Measurement of ambient radon and MeV-scale calorimetry in the MicroBooNE LArTPC

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on behalf of the MicroBooNE Collaboration
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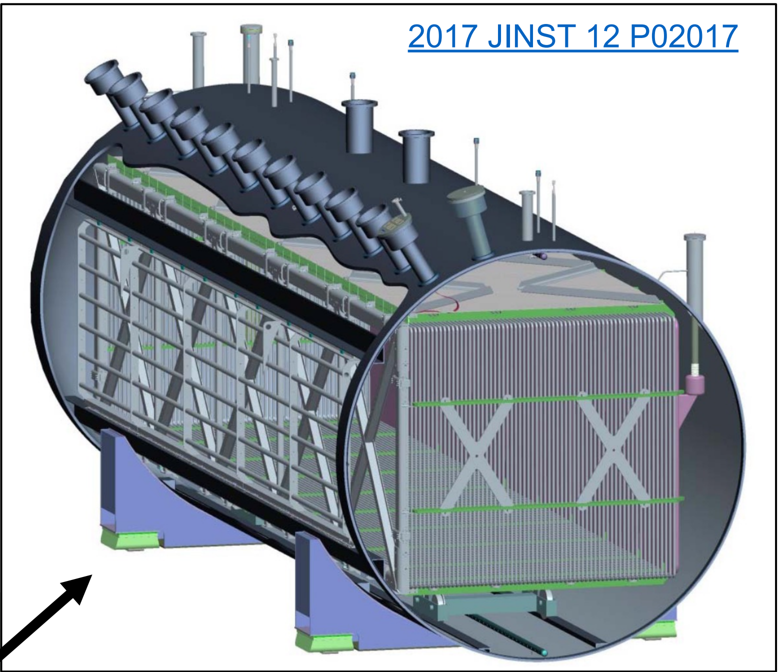
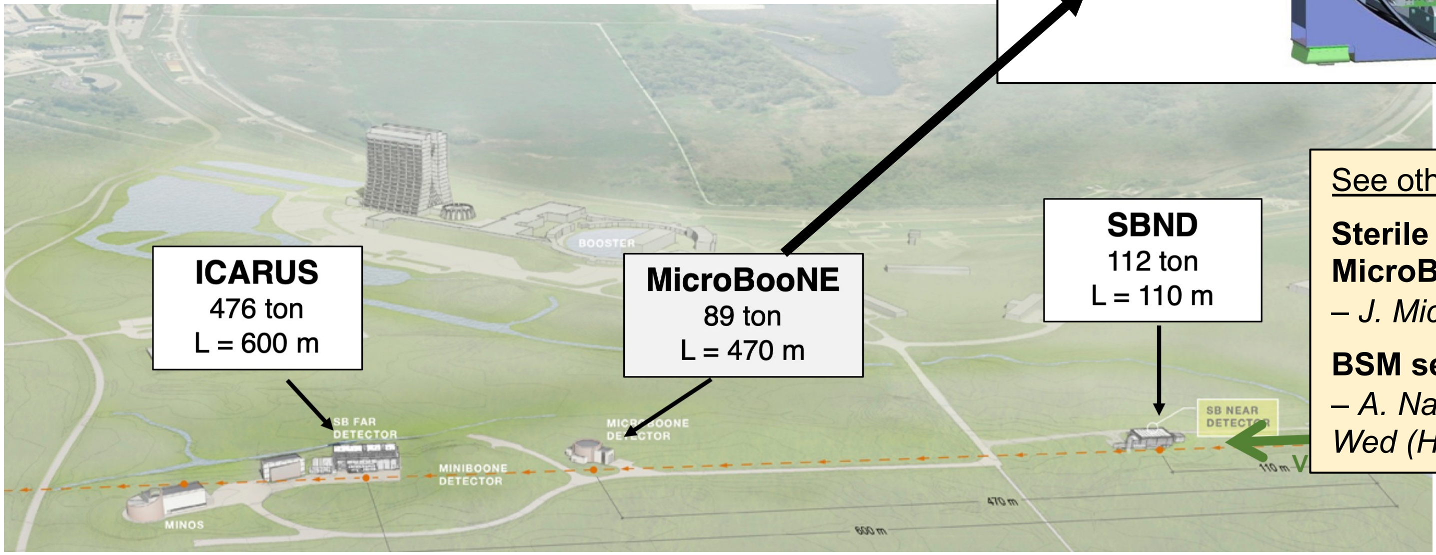
Topics in Astroparticle and Underground Physics (TAUP)
University of Vienna
August 28 – Sept 1, 2023

The MicroBooNE Experiment

- Surface-level LArTPC, 85 metric ton active volume (10.4×2.5×2.3 m^3)
- Ran in Fermilab's Booster Neutrino Beamline from 2015-2021
- Primary goal: understand "low-energy" (~200 MeV) ν_e excess observed by MiniBooNE in the same beamline

2017 JINST 12 P02017



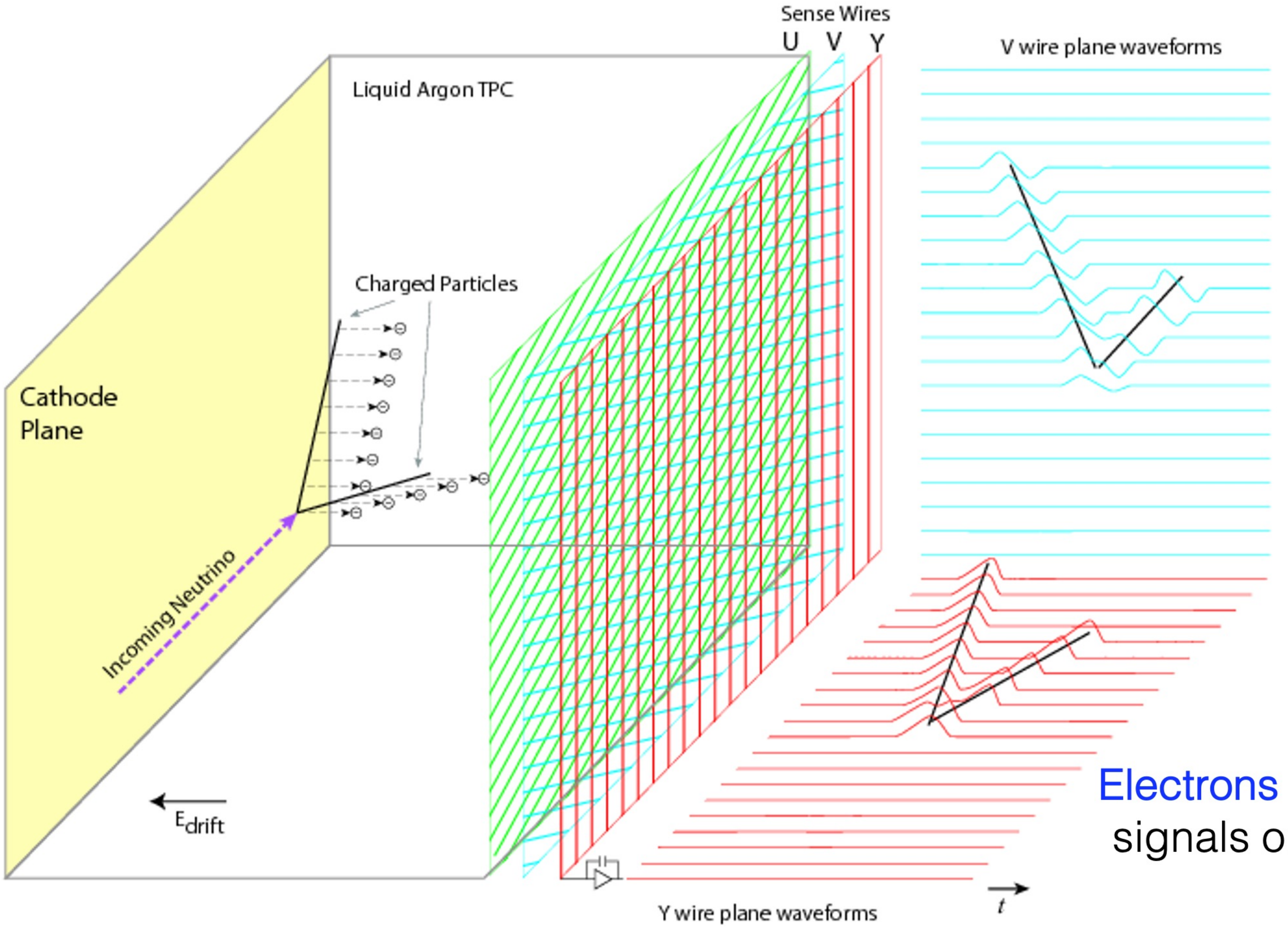


See other talks:

Sterile neutrino searches at MicroBooNE
– J. Micallef, 2pm Mon

BSM searches at MicroBooNE
– A. Navrer-Agasson, 4:15pm Wed (Hörsaal 7)

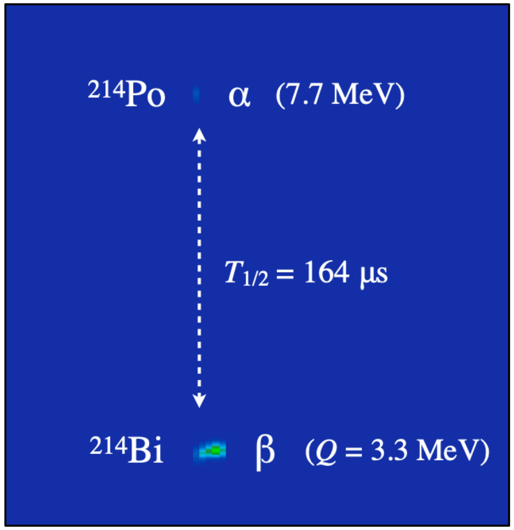
LArTPC



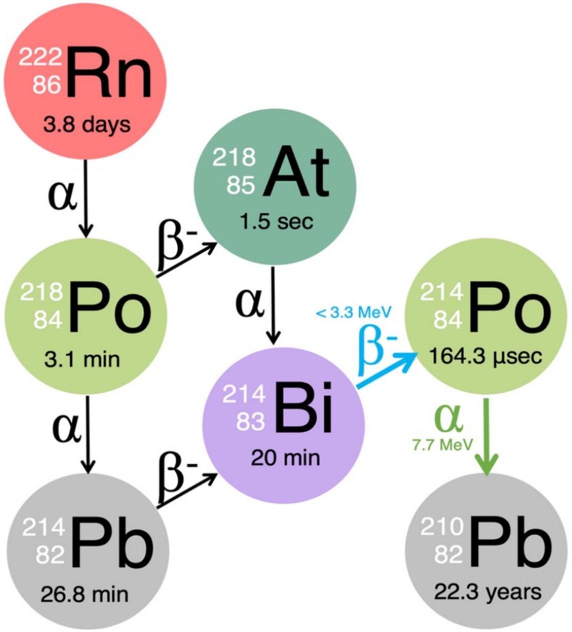
Electrons induce signals on wires

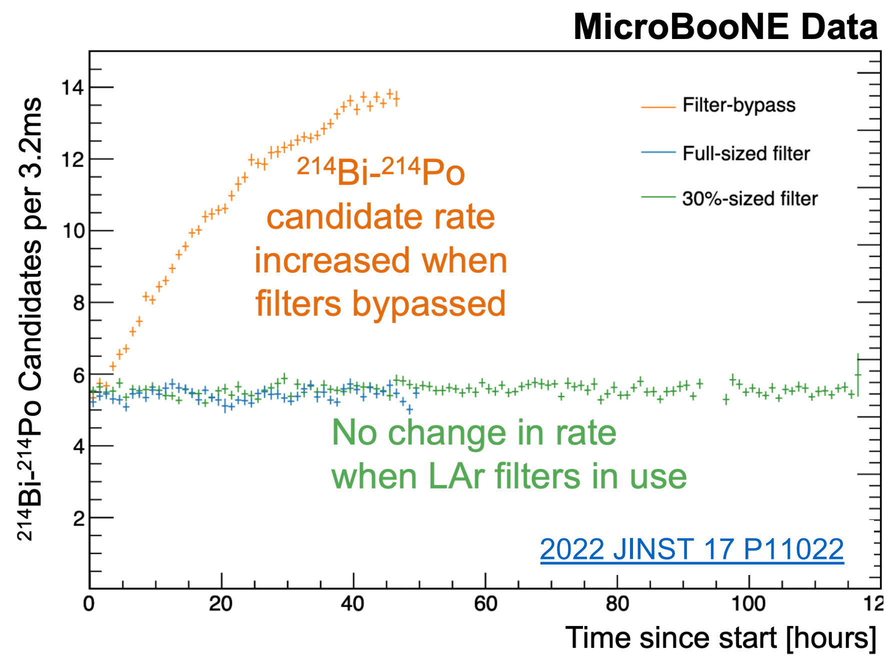
Radon in LArTPCs

- ^{222}Rn radiopurity target for DUNE: < *1 mBq/kg*
- MicroBooNE LArTPC previously demonstrated Rn (doped into the LAr) was removed by its liquid filtration system
  - *but*: unknown backgrounds prevented measuring ambient rate and β / α energy spectra



[2022 JINST 17 P11022]

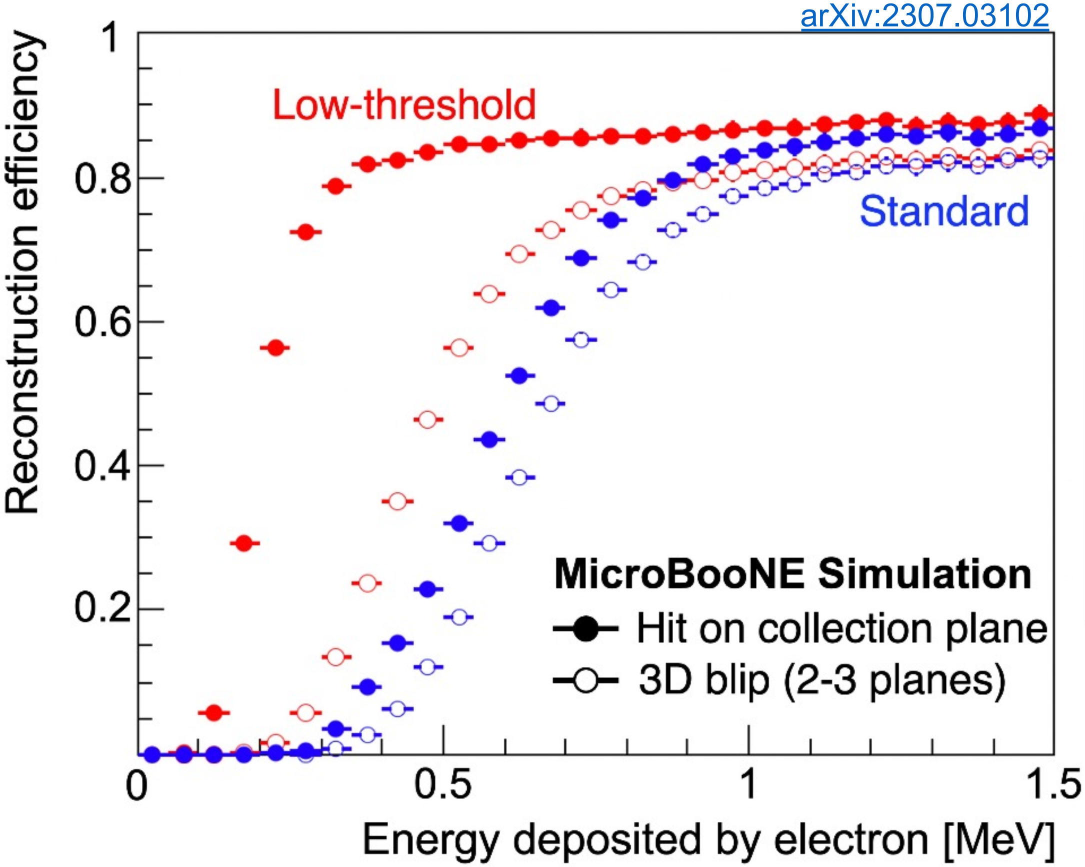




Energy thresholds

- Datasets were processed with ***lowered thresholds***
  - *-30% on induction planes*
  - *-70% on collection plane*

arXiv:2307.03102



Configuration	50% Eff. Threshold [keV] Standard settings	Low-threshold settings
1st induction plane	730	530
2nd induction plane	750	540
Collection plane	620	210
3D-matched blip, 2-3 planes	670	450
3D-matched blip, 3 planes	770	600

TABLE I. True electron-deposited energy at which the reconstruction efficiency reaches 50% of its maximum achievable value for the standard and low-threshold settings.

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  - *-70% on collection plane*

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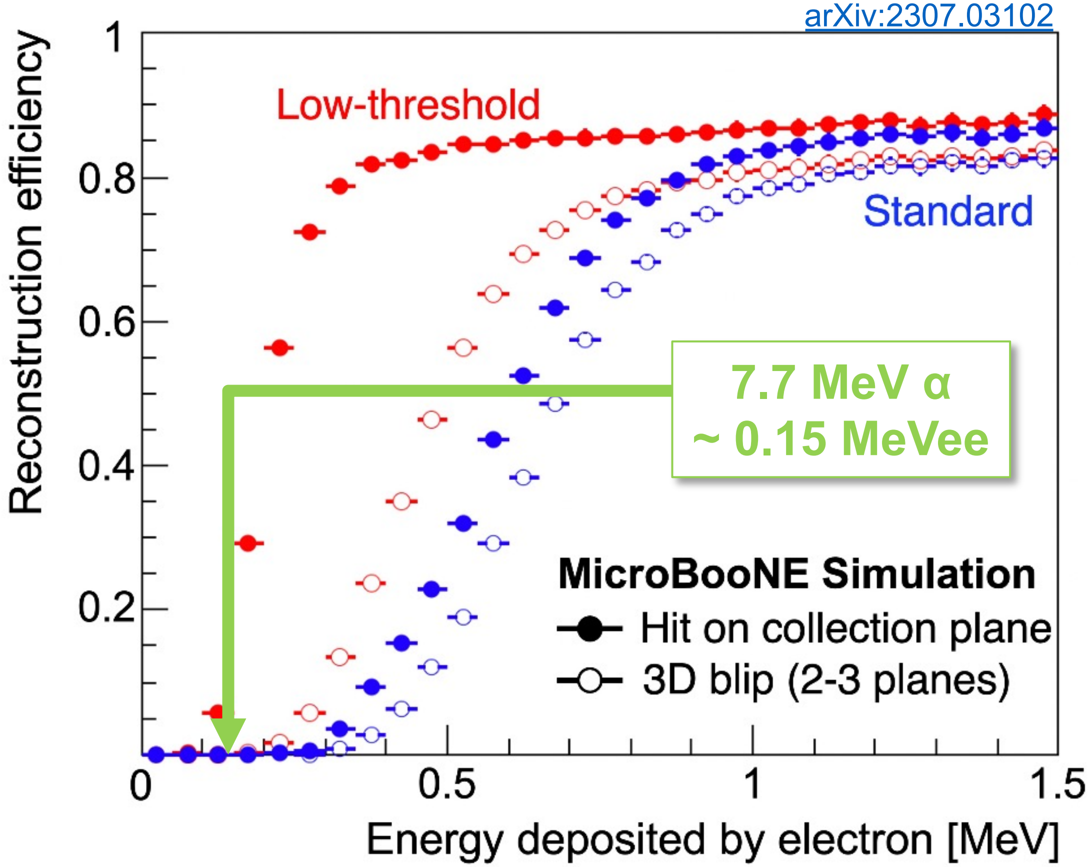
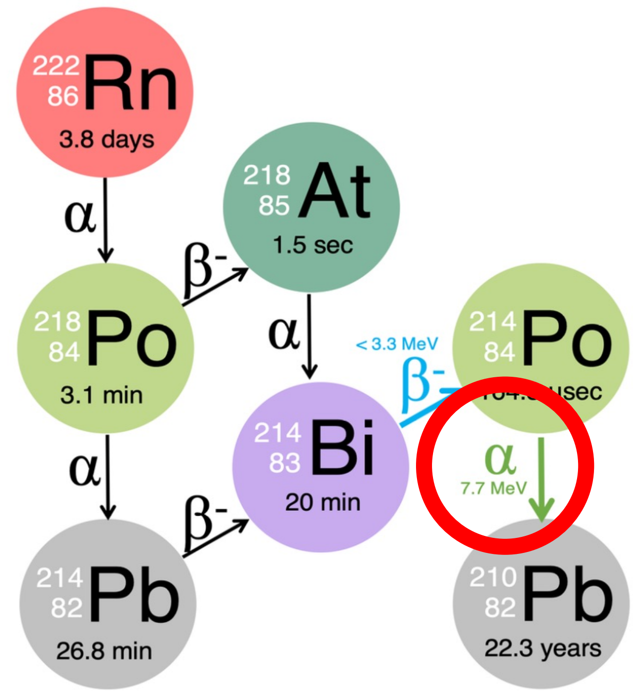
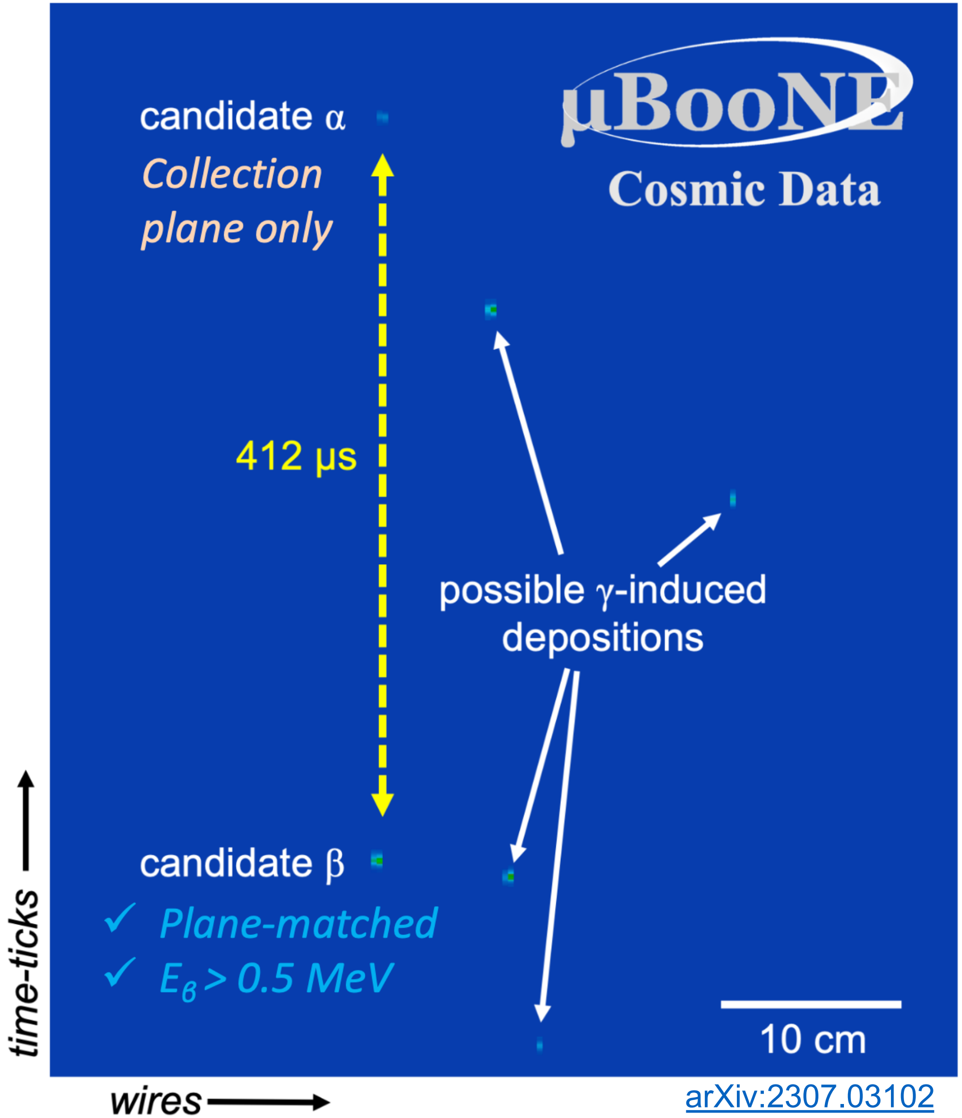


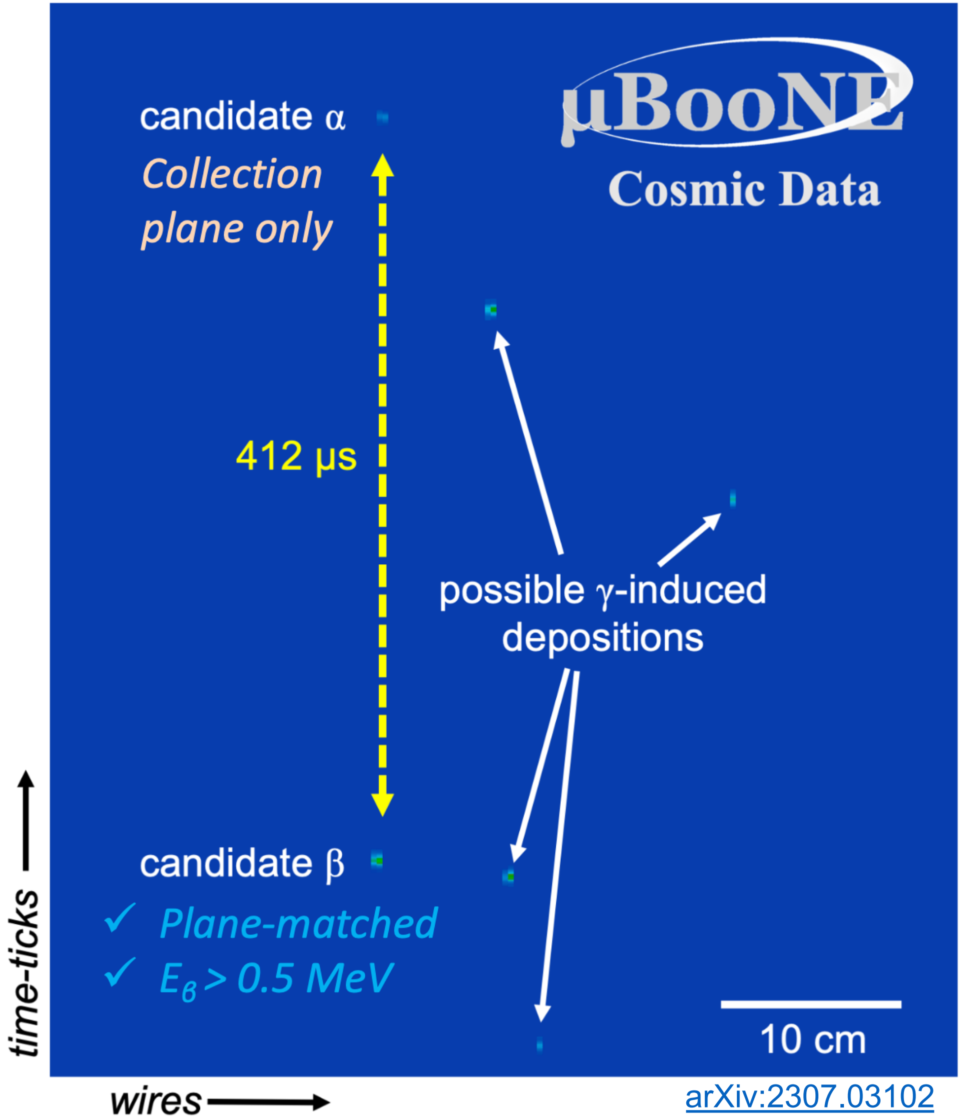


Bi-Po signal and background selection



arXiv:2307.03102

Bi-Po signal and background selection



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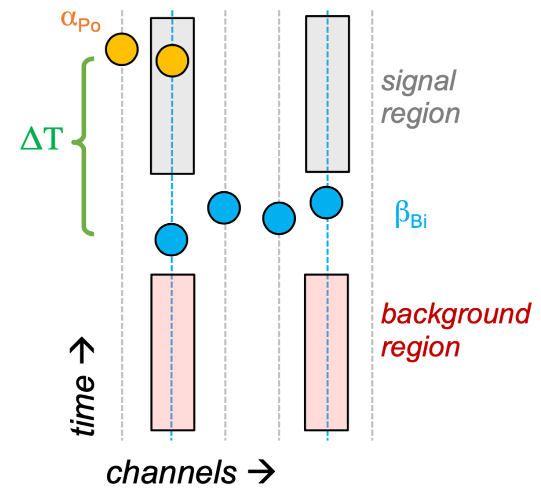
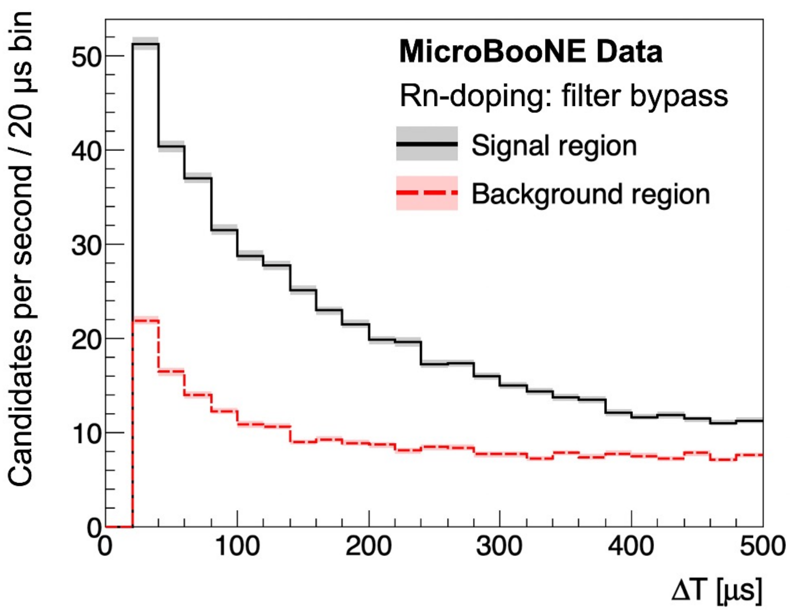
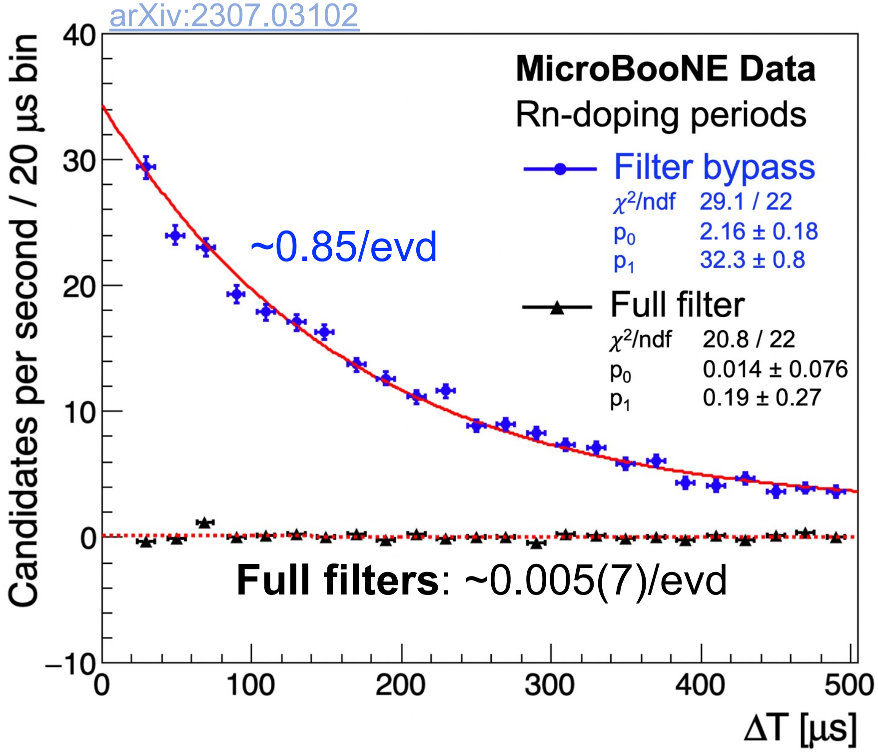
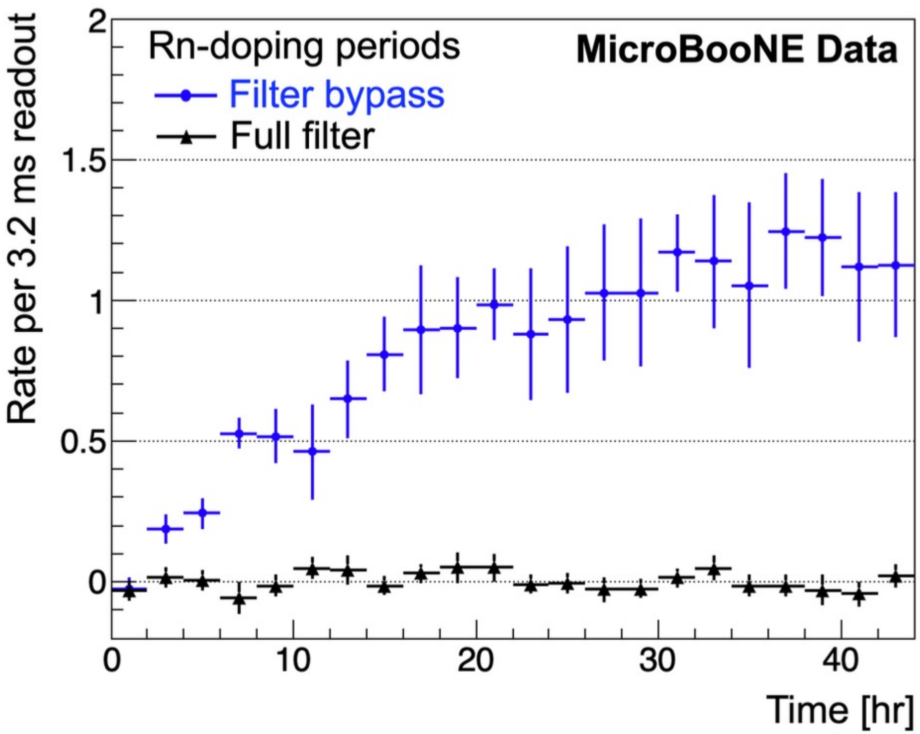




Measuring the rate

arXiv:2307.03102





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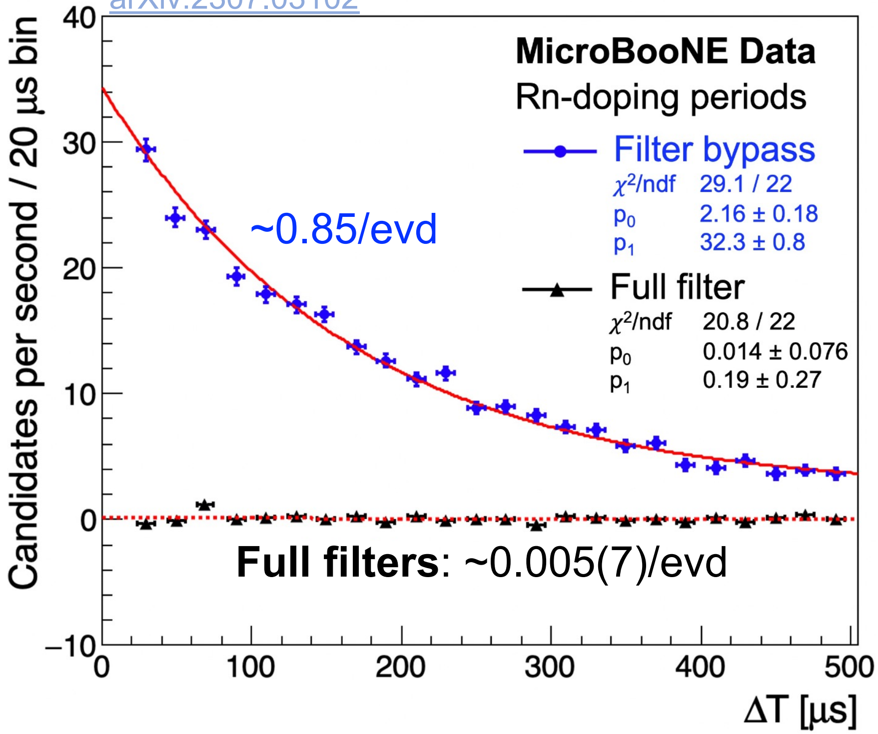
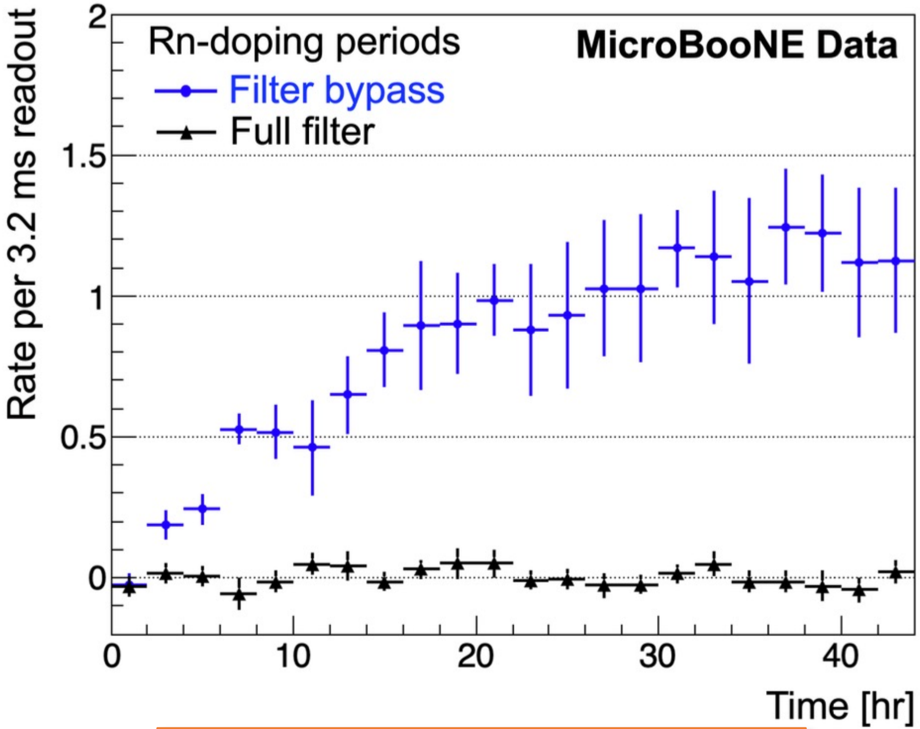
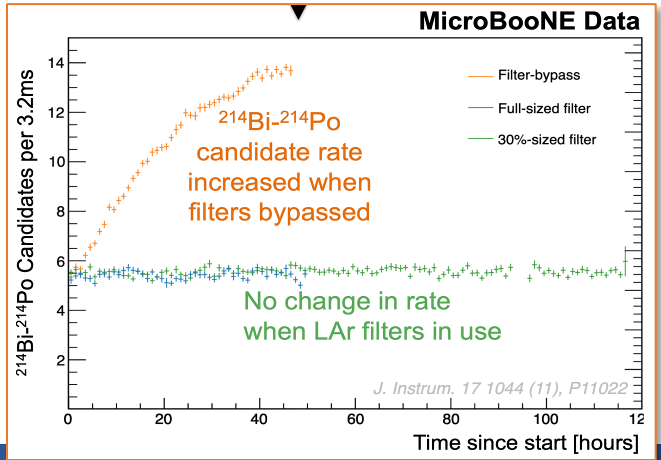


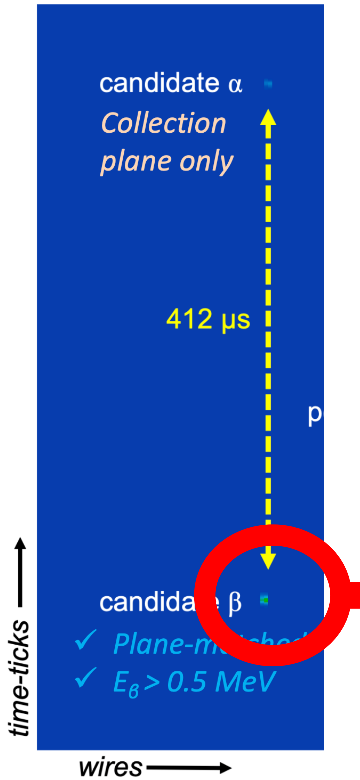


Previous study's background rate (~5.5 candidates/evd) has been successfully removed



Monte Carlo calorimetric validation: 0-3.3 MeV β_{Bi}

Same BG subtraction applied to β *energy spectrum*



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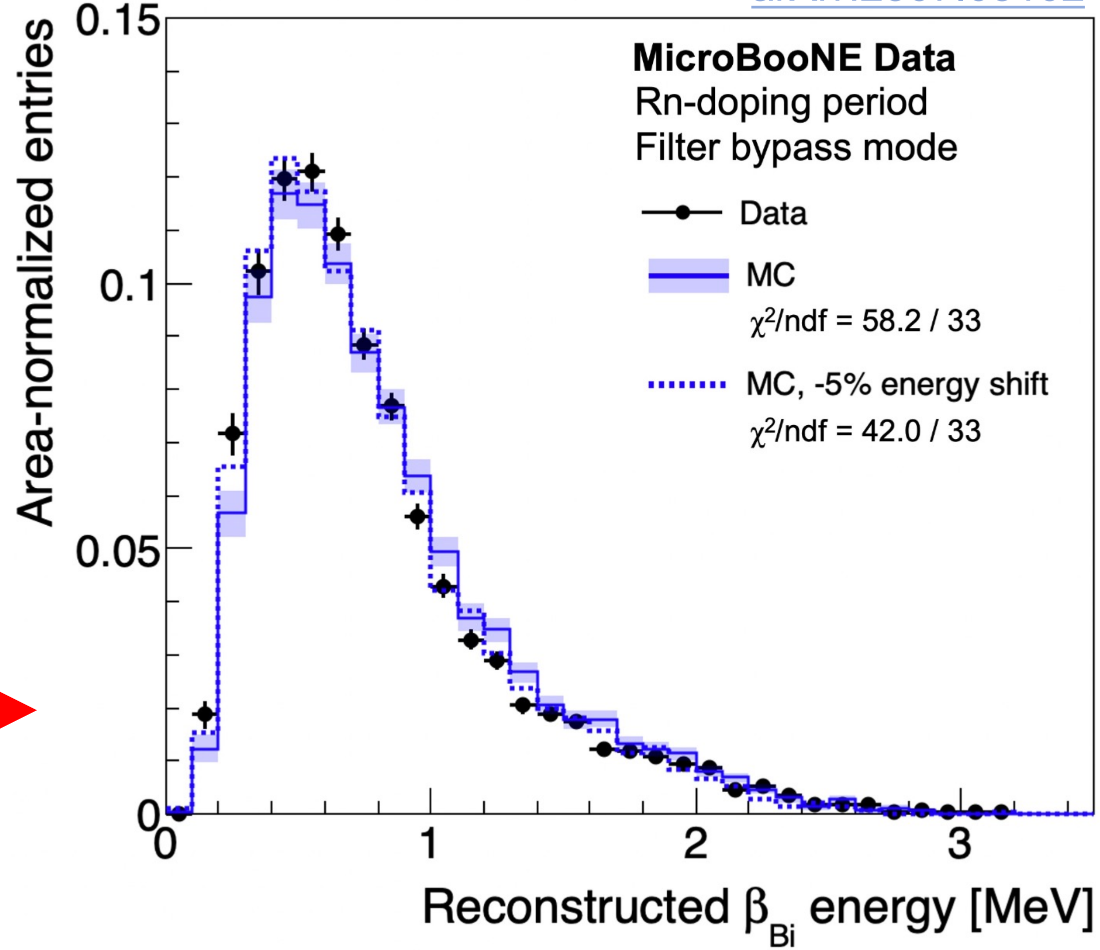
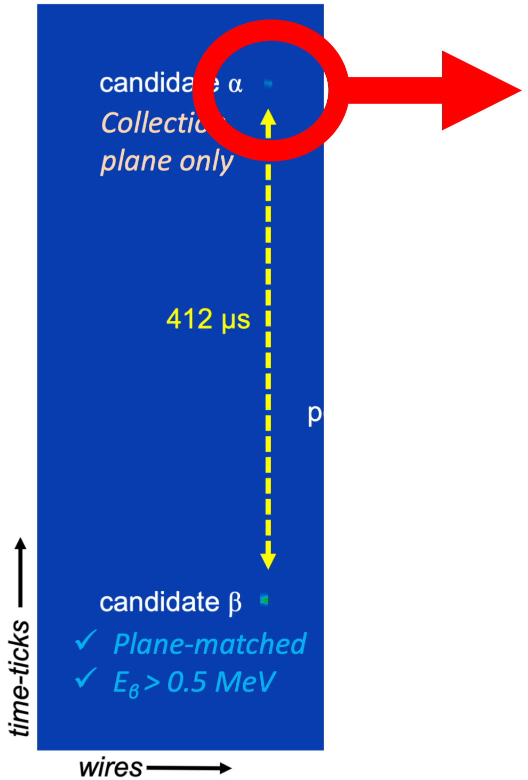


Monte Carlo calorimetric validation: 7.7 MeV α_{Po}

... and same for the α_{Po} energy spectrum

(large uncertainties in charge yield/quenching)



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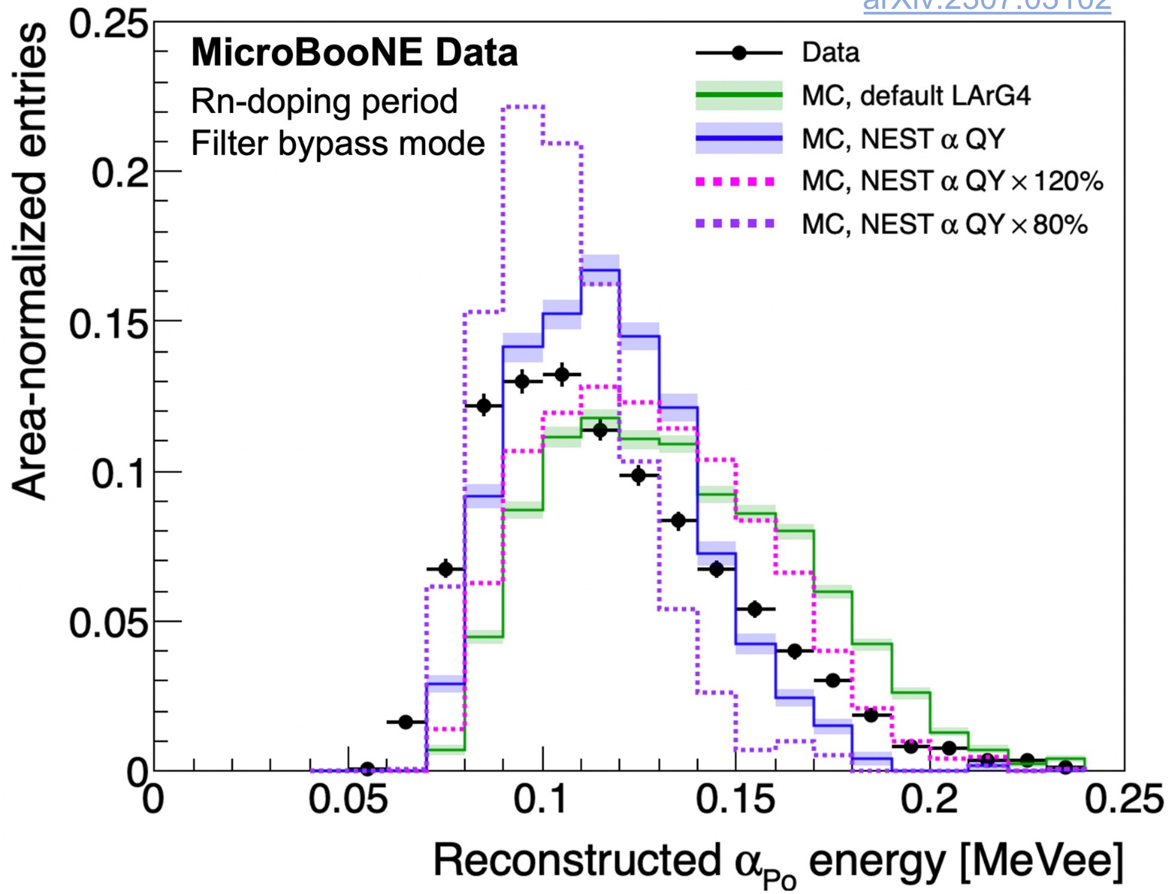
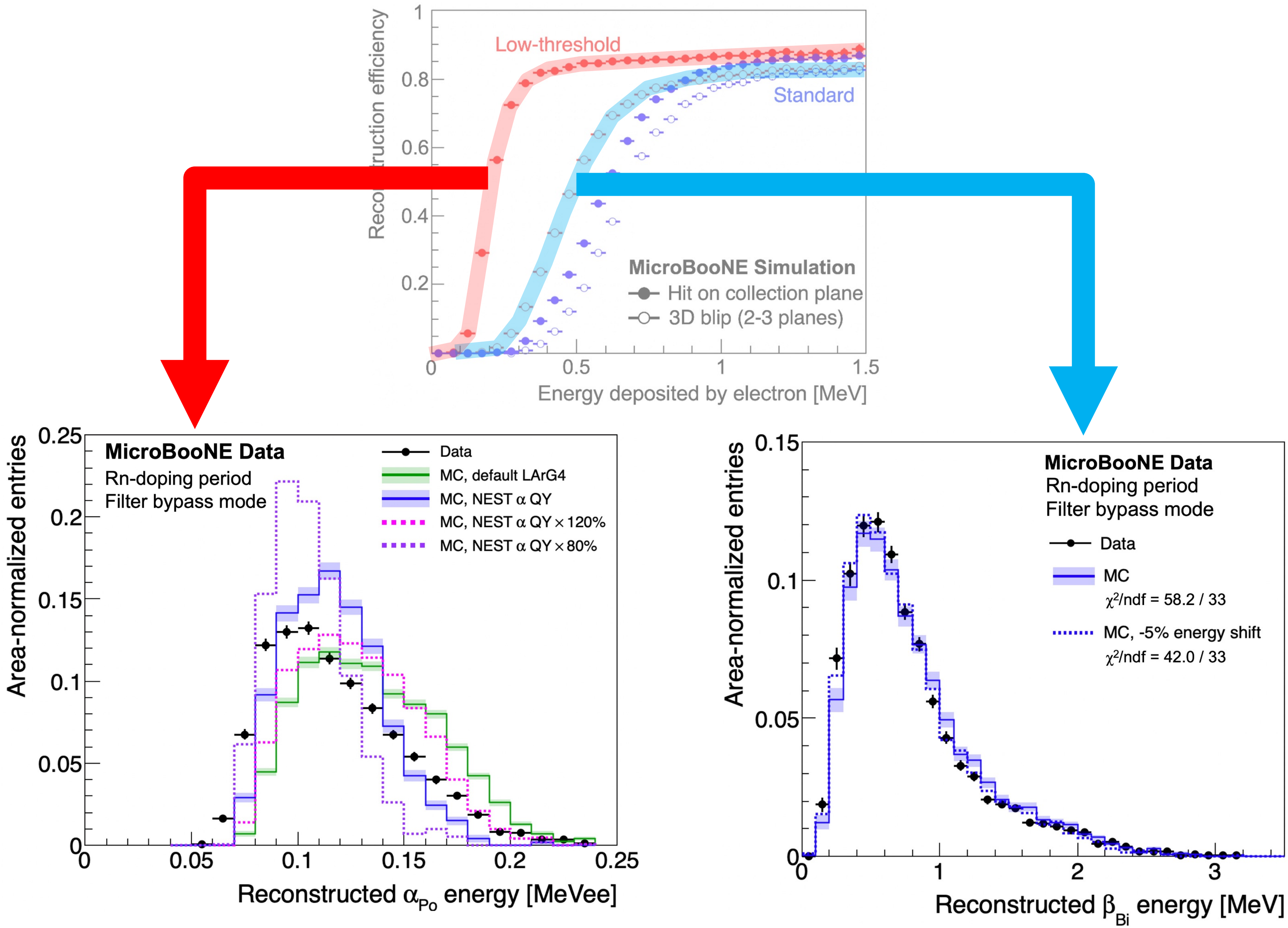
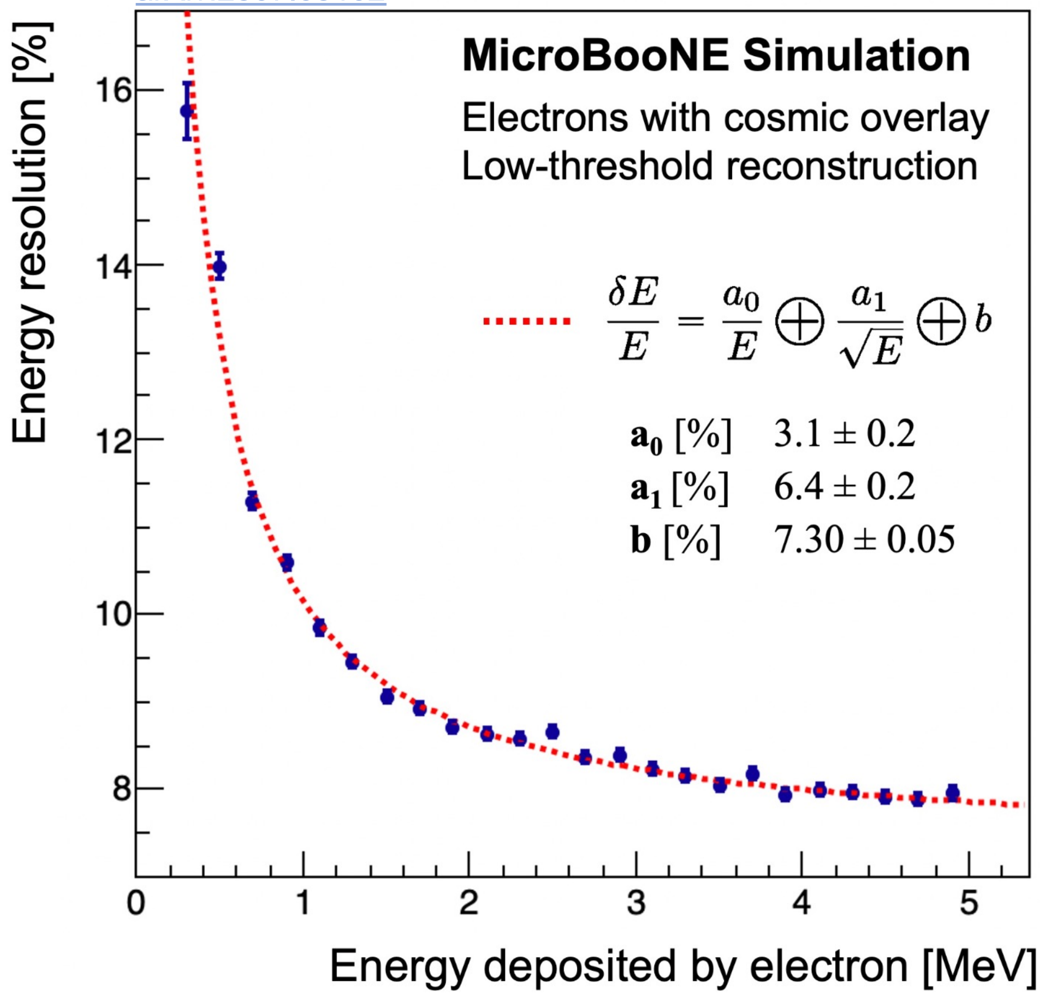




Reconstruction efficiency
Low-threshold
Standard
MicroBooNE Simulation
Hit on collection plane
3D blip (2-3 planes)
Energy deposited by electron [MeV]
MicroBooNE Data
Rn-doping period
Filter bypass mode
Data
MC, default LArG4
MC, NEST α QY
MC, NEST α QY × 120%
MC, NEST α QY × 80%
Area-normalized entries
Reconstructed α_{Po} energy [MeVee]
MicroBooNE Data
Rn-doping period
Filter bypass mode
Data
MC
χ^2/ndf = 58.2 / 33
MC, -5% energy shift
χ^2/ndf = 42.0 / 33
Area-normalized entries
Reconstructed β_{Bi} energy [MeV]

Monte Carlo predicted energy resolution

arXiv:2307.03102



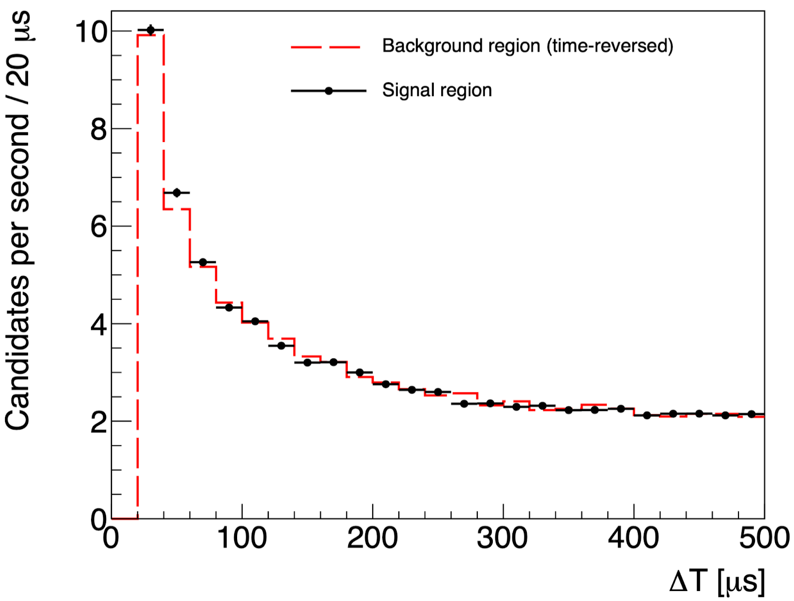
MC electron resolution:

- 10% at 1 MeV
- 8% at 5 MeV

DUNE requirements for:

- SNe ν: ~10-20%
  Euro. Phys. J. 81, 423 (2021)
- Solar ν: ~7% for > 5 MeV
  Phys. Rev. Lett. 123, 131803 (2019)

Measuring ambient rate in standard conditions



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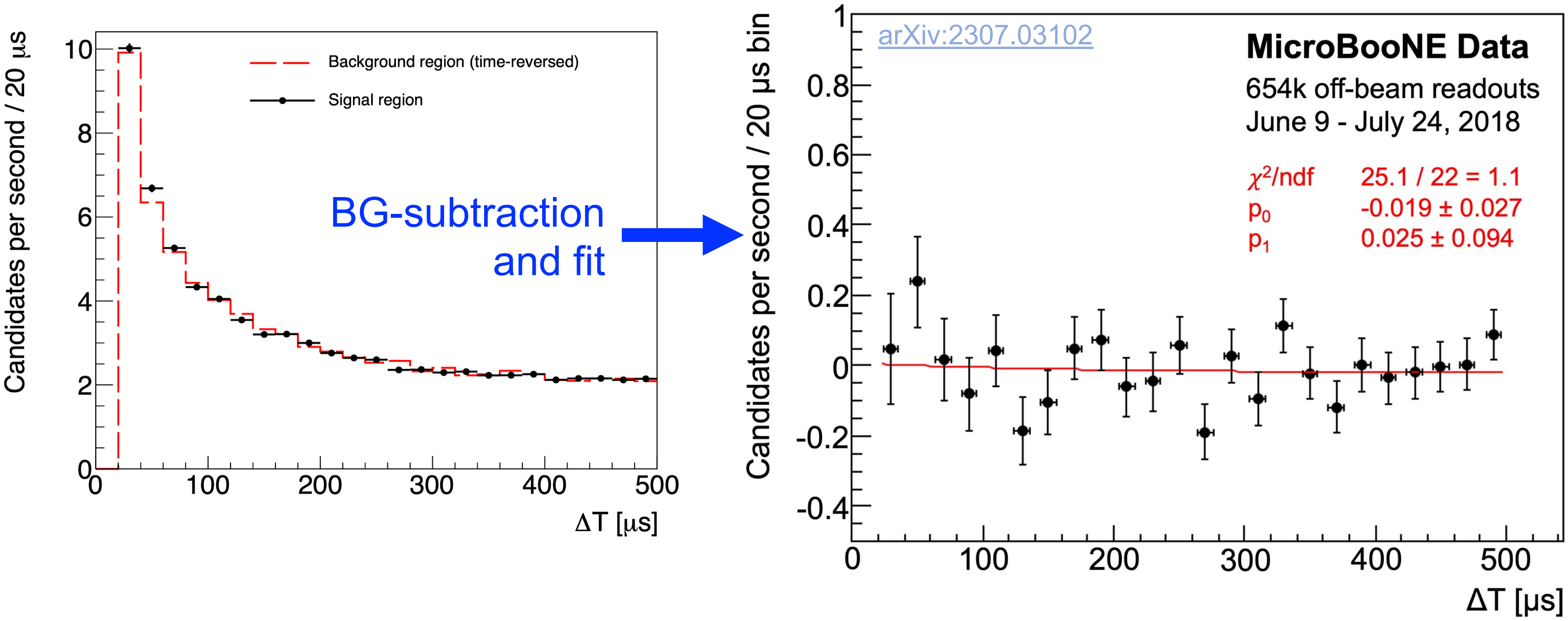

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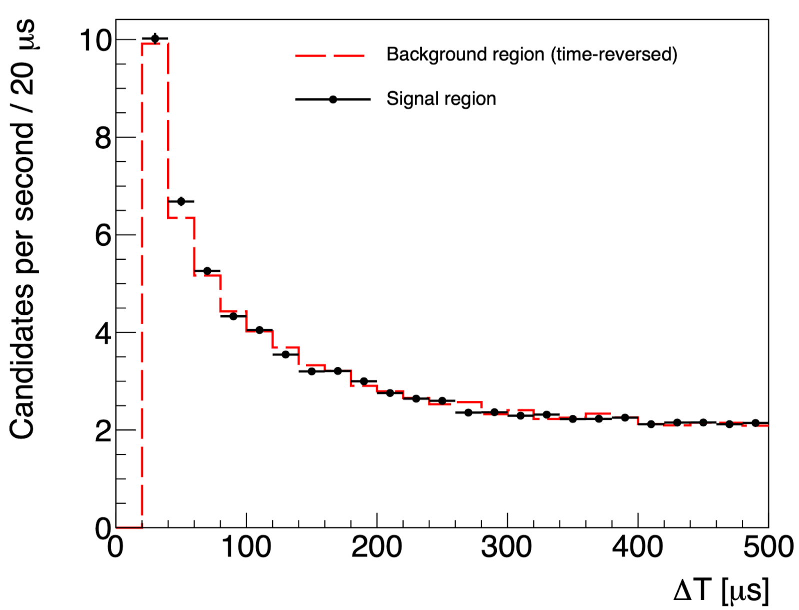
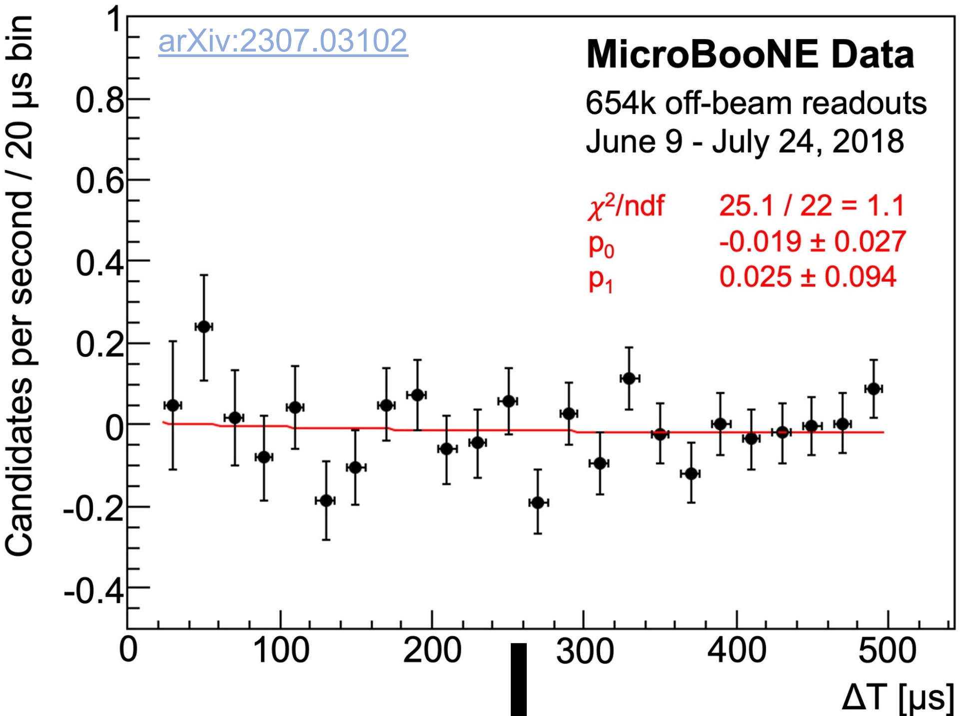




DUNE target: < 1 mBq/kg

n = (0.7 ± 2.5 (stat) ± 1.4** (syst))$\times 10^{-3}$ decays/readout

R* = 0.04 ± 0.15 (stat) ± 0.09 (syst) mBq/kg
= 0.04 ± 0.17 mBq/kg
< 0.38 mBq/kg at 95% CL

$^{*}R\ [\mathrm{Bq/kg}] = \dfrac{n/\epsilon}{85000\ \mathrm{kg}}$

**Systematic on *n* from fixing flat background-term *p0* to 0 & re-fitting

Conclusions (1/2)

- MicroBooNE has developed a technique to measure absolute ^{222}Rn rate in-situ with LArTPC wire readout data
- 75-100 keV threshold demonstrated – lowest achieved in any single-phase LArTPC neutrino detector
- **No Rn detected:** < 0.38 mBq/kg at 95% CL

Published to arXiv: arXiv:2307.03102

In review by PRD

Measurement of ambient radon daughter decay rates and energy spectra in liquid argon using the MicroBooNE detector

P. Abratenko,[35] O. Alterkait,[35] D. Andrade Aldana,[15] L. Arellano,[20] J. Asaadi,[34] A. Ashkenazi,[32] S. Balasubramanian,[12] B. Baller,[12] G. Barr,[25] D. Barrow,[25] J. Barrow,[21,32] V. Basque,[12] O. Benevides Rodrigues,[15] S. Berkman,[12] A. Bhanderi,[20] A. Bhat,[7] M. Bhattacharya,[12] M. Bishai,[3] A. Blake,[17] B. Bogart,[22] T. Bolton,[16] J. Y. Book,[14] L. Camilleri,[10] Y. Cao,[20] D. Caratelli,[4] I. Caro Terrazas,[9] F. Cavanna,[12] G. Cerati,[12] Y. Chen,[28] J. M. Conrad,[21] M. Convery,[28] L. Cooper-Troendle,[26,39] J. I. Crespo-Anadón,[6] R. Cross,[38] M. Del Tutto,[12] S. R. Dennis,[5] P. Detje,[5] A. Devitt,[17] R. Diurba,[2] Z. Djurcic,[1] R. Dorrill,[15] K. Duffy,[25] S. Dytman,[26] B. Eberly,[30] P. Englezos,[27] A. Ereditato,[7,12] J. J. Evans,[20] R. Fine,[18] O. G. Finnerud,[20] W. Foreman,[15] B. T. Fleming,[7] N. Foppiani,[14] D. Franco,[7] A. P. Furmanski,[23] D. Garcia-Gamez,[13] S. Gardiner,[12] G. Ge,[10] S. Gollapinni,[33,18]

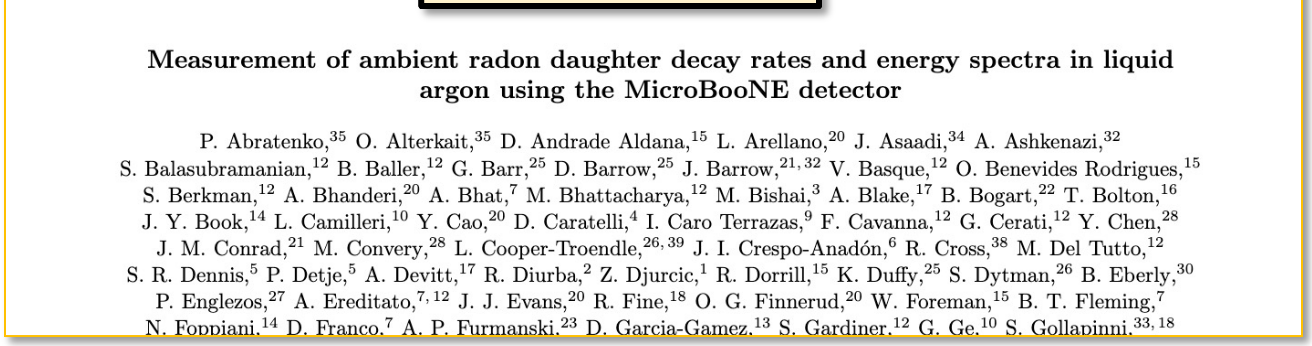
Conclusions (2/2)

- Existing wire-readout technology and reconstruction tools sufficient for DUNE to achieve its baseline goals
  - ✓ Sensitivity to ~100 keV w/lowered thresholds
  - ✓ < 10% charge-based electron energy resolution

- Existing LArTPC liquid filtration achieves high radon radiopurity, well-below DUNE's requirements

Published to arXiv: [arXiv:2307.03102](https://arxiv.org/abs/2307.03102)

In review by PRD



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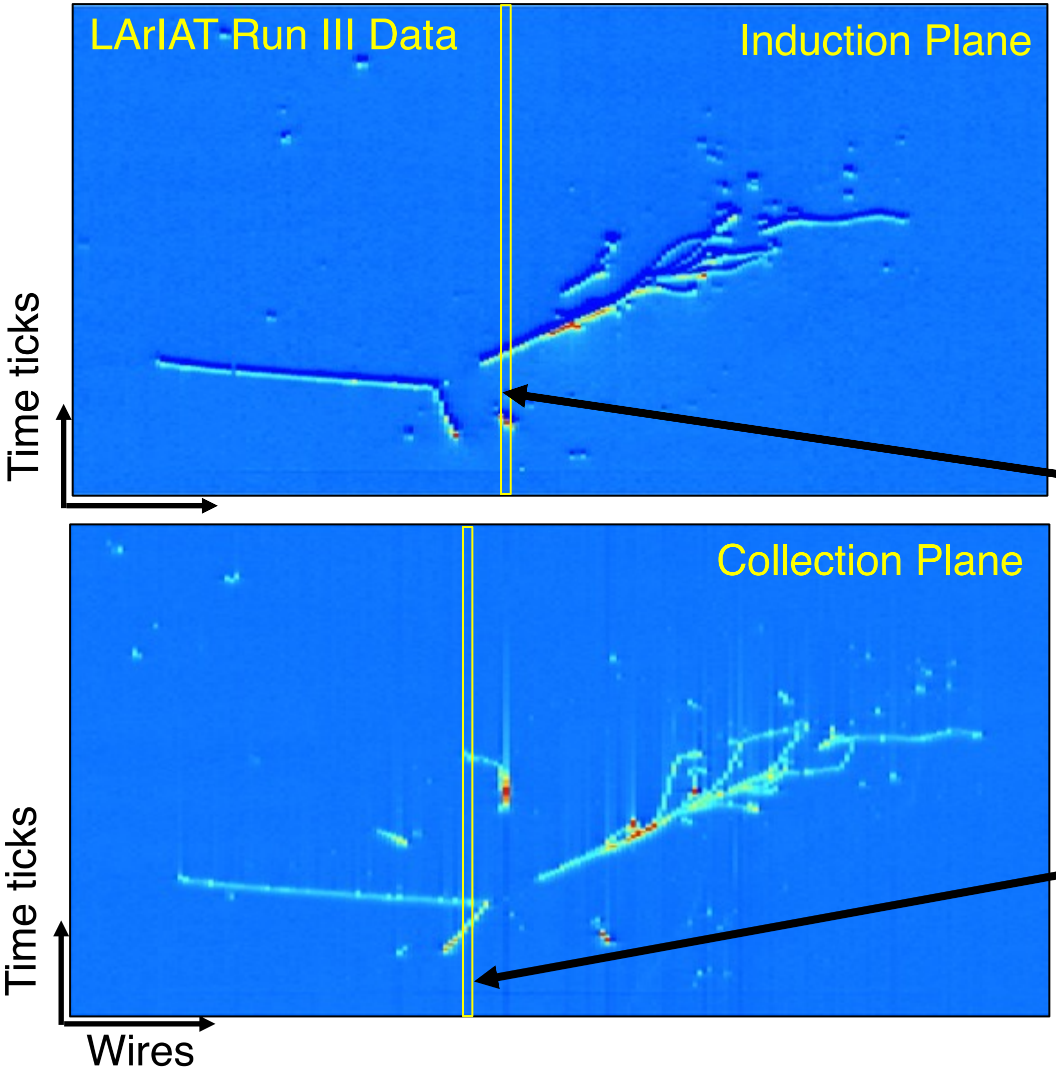
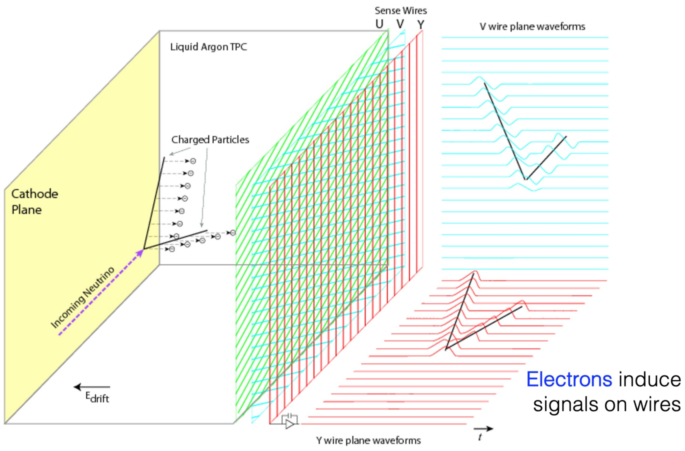
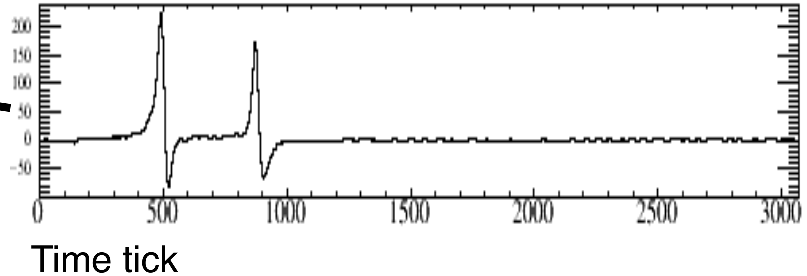
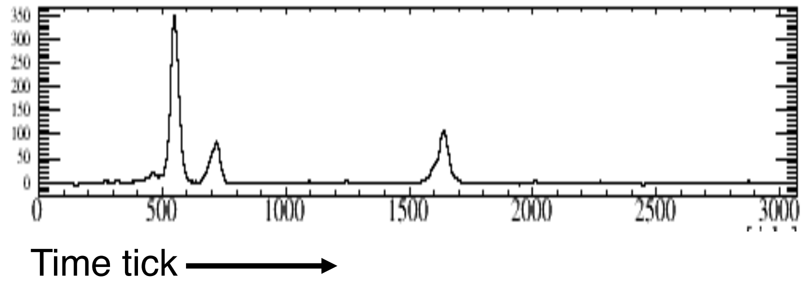
BACKUP

Liquid argon time projection chamber (LArTPC)

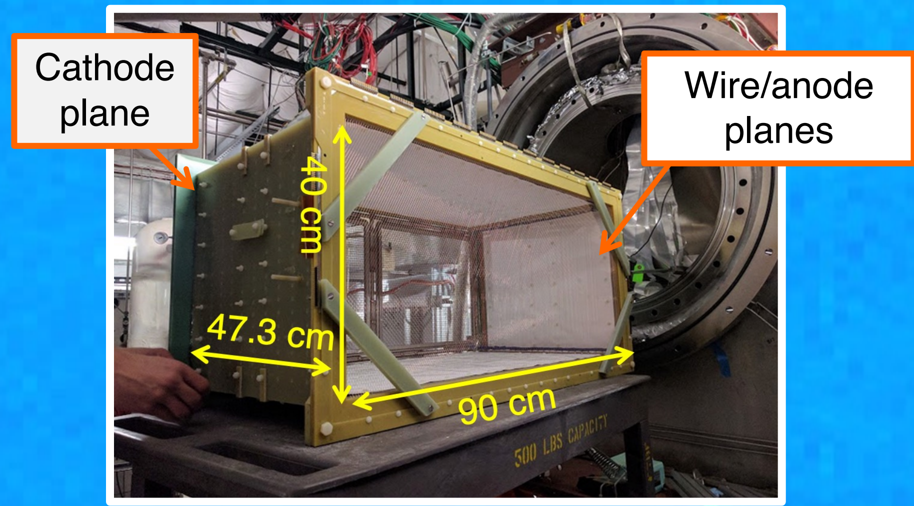


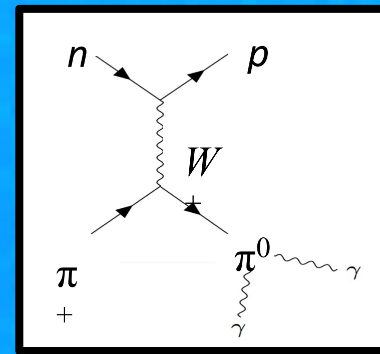




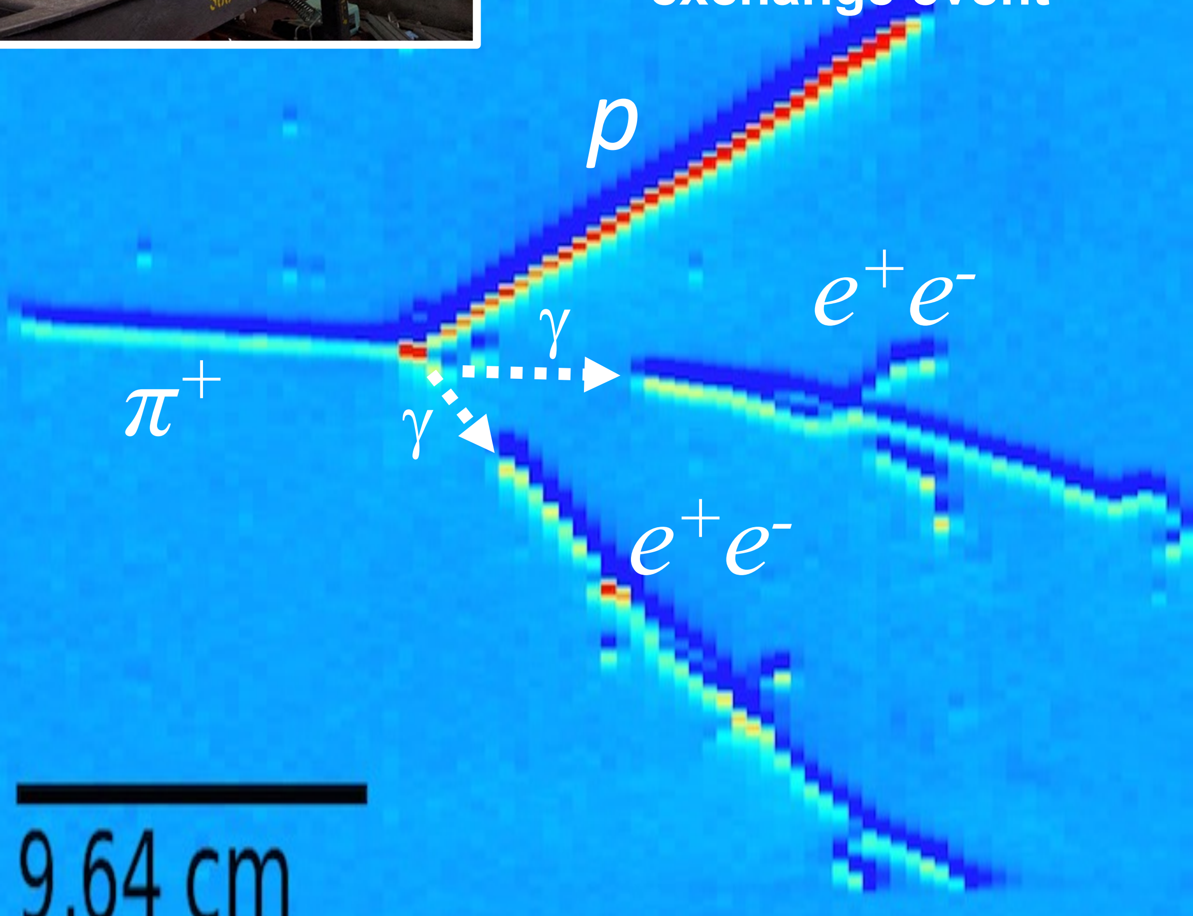


LArIAT Data



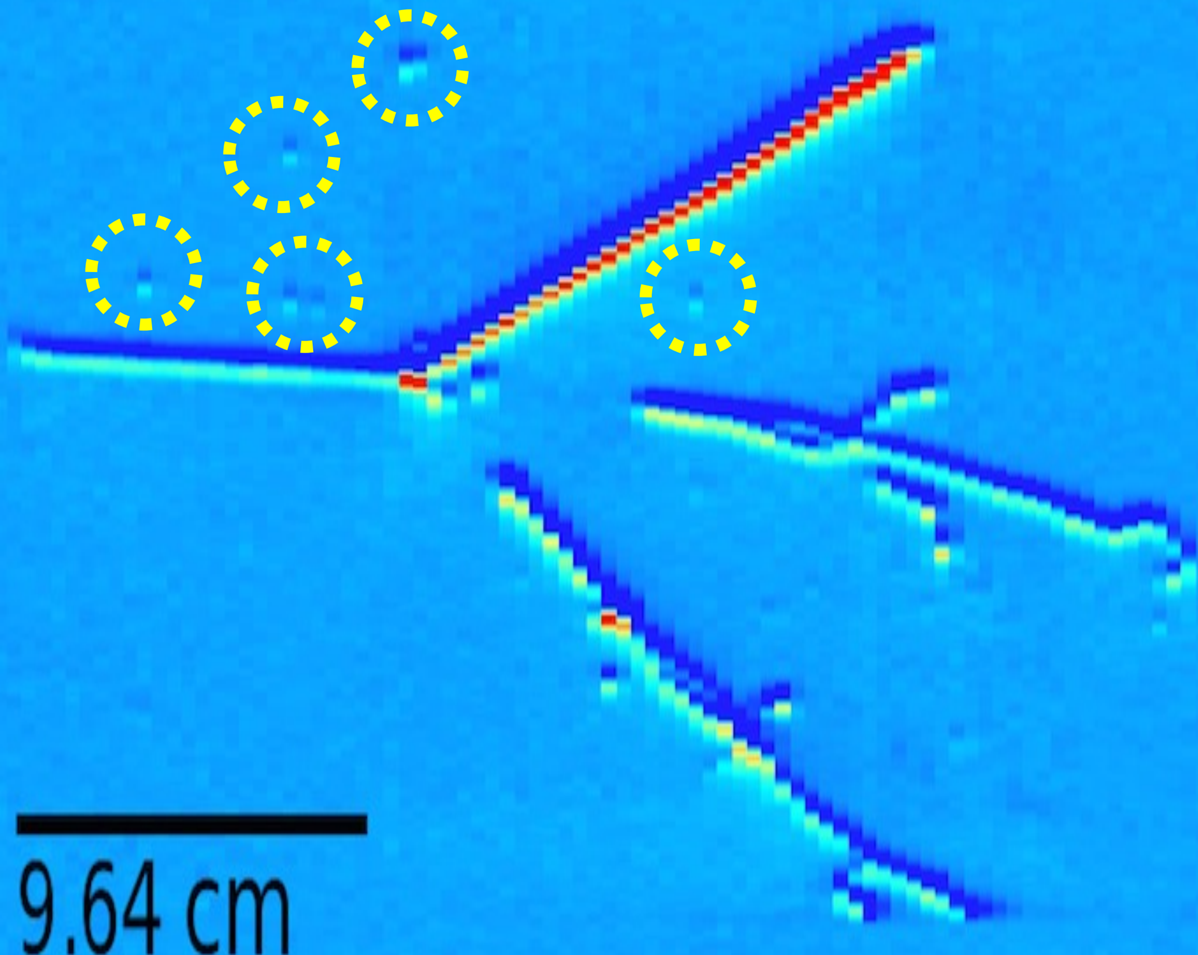


Pion charge-exchange event



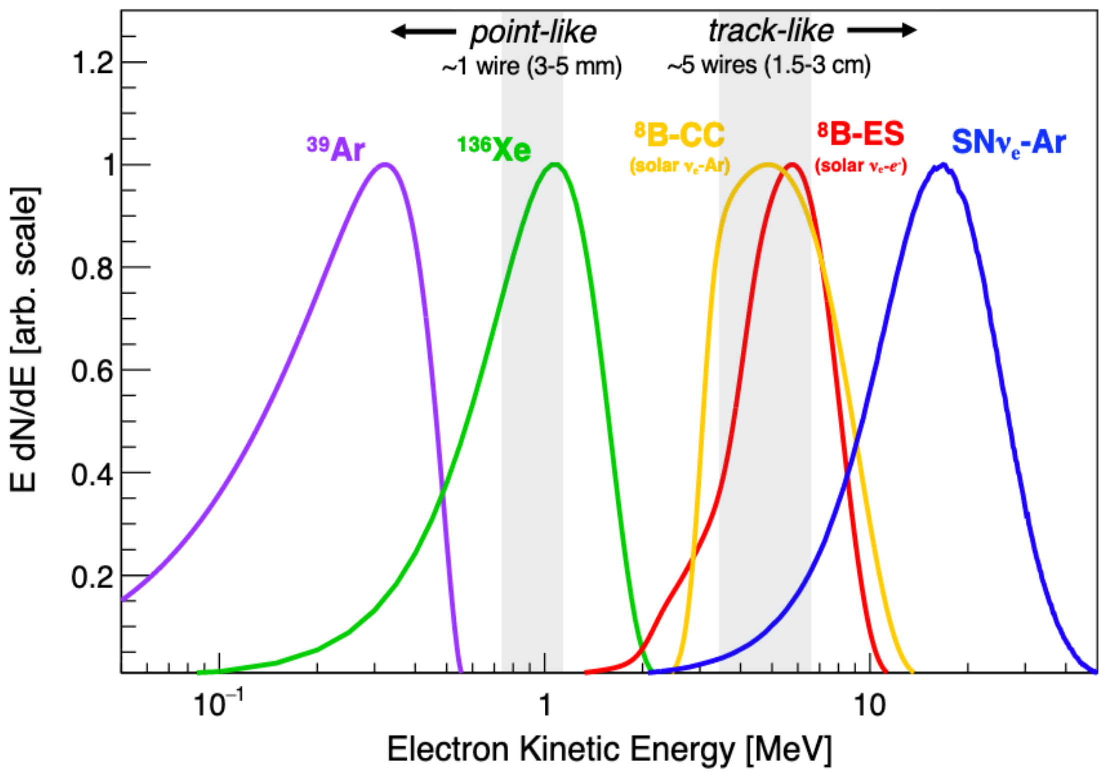
LArIAT Data

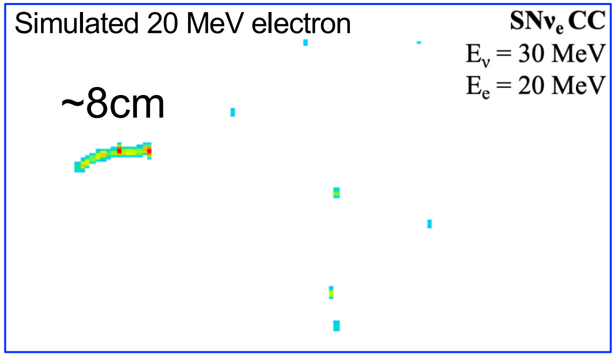
MeV-scale activity ("blips") from de-excitation γ's and neutrons



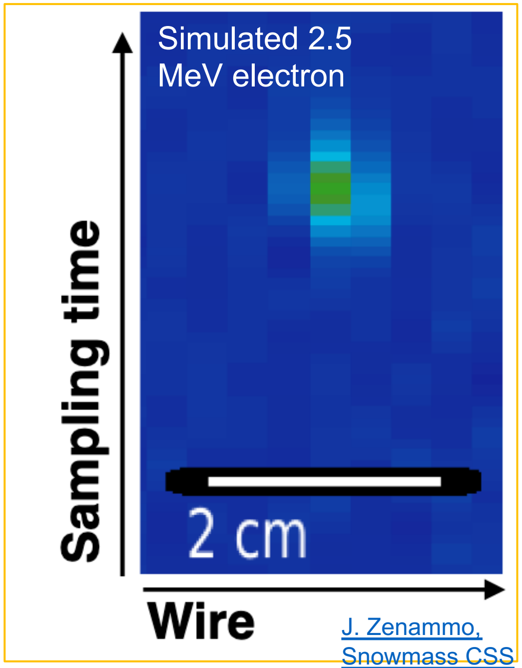
Energy scales in LAr

arxiv:2203.00740





"Benefits of MeV-scale reconstruction capabilities in large LArTPCs"
Phys. Rev. D. 102 092010

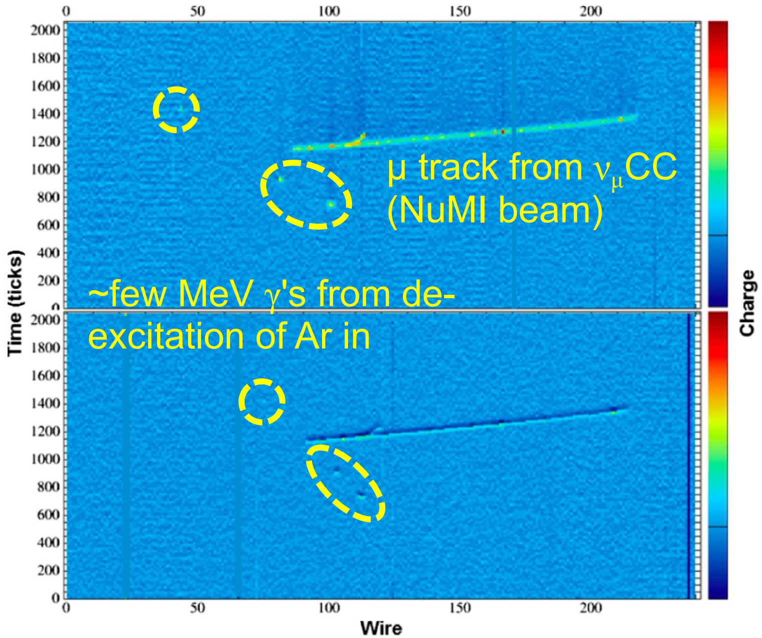


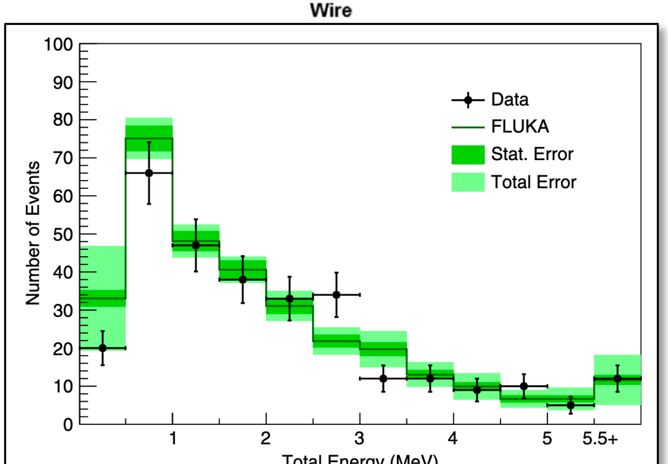
J. Zenammo, Snowmass CSS

Some history of MeV-scale studies

ArgoNeuT

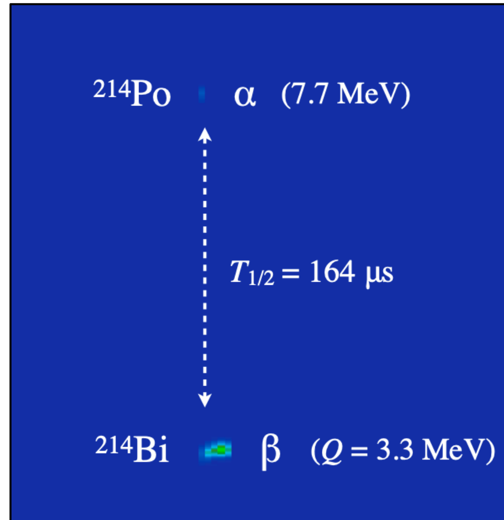
[Phys Rev D 99, 012002]

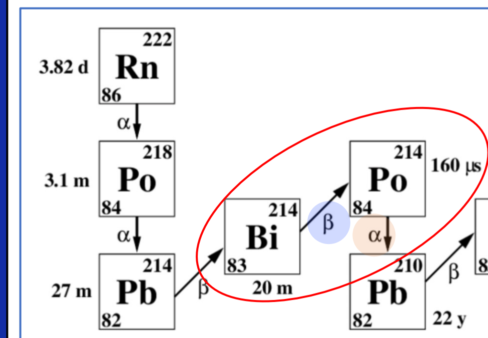


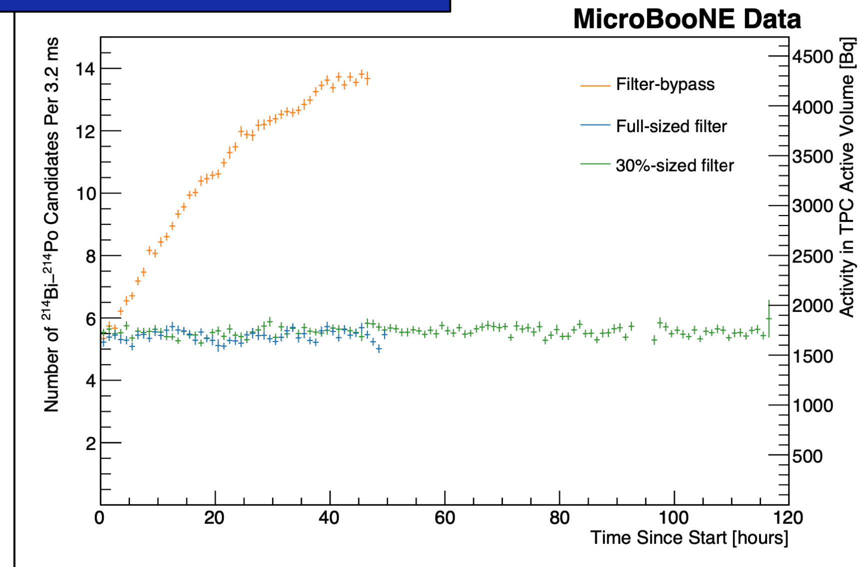


MicroBooNE

[2022 JINST 17 P11022]







Charge → energy calculation

Collected charge (Q) must be converted into deposited energy

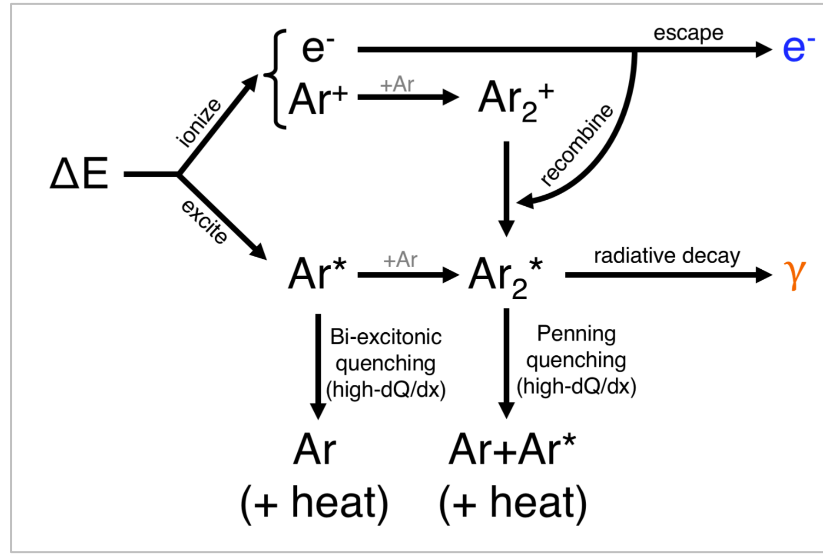
Number of electrons collected

$$E = Q \times R^{-1} \times (24\ \text{eV})$$

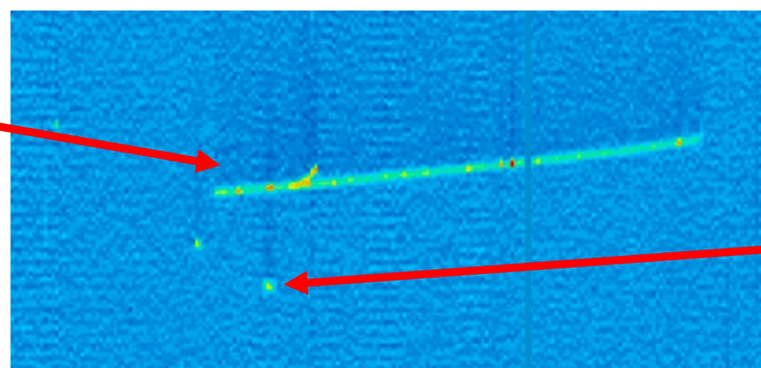
Electron recombination factor (function of **dE/dx** and **E-field**)

Average energy required to make e^-/Ar^+ pair

arXiv: 1909.07920

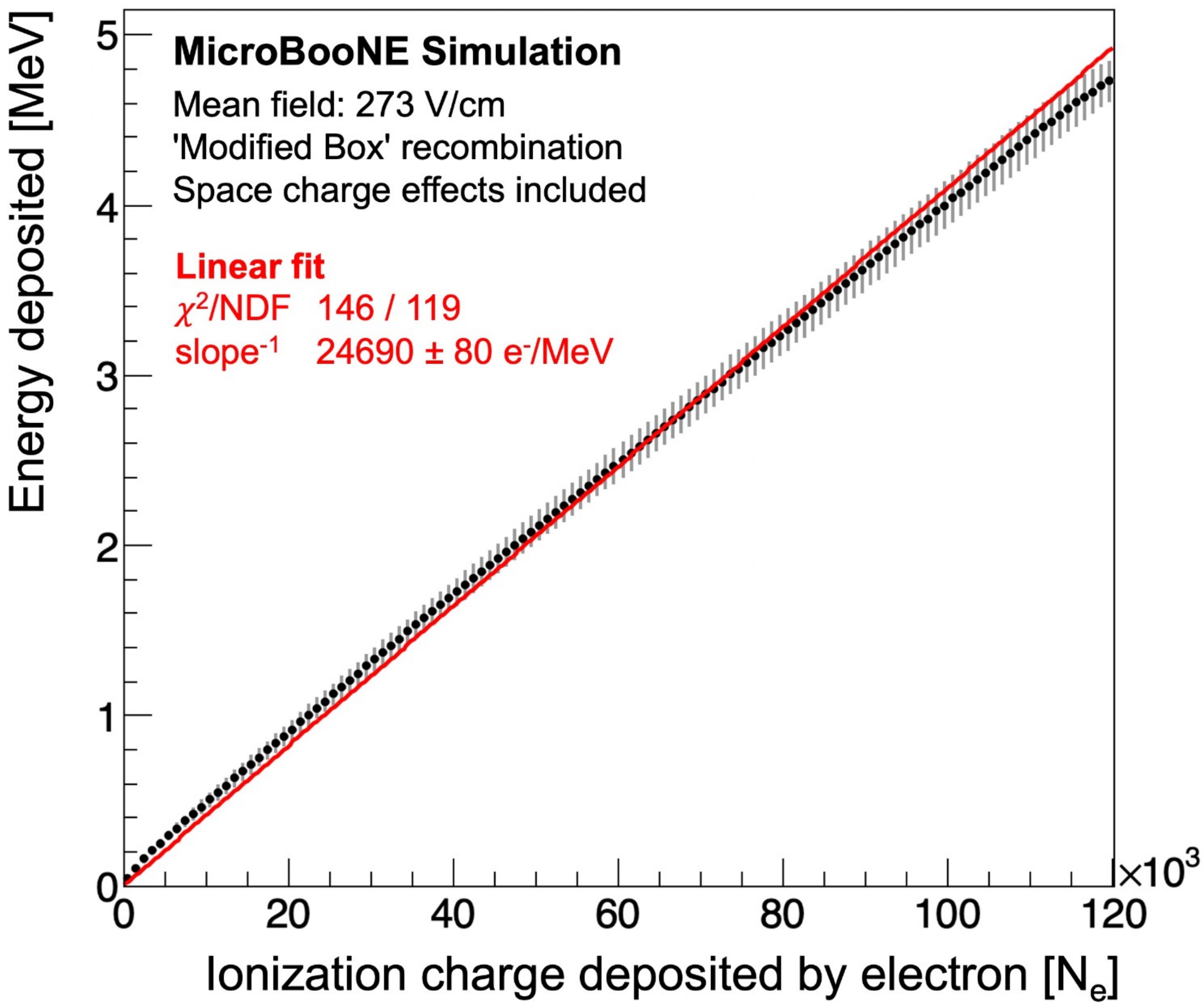


For *tracks,* we know the length and therefore dQ/dx for each hit.

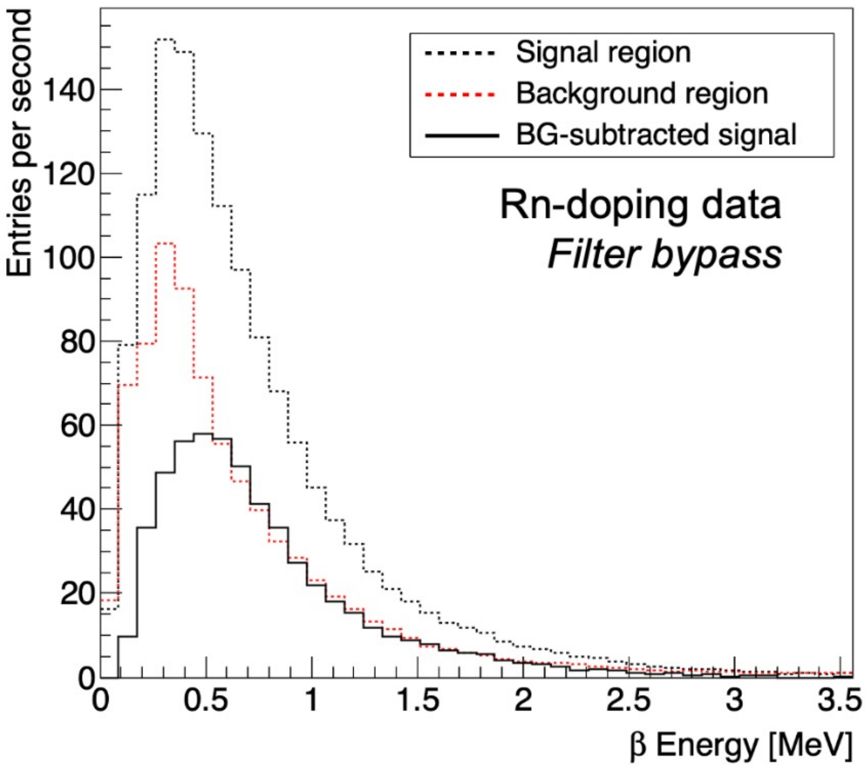


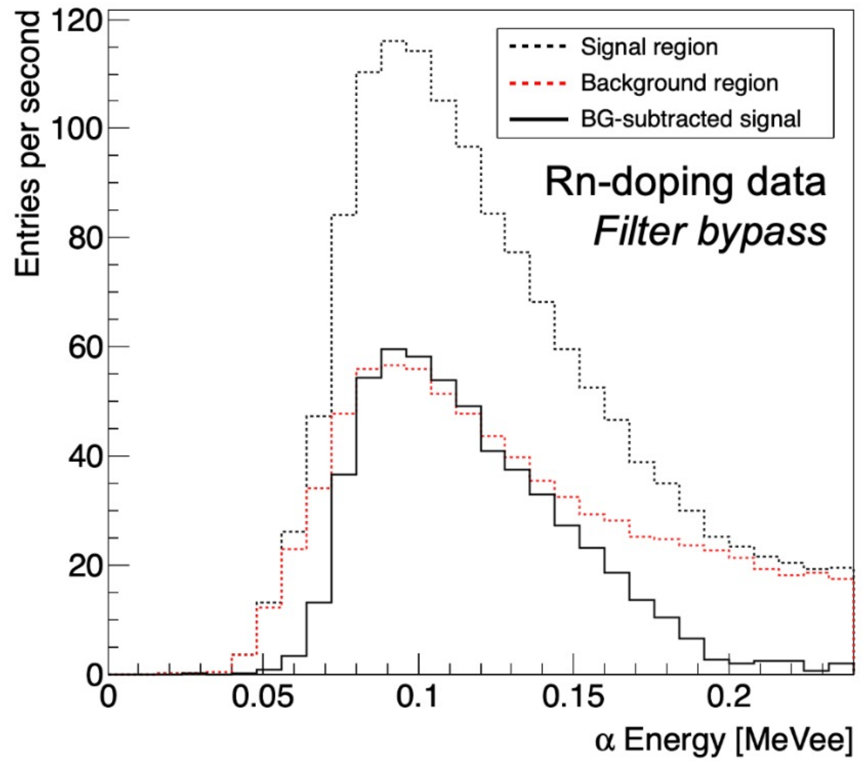
For *blips*, no spatial extent: we lose that "dx" information!

Charge vs energy for electrons



Energy spectra backgrounds





Monte Carlo efficiency

α QY: +/-20%

D_L: ± 1σ, D_T: ± 30%

All charge scaled +/-5%

'Birks' model, and enhanced recombination fluctuations

Systematic	Uncertainty
Alpha QY	± 43%
Electron diffusion	+26%, -17%
Energy scale	± 15%
Recombination modeling	± 1.9%
Total	+52%, -49%

Final efficiency for BiPo rate measurement:
ε = (6 ± 3) %

Contributions to efficiency

	Relative probability (NEST)	Relative probability (LArG4)
Volume remaining after 2D cosmic track-masking	~86%	same
Bi214 beta decays producing collection plane hits*	~51%	same
Bi214 blips plane-matched	~62%	same
Po214 alphas producing collection plane hits	~22%	~43%
Total	**~6%**	**~12%**

* Using 'low-threshold' reconstruction

New result from MicroBooNE

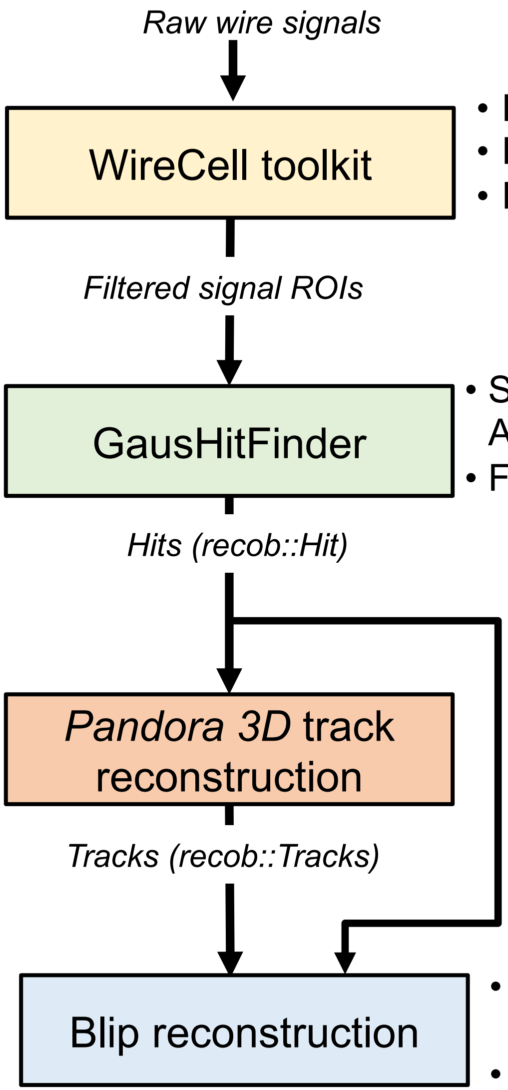
- Showcase of new tools developed for MeV-scale reconstruction in LAr that can directly benefit the astrophysical ν community
  - Based on traditional algorithmic approach: WireCell signal processing, gaussian-based hit finding ('gaushit')
  - Tested on real LArTPC physics data
  - Available for immediate implementation in DUNE

Published to arXiv last week: arXiv:2307.03102

Measurement of ambient radon daughter decay rates and energy spectra in liquid argon using the MicroBooNE detector

We report measurements of radon daughters in liquid argon within the MicroBooNE time projection chamber (LArTPC). The presence of radon in MicroBooNE's 85 metric tons of active liquid argon bulk is probed with newly developed charge-based low-energy reconstruction tools and analysis techniques to detect correlated ^{214}Bi-^{214}Po radioactive decays. Special datasets taken during periods of active radon doping enable new demonstrations of the calorimetric capabilities of single-phase neutrino LArTPCs for β and α particles with electron-equivalent energies ranging from 0.1 to 3.0 MeV. By applying ^{214}Bi-^{214}Po detection algorithms to beam-external physics data recorded over a 46-day period, no statistically significant presence of radon is detected, corresponding to a limit of < 0.38 mBq/kg at the 95% confidence level. The obtained radon radiopurity limit – the first ever reported for a noble element detector incorporating liquid-phase purification – is well below the target value of the future DUNE neutrino detector.

Reconstruction workflow in MicroBooNE



WireCell toolkit:
- Noise filter
- De-convolution
- ROI-finding

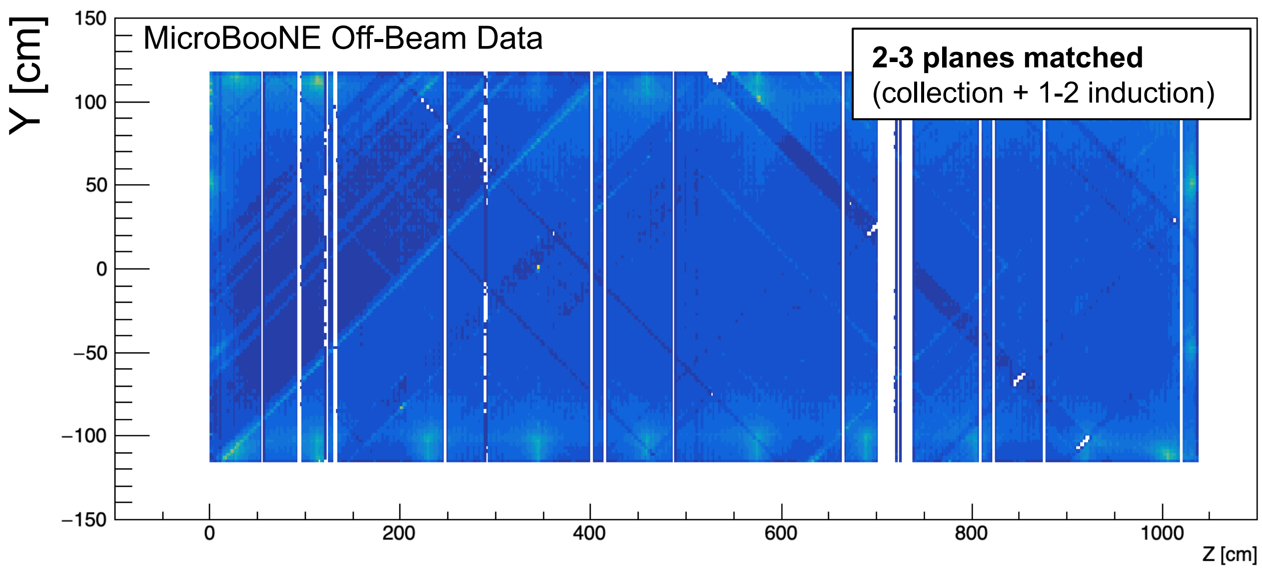
GausHitFinder:
- Search each ROI for ADC above threshold
- Fit pulses to Gaussians

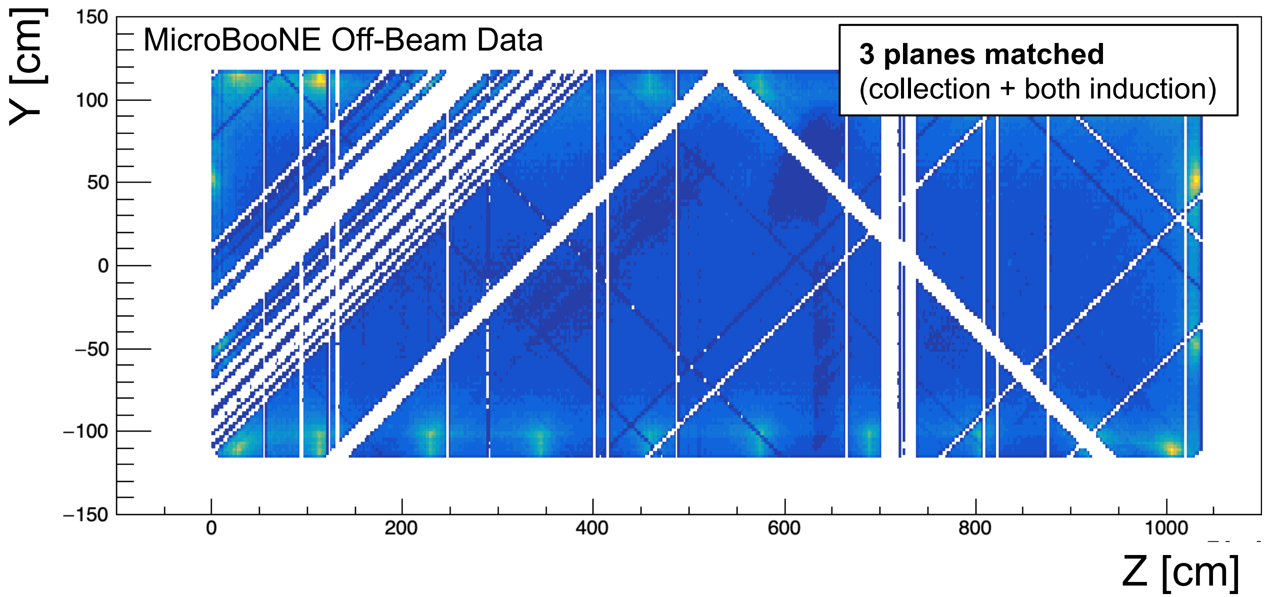
Blip reconstruction:
- Take non-tracked hits, perform plane matching
- Reconstructs 3D blips

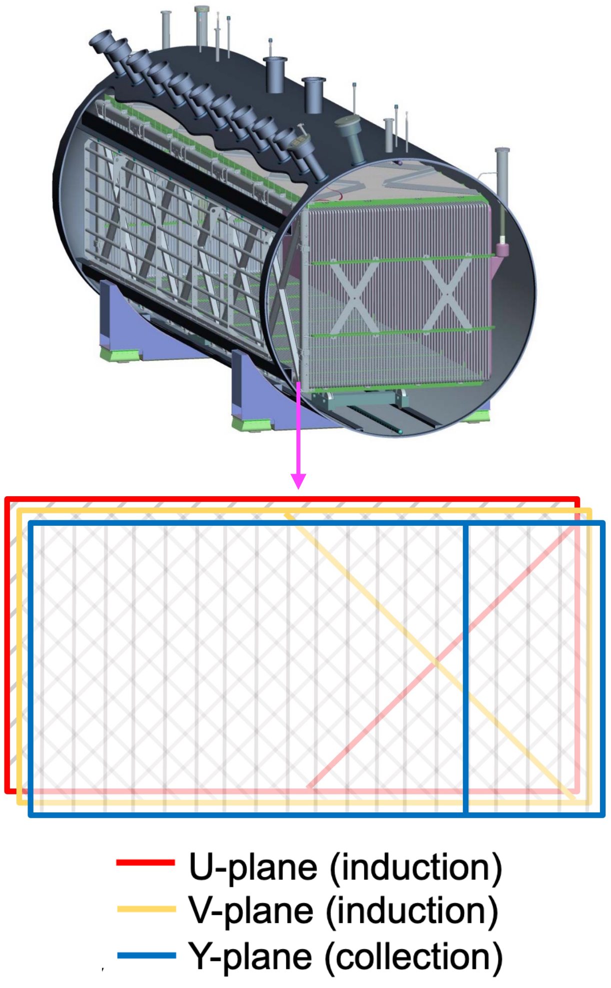
New tools for MeV-scale reconstruction: ***BlipReco***

- Techniques from previous analyses, pioneered in ArgoNeuT, were packaged into dedicated algorithm class in MicroBooNE's LArSoft repository
- Flexible integration into other reco/analysis modules
- Goal: experiment-agnostic LArSoft tool and eventual 'Blip' data object

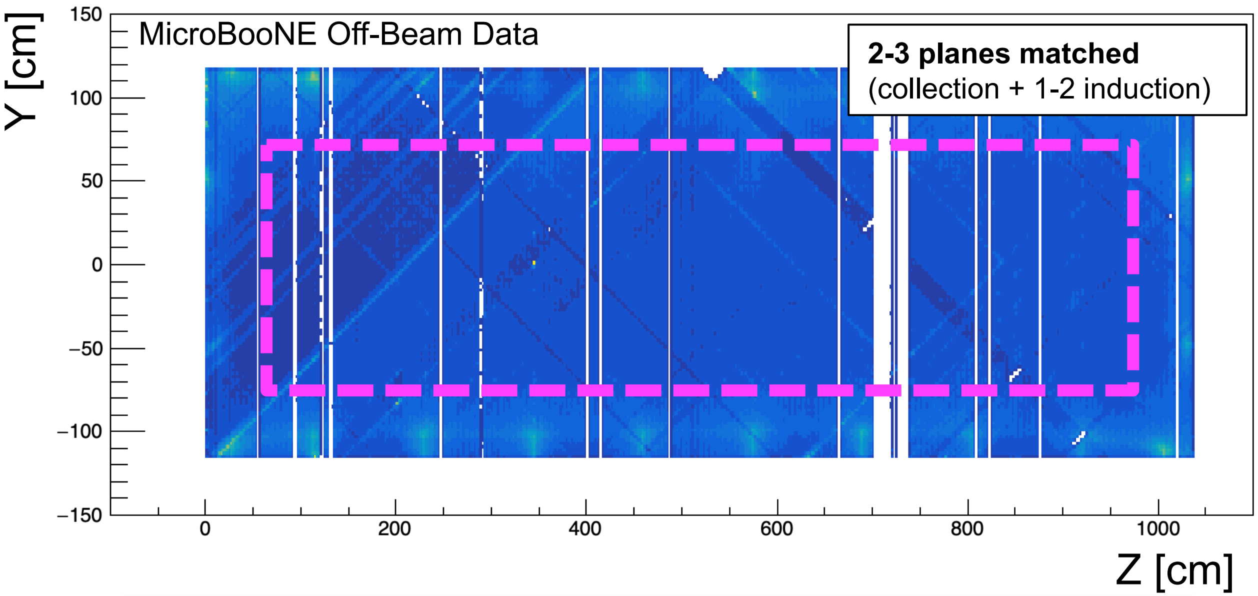
All ambient blip activity

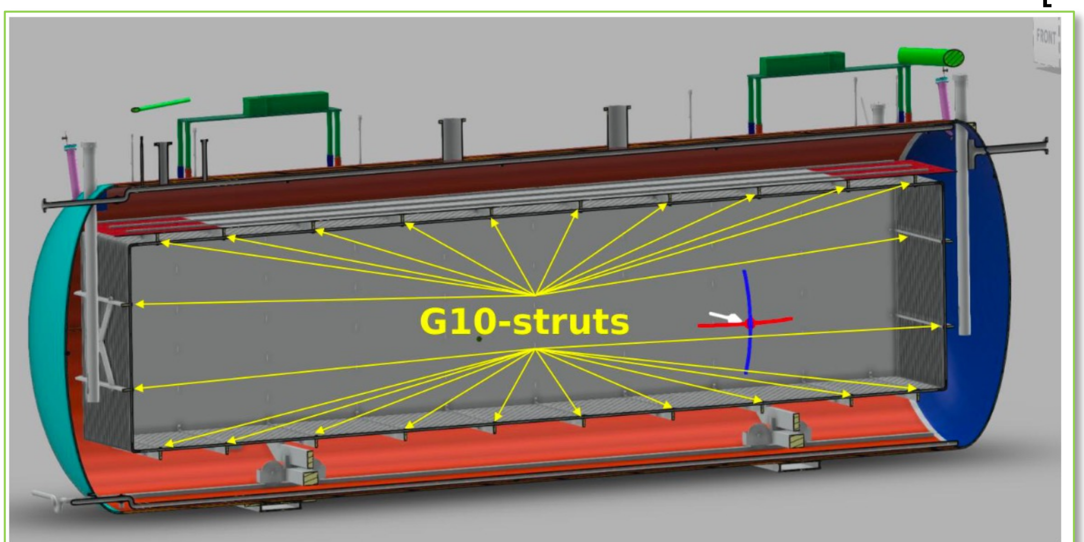


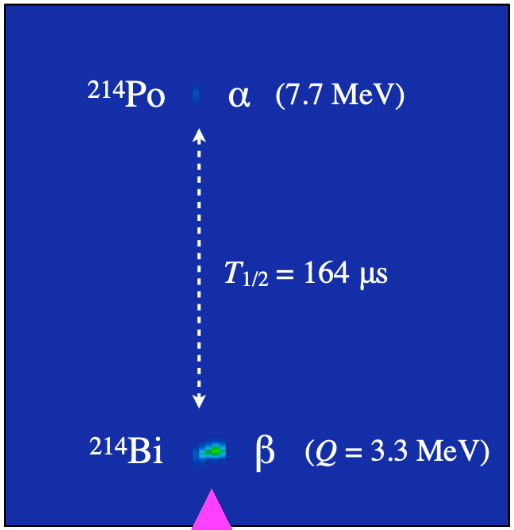




All ambient blip activity





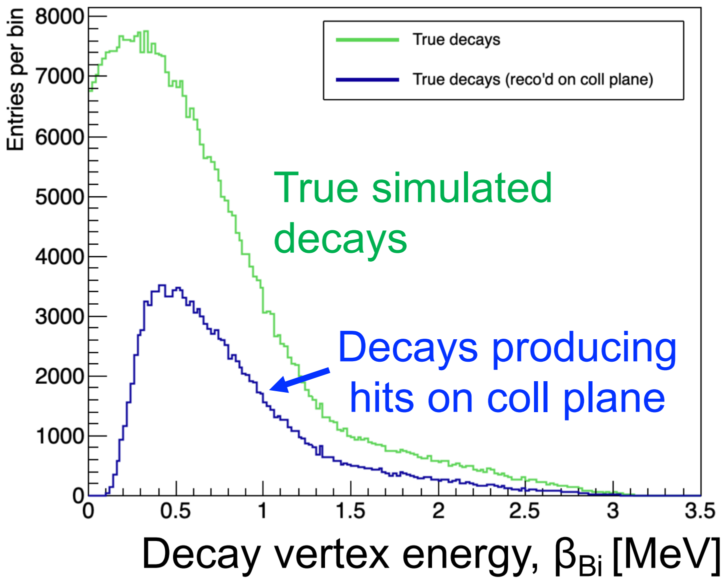


β_{Bi} candidate:
3D plane-matched blip

Enables fiducialization in YZ

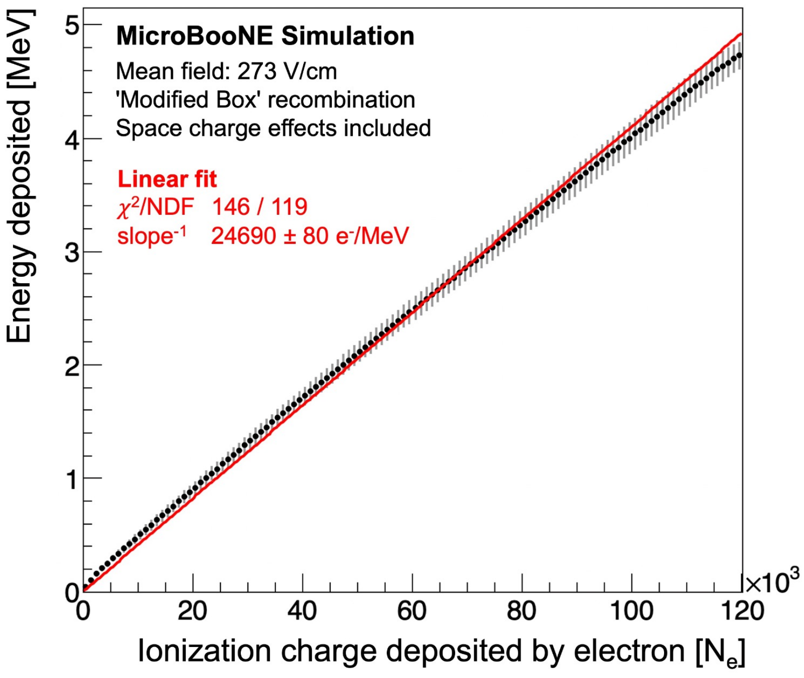
Monte Carlo

- Simulated ^{214}Bi-^{214}Po final-states ($\beta + \alpha + N\gamma$) overlaid with cosmic data
- Identical reconstruction/analysis as data
- **Calorimetry**: linear *charge-to-energy, assuming recombination for low-E electrons (dE/dx ~ 2.8 MeV/cm)*



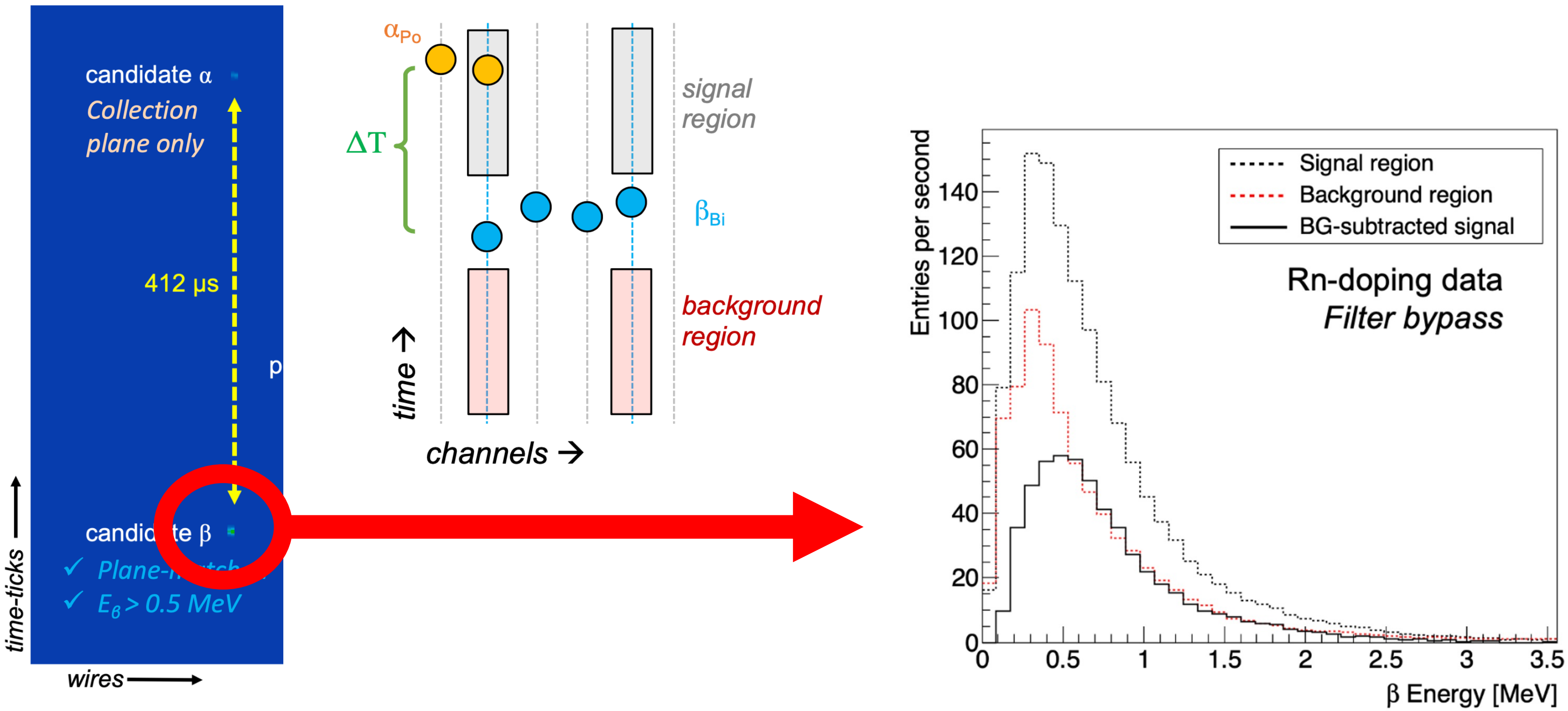
$$E_{\text{reco}} = \frac{Q}{\mathcal{R}(dE/dx, \mathcal{E}_{\text{local}})} \times W_{\text{ion}}$$

$$E_{\text{reco}}\ [\text{MeVee}] = \frac{Q}{0.584} \times W_{\text{ion}}$$



Monte Carlo calorimetric validation: 0-3.3 MeV β_{Bi}

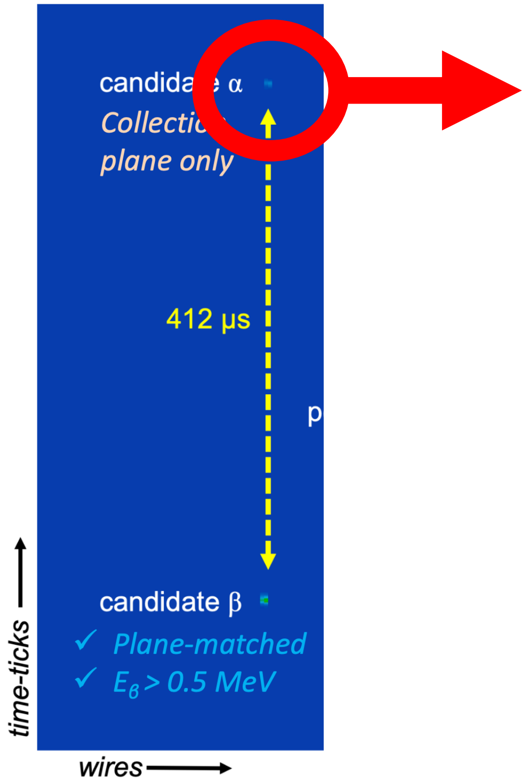
Same BG subtraction applied to β *energy spectra*



Monte Carlo calorimetric validation: 7.7 MeV α_{Po}

Using NEST-parameterized alpha charge-yield (QY) model

https://zenodo.org/record/7577399



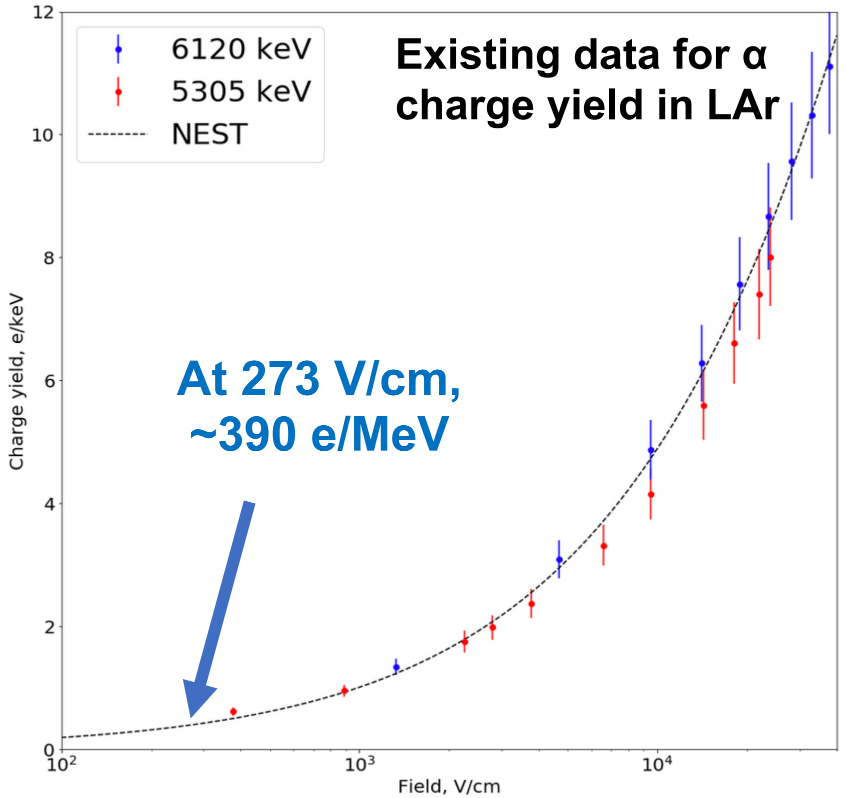
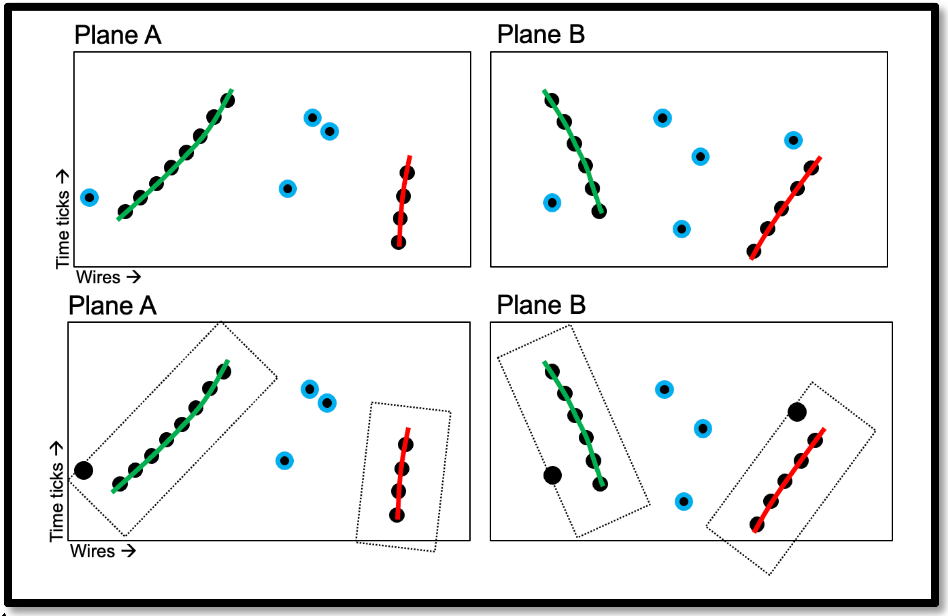
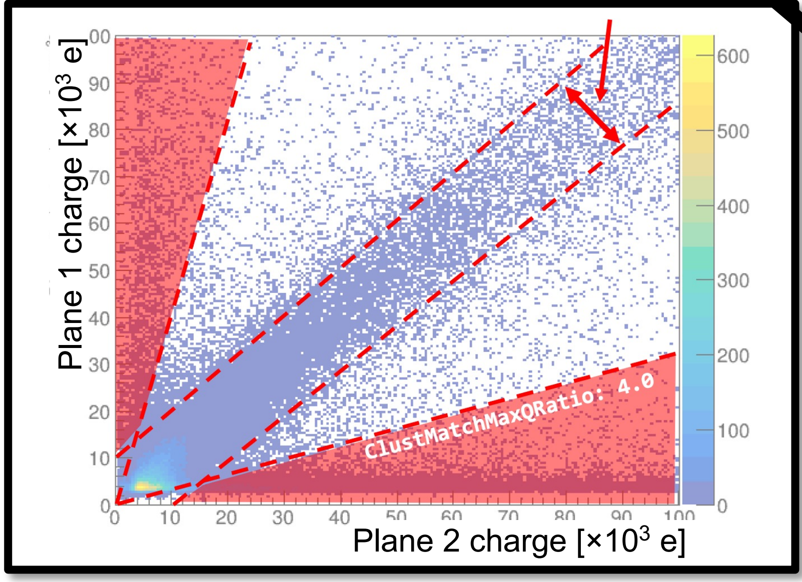


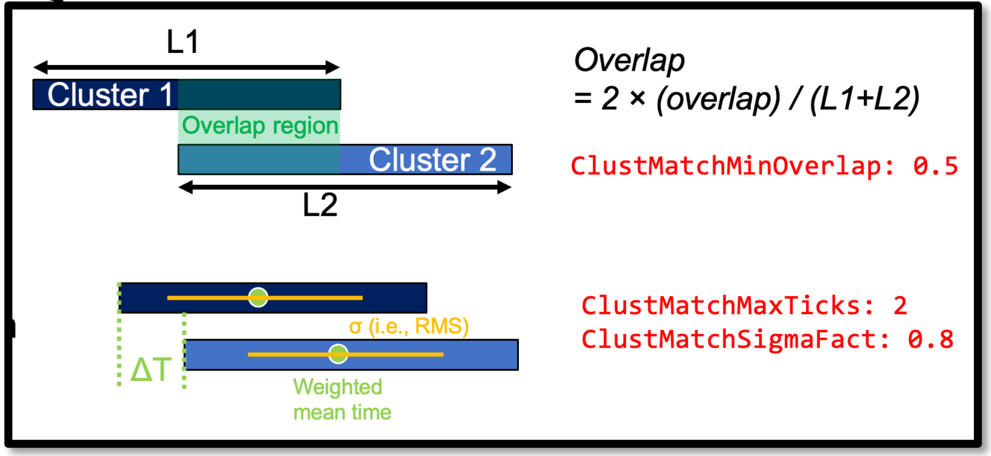
Figure 9: Charge yield model comparison with data from Po-210 and Cf-252

BlipReco: geometric reconstruction

1. **Isolated hits identification**
   Hits *within* tracks > configurable length are vetoed; optional 2D masking in regions surrounding long tracks
2. **Hit clustering per plane**
   Hit width ('RMS') defines proximity threshold for clustering in wire-time space
3. **Cluster plane-matching**
4. **Geometric requirement**
   Wires must cross!
5. **Relative charge comparison**







https://cdcvs.fnal.gov/redmine/projects/ubreco/repository/show/ubreco/BlipReco?rev=feature%2Fwforeman_blipreco

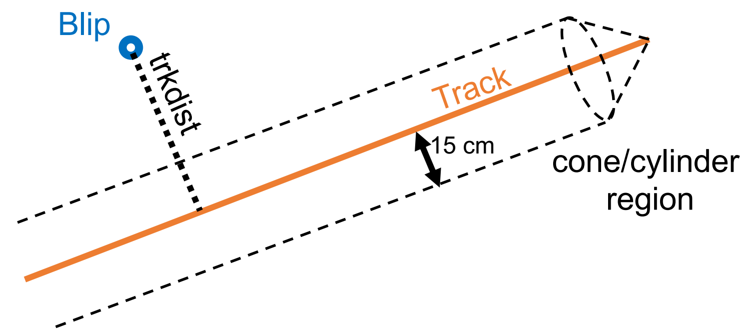
BlipReco code structure

`ubreco/BlipReco` (3.3 MB total)

```
Alg
BlipAna_module.cc
blipreco_badchannels.txt
blipreco_configs.fcl
BlipRecoProducer_module.cc
CMakeLists.txt
job
ParticleDump_module.cc
TrackMasker_module.cc
Utils
```

Utils

```
BlipUtils.cc
BlipUtils.h
classes_def.xml
classes.h
CMakeLists.txt
DataTypes.h
```



"Blip" data object prototype (C++ struct)

- Encodes XYZ, charge, & energy of 3D blips
- Includes distance to nearest track & track cone-cylinder region flag
- Truth-matching information also encoded

DataTypes.h

```cpp
struct Blip {

  int       ID            = -9;       // Blip ID / index
  bool      isValid       = false;    // Blip passes basic checks
  int       TPC           = -9;       // TPC
  int       NPlanes       = -9;       // Num. matched planes
  int       MaxWireSpan   = -9;       // Maximum span of wires on any plane cluster
  float     Charge        = -9;       // Charge on calorimetry plane
  float     Energy        = -999;     // Energy (const dE/dx, fcl-configurable)
  float     EnergyESTAR   = -999;     // Energy (ESTAR method from ArgoNeuT)
  float     Time          = -999;     // Drift time [ticks]
  float     ProxTrkDist   = -9;       // Distance to cloest track
  int       ProxTrkID     = -9;       // ID of closest track
  bool      inCylinder    = false;    // Is it in a cone/cylinder region?

  TVector3  Position;                 // 3D position TVector3
  float     SigmaYZ       = -9.;      // Uncertainty in YZ intersect [cm]
  float     dX            = -9;       // Equivalent length along drift direction [cm]
  float     dYZ           = -9;       // Approximate length scale in YZ space [cm]

  // Plane/cluster-specific information
  blip::HitClust clusters[kNplanes];

  // Truth-matched energy deposition
  blip::TrueBlip truth;

  // Prototype getter functions
  double X() { return Position.X(); }
  double Y() { return Position.Y(); }
  double Z() { return Position.Z(); }
```

DataTypes.h

```cpp
// True energy depositions
struct TrueBlip {
  int       ID            = -9;       // unique blip ID
  int       TPC           = -9;       // TPC ID
  float     Time          = -999e9;   // time [us]
  float     Energy        = 0;        // energy dep [MeV]
  int       DepElectrons  = 0;        // deposited electrons
  int       NumElectrons  = 0;        // electrons reaching wires
  float     DriftTime     = -9;       // drift time [us]
  int       LeadG4ID      = -9;       // lead G4 track ID
  int       LeadG4Index   = -9;       // lead G4 track index
  int       LeadG4PDG     = -9;       // lead G4 PDG
  float     LeadCharge    = -9;       // lead G4 charge dep
  TVector3  Position;                 // XYZ position
```

BlipReco code structure

- Single call to algorithm is all that's required
  - Alg takes pointer to entire `art::Event` and does all the magic behind the scenes
  - Returns a vector of 'Blip' objects that the user is free to incorporate into their analysis or reconstruction as they see fit

```
//==========================================
// Run blip reconstruction:
//==========================================

fBlipAlg->RunBlipReco(evt);

//
//  In the above step, we pass the entire art::Event to the algorithm,
//  and it creates a single collection of blip 'objects', a special data
//  struct in the 'blip' namespace defined in BlipUtils.h.
//
//  We can then retrieve these blips and incorporate them into
//  our analysis however we like:
//
//    std::vector<blip::Blip> blipVec = fBlipAlg->blips;
//
//  The alg also creates collections of 'HitInfo' and 'HitClust'
//  structs used in the blip reconstruction process, which can be
//  accessed in the same way as blips.
//
//    * HitInfo simply saves some calculations for each hit that aren't
//      present in the native recob::Hit object, like drift time, associated
//      G4 particle IDs, etc.
//
//    * HitClust is just a cluster of hits on a specific plane; these are
//      used to create 3D blips by plane-matching.
//
```

Example of looping through blips and filling histograms of XYZ, energy, and true energy

```
for(auto& blip : blipVec ) {
  h_histogram_X     ->Fill( blip.x );
  h_histogram_Y     ->Fill( blip.y );
  h_histogram_Z     ->Fill( blip.z );
  h_histogram_E     ->Fill( blip.Energy );
  h_histogram_TrueE ->Fill( blip.truth.Energy );
}
```