

Status of Measuring Cross Sections of Hadrons on Argon with ProtoDUNE-SP

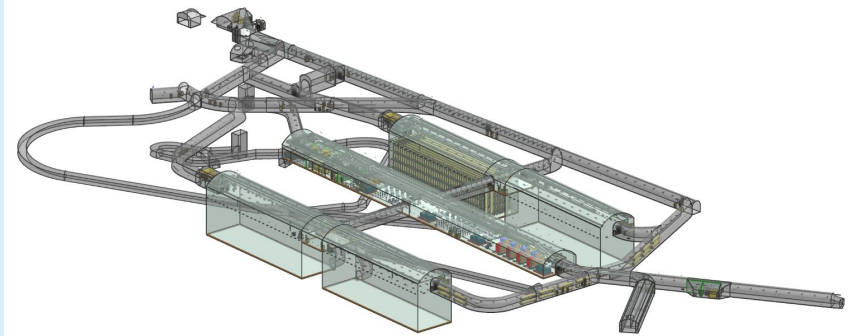
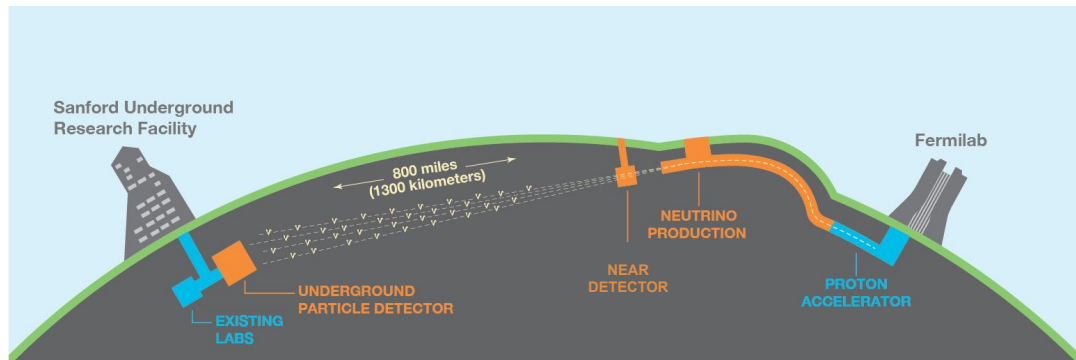
Jingyuan Shi for the DUNE Collaboration

ICHEP

18-July-2024

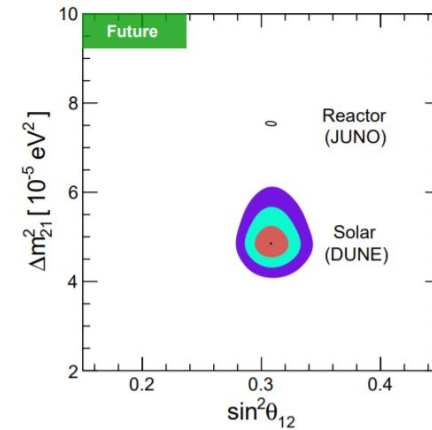
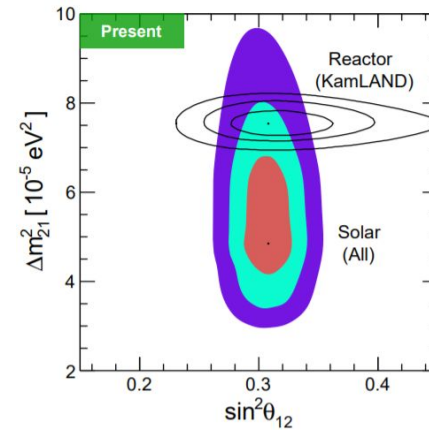
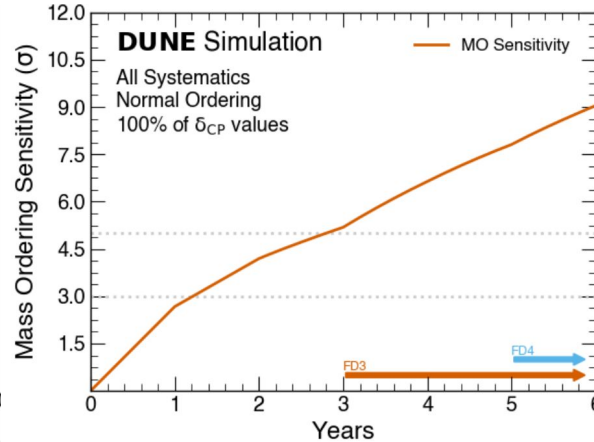
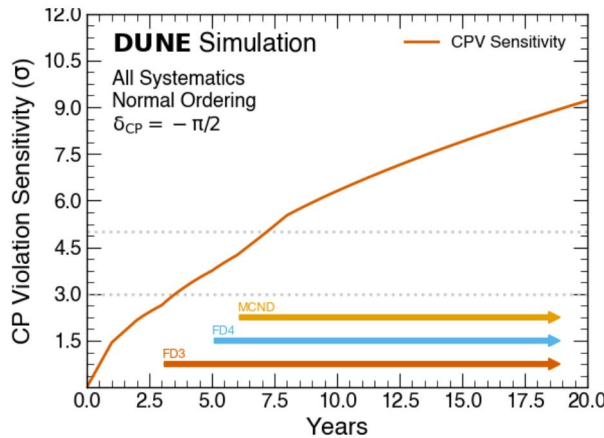
DUNE

- Sending neutrinos from Fermilab to SURF: 1300 km away.
 - Upgradable to over 2MW intensity.
- Near-far detector configuration.
 - Movable Near Detector components.
- 1.5 km deep underground to “shut out the cosmos”.
 - About 5 magnitudes fewer cosmic muons compared with surface.
- Contains 4 x 17.5 kt of liquid argon.
 - HD (horizontal drift), VD (vertical drift) and opportunity.



DUNE physics goal

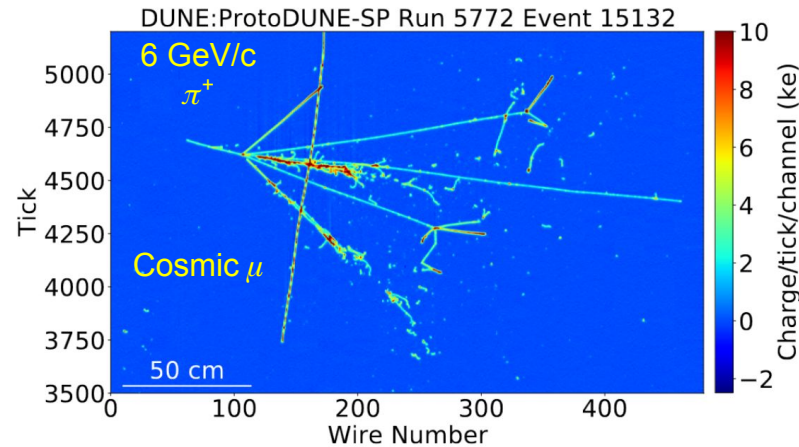
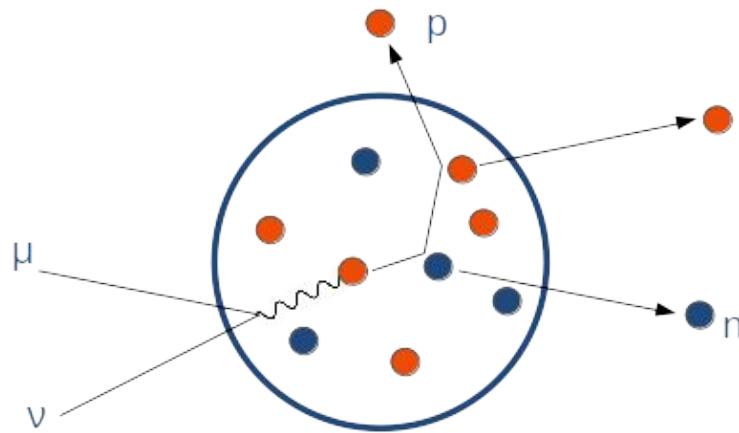
- CP-violation phase δ in the PMNS matrix.
- Neutrino mass ordering.
 - 5σ sensitivity in 3 years assuming worst-case oscillation scenarios.
- Precise measurement of other PMNS matrix elements.
- Supernova neutrino energy spectrum.
- Proton decay search: $p \rightarrow K^+ + \nu$.



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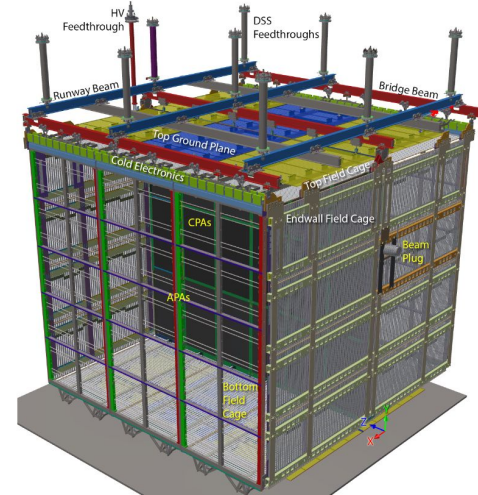
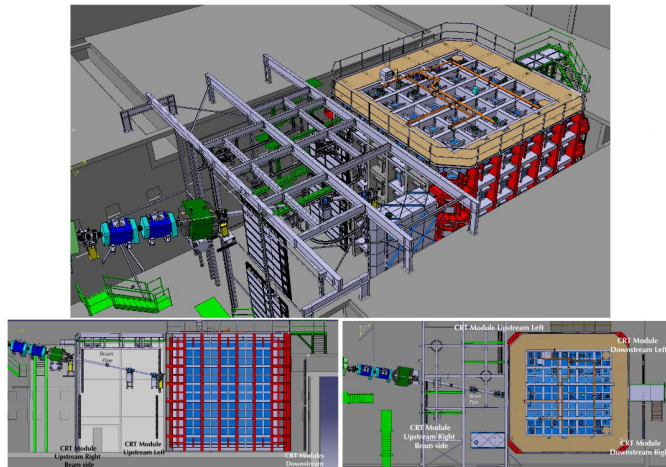
Final State Interactions (FSI)

- Final State Interaction (FSI) modelling:
 - One of the largest sources of uncertainty in current experiments.
- Limited knowledge of argon-neutrino cross section.
- Limited knowledge of argon-hadron cross section.



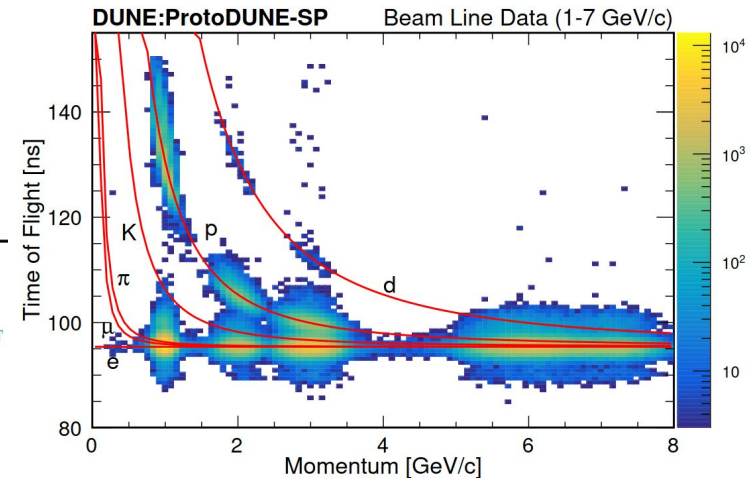
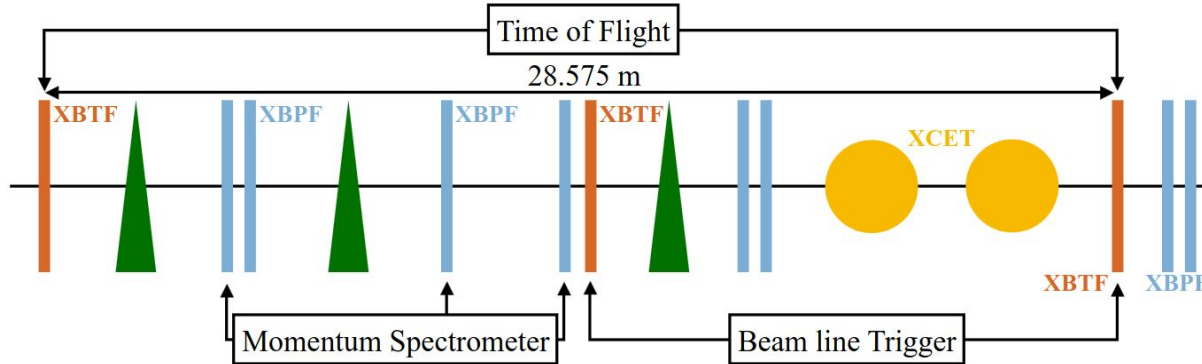
ProtoDUNE Single Phase (SP)

- Test bed for DUNE HD both in hardware and software.
- Full-scale prototype with ~800 tonnes of liquid Argon.
 - The largest monolithic LArTPC ever built.
- Took test beam particles instead of neutrinos to improve our knowledge of argon-hadron cross-section.



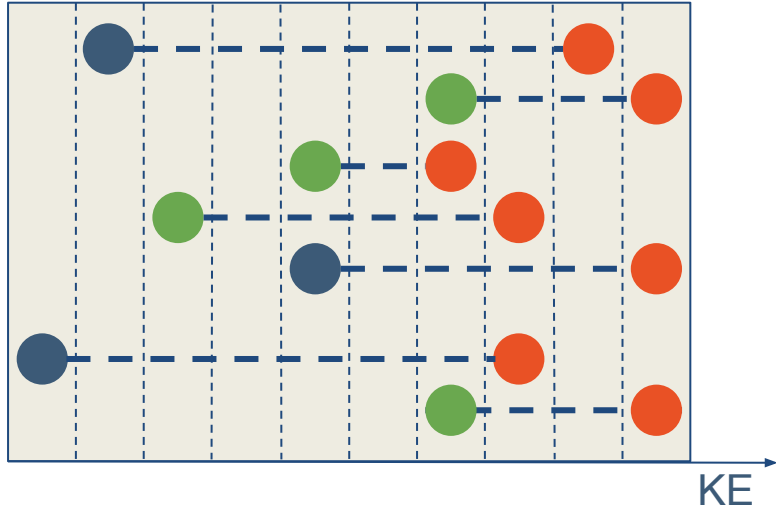
The H4-VLE beam

- Beam line instrumentation provides **tracking, PID and momentum** measurement.
- Beam particles' Time Of Flight (TOF) as a function of momentum.
- Injected e^+ , μ^+ , π^+ , p and K^+ from 0.3 to 7 GeV/c.

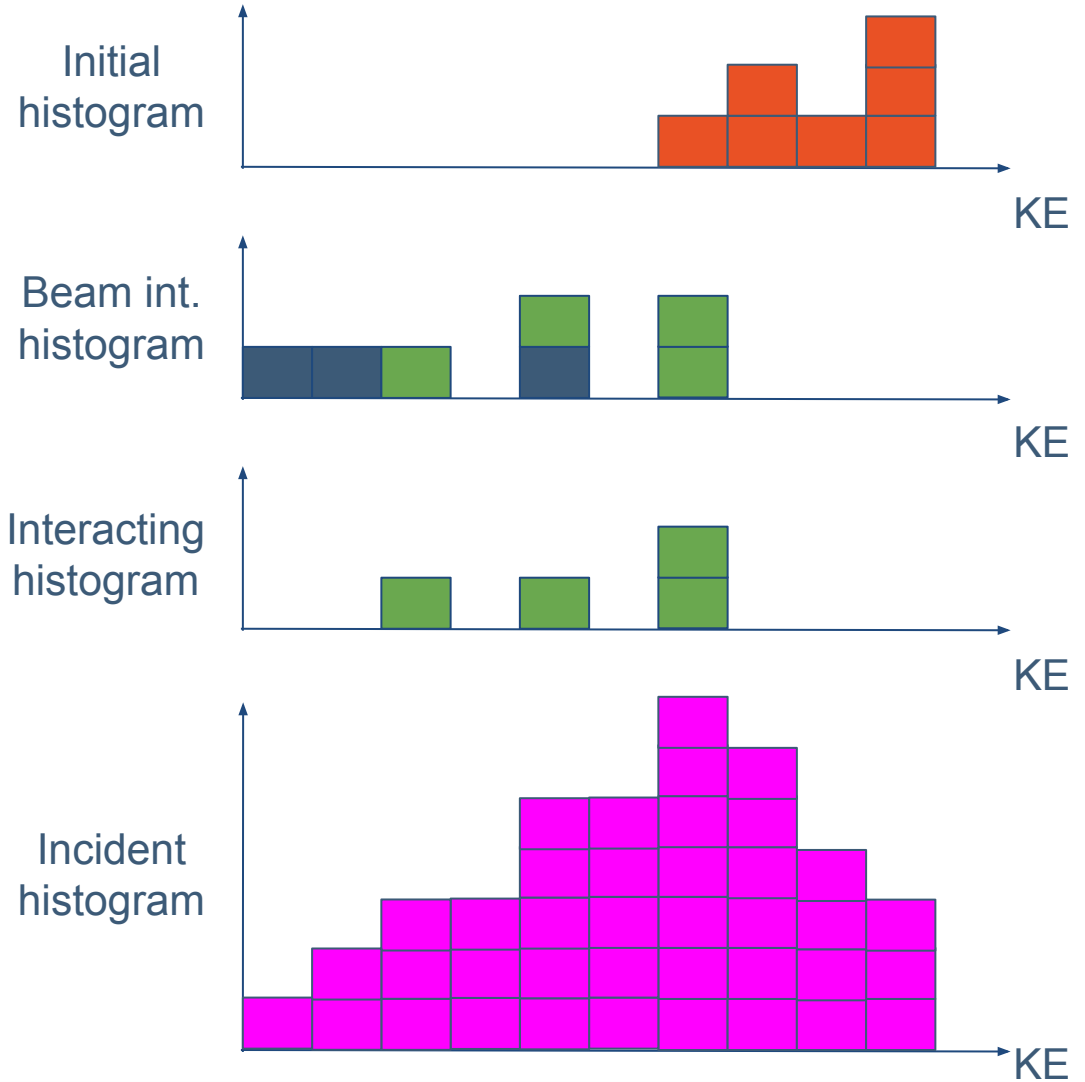


Thin slice method

$$\sigma \propto \alpha \times \ln \left(\frac{N_{\text{inc.}}(\text{KE})}{N_{\text{inc.}}(\text{KE}) - N_{\text{int.}}(\text{KE})} \right)$$

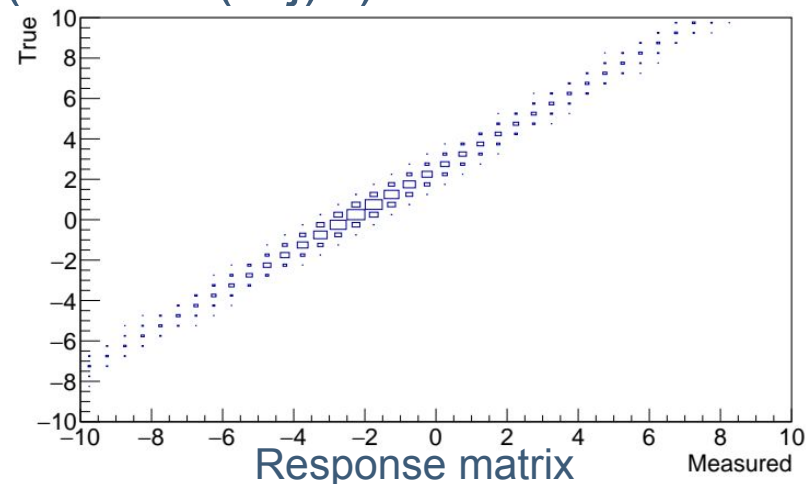
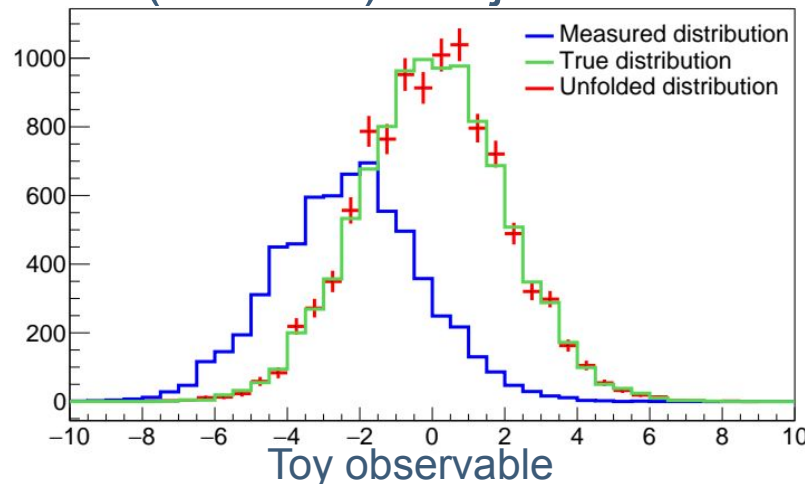


- Proton other interactions
- Proton inelastic collision
- Proton front-face



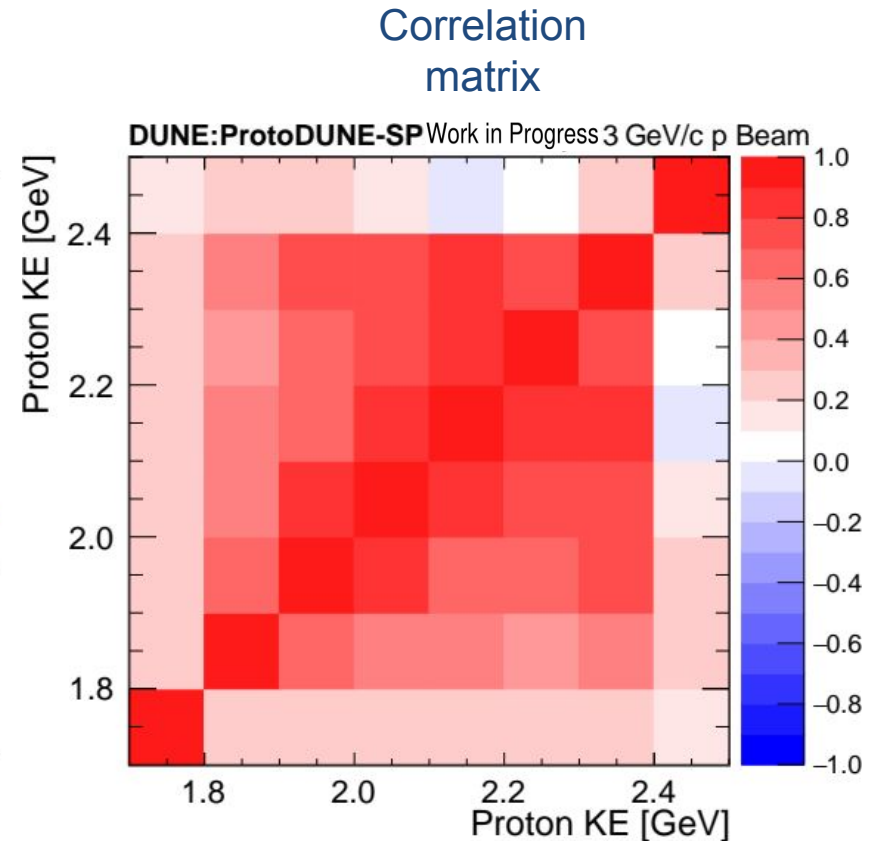
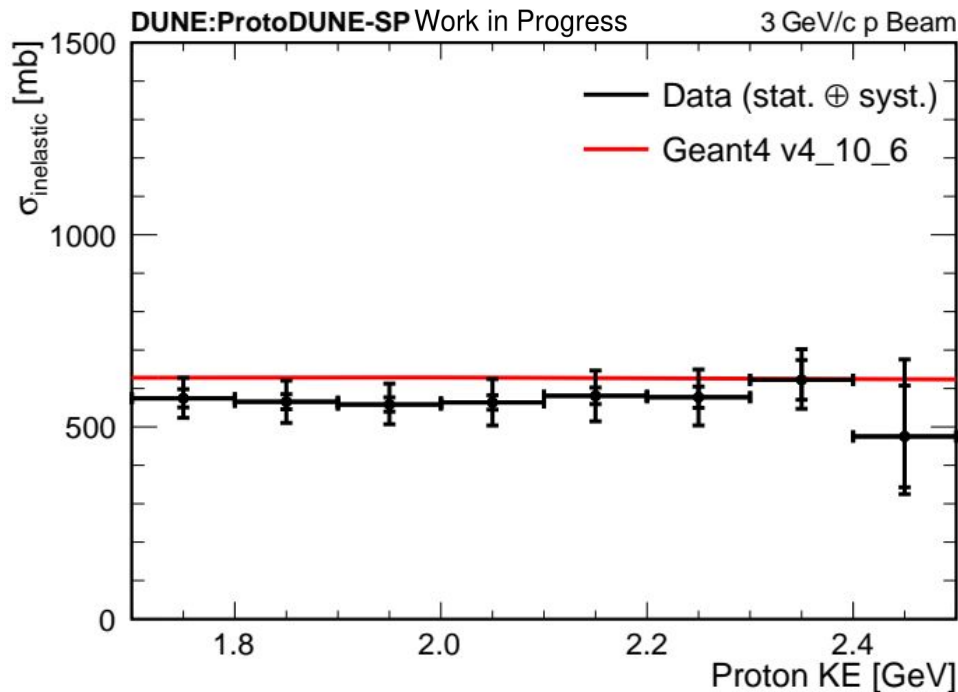
Unfolding

- Results will be presented in **truth** space.
 - Enables direct comparison among models.
- Unfolding is required to transfer reconstruction back to truth.
- Example of unfolding with toy data:
 - Left: comparison of measured, true and **unfolded distribution**. Right: the **response** (reco-true) matrix.
- $\text{Reco} = (\text{True} * \epsilon) * R_{ij} \rightarrow \text{Unfold} = (\text{Reco} * (R_{ij})^{-1})/\epsilon$



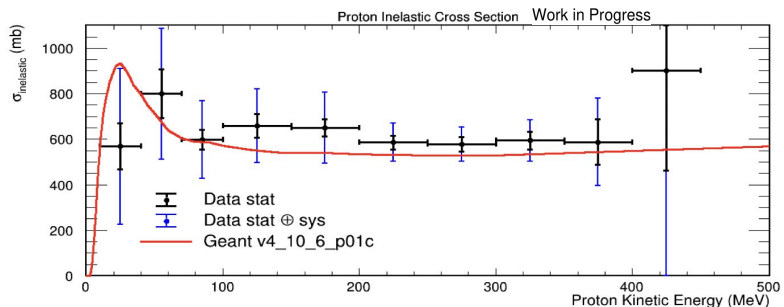
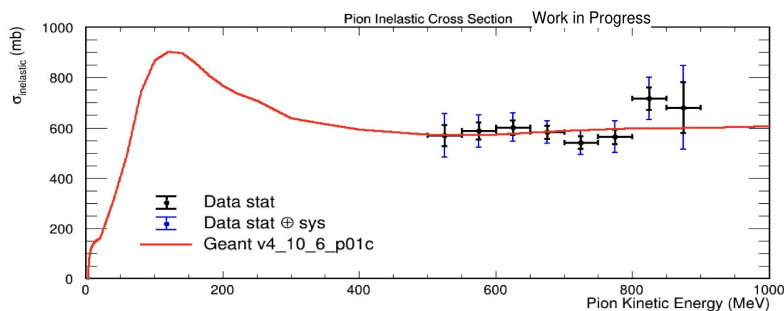
3 GeV/c proton inclusive cross section

- Best fit to a single value:
 - 572.64 ± 22.70 mb

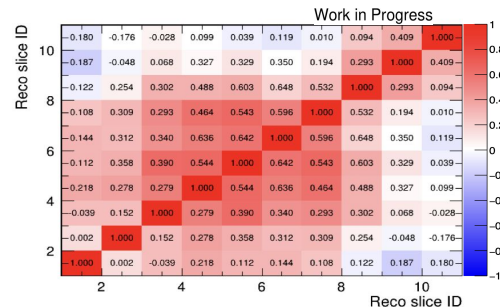
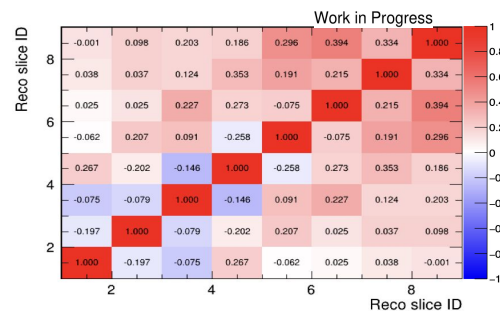


1 GeV/c p and π^+ inclusive cross section

- For more details, please see Yinrui's poster on Friday:
[Pion-argon and proton-argon inclusive cross-section measurement using ProtoDUNE-SP 1 GeV beam data](#)

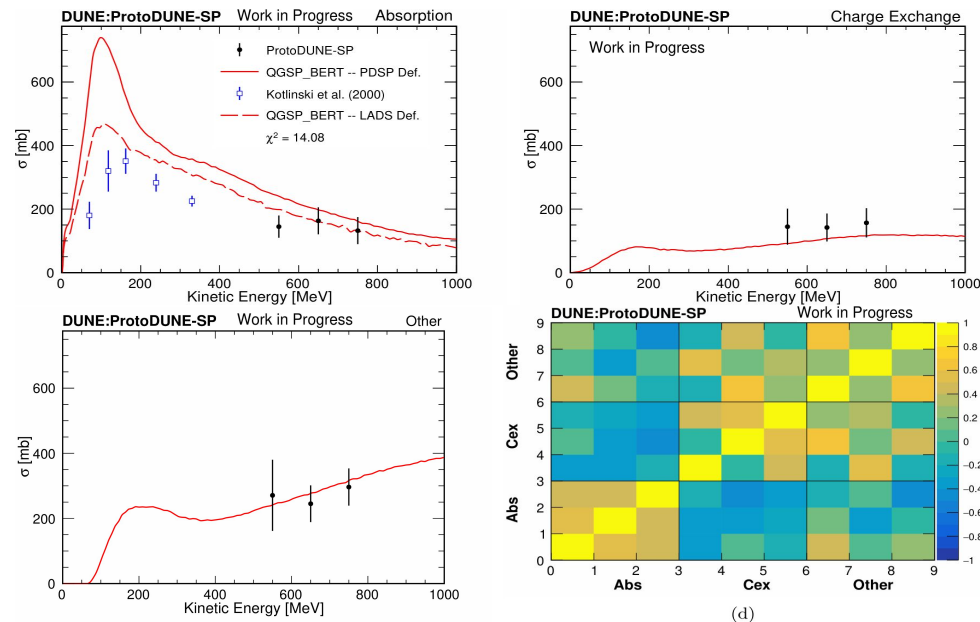


Correlation matrix



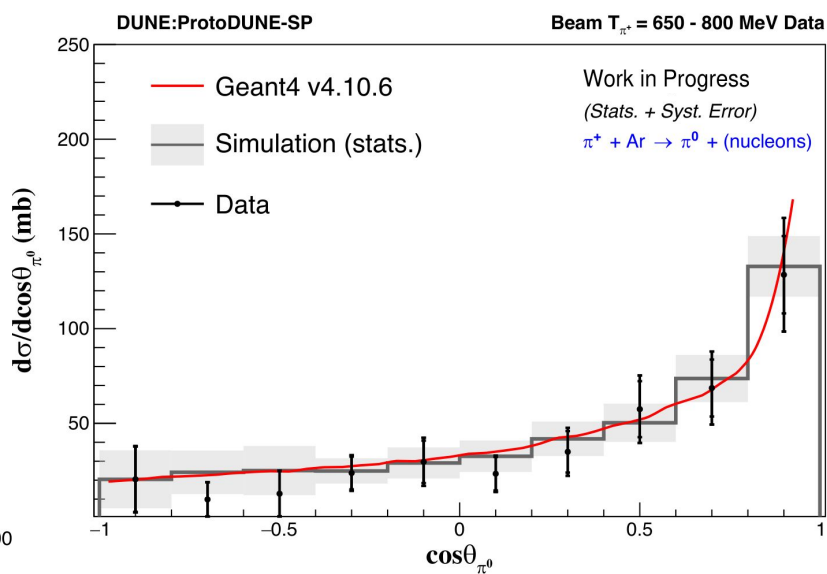
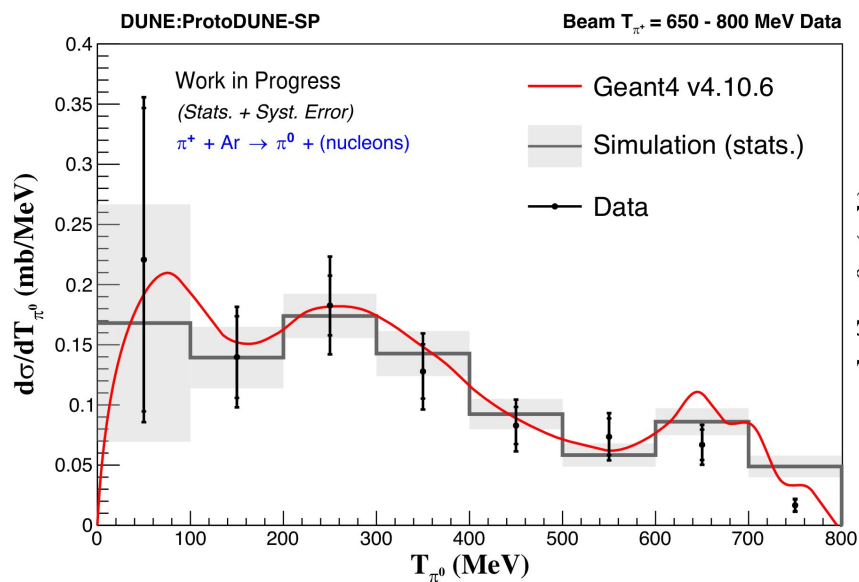
1 GeV/c π^+ exclusive cross section

- Absorption: no pions of any charge emitted from the nucleus.
 - Comparison with the LADS experiment.
- Charge Exchange: a single π^0 is emitted.
- Other: quasielastic, double charge exchange and pion production.



1 GeV/c π^+ CEX differential cross section

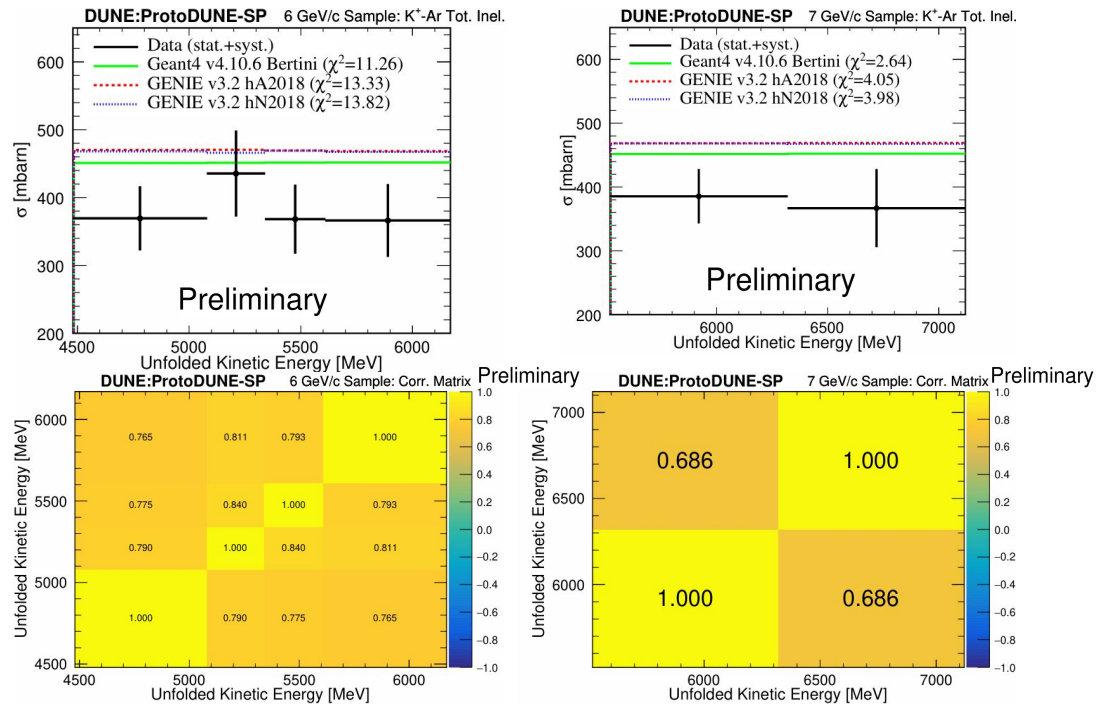
- First differential cross section of π^+ charge exchange in ProtoDUNE-SP.
- θ is the angle between final state π^0 and Z axis.



[K. Yang, Measurement of the pion charge exchange differential cross section on Argon with the ProtoDUNE-SP detector, PhD Thesis, University of Oxford, 2023](#)

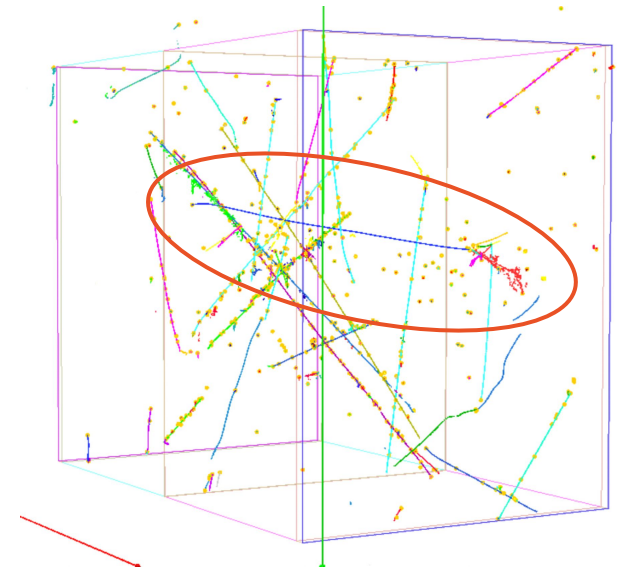
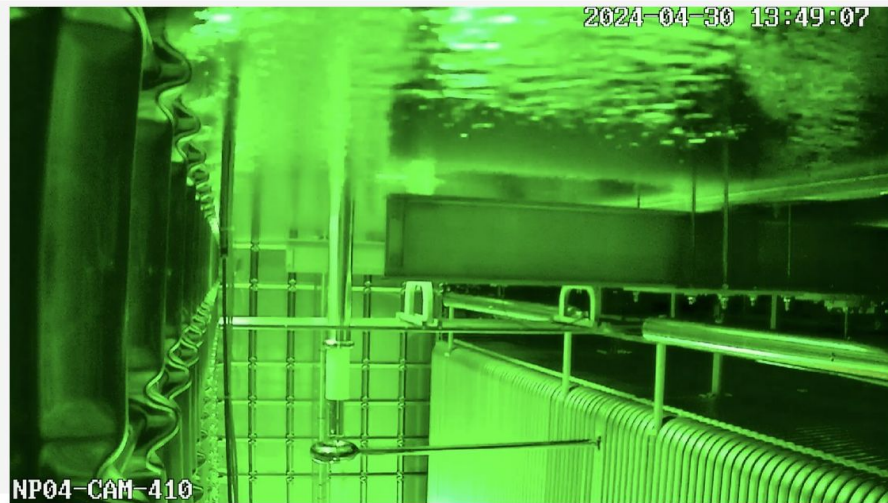
6/7 GeV/c K^+ inclusive cross section

- For more details, please see **Richie's** poster on Friday: **Measurements of a Total Inelastic K^+ -Argon Cross Section at ProtoDUNE-SP**
- Results will be published soon!



ProtoDUNE-HD

- Increased statistics of **low energy** hadrons:
 - major neutrino final states in DUNE.
- Started **taking data** from late May.
- Probing negatively charged particles.
- Please see **Luis's** poster on Friday: [Status of ProtoDUNE-II](#)



Summary

- DUNE has a broad and exciting physics programme.
 - Including the search for CP-violation in the neutrino sector.
- ProtoDUNE-SP is an engineering prototype for DUNE with its own physics programme.
 - Will provide important measurements of hadron-argon cross sections.
 - These results will reduce the systematics in the DUNE analyses.
- The first series of results have been released.
- ProtoDUNE-HD started taking data.
 - More measurements coming.

- Stay tuned for publication from ProtoDUNE-SP analysis!