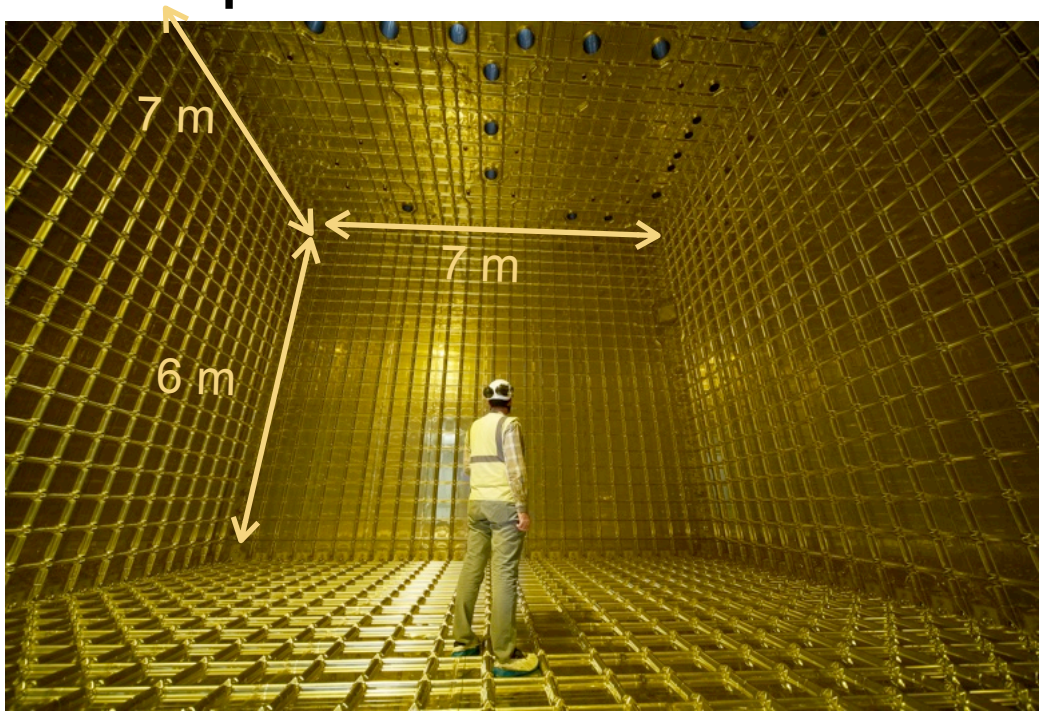
ProtoDUNE—prototypes for DUNE FD

JINST 15 (2020) 12, P12004

- Kiloton-scale prototype detectors were built at CERN.
  - Run 1 operated between 2018 and 2020 comprises two detectors, each containing 770-ton liquid argon.



A picture inside ProtoDUNE



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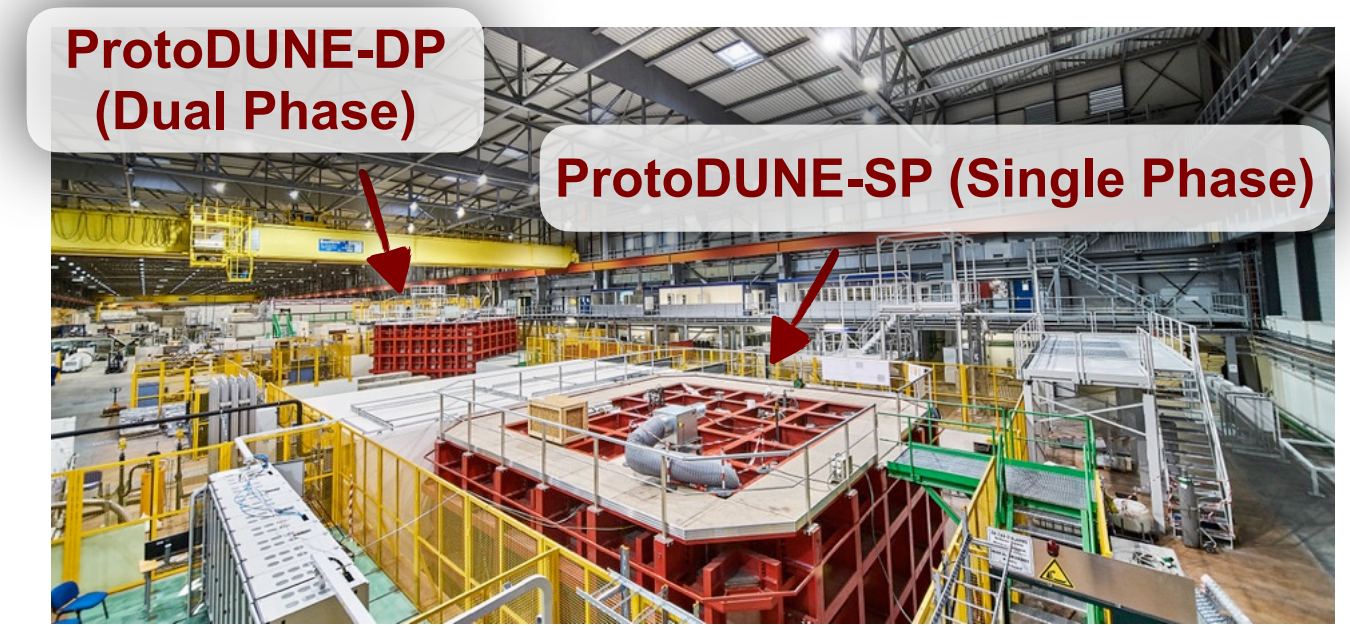
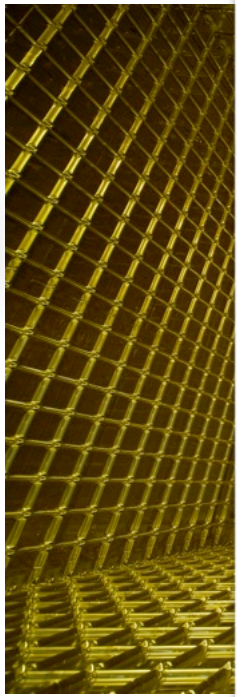
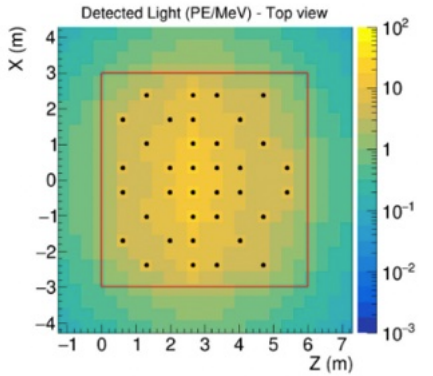


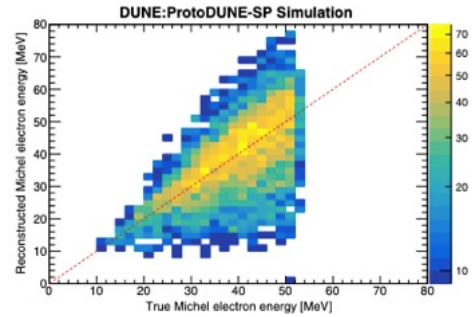


ProtoDUNE—prototypes for DUNE FD

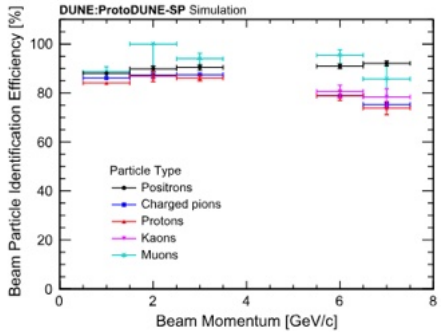
- ProtoDUNE aims to validate construction techniques and operational performance for future DUNE FD.
  - More than ten papers have been published by ProtoDUNE.
- ProtoDUNE also has a physics purpose: to study the liquid argon response to charged particles of different types and energies.
  - First physics result published:
    First measurement of the total inelastic cross section of positively charged kaons on argon at energies between 5.0 and 7.5 GeV
    PRD 110, 092011



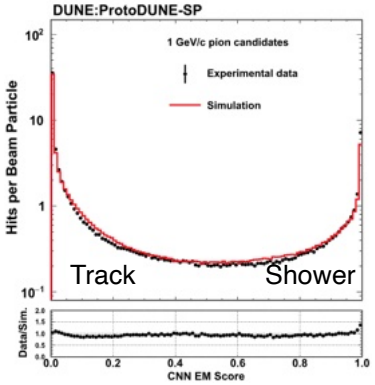
Map of detected light EPJC 82 7, 618



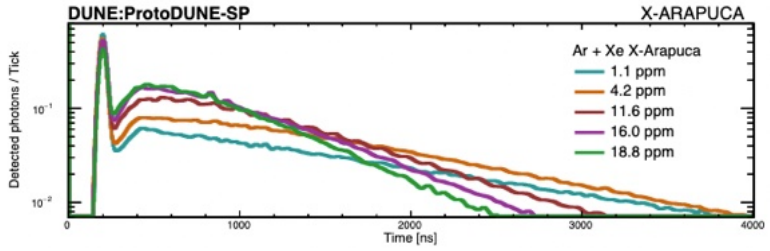
Michel electron Ereco vs Etrue PRD 107, 092012



Beam identification efficiency EPJC 83 7, 618



CNN score for pions EPJC 82 10, 903

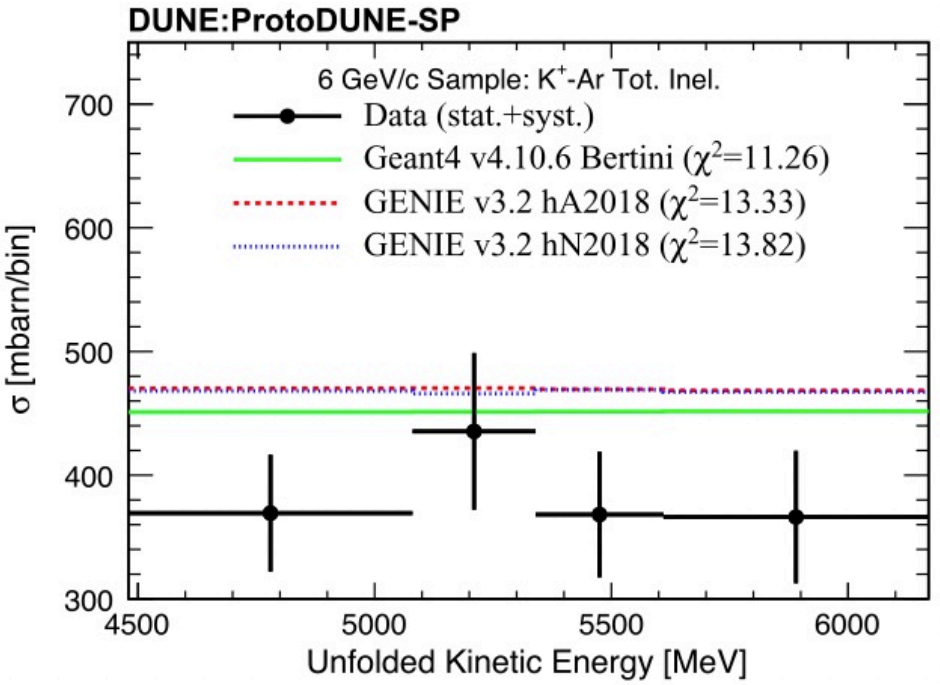


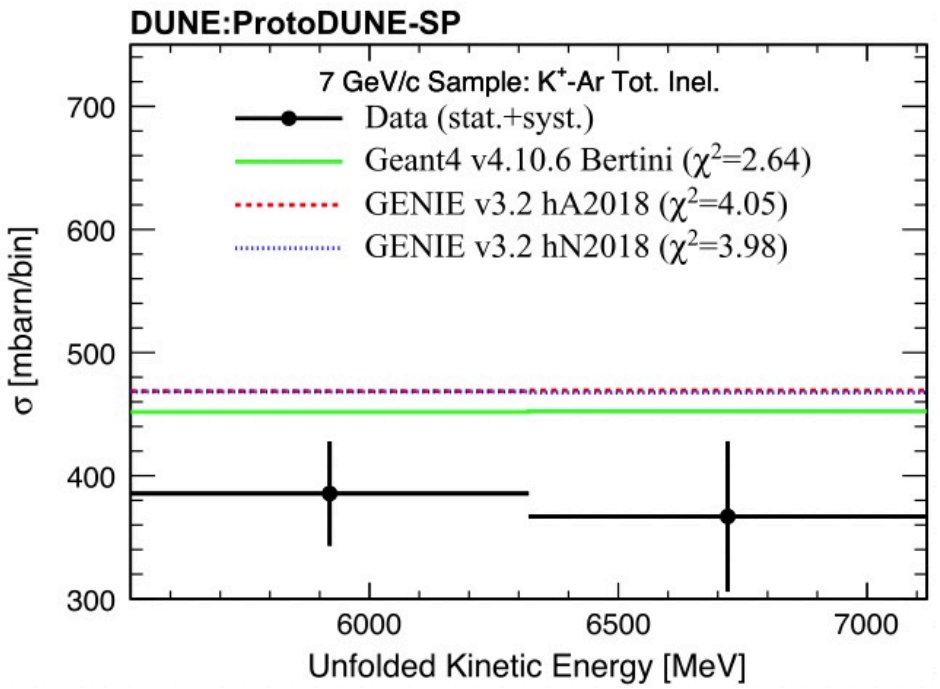
Waveform changing with xenon concentration
JINST 19, P08005

First physics result by DUNE!

Phys.Rev.D 110 (2024) 9, 092011
(leading analyzer: R. Diurba)

- The K^+—Ar total inelastic (inclusive) cross section is measured for the first time, with the kaon kinetic energy between 5 and 7.5 GeV.

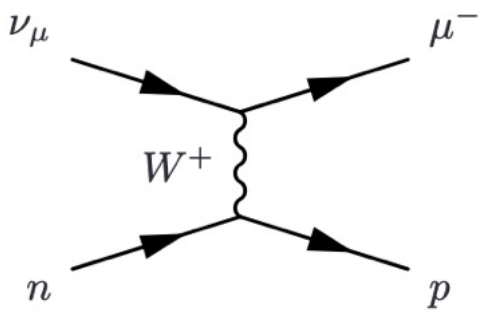




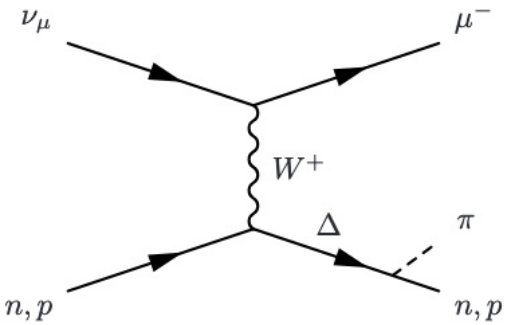
Tension between model predictions and the measured cross sections.

Neutrino-argon interaction

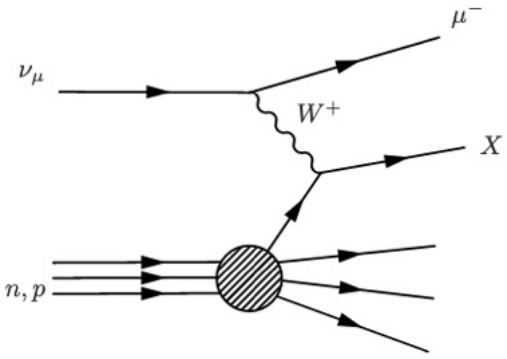
- DUNE detects neutrinos by their interactions with argon.



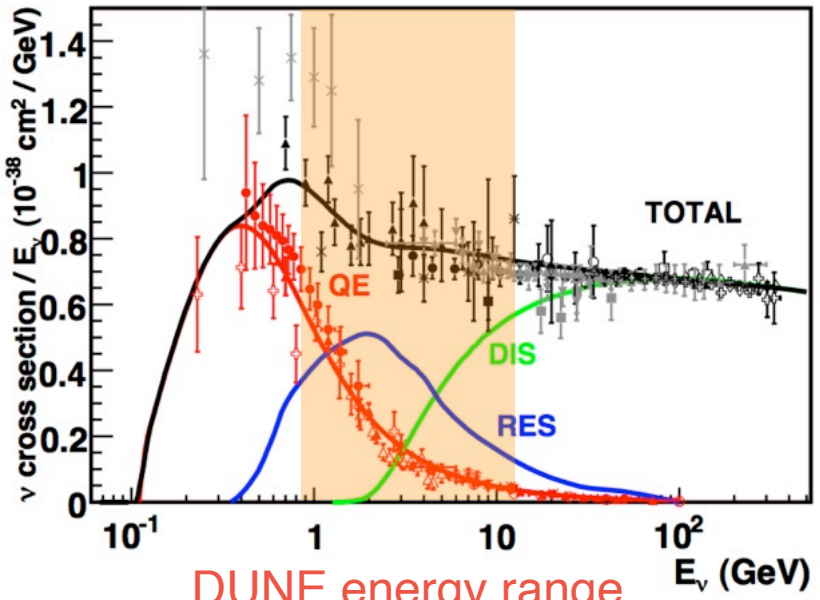
Quasi-elastic scattering
(QE)



Resonant pion production
(RES)



Deep inelastic scattering
(DIS)



DUNE energy range

- Theoretical calculations on neutrino-nucleon interactions are challenging due to the nucleon's internal structure.
  - Experimental measurements are essential for refining models.

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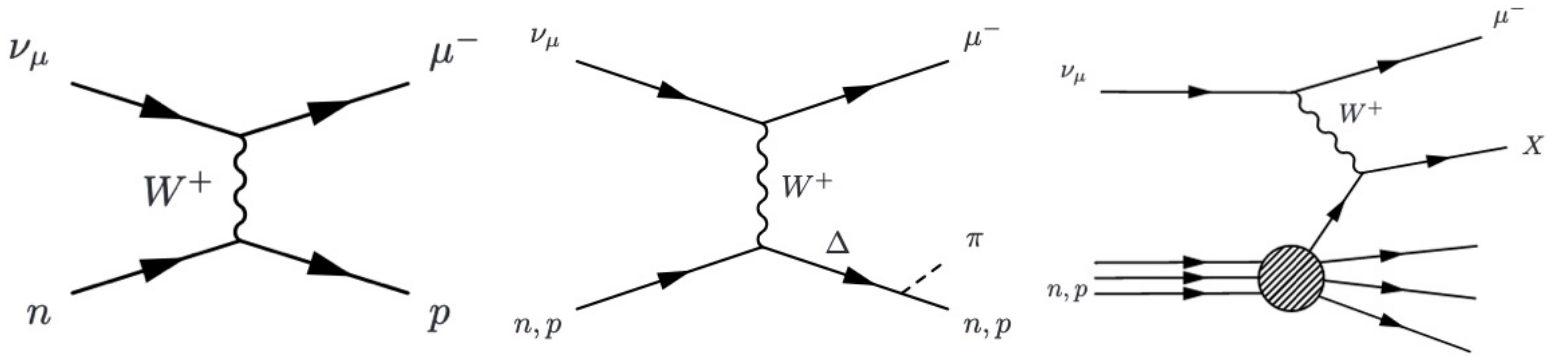
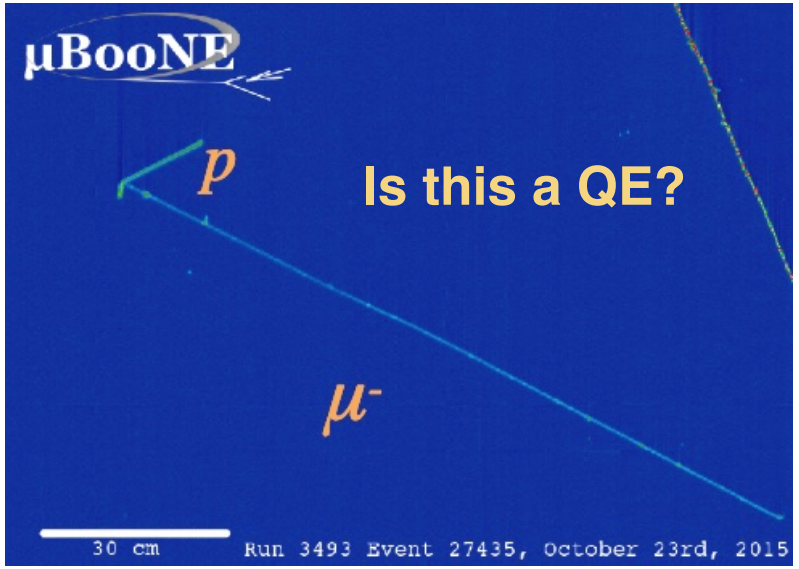


Quasi-elastic scattering **(QE)**

Resonant pion production **(RES)**

Deep inelastic scattering **(DIS)**



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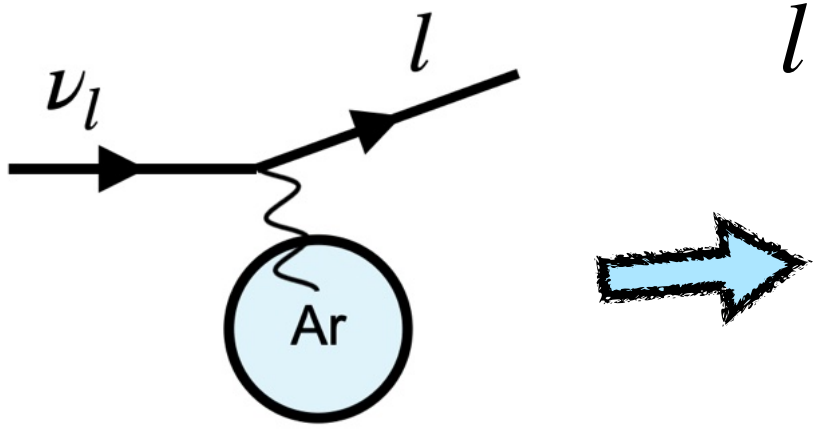
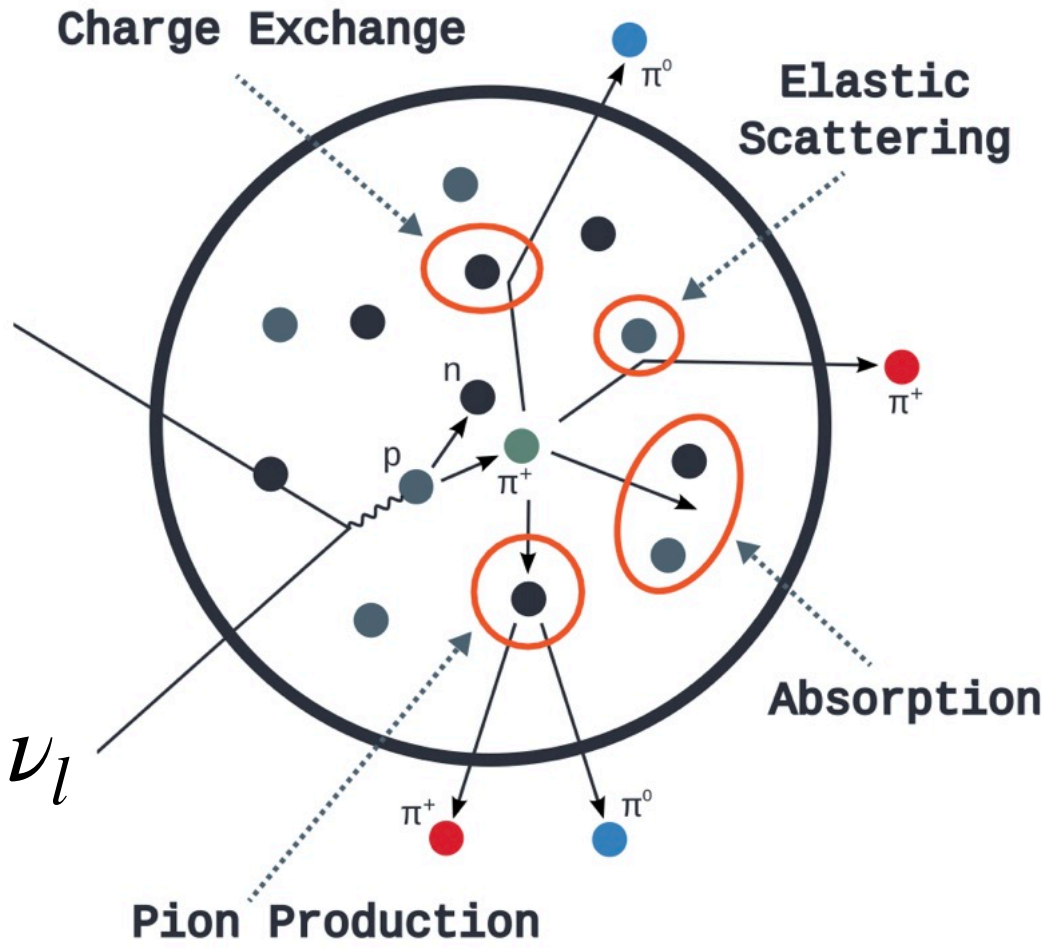
Final-state interactions (FSI)

- The initially produced hadrons may undergo further scattering with nucleons before exiting the nucleus. This effect is referred to as FSI.



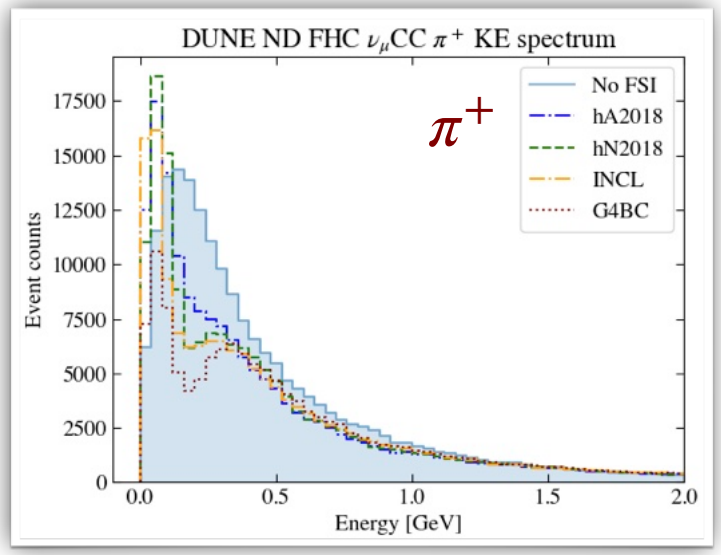


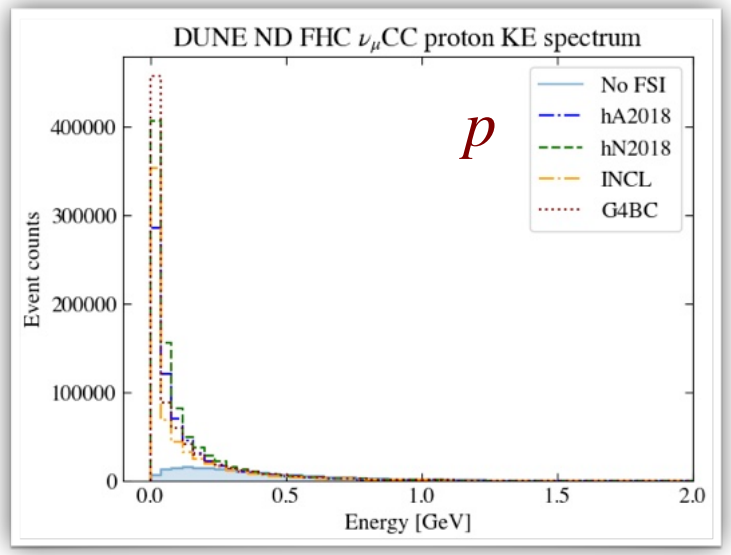
FSI alters final-state kinematics and even changes types of detected particles.

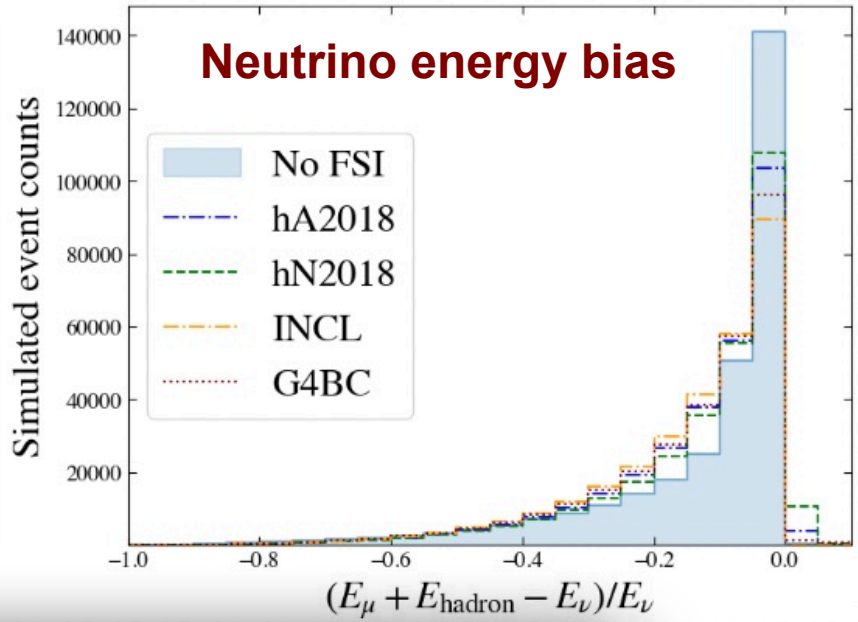
Final-state interactions (FSI)

- FSI is a major source of systematic uncertainty in current neutrino oscillation experiments (e.g. T2K, NOvA).
- In DUNE energy range, ~80% pions and ~50% protons undergo FSI.

Phys.Rev.D 104 (2021) 5, 053006





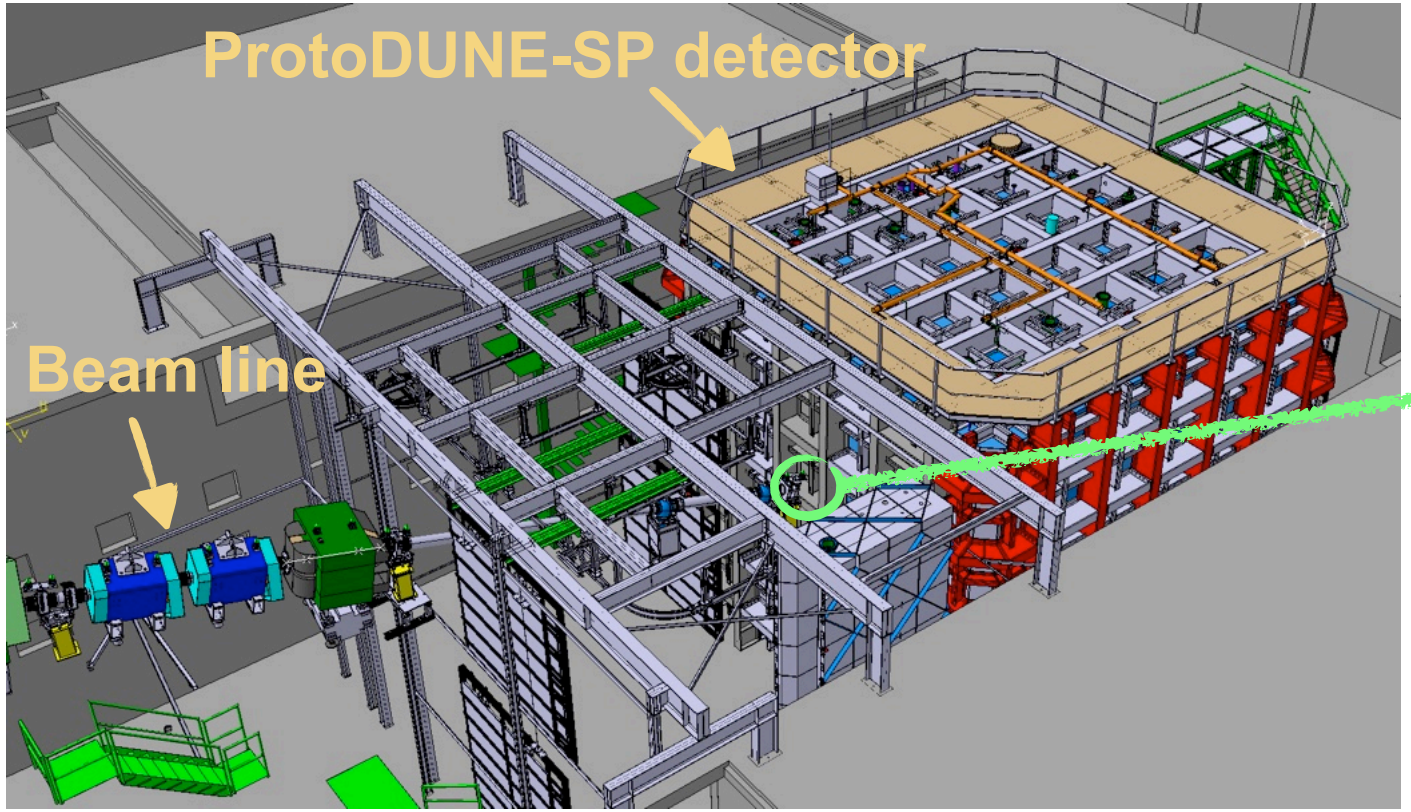


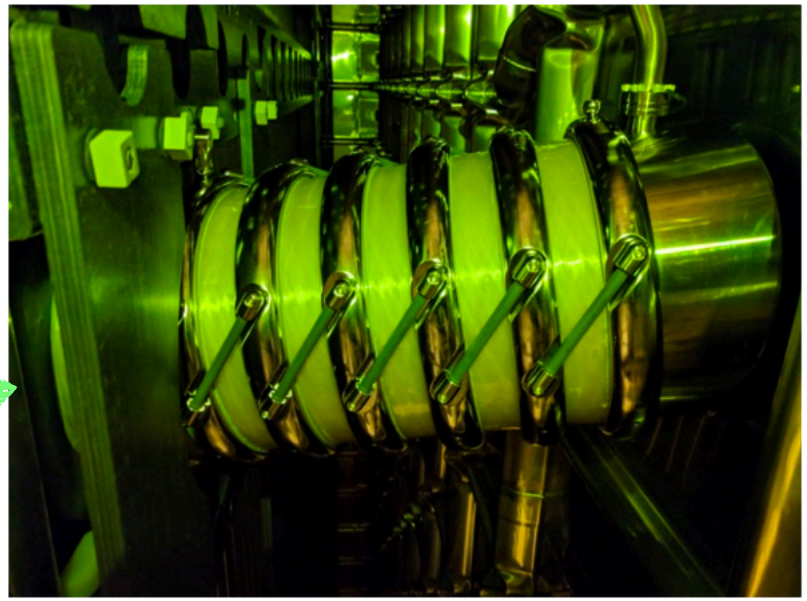
To better model FSI, knowledge on hadron-argon interaction is required.

ProtoDUNE with a hadron beam

Phys.Rev.Accel.Beams 20 (2017) 11, 111001

- A mix-particle beam was implemented to ProtoDUNE-SP, including hadrons like π^+, p, K^+ with different momentum settings ranging from 0.3 to 7 GeV.





A beam plug filled with nitrogen connecting the beam and the detector volume

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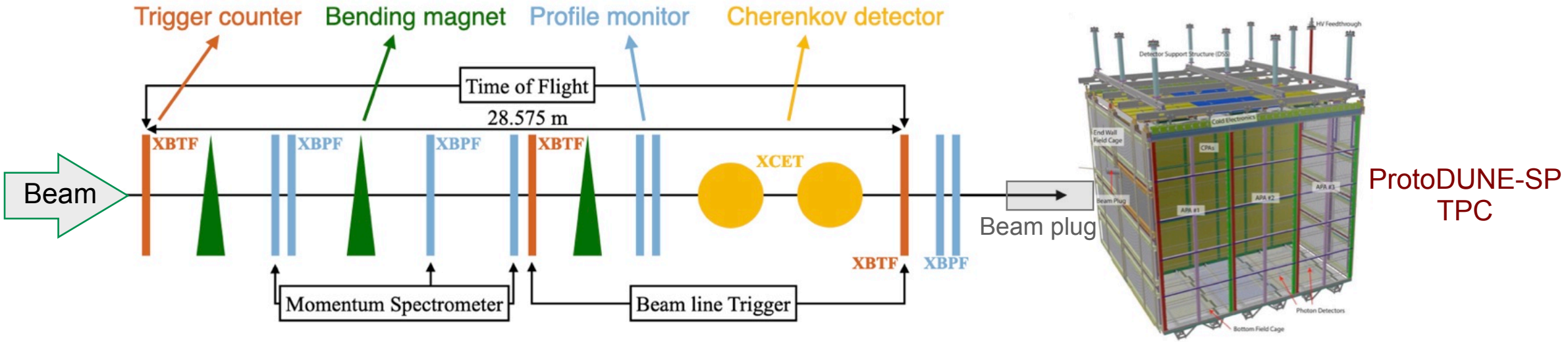

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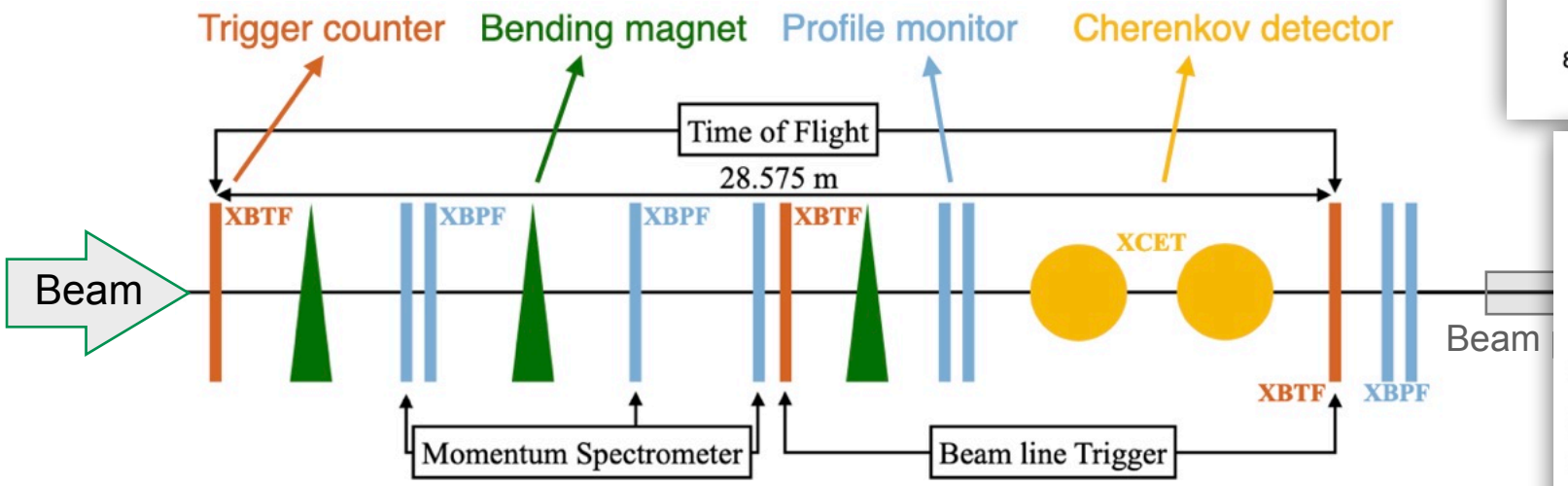
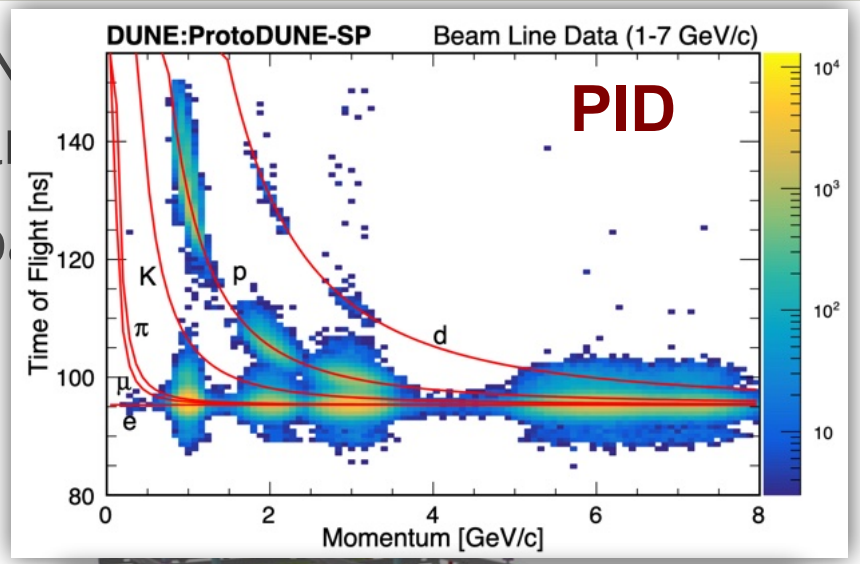
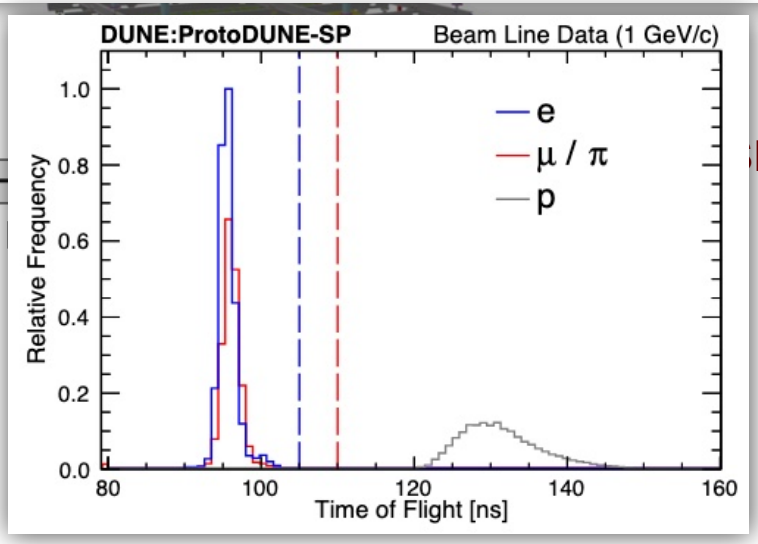
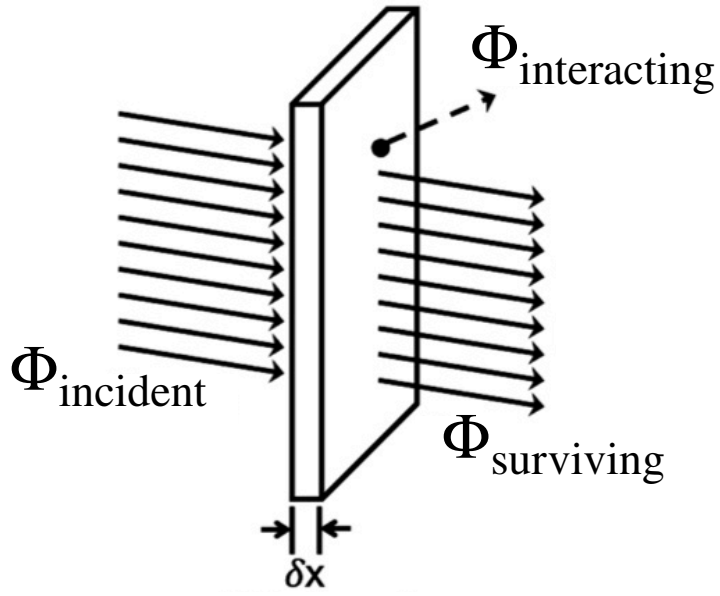






Hadron-argon cross-section measurement

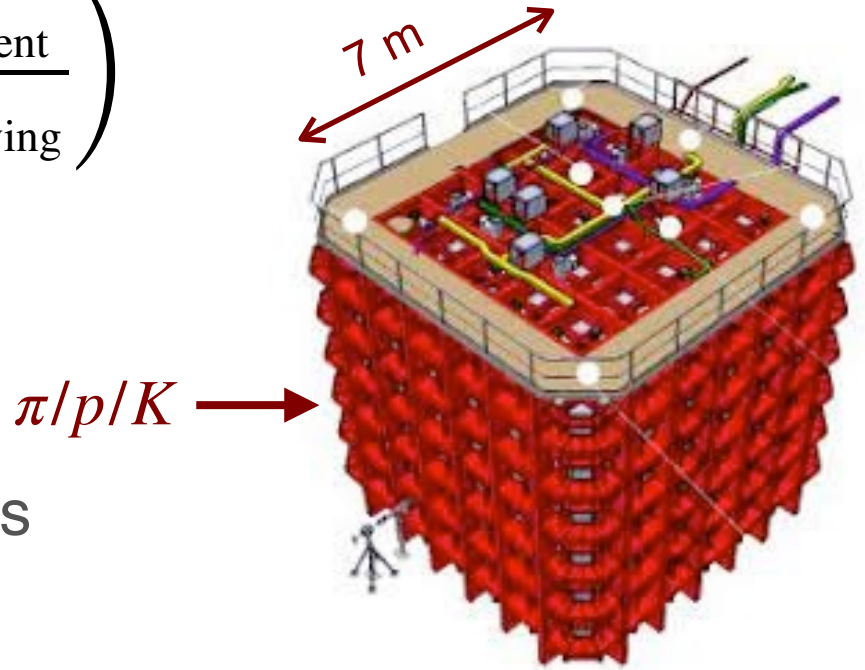
- Hadron-nucleus cross section is usually measured by thin-target experiments.



$$\frac{d\Phi}{dx} = -n\sigma\Phi \quad \text{(Definition of cross section } \sigma\text{)}$$

$$\Rightarrow \sigma = \frac{1}{n\delta x} \ln\left(\frac{\Phi_{\text{incident}}}{\Phi_{\text{surviving}}}\right)$$

Number density of the target material



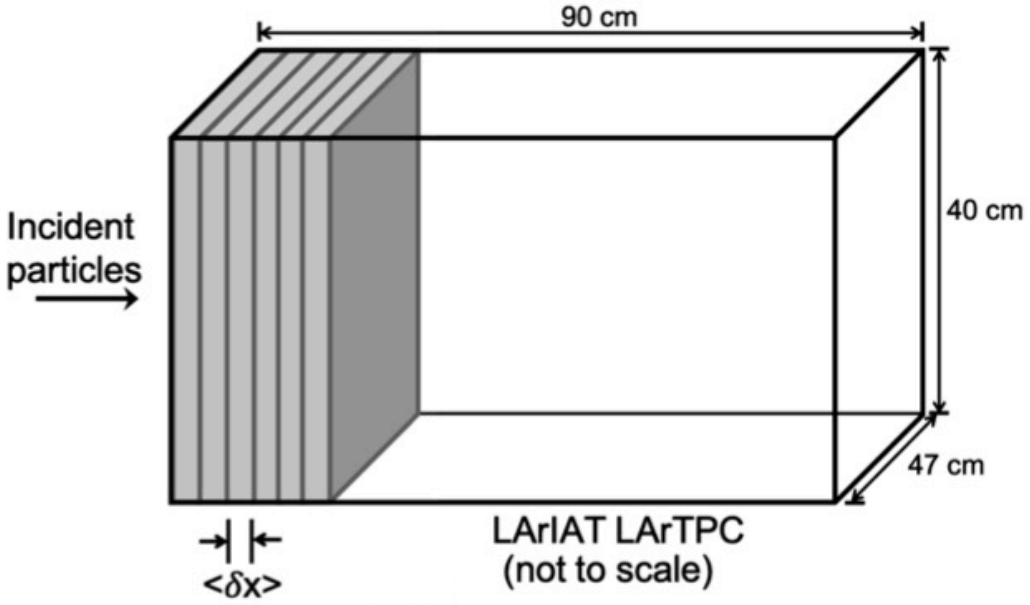
ProtoDUNE detetor

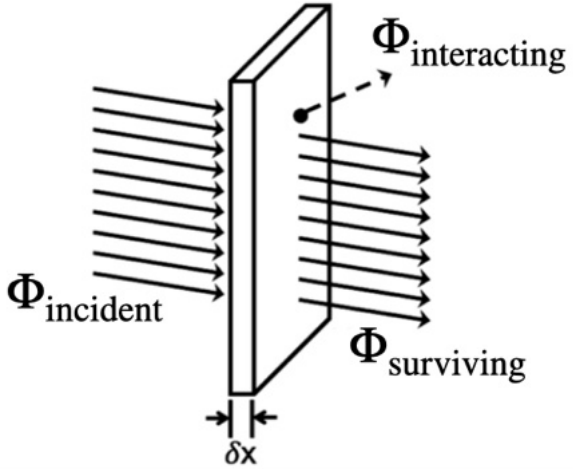
- However, a LArTPC is not a “thin” target for hadrons
  - Interaction length on the order O(10 cm)

Hadron-argon cross-section measurement

Phys.Rev.D 106 (2022) 5, 052009

- LArIAT (Liquid Argon In A Testbeam) collaboration proposed the **thin-slice method** to measure hadron-argon cross section using a 260-kg LArTPC.
  - Each slice serves as an individual thin-target experiment.
  - Count $N_{\text{interacting}}$ and N_{incident} in each energy bin.





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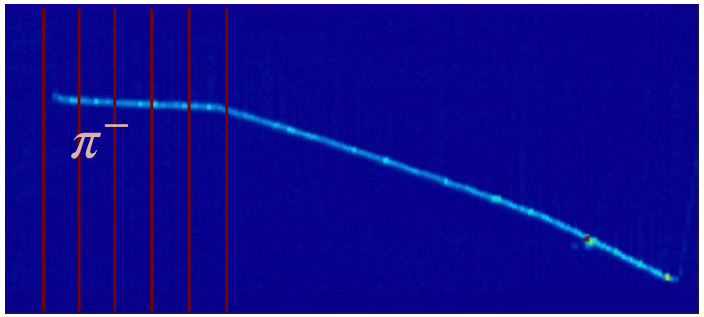

LArIAT event display

Hadron-argon cross-section measurement

Phys.Rev.D 106 (2022) 5, 052009

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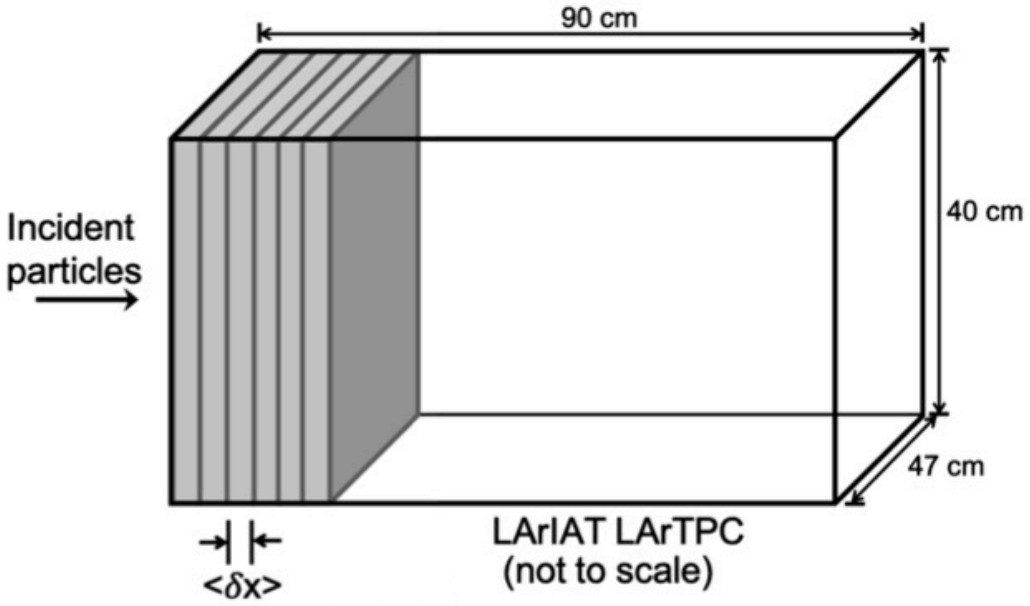
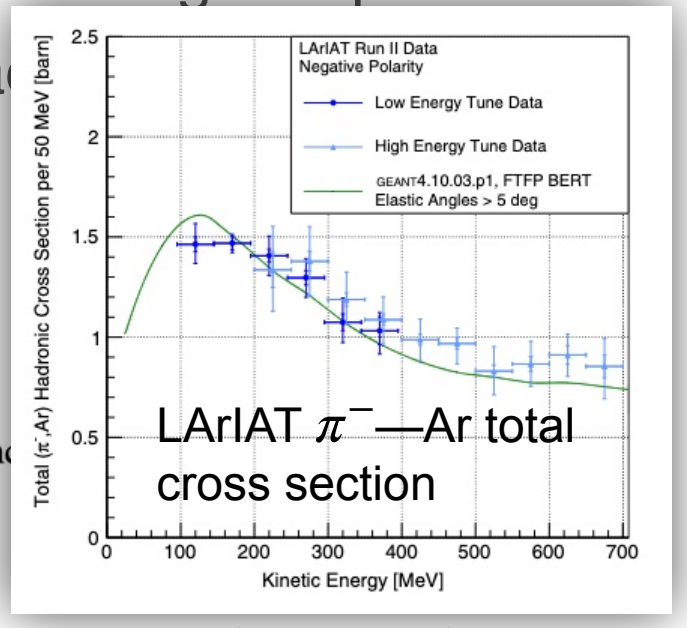


Φ_{inc}



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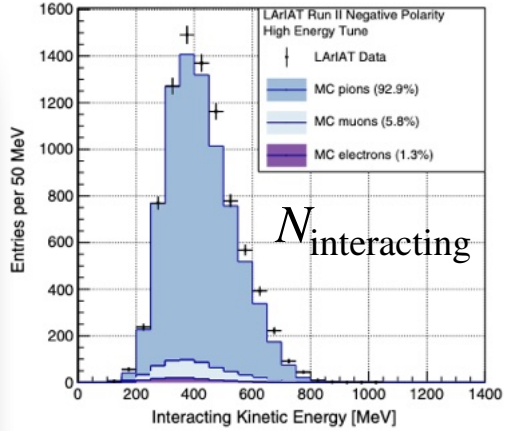
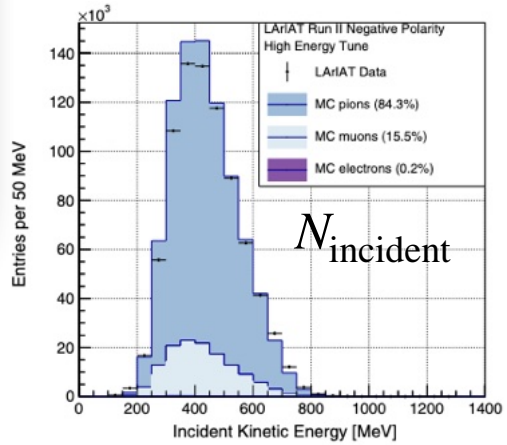
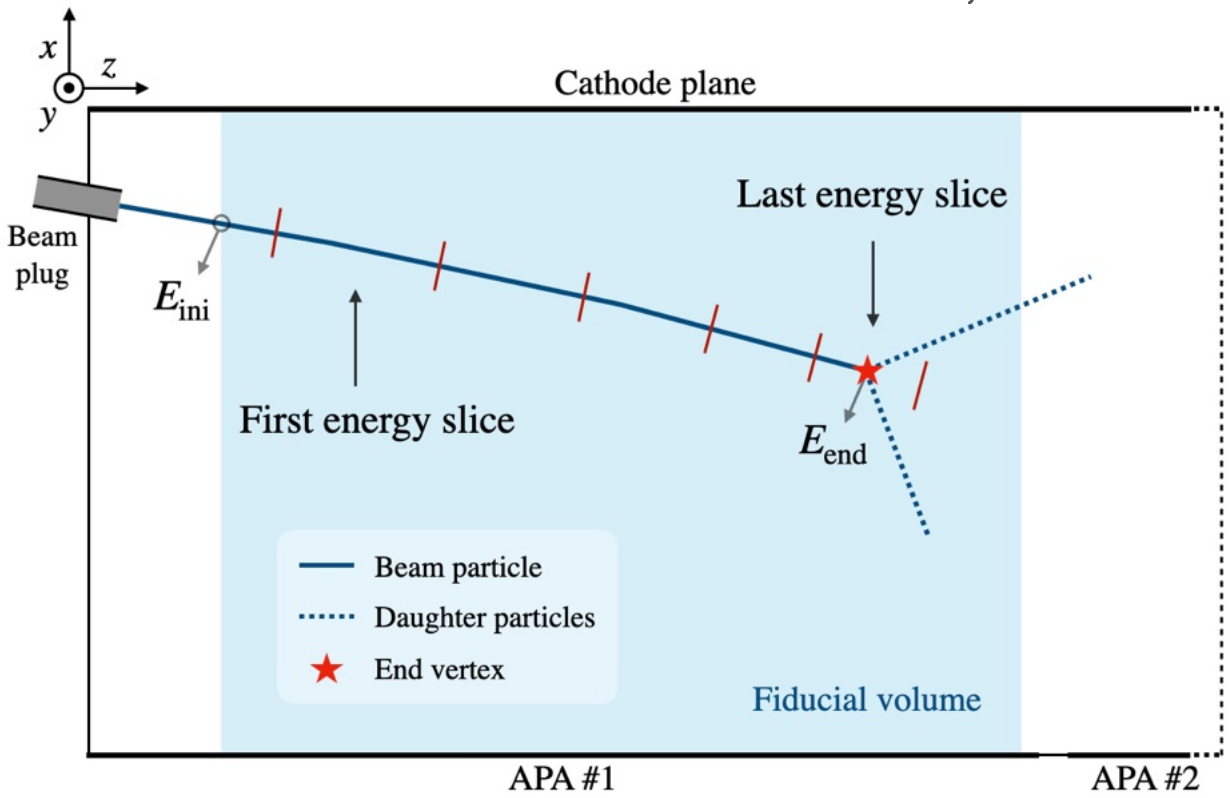


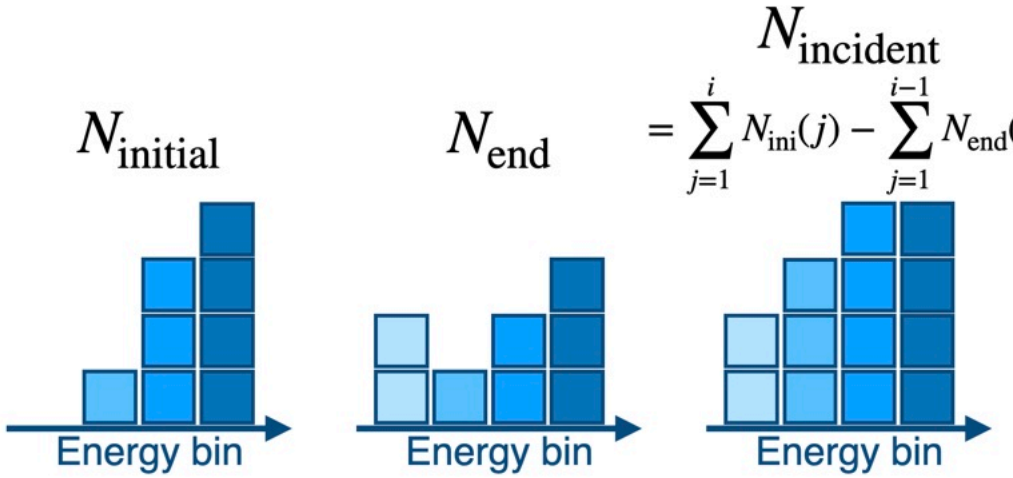


Energy-slicing method

Ph.D. Thesis (F. Stocker), Instruments 8 (2024) 1, 15

- ProtoDUNE with a much larger size subjects to a considerable amount of cosmic rays, making it hard to granularize the beam track by wire pitch.
- Based on the thin-slice method, we developed the energy-slicing method.



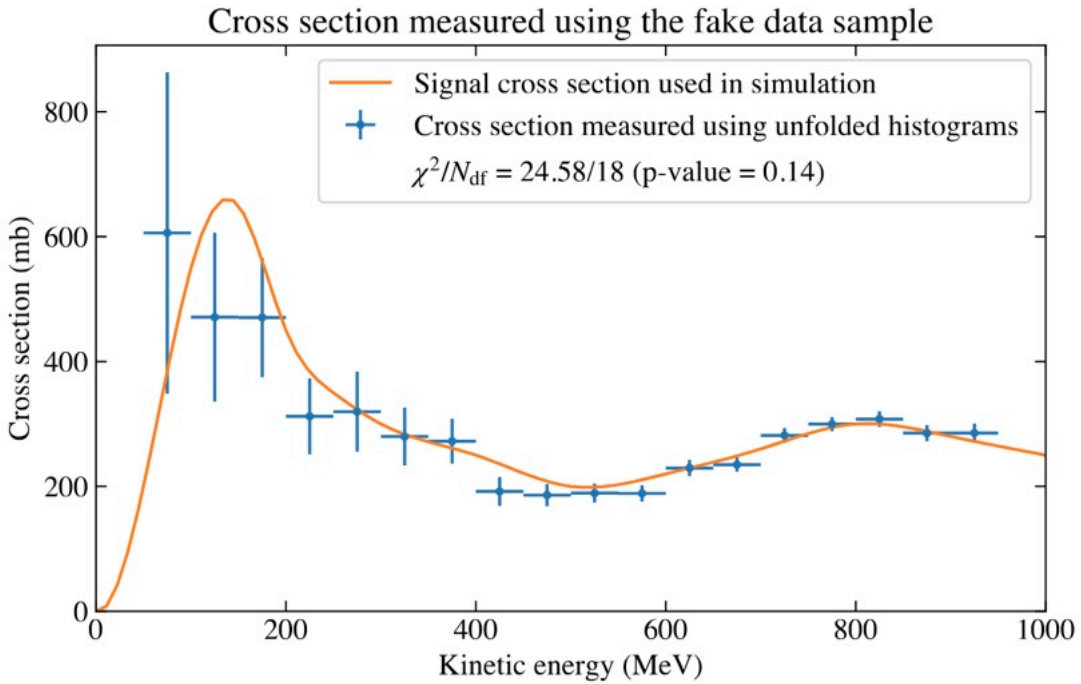


The cross section is calculated by

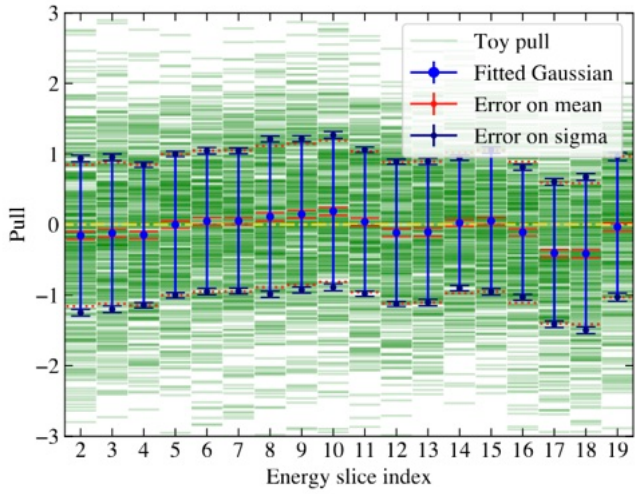
$$\sigma(E) = \frac{N_{int}(E)}{nN_{end}(E)\delta E}\frac{dE}{dx}(E)\ln\left(\frac{N_{inc}(E)}{N_{inc}(E) - N_{end}(E)}\right)$$

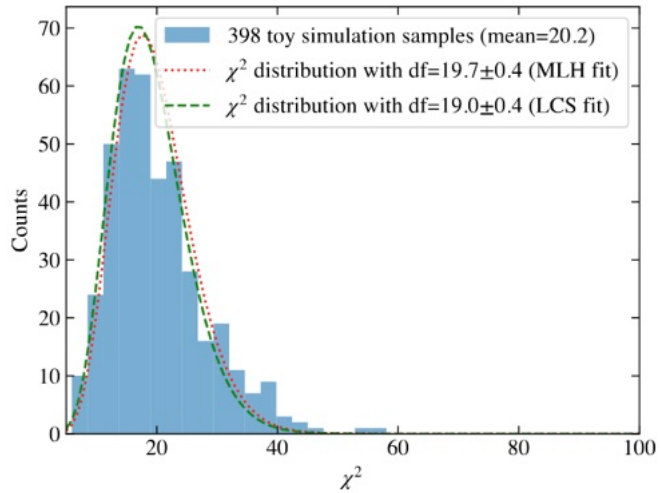
Energy-slicing method

- The energy-slicing method enables more sophisticated statistical techniques including unfolding with analytical error propagation.
  - *A Modified Slicing Method with Multi-Dimensional Unfolding to Measure Hadron-Argon Cross Sections* (Instruments 8 (2024) 1, 15)



Toy validation with a dedicated fake data simulation



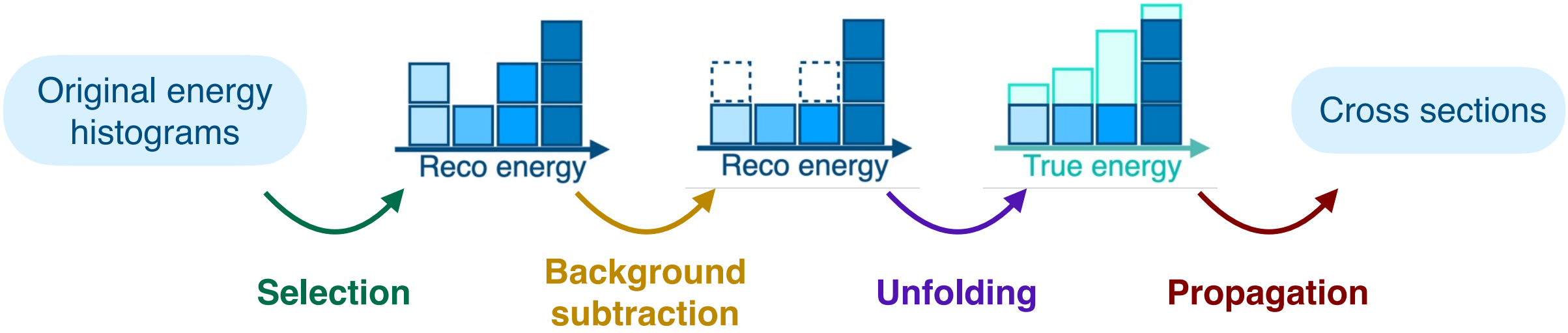


- Check it out this tutorial if interested to use!

ProtoDUNE analysis overview

DUNE-doc-30273 (AnaNote)

- This work focuses on the analysis of the π^+—Ar and p—Ar inclusive cross section measurements using the 1 GeV/c beam sample.



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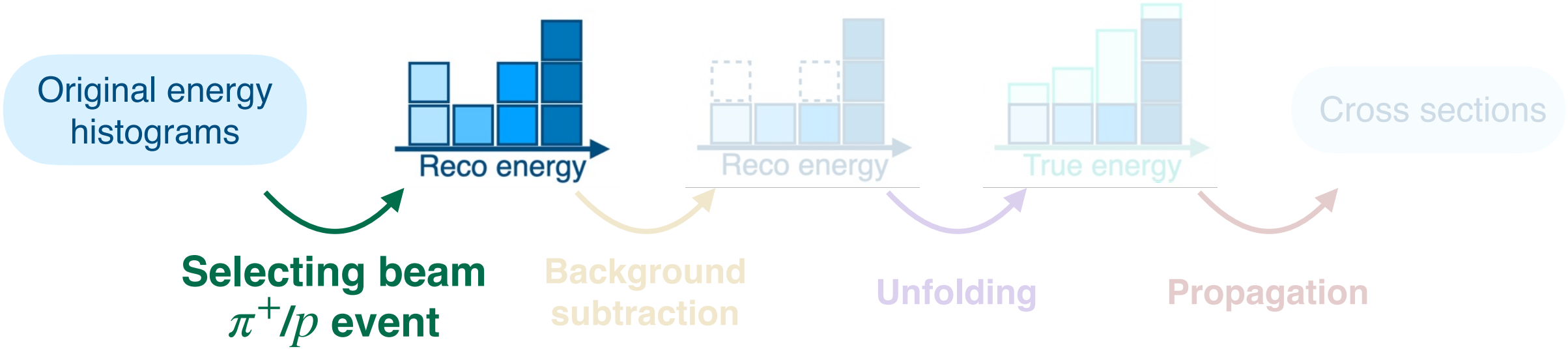

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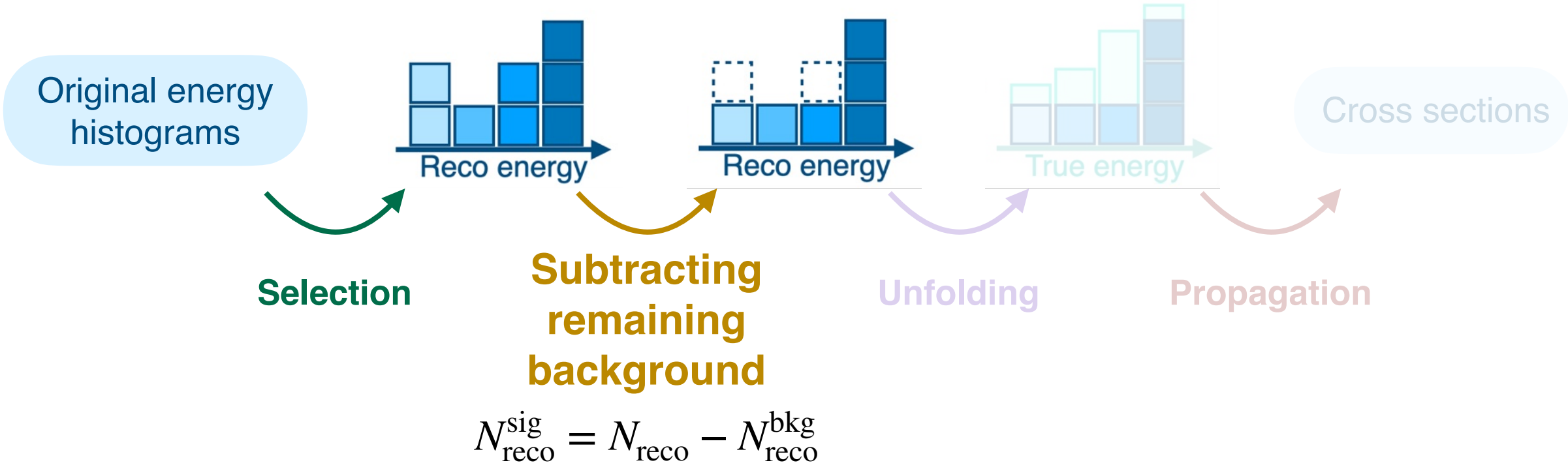

$$N_{\text{reco}}^{\text{sig}} = N_{\text{reco}} - N_{\text{reco}}^{\text{bkg}}$$

ProtoDUNE analysis overview

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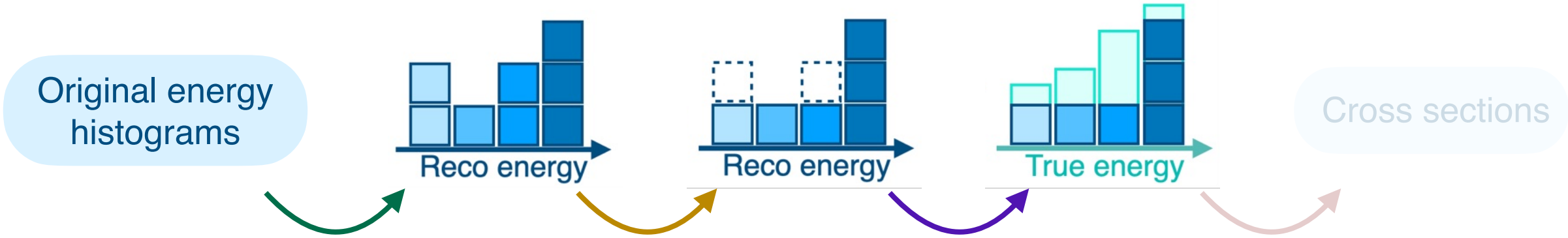

$$N_{\text{true}}^{\text{sig}} = M_{\text{unfolding}} \cdot N_{\text{reco}}^{\text{sig}}$$

ProtoDUNE analysis overview

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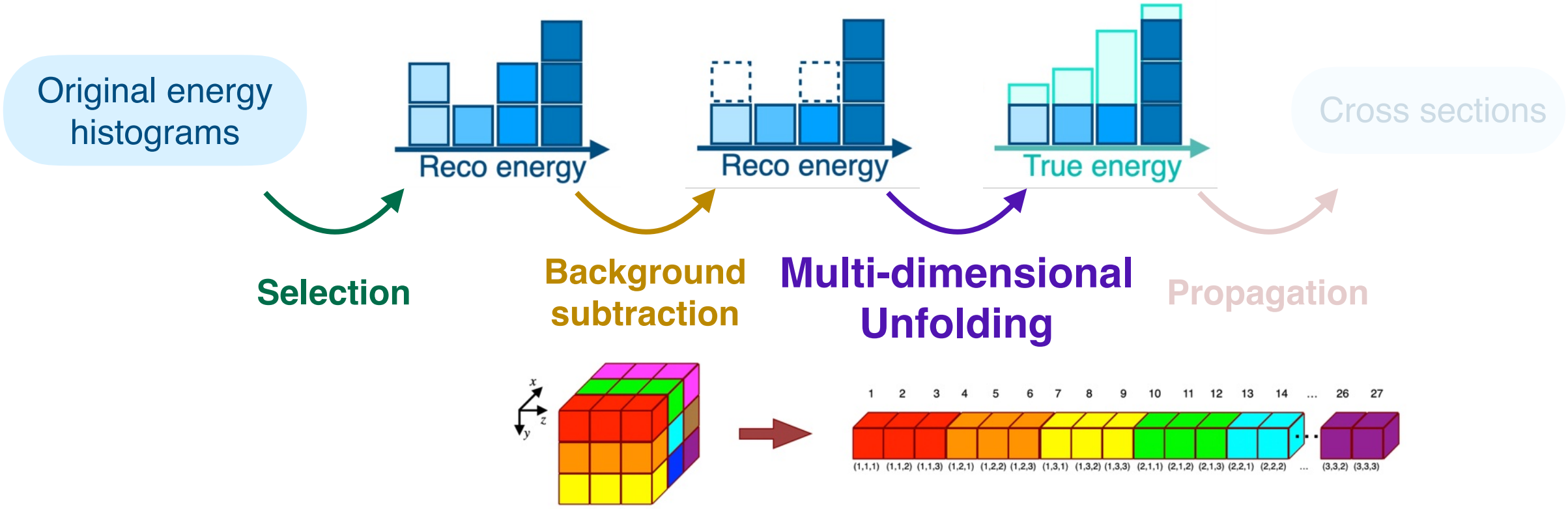

ProtoDUNE analysis overview

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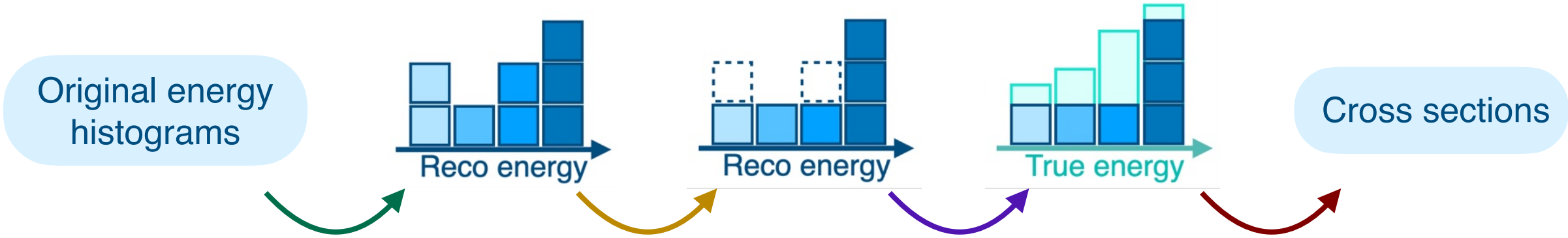
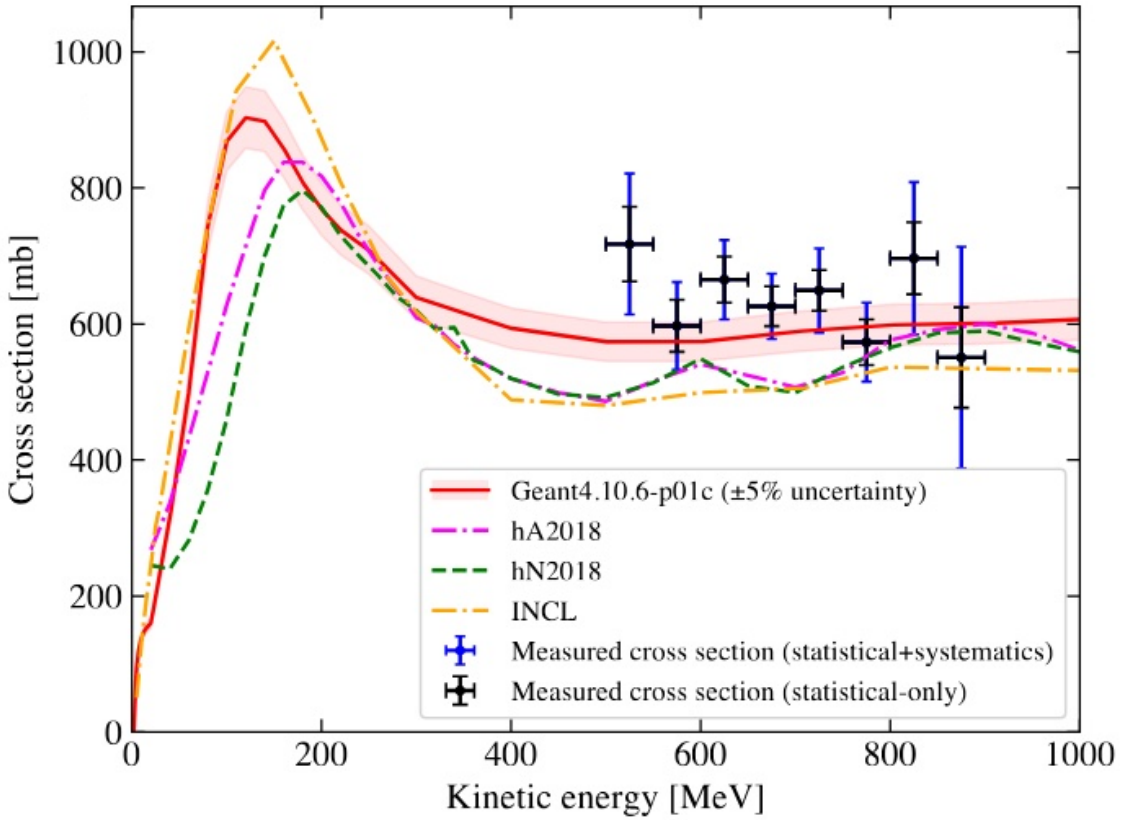


$$\sigma(E) = \frac{N_{\text{int}}(E)}{nN_{\text{end}}(E)\delta E}\frac{dE}{dx}(E)\ln\left(\frac{N_{\text{inc}}(E)}{N_{\text{inc}}(E) - N_{\text{end}}(E)}\right)$$

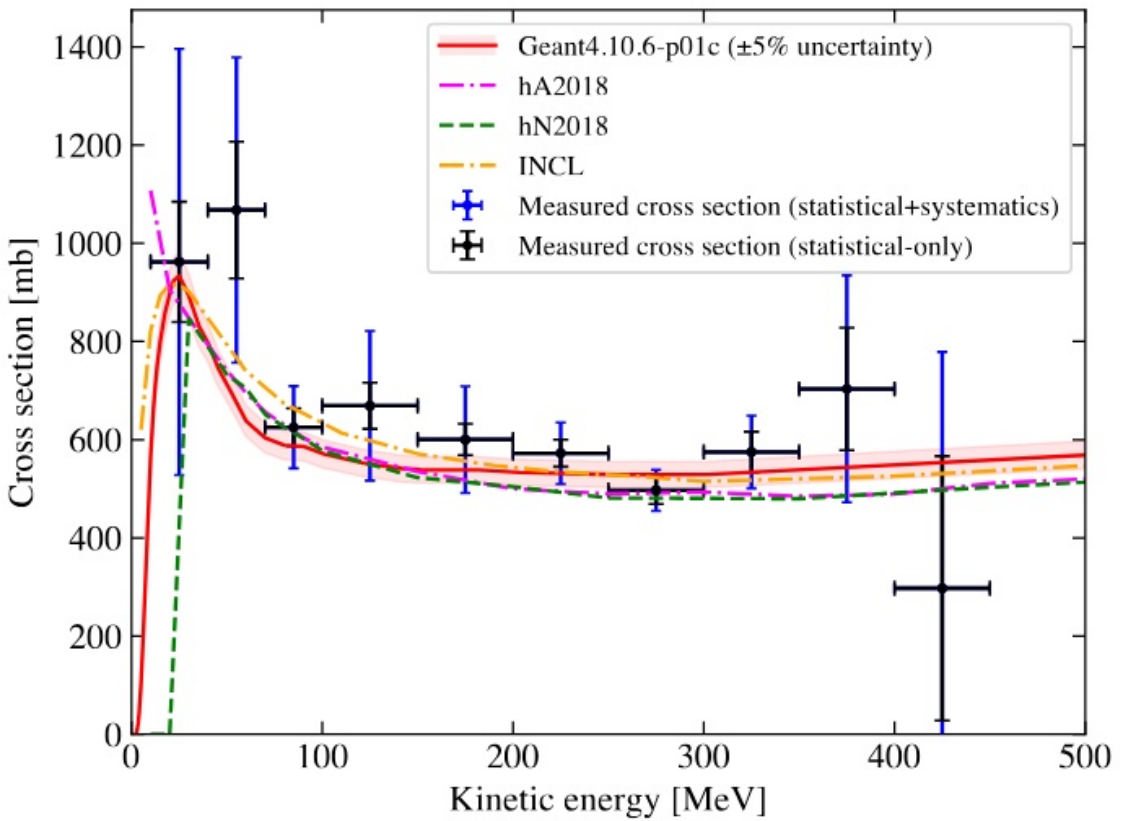
Data cross-section results

Paper under DUNE review

$\pi^+ - \mathrm{Ar}$



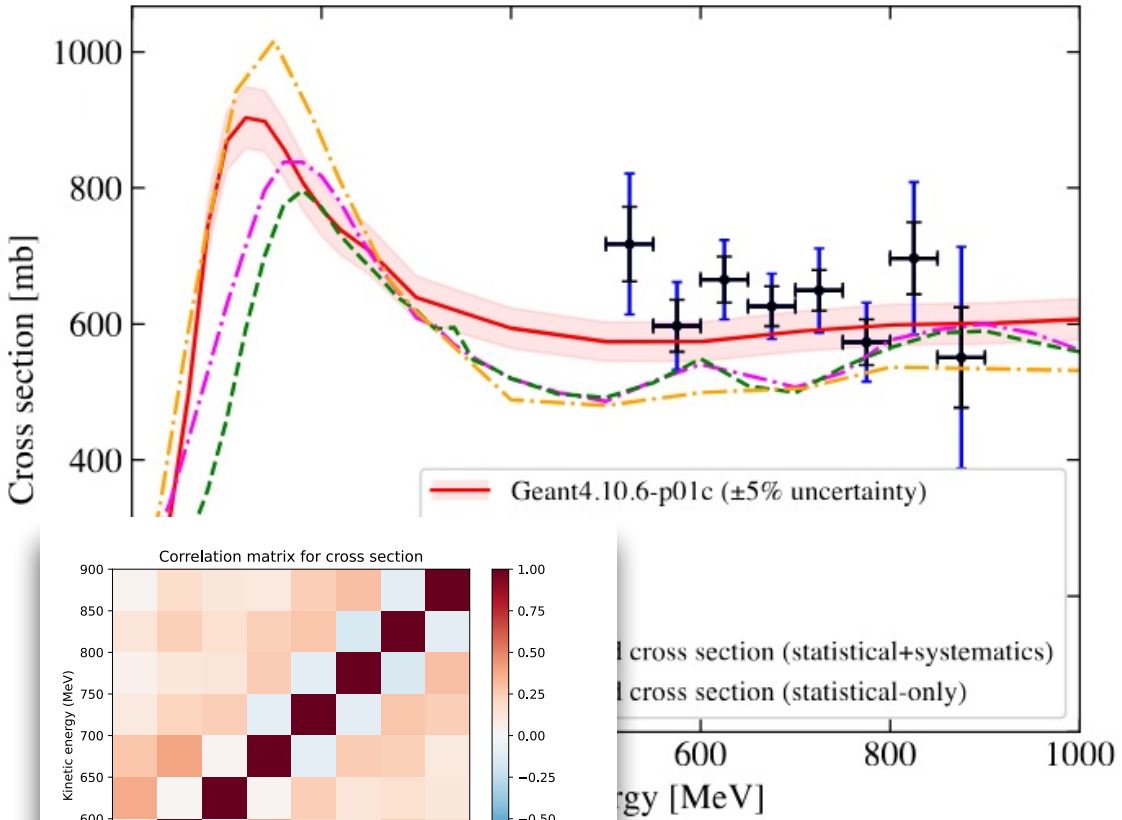
$p - \mathrm{Ar}$



Data cross-section results

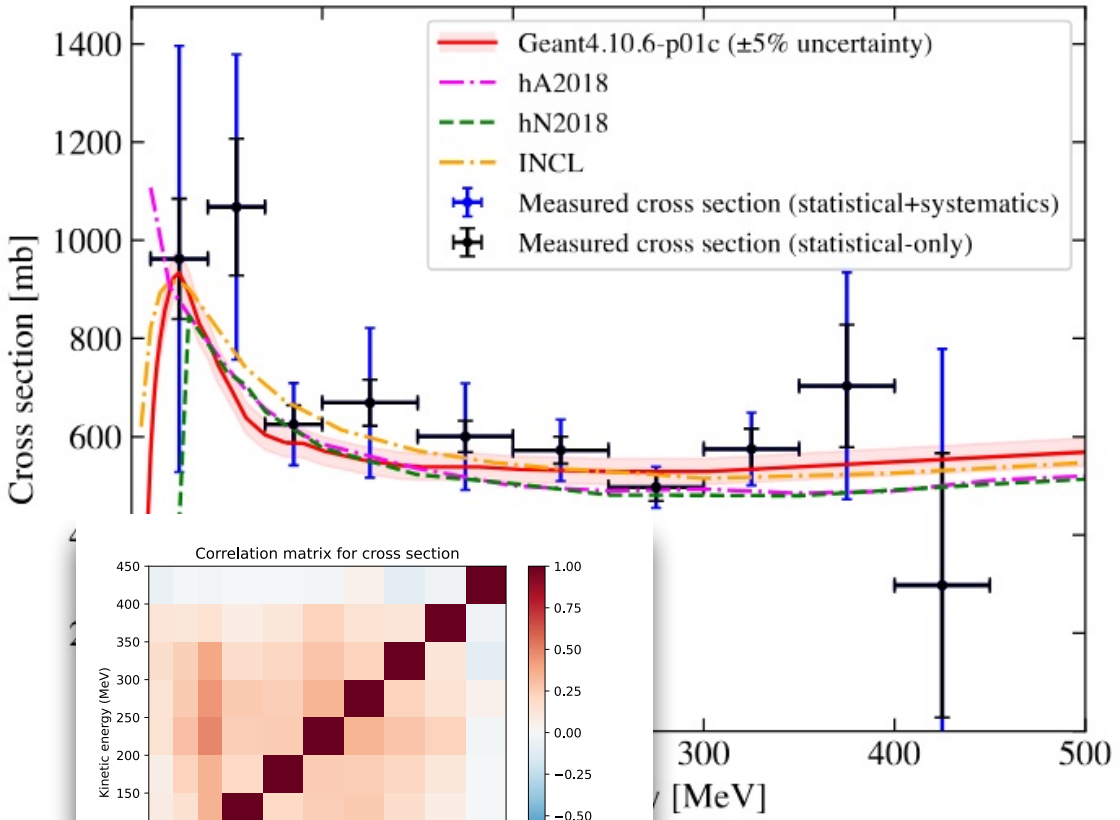
Paper under DUNE review

$\pi^+ - \mathrm{Ar}$



Correlation matrices

$p - \mathrm{Ar}$

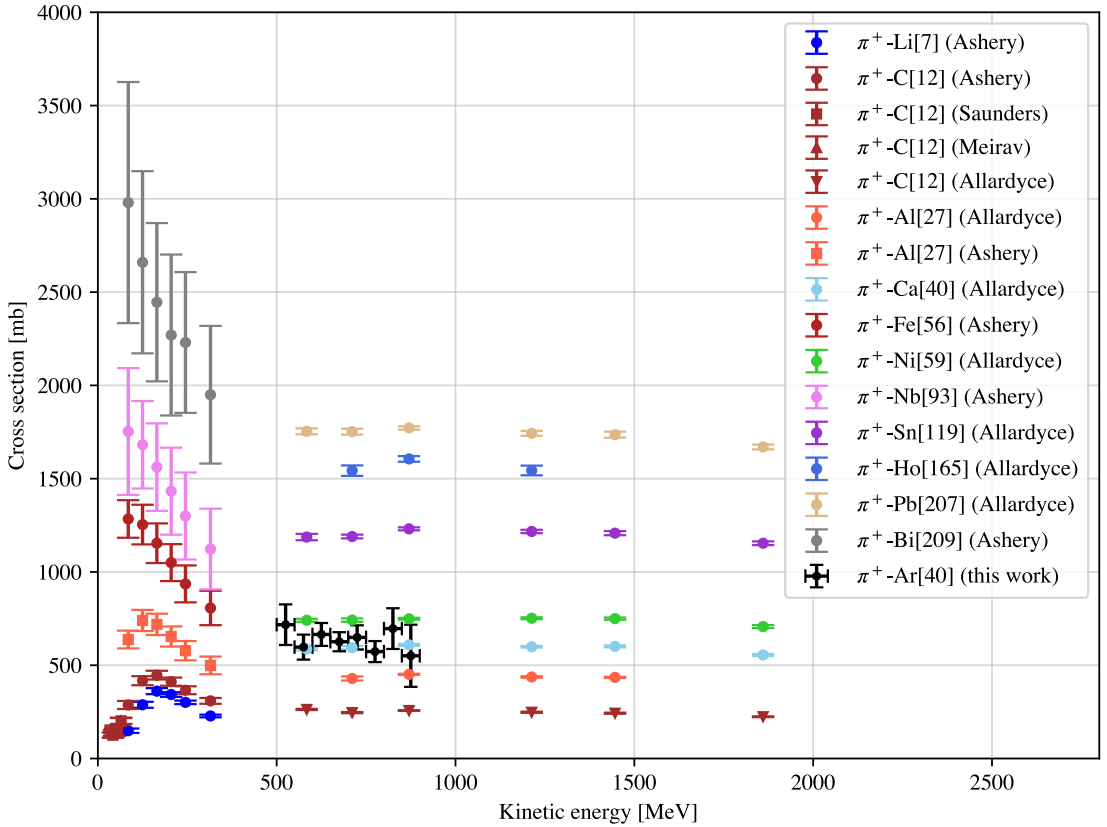


No tension observed.

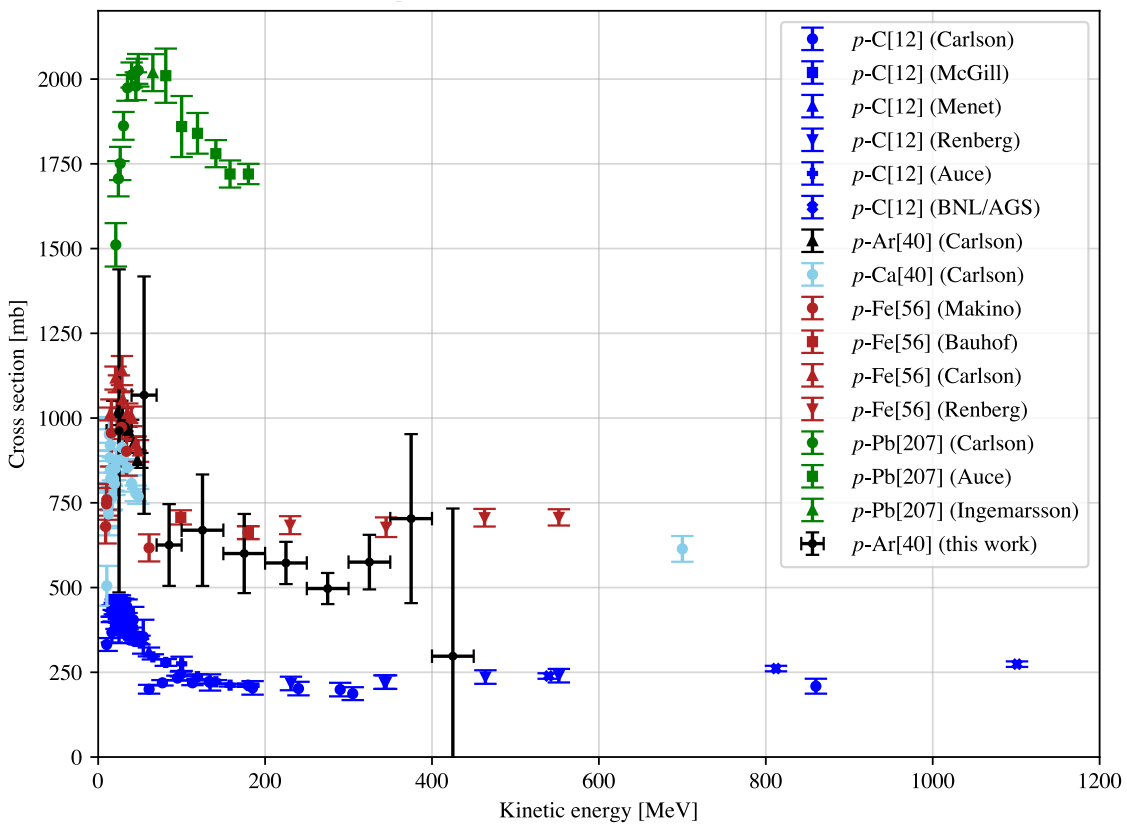
Argon results overlaid with other targets

Paper under DUNE review

π^+—nucleus total cross section



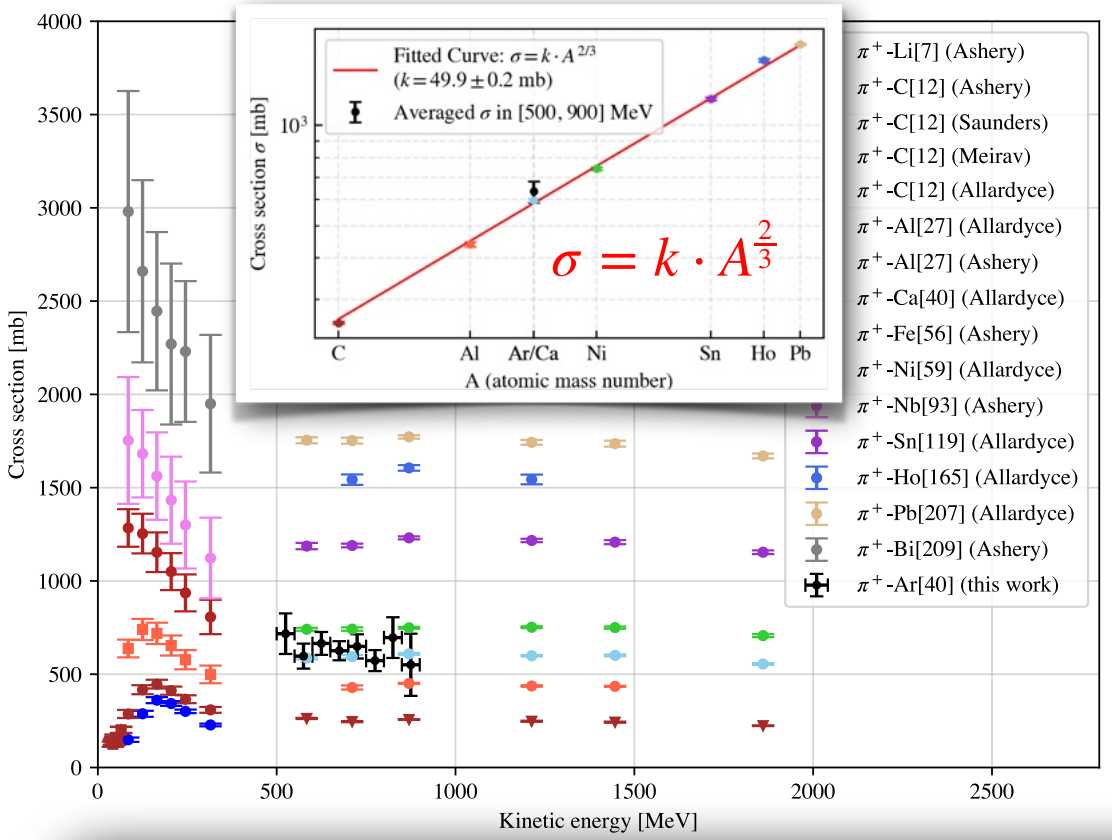
p—nucleus total cross section



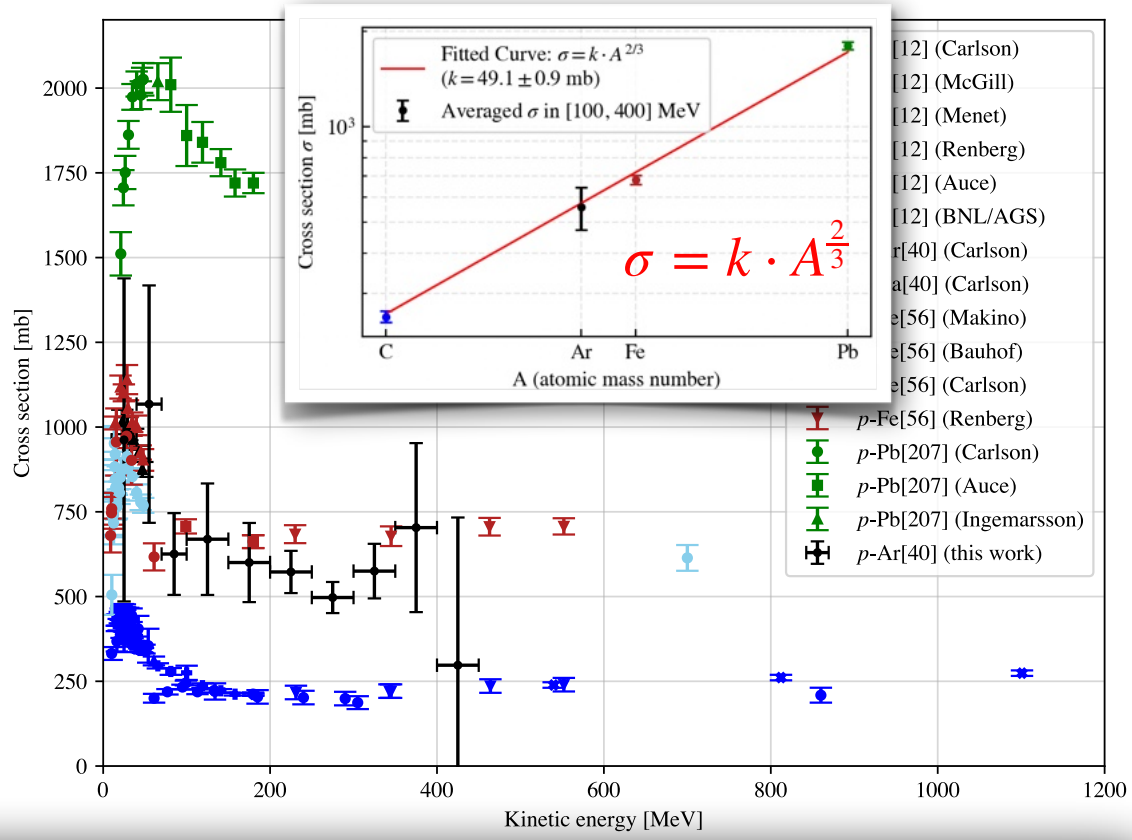
Argon results overlaid with other targets

Paper under DUNE review

π^+—nucleus total cross section



p—nucleus total cross section

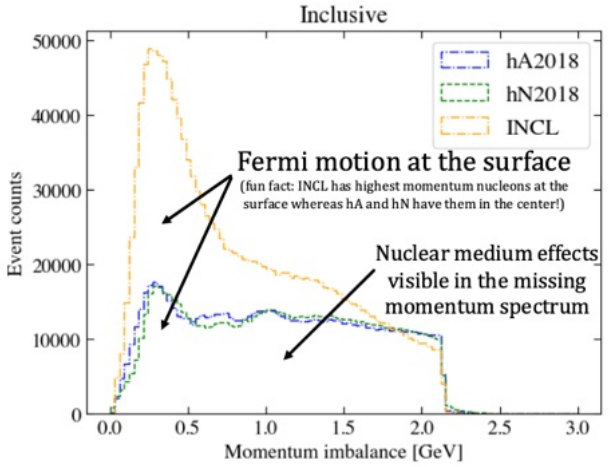


This work presents the first π^+ and p data on argon in the energy range relevant to DUNE!

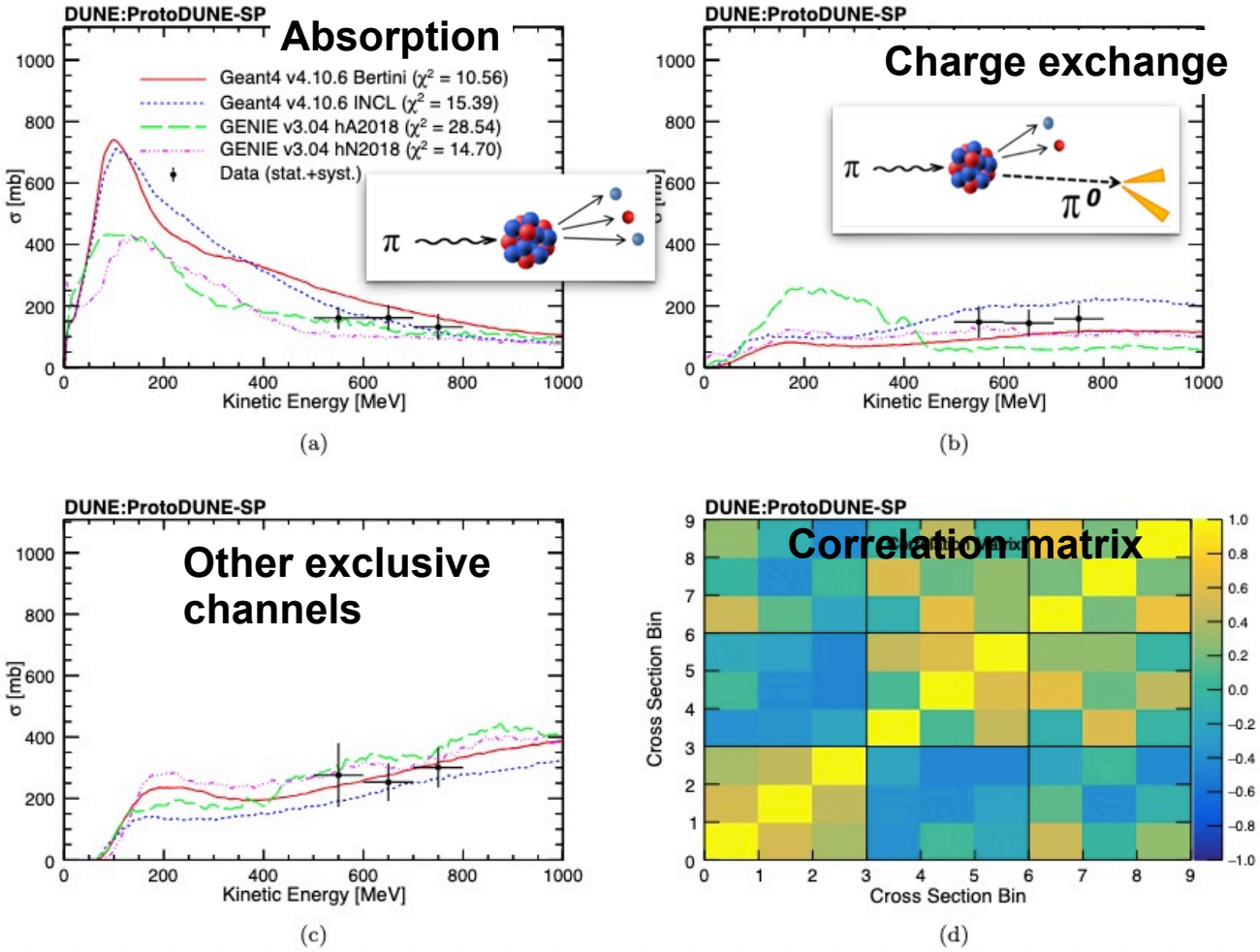
More cross-section results

- Cross sections separated by final states (exclusive cross section) and differentiated by other kinematic observables (differential cross section) offer greater discriminating power among FSI models.

Differential cross section over momentum imbalance
(Related talk)



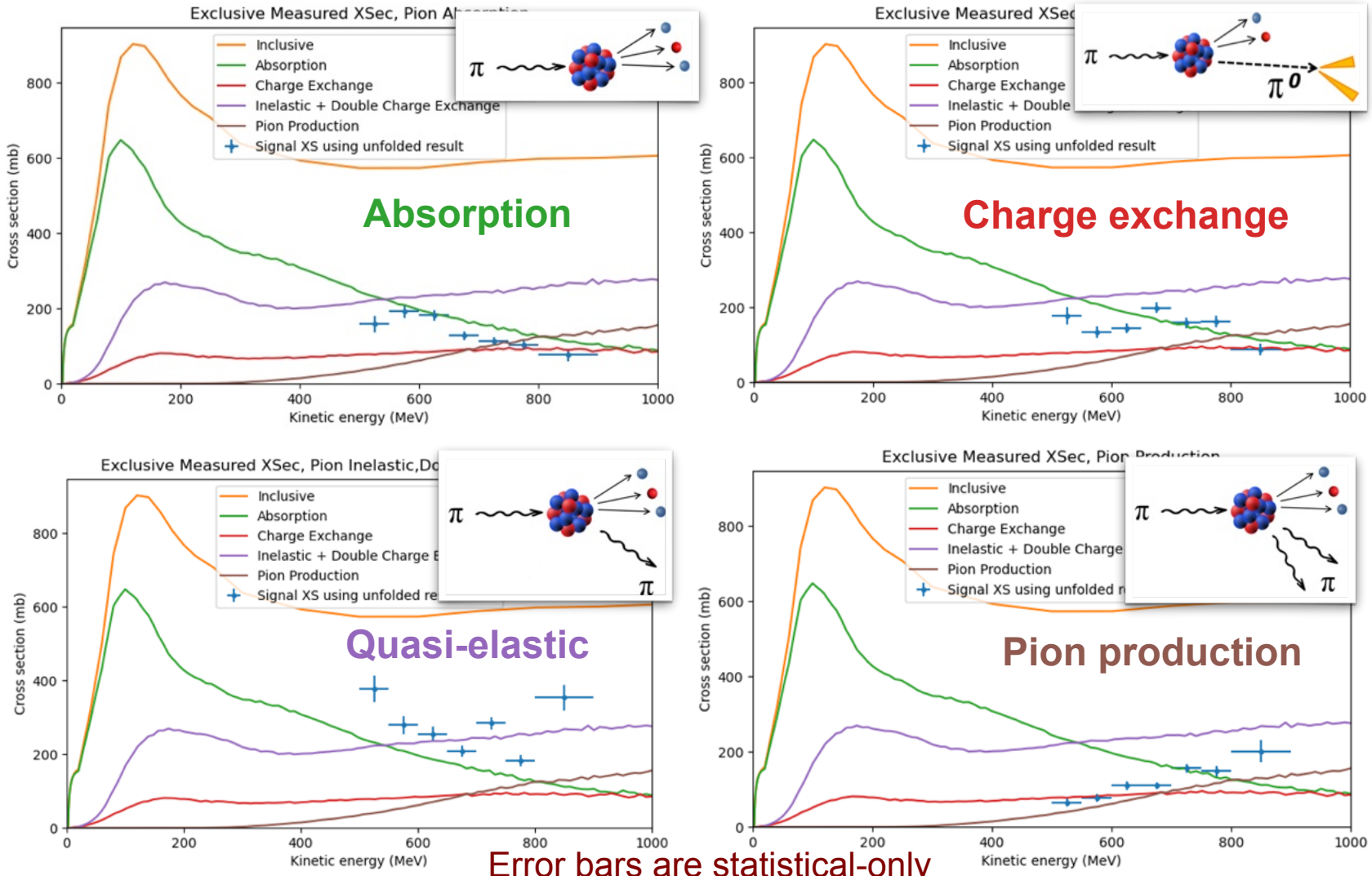
Pion exclusive cross sections
DUNE-doc-25756 (AnaNote) (leading analyzer: J. Calcutt)



Applying the slicing method

Bachelor's Thesis (J. Rositas)

- A simultaneous measurement of exclusive channels is performed using the slicing method.
- The preliminary results are consistent with DUNE-doc-25756 performed with the likelihood fitting method.
- Further studies in progress. (analysis repo)



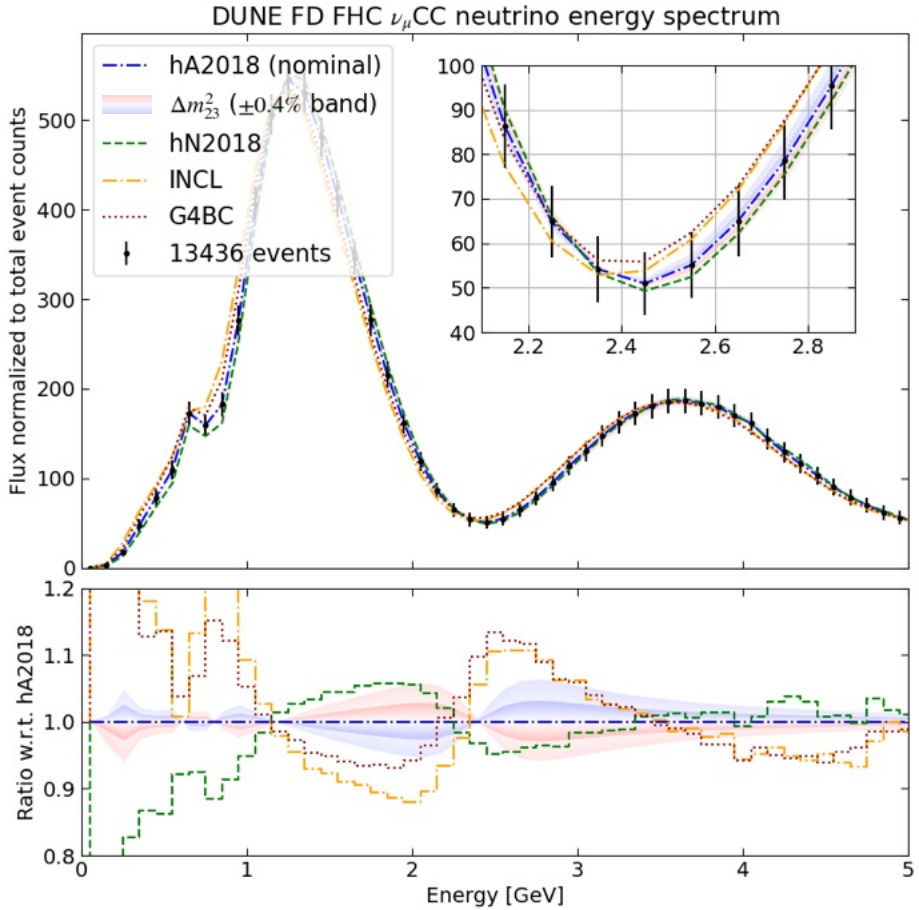
Error bars are statistical-only

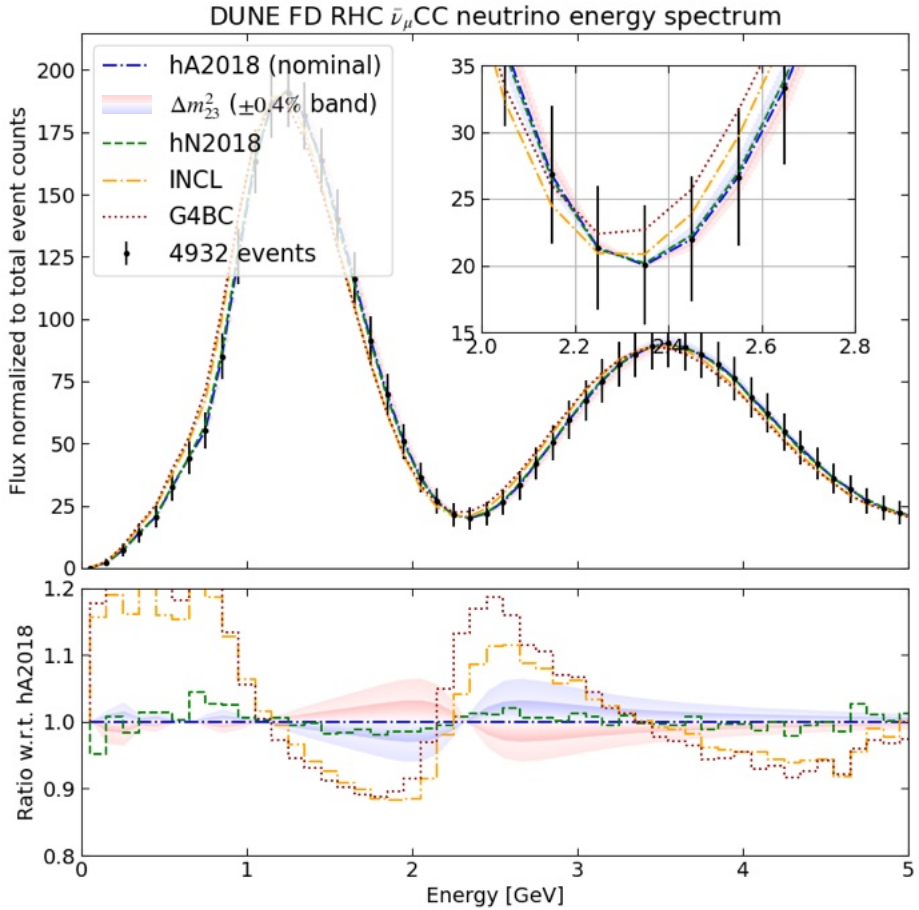
FSI's impact on oscillation sensitivity

WIP with S. Dolan and L. Munteanu

Δm^2_{23} sensitivity in the ν_μ disappearance analysis

Assuming ten-year exposure (624 kt-MW-years) for DUNE



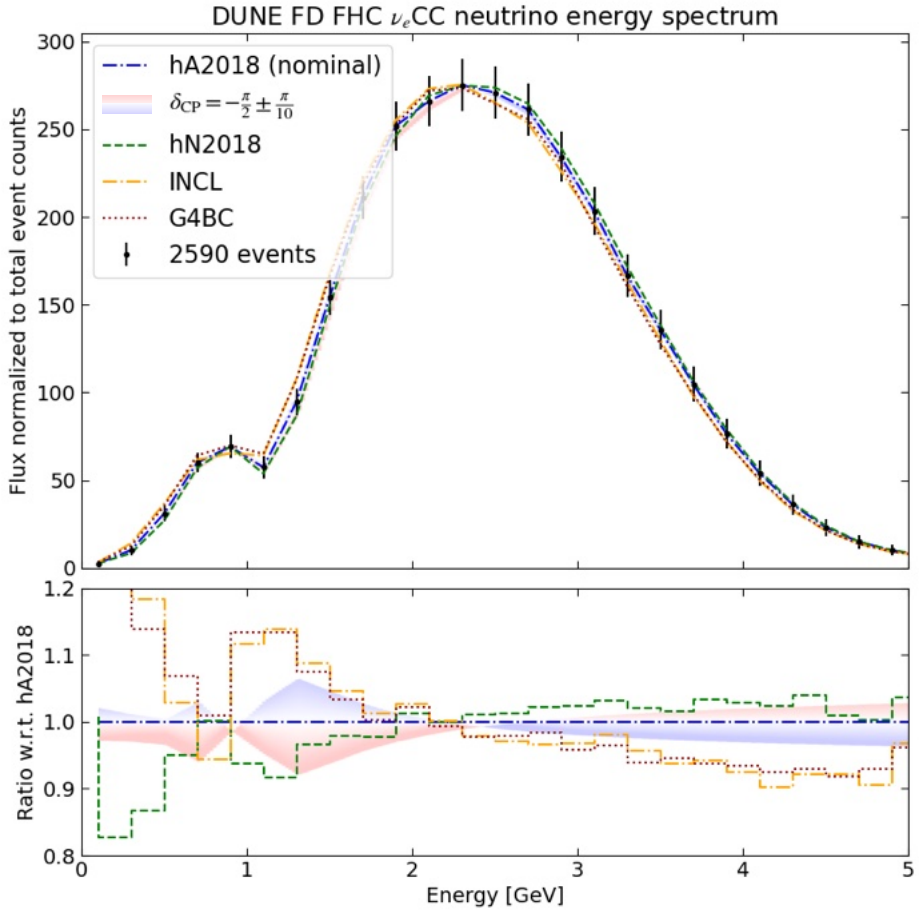


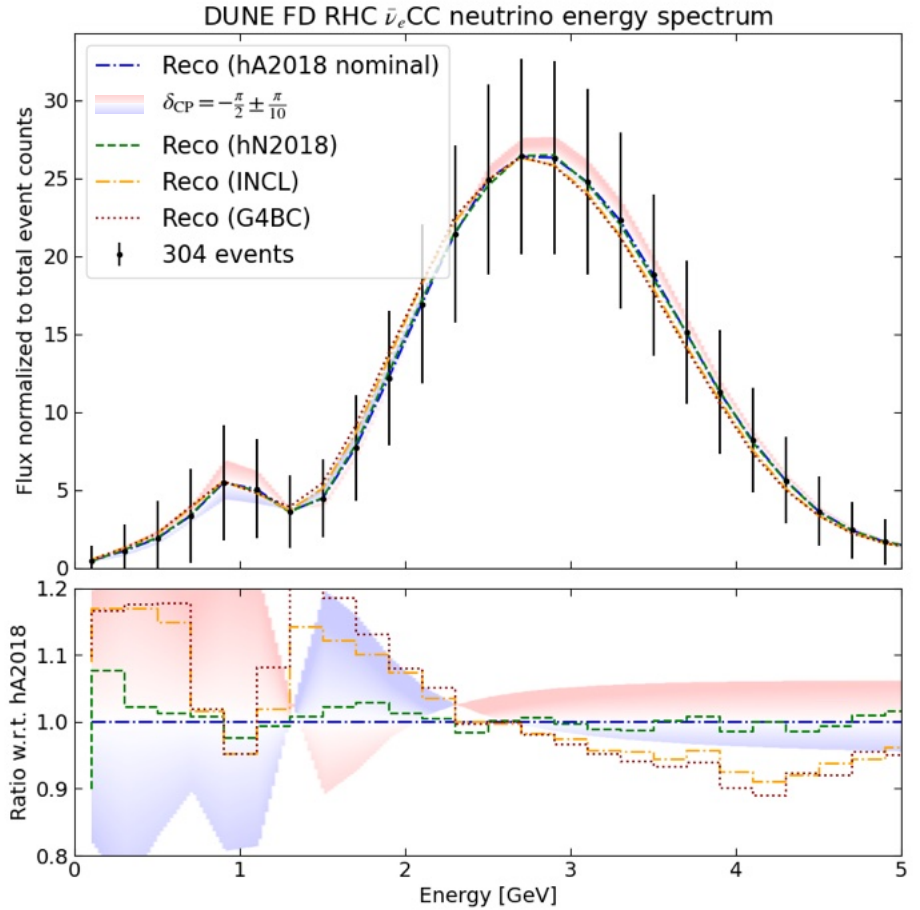
FSI's impact on oscillation sensitivity

WIP with S. Dolan and L. Munteanu

δ_{CP} sensitivity in the ν_e appearance analysis

Assuming DUNE ten-year exposure and maximal CP violation ($\delta_{CP} = -\pi/2$)





FSI's impact on oscillation sensitivity

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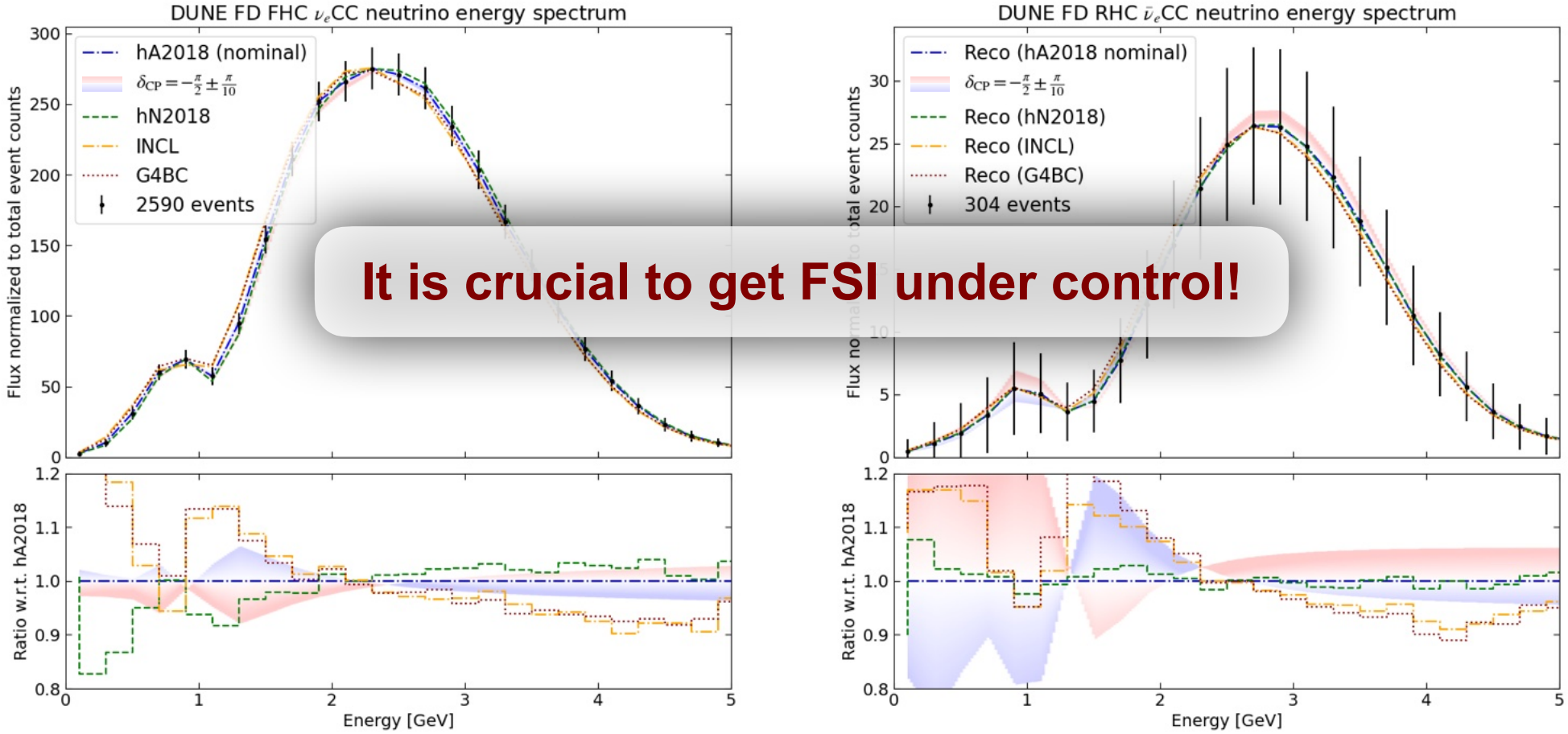
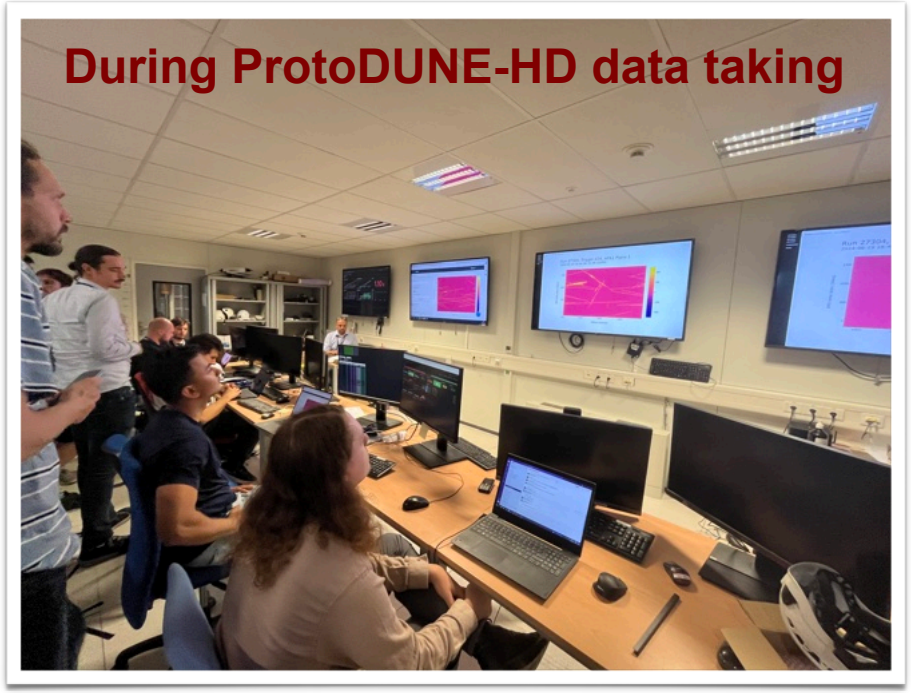


It is crucial to get FSI under control!

Outlook for ProtoDUNE-II

- ProtoDUNE-II comprises two new LArTPC detectors (corresponding to two designs of DUNE FD)
  - ProtoDUNE-HD (Horizontal Drift) collected data in summer 2024; while ProtoDUNE-VD (Vertical Drift) began operations this summer.
- ProtoDUNE-HD took hadron beam data
  - Focusing on DUNE hadron energy range
  - Both positive and negative beam charges
  - Double the statistics w.r.t. ProtoDUNE-I
- With lessons learned from ProtoDUNE-I, ProtoDUNE-II aims to improve the methods and reduce systematics in hadron analyses.



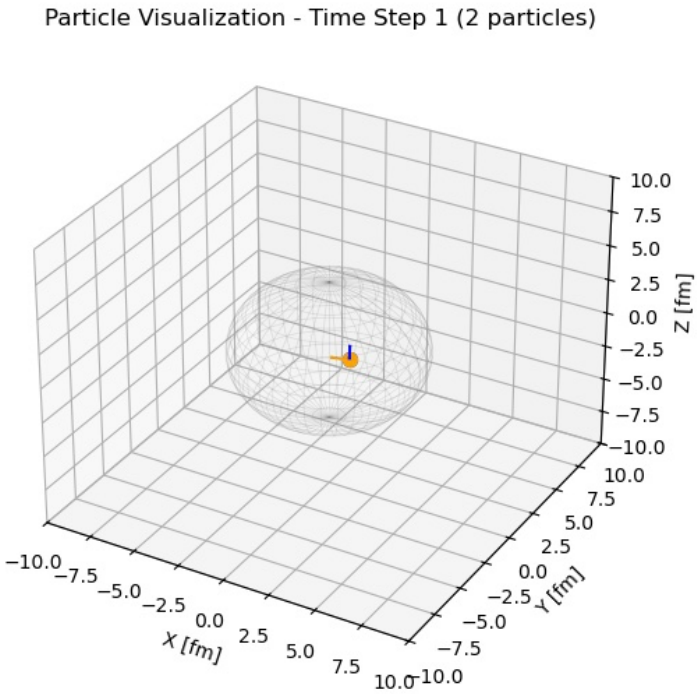
Surrogate model for FSI simulation

WIP with K. V. Tsang and K. Terao

- GiBUU (Giessen Boltzmann-Uehling-Uhlenbeck) is an advanced model providing a unified theory and transport framework for neutrino-nucleus reactions.
- We are a building a GPT-like model with GiBUU data as input to learn the particle evolution within the nucleus.
  - Language: [Word word. Word word word. …]
  - Particles: [$p_1(t_1)$, $p_2(t_1)$, End_of_Step, $p_1(t_2)$, $p_2(t_2)$, $p_3(t_2)$, End_of_Step, …]

Class; features (x, y, z, P_x, P_y, P_z)

Each token only attend to tokens in the previous step and the current step.

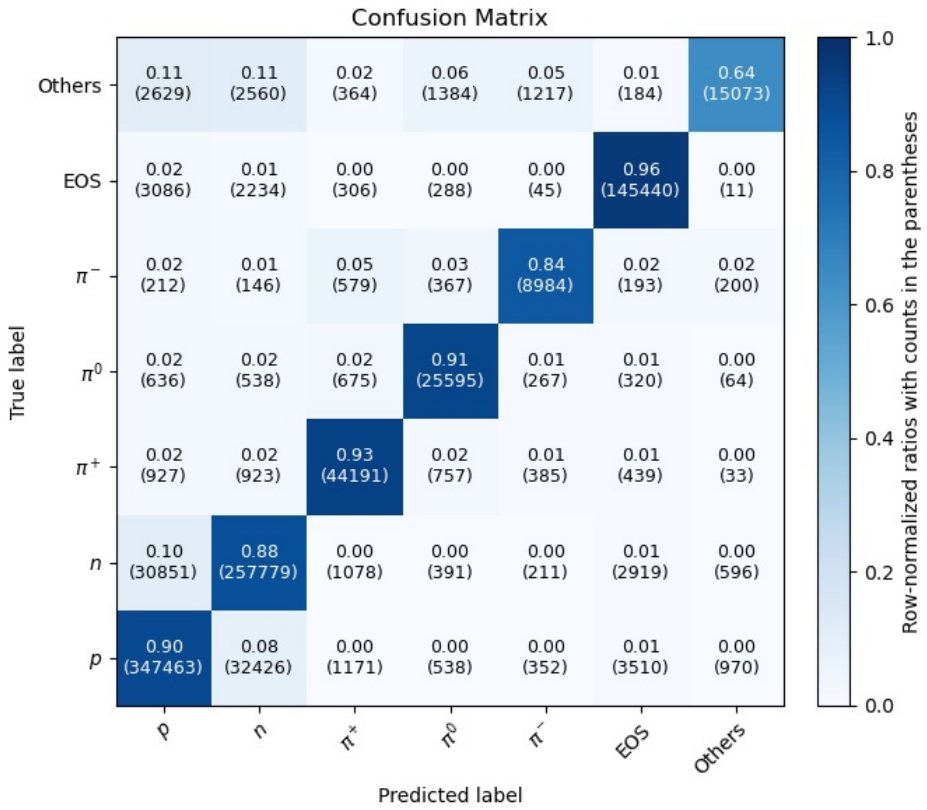


Surrogate model for FSI simulation

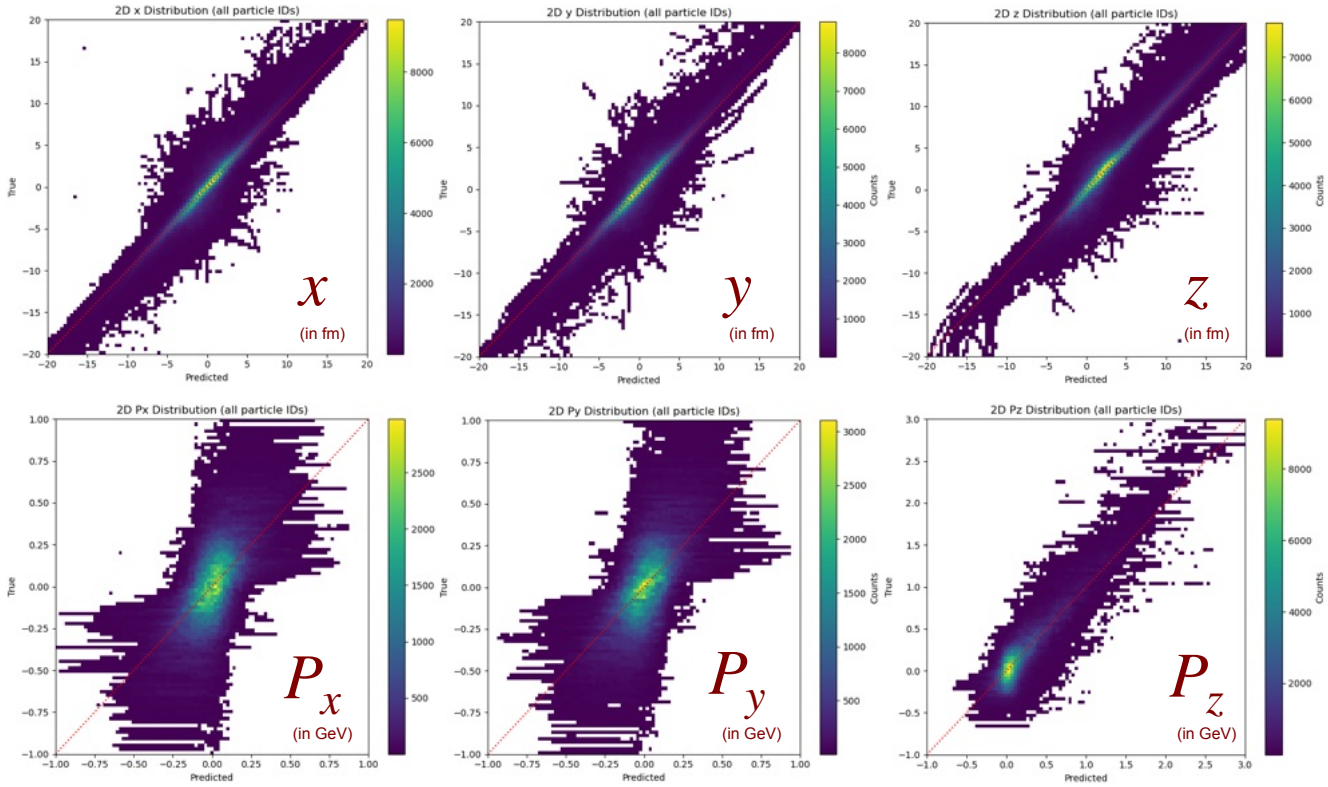
WIP with K. V. Tsang and K. Terao

- A preliminary test with 19k events look promising!
  - Class accuracy in general: 89.3%

More to come!



Features (true vs predicted)



As the saying goes…

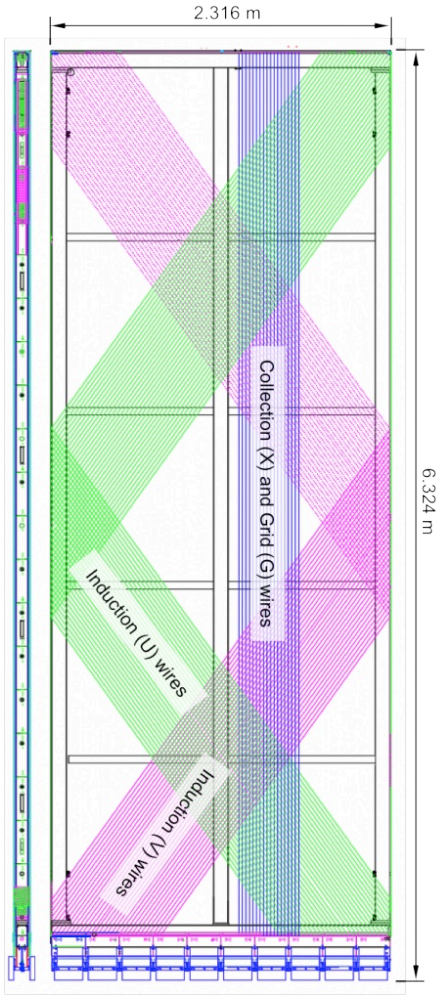
Figure: Dune 45 Sossusvlei, Namibia


DUNE is not built in one day


DUNE is not built in one day,
but some people have to build it.

DUNE Chicago factory for APA production

(Anode-Plane-Assemblies)



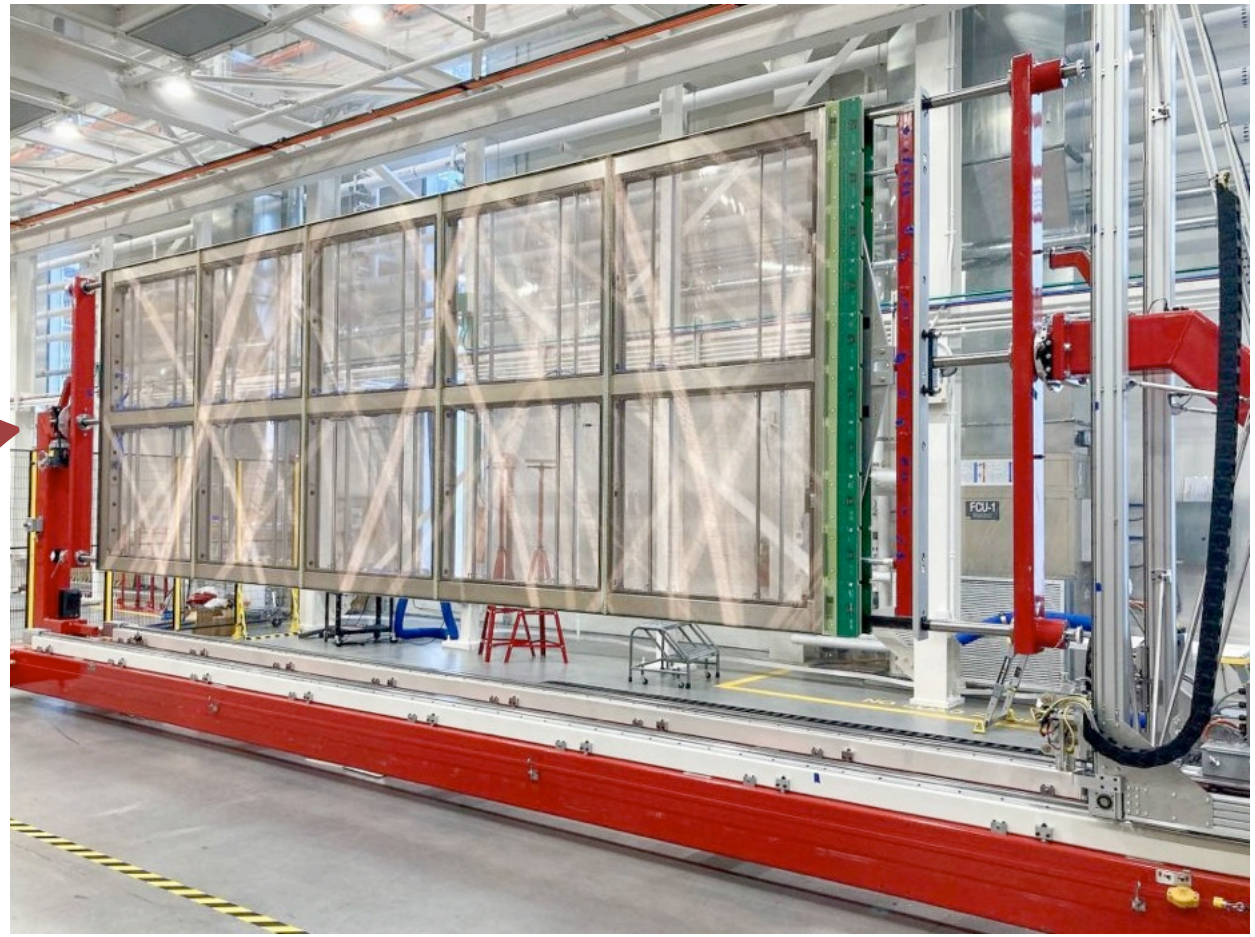
DUNE Chicago factory for APA production

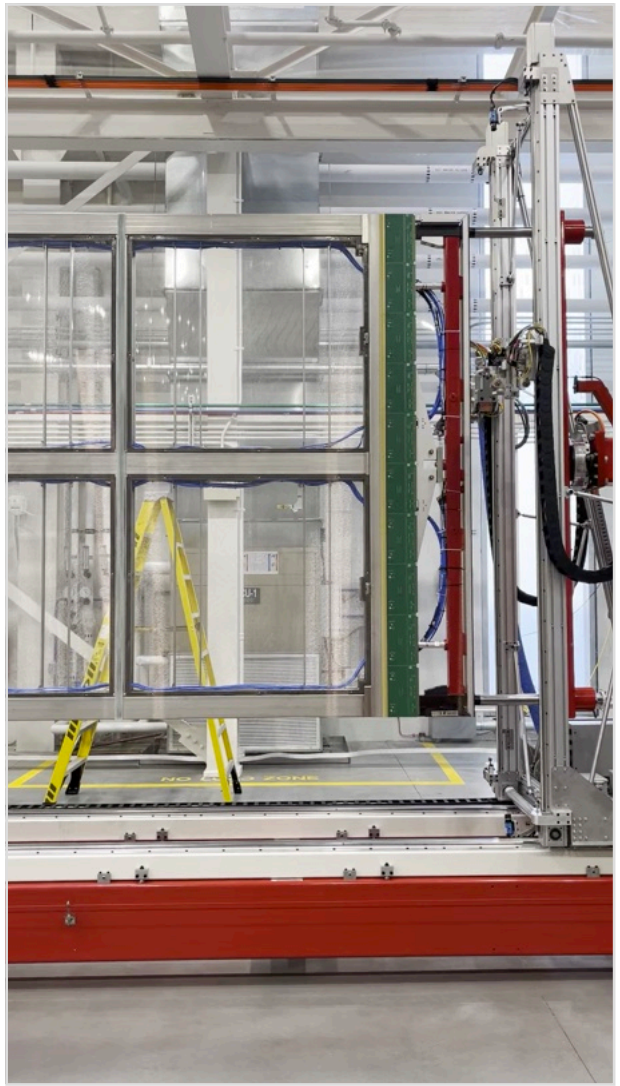
- Frame preparation

DUNE Chicago factory for APA production

- Winding

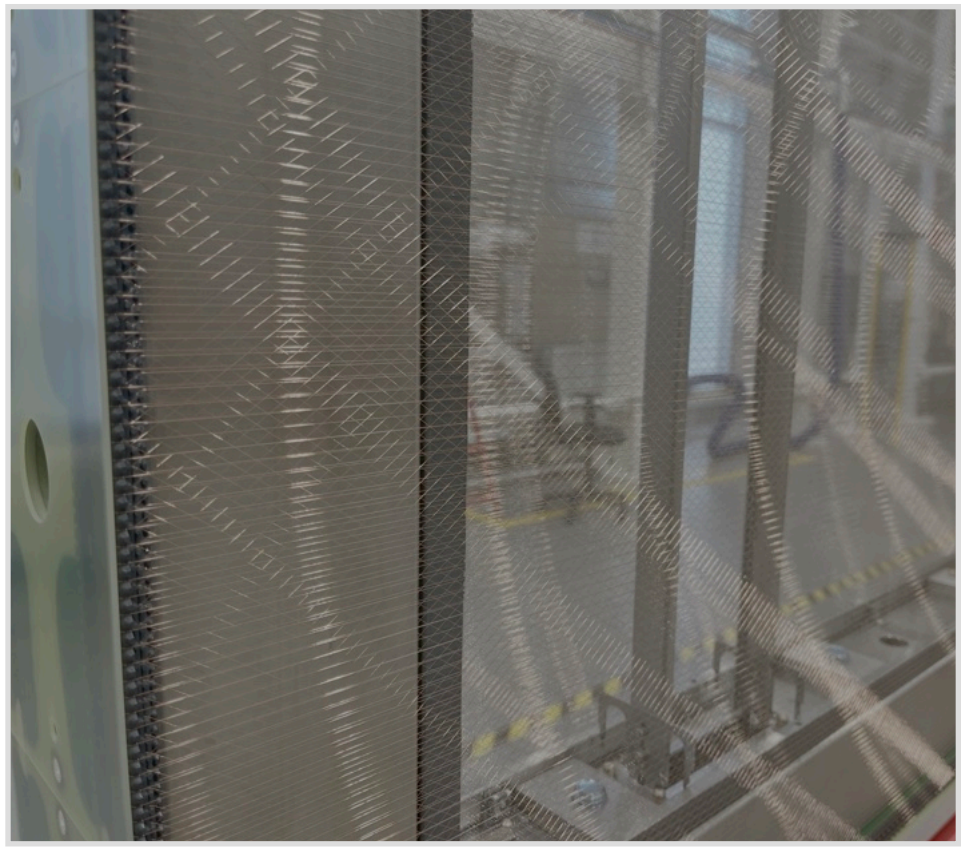
Winder

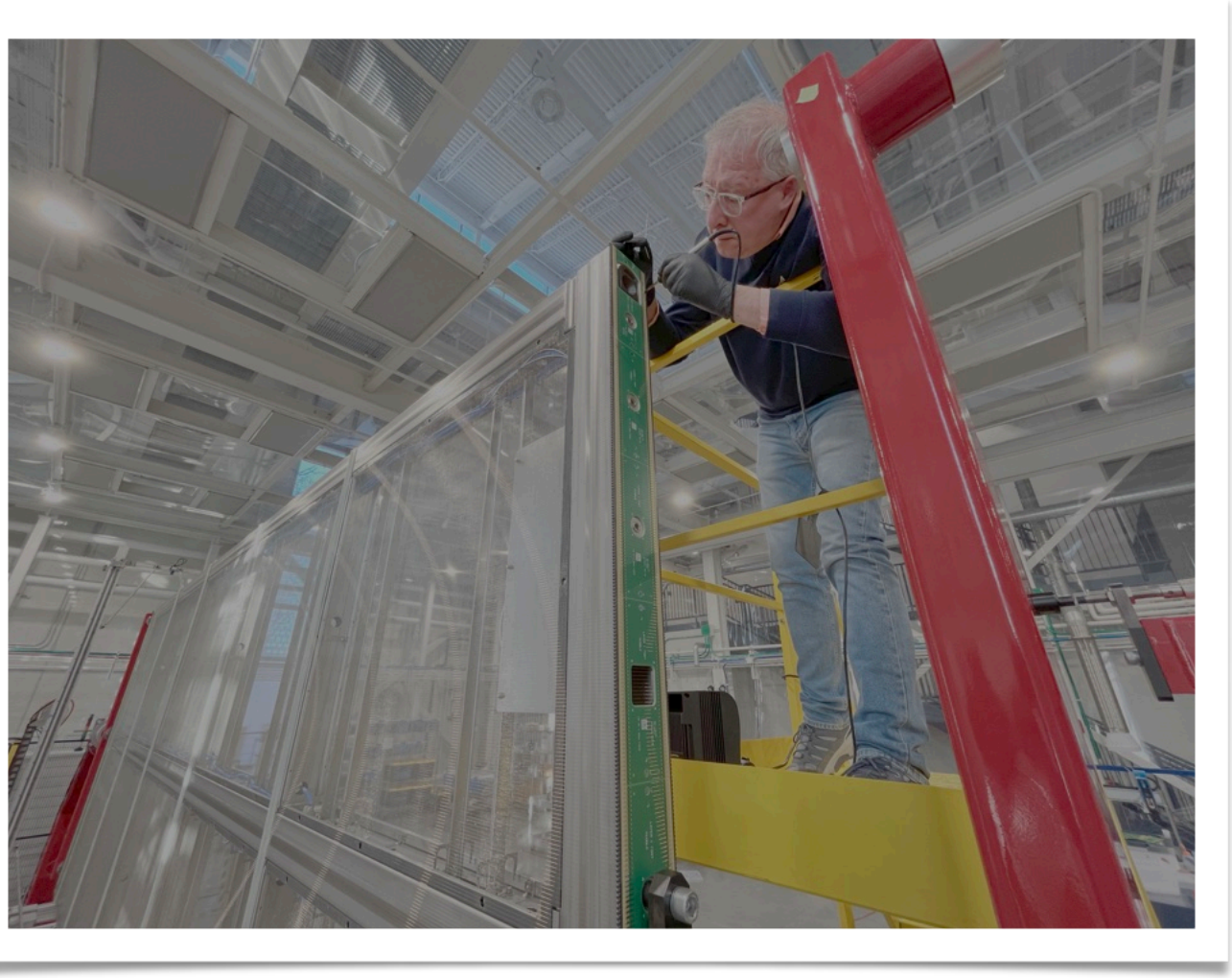




DUNE Chicago factory for APA production

- Winding





DUNE Chicago factory for APA production

- Protection panels

Conclusion

- FSI is a key component in neutrino-nucleus interactions, which can significantly impact DUNE's neutrino oscillation sensitivities.
- ProtoDUNE, beyond its role in detector R&D, advances DUNE physics by providing hadron-argon scattering data essential for refining FSI modeling.
- ProtoDUNE has published the first kaon-argon cross-section measurement, and the pion and proton inclusive/exclusive results are coming soon.
- Looking ahead, continued efforts in both theoretical guidance and experimental improvements will be vital to bringing FSI under control and ensuring DUNE achieves its ambitious physics goals.

Stay tuned for more results!

Thank you for your attention:)

Back-ups