ND-LAr Analysis: Status and Outlook

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ND Consortium Management Board Meeting

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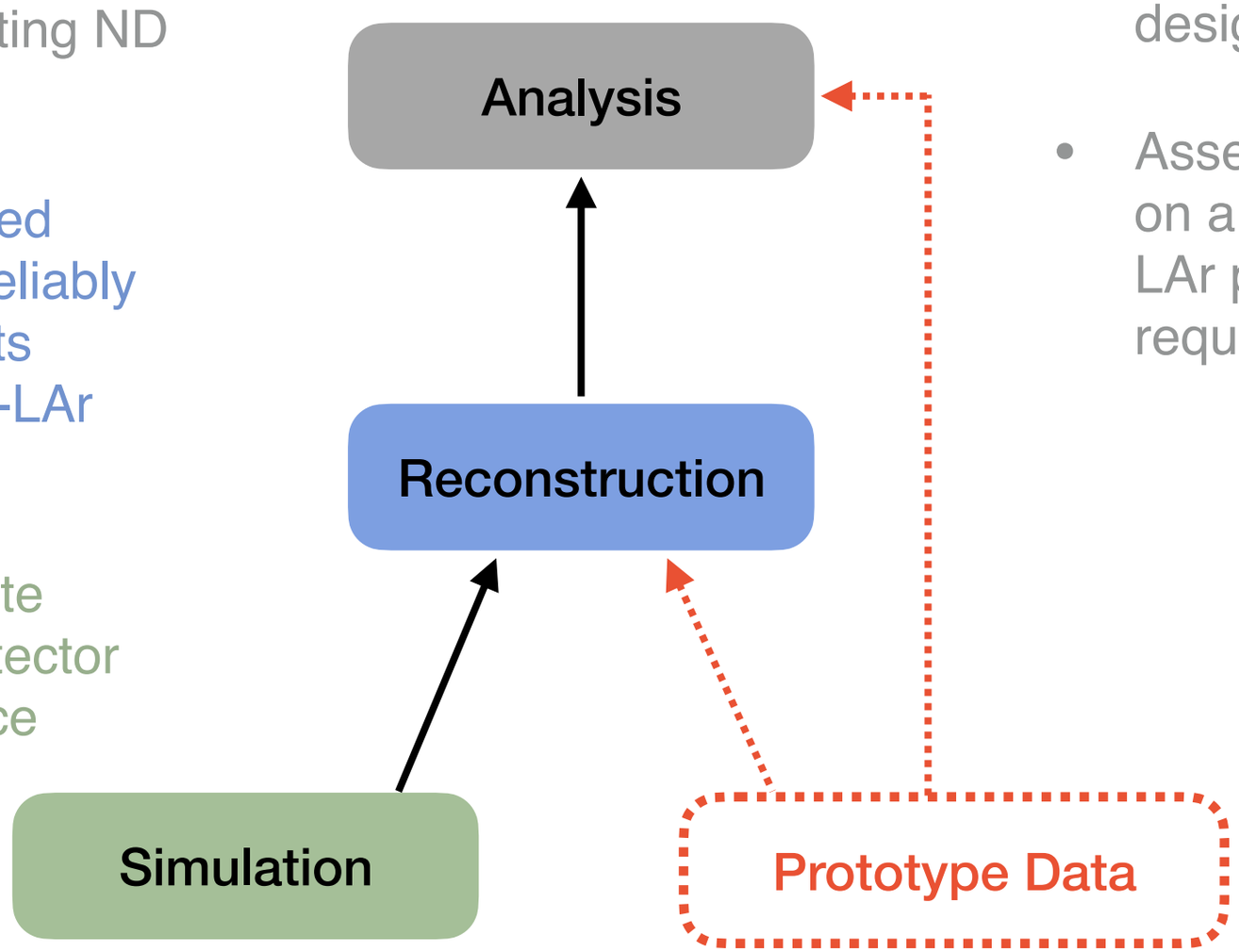
RUTGERS
UNIVERSITY | NEW BRUNSWICK

Outline

- Analysis goals & requirements
- Overview of analysis tools
  - DUNE ND Software
  - ND-LAr Simulation
  - ND-LAr Reconstruction
  - Module-0 Analysis
  - ND-LAr Analysis
- Main targets and rough schedule
- Conclusions

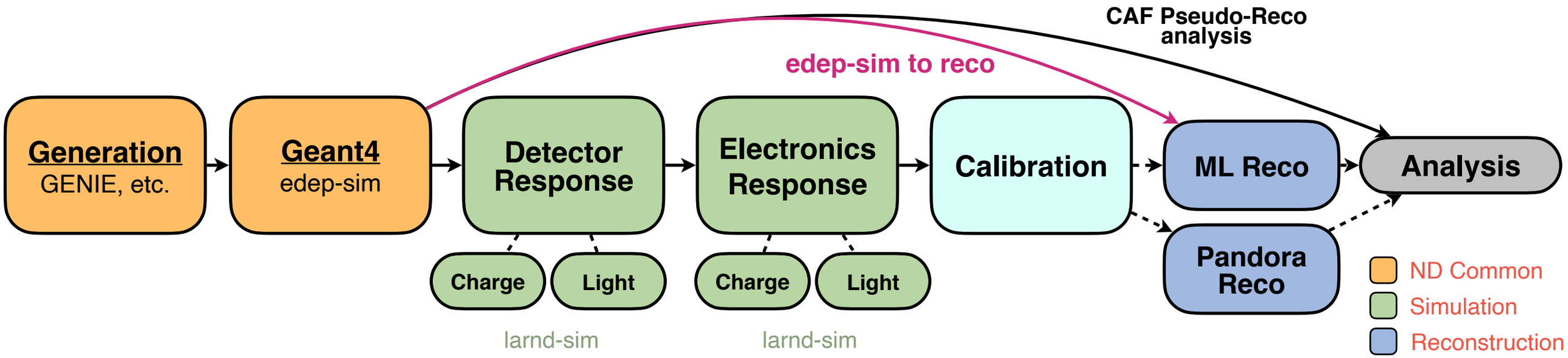
Overall Goals

- 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

Software Chain Overview

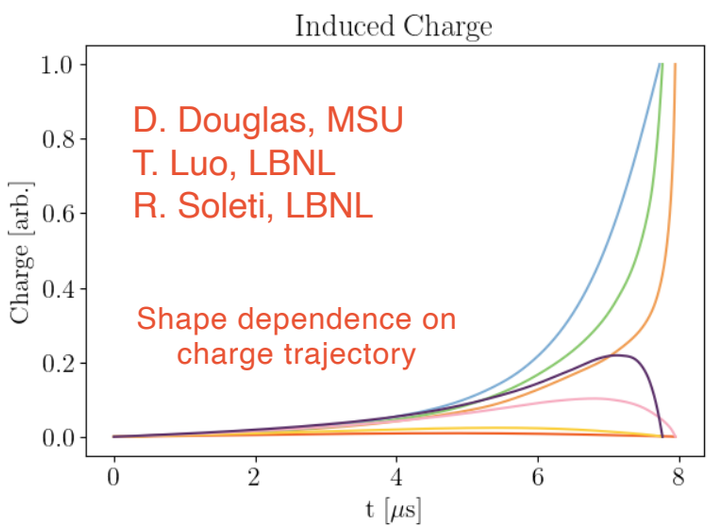


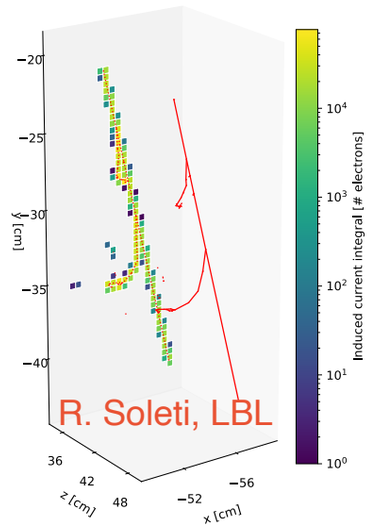
- Sharing common tools with other ND detectors, coordinated via the ND Sim/Reco group
- Custom detector simulation purpose-built for pixel-readout LArTPCs and large photodetector coverage
- Machine-Learning (ML) and Pandora reconstructions being pursued in parallel
- Analysis files based on parametric reconstruction or reconstruction of Geant4 simulation to support high-level analysis in parallel with ongoing end-to-end tool development

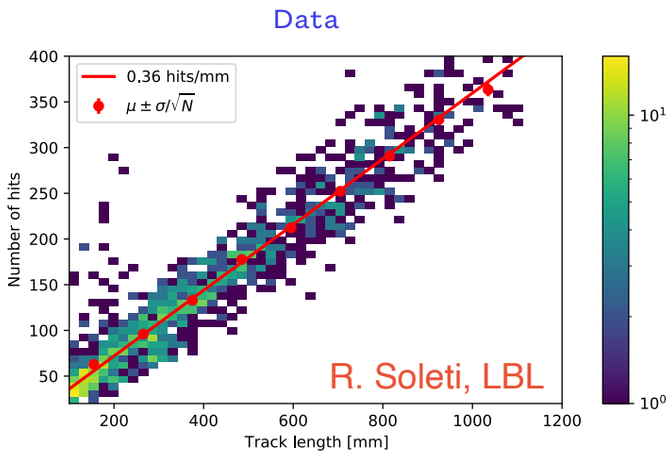
ND-LAr Simulation

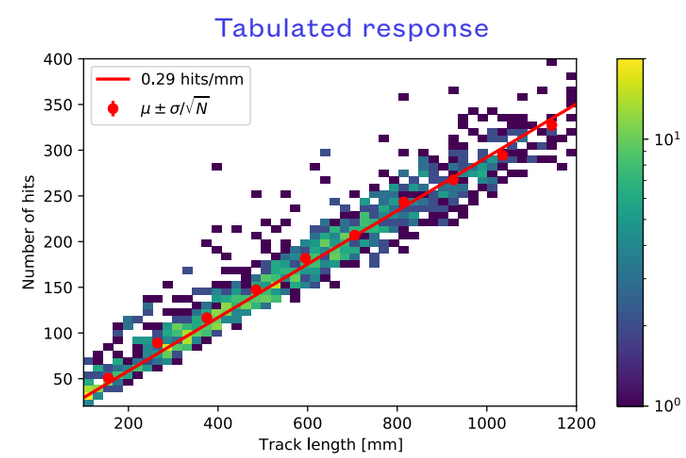
Detector Simulation (larnd-sim)

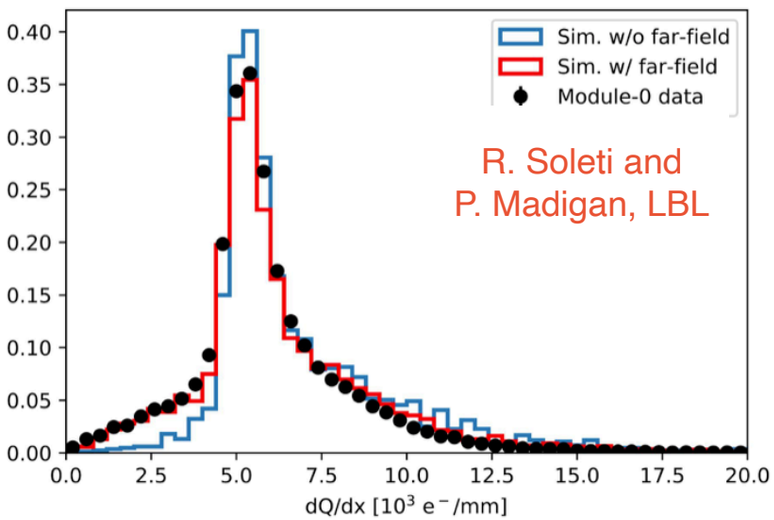
- **Novel drift & response simulation for pixelated LArTPCs has been developed**
- Important features:
  - 10,000x acceleration with GPUs
  - Outputs in LArPix data format
  - Incorporates MC truth matching
  - Allows to simulate prototypes or ND-LAr
- Recent development highlights:
  - Support for unique channel electronics thresholds
  - Improved charge and far-field current response models
    - Tuning from Module-0 data/MC comparisons
  - Full spill simulation (next slides)





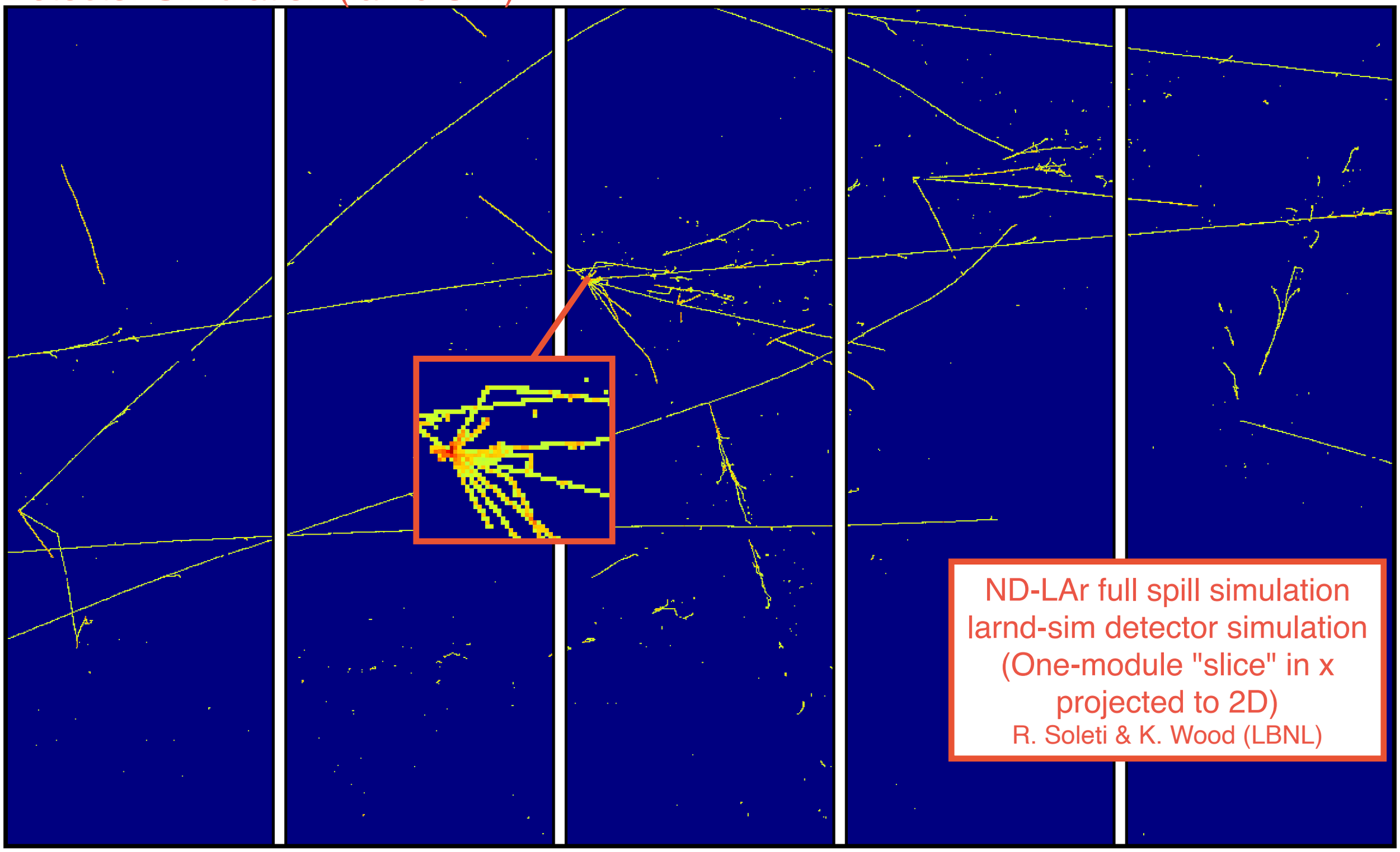






ND-LAr Simulation

Detector Simulation (larnd-sim)

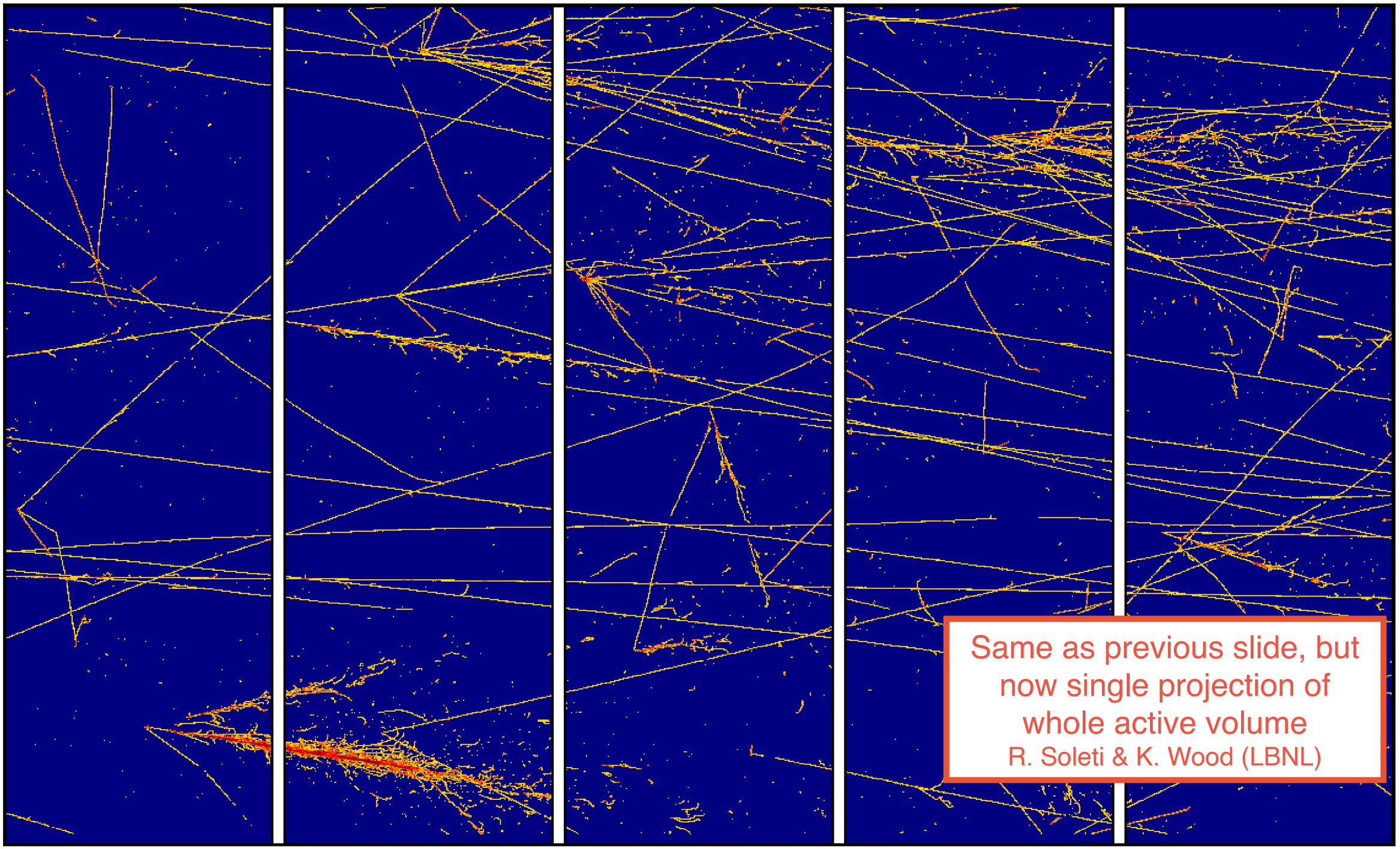


ND-LAr full spill simulation
larnd-sim detector simulation
(One-module "slice" in x projected to 2D)

R. Soleti & K. Wood (LBNL)

ND-LAr Simulation

Detector Simulation (larnd-sim)



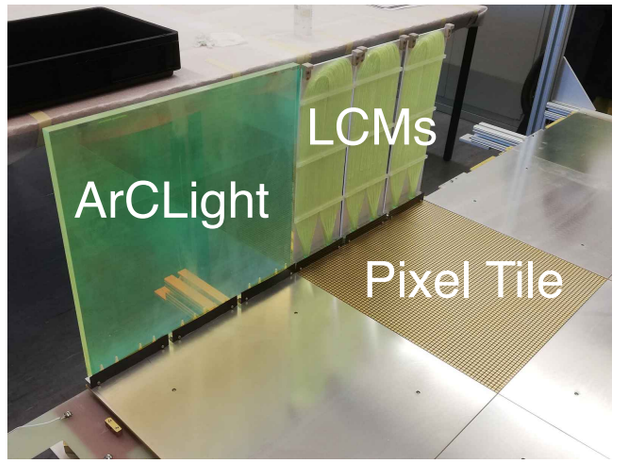
Same as previous slide, but now single projection of whole active volume

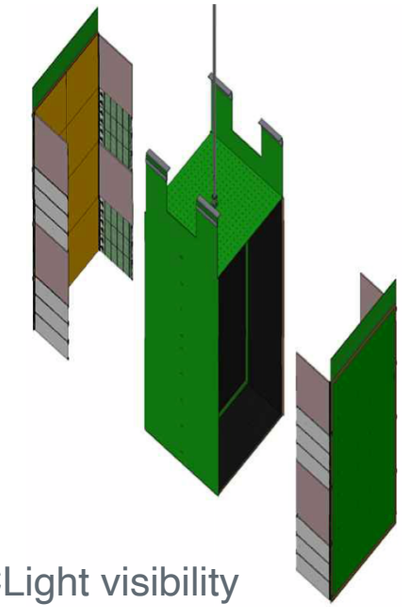
R. Soleti & K. Wood (LBNL)

ND-LAr Simulation

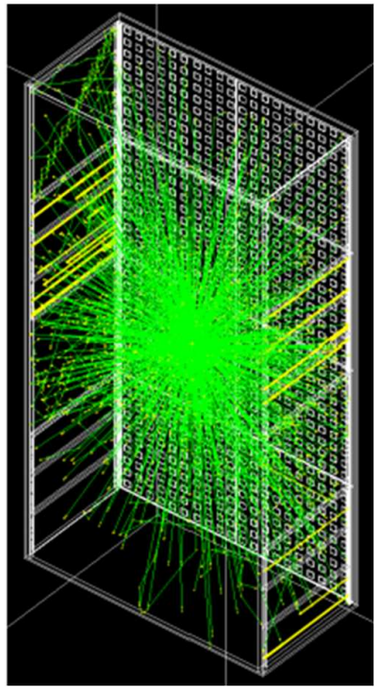
Detector Simulation (larnd-sim)

- **Light simulation based on photon propagation model:**
  - Models photon production, recombination using Geant4 output
  - Visibility + timing maps (lookup tables) built from a dedicated Geant4 simulation
- Integrated into larnd-sim, but some aspects missing:
  - Full SiPM + electronics response
  - Output in data format
- Essential to study Q/L matching, interaction pileup

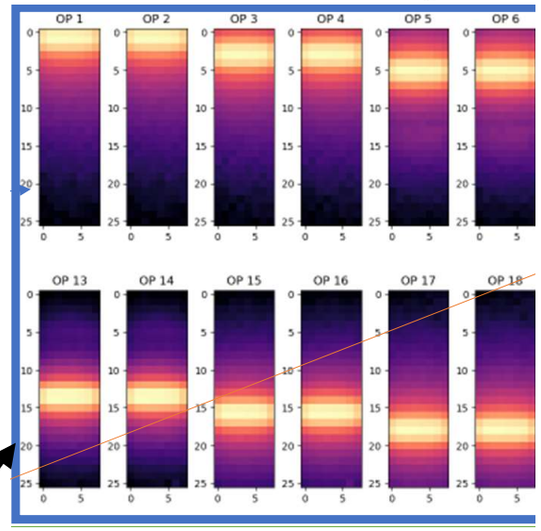




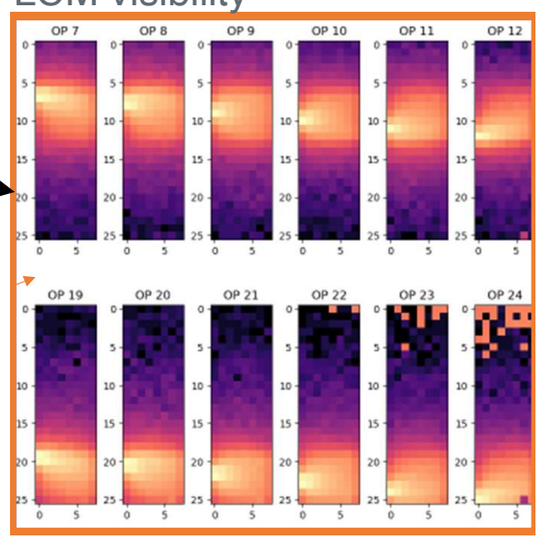
Geant4 simulation (P. Koller, Bern)

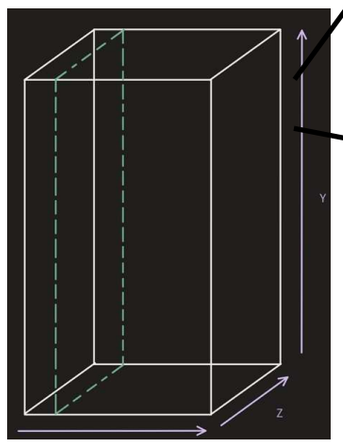


ArCLight visibility



LCM visibility



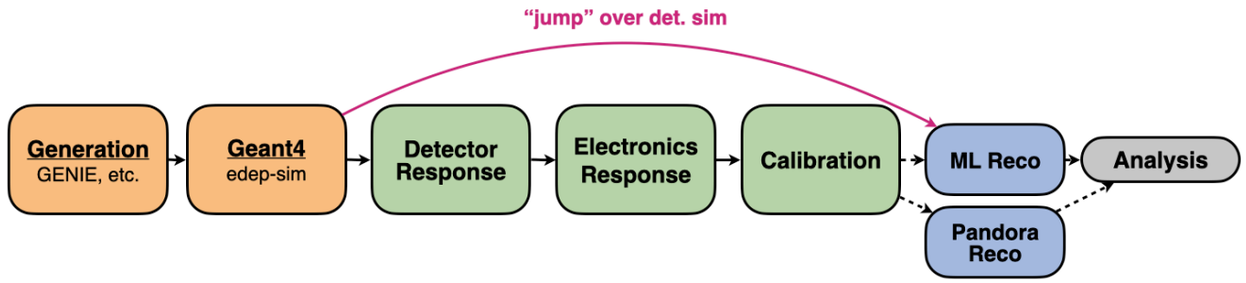


Validation (E. Taira)

ND-LAr Reconstruction

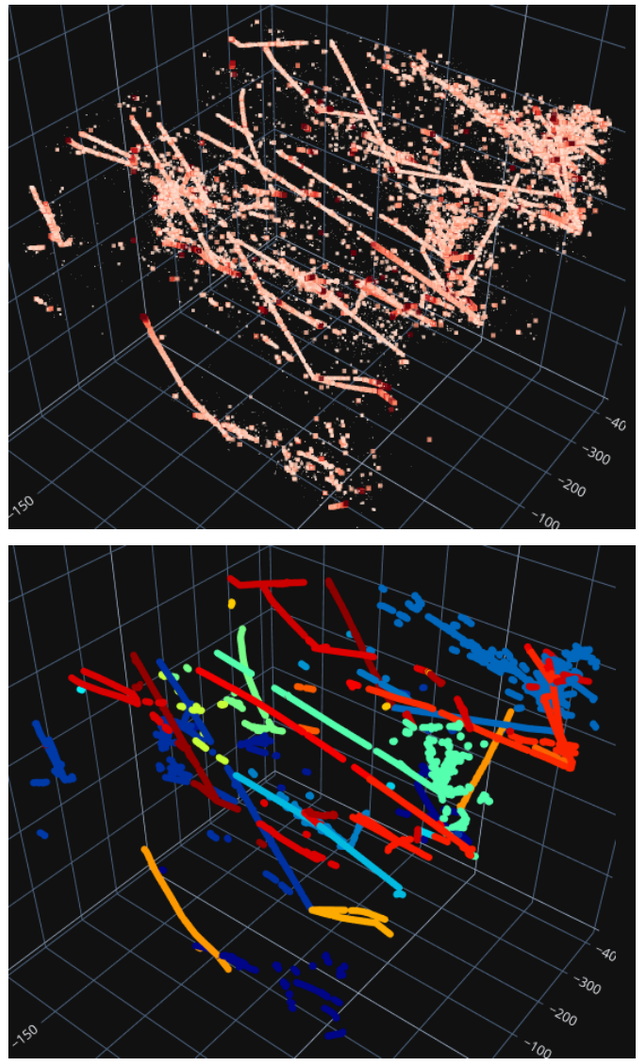
ML-Based Event Reconstruction

- **ML-Reco: Deep Learning-based Reco for ND-LAr**
  - Toolkit developed by SLAC and used in other LArTPC experiments, adapted to native 3D readout of ND-LAr
  - A complete end-to-end LArTPC reco chain
- Operates on voxelized Geant4-level edep-sim output



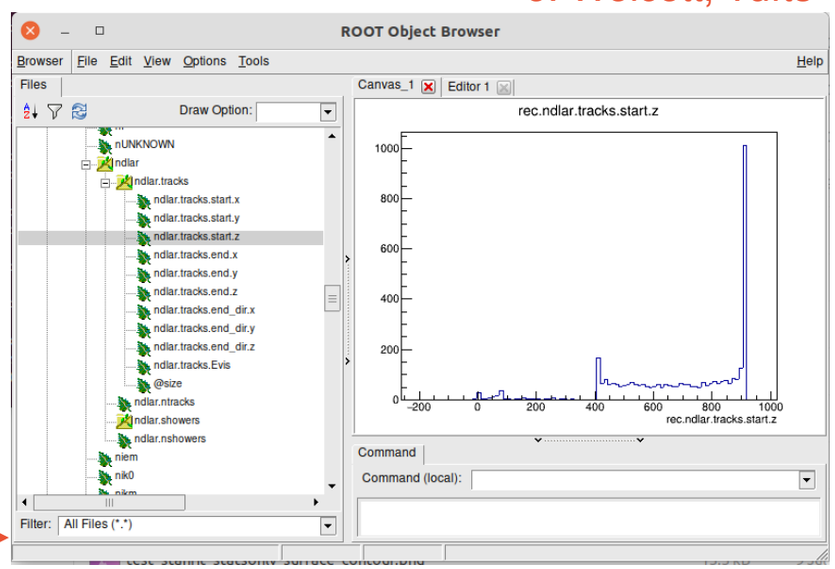
  - Work well underway to input larnd-sim format (S. Fogarty, CSU & Z. Hulcher, SLAC)
- CAF (analysis tree) output available, now in the validation stage
  - Small full spill samples
  - Bringing more people into validation/ development
  - **Gateway to high-level analyses**

Pileup beam MC event



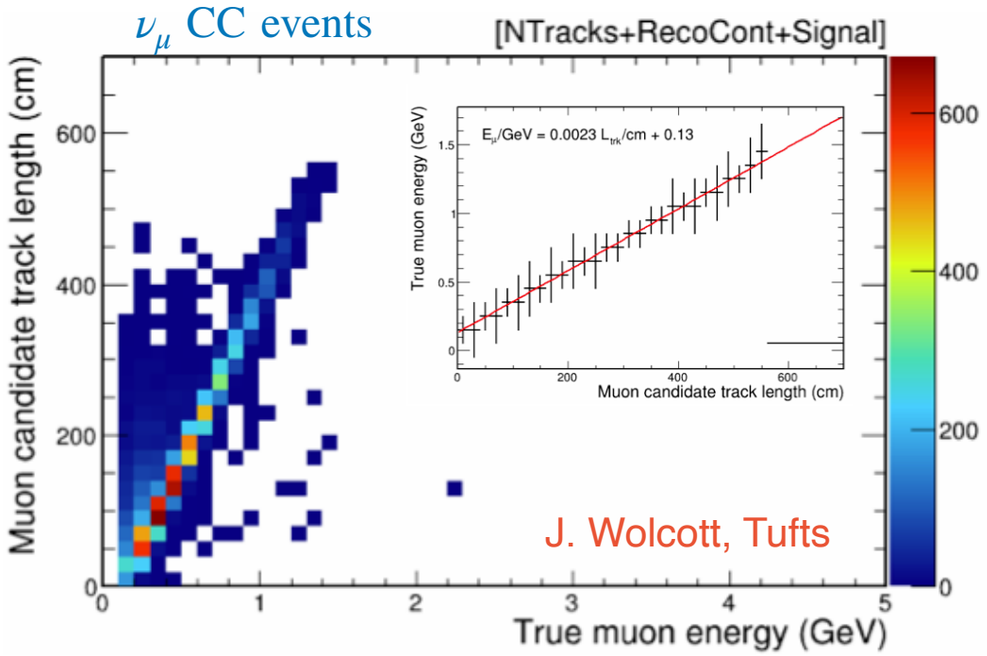
J. Wolcott, Tufts

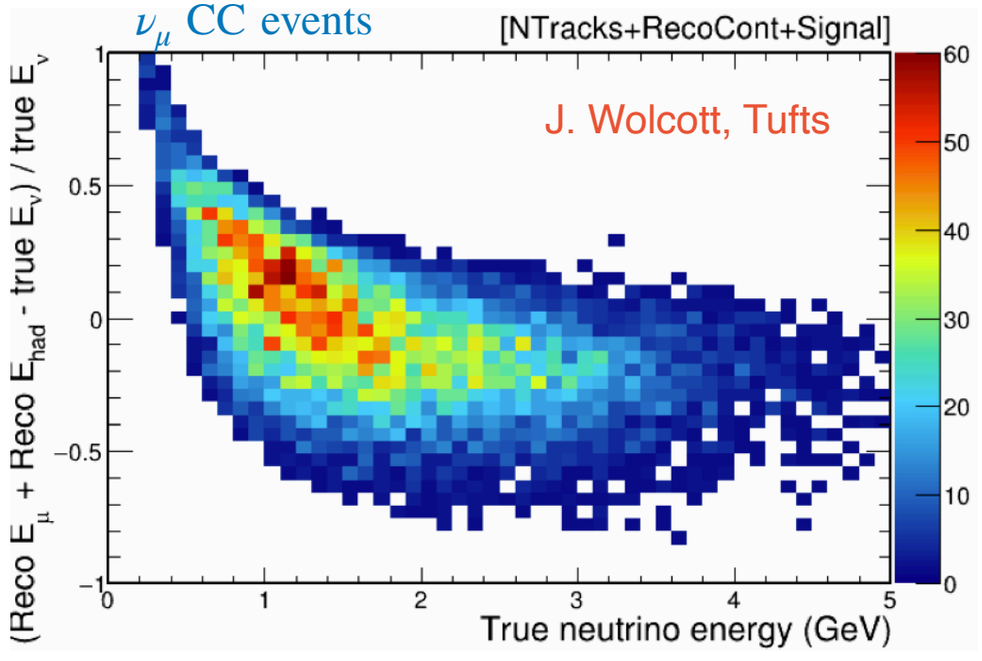
Prototype CAF output



ND-LAr Reconstruction

ML-Based Event Reconstruction





- Can already do basic studies with CAFs
  - Example: proof-of-principle ν_μ CC energy estimator (left plots)
  - Example: selection efficiency of π^0 and ν_e CC events (bottom table)
- Efforts underway to:
  - Streamline "plumbing" for productions
  - Identify & fix bugs (e.g. shower grouping)
- Understand what variables to add

R. Mandujano, UCI

	π^0	$\nu_e CC$
Front Vertex Cut	90.56%	94.81%
Back Vertex Cut	85.54%	83.77%

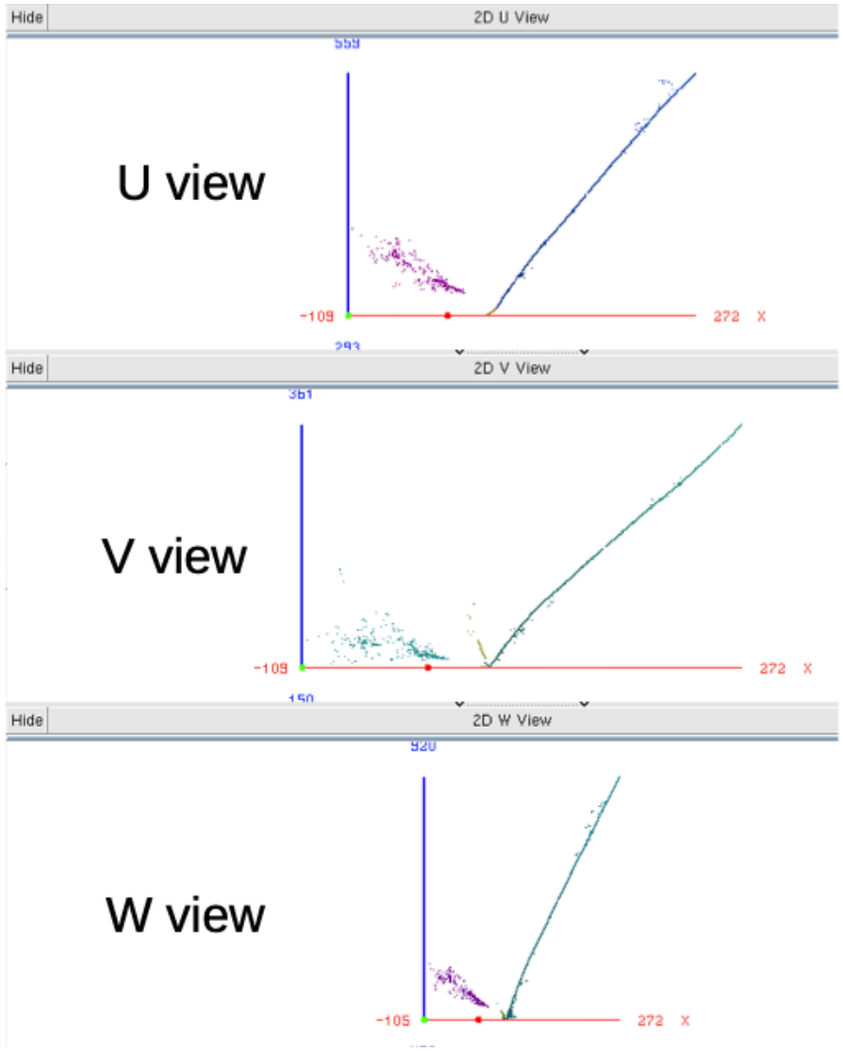
(as expected, performance degrades near back end)

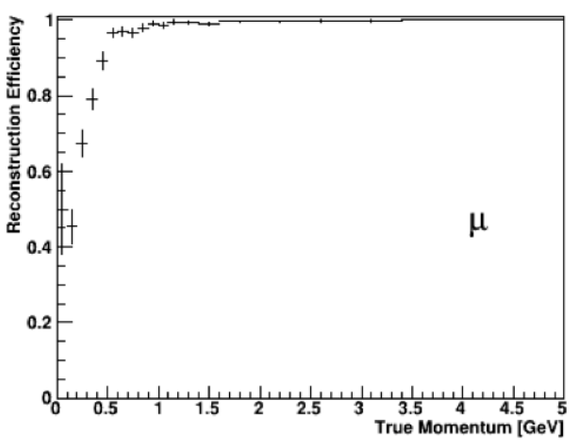
(J. Back, Warwick & A. Moor, Cambridge)

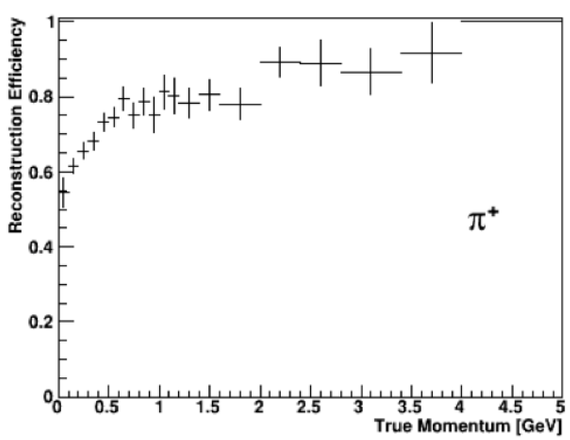
ND-LAr Reconstruction

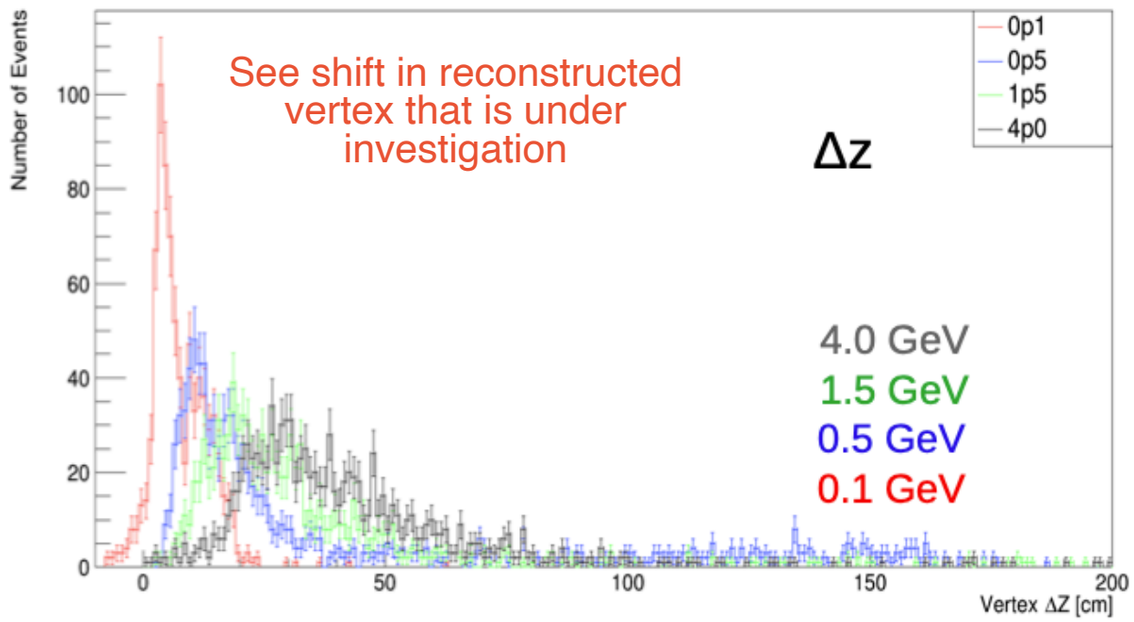
Pandora Event Reconstruction

- **Pandora pattern recognition being applied to ND-LAr in parallel**
  - Mature, widely used set of reco tools in wire-based LArTPCs including DUNE FD
- Also starts with edep-sim input
- Currently works in 2D projections to leverage existing toolchain
  - See reasonable performance with MC single particles & neutrino events
  - Plan to:
    - Update 2D algorithms for ND
    - Develop 3D algorithms



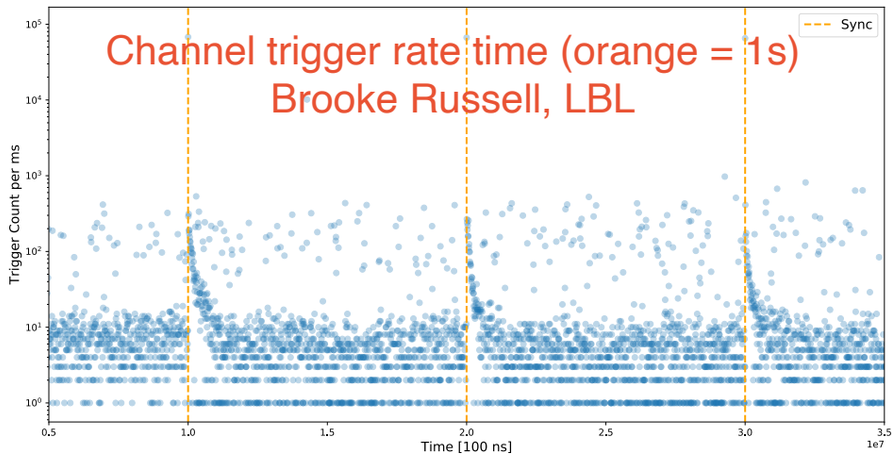


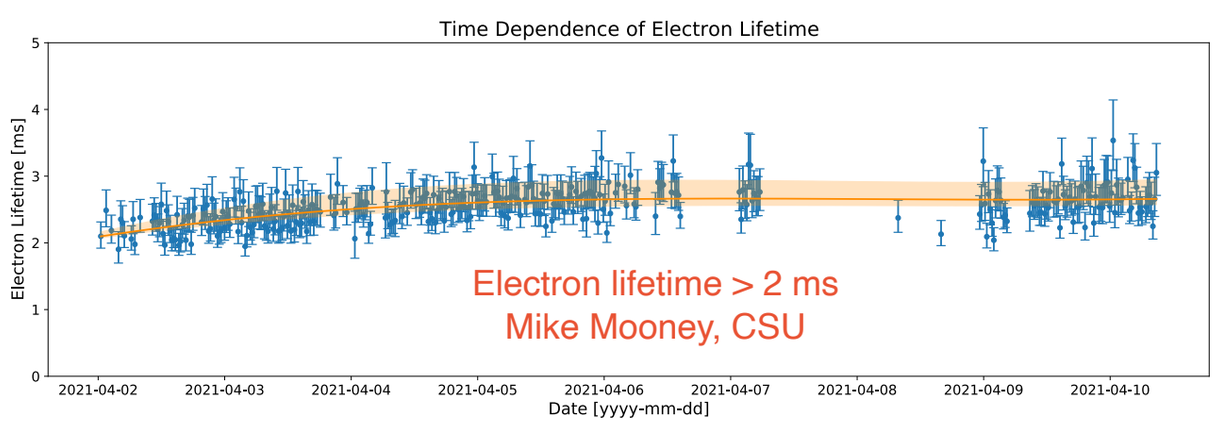




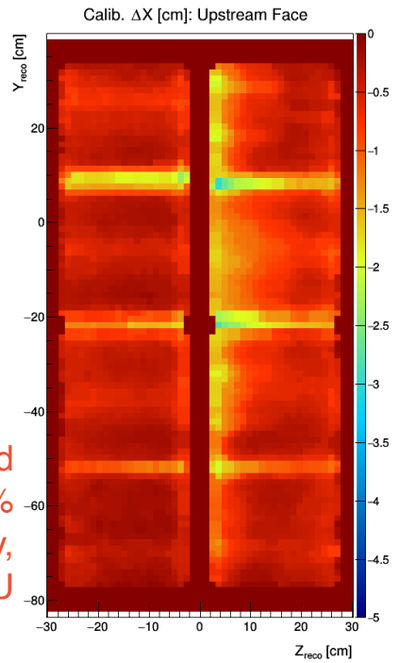
Module-0 Analysis

Detector Performance



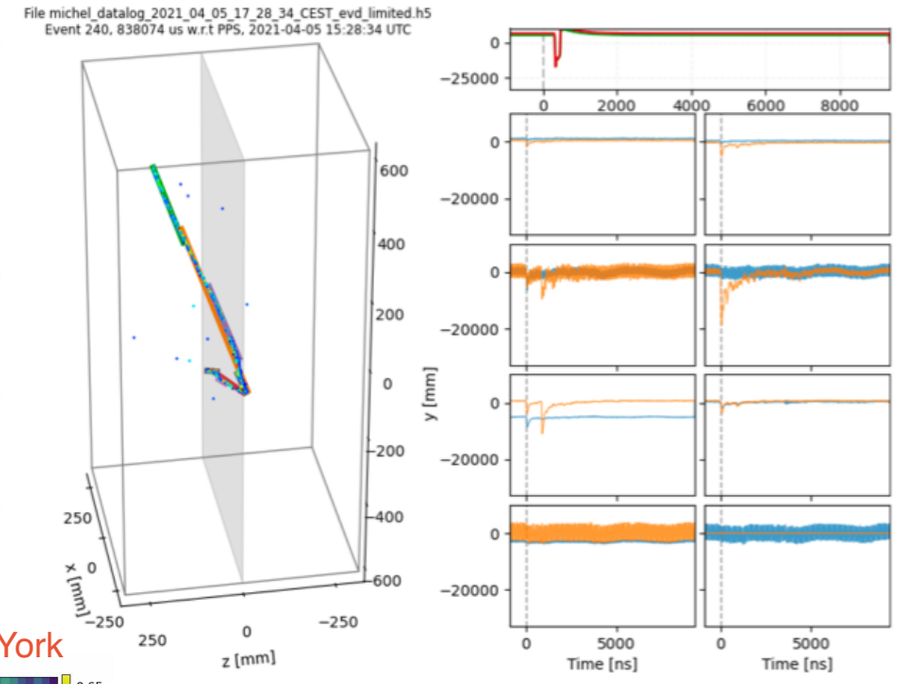


- Joint effort of many (N>10) consortium institutions
- Channel-level analysis of charge (LArPix) and light (ArCLight, LCM) systems (also provides MC tuning)
- Track-level studies electron lifetime, field uniformity, calorimetry
- Validations of key ND-LAr design requirements:
  - Noise < 1k e- enc,
  - >92% active ch, no cold failures
  - Efficiency, triggering, timing, purity, resistive field cage shaping uniformity, ...

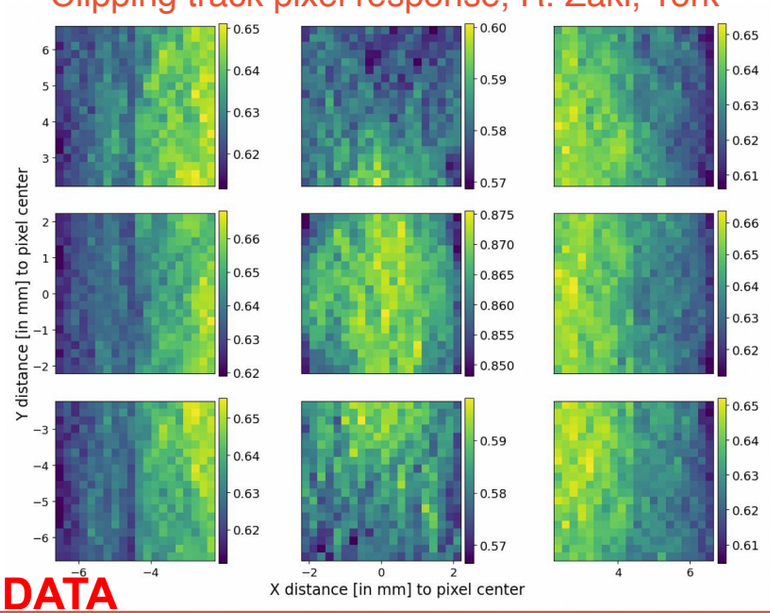


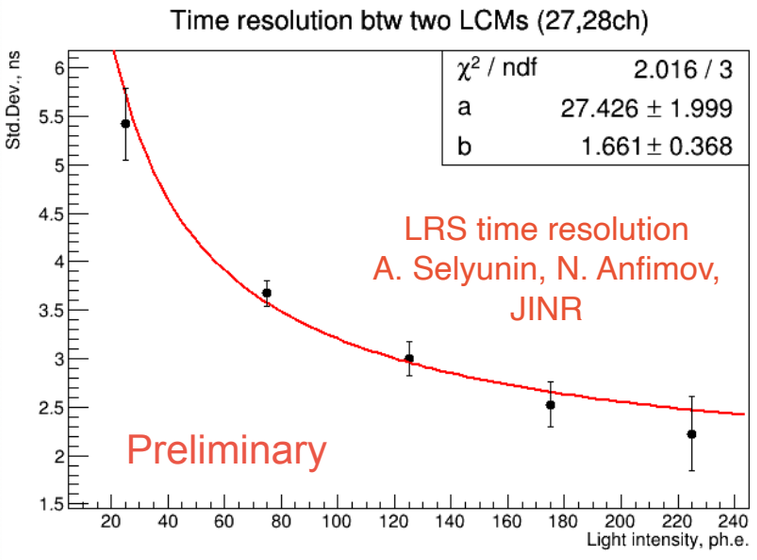
Electric field uniformity < 1%
Mike Mooney, CSU

Light-matched Michels (D. Porzio and J. Bürgi, Bern)



Clipping track pixel response, R. Zaki, York





Module-0 Analysis

Publication Status

- Paper dedicated to Module-0
  - Contains overview, performance of each system, and measurements with cosmics
  - Targets JINST
  - 40 pages, 44 figures
- First draft ready, but:
  - Some sections still need work
  - Different styles across manuscript
- Andy and Pedro trying to fix everything, but progress has been slow
  - Potential solution #0: keep going and hopefully find enough time (or additional help)
  - Potential solution #1: drop sections that are insufficient
  - Potential solution #2: write a short 5-10 page paper with highlights instead

Contents

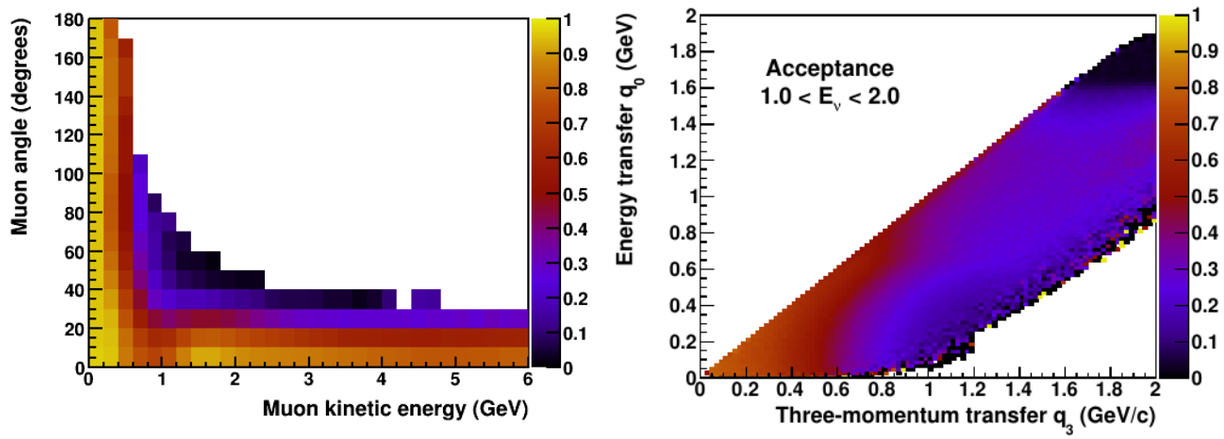
1 Overview

The Module-0 demonstrator is the first ton-scale prototype of the DUNE Liquid Argon Near Detector (ND-LAr) design. That detector will consist of a 7×5 array of $1\times1\times3$ m^3 detector modules [1] based on the ArgonCube detector concept [2], each housing two 50 cm drift Time Projection Chambers (TPCs) with roughly 30% optical detector coverage. Module-0, with dimensions $0.7\times0.7\times1.4$ m^3, represents the first fully-integrated prototype of the ND-LAr module design, bringing together the LArPix [3] pixelated 3D charge readout, advanced ArCLight [4] and Light Collection Module (LCM) [5] optical detectors, and field shaping provided by a low-profile resistive shell [6]. The prototype also tested the charge and light system control interfaces, data acquisition, triggering, and timing. Module-0 is the first of four functionally identical modules which together will comprise an upcoming 2×2 ND-LAr prototype, known as ProtoDUNE-ND. Following construction and initial tests with cosmic ray samples, this prototype will be deployed underground in the NuMI

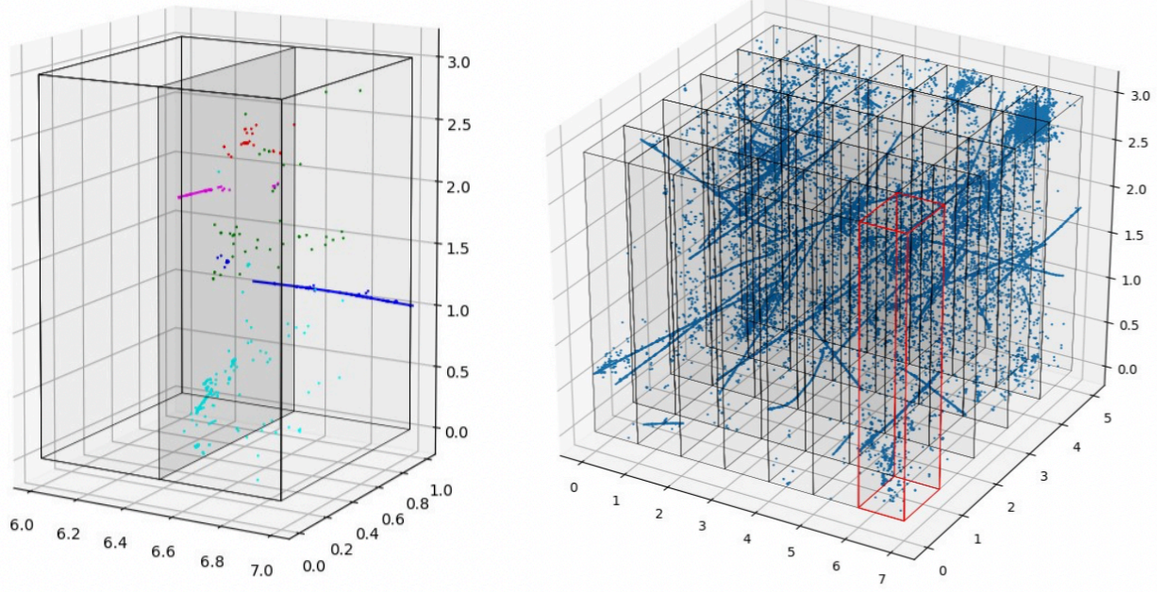
– 1 –

ND-LAr Physics Analysis

- Comprehensive suite of ND-LAr physics analyses performed using realistic pseudo-reconstruction for the ND CDR and FD TDR
  - e.g. LBL oscillation physics
- Revisit with updated detector modeling, full simulation and reconstruction tools
  - Geometry + Geant4 captures detector details, e.g. reconstruction across inactive regions and detectors
  - Most notably, effort towards next-generation LBL sensitivities is ramping up (next slides)



Muon and hadron acceptance, C. Marshall (Rochester)



Pileup & modularity, B. Russell (LBL)

ND-LAr Physics Analysis Targets

- **<u>Baseline</u> goal: assess reconstruction performance relative to ND-LAr requirements and pseudo-reconstruction parameters**
  - Already in progress: each parameter has a name next to it
  - Shooting for ~March 2022 for first pass
  - Challenges:
    - Some tools not fully ready, steep learning curve in some cases, and general busyness

Muon energy resolution	ND-LAr physics	5%	Contained, >1 m	LBL CAF
Muon angular resolution	ND-LAr physics		Analytic smearing	LBL CAF
Muon energy scale	ND-LAr physics	1%	Passive materials	ND CDR Sec. 2.7
Muon charge tagging	ND-LAr physics	100% FHC	RHC uses Michel tag	LBL CAF
Numu CC efficiency	ND-LAr physics			
Hadronic energy resolution	ND-LAr physics	0%	Calorimetric	LBL CAF
Vertex activity threshold	ND-LAr physics	20 MeV		ND CDR ND-C1.2.5
NC mis-ID rate	ND-LAr physics	Energy-dependent	See CAF	LBL CAF
Michel tag efficiency	ND-LAr physics	75%		LBL CAF
Electron shower energy resolution	ND-LAr physics	5%; 3%+1%/sqrt(E) per CAFs	GeV	ND CDR ND-C1.2.3
Electron shower angular resolution	ND-LAr physics	core<5mr, tail<12mr for Ee>2GeV	Analytic smearing in CAF	ND CDR ND-C1.2.4
Electron ID vs. mu, gamma, Pi0	ND-LAr physics			ND CDR ND-C1.2.2
Pi0 mid-ID rate	ND-LAr physics	15% for d<2 cm	SS is <50MeV, <10 mrad	LBL CAF
Nue CC efficiency	ND-LAr physics	100% at >700 MeV	Linear down to 300 MeV	ND CDR ND-C1.3
Nue CC purity	ND-LAr physics			ND CDR ND-C1.3
Nu+e ES efficiency	ND-LAr physics	2% stat uncert	>2500 ev/y	ND CDR ND-C1.2
Pileup mis-ID rate	ND-LAr physics	10%		LBL CAF
Pileup mis-ID energy bias	ND-LAr physics	0.5	GeV	LBL CAF
Interaction purity	ND-LAr physics	>97% averaged over interactions		ND-LAr SYS-003
Interaction completeness	ND-LAr physics	>97% averaged over interactions		ND-LAr SYS-004
Charge-light matching efficiency	ND-LAr physics	>97% averaged over interactions		ND-LAr SYS-005
Muon acceptance	ND-LAr physics	>0.1%, >10% typical		ND CDR Sec 2.5.3
Neutron multiplicity distribution	ND-LAr physics		Neutrino-induced	ND CDR Fig. 2.13
Neutron momentum distribution	ND-LAr physics		Neutrino-induced	ND CDR Fig. 2.13
Pi0 multiplicity distribution	ND-LAr physics		Neutrino-induced	ND CDR Fig. 2.20
Pi0 momentum distribution	ND-LAr physics		Neutrino-induced	ND CDR Fig. 2.20
Hadronic containment for FV	ND-LAr physics	95%		ND CDR Sec 2.5.1

(Organized a 4-day reconstruction <u>tutorial</u> in October 2021 that allowed us to expand our effort and to kickstart this work)

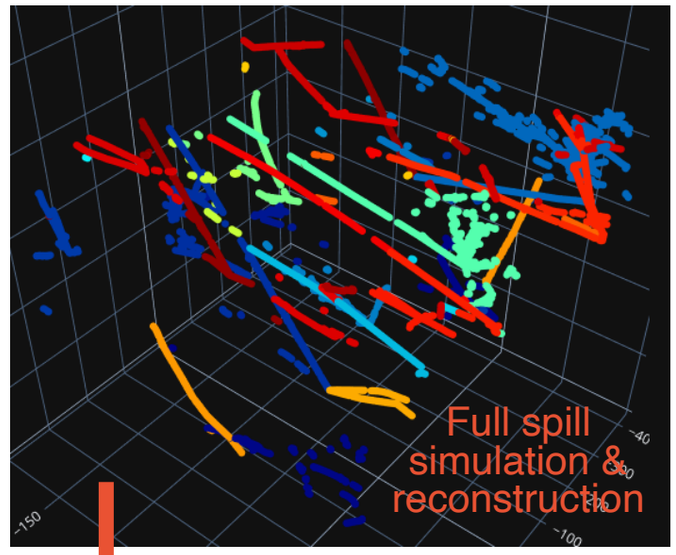
- **<u>More aggressive</u> goal: production of full end-to-end simulation and reconstruction samples**
  - Pursued in parallel with baseline goal: use the same tools
  - Want tools in place for **Preliminary Design Review** in summer 2022
  - LBL and other analyses will require several iterations
    - Aiming to complete first trial run for LBL group by ~March 2022 (see next slide)

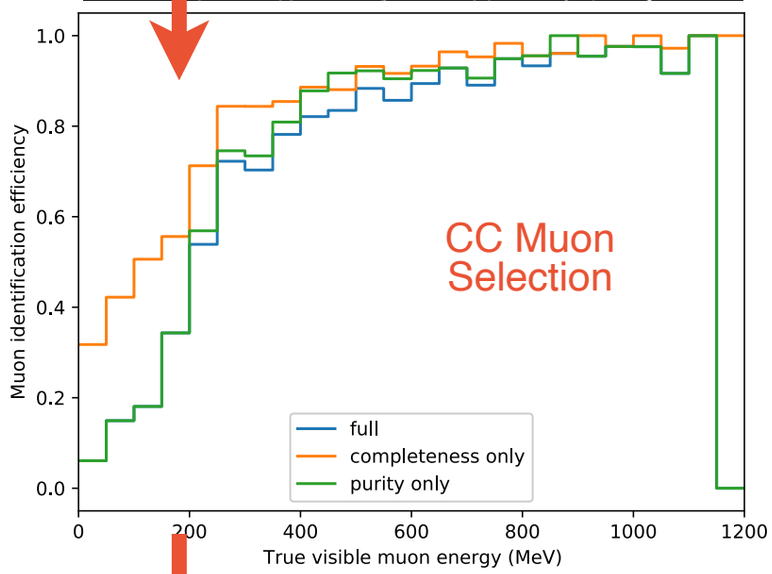
ND-LAr Physics Analysis

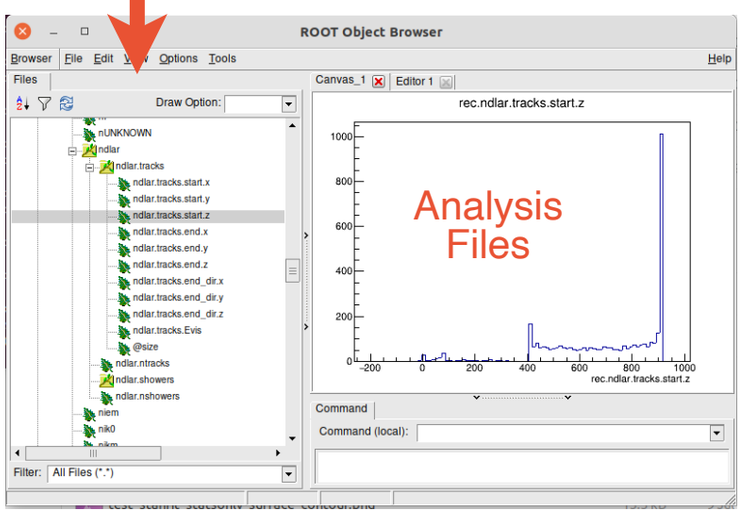
Long-Baseline Physics Targets

1. **Reproduce TDR analysis with full reconstruction**
   - **ν_μCC in E_μ, E_{had}, parametric detector systematics**
2. Improved systematics modeling
   - Model informed by low-level simulation variations
   - Dedicated point person (A. Mogan, CSU) brings MicroBooNE systematics experience
3. Long-term strategies
   - New approaches, e.g. differentiable simulation (K. Terao, SLAC)

Working closely with LBL and Interactions groups, and "DIRT-II" systematics task force, via group liaisons







Major Targets - Hardware Driven

- **Module-1 data analysis (~February 2022):**
  - Main goal: ensure overall "health" of module with cosmics
  - Repeat most analyses done on Module-0 & understand any new features seen
  - Plan to organize tutorial on data analysis basics to widen pool of analyzers and to organize the work (~February 2022)
  - Repeat process for modules 2-3
- **2x2 data analysis (~Fall 2022)**:
  - Main goals: demonstrate performance of ND-LAr design in beam environment, inform ND-LAr design, but also produce some physics in the process!
  - Need to have full end-to-end simulation and reconstruction before this detector comes online - matches timeline two slides ago
  - Plan to organize workshop on possible physics analyses in preparation for data-taking (~Summer 2022?)

Plans for Collaboration Meeting

- The ND-LAr Analysis parallel session is scheduled for **Thursday January 27 at 10am CT**
- Plan to have reports on the following fronts:
  - Big picture strategy
  - Charge and light simulations
  - MLReco and Pandora reconstructions
  - Updates on Module-0 analysis and/or data/MC comparisons
- Will also have a separate ND + LBL session: ←to be announced soon
  - Our group will likely contribute two talks:
    - Status & plans
    - First thoughts on ND-LAr systematics

Summary

- Significant progress on simulation and reconstruction building on shared DUNE ND efforts and tools
- Components in place for a complete end-to-end system
  - Detector geometry and response simulation for charge & light readout
  - Reconstruction (for Geant4 level) in analysis trees
- Reconstruction of detector simulations in progress, and ramping up revisiting CAF-based analysis of the ND CDR and FD TDR
- Module-0 analysis is providing valuable design feedback
- Excellent team, person-power remains a challenge
  - Expanded effort in support of Module-0 indicates a ramp-up in ND-LAr analysis involvement, CAFs enable higher-level analysis
  - Actively working to recruit more people, especially for high-level analysis
- **Subsystem leads: if you require analysis input for PDR, please let us know as soon as you can**