Neutrino energy scale measurements in DUNE using advanced computing

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On behalf of the DUNE Collaboration

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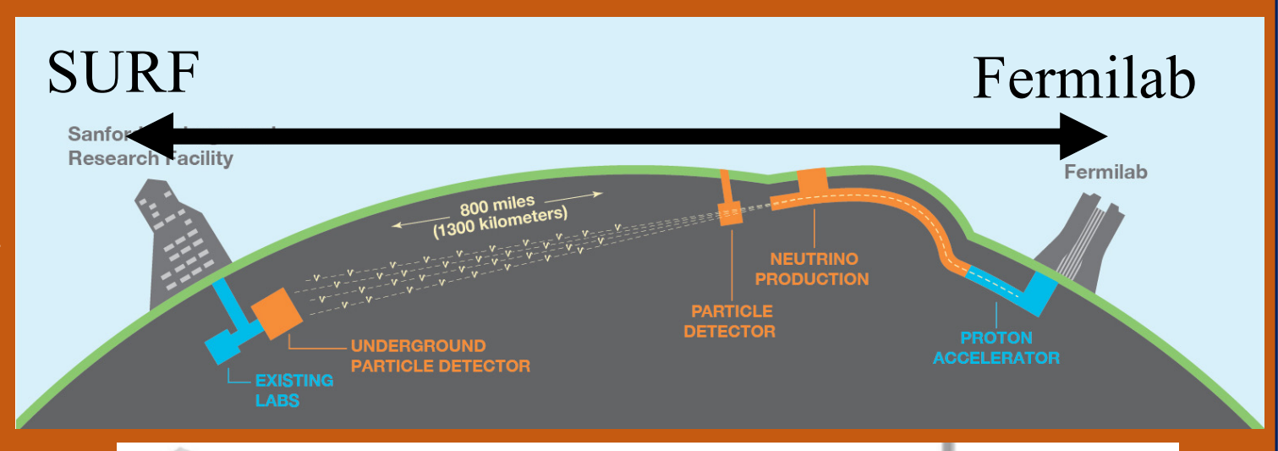
1. DUNE and DUNE-FD

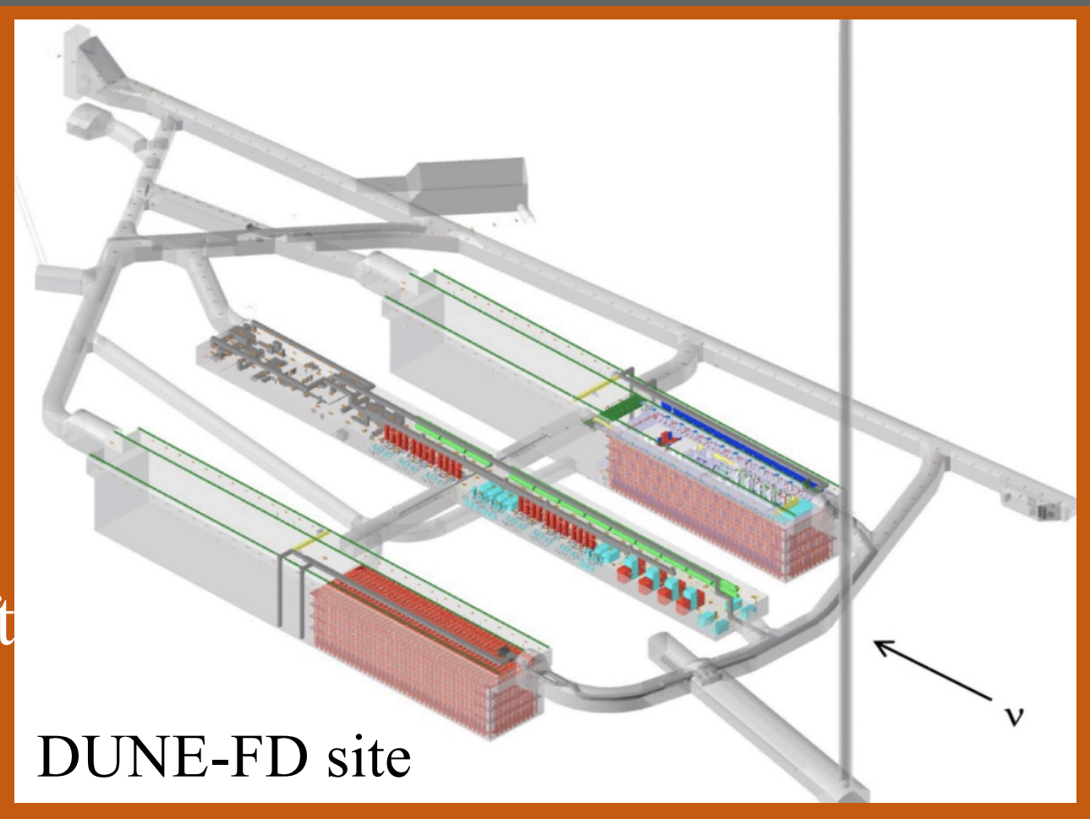
DUNE:

- 1300 km baseline
- 40 kton active mass Liquid Argon Time Projection Chamber (LArTPC) Far Detector (FD) at SURF, South Dakota, 1.5 km underground [1]
- Multiple technologies for the Near Detector (ND) [2] at Fermilab
- Will measure neutrino oscillation probability to determine mass ordering and CP violation phase via (anti)ν_e appearance and (anti)ν_μ disappearance; search for BSM physics and supernova neutrinos

DUNE-FD:

- Consists of four LArTPC modules each having a fiducial mass of 10 kt at SURF
- First module is a horizontal-drift LArTPC; second module will be a vertical-drift TPC; 3rd and 4th module technology R&D is ongoing.

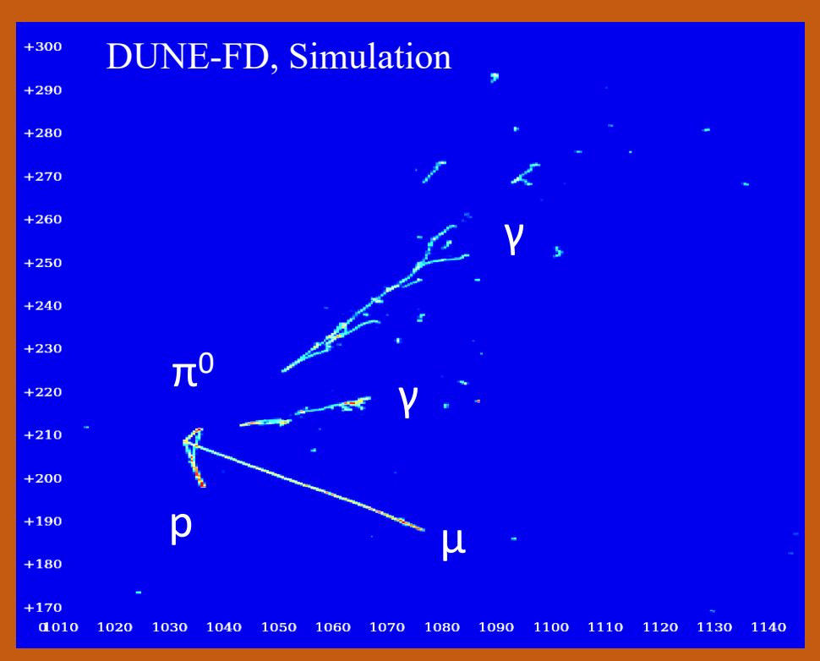


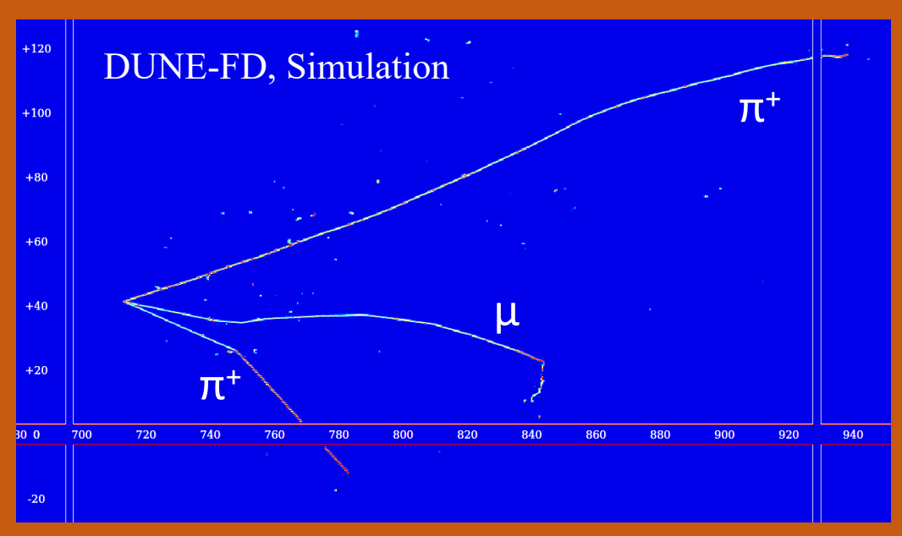


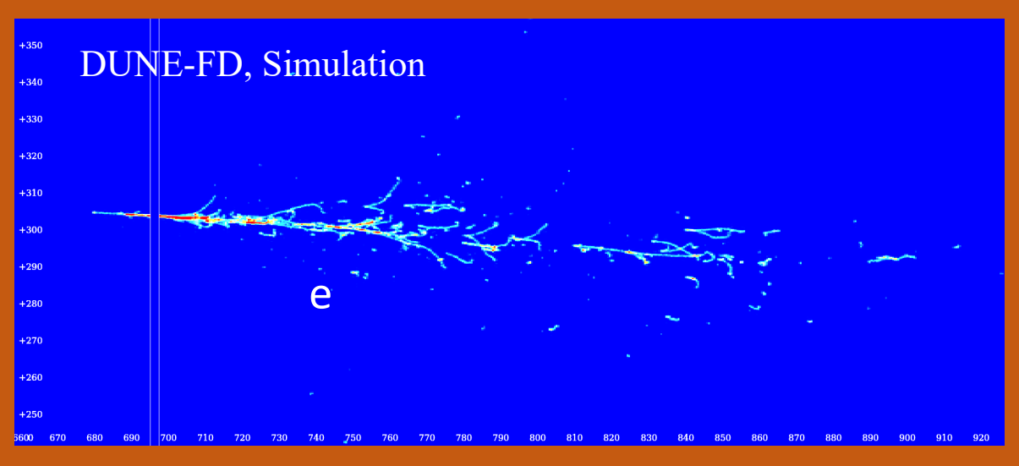
DUNE-FD site

2. Neutrino event displays

A few neutrino event displays from DUNE FD simulation. LArTPC experiments generate neutrino event images with unprecedented resolution.







3. ANL computing resources

Argonne Leadership Computing Facility

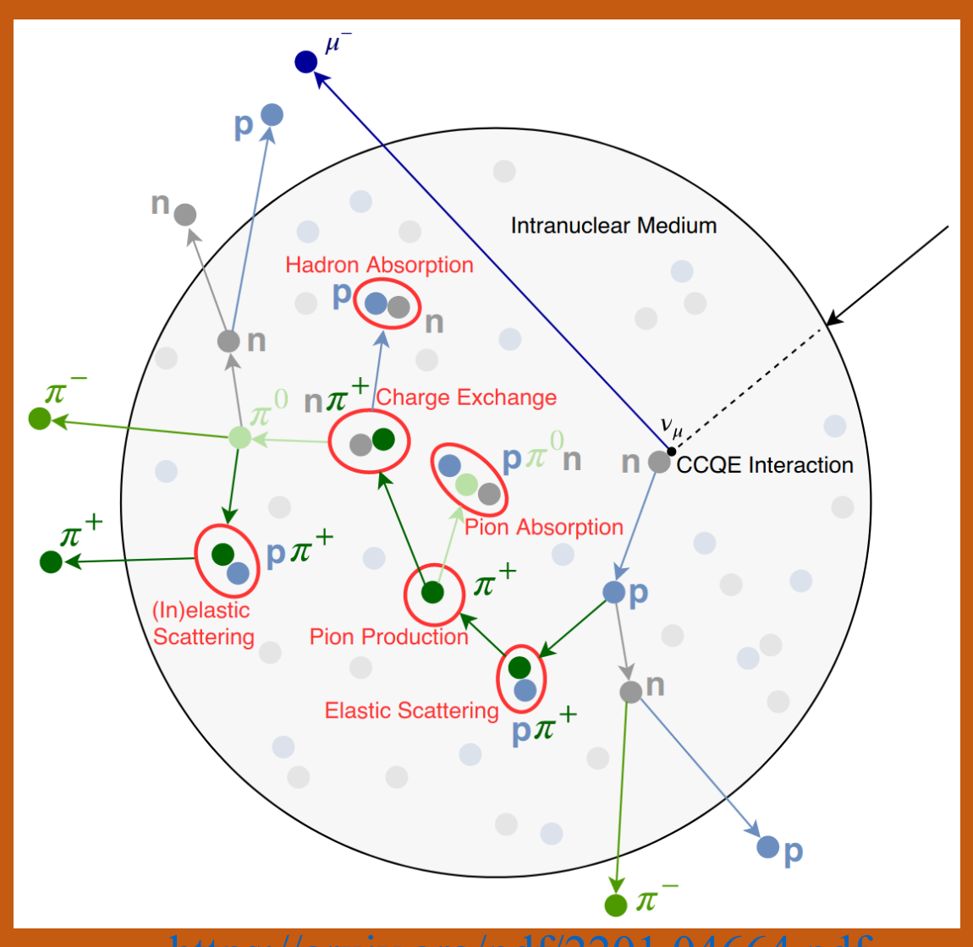
Resources	Description
Theta	11.7-petaflops supercomputer based on Intel processors
ThetaGPU	NVIDIA DGX A100 Tensor Core GPUs
ANL AI-Testbed	Machine learning based high-performance computing applications
Polaris	44-petaflop peak performance CPU/GPU, platform to test and optimize codes for Aurora
Aurora	ANL's first exascale supercomputer, projected peak performance of 2 exaflops

Laboratory Computing Resource Center

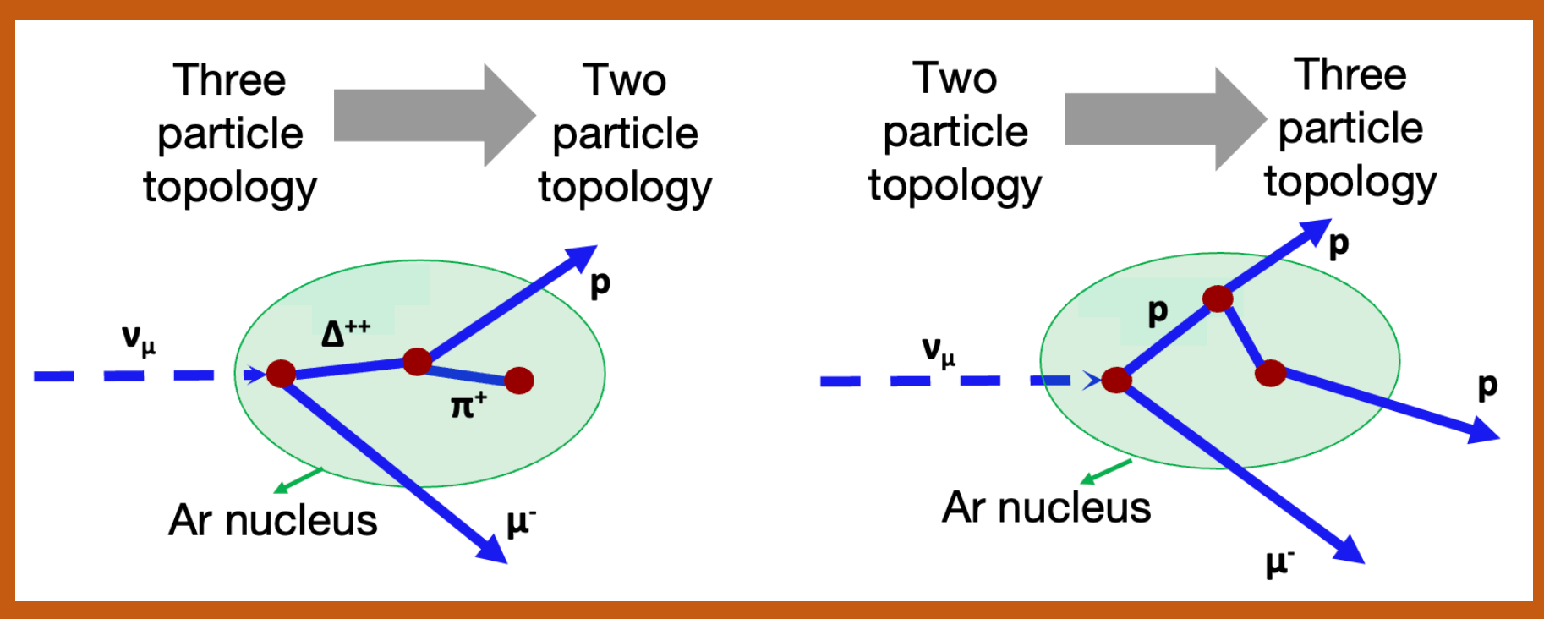
Resource	Description
Bebop	Intel Xenon CPUs with 1024 public nodes
Swing	NVIDIA AI100 GPUs with 6 public nodes

4. Final State Interactions

- When a neutrino interacts with the argon nucleus, the initial state particles are generated.
- The initial state hadrons undergo secondary interactions, called final state interaction (FSI), with the other nucleons within the same nucleus.
- FSIs provide an important way to mask the identity of the primary vertex and can totally change the topology of the interaction and can also impact the final state energy.



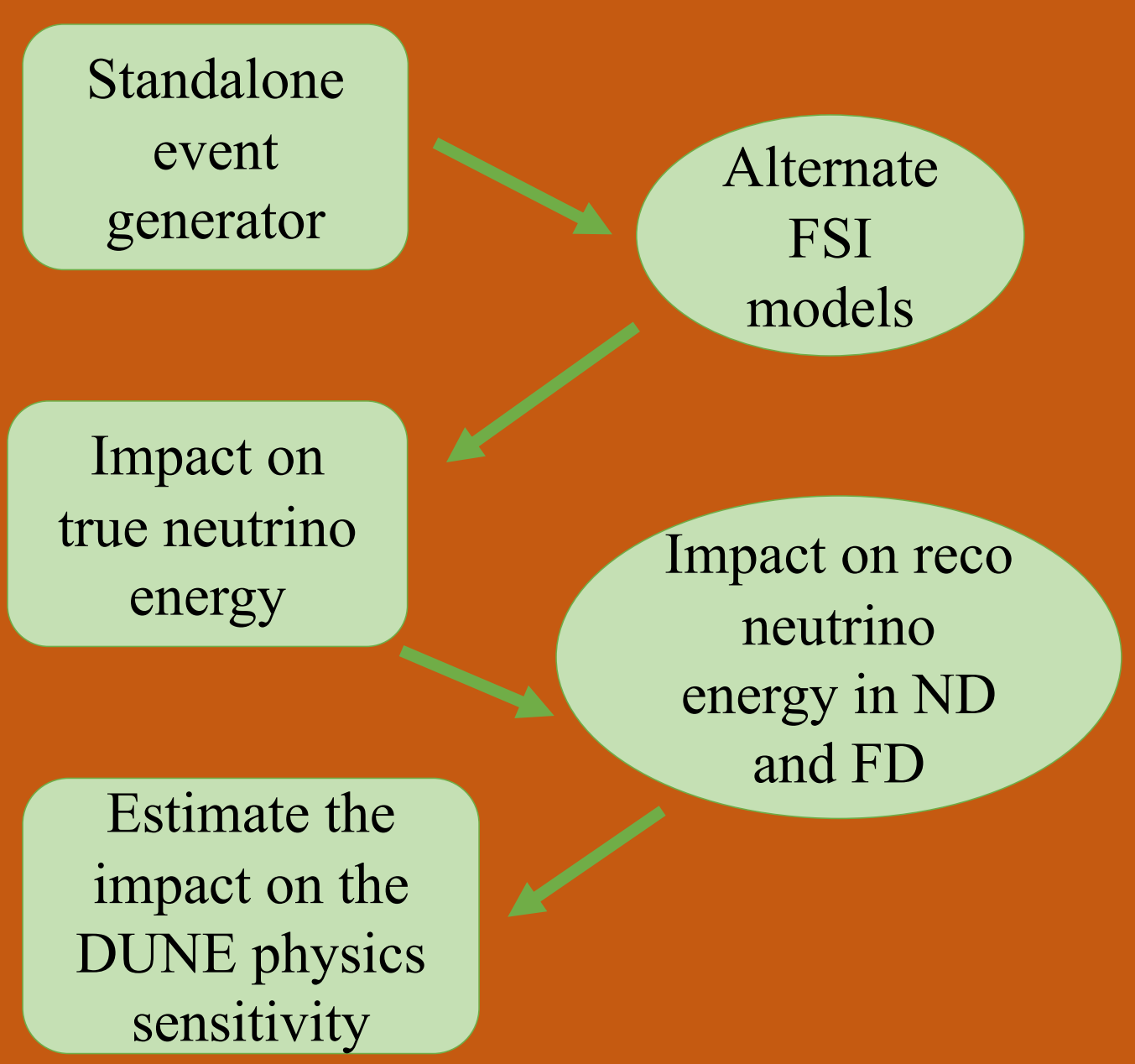
https://arxiv.org/pdf/2201.04664.pdf



FSI are dominant in heavier nuclei such as argon. They can change the topology of an interaction completely.

5. Sample generation and workflow

- 5k events were generated using GENIE (version 3.4 AR23_20i) [3] standalone neutrino event generator using ANL computing resources.
- The same initial state interactions were propagated to the following FSI models.
  - hA: the default model used in most current neutrino simulations. It only considers one hadron rescattering.
  - hN: it considers multiple rescatterings until the hadron escape the nucleus.
  - INCL++: the entire hadron-residual system changes through time steps.
  - Geant4: Bertini Cascades (G4BC) [4], more sophisticated model.
- Here we present the impact on the final state particle energies.
- We plan to see the impact on the reconstructed neutrino energy to estimate the impact on the DUNE physics sensitivity studies.


Standalone event generator

Alternate FSI models

Impact on true neutrino energy

Impact on reco neutrino energy in ND and FD

Estimate the impact on the DUNE physics sensitivity

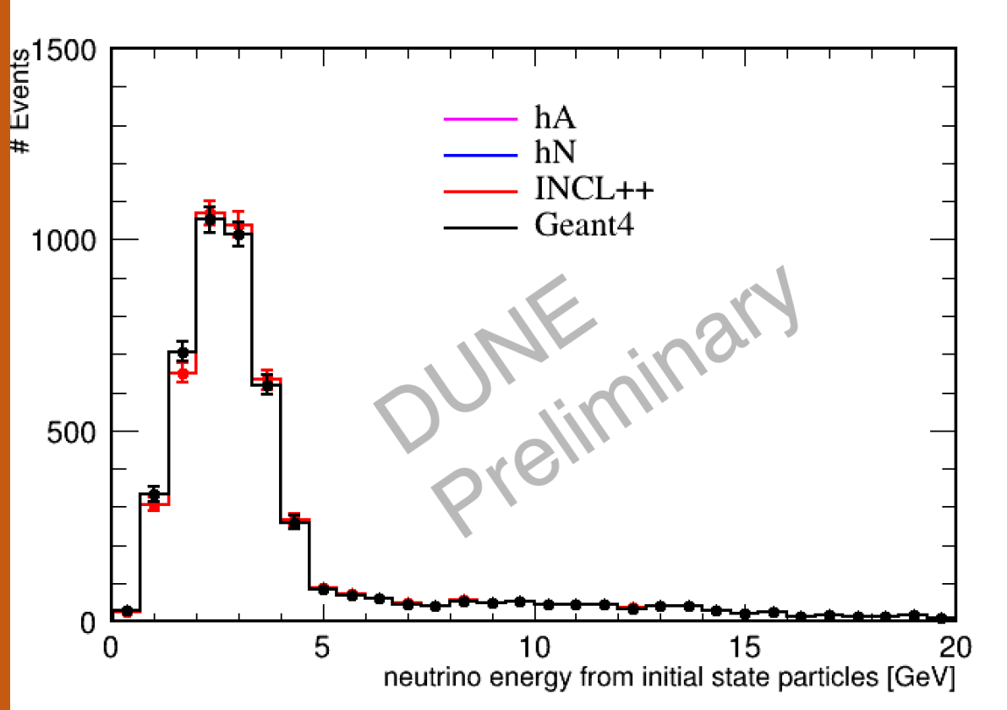
6. Initial and final state energy sum

- The sum of all initial and final state energies is calculated by

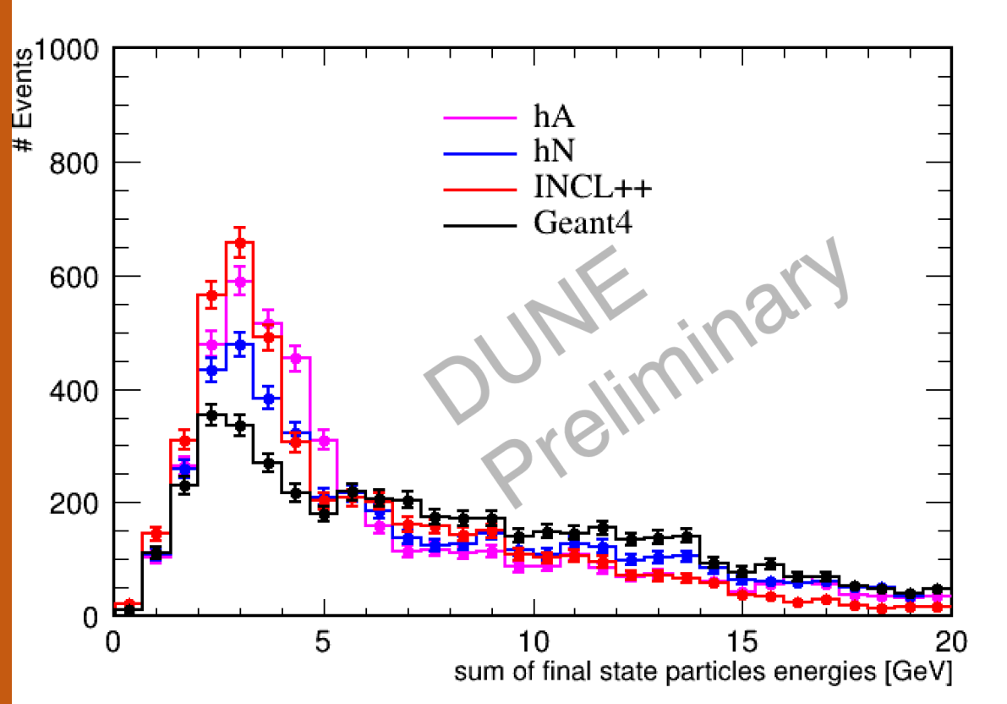
$$E_{i(f)} = E_h + E_l - E_n$$

where $E_{i(f)}$ is the initial (final) state particle energies; E_h is the initial (final) state hadronic energy sum; E_l is the primary lepton energy; and E_n is the hit nucleon energy.

- We see that the initial state energies are consistent as expected.
- There is a discrepancy from the default tune as large as ~45%.
- These discrepancies limit our model understanding and will impact the energy scale and reconstruction.



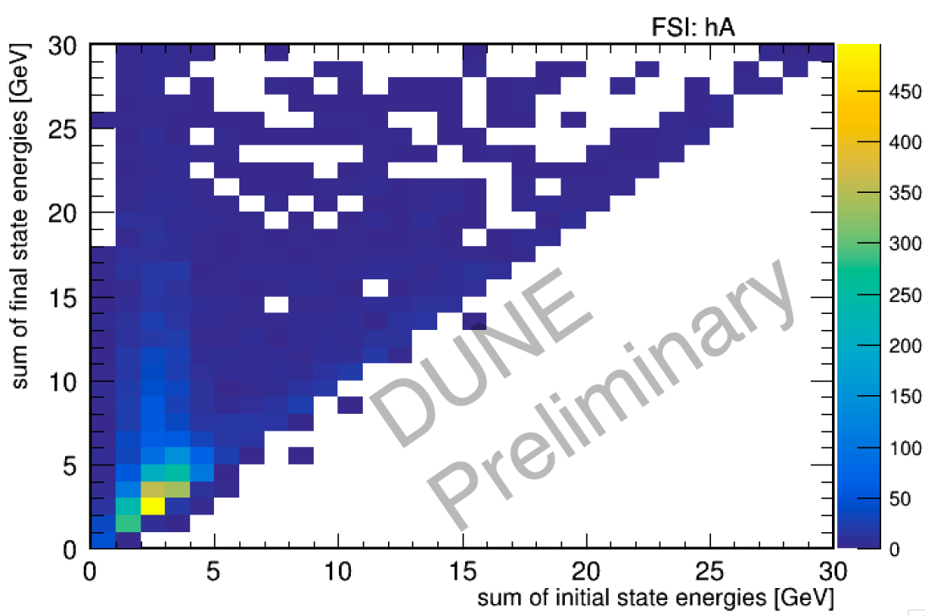
Initial state particle energy sum



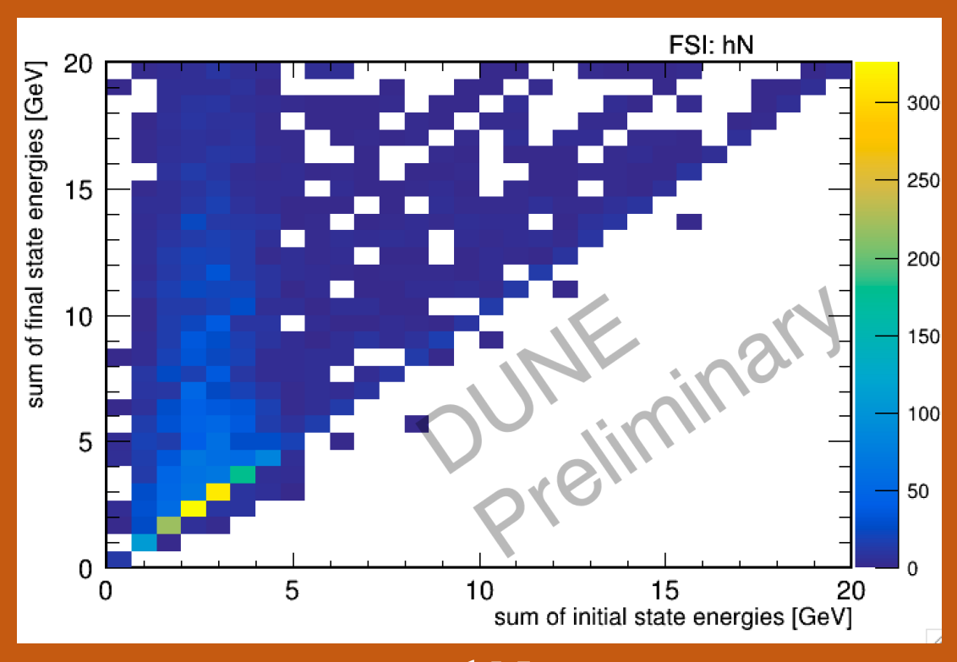
Final state particle energy sum

7. Observations and results

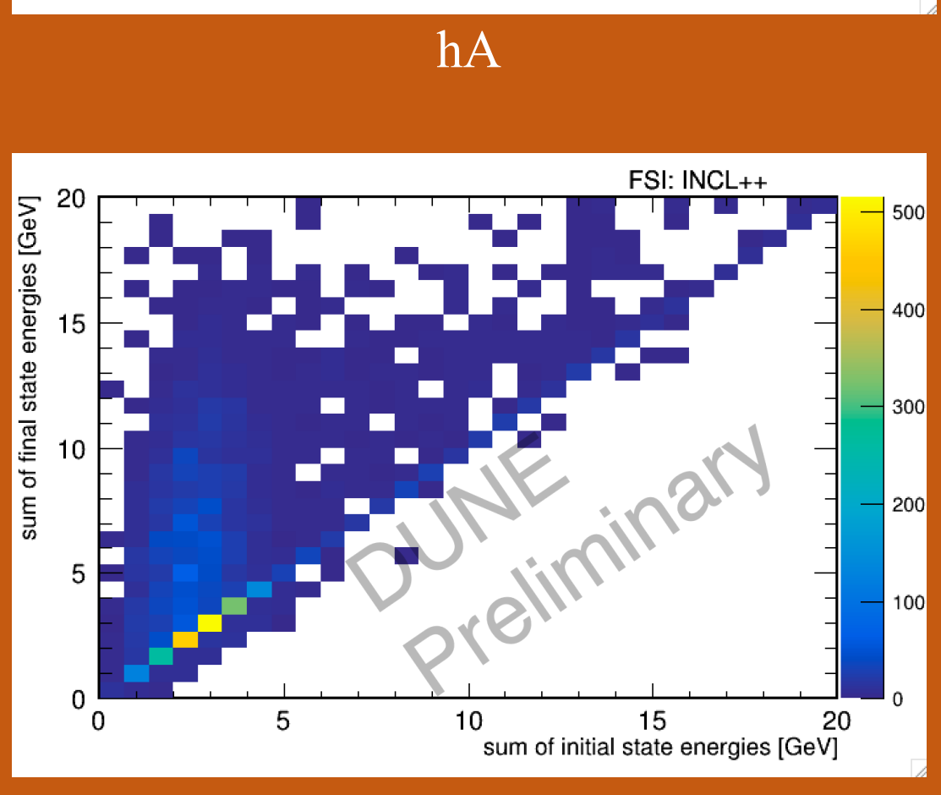
- Initial versus final state energies are plotted for different FSI models.
- There seems to be a better agreement in initial and final state energies for the models hN and INCL++.



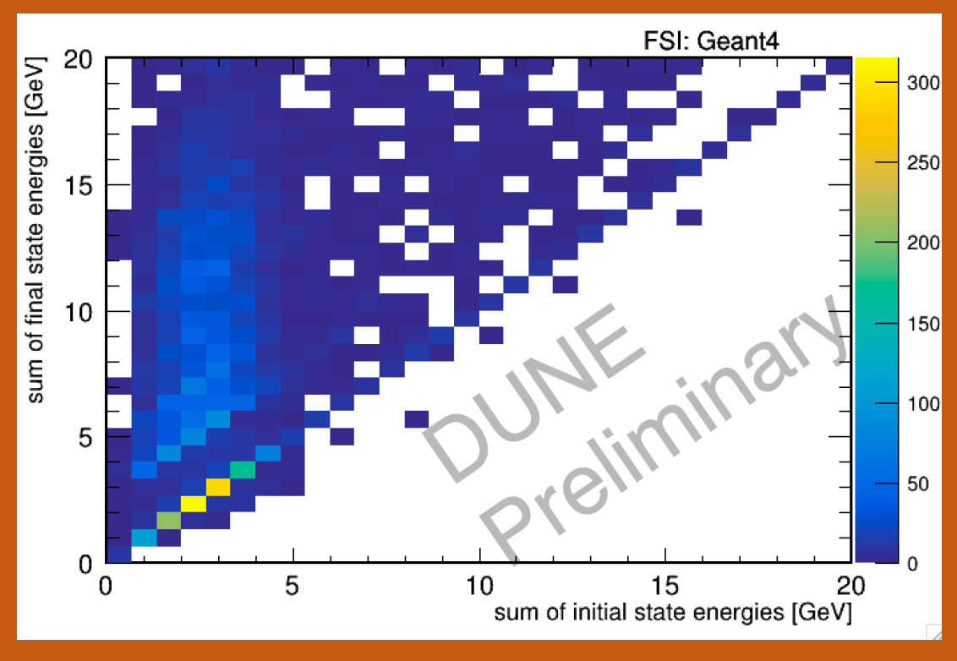
hA



hN

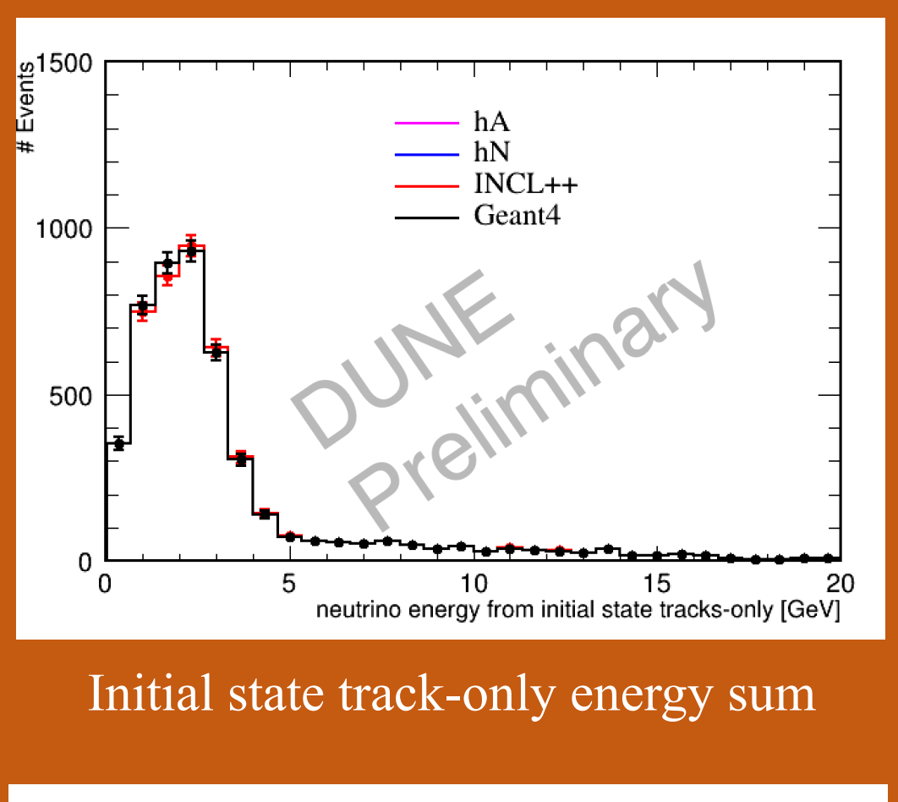


INCL++

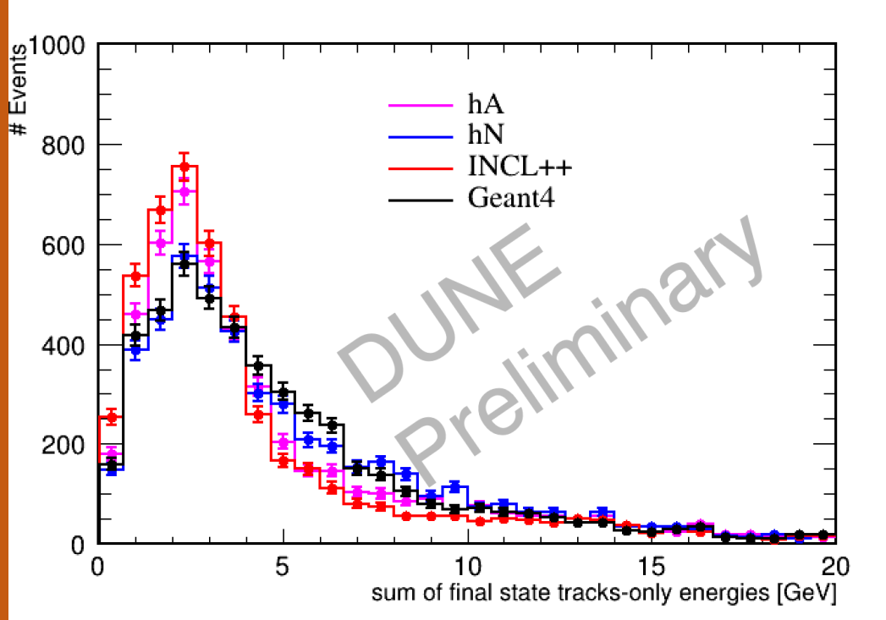


Geant4

For track-only energy sum, the discrepancy between initial versus final energy reduces to 23%. This may hint that the shower modelling is mostly different between different tunes.



Initial state track-only energy sum



Final state track-only energy sum

8. Summary and next steps

- This is the first demonstration of utilizing ANL computing for DUNE physics studies.
- We observed how FSI can impact the neutrino energy spectrum.
- In future, we plan to look into the dependence of the energy difference between different neutrino interaction types (QE, RES, DIS etc).
- We plan to reconstruct the neutrino energy using FD reconstruction tools.
- Calculate the effect of these uncertainties on the CP violation sensitivity studies

[1]: JINST 15, no. 08, T08008 (2020)
[2]: Instruments 5 (4), 31 (2021)
[3]: https://arxiv.org/abs/1510.05494
[4]: Nuclear. Ins. Meth. Phys. Res A 804 (2015) 175-188

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