Wire-Cell in MicroBooNE

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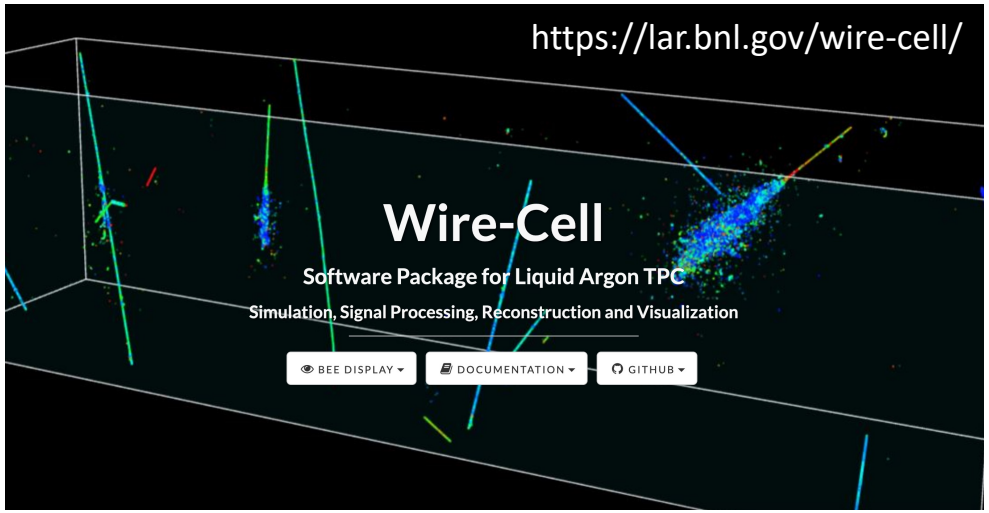
The Second Wire-Cell Reconstruction Summit

Apr 11, 2024

What is Wire-Cell?

First answer in Google search

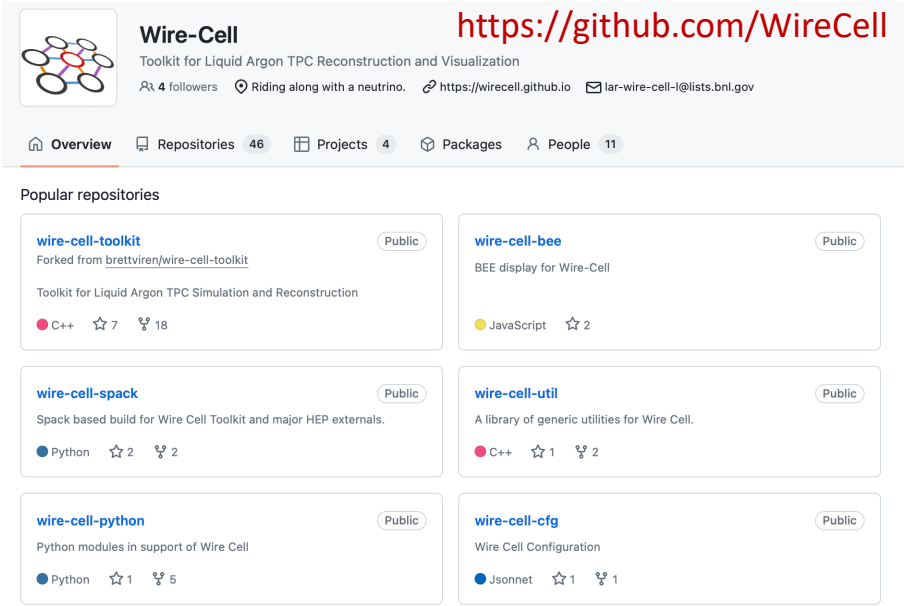


A collection of algorithms & software tools for LArTPC

Chao's talk yesterday

Second answer in Google search

https://github.com/WireCell



A Github repository created several years ago, containing a variety of codebases -- **wire-cell-toolkit, etc.**

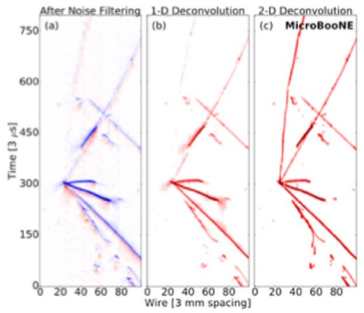
Brett's talk yesterday

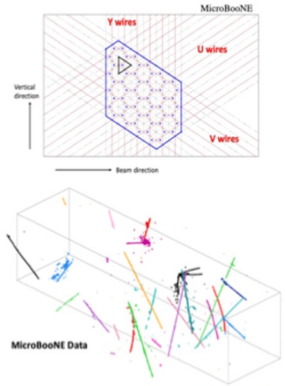
A brief history of Wire-Cell development

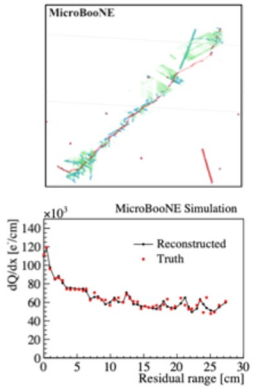
Including a realistic TPC simulation widely used in LArTPC experiments

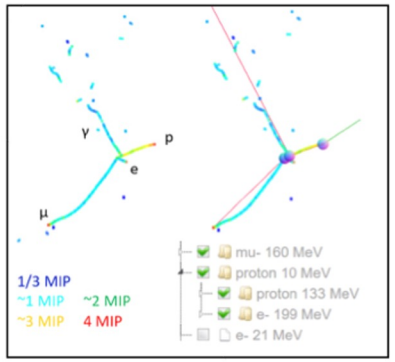
Development of Wire-Cell in MicroBooNE (2015-2021)

noise filtering signal processing	3D imaging clustering charge-light matching	3D trajectory & dQ/dx fitting cosmic muon tagger	multi-track fitting 3D vertexing particle identification









JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)

JINST 13 P05032 (2018)
JINST 16 P06043 (2021)

Phys. Rev. Applied 15 064071 (2021)
arXiv: 2012.07928 (2020)

JINST 17, P10037

Wire-Cell is a 3D tomographic event reconstruction for LArTPC. Started from the 3D event image reconstruction, it now covers a wide range of topics from TPC signal processing to 3D pattern recognition

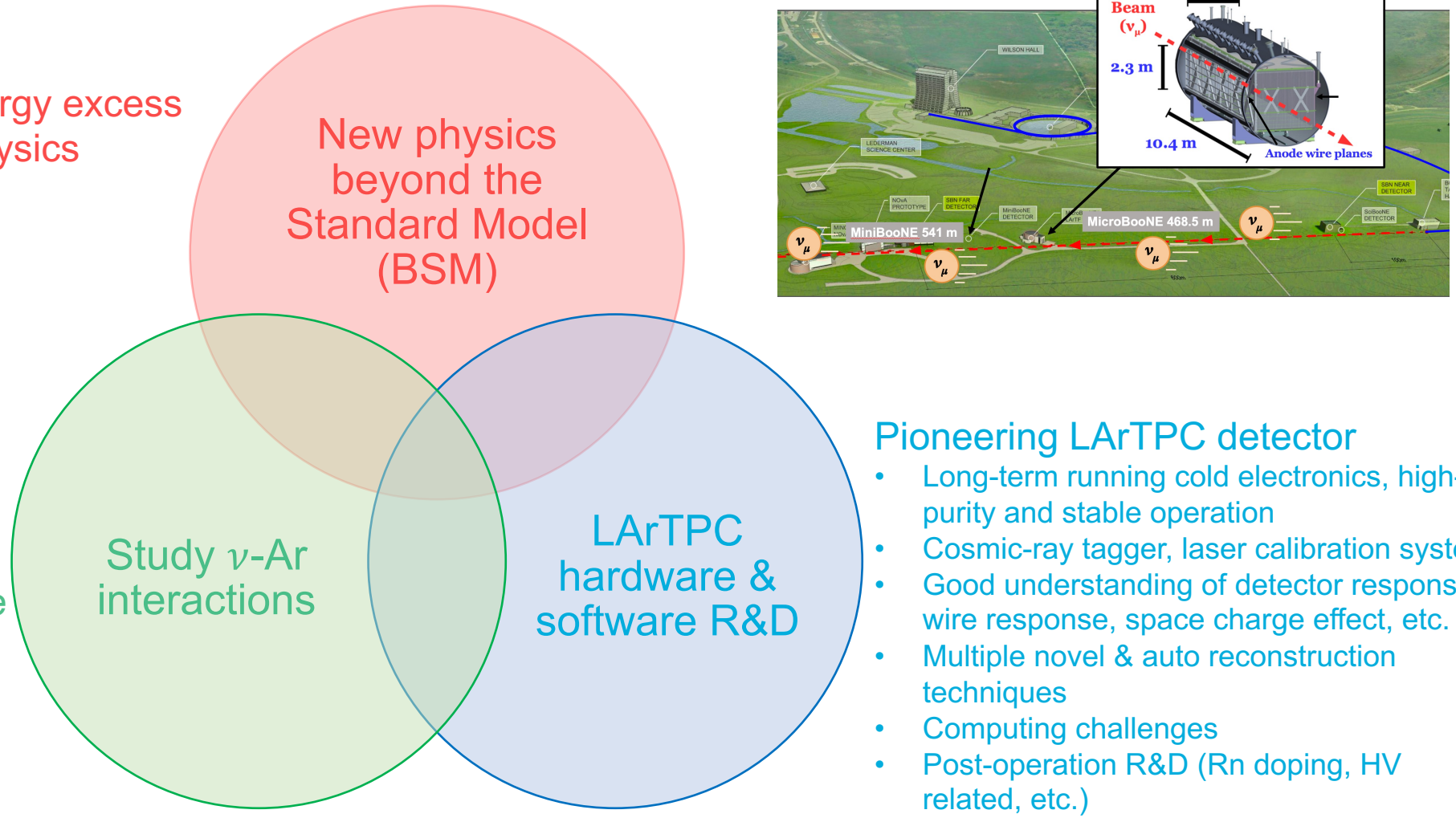
Starting with 3D imaging proof of principle and 2D deconvolution

Further developed and validated using MicroBooNE data and utilized in physics analyses in MicroBooNE

Xin's talk yesterday

MicroBooNE

Address MiniBooNE low-energy excess origin and search for new physics



Various exclusive and inclusive cross section measurements

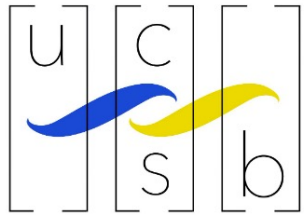
- Large $\nu - Ar$ data sample
- Leveraging the excellent PID capability of LArTPC

Pioneering LArTPC detector

- Long-term running cold electronics, high-purity and stable operation
- Cosmic-ray tagger, laser calibration system
- Good understanding of detector response: wire response, space charge effect, etc.
- Multiple novel & auto reconstruction techniques
- Computing challenges
- Post-operation R&D (Rn doping, HV related, etc.)

Wire-Cell group at MicroBooNE

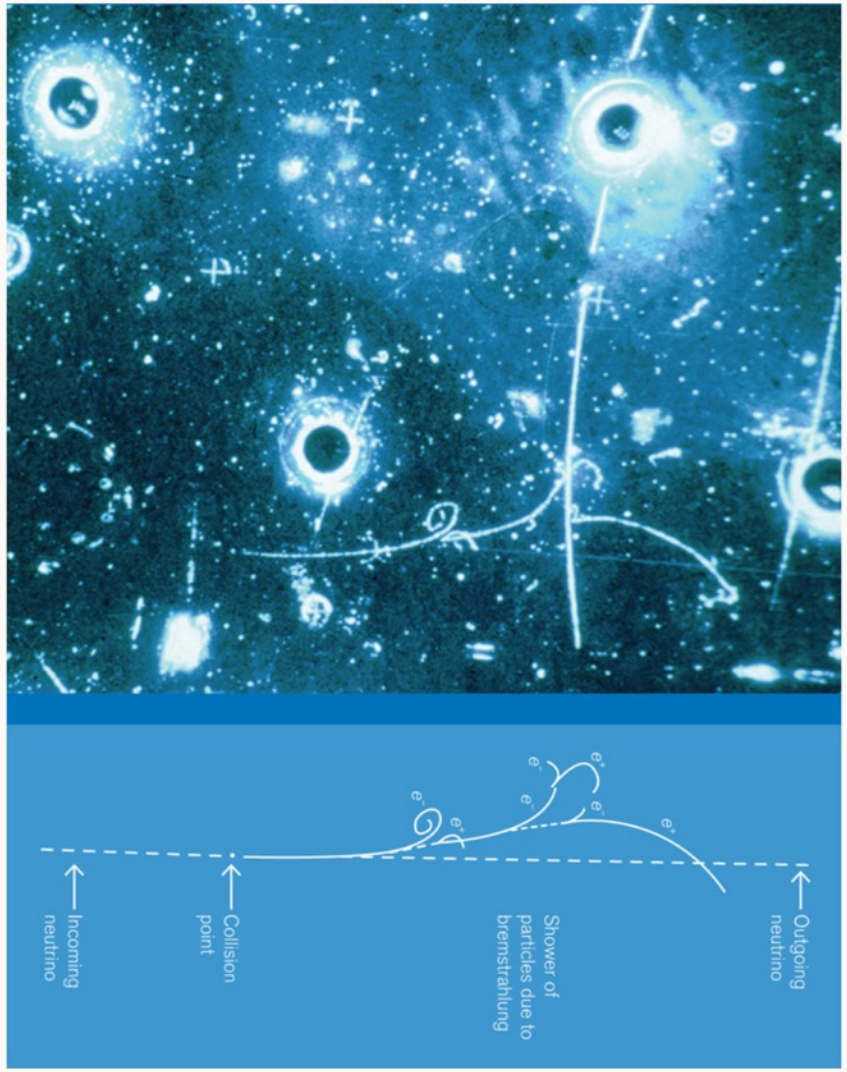
- The team creating and developing Wire-Cell software package
- Essentially the same team + new postdocs/students optimizing & applying Wire-Cell to achieve high-performance physics analyses



THE UNIVERSITY OF
CHICAGO

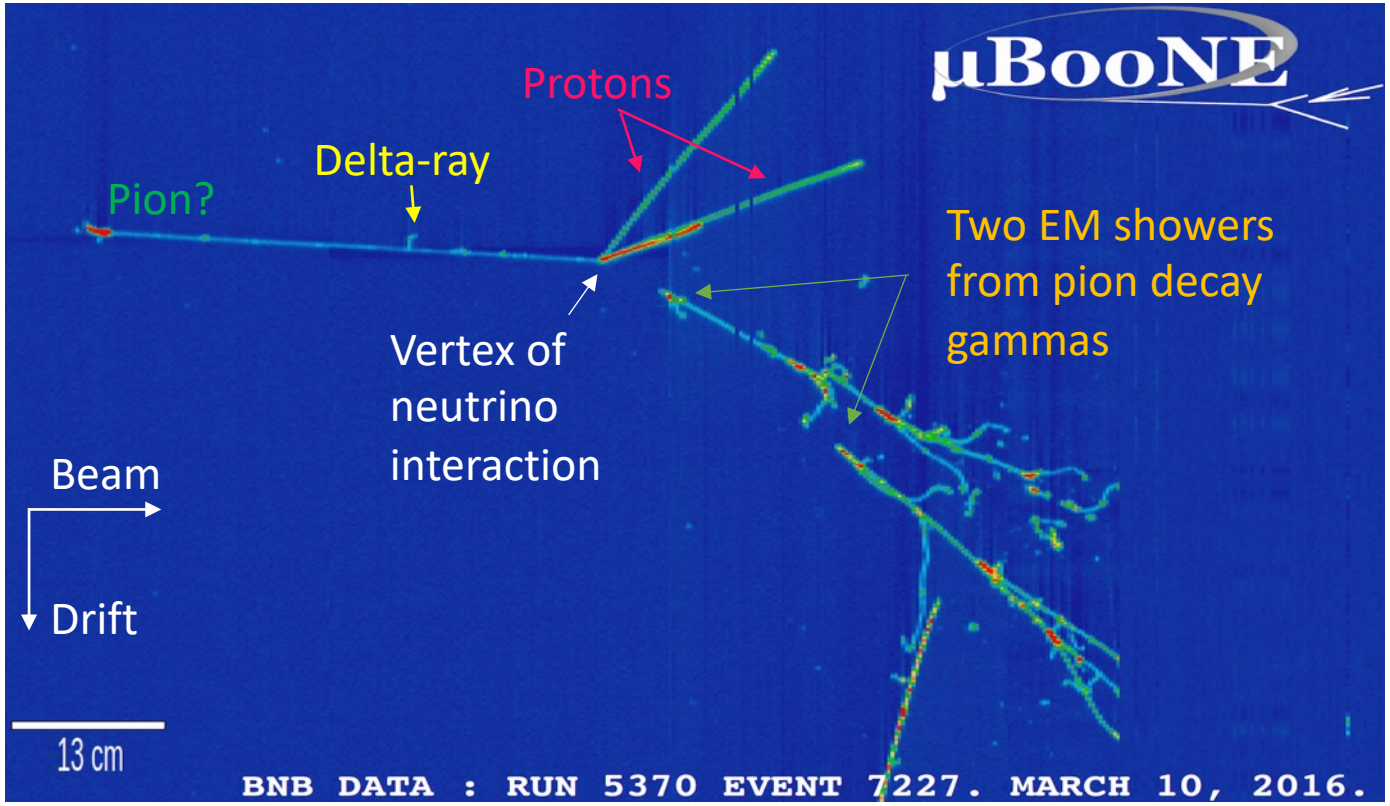
6 institutions, 15-20 members, faculty, postdocs, and students

50 years: from Bubble chamber to LArTPC



Gargamelle (1973): discovery of weak neutral current [$\nu_\mu e^- \rightarrow \nu_\mu e^-$]

LArTPC: fully active tracking calorimeter



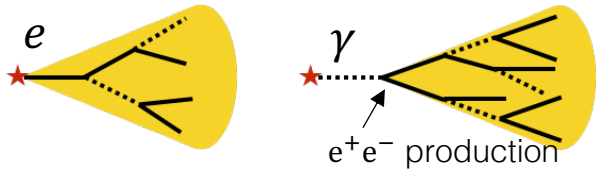
MicroBooNE (2016): a neutral current interaction of ν_μ

LArTPC: an enabling detector

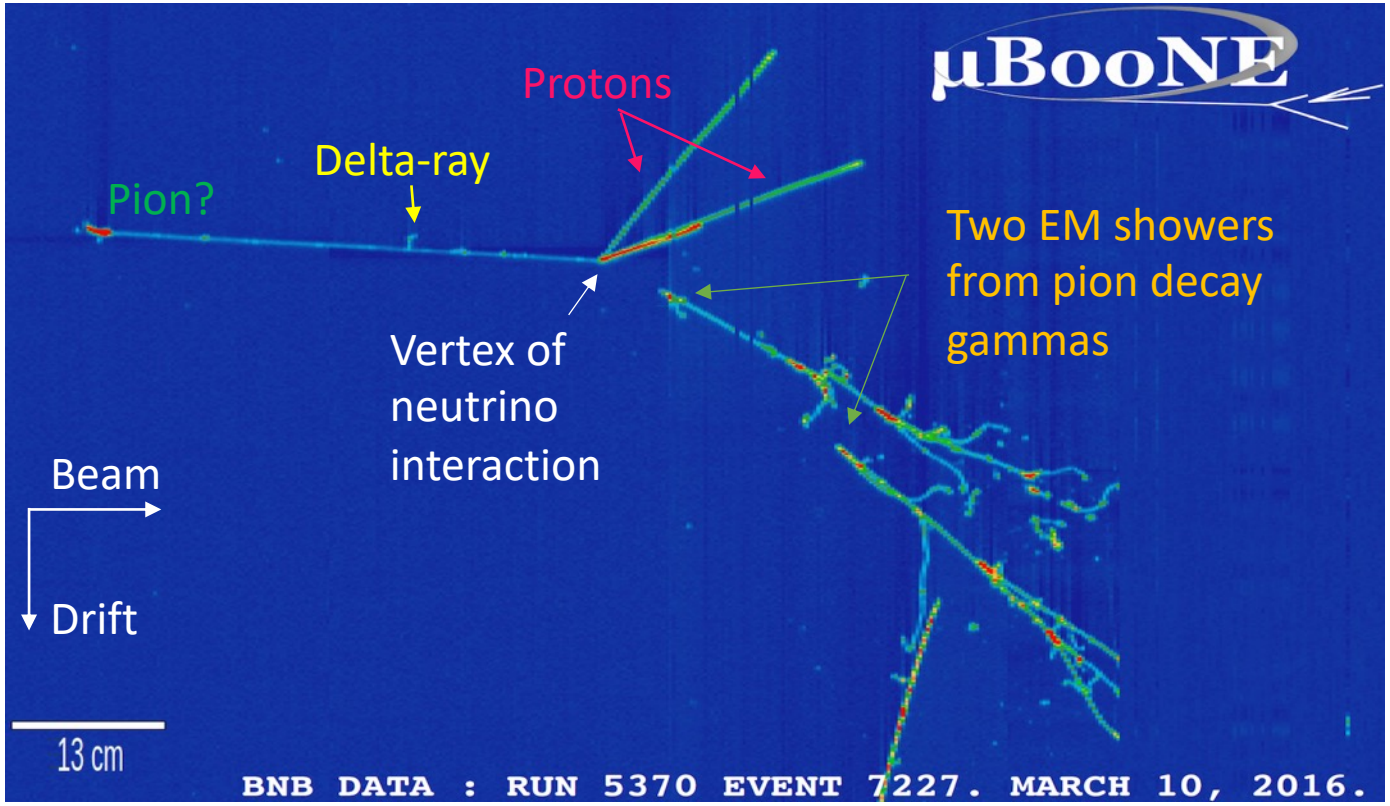
Capable of identifying different species of particles and reconstructing 3D images with fine-grained information

- Neutrino vertex
- Particle flow (mother-daughter relationship)
- Track (μ, π, p etc.) vs shower (e, γ EM cascade)

- **e vs γ ($\mathrm{e}^+\mathrm{e}^-$ pair production) separation addressing MiniBooNE anomaly**
  - Gap between shower start point and neutrino vertex?
  - dE/dx in shower stem (1 MIP vs 2 MIPs)
  - Split of $\mathrm{e}^+\mathrm{e}^-$ pair (large opening angle)



LArTPC: fully active tracking calorimeter



MicroBooNE (2016): a neutral current interaction of ν_μ

Event Reconstruction in LArTPC

- In essence, while hardware provides the physical foundation for technology, software enables its functionality and utility.

- Event reconstruction in LArTPC can maximize the scientific capabilities inherent in the LArTPC technology, yielding significant physics outcomes.

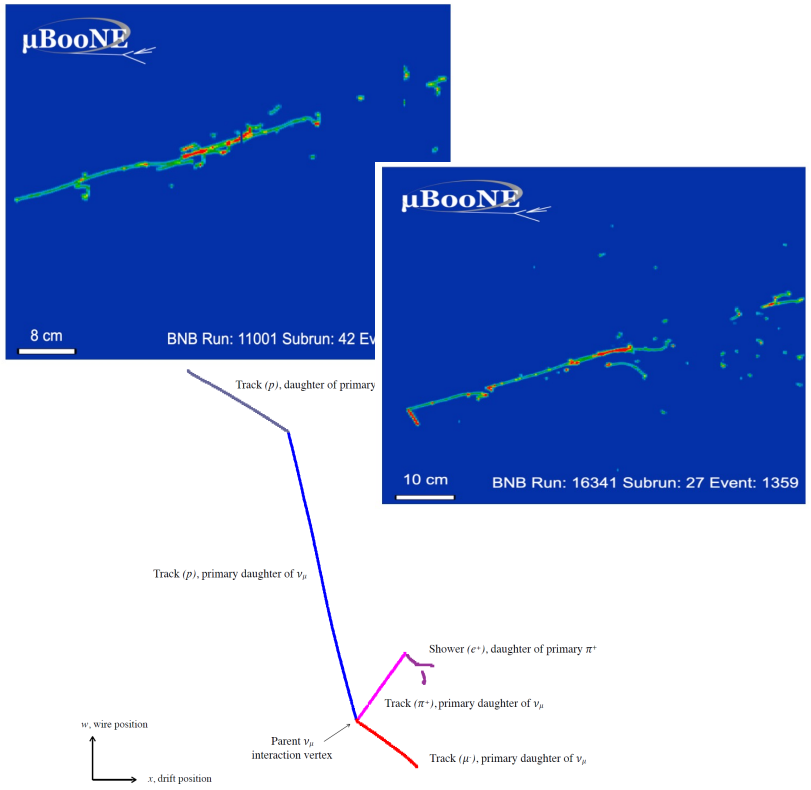
"Hardware eventually fails, software lives forever." - Paul Ginsparg, physicist and creator of the arXiv repository.

Event Reconstruction in MicroBooNE

Different novel reconstruction approaches developed in MicroBooNE

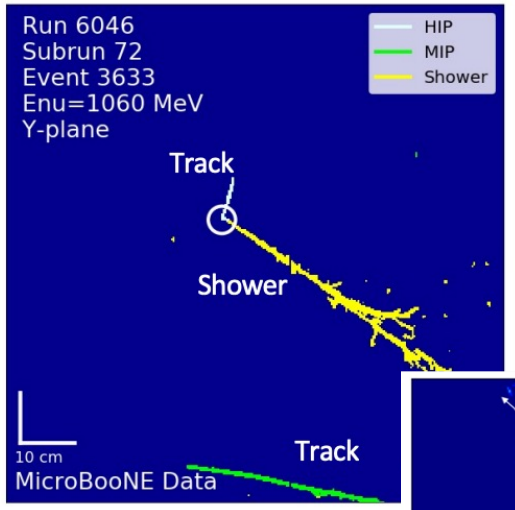
Pandora reconstruction

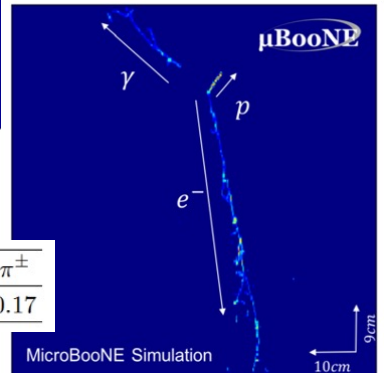
The most general pattern recognition algorithm with the longest history
Eur. Phys. J. C78, 82 (2018)
(various cross section results and new physics searches)



Deep-learning reconstruction

Built upon the deep learning revolution in the area of computer vision; first of their kind applications in a LArTPC
PRD 103, 052012 (2021)
PRD 103, 092003 (2021),
PRD 99, 092001 (2019)

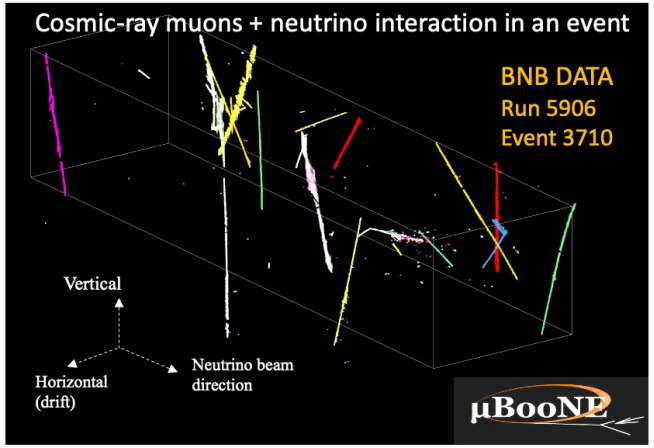


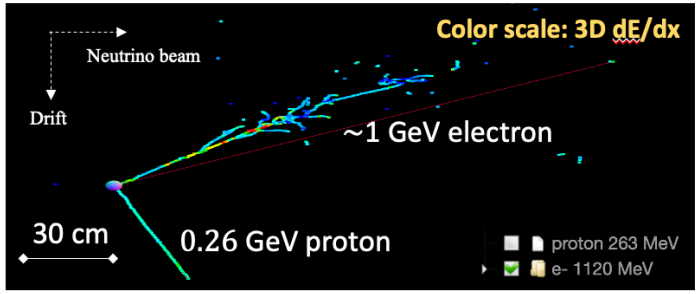


	p	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.89	0.95	0.85	0.06	0.17

Wire-Cell reconstruction

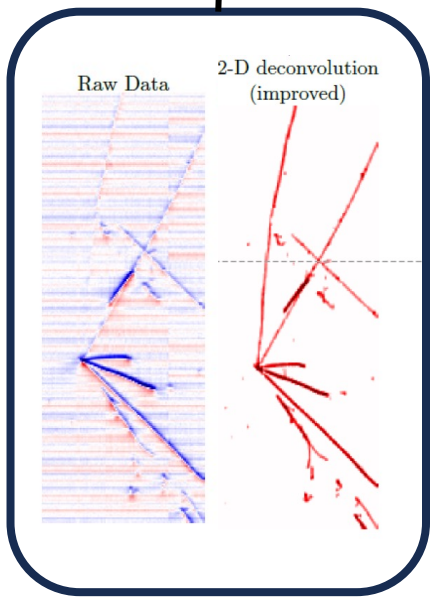
Tomographic 3D imaging/clustering and other 3D-based pattern recognition
JINST 17 P01037 (2022)
PRApplied 15 064071 (2021)
JINST 16 P06043 (2021)
JINST 13 P05032 (2018)

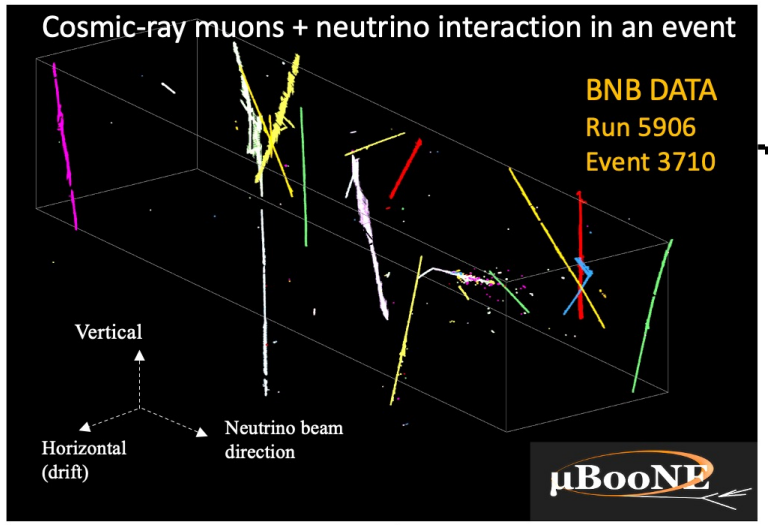




Wire-Cell Event Reconstruction

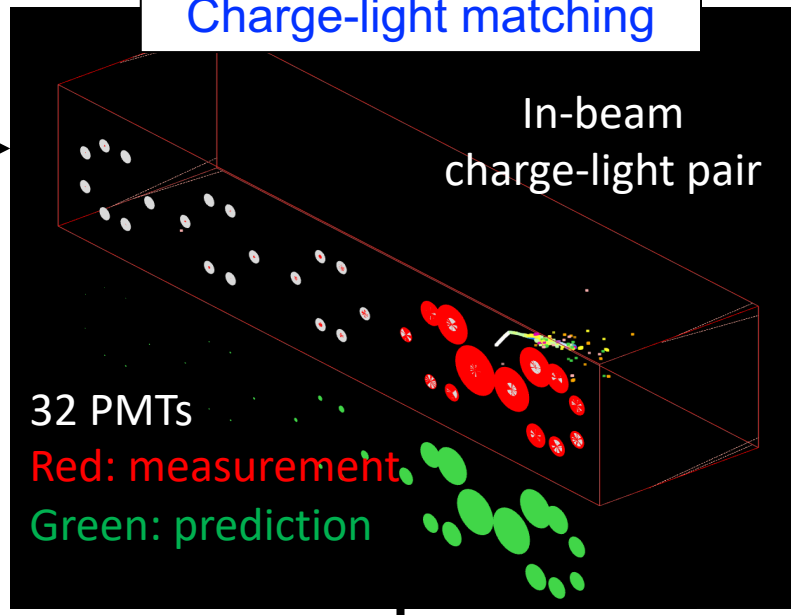
functionally identical extraction of charge for three wire planes



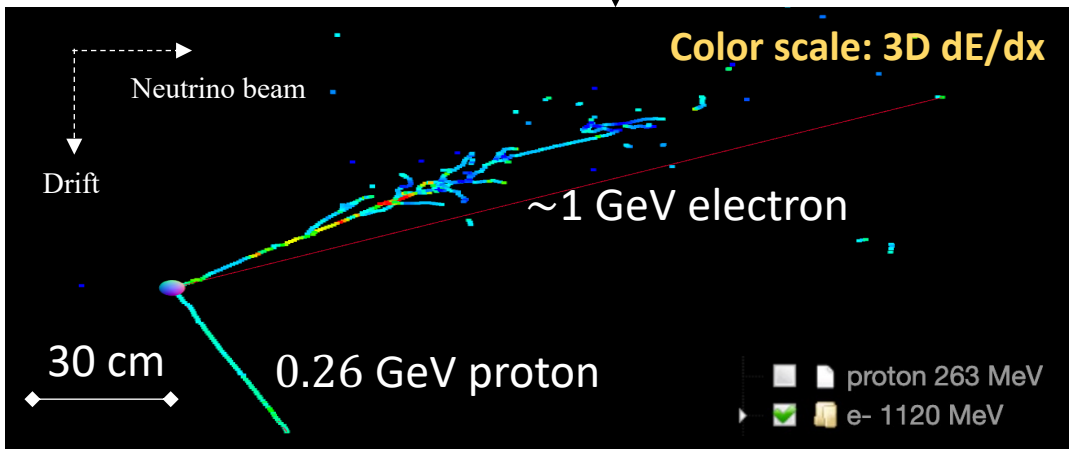


3D imaging, clustering

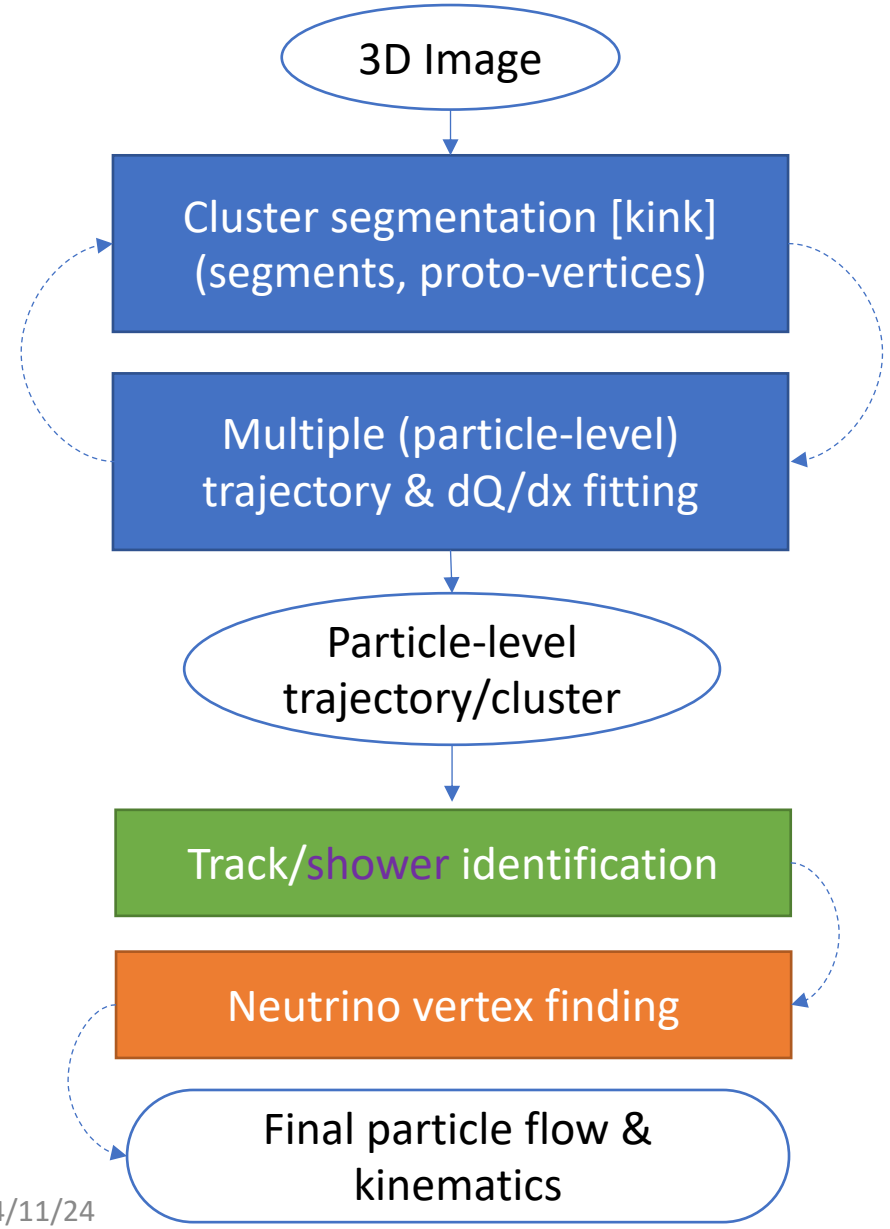
Charge-light matching



3D pattern recognition
- neutrino vertexing
- particle identification
- particle flow
- kinetic energy



Development of Wire-Cell 3D pattern recognition in MicroBooNE



Challenges

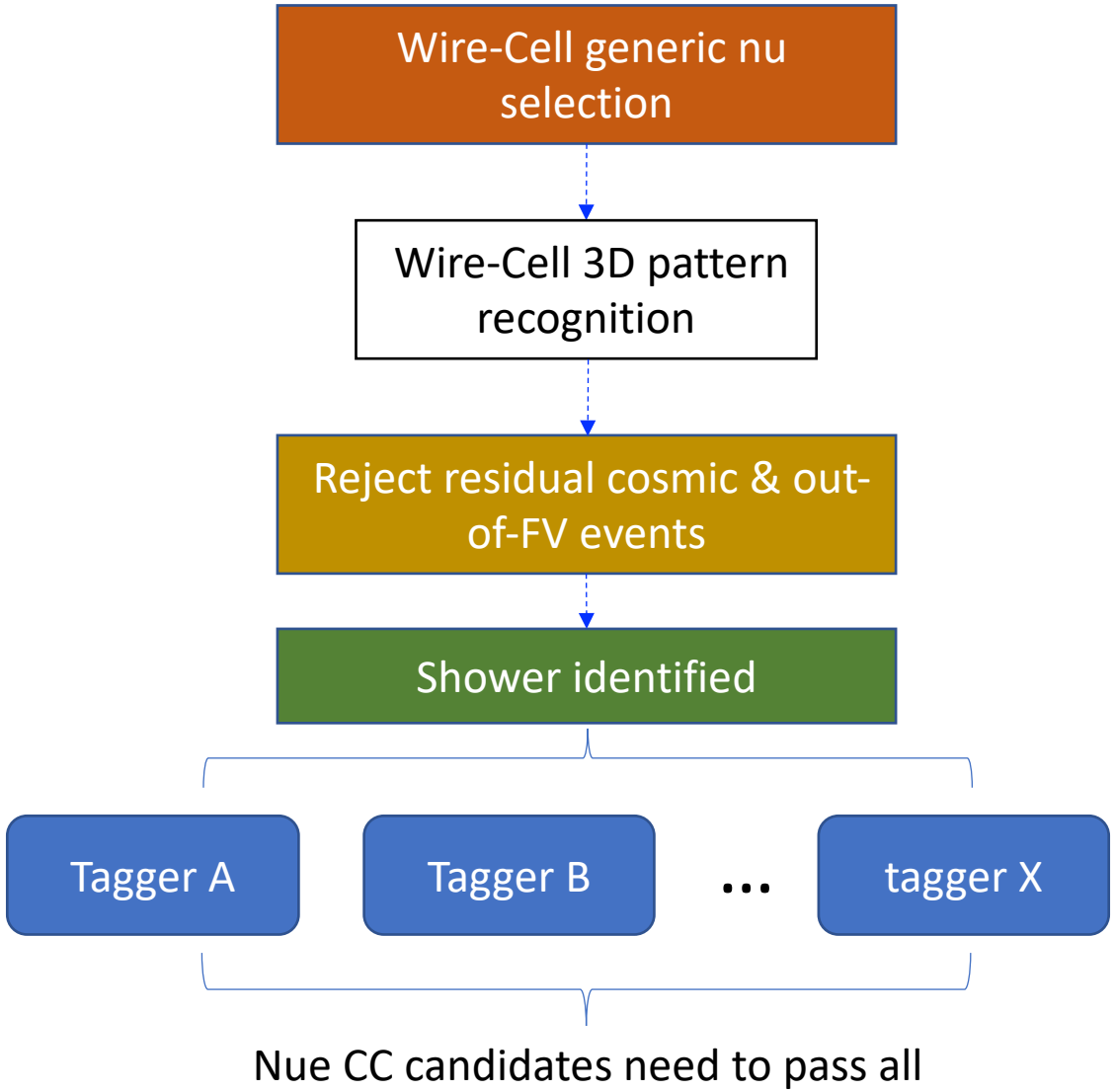
- A huge amount of 3D points
- Wire readout ambiguity, particularly for isochronous track
- Broken tracks (prolonged tracks or non-functional channels)

Strategy

- ✓ Eye-scan oriented development (traditional approaches in the first iteration)
- ✓ Directly on real data
  - ✓ Complex topology first
  - ✓ O(1) event → O(10) events
- ✓ Validation (optimization) by MC

The first version ready in April 2020

Wire-Cell nue CC tagger (developed in April-August 2020)

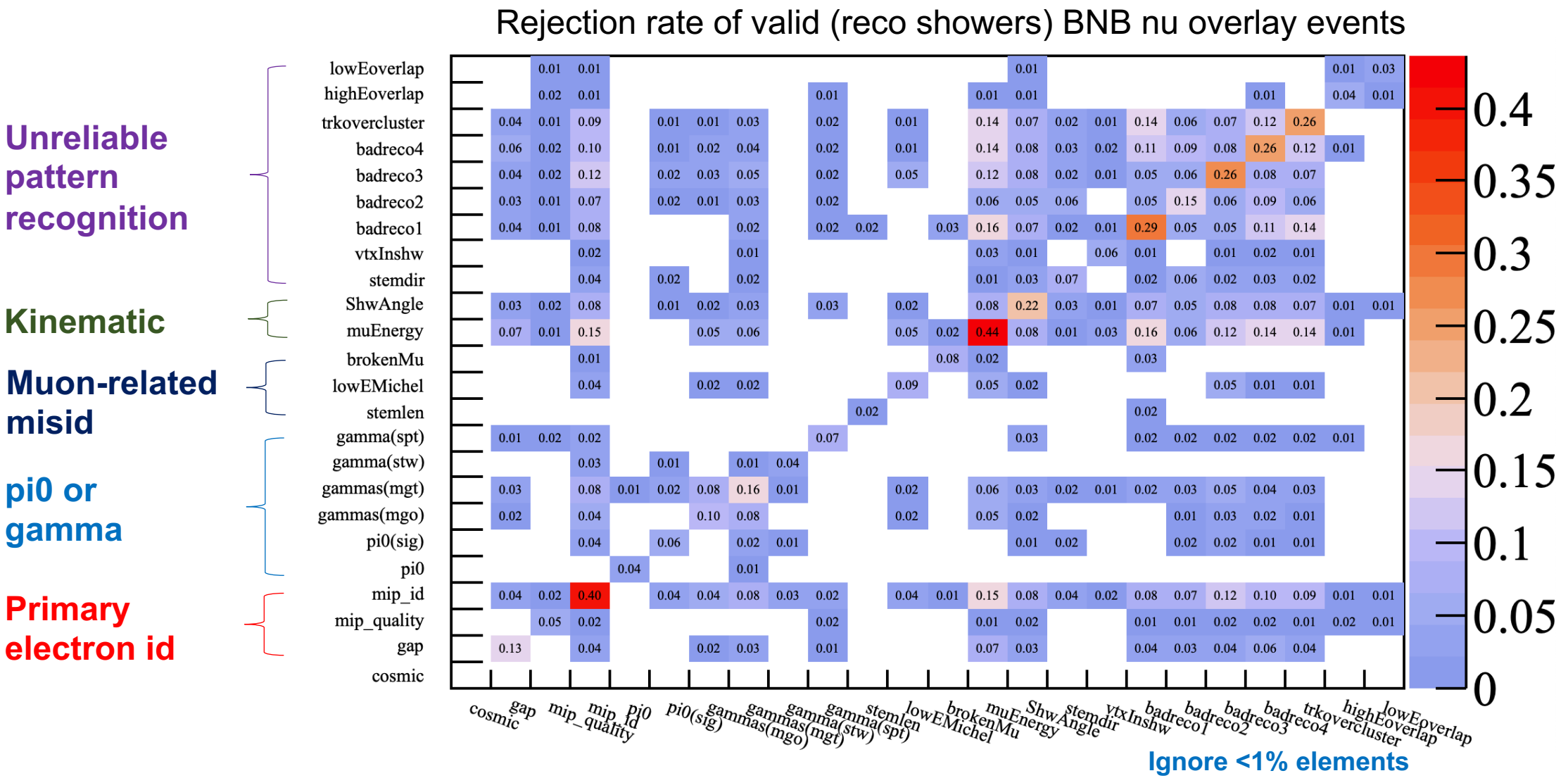


Basic strategy of “Gen 1” nue CC tagger:

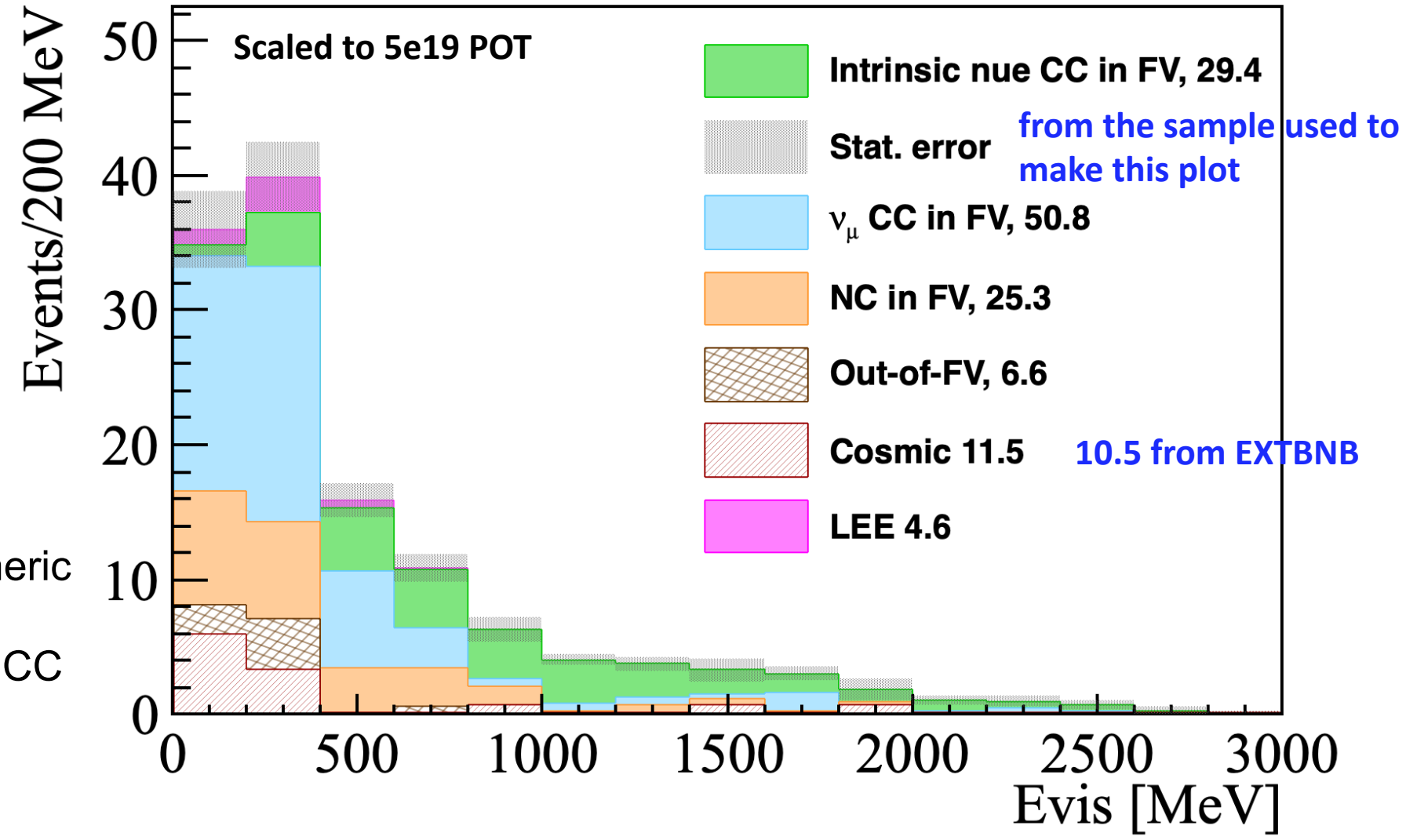
- Traditional algorithms
- Hand-scan → human feature engineering
  - Various taggers to reject specific types of background
- Iterative optimization

nue CC sub-taggers [24 in total]

Numbers are relative to all rejected events



“Gen 1” cut-based nue CC tagger result



- Overall tagging (post generic selection) efficiency
  - 35% for intrinsic nue CC
  - 25% for LEE
- Poor purity in low energy region (LEE interest)

Issues of the “Gen 1” strategy and Game change

Issues of “Gen 1” nue CC tagger:
- BNB nue CC vs. other nu = 1:200 (NuMI 1:10)
- Capacity of hand-scan
  - <1000 events
  - 1% error rate → 1% x 200 w.r.t. nue CC

Basic strategy of “Gen 2” nue CC tagger:
- Machine learning algorithms
  - Shallow learning e.g. BDT to enhance purity
  - Deep learning to enhance vertexing efficiency
  - High statistic training to cover more “corner cases”

Slow progress & Unstable

Rapid & Robust

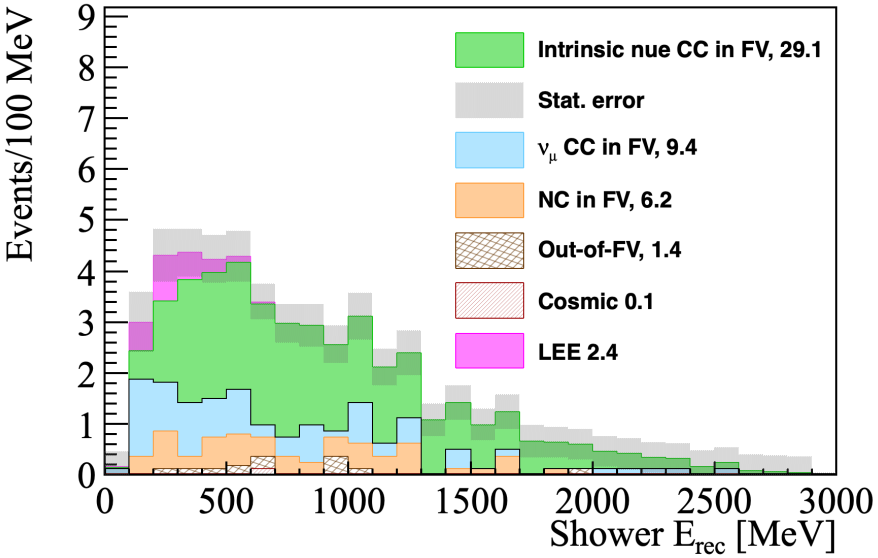
Reco products, knowledge and human learned features in previous “Gen 1” development as input is vital to ensuring the performance

NueCC candidate energy spectra

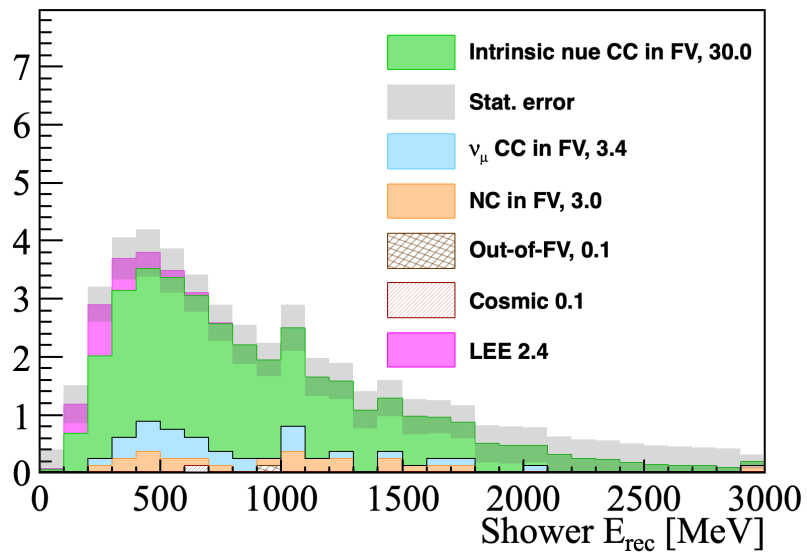
Run1, scaled to **5e19 POT**
Contained + uncontained

Roughly the same overlay MC samples [not used in the training]
BNB overlay sample: ~4.0e20 POT

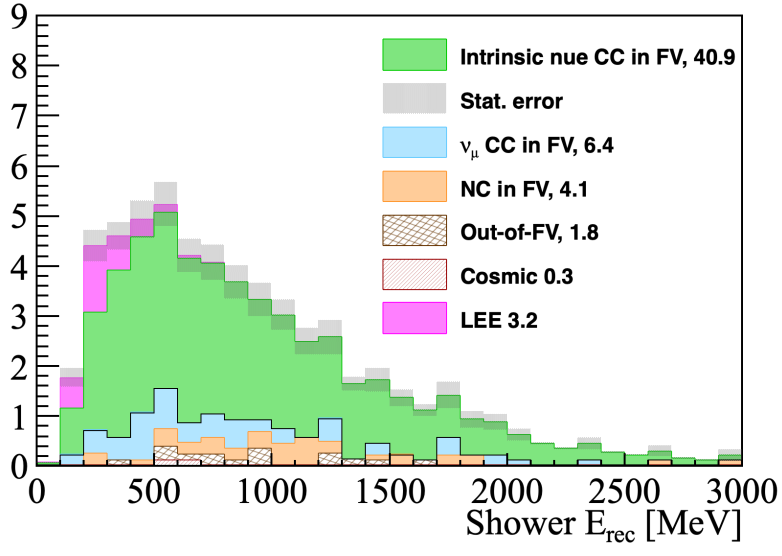
TMVA BDT



XGBOOST BDT



DL vertex+ XGBOOST BDT



Tuned to have similar **efficiency**

Intrinsic nue purity: 63% → 82%
Bin [2, 4] LEE/others:
2.1/9.8 vs. 2.0/5.9

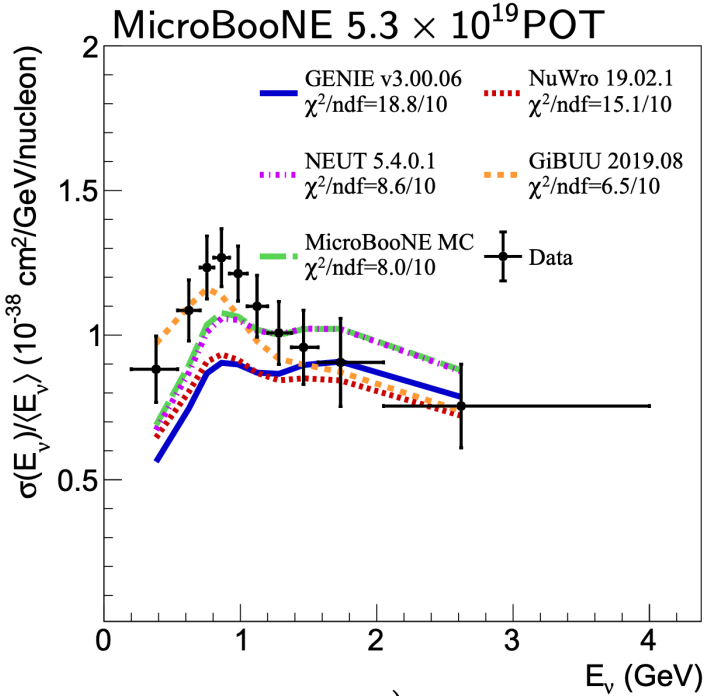
Tuned to have similar **purity**

Intrinsic nue selection eff.: 37% → 51%
Bin [2, 4] LEE/others:
2.0/5.9 vs. 2.8/8.2

Scientific achievements (not exhaustive list)

Wire-Cell based MicroBooNE flagship physics analyses

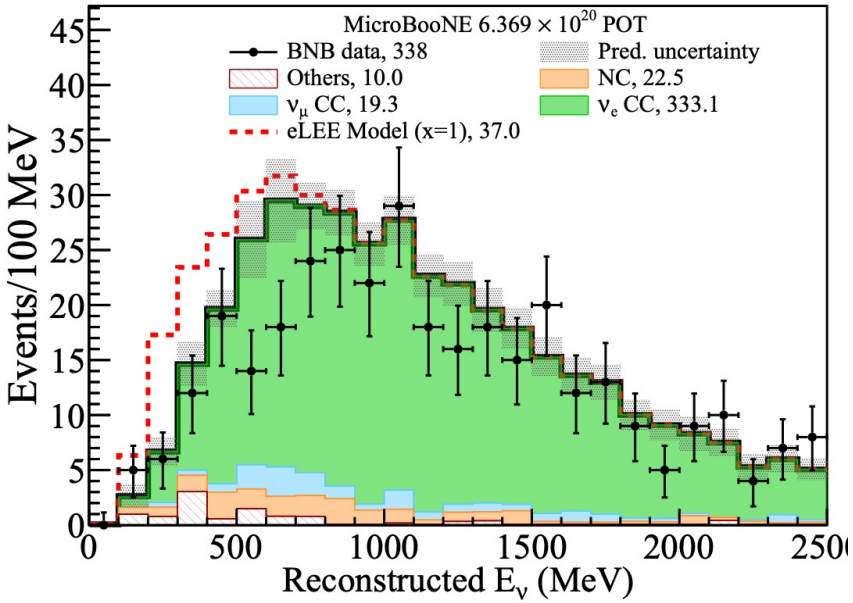
Phys. Rev. Lett. 128, 151801 (2022)



ν_μ CC inclusive xsec

First measurement of energy-dependent $\nu - Ar$ cross section. High efficiency (64%) & high purity (93%) ν_μ CC selection. Robust energy reconstruction

Phys. Rev. Lett. 128, 241801 (2022)
Phys. Rev. D 105, 112005 (2022)

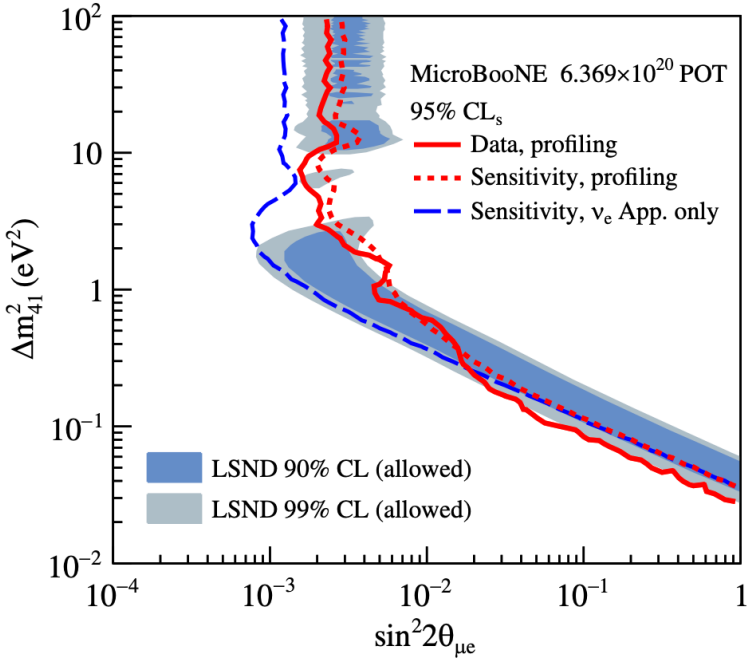


Search for low-energy excess ν_e

Relatively high efficiency (46%) & high purity (82%) ν_e CC selection

>3σ exclude an empirical model of LEE derived from MiniBooNE

Phys. Rev. Lett. 130, 011801(2023)



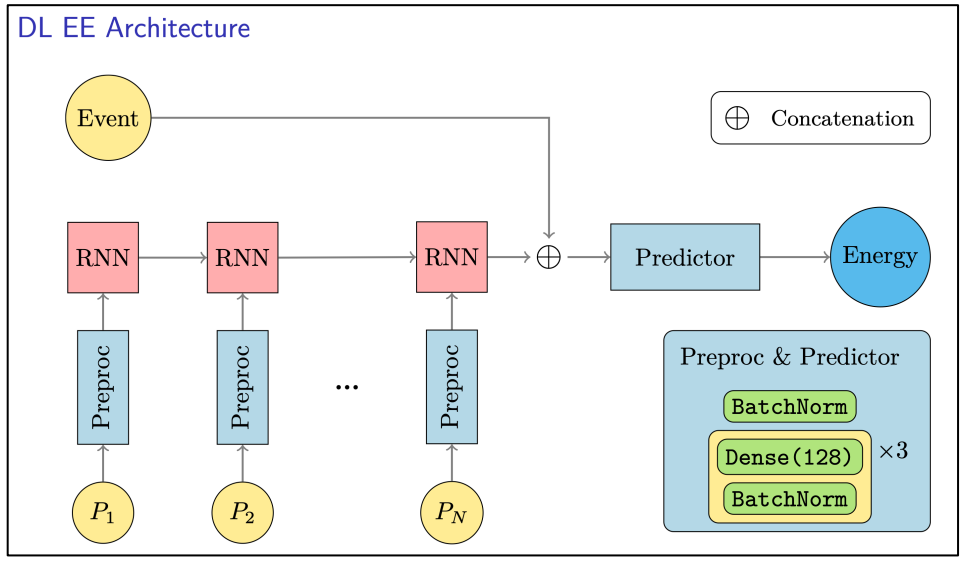
Sterile neutrino oscillation

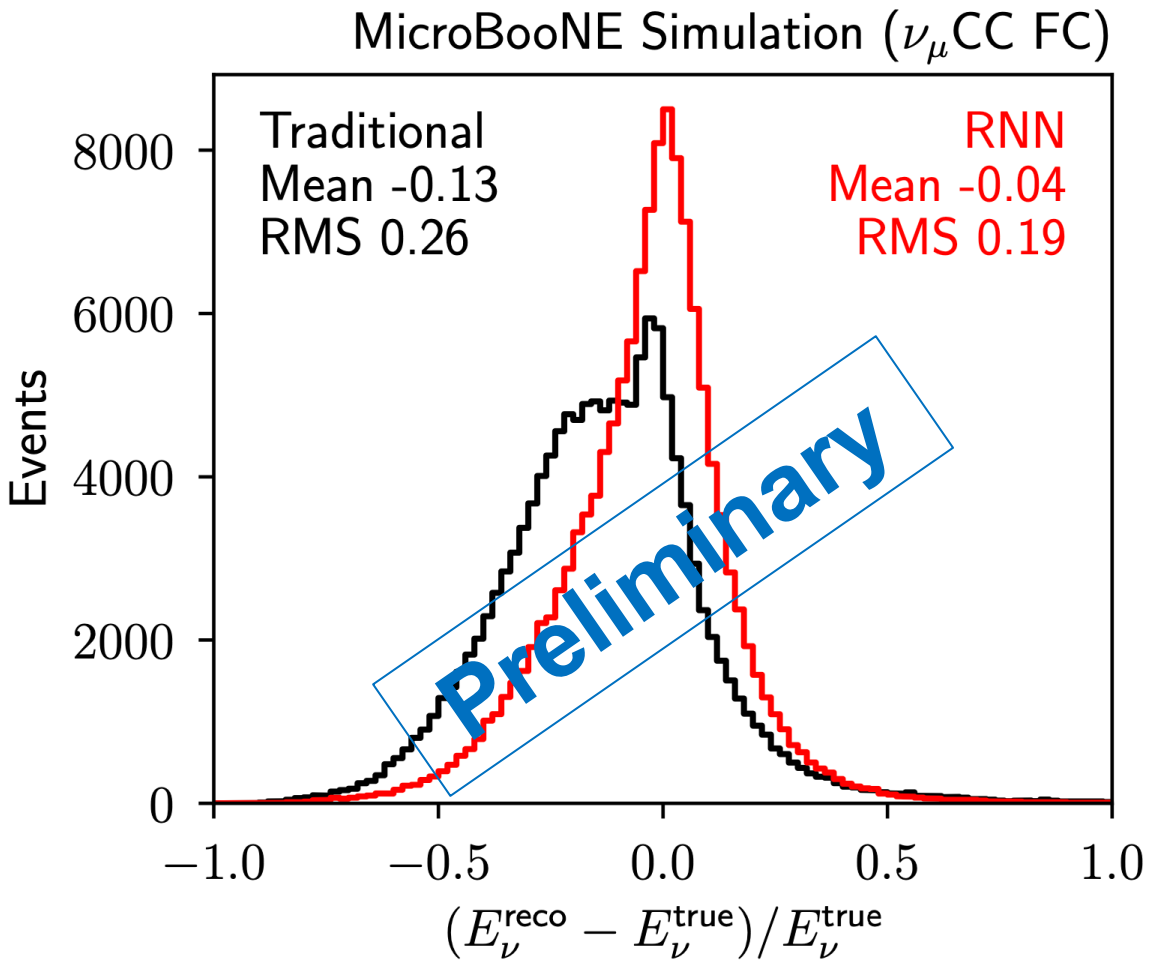
First constraint on eV scale sterile neutrino oscillation in SBN program; and first such analysis considering a complete 3+1 (app. + disapp.) model

Ongoing reconstruction effort - WireCell in MicroBooNE

Neutrino energy reconstruction using a recurrent neural network

Wire-Cell PID information as input





Looking Forward

- Sharing algorithms for other experiments
  - porting from wire-cell-prototype to wire-cell-toolkit
- Sharing knowledge and expertise to other experiments
  - happening now
  - see SBND and ProtoDUNE talks
- Benefit from new developments in other experiments
- Improvement on clustering/pattern recognition for single photon or e+e- pair searches in the context of exotic physics models
- Open-minded to use other reconstruction tools or in synergy with other reconstruction paradigms
  - exchange ideas and knowledge of the detector gained in the development of reconstruction tools --> well defined problem domain and do better
  - e.g. DL-assisted neutrino vertexing; RNN energy estimator; DNN ROI …