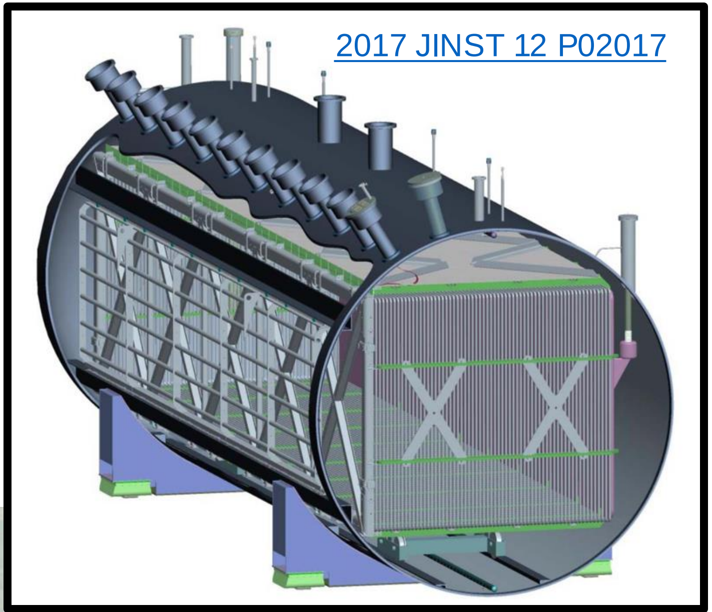
New MeV-scale capabilities in the MicroBooNE liquid argon time projection chamber

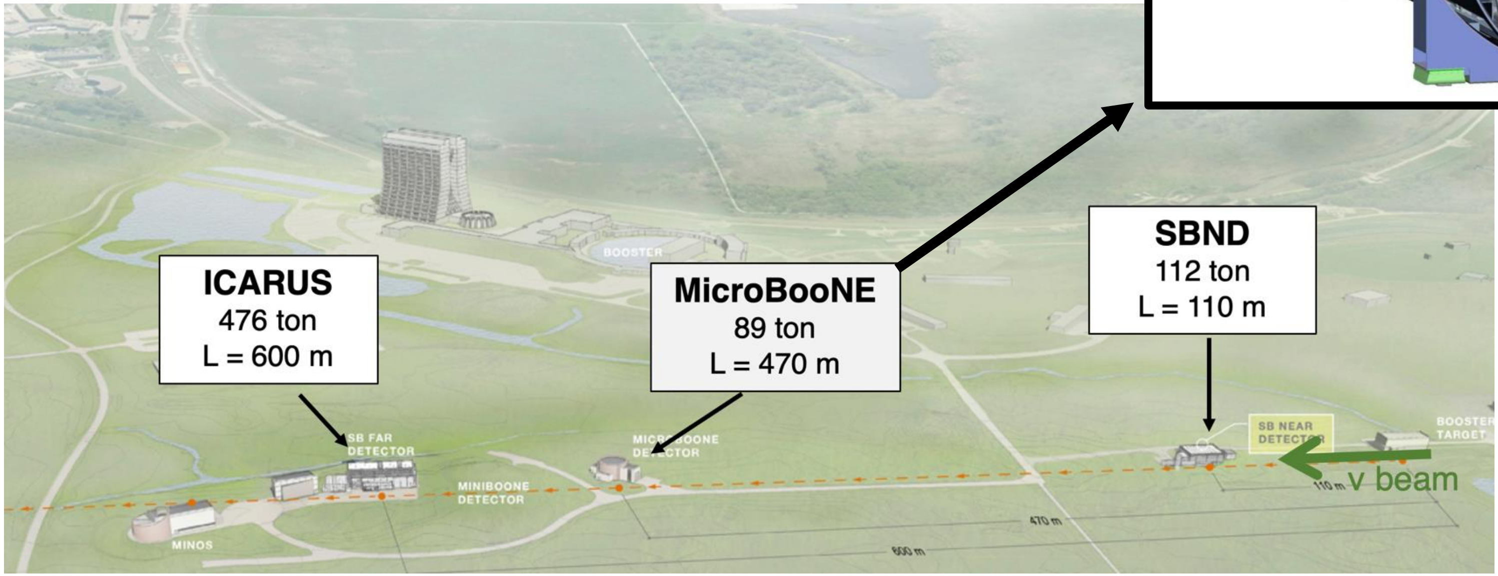
NuFact 2024
Argonne National Laboratory
September 18, 2024

Will Foreman (LANL)
on behalf of the MicroBooNE Collaboration

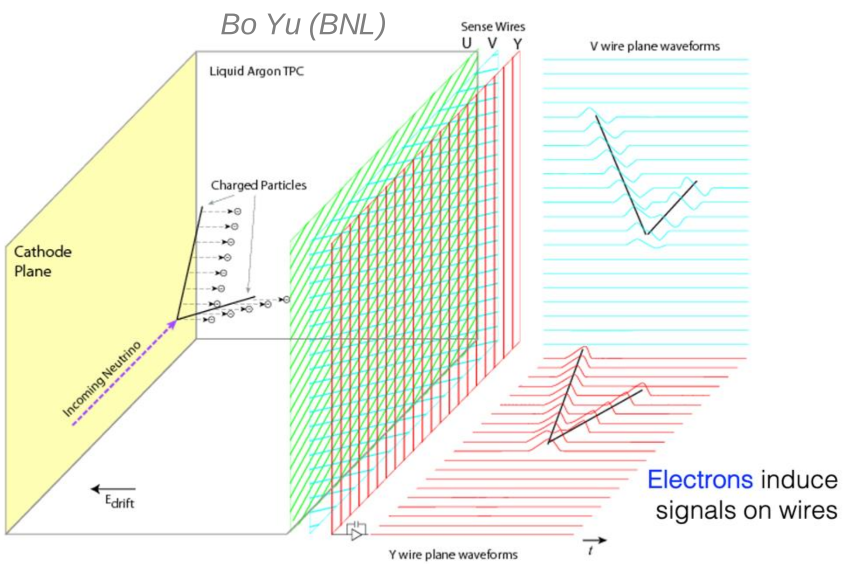
MicroBooNE

- Surface-level LArTPC, 85 metric ton active volume
- Exposed to Fermilab's Booster and NuMI neutrino beamlines from 2015-2021
- Primary goal: investigate "low-energy" (~200 MeV) ν_e excess observed by MiniBooNE

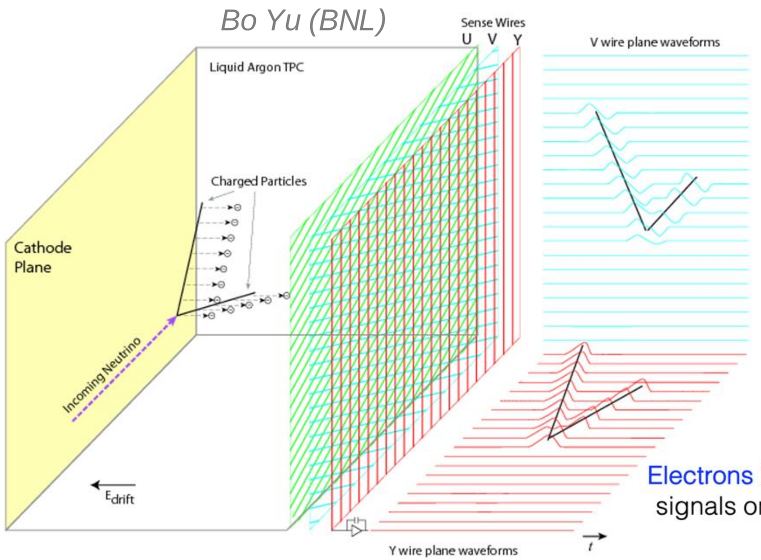




Energy scales in MicroBooNE events

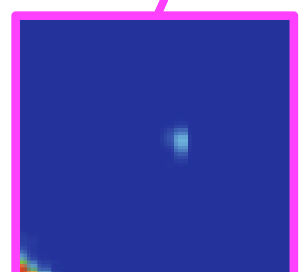


Energy scales in MicroBooNE events



Electrons induce signals on wires

Blips encode lots of interesting information that can be “missed” by high-energy reconstruction algorithms



blip

E ~ O(0.1-1 MeV)

Compton scattered γ-rays, neutron inelastic collisions

Benefits of MeV-scale sensitivity

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

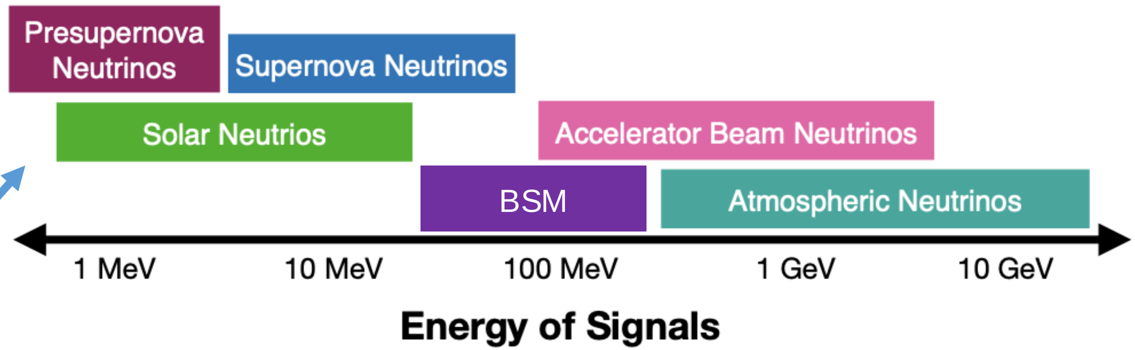
Topical Review

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]

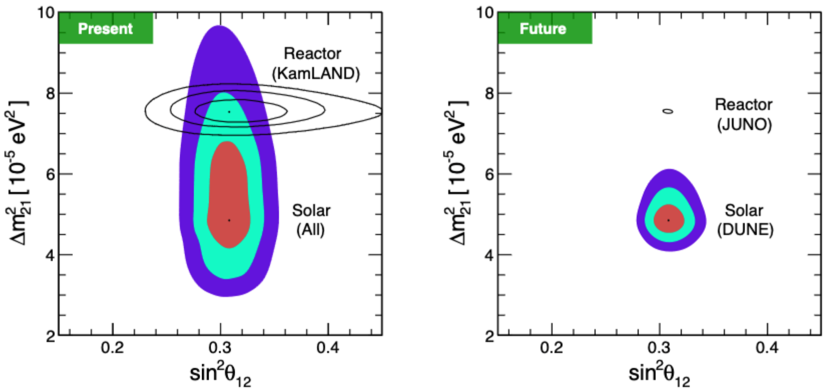
Whitepaper from Snowmass
J. Phys. G: Nucl. Part. Phys. 50 033001

Benefits of MeV-scale sensitivity



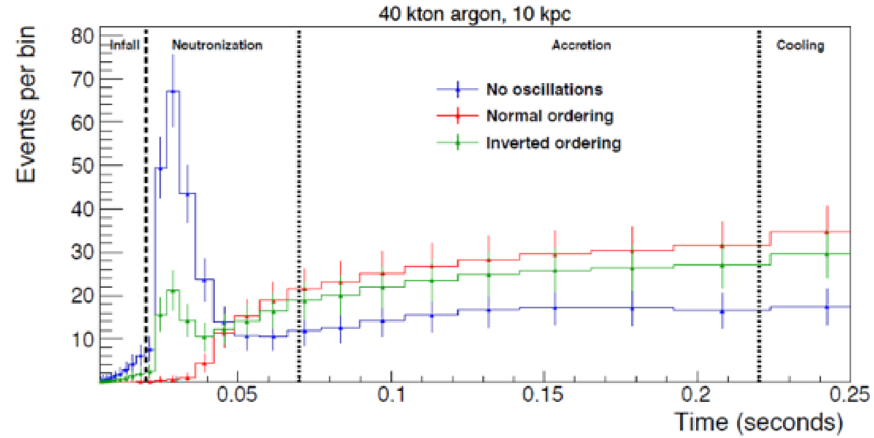
θ_{12}, Δm_{12}^2, and solar neutrino fluxes

Phys. Rev. Lett. 123, 131803

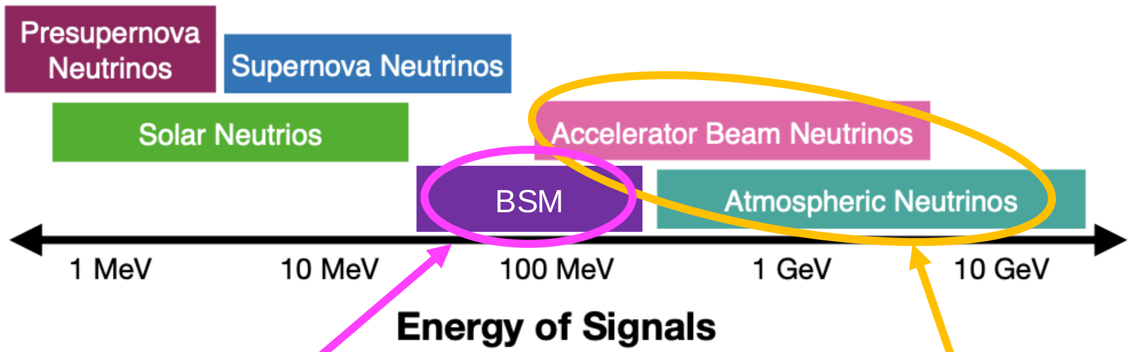


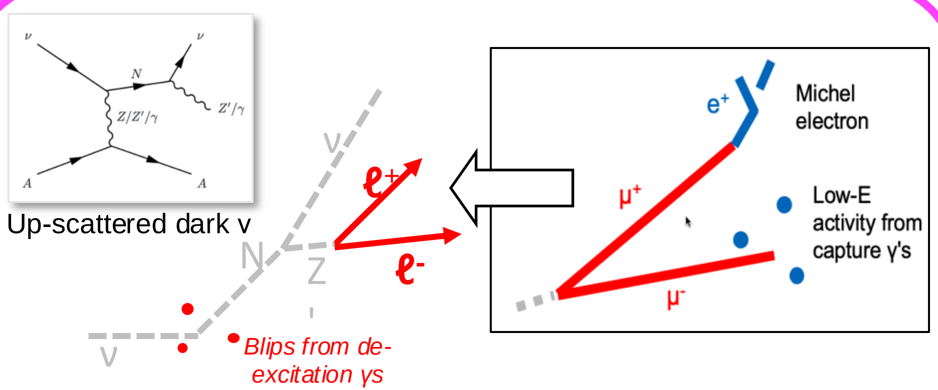
Mass ordering determination from SNBν

2020 J. Phys: Conf Ser 1342



Benefits of MeV-scale sensitivity

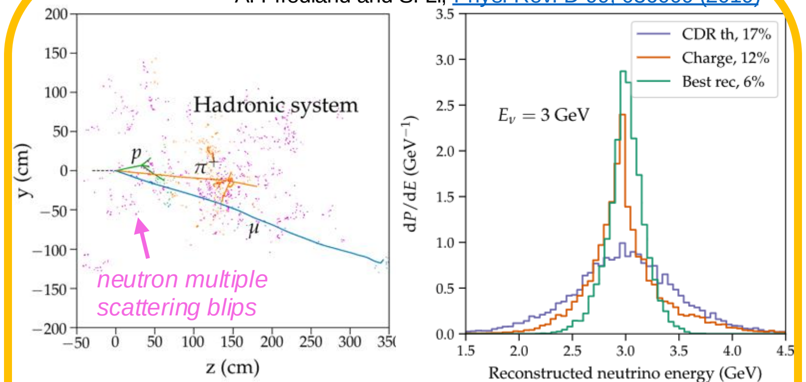




Particle ID → better identification of particles and BSM signatures via nuclear capture + deexcitation γ-rays

W. Castiglioni et al, [Phys.Rev.D 102 9, 092010 (2020)]

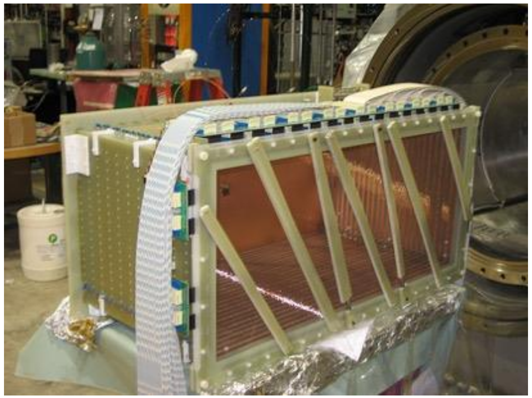
A. Friedland and S. Li, [Phys. Rev. D 99, 036009 (2019)]

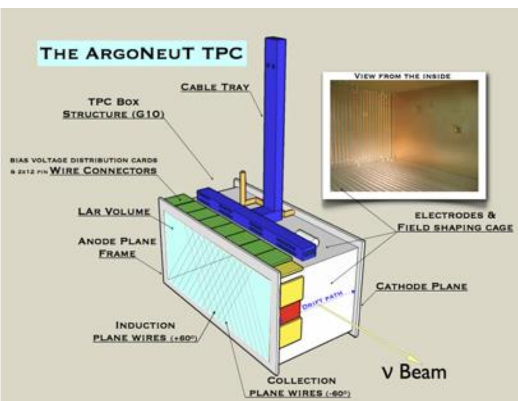


Neutron detection → better energy resolution + event ID in hadronic νAr final-states

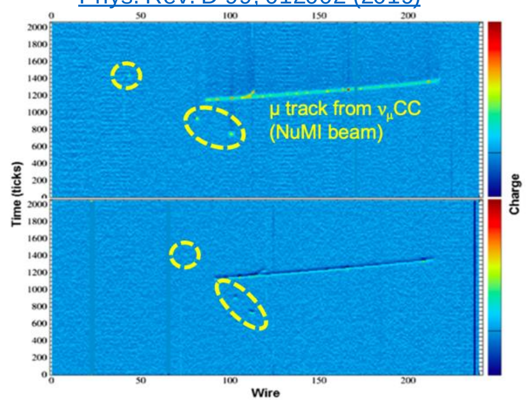
Past demonstrations in small LArTPCs

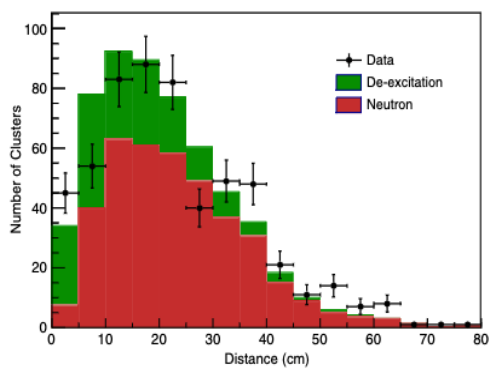
ArgoNeuT → *measured de-excitation γ/n from ν_μCC interactions* → *searched for millicharged particles (BSM)*



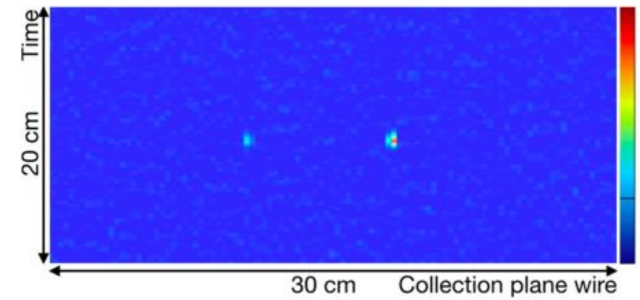


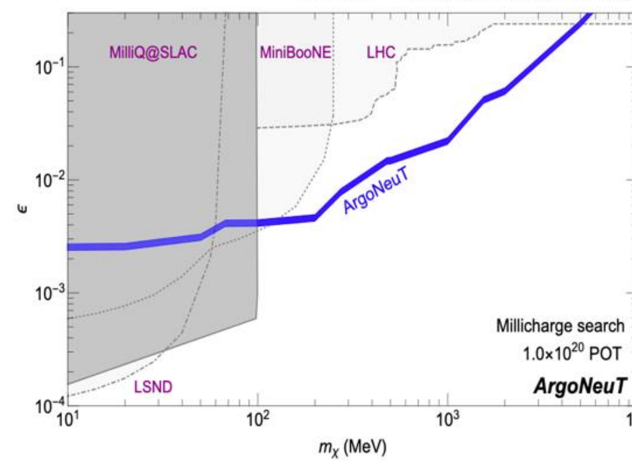
ArgoNeuT Collaboration, Phys. Rev. D 99, 012002 (2019)





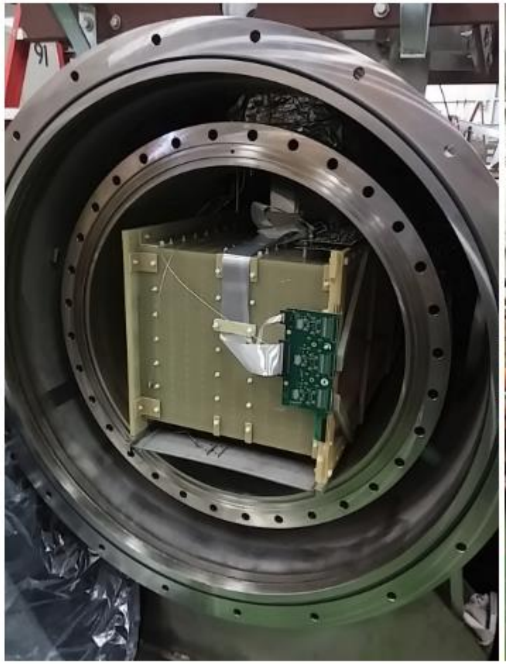
ArgoNeuT Collaboration, Phys Rev Lett. 124, 131801 (2020)





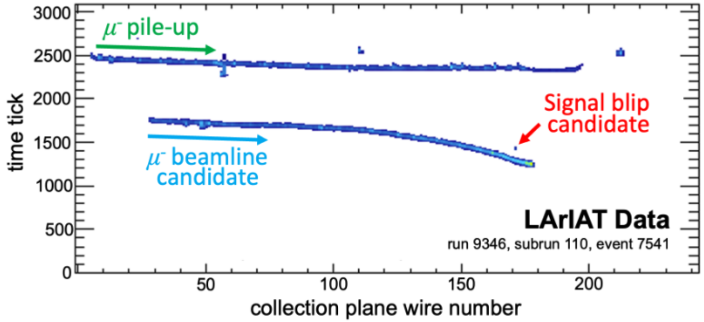
~~Past~~ *new* demonstrations in small LArTPCs

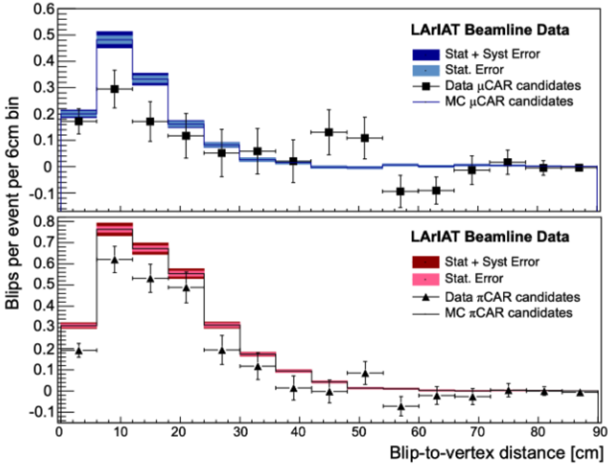
LArIAT LArTPC test-beam experiment



measured π and μ capture products

LArIAT Collaboration, [arxiv:2408.05133 (2024)]





See poster by Miguel Hernandez

Measurements of Pion and Muon Nuclear Capture at Rest on Argon in the LArIAT Test Beam Experiment

Remaining challenges

- Successful demonstrations in a small LArTPC... 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

Remaining slides will focus on two recent results from MicroBooNE

JINST 17 P11022 (2022)

PUBLISHED: November 10, 2022

Observation of radon mitigation in MicroBooNE by a liquid argon filtration system

The MicroBooNE collaboration

P. Abratenko,[ah] J. Anthony,[d] L. Arellano,[s] J. Asaadi,[ag] A. Ashkenazi,[ae] S. Balasubramanian,[k] B. Baller,[k] C. Barnes,[u] G. Barr,[x] J. Barrow,[t,ae] V. Basque,[k] L. Bathe-Peters,[m] O. Benevides Rodrigues,[ad] S. Berkman,[k] A. Bhanderi,[s] A. Bhat,[ad] M. Bhattacharya,[k] M. Bishai,[b] A. Blake,[p] T. Bolton,[o] J.Y. Book,[m] L. Camilleri,[i] D. Caratelli,[c,k] I. Caro Terrazas,[h] F. Cavanna,[k] G. Cerati,[k] Y. Chen,[a,aa] D. Cianci,[i] J.M. Conrad,[t] M. Convery,[aa] L. Cooper-Troendle,[ak] J.I. Crespo-Anadón,[e] M. Del Tutto,[k] S.R. Dennis,[d]

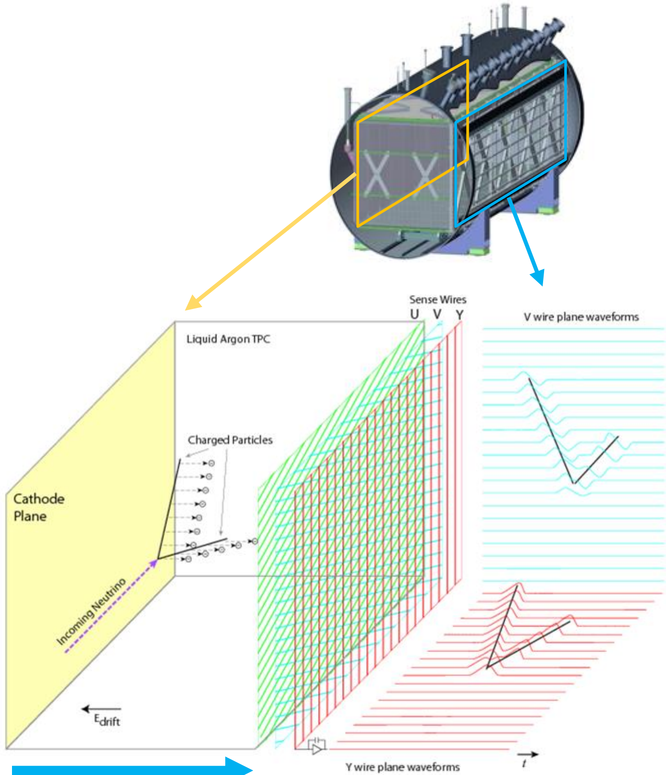
Phys Rev D 109, 052007 (2004)

PHYSICAL REVIEW D **109,** 052007 (2024)

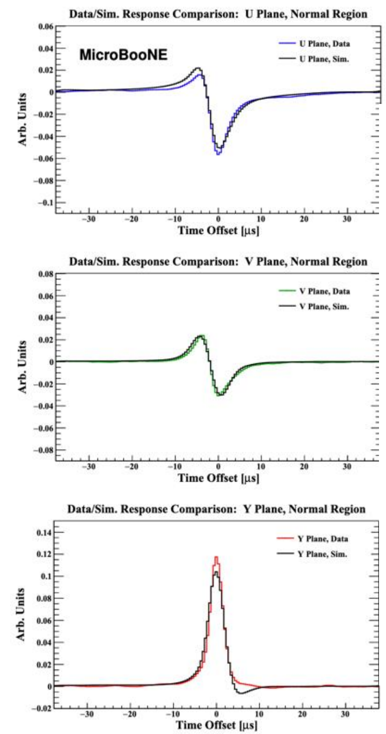
Measurement of ambient radon progeny decay rates and energy spectra in liquid argon using the MicroBooNE detector

P. Abratenko,[36] O. Alterkait,[36] D. Andrade Aldana,[15] L. Arellano,[20] J. Asaadi,[35] A. Ashkenazi,[33] S. Balasubramanian,[12] B. Baller,[12] G. Barr,[26] D. Barrow,[26] J. Barrow,[21,33] 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]

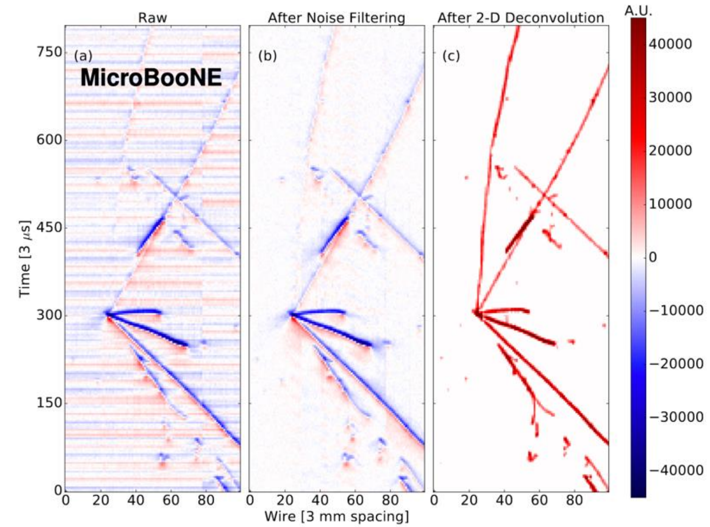
Signal processing in MicroBooNE



Drift ~ 2.3 ms



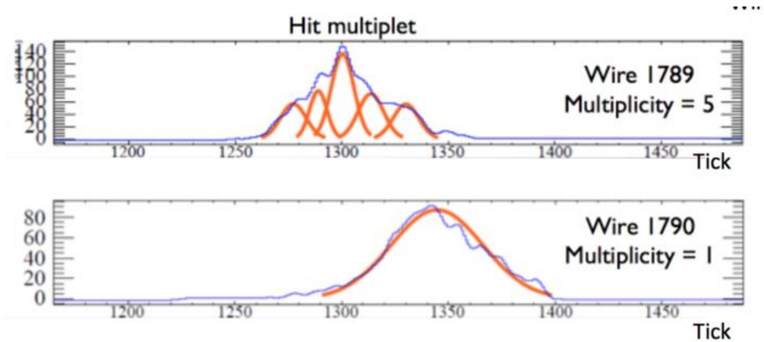
[JINST 13 P07007 (2018)]



[JINST 13 P07007 (2018)]

Detector readout → **Signal digitization**
0.5 μs/tick, 3.2ms total readout saved → **Filtering/deconvolution**
Equivalent noise charge ENC ~ 300 e^- per ADC

Signal processing in MicroBooNE

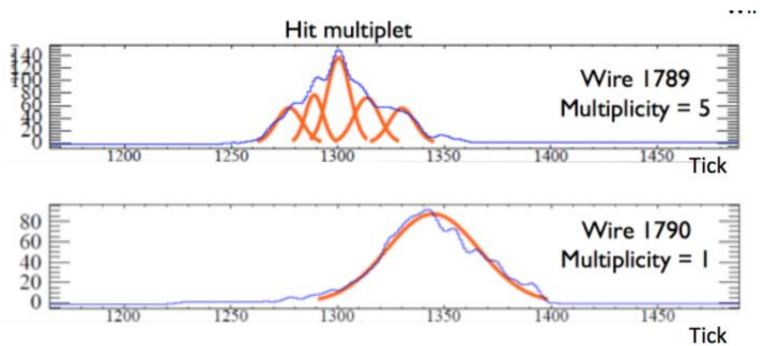


JINST 12 P07010 (2017)

Hit-finding → Gaussian fits to pulses on each wire to reconstruct arriving charge

3D track/shower reconstruction

Signal processing in MicroBooNE

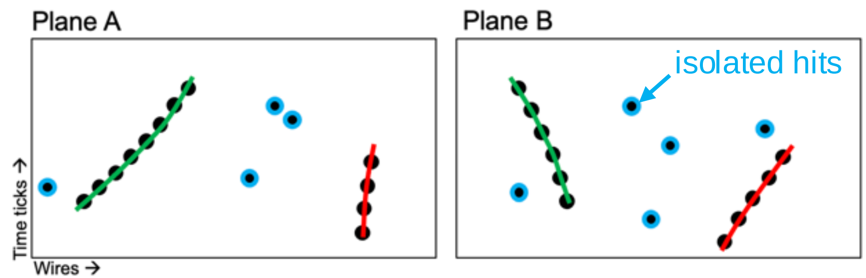


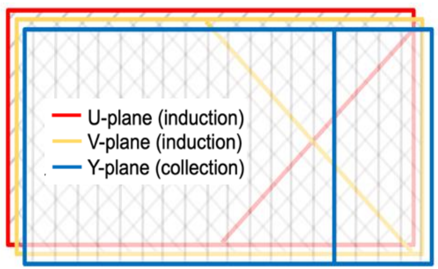
JINST 12 P07010 (2017)

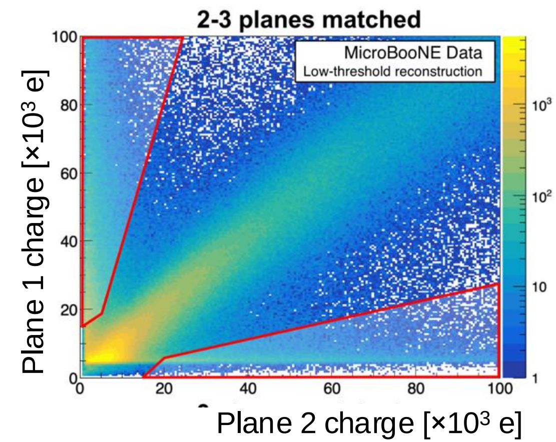
Hit-finding → Gaussian fits to pulses on each wire to reconstruct arriving charge

3D track/shower reconstruction

3D blip reconstruction



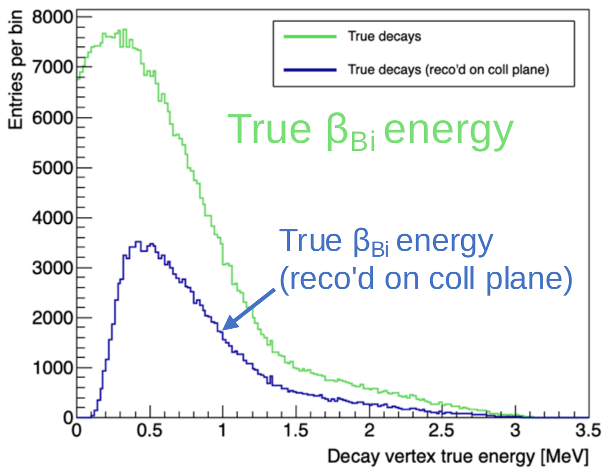


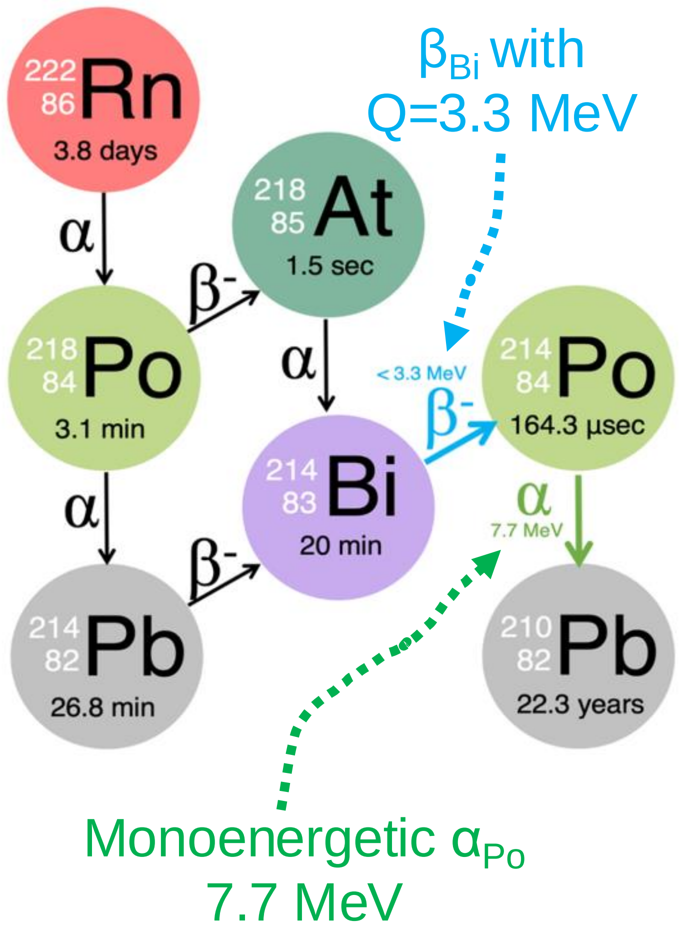


(1) Isolated hits clustered on each wireplane
(2) Clusters time-matched between planes
(3) Crossing-wire requirement
(4) Relative charge comparison

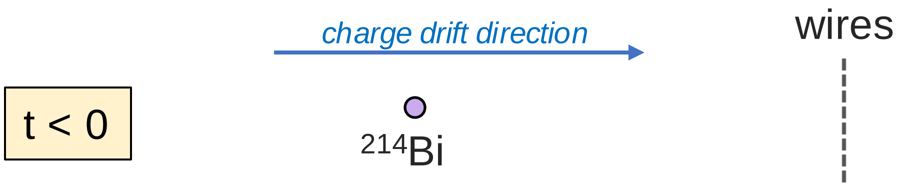
Radon R&D studies in MicroBooNE

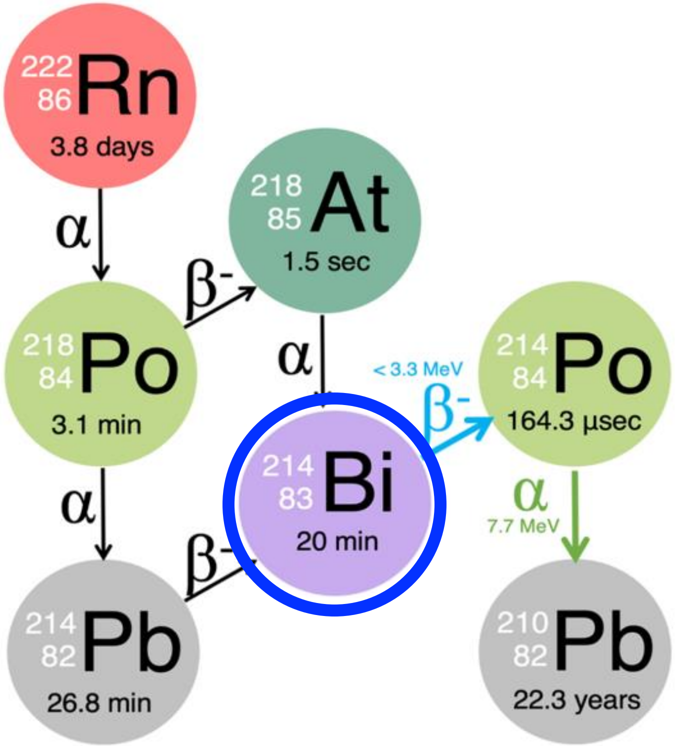
- To test its MeV-scale sensitivity, radon was introduced into Lar circulation during a special 2021 R&D run
  - ^{222}Rn has a 3.8 day half-life
    mixes diffusely throughout active volume
  - ^{214}Po has a short (164 μs) half-life
    can tag ^{214}Bi→^{214}Po decay



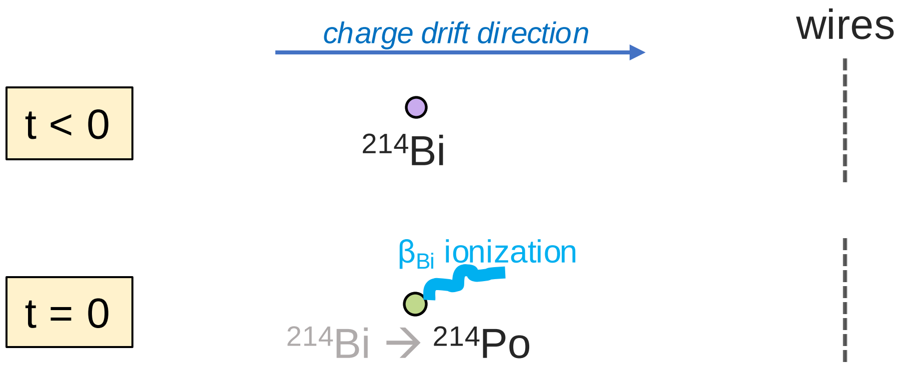


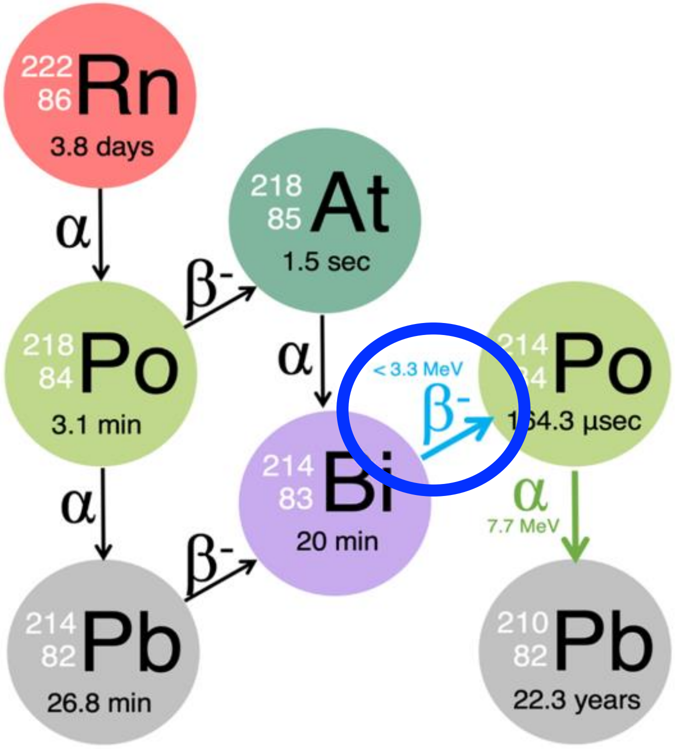
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



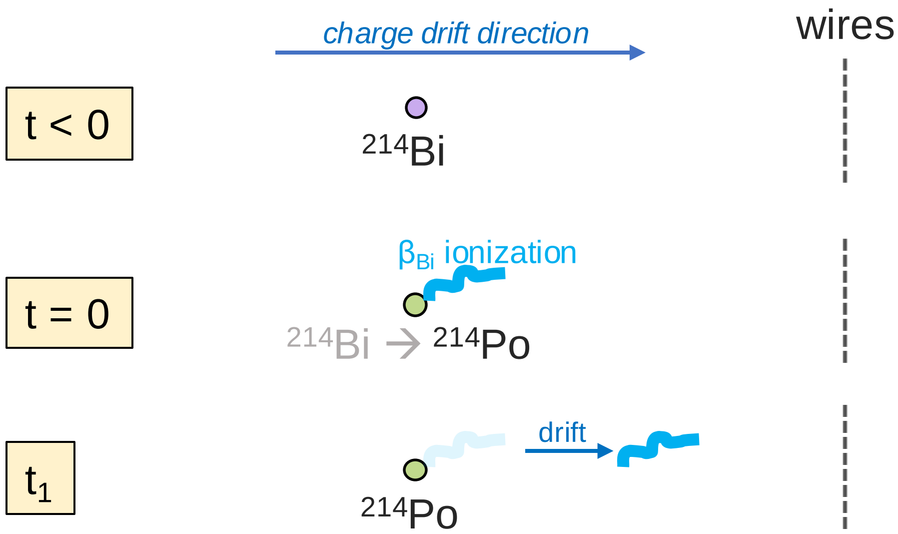


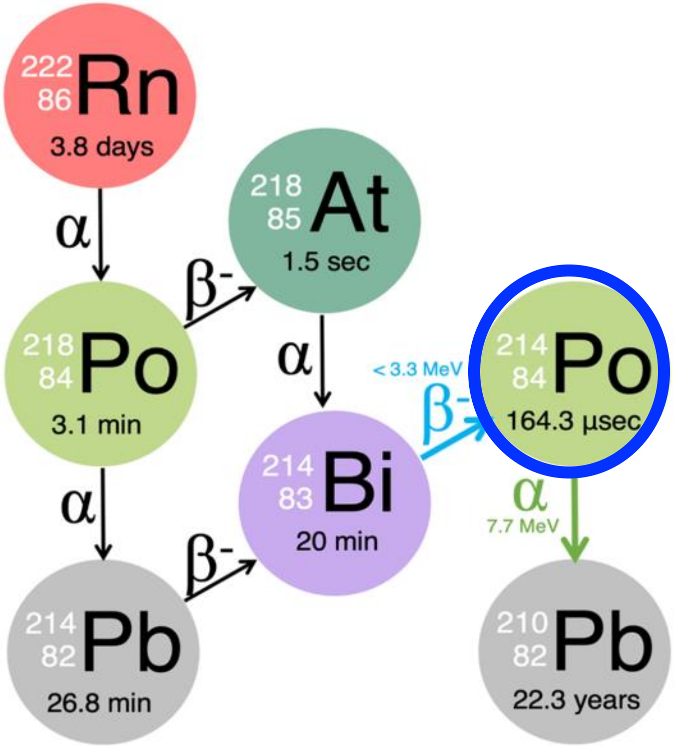
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



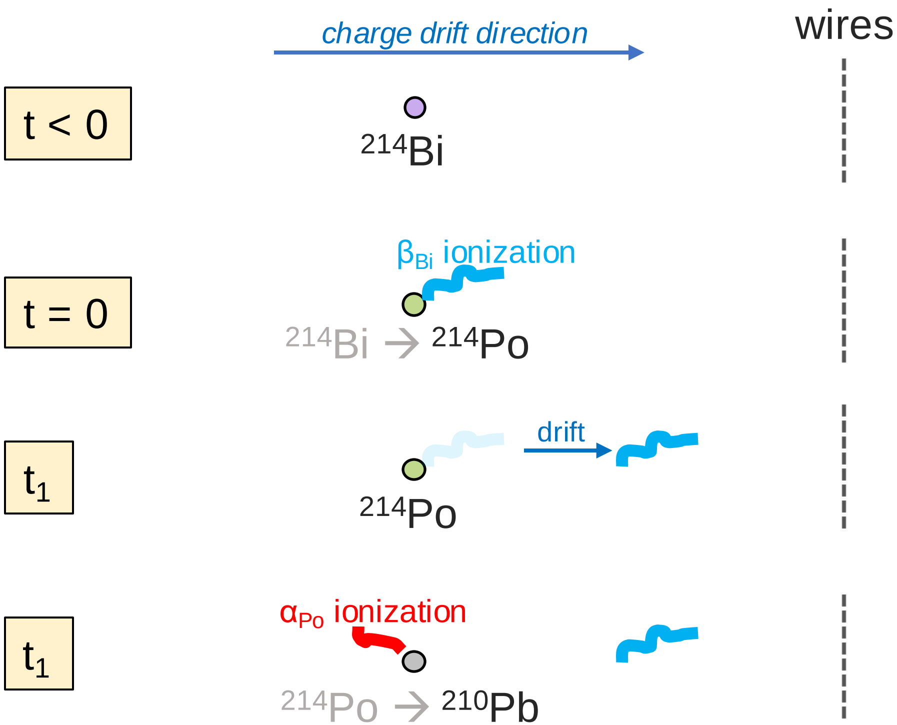


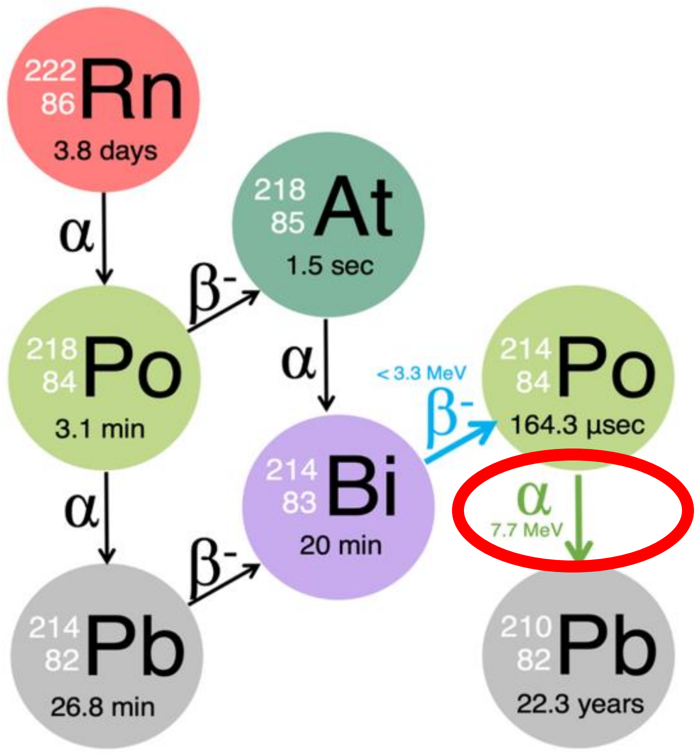
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



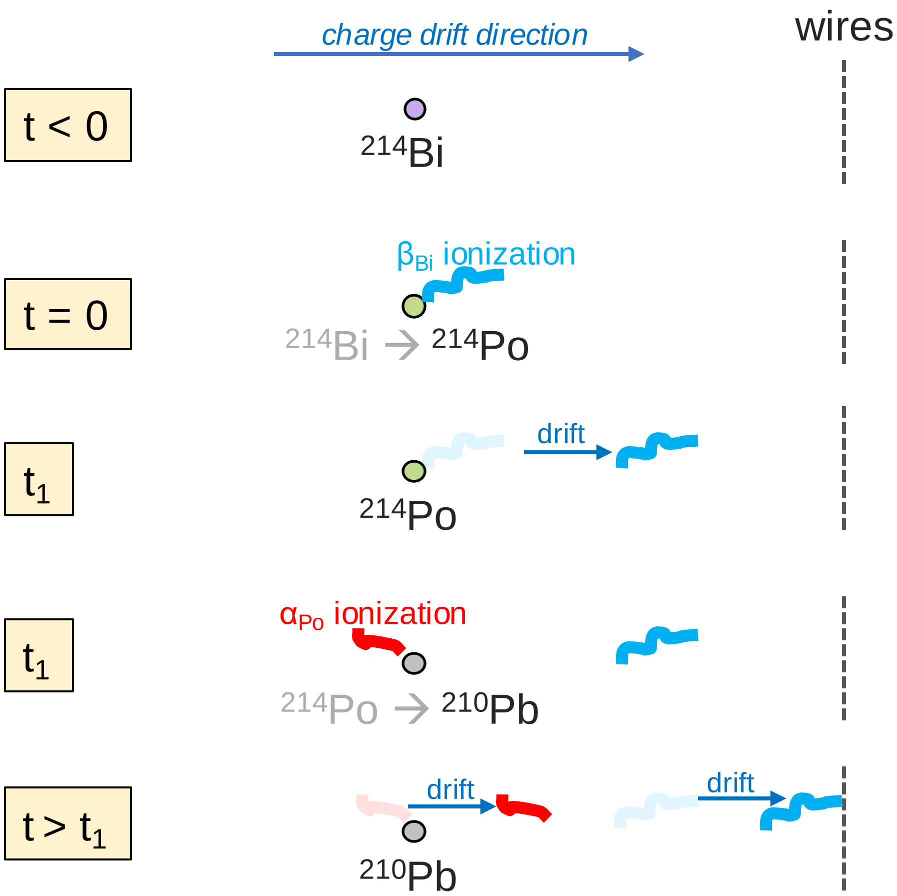


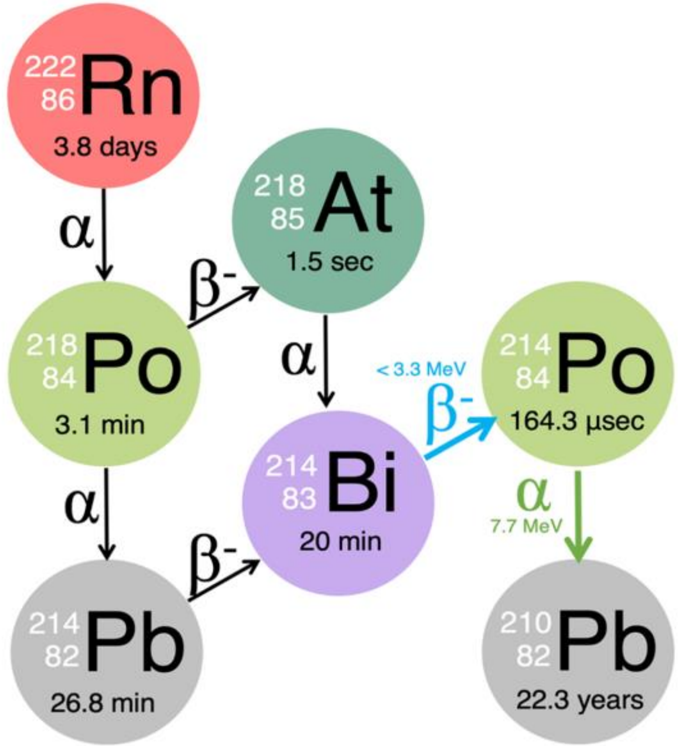
$^{214}Bi \rightarrow {}^{214}Po$ Decay Tagging



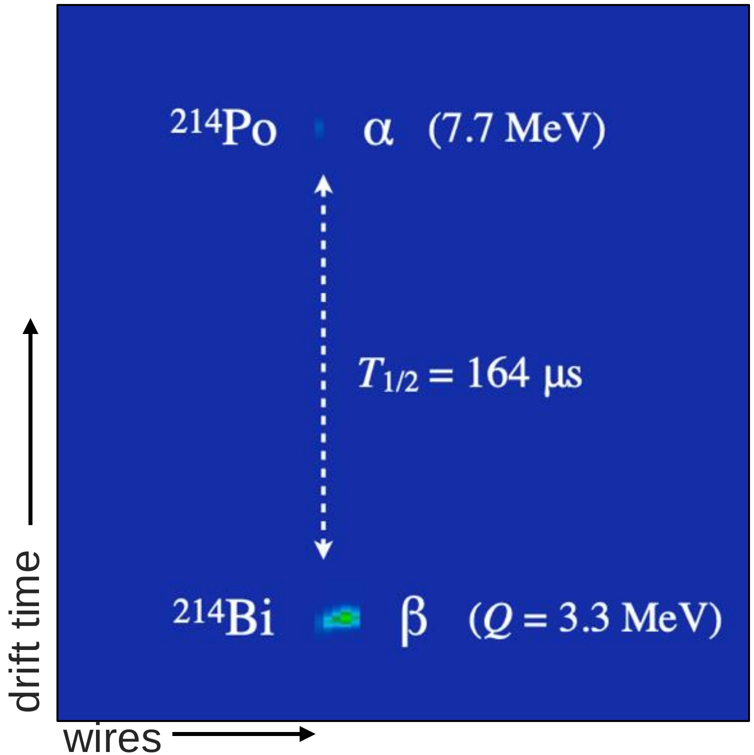


^{214}Bi → ^{214}Po Decay Tagging

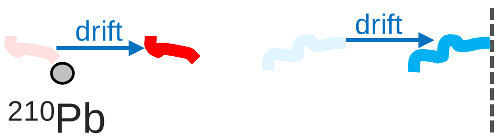


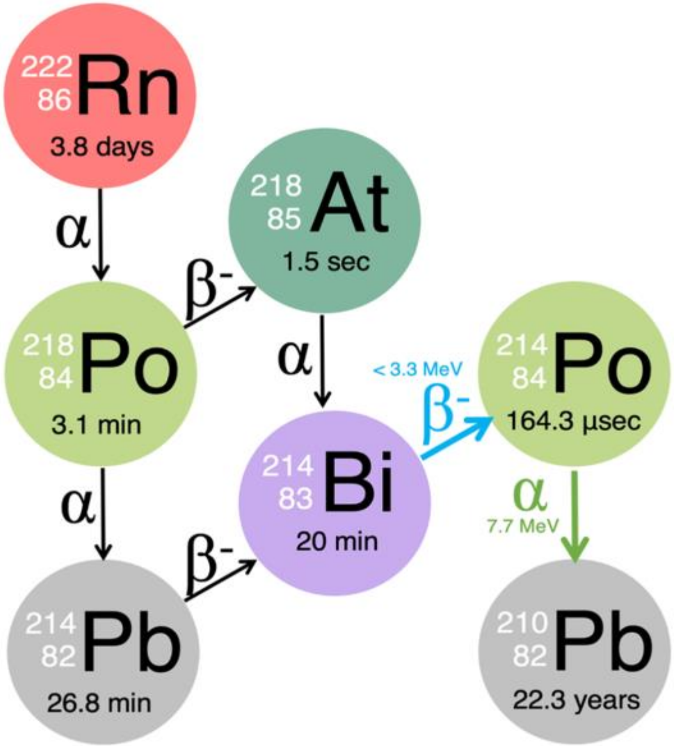


^{214}Bi → ^{214}Po Decay Tagging

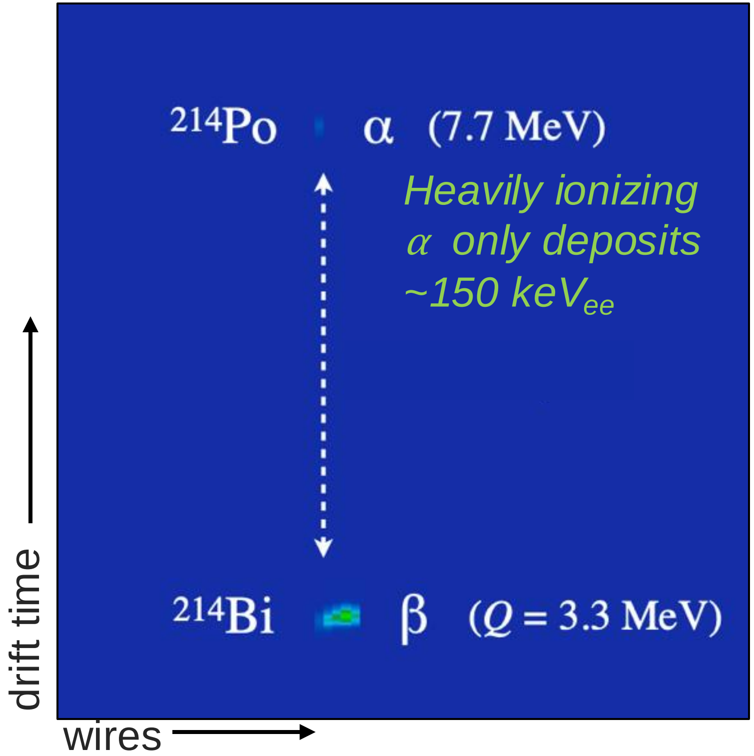


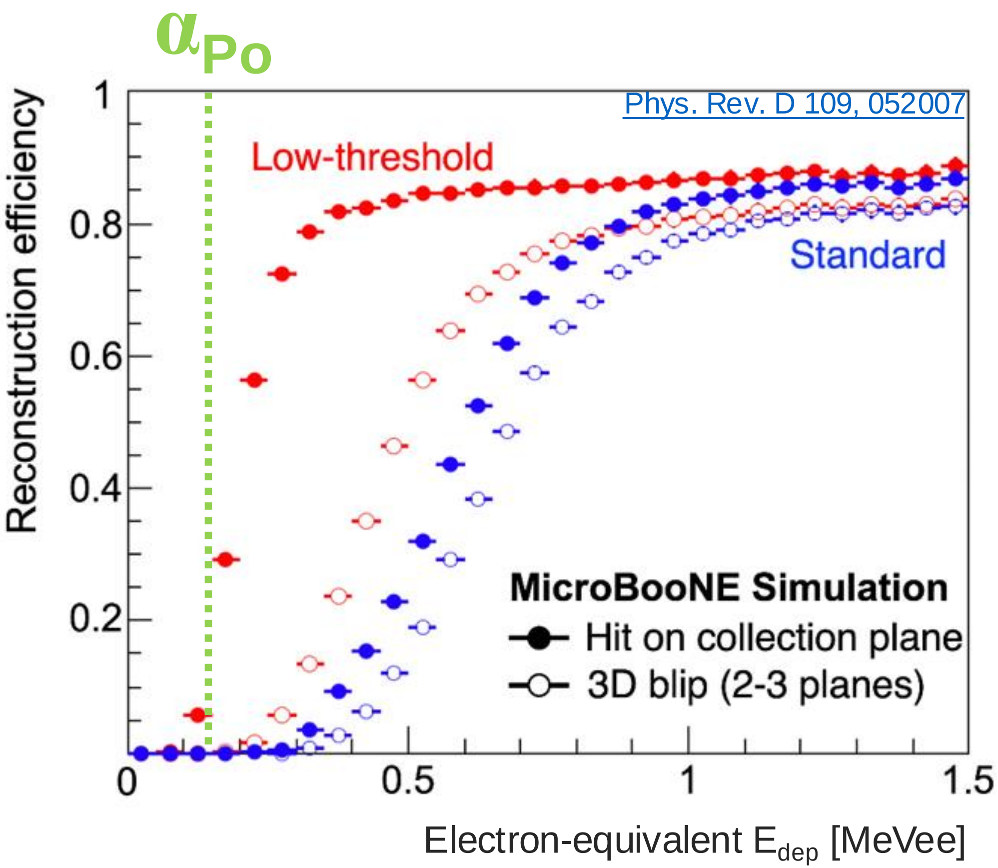
t > t_1





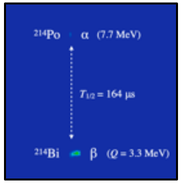
Energy scale of signals

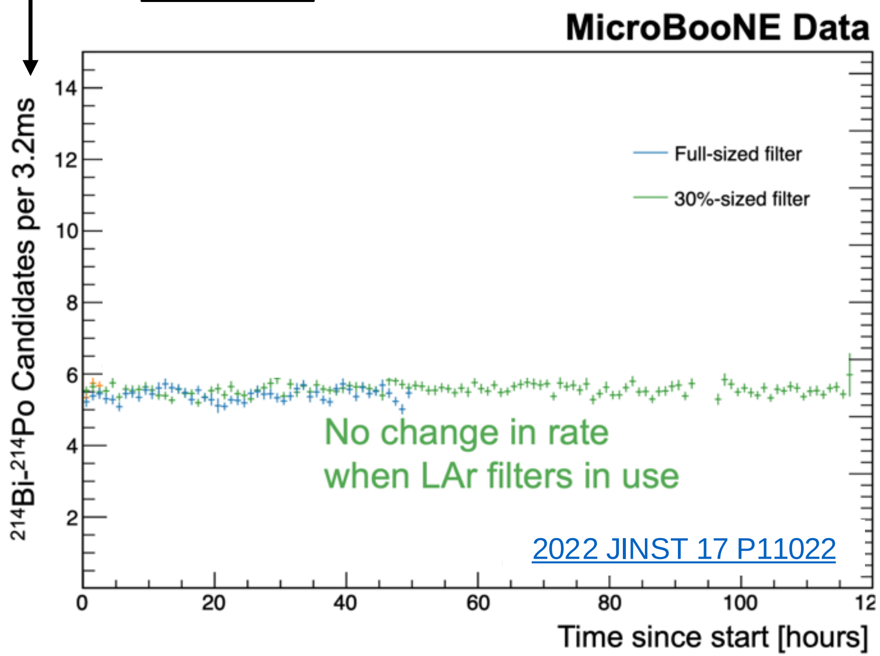




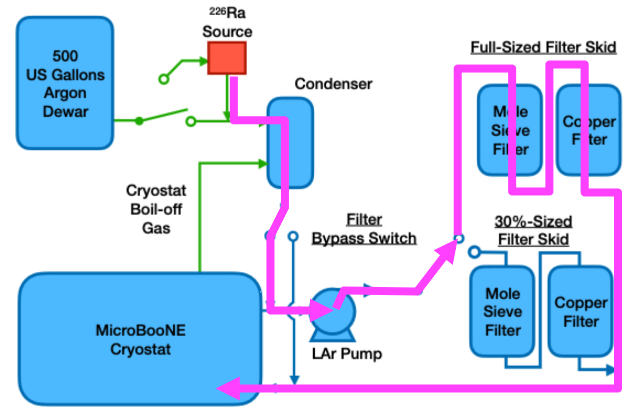
Reconstruction settings tweaked to expand sensitivity to lower energies

Bi-Po candidate rate in radon-doped LAr

Rate () on collection plane only



Usual filter configuration



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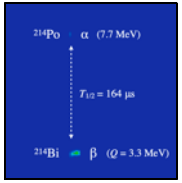
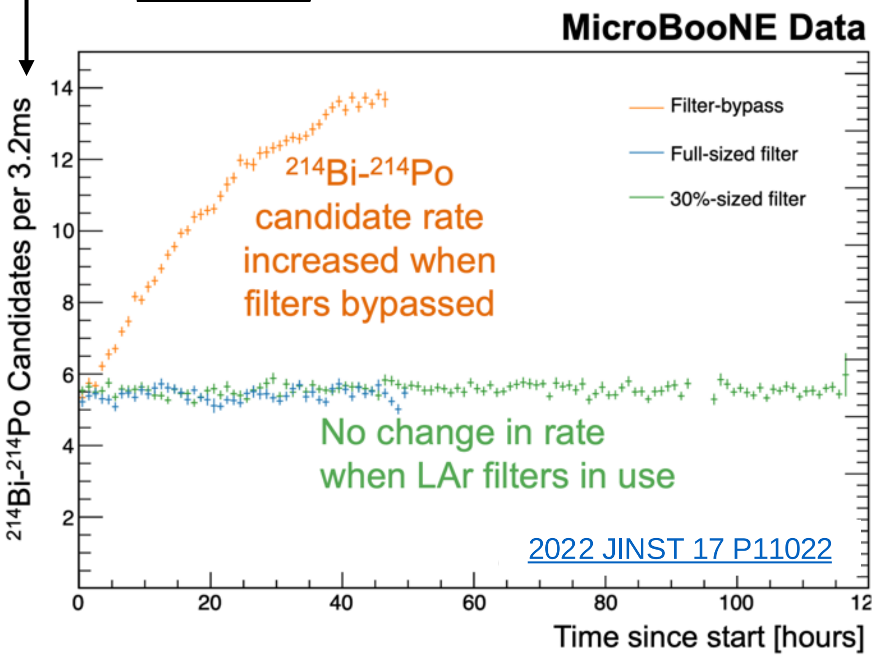
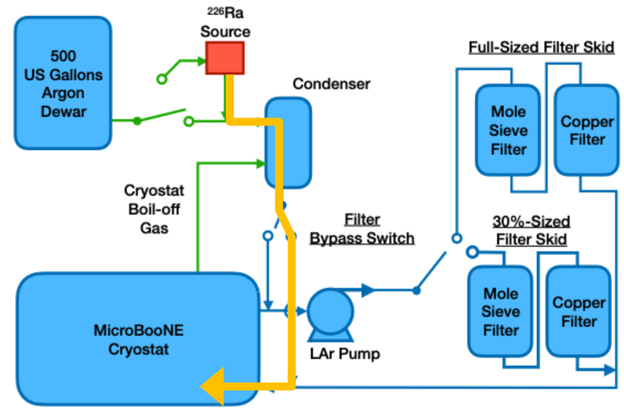
Rate () on collection plane only



"Filter bypass"



> 99.9997% of Rn removed by 77L filter

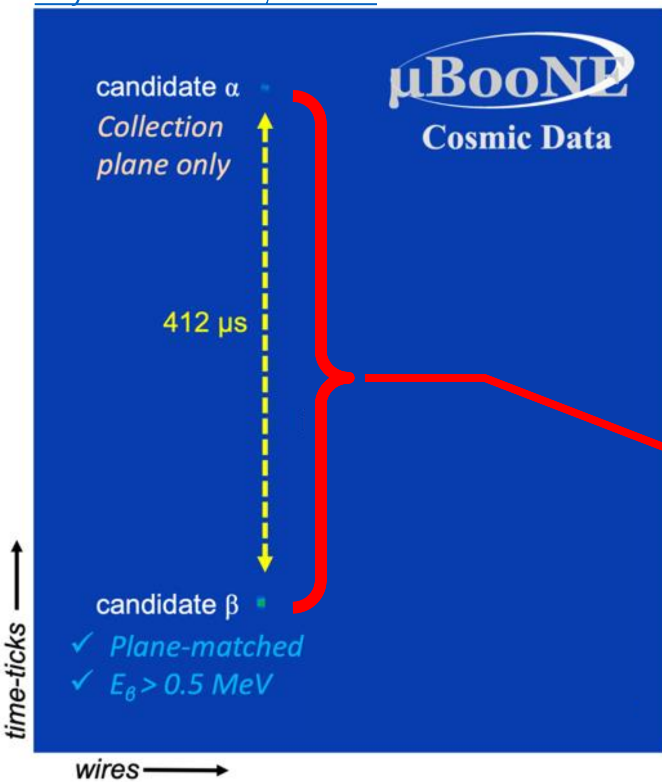
Surprising results:

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

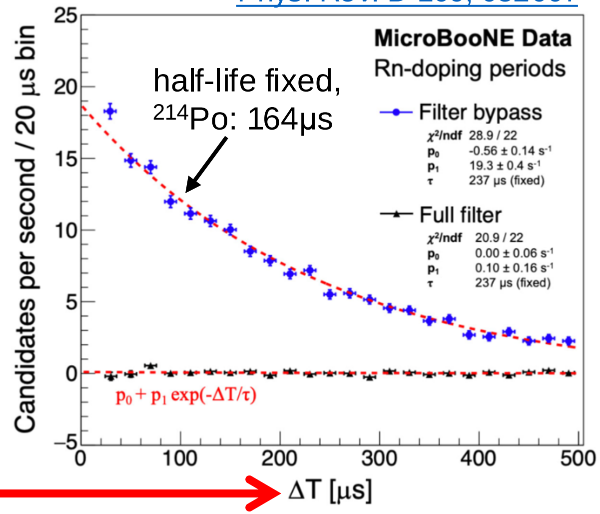
Follow-up study

- Improved reconstruction and developed technique to subtract backgrounds using a parallel sideband selection

Phys. Rev. D 109, 052007



Phys. Rev. D 109, 052007



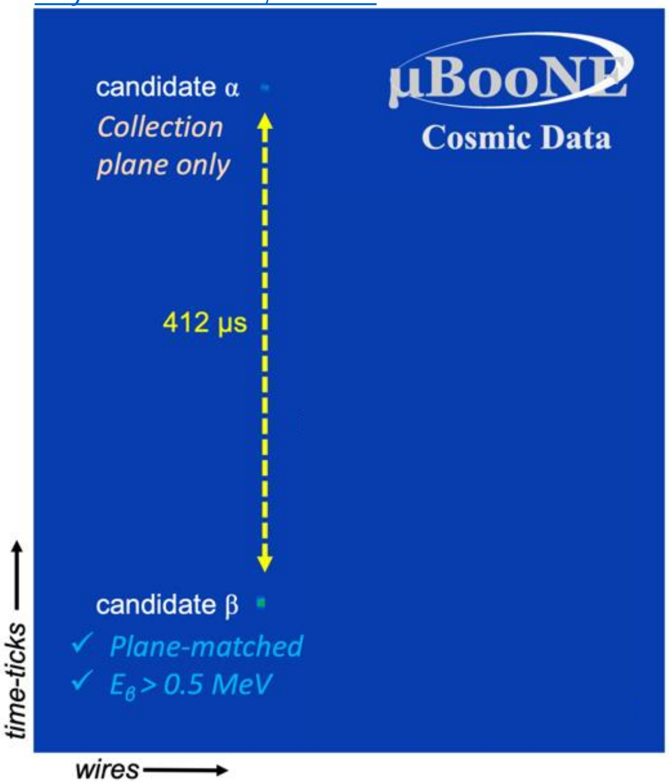
Filter bypass:
0.73 ± 0.05 per event

Full filter:
< 10^{-2} per event

Follow-up study

- Improved reconstruction and developed technique to subtract backgrounds using a parallel sideband selection

Phys. Rev. D 109, 052007



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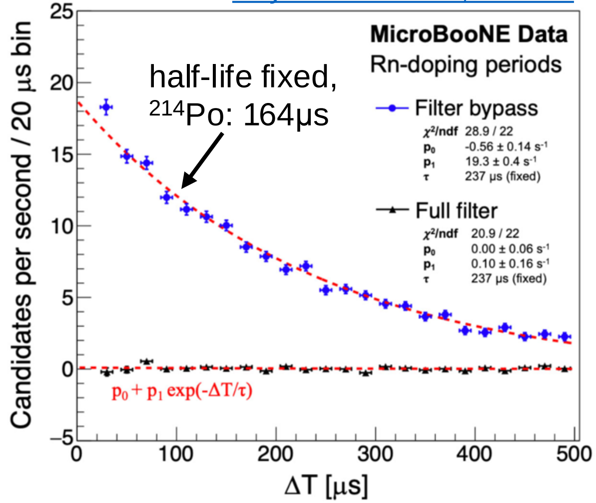
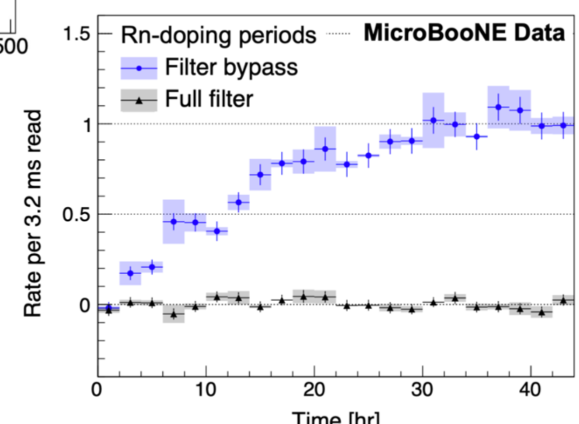


Filter bypass:
0.73 ± 0.05 per event

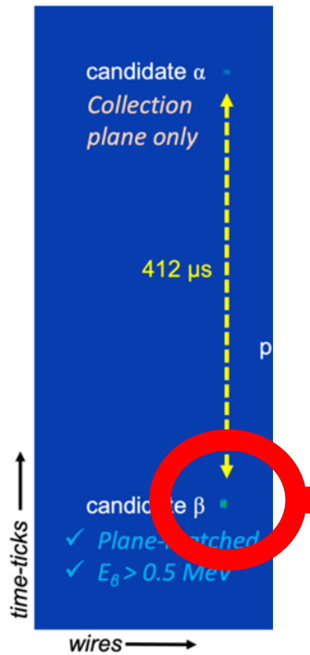
Full filter:
< 10^{-2} per event

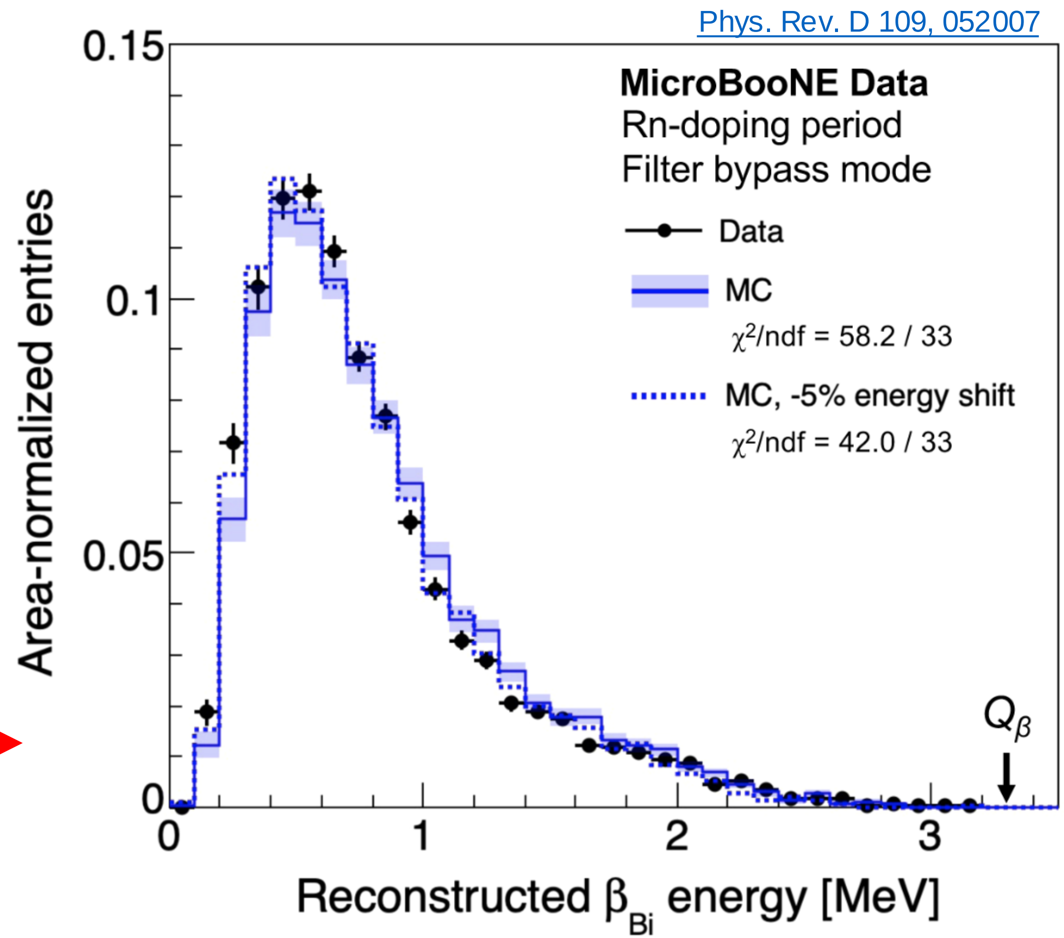
Repeating procedure for separate 2-hour time periods



Calorimetric validation: 0-3.3 MeV β_{Bi}

Same technique applied to β *energy spectrum*

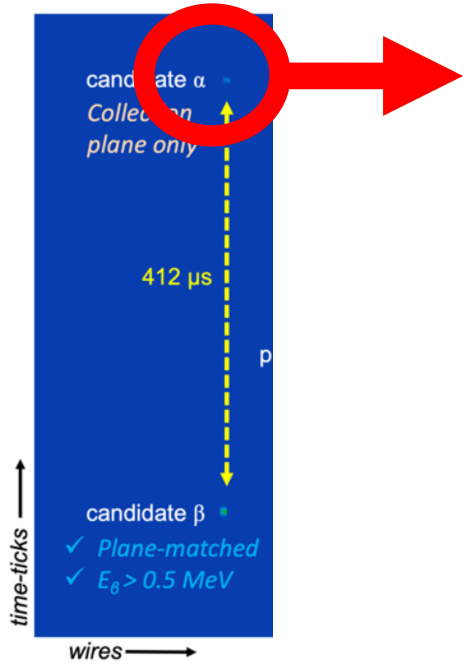




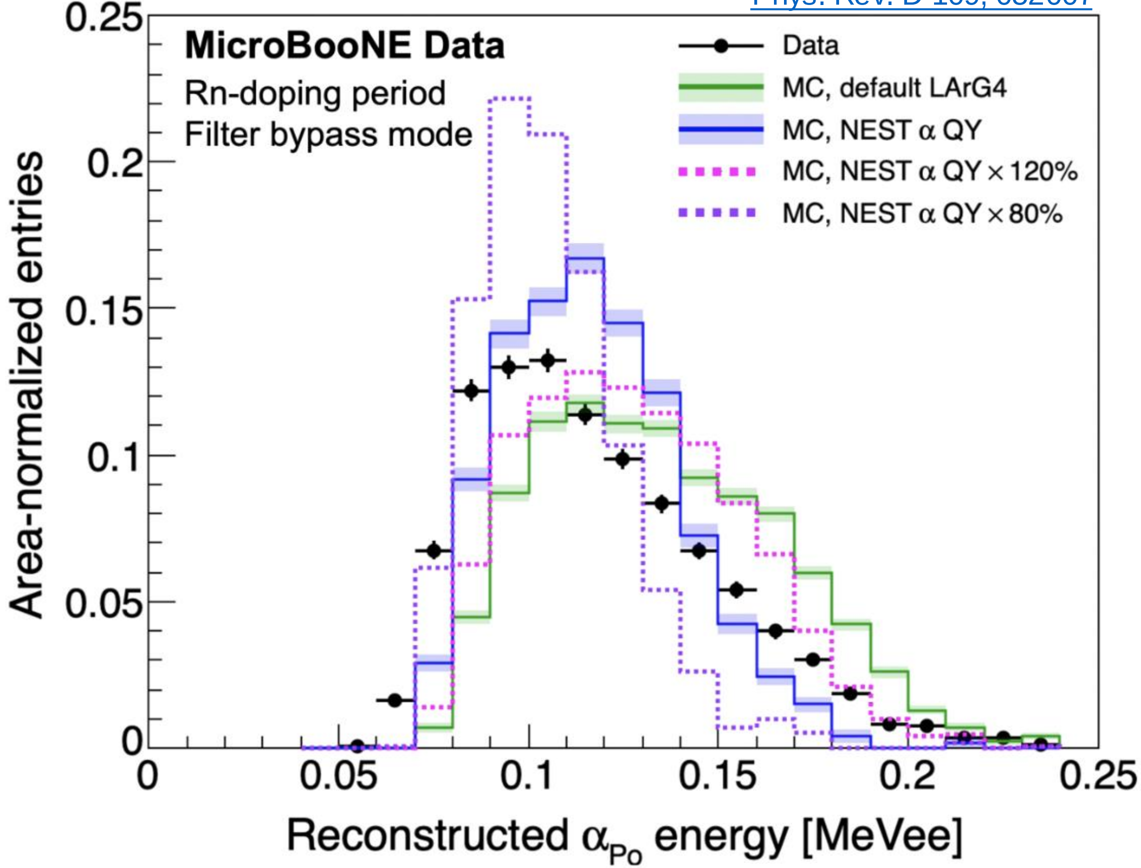
Calorimetric validation: 7.7 MeV α_{Po}

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

(large uncertainties in charge yield/quenching)

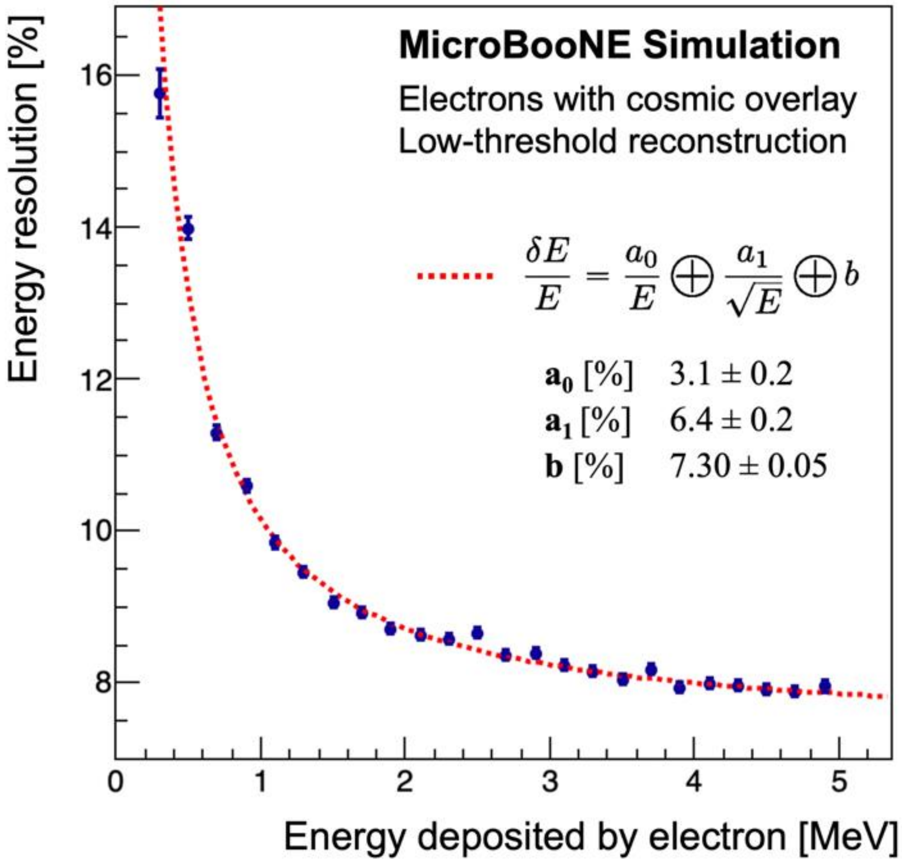


Phys. Rev. D 109, 052007



Calorimetric energy resolution from MC

Phys. Rev. D 109, 052007



With MC validated on data, we can extract the energy resolution

MC electron resolution:

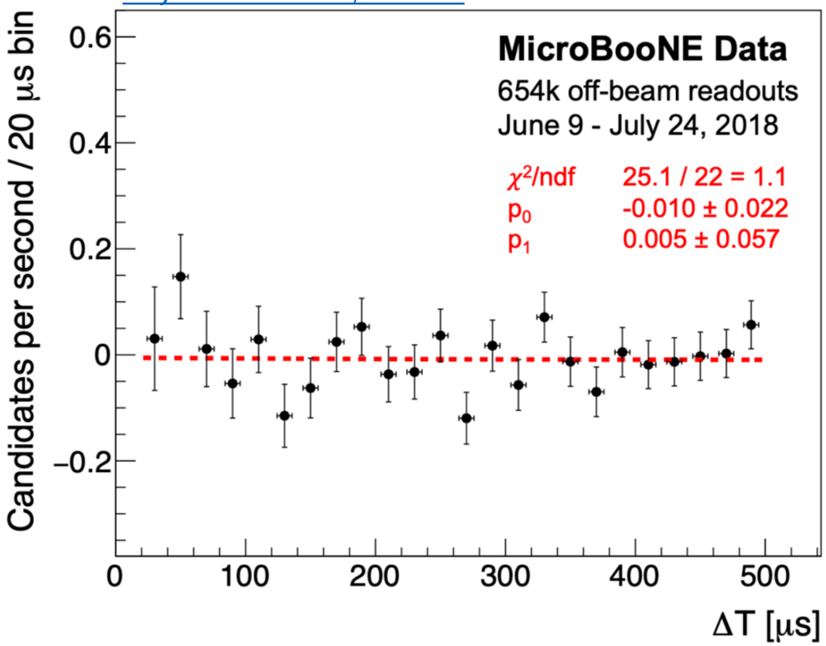
- 10% at 1 MeV
- 8% at 5 MeV

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)

Searching for ambient radon in physics data

Phys. Rev. D 109, 052007



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

Searching for ambient radon in physics data

Phys. Rev. D 109, 052007

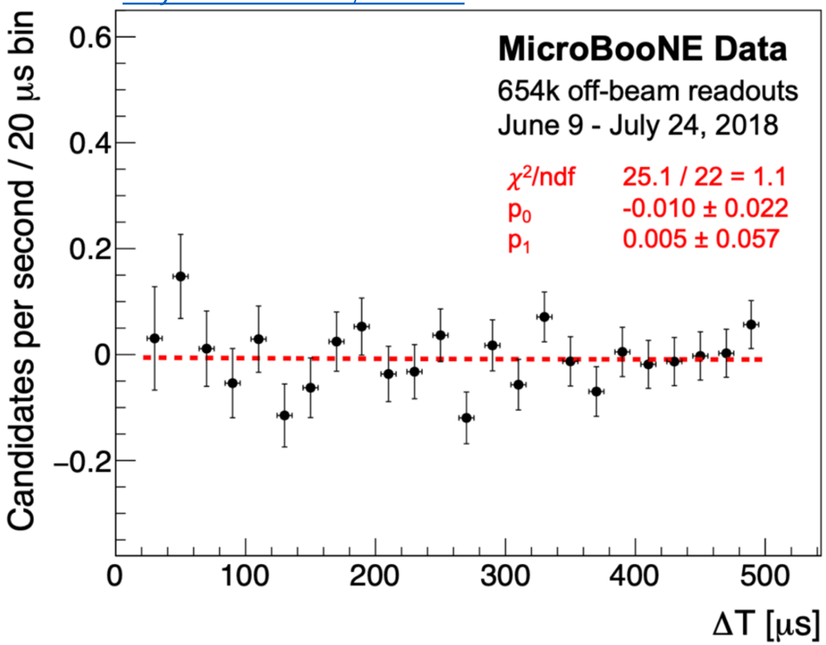
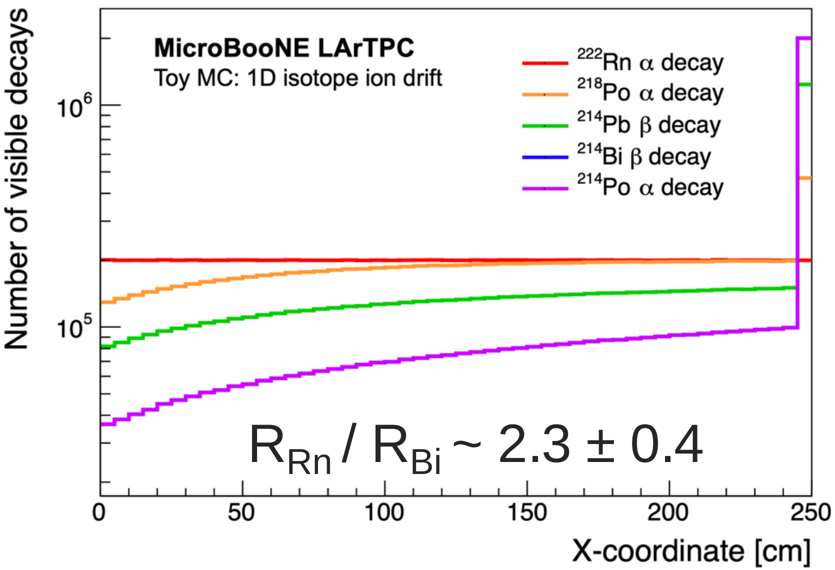


Plate-out effects estimated with toy MC to convert ^{214}Bi rate to ^{222}Rn rate



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

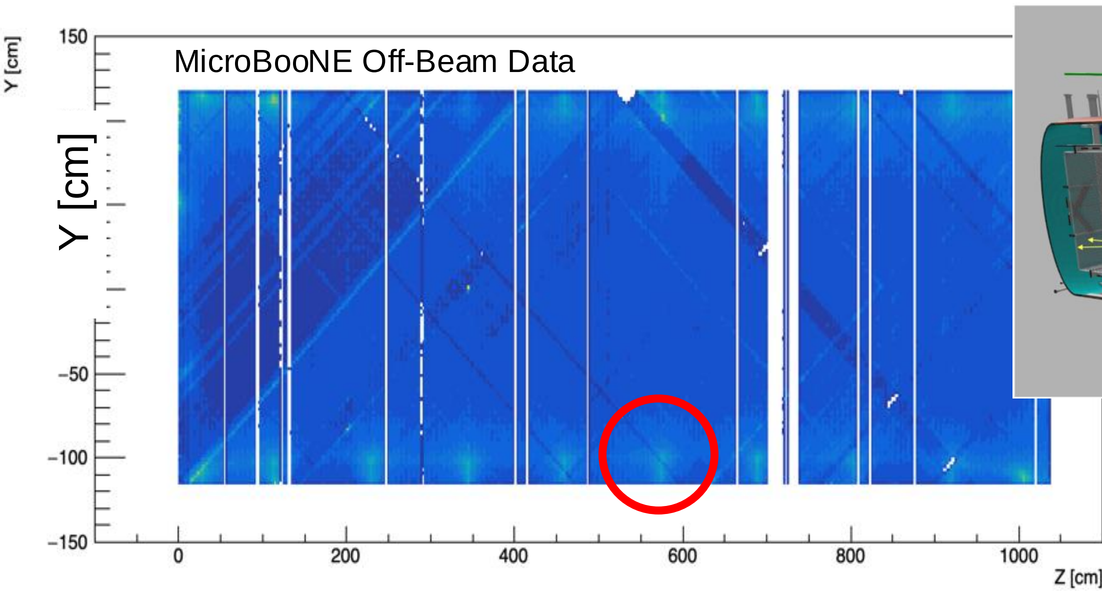
R_{Rn} < 1 mBq/kg
(DUNE target)

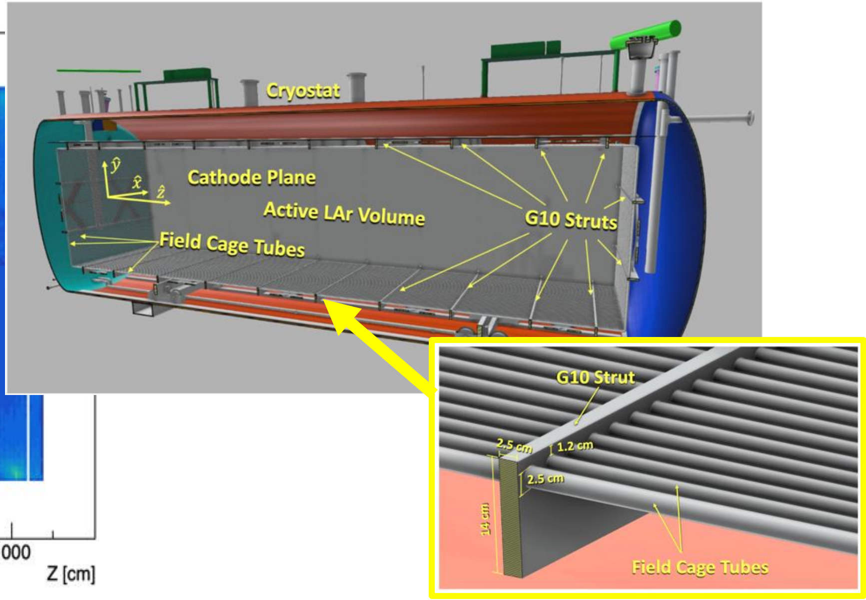
Ongoing work using ambient blips

- Using G10 'hotspots' at edge of detector as MeV-scale calibration source (Compton edge from radioactive ^{208}Tl γ)
- Identifying proton-like blips in cosmogenic data

See poster by Diego Andrade!

[Demonstrating MeV-Scale Physics Capabilities of Large Neutrino LArTPCs with Ambient Blip Activity in MicroBooNE]

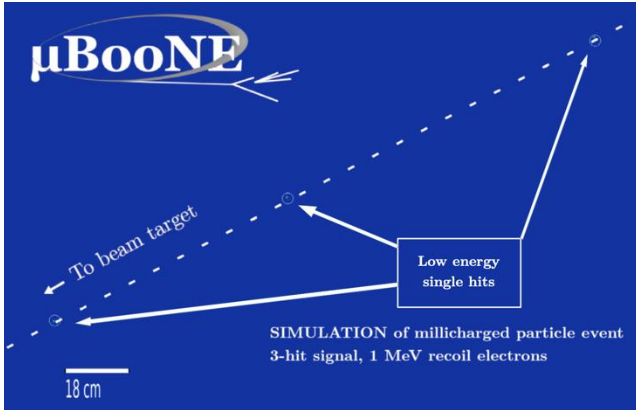


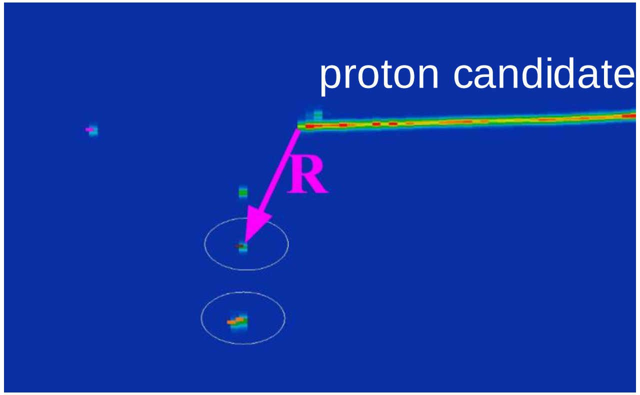


Conclusions

- MicroBooNE is working to expand calorimetric capabilities of LArTPCs by pushing to unprecedented MeV-scale energies
  - 100 keV threshold
  - ~10% resolution at 1 MeV
- Developed method of monitoring ^{222}Rn contamination in-situ using standard data
- New custom tools are being integrated in other BSM and GeV-scale ν analyses
  - Millicharged particle searches
  - NC ν-p elastic scattering
  - Low-energy proton vertex finding for single shower events (1g0p)

Thank you!





BACKUP

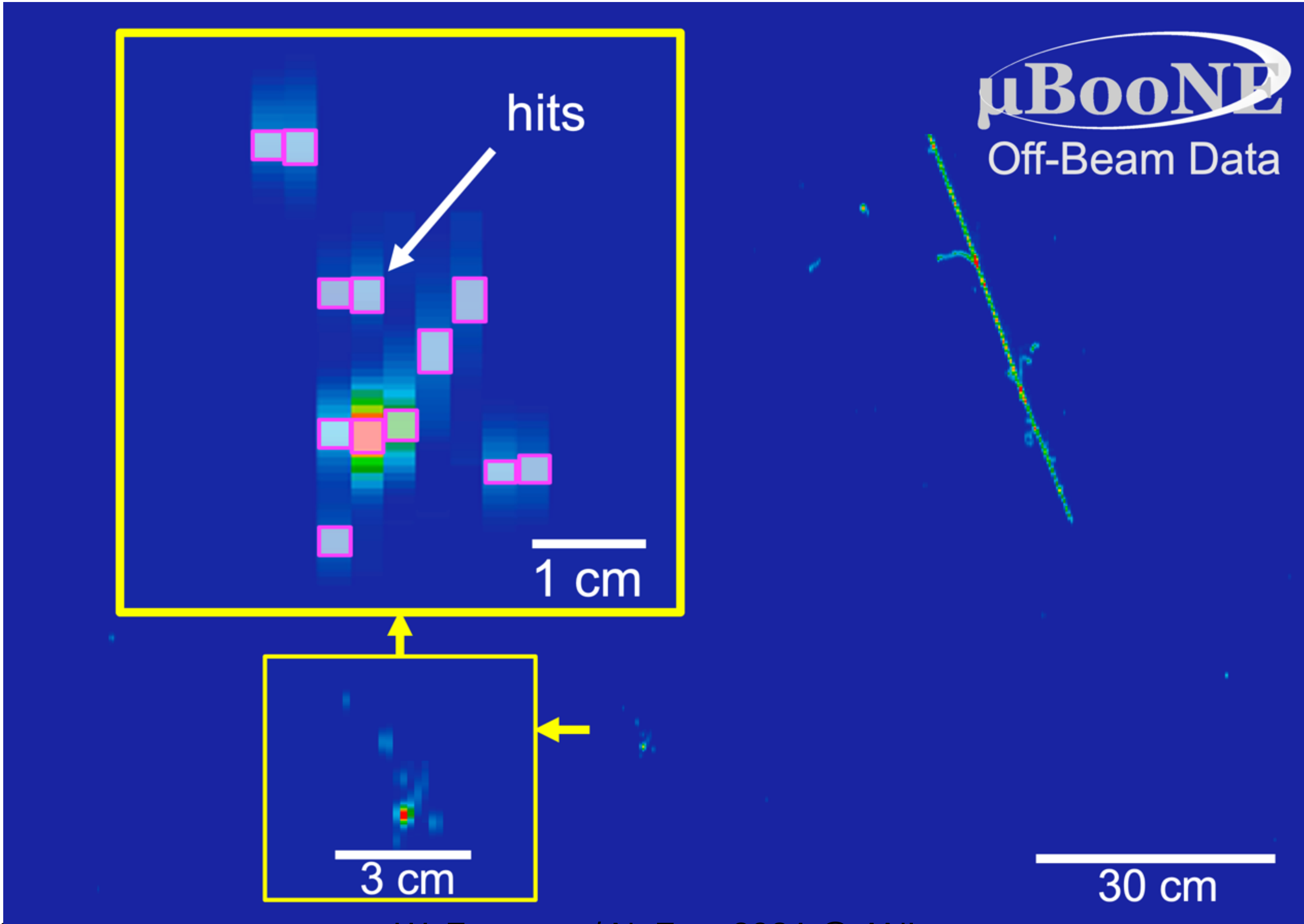
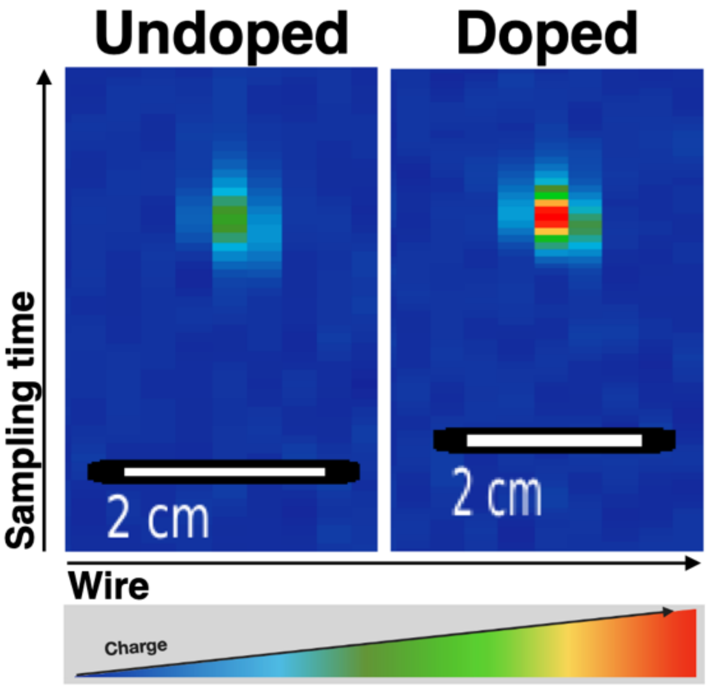
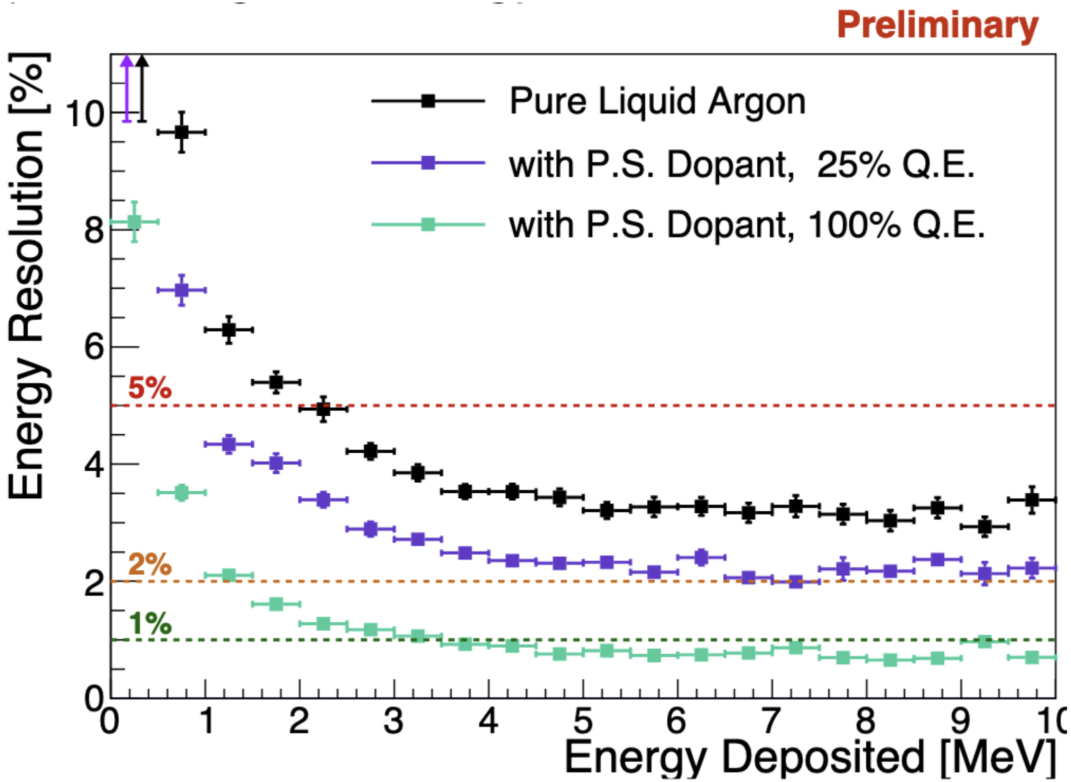

hits
1 cm
3 cm
µBooNE
Off-Beam Data
30 cm

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 $\varphi(^8\mathrm{Bi})$ by measuring two interaction channels via crude angular cuts:

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

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

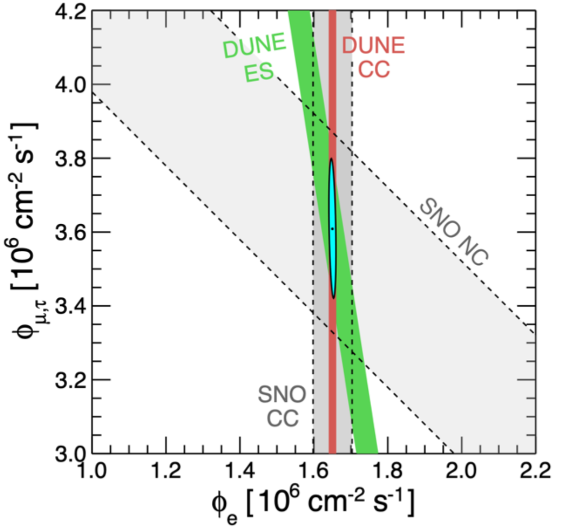


FIG. 3. Estimated precision of the ν_e and $\nu_{\mu,\tau}$ content of the ^{8}B flux, present (SNO [5, 53]) and future (DUNE), with the ellipse for DUNE alone. Based on a simplified analysis, with only statistical uncertainties (1σ) but assuming 2 d.o.f., and with SNO fluxes slightly rescaled to match 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)](https://doi.org/10.1103/PhysRevD.99.036009)

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.

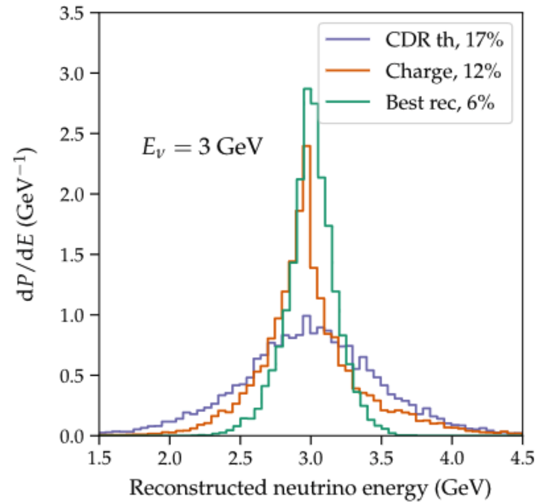


FIG. 14. Simulations of reconstructed neutrino energies for $E_\nu = 3$ GeV true energy in the CC $\nu_e + {}^{40}$Ar scattering process. The histograms correspond to three different sets of assumptions, as described in the text.

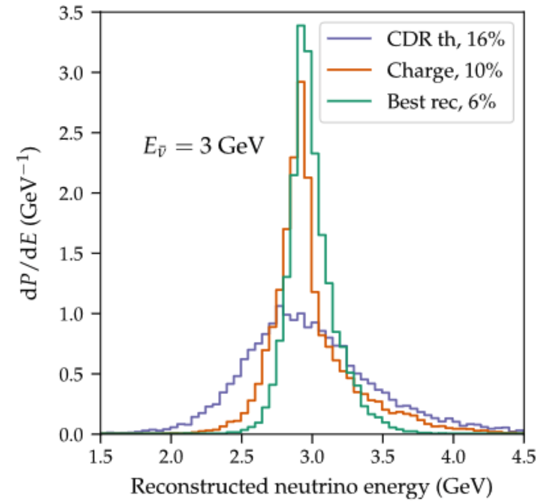


FIG. 15. Same as Fig. 14, but for $\bar{\nu}_e + {}^{40}$Ar scattering.

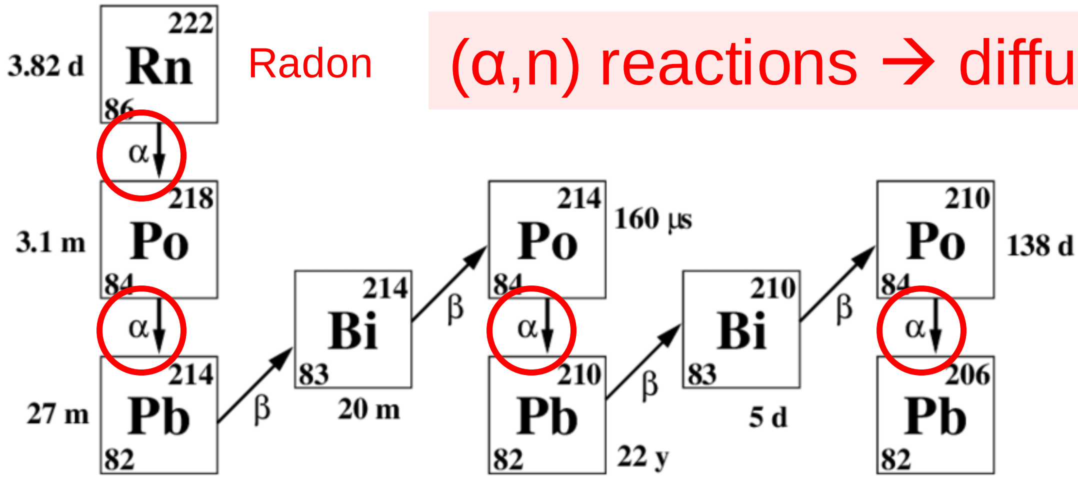
Understanding the energy resolution of liquid argon neutrino detectors

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)

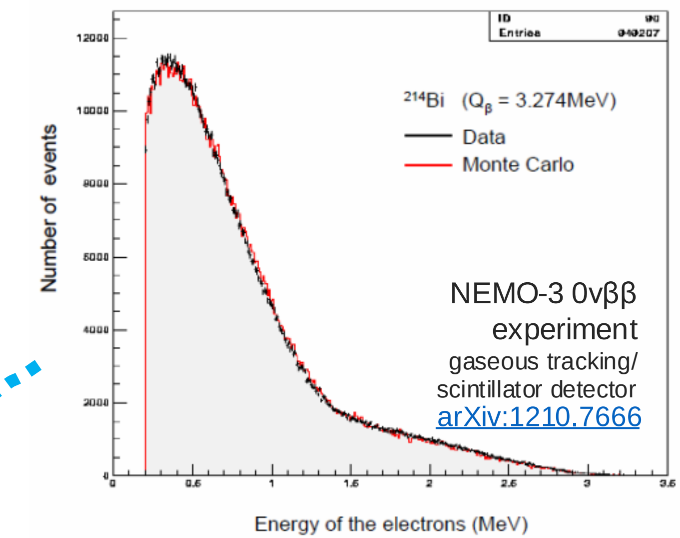
Diffuse neutron BGs from radon

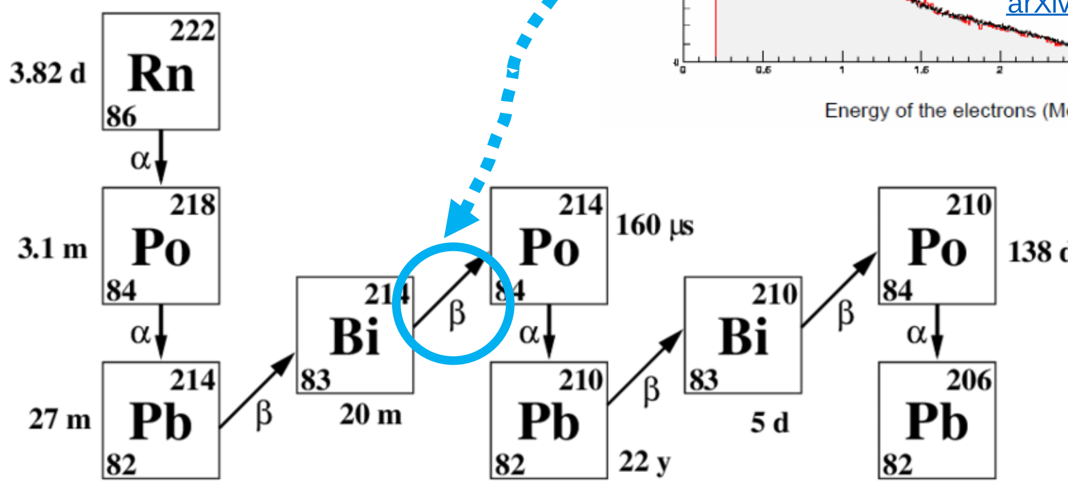
(α,n) reactions → diffuse neutrons



Remaining ~~Challenges~~ *Opportunities?*

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



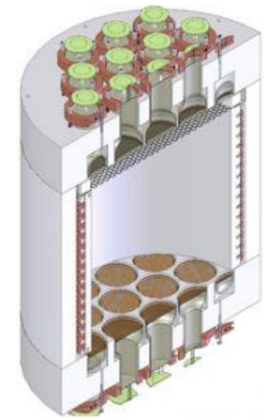


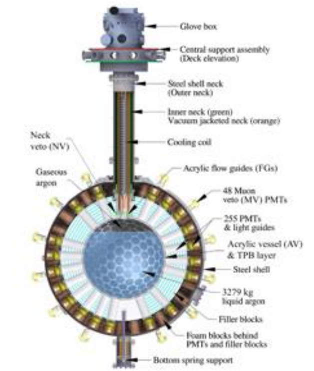
Radon in dark matter experiments

- 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



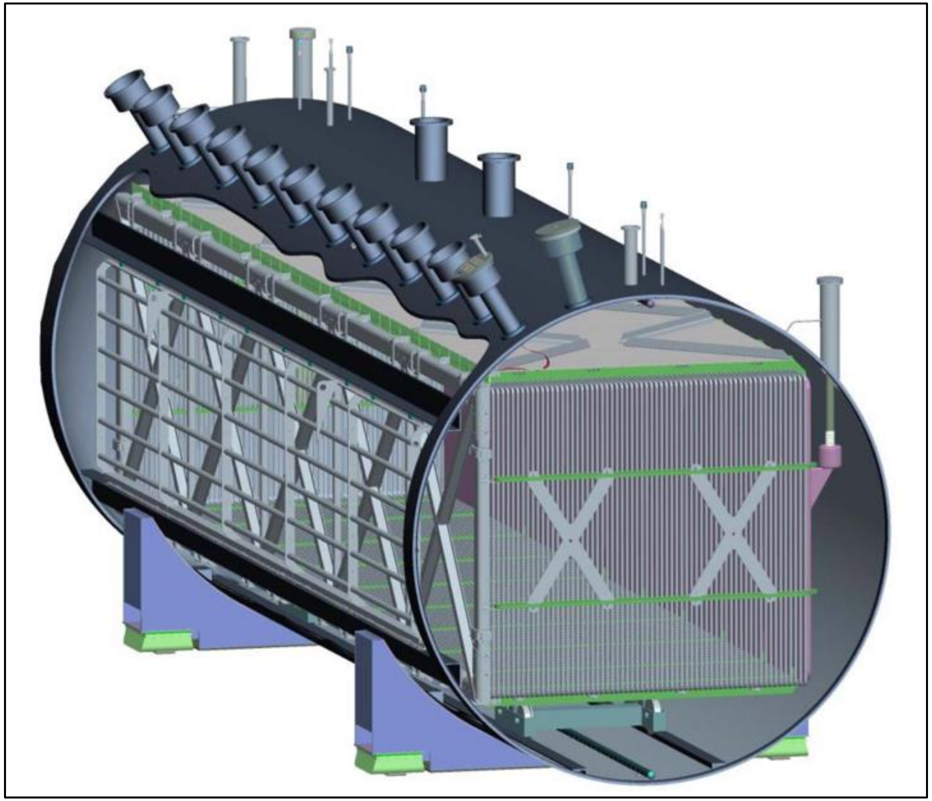


[1] Phys Rev D 98, 102006 (2018)
[2] Phys Rev D 100, 022004 (2019)

Bq = decays per second

The MicroBooNE Detector

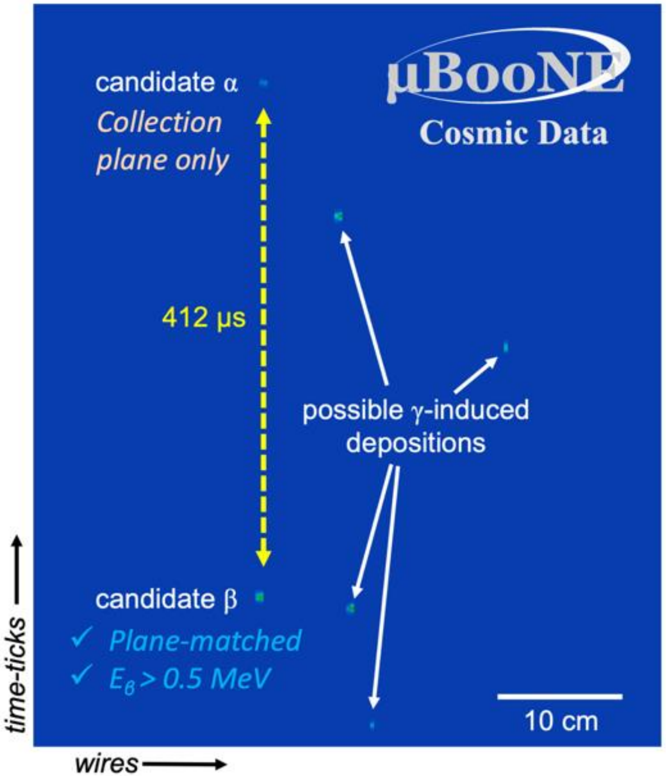
2017 JINST 12 P02017



~10m × 2.5m × 2.3m

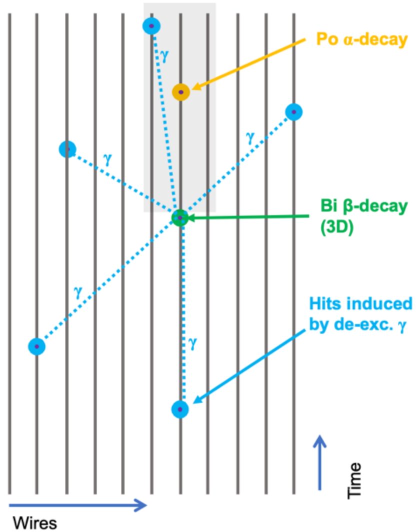
Signal backgrounds

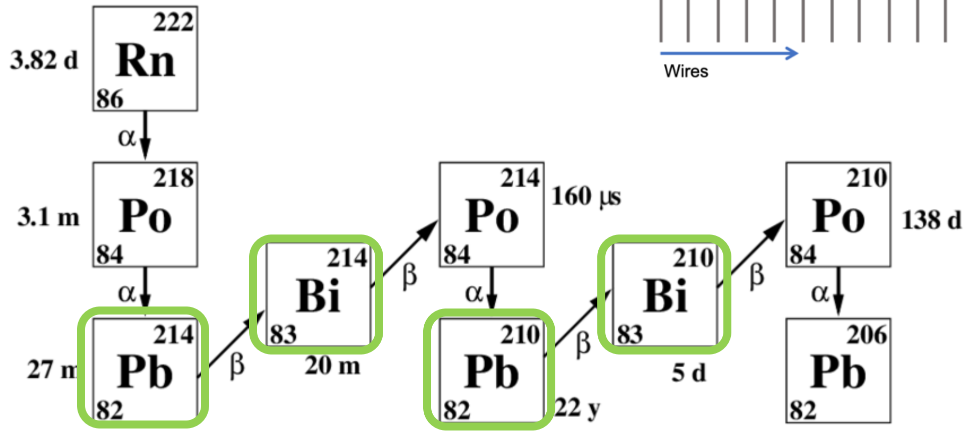
arXiv:2307.03102



^{214}Bi → ^{214}Po + β + Nγ

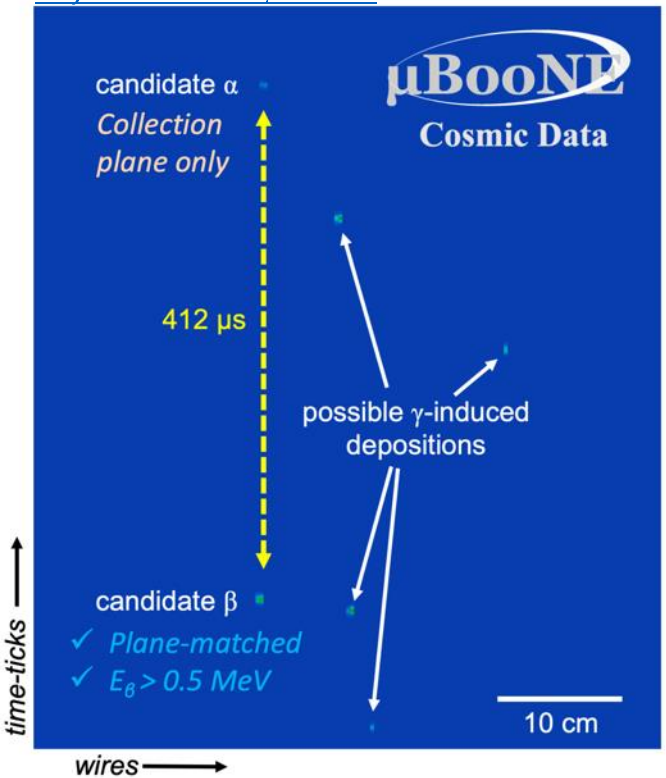
BiPo signal can be faked by other beta-emitting isotope decays



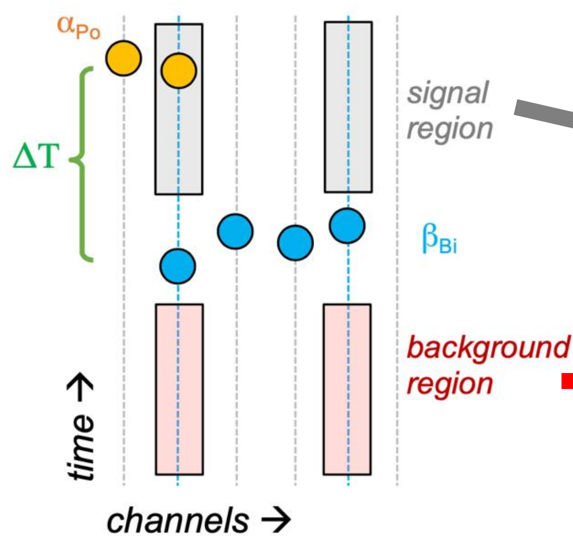


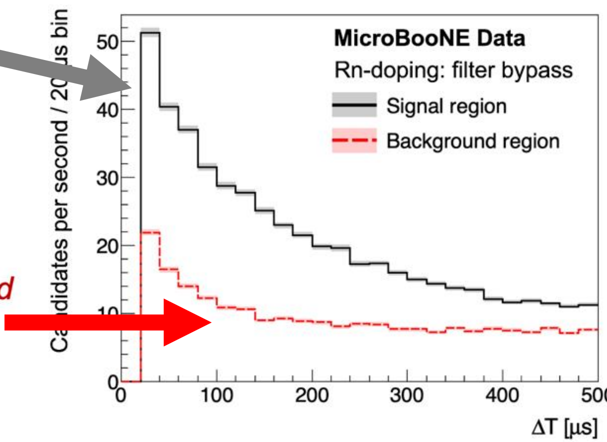
Follow-up studies / improvements

Phys. Rev. D 109, 052007



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



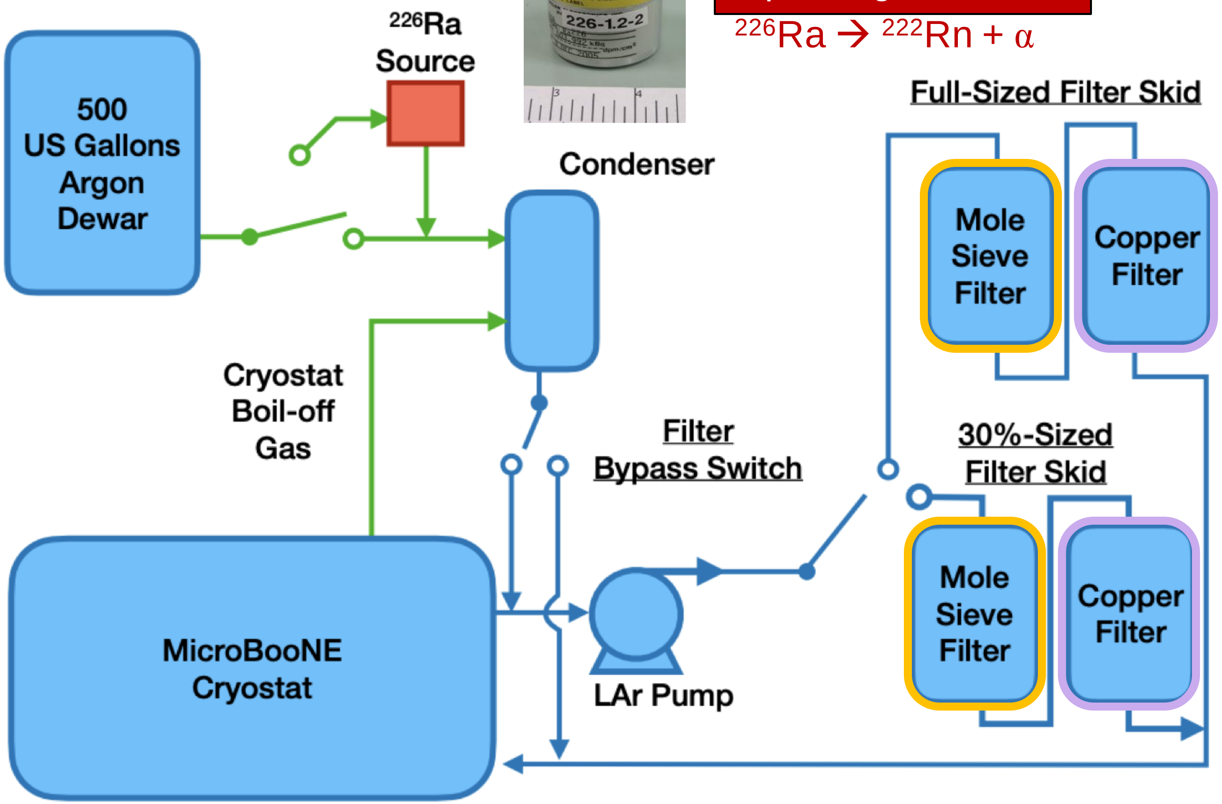


Doping radon into MicroBooNE

500 kBq radium source attached to input Ar gas line

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

Filters aim to remove electronegative contaminants



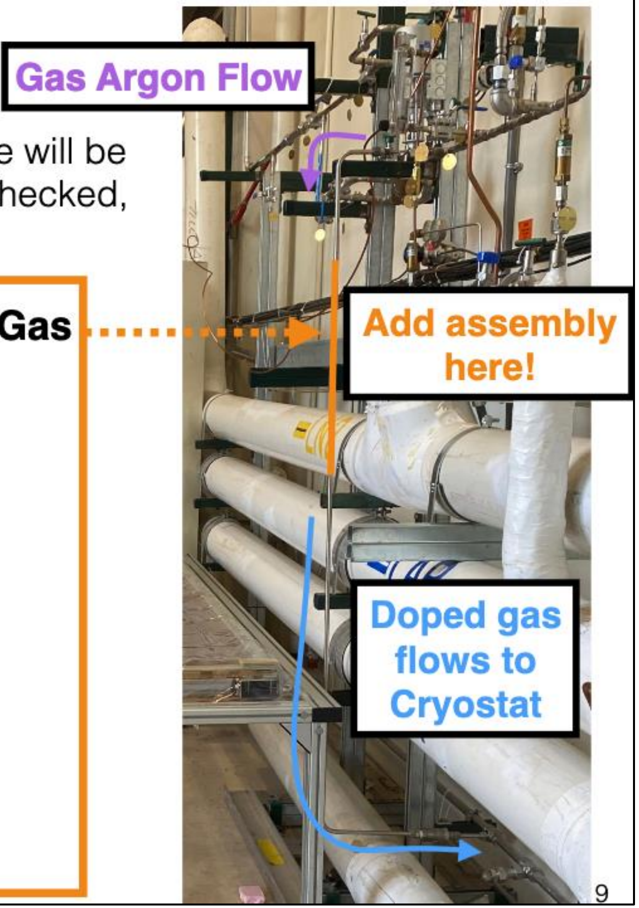
4Å molecular sieve
1.6-2.6 mm beads
removes water

Copper filter
Cu-0226 S
removes O_2

Doping radon into MicroBooNE

Design by Mike Zuckerbrot

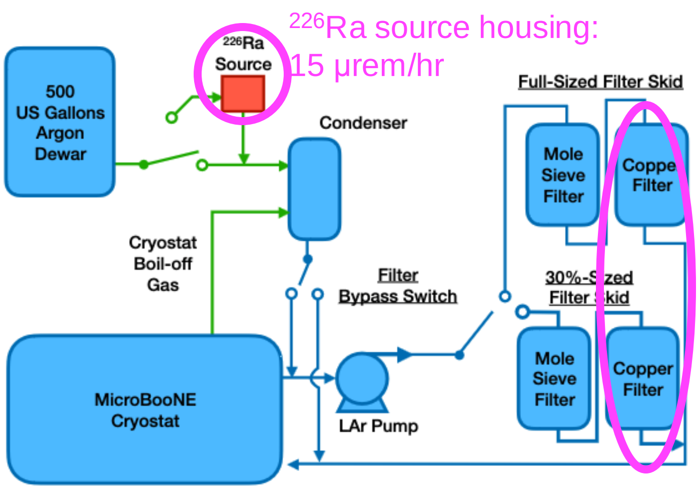
The original pipe will be cut, a conflat tee will be pressure fit, the source will be added, the tee will be sealed, the system will vacuum pumped, leak checked, and then operated



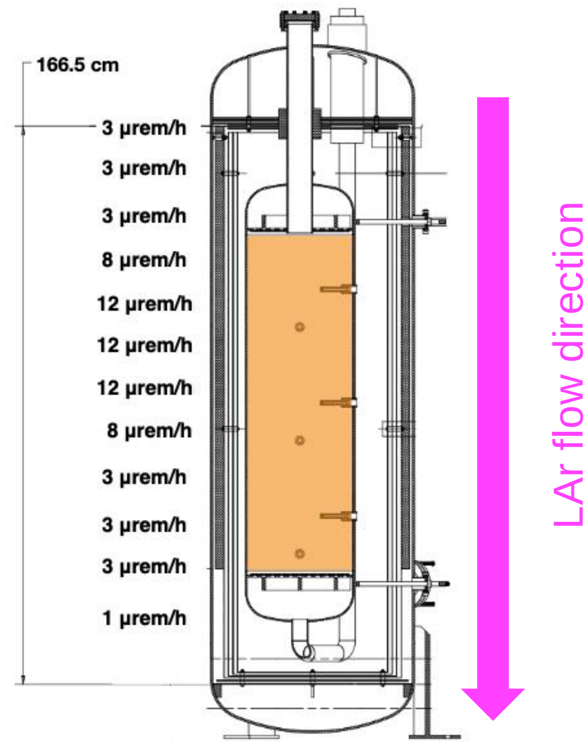
J. Zennamo, Fermilab

9

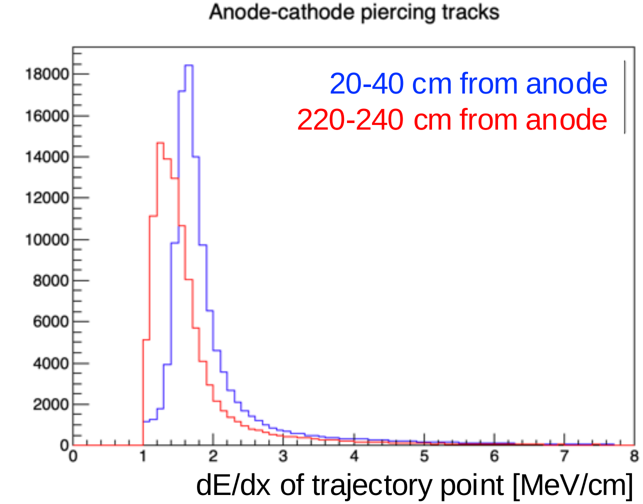
Radiological survey

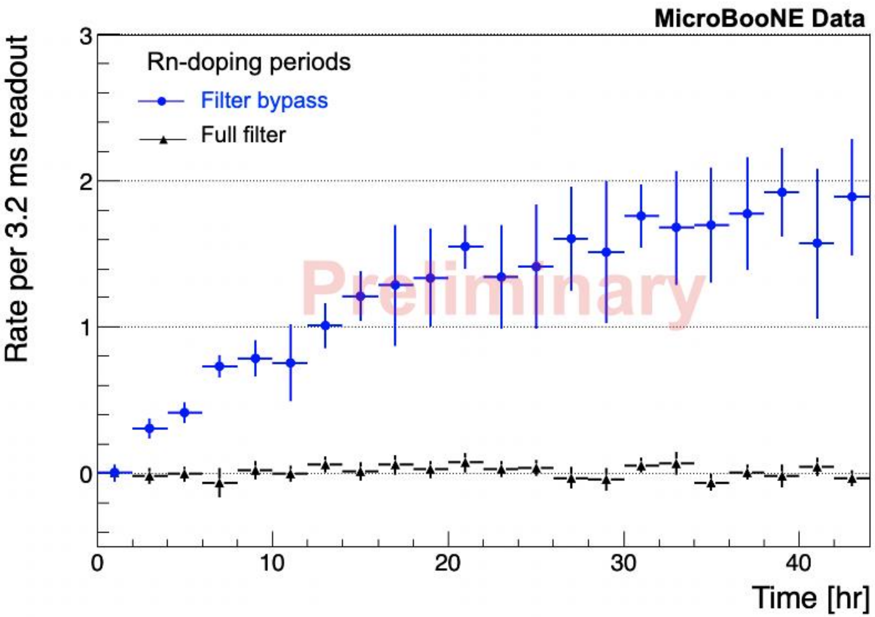


Confirmed accumulation of radon in copper filter



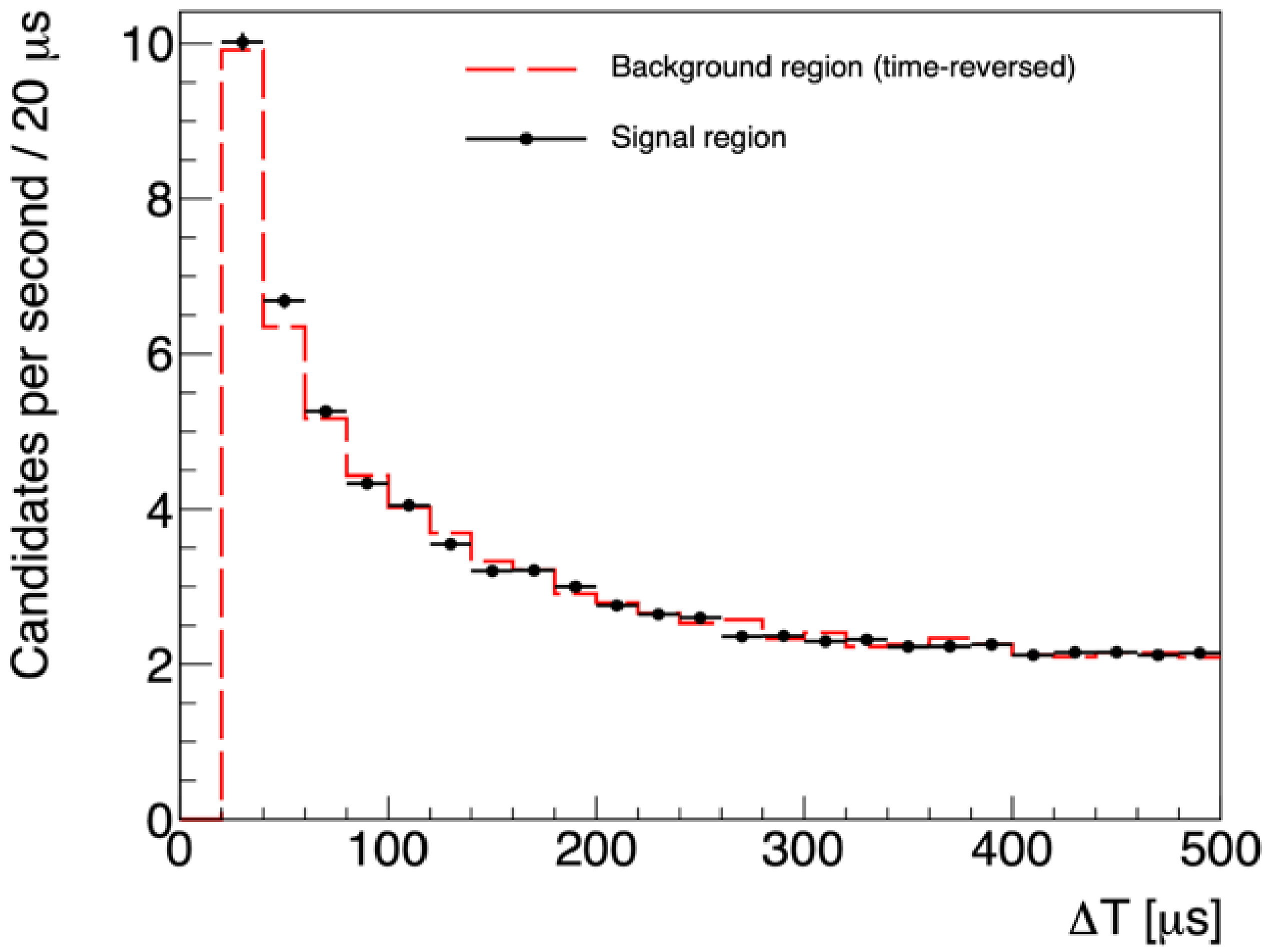
- Looked at ratio of dE/dx for segments of ACP tracks near and far from the wire planes
- Confirmed average ~8 ms lifetime (weighted by β candidates over time), consistent with previous estimate from scaling the Bi214 beta spectrum





cale

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

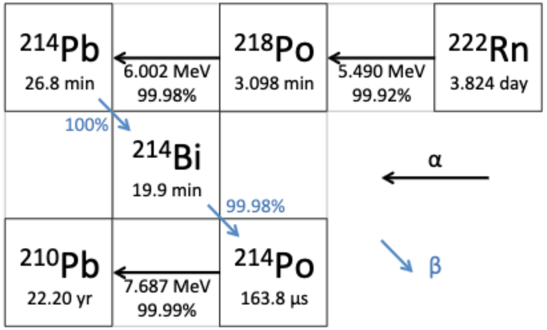
Phys Rev C 92, 045504

Results from LXe in EXO-200

222Rn → 218Po^{+} $f_{\alpha} = 50.3 \pm 3.0\%$)
v_d ~0.3 cm^2 / (kV s)

214Pb → 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



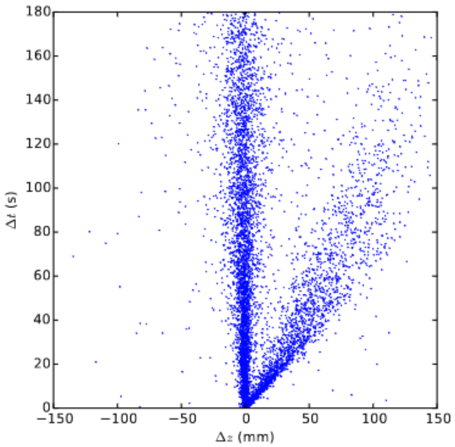


Figure 8. (Color online) Scatter plot of ^{218}Po drift distance versus time between the ^{222}Rn and ^{218}Po decays. Displacement (Δz) is defined as positive when movement is towards the cathode.

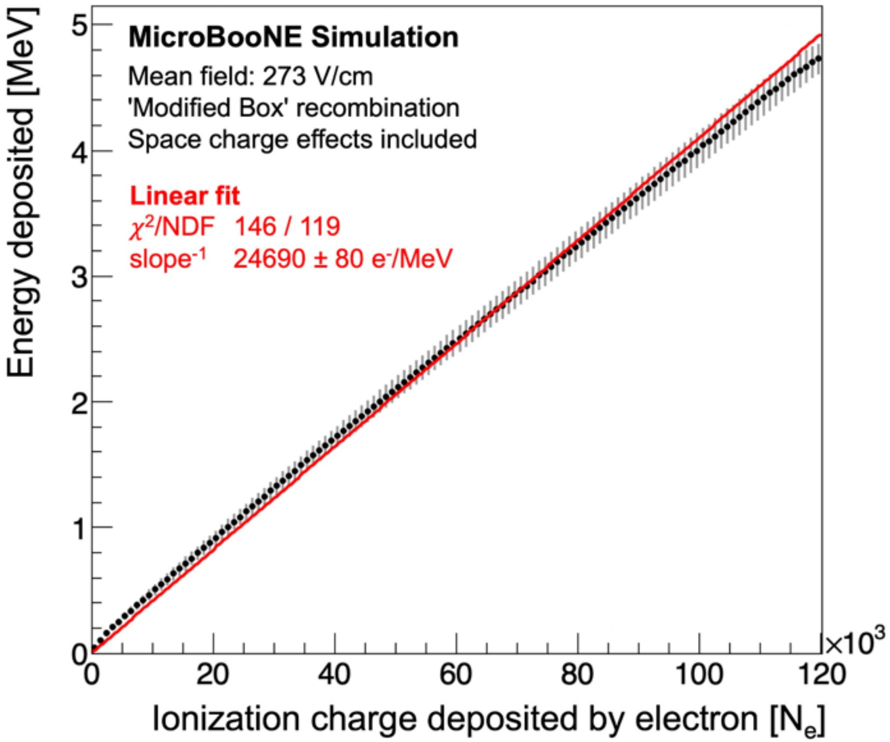
Toy MC assumptions

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



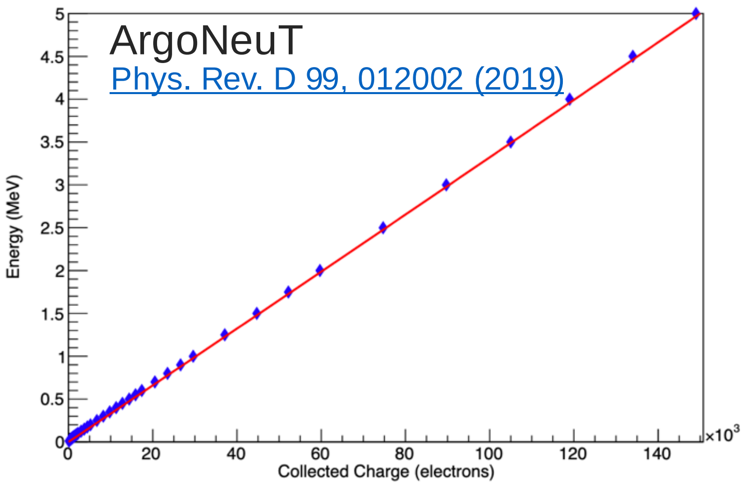
$$E_{\text{reco}}\ [\text{MeVee}] = \frac{Q}{0.584} \times W_{\text{ion}}$$

MicroBooNE + LArIAT: Michel electron showers

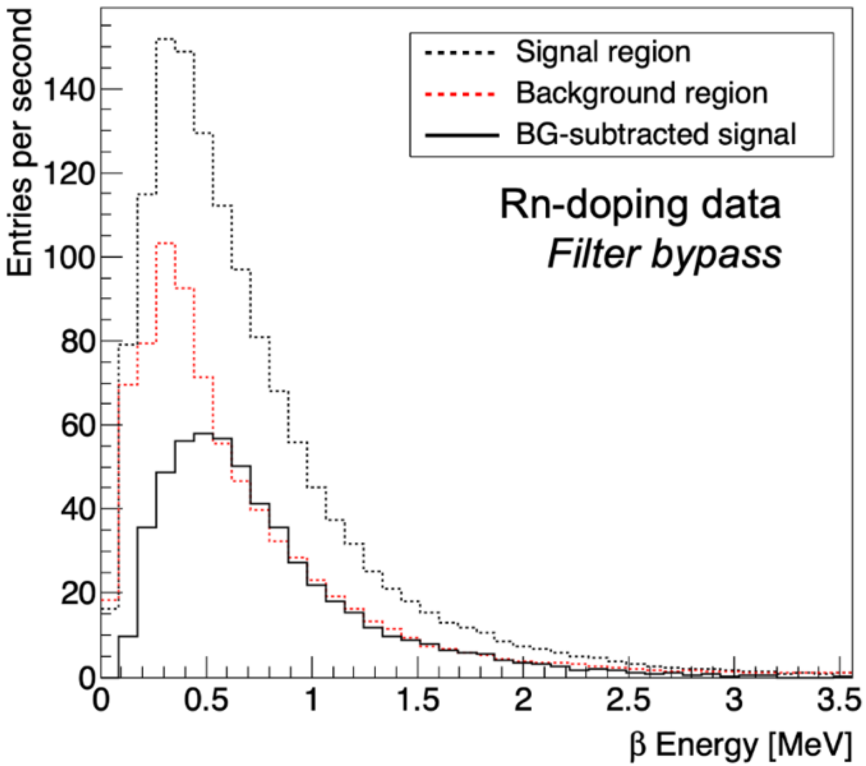
- For blips, assumed constant dE/dx (i.e., constant recombination)

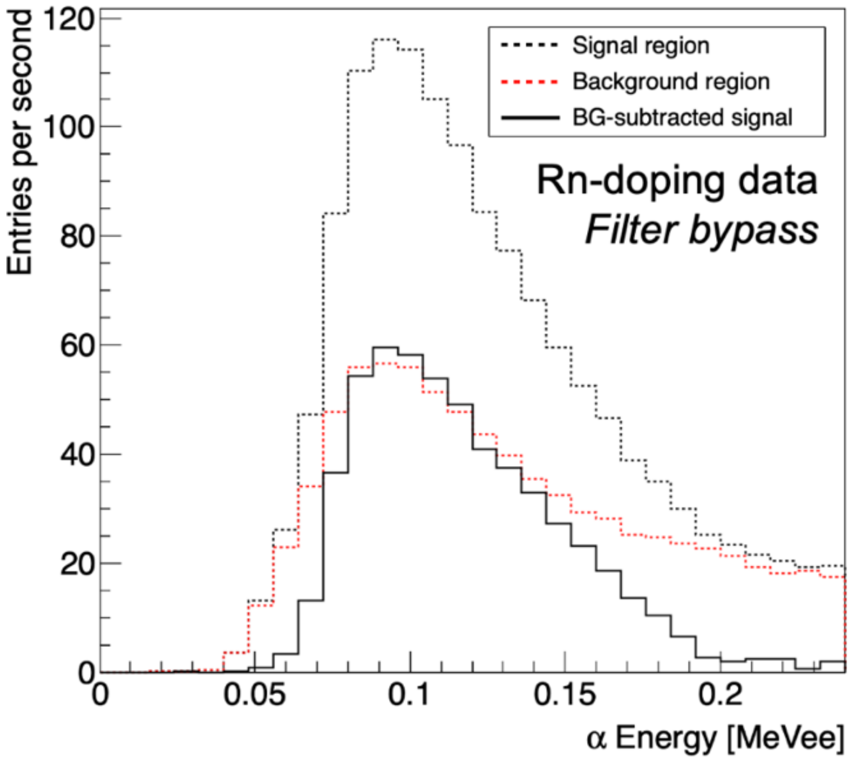
ArgoNeuT: Nuclear de-excitation γ analysis

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

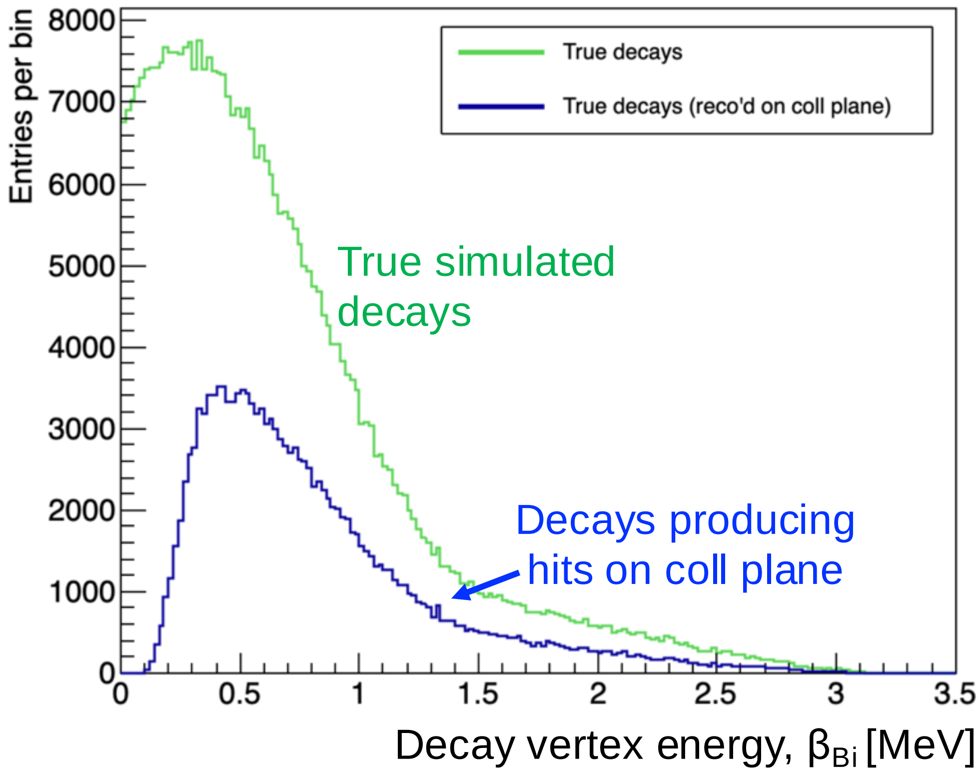


Energy spectra backgrounds





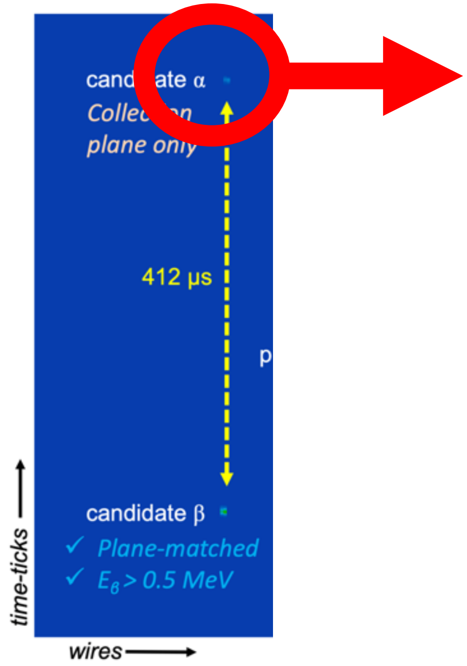
Simulated energy spectra



Calorimetric validation: α_{Po}

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

https://zenodo.org/record/7577399



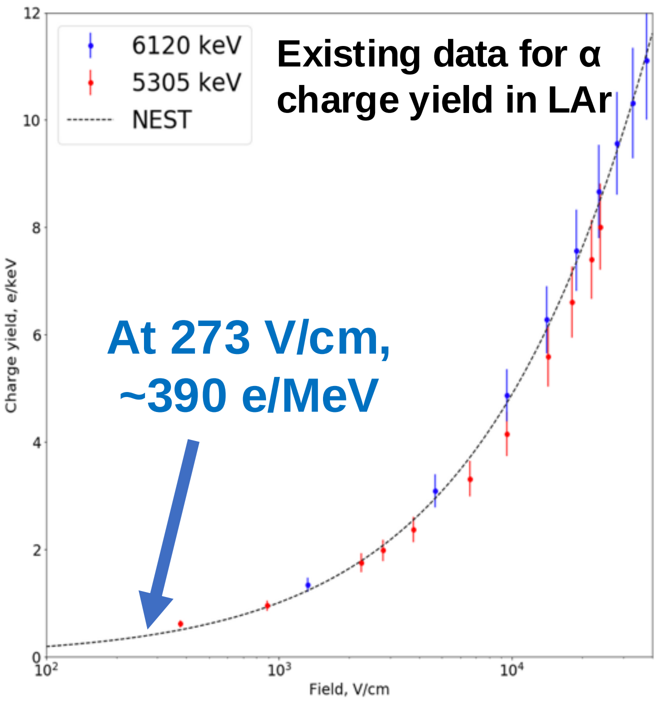
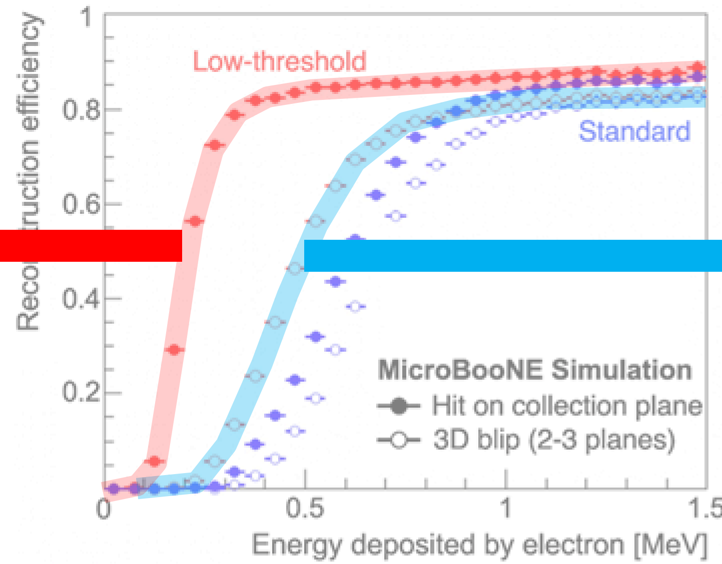
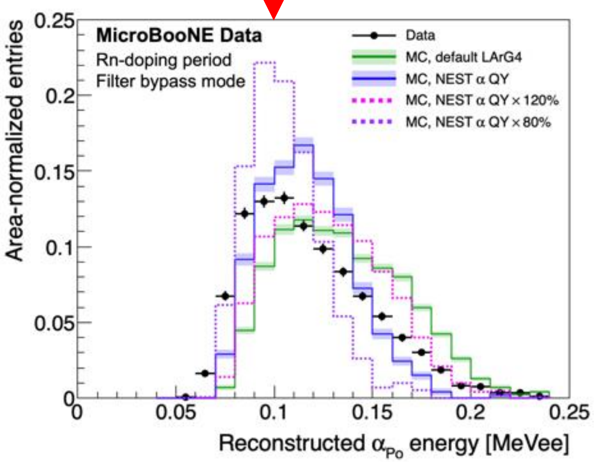
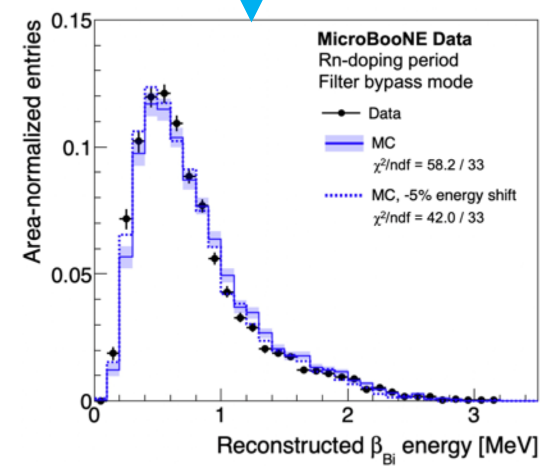


Figure 9: Charge yield model comparison with data from Po-210 and Cf-252





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

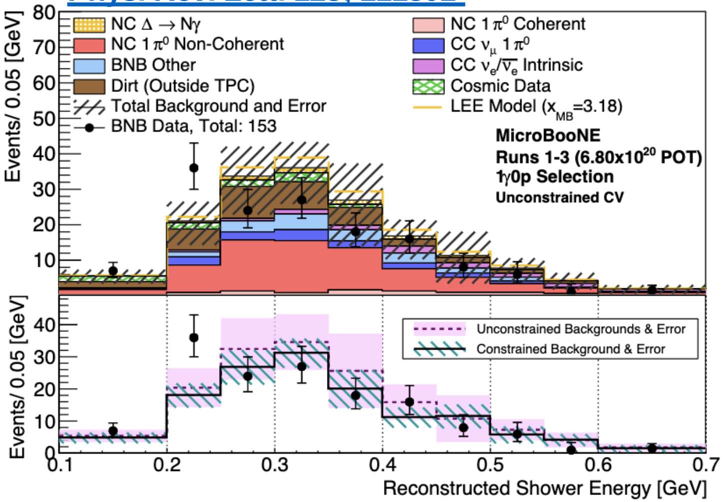
Contributions to efficiency

	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%**

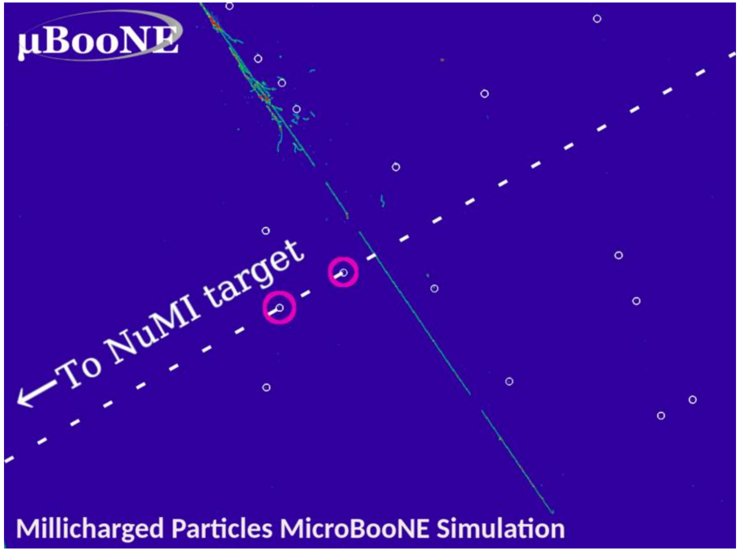
* Using ‘low-threshold’ reconstruction

Broader implications for SBN / MicroBooNE

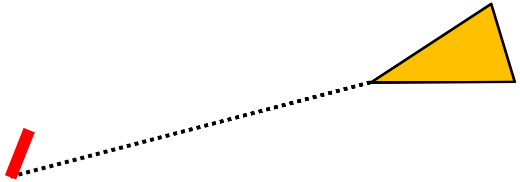
Phys. Rev. Lett. 128, 111801



Low-energy proton detection for 1g0p background discrimination



Beam-induced BSM like millicharged particle signatures



low-E proton
(missed by Pandora tracker?)

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