THE MICROBOONE EXPERIMENT AND THE LOW-ENERGY EXCESS

International Conference on Neutrinos and Dark Matter

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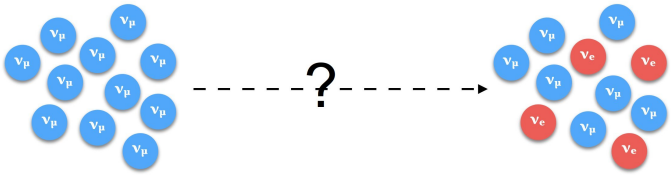
January 11, 2019

University of Oxford, Harvard University

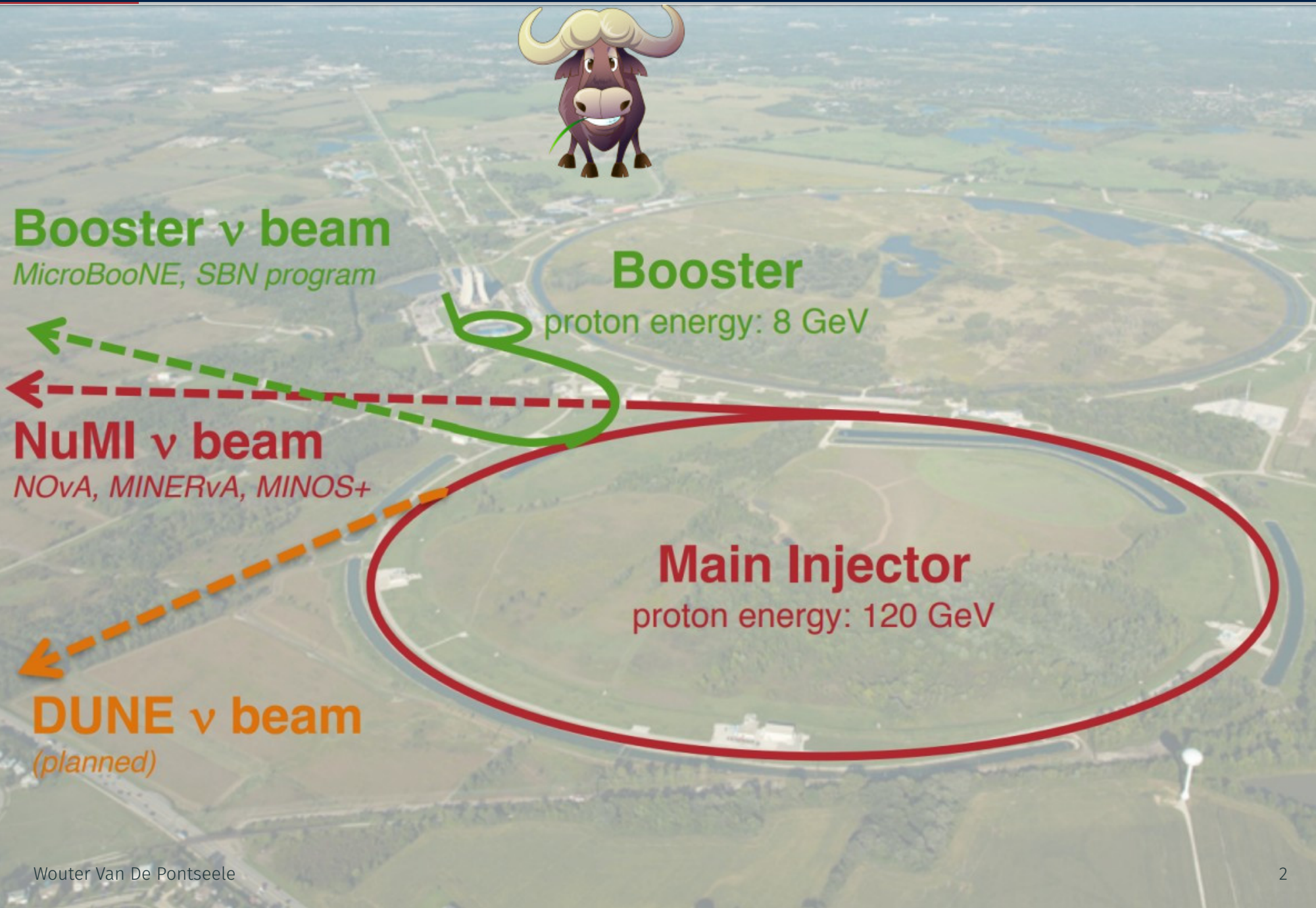
Outline

- **Three neutrino picture** is well understood.
- **Anomalous results** in past neutrino measurements.

1. The low-energy excess.
2. The MicroBooNE experiment.
3. Recent cross-section results.
4. The search for an anomaly.



Neutrino Beams at Fermilab



A step back in time: A puzzling collection of anomalies

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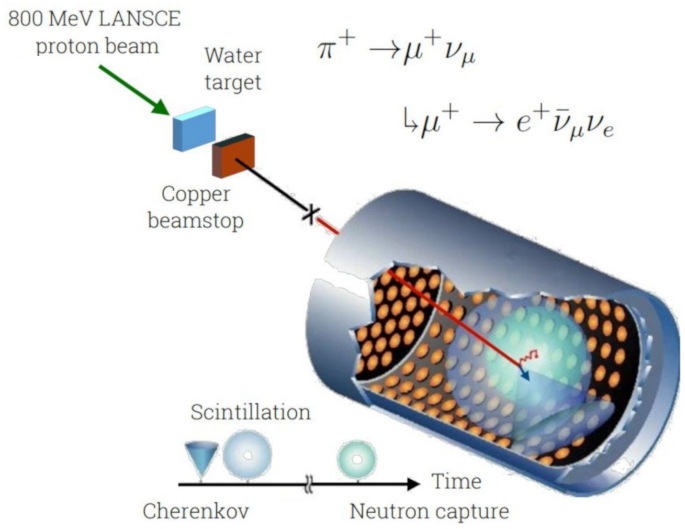

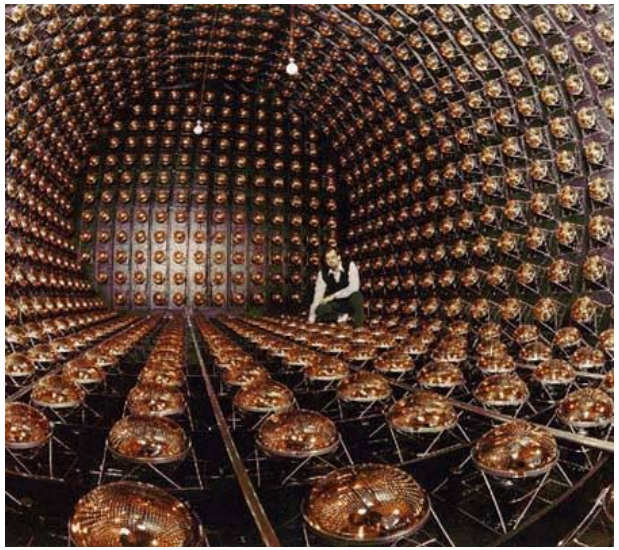

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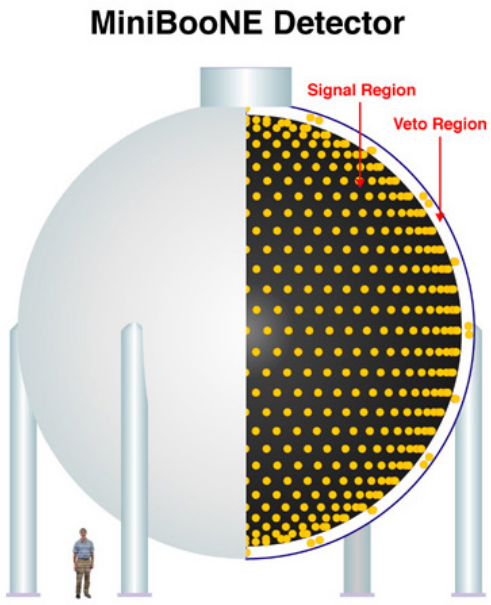
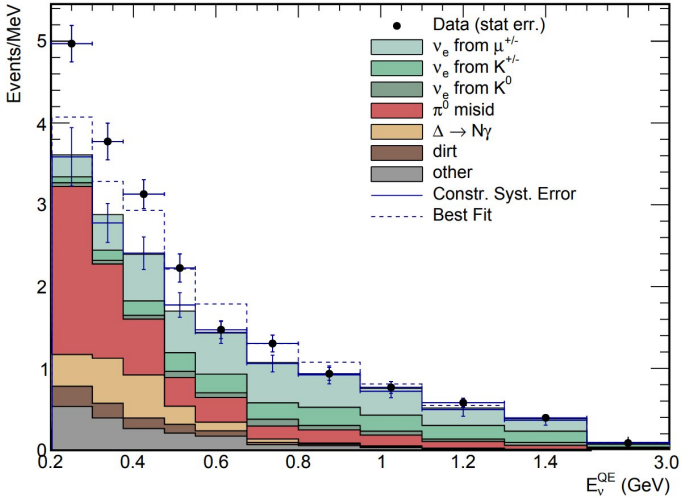
The MiniBooNE Low-Energy Excess [2]

- In Fermilab's Booster Neutrino Beam, since 2002.
- Mineral Oil Cherenkov detector.
- Doubled statistics in 2018.
- Excess of events observed, as in LSND.





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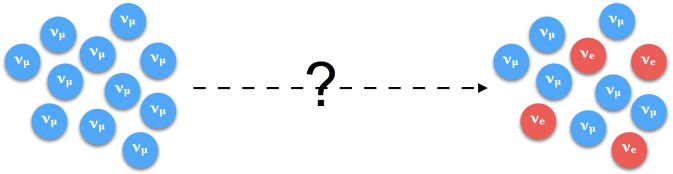
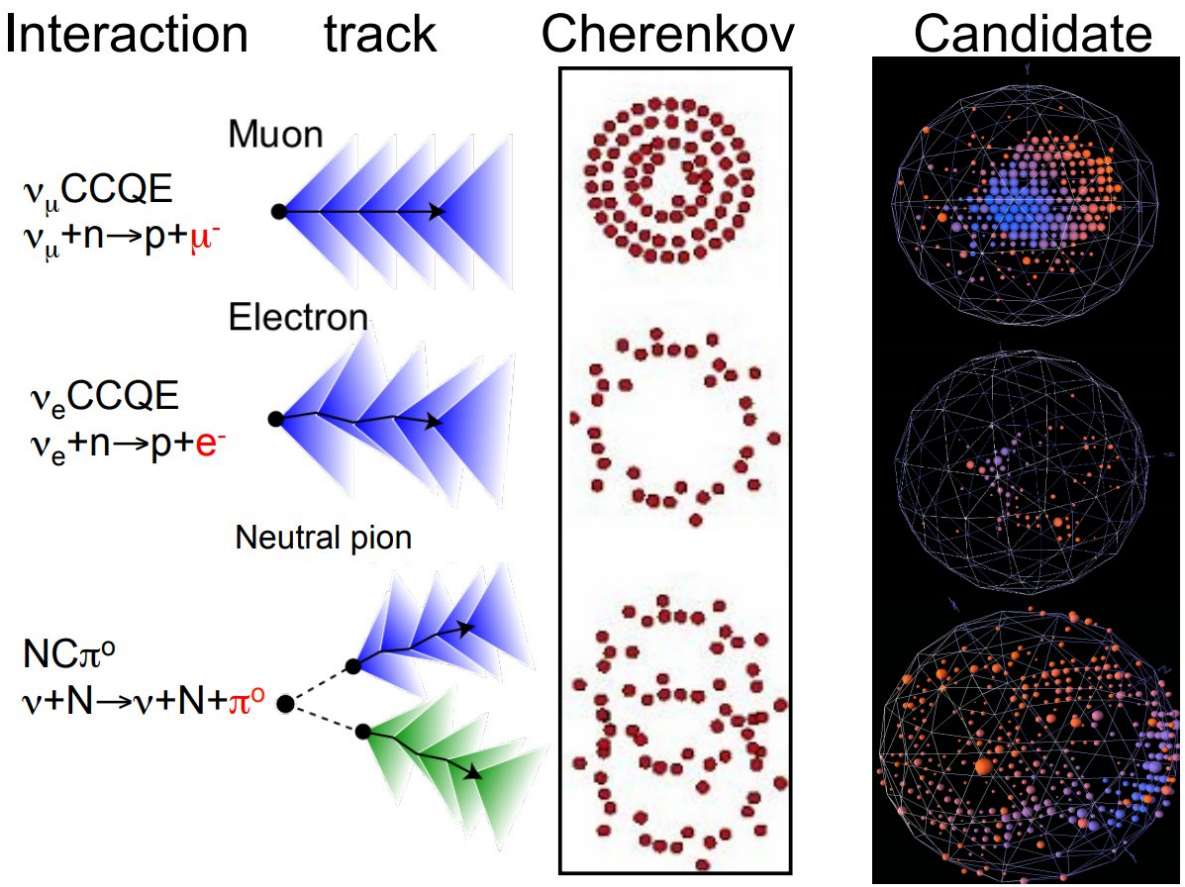
3. **MicroBooNE**: same L, E with different technology.



Particle Identification in MiniBooNE



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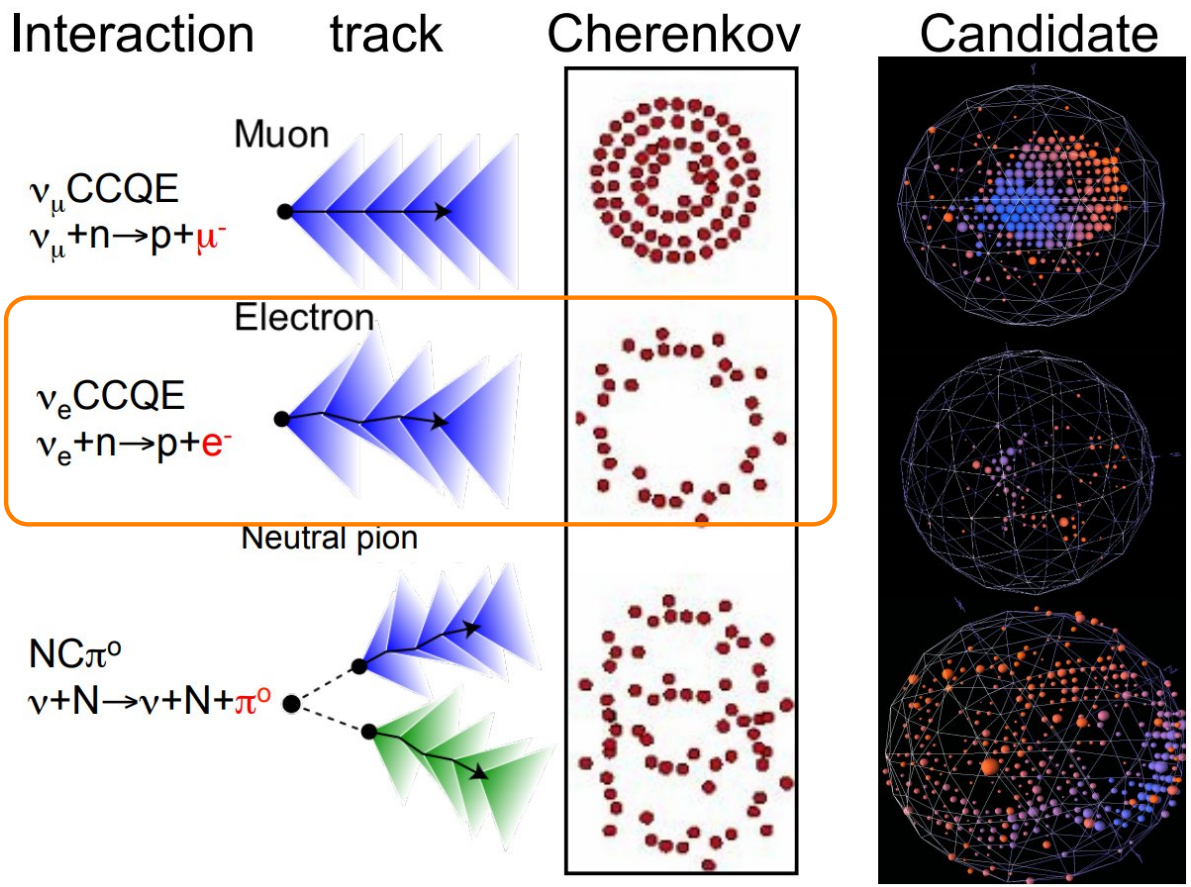
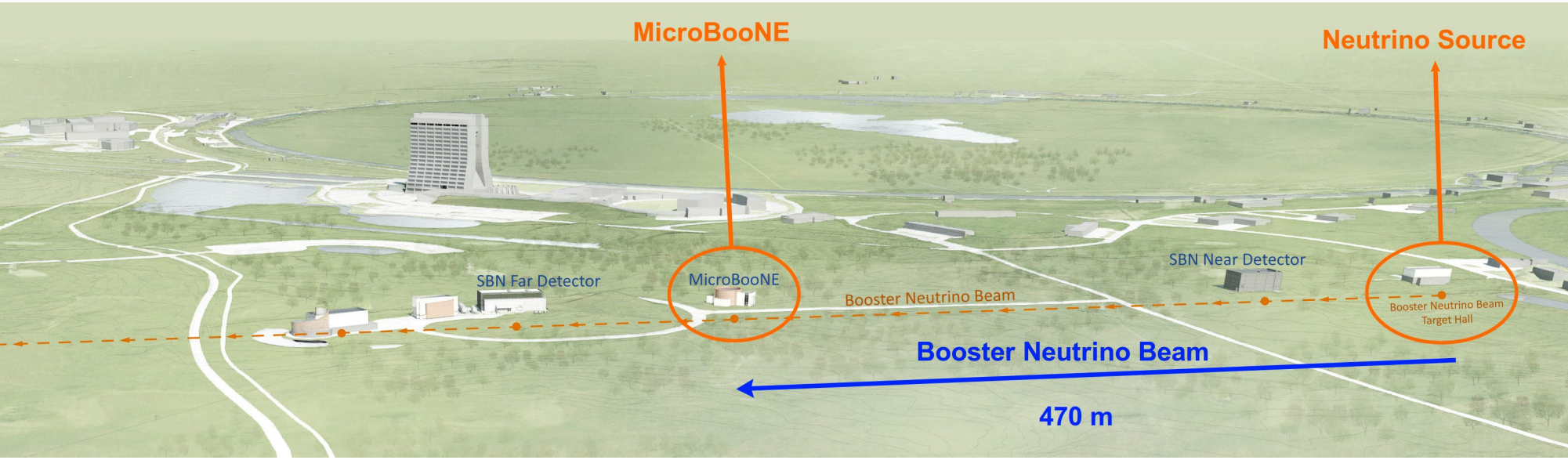


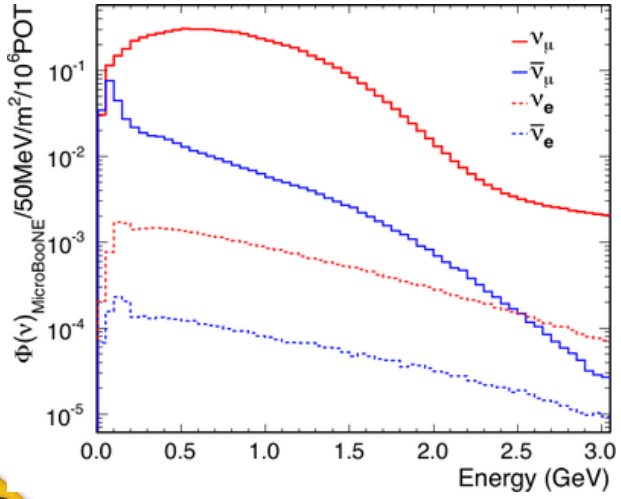
MiniBooNE sees an **excess of low energetic electromagnetic events**.
No discrimination between a single photon and an electron + insensitive to protons.
The **origin of the excess remains unclear**.

The MicroBooNE experiment

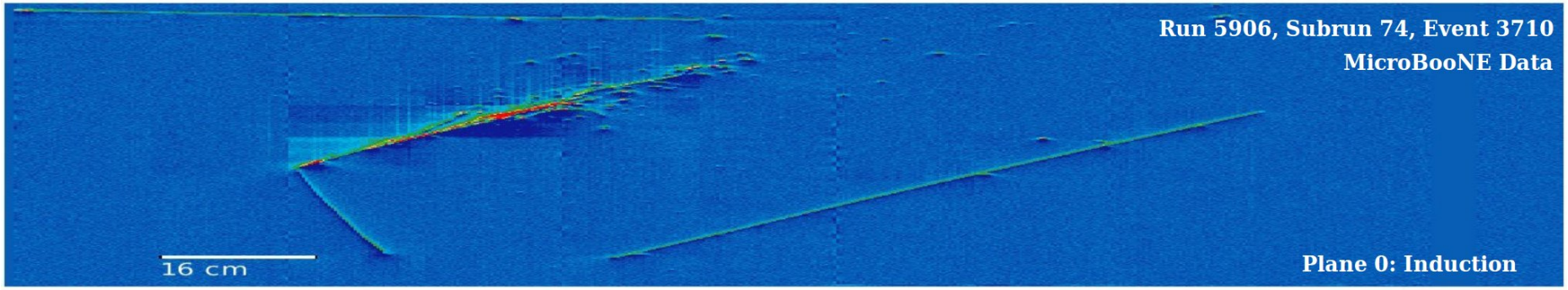


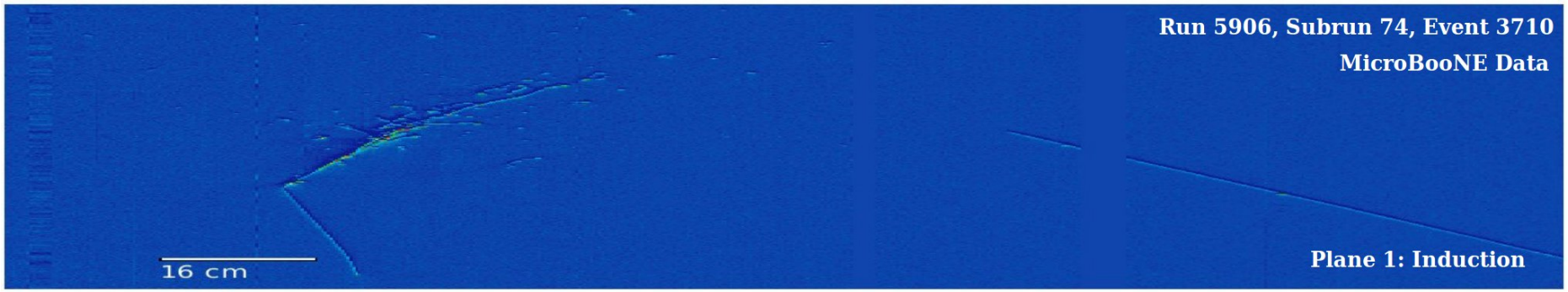
Physics Goals

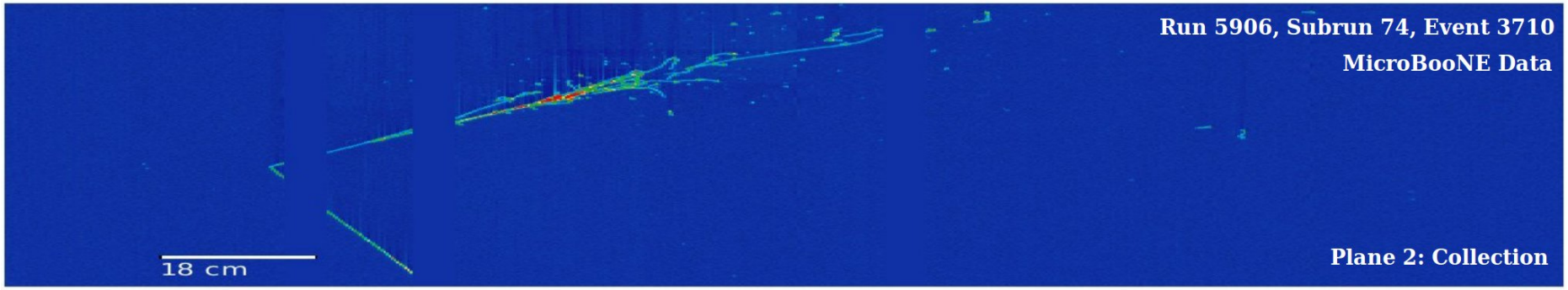
- Liquid Argon Time Projection Chamber (LArTPC) **R&D**.
- Address electromagnetic **low-energy excess** observed by MiniBooNE.
- **Cross-section** measurements on argon.
- First step in the **Fermilab short baseline neutrino program.**



MicroBooNE Data Event







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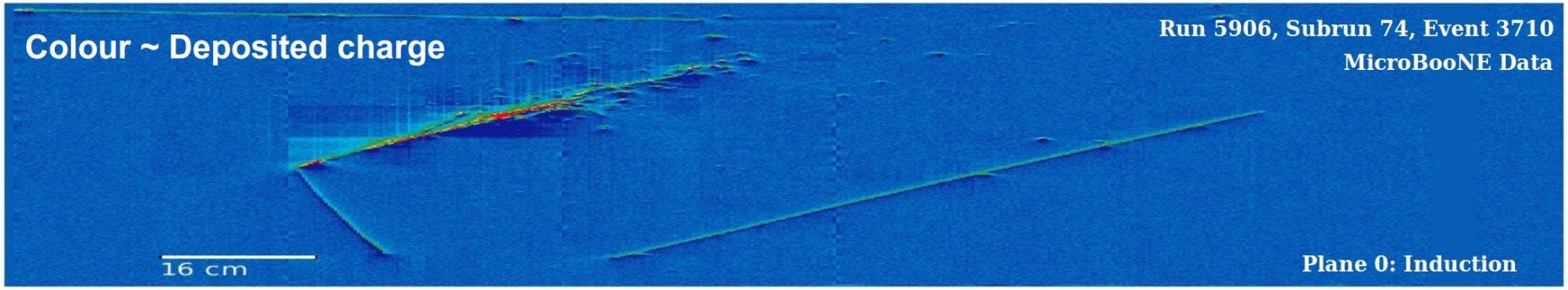

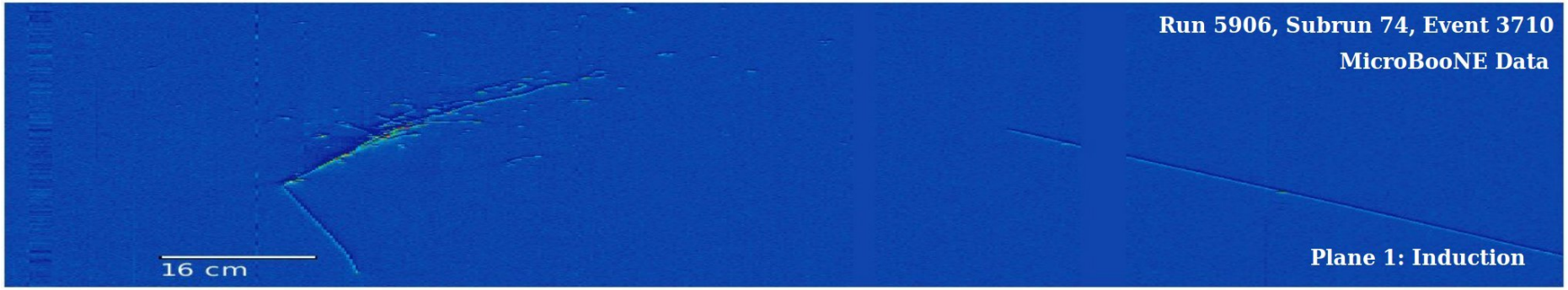

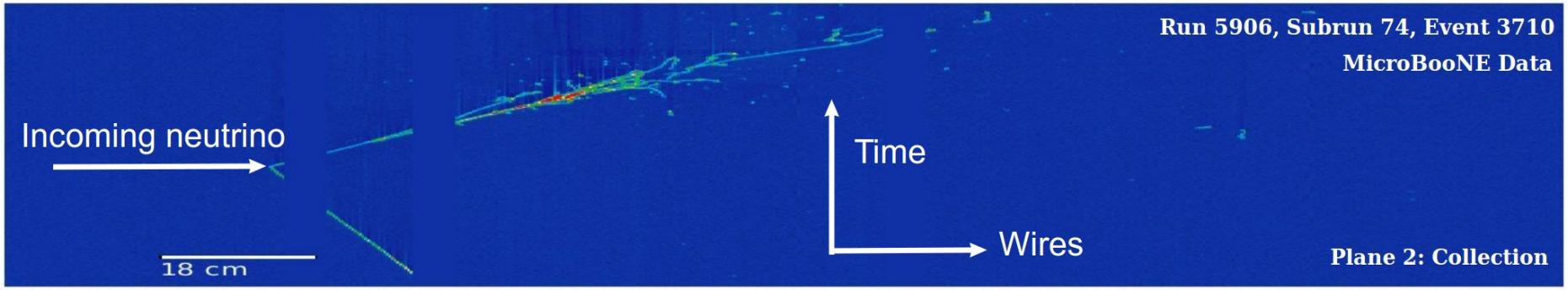

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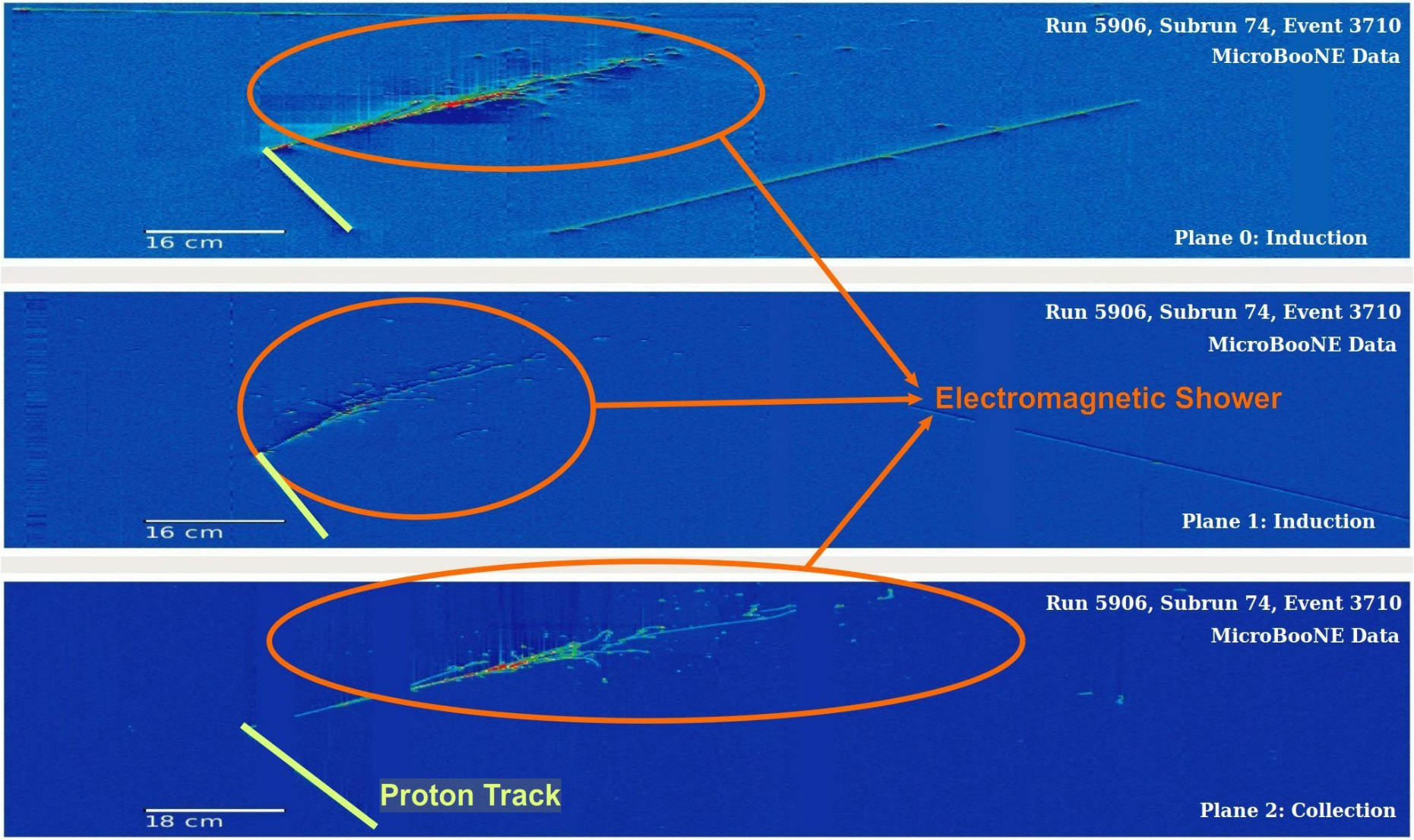


How to Resolve the Low-Energy Excess Anomaly

Detector Understanding

- Signal processing.
- Detector calibration.
- Event reconstruction.

Neutrino-Argon Interactions

- First low-energy ν-Ar data, probe little known nuclear effects.
- π^0 production can mimic electrons.

Systematic Uncertainties

- Neutrino flux from beam.
- Cross-section modelling.
- Detector effects.

Search for the Excess

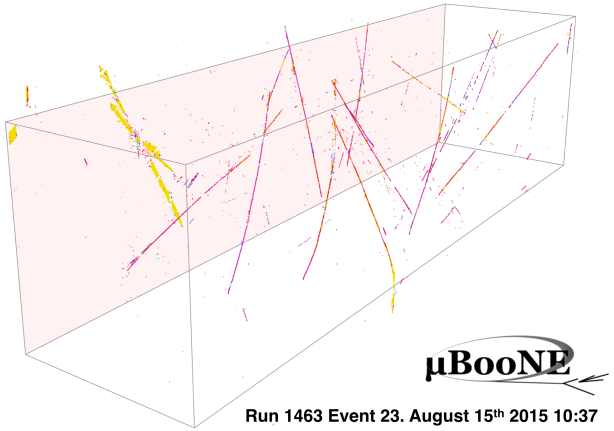
- Different signatures:
  - e/γ
  - proton tracks, vertex activity
  - energy range
- Selection
- Statistical tests and methods

Detector Understanding: LAr Event Reconstruction Techniques

Three different reconstruction approaches in MicroBooNE:

- First time **fully automatic** event reconstruction used in LArTPC.
- Serve to **cross-check** each other in parallel efforts.
- Essential build-up of **expertise for DUNE, SBND and ICARUS**.

WireCell Tomographic Imaging



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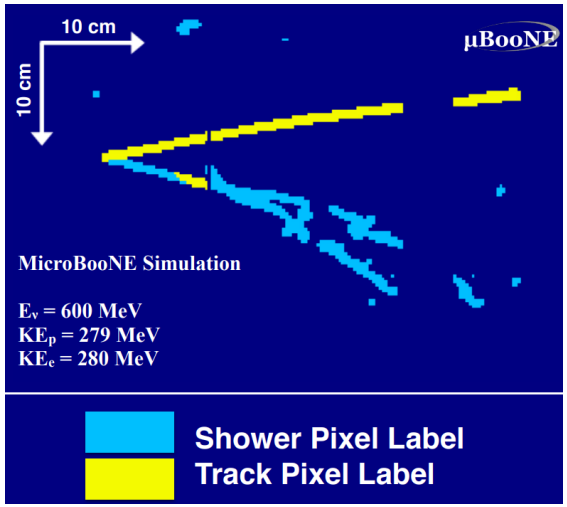
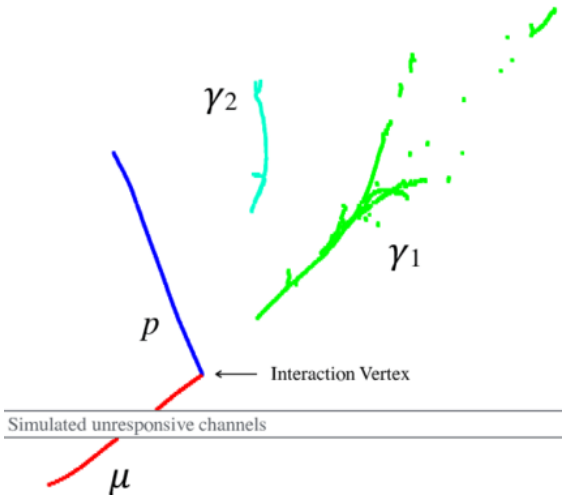
Deep-Learning



Phys. Rev. D 99, 092001 [3]

Pandora Multi-Algorithm

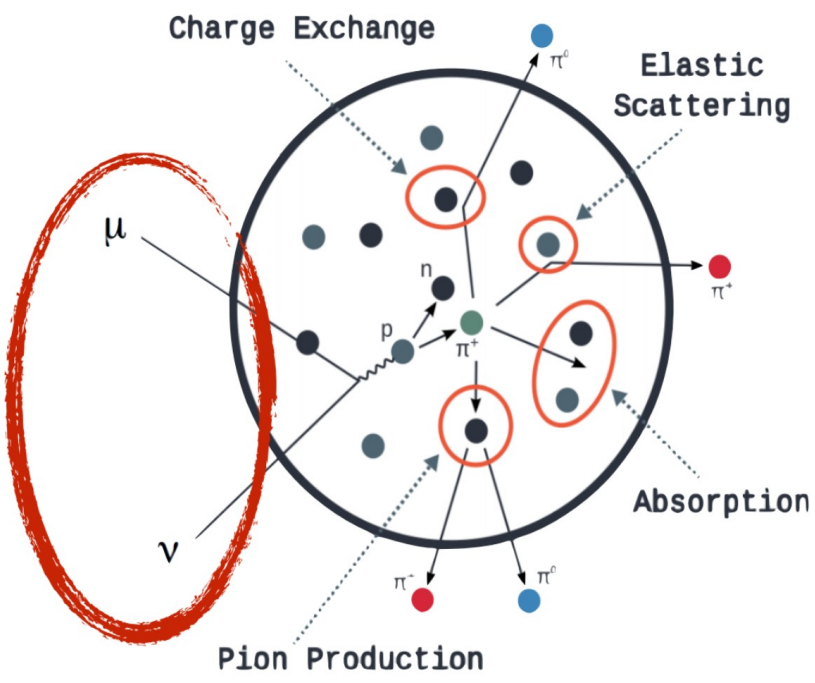


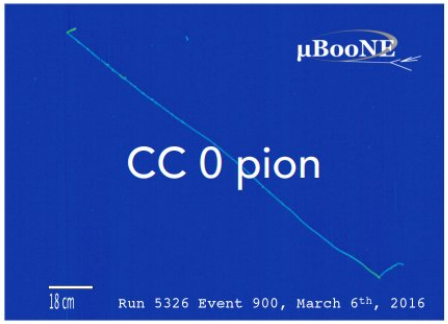
Eur. Phys. J. C. 2019. [4]

Neutrino-Argon Interactions

1. Determination of ν **interaction rates**.
2. Understand the **nuclear model**: neutrino-nucleus scattering model and intranuclear processes.
3. **Comparison** with **generators**: GENIE 2/3, NuWro, GiBUU.

→ Impact energy reconstruction.
→ Necessary for oscillation measurement.





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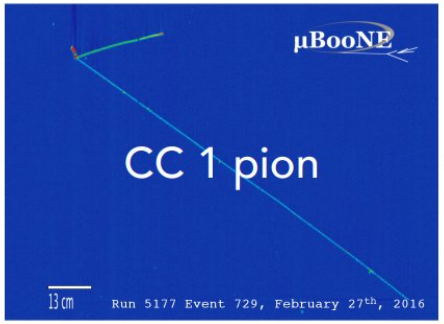

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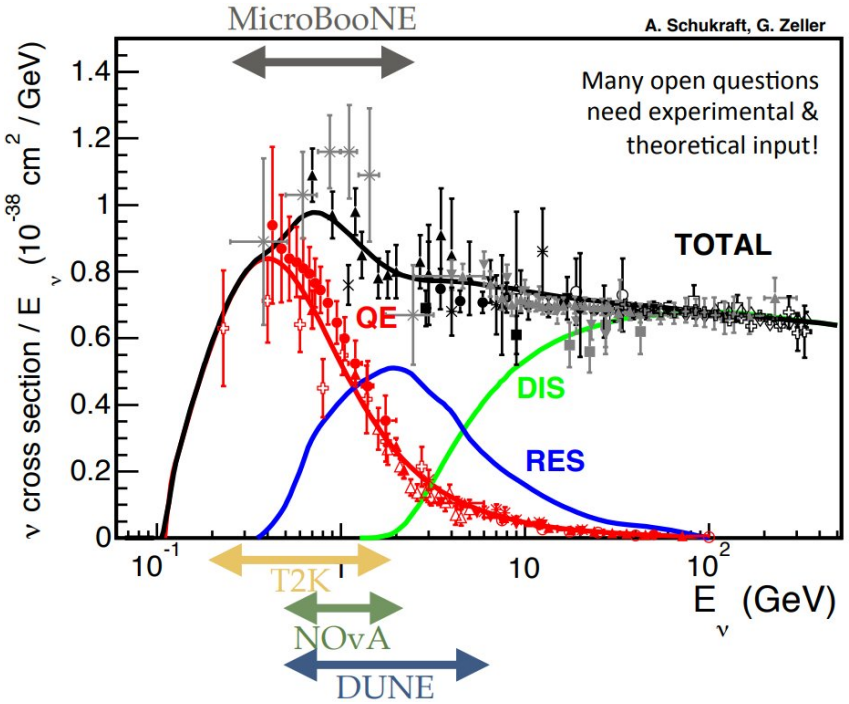

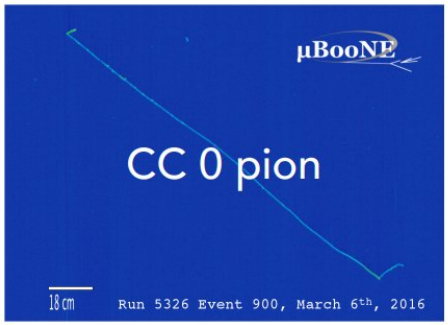

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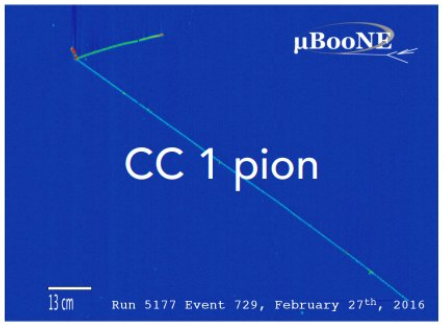

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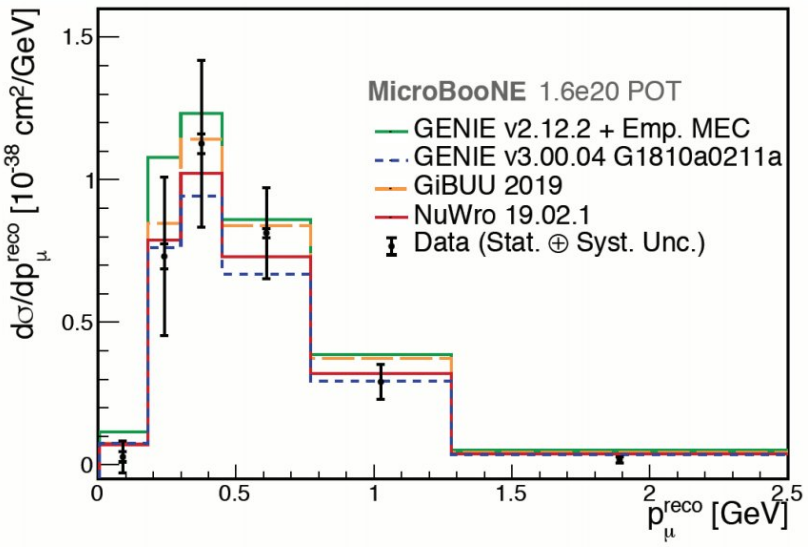
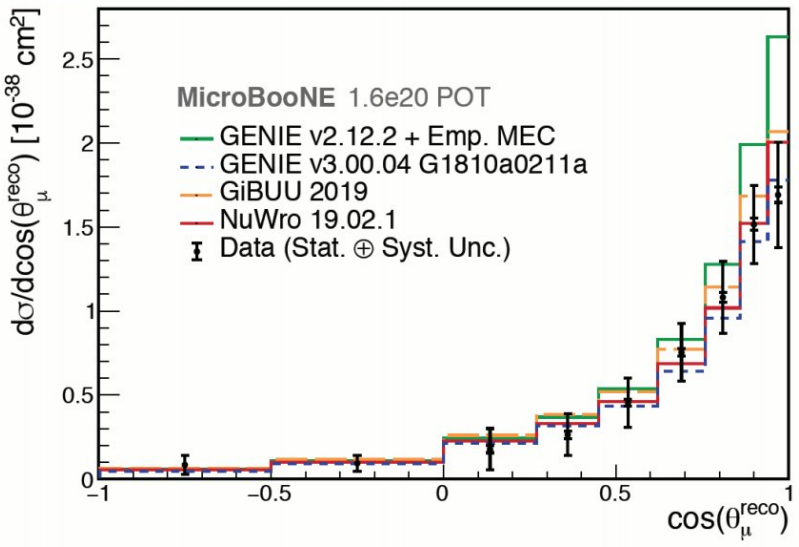
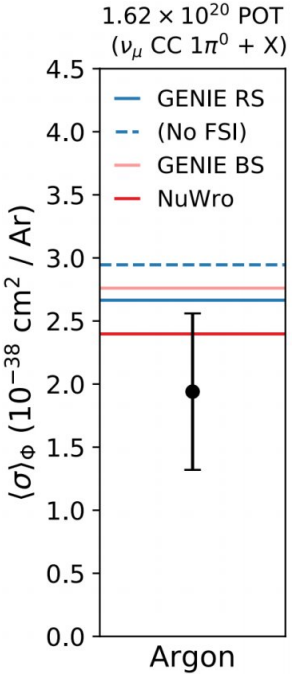
Neutrino-Argon Interactions: Published MicroBooNE results





First Cross-section results from MicroBooNE

- Using Run 1 data-set, ≈13 % of total POT collected.
- Measurement of Inclusive Muon Neutrino Charged-Current Differential Cross Sections on Argon [5]
- Measurement of ν_μ Charged-Current π^0 Production on Argon [6]



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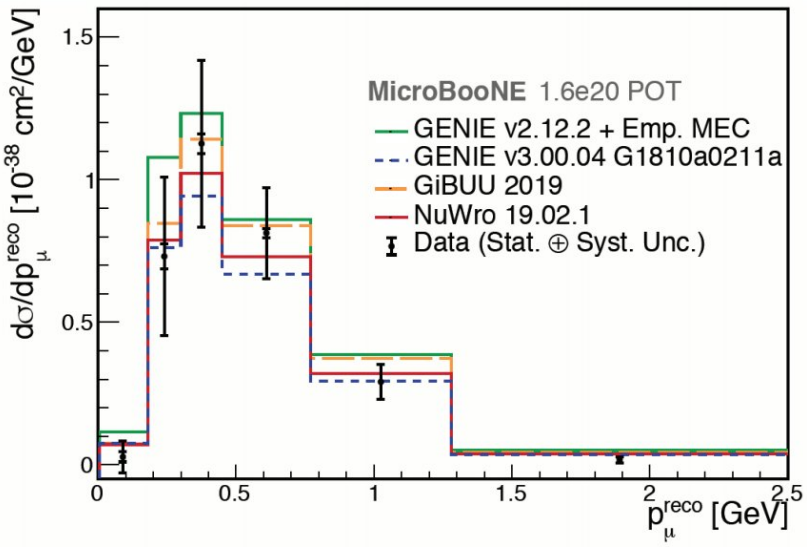

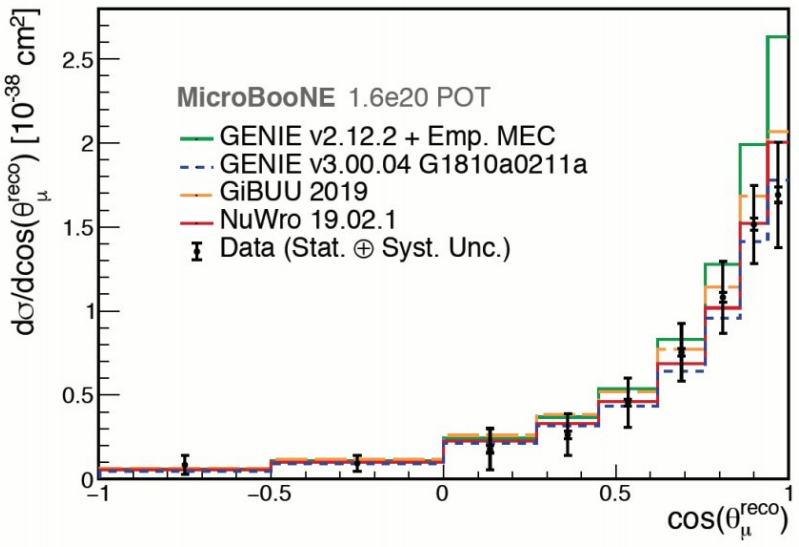

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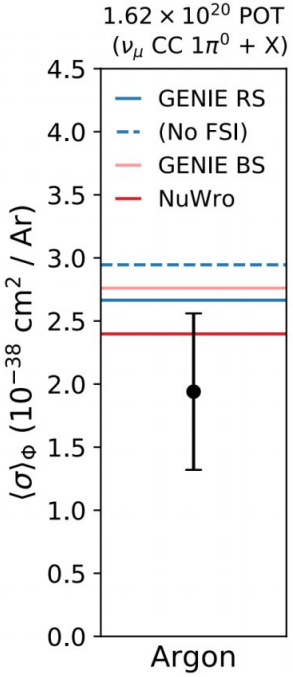
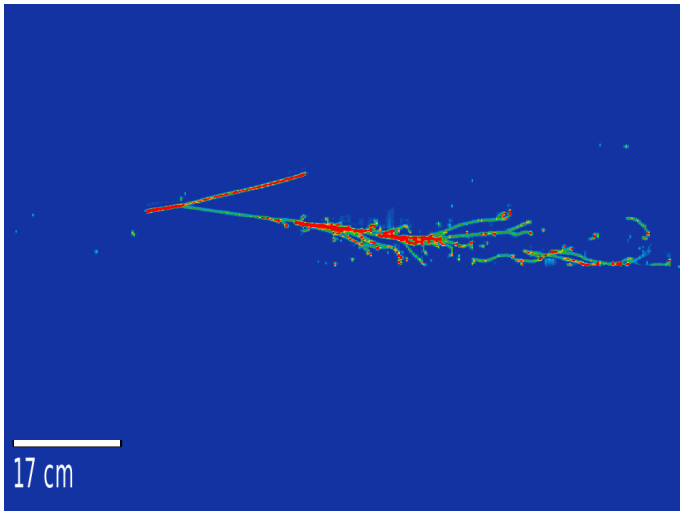
Cross-section talk tomorrow by Steve Dytman!

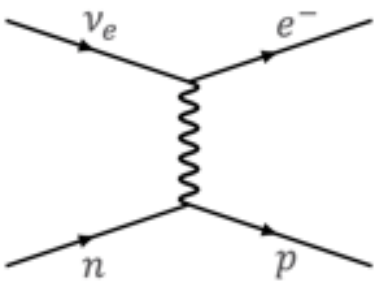


Two possible models to explain the low-energy excess

Electron-like Search

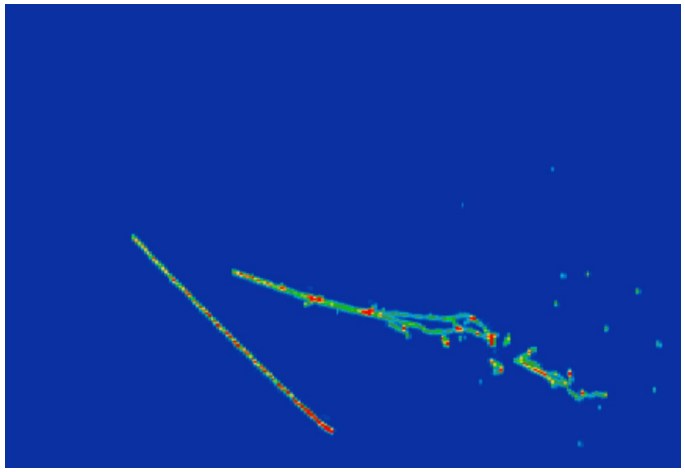
Electron neutrinos from oscillation

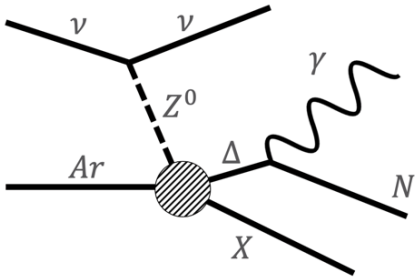




Photon-like Search

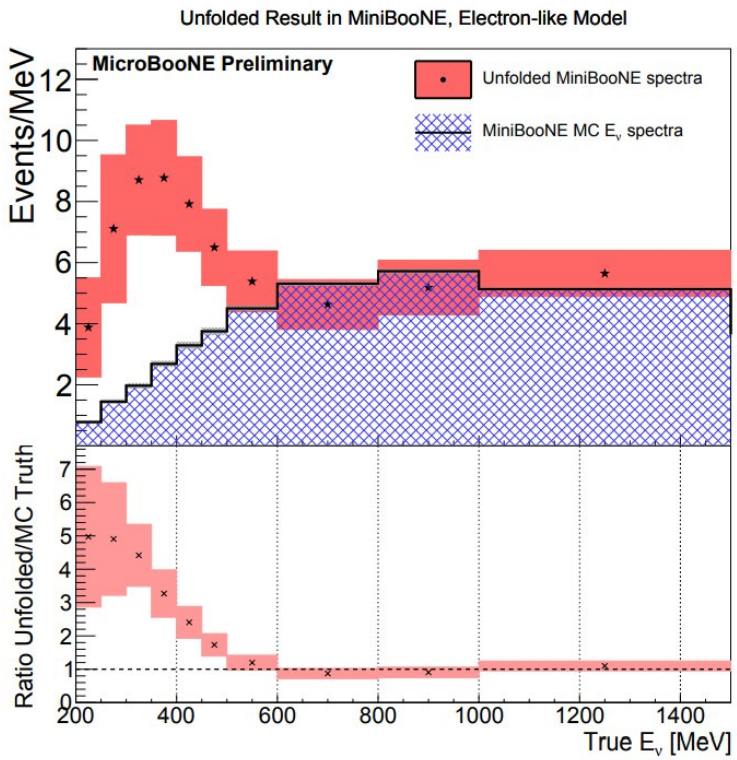
Neutral current $\Delta \to N\gamma$



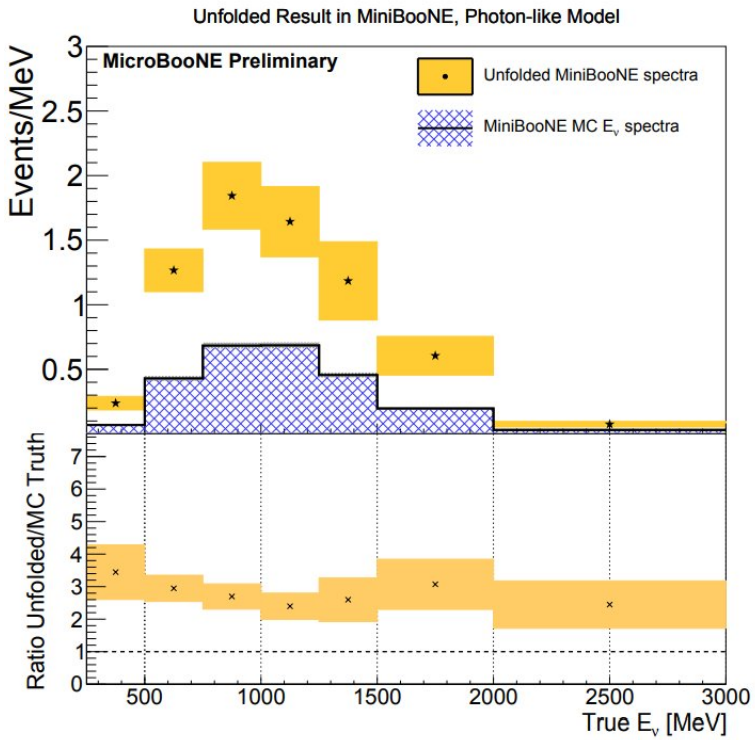


Unfolding the MiniBooNE excess (MICROBOONE-NOTE-1043-PUB)

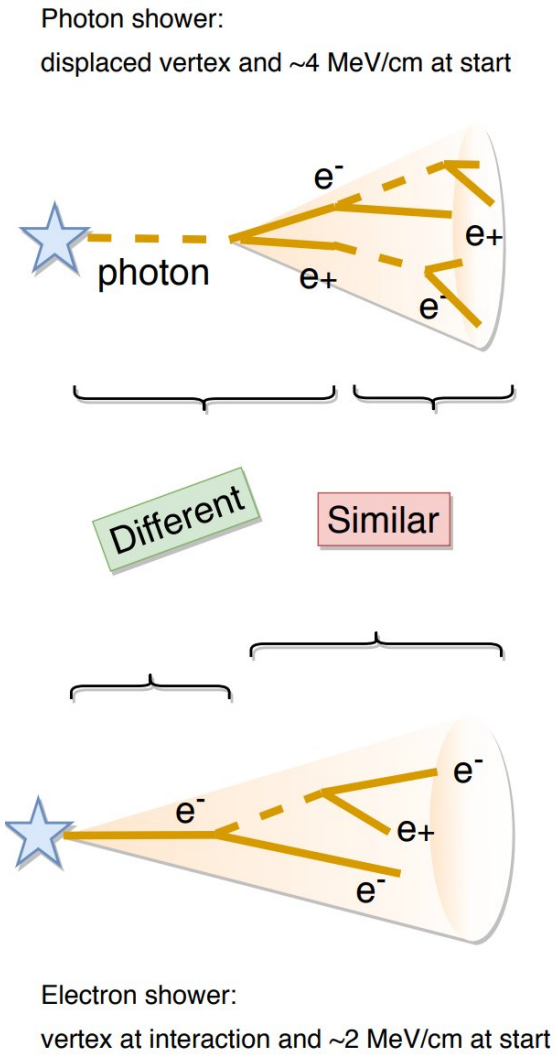
Electron-like Search



Photon-like Search

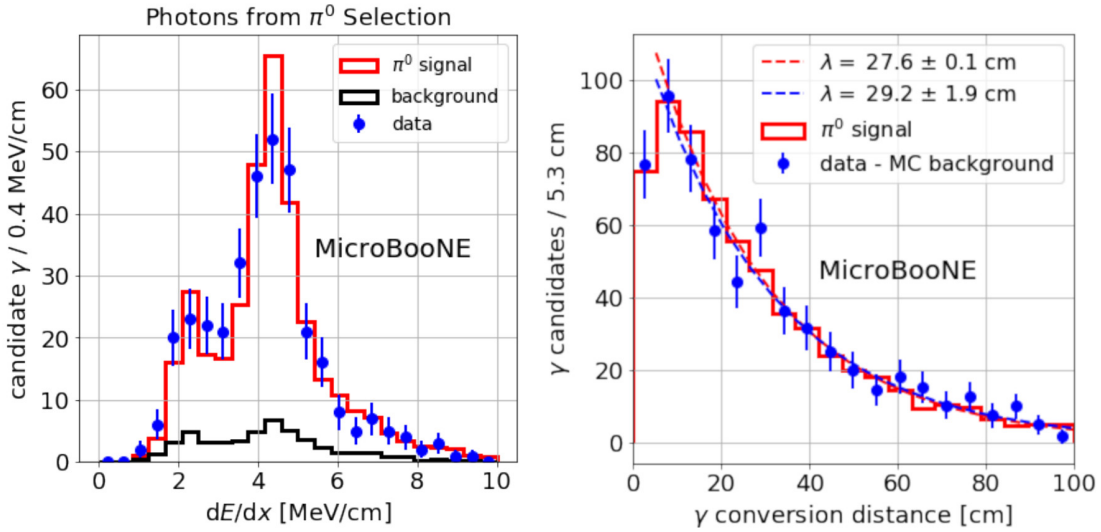


Particle Identification: Photons vs Electrons



- e/γ separation due to **differences** in the **start** of the electromagnetic **shower**.
- **Demonstrated using photons** from π^0 decay [7].

1. dE/dx
2. Detached shower start point



Photon-like Search: Selection Status

- Neutral current "$\Delta \rightarrow N\gamma$" has never been measured in neutrino scattering $\rightarrow$ large cross-section uncertainties .
- Boosted decision trees to reject:
  1. Cosmogenic backgrounds
  2. Neutrino induced backgrounds
- **Dominating background** is neutral current π^0 $\rightarrow$ Second shower difficult to reconstruct!

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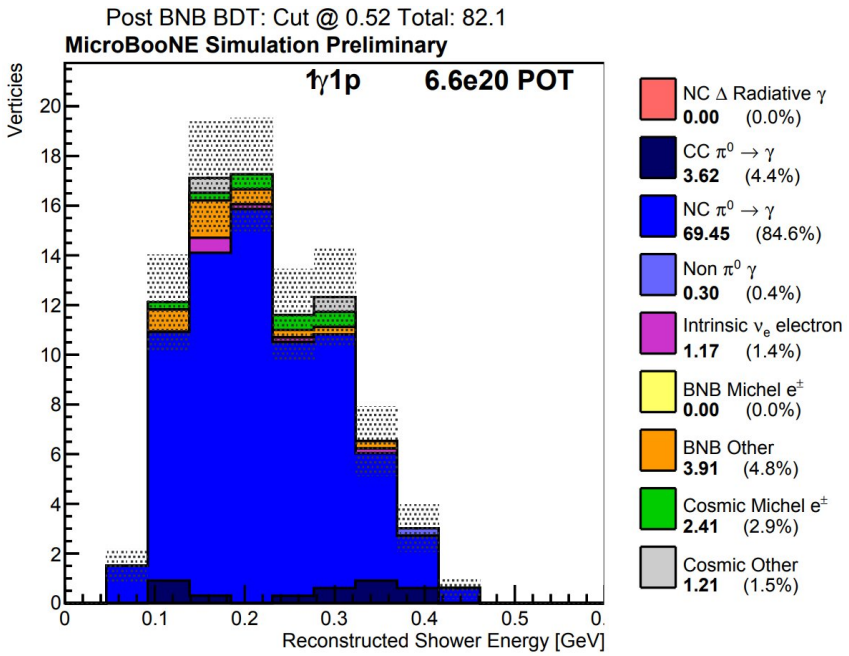
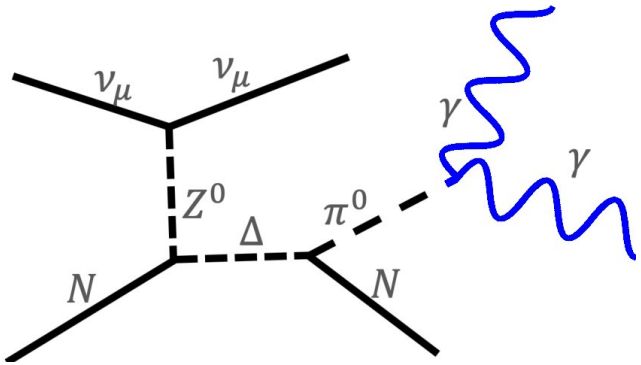




Electron-like Search: Selection Status

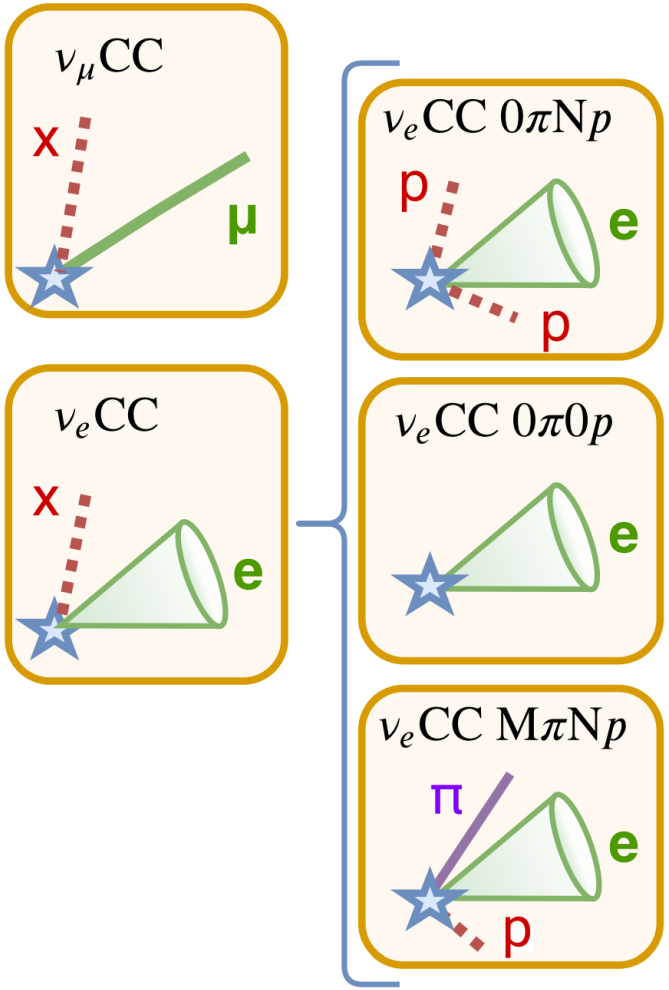
- $\approx$ 15k **cosmic muons** per neutrino interaction.
- $\approx$ 200 ν_μ per ν_e in the **beam** if no additional oscillations.

$\rightarrow$ **Needle in haystack** situation!

- **Blinded** search: Selection being developed on 4% of the data (Booster Neutrino Beam).
- **Covering all bases!**
  Simultaneously targeting **different final states**:
  - $1e0\pi Np$: low energy, vertex activity, **golden channel**.
  - $1e0\pi 0p$: lowest energy, difficult to select.
  - $1eX$: Inclusive channel, important model independent cross-check.

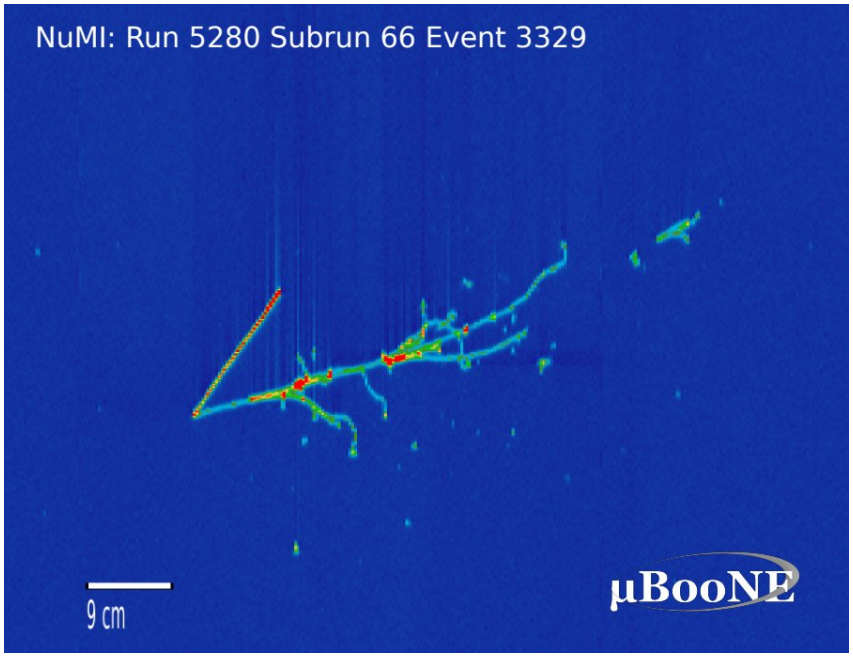
$\rightarrow$ Current status: MICROBOONE-NOTE-1038-PUB

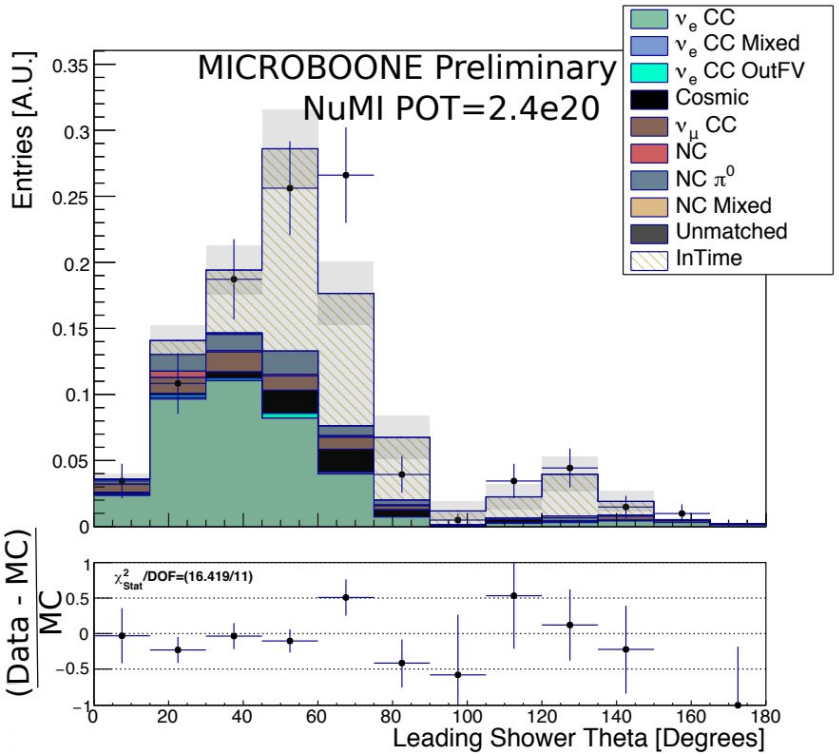
$\rightarrow$ **New results soon!**



Electron-like Search: NuMI ν_e Selection

The Off-axis **NuMI** beam offers the chance to develop an **inclusive electron neutrino** selection at similar energy on a **large data-set**.





MICROBOONE-NOTE-1054-PUB

Constraining the uncertainties with muon neutrinos

ν_μ and ν_e have much in **common**:

- **Flux**: both species of neutrinos come from the same beam, from decays of the same populations of hadrons.

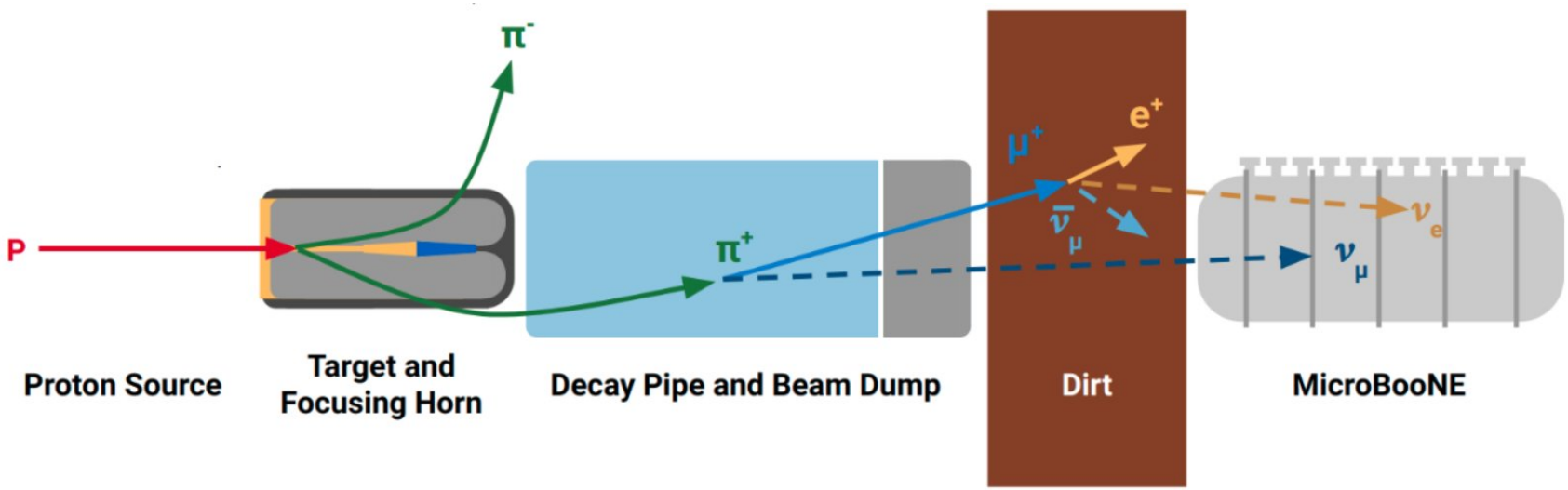
Dominant production modes:

$\nu_\mu : \pi^+ \to \mu^+ \nu_\mu$ 94%

$\nu_e : \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ 52%

Other sources of systematic uncertainty:

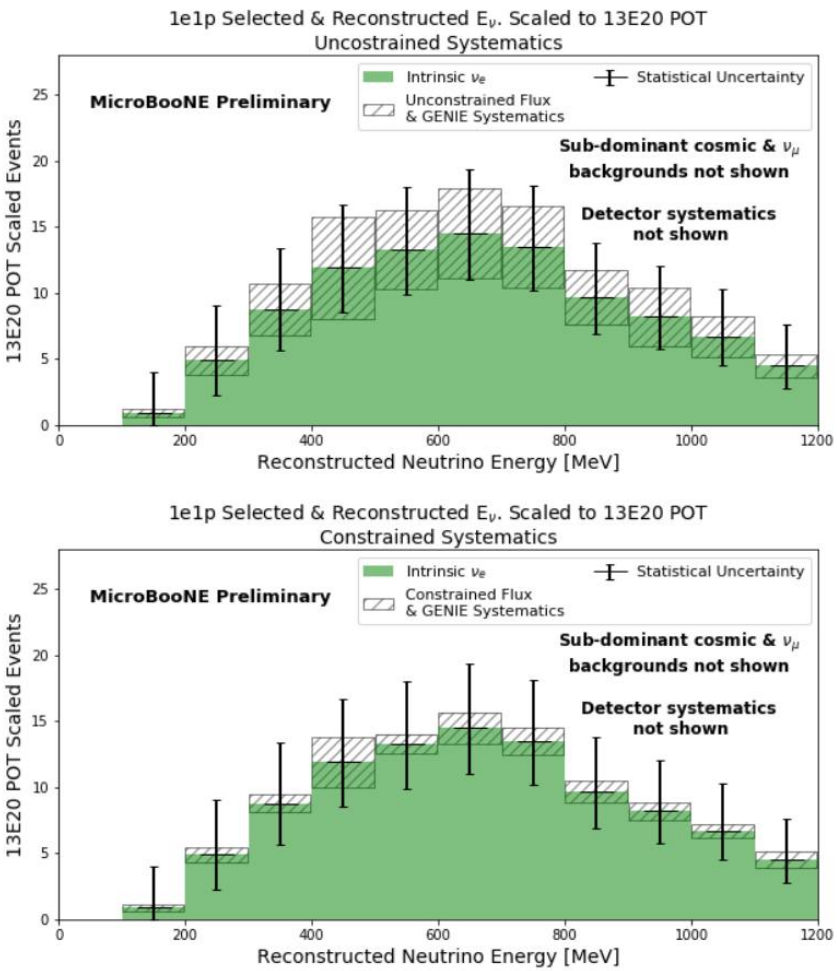
- **Cross-Section**: both neutrinos interact with argon nuclei.
- **Detector**: systematic detector effects affect different channels in the same way.



Constraining the uncertainties with muon neutrinos

→ **Reduced systematic uncertainties** in a combined analysis:

1. Using multiple selections and observables.
2. Taking into account correlated systematic uncertainties through a covariance matrix.



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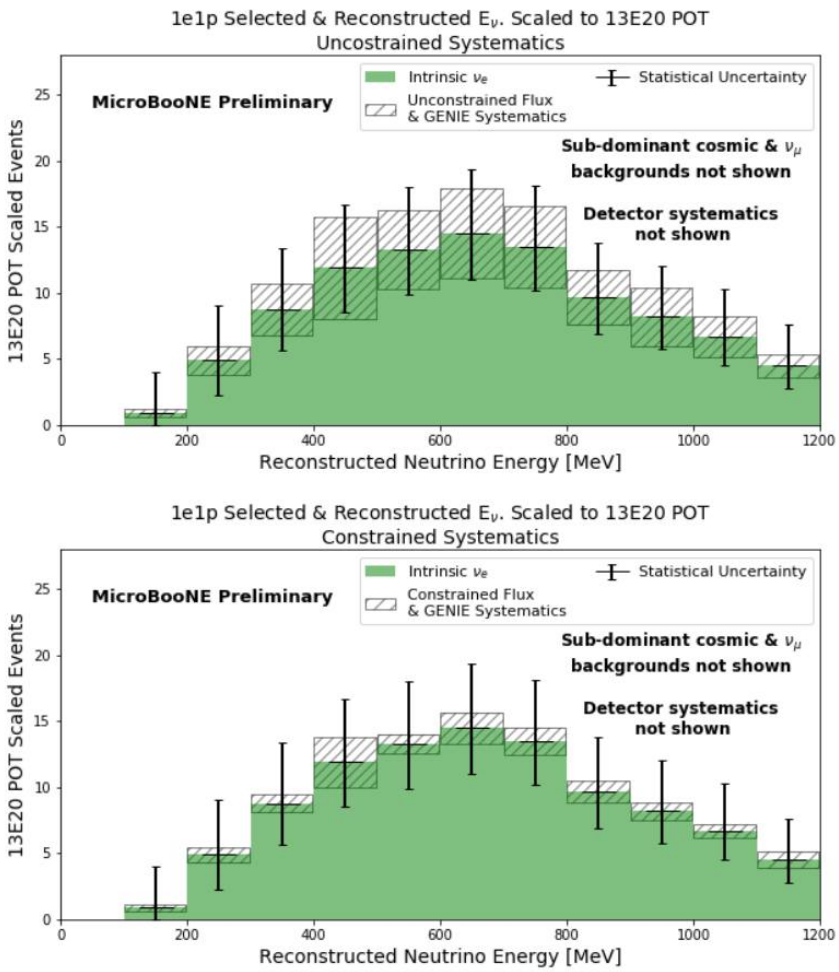
Constraining the uncertainties with muon neutrinos

→ **Reduced systematic uncertainties** in a combined analysis:

1. Using multiple selections and observables.
2. Taking into account correlated systematic uncertainties through a covariance matrix.



Simulation-based exercise of **constraining the flux and cross-section systematics** on the ν_e selection using muon neutrinos.

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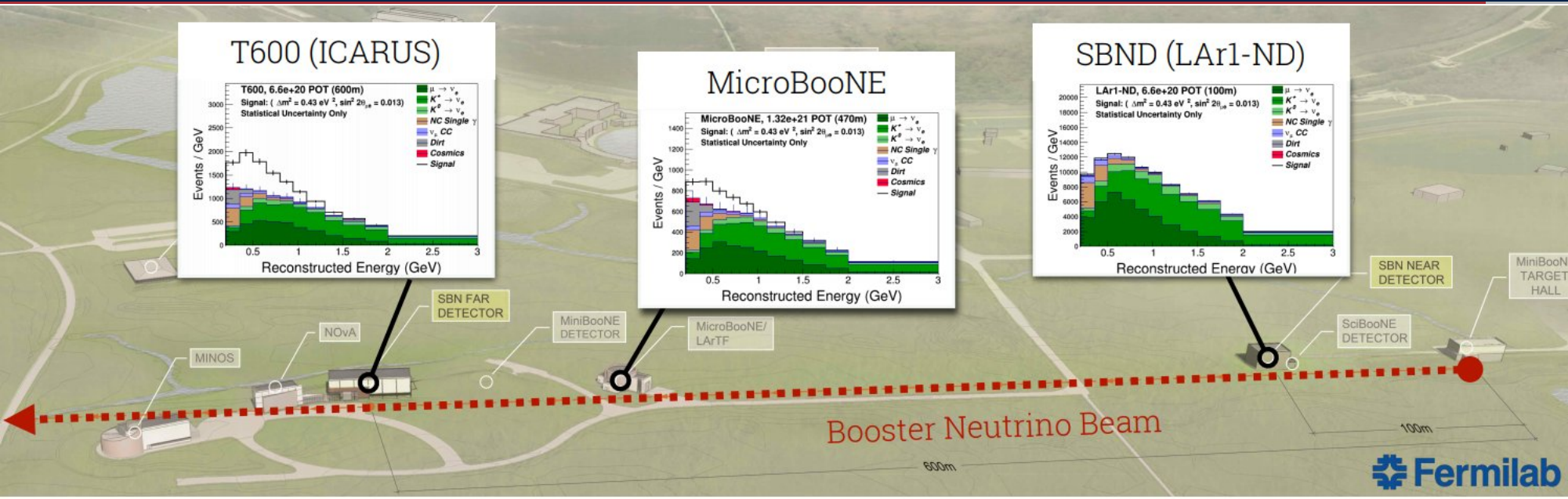
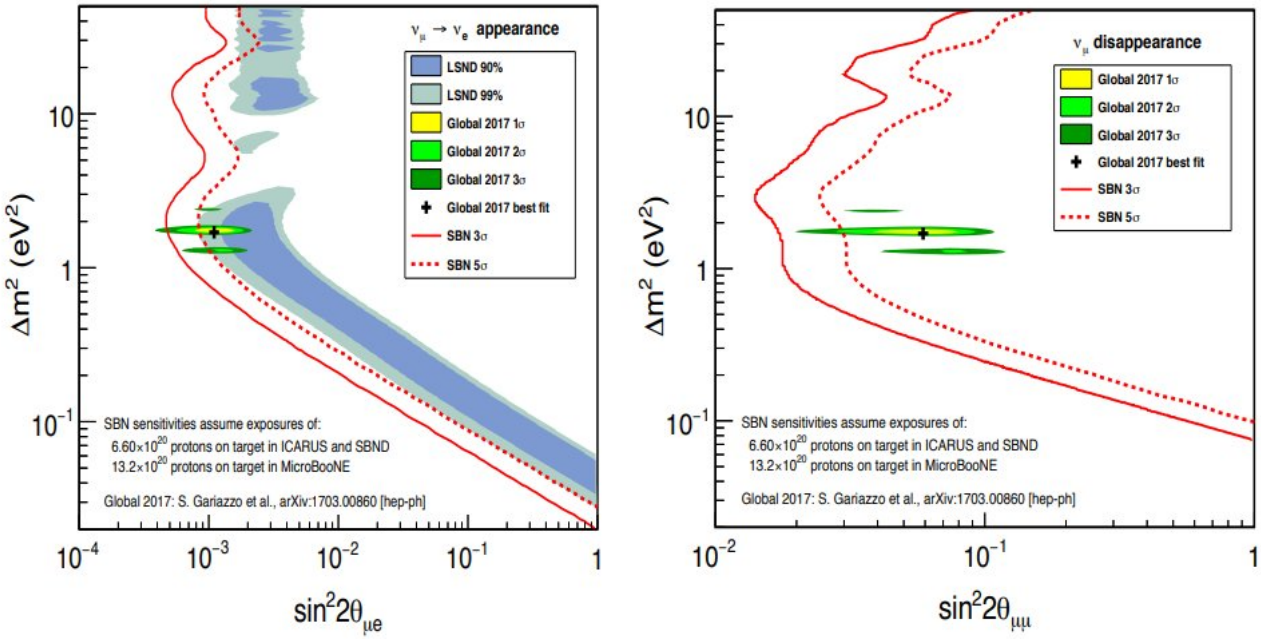
The Short Baseline Programme (SBN) at Fermilab [8]



Sensitivity to the short-baseline anomaly



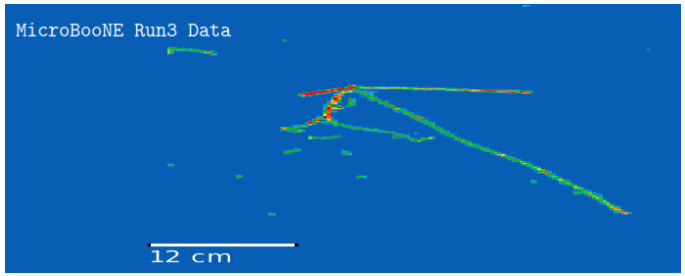
Conclusion

What MicroBooNE Has Archived So Far

- Fully automatic event reconstruction and LArTPC R&D!
- ν_μ Charged-Current inclusive double differential cross-section [5].
- Charged-Current π^0 measurement and π^0 mass peak [6].

Progress towards Low Energy Excess

- Explicit selections targeting both electron and photon channels.
- ν_μ sample is being used to constrain flux and cross-section uncertainties.
- **First low energy excess result soon.**



Thank you!
& Questions

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Neutrino Oscillations: the current picture

- Mixing between neutrino flavour and mass eigenstates: PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}) = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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- Propagation through vacuum over a length L for mass eigenstate ν_i:

$$|\nu_i(L)\rangle \approx e^{-i\frac{m_i^2 L}{2E}} |\nu_i(0)\rangle \,.$$

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$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}) \approx \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.3 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.8 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Propagation through vacuum over a length L for mass eigenstate ν_i:

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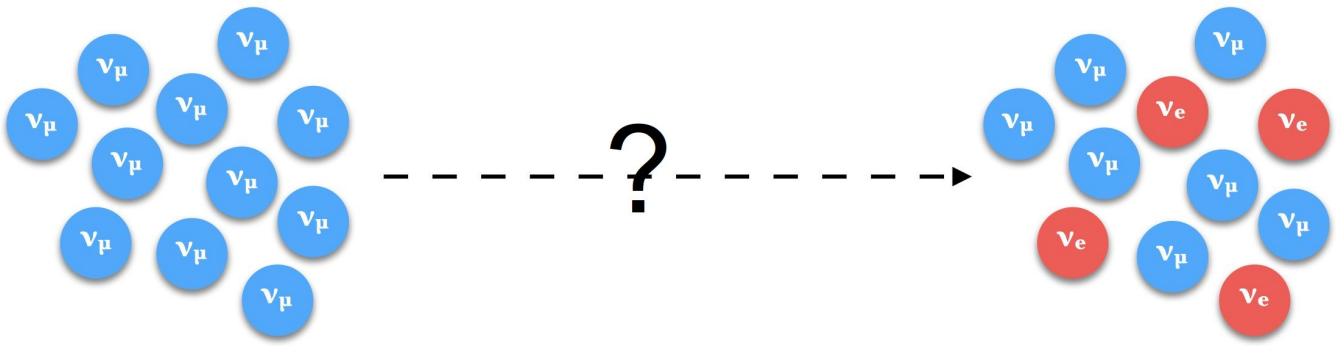
The combination leads to neutrino flavour oscillations!



- Let's add a sterile fourth neutrino to the game!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \boldsymbol{\nu_S} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boldsymbol{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \boldsymbol{U_{\mu 4}} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boldsymbol{U_{\tau 4}} \\ \boldsymbol{U_{S1}} & \boldsymbol{U_{S2}} & \boldsymbol{U_{S3}} & \boldsymbol{U_{S4}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boldsymbol{\nu_4} \end{pmatrix}$$

Neutrino Oscillations & the Sterile Neutrino Hypothesis

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- Consider experiments where $\frac{E}{L} \approx \Delta m^2_{41}$ and $\Delta m^2_{41} >> \Delta m^2_{21}, \Delta m^2_{32}$.
- If we are only sensitive to electron and muon flavours in the detector:

$$\boldsymbol{U_{e4}}, \boldsymbol{U_{\mu 4}} \text{ and } \boldsymbol{\Delta m^2_{41}}$$

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$$P(\nu_e \to \nu_e) = 1 - 4(1 - \mid \boldsymbol{U_{e4}} \mid^2) \mid \boldsymbol{U_{e4}} \mid^2 \sin^2(1.27 \boldsymbol{\Delta m^2_{41}} \frac{L}{E}) \qquad (\nu_e \text{ disappearance})$$

$$P(\nu_\mu \to \nu_\mu) = 1 - 4(1 - \mid \boldsymbol{U_{\mu 4}} \mid^2) \mid \boldsymbol{U_{\mu 4}} \mid^2 \sin^2(1.27 \boldsymbol{\Delta m^2_{41}} \frac{L}{E}) \qquad (\nu_\mu \text{ disappearance})$$

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Appearance and disappearance signals are related!

A step back in time: A puzzling collection of anomalies

Radiochemical Experiments

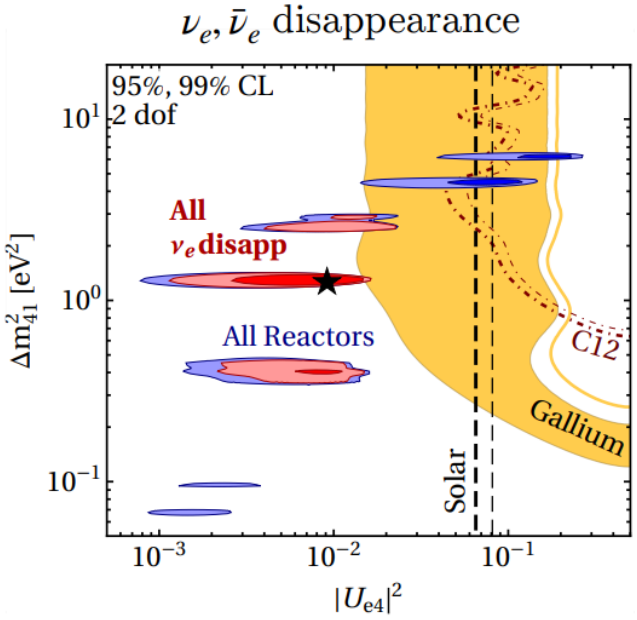
- The SAGE and GALLEX experiments both observed a deficit of electron neutrinos with radioactive isotope sources.

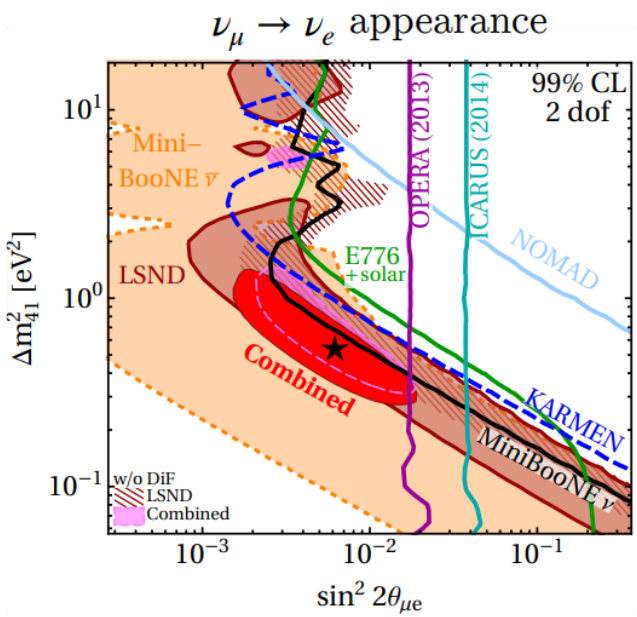
Reactor Experiments

- 3.5% deficit of electron anti-neutrinos in several reactor experiments.

Accelerator Experiments

- Excess of electron neutrinos and anti-neutrinos in the LSND and MiniBooNE experiments.





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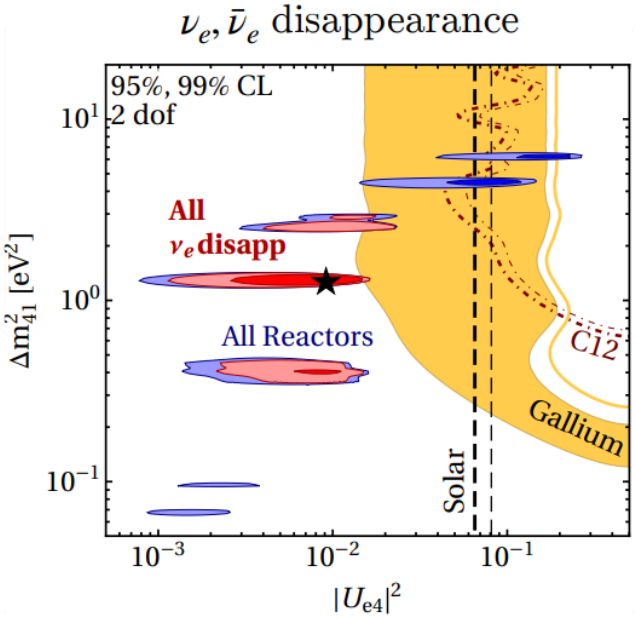
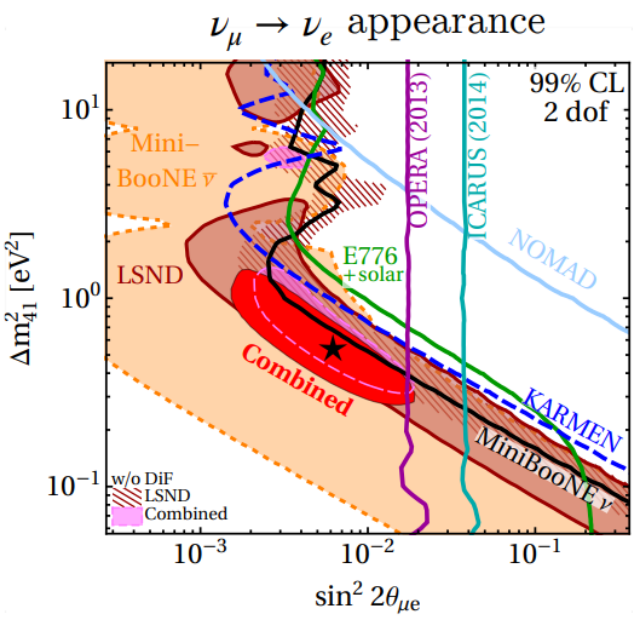
Hints towards sterile neutrino, but tension in global fits remains.

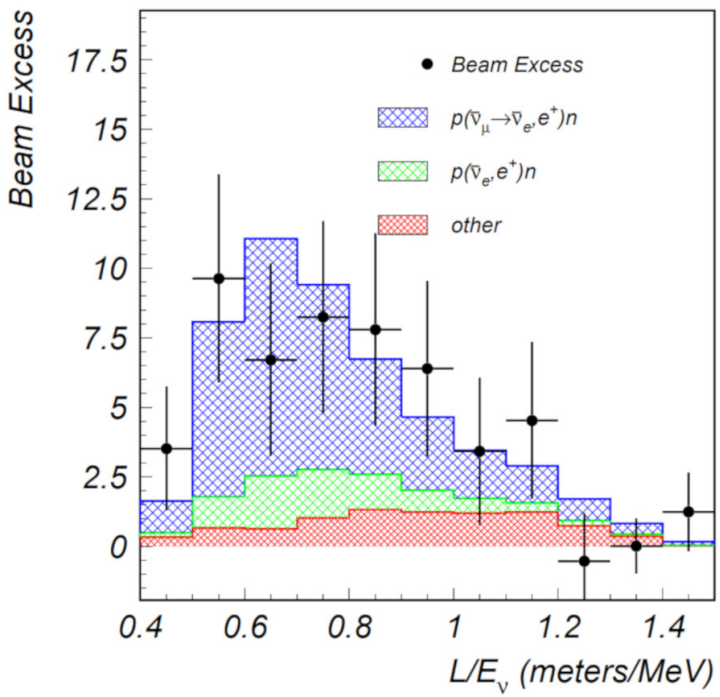


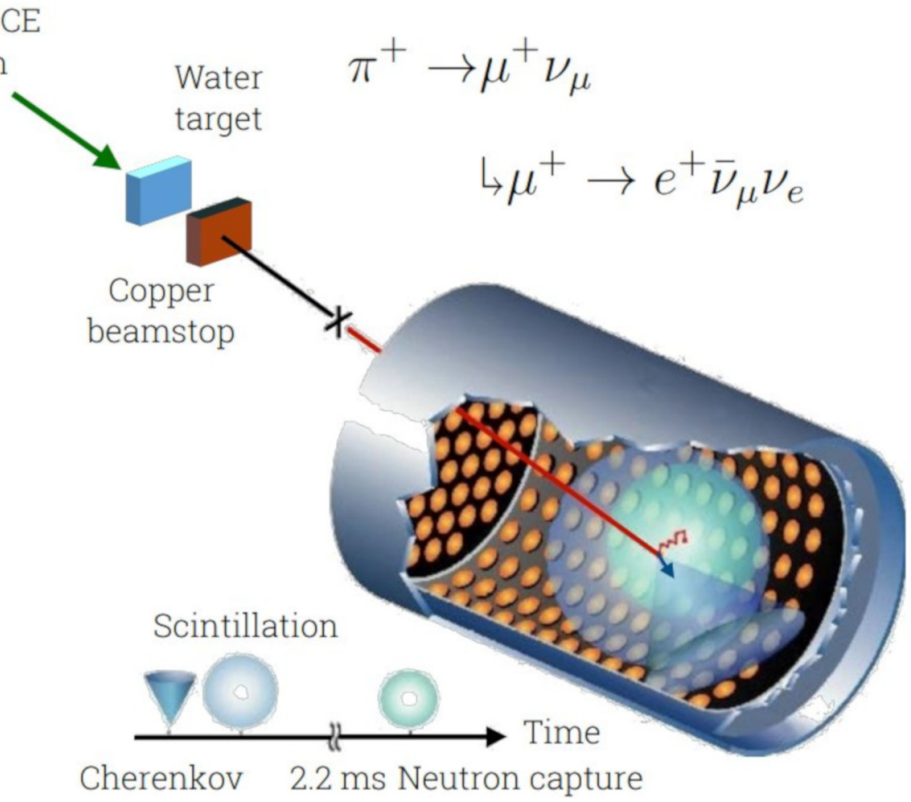


A step back in time: The LSND Exepriment

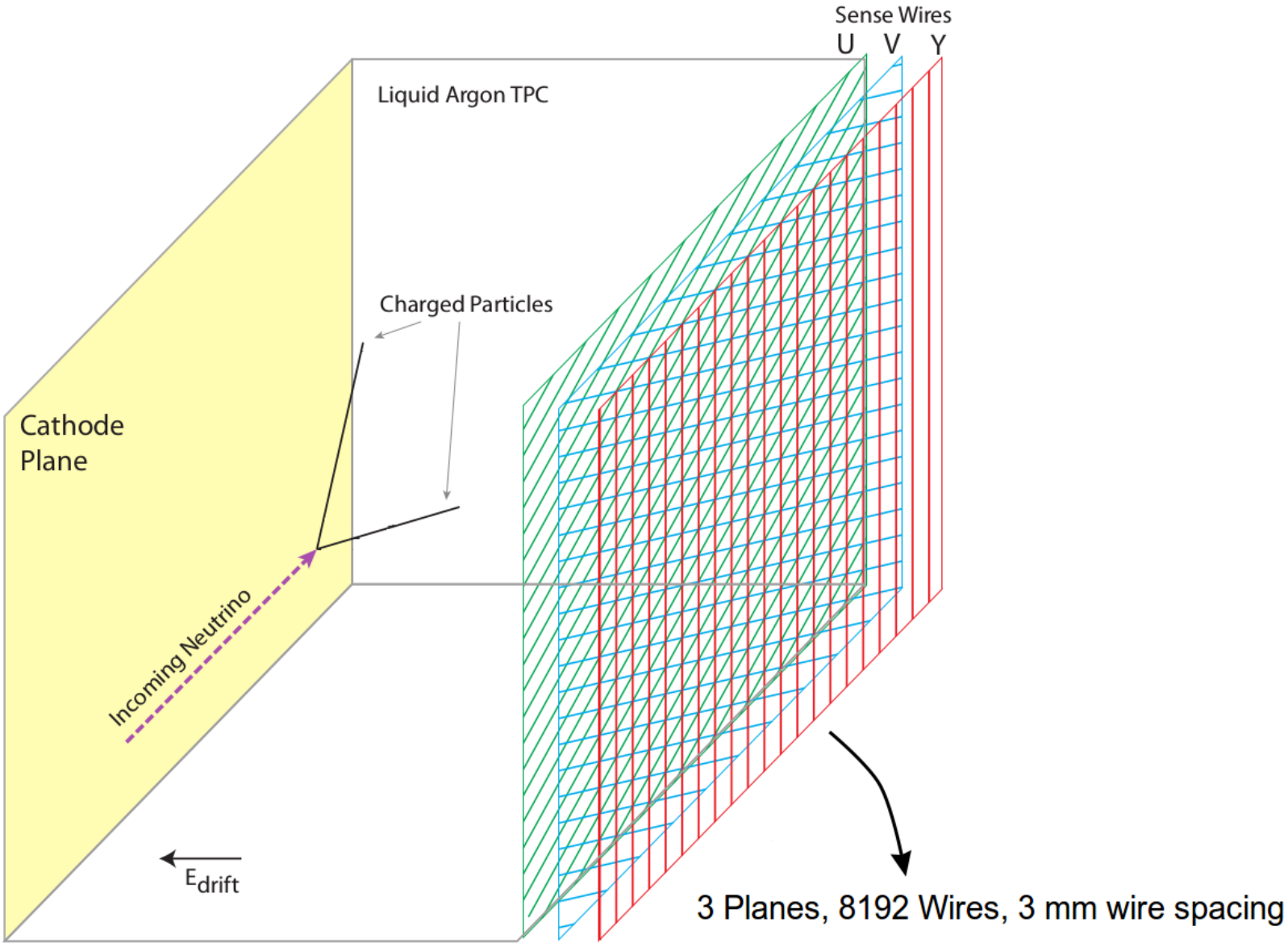
Liquid Scintillator Neutrino Detector at Los Alamos

- Data-taking 1993-1998.
- $\bar{\nu}_\mu$ from μ^+ Decay at rest.
- 3.8σ excess consistent with ν_e appearance ($\Delta m \approx 1\,\mathrm{eV}^2$).





Liquid Argon Time Projection Chamber



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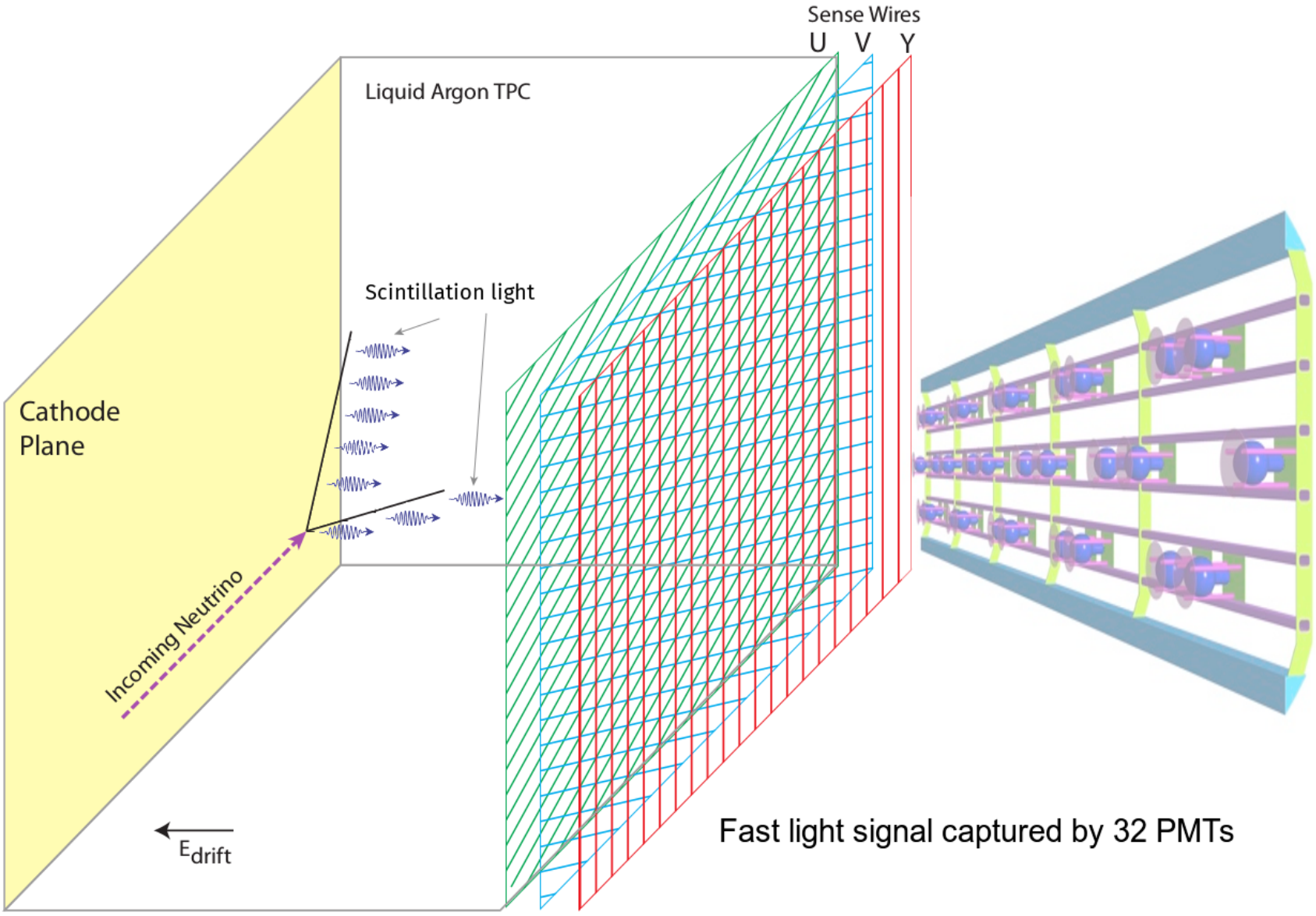

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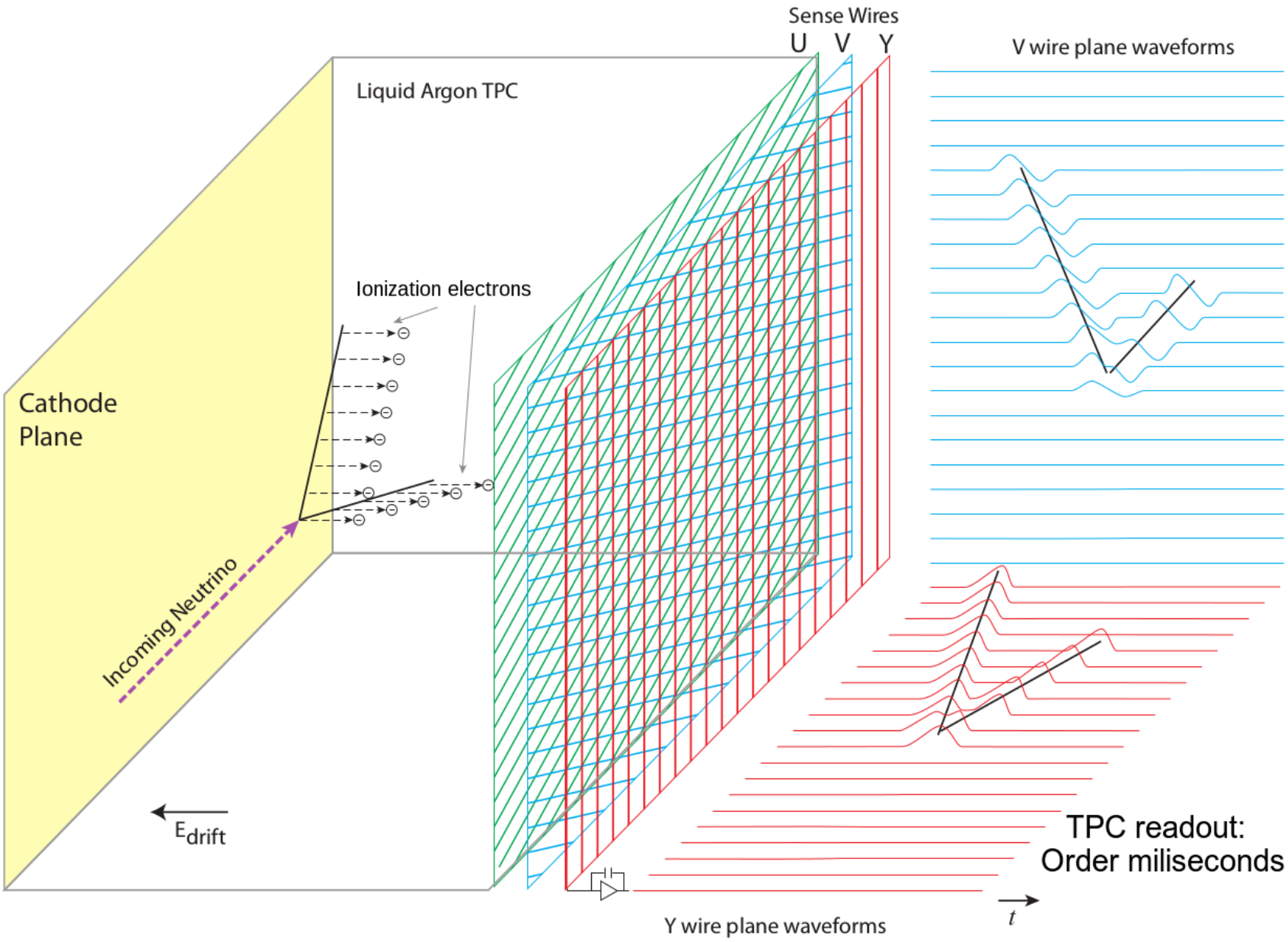
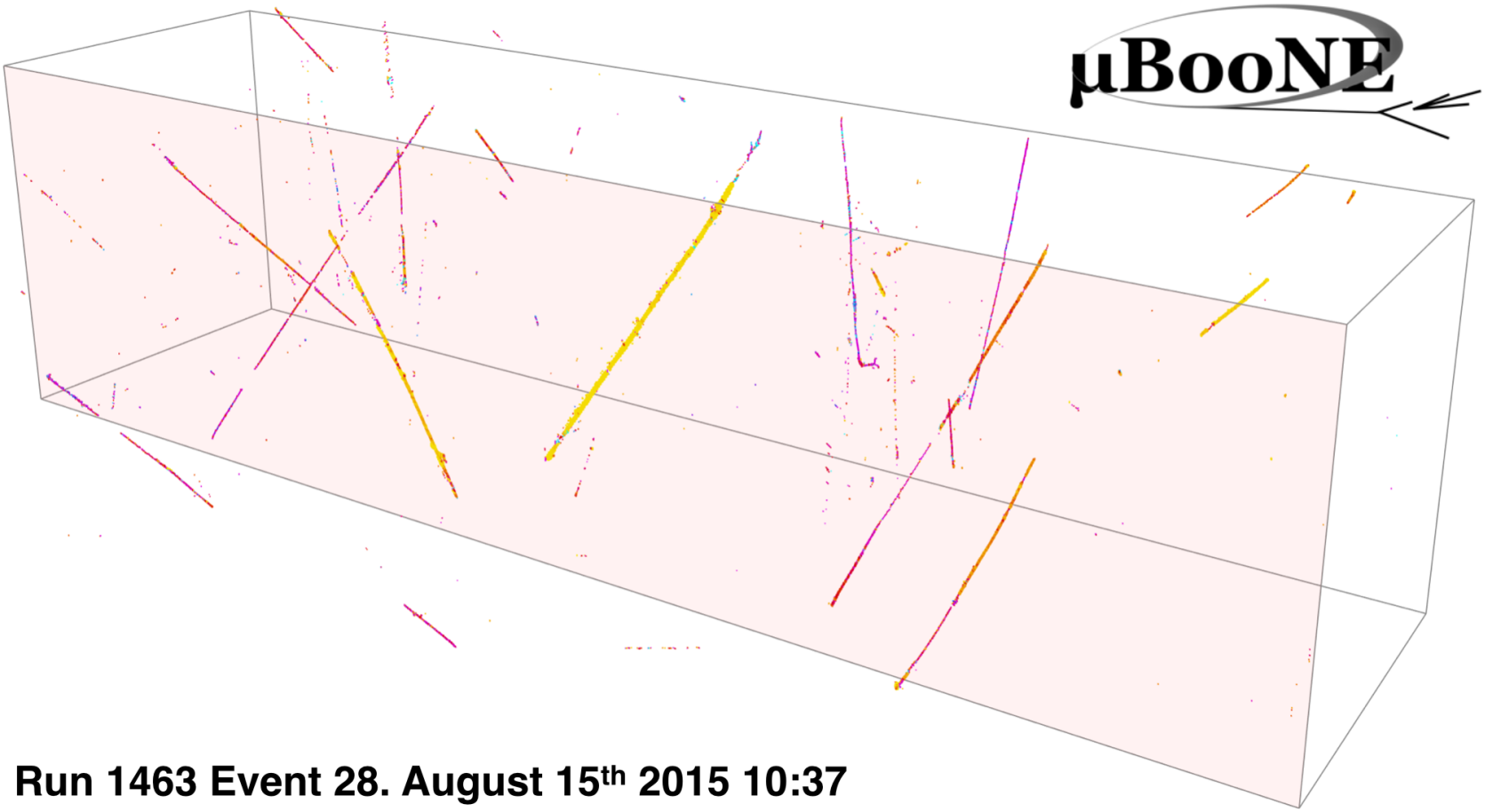


Back to reality: Events contain a lot of cosmic charge deposits



Cosmic Activity @ MicroBooNE

- MicroBooNE is a surface detector.
- 5 kHz cosmic muon rate.
- Approximately 24 muons per triggered event

→ **Cosmic activity is the dominant background!**
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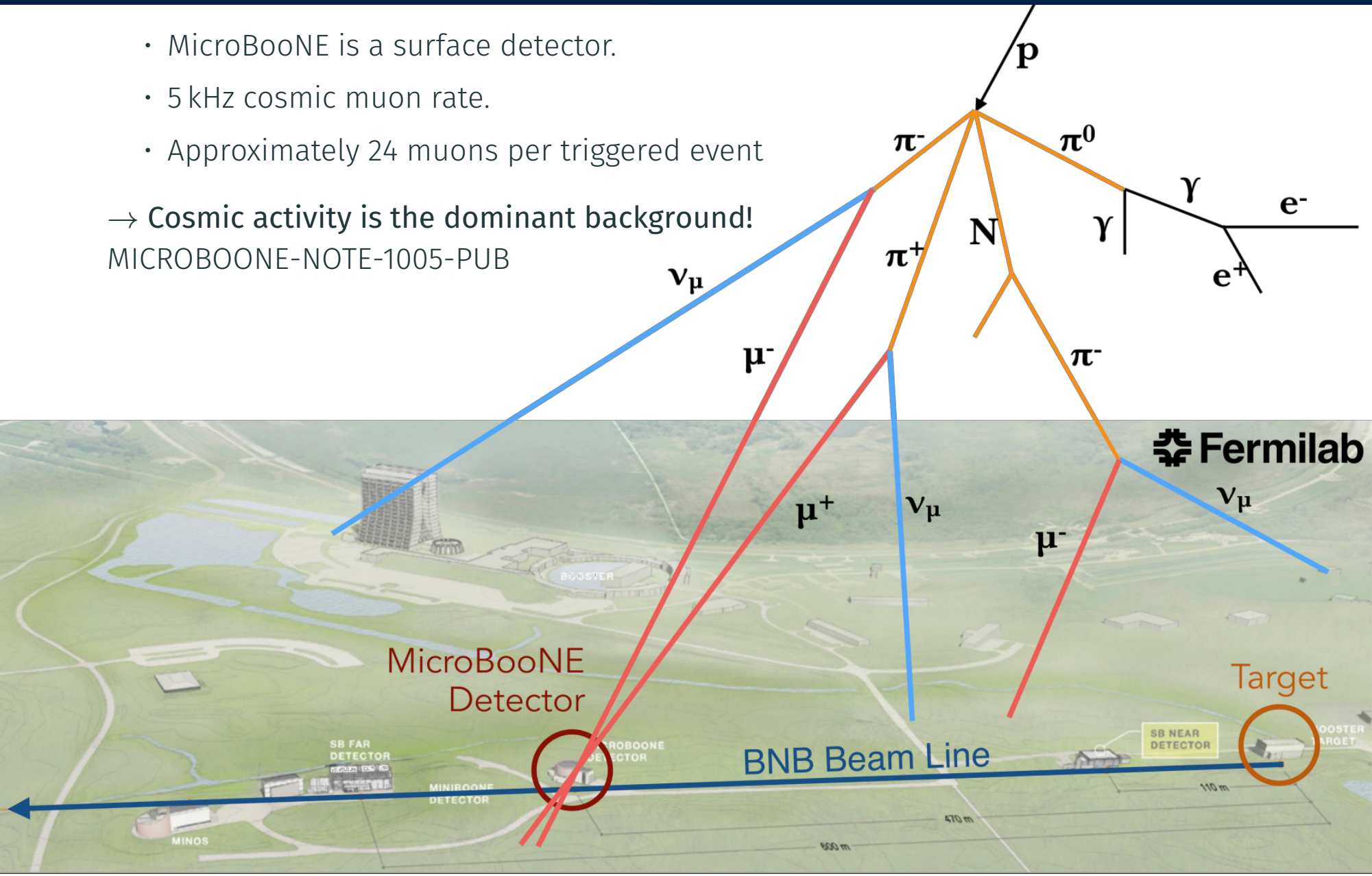
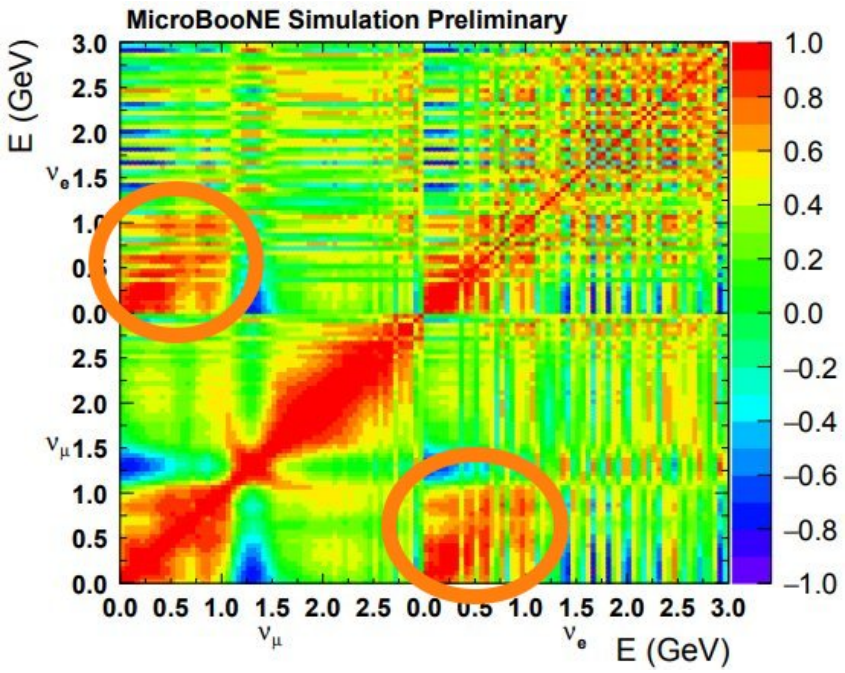


Constraining the uncertainties with muon neutrinos

ν_μ and ν_e have much in common:

- **Flux**: both species of neutrinos come from the same beam, from decays of the same populations of hadrons.
- **Cross-Section**: both neutrinos interact with argon nuclei.
- **Detector**: systematic detector effects affect different channels in the same way.



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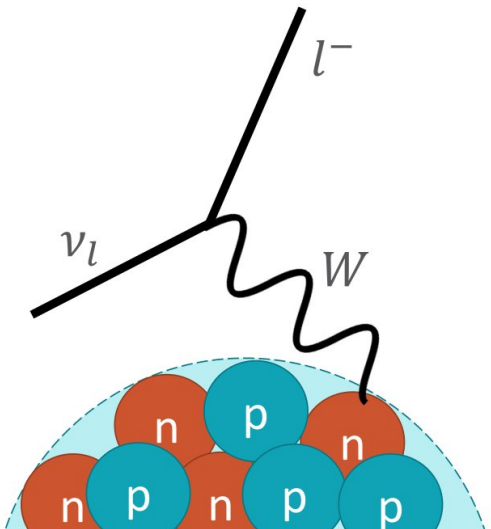
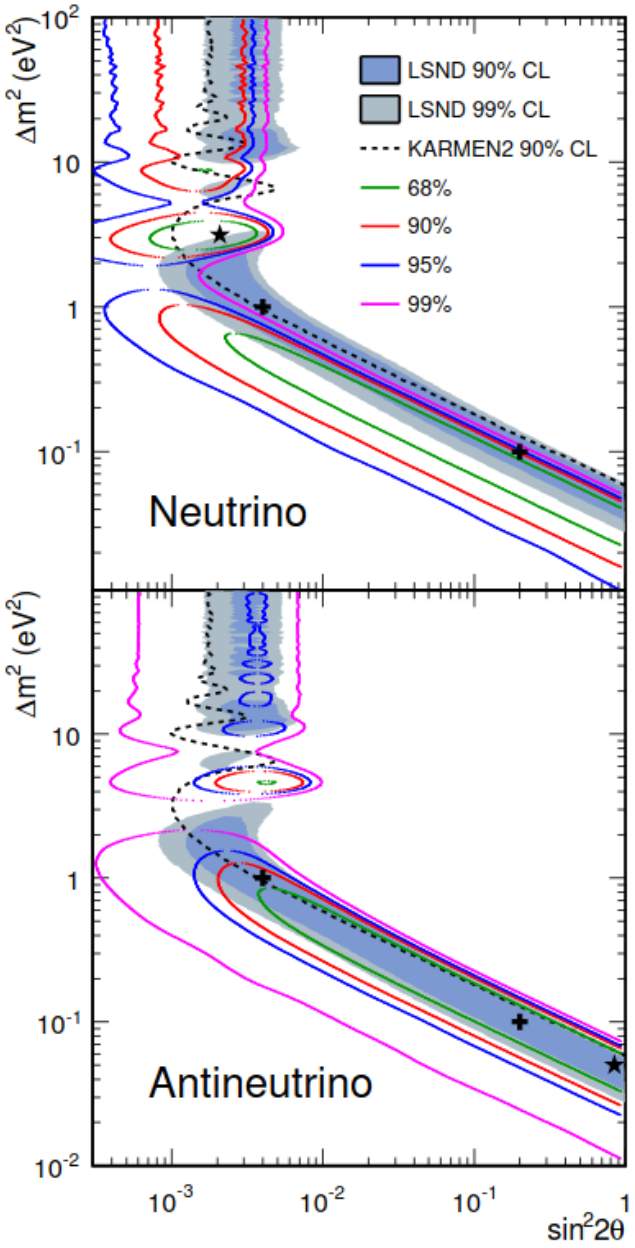
Strong **correlation** between the ν_μ and ν_e cross-section **at low energies**.



MiniBooNE/LSND



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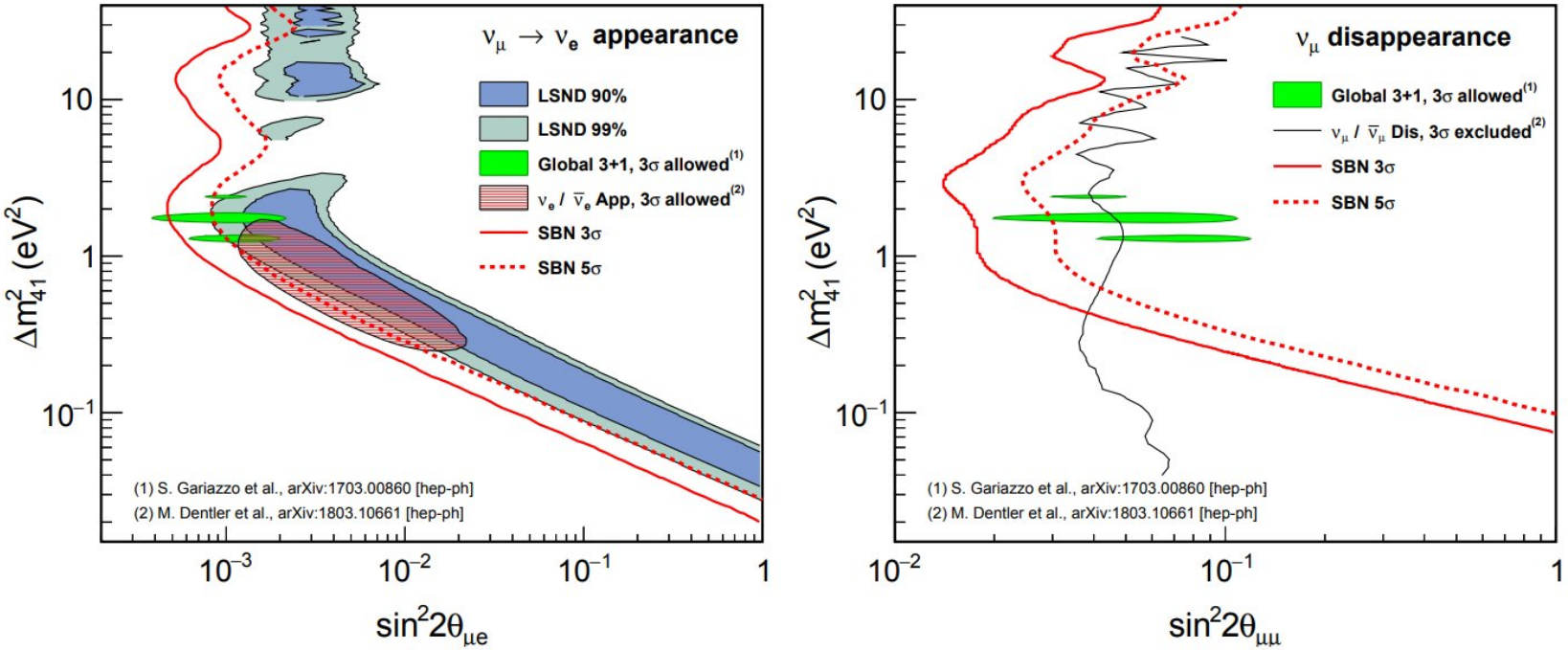

Figure 7

SBN 3σ (solid red line) and 5σ (dotted red line) sensitivities to a light sterile neutrino in the $\nu_\mu \to \nu_e$ appearance channel *(left)* and $\nu_\mu \to \nu_\mu$ disappearance channel *(right)*. For comparison, the LSND preferred region at 90% C.L. (shaded blue) and 99% C.L. (shaded gray) is presented (19). Moreover, the global ν_e appearance (shaded red) and global ν_μ disappearance (black line) 3σ regions from Ref. (33) are also included. Finally, the 3σ global best fit regions from Ref. (35) are shown in green. The sensitivities are reproduced from the SBN proposal (15).

Muon Neutrinos to constrain the Booster Neutrino Beam flux

- ν_μ flux peaks at ≈0.8 GeV.
- Small ν_e component: ≈0.57 %.

→ ν_e's from Kaons at lowest energies can be constrained by high energy ν_μ's.