Recent Demonstrations at ~MeV energies in the MicroBooNE Experiment

Will Foreman (IIT)

on behalf of the MicroBooNE Collaboration

Short-Baseline Theory-Experiment Workshop

LANL / Santa Fe, NM

April 2-5, 2024

MeV-scale physics in LArTPCs

[Phys. G: Nucl. Part. Phys. 50 033001]

IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **50** (2023) 033001 (60pp) https://doi.org/10.1088/1361-6471/acad17

Topical Review

Low-energy physics in neutrino LArTPCs

S Andringa[1], J Asaadi[2], J T C Bezerra[3], F Capozzi[4], D Caratelli[5], F Cavanna[6], E Church[7], Y Efremenko[8], W Foreman[9], A Friedland[10], S Gardiner[6], I Gil-Botella[11], A Himmel[6], T Junk[6], G Karagiorgi[12], M Kirby[6], J Klein[13], G Lehmann-Miotto[14], I T Lepetic[15], S Li[6], B R Littlejohn[9,*], M Mooney[16], J Reichenbacher[17], P Sala[18], H Schellman[19], K Scholberg[20,*], M Sorel[4], A Sousa[21], J Wang[17], M H L S Wang[6], W Wu[6], J Yu[2], T Yang[6] and J Zennamo[6]

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[2] University of Texas, Arlington, TX, United States of America
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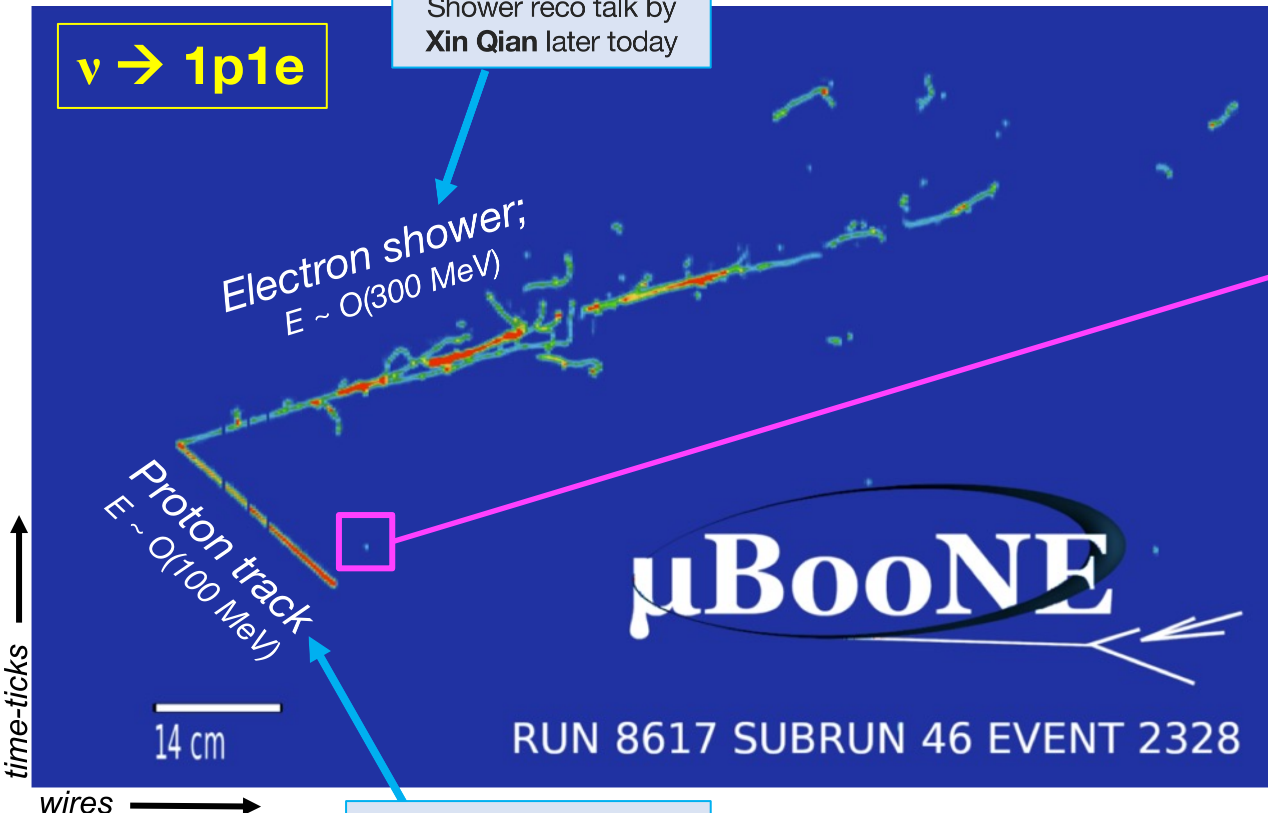
Topical Review resulting from Snowmass

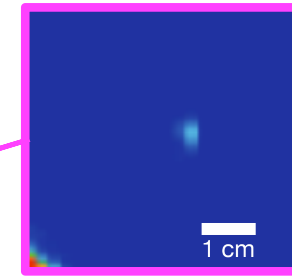
(Way more than can be fit into a 25 minute talk)

A brief tour of energy scales...

Shower reco talk by **Xin Qian** later today



Track reco talk by **Alice Campani** later today



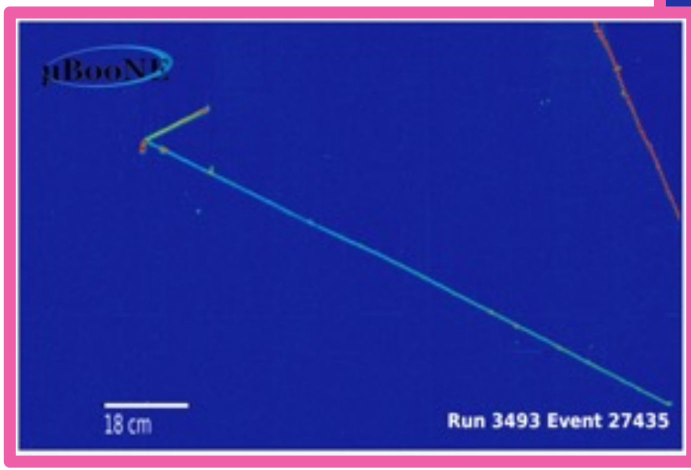
blip

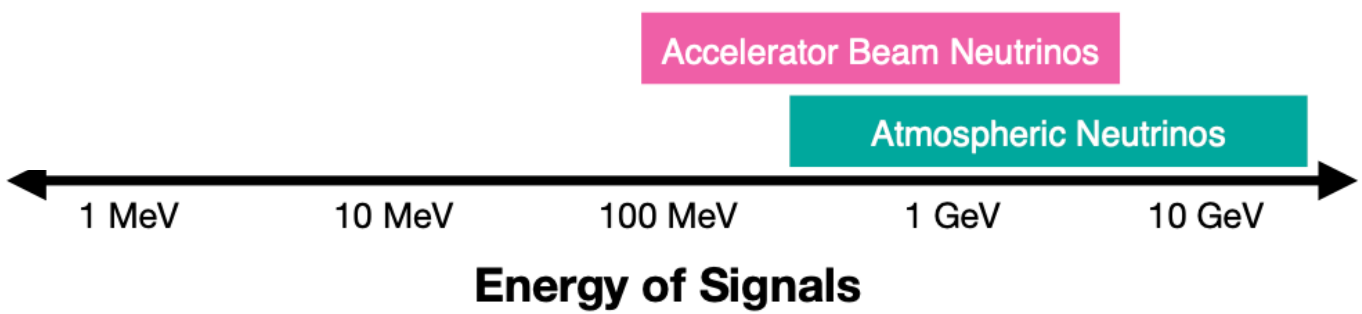
E ~ O(0.1-1 MeV)

Compton scattered γ-rays, neutron inelastic collisions

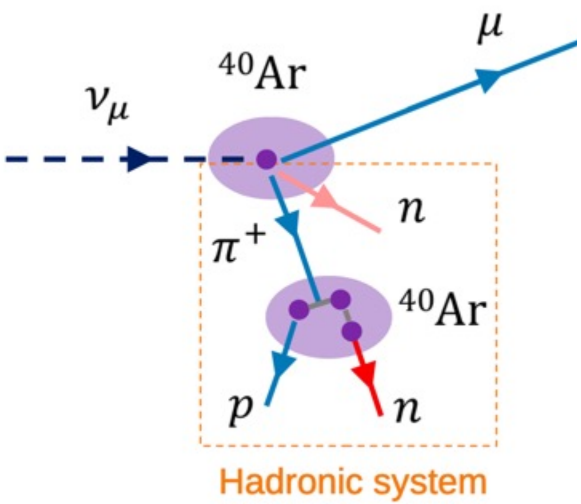
Primary energy scales for accelerator ν's

SBN neutrino signals
~100s of MeV to ~10 GeV

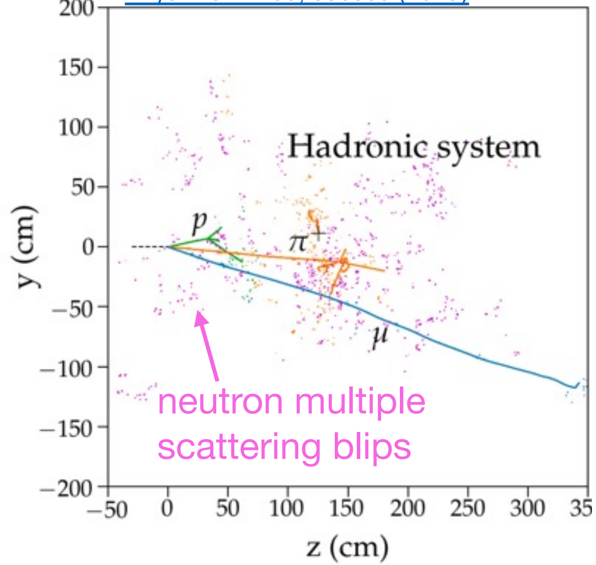


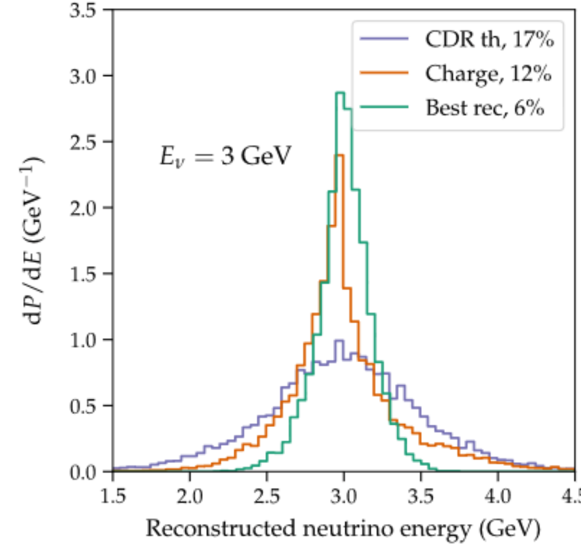


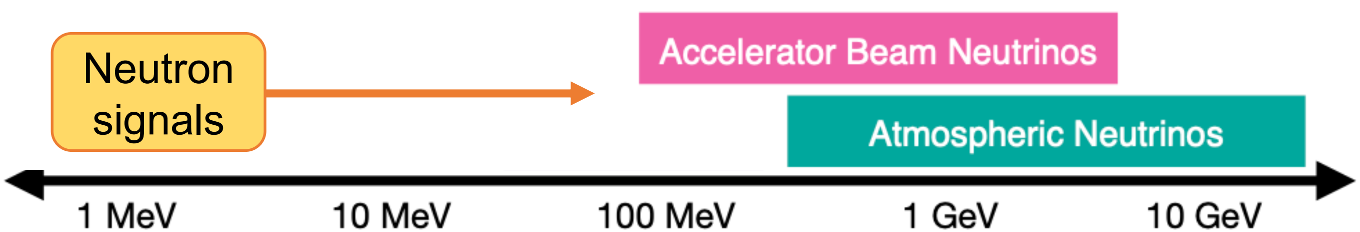
Neutron detection in GeV-scale ν events



Phys. Rev. D 99, 036009 (2019)



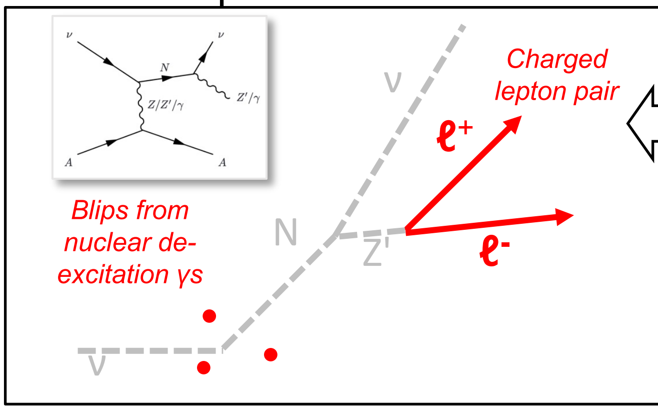




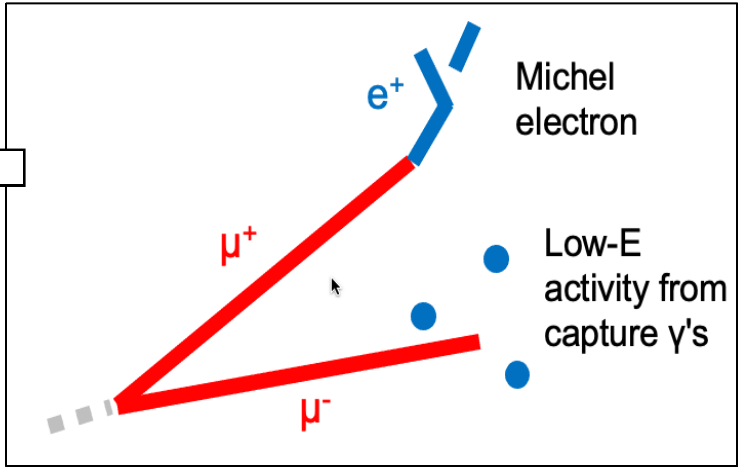
Energy of Signals

Particle discrimination for BSM searches

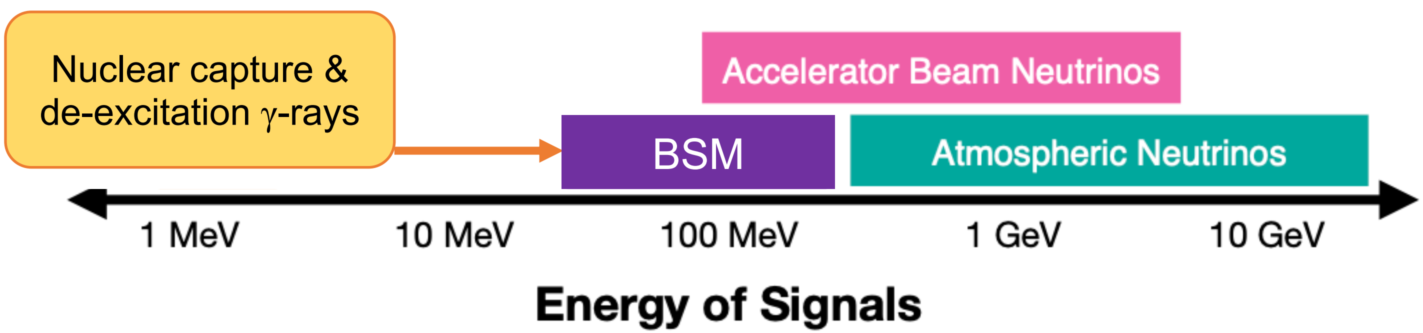
Up-scattered dark ν



Charge & π/μ discrimination



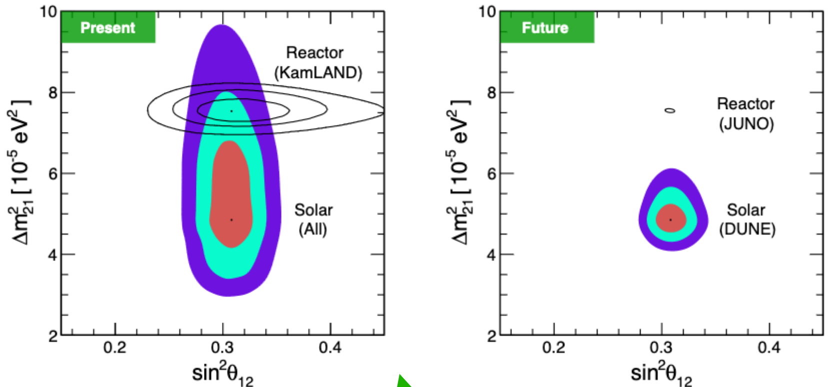
Benefits of MeV-scale reconstruction capabilities in large liquid argon time projection chambers
[Phys.Rev.D 102 9, 092010 (2020)]



Astrophysical neutrinos (not SBN, but still cool)

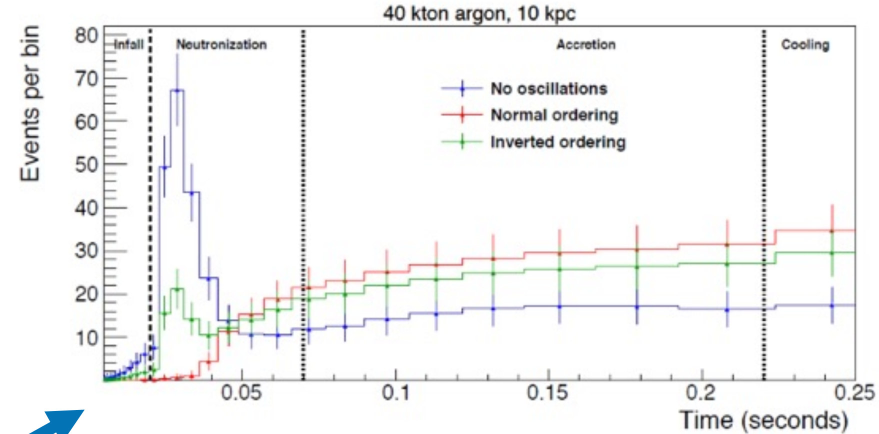
θ_{12}, Δm_{12}^2, and solar neutrino fluxes

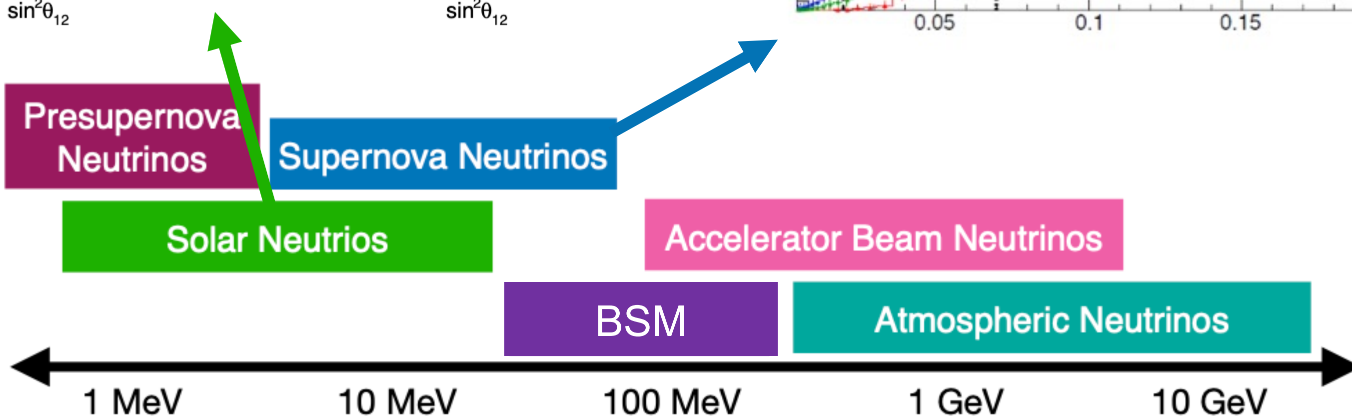
Phys. Rev. Lett. 123, 131803



Mass ordering determination

2020 J. Phys: Conf Ser 1342

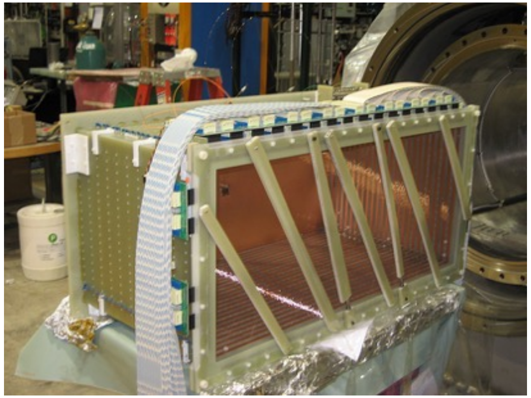


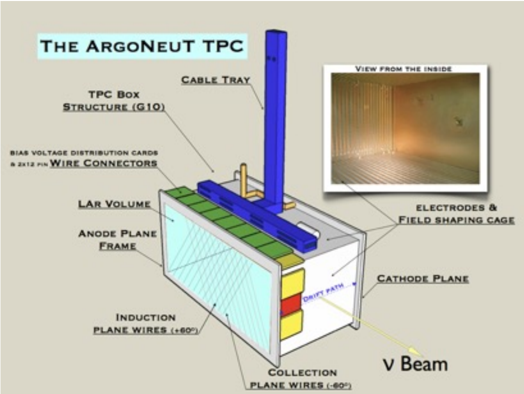


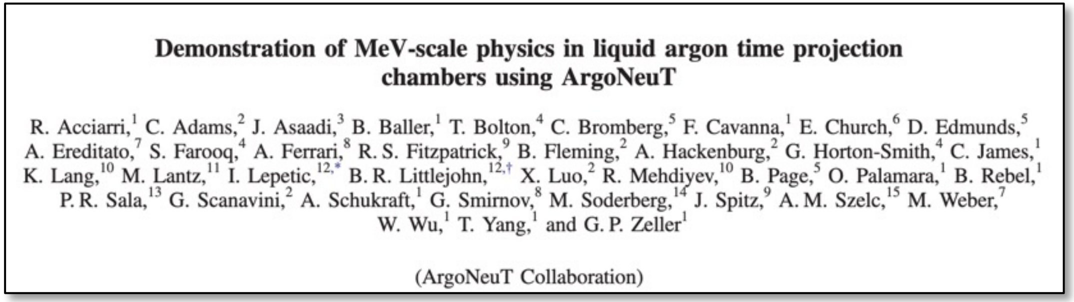
Energy of Signals

Demonstrations in ArgoNeuT

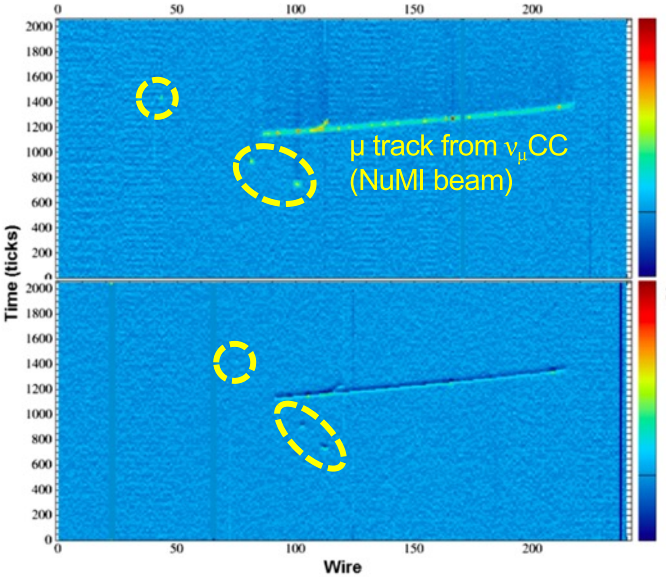
ArgoNeuT

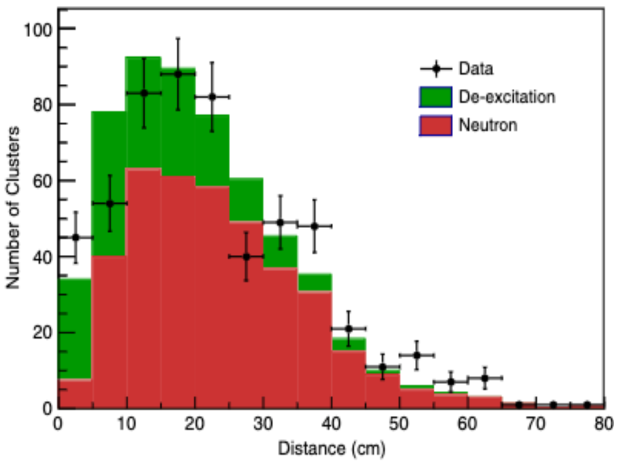






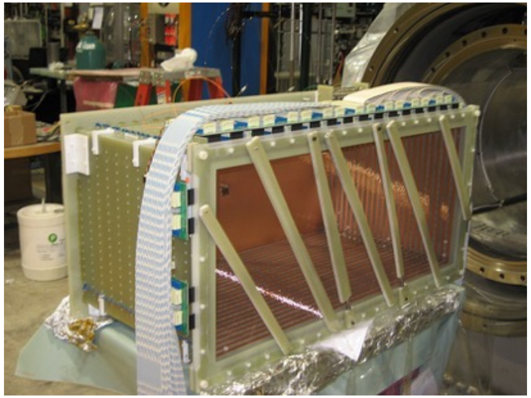
Phys. Rev. D 99, 012002 (2019)

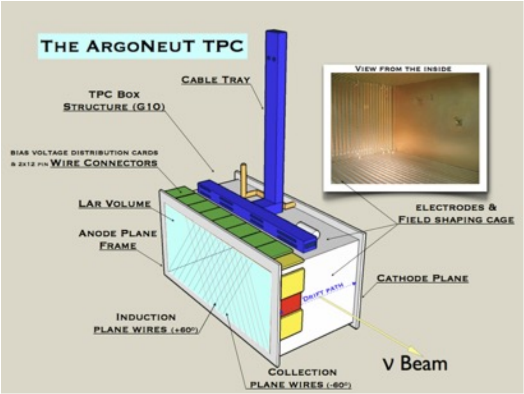




Demonstrations in ArgoNeuT

ArgoNeuT



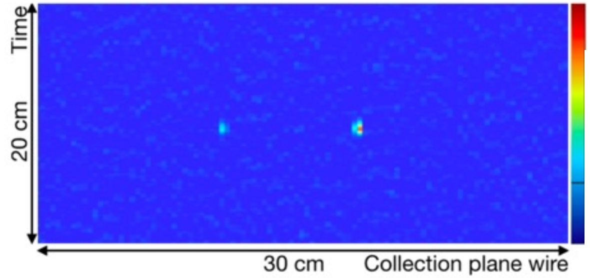


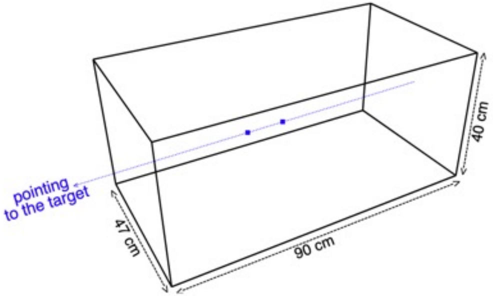
Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab

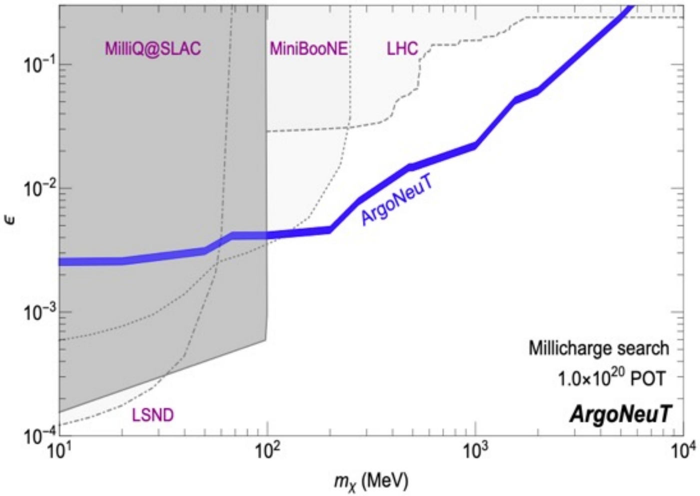
R. Acciarri,[1] C. Adams,[2] J. Asaadi,[3] B. Baller,[1] T. Bolton,[4] C. Bromberg,[5] F. Cavanna,[1] D. Edmunds,[5] R. S. Fitzpatrick,[6] B. Fleming,[7] R. Harnik,[1] C. James,[1] I. Lepetic,[8,*] B. R. Littlejohn,[8] Z. Liu,[9] X. Luo,[10] O. Palamara,[1,†] G. Scanavini,[7] M. Soderberg,[11] J. Spitz,[6] A. M. Szelc,[12] W. Wu,[1] and T. Yang[1]

(ArgoNeuT Collaboration)

[Phys Rev Lett. 124, 131801 (2020)]







Demonstrations in ArgoNeuT

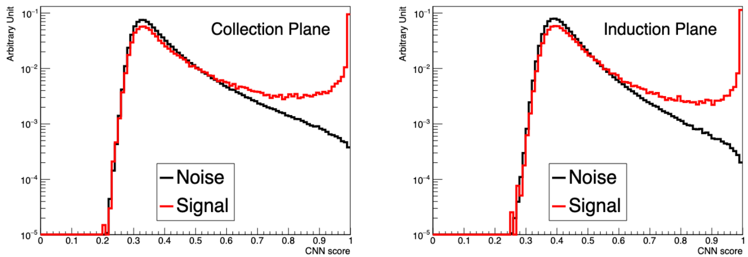
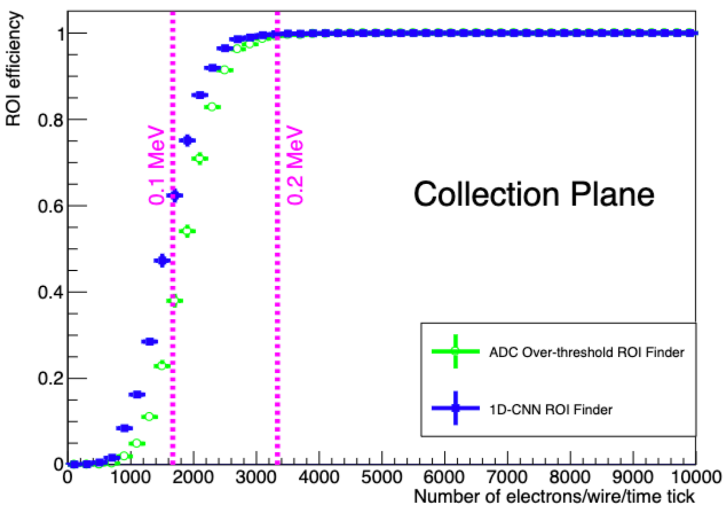


Figure 7. 1D-CNN scores for simulated noise and signal wavefoms in the induction plane (right) and the collection plane (left).



CNN-based wire ROI finder

[JINST 17 (2022) P01018]

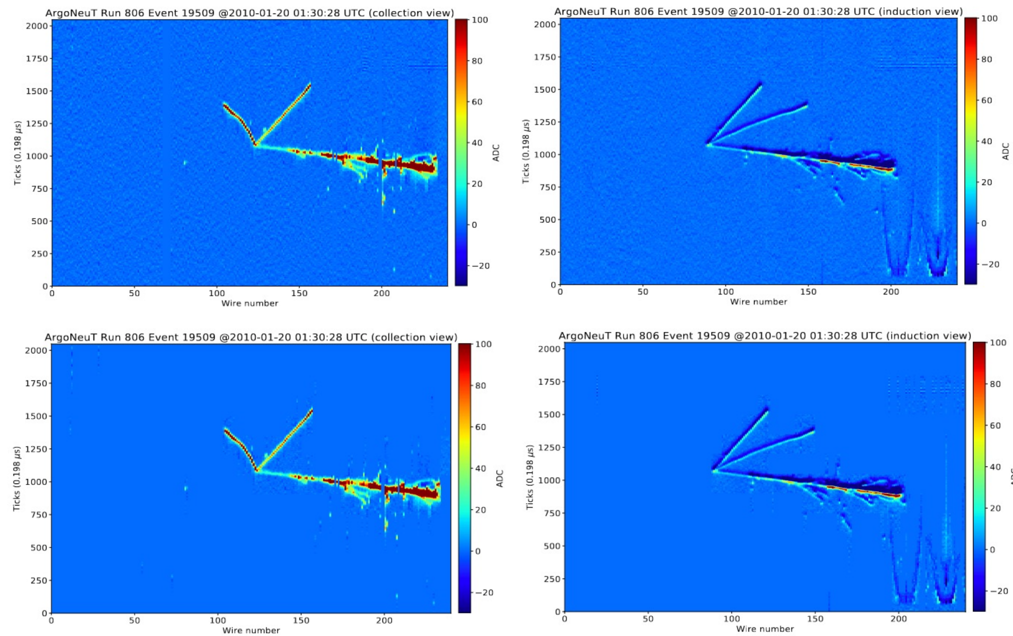


Figure 8. Event display after applying the 1D-CNN ROI finder for the event shown in Figure 1 and Figure 2.

Remaining Challenges

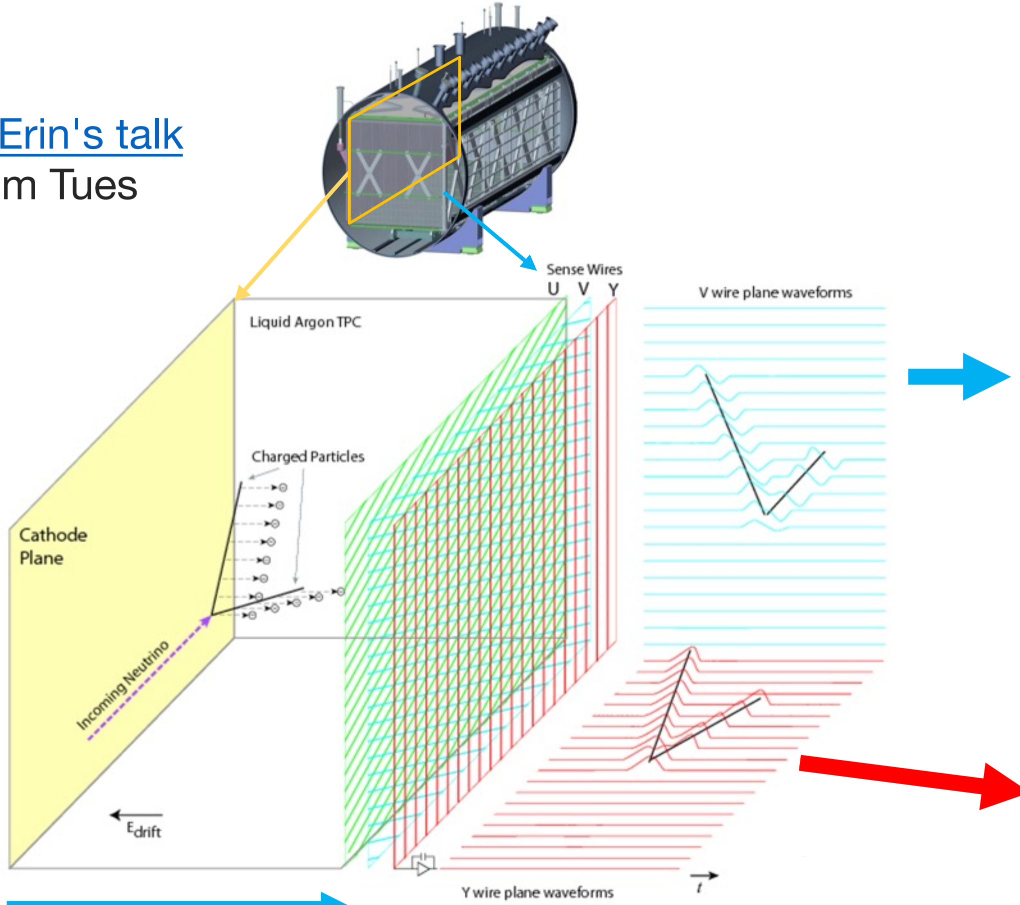
- Successful demonstrations in a small LArTPC... but can we do the same in large ones?
  - Lowering thresholds
  - Precise energy reconstruction
  - Controlling low-energy backgrounds

Critical for maximizing SBN's and DUNE's physics potential

Recent results from MicroBooNE address all three!

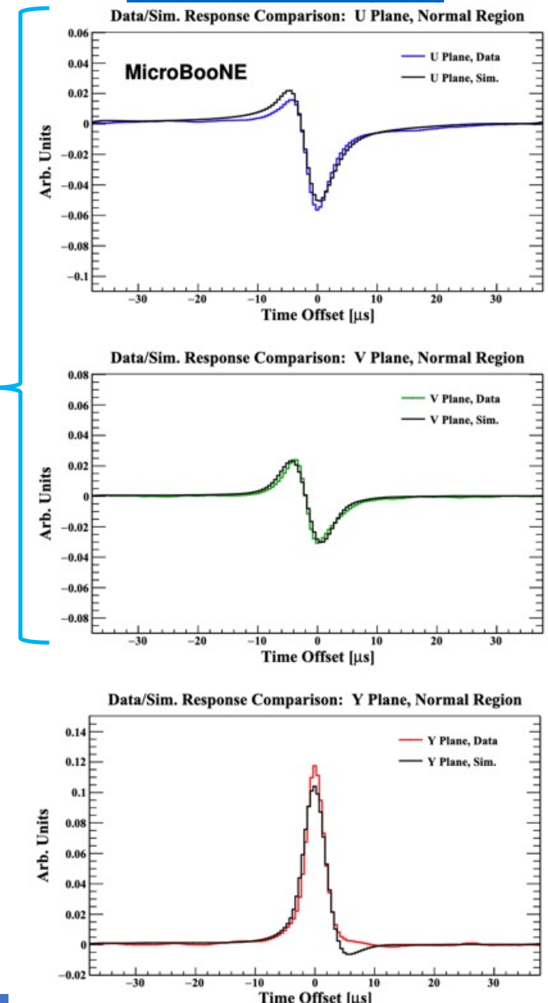
Signal readout and processing

SEE Erin's talk
from Tues



Drift ~ 2.3 ms

JINST 13 P07007 (2018)



Signal readout and processing

Raw wire signals

↓

WireCell toolkit

Filtered signal ROIs

↓

GausHitFinder

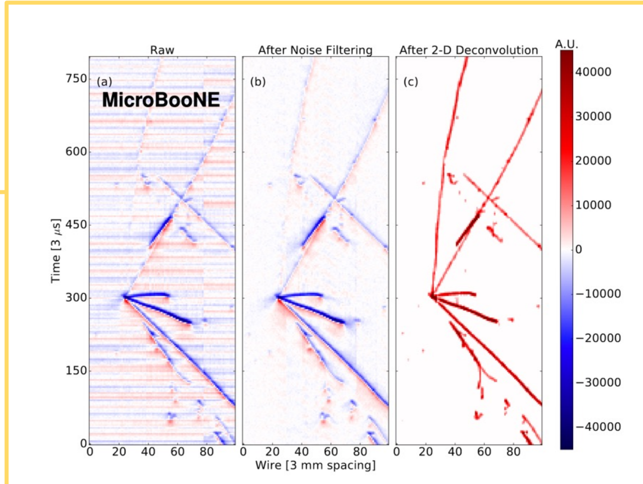
Hits (recob::Hit)

↓

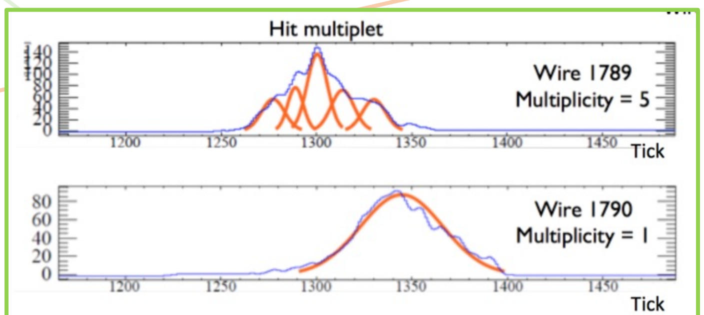
***Pandora 3D* track reconstruction**

Tracks (recob::Tracks)

↓

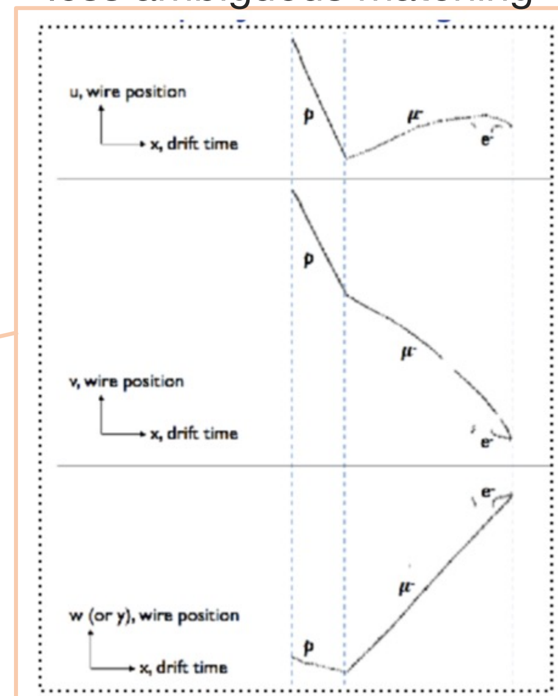


JINST 13 P07007 (2018)

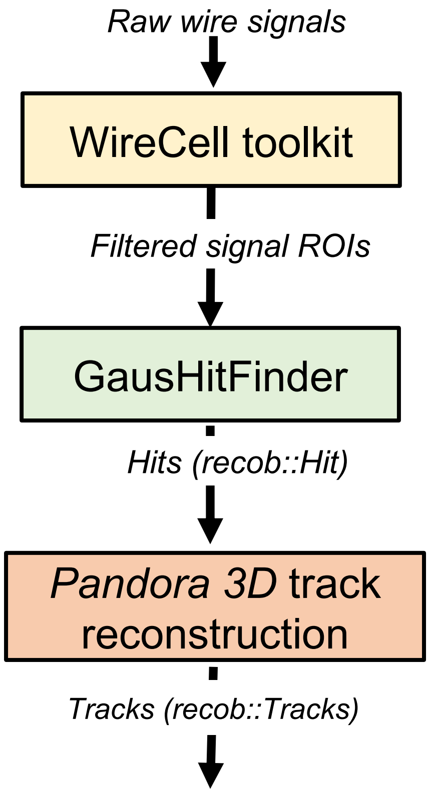


JINST 12 P07010 (2017)

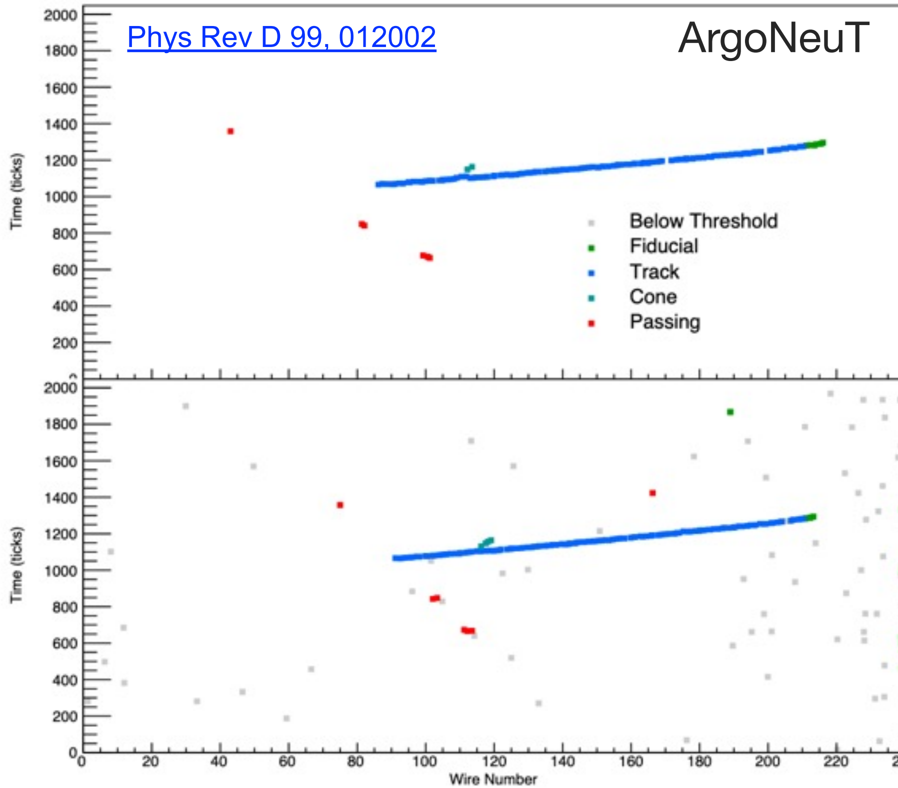
Long/extended patterns = less ambiguous matching



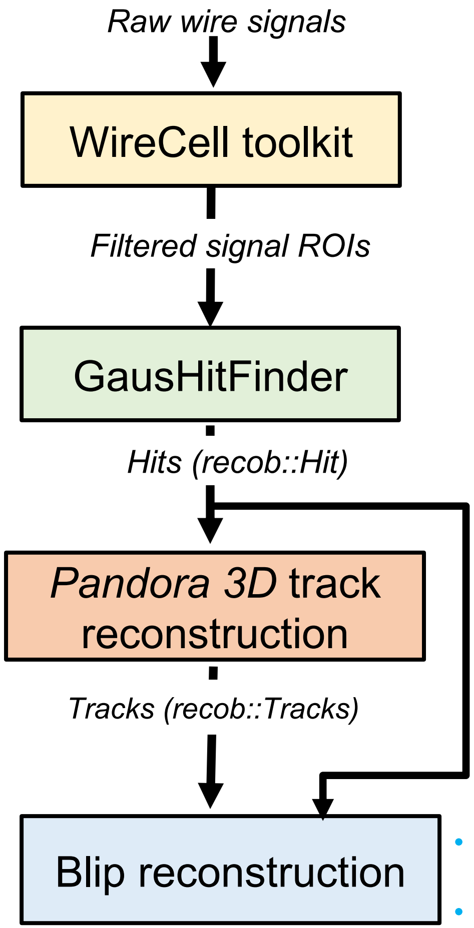
Signal readout and processing



For blips, avoiding false matches becomes a challenge



Signal readout and processing



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

[MICROBOONE-NOTE-1076-PUB (2020)]

MeV-scale Physics in MicroBooNE

MICROBOONE-NOTE 1076-PUB

The MicroBooNE Collaboration

[MICROBOONE-NOTE-1050-PUB (2018)]

Study of Reconstructed ^{39}Ar Beta Decays at the MicroBooNE Detector

The MicroBooNE Collaboration*

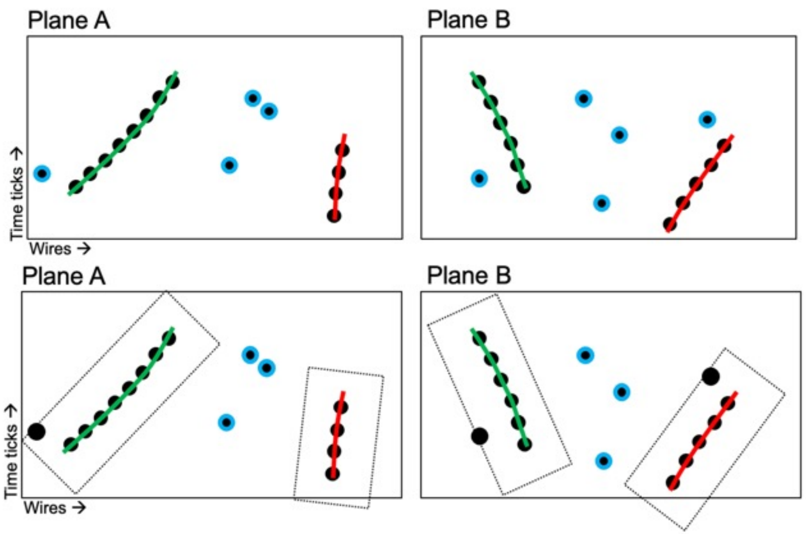
Blip Reconstruction

– Techniques pioneered in ArgoNeuT have been further developed in MicroBooNE

– Dedicated algorithm class has since been written encompassing these tools → *flexible integration into other reco & analysis workflows*
  - *Millicharged particle searches*
  - *ν NC1p selection background mitigation*
  - *Neutron tagging*
  - *Radiogenic calibrations*

Blip reconstruction in a nut-shell

1. **Isolated hits identification**
   Hits *within* tracks > configurable length are vetoed; optional 2D masking in regions surrounding long tracks

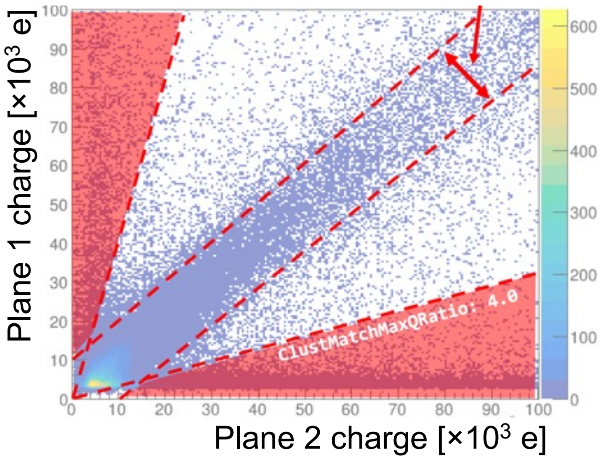


2. **Hit clustering per plane**
   Hit width ('RMS') defines proximity threshold for clustering in wire-time space

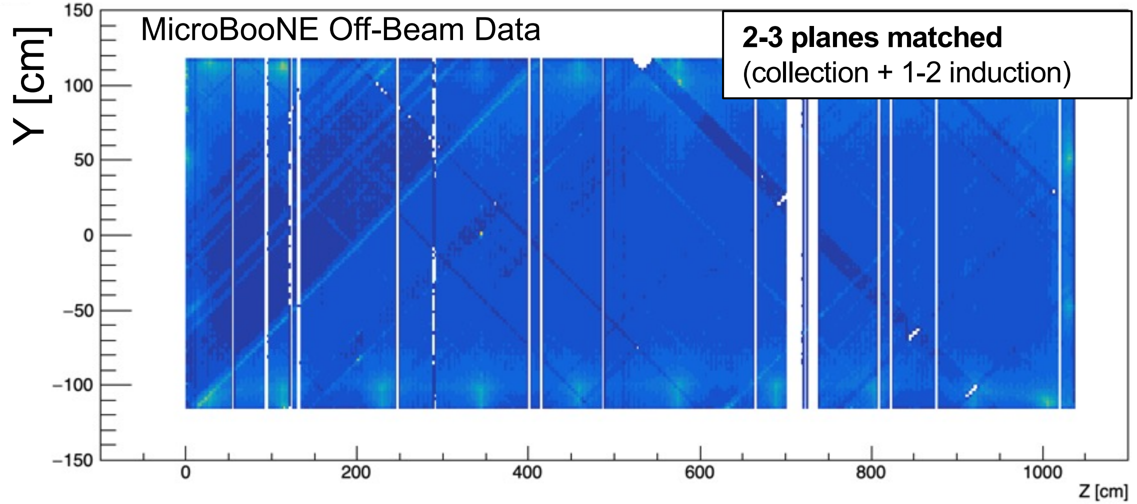
3. **Cluster plane-matching**

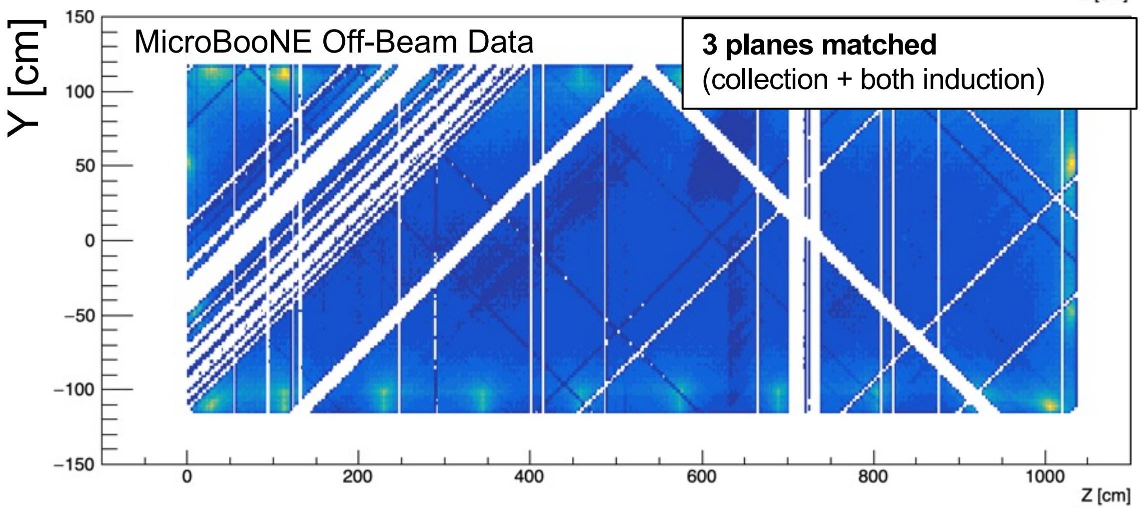
4. **Crossing-wire requirement**

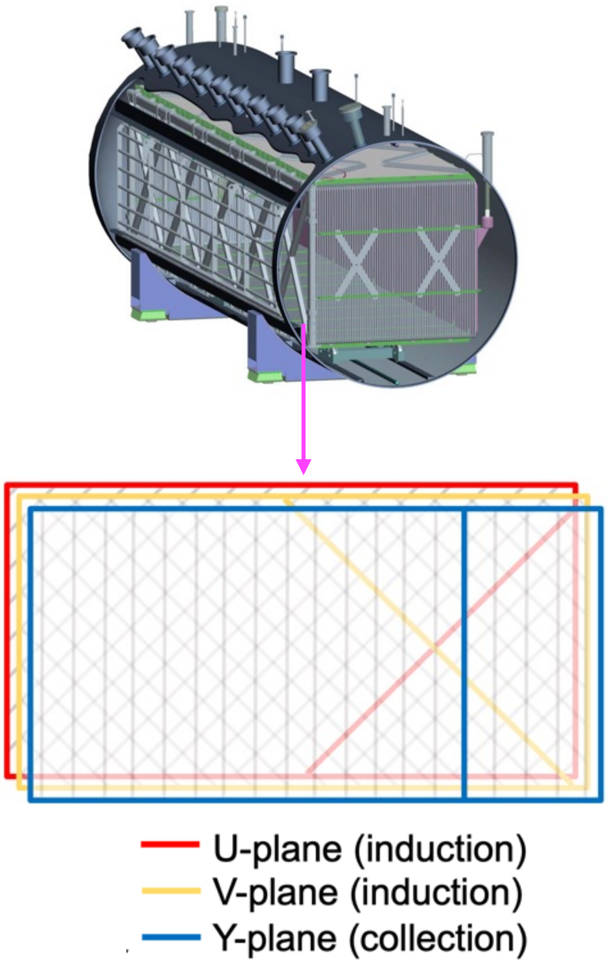
5. **Relative charge comparison**



Ambient blips in MicroBooNE data

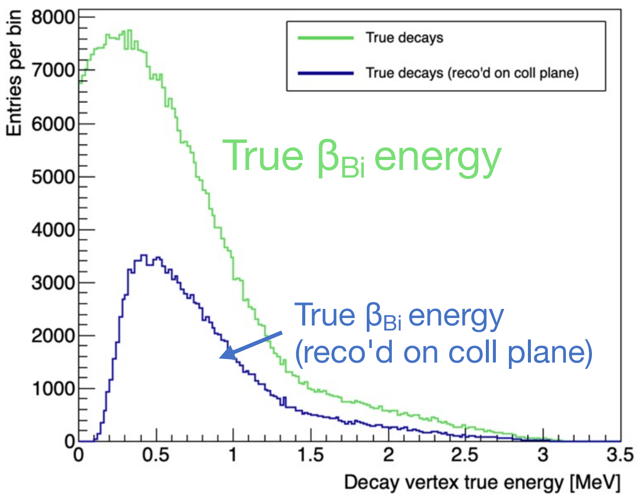


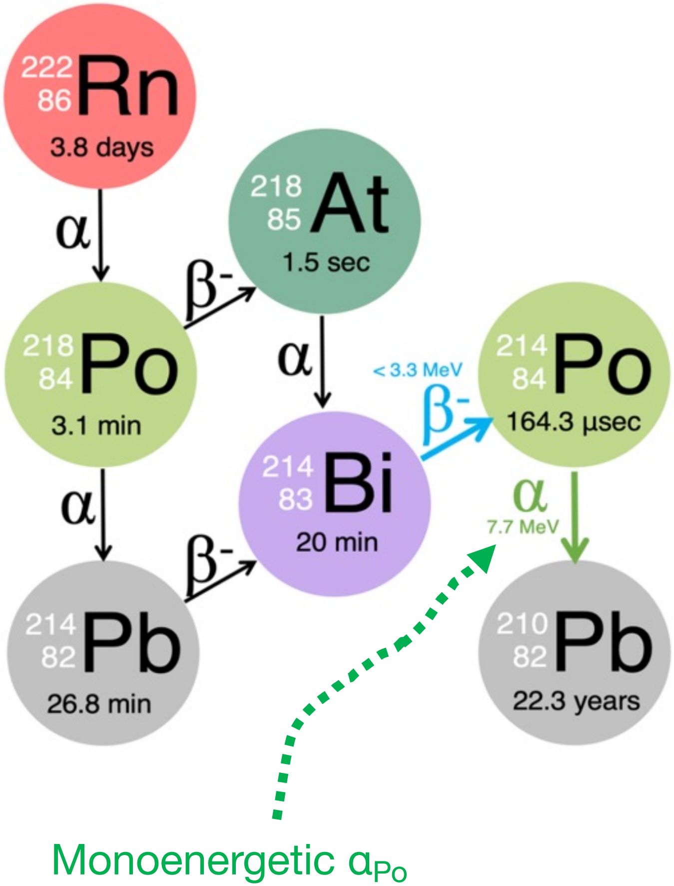




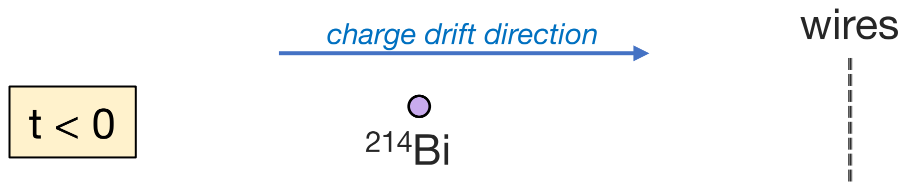
Radon studies in MicroBooNE

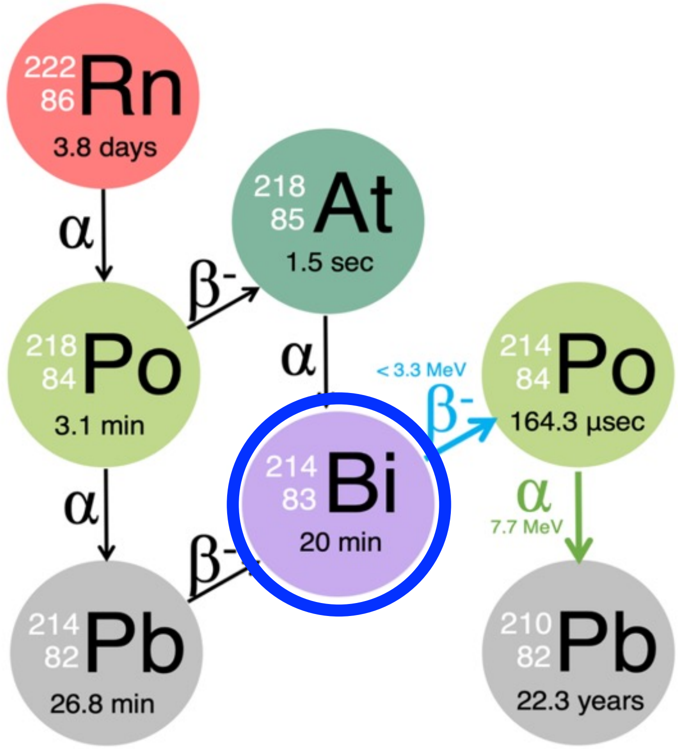
- During its **2021 R&D run**, MicroBooNE explored radon's calibration potential by doping Rn into the active volume of LAr
  - **^{222}Rn has a 3.8 day half-life** → *mixes throughout active volume*
  - **^{214}Po has a short 164 μs half-life** → can tag the associated ^{214}Bi β



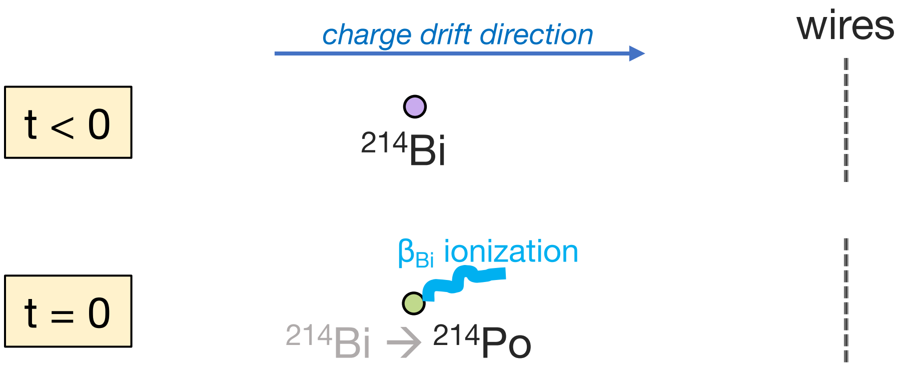


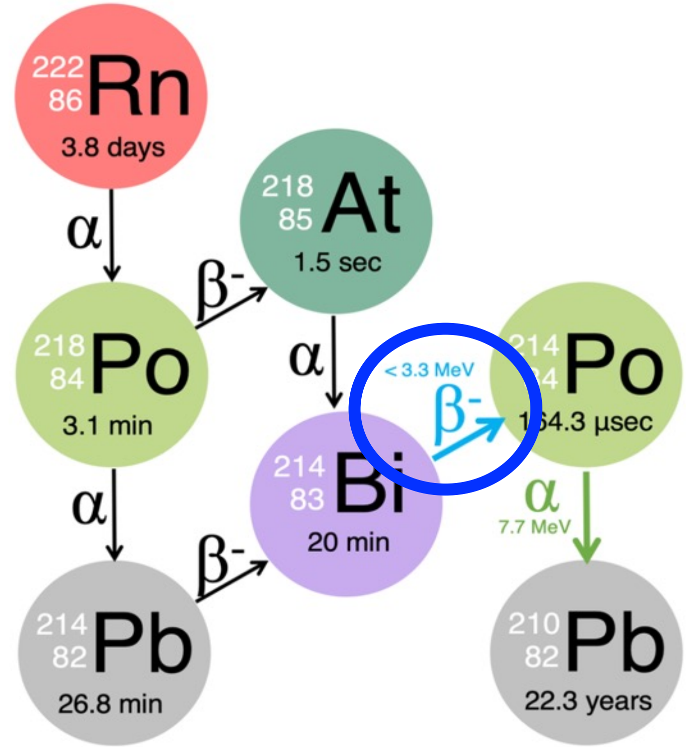
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



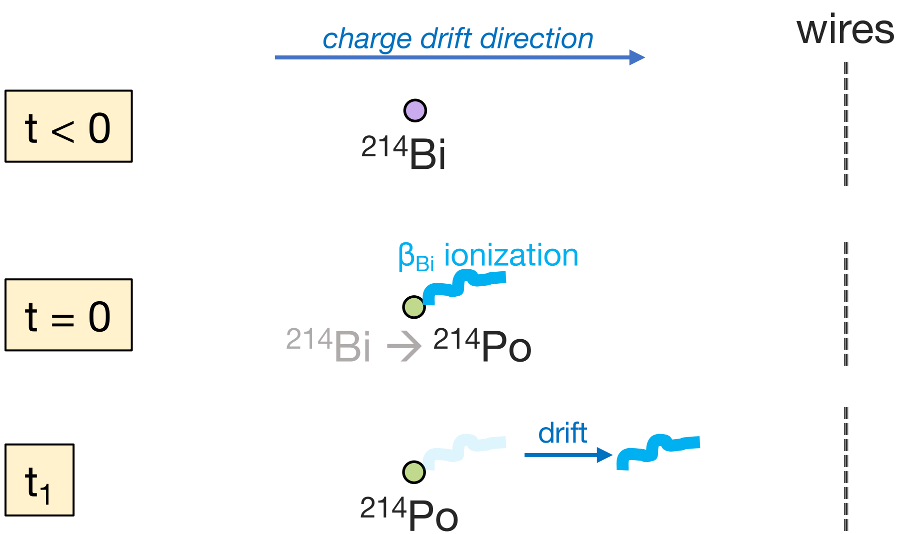


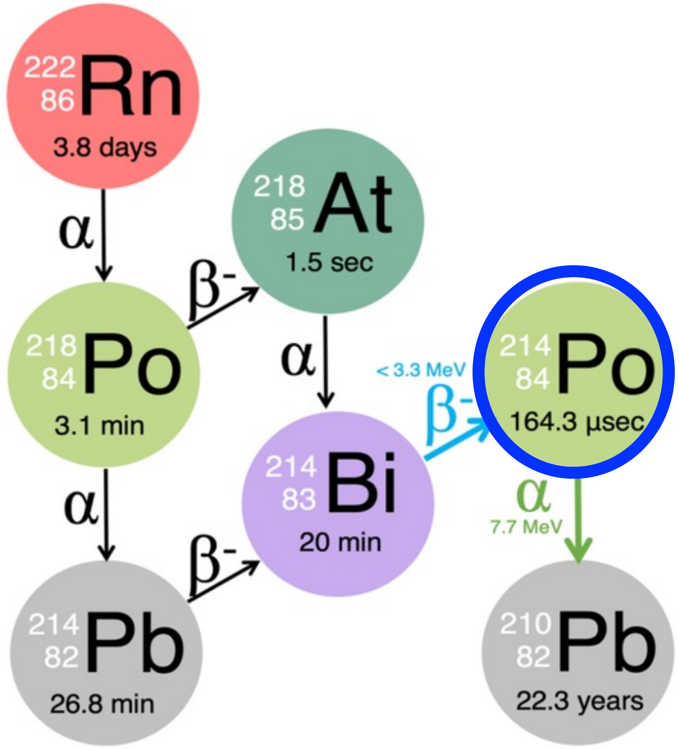
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



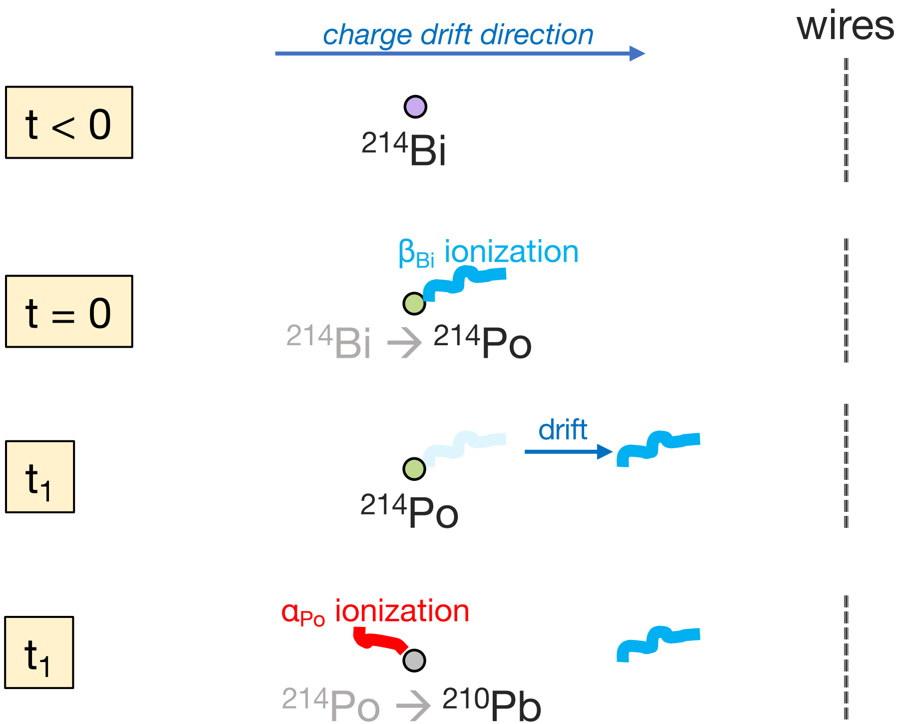


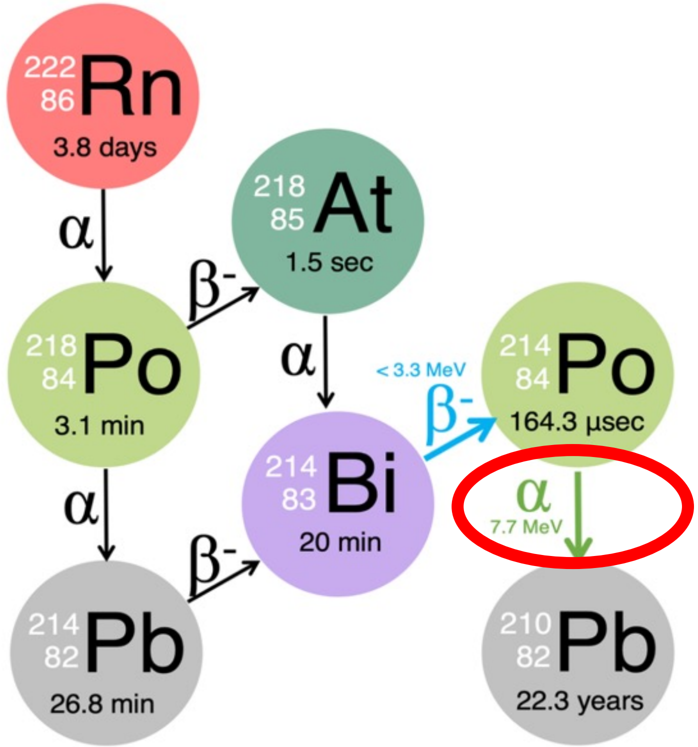
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



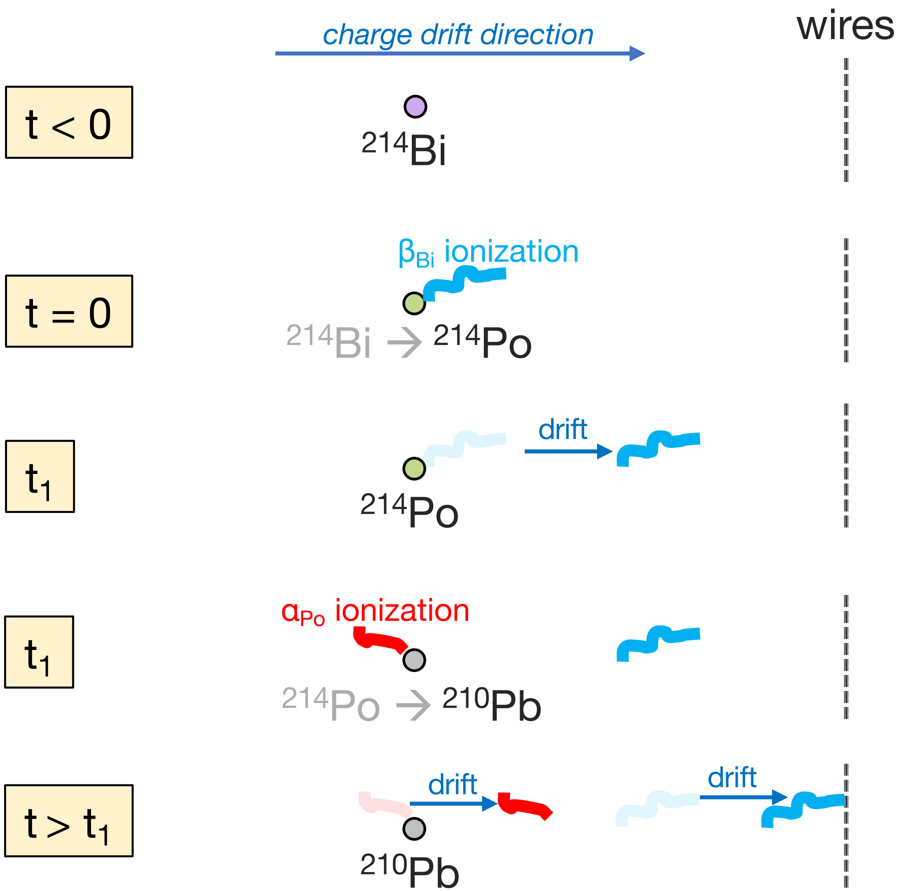


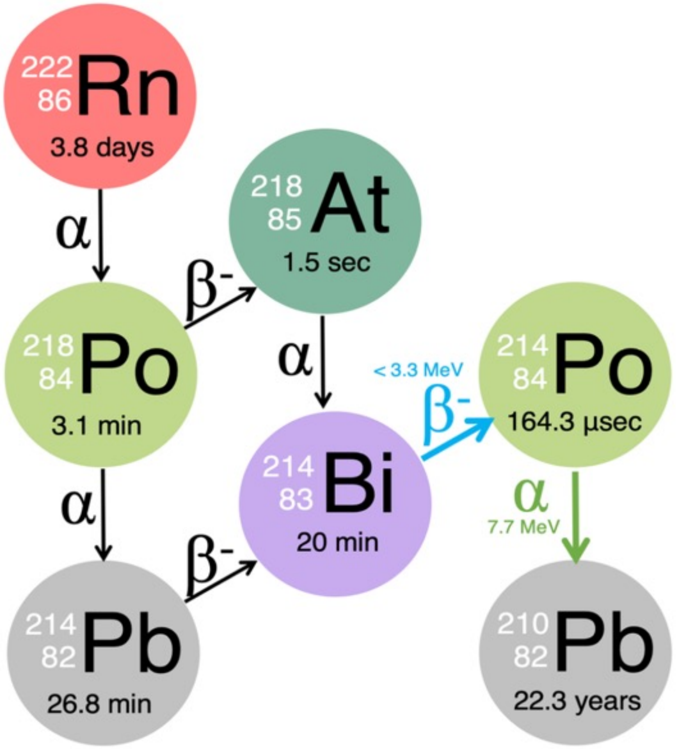
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



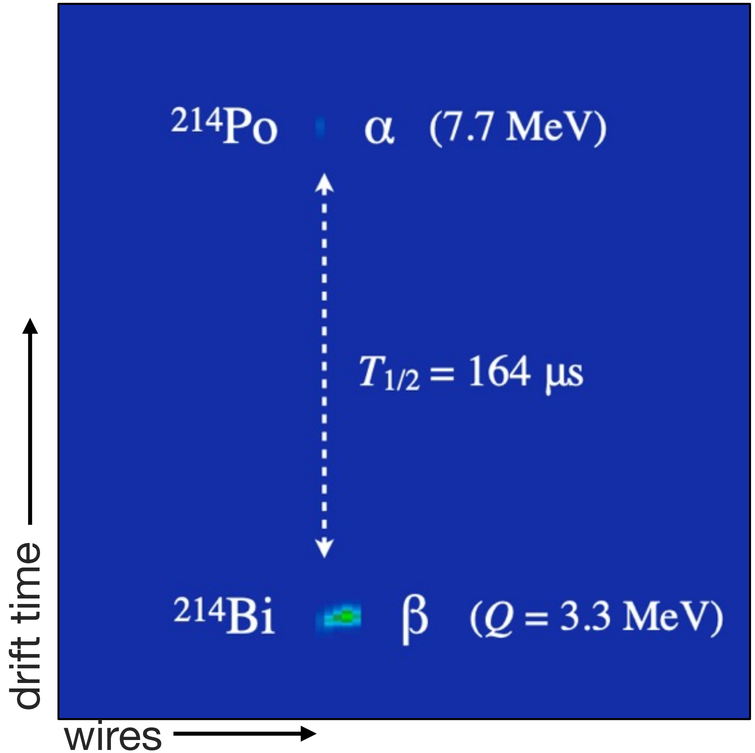


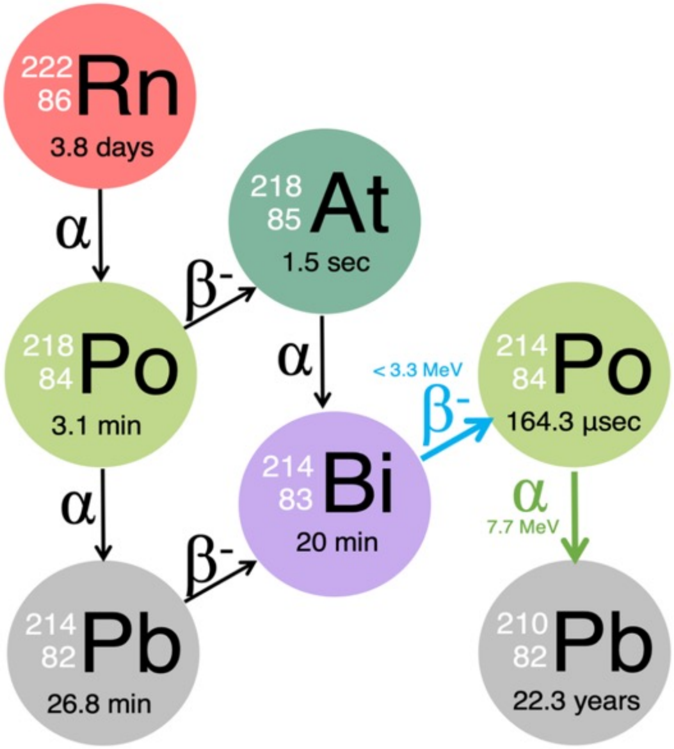
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging





^{214}Bi → ^{214}Po Decay Tagging





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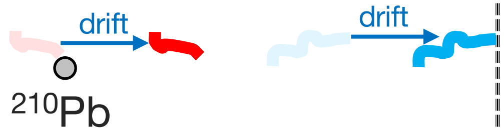
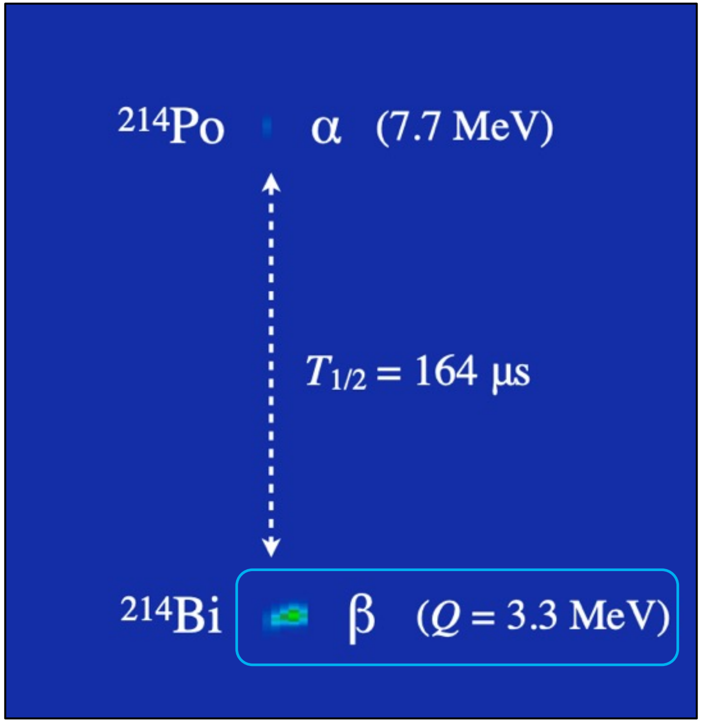


$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



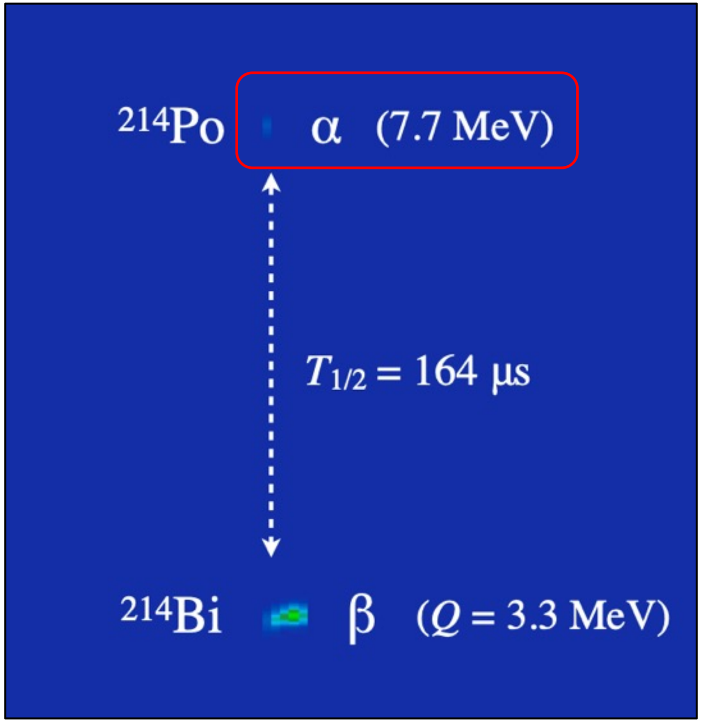
Electron

dE/dx ~ 2 MeV/cm

Mean ~ 15,000 e^-

up to ~80,000 e^-

$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



Heavily ionizing alpha

dE/dx ~ O(100) MeV/cm

Extreme "charge quenching"

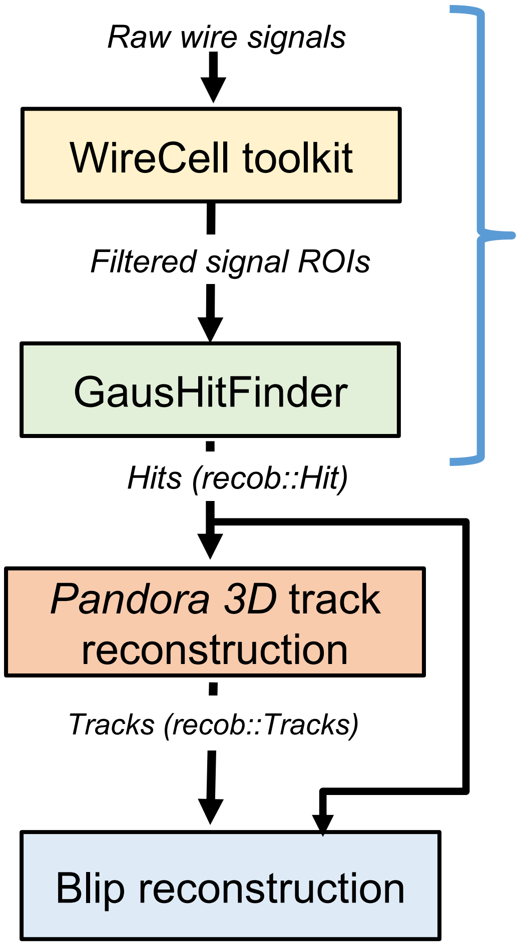
(e^- -Ar^+ recombination + collisional effects)

→ *Signal is fainter, < ~4000 e^-*

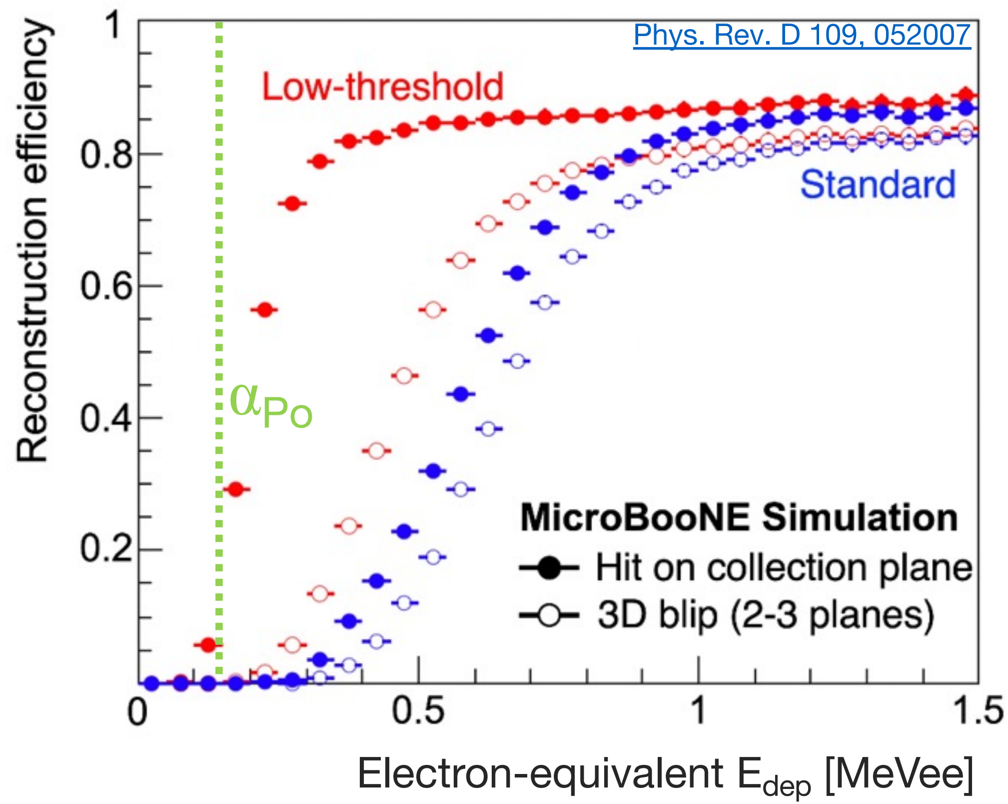
7.7 MeV α deposits only as much charge as a ***~150-200 keV electron!***

('Electron-equivalent energy' = MeVee, KeVee)

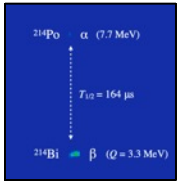
Lowering the energy thresholds

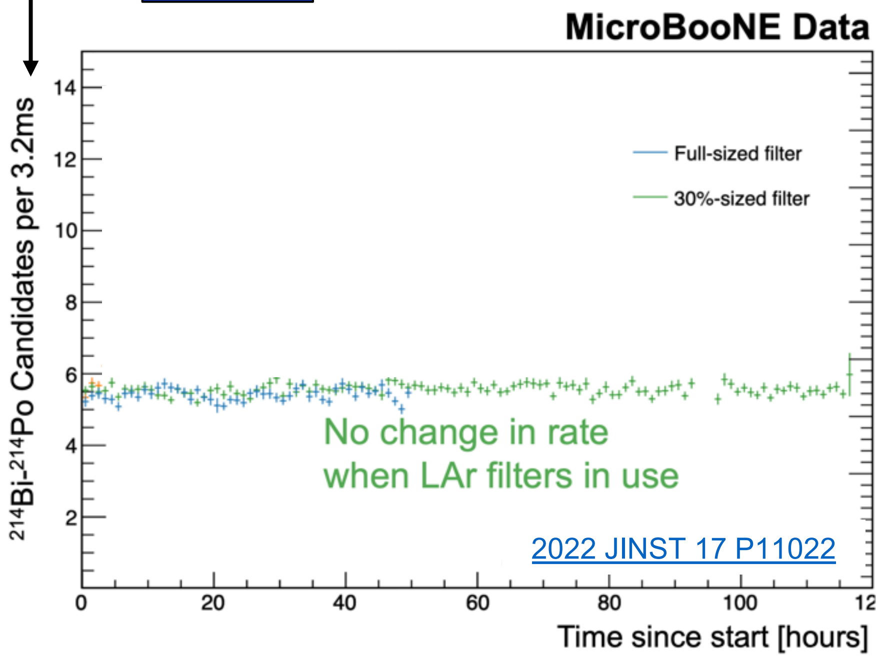


Settings tweaked to achieve lower energy threshold

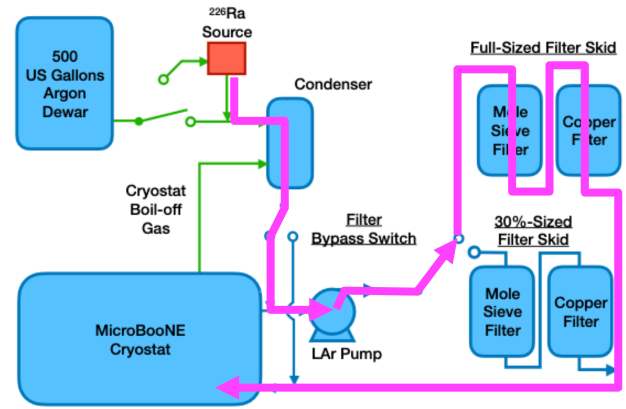


Bi-Po candidate rate in radon-doping data

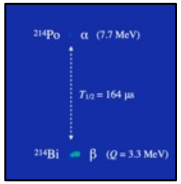
Rate () on collection plane only



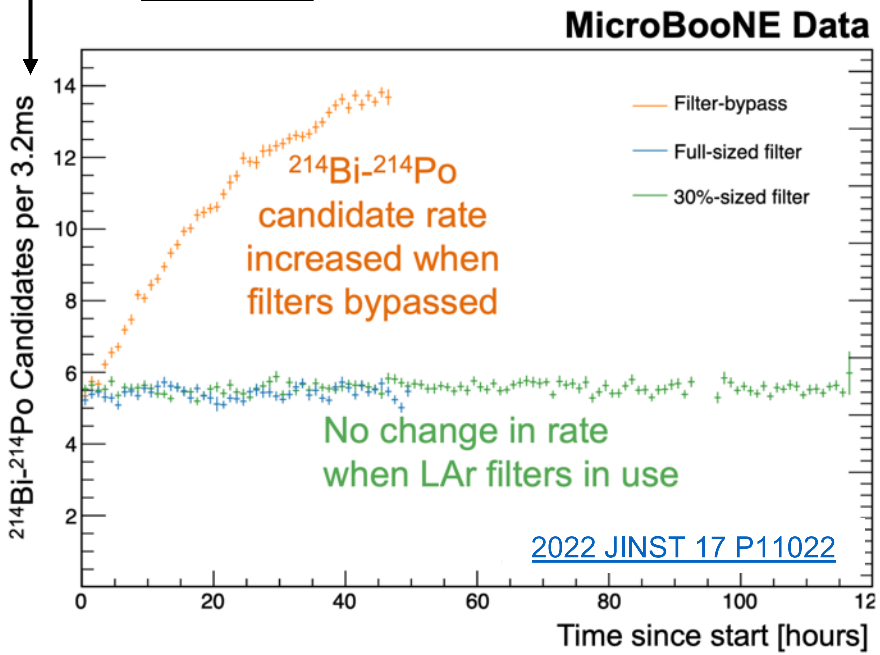
Usual filter configuration



Bi-Po candidate rate in radon-doping data

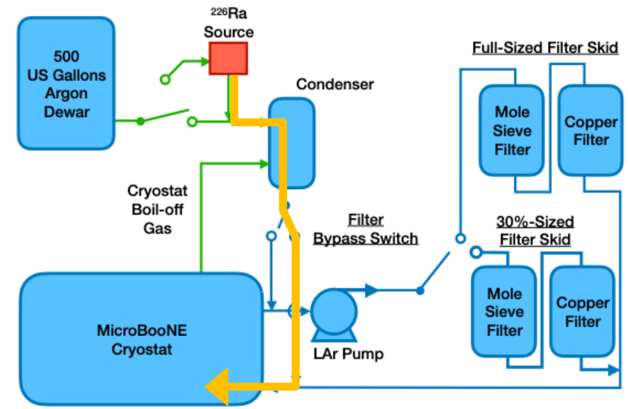
Rate (

) on collection plane only



> 99.9997% of Rn removed by 77L filter

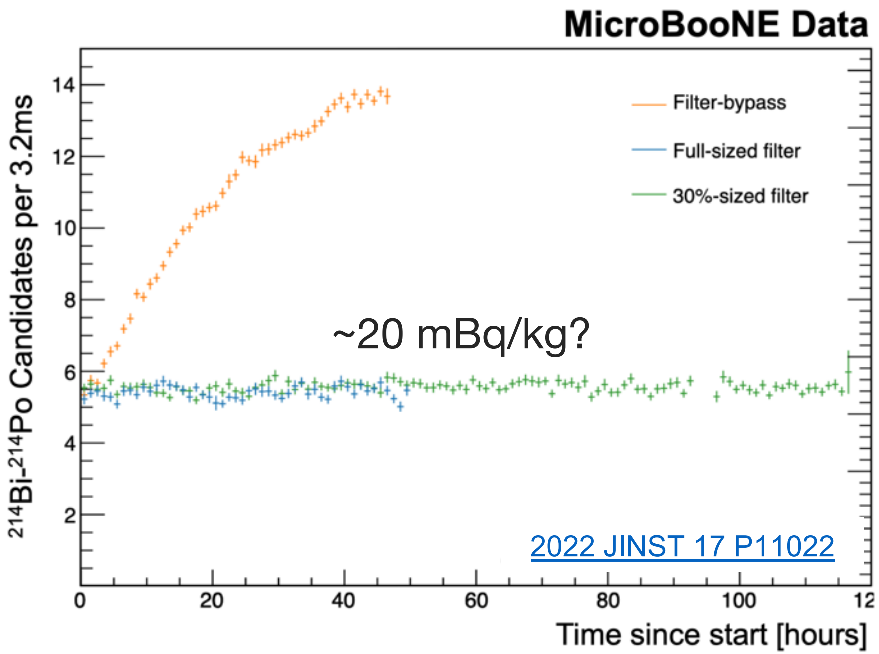
"Filter bypass"



Exciting results:

1. Data-based confirmation of sensitivity at < 1 MeVee
2. Radon backgrounds removed by electronegative filtration

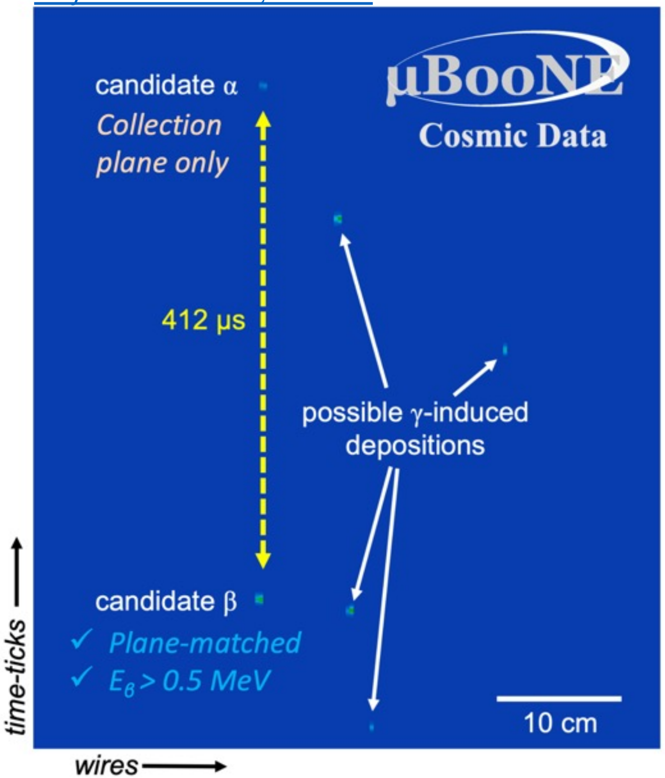
Remaining questions...



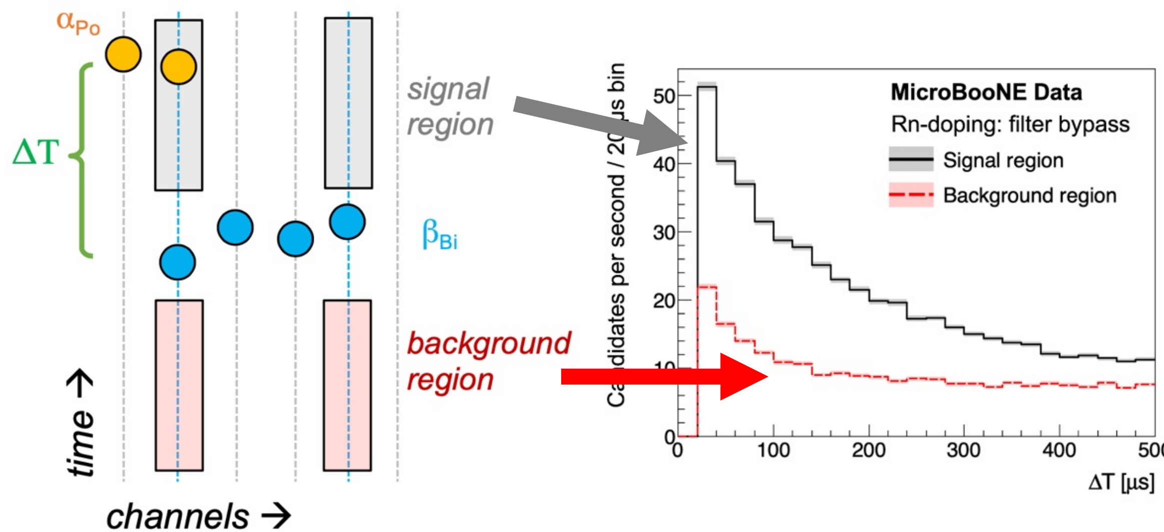
- **What *is* the ambient Rn rate?**
- Background rate from previous study would be equivalent to ~20 mBq/kg
- Higher purity selection is needed to resolve this

Taking a closer look...

Phys. Rev. D 109, 052007

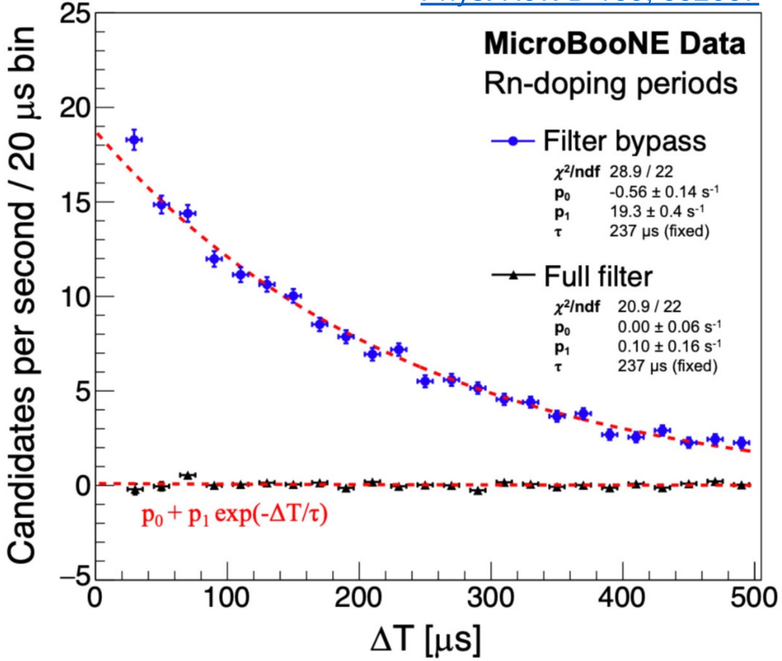


- Follow-up study performed with improved reconstruction and signal selection
- Background determination via side-band

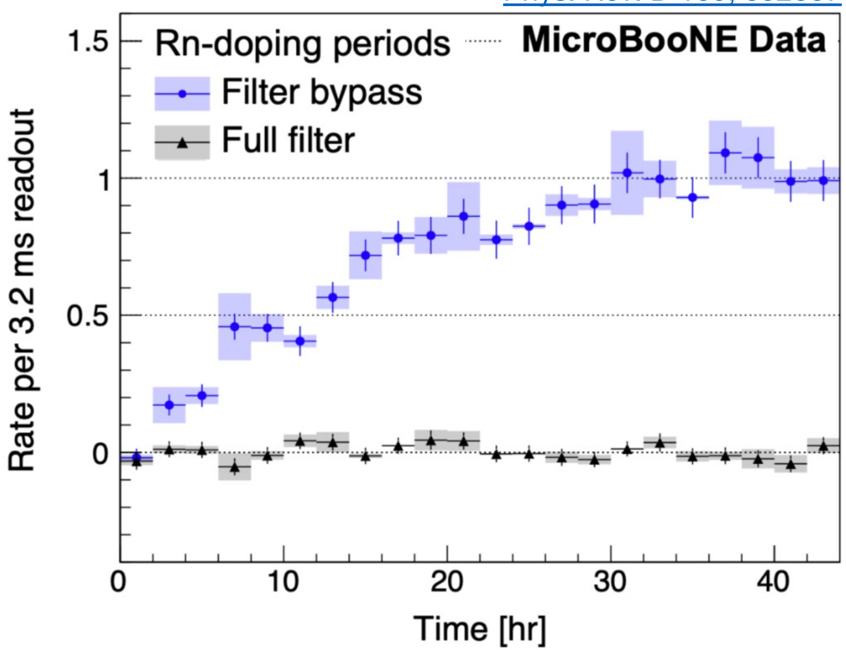


Results on radon-doped data

[Phys. Rev. D 109, 052007](#)

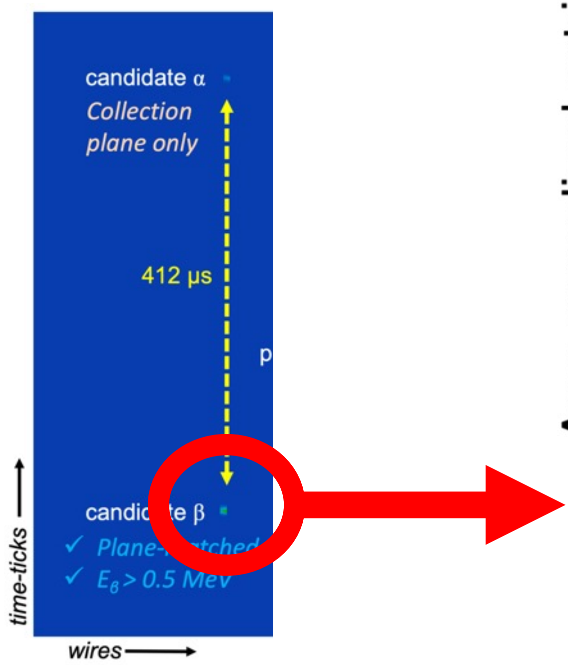


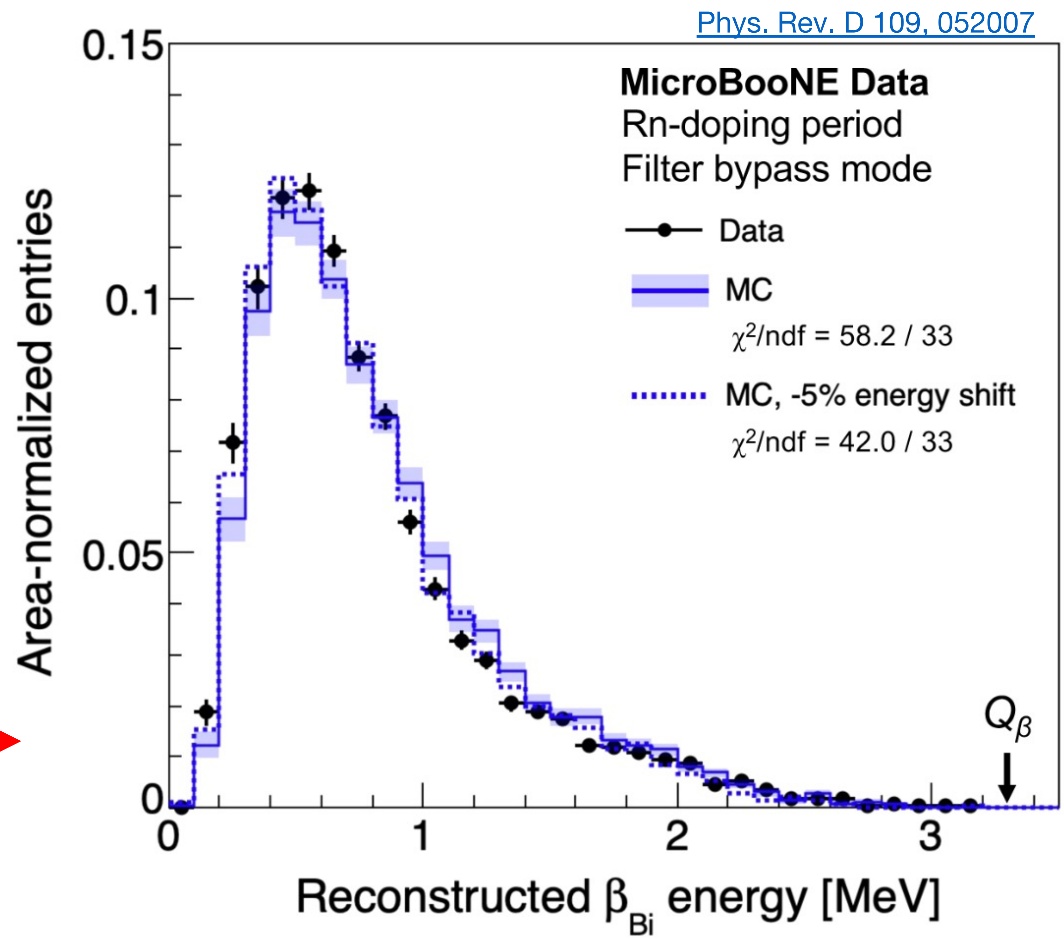
[Phys. Rev. D 109, 052007](#)



Calorimetric validation: 0-3 MeV β_{Bi}

Same BG subtraction applied to β *energy spectrum*

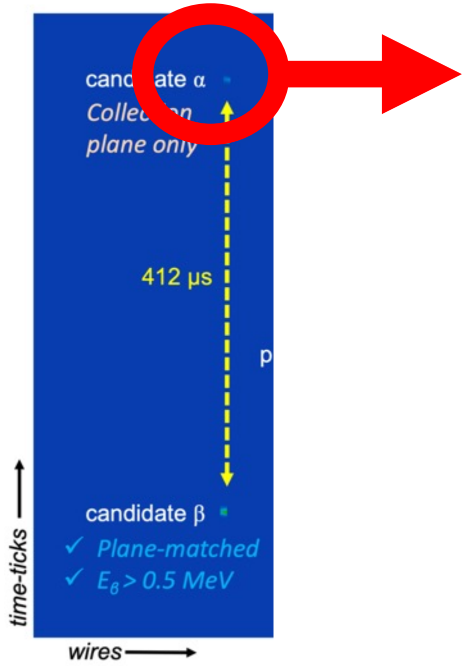




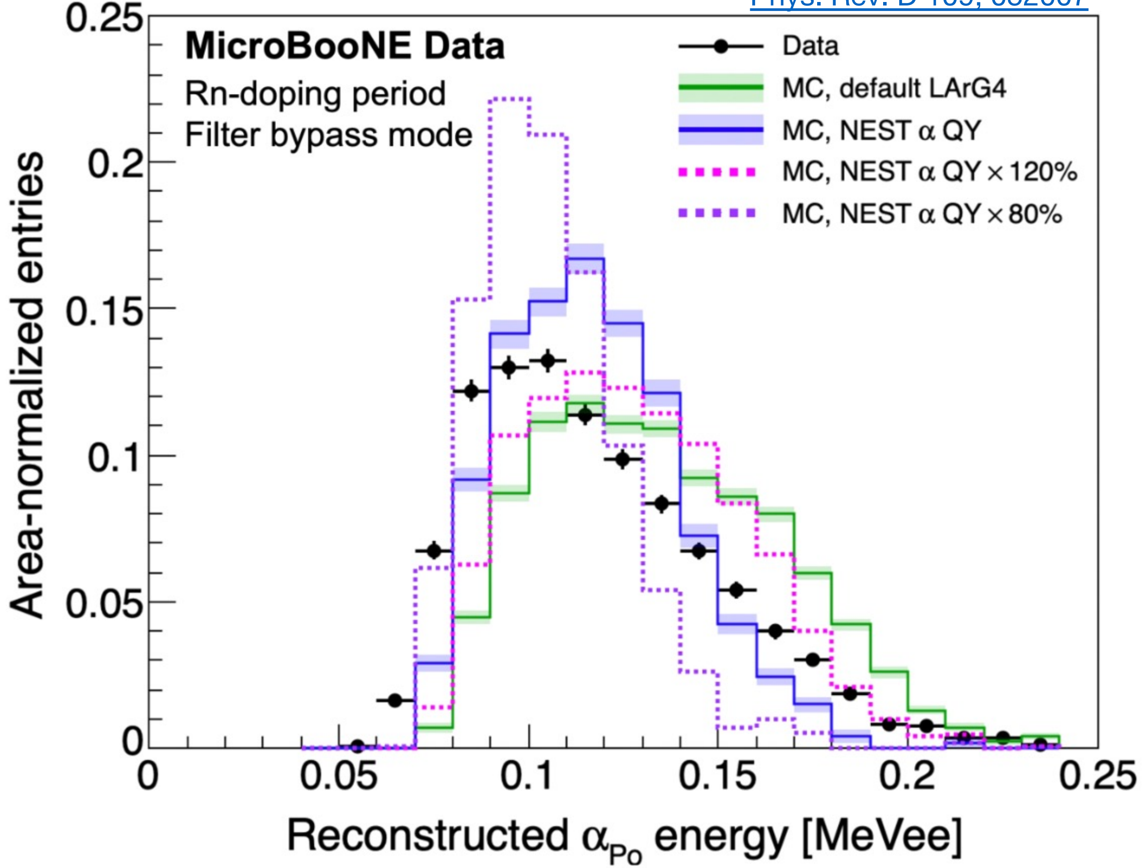
Calorimetric validation: 7.7 MeV α_{Po}

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

(large uncertainties in charge yield/quenching)

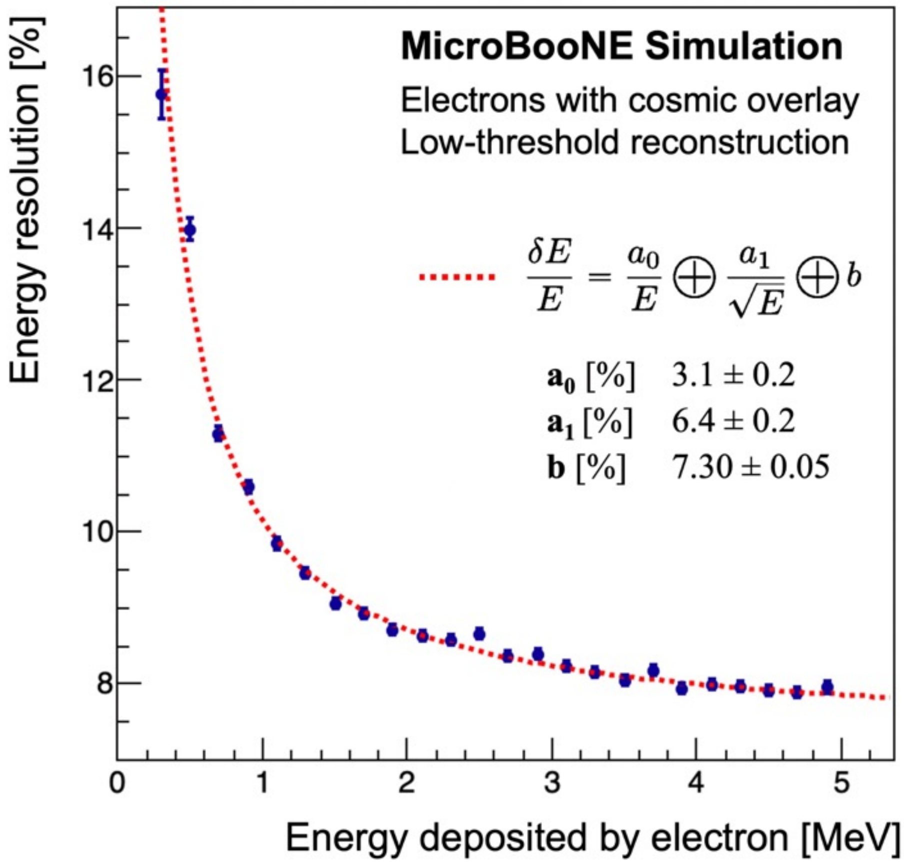


Phys. Rev. D 109, 052007



MC energy resolution

arXiv:2307.03102



MC electron resolution:

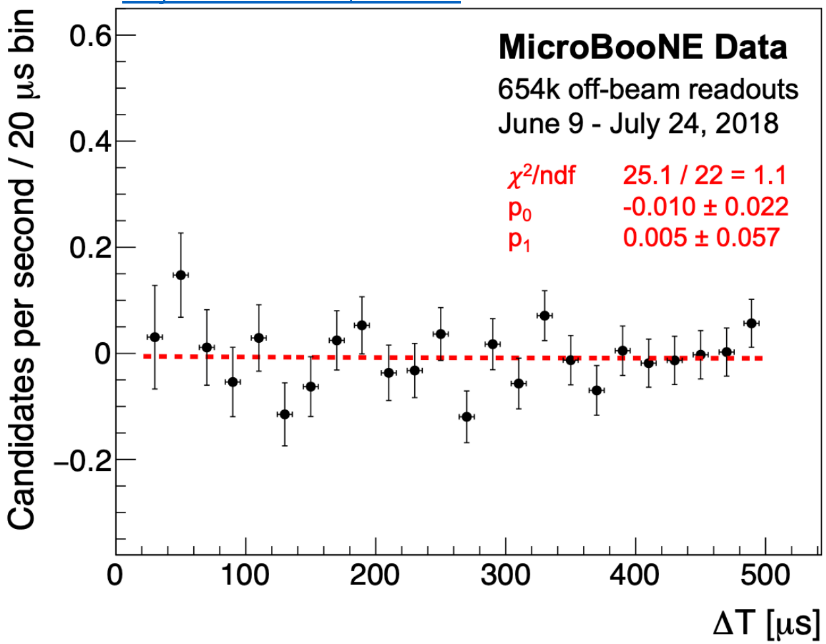
- 10% at 1 MeV
- 8% at 5 MeV

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)

Bi→Po rate in physics data

Phys. Rev. D 109, 052007



n = (0.2 ± 2.3)×10^{-3} decays/readout

R_{Bi} = 0.01 ± 0.16 (stat) ± 0.06 (syst) mBq/kg
= 0.01 ± 0.17 mBq/kg
< 0.35 mBq/kg at 95% CL

Bi→Po rate in physics data

Phys. Rev. D 109, 052007

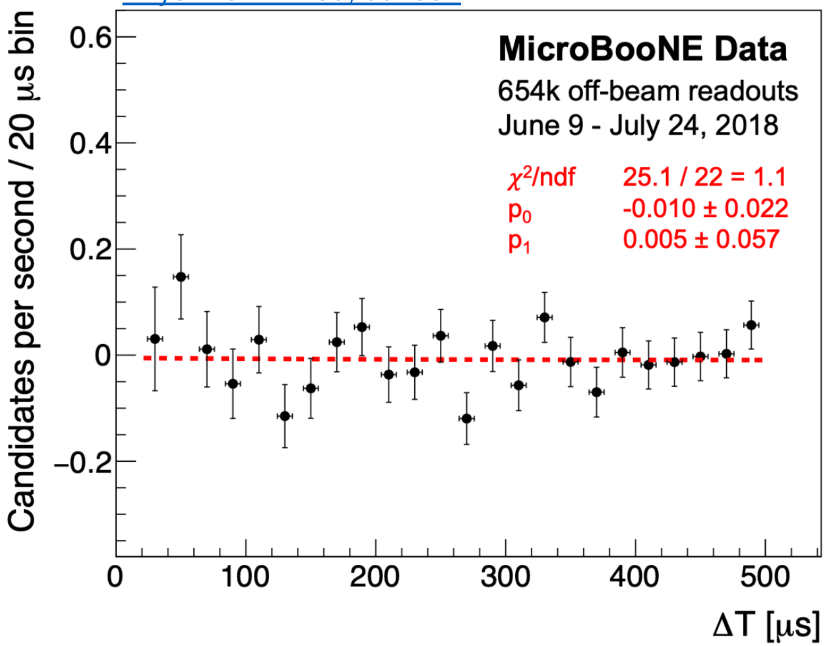
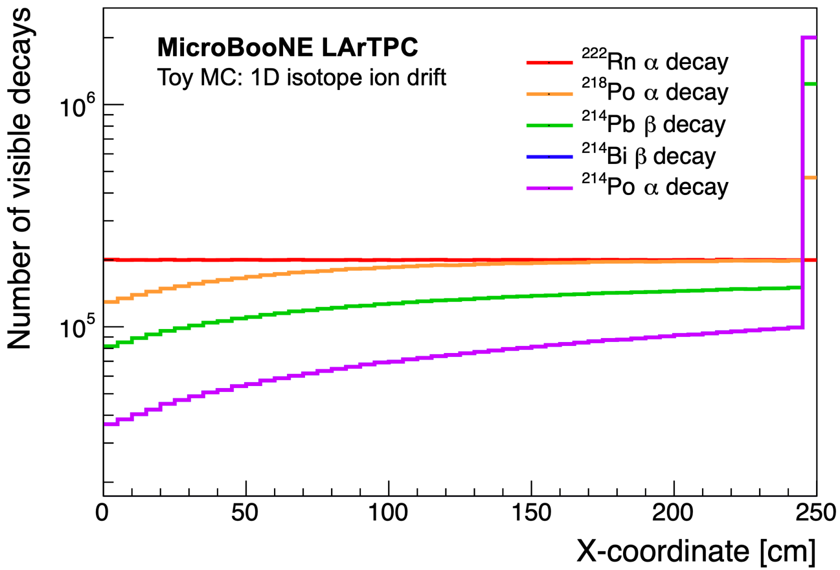


Plate-out effects estimated with toy MC to convert ^{214}Bi rate to ^{222}Rn rate



n = $(0.2 \pm 2.3)\times10^{-3}$ decays/readout

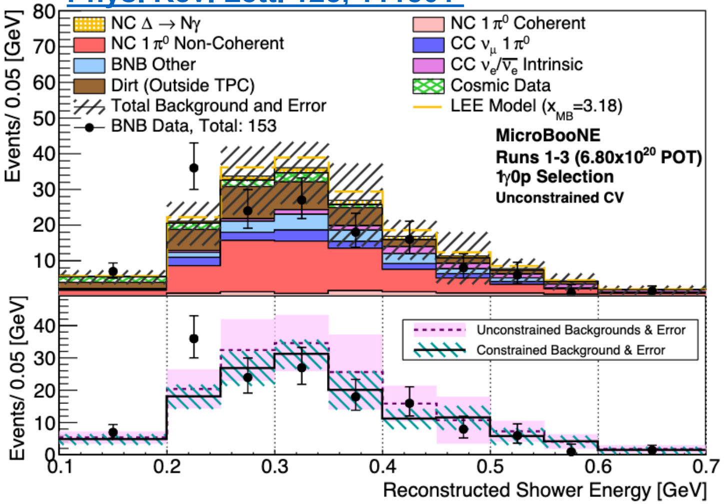
R_{Bi} = 0.01 ± 0.16 (stat) ± 0.06 (syst) mBq/kg
= 0.01 ± 0.17 mBq/kg
< 0.35 mBq/kg at 95% CL

$R_{Rn} / R_{Bi} \sim 2.3 \pm 0.4$

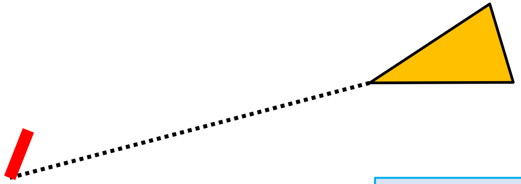
$R_{Rn} \sim 0.03 \pm 0.38$ mBq/kg

Broader implications for SBN / MicroBooNE

Phys. Rev. Lett. 128, 111801

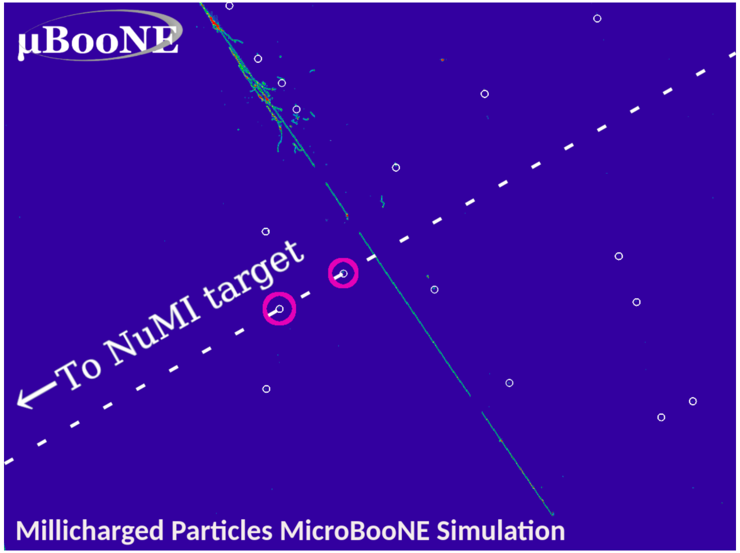


Low-energy proton detection for 1g0p background discrimination



low-E proton
(missed by Pandora tracker?)

See talk on LEE in μB from Erin Yandel



Beam-induced BSM like millicharged particle signatures

See talk on BSM in μB from Justin Evans

Conclusions

- MeV-scale features in LArTPC events contain information that can enhance the physics potential of SBN experiments

- MicroBooNE has demonstrated MeV-scale capabilities to unprecedented levels for a large LArTPC

- Tools are being incorporated into other analyses and experiments

Thanks!

BACKUP

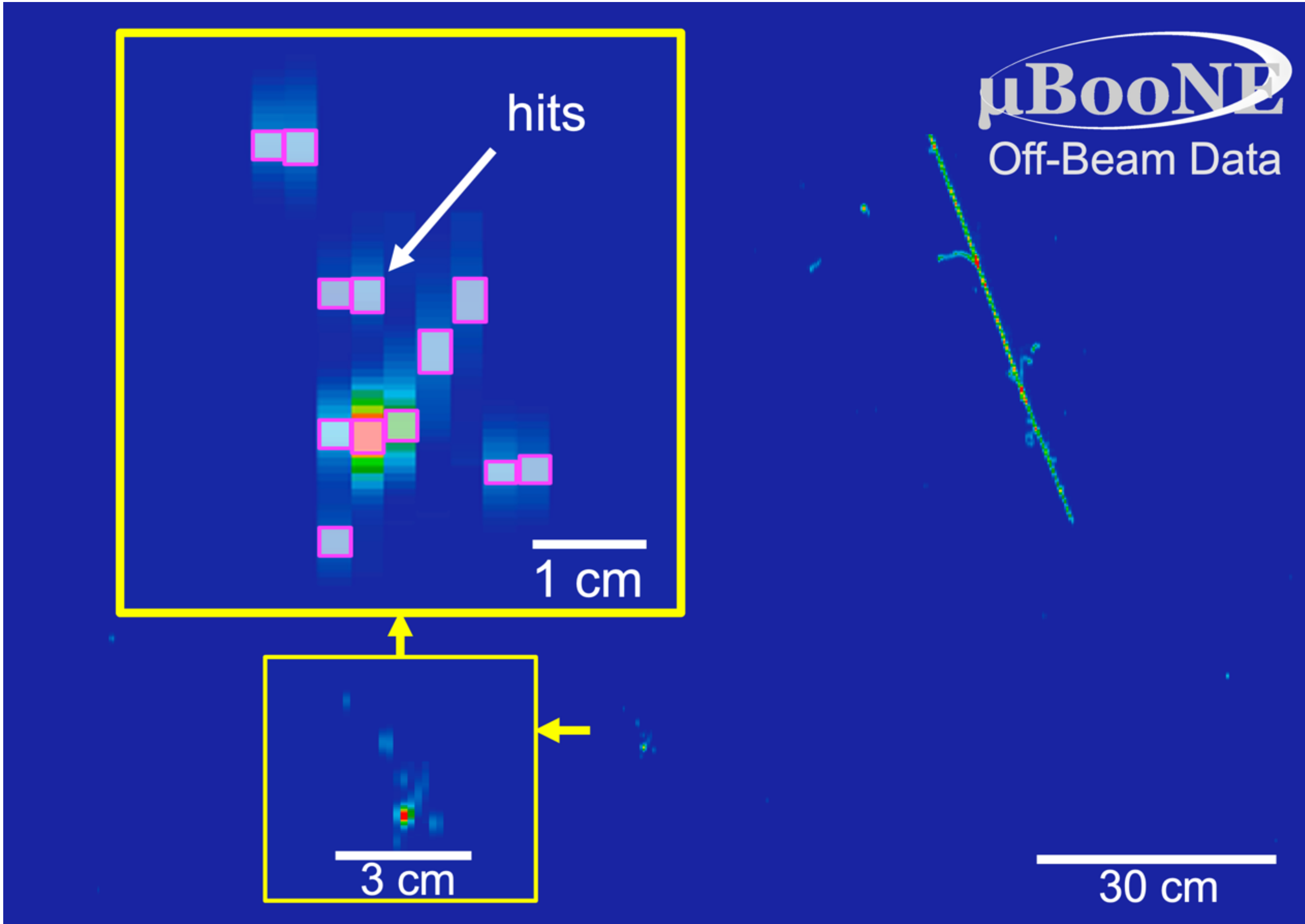
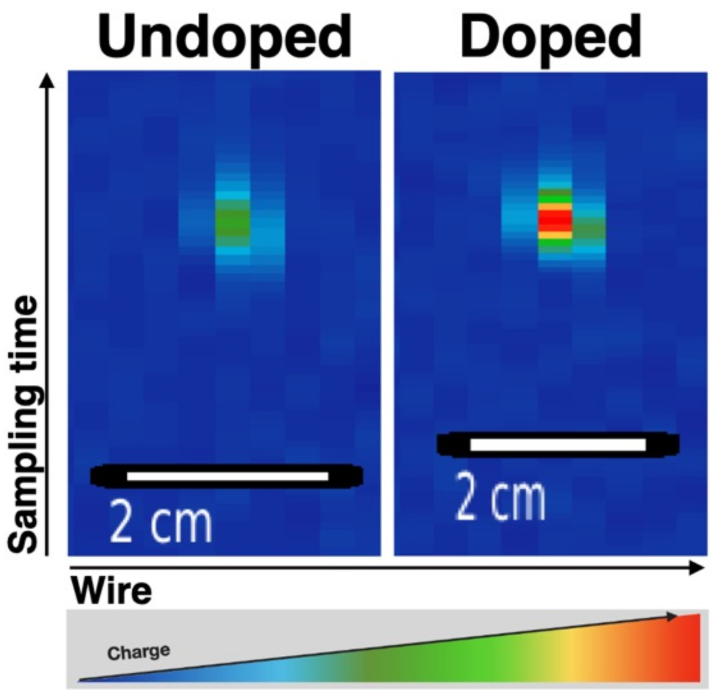
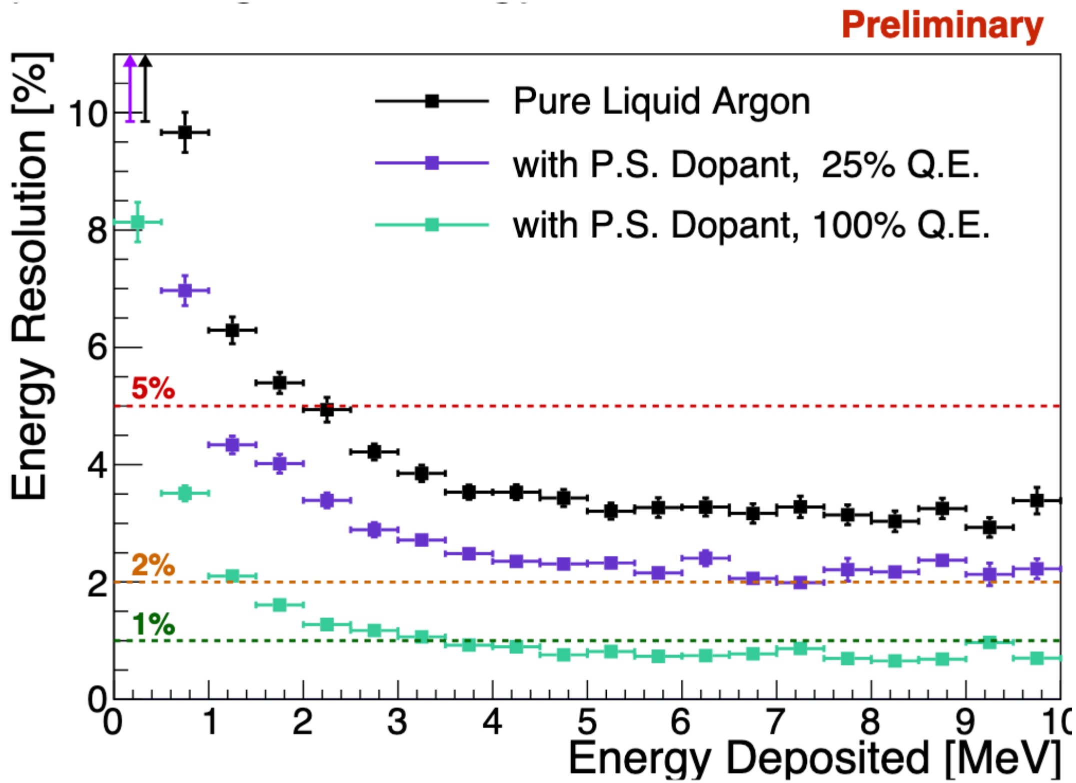

hits
1 cm
3 cm
μBooNE
Off-Beam Data
30 cm

Photo-ionizing dopants





Improving LArTPC Performance with Photo-Ionizing Dopants, Joseph Zennamo

Solar neutrinos in DUNE

DUNE as the Next-Generation Solar Neutrino Experiment

[Phys. Rev. Lett. 123, 131803]

Δm_{12}^2 probed by day-night flux asymmetry

$$A_{D/N} = (D - N)/\tfrac{1}{2}(D + N)$$

Can break degeneracy between θ_{12} and $\phi(^8\mathrm{Bi})$ by measuring two interaction channels via crude angular cuts:

$$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^* \longrightarrow R_{\mathrm{Ar}} \propto \phi(^8\mathrm{B}) \times \sin^2\theta_{12}$$

$$\nu_{e,\mu,\tau} + e^- \to \nu_{e,\mu,\tau} + e^- \longrightarrow R_e \propto \phi(^8\mathrm{B}) \times \left(\sin^2\theta_{12} + \tfrac{1}{6}\cos^2\theta_{12}\right)$$

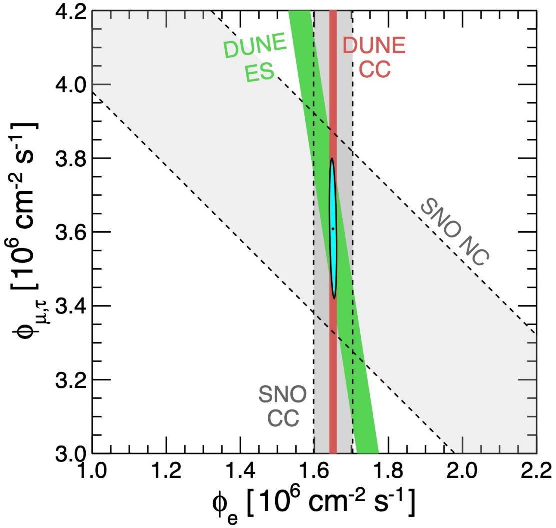


FIG. 3. Estimated precision of the ν_e and $\nu_{\mu,\tau}$ content of the ^{8}B flux, present (SNO [5, 53]) and future (DUNE), with the ellipse for DUNE alone. Based on a simplified analysis, with only statistical uncertainties (1σ) but assuming 2 d.o.f., and with SNO fluxes slightly rescaled to match their global-fit ^{8}B flux. Note small axis ranges. Full analysis in text.

Energy resolution improvements in LAr

Phys. Rev. D 99, 036009 (2019)

TABLE I. Detection thresholds according to the DUNE CDR document [5]. The values given correspond to the kinetic energy of each particle.

	p	$\pi^{\pm}$	γ	μ	e	others
Thresholds (MeV)	50	100	30	30	30	50

(1) *CDR thresholds*: Any particle created below the thresholds listed in Table I is lost.
(2) *Total charge calorimetry*: Thresholds are set to zero and no information about the hadronic system other than the total ionization charge is used.
(3) *Detailed event reconstruction*: Thresholds are low and recombination corrections are applied to each particle in the event individually.

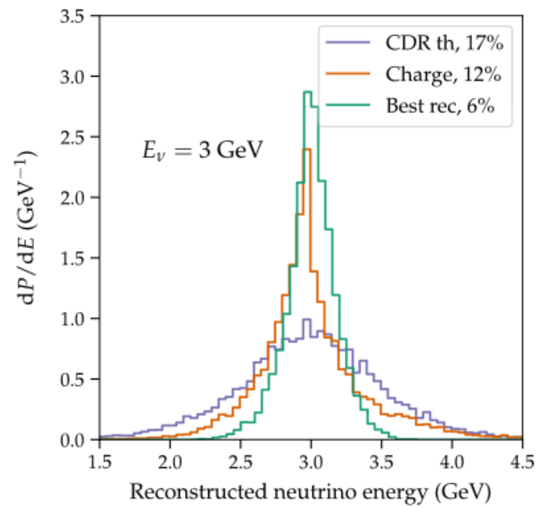


FIG. 14. Simulations of reconstructed neutrino energies for $E_{\nu} = 3$ GeV true energy in the CC $\nu_e + {}^{40}$Ar scattering process. The histograms correspond to three different sets of assumptions, as described in the text.

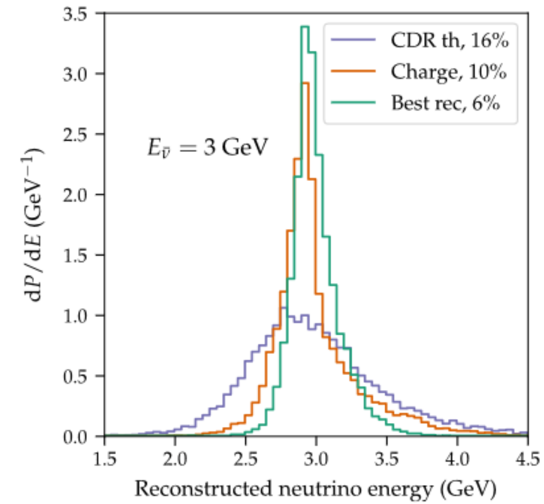
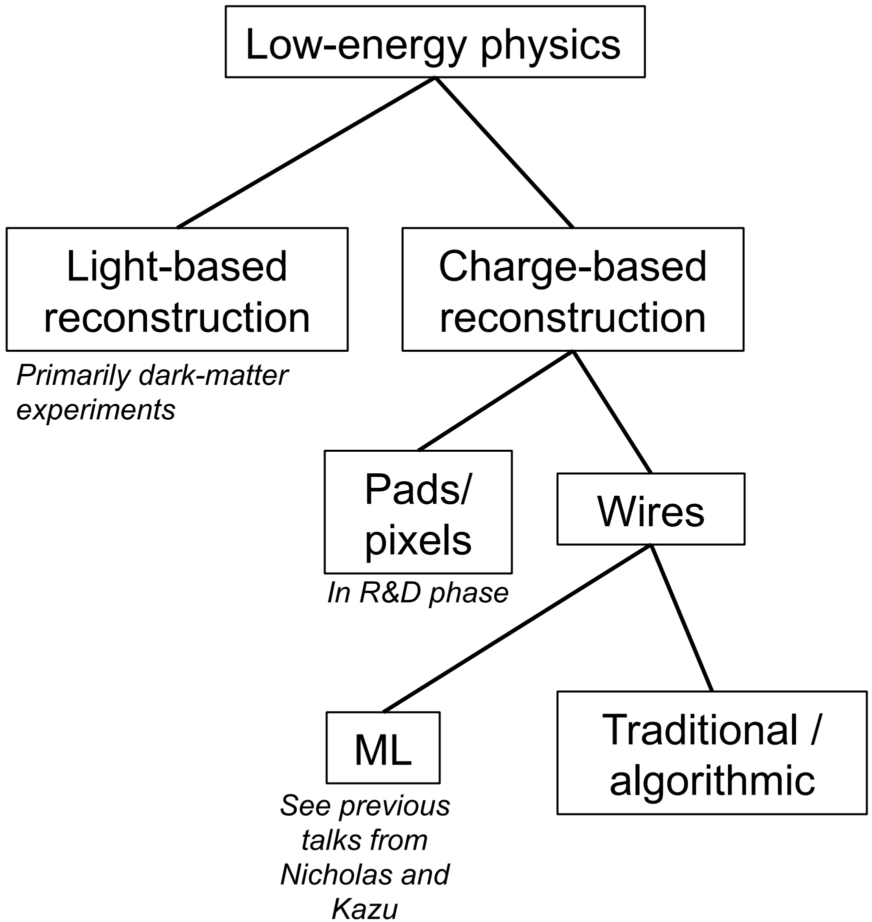


FIG. 15. Same as Fig. 14, but for $\bar{\nu}_e + {}^{40}$Ar scattering.

Understanding the energy resolution of liquid argon neutrino detectors

Alexander Friedland* and Shirley Weishi Li†
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA

(Received 13 December 2018; published 13 February 2019)



Traditional reconstruction

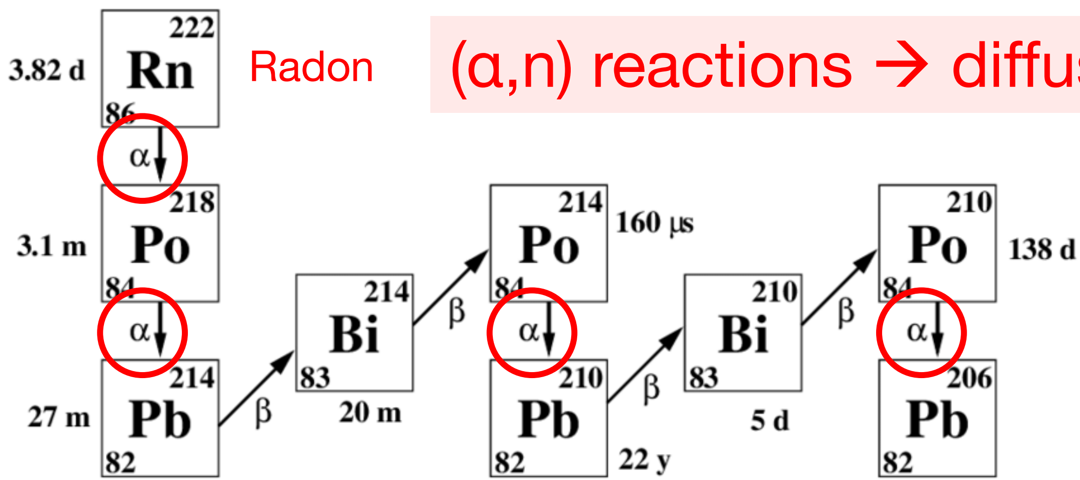
- Wire signals are noise-filtered and processed with deconvolution algorithms
- ADC thresholded hit-finding via Gaussian fits to pulses
- Advantages:
  - Software infrastructure in place in LArSoft & demonstrated with published results
  - Based on 'first-principles', no need to train a network
- Disadvantages:
  - Lowering thresholds is challenging
  - Limited by noise floor

Remaining Challenges

- Successful demonstrations in smaller LArTPCs... but can we do the same in large ones?
  - Lowering thresholds
  - Precise energy reconstruction
  - Controlling low-energy backgrounds

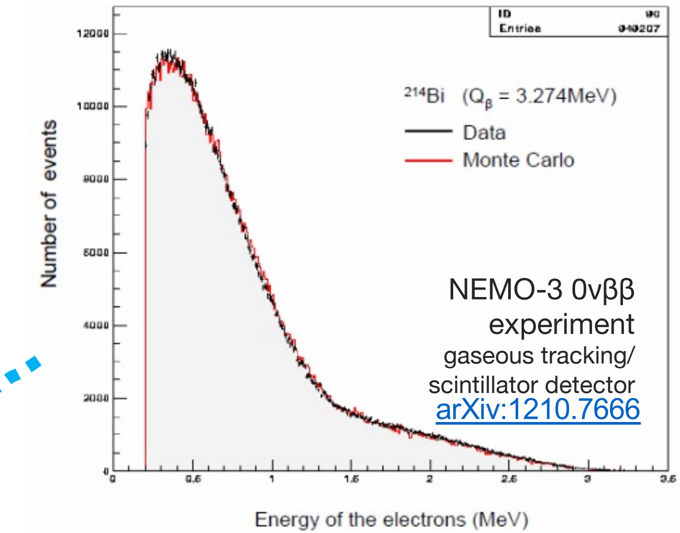
Critical for maximizing SBN's and DUNE's physics potential

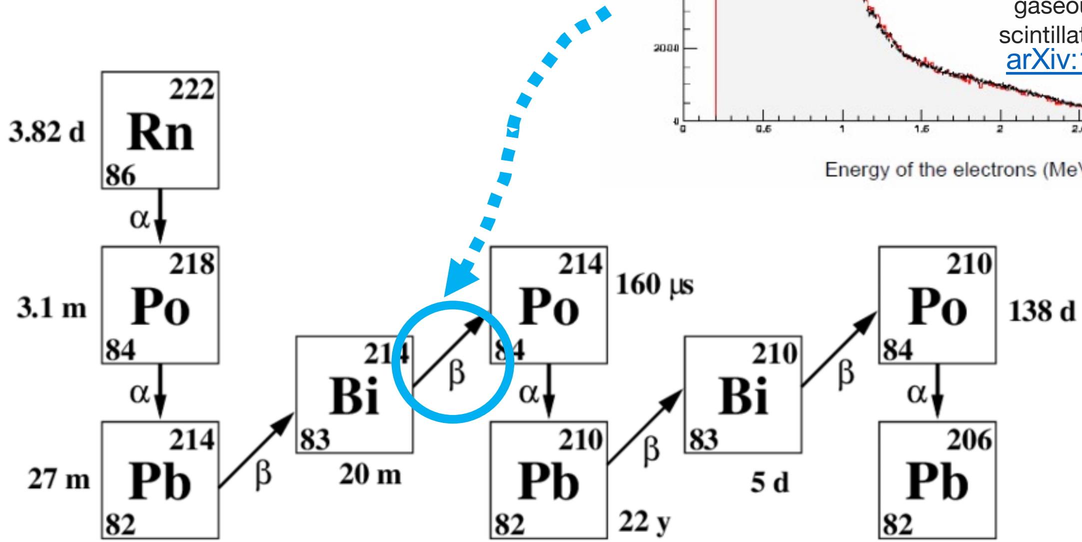
(α,n) reactions → diffuse neutrons



Remaining ~~Challenges~~ *Opportunities?*

Short ^{214}Po half-life makes it taggable (delayed coincidence w/ ^{214}Bi β decay)



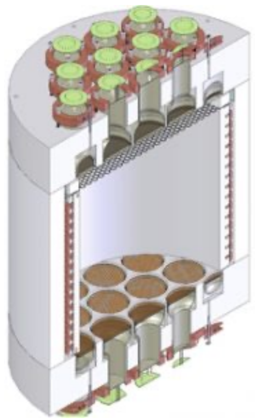


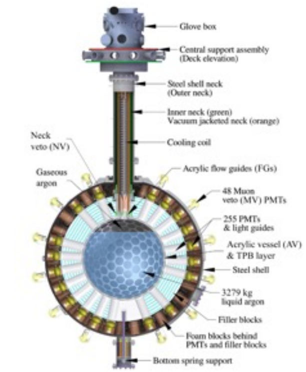
Radon in dark matter experiments

- Existing methods of radio-purification in LAr:
  - rigorous material screening
  - outgassing campaigns
  - specialized systems for filtering Rn from gaseous argon
- DUNE aims to achieve < 1 mBq/kg to accomplish the goals laid out in previous slides
- *How will we accomplish this?*
  - Filtration in the gaseous phase will be more challenging at large scale

^{222}Rn Levels

[1]DarkSide-50: ~2.1 μBq/kg
[2]DEAP-3600: < 0.2 μBq/kg



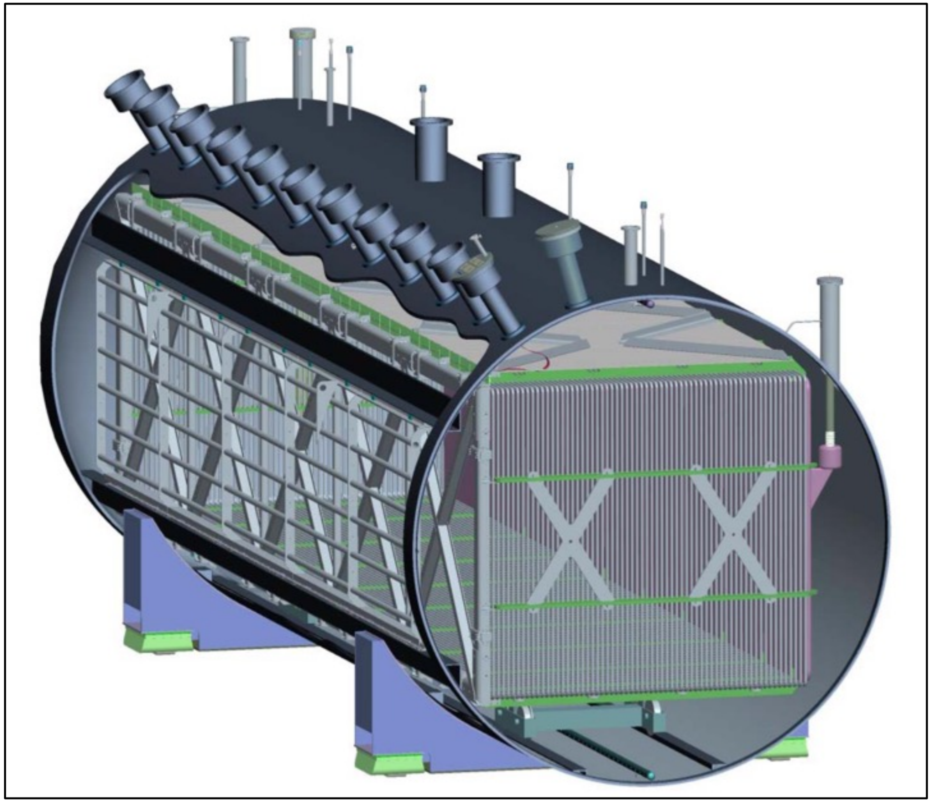


[1] Phys Rev D 98, 102006 (2018)
[2] Phys Rev D 100, 022004 (2019)

Bq = decays per second

The MicroBooNE Detector

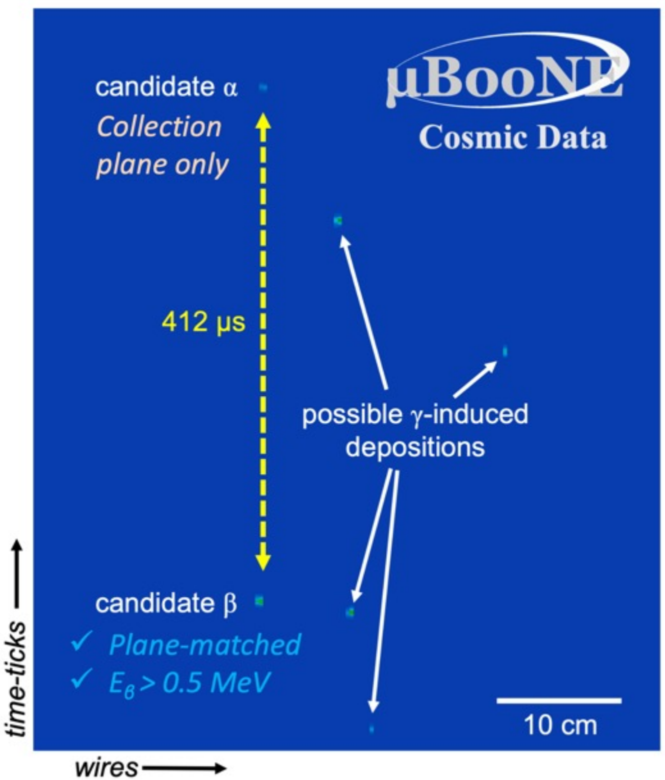
2017 JINST 12 P02017



~10m × 2.5m × 2.3m

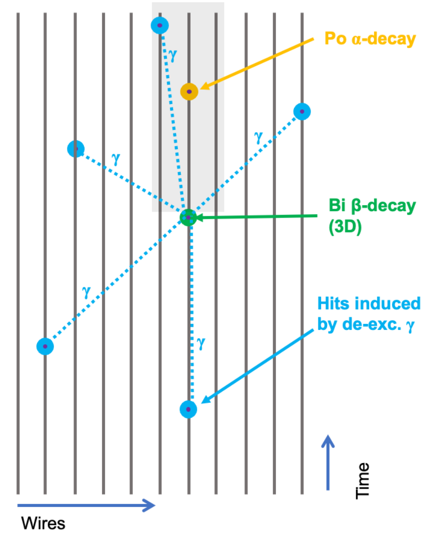
Signal backgrounds

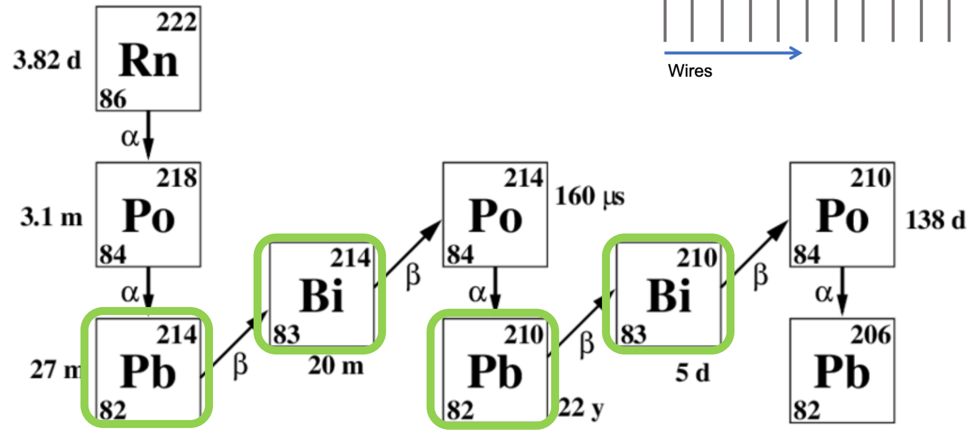
[arXiv:2307.03102](https://arxiv.org/abs/2307.03102)



$$^{214}\text{Bi} \rightarrow {}^{214}\text{Po} + \beta + N\gamma$$

BiPo signal can be faked by other beta-emitting isotope decays

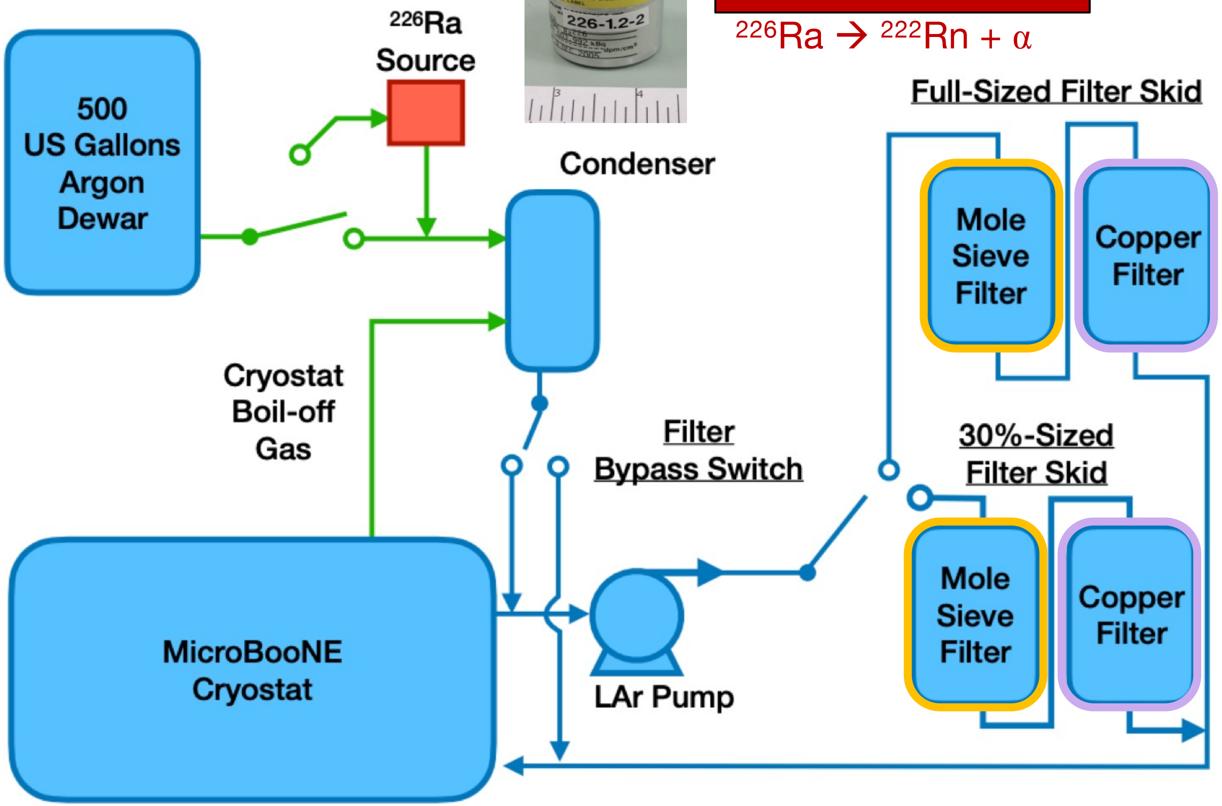




Doping radon into MicroBooNE

500 kBq radium source attached to input Ar gas line

$^{226}Ra \rightarrow {}^{222}Rn + \alpha$

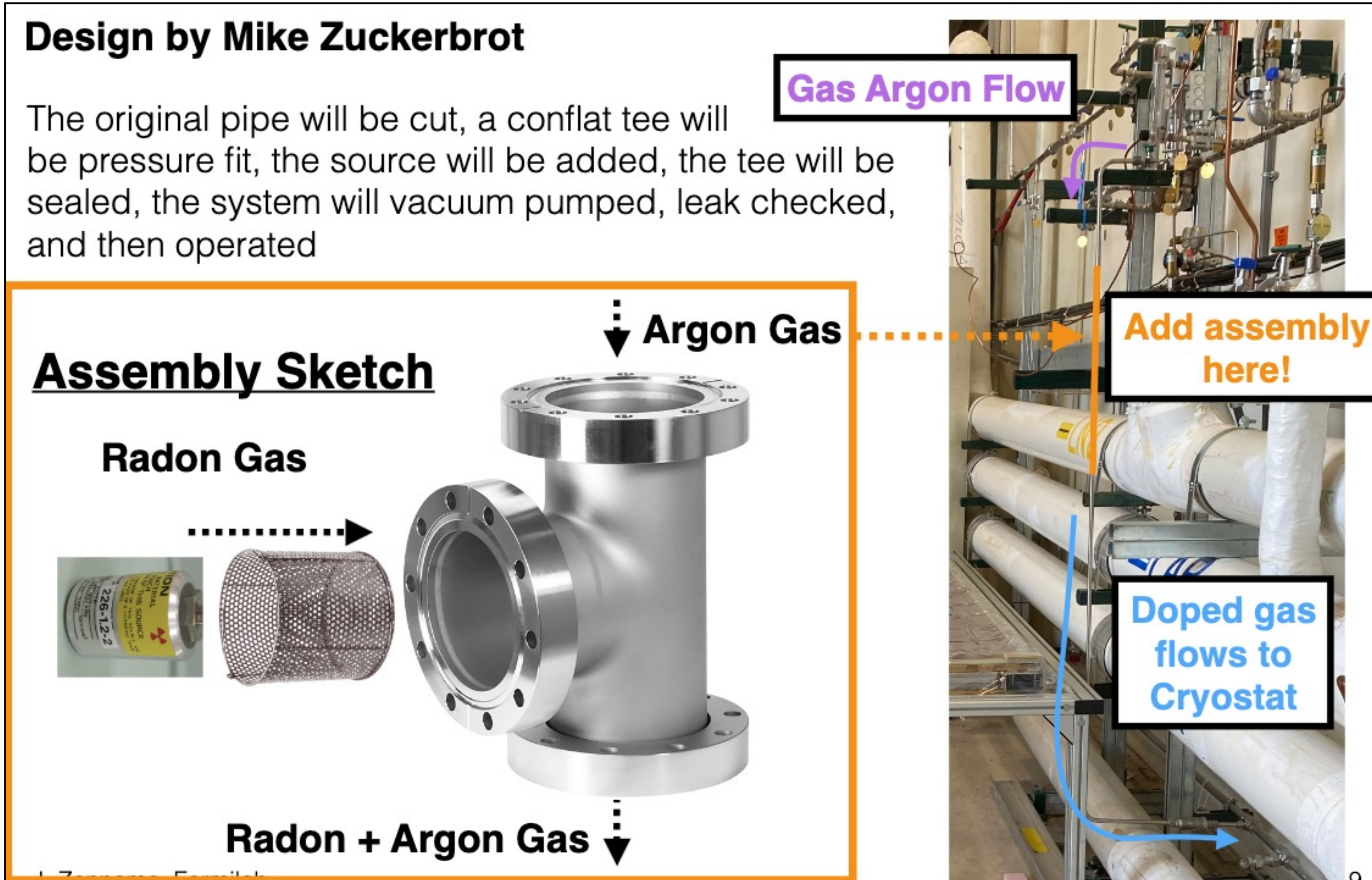


Filters aim to remove electronegative contaminants

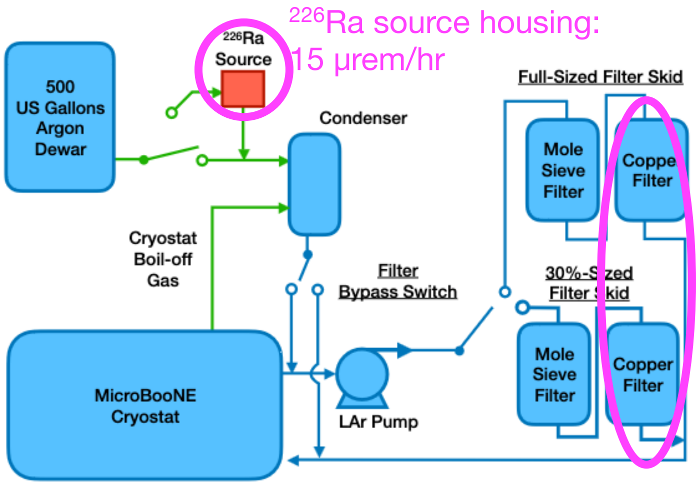
4Å molecular sieve
1.6-2.6 mm beads
removes water

Copper filter
Cu-0226 S
removes O_2

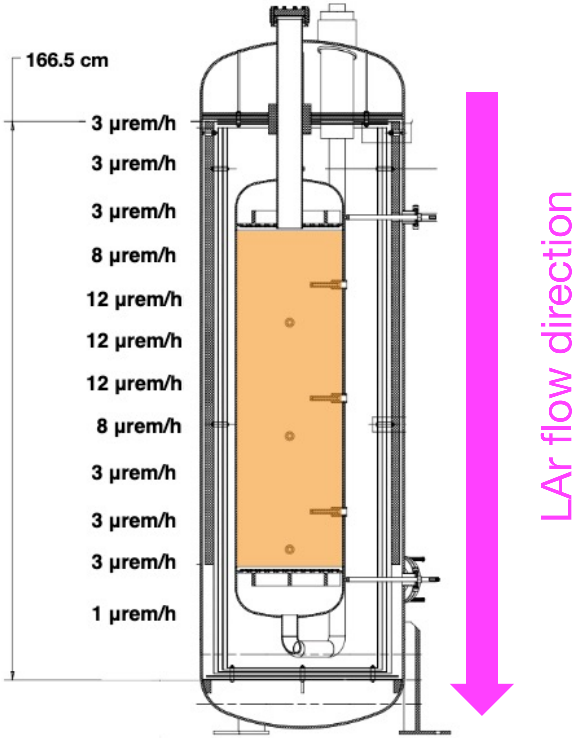
Doping radon into MicroBooNE



Radiological survey

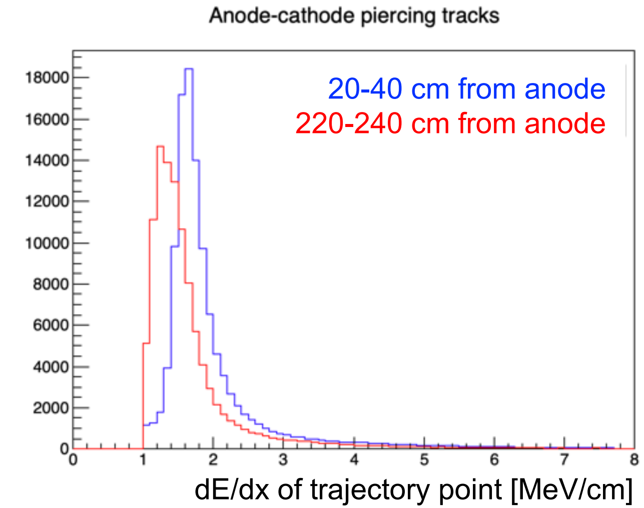


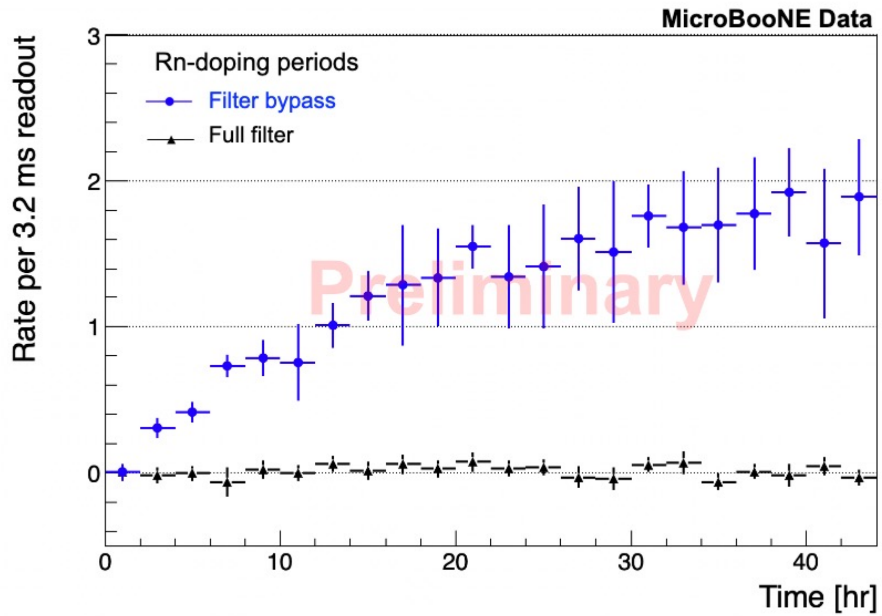
Confirmed accumulation of radon in copper filter



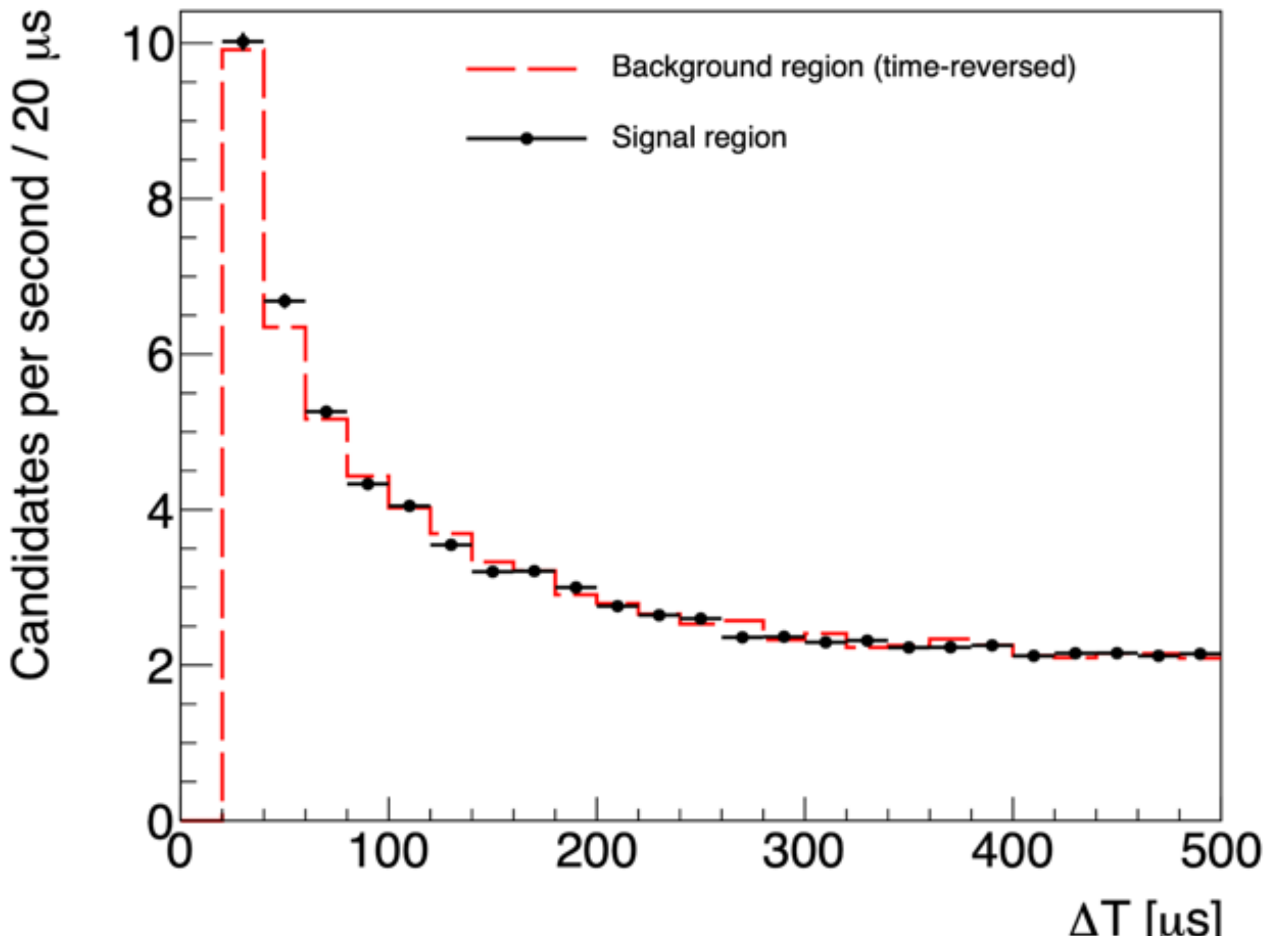
- Looked at ratio of dE/dx for segments of ACP tracks near and far from the wire planes
- Confirmed average ~8 ms lifetime (weighted by β candidates over time), consistent with previous estimate from scaling the Bi214 beta spectrum

scale





Time period [hrs]	Far/near dEdx ratio	Equivalent lifetime [ms]
0-5	1.01(2)	> 180
5-10	0.940(8)	29 +/- 12
10-15	0.902(8)	18 +/- 3
15-20	0.855(11)	12 +/- 2
20-25	0.828(12)	9.6 +/- 1.8
25-30	0.820(9)	9.2 +/- 0.5
30-35	0.776(6)	7.2 +/- 0.5
35-40	0.758(7)	6.6 +/- 0.6
40-45	0.735(7)	5.9 +/- 0.4



Candidates per second / 20 μs
10
8
6
4
2
0
0
100
200
300
400
500
ΔT [μs]
Background region (time-reversed)
Signal region

Ion mobility in LAr

Some fraction of isotopes are positive ions → drift toward cathode at very slow speeds

Phys Rev C 92, 045504

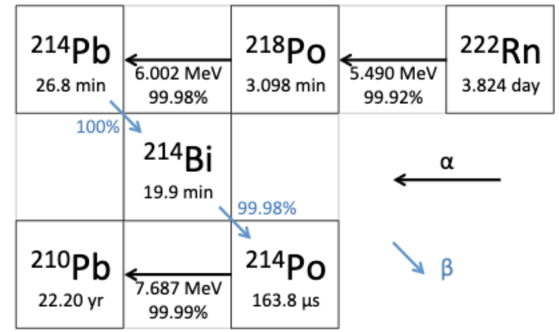
Results from LXe in EXO-200

$222Rn \rightarrow 218Po^{+}$ $f_{\alpha} = 50.3 \pm 3.0\%)$

v_d ~0.3 cm^2 / (kV s)

$214Pb \rightarrow 214Bi^{+}$ $f_{\beta} = 76.5 \pm 5.7\%$

Implies that measured Bi→Po rate can't be directly translated to a ^{222}Rn rate, as some isotopes will have drifted and plated onto cathode



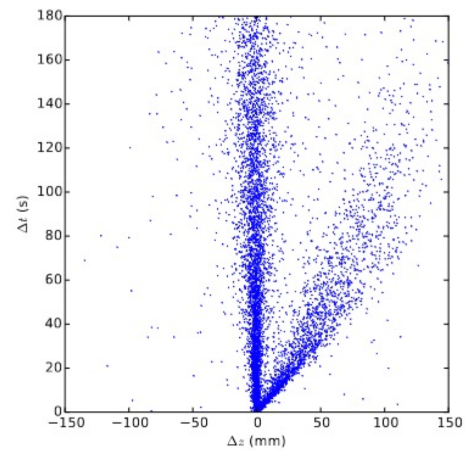


Figure 8. (Color online) Scatter plot of ^{218}Po drift distance versus time between the ^{222}Rn and ^{218}Po decays. Displacement (Δz) is defined as positive when movement is towards the cathode.

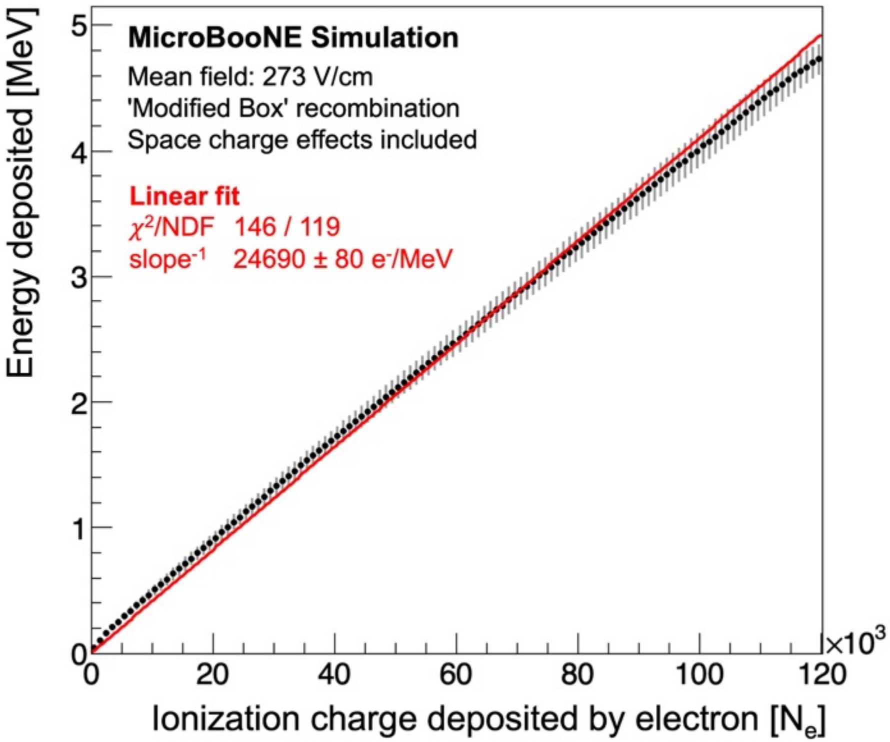
Toy MC assumptions

Decay Daughter	Half-life	Mean lifetime = $T_{1/2}$ / ln(2)	Ion fraction	Drift speed at 273 V/cm
218Po	3.1 min	4.5 min	37% +/- 3% [80]	0.23 cm/s [80]
214Pb	27 min	39 min	**Estimated 37%**	**Estimated 0.23 cm/s**
214Bi	20 min	29 min	**Estimated 56%** [81]	**Estimated 0.23 cm/s**
214Po	164 us	237 us	Not relevant	Not relevant

[80] P. Agnes *et al.* (DarkSide), Measurement of the ion fraction and mobility of 218Po produced in 222Rn decays in liquid argon, J. Instrum. **14**, P11018 (2019).

[81] Albert and others (EXO-200 Collaboration), Measurements of the ion fraction and mobility of $\alpha-$ and β-decay products in liquid xenon using the EXO-200 detector, Phys. Rev. C **92**, 045504 (2015).

Converting charge to energy



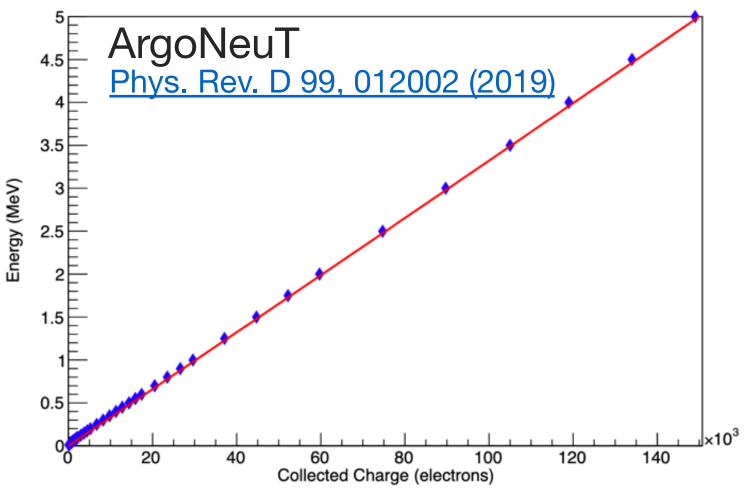
$$E_{\text{reco}}\ [\text{MeVee}] = \frac{Q}{0.584} \times W_{\text{ion}}$$

MicroBooNE + LArIAT: Michel electron showers

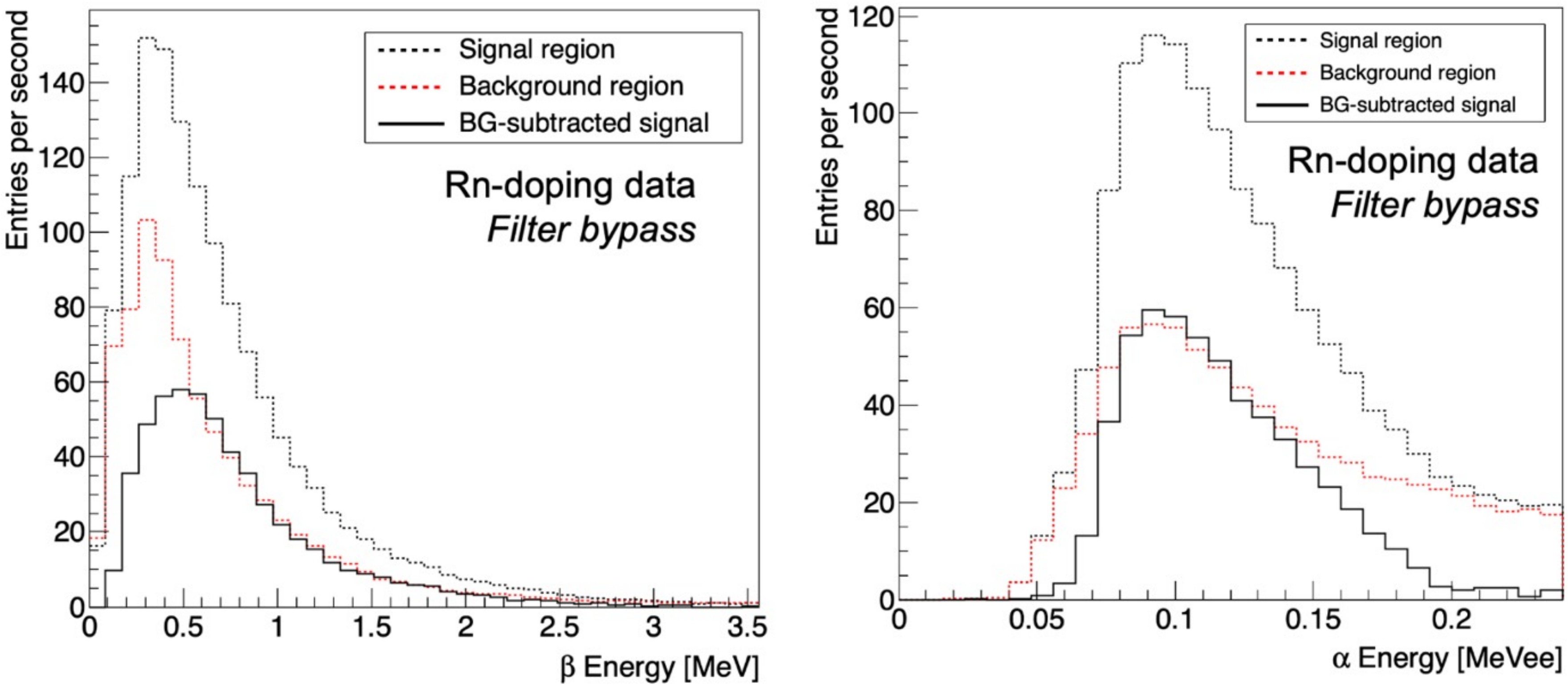
- For blips, assumed constant dE/dx (i.e., constant recombination)

ArgoNeuT: Nuclear de-excitation γ analysis

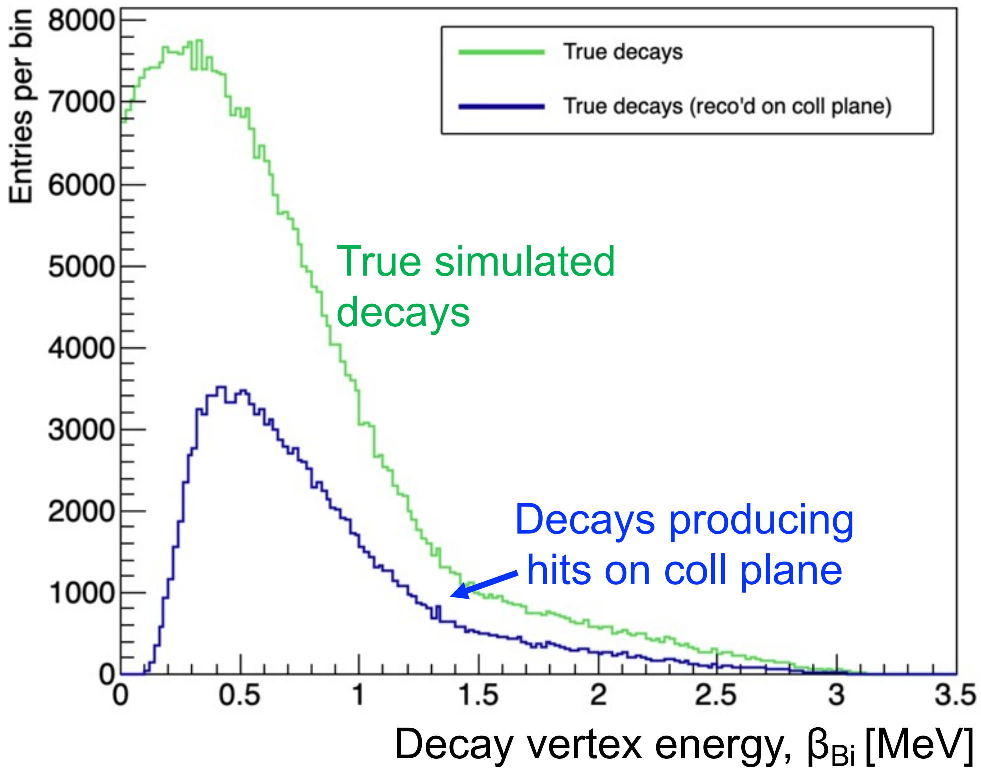
- Used NIST data on low-E e^-, together with recombination, to directly relate Q_{reco} to energy



Energy spectra backgrounds



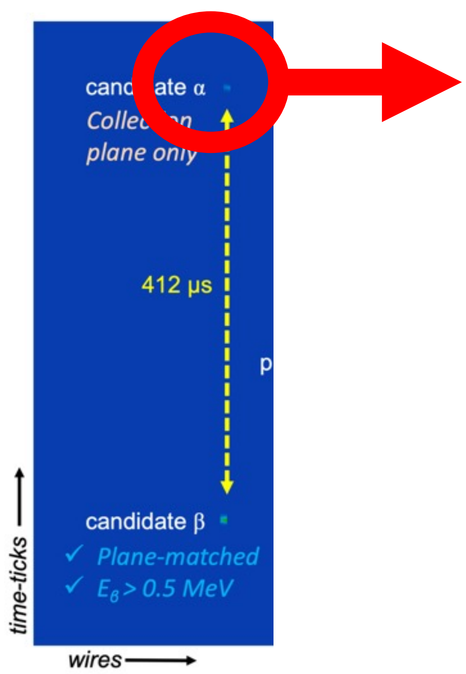
Simulated energy spectra



Calorimetric validation: α_{Po}

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

https://zenodo.org/record/7577399



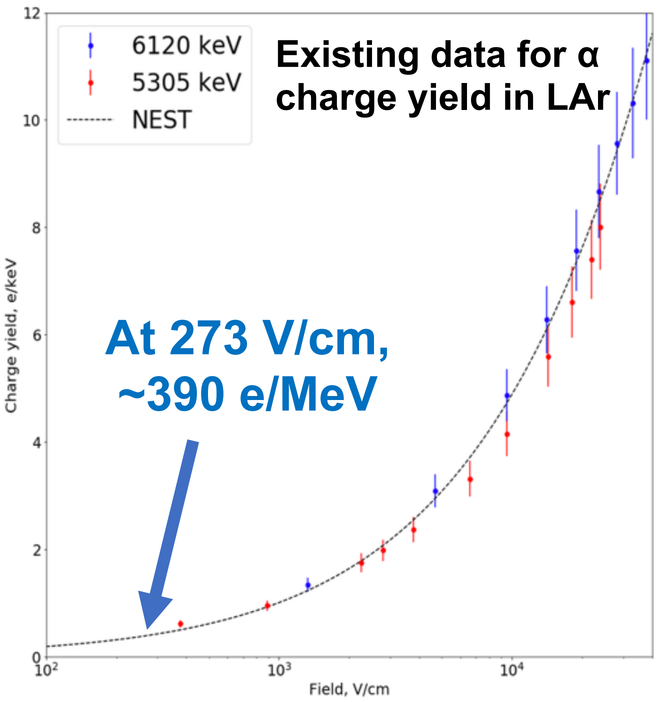
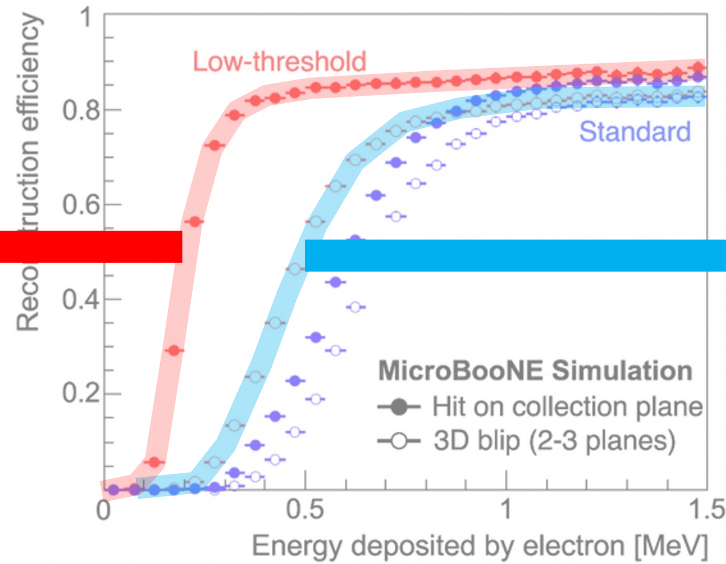
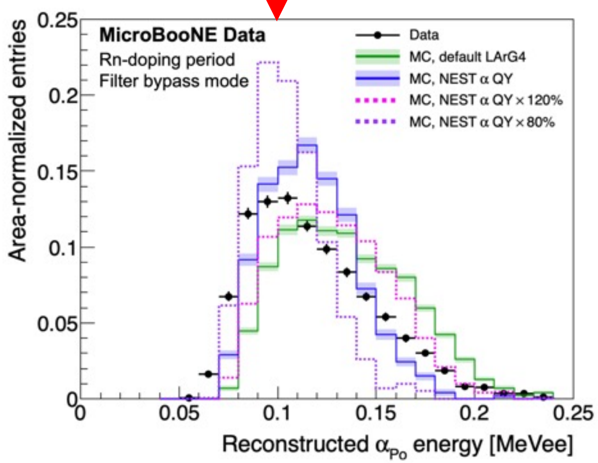
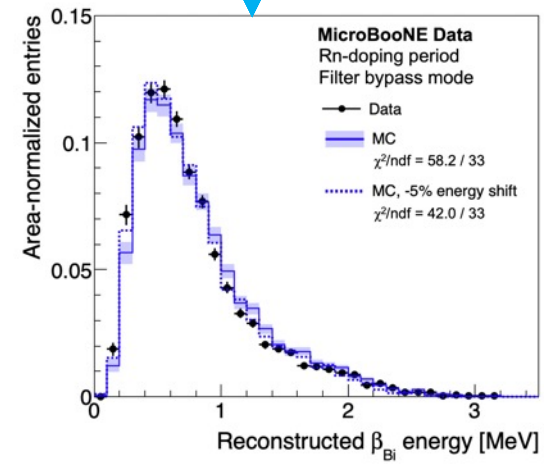


Figure 9: Charge yield model comparison with data from Po-210 and Cf-252





Heavily sculpted
by hit-finding
thresholds



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:
$\varepsilon = (8.3 \pm 4.2)\ \%$

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

BlipReco code structure

`ubreco/BlipReco` (3.3 MB total)

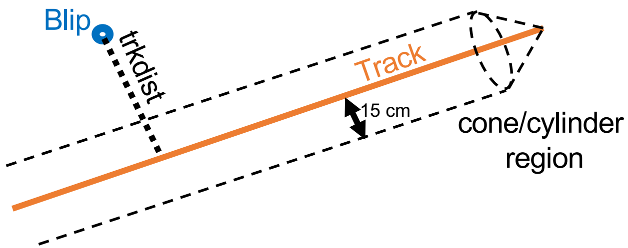
```
Alg
BlipAna_module.cc
blipreco_badchannels.txt
blipreco_configs.fcl
BlipRecoProducer_module.cc
CMakeLists.txt
job
ParticleDump_module.cc
TrackMasker_module.cc
Utils
```

Utils

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

DataTypes.h

```
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(); }
```



"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

```
// 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
```