131.ND.02 ND-LAr Physics and Design

Andrew Mastbaum and Pedro Ochoa-Ricoux, ND-LAr Analysis Coordinators

ND-LAr Preliminary Design Review

27 June 2022

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Who we are:

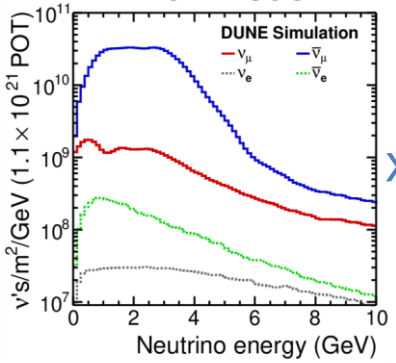
- Andrew Mastbaum:
  - Assistant Professor, Department of Physics and Astronomy, Rutgers University
  - Background in accelerator neutrinos (SBND, MicroBooNE, DUNE, ANNIE), neutrino astrophysics and neutrinoless double-beta decay (SNO, SNO+, Theia)
  - Analysis Tools & Techniques co-coordinator in MicroBooNE
- Pedro Ochoa-Ricoux:
  - Associate Professor of Physics, University of California, Irvine
  - Background in reactor (Daya Bay, JUNO) and accelerator (MINOS, DUNE) neutrino experiments, as well as in collider experiments (ATLAS) and R&D (LiquidO).
  - Analysis co-coordinator/convener in Daya Bay and JUNO

Outline

- DUNE Physics and ND-LAr Requirements
- Recommendations from Previous Reviews
- Status of Simulation & Analysis tools
- Pathway to FDR
- Summary

The ND's role in DUNE's oscillation measurements

Flux Model



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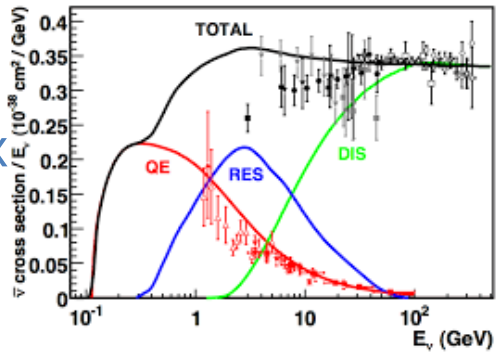
Interaction Model



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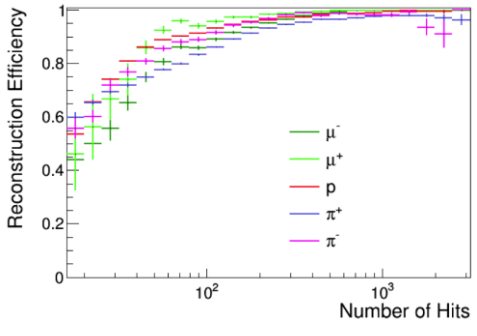
Detector Model



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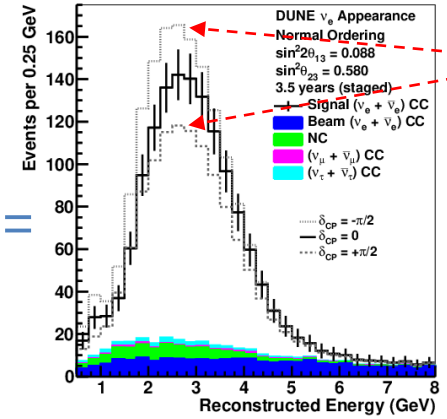
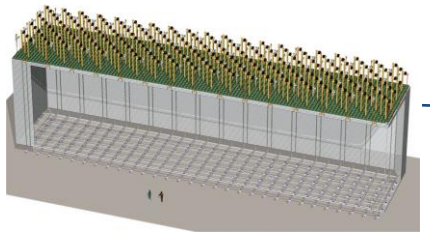
FD Prediction



max CP violation signal!
Control of systematics essential for physics reach

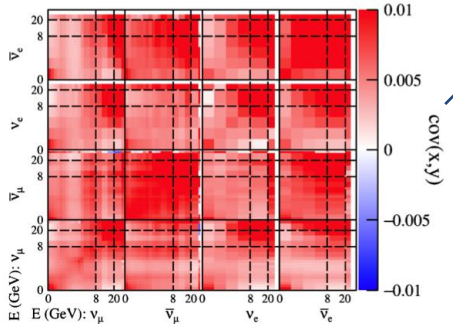
FD Data



Fitting Framework

Oscillation Results

Systematics



DUNE is a **precision** neutrino oscillation experiment

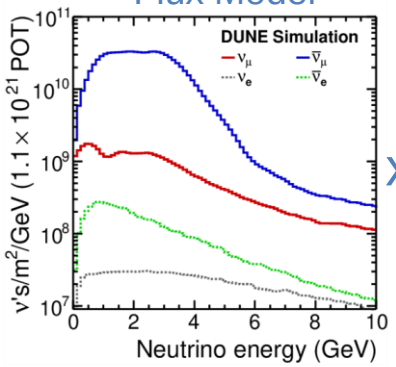
Main strategy: compare FD data to unoscillated prediction and determine what parameters best describe the difference

Challenge: large uncertainties in flux, interaction, and detector models

The ND's role in DUNE's oscillation measurements

Technical requirements: **ND-00** (predict FD spectrum), ND-01, ND-02, ND-03

Flux Model



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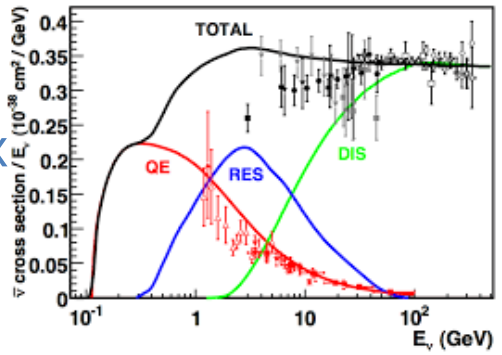
Interaction Model



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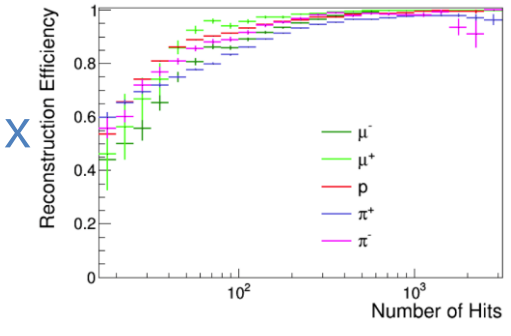
Detector Model



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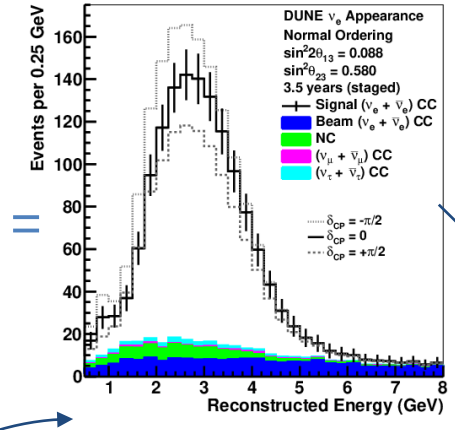
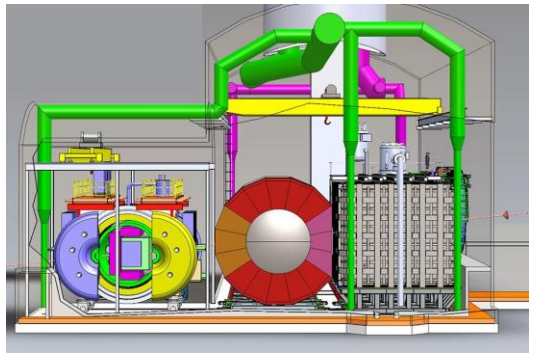
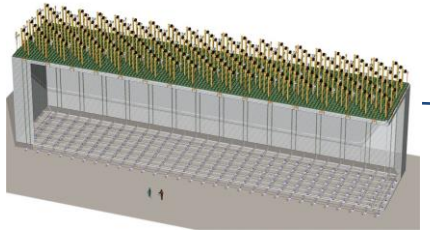
FD Prediction



ND Data



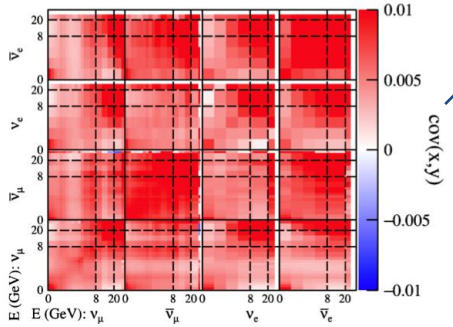
FD Data



Fitting Framework

Oscillation Results

Systematics



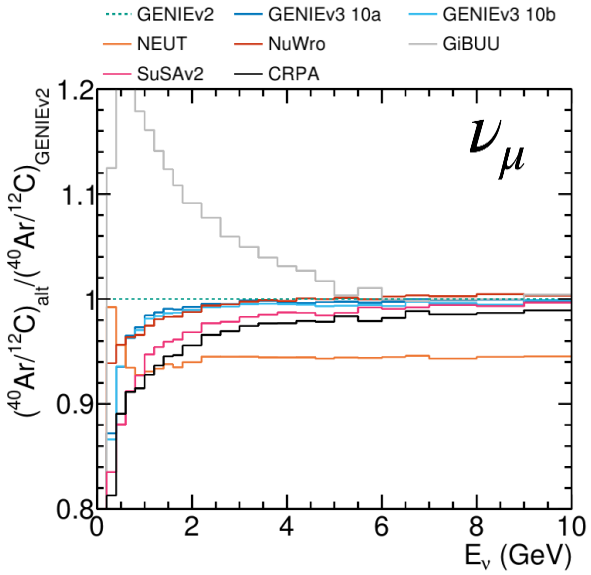
The ND has an essential role: constrain uncertainties in FD prediction by measuring the **same** (flux × interaction × detector model)

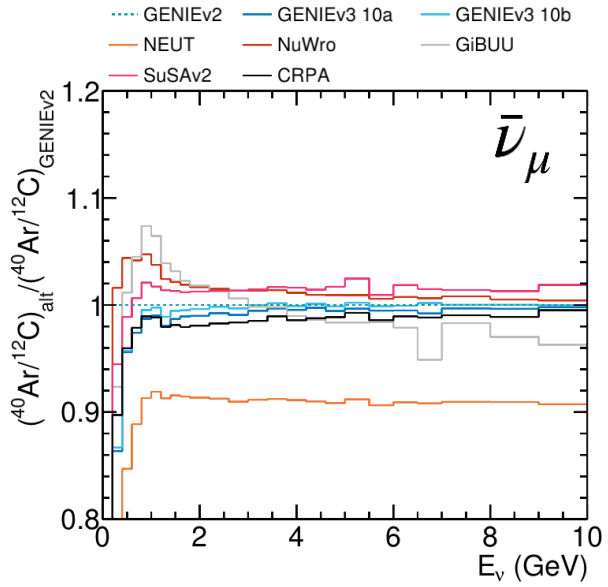
LBNF/DUNE

Requirement #1: same target as the FD

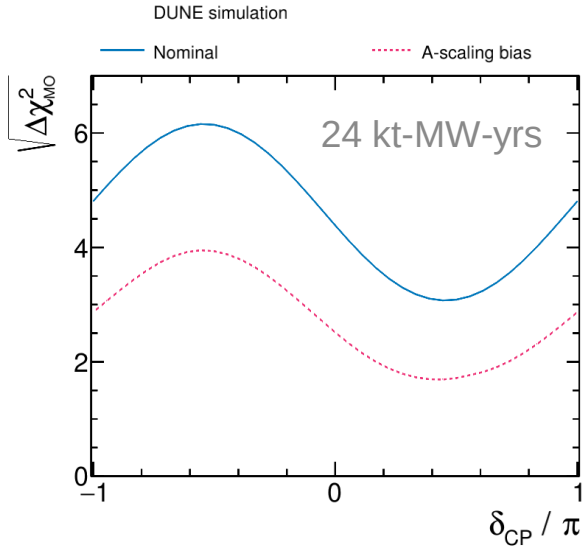
Large uncertainties introduced by extrapolating from a different target

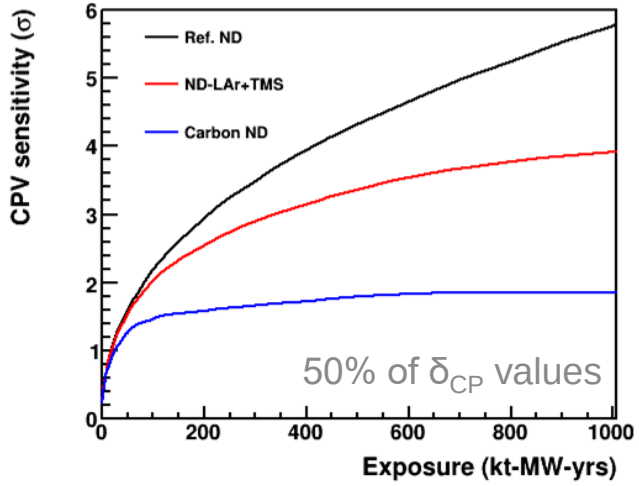
Can be estimated by comparing the cross-section of argon to carbon between different event generators





Significant degradation in the physics reach





Technical requirement: **ND-01** (transfer measurements to FD)

Requirement #2: same response function as the FD

Spectral information essential to DUNE's oscillation goals

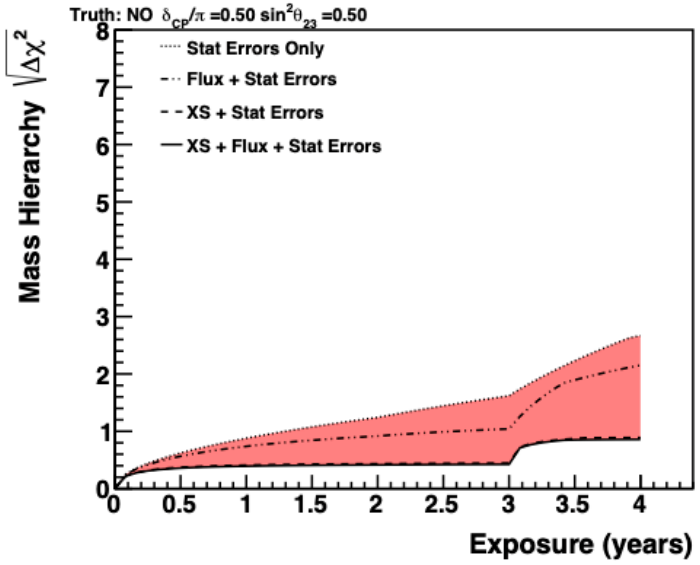
A neutrino interaction reconstructed with X GeV in the FD must be reconstructed with the same X GeV in the ND

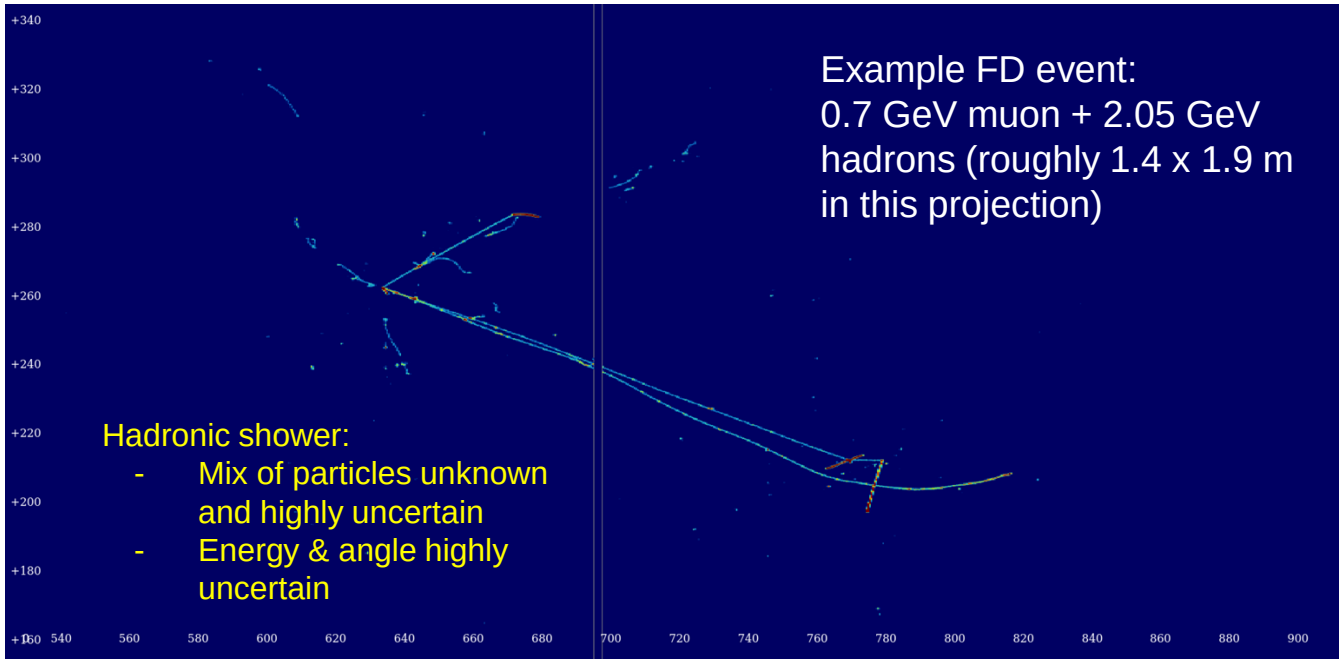
Strategy:

- Muons: measure them in TMS with same resolution as range in FD
- Hadronic showers: fully contain them and measure energy via calorimetry in LAr, as in FD

Technical requirement: **ND-01** (transfer measurements to FD)

NMO significance with single-bin counting experiment significantly reduced compared to full spectral measurement with full systematics





Requirement #2: same response function as the FD

Technical requirements: **SYS-001, SYS-002** (fiducial mass and active size)

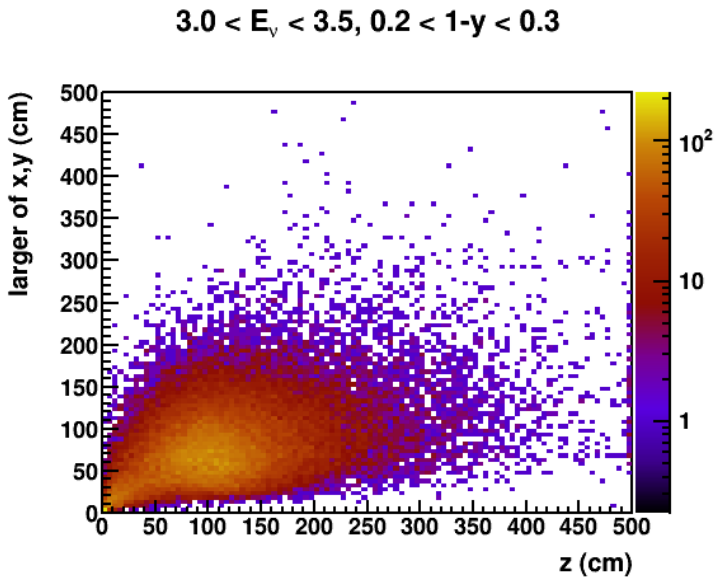
Consequence: ND-LAr must be large enough

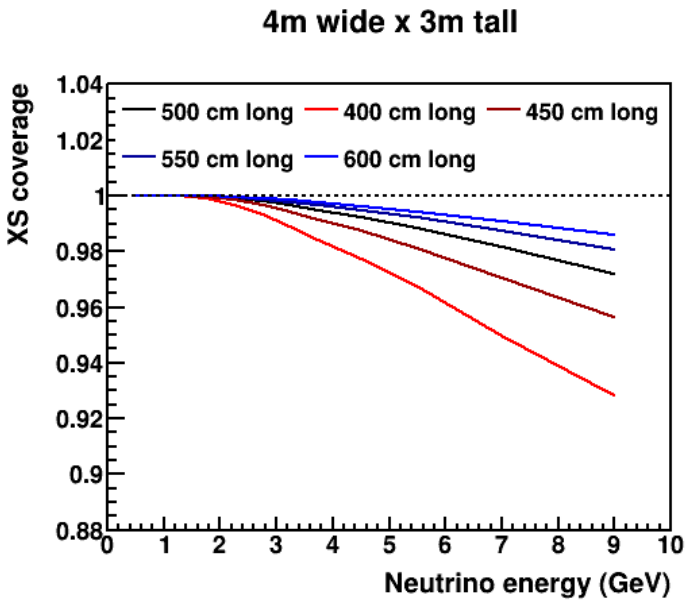
Active volume dimensions determined using simulated events in LAr to ensure containment of hadronic system

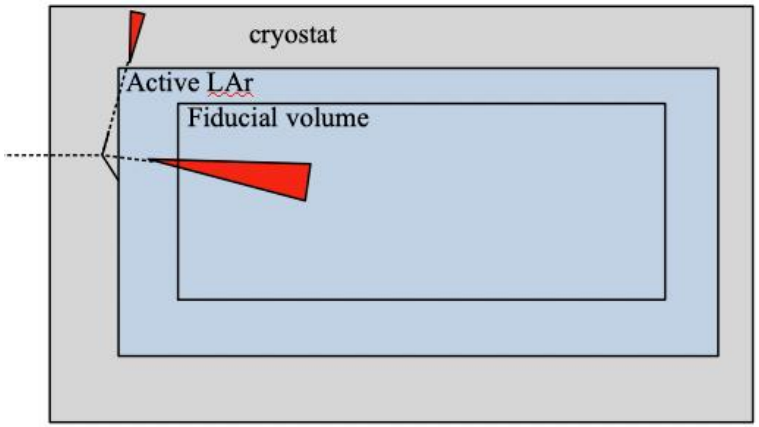
But also:

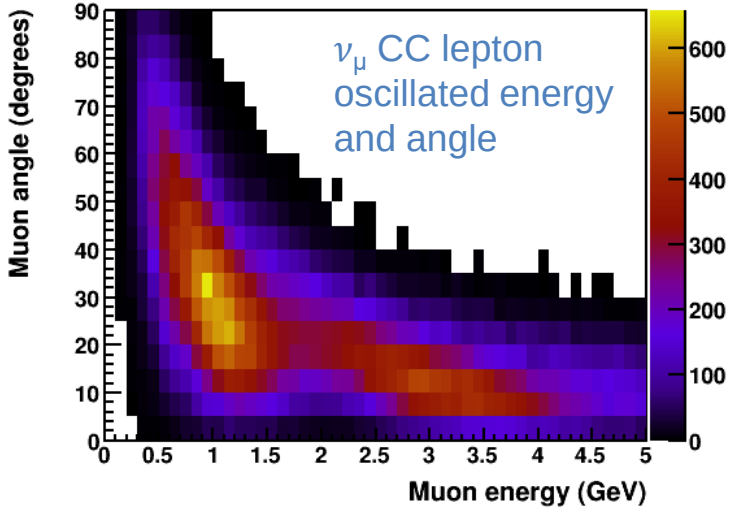
- Need active veto around the detector: using LAr itself is the simplest and most reliable option
- Need containment of muons at high angles (or side spectrometers, which is unfeasible)

Conclusion: **$7 \times 5 \times 3$ m^3**







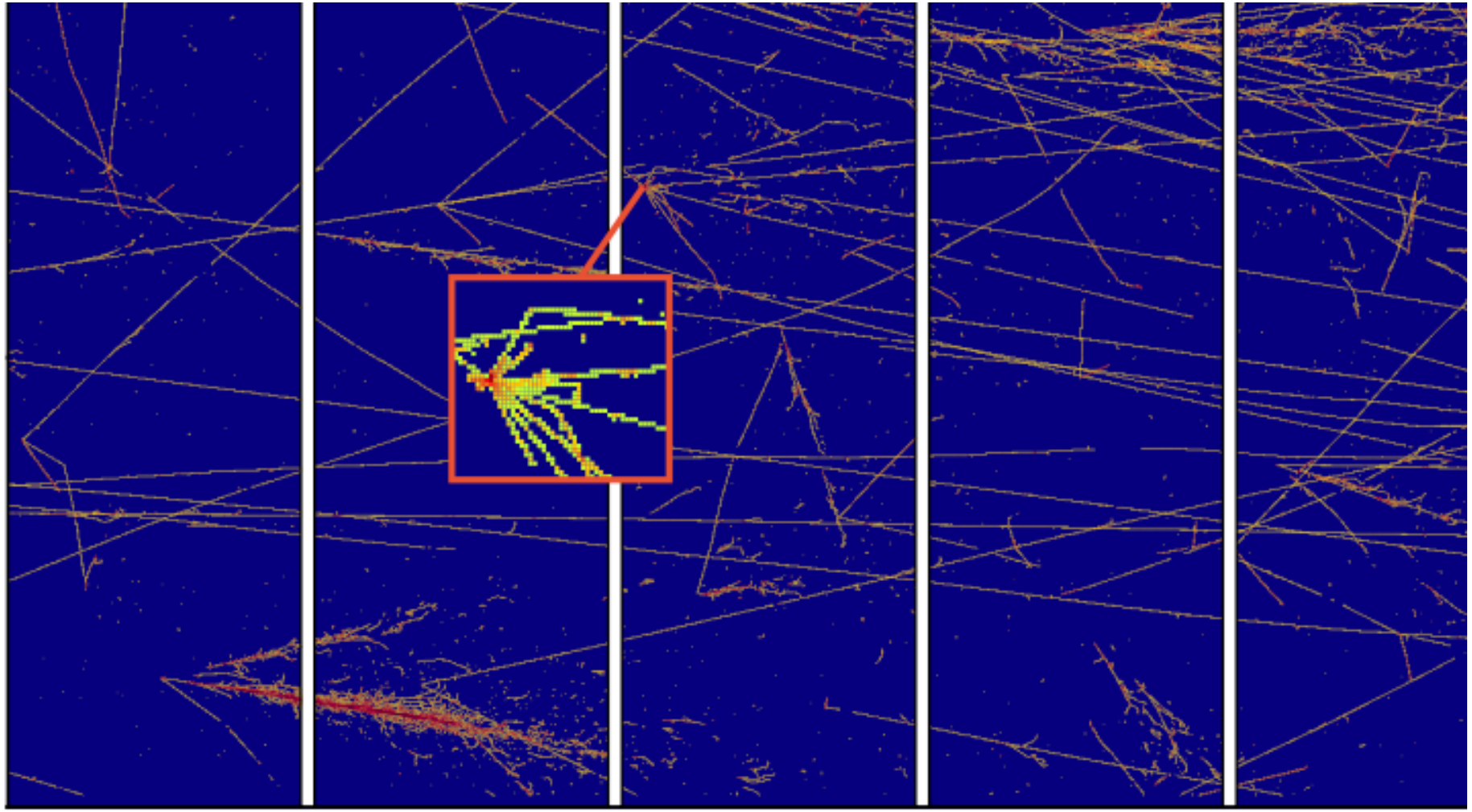


Requirement #3: pixelated charge readout

ND-LAr also faces a unique challenge: each 1.2 MW beam spill results in ~55 interactions

Example of simulated 10 μs spill in ND-LAr

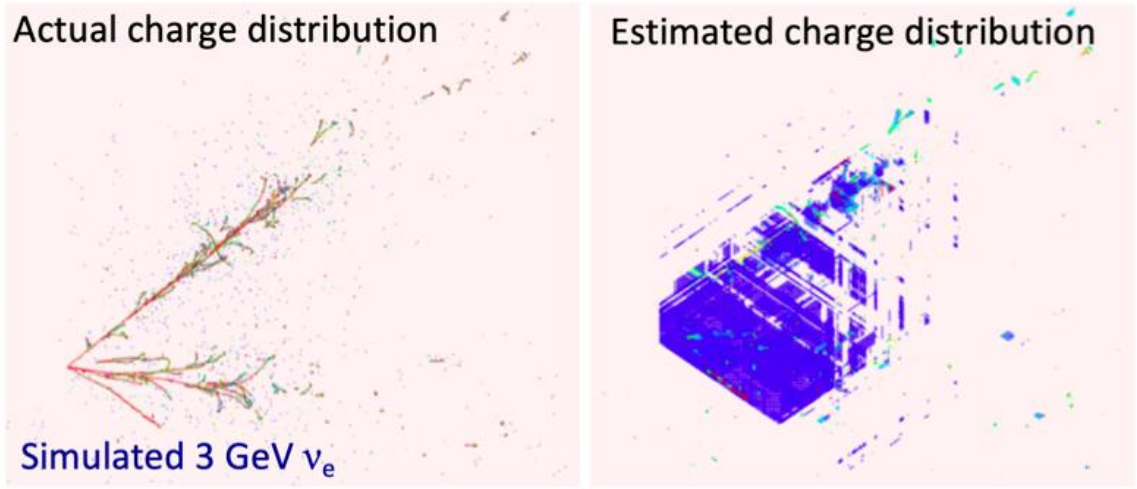
Beam (1.2 MW)



Technical requirement: **ND-06** (operation in high-rate environment)

Requirement #3: pixelated charge readout

Large event pile-up exacerbates ambiguities in projective wire readout

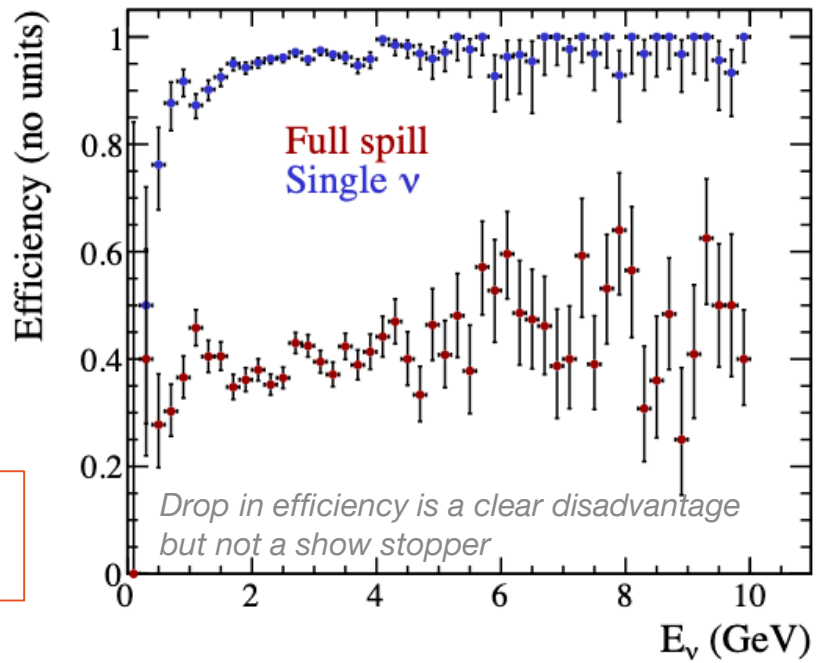


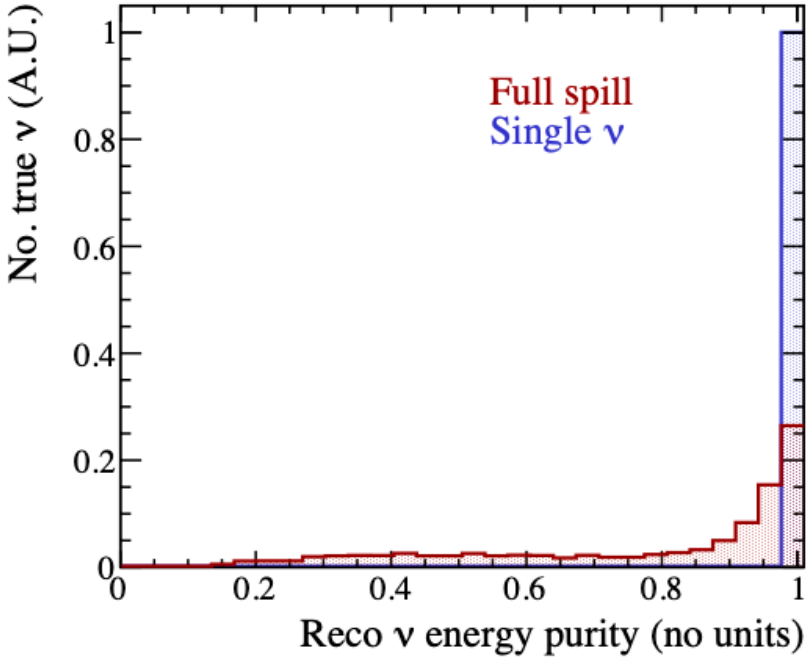
Case in point: SBND detector running PANDORA reconstruction with simulated single ν's vs. 1.2 MW LBNF beam spills:

- Sharp drop in efficiency
- Significant contamination from other interactions

Conclusion: need pixelated charge readout for **real 3D reconstruction**

Technical requirements: **SYS-003, SYS-004** (pile-up rejection and 3D charge)





Requirement #4: modularization

In a LArTPC, charge readout provides topological information and light readout provides timing

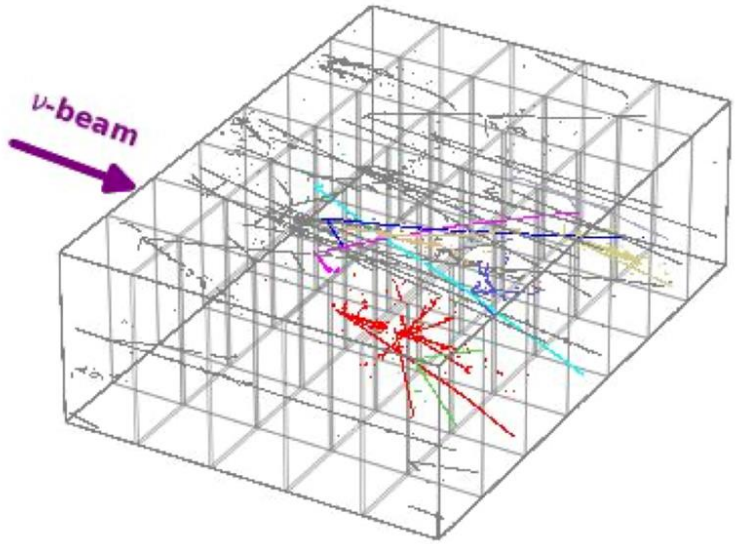
Challenges for a monolithic ND-LAr:

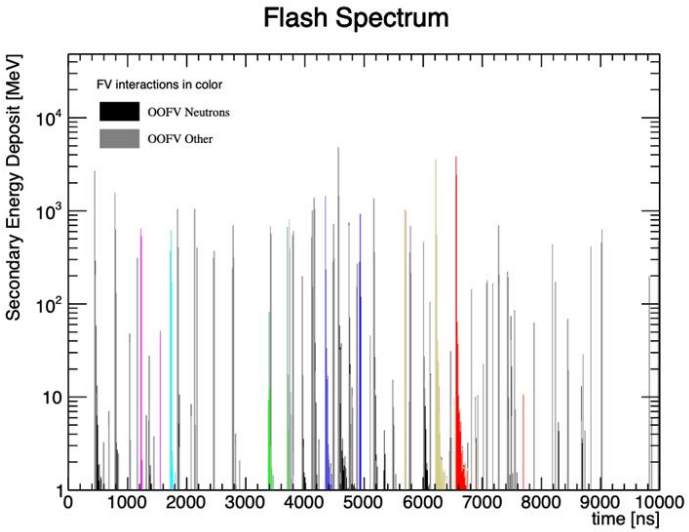
- Combinatorics: impossible to match O(50) light signals to O(50) charge deposits
- Cannot separate all light signals

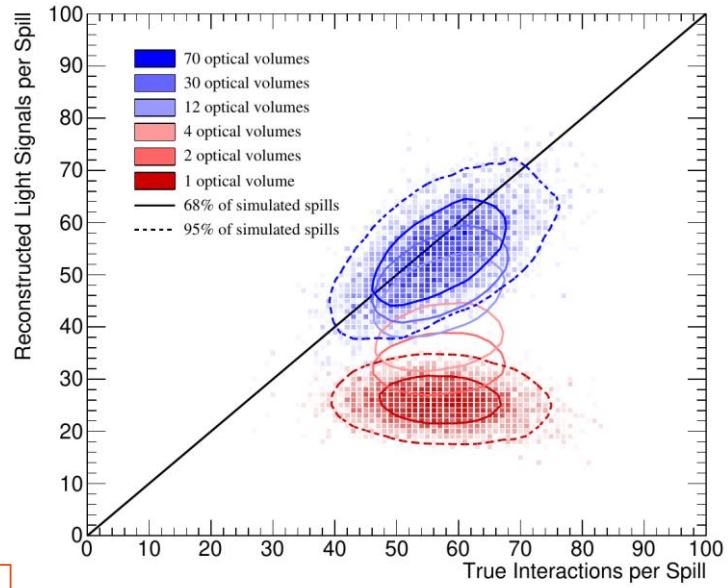
Study with simple reconstruction and light-charge matching shows clear degradation in energy reconstruction with decreasing modularity

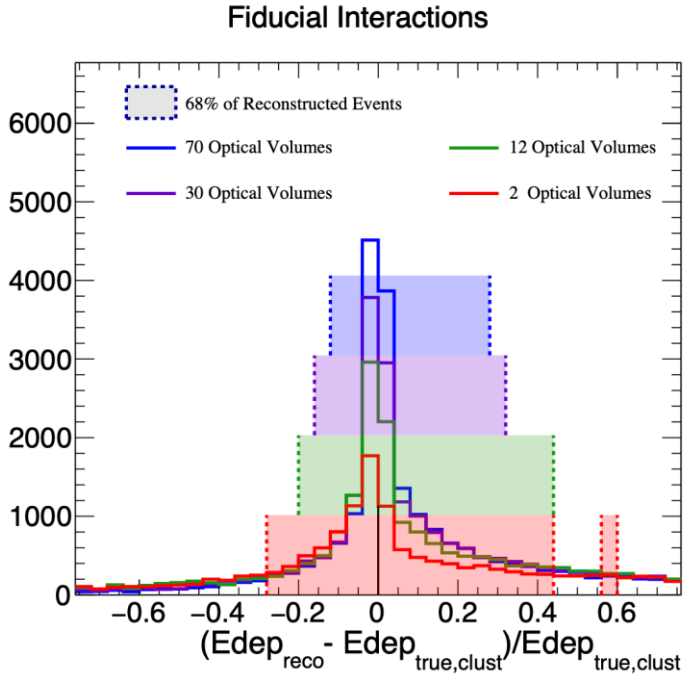
Other advantages of modularization: simplification of construction and testing, reduced cathode voltage

Technical requirement: **SYS-005** (charge-light matching)









Establishment of Requirements

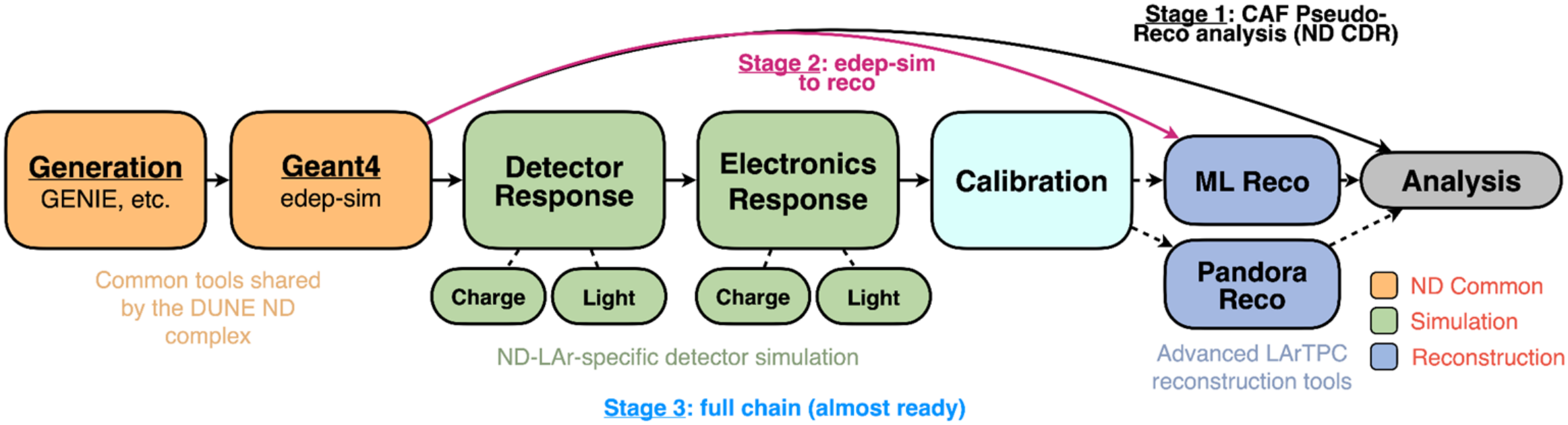
- High-level requirements:
  - Well understood! ✓
    - Everything from previous slides: LArTPC, size, pile-up tolerant… etc.
    - Fix the conceptual design of the detector
- Low-level requirements:
  - In progress ?
    - Examples: dead volume that can be tolerated, failure of electronics channels vs. time, … etc.
  - Requires a more detailed simulation and reconstruction
  - Have a clear path for addressing these (rest of this talk)

Recommendations from past reviews

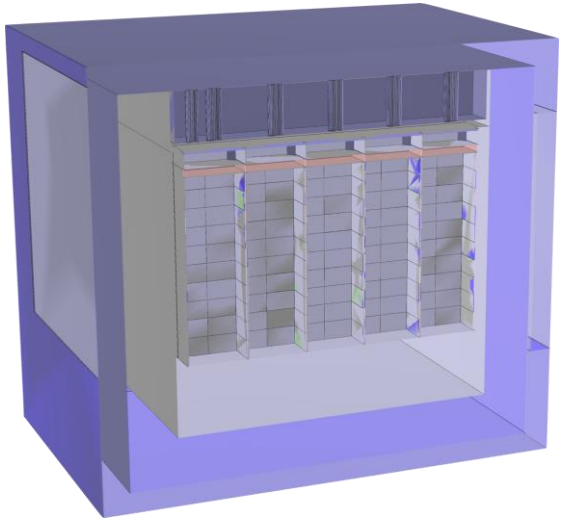
- Relevant recommendations have centered on:
  - Simulation and Analysis
    - Developing a complete end-to-end ND-LAr simulation and reconstruction workflow
    - Integrating simulated/reconstructed event samples into DUNE oscillation analysis
  - Analysis supporting ND-LAr design and subsystems
    - Requirements regarding detector size, geometry, and modularity
    - Subsystem design: E.g. maximum tolerable E field nonuniformity, inactive materials, …
- To address these recommendations and support design validation and DUNE physics, we have undertaken to:
  - Develop a detailed microphysical detector simulation
  - Deploy two complementary advanced event reconstruction paradigms
  - Benchmark and tune our simulation using mid-scale prototype detector data
  - Engage deeply with DUNE Physics efforts toward an enhanced sensitivity analysis employing fully simulated and reconstructed Near Detector event samples and a highly detailed model of systematic uncertainties

Simulation and Analysis Tools

- Study prototype data and provide actionable feedback for detector design considerations. Assess whether the prototype data indicates we are on a path to meet ND-LAr performance requirements.
- Perform ND-LAr simulations to support broader DUNE physics analysis efforts, including demonstrating ND deliverables with a realistic simulation. Incorporate an up-to-date understanding of detector design and performance, and automated reconstruction.

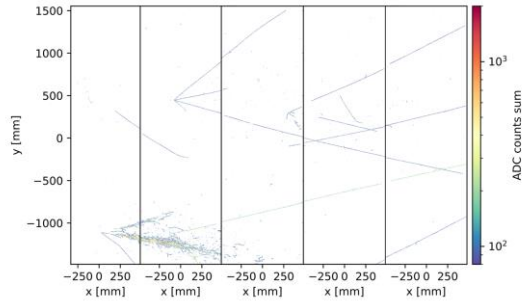


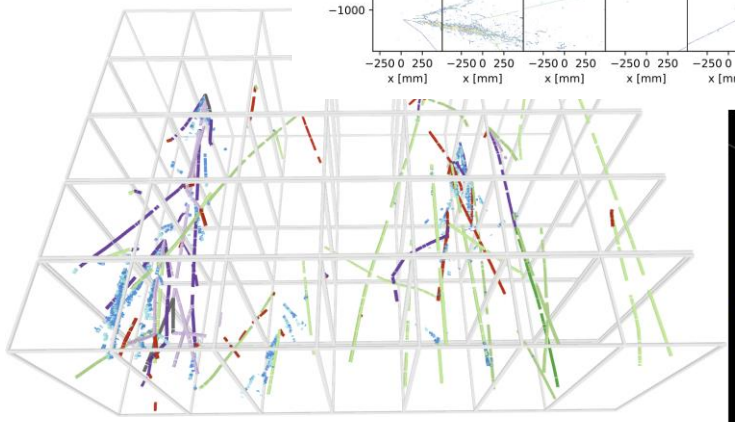
Simulation and Analysis Tools: Detector Simulation

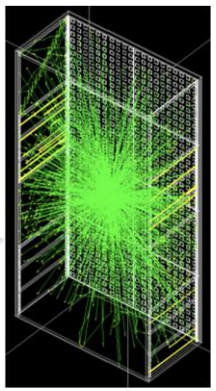


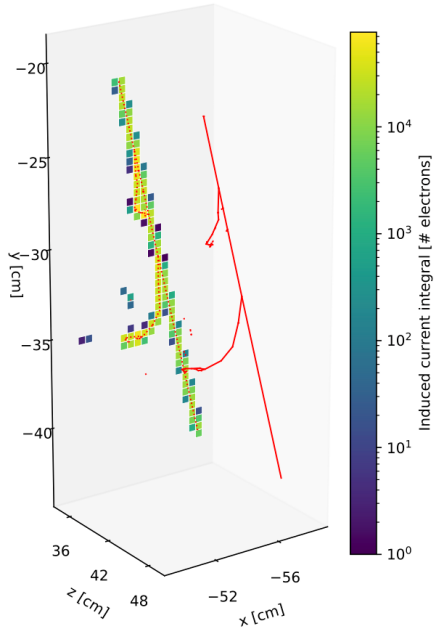
- Detailed microphysical ND-LAr and prototype geometry
- Cryostat features e.g. composite window and scintillator panels
- Realistic material budget and inactive regions

- Advanced charge and light response simulation developed for pixel-based LArTPCs (github)
- 10,000× acceleration with GPUs
- Outputs in LArPix data format









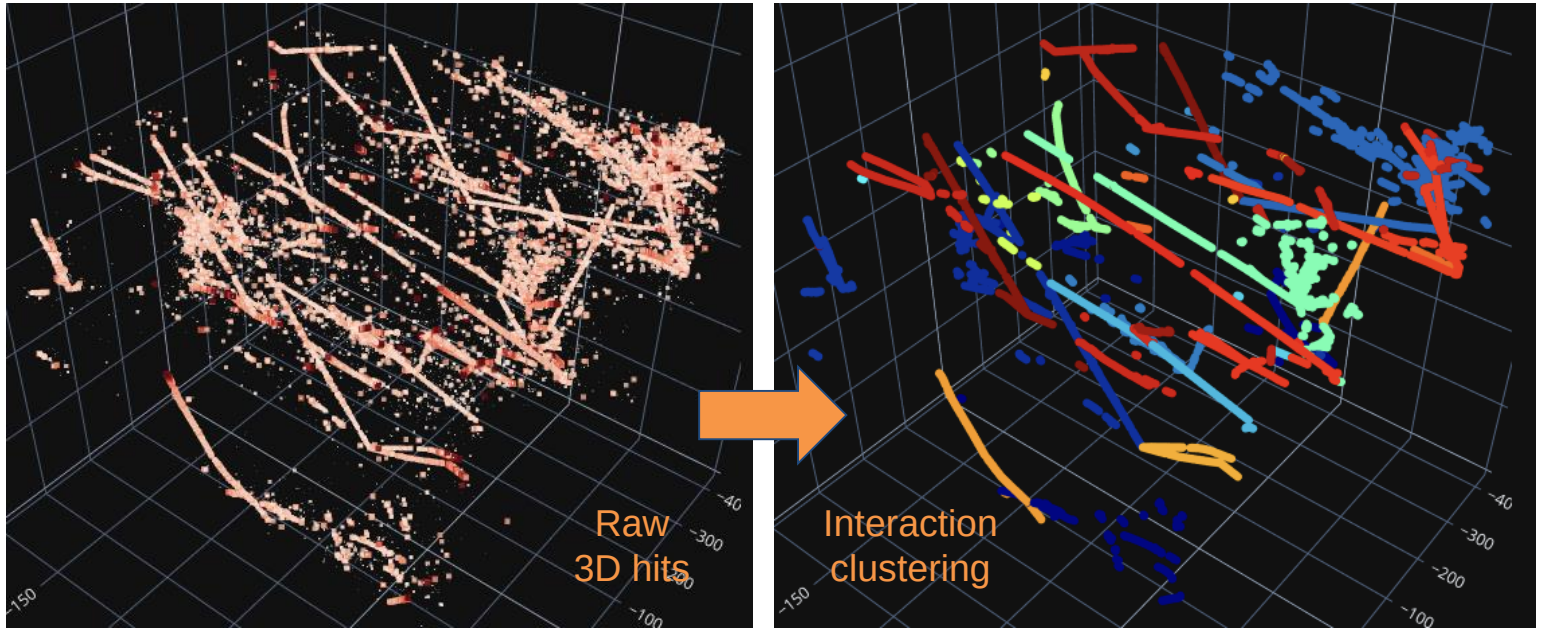
- Simulations of Module-N and 2×2 prototypes
- Module-0/1 data/MC comparisons used to tune & improve MC modeling

Simulation and Analysis Tools: Reconstruction

Two advanced reconstruction paradigms:

EPJC 75:9, 439 (2015), EPJC 78:1, 82 (2018)

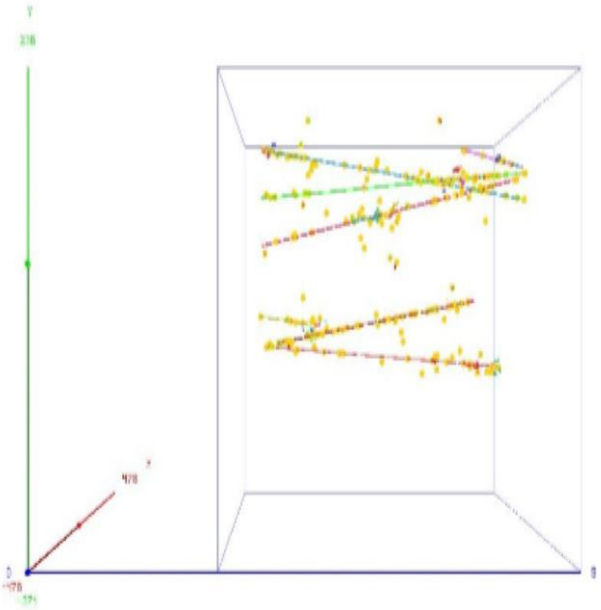
Machine-Learning Based Reconstruction



- Multi-algorithm deep-learning assisted full event reconstruction (github)
- Successfully deployed in the MicroBooNE, SBN, ICARUS, and ProtoDUNE wire-based LArTPCs
- Already working with ND-LAr's native 3D readout and outputting into common analysis files (CAFs)

arxiv:2102.01033
arxiv:2007.03083
PRD 104, 072004 (2021)
PRD 104, 032004 (2021)

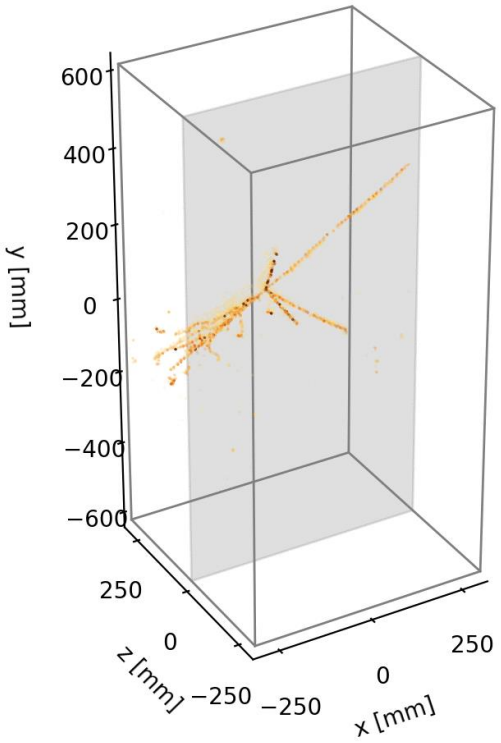
Pandora



- Highly customizable particle-flow based event reconstruction (github)
- Used in DUNE FD, MicroBooNE, SBN, ProtoDUNE, etc.
- Currently working in 2D projections to leverage existing toolchain, 3D algorithms coming soon

Simulation and Analysis Tools: Prototype Data Analysis

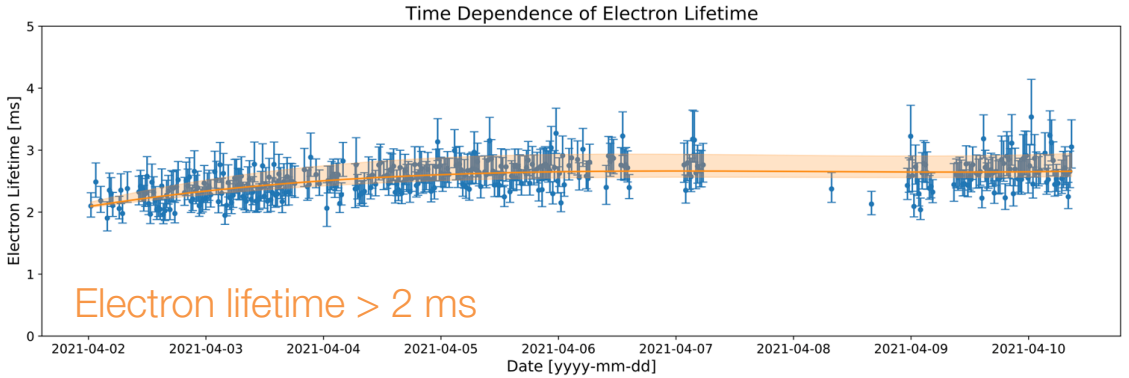
Article under review
(EDMS 2746204)



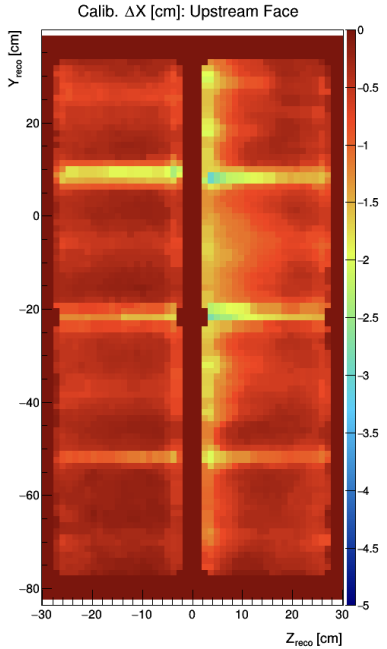
Imaged cosmic rays from Module-1 prototype data February 2022

- ND-LAr and prototypes use a common simulation & analysis infrastructure
- Prototype data analysis is addressing key design requirements
- Prototype data to simulation comparisons already used to enhance and tune detector modeling
  - Automatically feeds into ND-LAr simulation
- Complete detector simulation & reconstruction supports detailed design maturation and a new generation of DUNE physics analysis

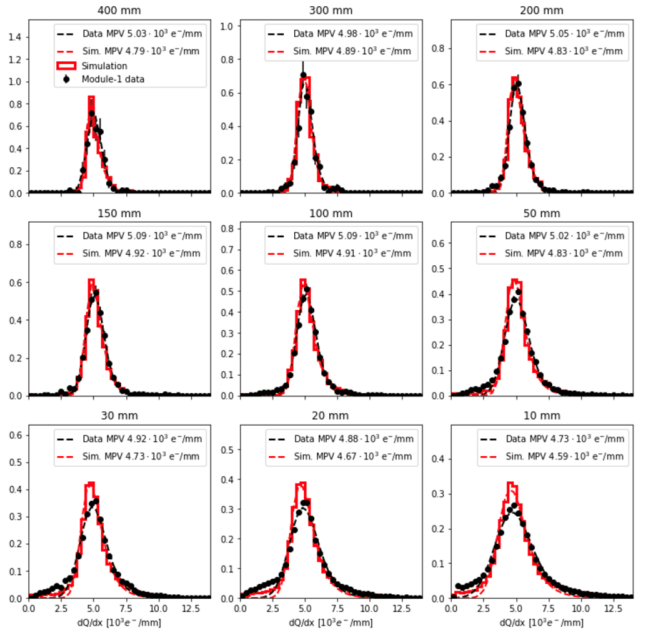
Module-0 Prototype Analysis



Electron lifetime > 2 ms



E field uniformity <1%



Data/MC for track *dE/dx*

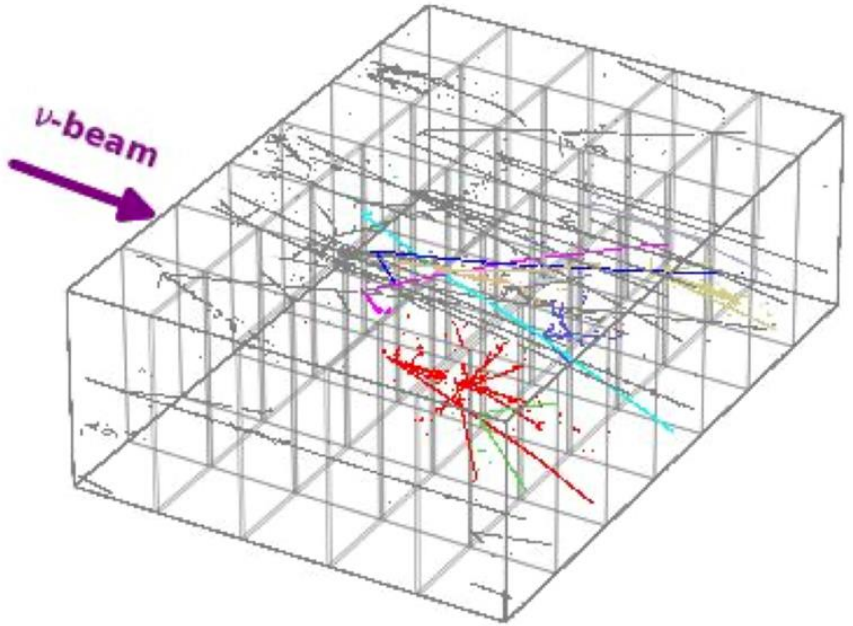
Pathway to the FDR

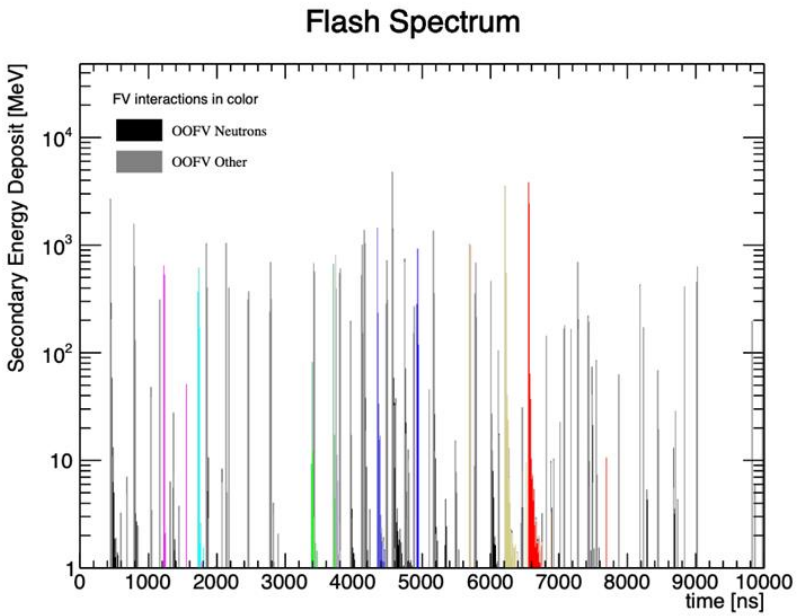
- Finalize the complete “end to end” simulation and analysis chain
  - Tuning and optimization of reconstruction algorithms using novel 3D readout and rich optical detection information from hybrid high-coverage light system
- Support the 2×2 Demonstrator analysis
  - Excellent opportunity to exercise the full system including reconstruction of GeV-scale neutrino interactions in a multi-module environment with matching to an external tracker
- Support subsystem requirement validation
  - Leverage our detailed, increasingly data-driven microphysical simulation to extrapolate prototype performance to ND-LAr, validate design and retire design risks
- Integrate fully simulated and reconstructed samples into DUNE oscillation analysis
  - Support a next generation of DUNE sensitivity studies with a much more complete and sophisticated model of the DUNE ND complex
  - Our group is strongly engaged with this collaboration effort, including a detailed reassessment of key systematic uncertainties
- Support analysis with prototypes
  - 2x2 and FSD

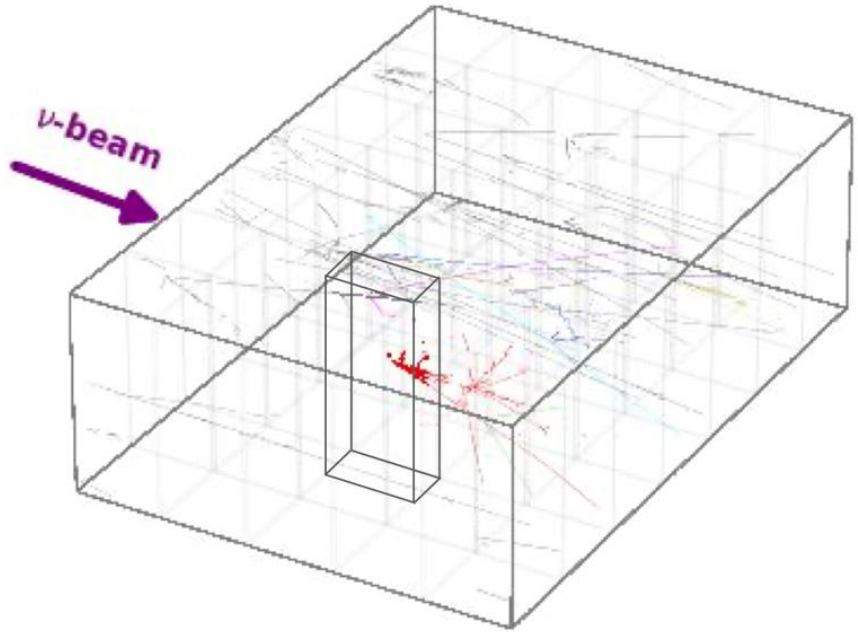
Summary

- ND-LAr is essential to DUNE's oscillation physics program
- ND-LAr is only option on the table that meets the high-level requirements:
  - LArTPC
  - Same response as FD
  - Pile-up resistant
- Significant progress towards full end-to-end simulation and reconstruction building on shared ND efforts and tools
  - Synergy with prototyping effort
  - Provides a path to addressing low-level requirements

Backup Slides


ν-beam


Flash Spectrum
FV interactions in color
OOFV Neutrons
OOFV Other
Secondary Energy Deposit [MeV]
time [ns]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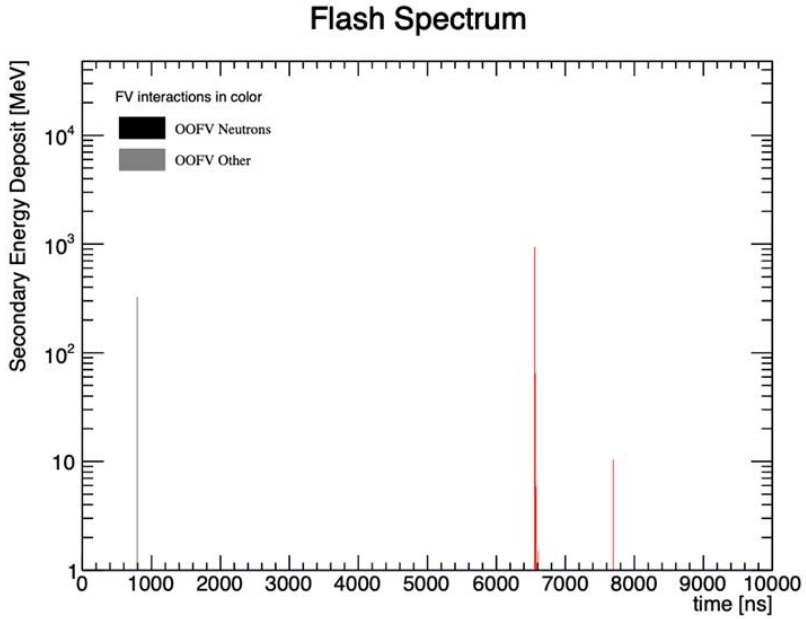
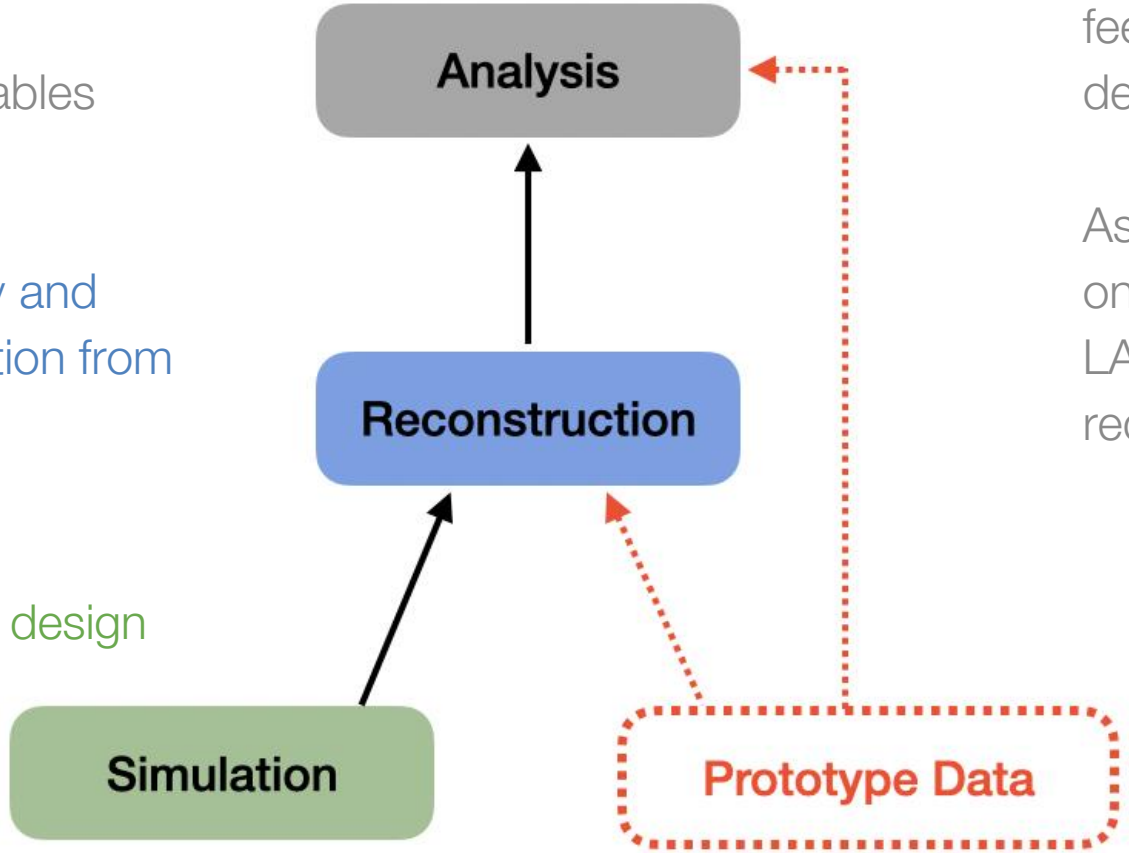

Flash Spectrum
FV interactions in color
OOFV Neutrons
OOFV Other
Secondary Energy Deposit [MeV]
time [ns]

Scope of ND-LAr Analysis Group

Support broader DUNE physics analysis efforts, including demonstrating ND deliverables

Develop an automated reconstruction that reliably and optimally extracts information from ND-LAr interactions

Incorporate up-to-date understanding of detector design & performance



Provide actionable feedback for detector design considerations

Assess whether we are on a path to meet ND-LAr performance requirements