Advancements in LArTPC event reconstruction on MicroBooNE data

Maria Brigida Brunetti
On behalf of the MicroBooNE Collaboration

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μBooNE

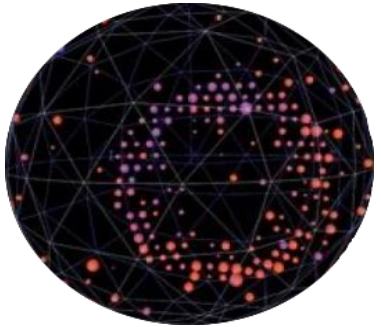
WARWICK
THE UNIVERSITY OF WARWICK

The MicroBooNE experiment

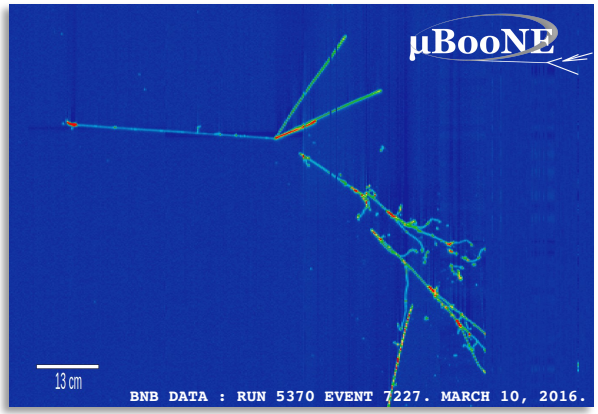
- Goals: Investigate MiniBooNE low-energy excess, search for BSM physics (including sterile neutrinos), perform $\nu - \mathrm{Ar}$ cross-section measurements
- LArTPC technology yielding high-resolution images of particle interactions, and scintillation light provides fast timing information
- Ability to separate between photons and electrons (MiniBooNE limitation)

Superb imaging capabilities require state-of-the-art reconstruction techniques

MiniBooNE event display



MicroBooNE event display

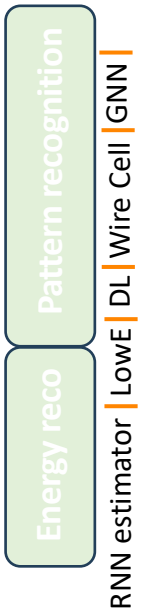


Reconstruction advancements at MicroBooNE

In order to fully interpret LArTPC images, the following steps are crucial:

1. Pattern recognition
   - Pandora multi-algorithm reconstruction
   - New Deep-Learning Based reconstruction (DLGen2)
   - Wirecell reconstruction
   - Graph Neural Network-based reconstruction (NuGraph2)
   - Techniques to reconstruct low-energy signatures
2. Energy reconstruction
   - New Deep-Learning Based energy estimator

This talk provides a very gentle overview of these techniques

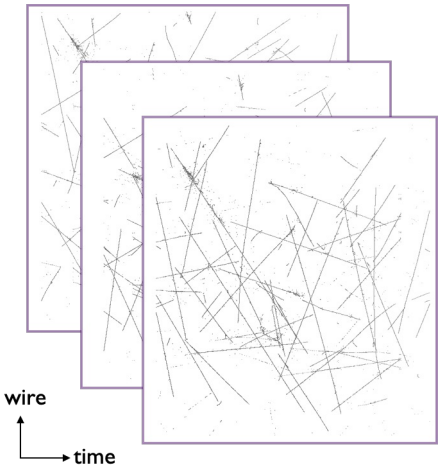


Eur. Phys. J. C 78, 82 (2018)

PandoraPFA

Pandora Multi-Algorithm Approach

- Many logical steps to go from input **hits** (charge measurement on single wire at given time) to 3D hierarchies



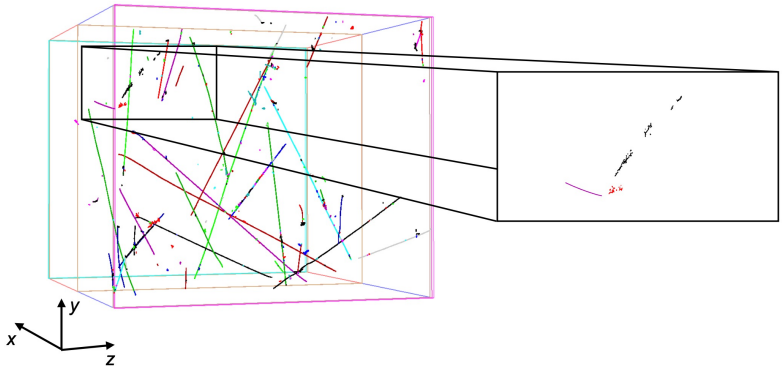
2D pattern recognition

2D → 3D matching

Vertex finding

Hierarchy building

Track/shower ID



- Build up events gradually > 100 algorithms to address specific topologies
- Can construct algorithm chains tailored for different detectors and analyses

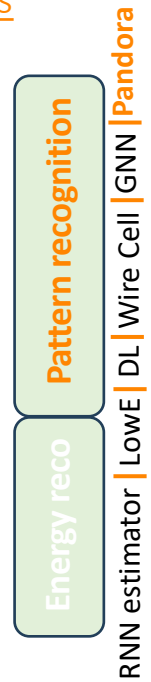
Pattern recognition

Energy reco

RNN estimator | LowE | DL | Wire Cell | GNN | Pandora

Pandora Multi-Algorithm Approach (2)

MicroBooNE is a surface-based detector: need to account for the presence of cosmic ray muons



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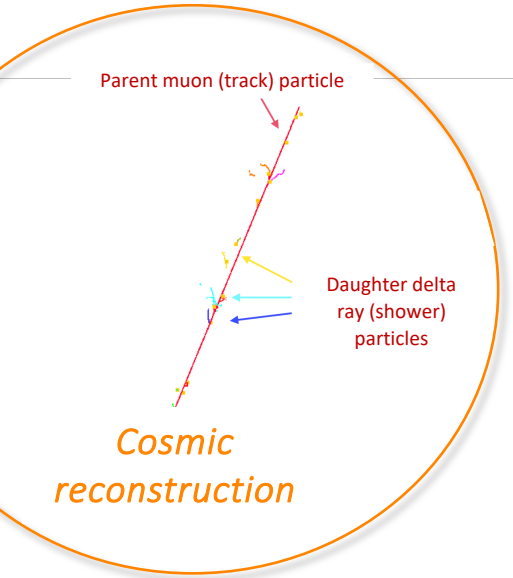

1. Run cosmic reconstruction, set aside “clear” cosmic ray muons

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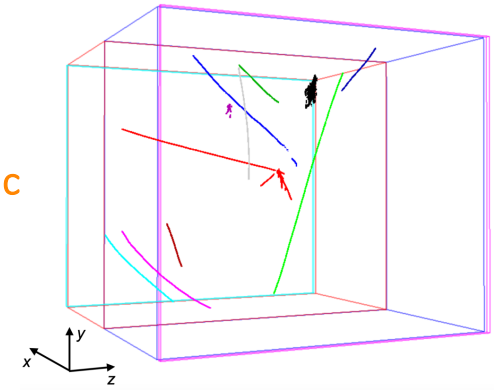
2. Divide remaining hits in group that represent individual cosmic or neutrino interactions



Eur.Phys.J.C 83 (2023) 7, 618

Pattern recognition | Cosmic | Neutrino | Pandora

Energy reco | LowE | DL | Wire Cell | GNN | RNN estimator

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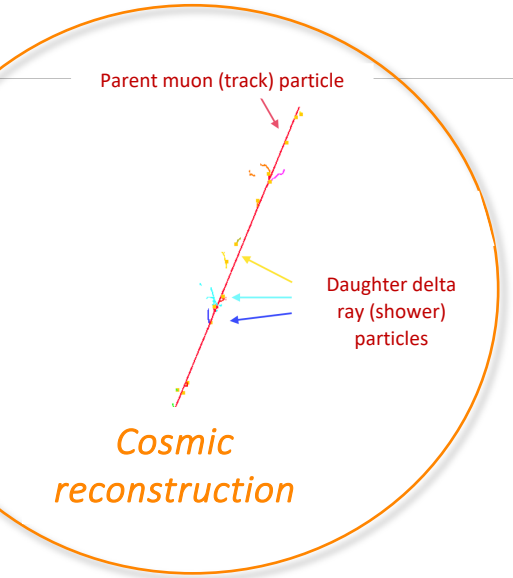
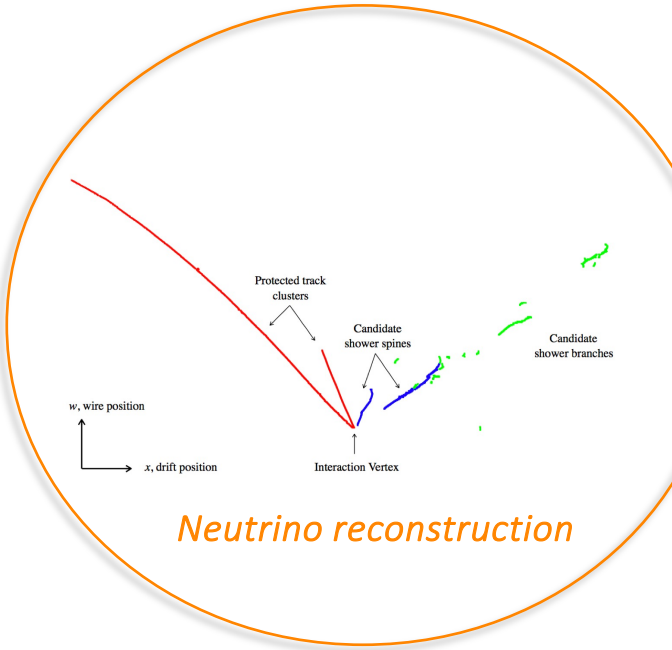


1. Run cosmic reconstruction, set aside “clear” cosmic ray muons
2. Divide remaining hits in group that represent individual cosmic or neutrino interactions
3. Run both cosmic and neutrino reconstruction on each group



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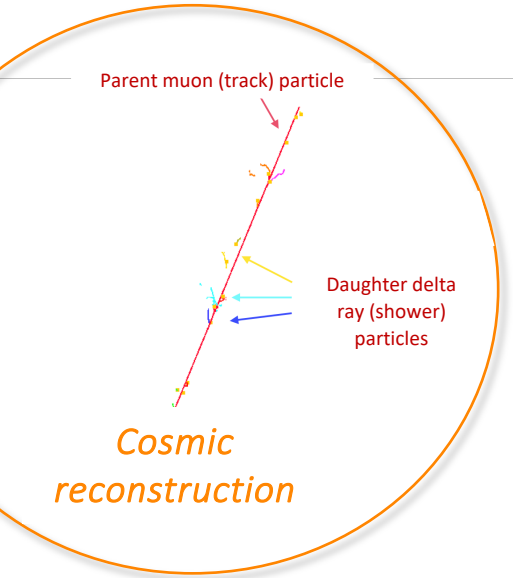

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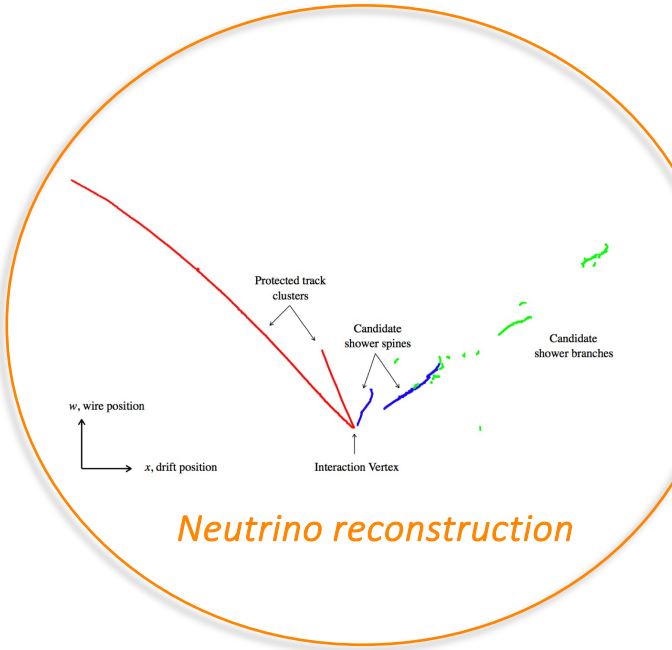
4. **Pick best outcome**



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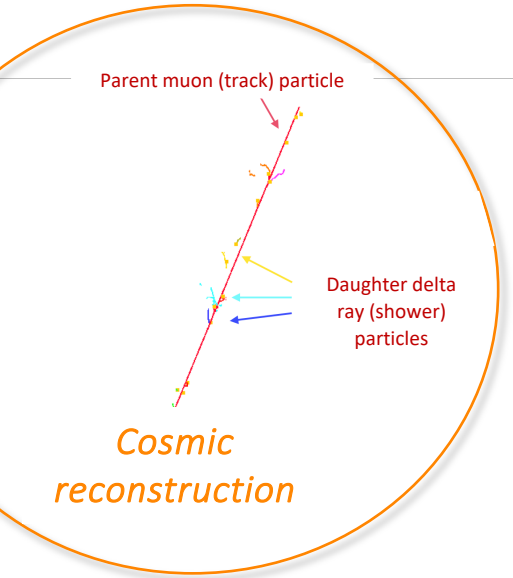

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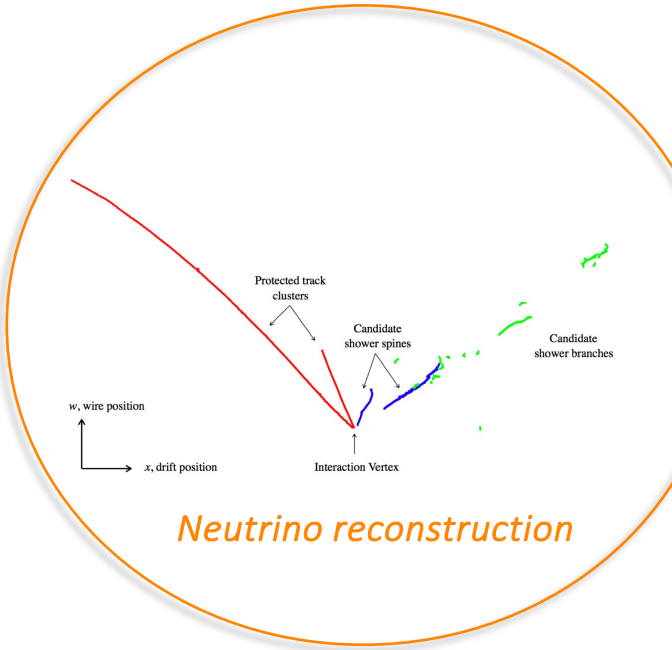


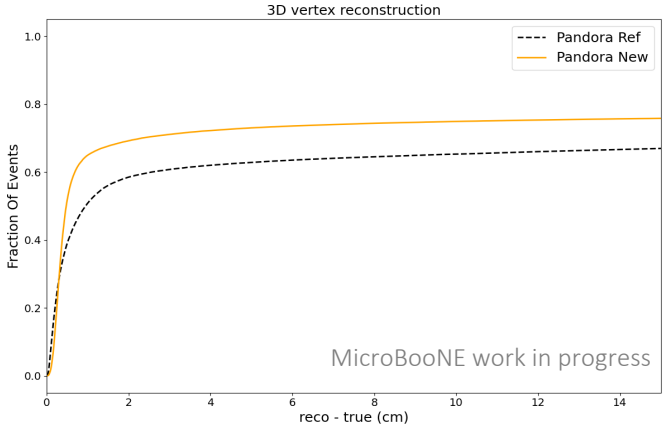
Pandora used in > 20 publications at MicroBooNE

Also see Andy Chappell’s talk on Pandora for DUNE

Pandora recent developments for MicroBooNE

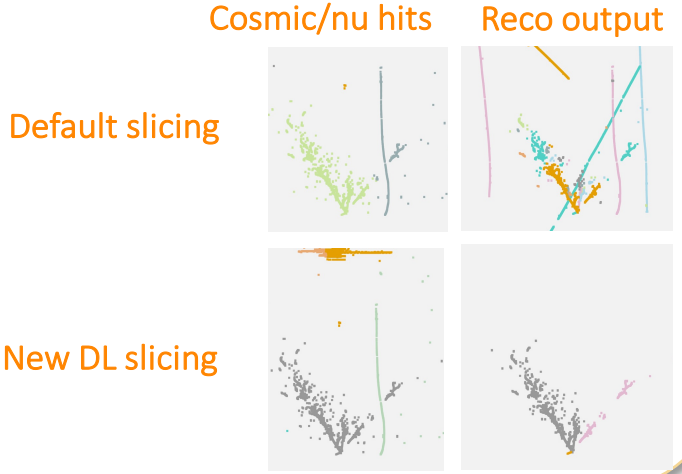
New vertex-finding technique

- Vertex crucial anchor in reconstruction
- New CNN-based vertex finding algorithm
- 14% more vertices found within 1 cm



New neutrino interaction reconstruction technique

- Correct ν interaction reconstruction crucial to deliver good input to analysis
- New DL technique under development

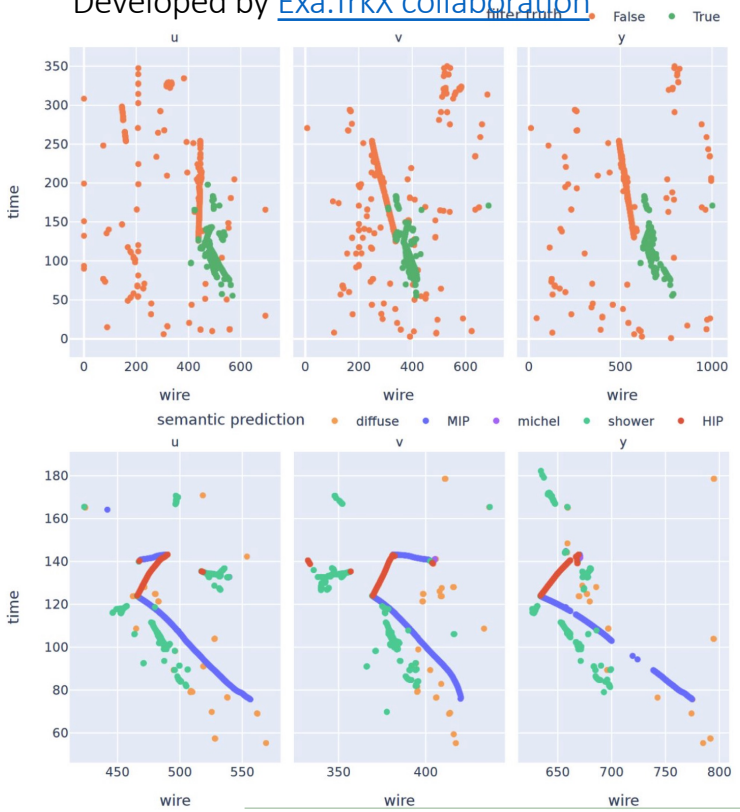


Pattern recognition | Energy reco

RNN estimator | LowE | DL | Wire Cell | GNN | Pandora

NuGraph2: A Graph Neural Network for Neutrino Event Reconstruction

Developed by Exa.TrkX collaboration



- Input features:
  - Hit wire, peak time, RMS, Integral
- A graph connecting 2D hits within planes (*planar graph nodes*)
- A *nexus graph* to connect hits across planes to same 3D space-points
- Information flows in 5 message passing iterations across planar and nexus edges
- After last step, two decoders extract physics output:
  - filter (neutrino vs background hit)
  - semantic (label hits by particle type).

Pattern recognition

Energy reco

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NuGraph2: A Graph Neural Network for Neutrino Event Reconstruction

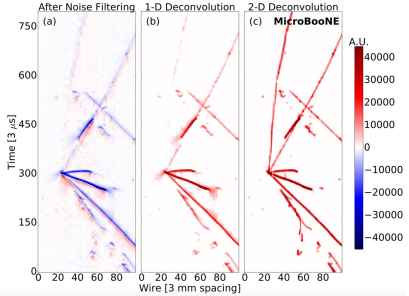
- Trained on the [MicroBooNE open data sets]
- Accuracy:
  - 98% filter (**neutrino** vs **background hit**)
  - 95% semantic decoder (**hit particle type**)
- NuGraph2 can identify cosmics close to the ν interaction and resolve non-trivial topologies.
- **First tests** on data passing loose ν_e CC preselection show semantic decoder correctly tags shower hits both from primary electrons and photons from π^0 background
- Data/MC domain shift and network explainability under study

Pattern recognition | GNN | Wire Cell | DL | LowE | RNN estimator | Pandora

Energy reco

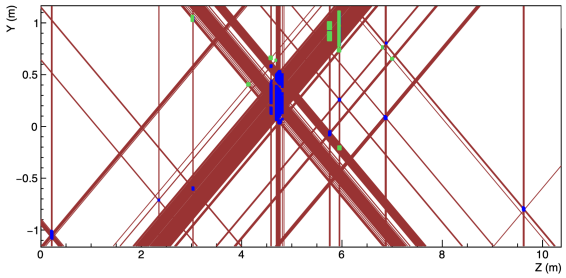
Wire-cell LArTPC reconstruction: tomographic approach

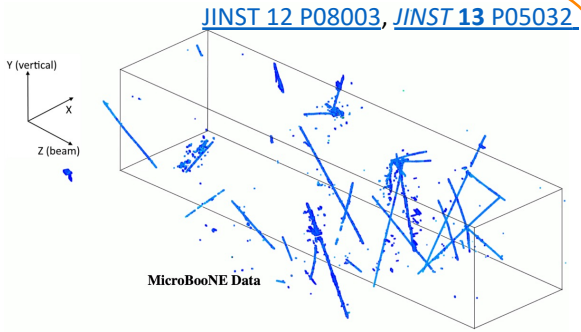
1.



Noise filtering and signal processing

2.





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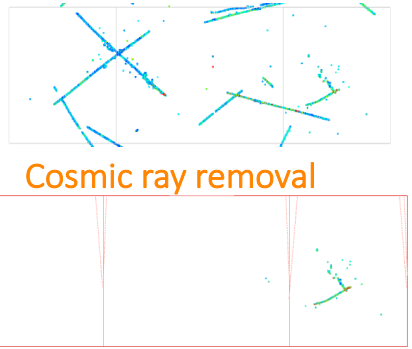
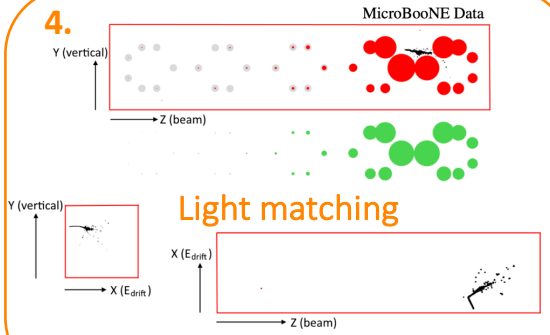
3D imaging and space-point solving

5.



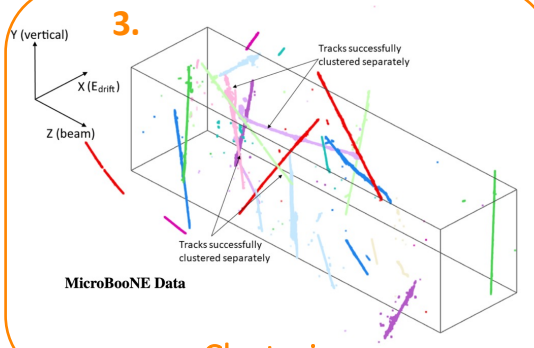
Cosmic ray removal

4.



Light matching

3.



Clustering

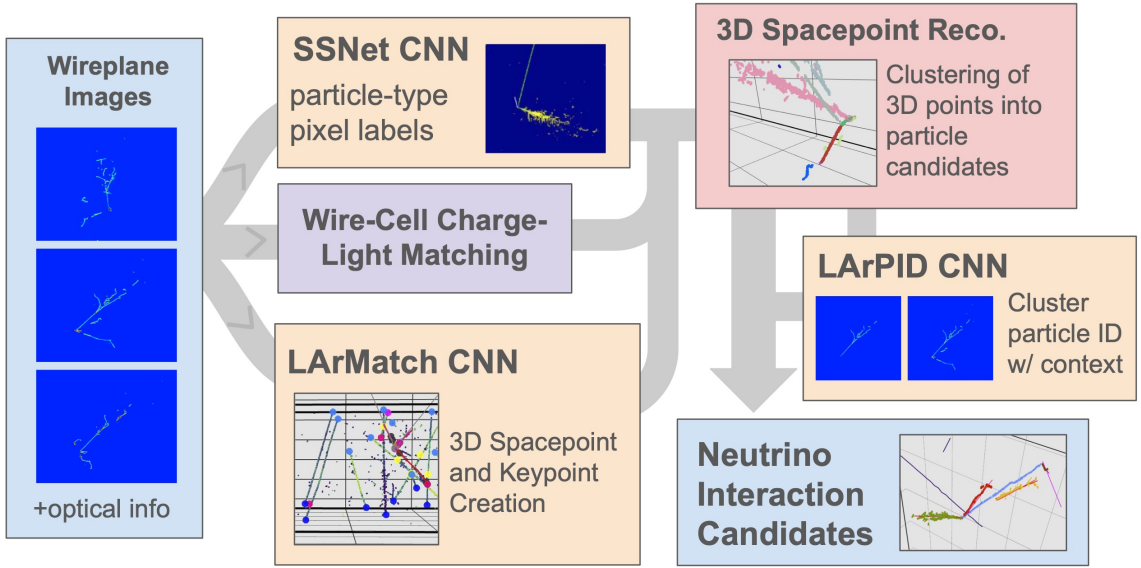
Pattern recognition

Energy reco

RNN estimator | LowE | DL | Wire Cell | GNN | Pandora

New DL-Based LArTPC Reconstruction

- A New CNN-Based Reconstruction Framework (MICROBOONE-NOTE-1123-PUB)

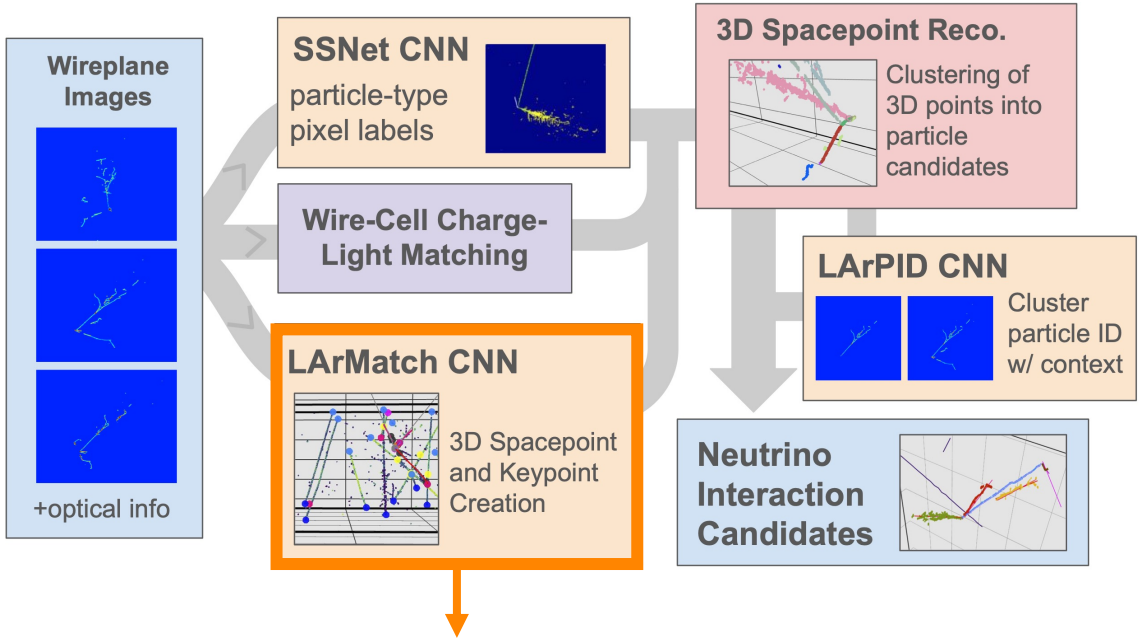


Pattern recognition | DL | Wire Cell | GNN | Pandora

Energy reco | LowE | DL | RNN estimator

- Builds on previous DL-based framework designed for quasi-elastic CC ν_e LEE search to allow for generic neutrino interaction reconstruction

New DL-Based LArTPC Reconstruction



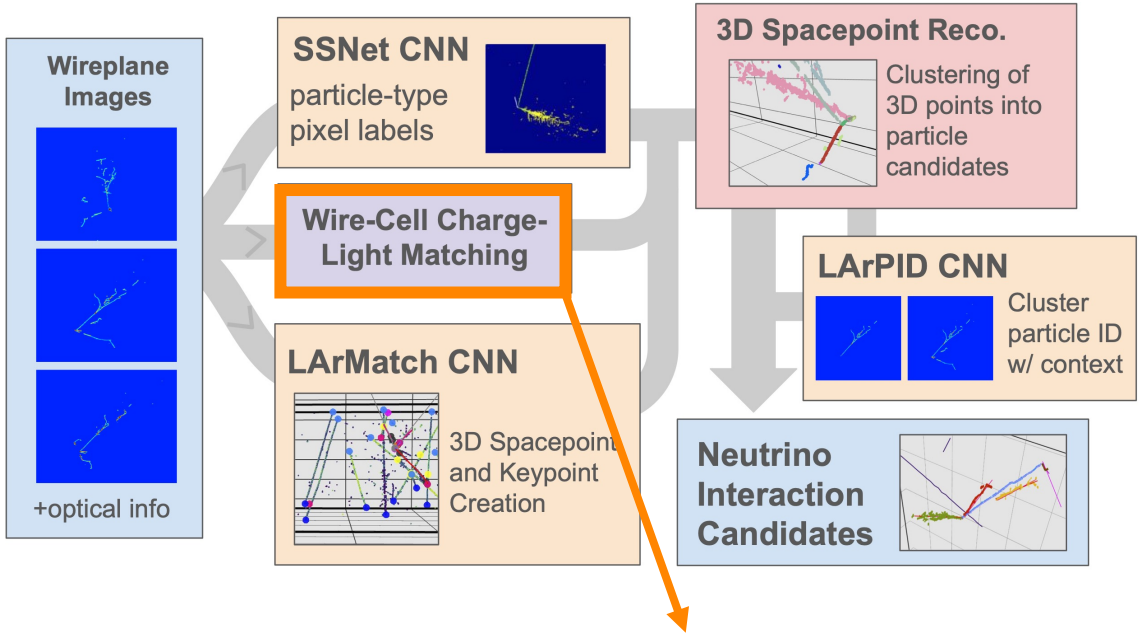
Find true 3D energy deposition points and keypoints

Pattern recognition

Energy reco

RNN estimator | LowE | DL | Wire Cell | GNN | Pandora

New DL-Based LArTPC Reconstruction



Pattern recognition

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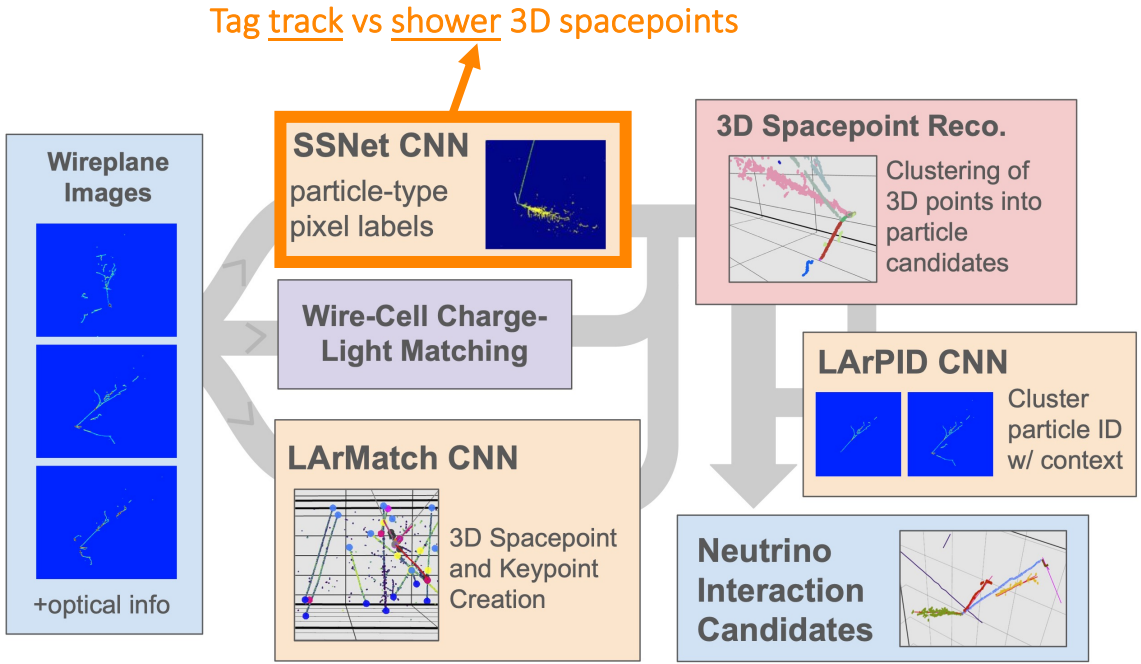

Pattern recognition | DL | Wire Cell | GNN | Pandora

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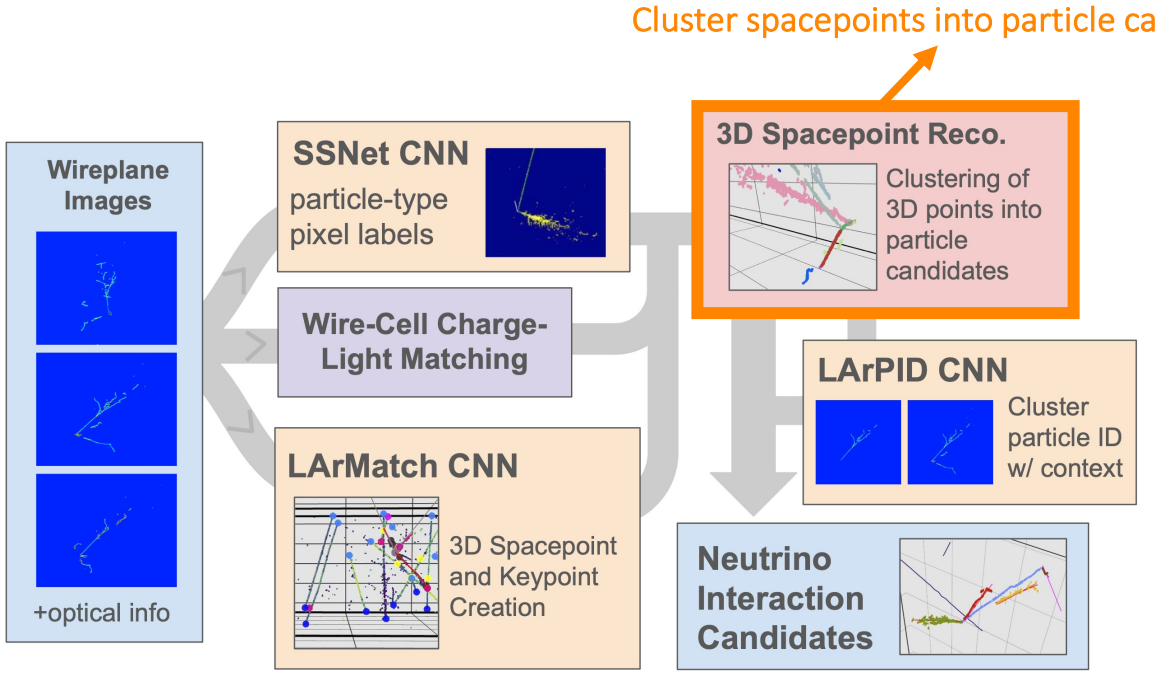

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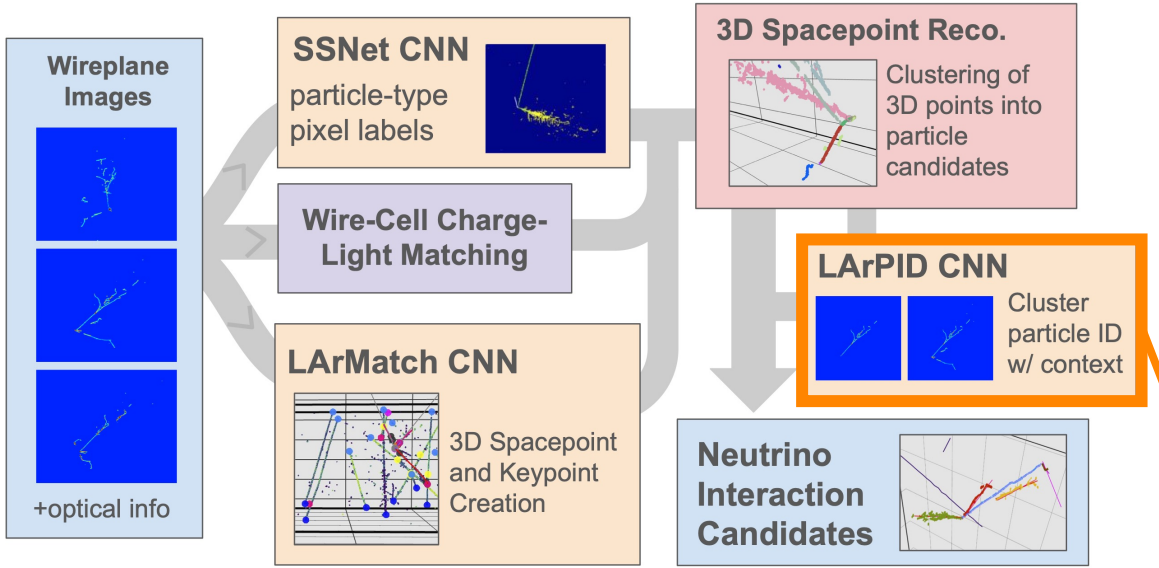

Pattern recognition

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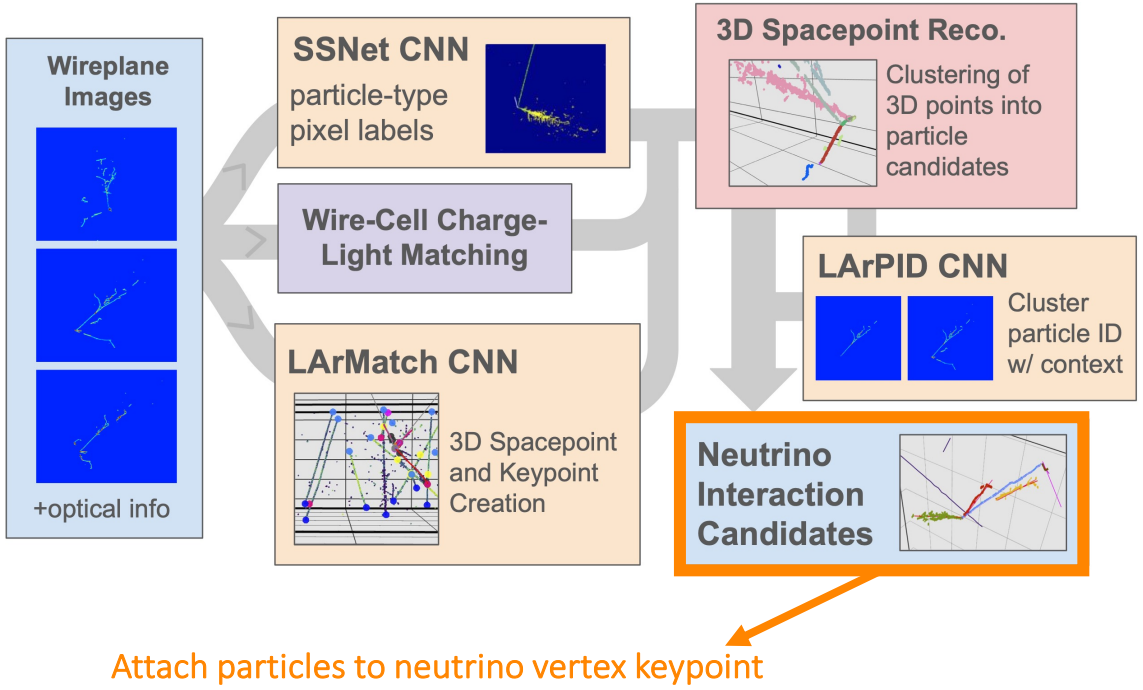

Pattern recognition

Energy reco

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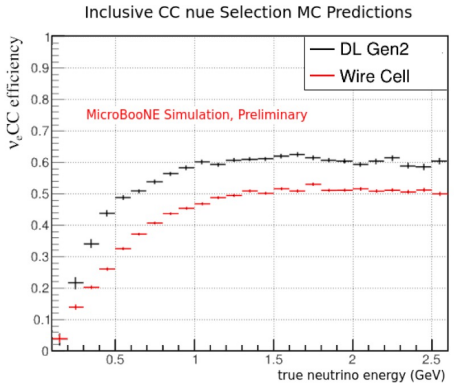
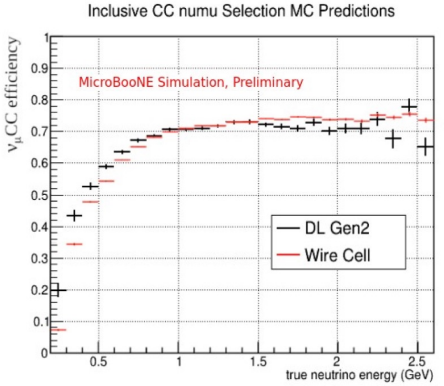
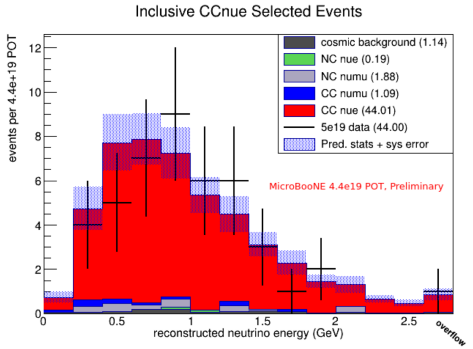
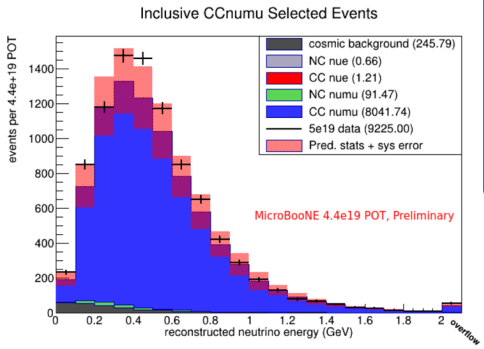
New DL-Based LArTPC Reconstruction (2)

- ν_μ and ν_e selections developed using LArPID scores for clusters attached to neutrino interaction candidates
- High purity and efficiency; compare favorably to MicroBooNE's previous-best results
- Good data/MC consistency in high-level kinematic distributions
- Not yet finalised analysis, but shows promise for future analyses









Pattern recognition

Energy reco

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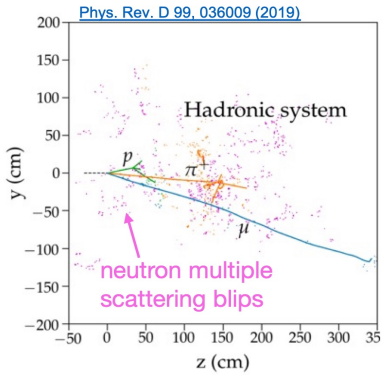
Low-energy signatures in LArTPCs

Broad range of energy scales in LArTPCs

Reconstructing low-energy signatures critical for maximising SBN and DUNE physics potential

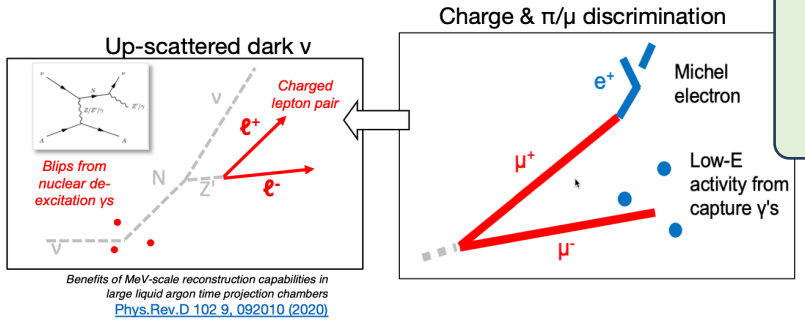
Neutrino interactions

- Neutron detection in GeV scale ν events
- → Precise energy reconstruction
- Astrophysical ν reconstruction



BSM processes

- Particle identification



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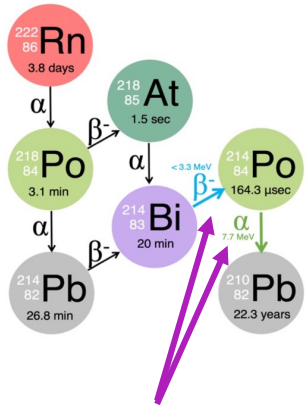
Techniques for low-energy signatures at MicroBooNE

- Blip reconstruction: Isolated hits are identified on each plane, and timing/charge metrics used to match between planes

Techniques for low-energy signatures at MicroBooNE

- Blip reconstruction: Isolated hits are identified on each plane, and timing/charge metrics used to match between planes
- During 2021 R&D run, active LAr volume doped with Rn



Detect β produced in association with 214-Po, and α from its decay

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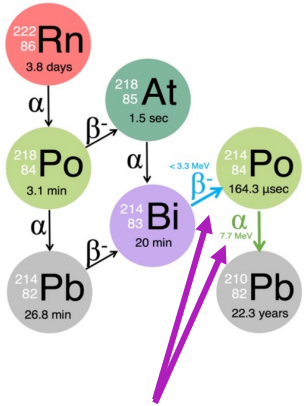

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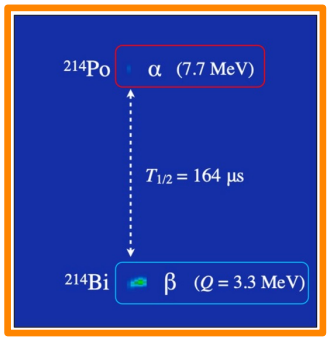

Study detector response (e.g. α charge quenching)

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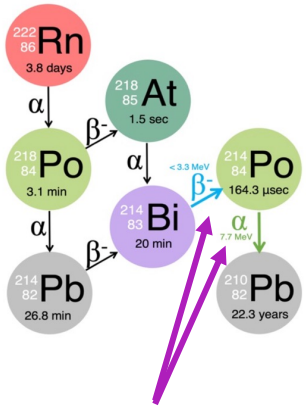

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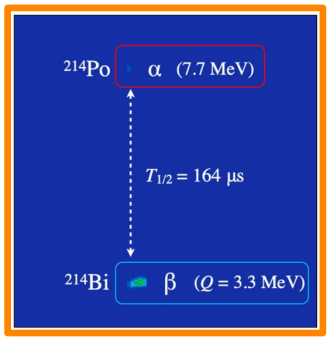

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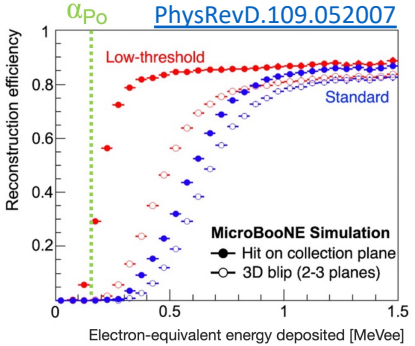
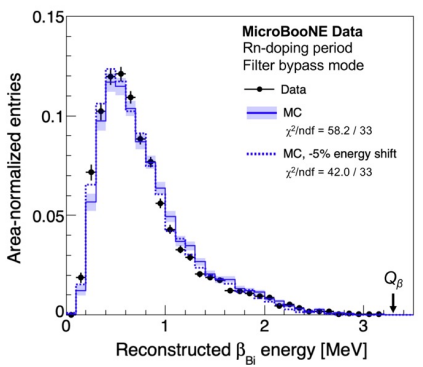


Tweak signal-processing and hit-finding → lower thresholds

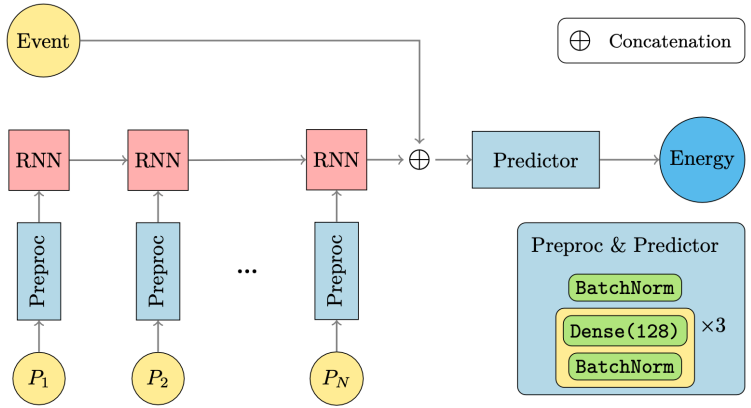


Reco β energy spectrum demonstrates charge-based reco capabilities

RNN energy estimator

- Oscillation probability depends on energy → energy estimation of crucial importance
- Traditional approach (for CC): $E_\nu = E_l + E_{had} + E_{binding}$
- Does not account for energy lost to undetected particles (e.g. neutrons, neutrinos, …)

- New RNN approach to consider kinematic correlations for final-state particles, and deal with varying-length input
- Use Wirecell-reco particle-level (tracks start/end, PID, momentum) and event-level (containment, ν_μ vs ν_e) variables
- Maintains a fixed-size memory state of the past tokens, and at the end infers neutrino and primary lepton energy



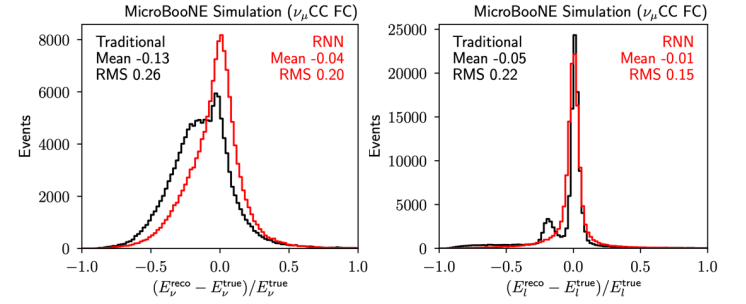
Pattern recognition

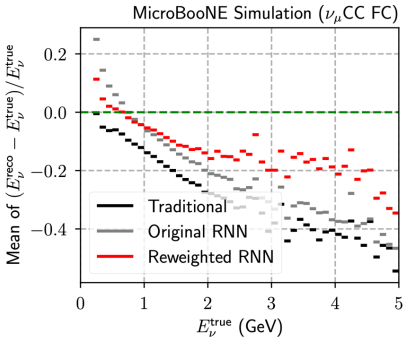
Energy reco

RNN estimator | LowE | DL | Wire Cell | GNN | Pandora

RNN energy estimator (2)

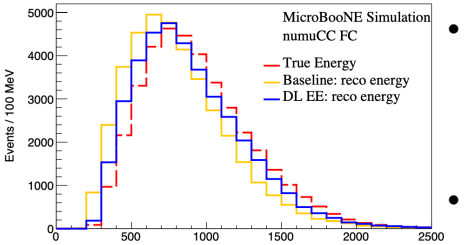
Energy estimation performance

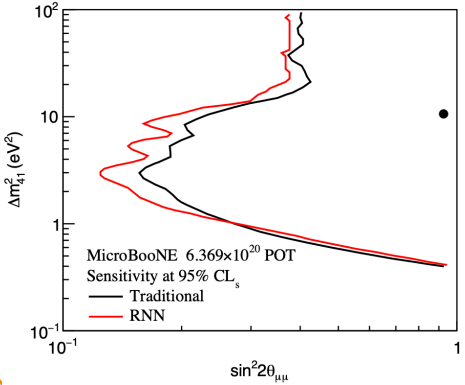




- Reweighting applied to reduce bias
- RMS and bias compare favourably with traditional method

Impact on analysis





- DL energy estimator reproduces true energy better than traditional method
- Better sensitivity to oscillation parameters and to sterile neutrinos
- Study goodness-of-fit via conditional covariance tests, constraining on muon kinematics and hadronic energy .

arXiv:2406.10123

Conclusions

- Many new reconstruction techniques under development at MicroBooNE
- Improvements on multiple fronts:
  - New Pandora DL vertex reconstruction: 14% more reco vertices within 1 cm from true vertex
  - NuGraph2 shows 98% signal vs background accuracy and 95% semantic PID accuracy
  - ν_e and ν_μ selections using a new DL-based reconstruction show improvement on previous results
  - Novel techniques to reconstruct low-energy signatures and study detector response were developed
  - New RNN-based energy reconstruction yields better RSM and bias compared to traditional approach
- Developments currently have been/are being tested on data
- Expected to enhance MicroBooNE analysis sensitivity
- Stay tuned ☺