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Recent Results from MicroBooNE

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NNN 2024 Rio de Janeiro

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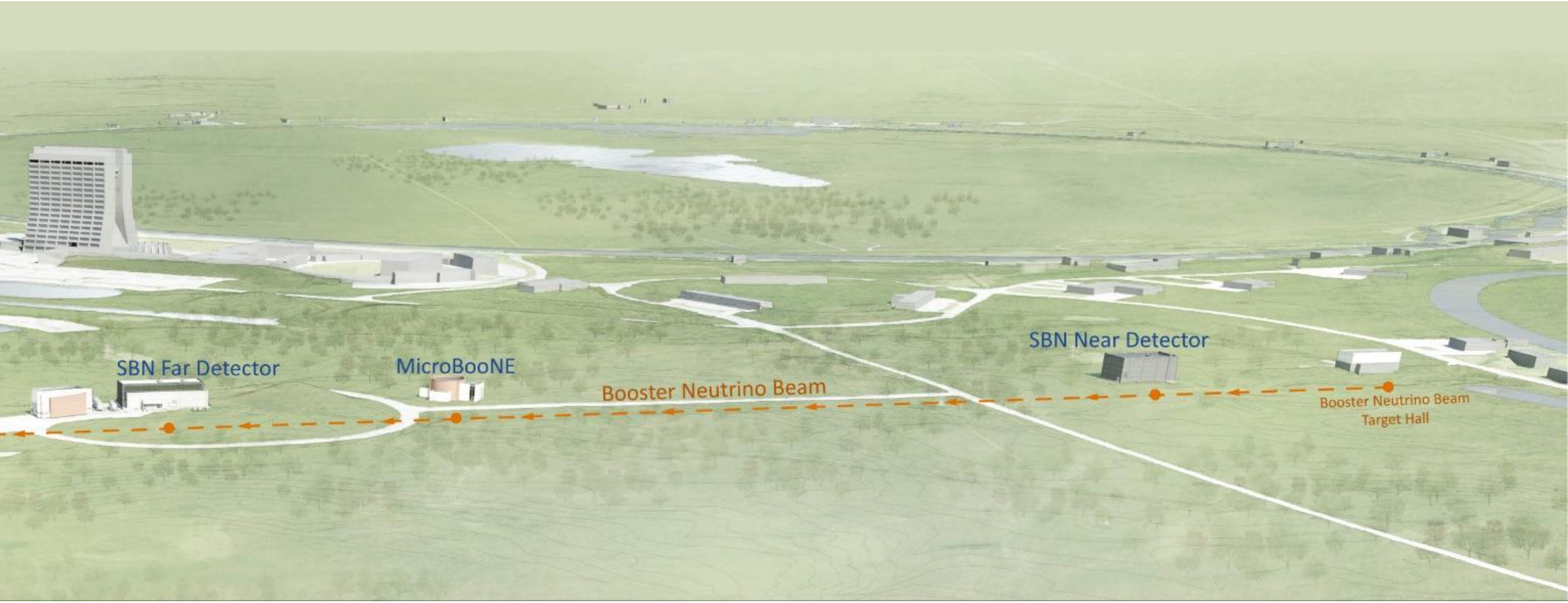
Talk Contents

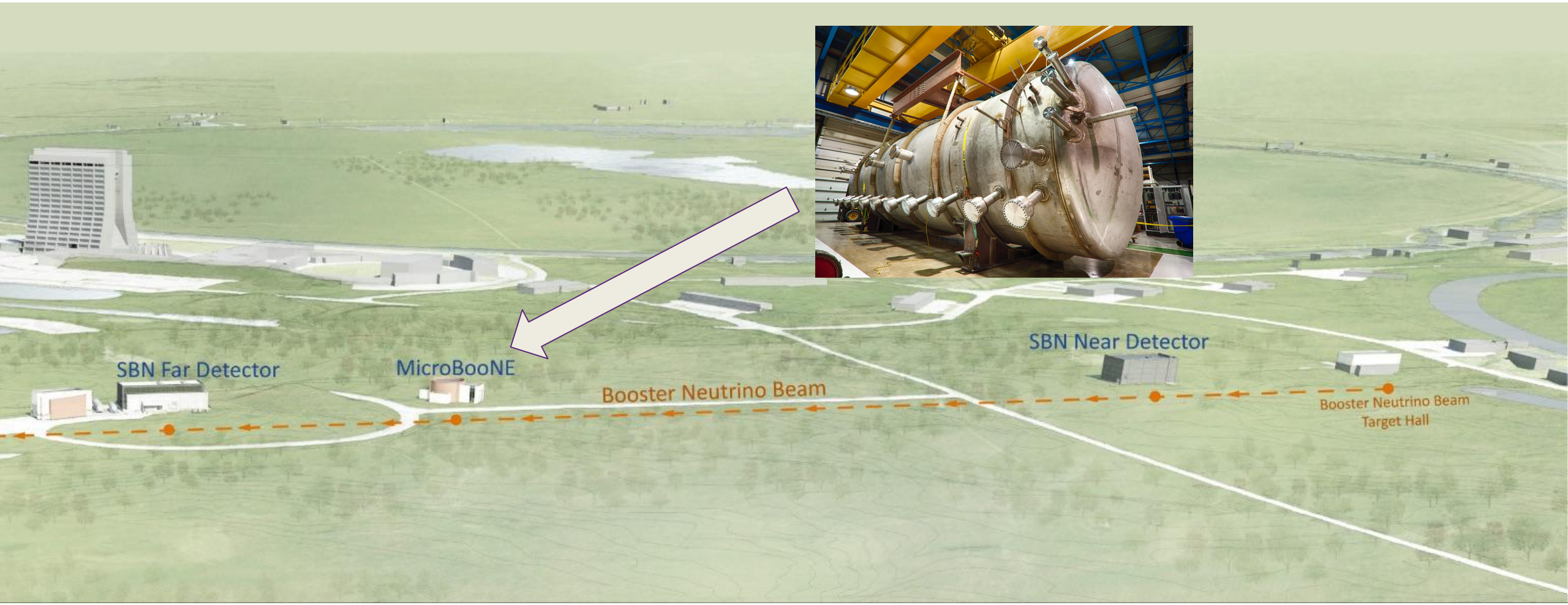
1. Overview of MicroBooNE.
2. Oscillations and Short-Baseline Anomalies.
3. Searches for BSM particles.
4. Neutrino-Nucleus Cross Sections.
5. Summary.

I'll also mention some of the outputs of our detector physics/reconstruction programs along the way

The Micro-Booster-Neutrino-Experiment

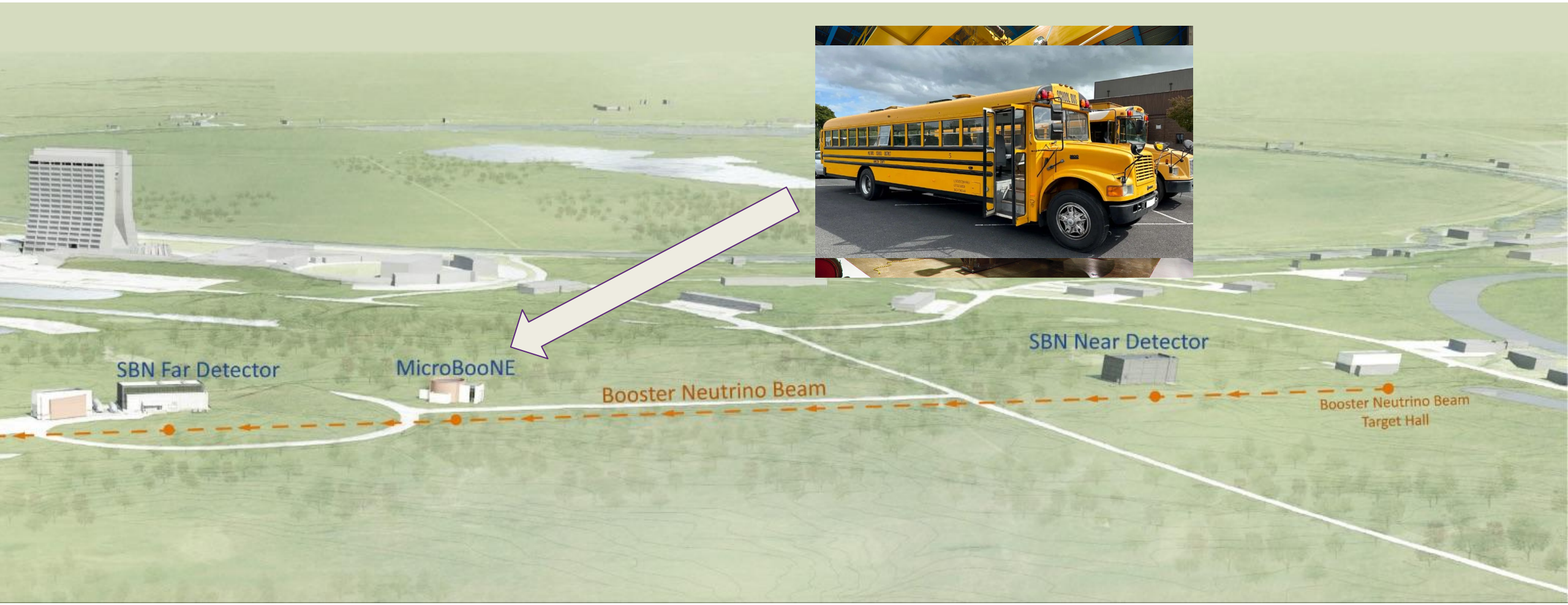


The Micro-Booster-Neutrino-Experiment



The detector comprises an approx. 10m long cryostat, filled with liquid argon.

The Micro-Booster-Neutrino-Experiment



Active volume is about the same size as a school bus.

The Liquid Argon Time Projection Chamber

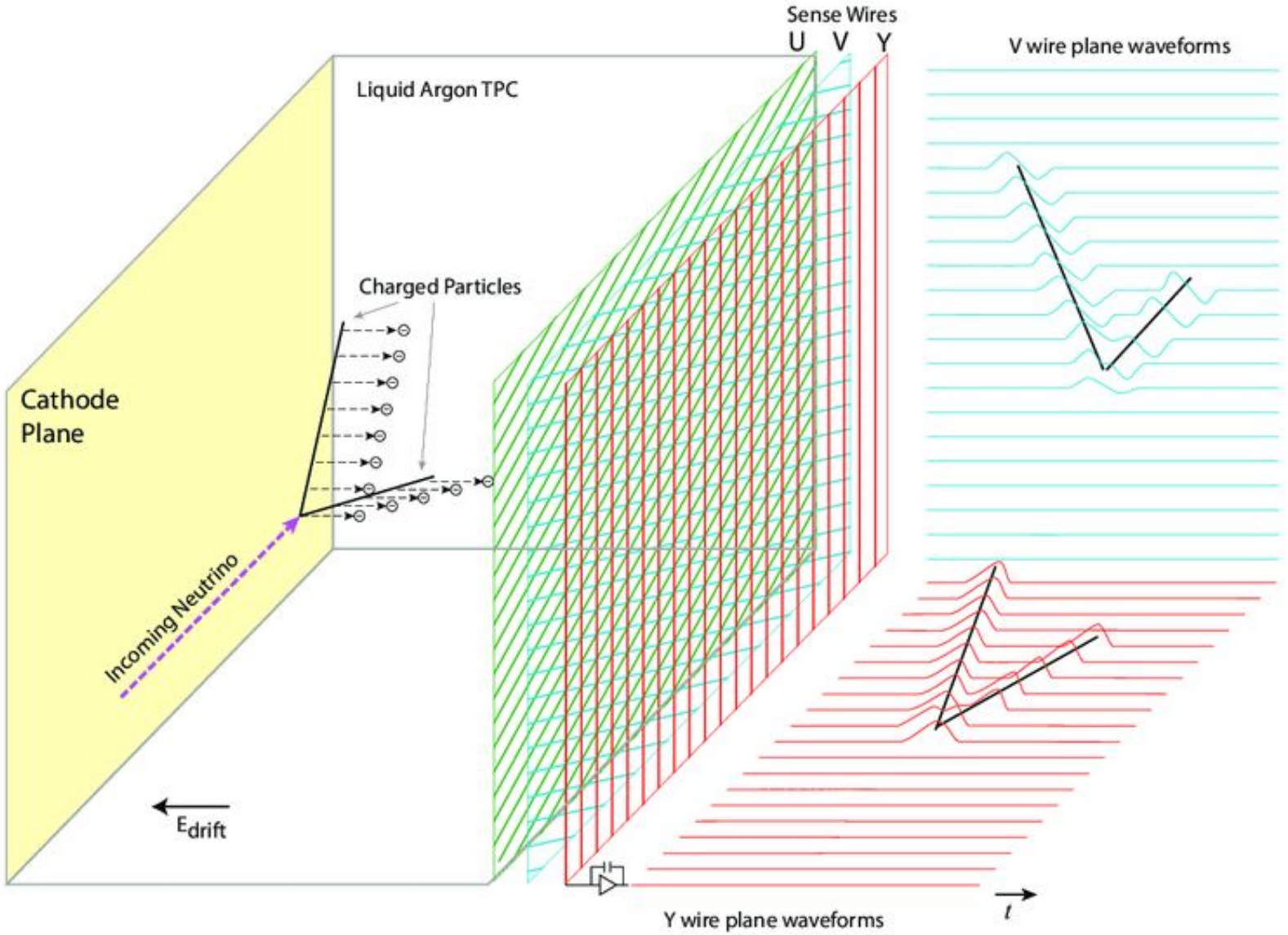
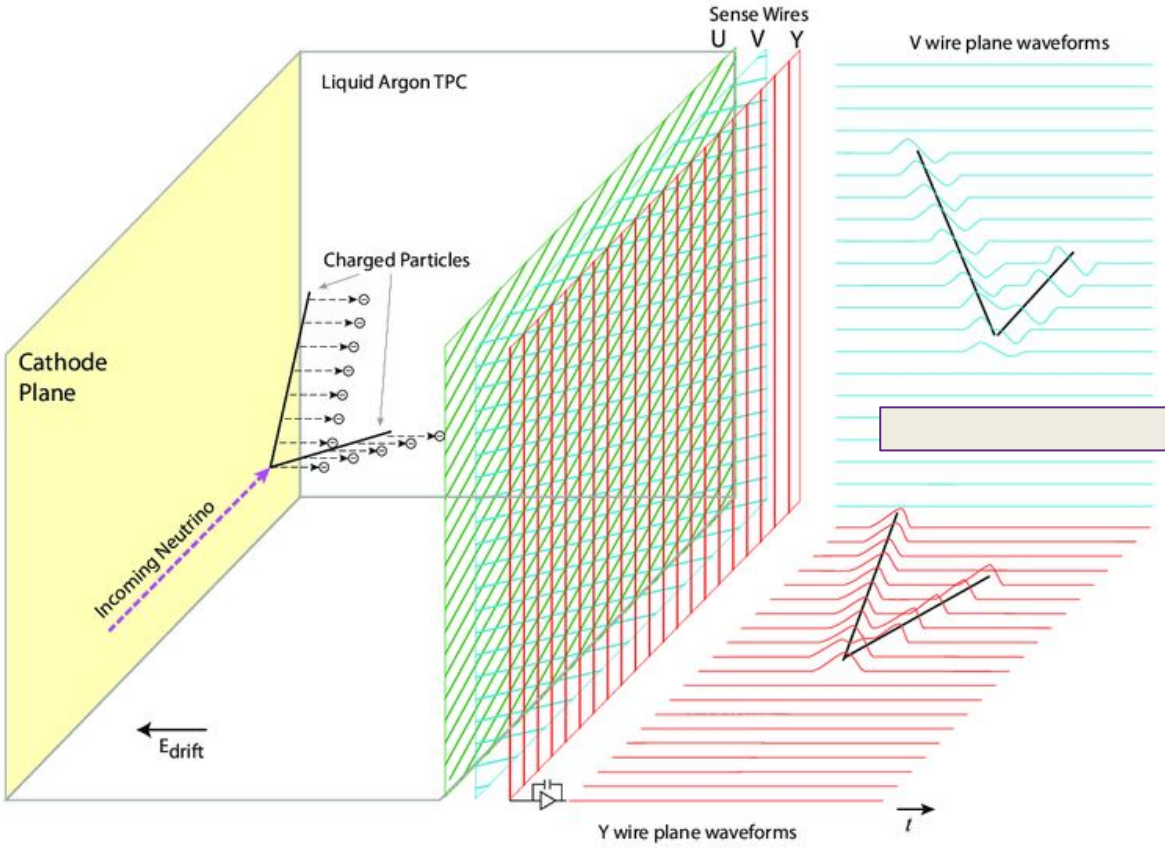


Figure from JINST 12.02 (2017), P02017.

The LArTPC - Tracking and Calorimetry



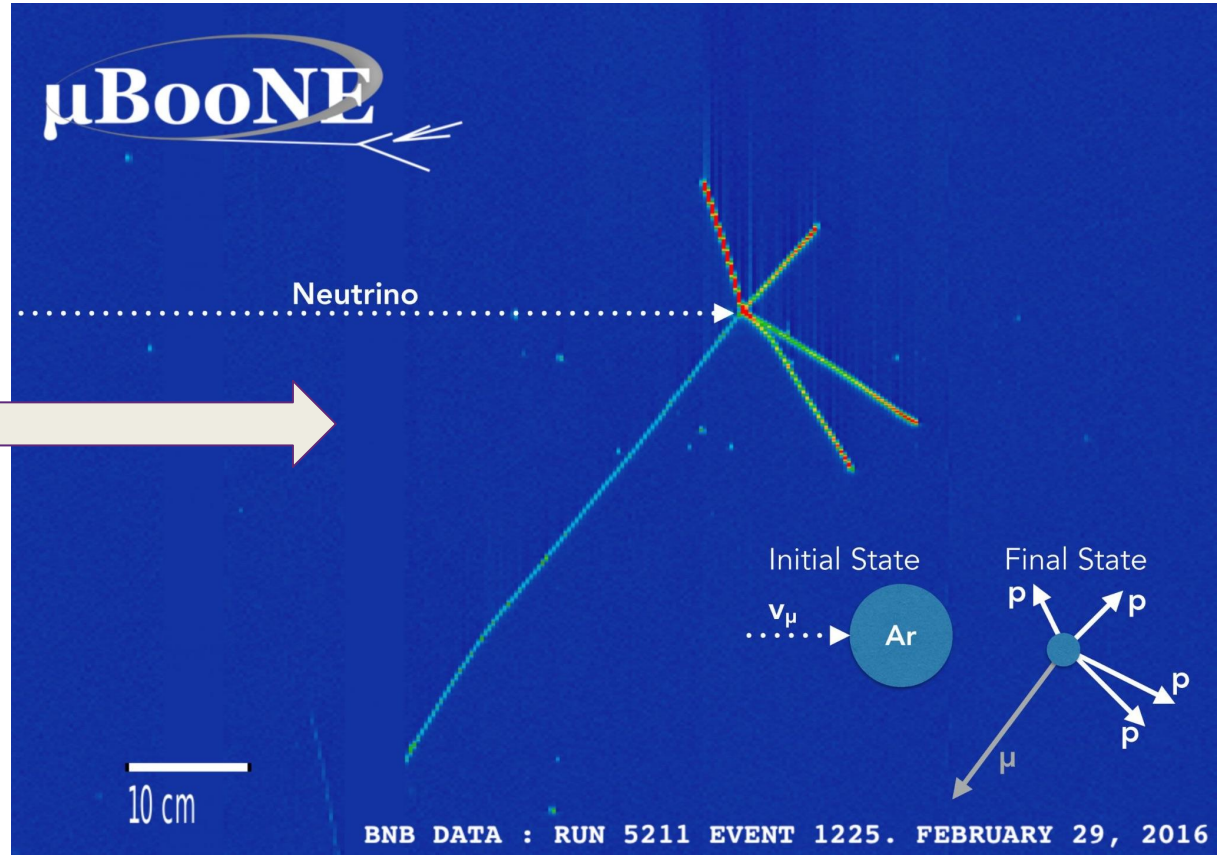


Figure from JINST 12.02 (2017), P02017.

+ 2 other images from different angles

Particle Identification - Topology

- We identify final states by looking for a neutrino vertex with tracks and showers.

Track-like	Shower-like
p, μ, $\pi^{\pm}$, $K^{\pm}$	e, γ

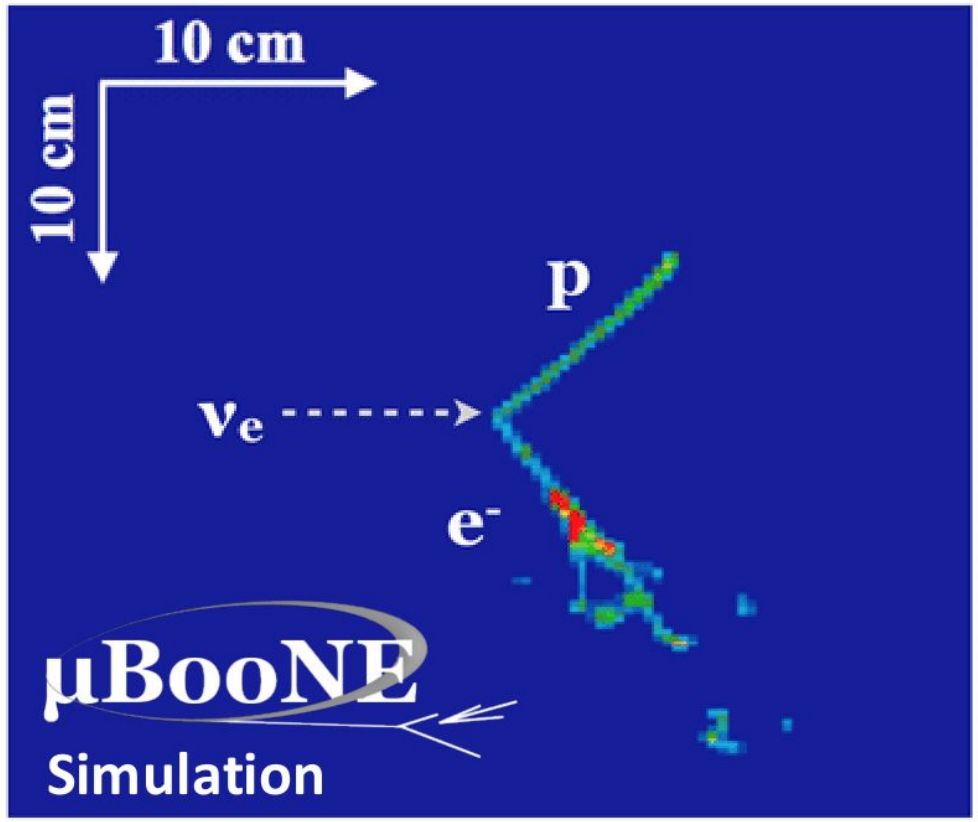


Figure from Phys. Rev. D 99, 092001.

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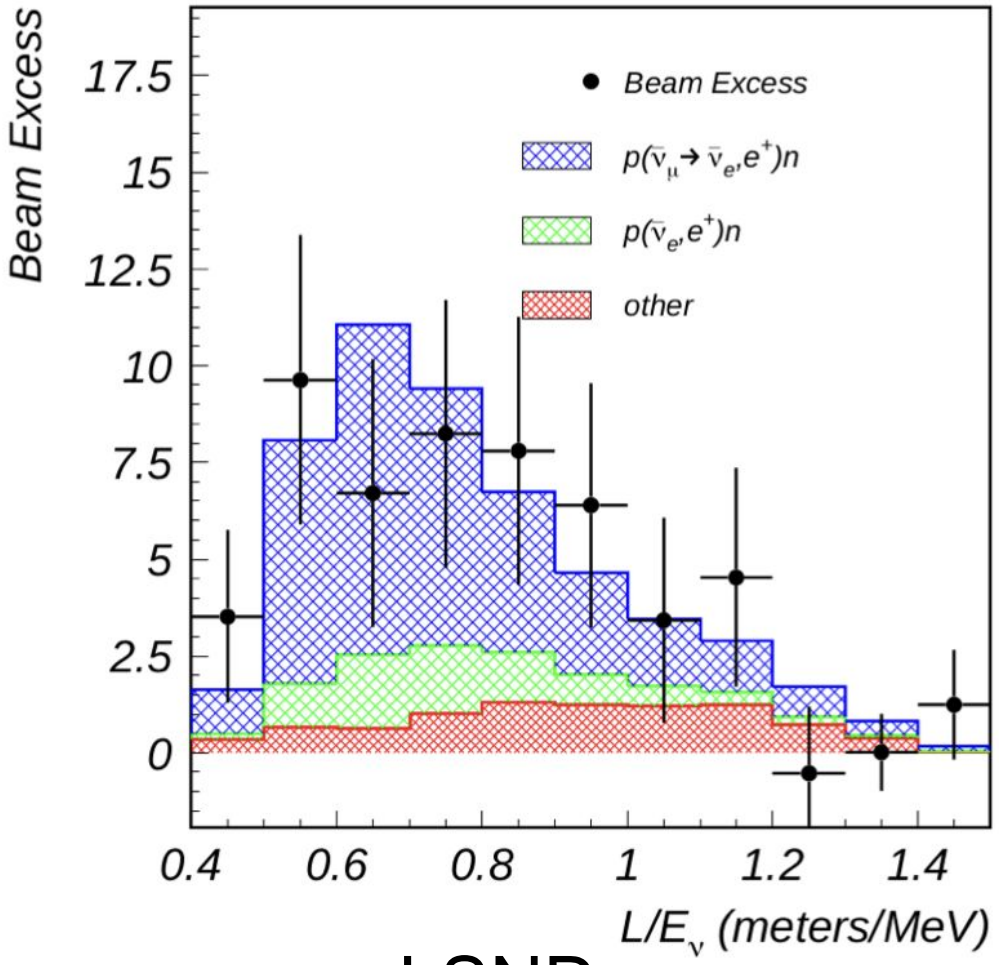
Oscillations and Short Baseline Anomalies

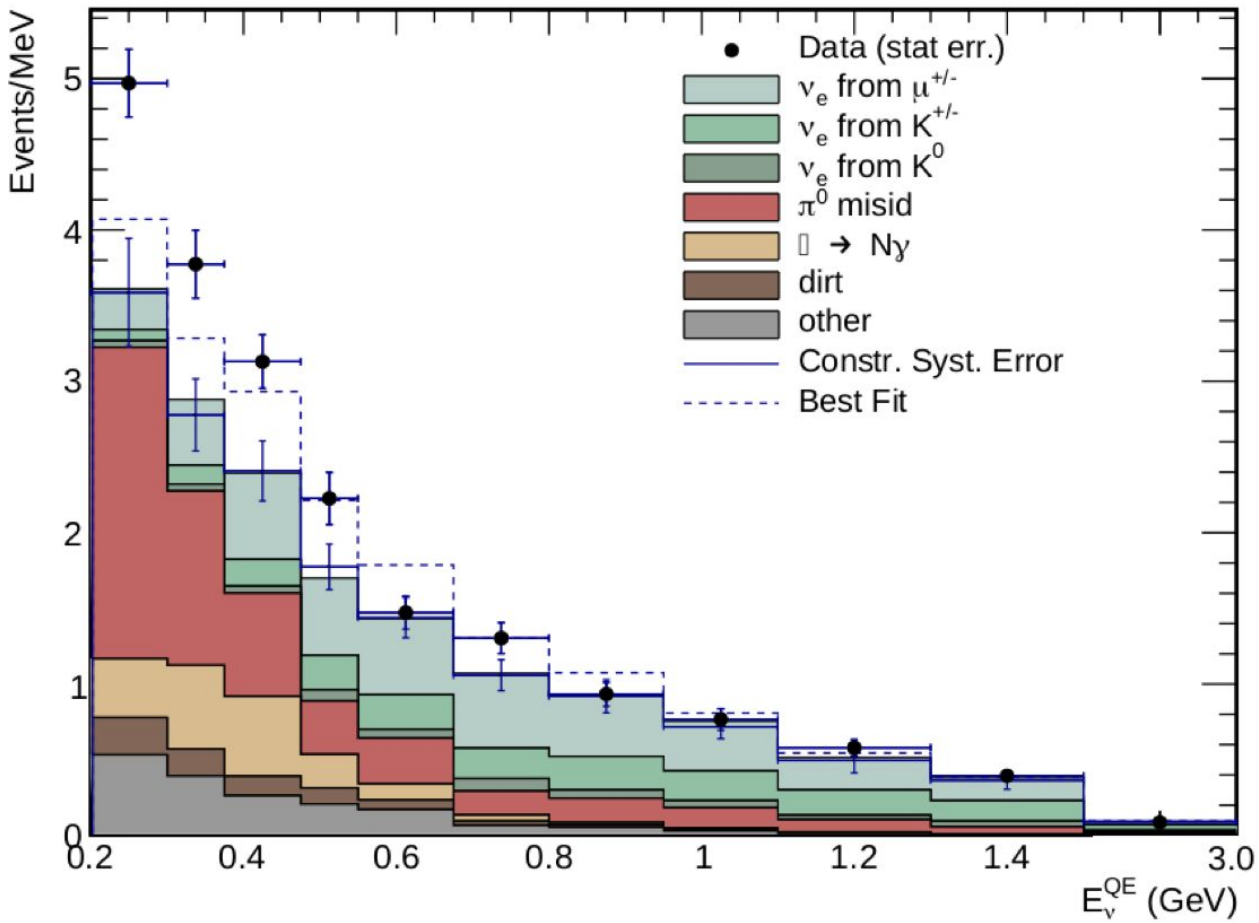
The LSND and MiniBooNE Anomalies

Phys. Rev. D **64**, 112007



LSND

Phys. Rev. Lett. 121, 221801

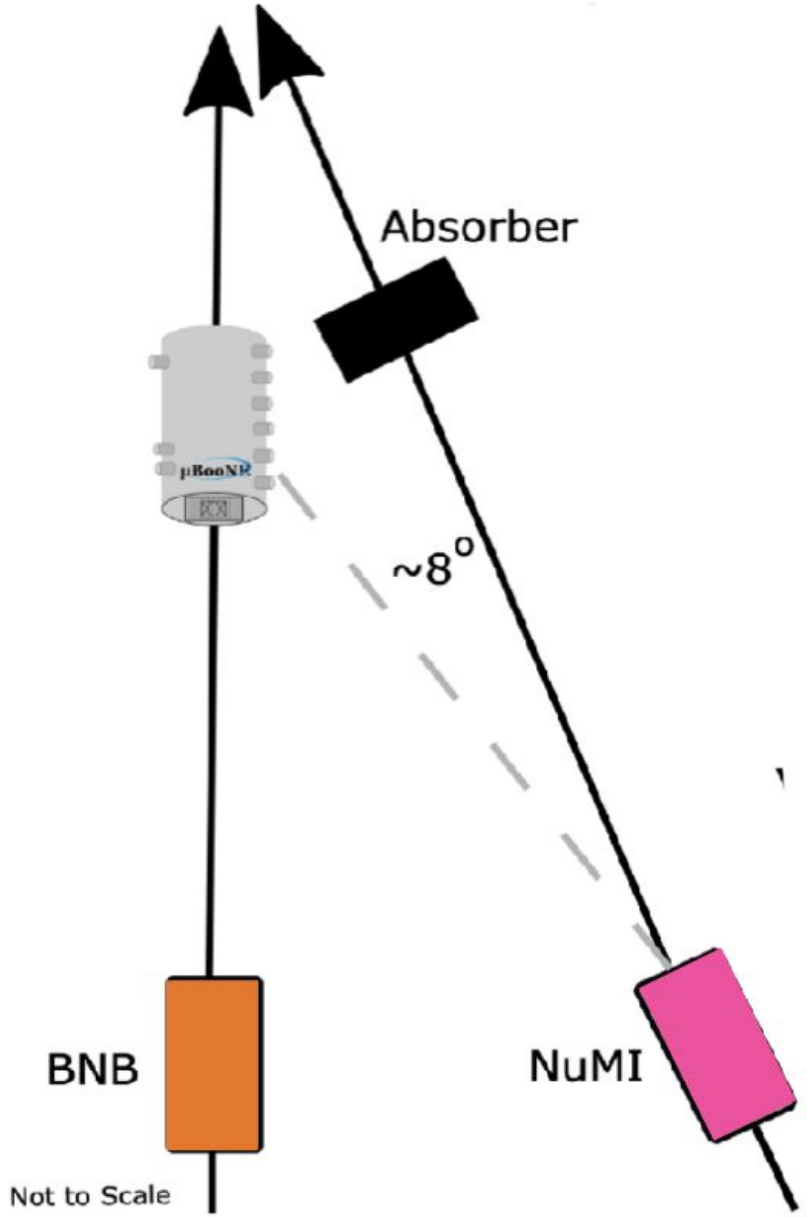


MiniBooNE

Both as of yet unexplained ν_e-appearance-like signals

The Beams

- MicroBooNE is also situated in the Booster Neutrino beam and approximately the same baseline as MiniBooNE.



To ν_e or Not To ν_e

- There are other possible explanations to these anomalies:
  - Mis-modelling of π^0 background.
  - Enhanced rate of NC produced Δ baryons decaying to photons.
- MicroBooNE can distinguish electrons from photons - can test these explanations.

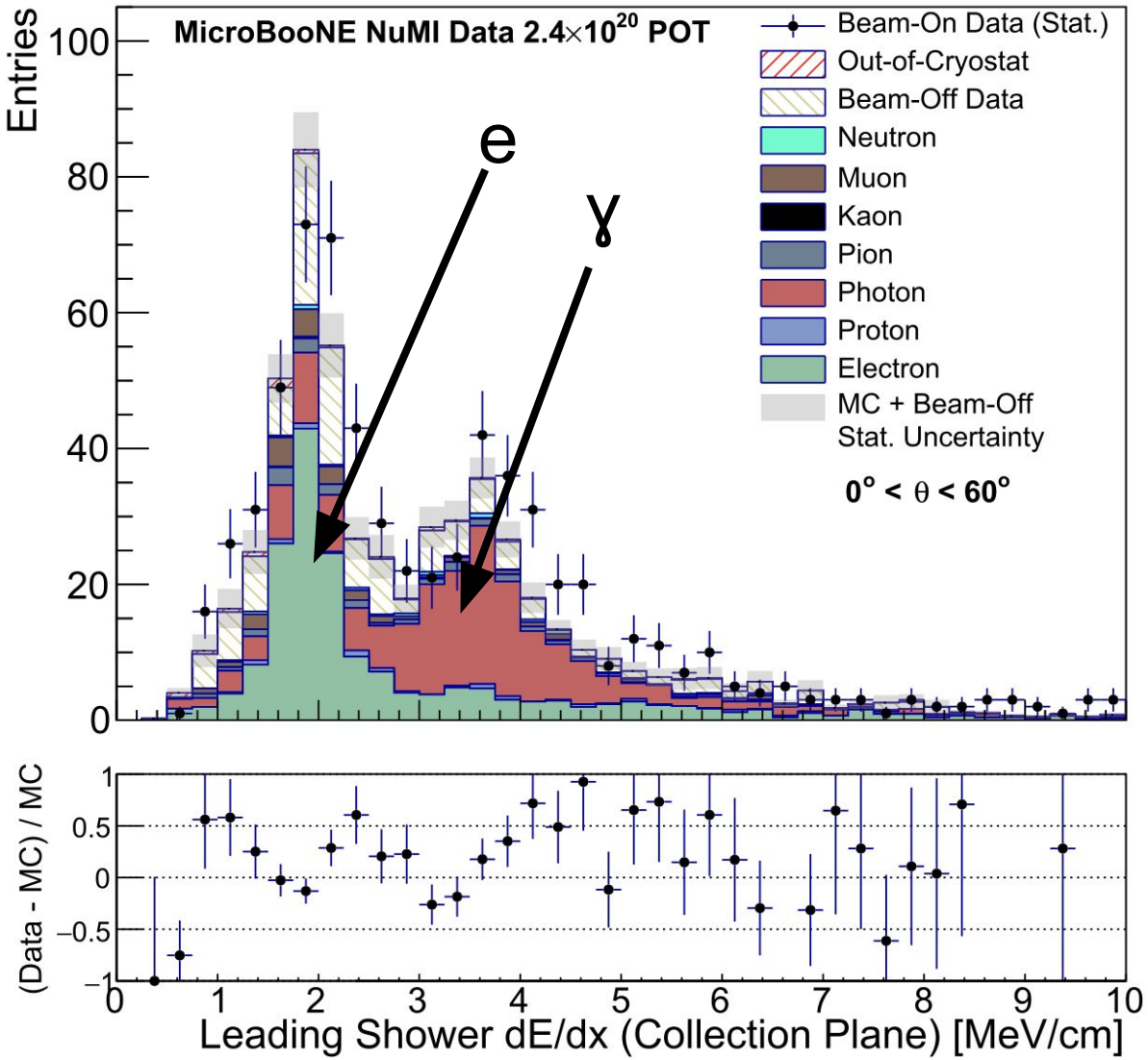
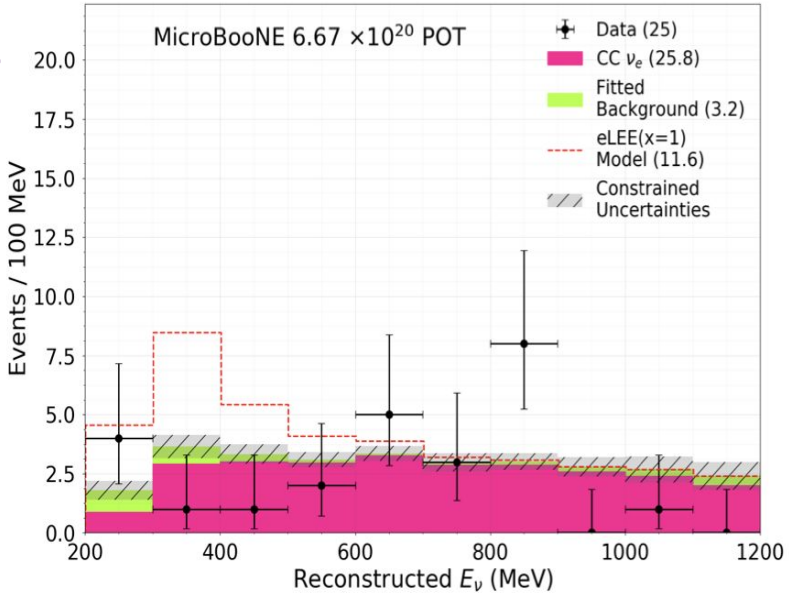


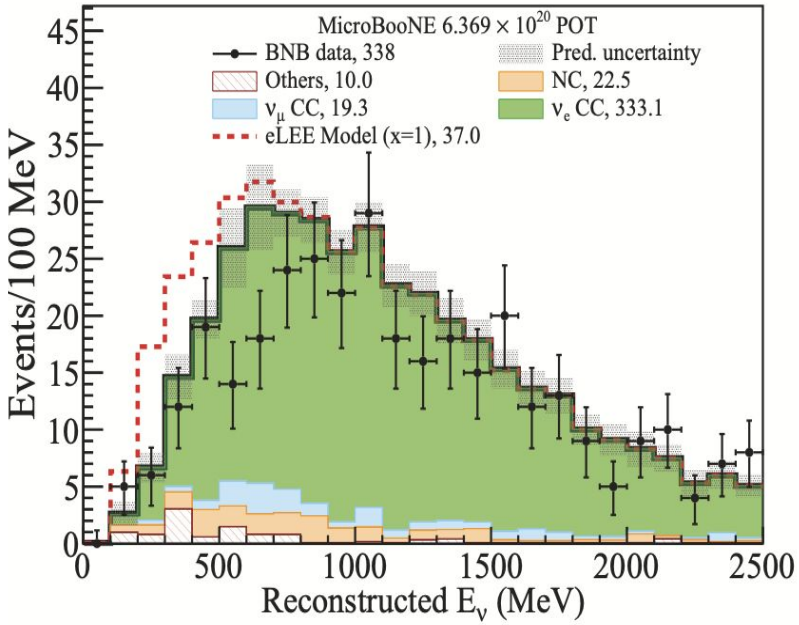
Figure from [Eur. Phys. J. ST 230.24 (2021), pp. 4275–4291.]

LEE - ν_e - Past Results

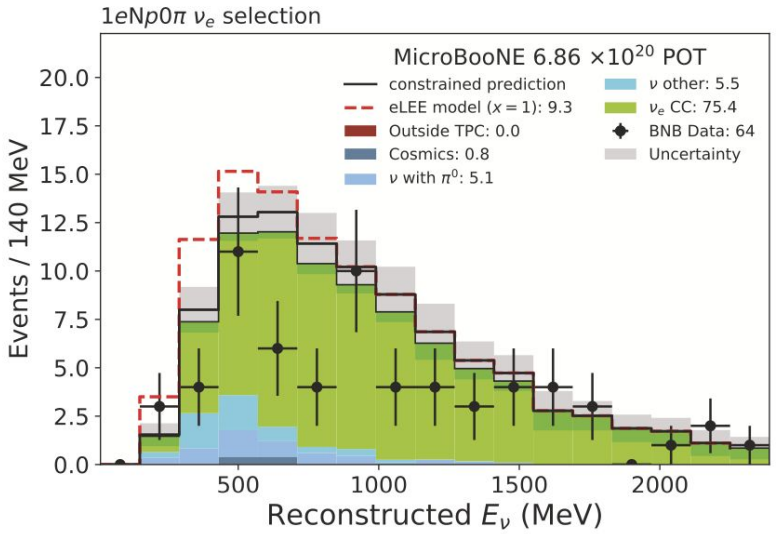
Three independent analyses using different reconstruction/analysis frameworks - published in 2022.

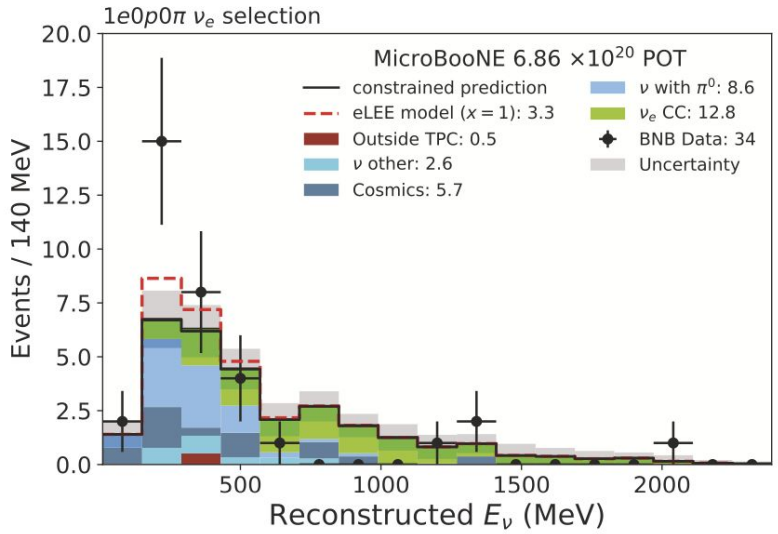


Deep Learning [Phys. Rev. D 105, 112003]

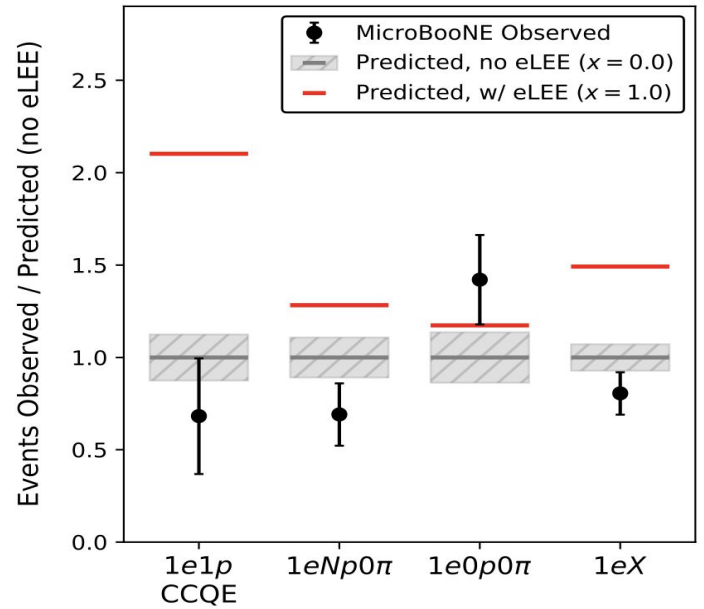


Wirecell [Phys. Rev. D 105, 112005]



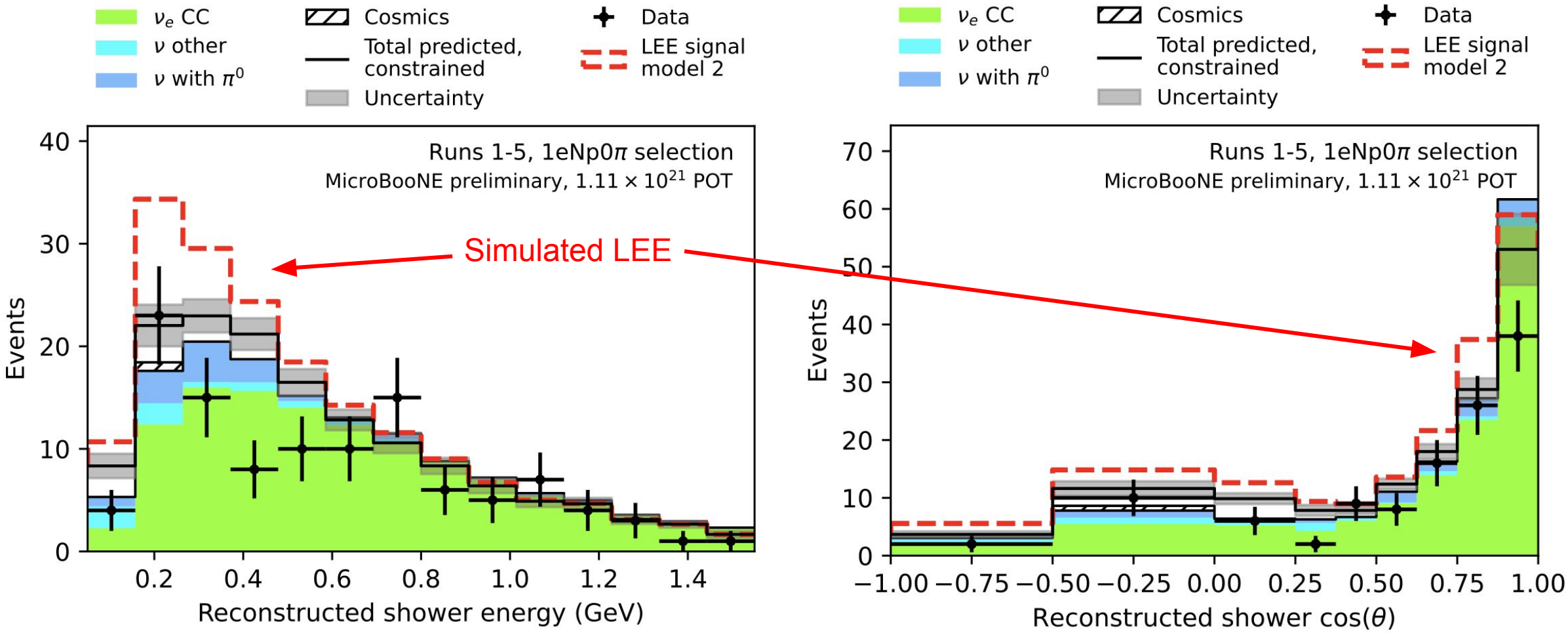


Pandora [Phys. Rev. D 105, 112004]



Summary [Phys. Rev. Lett. 128, 241801]

LEE - ν_e - Updated Search

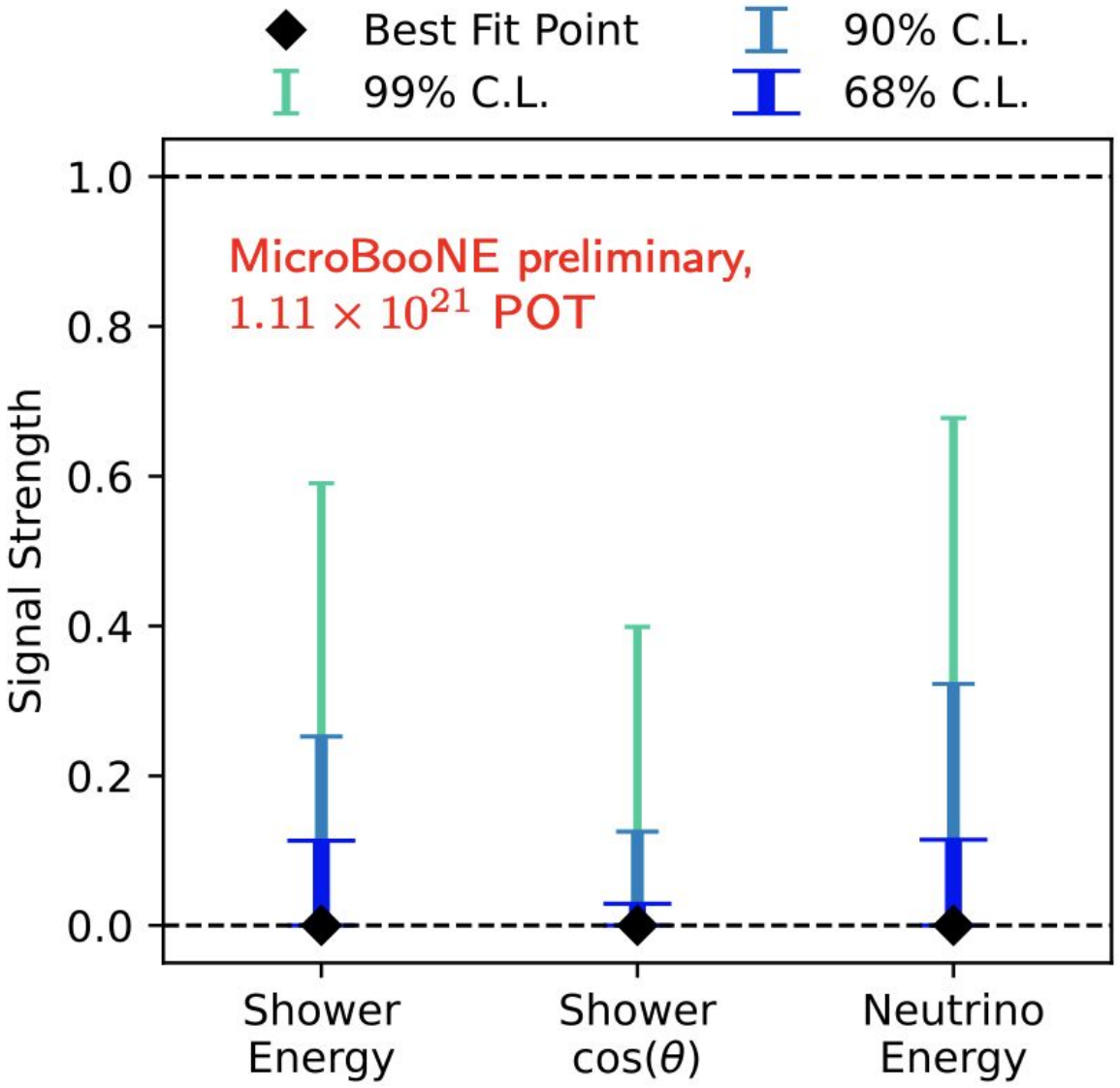


Obtain model of MiniBooNE signal by unfolding excess, then pass through our ν_e detector response and efficiency - MICROBOONE-NOTE-1127-PUB.

LEE - ν_e - Updated Search

- Compare predicted LEE with data in several variables and channels.
- Multiple statistical tests applied, data consistent with no excess.

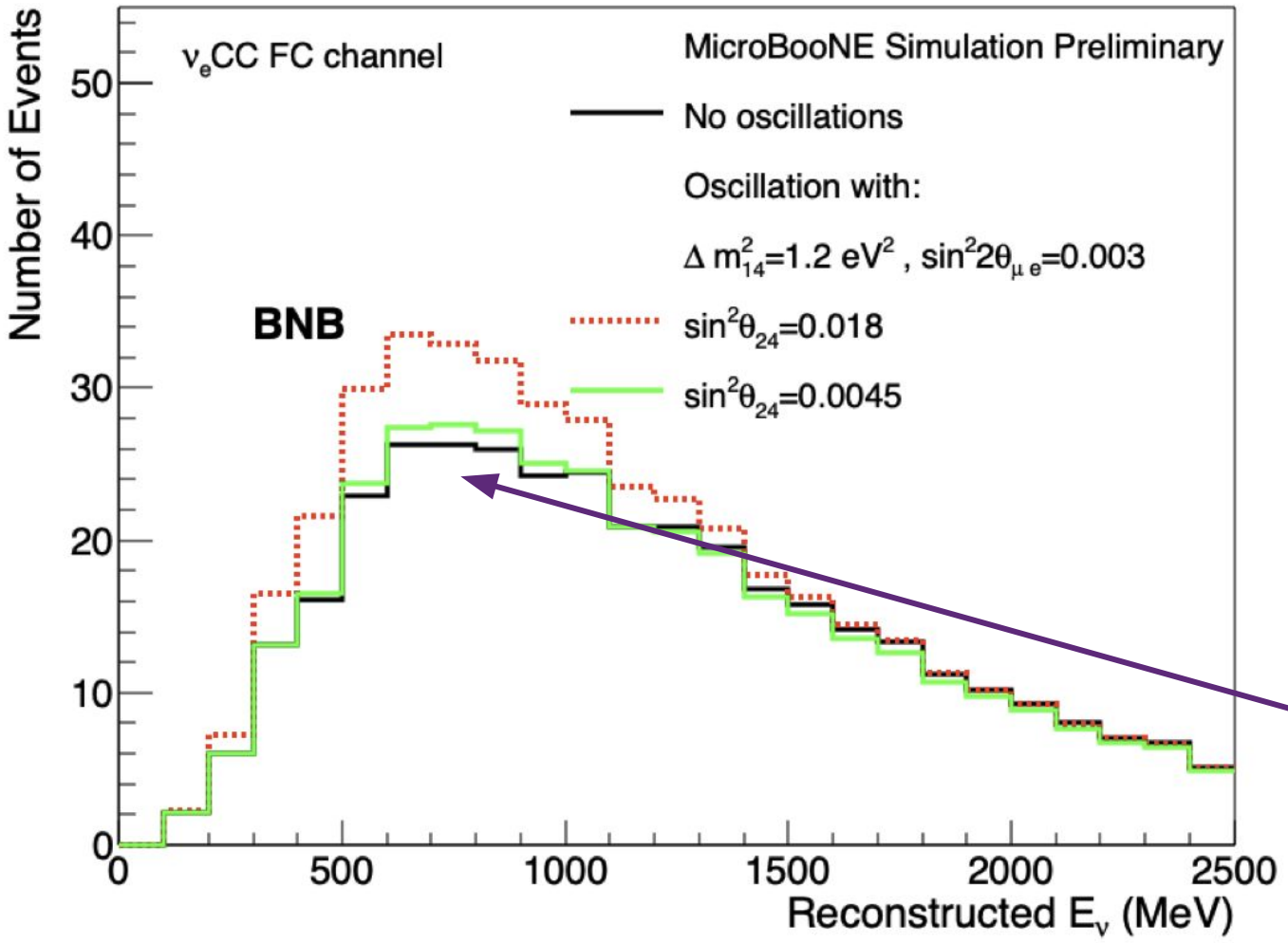
MICROBOONE-NOTE-1127-PUB



Confidence intervals on LEE signal strength.

3+1 Sterile Neutrinos - Degeneracies

MICROBOONE-NOTE-1132-PUB

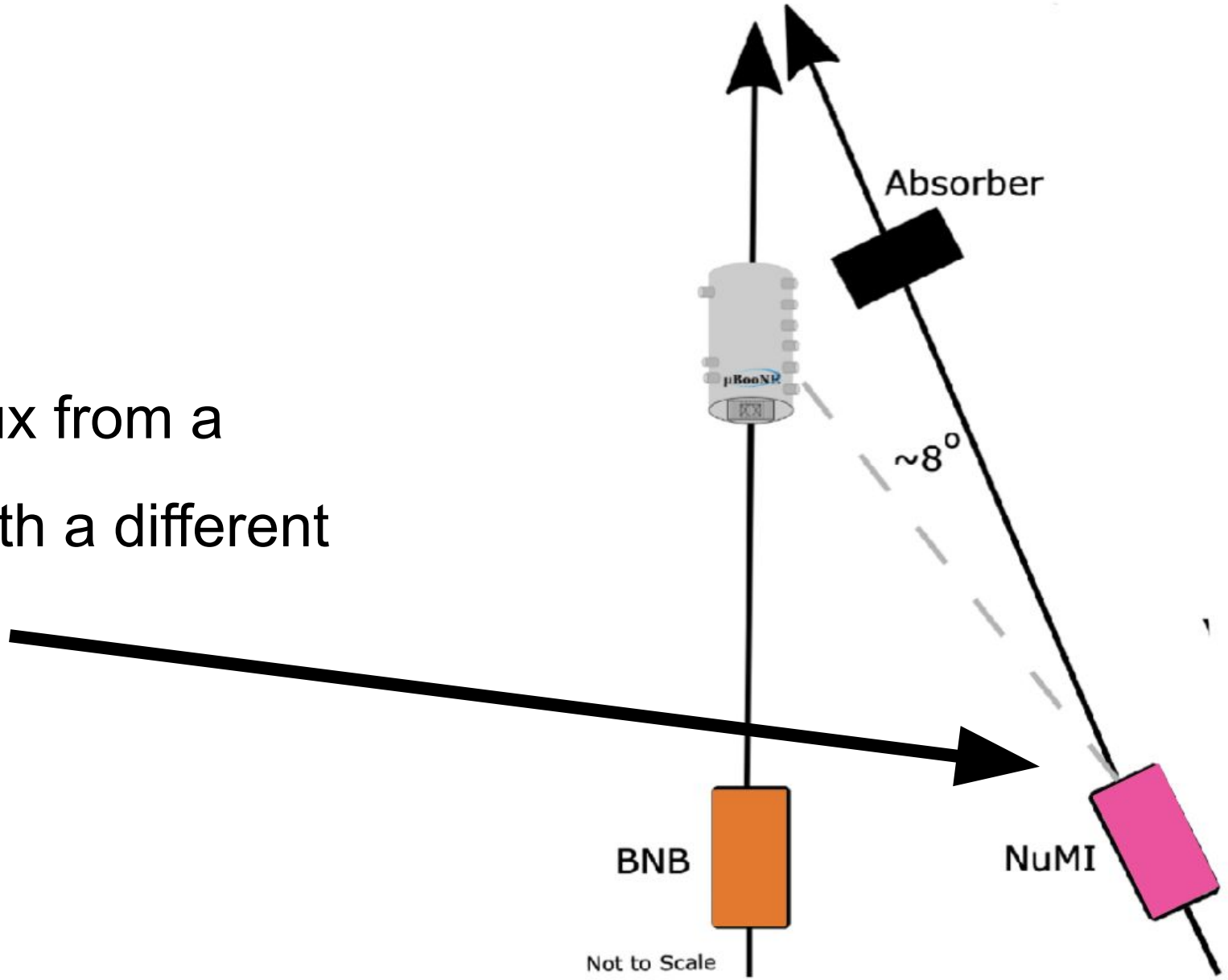


- Introduce 4th (sterile) flavour with mixing θ_{24}.
- BNB alone is insensitive to some regions of θ_{24}.

Green follows black → BNB flux alone can't probe $\sin^2\theta_{24}$ = 0.0045.

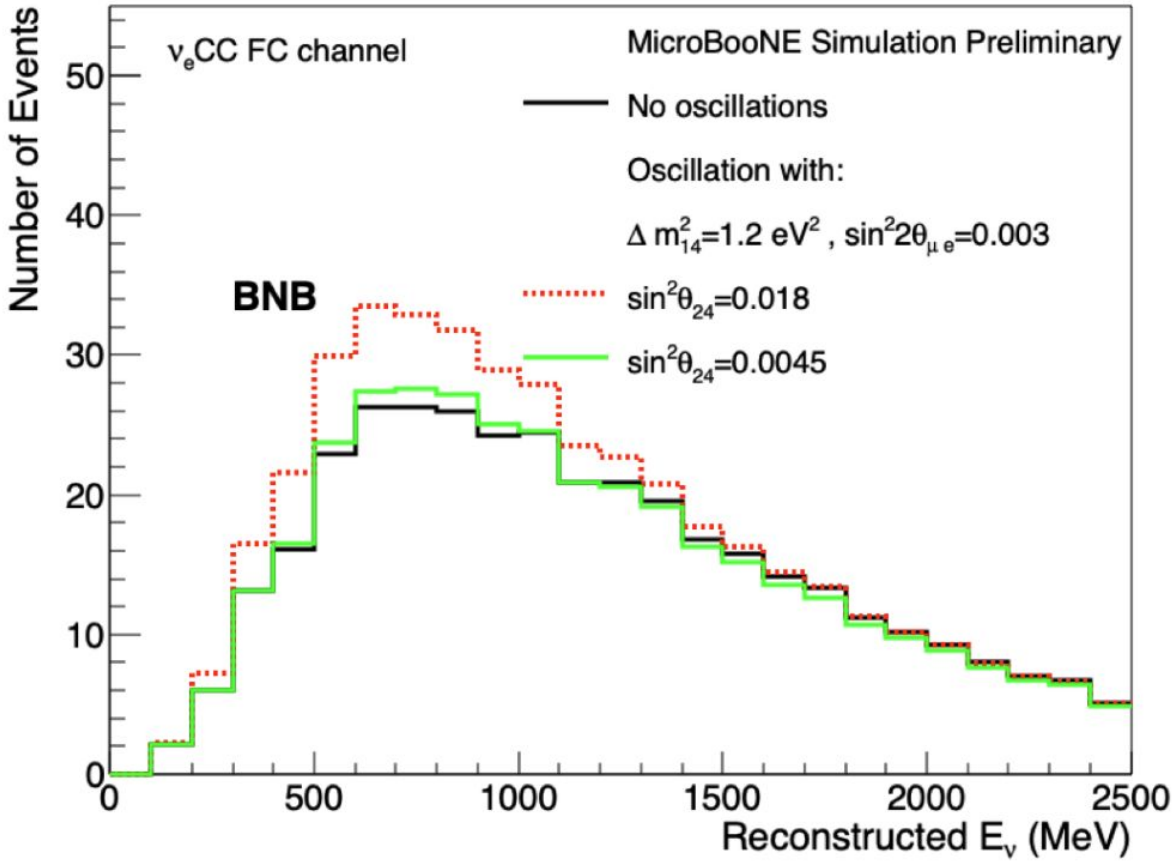
The Beams

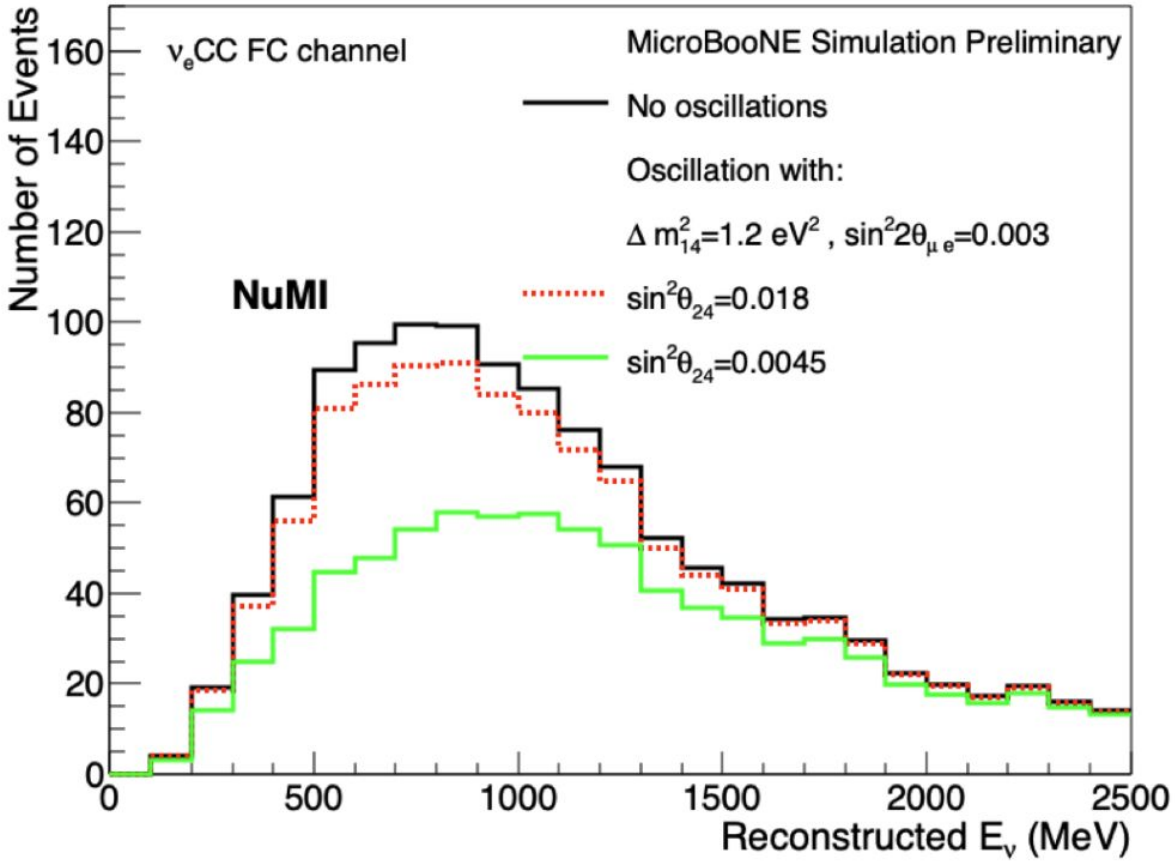
- MicroBooNE receives flux from a second beam - NuMI, with a different baseline and spectrum.



3+1 Sterile Neutrinos - Two Beams

- We can use data from NuMI to break this degeneracy.

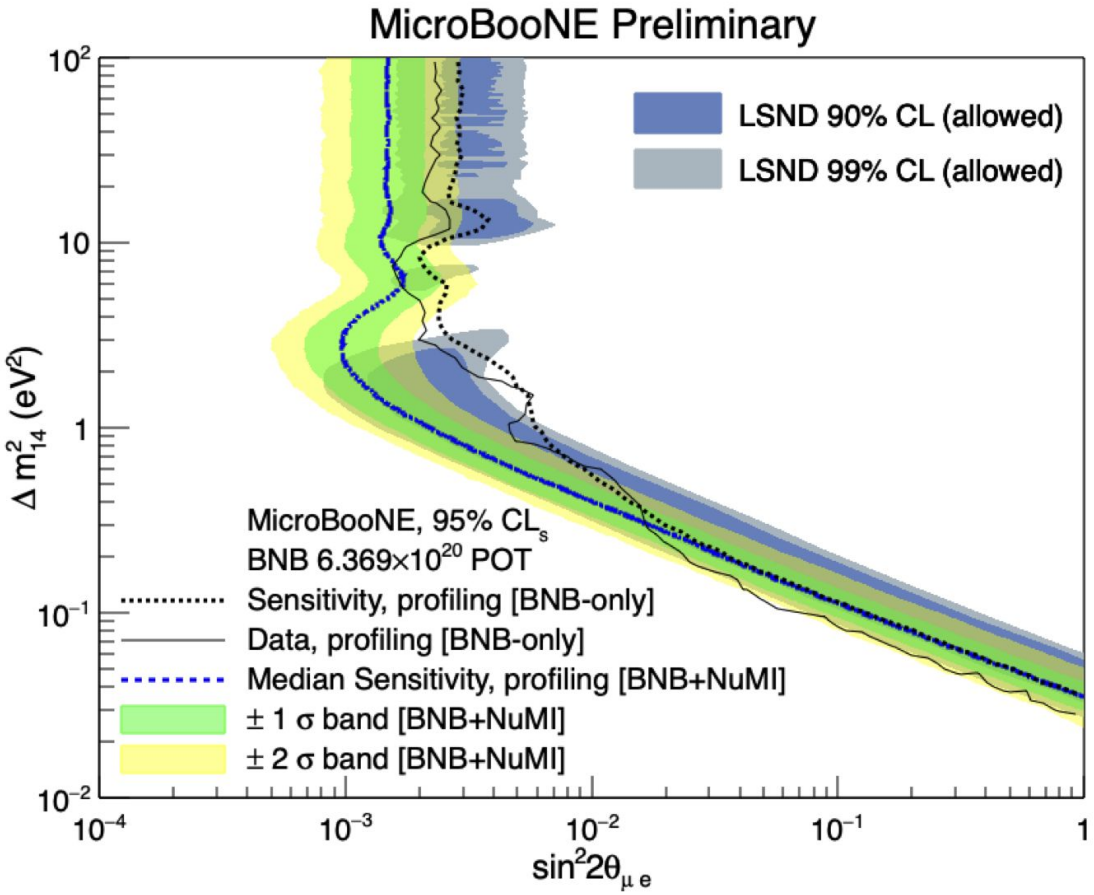


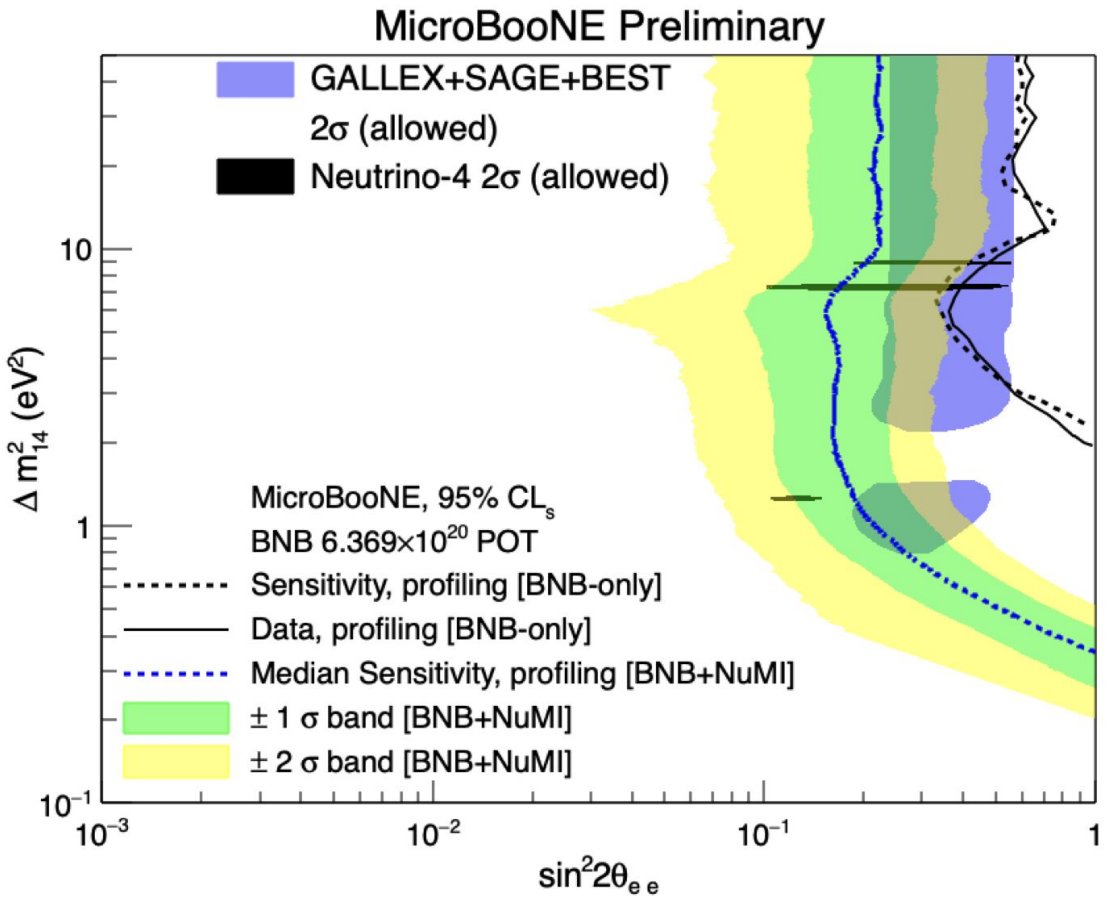


MICROBOONE-NOTE-1132-PUB

3+1 Sterile Neutrinos - Sensitivity

- Introducing NuMI data greatly improves sensitivity.



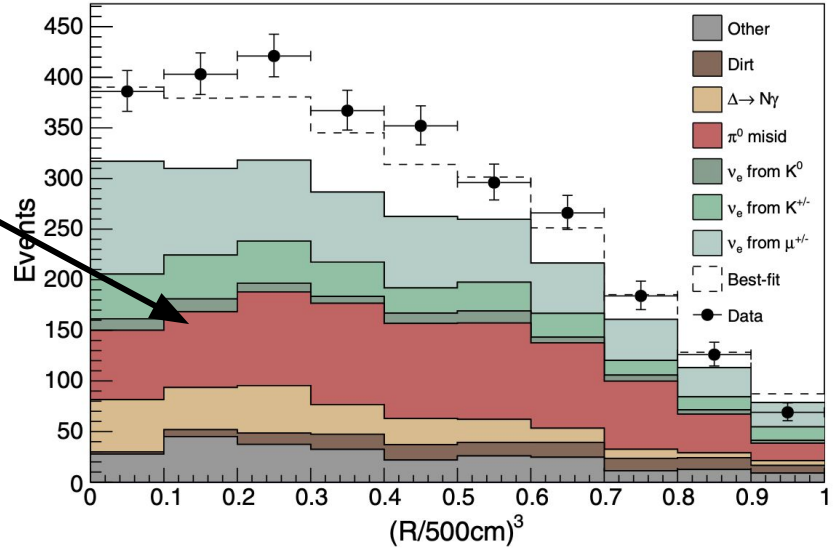


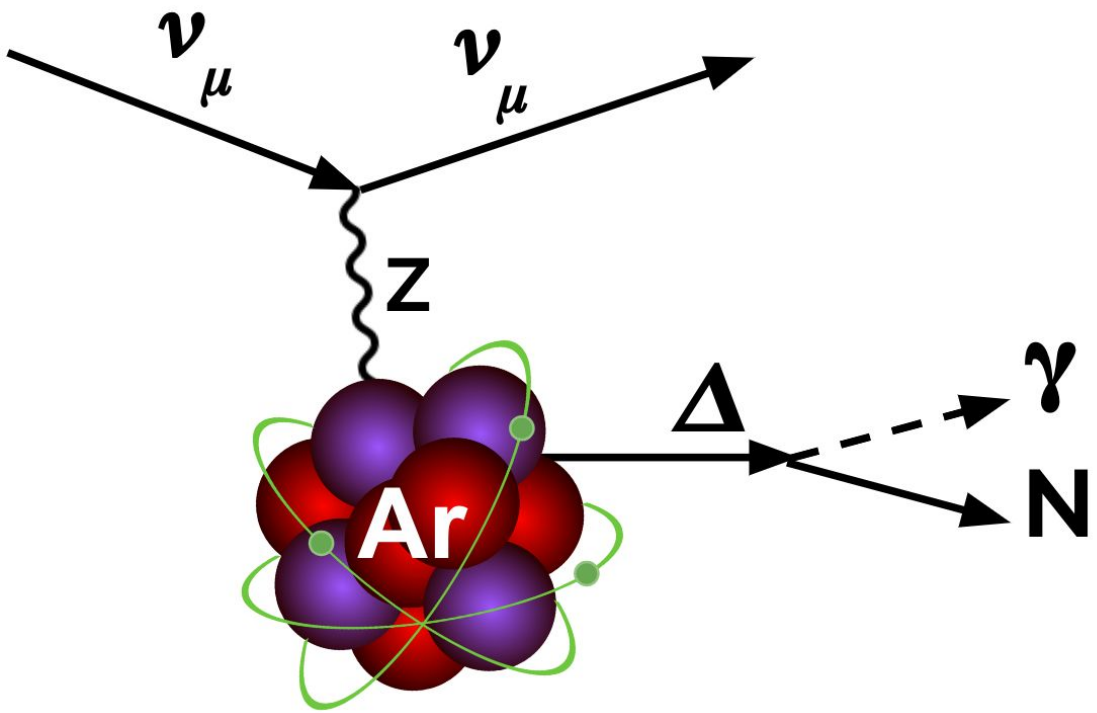
MICROBOONE-NOTE-1132-PUB

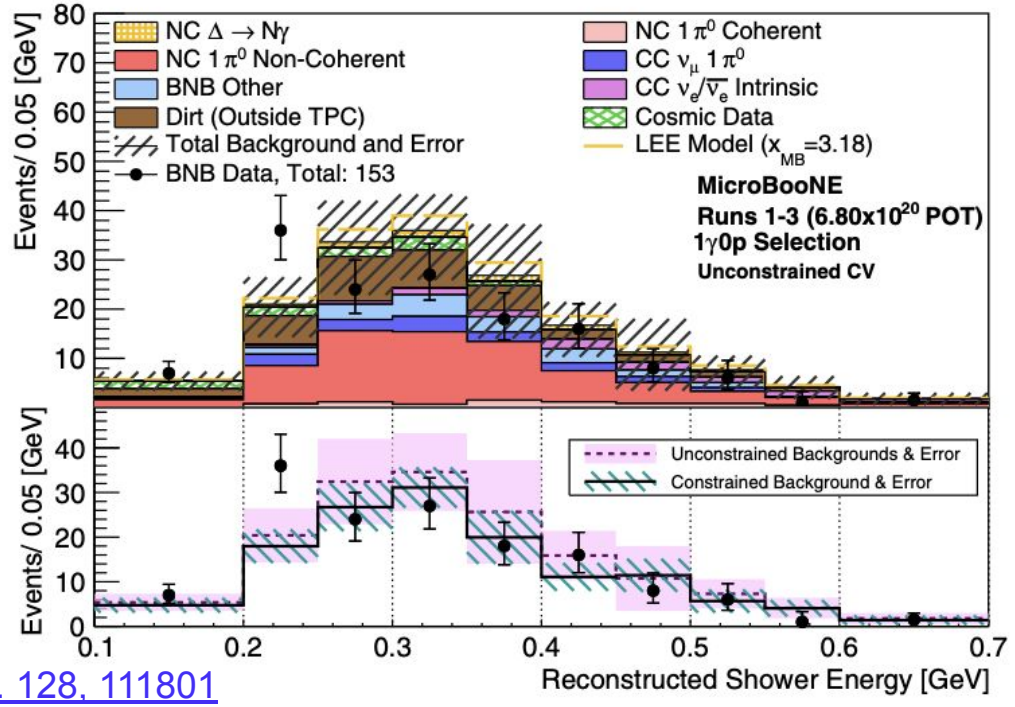
LEE - Photons - Past Results

- Rescaling of Δ→γ background fits radial distribution of MiniBooNE excess best out of non-osc explanations.
- First result from MicroBooNE published in 2022. Disfavour this explanation.
- Updated search with better reconstruction in progress, MicroBooNE PN 1126.

Phys. Rev. D 103, 052002





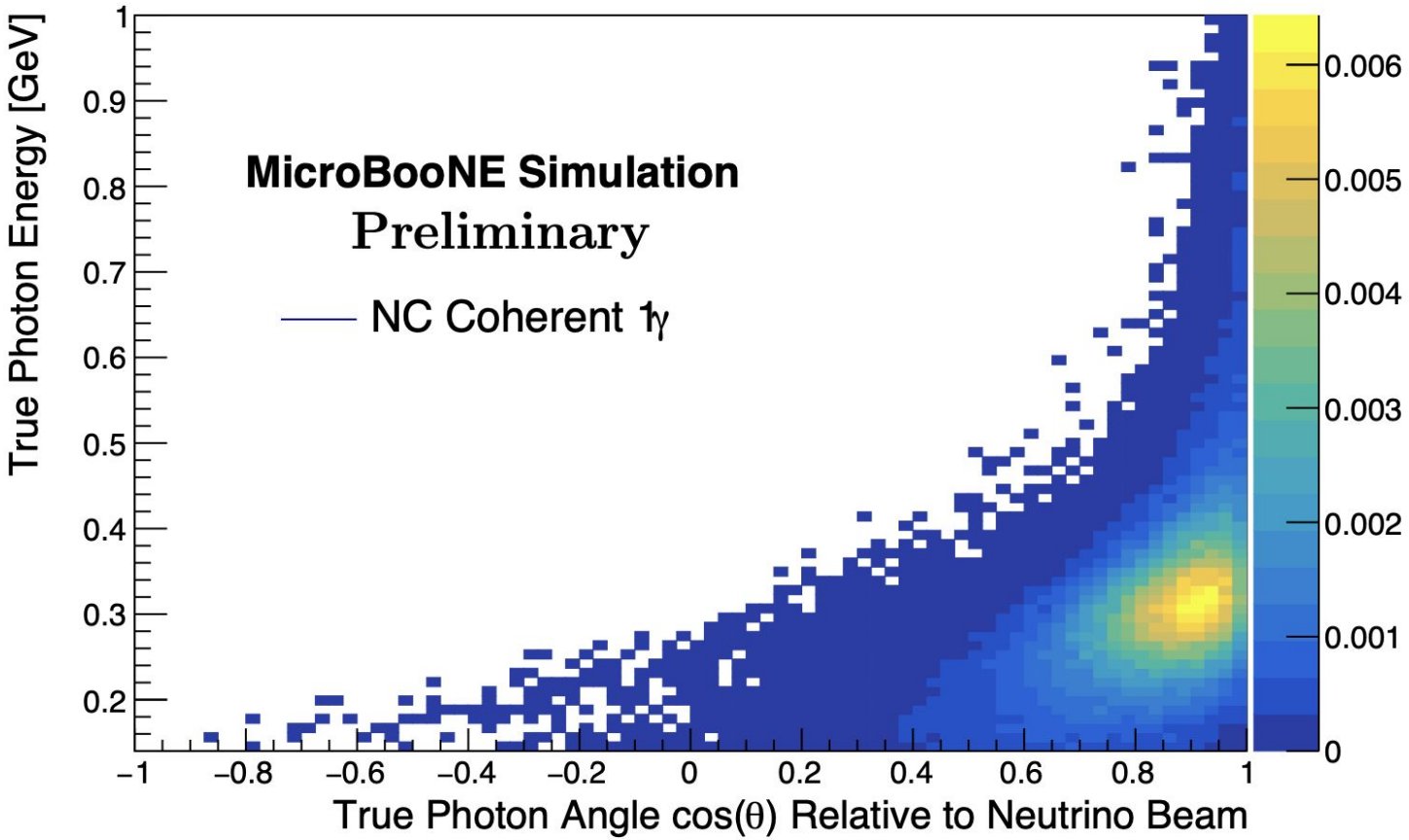


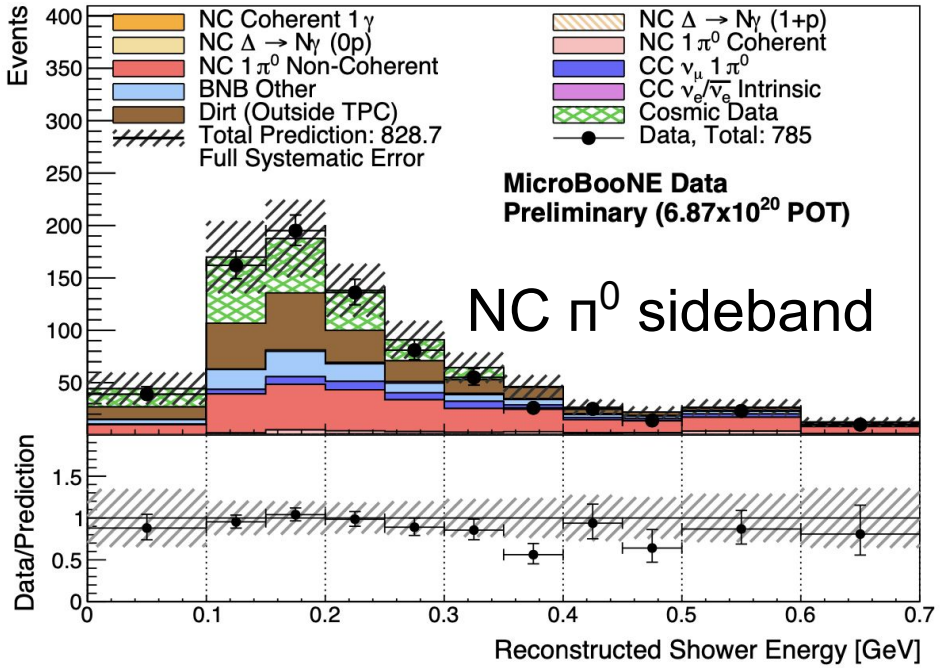
Phys. Rev. Lett. 128, 111801

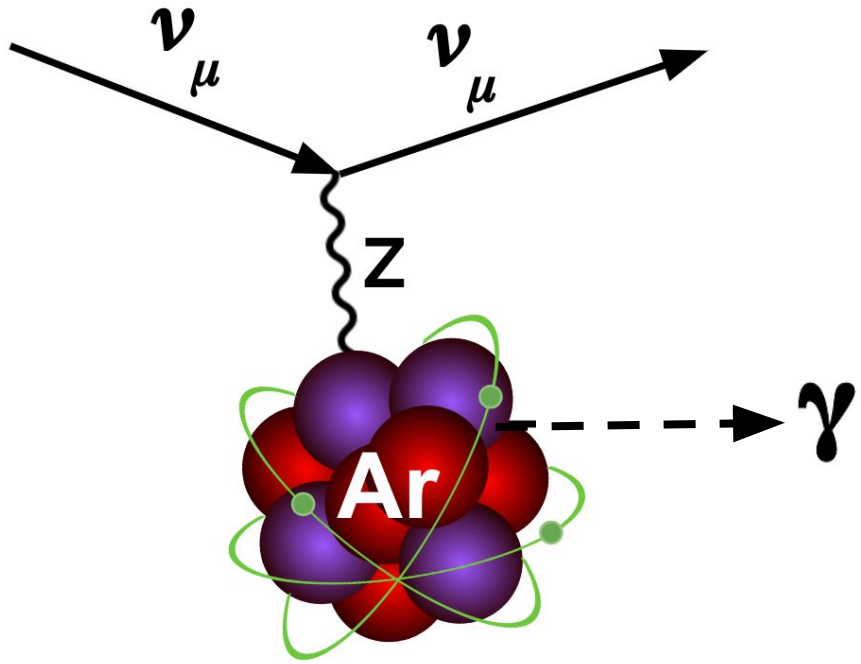
LEE - Photons - NC Coherent

- Source of very forward going single photons, direction main selection handle
- Sideband validations/systematics ongoing.

MicroBooNE PN 1131

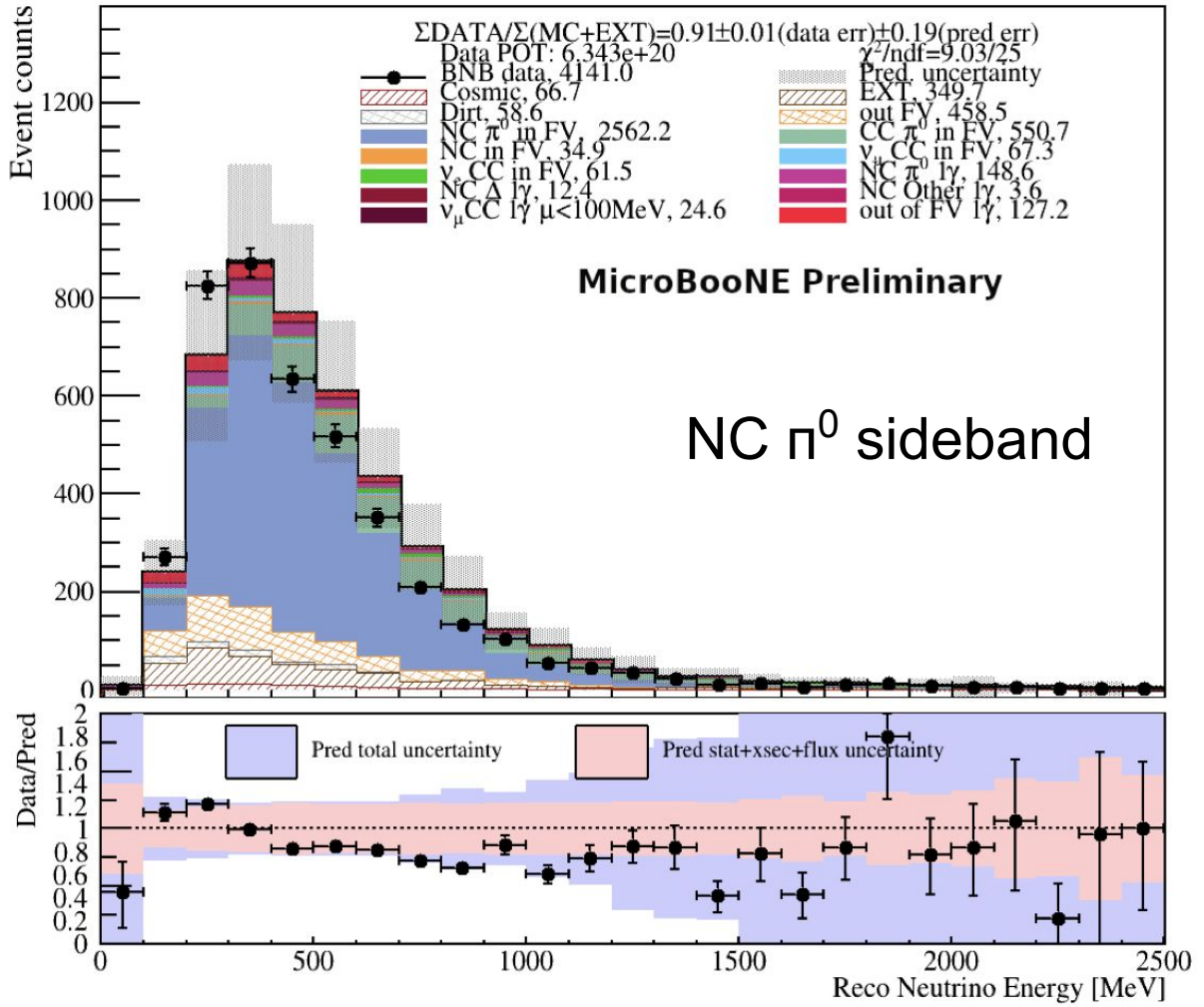






LEE - Photons - Inclusive

- Inclusive search for single photons/highly colinear* pairs of photons.
- Selections complete, systematics and sideband checks currently in progress.

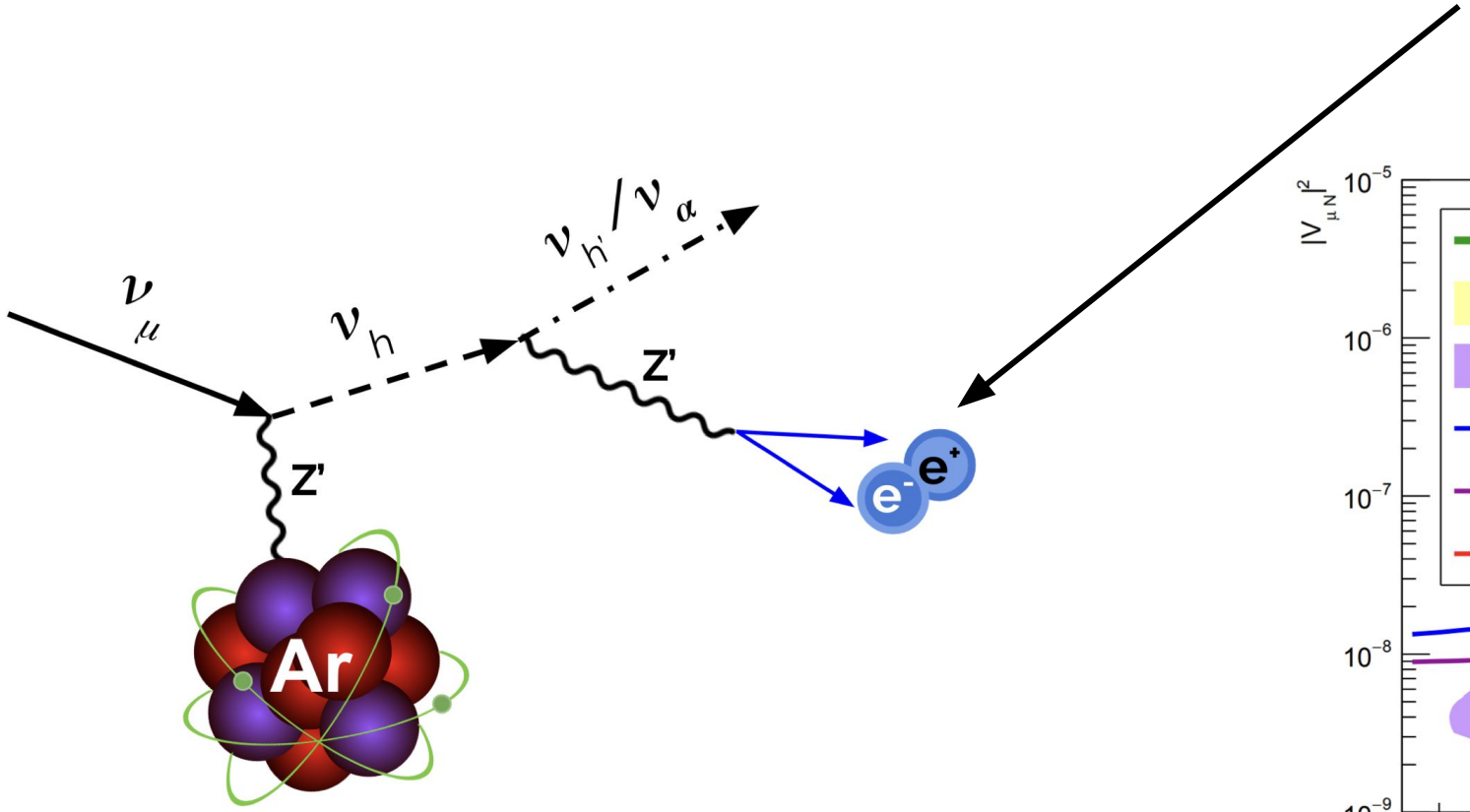


*opening angle < 20°.

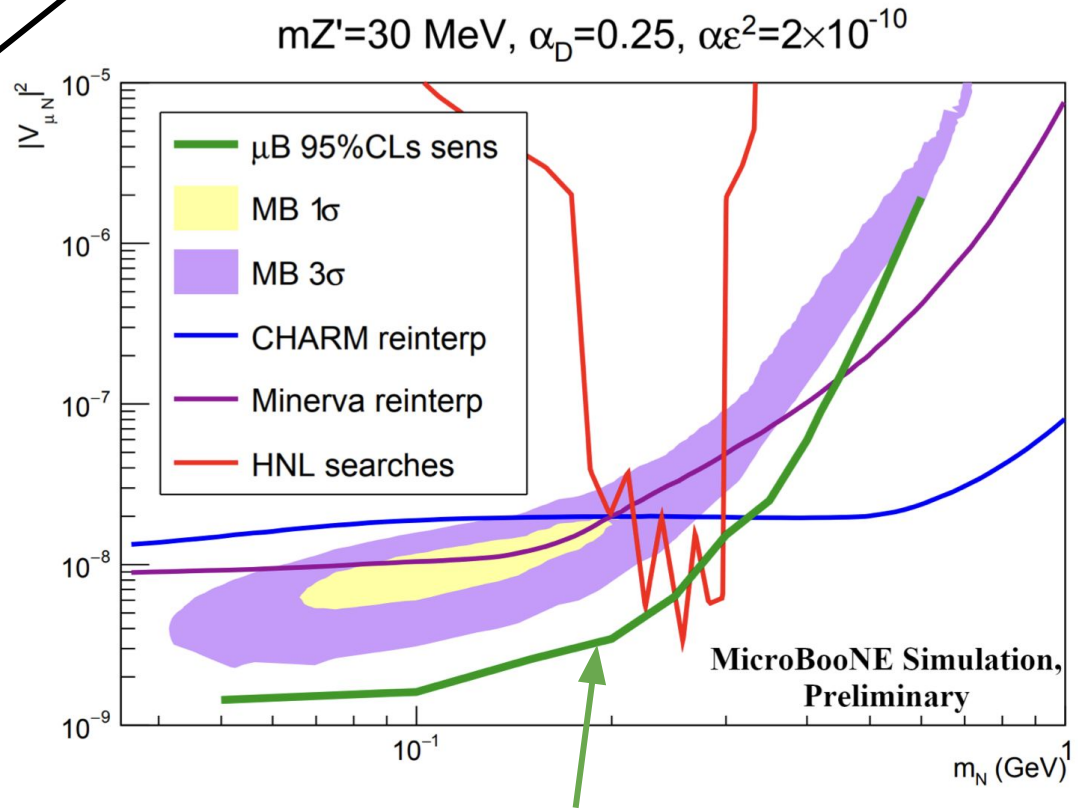
MicroBooNE PN 1125

LEE - BSM

Models propose LEE is result of process in which SM neutrino upscatters via exchange of dark boson (Z') into sterile neutrino, which decays via Z' into an e^+e^- pair.



MICROBOONE-NOTE-1124-PUB



Models proposed in Phys. Rev. D 99, 071701 (2019) and Phys. Rev. Lett. 121, 241801 (2018).

MicroBooNE has sensitivity to test the entire parameter space favoured by MiniBooNE.

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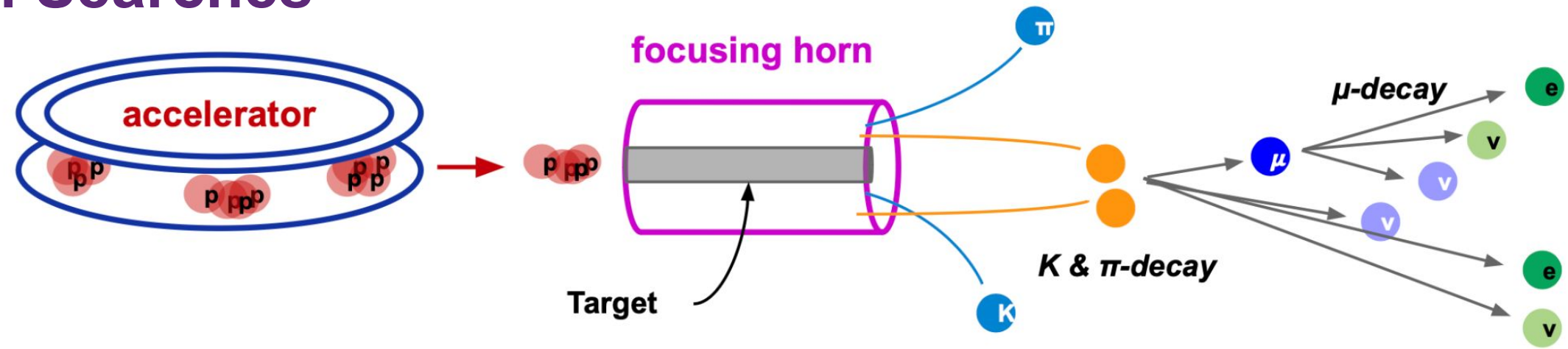
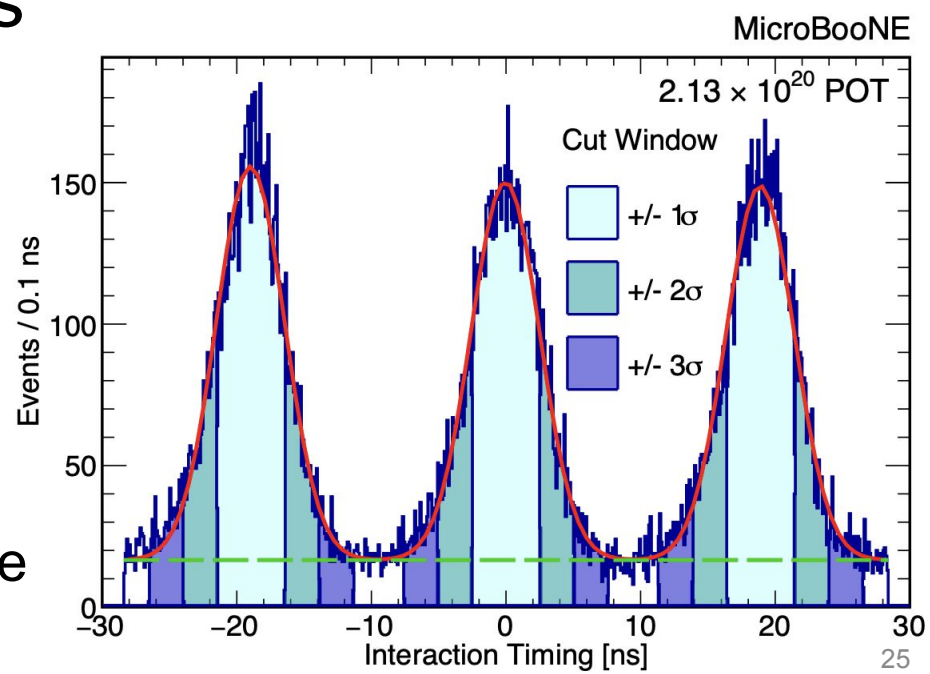
BSM Searches

BSM Searches

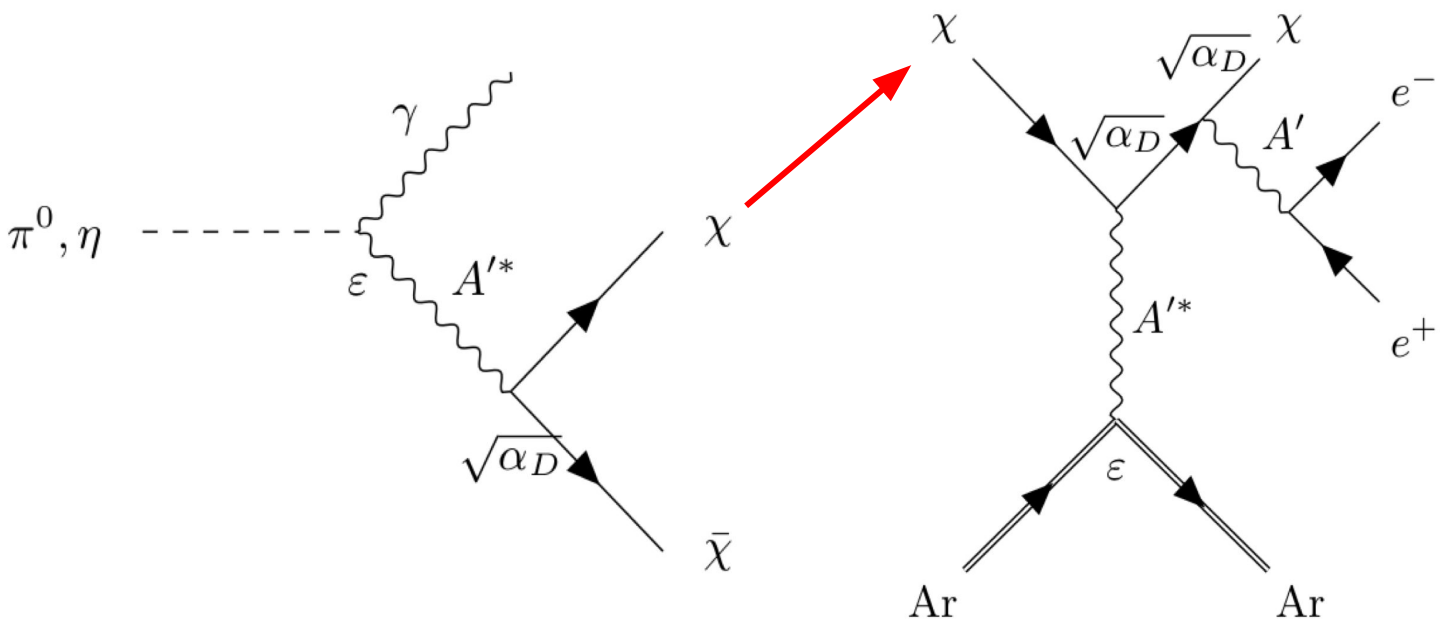


Our accelerators produce large volumes of hadrons - we can search for new decay modes with small BR predicted by BSM theories.



Tangent: we've also achieved ns-level timing resolution. This provides time of flight info for future BSM searches. See Phys. Rev. D **108**, 052010.

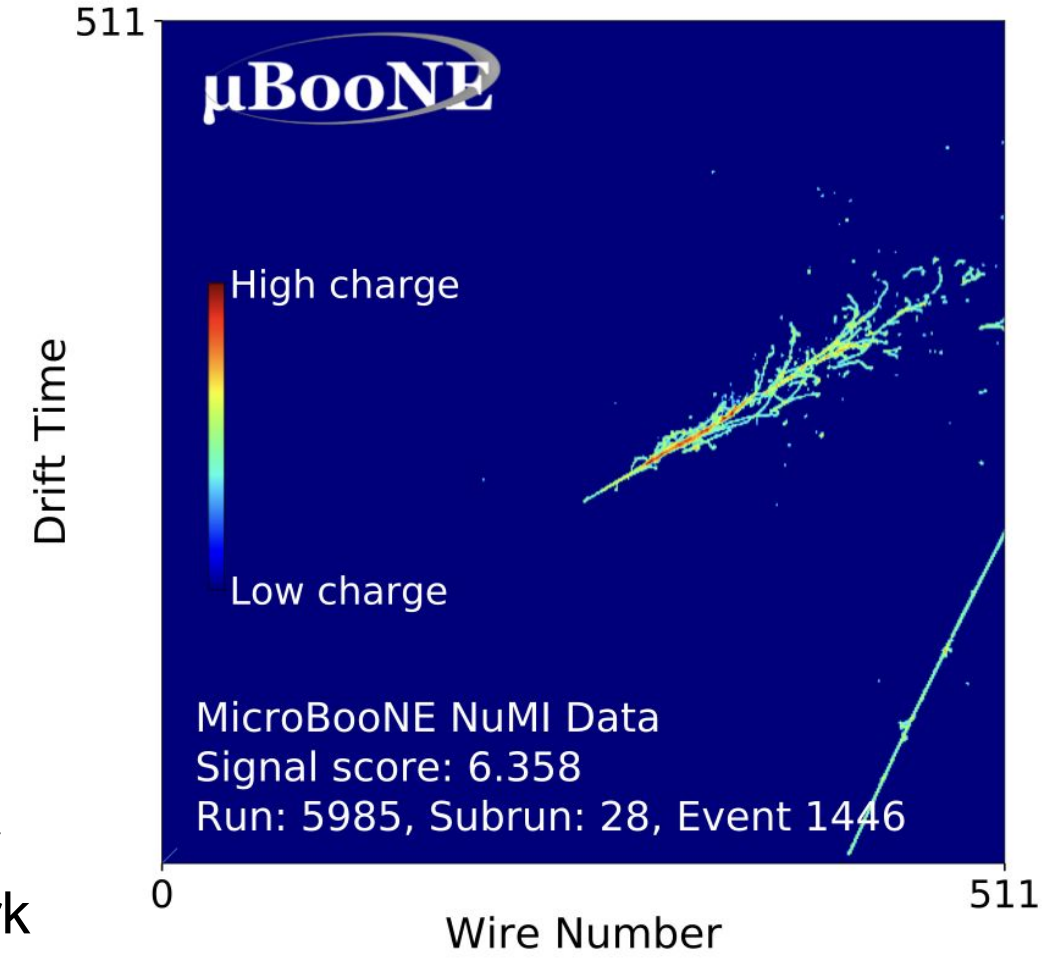
Dark Tridents



Dark matter particle □ produced in decays of π^0 and ηs produced in the NuMI target.

These propagate to MicroBooNE where they interact, producing a dark photon which decays to e^+e^-

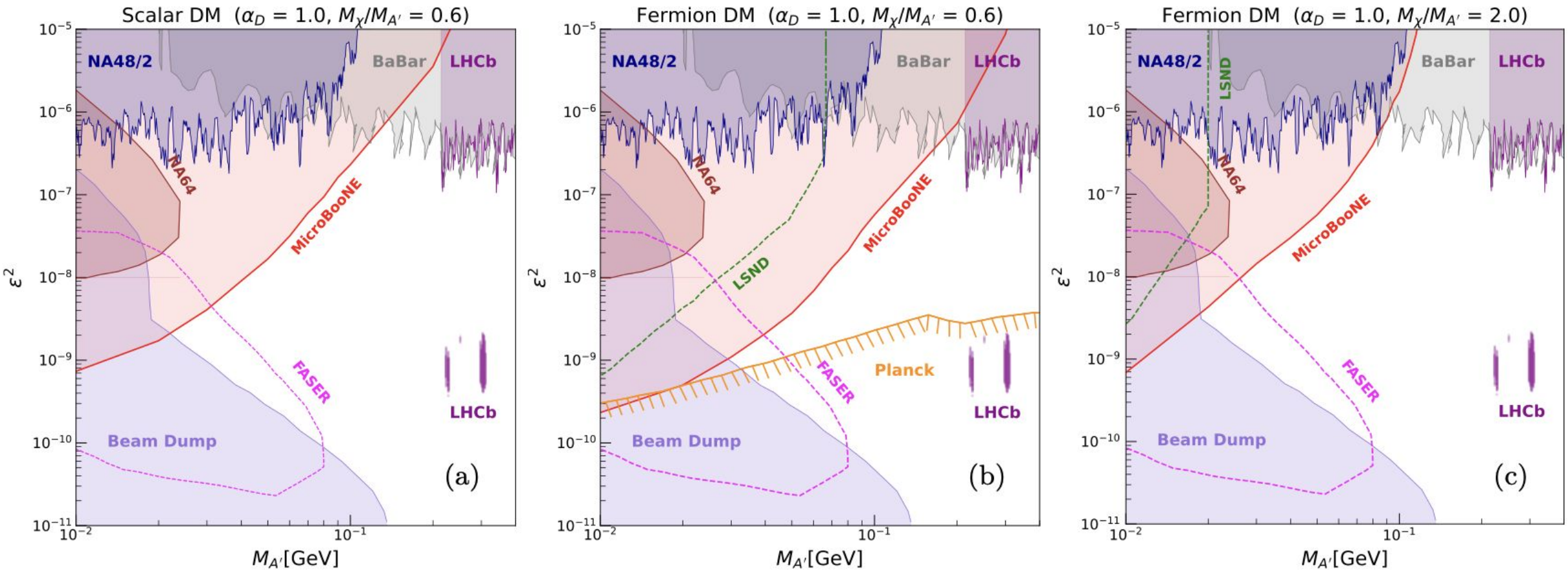
[Phys. Rev. Lett. 132, 241801]



e^+e^- Candidates selected with CNN.

Dark Tridents

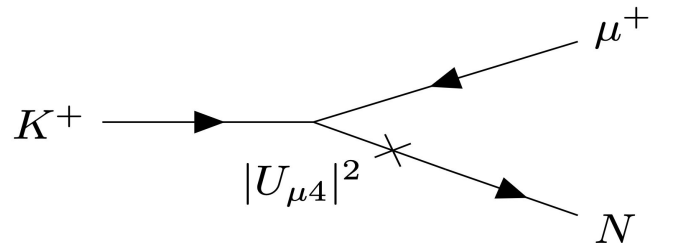
Phys. Rev. Lett. 132, 241801



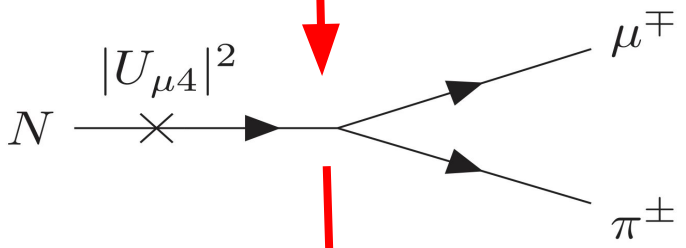
- Exclude new regions of parameter space.

Heavy Neutral Leptons

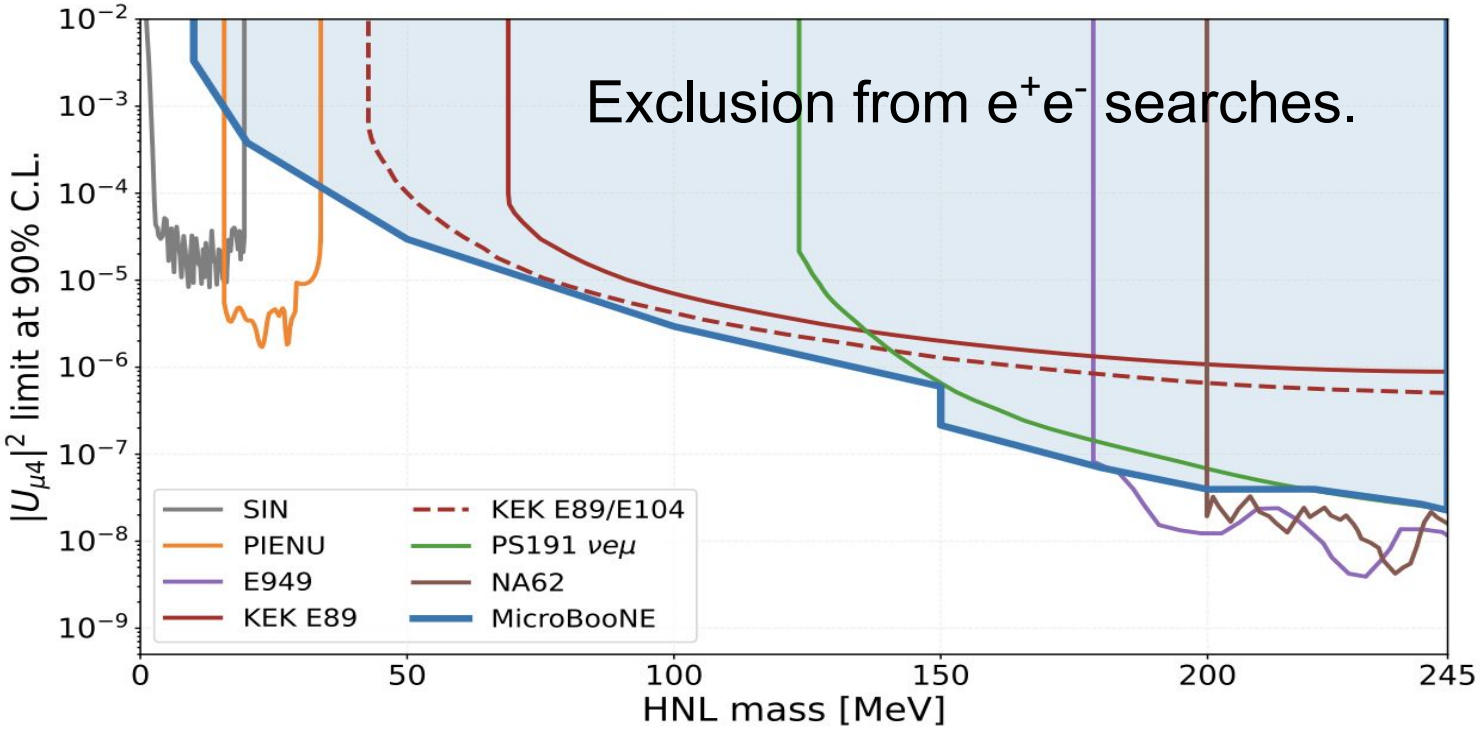
Predicted decay of charged kaons to SM lepton + HNL.

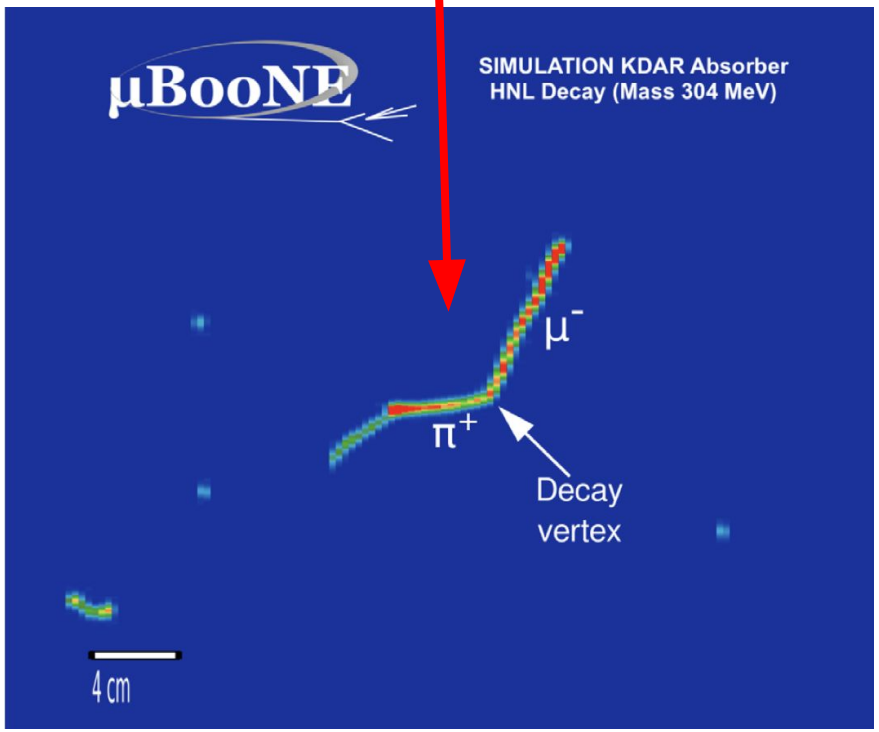


HNL then decays to a few different final states.



Phys. Rev. Lett. 132, 041801





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Neutrino Cross Section Physics

Published Cross Section Results

CC inclusive

- 1D ν_μ CC inclusive @ BNB, Phys. Rev. Lett. 123, 131801 (2019)
- 1D ν_μ CC E_ν @ BNB, Phys. Rev. Lett. 128, 151801 (2022)
- 3D CC E_ν @ BNB, arXiv:2307.06413
- 1D ν_e CC inclusive @ NuMI, Phys. Rev. D104, 052002 (2021) Phys. Rev. D105, L051102 (2022)
- 2D ν_μ CC0pNp inclusive @ BNB, Phys. Rev. Lett. 133, 041801 Phys. Rev. D 110, 013006

Pion production

- ν_μ NCπ^0 @ BNB, Phys. Rev. D 107, 012004 (2023)
- 2D ν_μ NCπ^0 @ BNB, arXiv:2404.10948
- ν_μ CCπ^0 @ BNB, arXiv:2404.09949 accepted for publication to PRD

CC0π

- 1D ν_e CCNp0π @ BNB, Phys. Rev. D 106, L051102 (2022)
- 1D & 2D ν_μ CC1p0π transverse imbalance @ BNB, Phys. Rev. Lett. 131, 101802 (2023) Phys. Rev. D 108, 053002 (2023)
- 1D & 2D ν_μ CC1p0π generalized imbalance @ BNB, Phys. Rev. D 109, 092007 (2024)
- 1D ν_μ CC1p0π @ BNB, Phys. Rev. Lett. 125, 201803 (2020)
- 1D ν_μ CC2p @ BNB, arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB, Phys. Rev. D102, 112013 (2020)
- 2D ν_μ CCNp0π @ BNB, arXiv:2403.19574

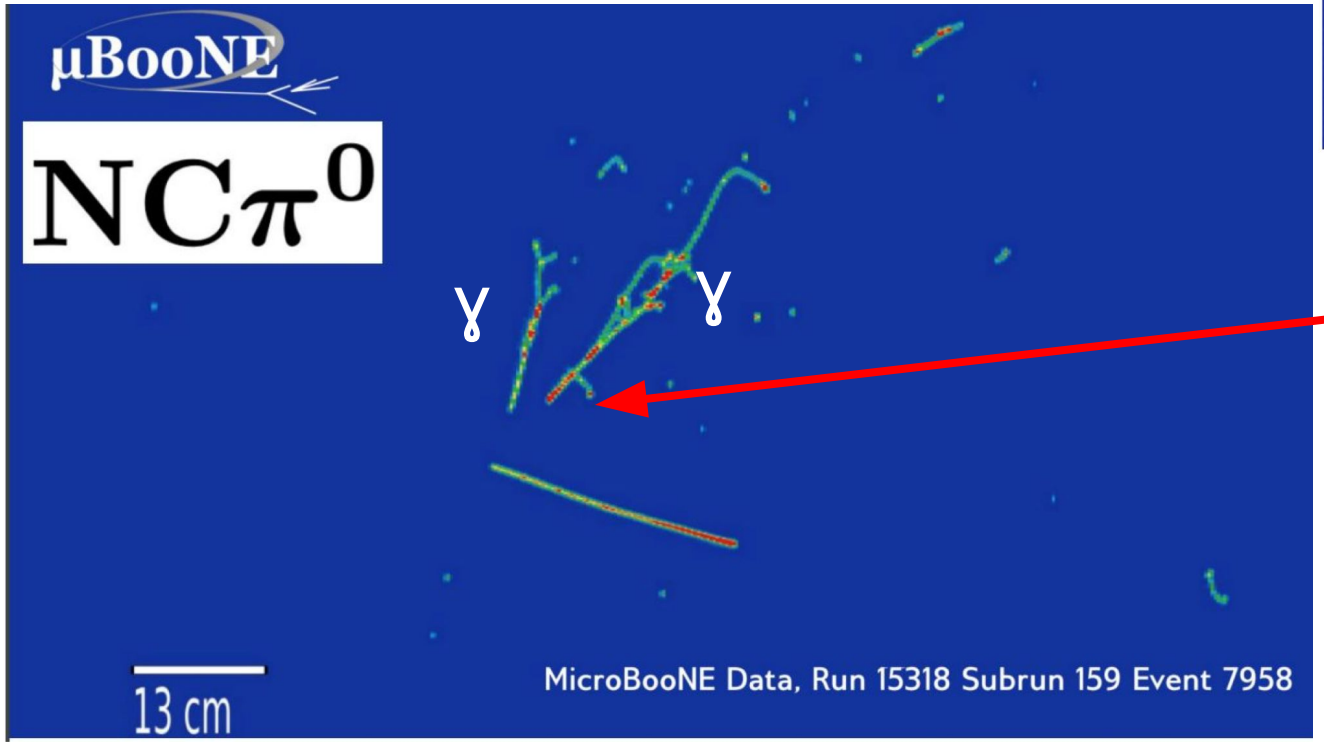
Rare channels

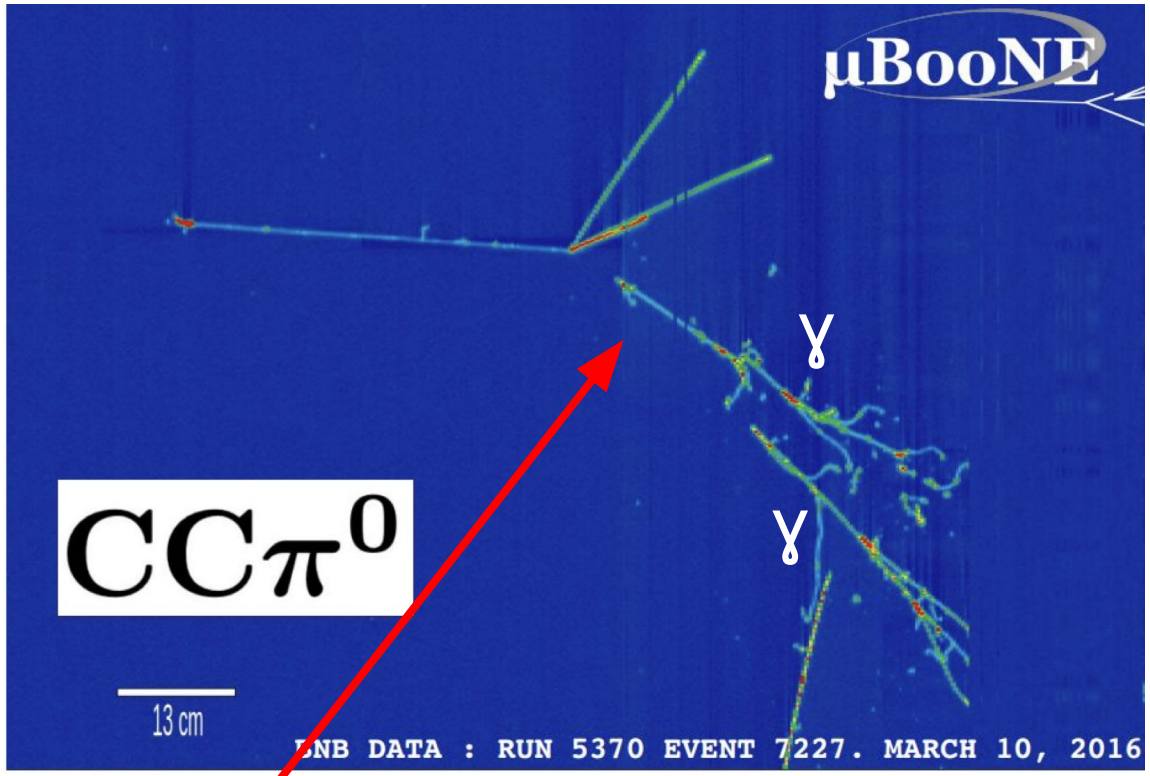
- η production @ BNB, Phys. Rev. Lett. 132, 151801 (2024)
- Λ production @ NuMI, Phys. Rev. Lett. 130, 231802 (2023)

Neutral Pions

- Dangerous source of background in ν_e searches.
- Sensitive to resonance production.

arXiv:2404.10948





arXiv:2404.09949

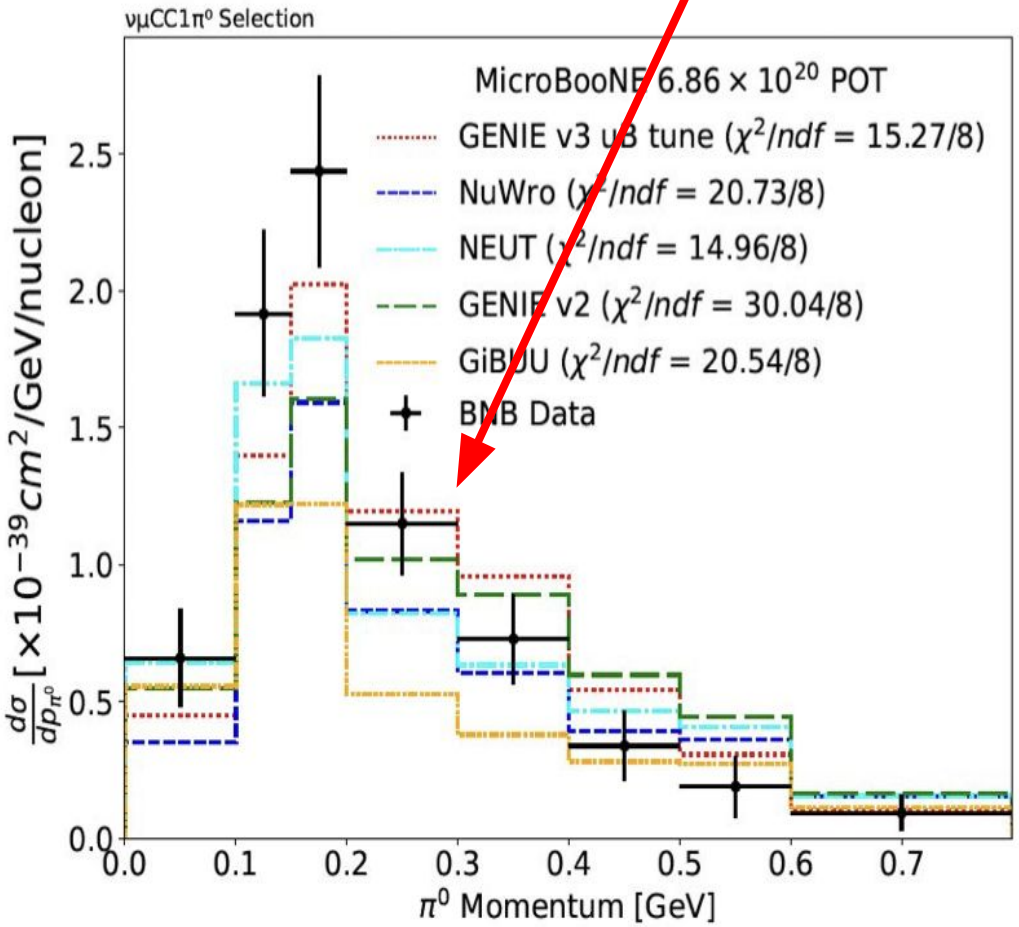
$\pi^0 \rightarrow \gamma\gamma$

Separate CC and NC measurements!

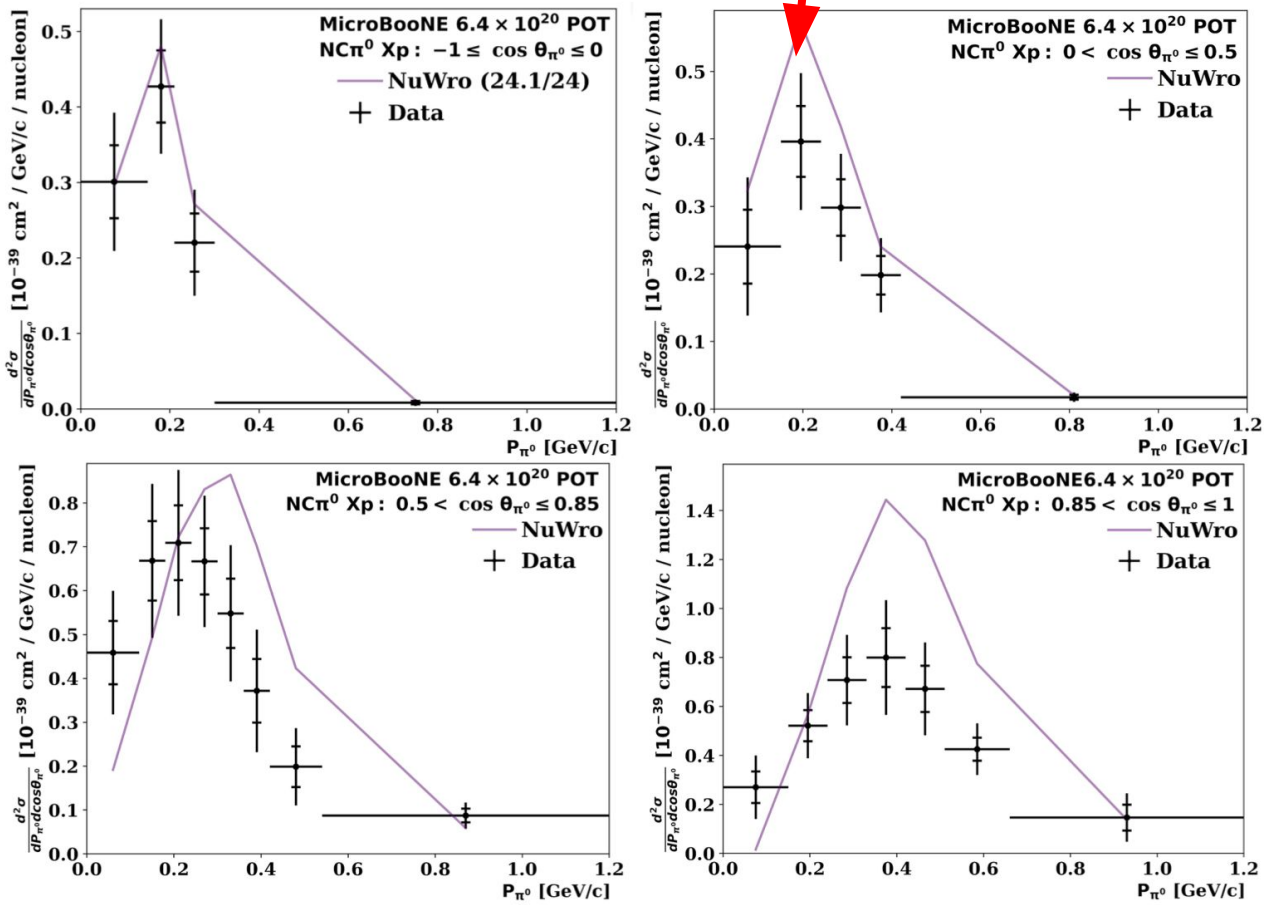
CC Neutral Pion Production

- Underpredictions in CC channel and overpredictions in NC channel.

arXiv:2404.09949

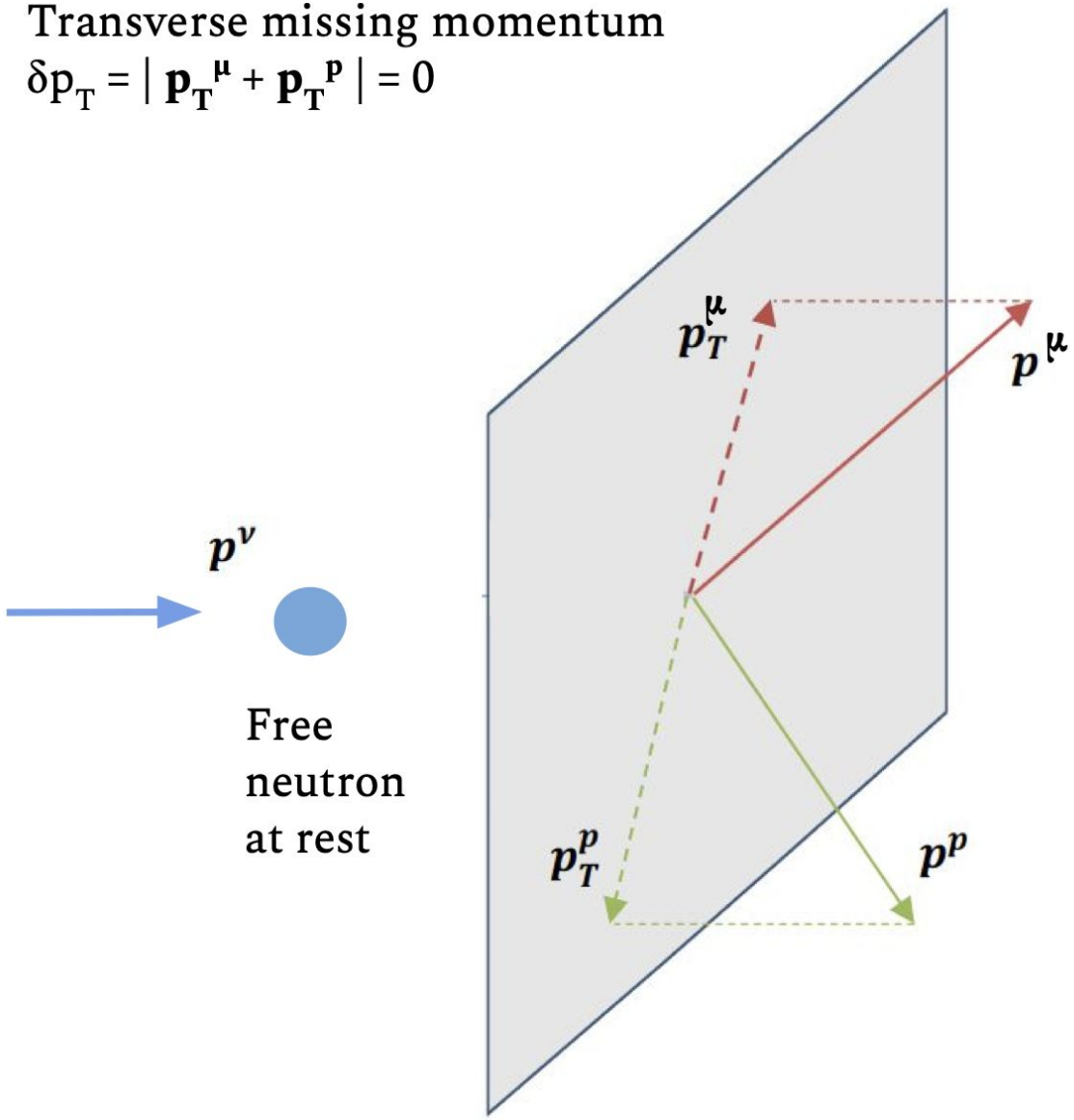


arXiv:2404.10948

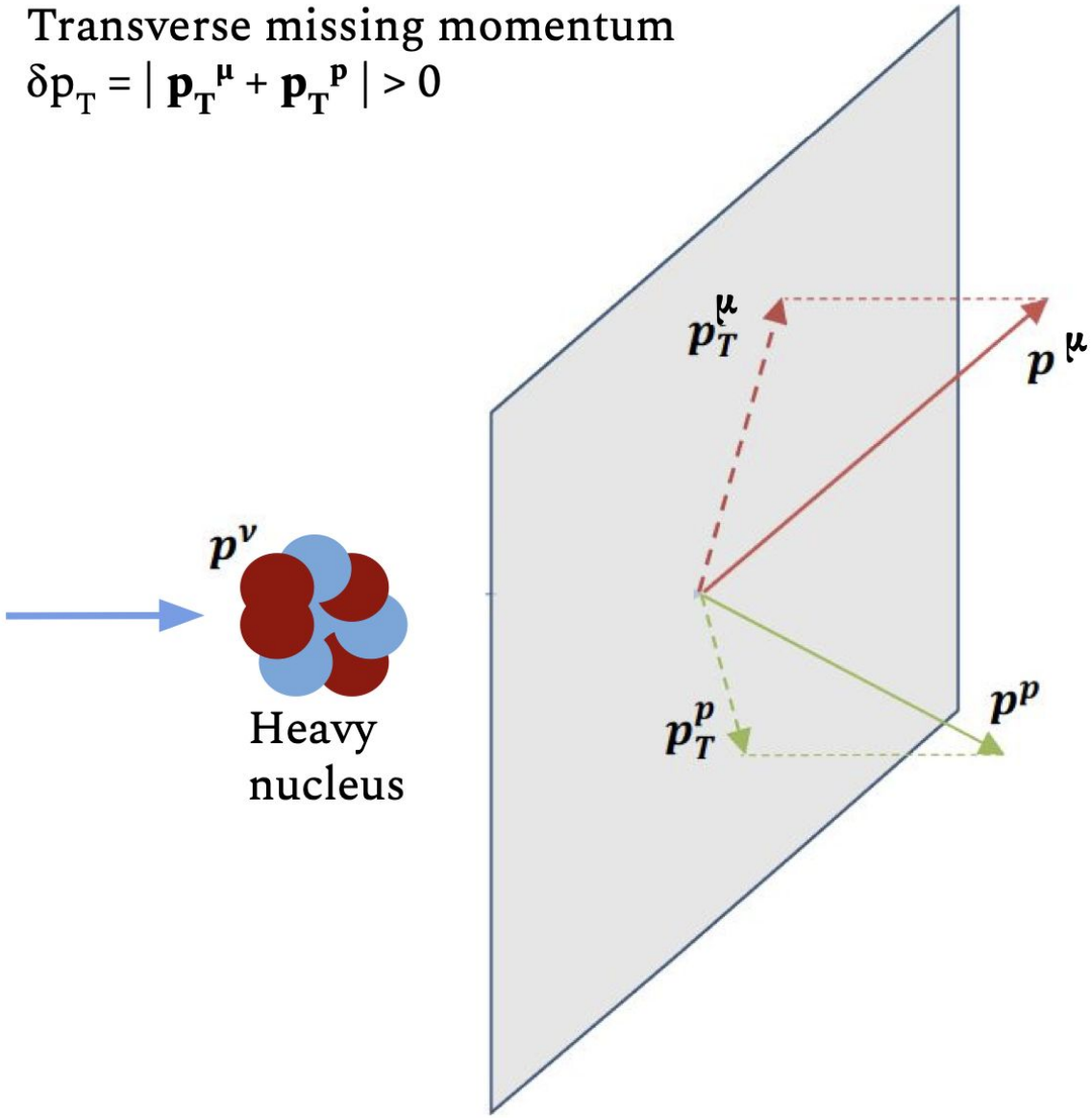


Kinematic Imbalance

Transverse missing momentum
$\delta p_T = | \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} | = 0$

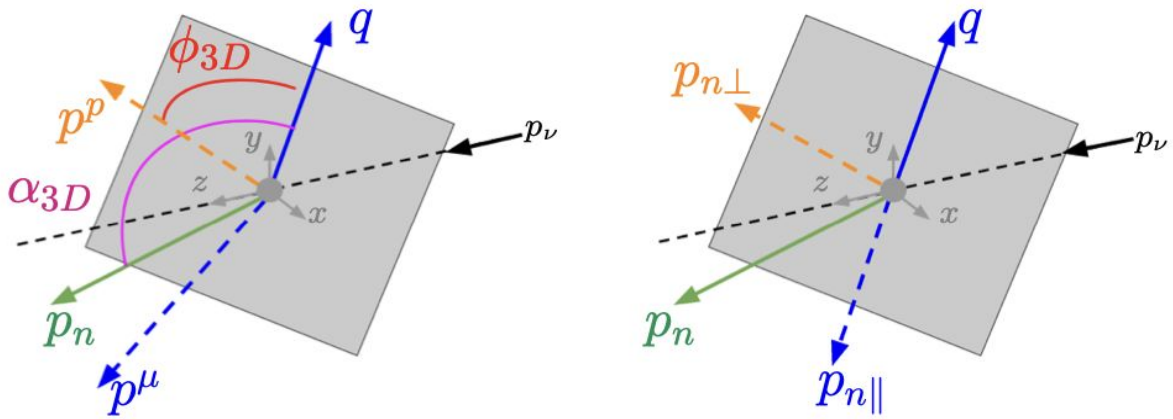


Transverse missing momentum
$\delta p_T = | \mathbf{p_T}^{\mu} + \mathbf{p_T}^{p} | > 0$



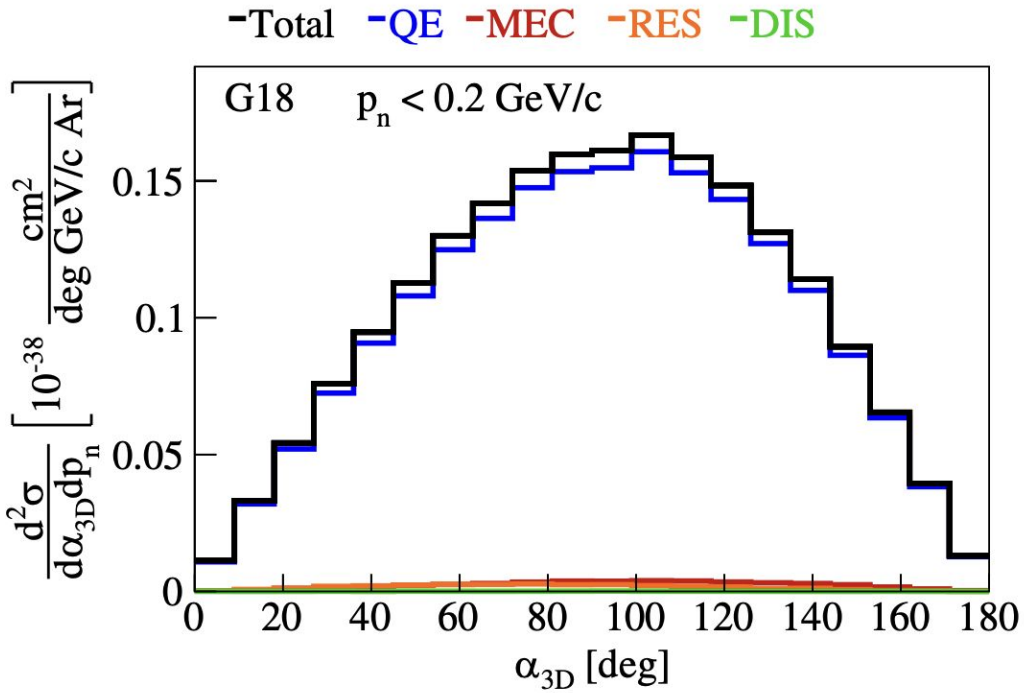
Generalised Kinematic Imbalance

Phys. Rev. D 109, 092007



$$p_n = |\vec{p}_n| = \sqrt{p_L^2 + \delta p_T^2},$$
$$\phi_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_p}{|\vec{q}||\vec{p}_p|}\right),$$
$$\alpha_{3D} = \cos^{-1}\left(\frac{\vec{q}\cdot\vec{p}_n}{|\vec{q}||\vec{p}_n|}\right).$$
$$p_{n\perp,x} = (\hat{q}_T \times \hat{z})\cdot\vec{p}_n,$$
$$p_{n\perp,y} = (\hat{q}\times(\hat{q}_T\times\hat{z}))\cdot\vec{p}_n,$$
$$p_{n\perp} = \sqrt{(p_{n\perp,x})^2 + (p_{n\perp,y})^2} = |p_n|\sin(\alpha_{3D}),$$
$$p_{n\parallel} = \hat{q}\cdot\vec{p}_n = |p_n|\cos(\alpha_{3D}).$$

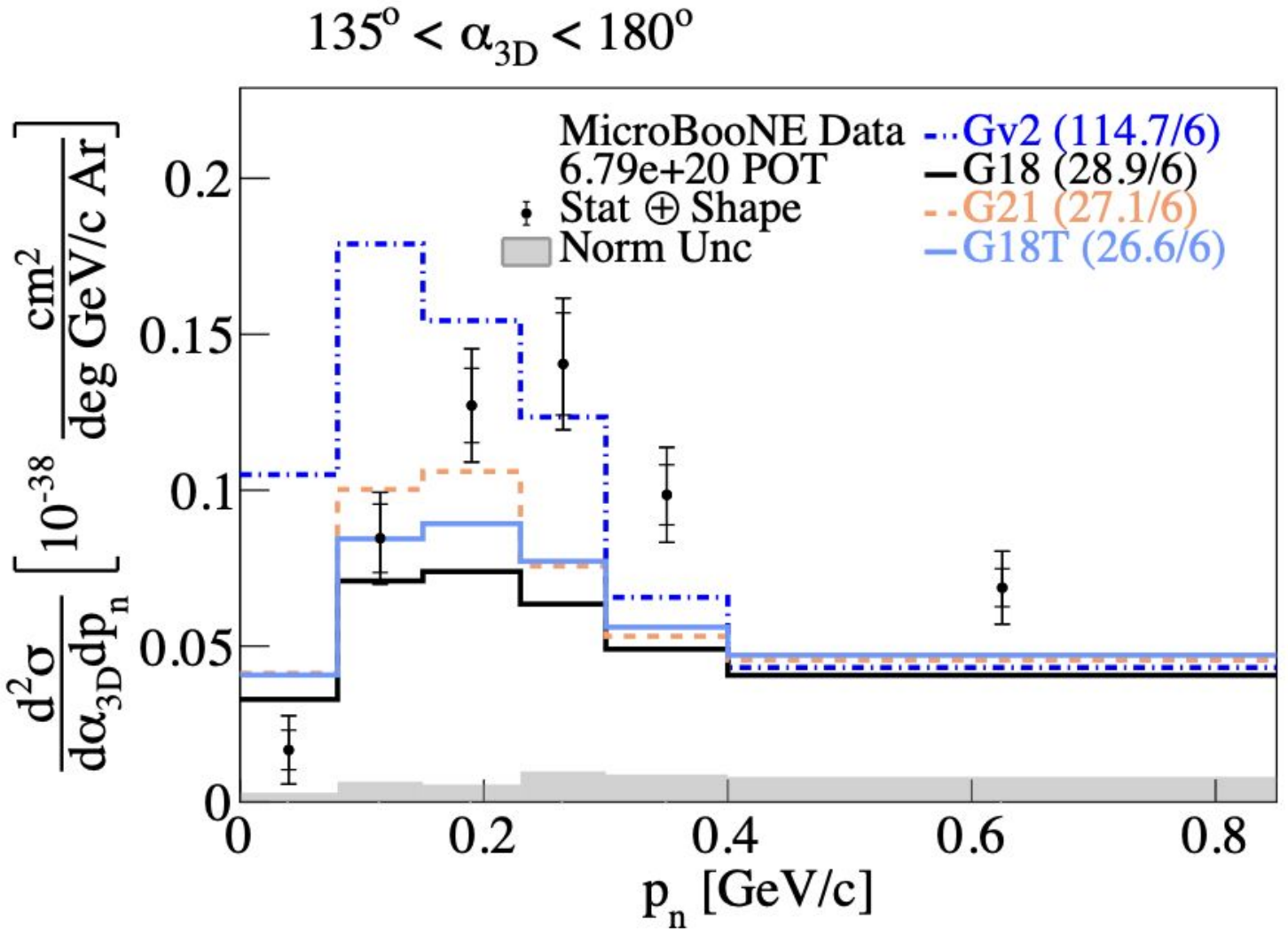
Generalised kinematic imbalance (GKI) variables.



Cutting on p_n enables separation of the quasielastic region from other interactions

Generalised Kinematic Imbalance

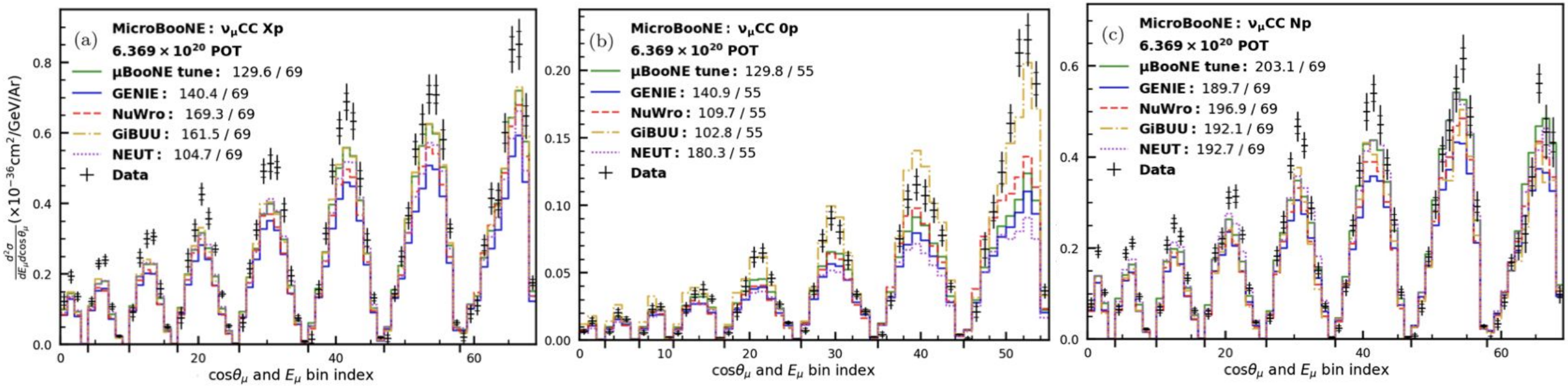
- Double differential cross sections w.r.t. two GKI variables.
- Expose inconsistencies between the generators and between generators and our data.



Phys. Rev. D 109, 092007

Multiple Channel Measurements

Phys. Rev. Lett. 133, 041801



Any number of protons

No protons

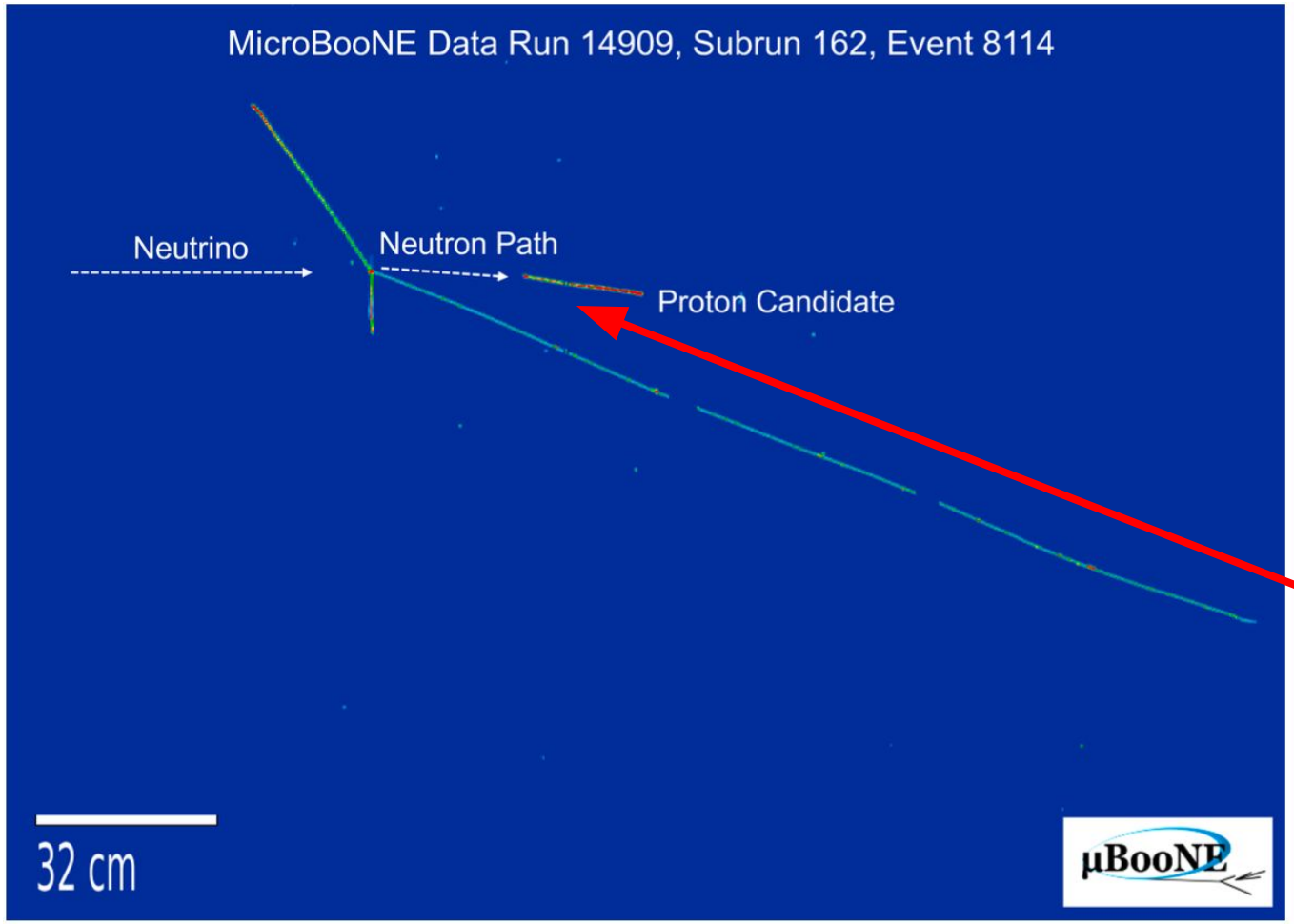
>= 1 protons

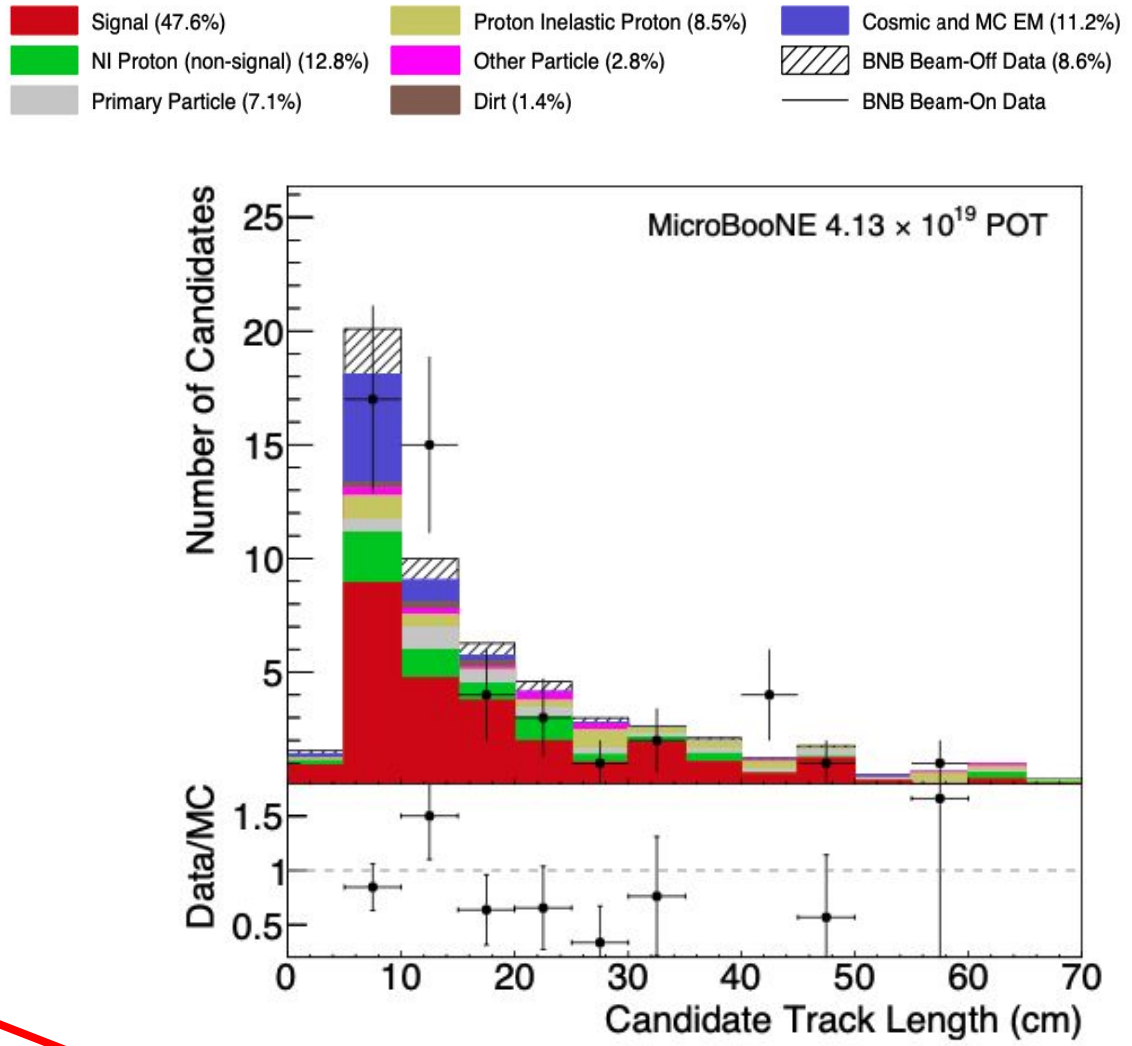
- Simultaneous measurements of final states with and without protons with fits of generators to both including their correlations.

Neutron Detection

- Significant source of missing energy in neutrino interactions.

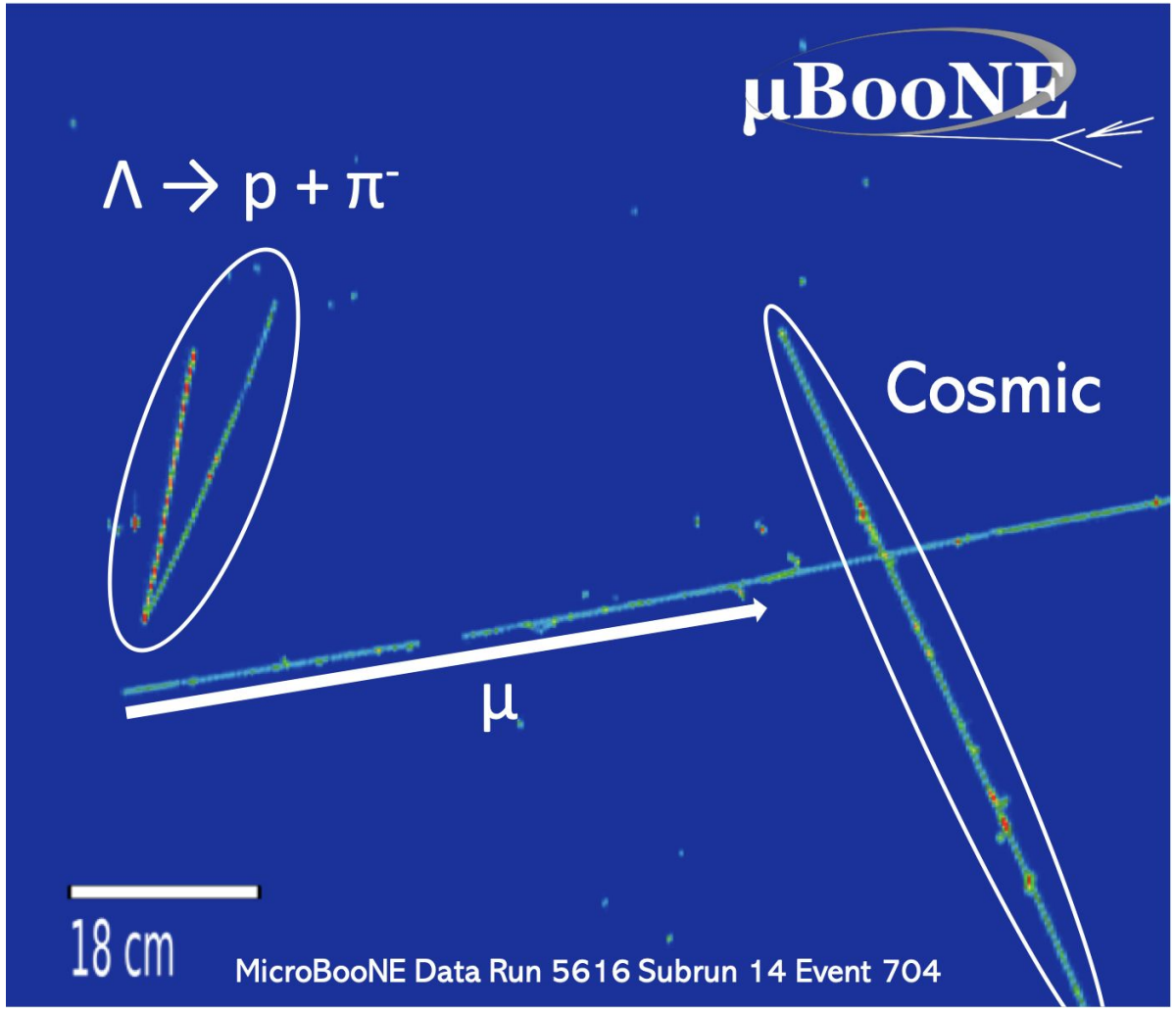
EPJ C 84 1052

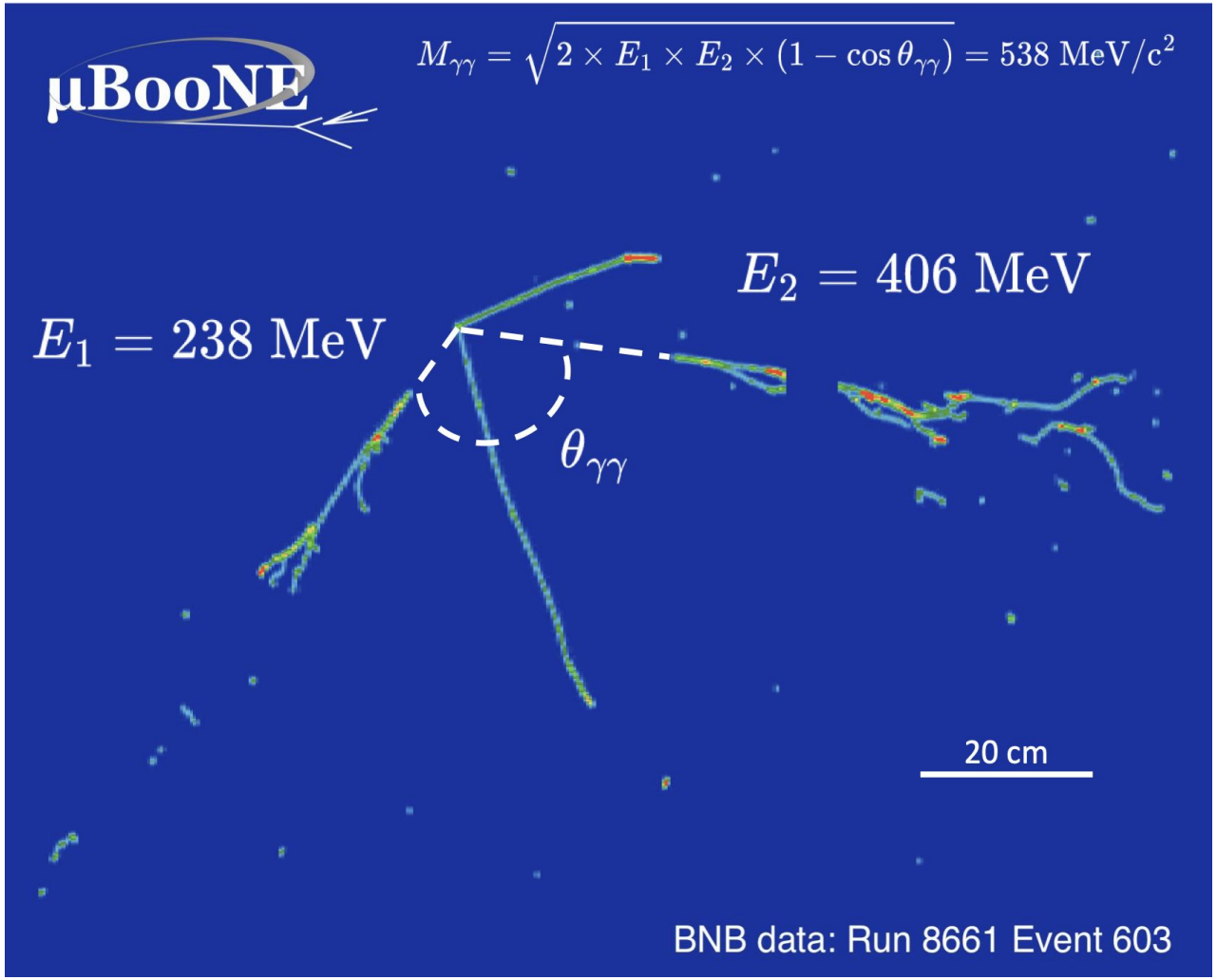




- Infer existence of neutron through interaction producing proton knockout.

Rare Processes - Published





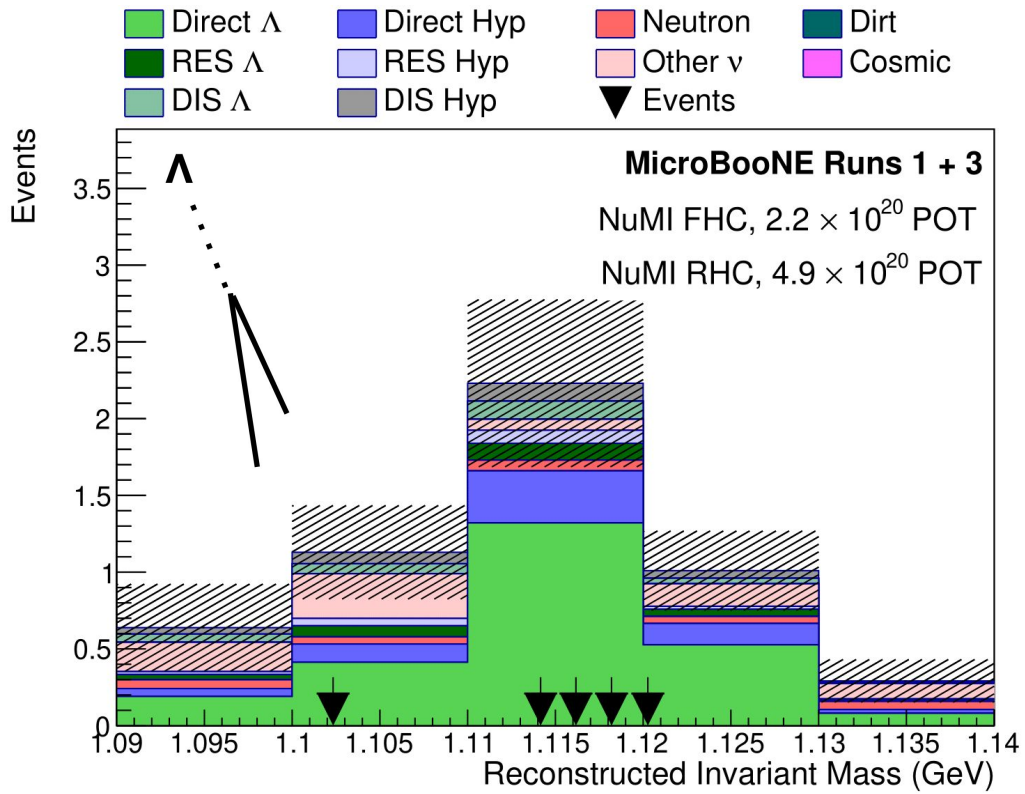
Λ Baryons [Phys. Rev. Lett. 130 23, 231802]

η Mesons [Phys. Rev. Lett. **132**, 151801]

Invariant Mass Spectra

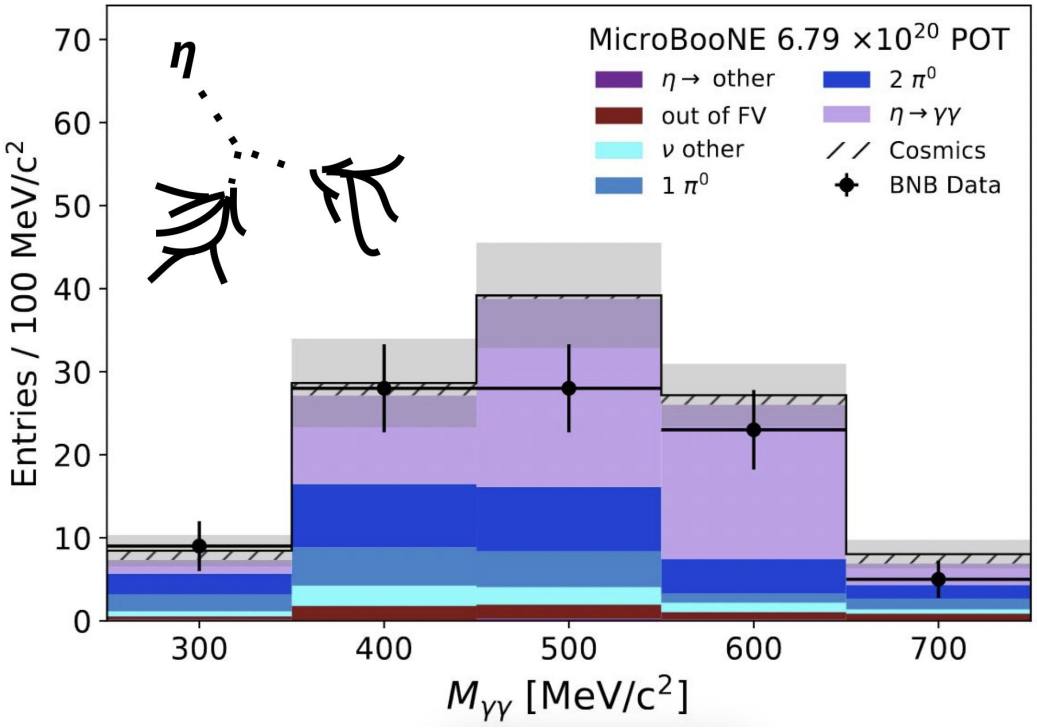
- A nice check is the look at the invariant masses of our selected Λ and η candidates.

Figure from Phys. Rev. Lett. 130, 231802.



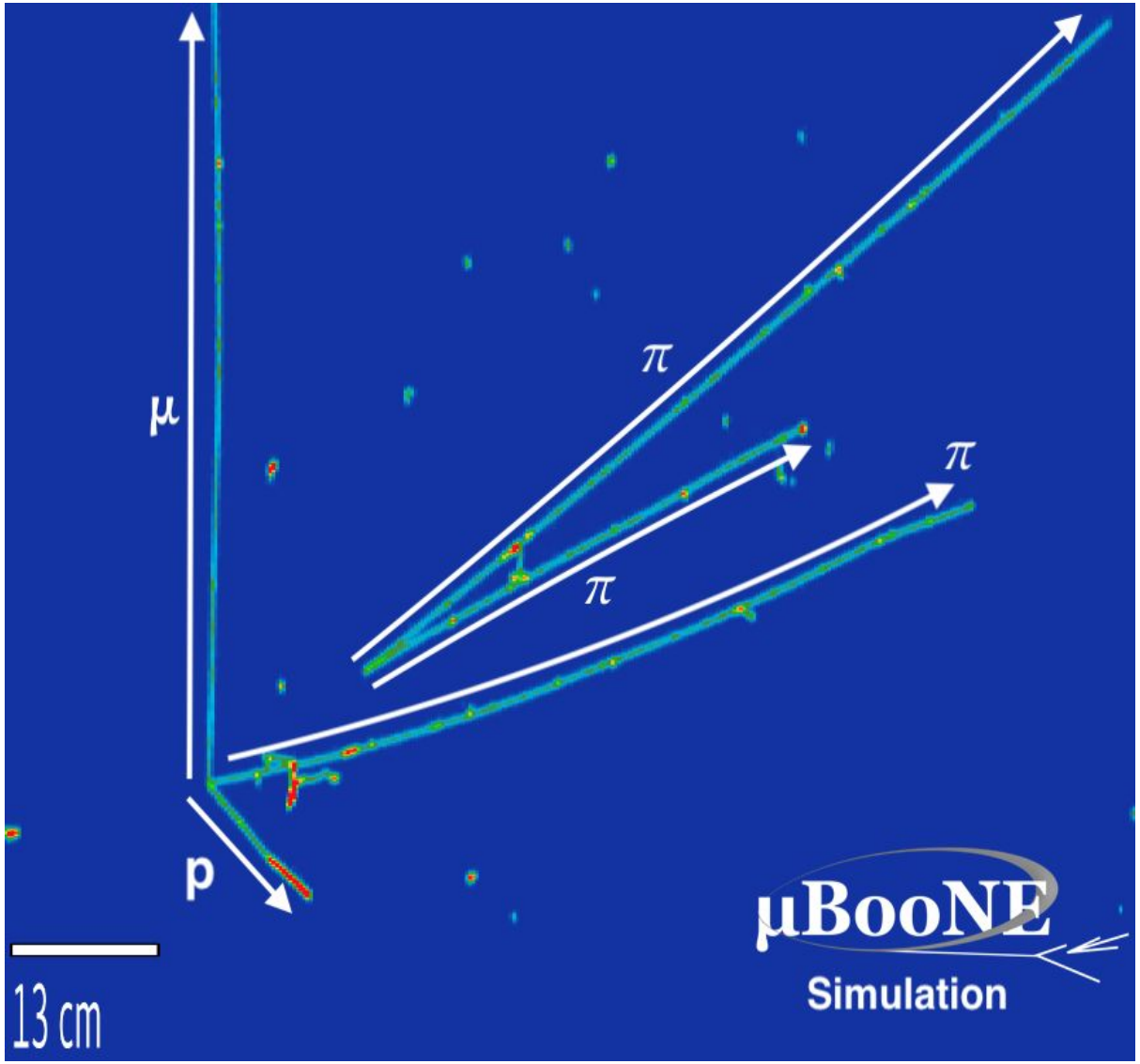
Lots of Λs around the true mass!

Figure from arXiv:2305.16249.

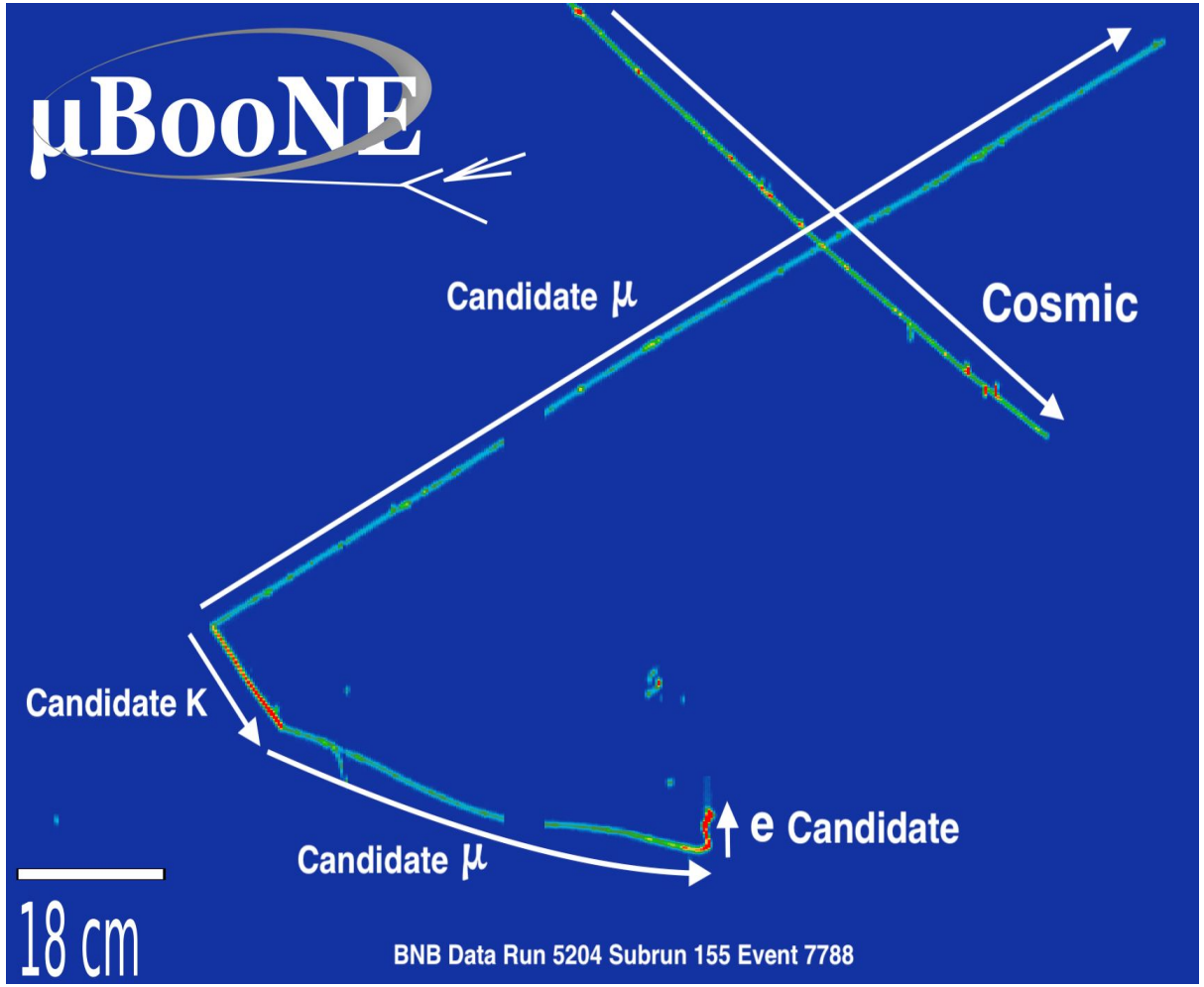


Rare Processes - In Progress

Dangerous backgrounds to $p \rightarrow \nu K^+$ searches.



Neutral Kaons



Charged Kaons

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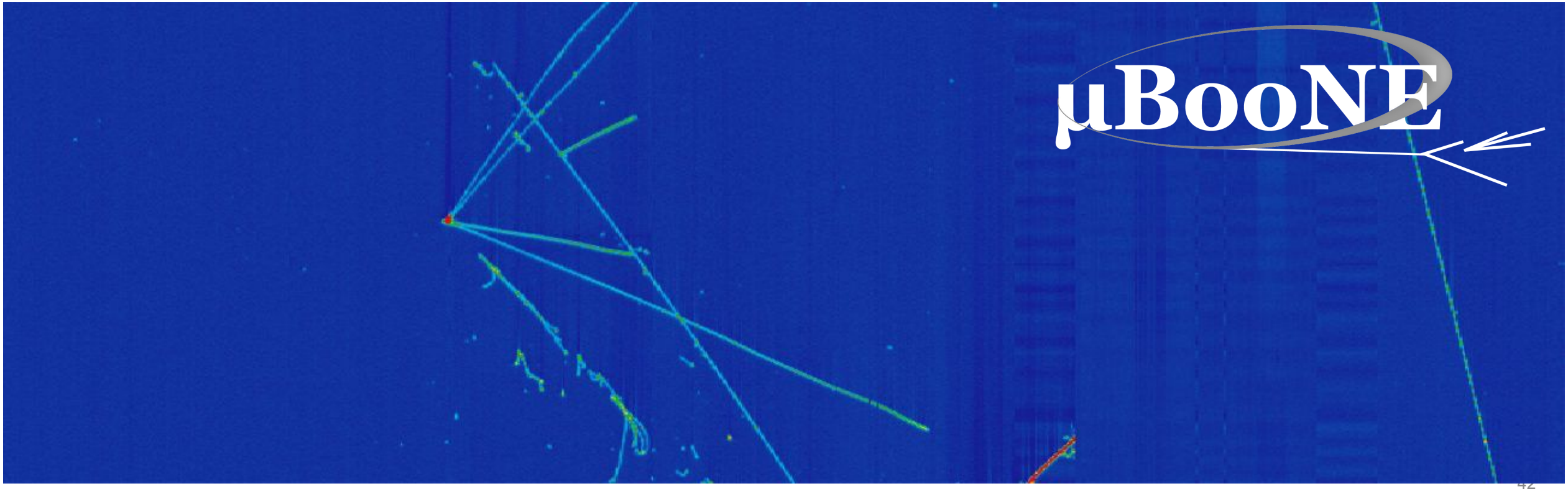
Summary

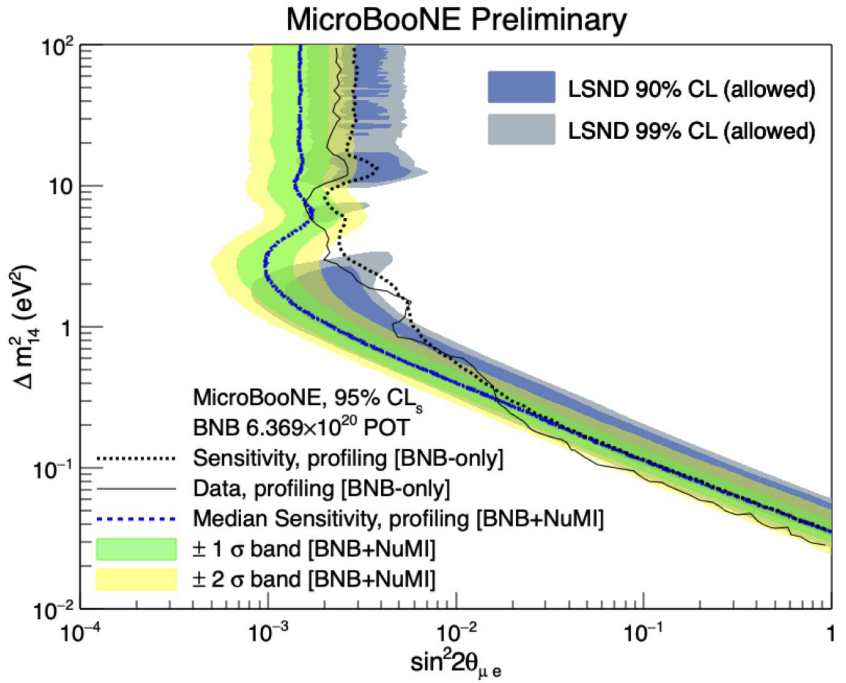
Summary

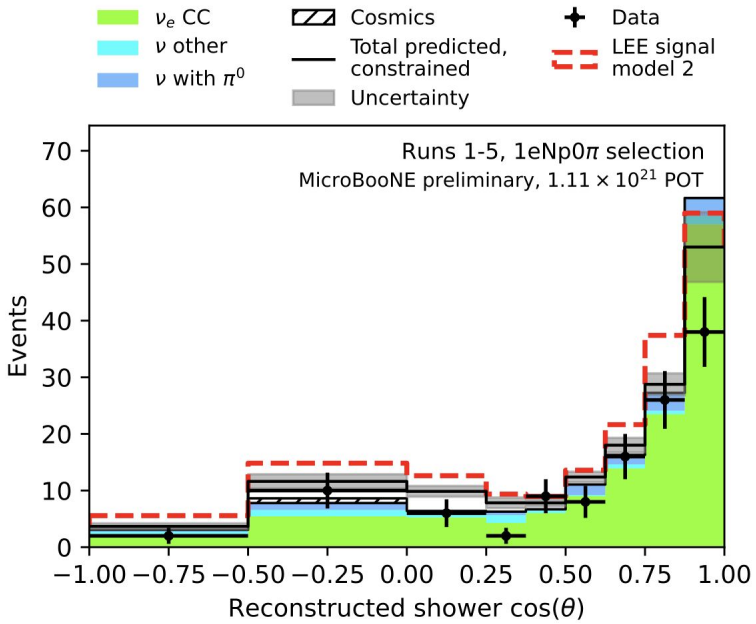
- MicroBooNE is LArTPC with a wide ranging physics program covering oscillations, BSM, neutrino-nucleus cross sections, reconstruction, and LArTPC detector physics.

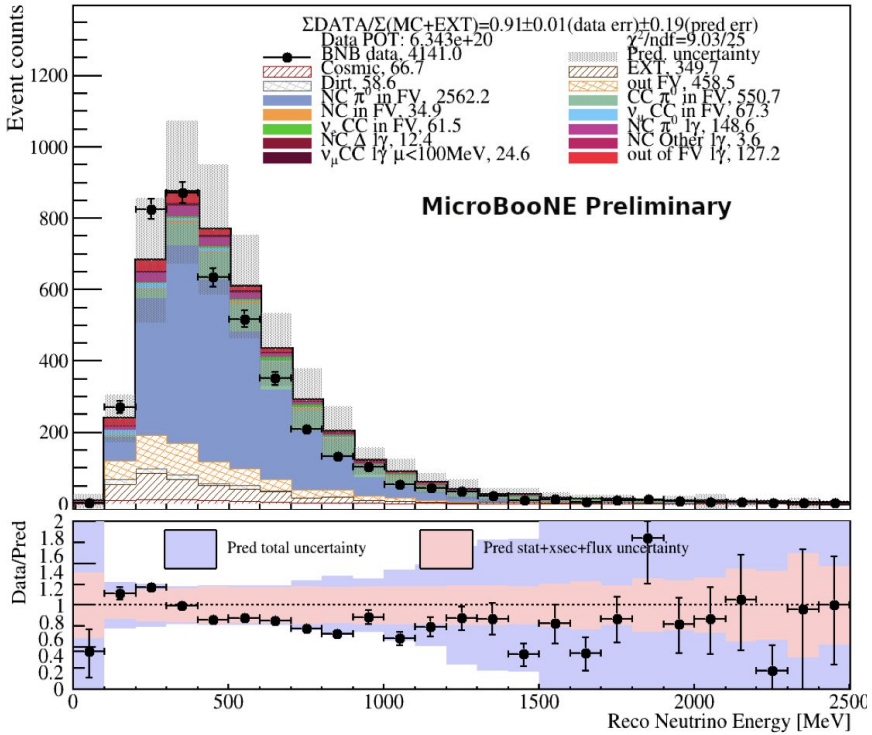


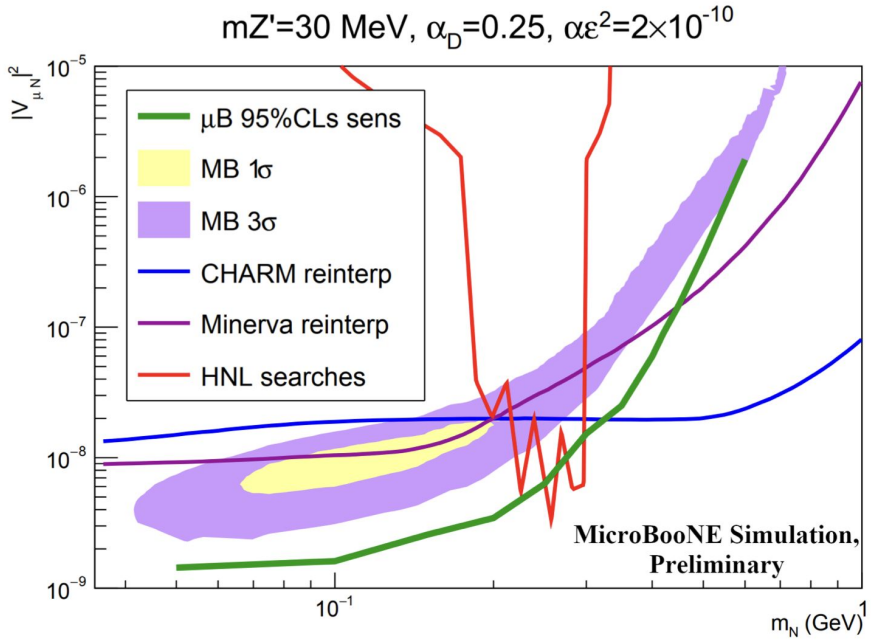
Summary

- We have a number of results probing the MiniBooNE and LSND anomalies.
- More are on the way.



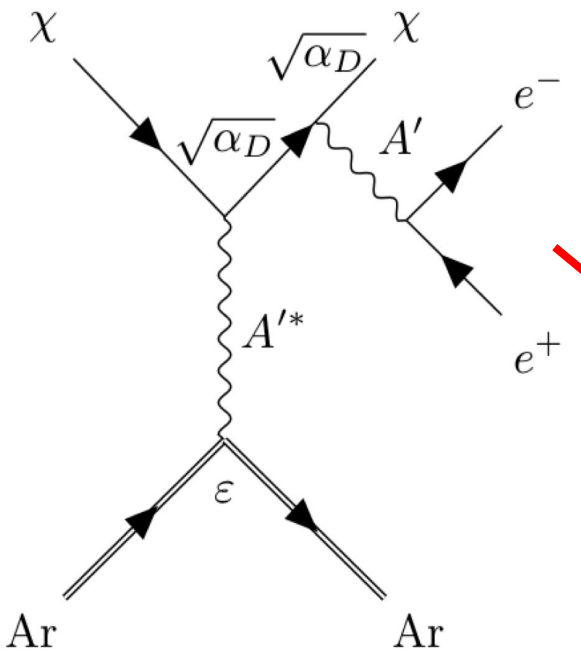


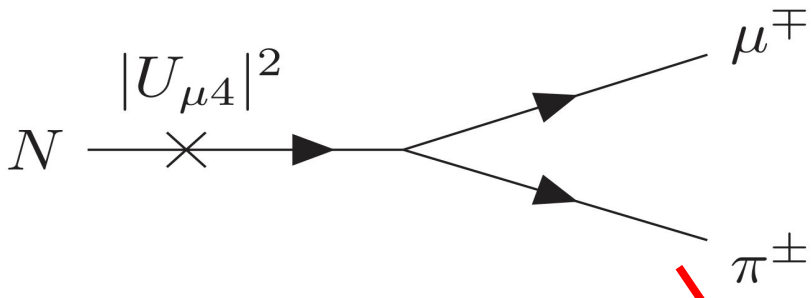


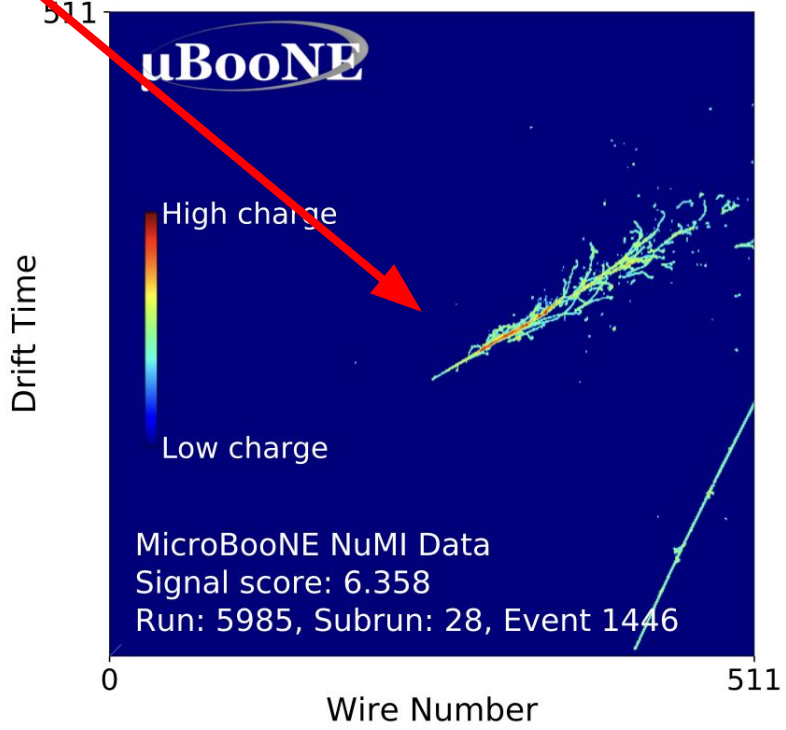


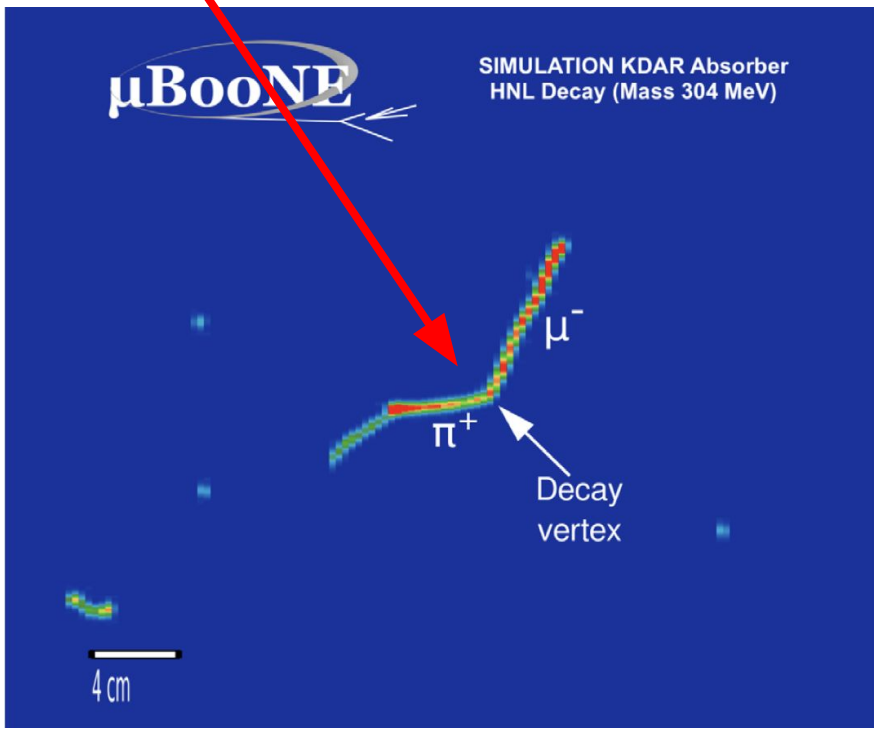
Summary

- We have a produced a number of results searching for BSM particles produced in our neutrino beams.



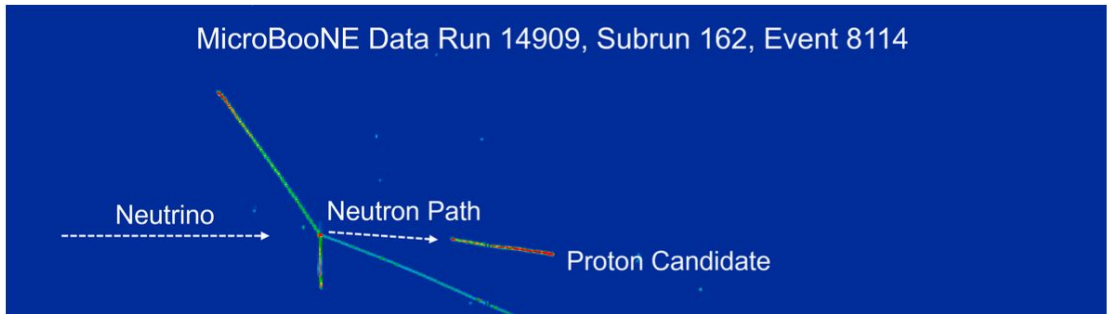


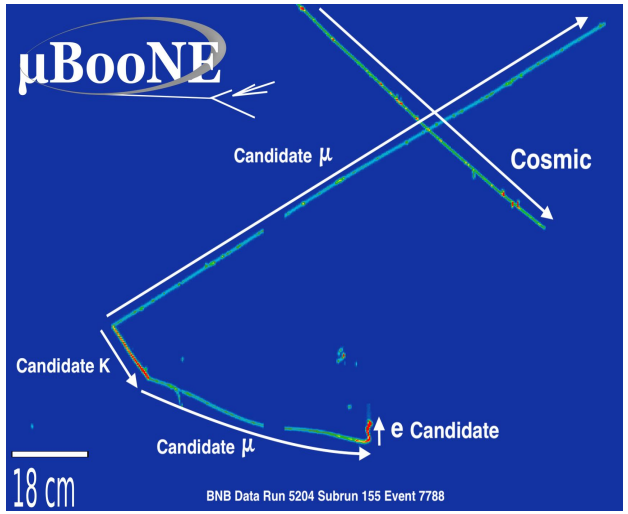


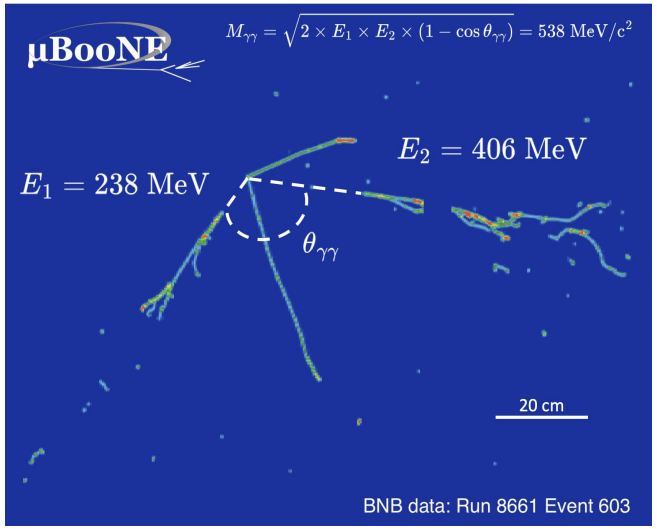


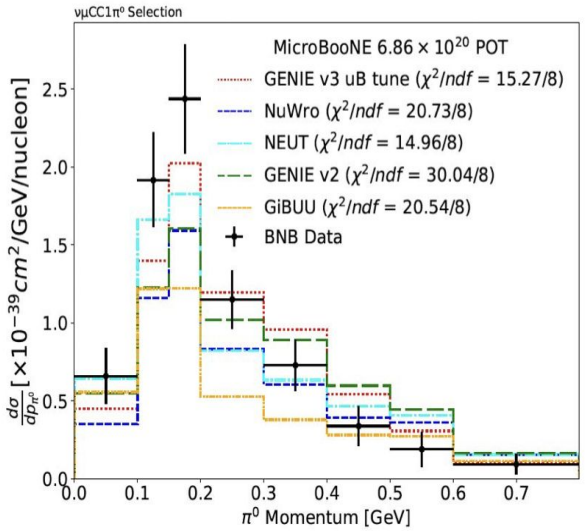
Summary

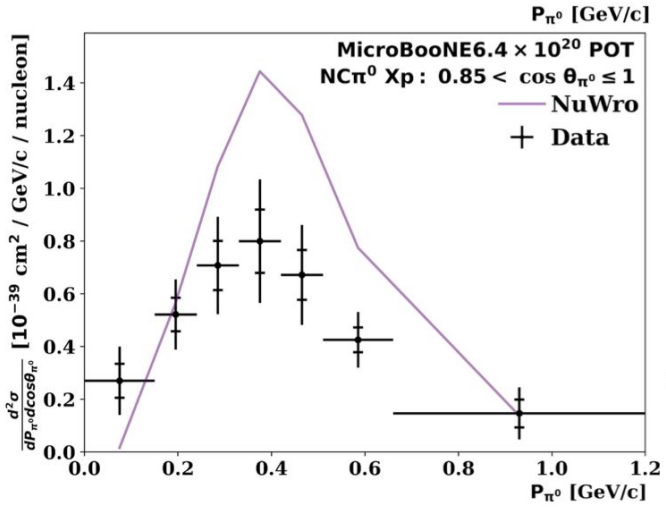
- Our program of cross section measurements includes new observables and final states, and leveraging multiple channels and their correlations to improve our understanding of nuclear effects.

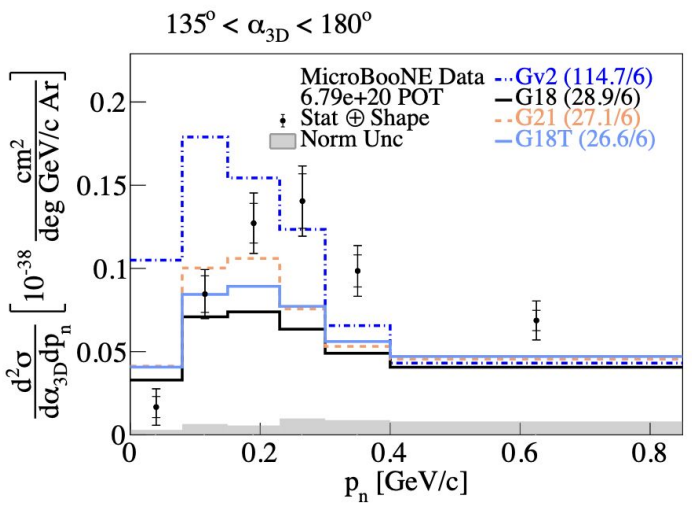


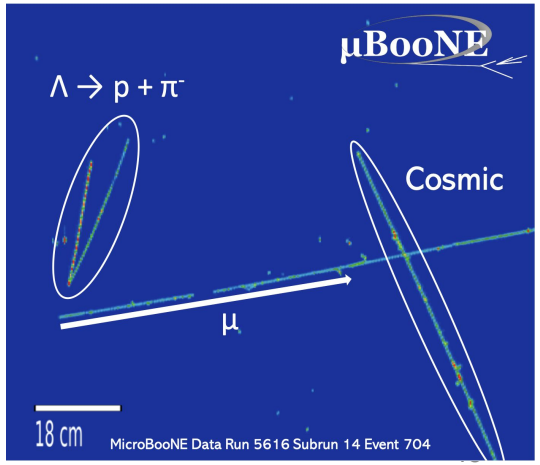












Thank You!

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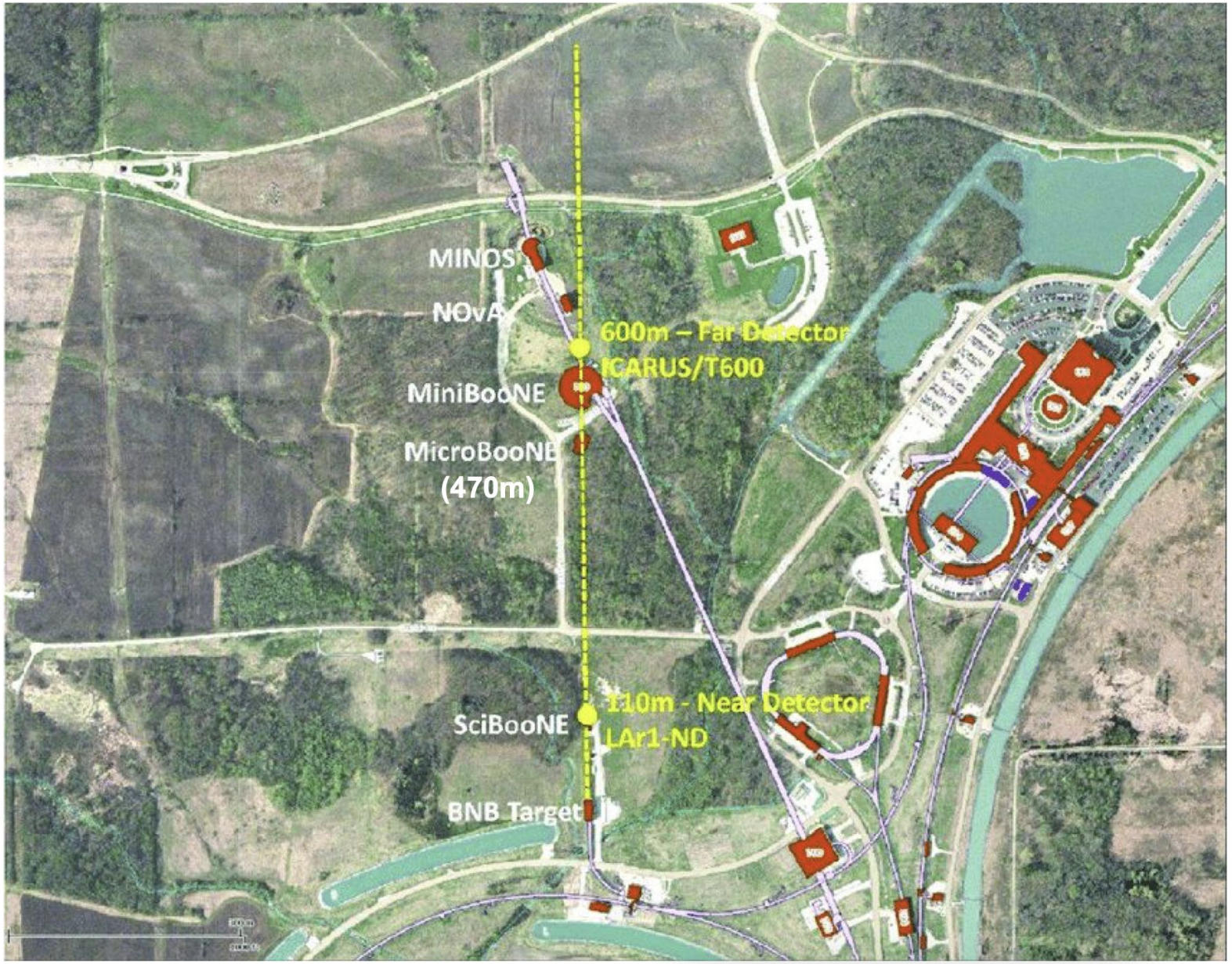
Backup Slides

The Beams

Figure from arXiv:1503.01520.



Particle Identification - Calorimetry

- Measure intensity of energy loss in the detector - main ingredient in particle ID.

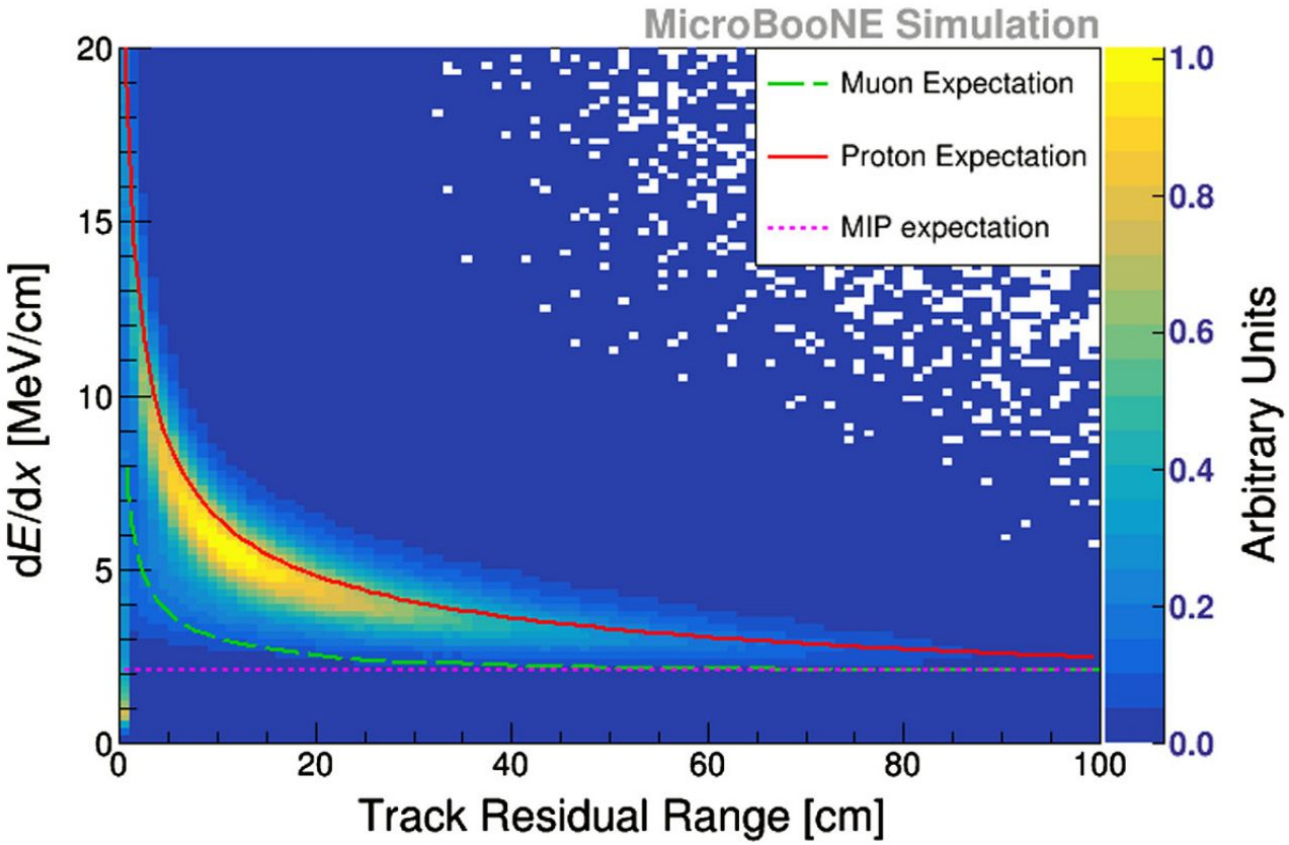


Figure from Phys. Rev. D 102, 112013.

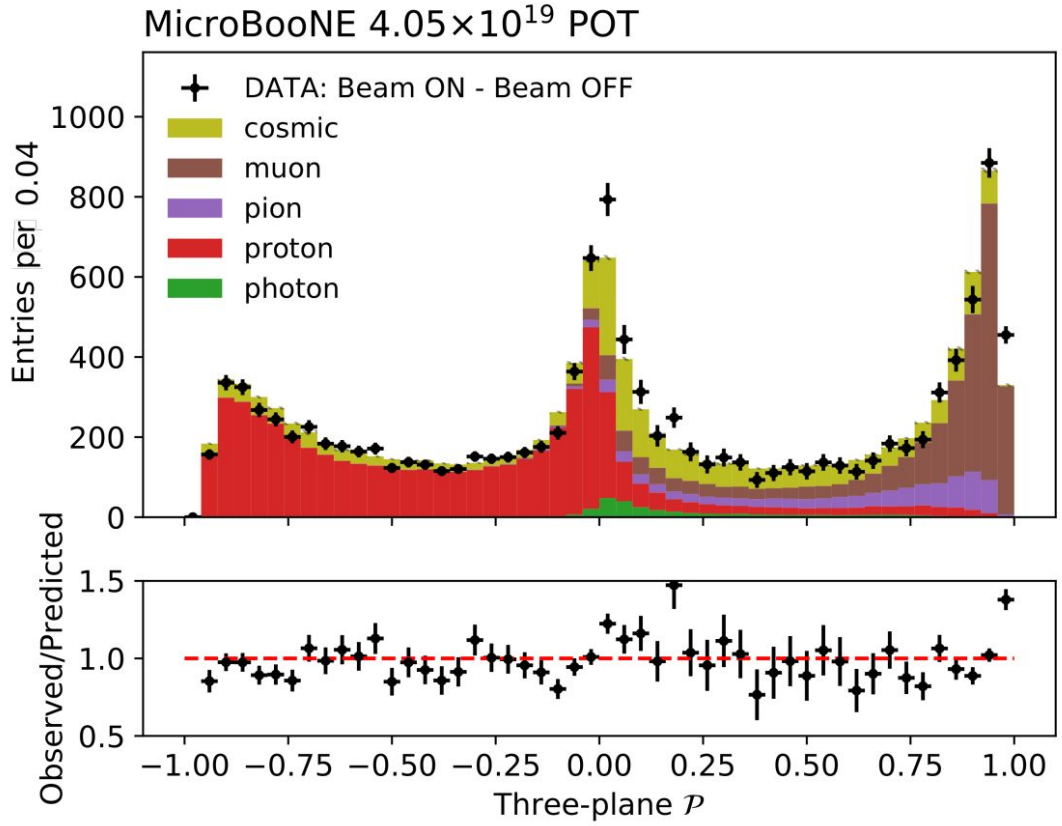
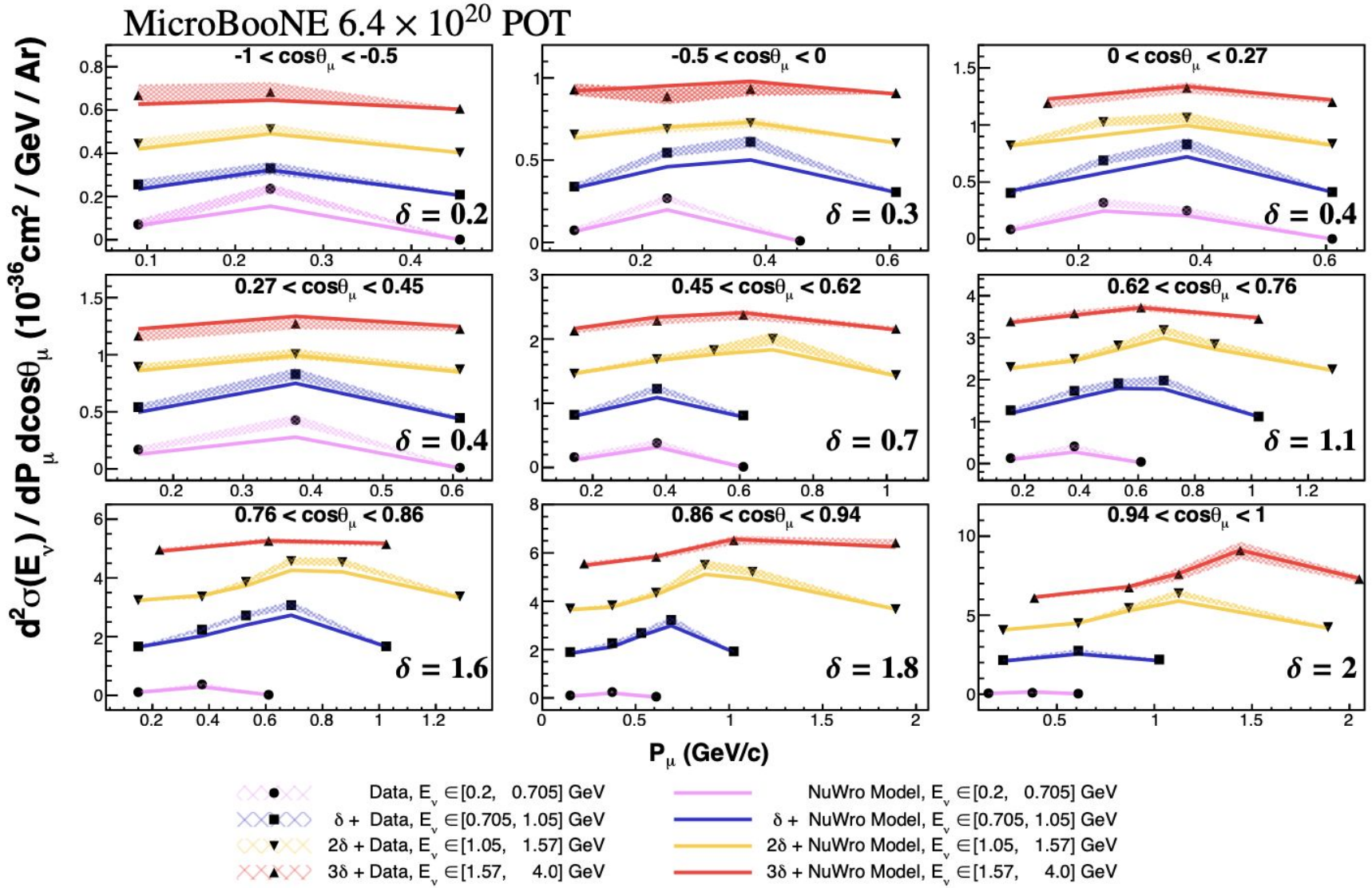


Figure from JHEP 12 (2021) 153.

Triple Differential Cross Sections

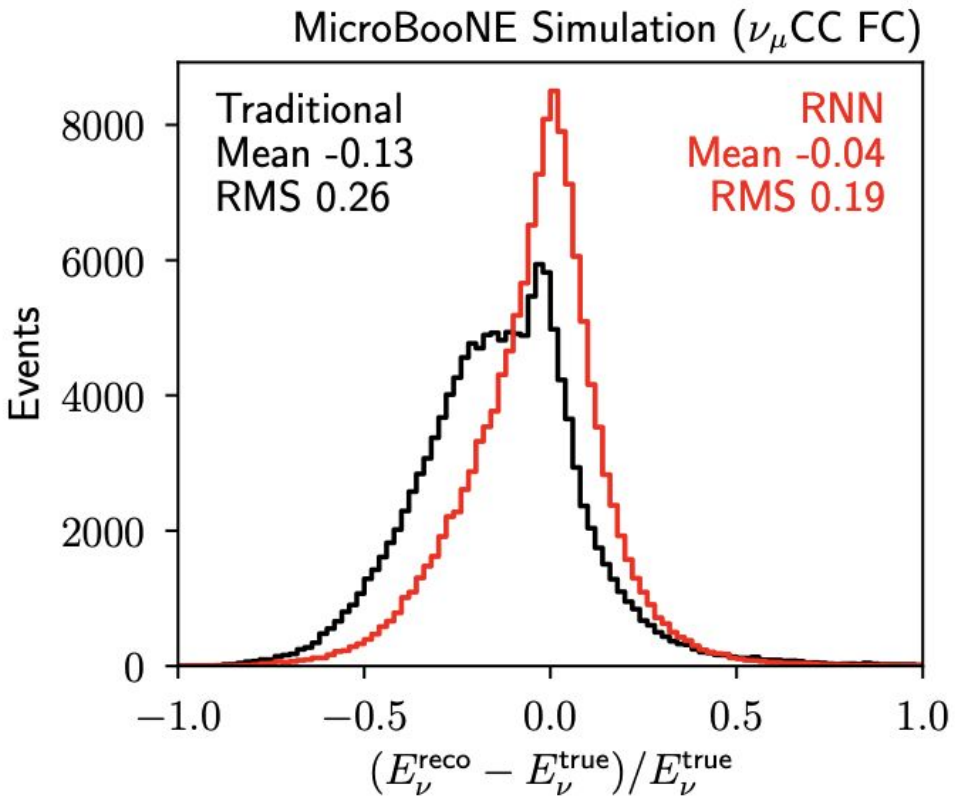
arXiv:2307.06413



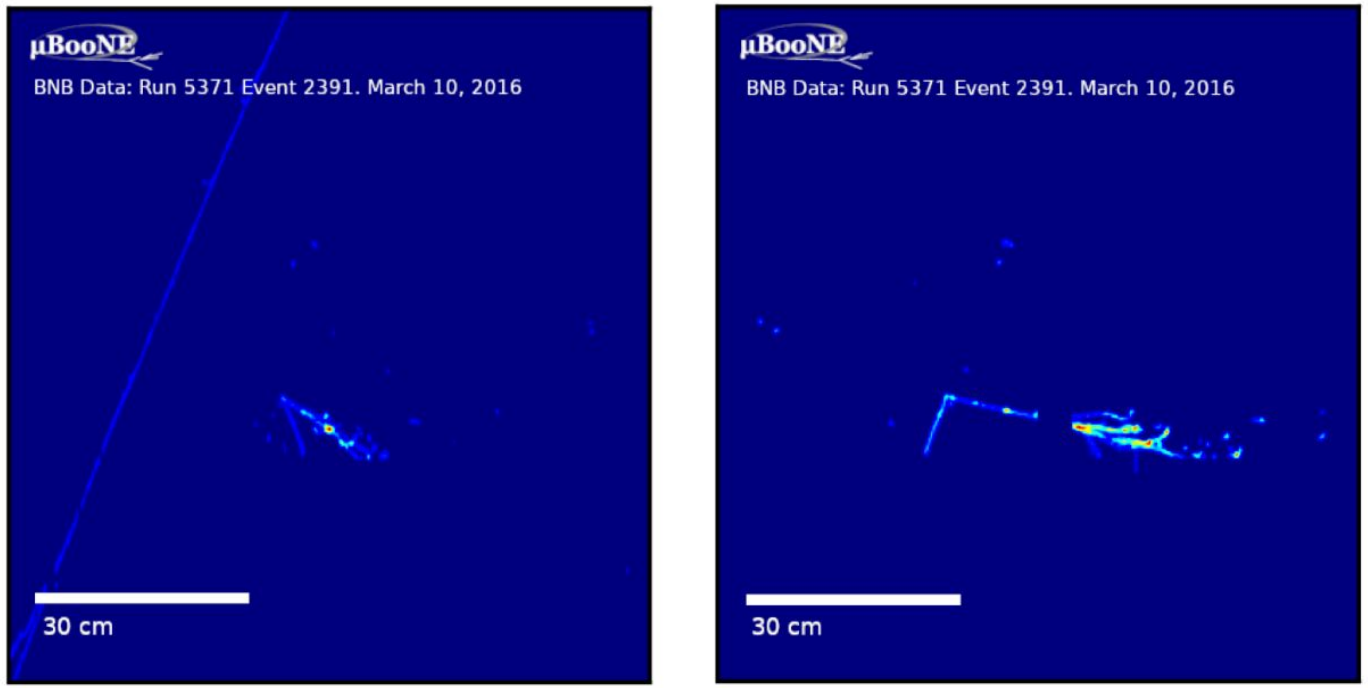
Reconstruction Development

- New recurrent neural network based energy reconstruction.
- CNN based particle ID.

arXiv:2406.10123



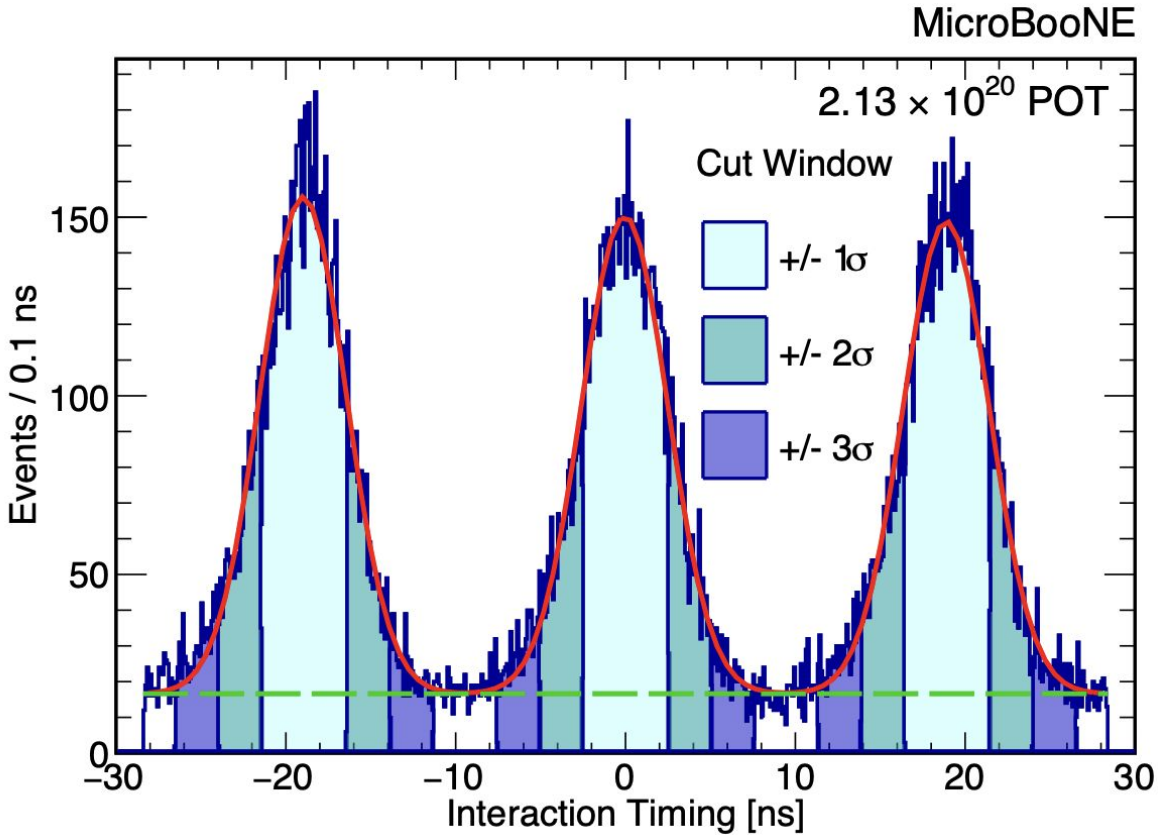
MicroBooNE Public Note 1123.



Nanosecond Timing Resolution

- BSM searches want to exploit time of flight information.
- Improved timing resolution enables better rejection of out-of-time cosmic background.
- Achieved through improvements in trigger stability, PMT waveform fitting and accounting for particle/light propagation times.

Phys. Rev. D **108**, 052010.



Neutrino interaction times reveal BNB bucket structure.

Low Energy (Blip) Reconstruction

- Doped LAr with radon-222 for a period of data taking in 2021.
- Detect α and ɣ produced by decay products.
- Modified signal processing used to detect low energy products.
- Useful for detection of radiogenic backgrounds in LArTPCs.

Phys. Rev. D **109**, 052007.