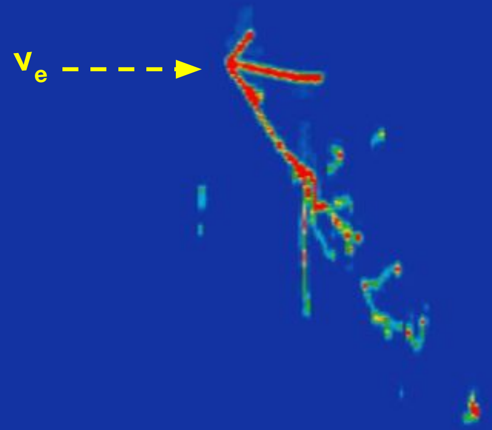

Adding pieces to the short-baseline neutrino puzzle: MicroBooNE Recent Results.

Elena Gramellini
Lederman Fellow, Fermilab
on behalf of the MicroBooNE Collaboration
LNF General Seminar, April 13^{th} 2022

Talk Roadmap

A history of **short baseline neutrino anomalies**

The **LArTPC technology** &
the **MicroBooNE** experiment

MicroBooNE Recent Results:

→ 3 complementary searches for a ν_e excess
→ the photon search

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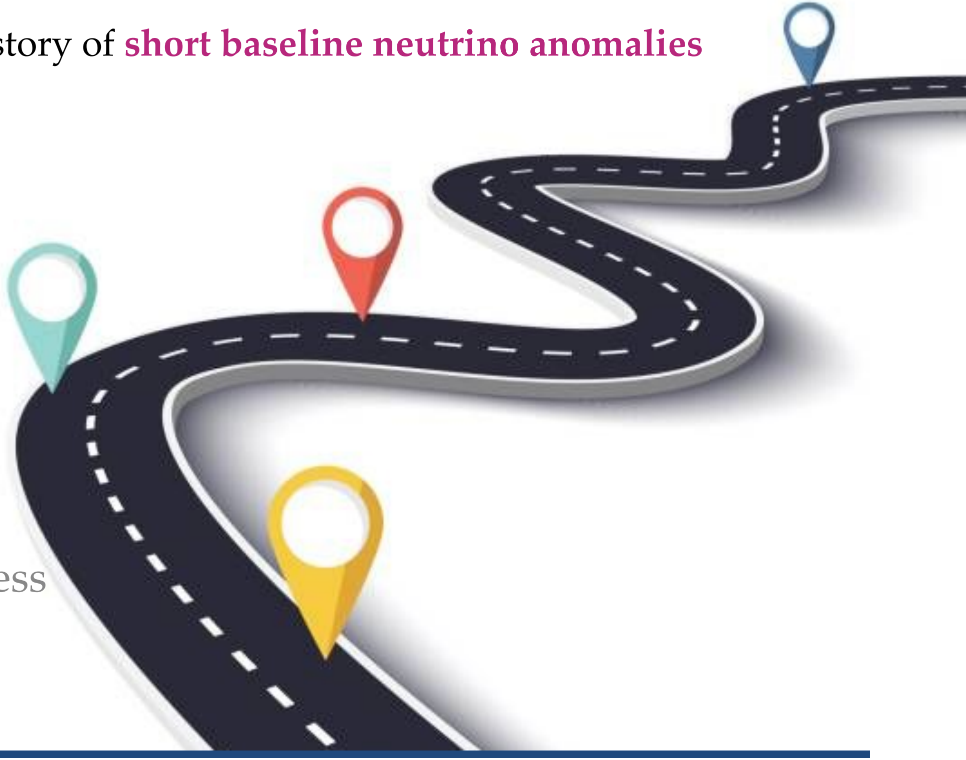
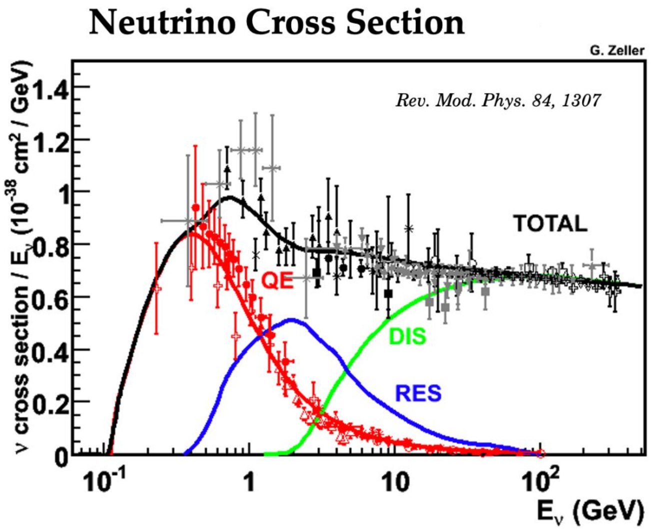
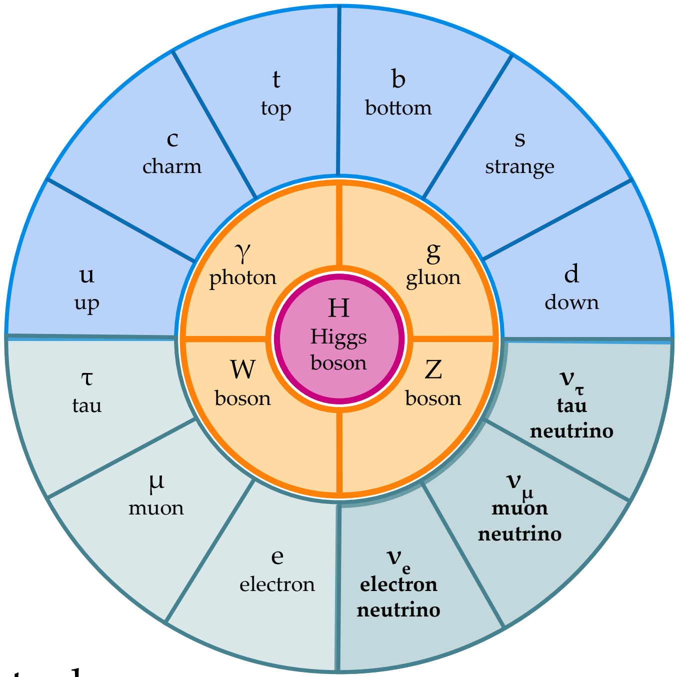


Neutrinos: puzzles of the Standard Model

Neutrinos are **the most abundant massive particles** in the universe…
…and one of the least understood.





Not surprising it took
26 years from formulation to first evidence!

Neutrino Oscillations: Massive Neutrinos are a 1st Glance at Physics Beyond the Standard Model!

2015

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Precision measurements of
3 flavor mass and mixing (~10%)

Many open questions:
- Mass Hierarchy
- Absolute Mass
- CP Violation in ν sector
- Nature of Neutrinos
- Neutrinos and Cosmology

BSM physics in Neutrino Sector
- New neutrinos
- New forces
- Exotic phenomena

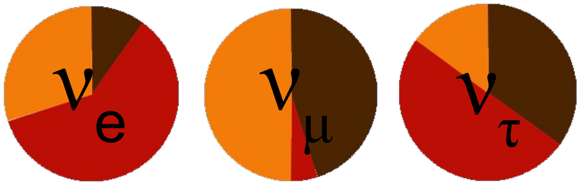
3-Flavors Neutrino Oscillations

Neutrinos interact via the **weak force** as **states of definite flavor**

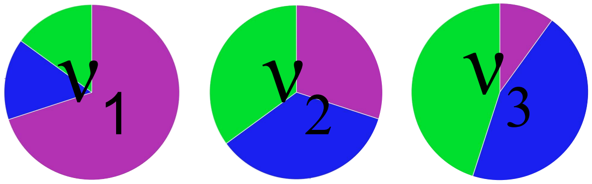
PMNS mixing matrix

but they **propagate** through space/time as **states of definite mass**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



linear combinations of each other



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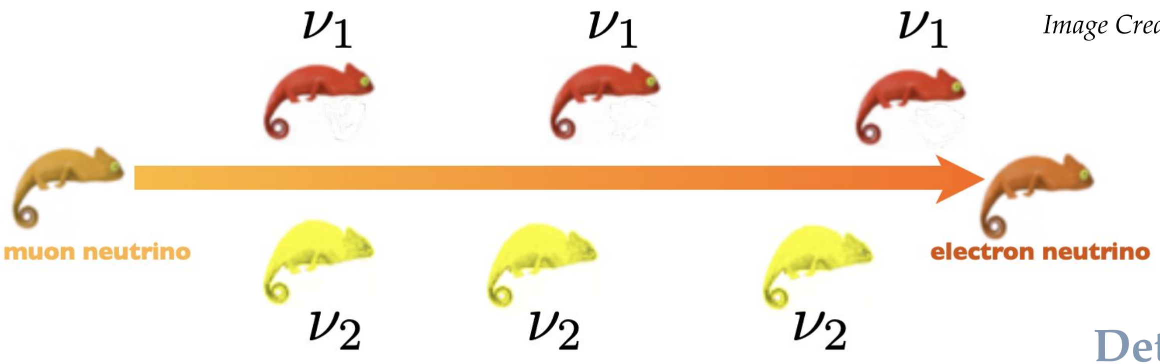
Measuring the mixing parameters with high precision gives us new information on neutrinos!

Neutrino Oscillations: A Simple 2 Flavors Example

Image Credit: S. Pascoli



Production

(Some) neutrinos come from particle's decay: Flavor States!

Propagation

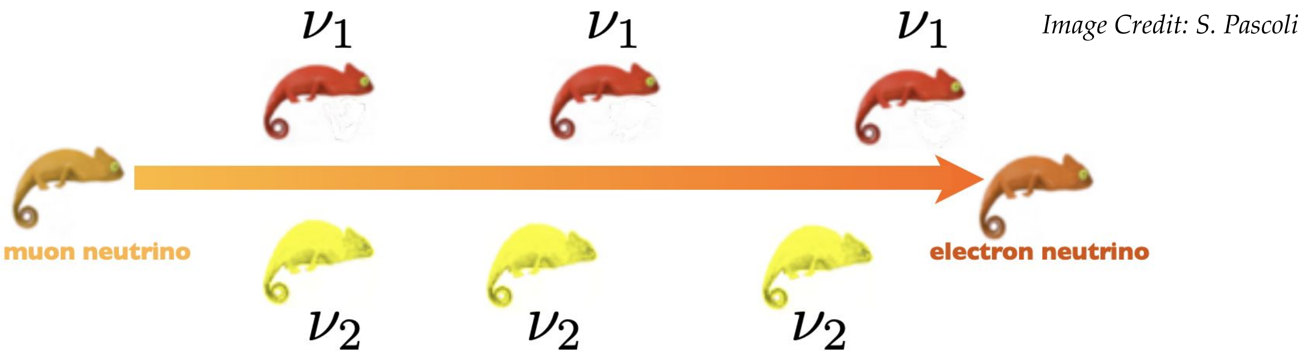
Quantum-Mechanic propagation: Mass States!

$$|\nu, t\rangle = \sum_i U^*_{\mu i} e^{-iE_i t} |\nu_i\rangle$$

Detection

They interact by exchanging a W/Z boson: Flavor States!

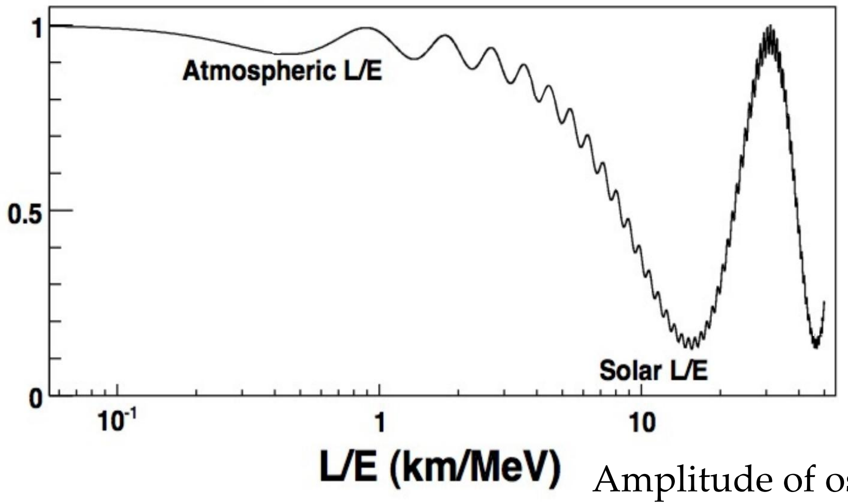
Neutrino Oscillations: A Simple 2 Flavors Example



Muon neutrino disappearance **Electron neutrino appearance**

$$P(\boldsymbol{\nu}_{\boldsymbol{\mu}} \rightarrow \boldsymbol{\nu}_{\boldsymbol{e}}) \sim sin^2 2\theta * sin^2\left(\Delta m^2 \frac{L}{E}\right)$$

Neutrino Oscillations: A Simple 2 Flavors Example



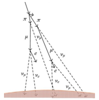
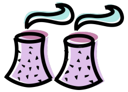
Baseline
(set by us, given the Δm^2 to explore)

Frequency of oscillation
(set by Nature)

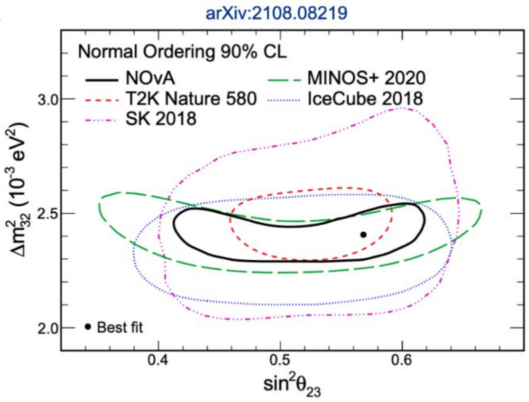
Amplitude of oscillation "large"
→ easy to detect

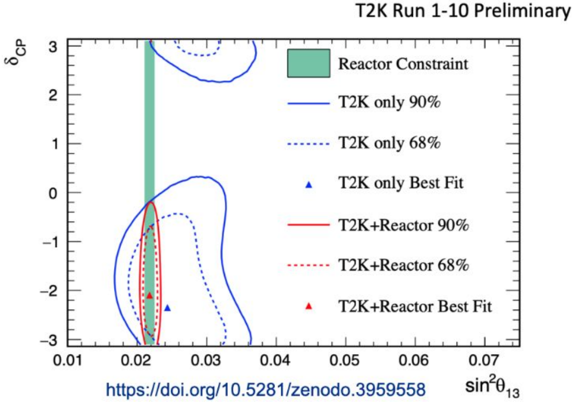
$$P(\nu_\mu \rightarrow \nu_e) \sim sin^2 2\theta * sin^2\left(\Delta m^2 \frac{L}{E}\right)$$

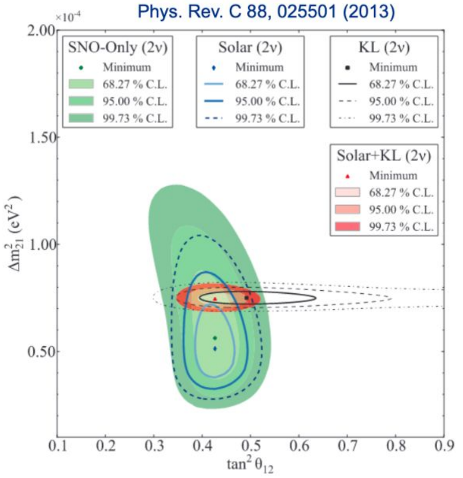
3-Flavors Neutrino Oscillations

Atmospheric  Reactor  Solar 

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$







Escaping 3-flavor oscillations

$\theta_{12}, \theta_{13}, \theta_{23}$	✓
$\Delta m^2, \delta m^2$	✓
N_ν	✓ ✗

$\left.\begin{array}{l} \\ \\ \end{array}\right\}$ Precision era (< 10%)

N Active: 3 ν
Sterile?

The existence of a 4th, sterile neutrino would arise as a deviation from the predicted 3-flavor oscillation pattern at a baseline corresponding to the appropriate Δm^2.

"PMNS+" matrix

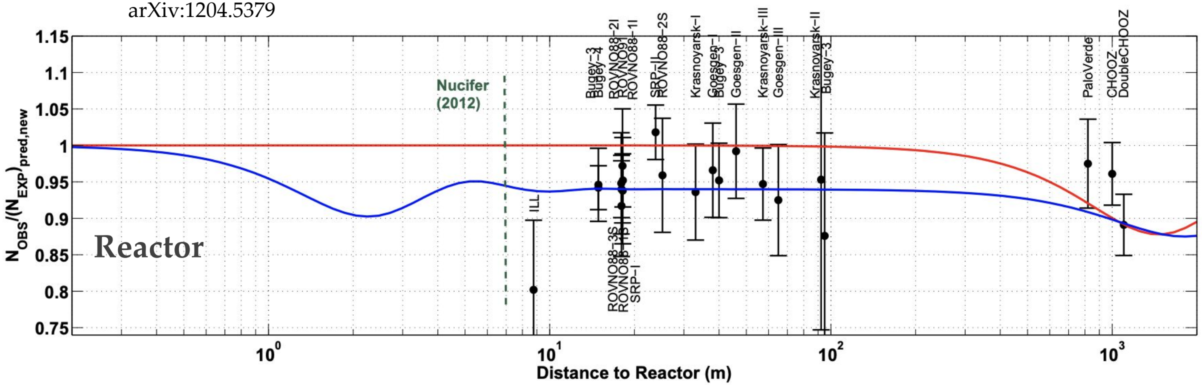
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & . \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & . \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & . \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{array}{ccccccc} + & & & & & & + \\ \nu_X & & . & . & . \; . & & \nu_4 \end{array}$$

Short-baseline ν anomalies

Observed in neutrino experiments in the last 20 years:
Deficit of anti-ν_e detected from nuclear reactors (reactor anomaly).

arXiv:1204.5379



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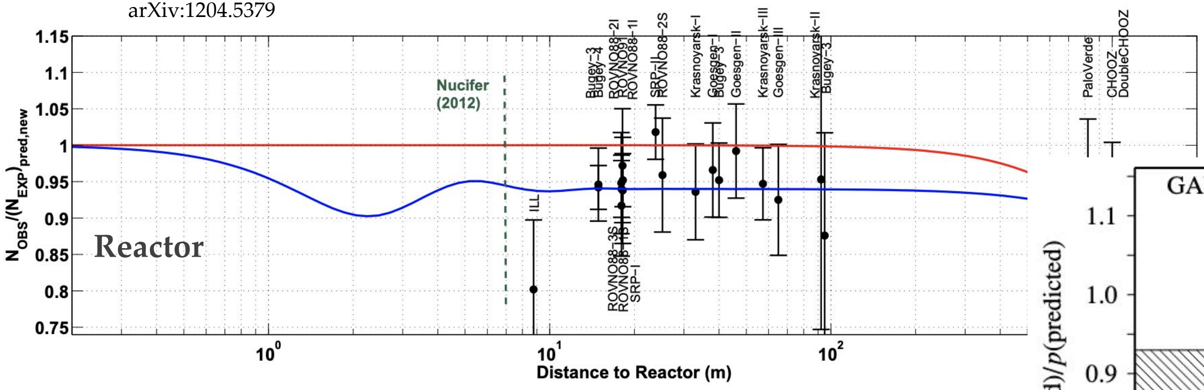
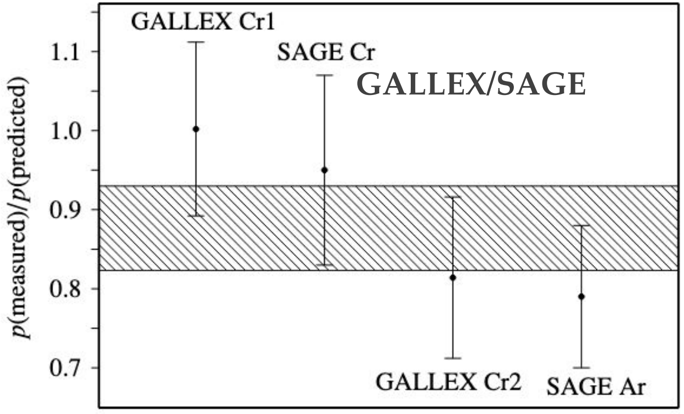


Phys. Rev. C 73, 045805 (2006)



Flux refinement for Reactors: Phys.Letters B Volume 829, (2022) 10
BEST experiment on Gallium: Phys.Rev.D 105 (2022) 5, L051703

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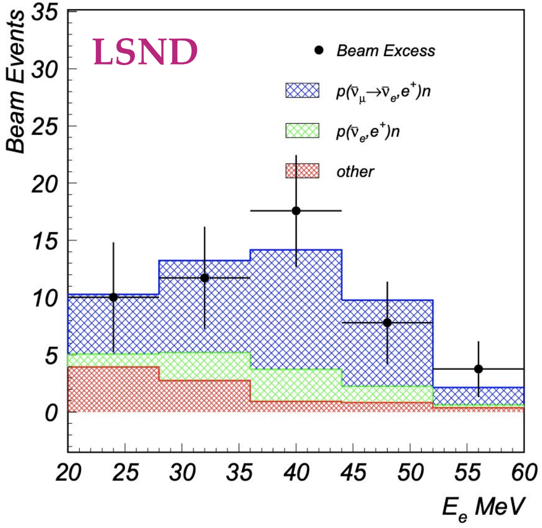
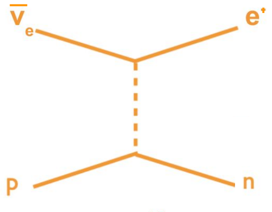
Phys. Rev. D 64 112007, 2001



E_ν = 20 – 55 MeV
Baseline L = 30m



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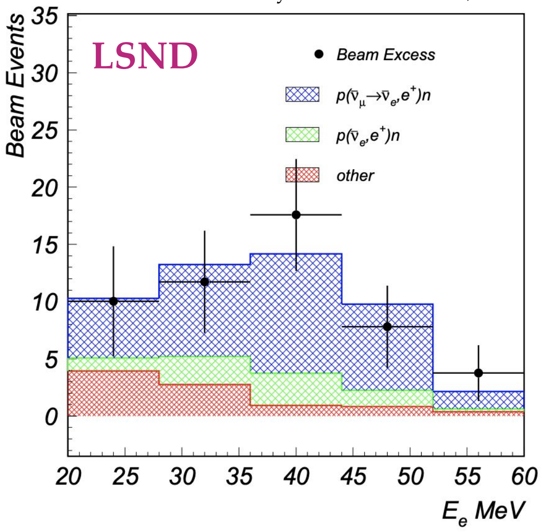
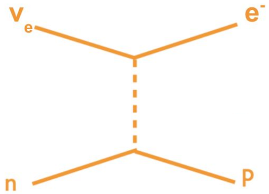
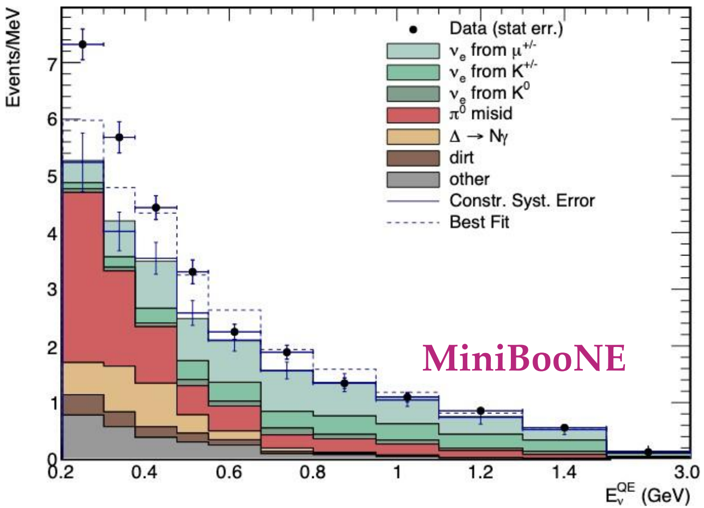


Similar L/E:
E_ν = 800 MeV
Baseline L = 540m



Phys. Rev. D 103, 052002 (2021)



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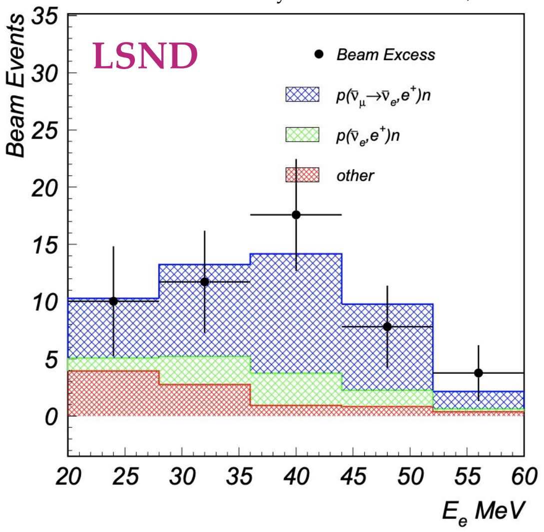

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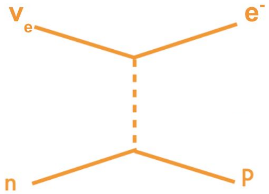

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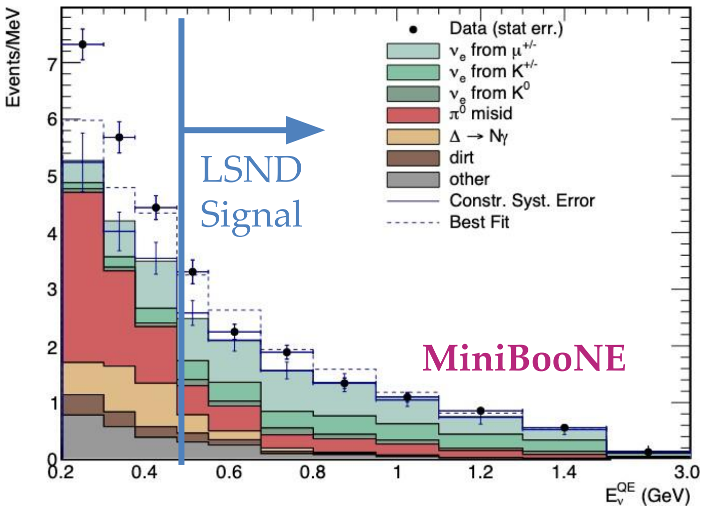

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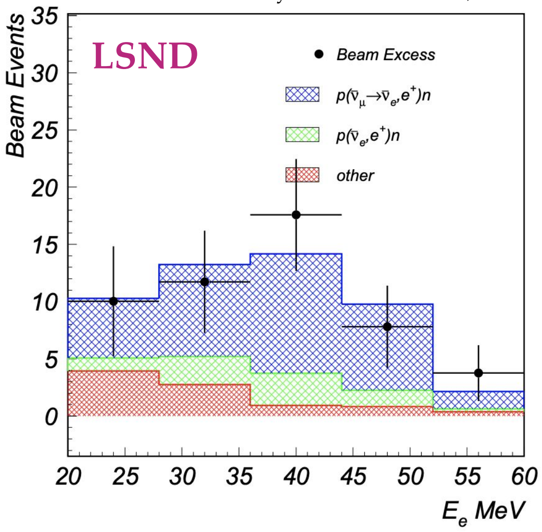

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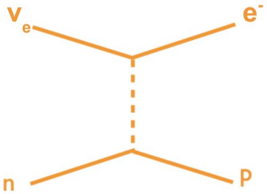

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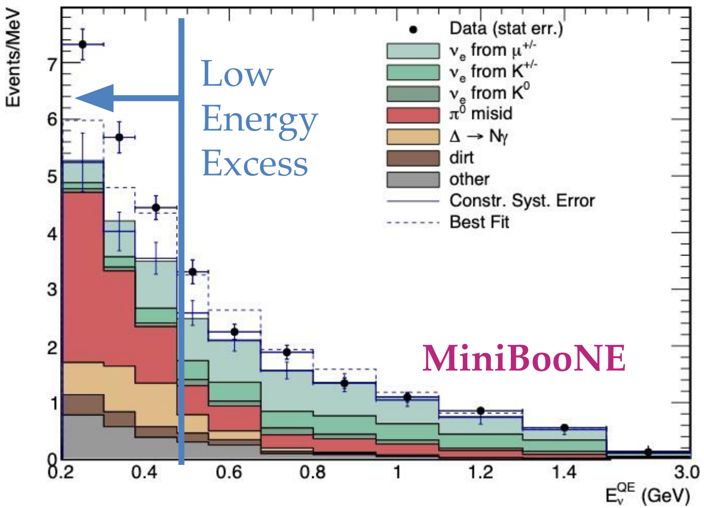

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Experiment	Type	Channel	Significance
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\bar{\nu}_e$ disappearance	3.0 σ
LSND	DAR accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$	4.5 σ 2.8 σ

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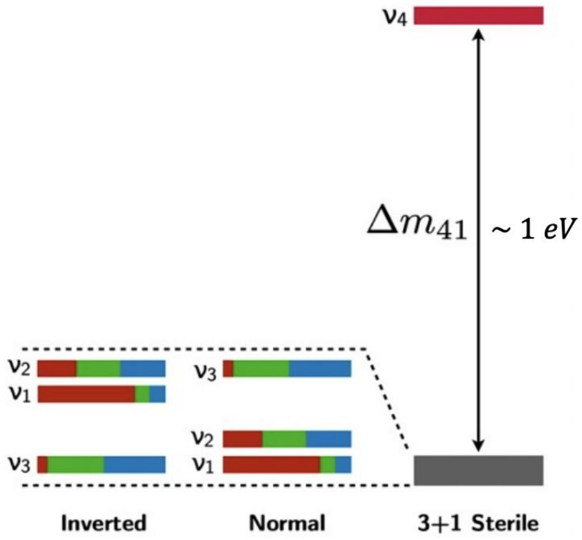


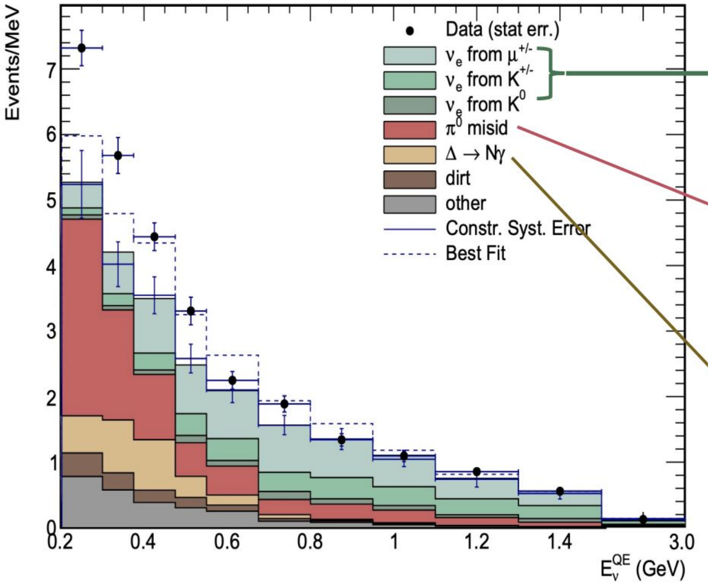
While independent explanations are not excluded, a unifying "vanilla" hypothesis exists: mixing of the standard neutrinos with a fourth, **non–weakly interacting sterile species**: motivates new experiments!

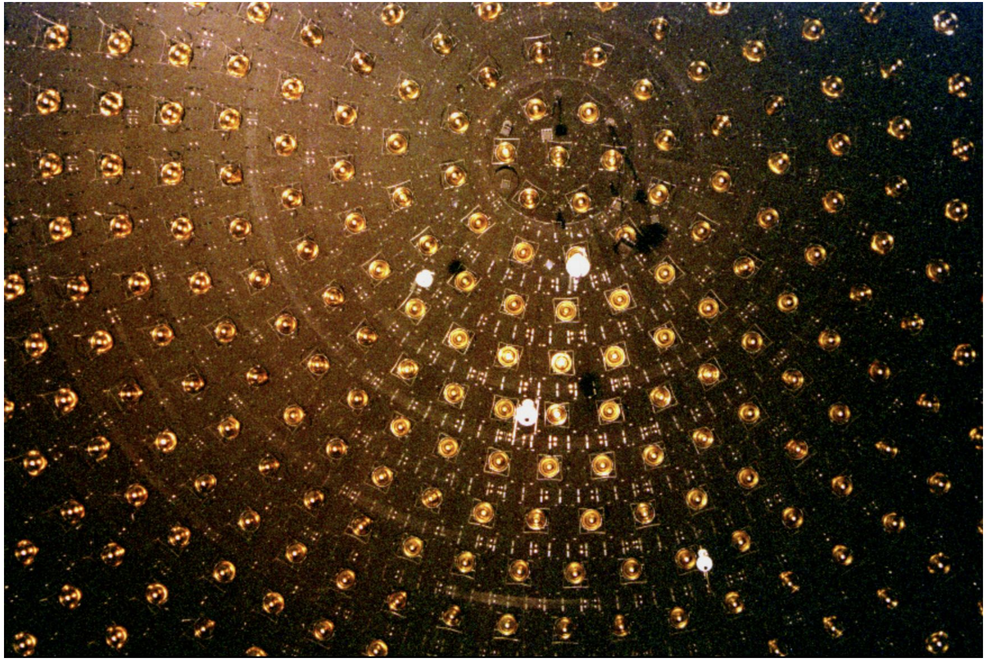
Disfavored by non-observation of ν_μ disappearance: motivates richer phenomenology!

MiniBooNE

MiniBooNE is a mineral oil Cherenkov Detector:
PID from the Cherenkov rings, no hadron information.

Phys. Rev. D 103, 052002 (2021)





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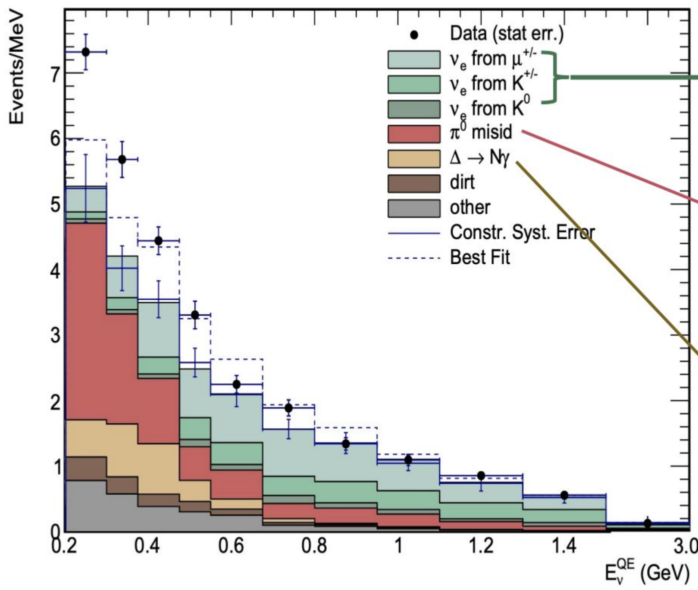

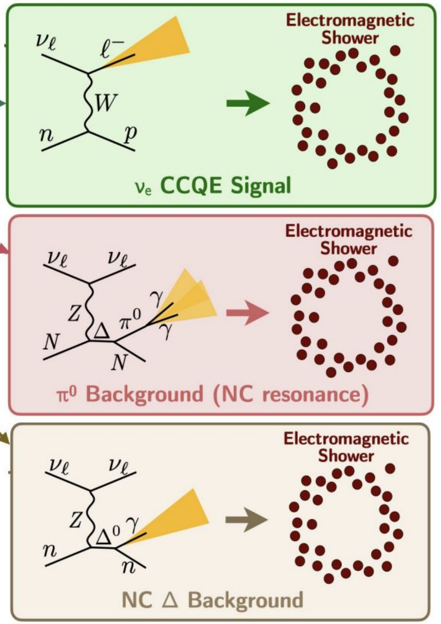

Indistinguishable

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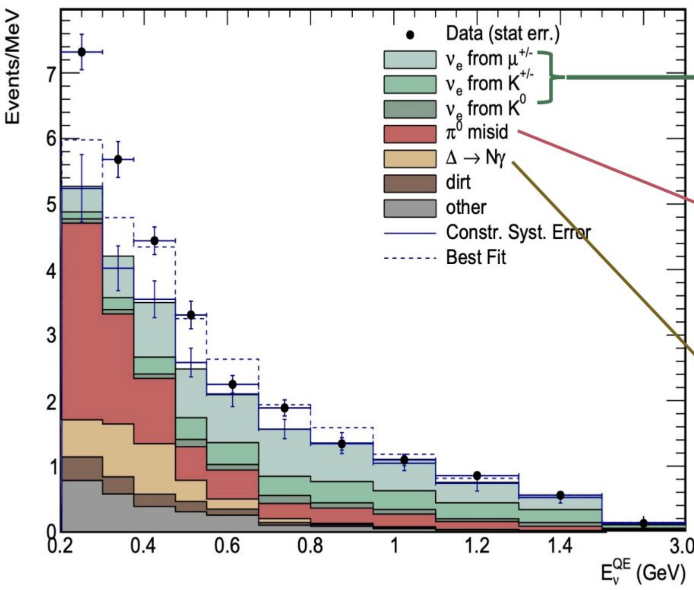

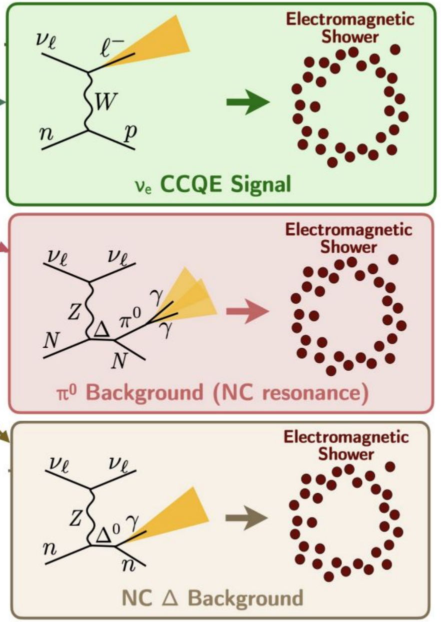

Low Energy Excess could be "electron-like" (eLEE) or "photon-like" (γLEE)

If photon-like (γLEE): could be a misunderstood background?

If electron-like (eLEE):
ν_e appearance at an L/E not consistent with standard three neutrino oscillations
→ a sterile neutrino?

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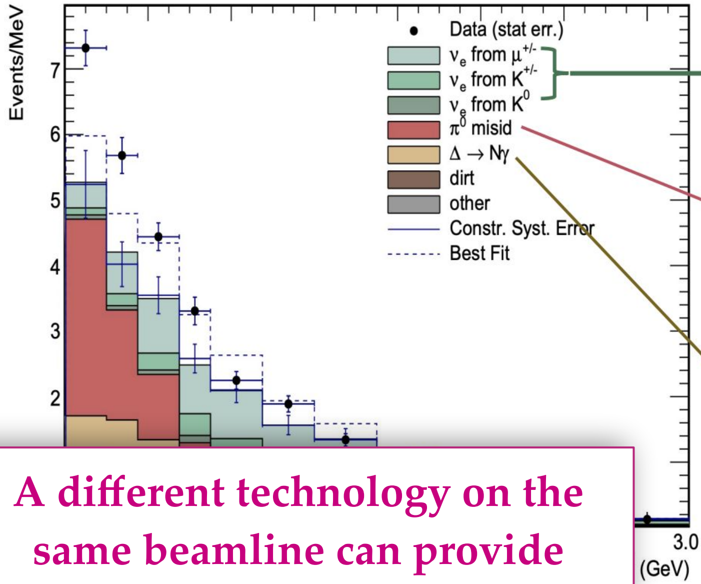

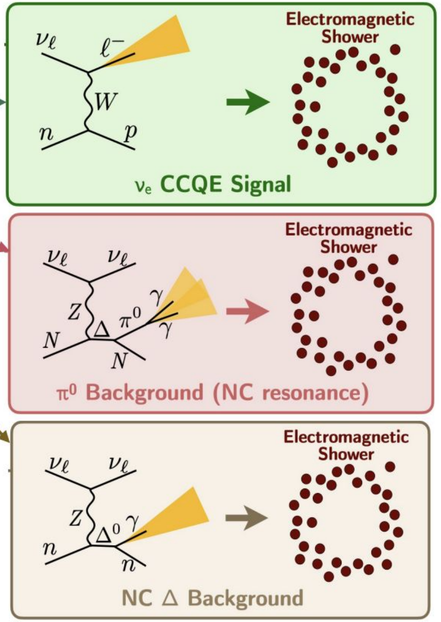

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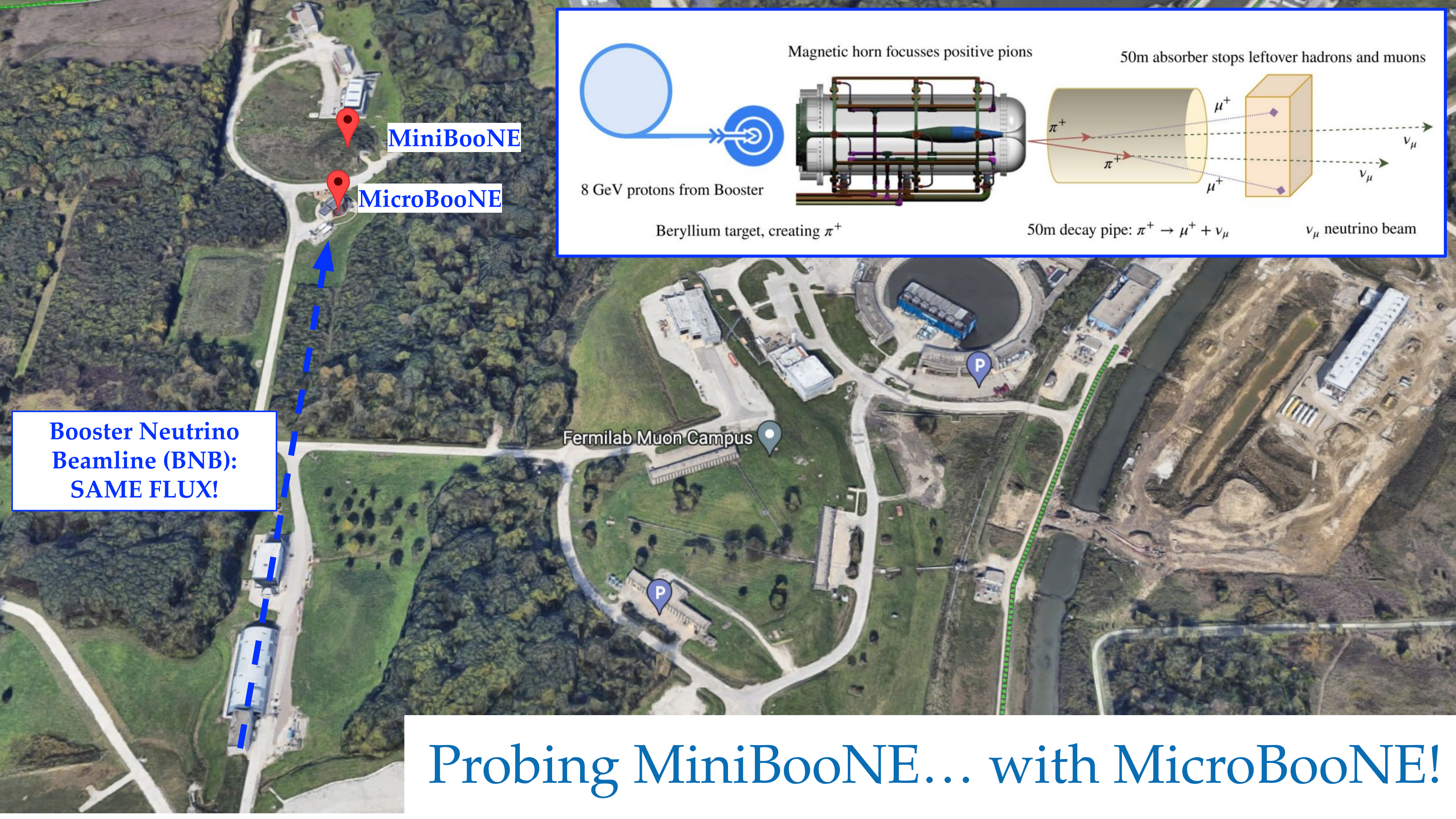
A different technology on the same beamline can provide more insights on the LEE

Probing MiniBooNE… with MicroBooNE!

Probing MiniBooNE… with MicroBooNE!



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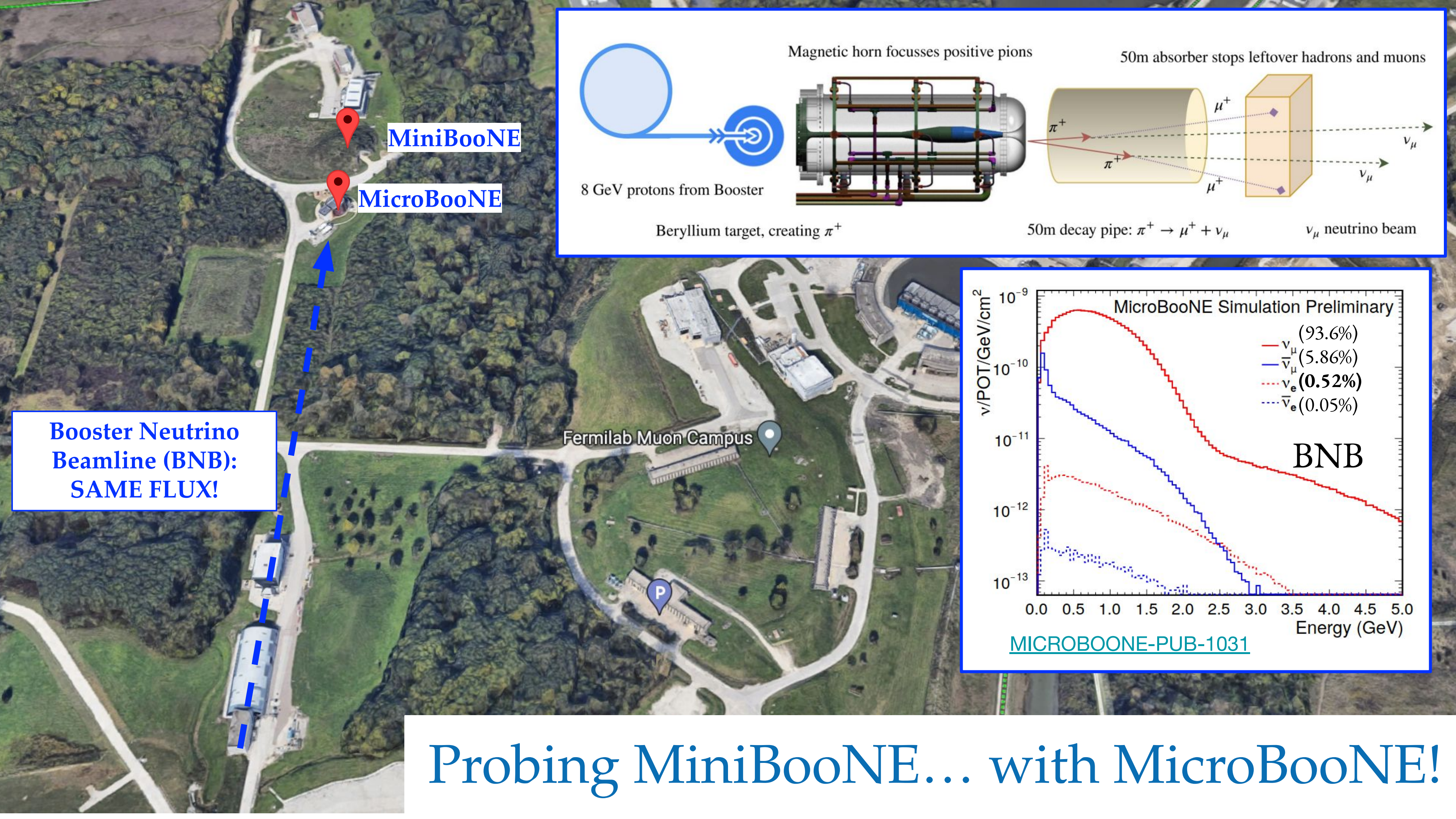

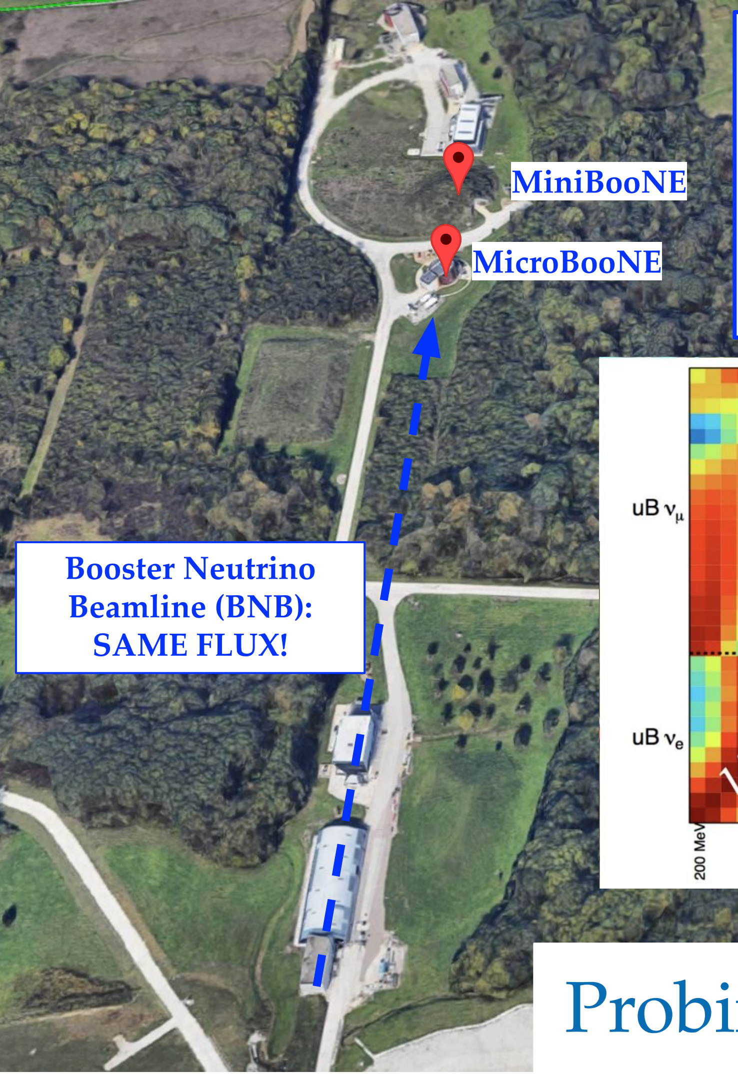

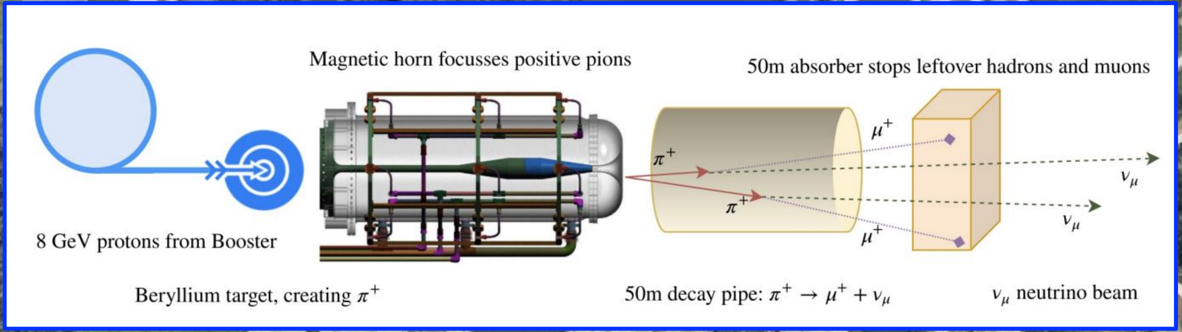

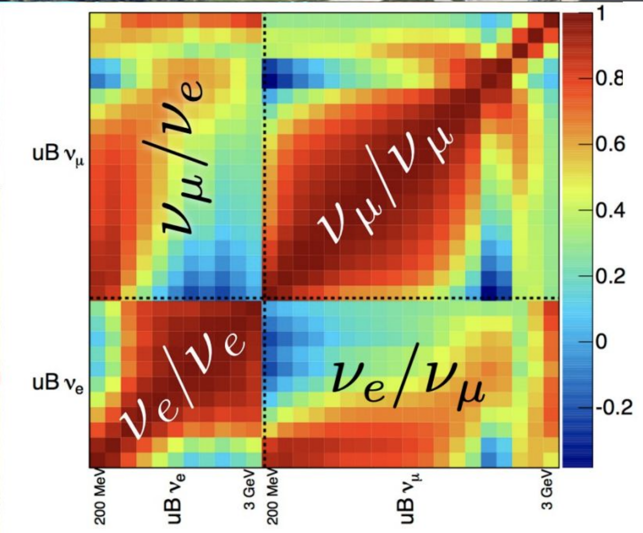

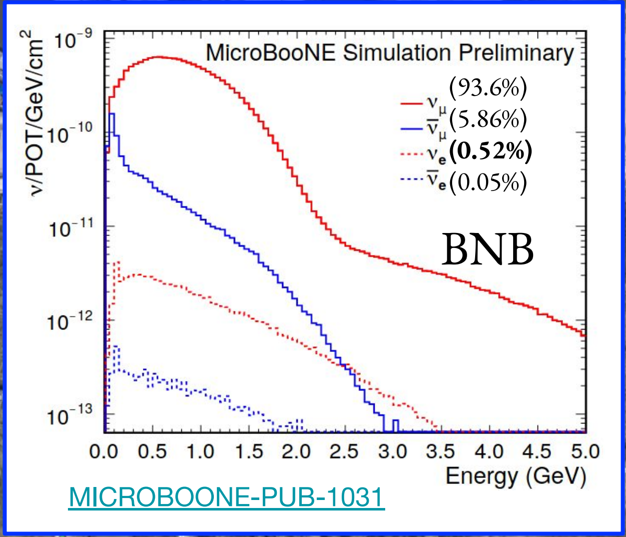

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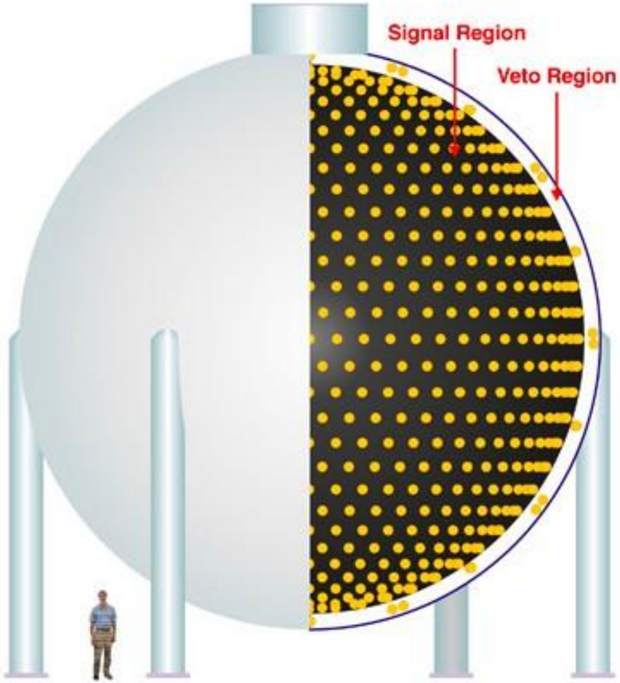
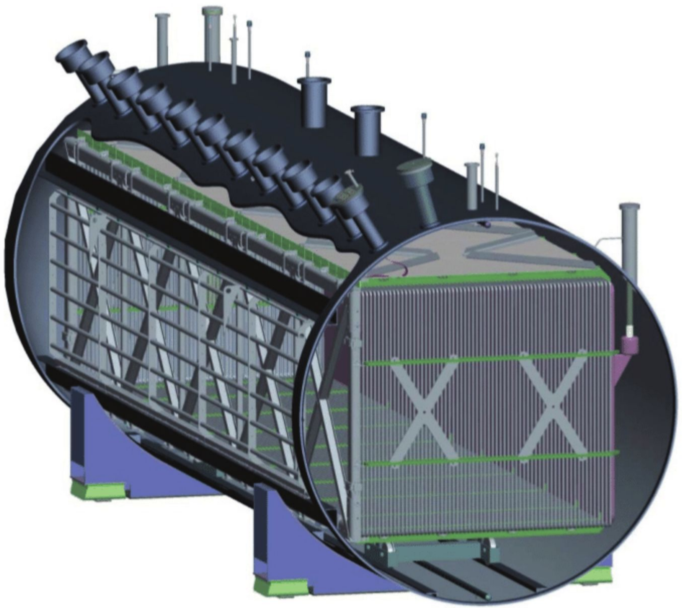
MiniBooNE



SUPERIOR
Electron-Photon
Discrimination

MicroBooNE



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Talk Roadmap

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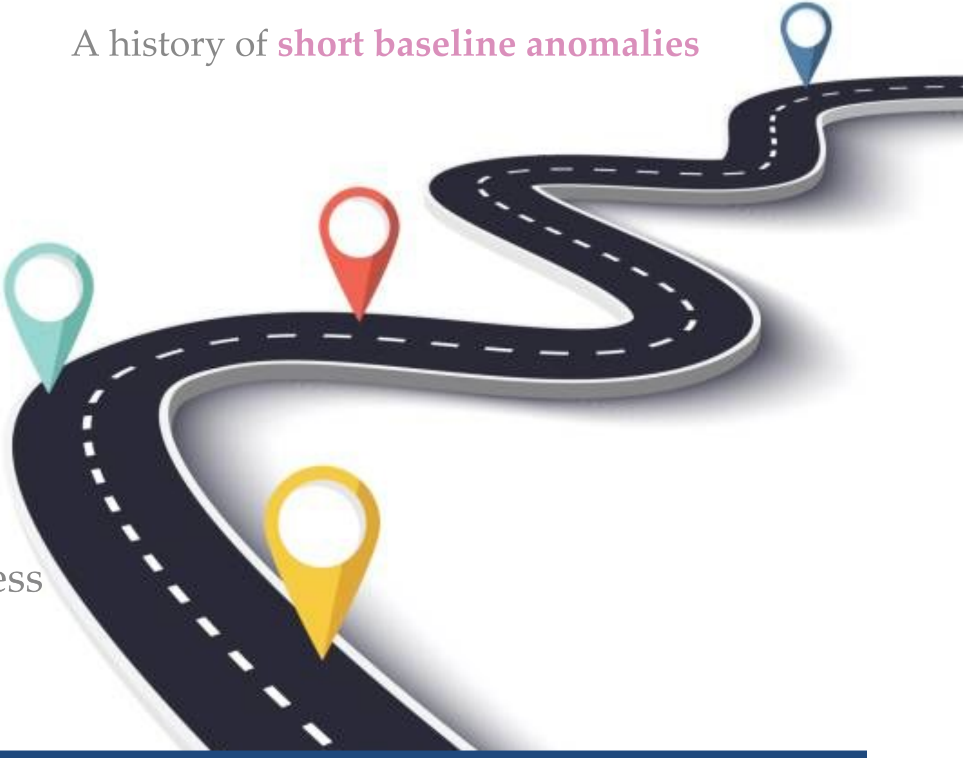

The **LArTPC technology** &
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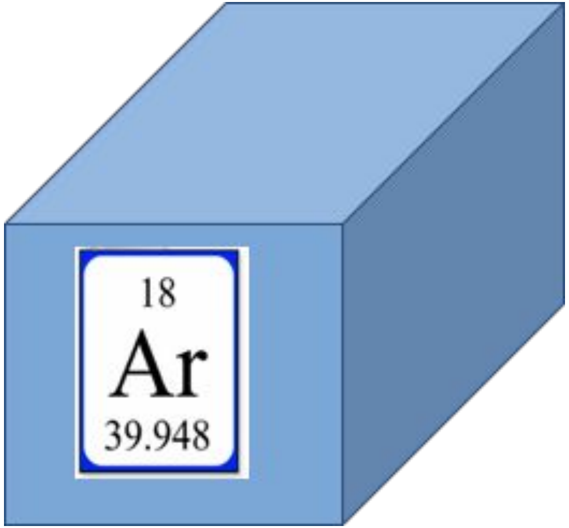
MicroBooNE Recent Results:
→ 3 complementary searches for a ν_e excess
→ the photon search

LArTPC*: a Crash Course

→ A block of Ar

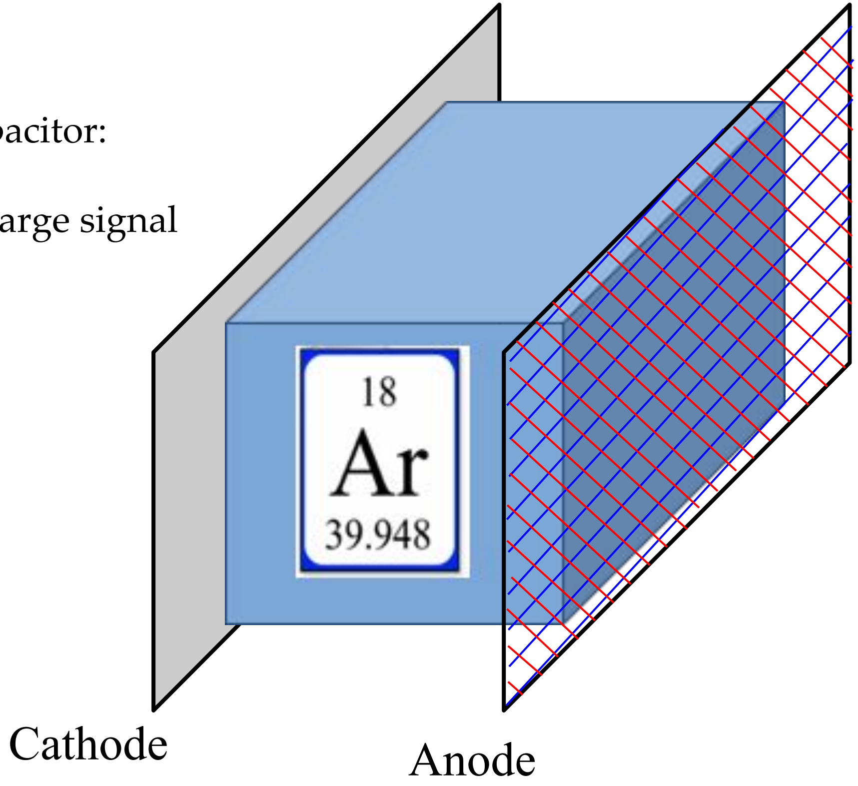


*LArTPC for ν pioneered in Italy by the ICARUS

LArTPC: a Crash Course

→ A block of Ar

→ Sandwich it in a parallel planes capacitor:
- Cathode at negative HV
- Segmented anode to see the charge signal



LArTPC: a Crash Course

→ A block of Ar

→ Sandwich it in a parallel planes capacitor:
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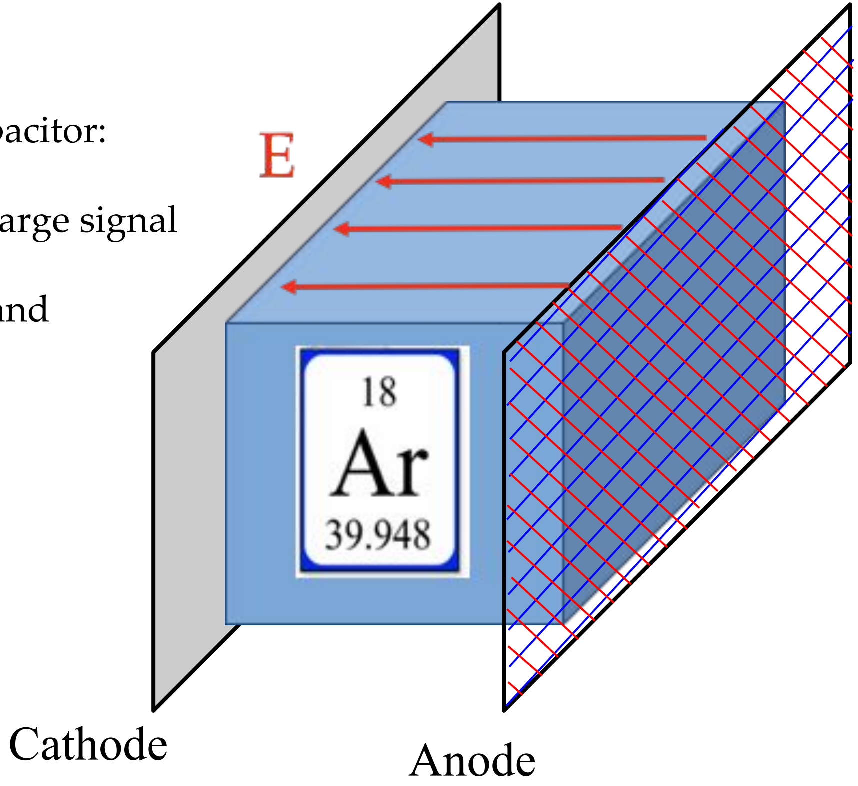
→ Create an electric field as uniform and as constant as possible



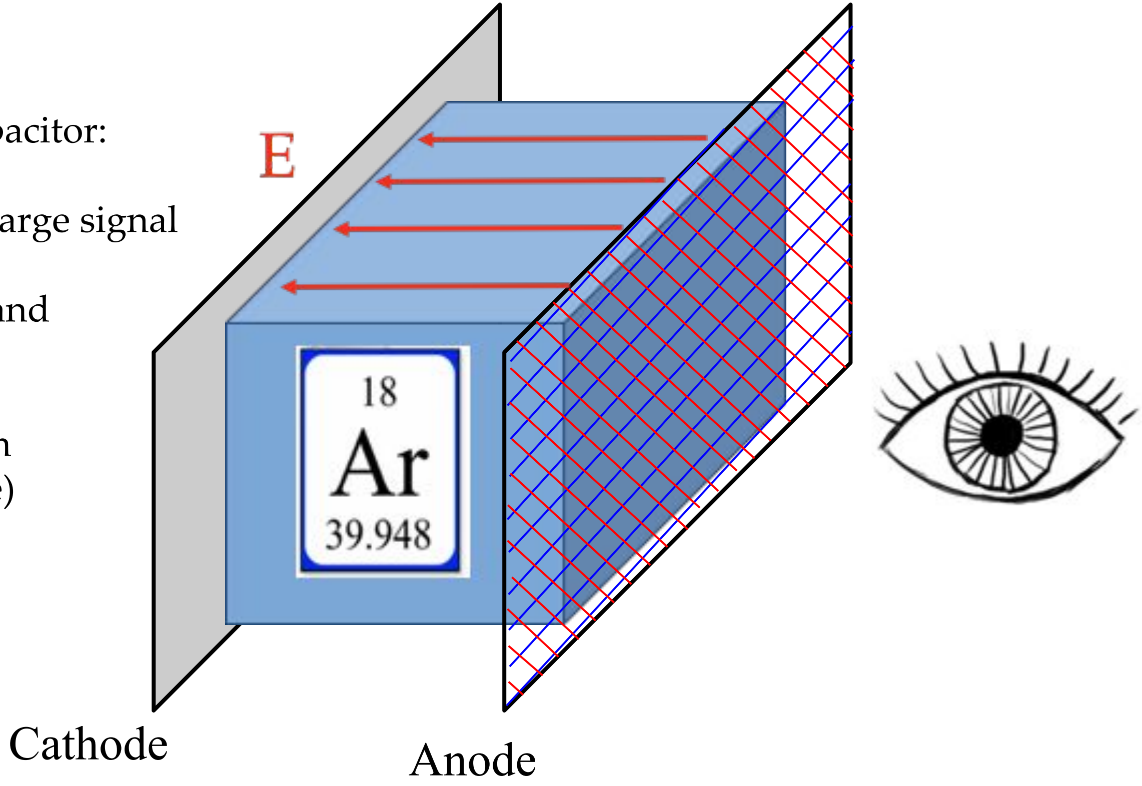
LArTPC: a Crash Course

→ A block of Ar

→ Sandwich it in a parallel planes capacitor:
- Cathode at negative HV
- Segmented anode to see the charge signal

→ Create an electric field as uniform and as constant as possible

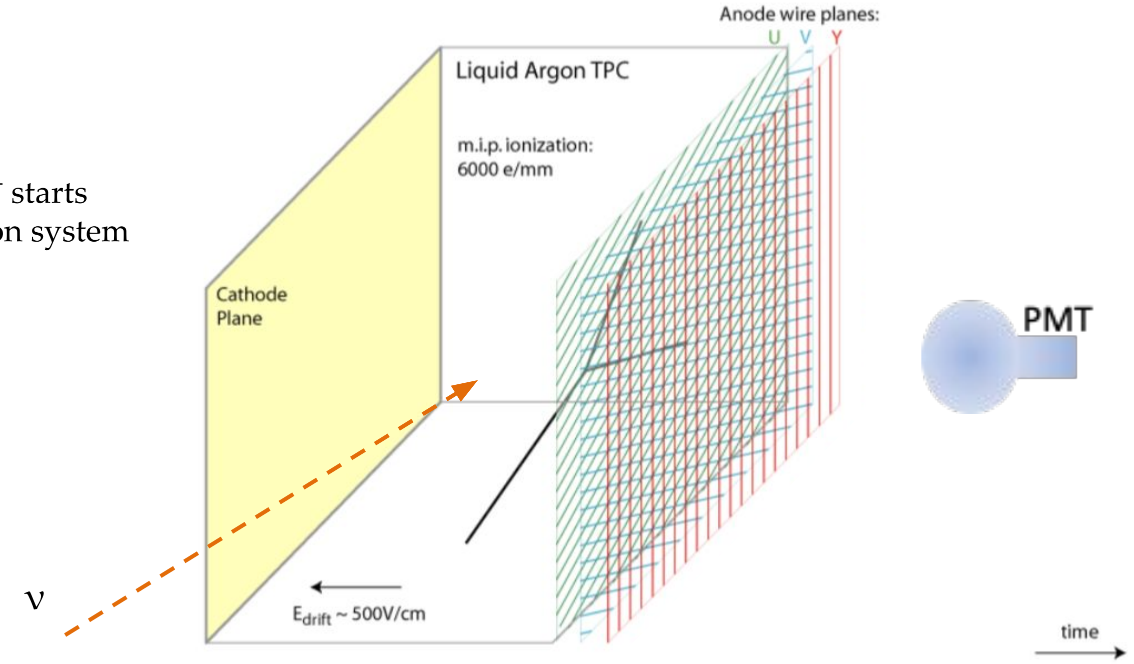
→ Equip with a light collection system (usually mounted behind the anode)



LArTPC: Working Principles

1. Energy loss by charged particles:
   Ionization and
   Excitation of Ar

2. Prompt scintillation light emission by Ar_2^+ starts clock: the light arrives to the light collection system in matter of ns



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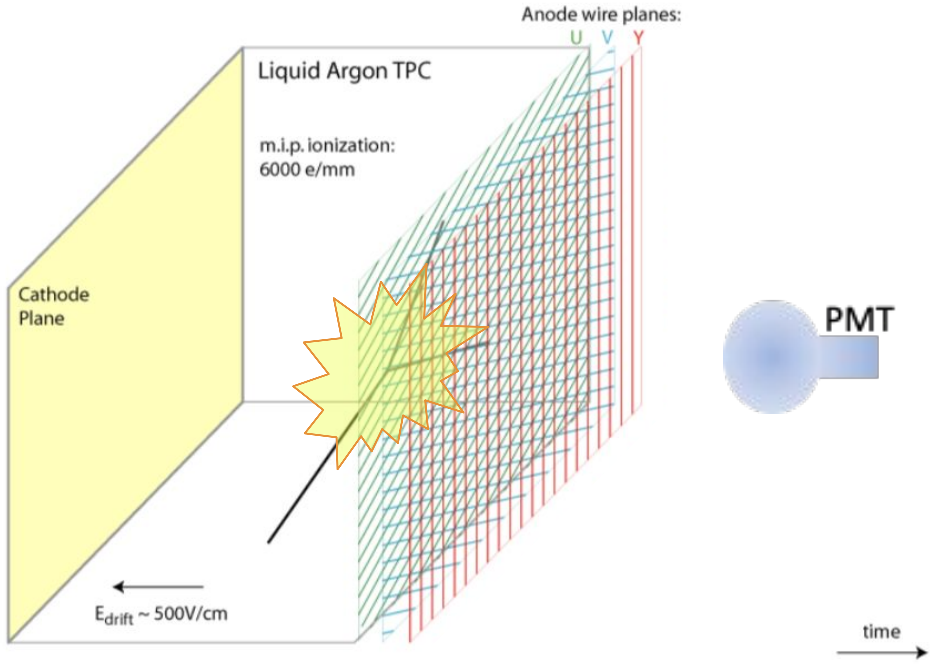


LArTPC: Working Principles

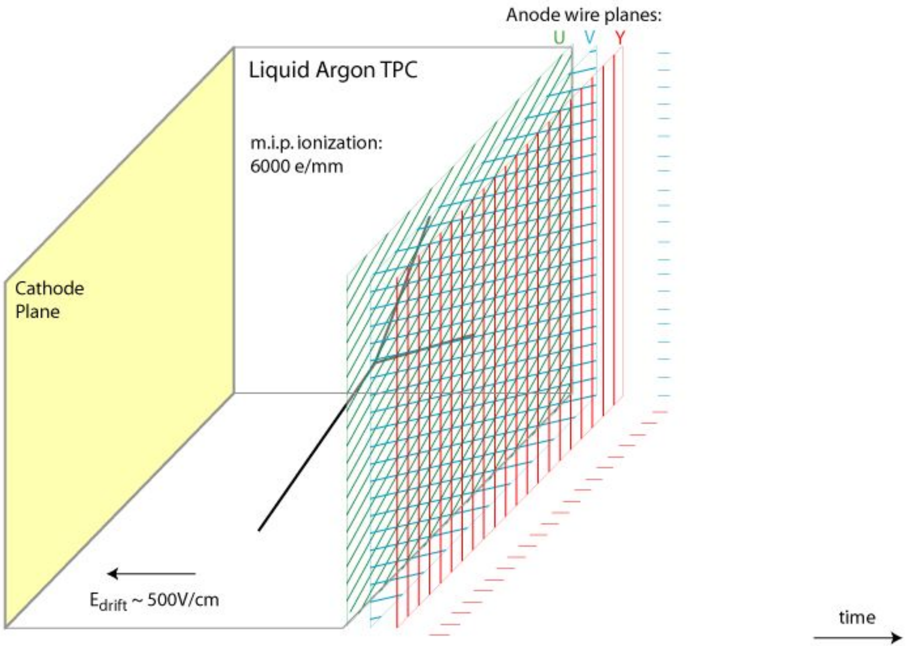
1. Energy loss by charged particles:
   Ionization and
   Excitation of Ar

2. Prompt scintillation light emission by Ar_2^+ starts clock: the light arrives to the light collection system in matter of ns

3. Electrons drift to anode: the charge arrives to the anode in matter of ms depending on detector size.
   (Ar^+ ions drift to cathode)

4. Moving electrons induce currents on wires

5. Tracks are reconstructed from wire signals and matched to recover a 3D images

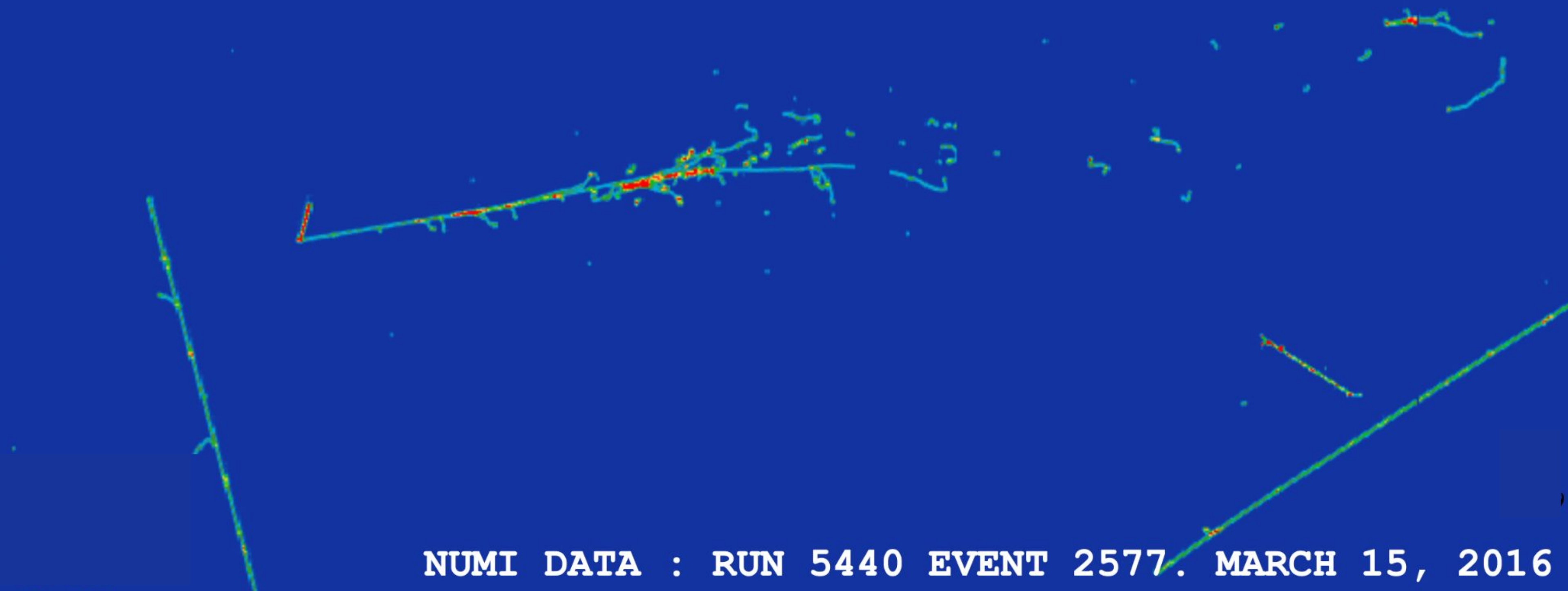


μBooNE

LArTPC in action

Extremely detailed 3D images + calorimetry + PID:

unprecedented tool for neutrino interactions & BSM physics



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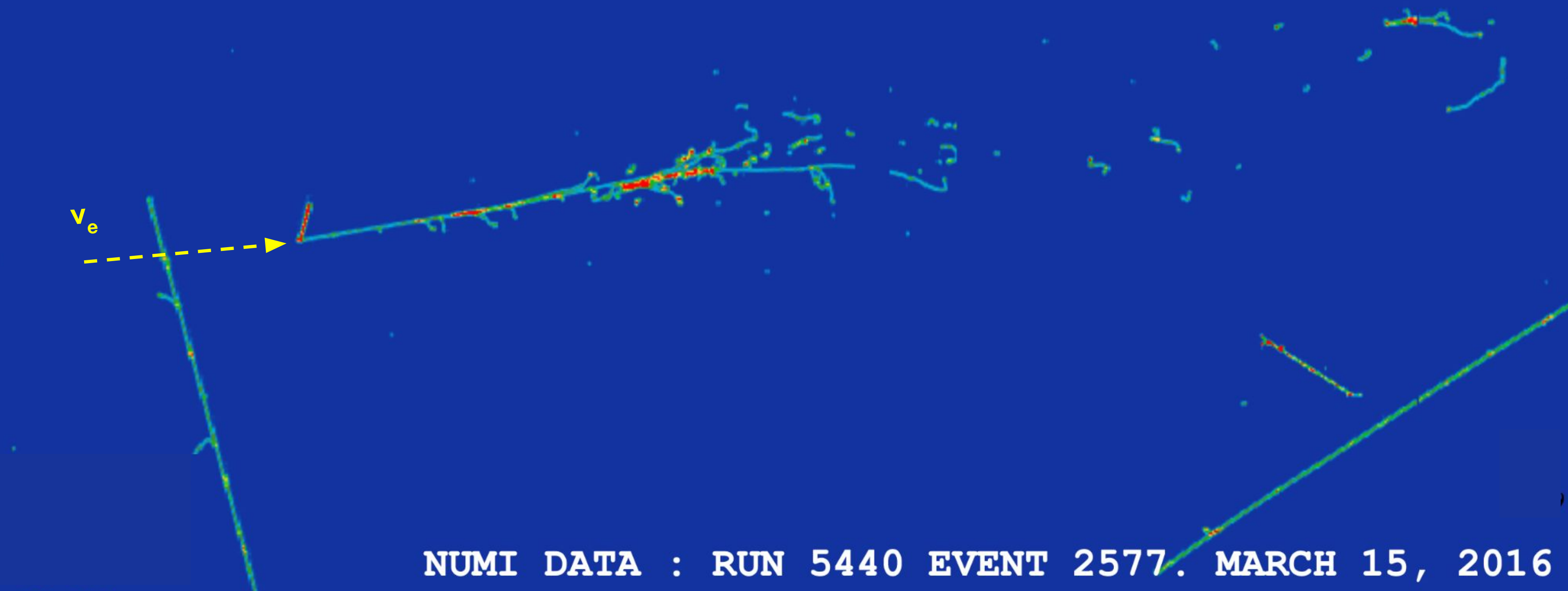

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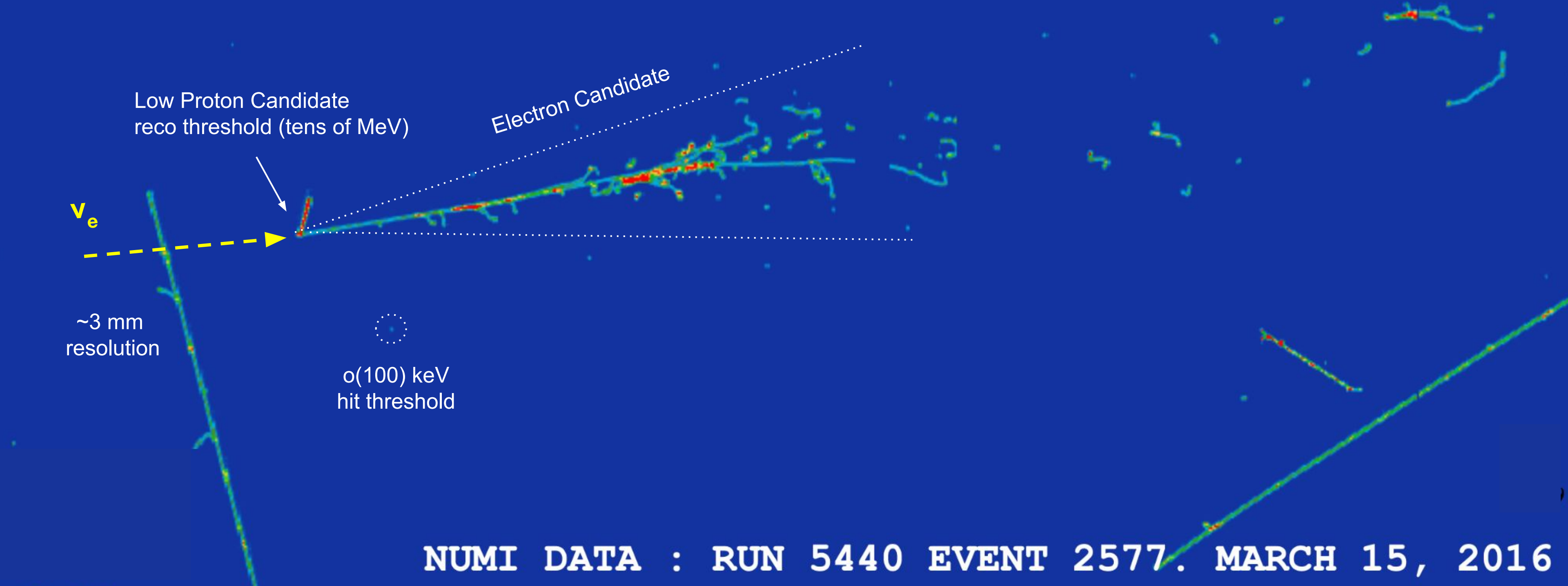

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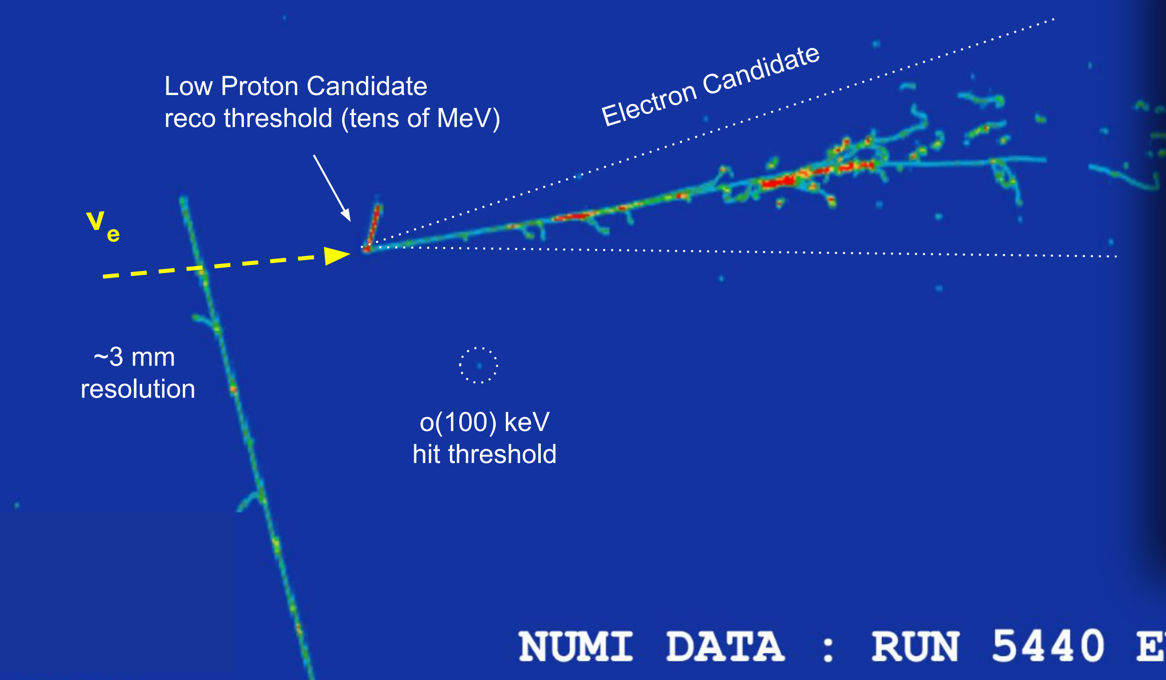
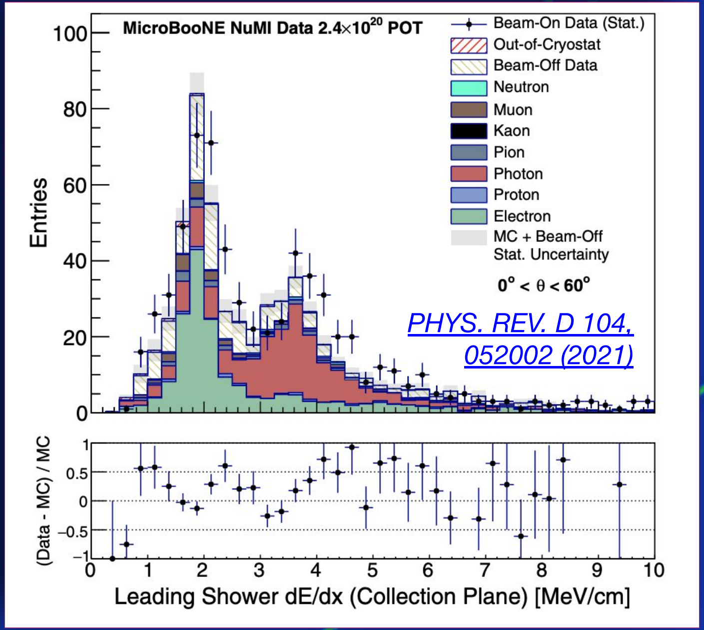
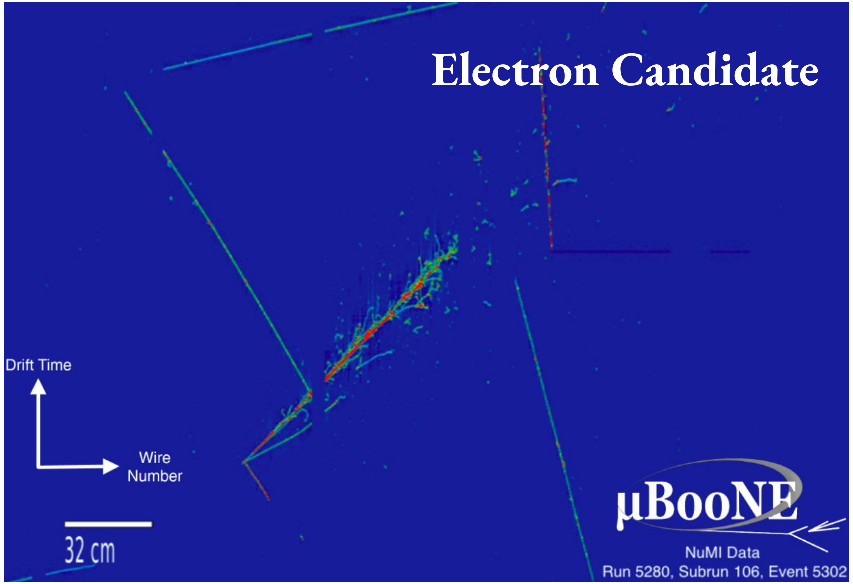
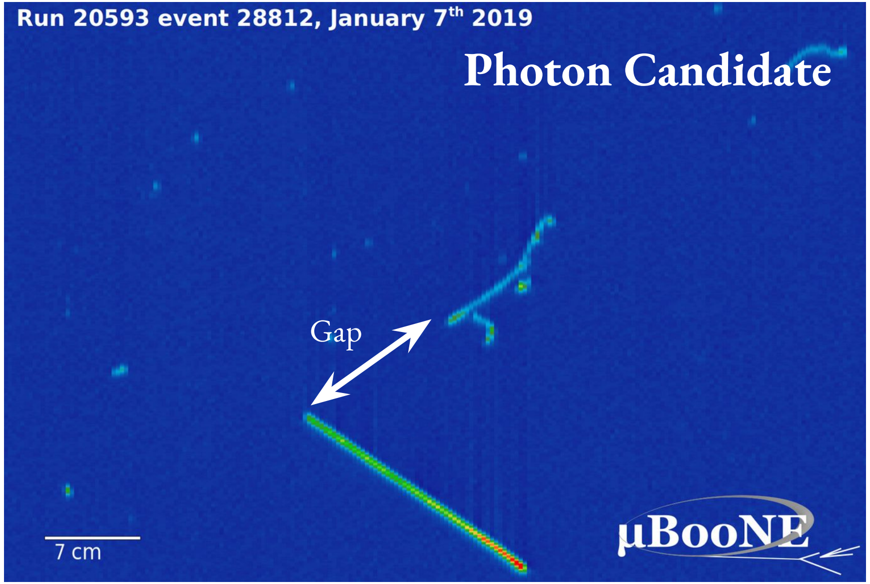




PHYS. REV. D 104, 052002 (2021)

Multiple handles to e-γ separation: topology

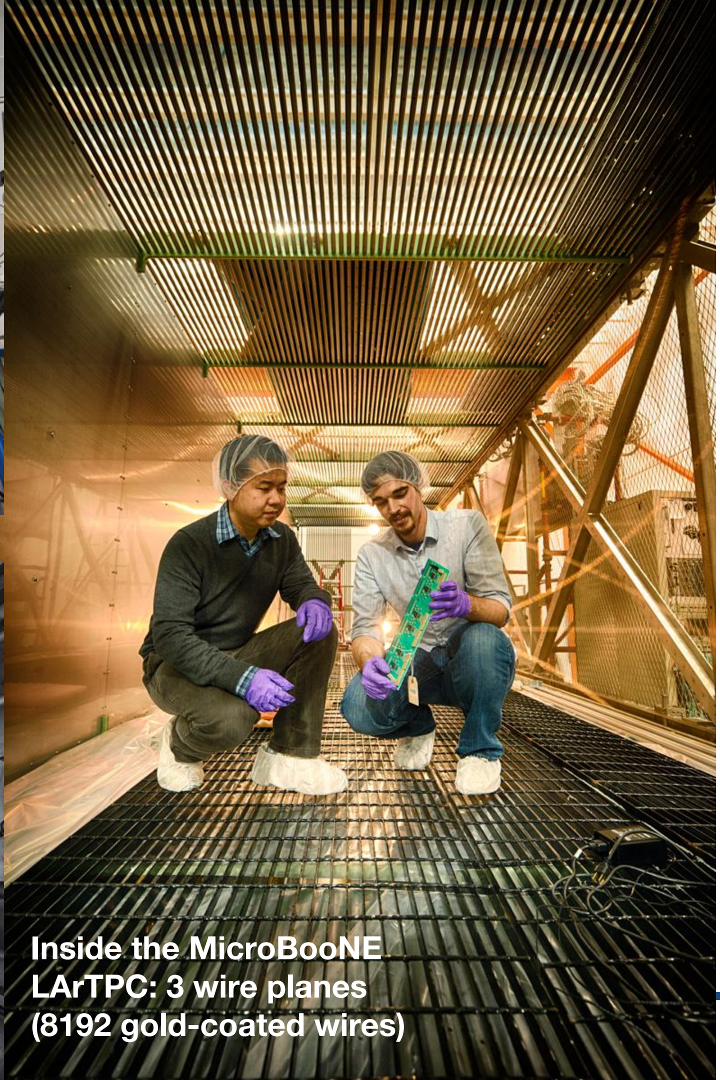




Quantified for the first time in a fully automated event reconstruction chain

[PHYS. REV. D 104, 052002 (2021)]

The MicroBooNE detector at a glance



μBooNE

Liquid Argon Time Projection Chambers!

Liquid Argon Time Projection Chambers!

Surface-based, 85 ton active volume liquid argon

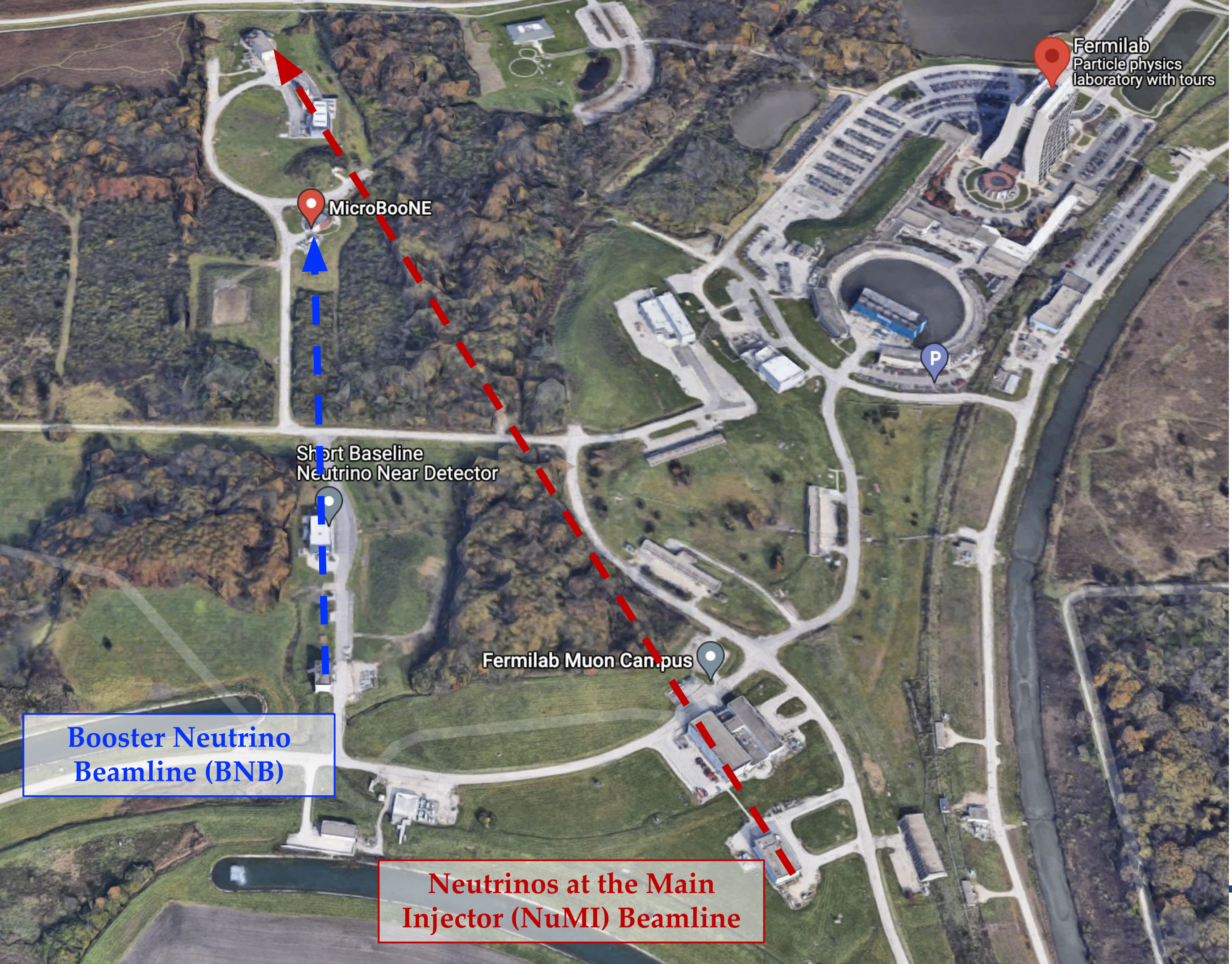
One drift chamber.

Field cage cathode held at -70 kV
UV laser calibration system

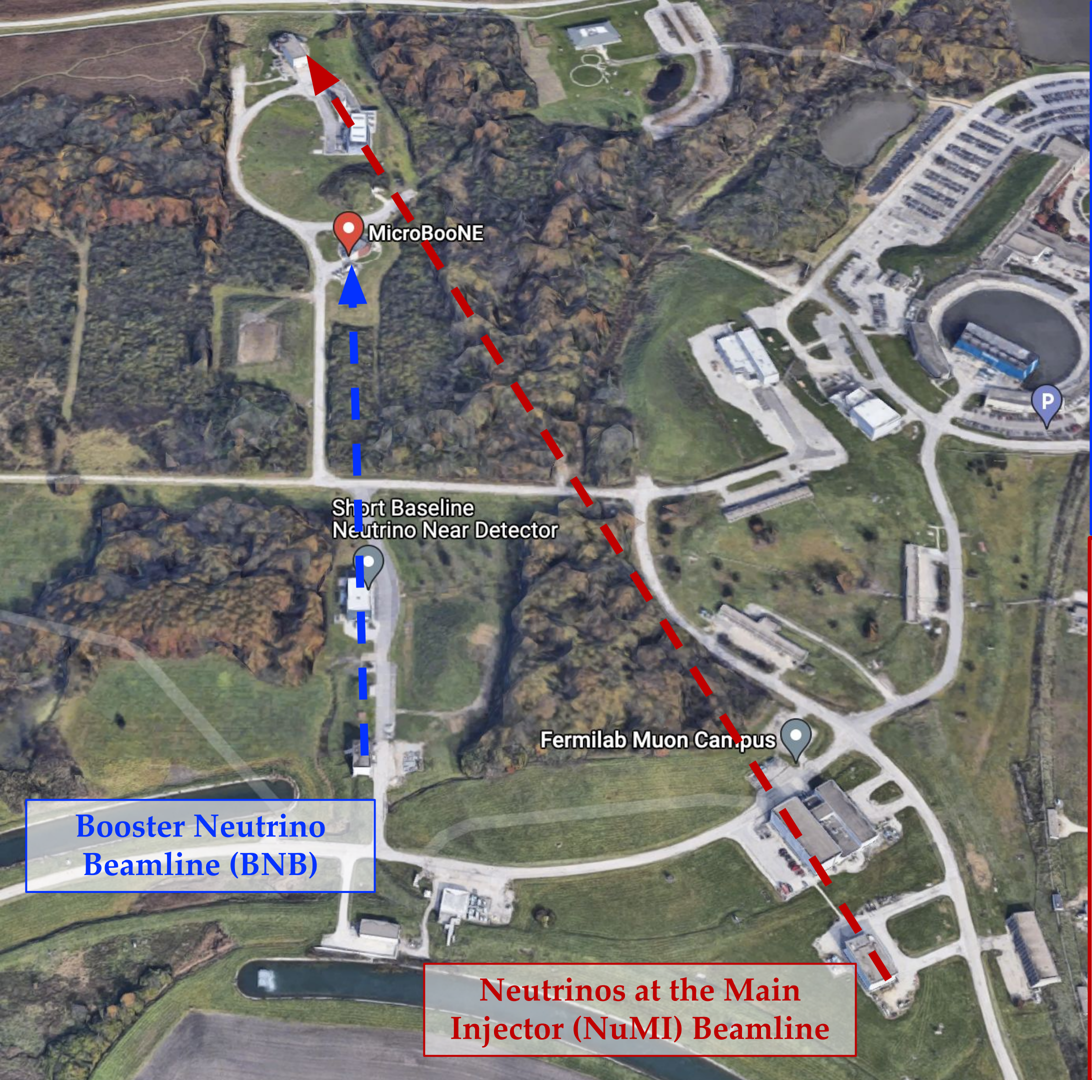
Start taking data Fall 2015

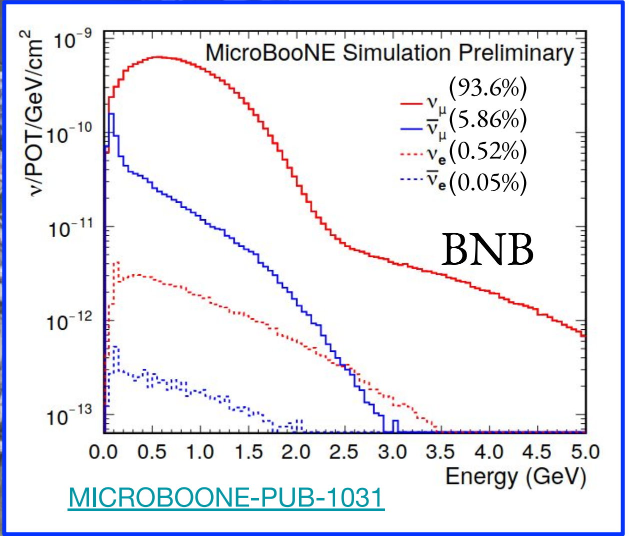
Collected the largest sample of ν-Ar interactions to date from both the FNAL beams.
5 years of physics run: completed!

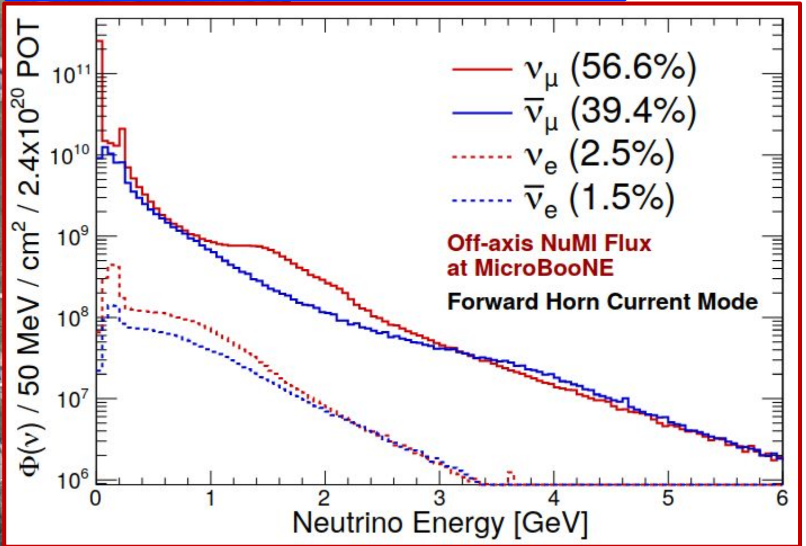
Neutrino beams @ MicroBooNE



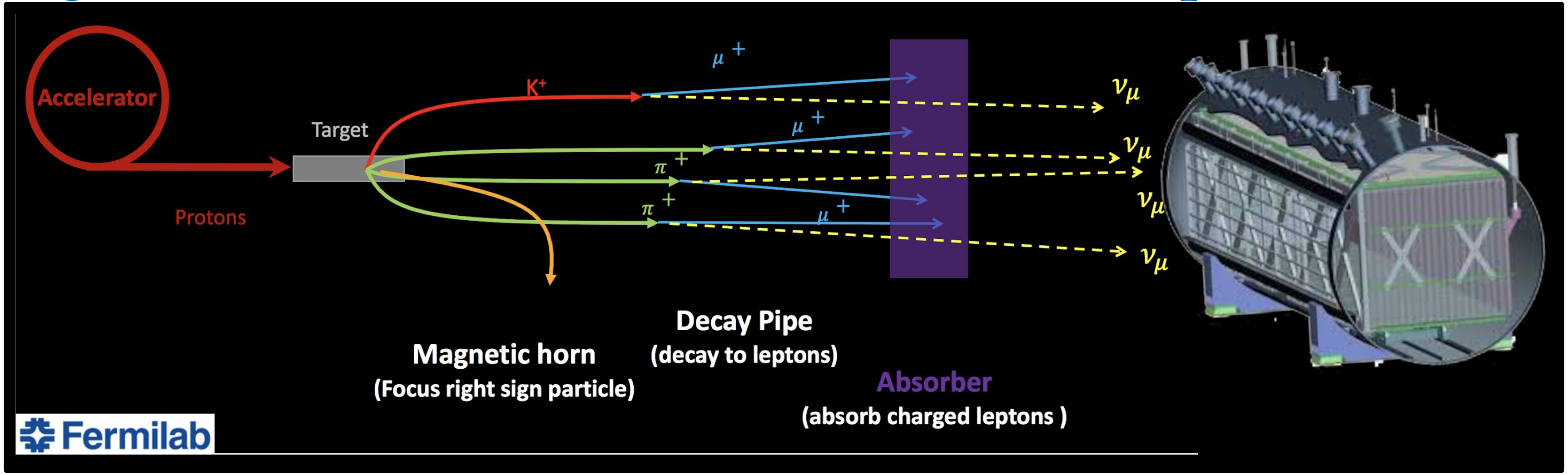
μBooNE


MicroBooNE
Short Baseline
Neutrino Near Detector
Fermilab Muon Campus
Booster Neutrino Beamline (BNB)
Neutrinos at the Main Injector (NuMI) Beamline


MicroBooNE Simulation Preliminary
ν_μ (93.6%)
$\bar{\nu}_\mu$ (5.86%)
ν_e (0.52%)
$\bar{\nu}_e$ (0.05%)
BNB
ν/POT/GeV/cm²
Energy (GeV)
MICROBOONE-PUB-1031

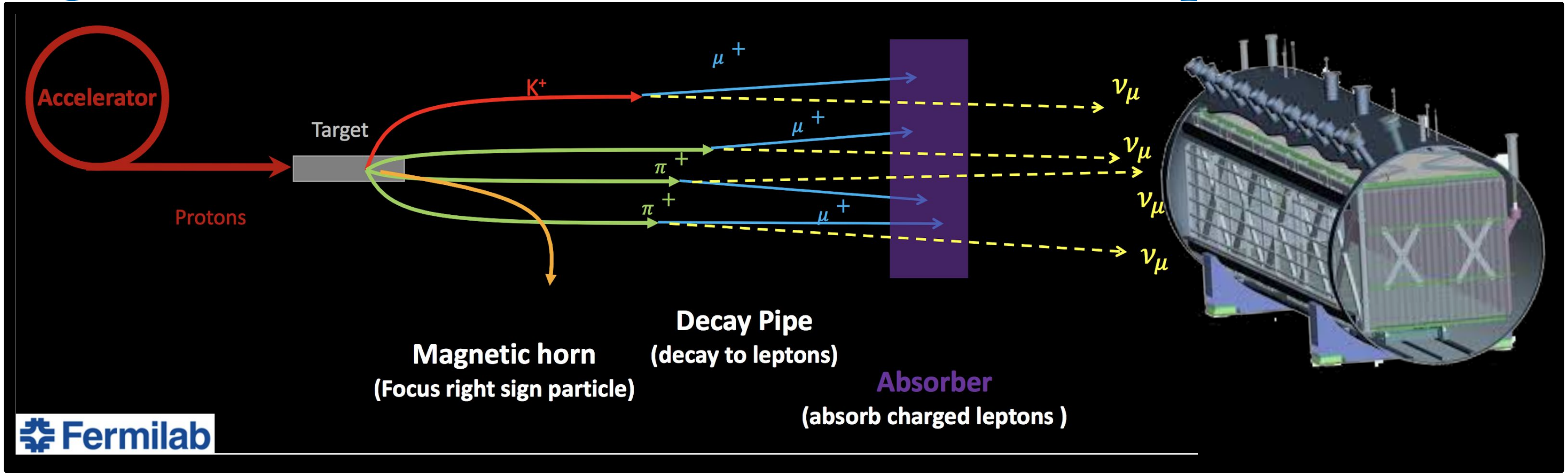

ν_μ (56.6%)
$\bar{\nu}_\mu$ (39.4%)
ν_e (2.5%)
$\bar{\nu}_e$ (1.5%)
Off-axis NuMI Flux
at MicroBooNE
Forward Horn Current Mode
Φ(ν) / 50 MeV / cm² / 2.4x10²⁰ POT
Neutrino Energy [GeV]

Ingredients for a successful on-beam ν experiment



1. Know your neutrino flux → MICROBOONE-NOTE-1031-PUB
2. Know your detector → JINST 15, P03022 (2020) (and many more)
3. Know how neutrinos interact → Tuned interaction model + XS measurements

Ingredients for a successful on-beam ν experiment



1. Know your neutrino flux → MICROBOONE-NOTE-1031-PUB
2. Know your detector → JINST 15, P03022 (2020) (and many more)
3. **Know how neutrinos interact → Tuned interaction model + XS measurements**

The nucleus is a complex system…

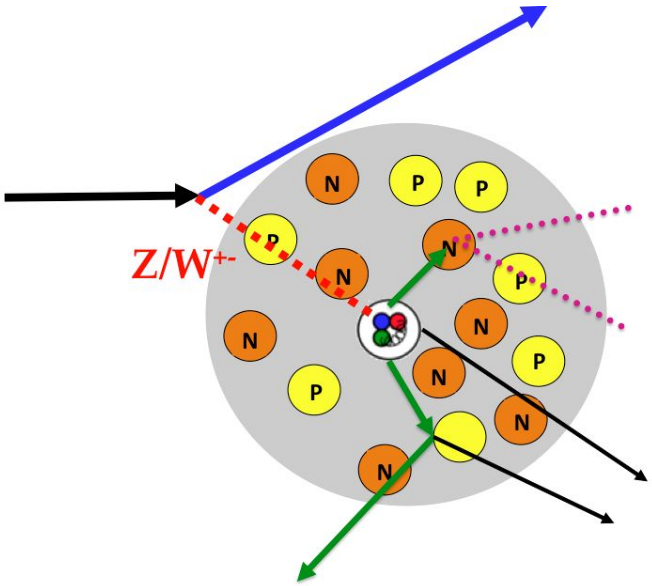
Signal-Background Migration

The nucleon is not at rest!
Fermi Motion must be modeled.

Strongly interacting nucleons
→ alteration of electroweak couplings (modeled w/RPA)

Interactions with correlated pair of nucleons:
→ Meson Exchange Current (**MEC**)
→ Short Range Correlations

Final State Interactions
→ re-interactions of the ν products within the nuclear medium



Significant uncertainty in ν_e/ν_μ CC cross section models due to limited experimental data in argon at low energy ~200MeV

The nucleus is a complex system…

Signal-Background Migration

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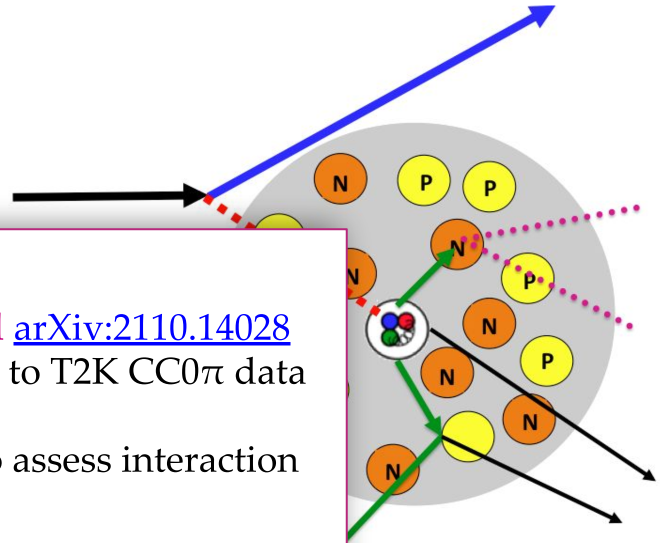
Strongly
→ altera
coupl

Interacti
→ Meso
→ Short

Final St
→ re-interactions of the ν products
within the nuclear medium

Improved neutrino interaction model [arXiv:2110.14028](https://arxiv.org/abs/2110.14028)
"Theory-driven" CCQE & MEC tuned to T2K CC0π data

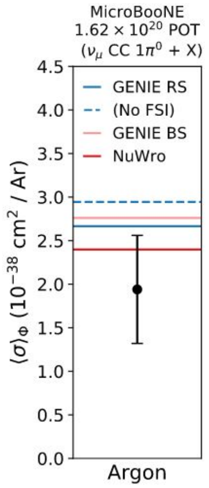
More than **50 parameters** are varied to assess interaction uncertainties.



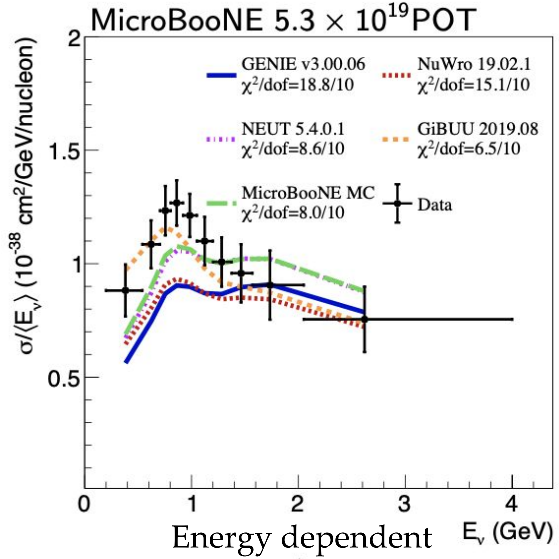
Significant uncertainty in ν_e/ν_μ CC cross section models due to limited experimental data in argon at low energy ~200MeV

… so we measure our own cross sections!

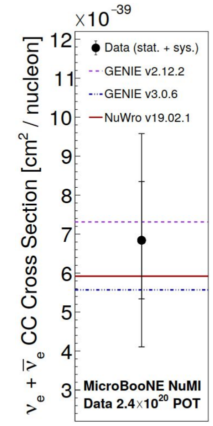
High statistics ν-Ar cross-section measurements targeting many interaction kinematics and final states, using both beams: the BNB to test ν_μ and NuMI to test ν_e



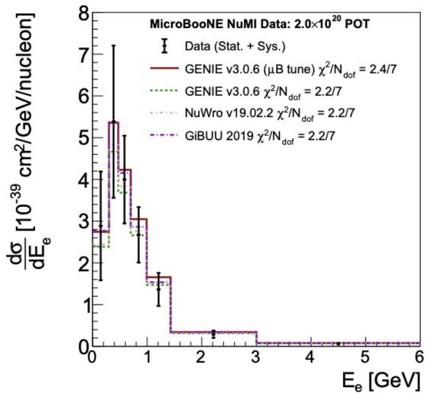
ν_μCC π^0 production
Phys. Rev. D99, 091102(R) (2019)



Energy dependent
ν_μCC inclusive
Phys.Rev.Lett. 128 (2022) 15

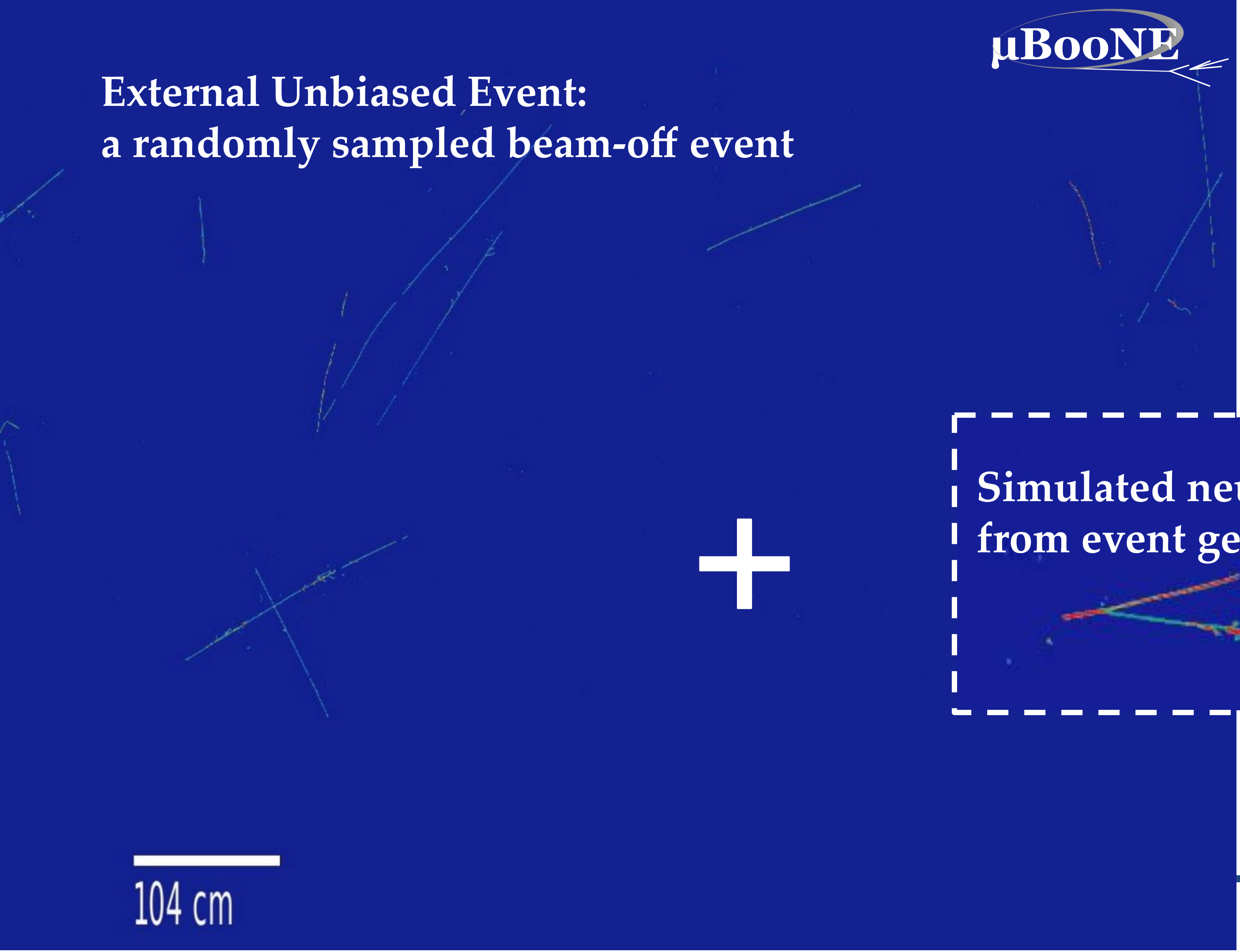


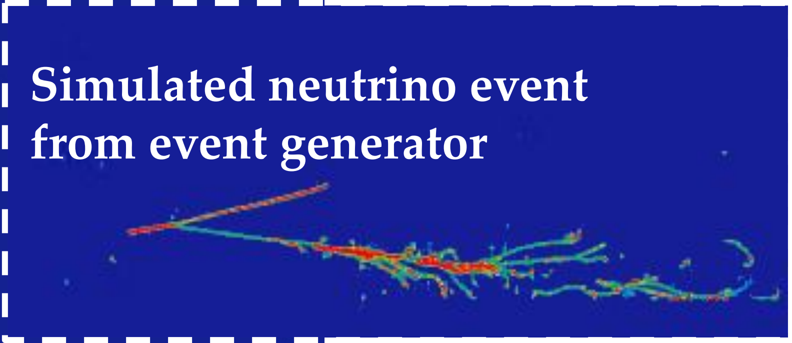
Flux Averaged
Inclusive ν_e+ν_eBar
Phys. Rev. D.104.052002

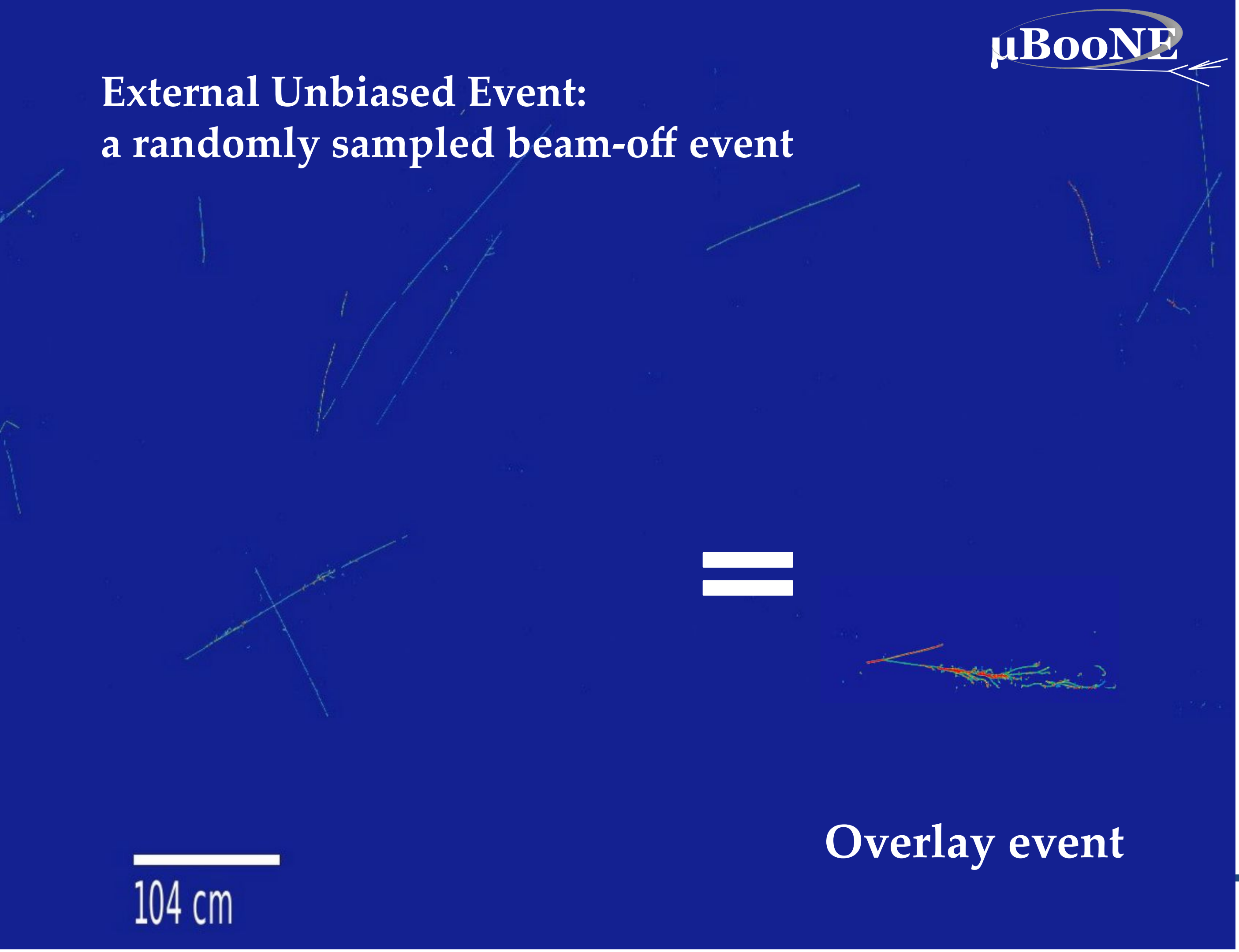


Inclusive ν_e + ν_eBar CC
differential
in energy and angle.
Phys. Rev. D 105, L051102

Data-Driven techniques to abate systematics







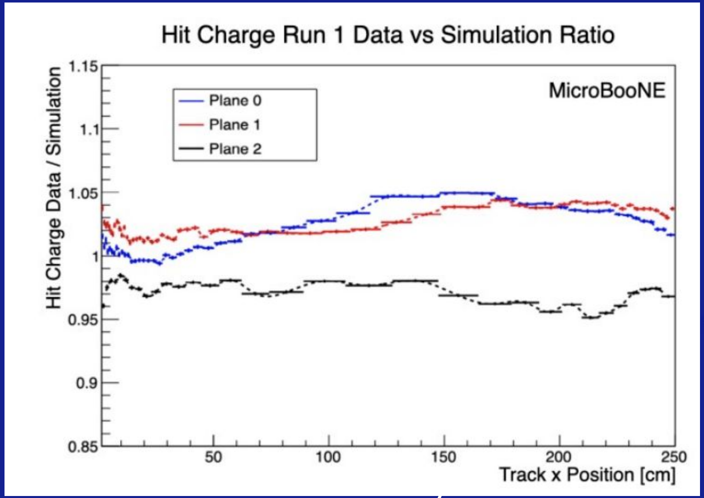
Data-Driven techniques to abate systematics

Each simulated waveform from a PMT channel or a TPC wire is added to the signal from the correlated channel in the cosmic data.

Reliable representation of cosmic background & noise models: **it's data**!

Data-Driven techniques to abate systematics

External Unbiased Event: a randomly sampled beam-off event

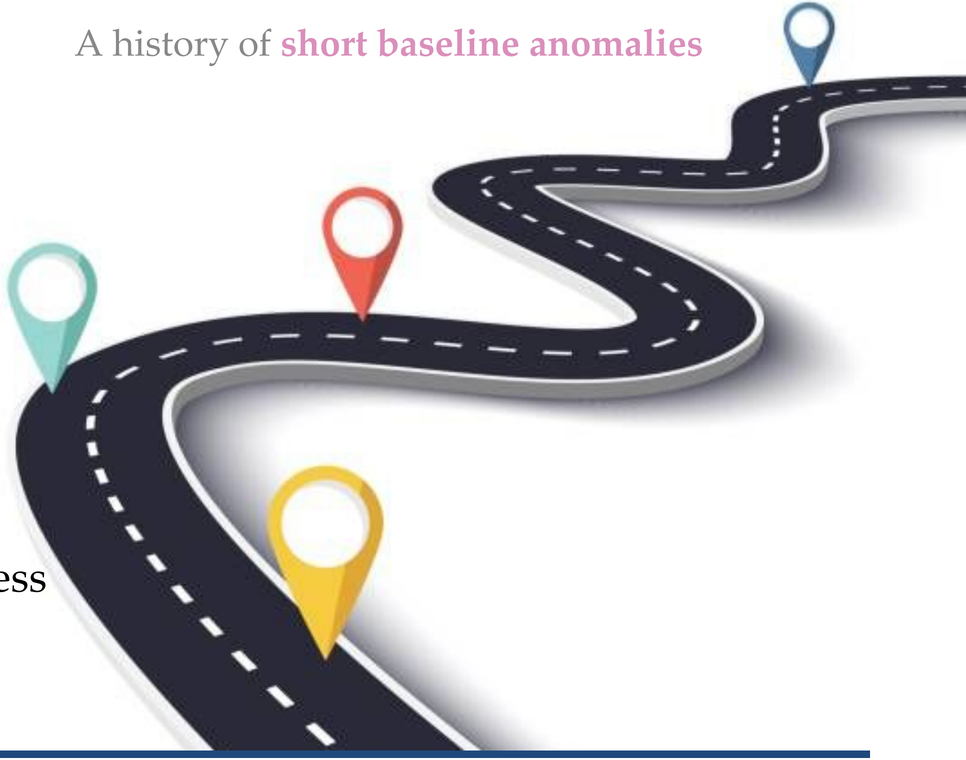


Detector systematics evaluated with a novel method to capture data/MC differences at the waveform level as a function of different kinematic variables.

Talk Roadmap

A history of **short baseline anomalies**

The **LArTPC technology** &
the **MicroBooNE** experiment



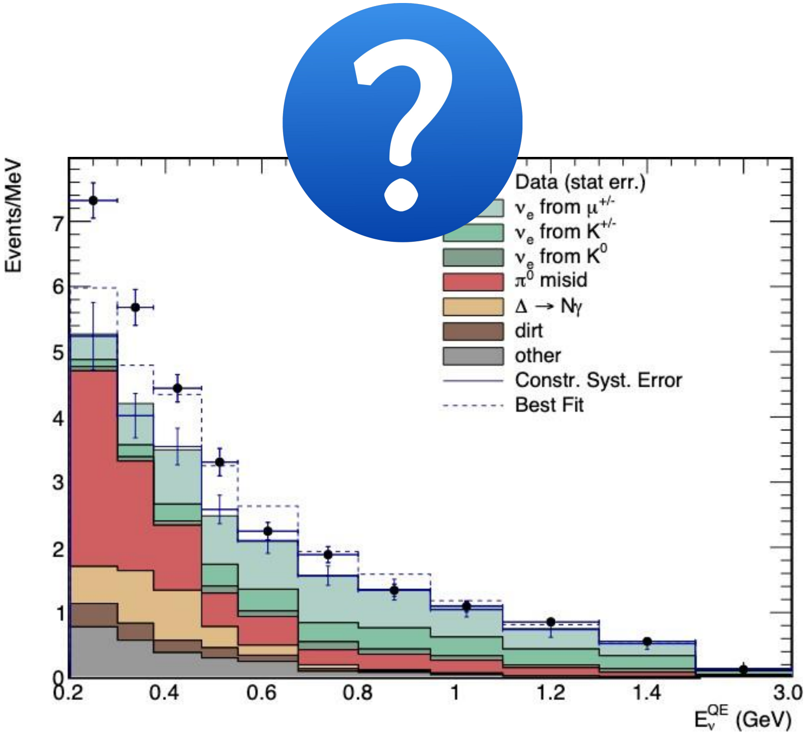
MicroBooNE Recent Results:
→ 3 complementary searches for a ν_e excess
→ the photon search

The core question: what's the MiniBooNE LEE?

The Electron Path

Excess of ν_e due oscillations through sterile neutrinos.

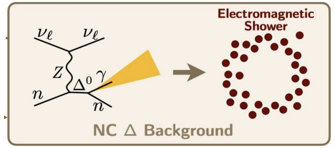
The LArTPC technology allows to probe many more final states compared to MiniBooNE.



The Photon Path

Mismodeled background?

NC π^0 rate & dirt backgrounds constrained in-situ, but…
NC Δ process never experimentally measured, just constrained by T2K and NOMAD: x3.18 higher XS can explain excess



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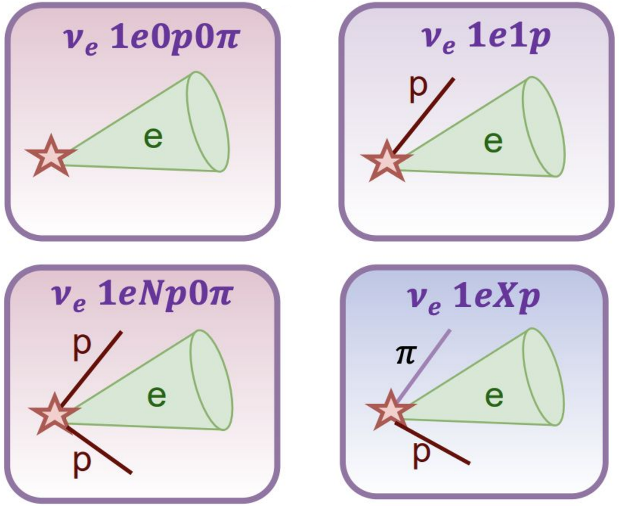
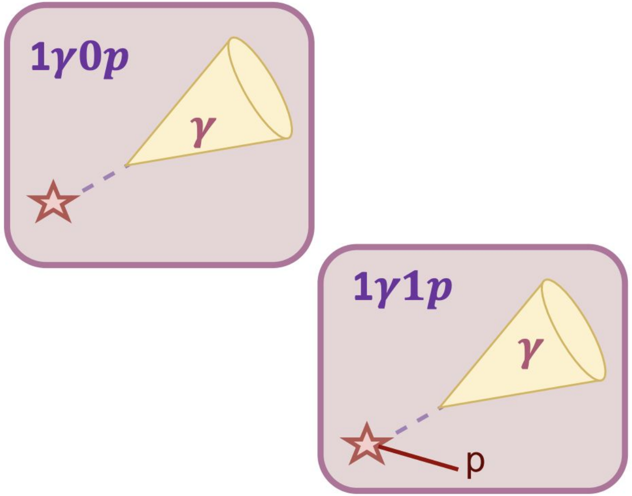
The Electron Path



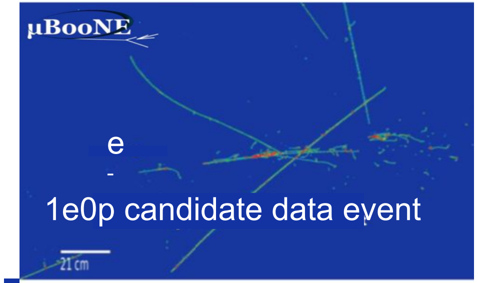
The Photon Path

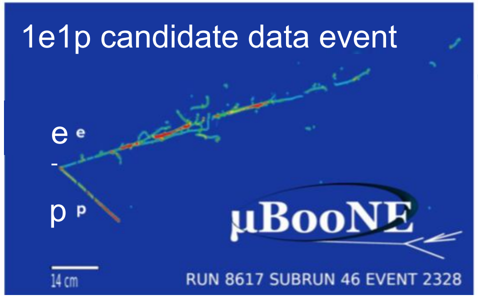


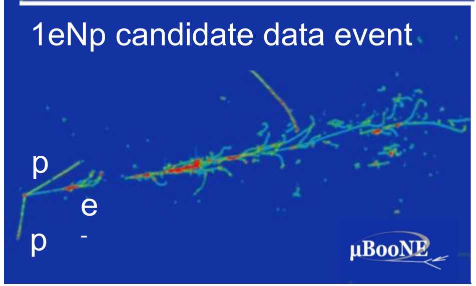
What would the LEE look like in μB?

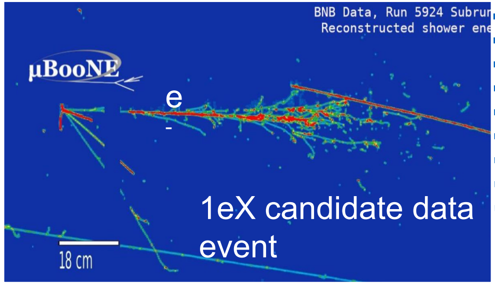
The Electron Path

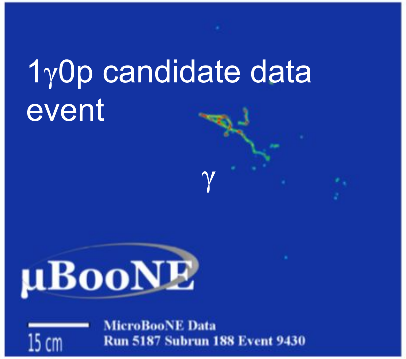
The Photon Path

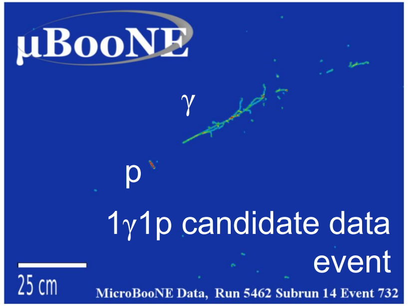












Signal Model: how should we model it?

The Electron Path

The Photon Path

Signal Model: how should we model it?

The Electron Path

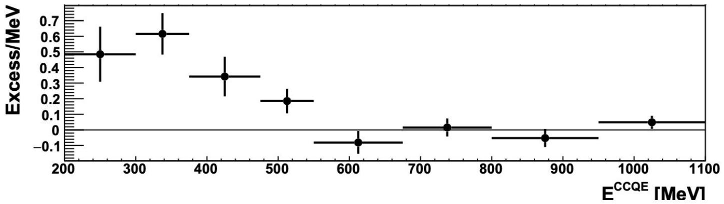
For our **first search**, we used an **empirical model of the excess**: cover a number of literatures explanations of the MiniBooNE observation.

MICROBOONE-NOTE-1043-PUB

The Photon Path

Signal Model: how should we model it?

The Electron Path

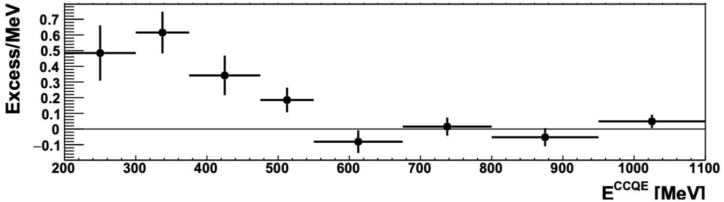


The Photon Path

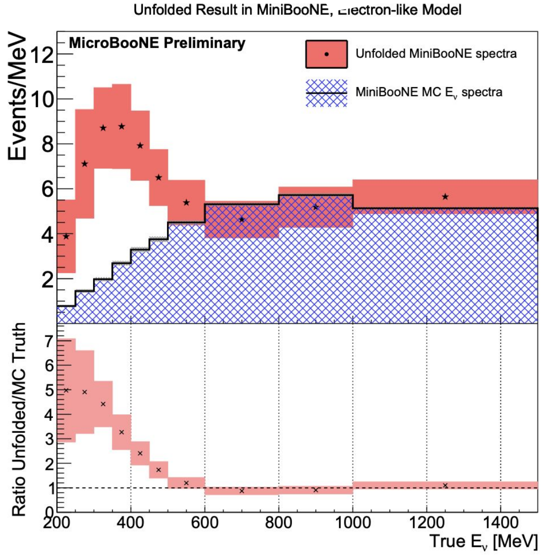
1) Take background subtracted excess of data events in MiniBooNE

Signal Model: how should we model it?

The Electron Path

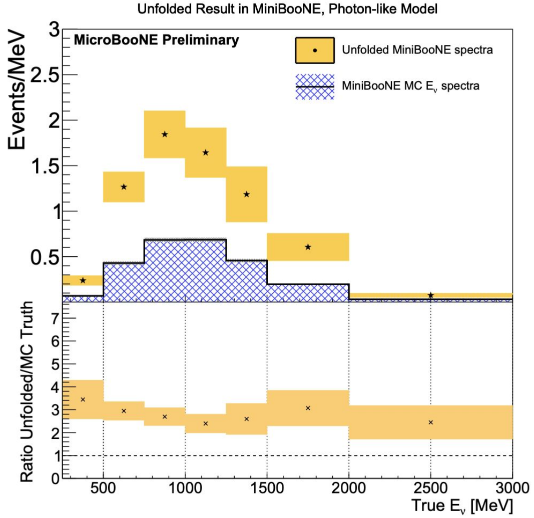


The Photon Path



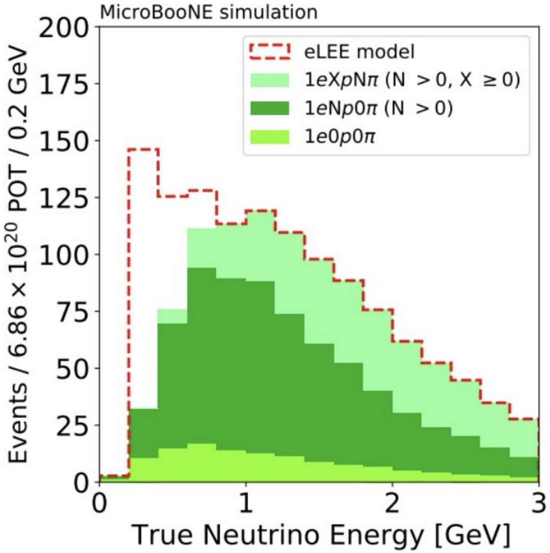
2) Assume excess is **intrinsic ν_e** & unfold to true energy

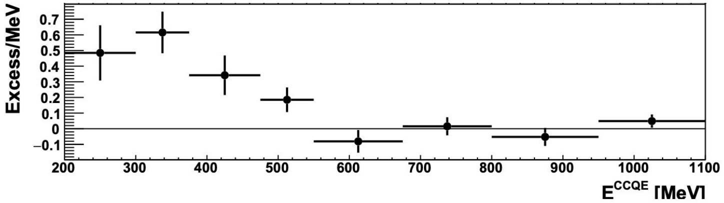
2) Assume excess is **$\Delta \rightarrow N\gamma$** & unfold to true energy



Signal Model: how should we model it?

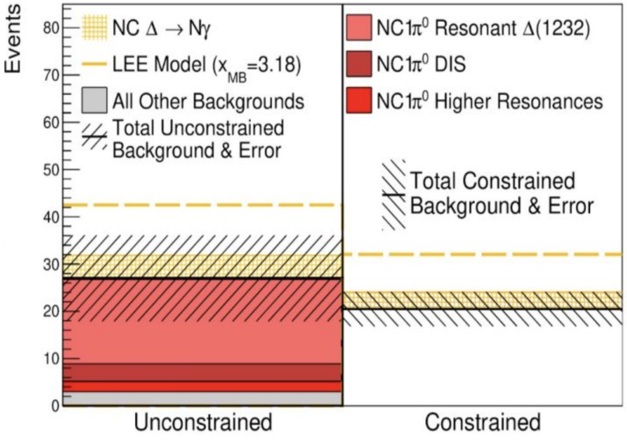
The Electron Path





3) Test MicroBooNE analyses against this benchmark signal

The Photon Path



A common strategy for multiple analyses

ν-ID/cosmic rejection

e or γ
ID

p, π tagging
μ rejection

Event selection +
sidebands

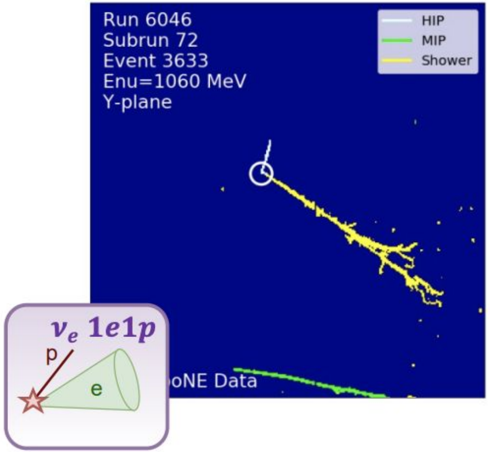
Constraint of
systematics

Results & Statistical
Interpretation

The Electron Path: 3 complementary analyses

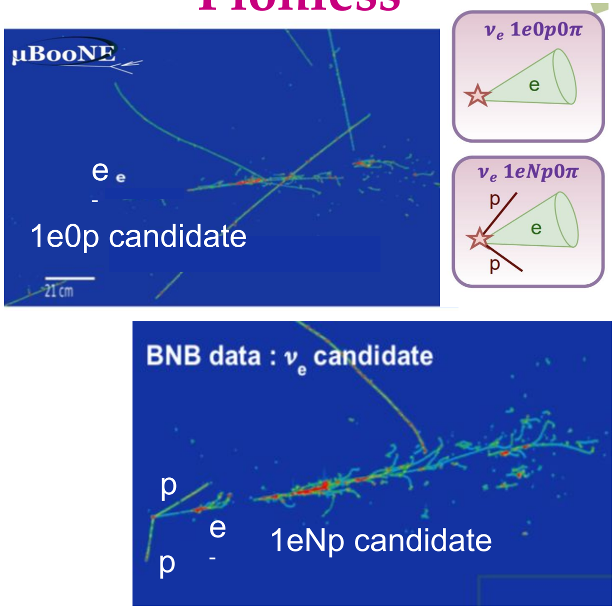
3 distinct signal definitions & 3 event reconstruction paradigms

CC-QE Like



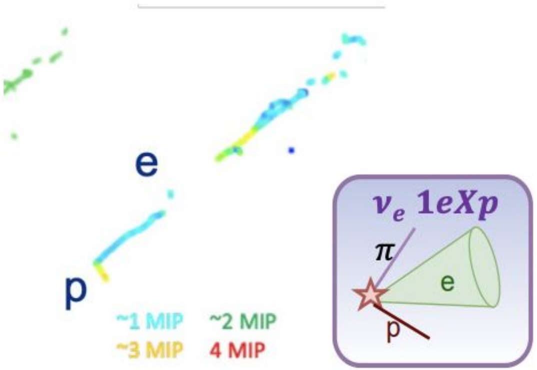
Deep Learning

Pionless



Pandora

Inclusive

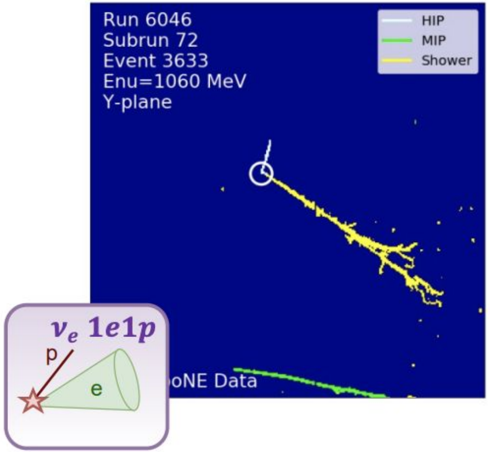


WireCell

The Electron Path: 3 complementary analyses

3 distinct signal definitions & 3 event reconstruction paradigms

CC-QE Like



Deep Learning

Use **Convolutional Neural Net** to label tracks and showers from input pixel image → Pioneering technique in LAr!

Targets **high purity of CCQE signal selection**:
the main interaction component at energy

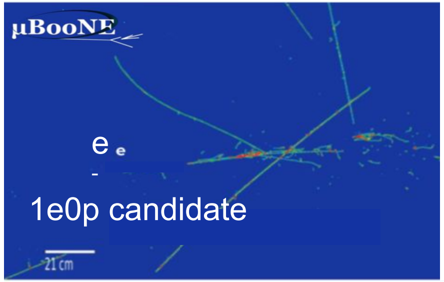
Constraint the selected events to be kinematically consistent with two-body scattering
→ reduction in systematics from interaction modeling

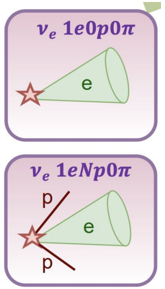
The Electron Path: 3 complementary analyses

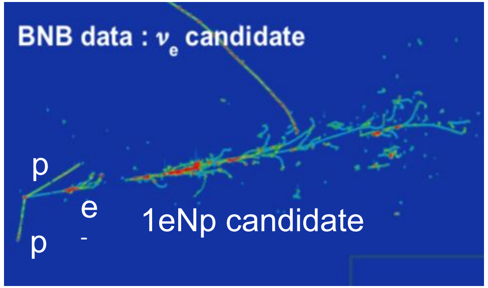
3 distinct signal definitions & 3 event reconstruction paradigms

Use **pattern recognition in 2D** to build 3D reconstruction of interaction, **leverage hit-based calorimetry**.

Pionless







Pandora

Focus on measuring ν_e **topologies also observed by MiniBooNE**: all events without visible pions.

1eNp is most sensitive to empirical model, while 1e0p mitigate uncertainties related to proton multiplicity, kinematics, and reconstruction.

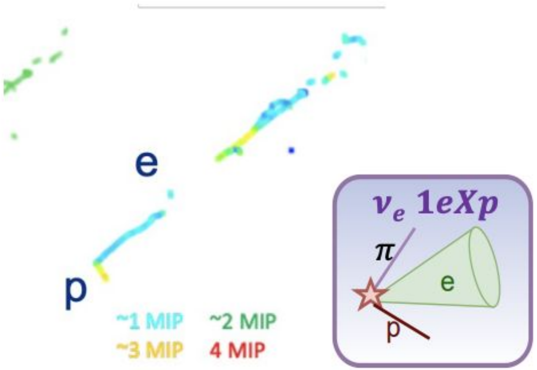
The Electron Path: 3 complementary analyses

3 distinct signal definitions & 3 event reconstruction paradigms

Inclusive

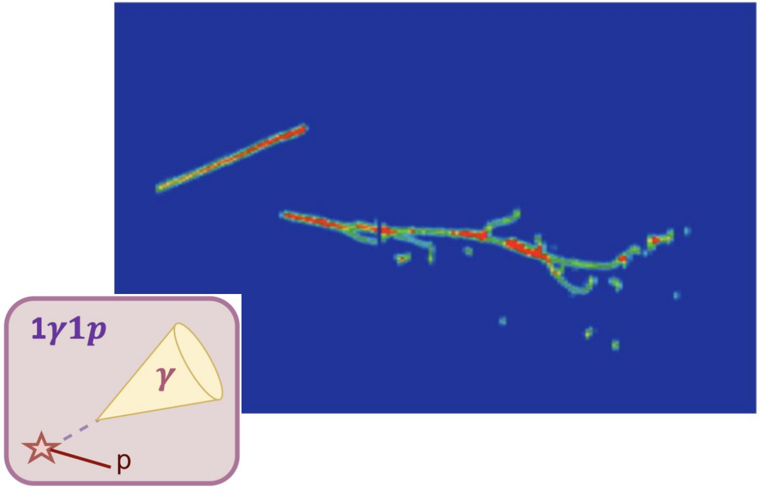
Use **novel tomographic image** reconstruction leveraging isochronous signals from the 3 wire planes to build 3D images.

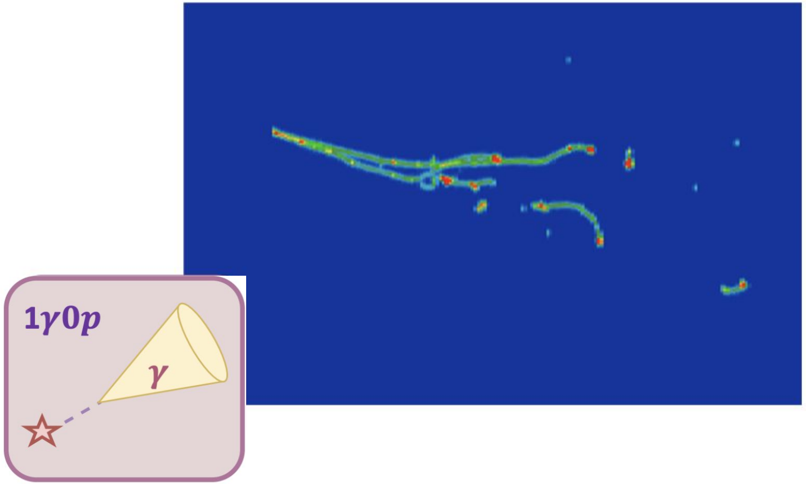
Fully inclusive selection: **high purity and high efficiency**
Least sensitive to the cross section model



WireCell

The Photon Path: Single Photon Search





Pandora event reconstruction

$\Delta \rightarrow N\gamma$ targeting $1\gamma1p$ and $1\gamma0p$ to maximize signal statistics

NC π^0 is main background

→ Topology: 2γ, but second shower can be difficult/impossible to reconstruct

→ In situ measurement used to constrain the background

A common strategy for multiple analyses

ν-ID/cosmic rejection

e or γ ID

p, π tagging
μ rejection

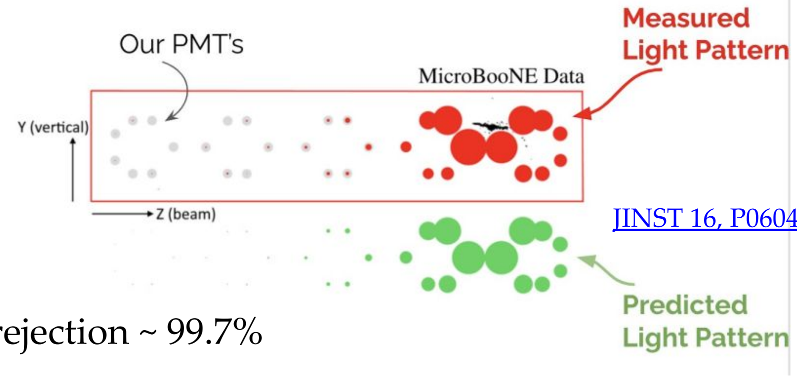
Event selection + sidebands

Constraint of systematics

Results & Statistical Interpretation

MicroBooNE is a surface detector:

→ Use light patterns in coincidence with the beam trigger to ID neutrinos.
→ 97% of triggered events contain only cosmics
→ Events typically contain ν + o(20) cosmic μ
→ Charge + PMT flashes match is used to isolate neutrino activity in active volume



[JINST 16, P06043 (2021)]

Cosmic rejection ~ 99.7%

A common strategy for multiple analyses

ν-ID/cosmic rejection

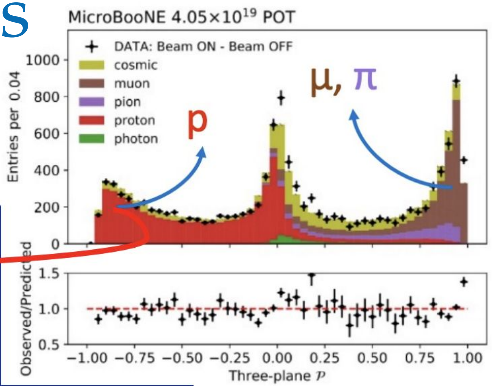
e or γ
ID

p, π tagging
μ rejection

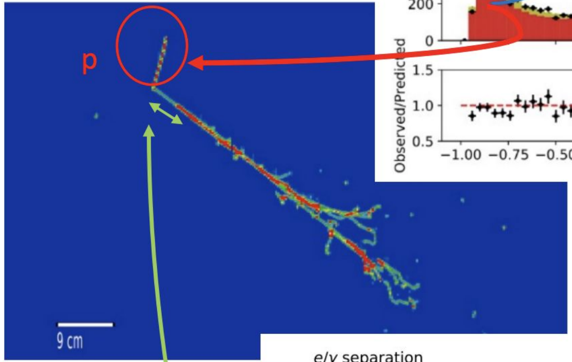
Event selection +
sidebands

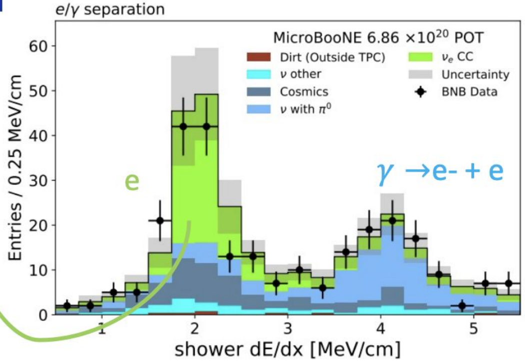
Constraint of
systematics

Results & Statistical
Interpretation



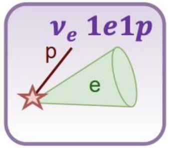
arXiv:2109.02460





3-planes calorimetry based PID
Hadrons/μ: novel technique for likelihood based PID (bragg peak ID)
e/γ: shower dE/dx

A common strategy for multiple analyses



Multi Particle IDentification: Image based classification particle ID score

ν-ID/cosmic rejection

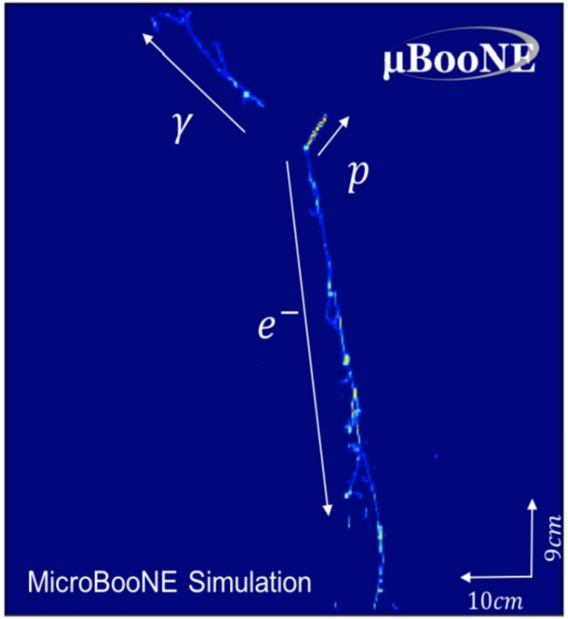
e or γ
ID

p, π tagging
μ rejection

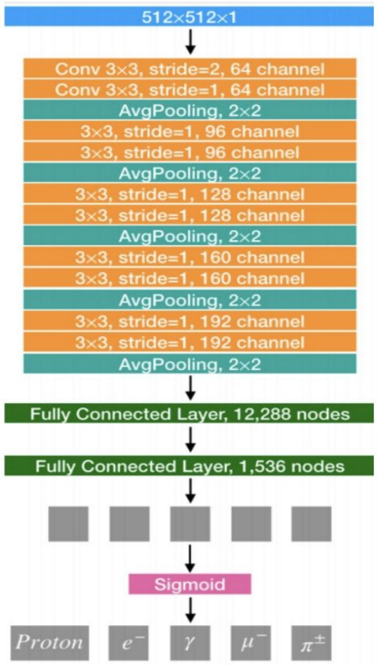
Event selection +
sidebands

Constraint of
systematics

Results & Statistical
Interpretation



	p	e^-	γ	μ^-	$\pi^\pm$
MPID Score	0.89	0.95	0.85	0.06	0.17



10.1103/PhysRevD.103.092003

A common strategy: use of BDTs

ν-ID/cosmic rejection

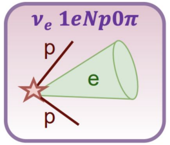
e or γ
ID

p, π tagging
μ rejection

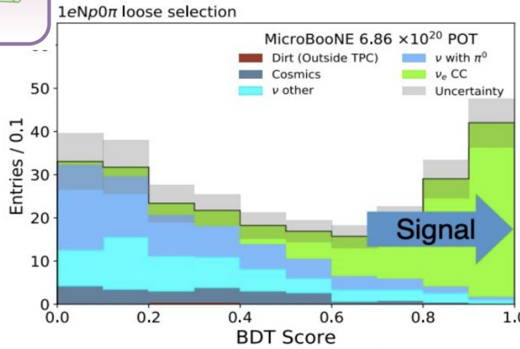
Event selection +
sidebands

Constraint of
systematics

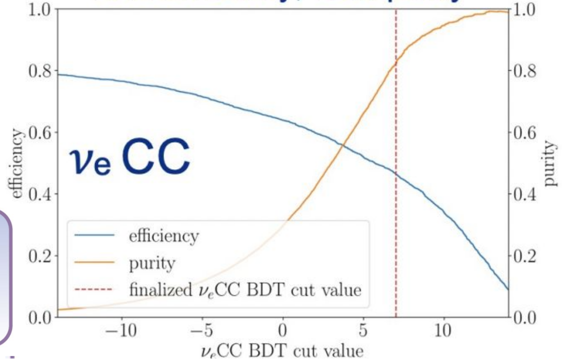
Results & Statistical
Interpretation

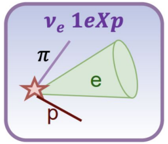


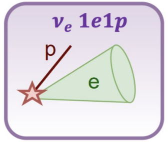
2 BDTs 16 detector variables



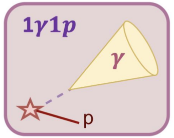
46% efficiency, 82% purity







1e1p:
19 kinematic variables
(e.g. QE consistency)
4 detector variables
(e.g. shower labeled
pixel fraction)



1γ1p:
5 boosted decision trees
to reject background

A common strategy: a performance example

ν-ID/cosmic rejection

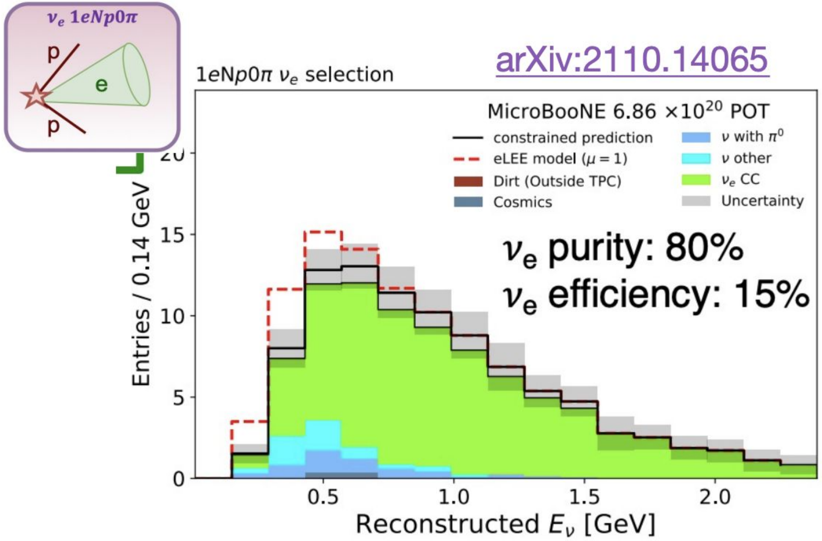
e or γ
ID

p, π tagging
μ rejection

Event selection +
sidebands

Constraint of
systematics

Results & Statistical
Interpretation



Reject over 99.7% of background events from cosmic muons or π^0
High purity ν_e selection

A common strategy: use of sidebands

Numerous sidebands used to:

→ calibrate shower reconstruction

(e.g. reco $\pi0$ mass within 5% of 135 MeV/c^2)

ν-ID/cosmic rejection

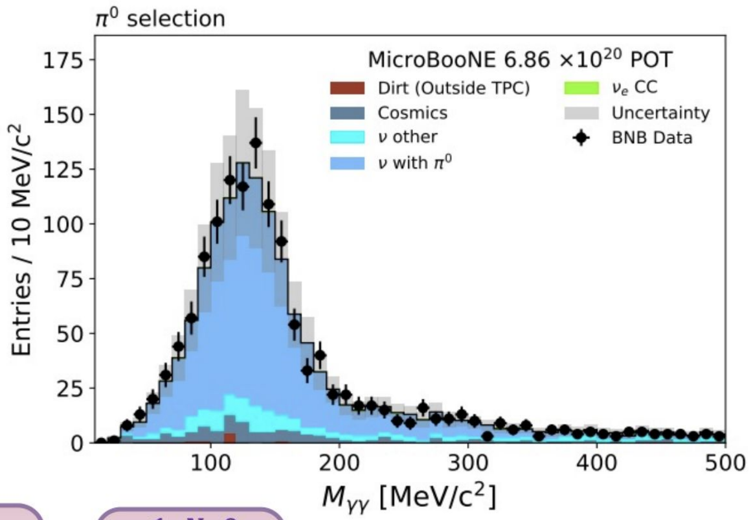
e or γ
ID

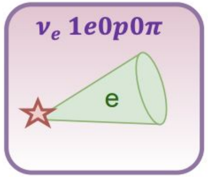
p, π tagging
μ rejection

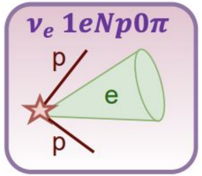
Event selection +
sidebands

Constraint of
systematics

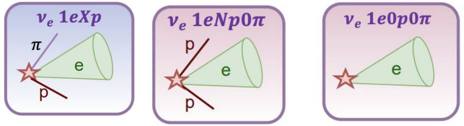
Results & Statistical
Interpretation







A common strategy: use of sidebands



Numerous sidebands used to:

→ test selections
→ test the interaction model: NuMI ν_e all ν_e-Ar cross section measurements to date
→ High intrinsic ν_e relative to BNB
→ Selections not tuned on NuMI data: applied after frozen, before unblinding BNB data

ν-ID/cosmic rejection

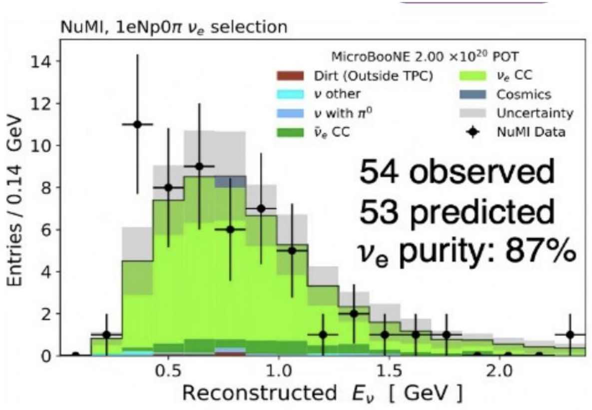
e or γ ID

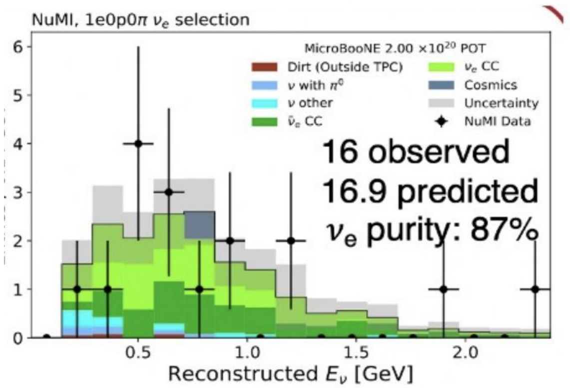
p, π tagging
μ rejection

Event selection + **sidebands**

Constraint of systematics

Results & Statistical Interpretation





A common strategy: use of sidebands

ν-ID/cosmic rejection

e or γ ID

p, π tagging
μ rejection

Event selection + **sidebands**

Constraint of systematics

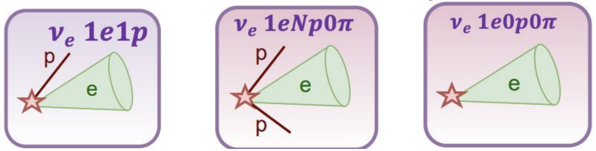
Results & Statistical Interpretation

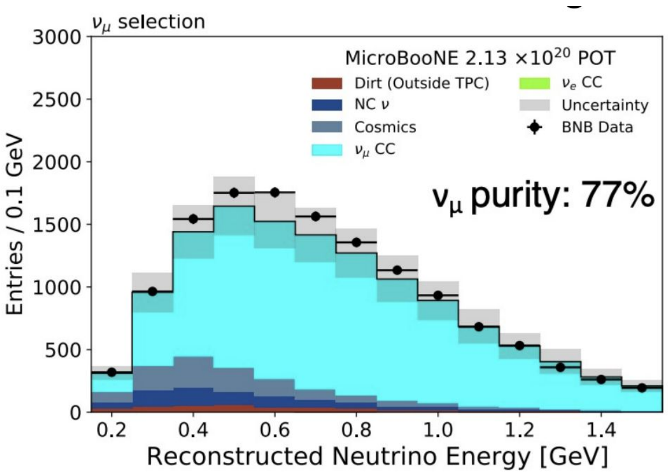
Numerous sidebands used to:

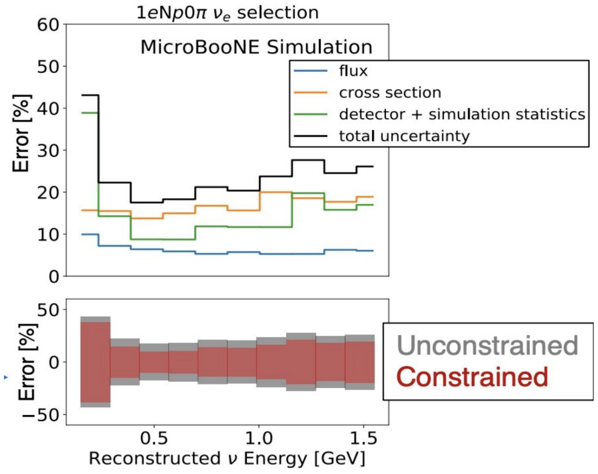
→ Constrain systematics with ν_μ selections:

Flux: ν_e and ν_μ same beamline, shared parents

Cross section: Both interact in argon







A common strategy: use of sidebands

Numerous sidebands used to:

→ Constrain systematics with ν_μ selections:

Flux: ν_e and ν_μ same beamline, shared parents

Cross section: Both interact in argon

ν-ID/cosmic rejection

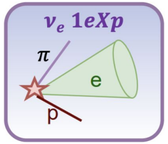
e or γ ID

p, π tagging
μ rejection

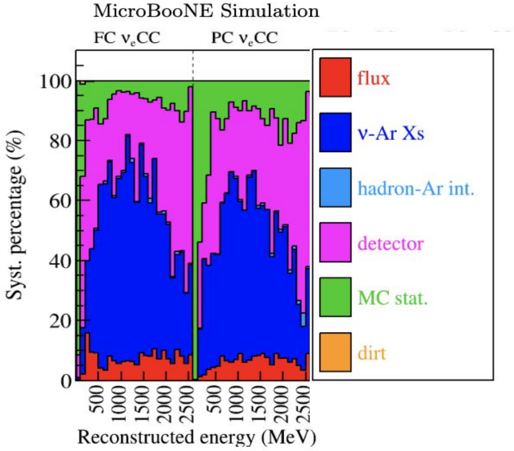
Event selection + **sidebands**

Constraint of systematics

Results & Statistical Interpretation



7-channel-fit to constrain systematics using combination of ν_e and ν_μ channels



A common strategy: use of sidebands

ν-ID/cosmic rejection

e or γ ID

p, π tagging
μ rejection

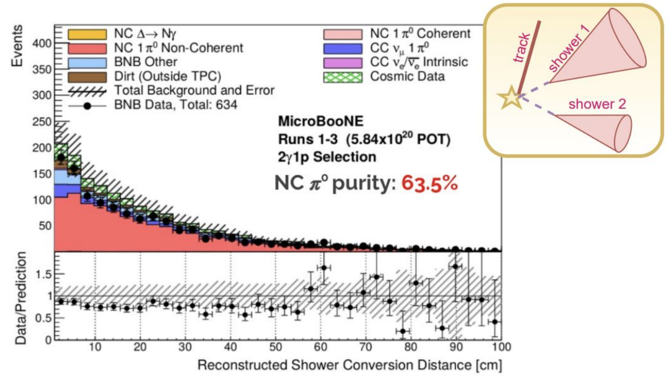
Event selection +
sidebands

Constraint of systematics

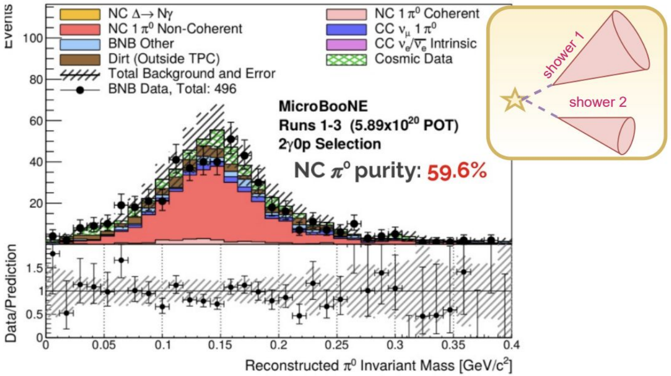
Results & Statistical Interpretation

Numerous sidebands used to:

→ Constrain π^0



High statistics π^0 samples: constrain the π^0 backgrounds in situ for $\Delta\rightarrow N\gamma$
validate shower reconstruction and energy measurement



Progressive Unblinding strategy

ν-ID/cosmic rejection

e or γ ID

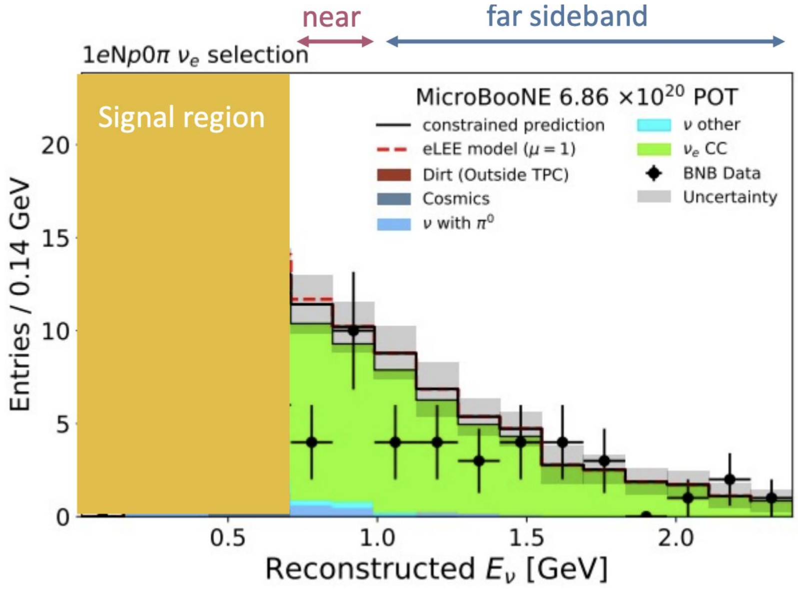
p, π tagging μ rejection

Event selection + **sidebands**

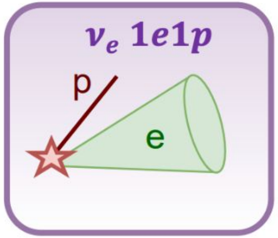
Constraint of systematics

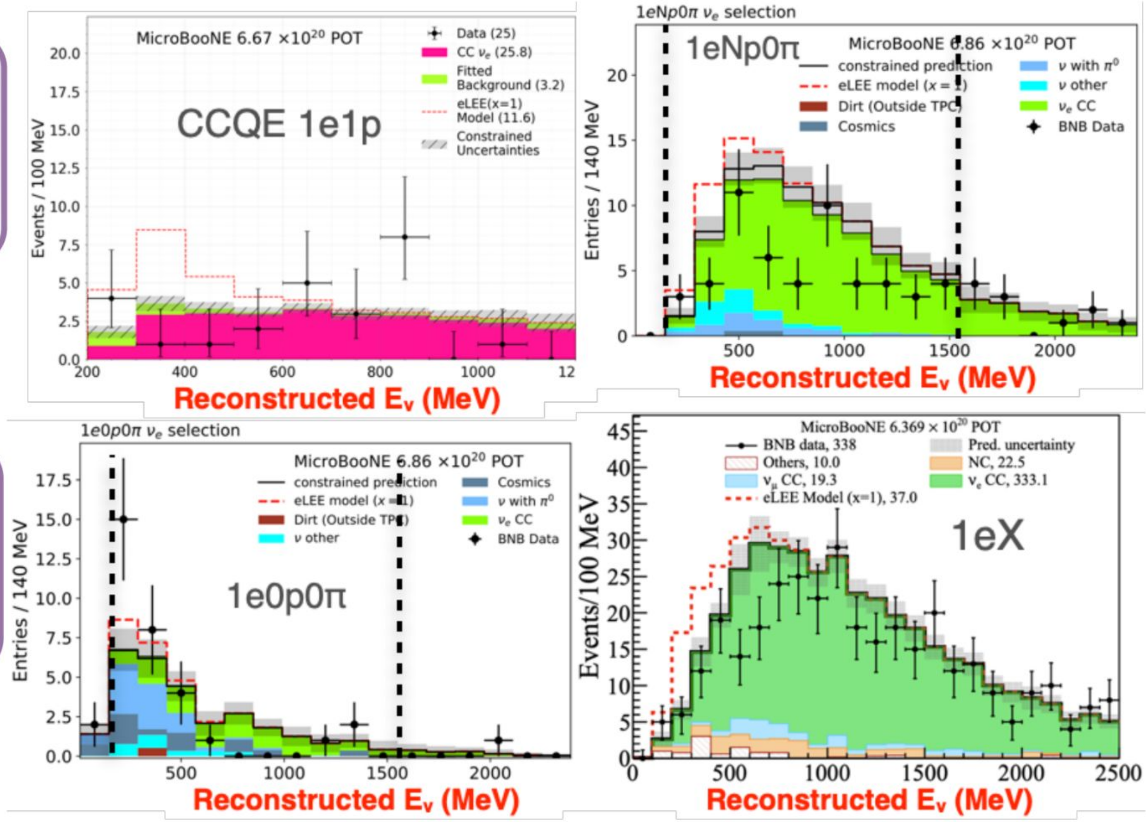
Results & Statistical Interpretation

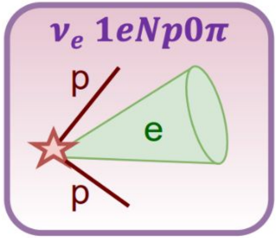
Data in non-signal region used to validate analysis strategy and modeling.
Selection are frozen before looking at sideband data.
Progressive unblinding: the energy threshold is lowered gradually towards full unblinding, sidebands

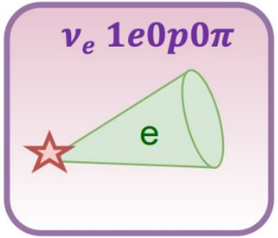


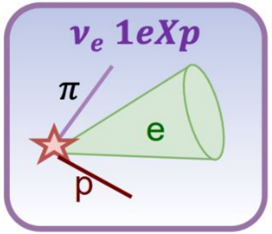
The Electron Path: Results



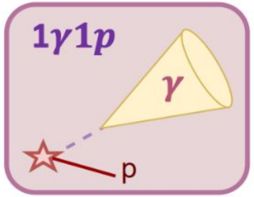




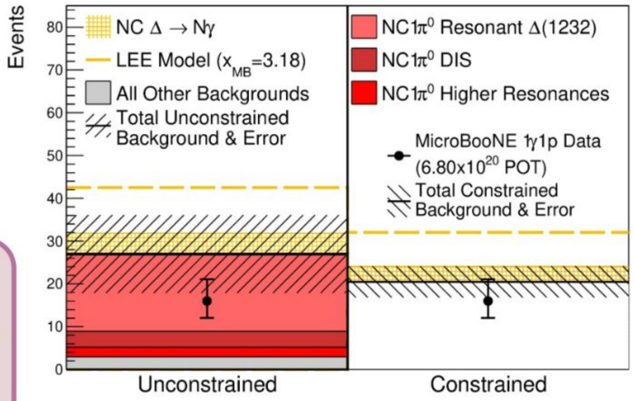




The Photon Path: Results



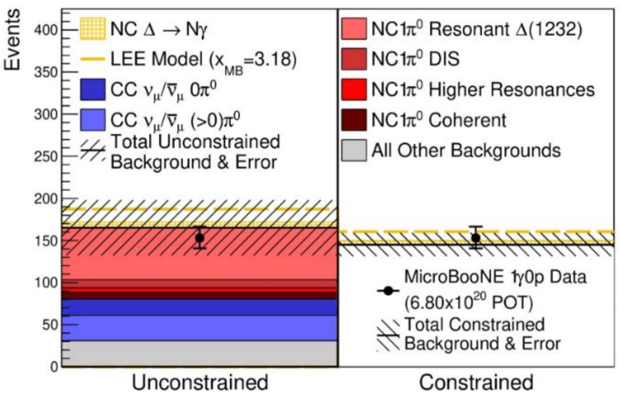
1γ1p



1γ1p	
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
$\text{NC } \Delta \to N\gamma$	+ 4.88
LEE ($x_{\text{MB}} = 3.18$)	+ 15.5

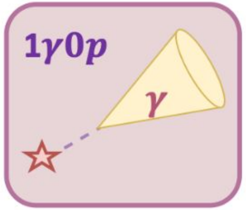
16
Data Events Observed

1γ0p



1γ0p	
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
$\text{NC } \Delta \to N\gamma$	+ 6.55
LEE ($x_{\text{MB}} = 3.18$)	+ 20.1

153
Data Events Observed



A common strategy: statistical interpretation

ν-ID/cosmic rejection

e or γ
ID

p, π tagging
μ rejection

Event selection +
sidebands

Constraint of
systematics

Results & Statistical
Interpretation

Two methods

Simple Hypothesis Test:
Probability of the data rejecting one hypothesis assuming the other is true, using a $\Delta\chi^2$ formalism.

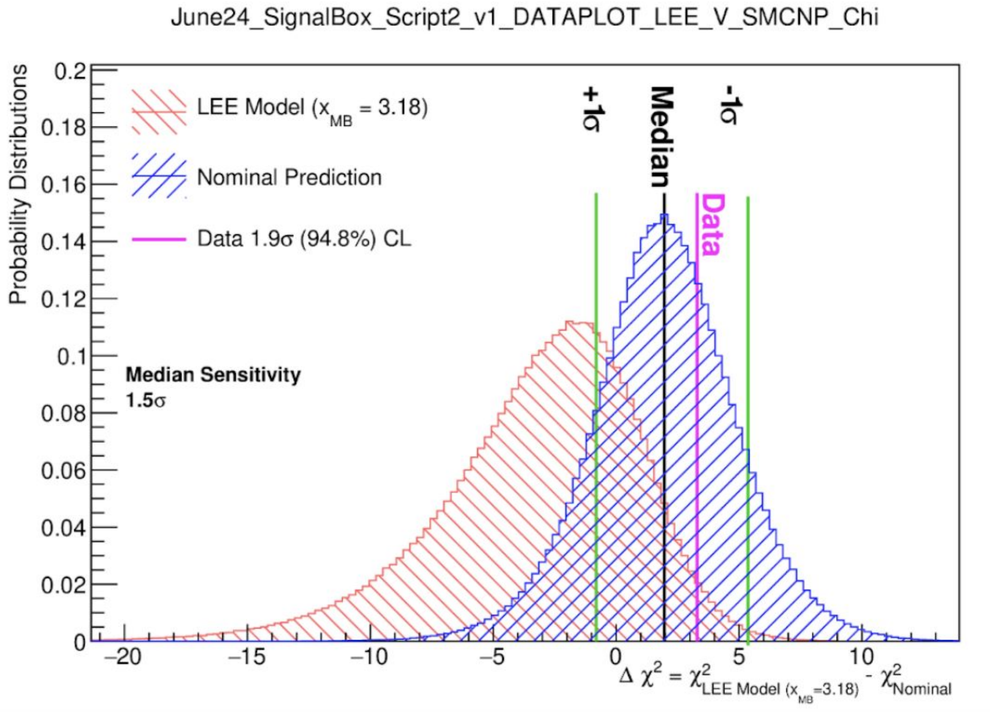
Signal Strength Comparisons:
Use Feldman-Cousins procedure to measure best fit signal strength:

ν_e: assuming a flat scaling of the eLEE model
γ: assuming a flat scaling of NC $\Delta \rightarrow N\gamma$ nominal GENIE expectation

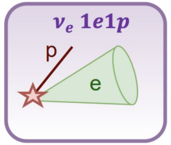
The Photon Path: Simple Hypothesis Test

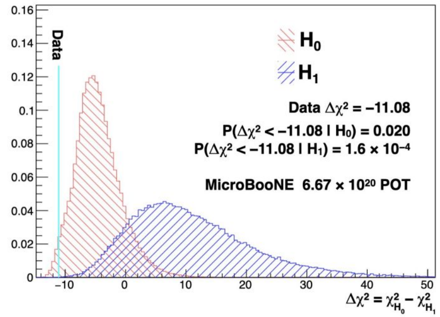
H$_0$: nominal GENIE prediction
H$_1$: γLEE model

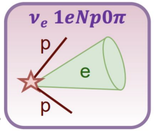
Data shows
no preference
for the excess hypothesis

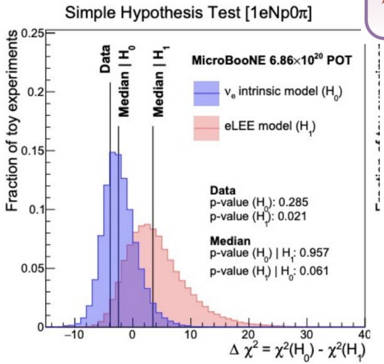


The Electron Path: Simple Hypothesis Test



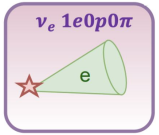


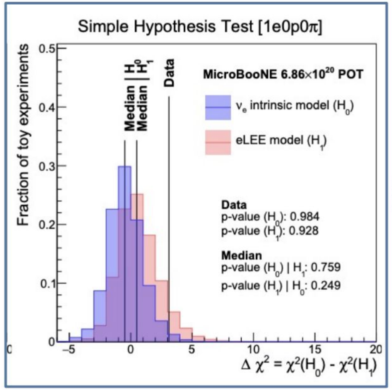


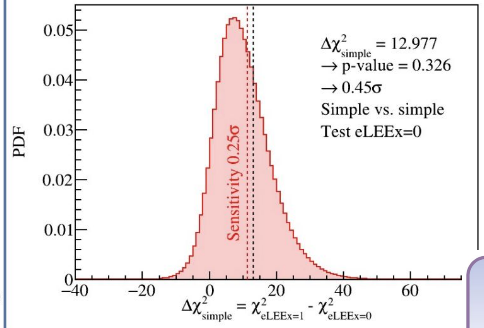


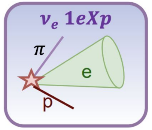
H$_0$: ν_e intrinsic model
H$_1$: ν_e intrinsic + eLEE

Data shows
no preference
for the excess hypothesis





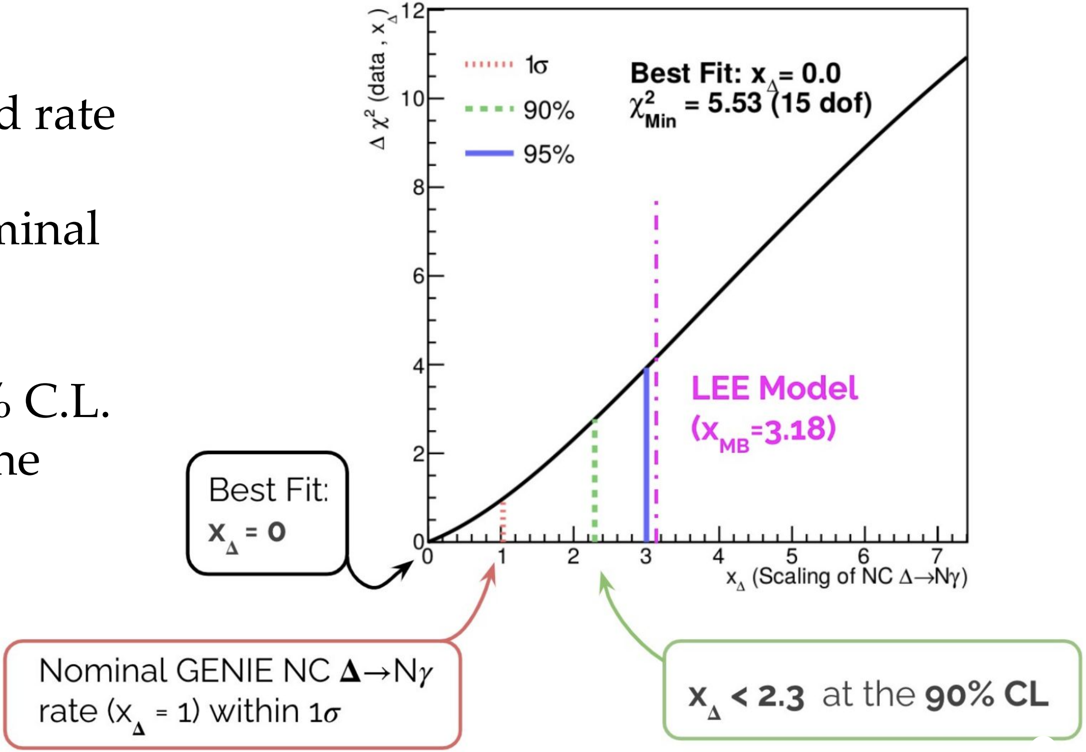




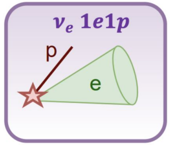
The Photon Path: Signal Strength

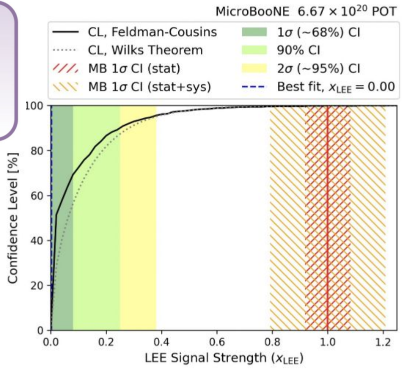
No evidence for an enhanced rate of single photons from NC $\Delta \rightarrow N\gamma$ decay above nominal GENIE expectations x3.18

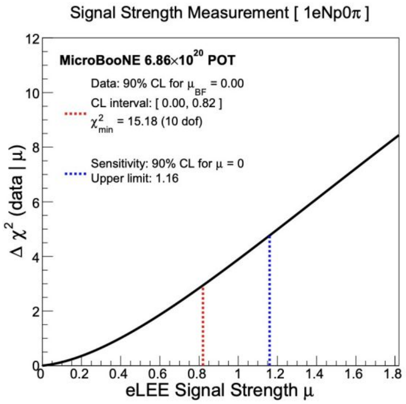
Scaling disfavoured at 94.8% C.L. > than 50 times better than the world's previous limit

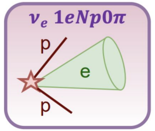


The Electron Path: Signal Strength

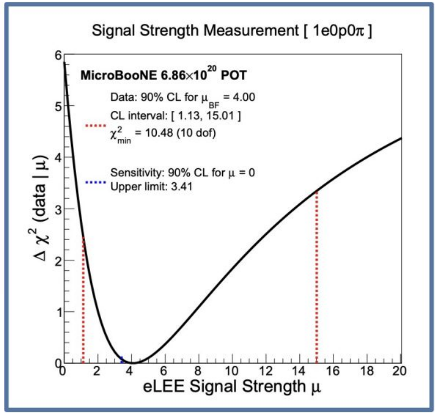


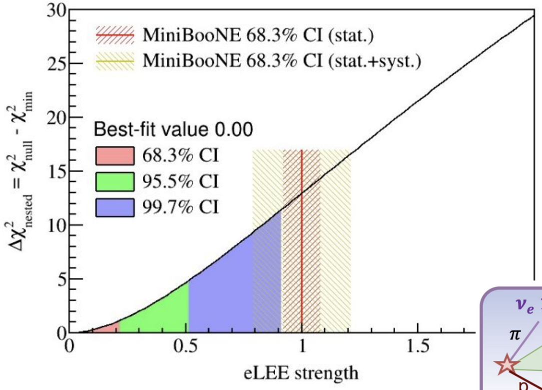


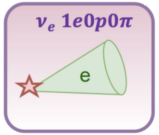


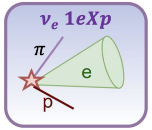


Energy-dependent scaling of ν_e beam content as in eLEE model is not favored

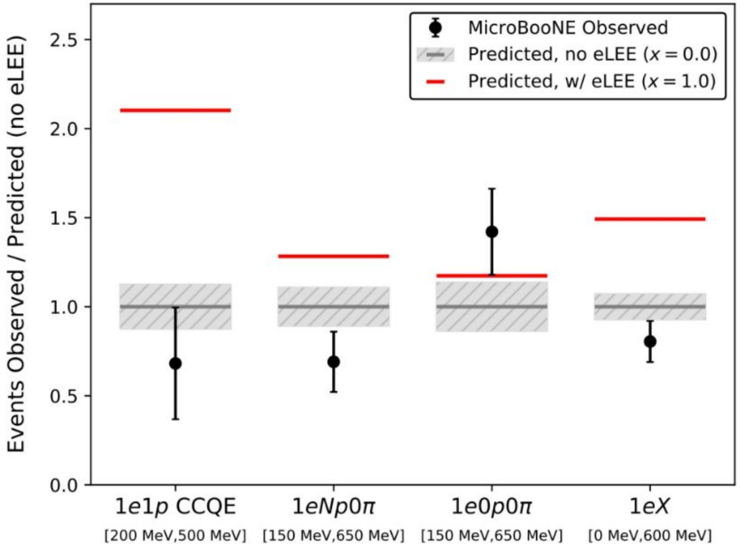


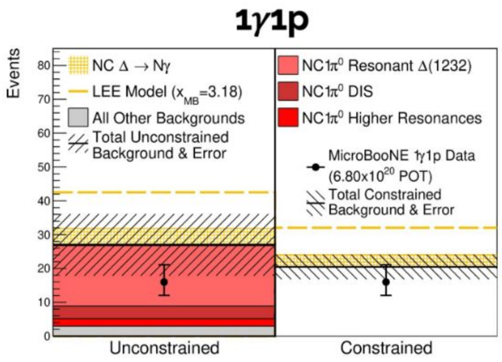


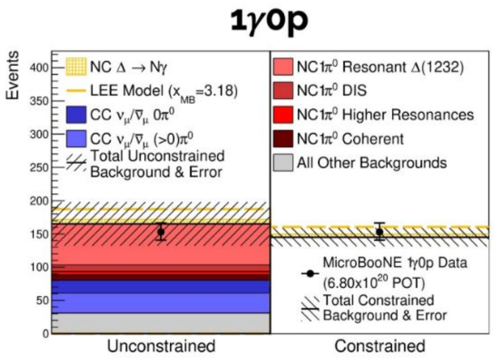




Summary of results





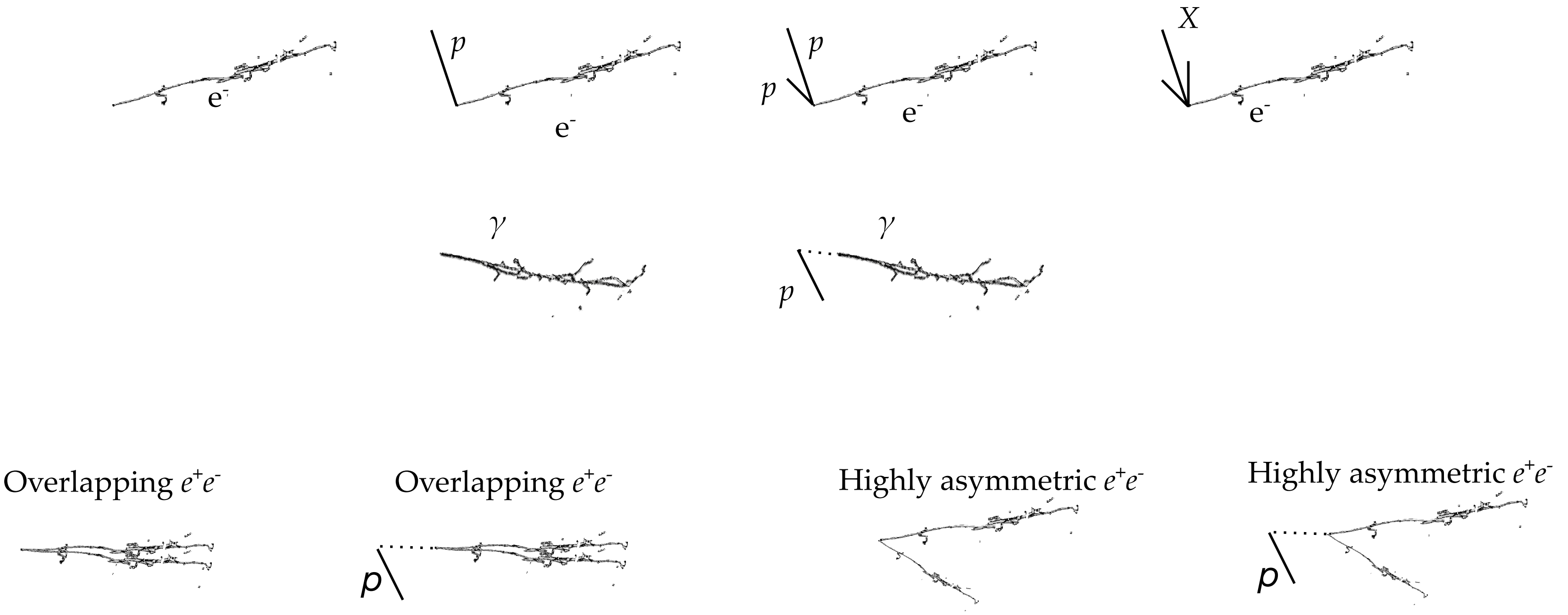


Investigated two hypotheses to see if the MiniBooNE excess originate from of ν_e or NC $\Delta \rightarrow N\gamma$

No evidence for excesses relative to prediction in either channel: 95% CL to 3σ

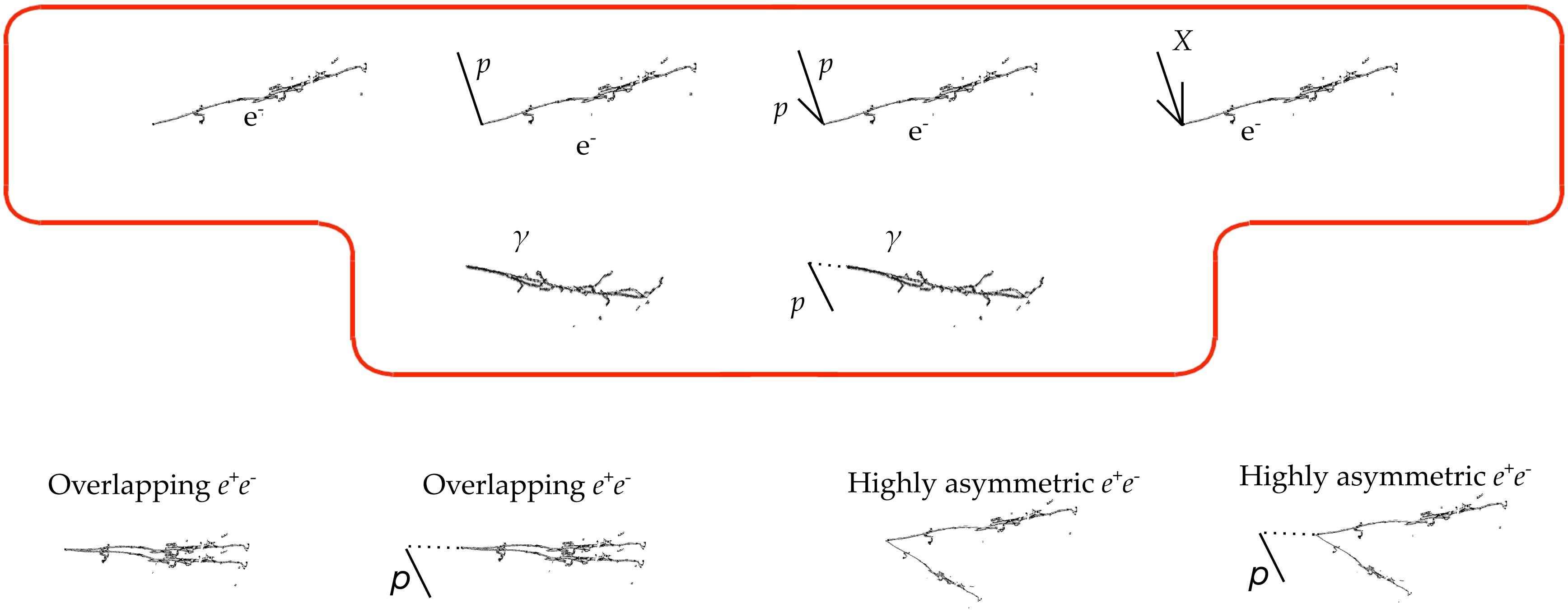
The Road Ahead

Topologies we can explore in LArTPC

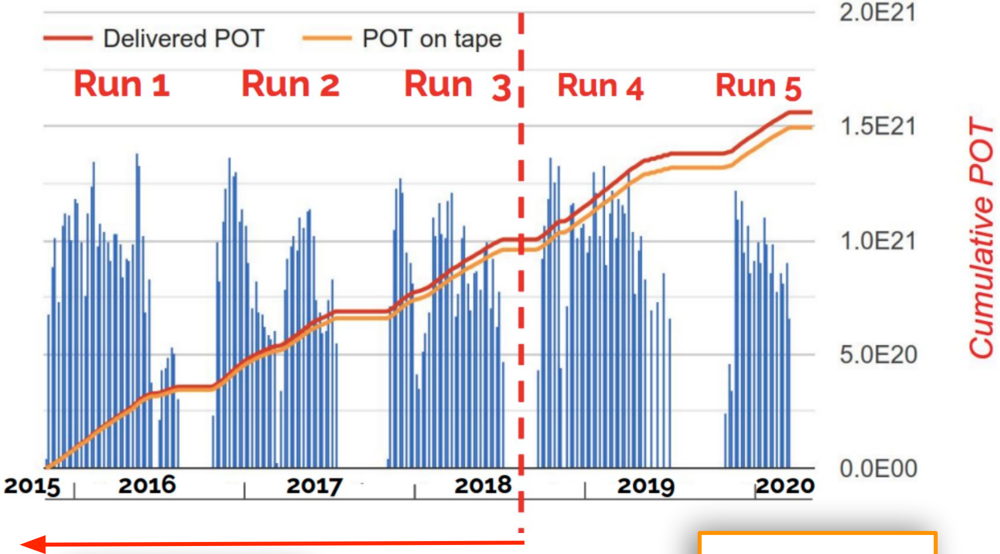


Topologies we can explore in LArTPC

MicroBooNE's first series of LEE search results



More Stat & Sneak Peeks



Data used for first results

x2 statistics on tape

Stat limited analyses: stay tuned for full dataset

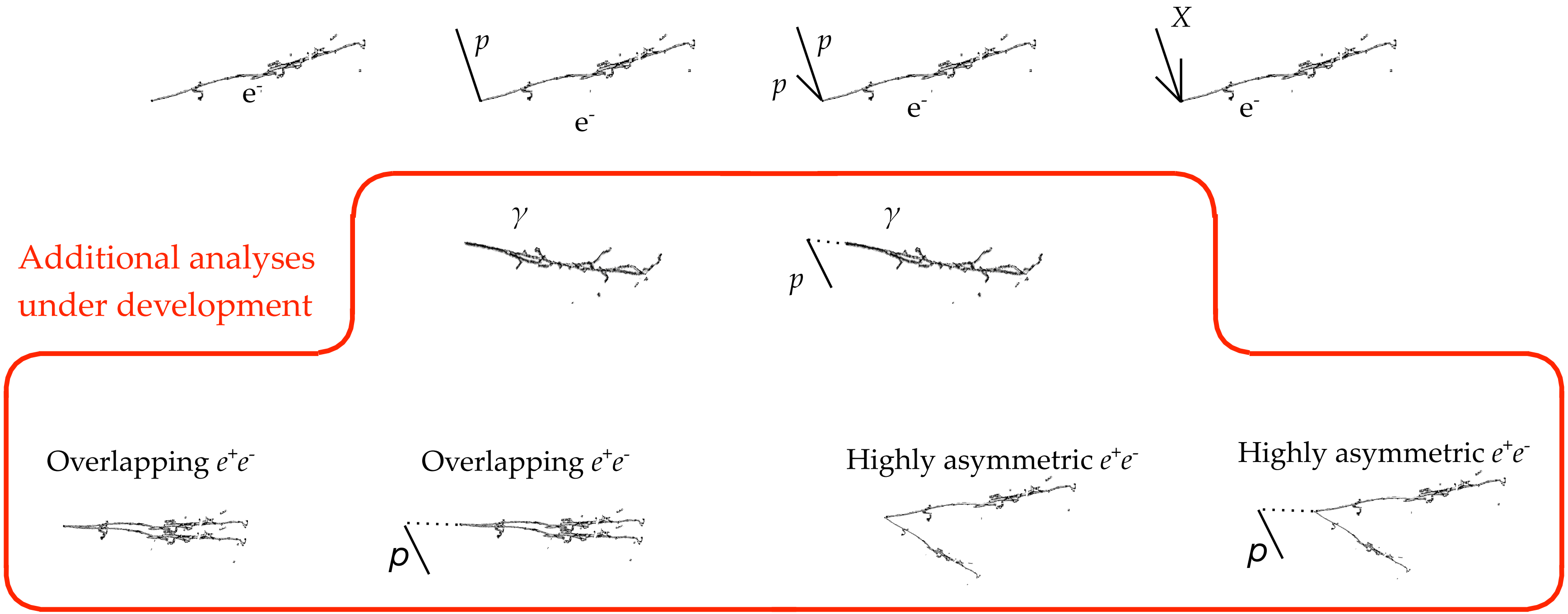
Coming soon: more oscillations!

Search for a 3+1 Sterile Neutrino with the MicroBooNE experiment using Deep-Learning-based reconstruction

Search for a Sterile Neutrino in a 3+1 Framework using Wire-Cell Inclusive Charged-Current ν_e Selection

ν_μ Disappearance in MicroBooNE using the DL LEE2 1μ1p CCQE Selection

Topologies we can explore in LArTPC



Evolving theory landscape

First series of results (1/2 the MicroBoONE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

* Requires heavy sterile/other new particles also

Evolving theory landscape

(Caution: not an exhaustive list!)

Decay of O(keV) Sterile Neutrinos to active neutrinos
- [13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
- [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141

New resonance matter effects
- [5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)

Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
- [7]Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470

Produces electrons

Decay of heavy sterile neutrinos produced in beam
- [4] Gninenko, Phys.Rev.D83:015015,2011
- [12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
- [15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
- [11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)

Produces photons

Decay of upscattered heavy sterile neutrinos
or new scalars mediated by Z' or more complex higgs sectors
- [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
- [2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
- [3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
- [10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)
- [6] Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)

Decay of axion-like particles
- [8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)

Produces $e^+ e^-$ pairs

A model-independent approach to any new particle
- [9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)

Evolving theory landscape

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- [6] Abdallah, Gandhi, Roy Phys. Rev. D 104, 055028 (2021)

D 104, 015030 (2021)

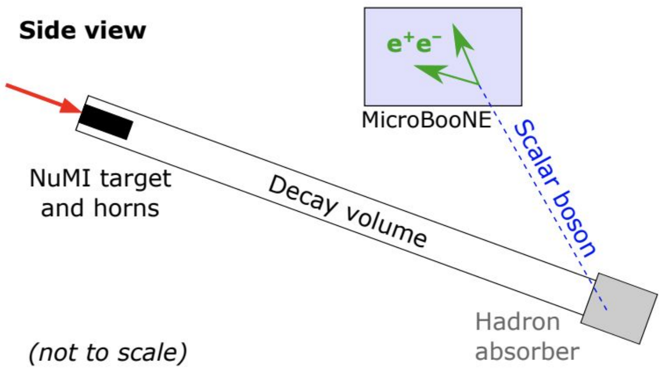
ew particle

5008 (2021)

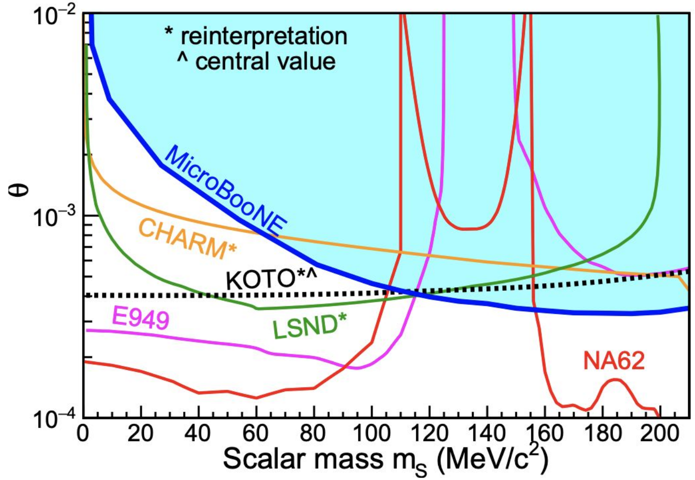
Produces $e^{+} e^{-}$ pairs

Searches for exclusive final state topologies in LArTPCs allow to distinguish between models!

Already started: H Portal → e^+e^- @ MicroBooNE



Search for e+e- decays from scalars coming from NuMI hadron absorber



Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
[Phys.Rev.Lett. 127 (2021) 15, 151803]

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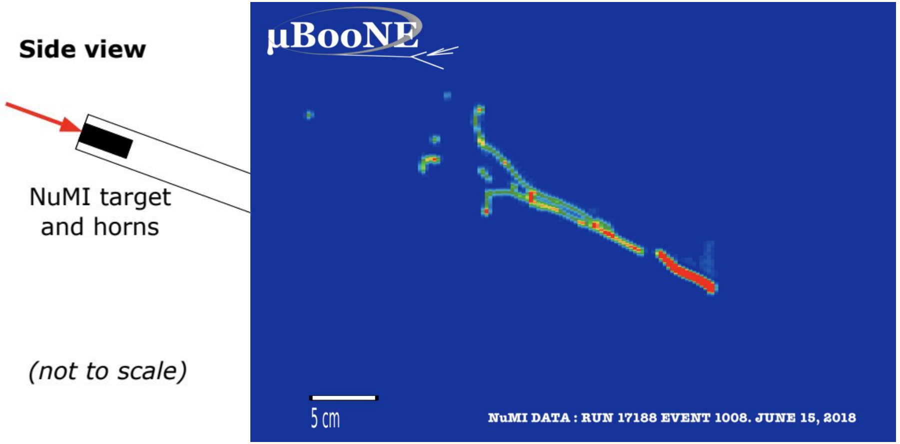
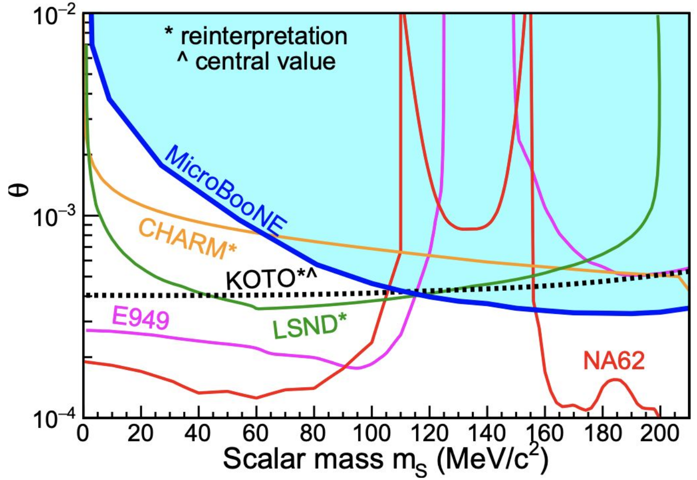




Search for e+e- decays from scalars coming from NuMI hadron absorber

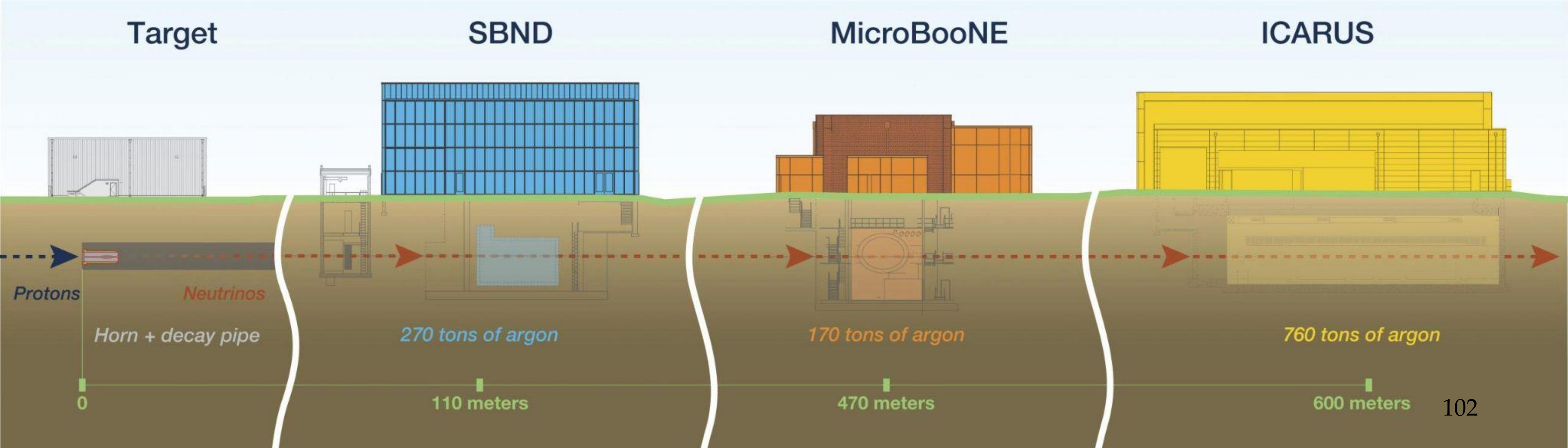
1 event observed → 95% C.L. excludes KOTO central value

Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector
[Phys.Rev.Lett. 127 (2021) 15, 151803]

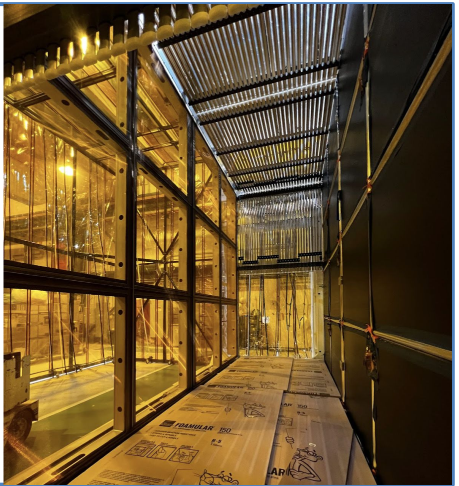
SBN: definitive test of short baseline oscillation

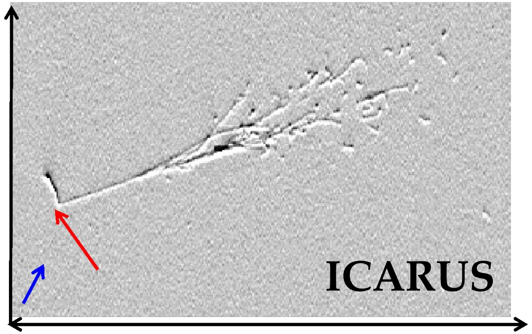
Fermilab Short-Baseline Neutrino Program will soon add further to this picture
→ **multiple detector analyses**

Same neutrino flux & **argon medium** (same cross-sections!)
→ measurement is highly correlated = **reduced systematics**



SBND
TPC
Building



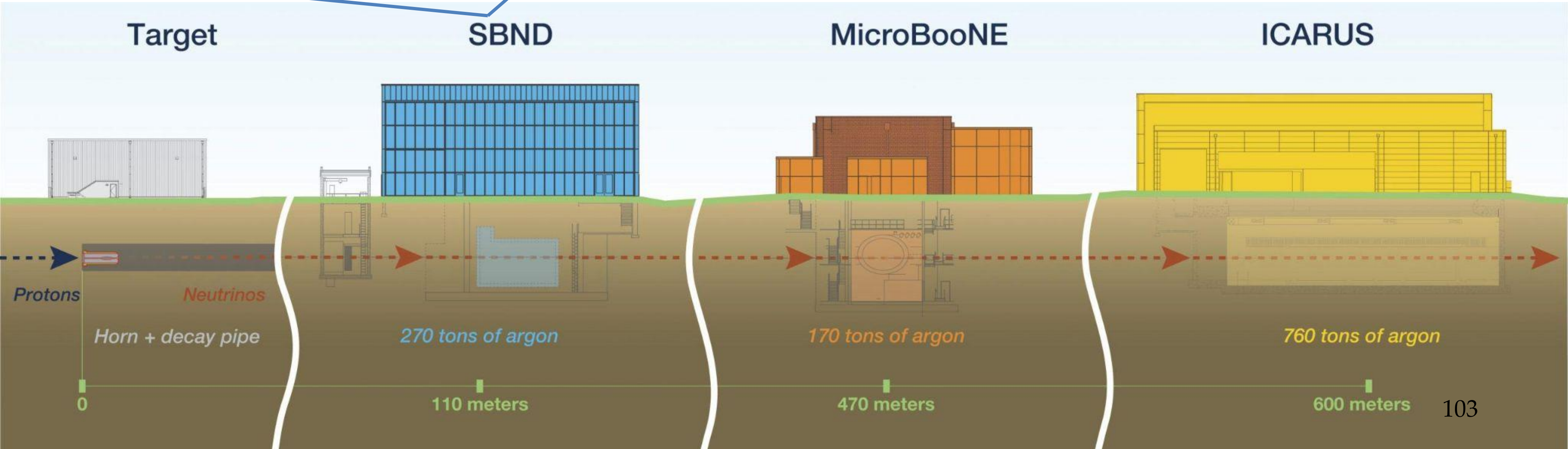


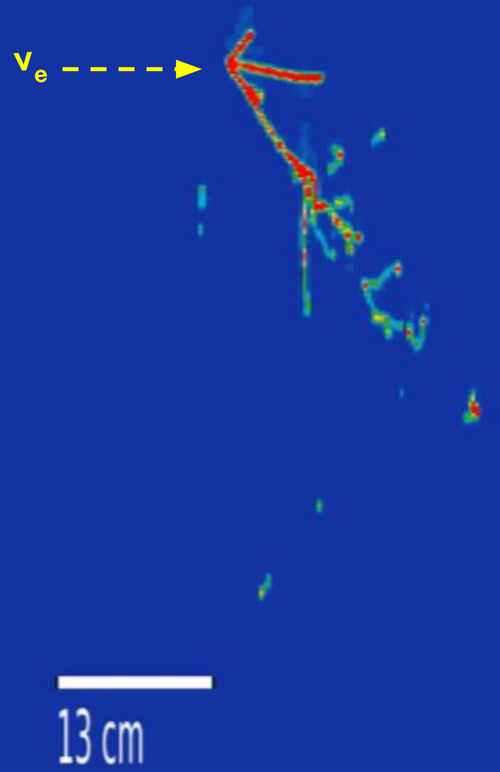
Event display of a
NuMI ν_e interaction candidate

SBND:
LAr filling starting early 2023

MicroBooNE:
done with datataking

ICARUS:
started taking ν data in 2021





Conclusions

We have completed our first search into the long-standing short-baseline neutrino puzzle:

our 5 complementary analyses found
no evidence for an excess
in the single electron
and in the $\Delta \rightarrow N\gamma$ single photon channels
with respect to the intrinsic beam content predictions.

MicroBooNE has demonstrated the excellent power of LArTPCs as the tool for precision measurement:
together with the SBN program,
we'll continue to leverage it to probe more BSM scenarios.

Thanks!

Upgrading the analysis

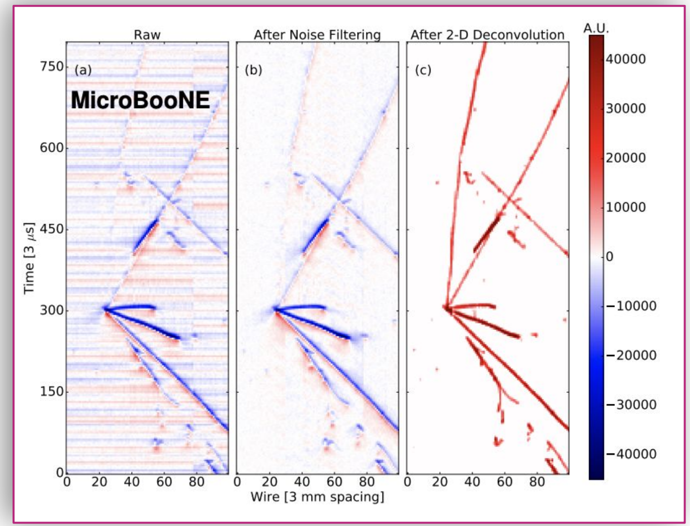
Analogous **signal definition** to the flux averaged analysis: ν_e and $\bar{\nu}_e$ w/ energy above 60 MeV and charged lepton energy > 120 MeV.

Better detector understanding: signal processing from all planes & improved calorimetry
JINST 13, P07006 (2018), JINST 13, P07007 (2018)

Reduced systematic uncertainties via a data driven method to assess detector systematics from waveforms
arXiv:2111.03556

Improved neutrino interaction model "theory-driven" CCQE & MEC tuned to T2K CC0π data arXiv:2110.14028

New approach to "modeling" cosmic background: overlay



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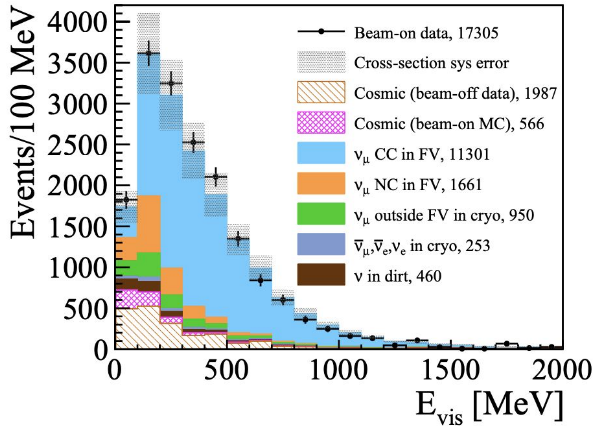
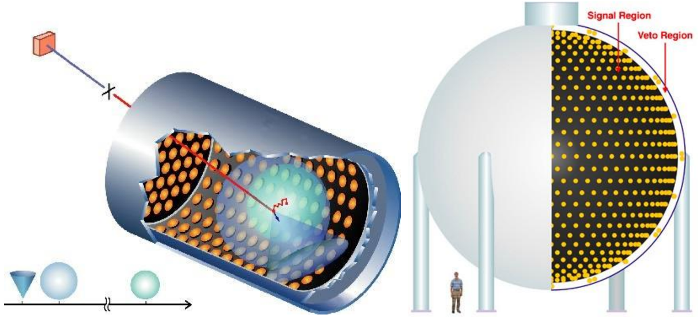


(b) Simulated neutrino interactions predicted by the "MicroBooNE tune" applied to GENIE v3.0.6 G18_10a_02_11a

Evolving technology: mass, precision & information

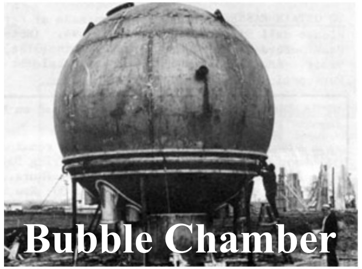
The history of neutrino detectors shows
how breakthroughs in instrumentation enable new discoveries.
What do we need to resolve the LEE puzzle?

Massive



Cherenkov

Precise



More Precise Information & Higher Statistics

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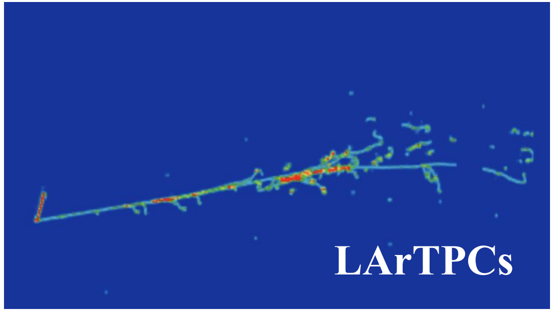
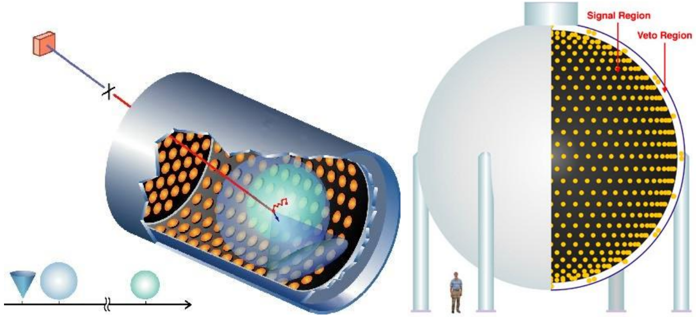
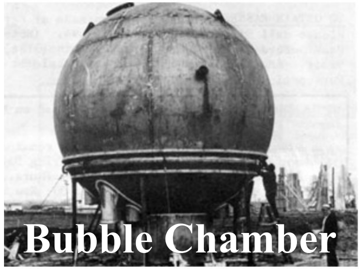
Precise & Massive!



Massive



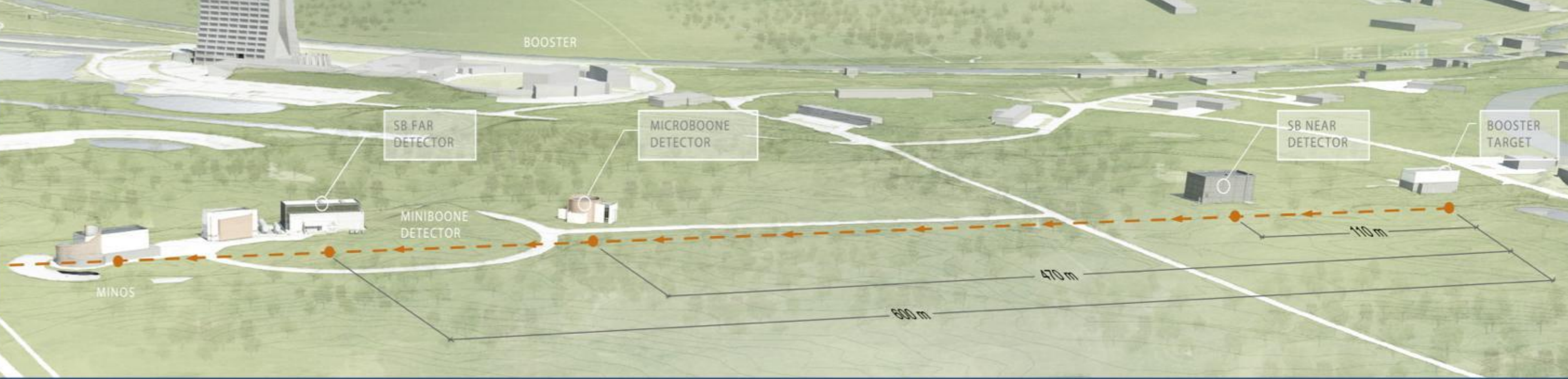
Precise

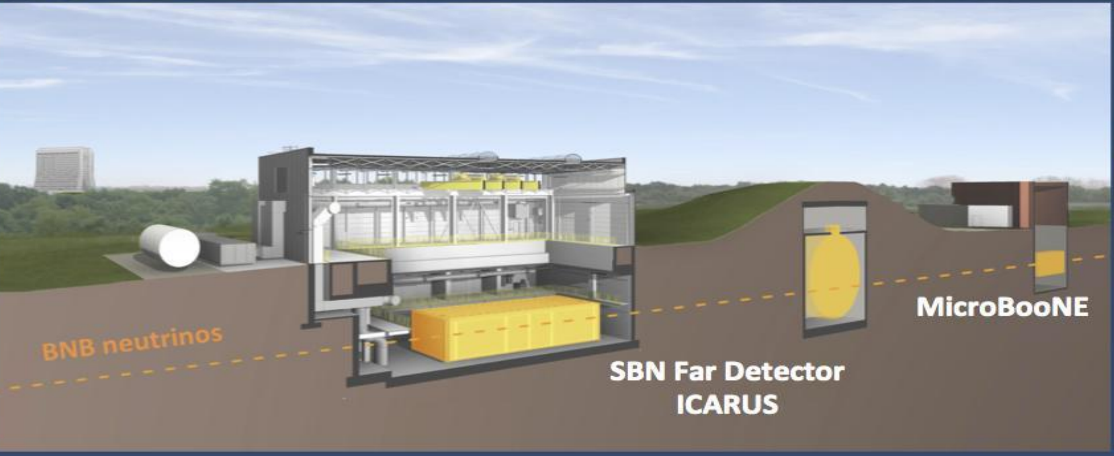


Cherenkov

More Precise Information & Higher Statistics

MicroBooNE is the **1st Liquid Argon Time Projection Chamber** of the **Short Baseline Neutrino** program @ FNAL.





LArTPC: a tool for discovery

LAr as total absorption calorimeter:
- Dual detection mechanism: ionization and scintillation light
  → multiple information channels

- Abundant and cheap
  → scalable detectors for
  → high statistics ν measurements

TPC as 4π charged particle detector
- 3D reconstruction with fully active volume

Sophisticated tools for event reconstruction are widely available.