μBooNE

UNIVERSITY OF OXFORD

MICROBOONE AND THE MYSTERY OF THE ~~MISSING~~ EXTRA NEUTRINOS

Kirsty Duffy
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University of Birmingham Particle Physics Group Seminar

55 cm

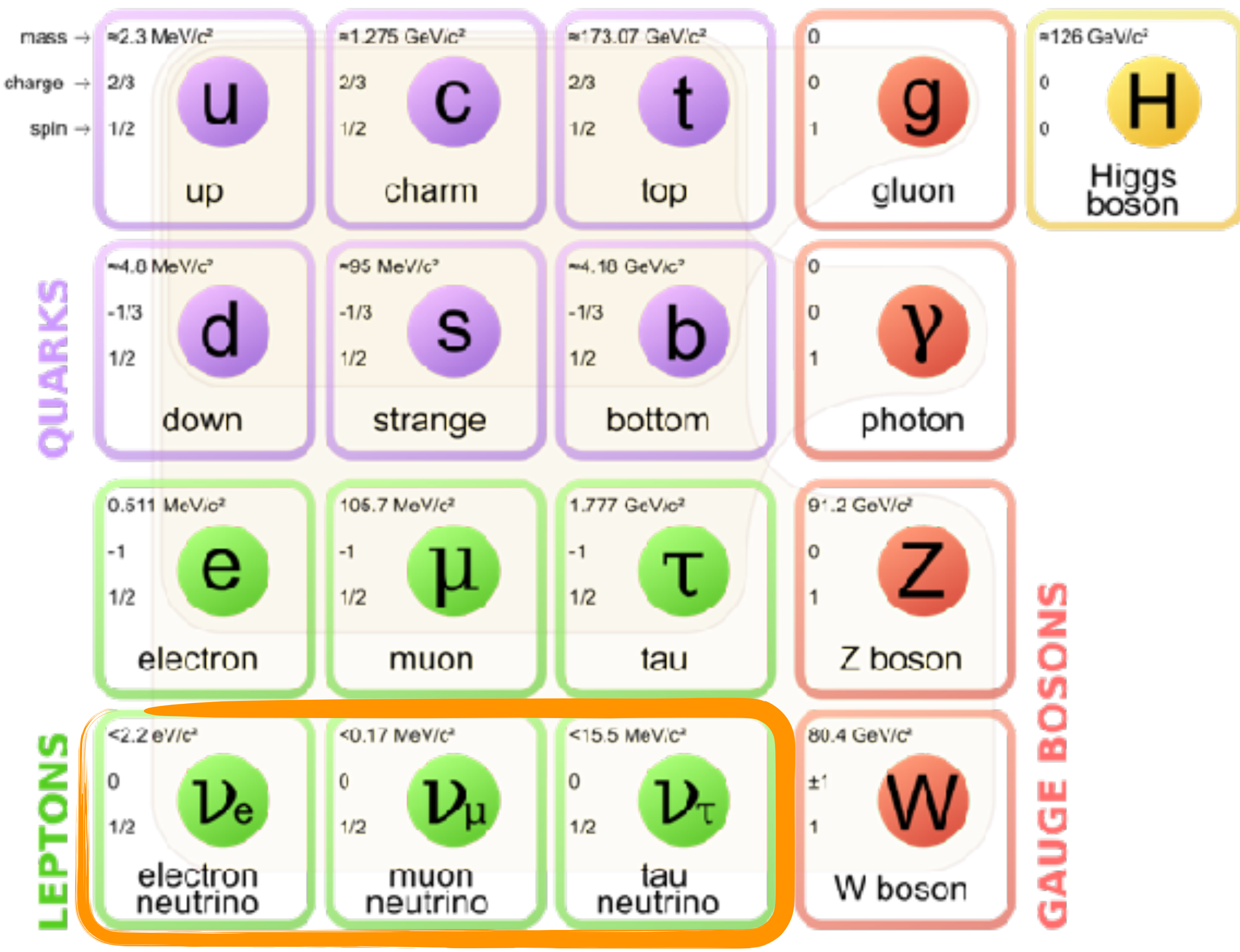
Run 3469 Event 53223, Oct

- Neutrinos are one of the **least-well-understood particles** in the Standard Model
- Neutrino oscillation is **beyond the Standard Model**, and opens the door to **exciting new possibilites**
- However, a lot remains that we **don't understand** (both within the 3-flavour oscillation picture and outside it)
- I present **new data** from the **MicroBooNE** experiment that sheds light on one of the existing anomalies

MY PERSONAL BIAS

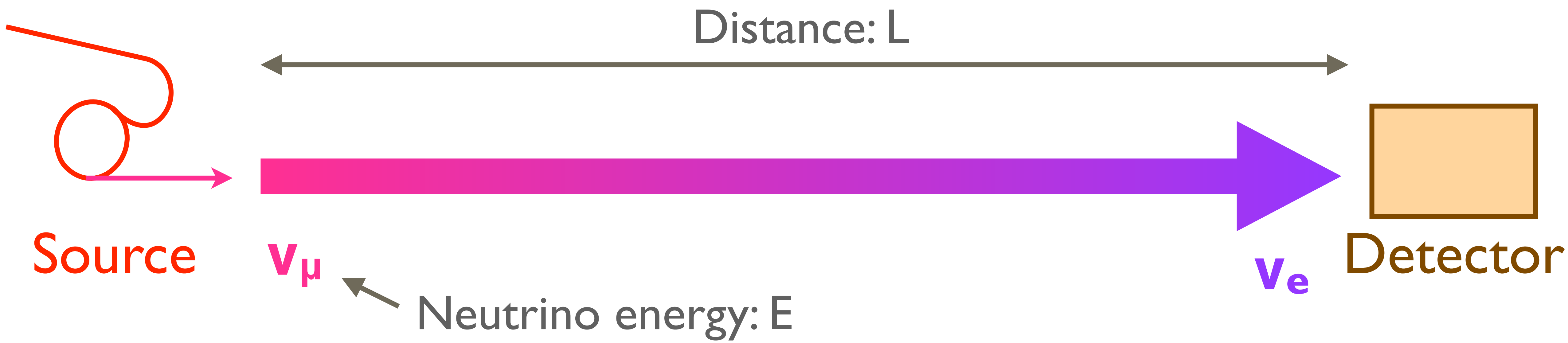
- Overview of (experimental) neutrino physics
- MiniBooNE anomaly
- MicroBooNE recent results

NEUTRINOS: WHAT WE KNOW



- Fundamental particles in the Standard Model
- Interact via weak force
- "Paired" with charged leptons

NEUTRINO OSCILLATION

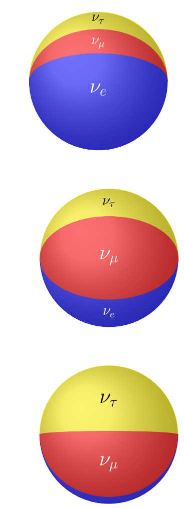


Muon neutrino disappearance

Electron neutrino appearance

TWO SETS OF EIGENSTATES

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



flavour

Interaction

mass

Propagation

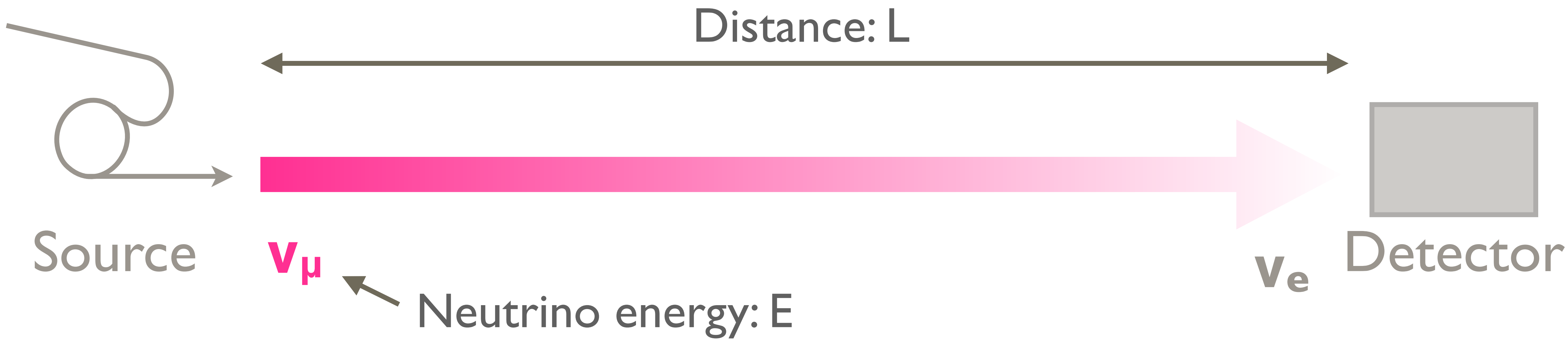
PMNS matrix

named after Pontecorvo, Maki, Nakagawa, and Sakata

Four free parameters:

Three mixing angles **θ_{12}, θ_{23}, θ_{13}**

One phase **δ_{CP}**



Probability to detect a neutrino of a given flavour **oscillates** as:

$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32} L}{4E} + (\text{solar, matter effect terms})$$

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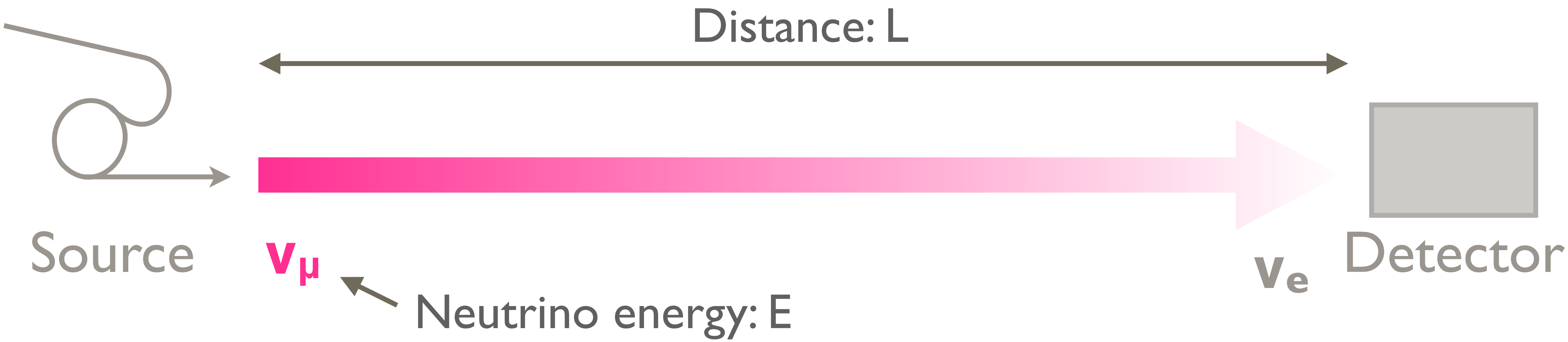

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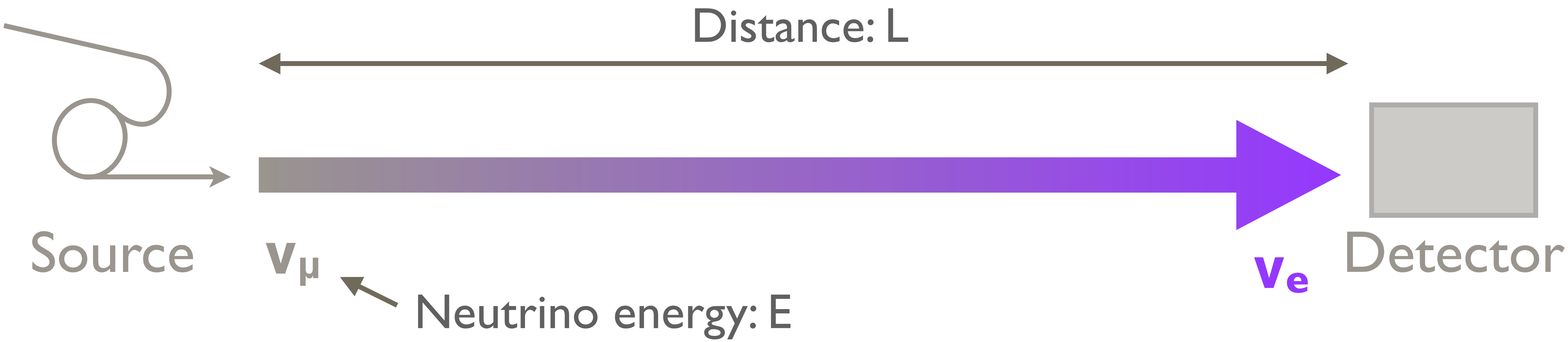
Reason #1 why neutrinos are exciting:

Neutrino oscillation

→ Neutrinos have mass

→ Physics beyond the Standard Model!



Muon neutrino disappearance

Electron neutrino appearance

$\bar{\nu}$ ν

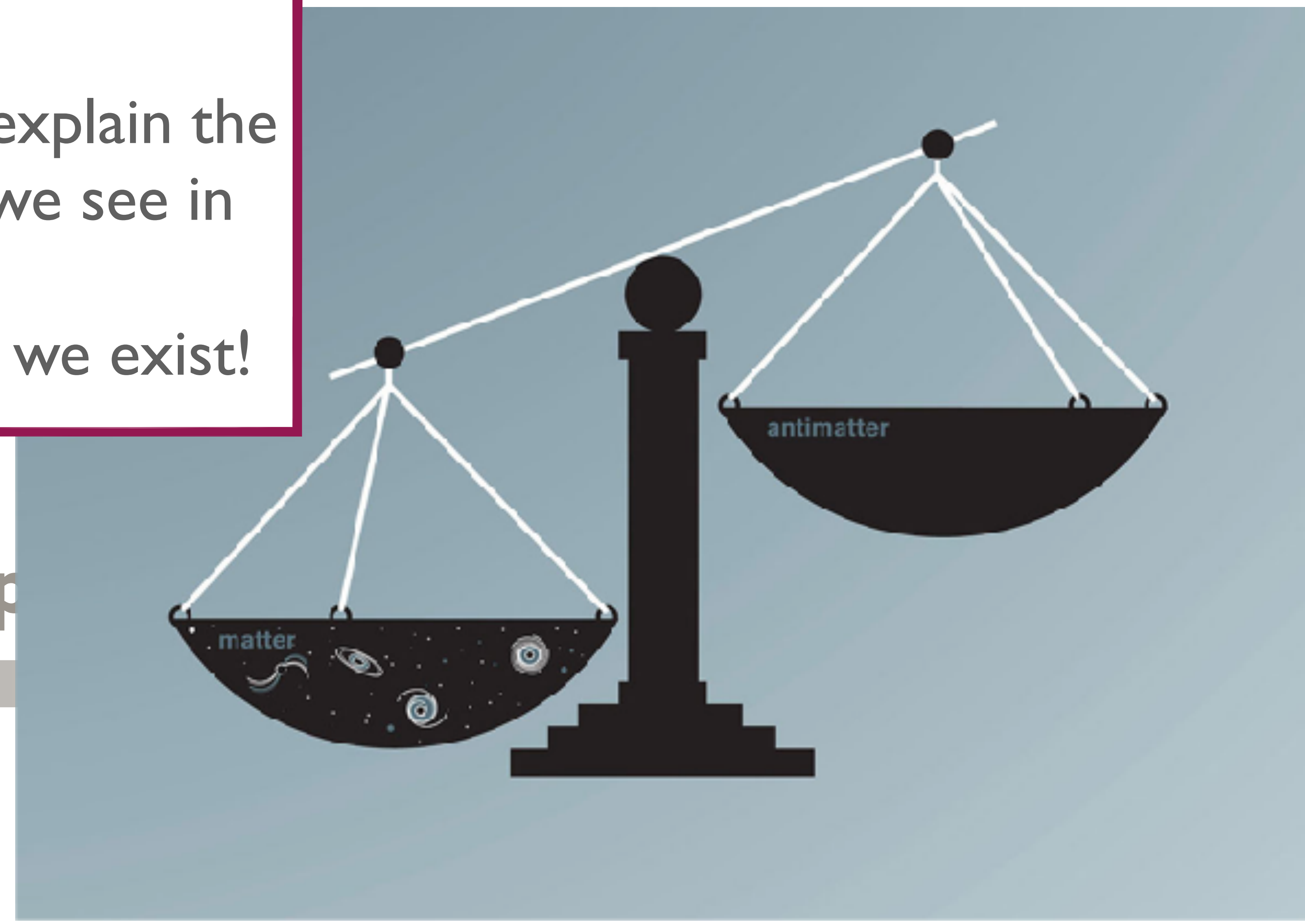
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \sim \text{something} +/- \text{something else} \times \sin\delta_{CP}$$

Reason #2 why neutrinos are exciting:

CP violation in neutrinos might explain the matter-antimatter asymmetry we see in the universe

→ neutrinos could explain why we exist!

: L



Muon neutrino disapp

Electron neutrino appearance

$\bar{\nu}$ ν

$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \sim$ something $+/-$ something else x $\sin\delta_{CP}$

Reason #3 why neutrinos are exciting:

There is a lot we don't know!

How do neutrinos interact in the nuclear medium?

Why is neutrino mixing so large?

Which neutrino is heaviest? Which is lightest?

Is neutrino oscillation different for neutrinos and antineutrinos?

How many neutrinos are there?

How much do neutrinos weigh?

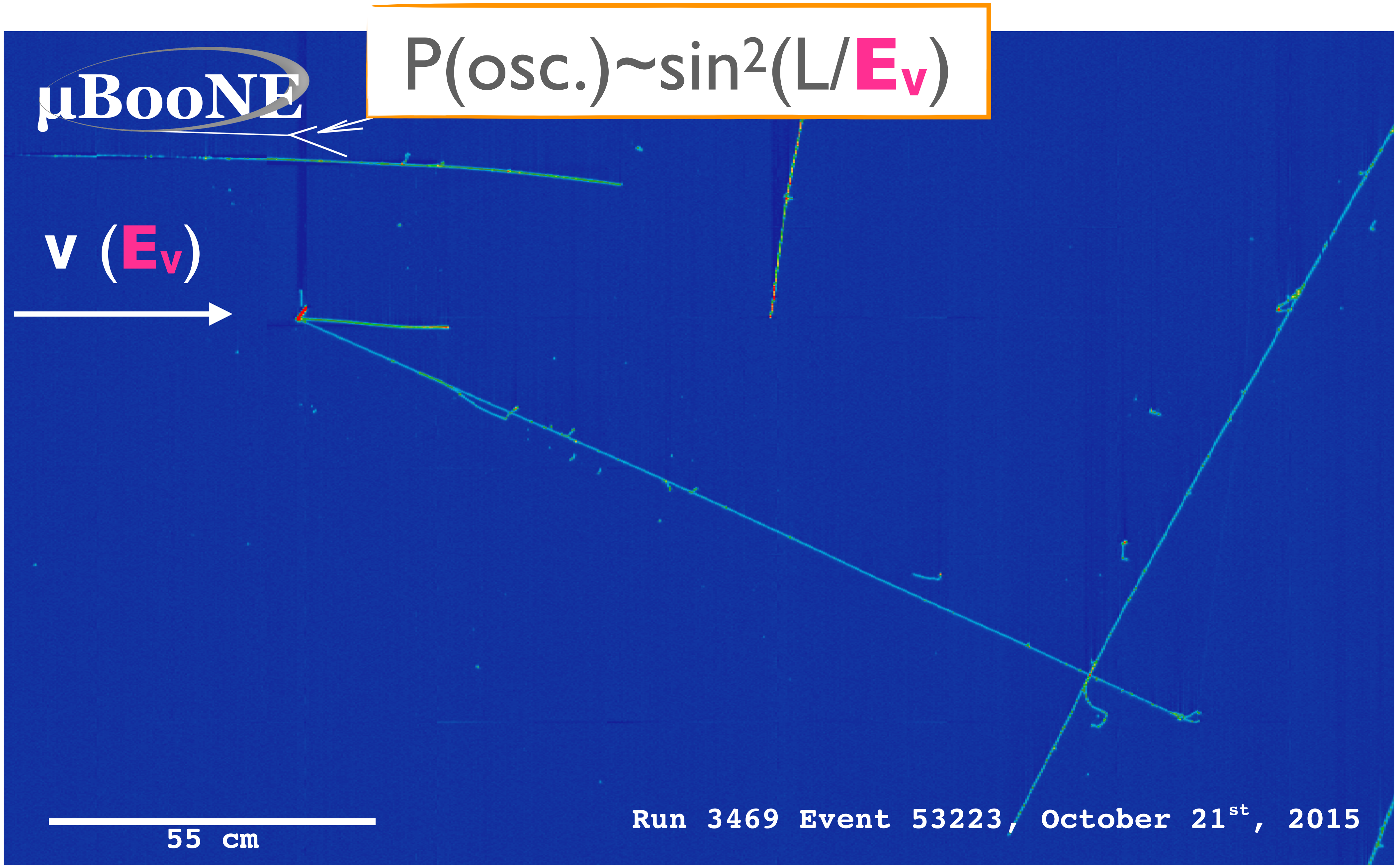
What else can neutrinos teach us?

Are neutrinos their own antiparticles?

Why are neutrino masses so much smaller than all other particles?

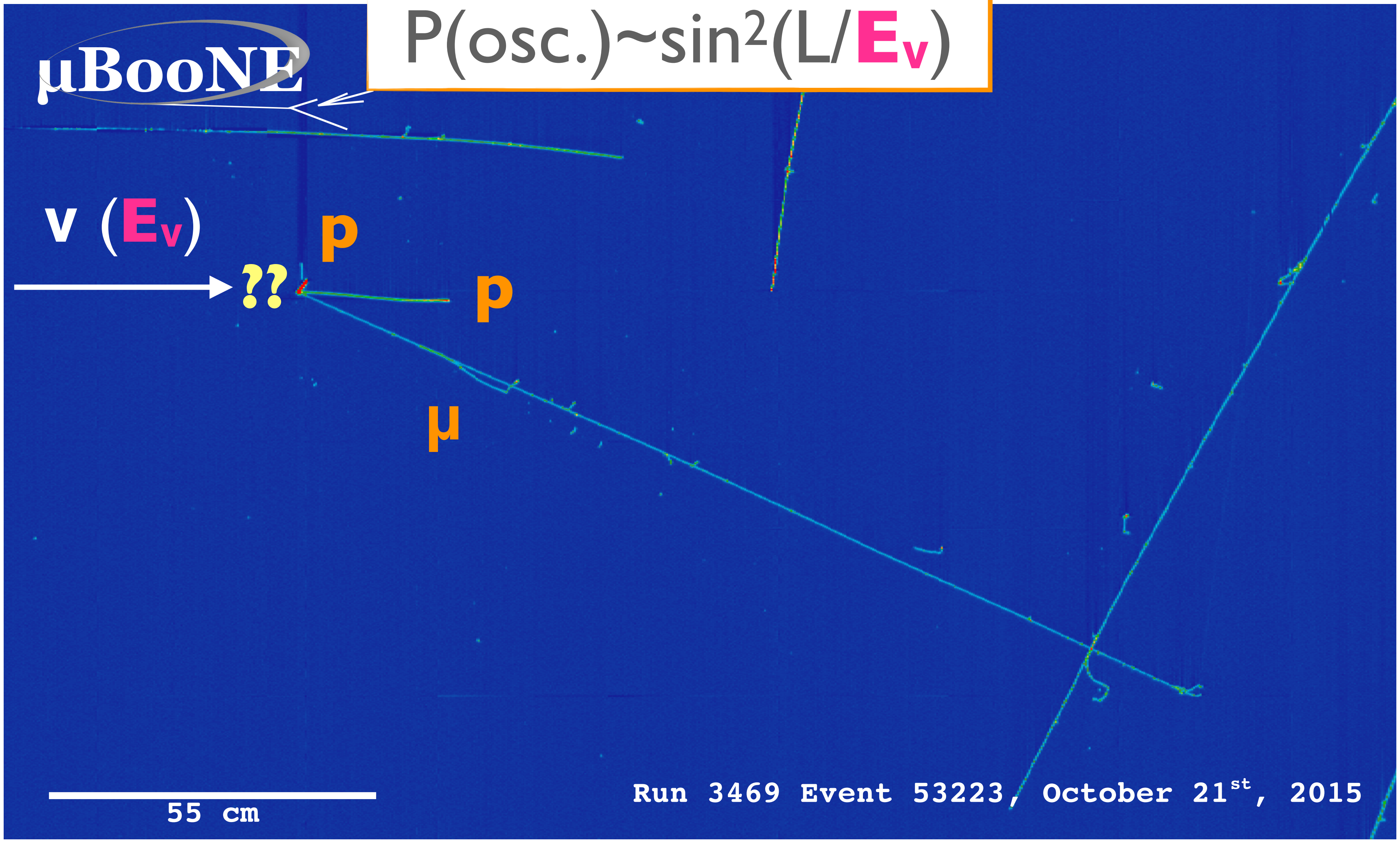
How do neutrinos interact in the nuclear medium?

NEUTRINO INTERACTIONS



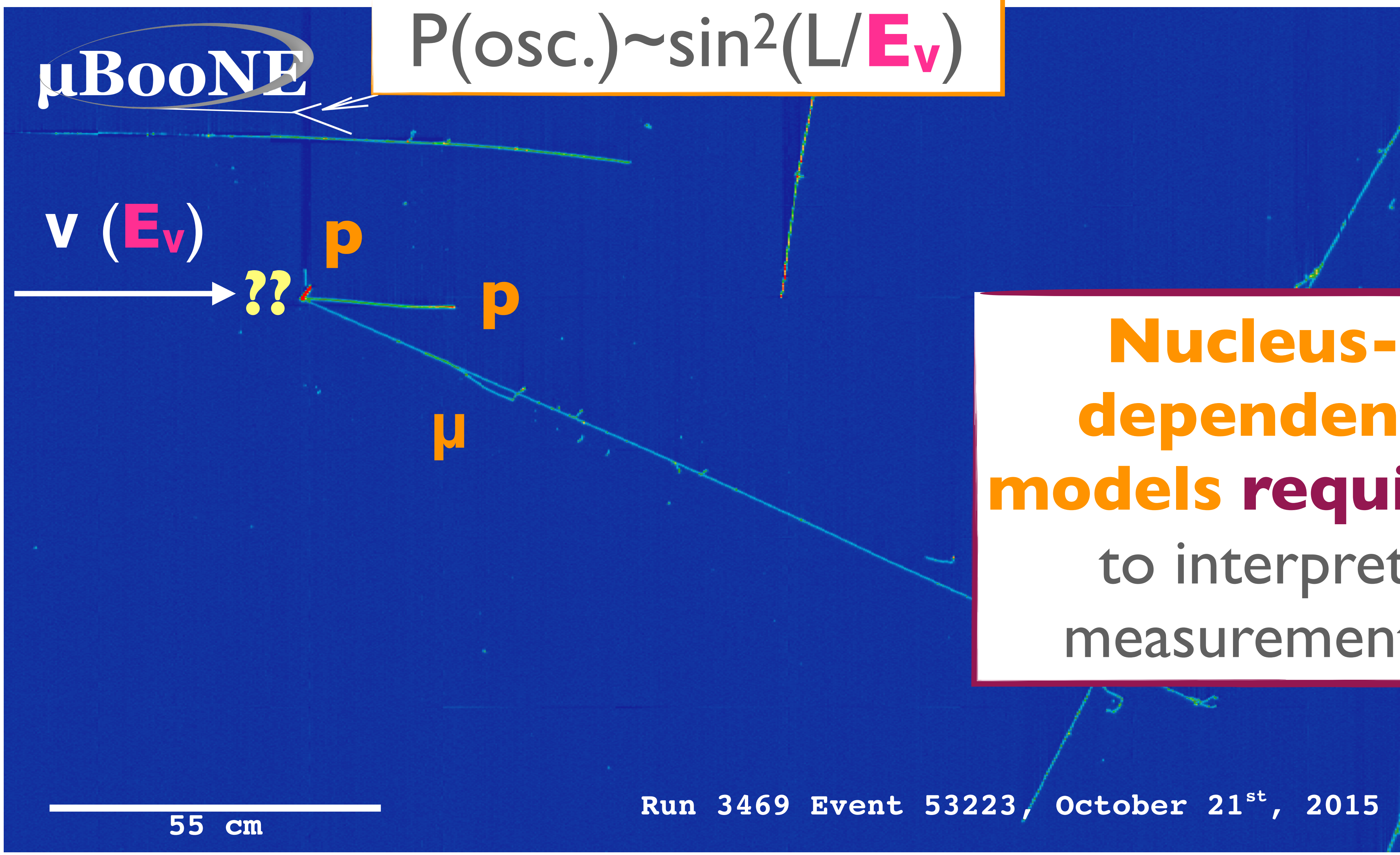
NEUTRINO INTERACTIONS

P(osc.)~$\sin^2(L/E_\nu)$



NEUTRINO INTERACTIONS

$P(osc.) \sim \sin^2(L/E_\nu)$



Nucleus-dependent models required to interpret measurements

MicroBooNE neutrino interaction measurements

- 9 publications, 18 public notes link
- 30+ world-leading measurements in progress

World's best data set of neutrino interactions on argon → vital input for future experiments using similar technology

7 new measurements released/ previewed at Neutrino 2022 last month!

How many neutrinos are there?

There have been a number of anomalies observed in the past 20-odd years that don't quite fit with the three-neutrino picture we know and love

Experiment	Type	Anomaly
LSND	DAR	$\bar{\nu}_e$ appearance
MiniBooNE	SBL accel.	ν_e appearance
MiniBooNE	SBL accel.	$\bar{\nu}_e$ appearance
GALLEX/SAGE/BEST	Source - e capture	ν_e disappearance
Reactors	Beta decay	$\bar{\nu}_e$ rate
		$\bar{\nu}_e$ shape
ANITA	High energy	High-energy events

Disclaimer: not an exhaustive list!

See also:
R. Guennette, "Short-Baseline Neutrinos", APS-DPF 2019 link
G. Karagiorgi, "Short-baseline neutrino experiments and phenomenology", INSS 2019 link
K. N. Abazajian et. al., Light Sterile Neutrinos: A White Paper, arXiv:1204.5379 [hep-ph] (2012) link

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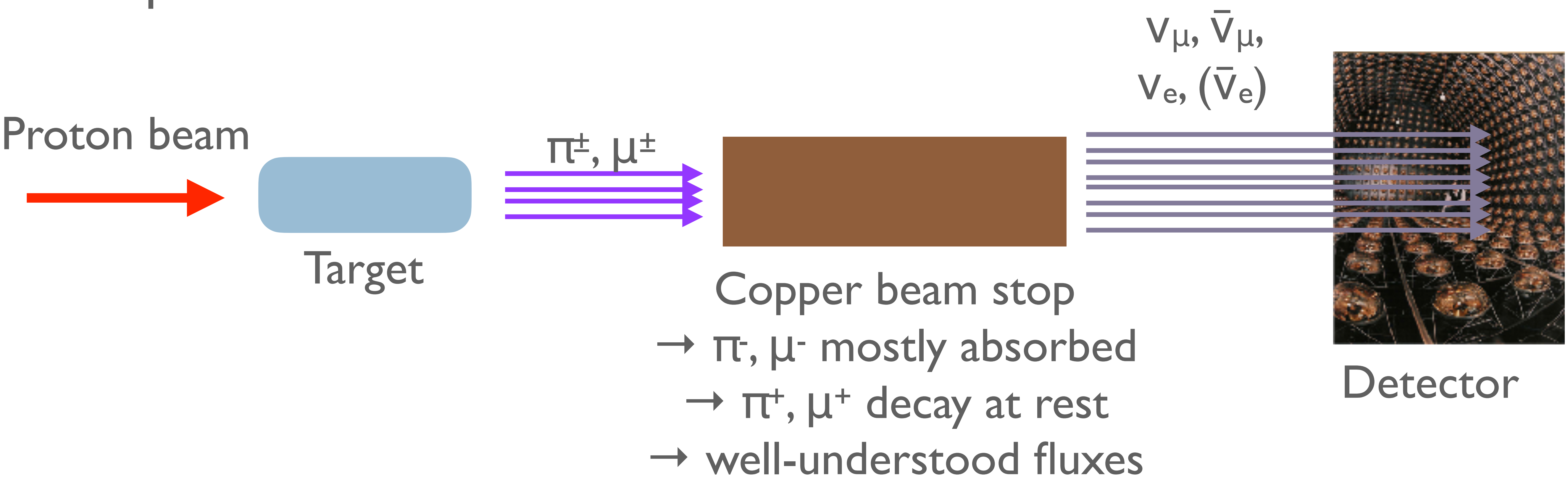
ANOMALIES: LSND

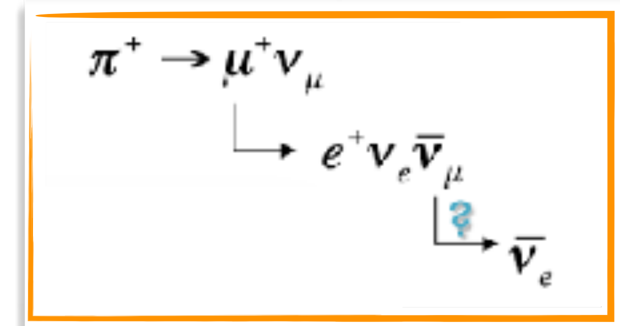
- **L**iquid **S**cintillator **N**eutrino **D**etector: μ^+ decay at rest experiment at Los Alamos National Lab

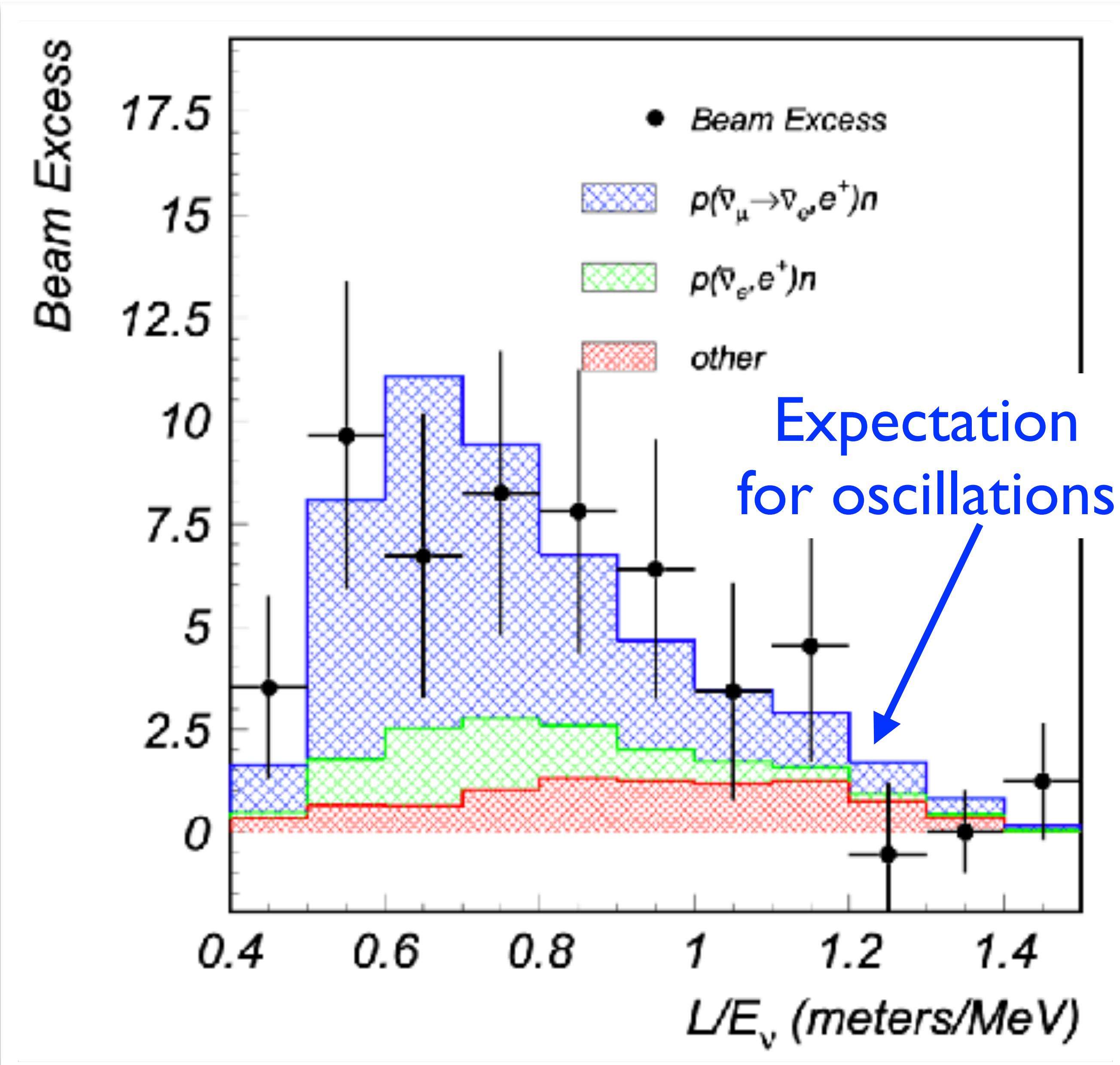


$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Phys. Rev. D 64, 112007

ANOMALIES: LSND

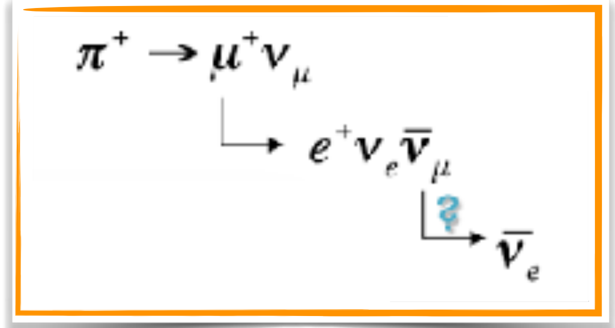


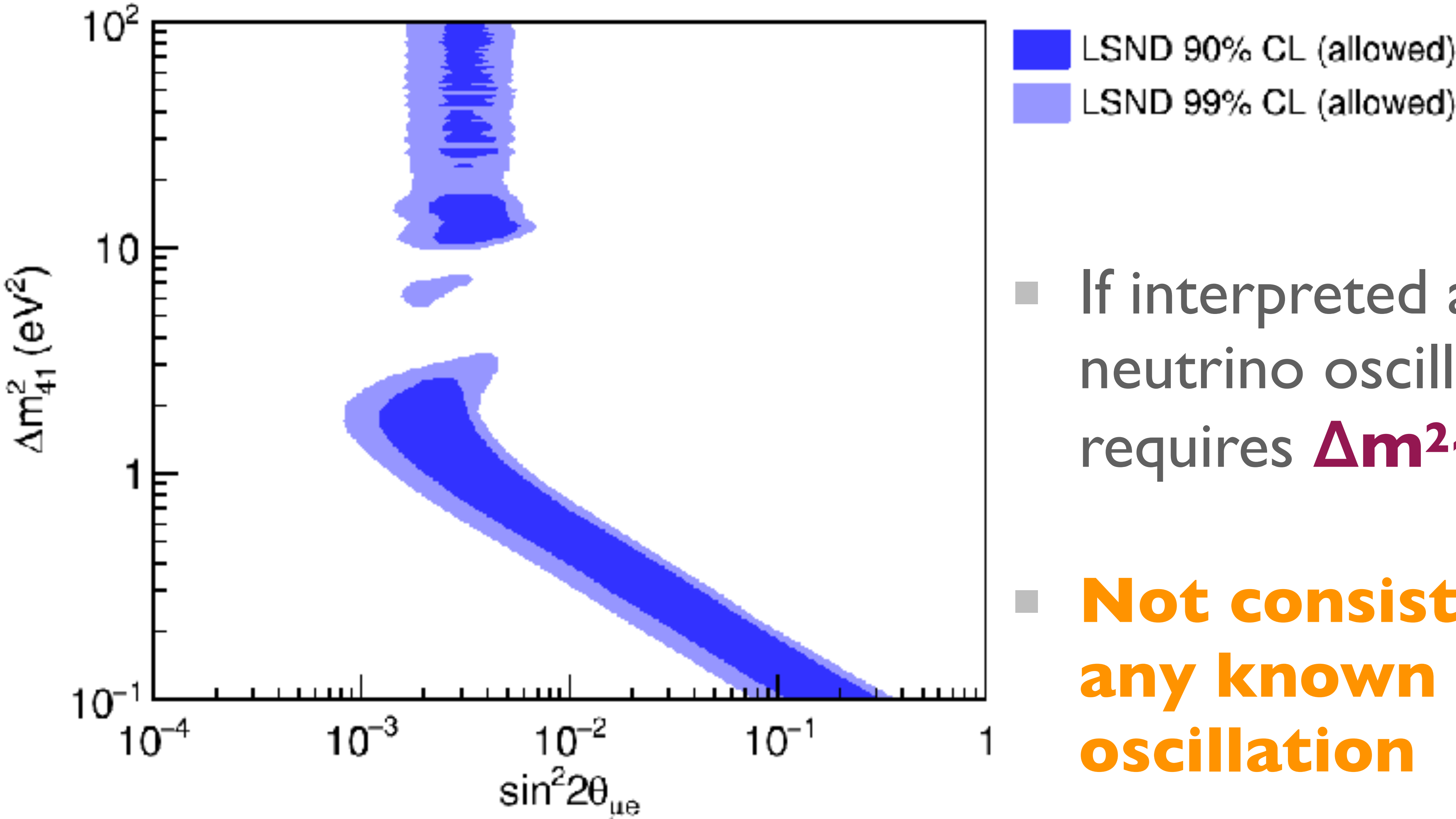


Phys. Rev. D 64, 112007

- Observed excess of $\bar{\nu}_e$ at 3.8σ
- If interpreted as two-flavour neutrino oscillation, requires **$\Delta m^2 \sim 0.2$-$10 eV^2$**
- **Not consistent with any known 3-flavour oscillation**

ANOMALIES: LSND





Phys. Rev. D 64, 112007

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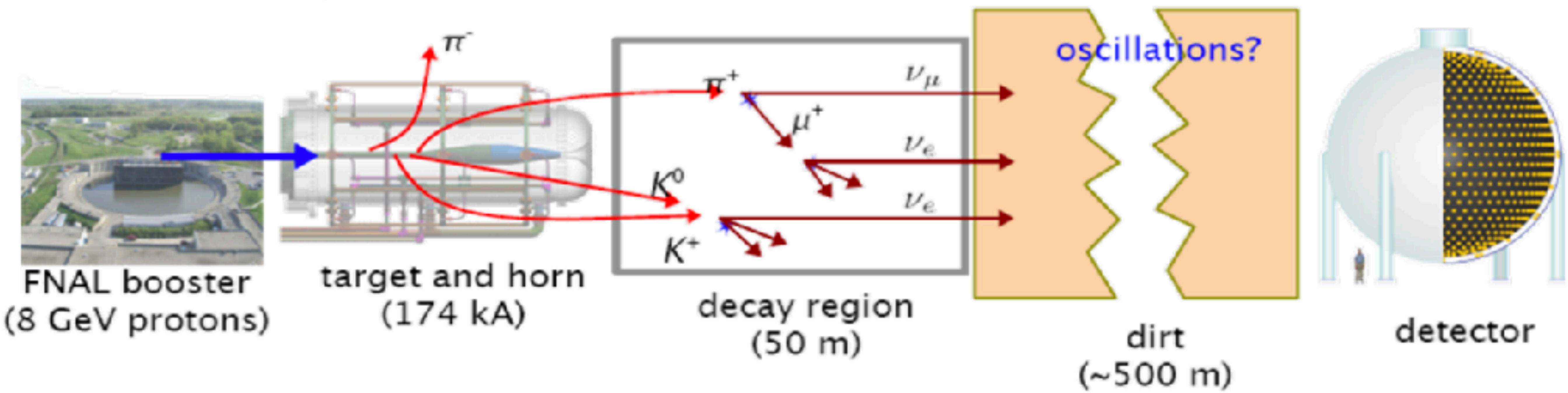
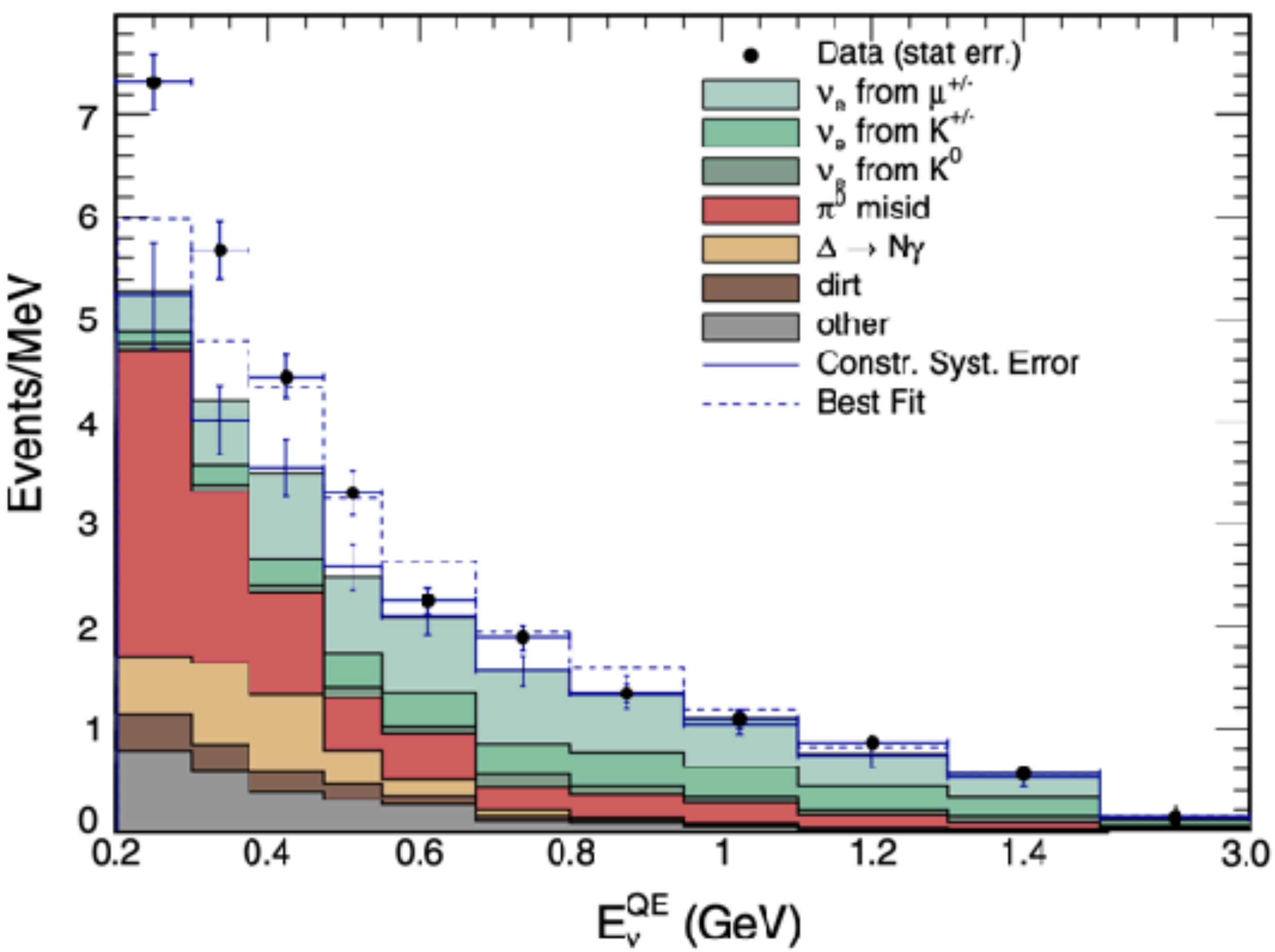
ANOMALIES: MINIBOONE



- Similar L/E as LSND: if an oscillation really exists, should see it here too
- Different energy, detector, beam, event signatures, backgrounds

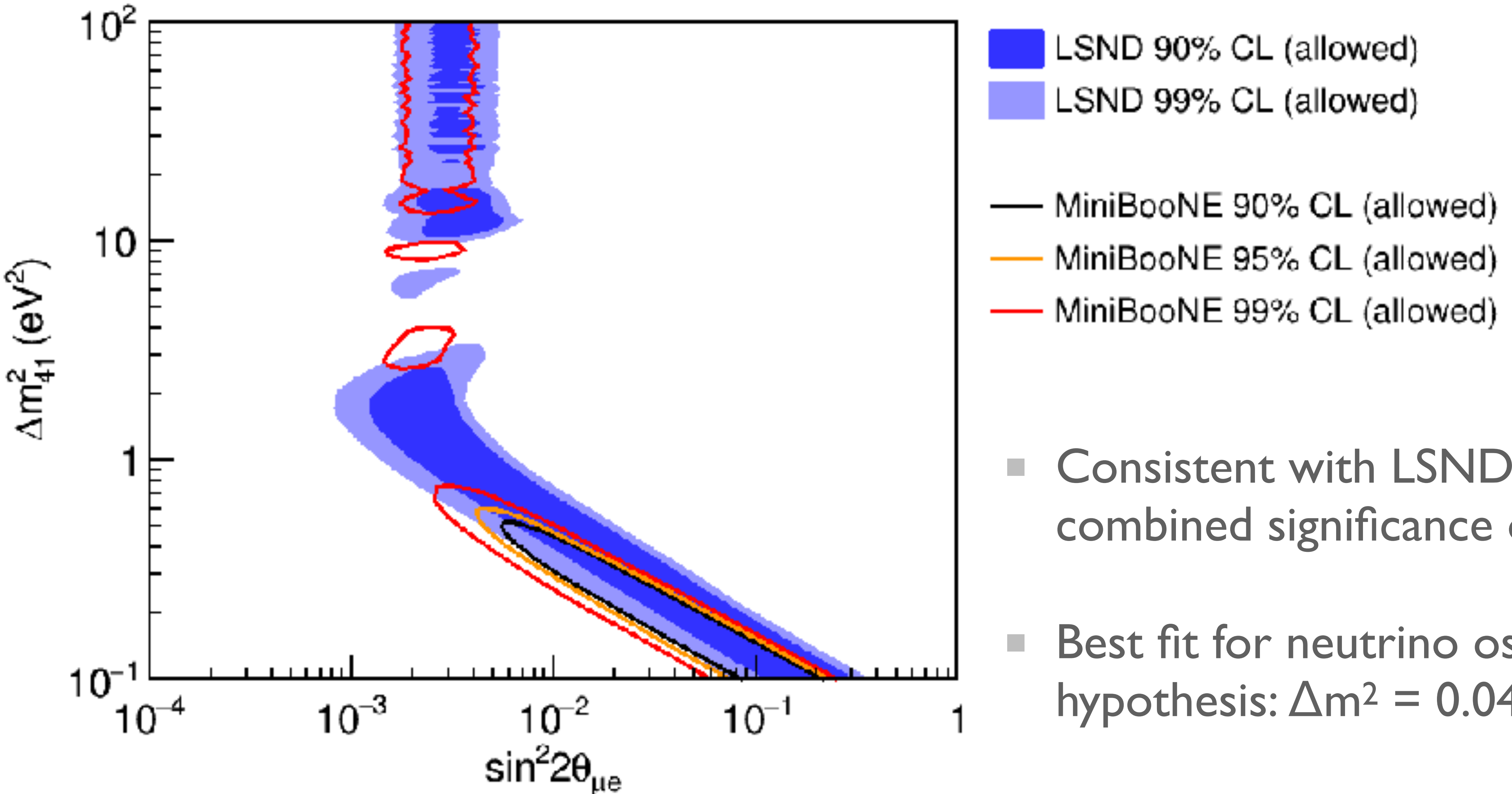
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



- Recently released updated results (2021) with x2 more data than original anomaly (2009)
- 4.8σ excess of measured ν_e and $\bar{\nu}_e$ over prediction, focused at low energy
- Consistent with LSND results: combined significance of 6.1σ
- Best fit for neutrino oscillation hypothesis: $\Delta m^2 = 0.04\ eV^2$

Phys. Rev. D 103, 052002

THE MINIBOONE LOW-ENERGY EXCESS (LEE)



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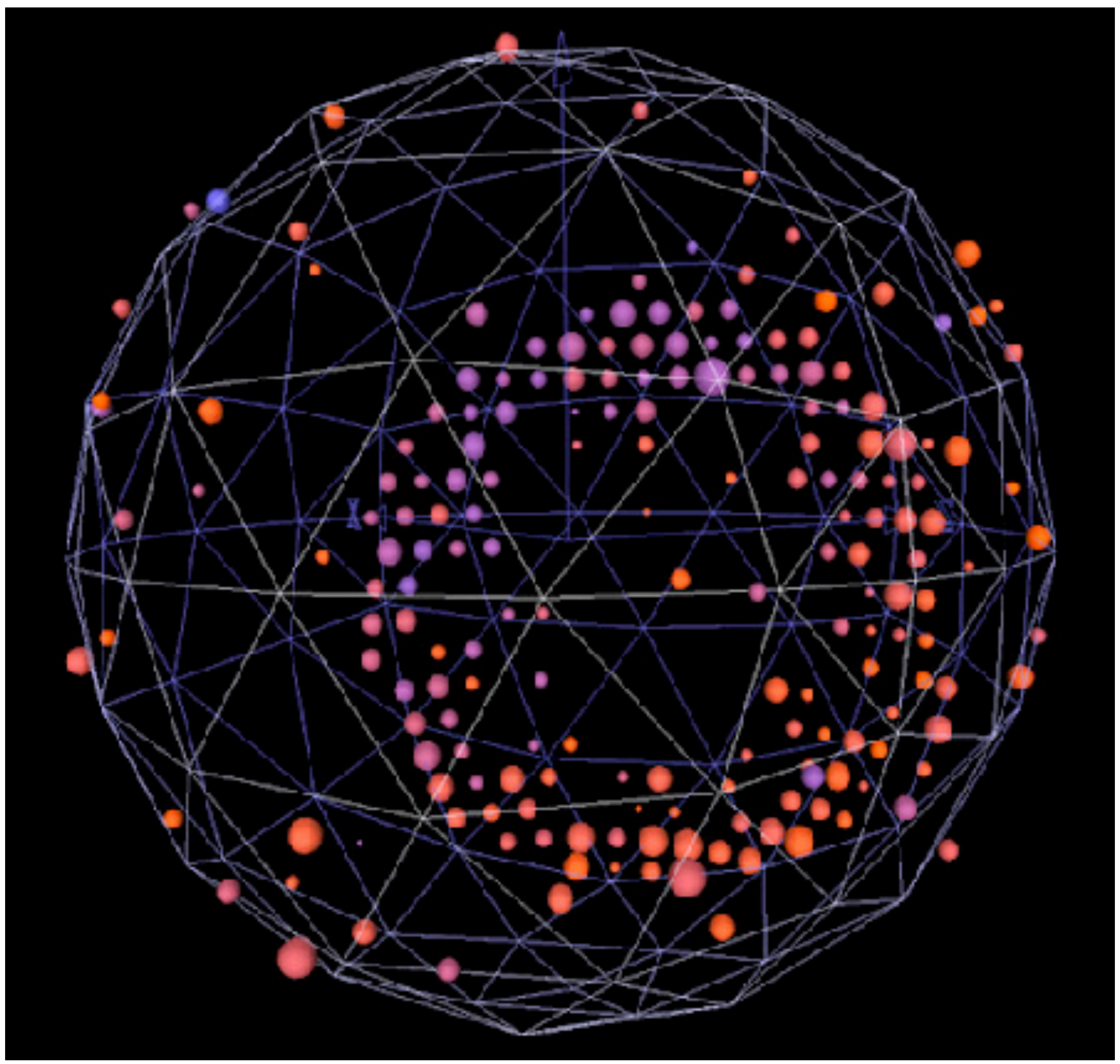
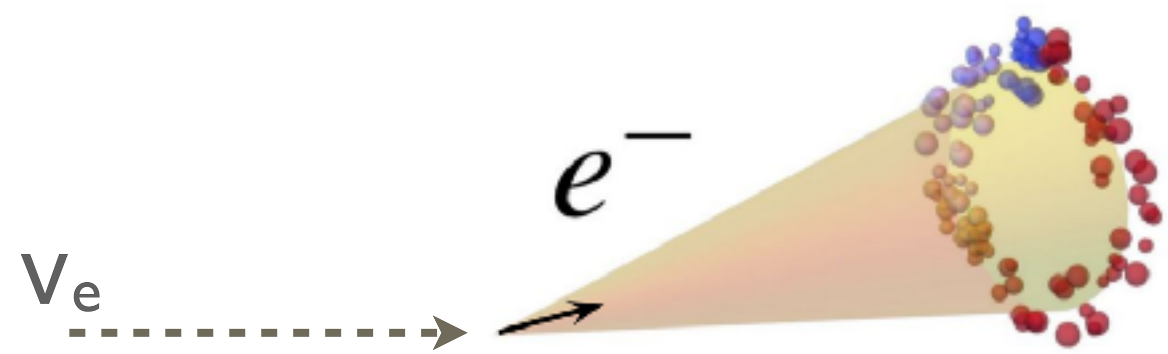
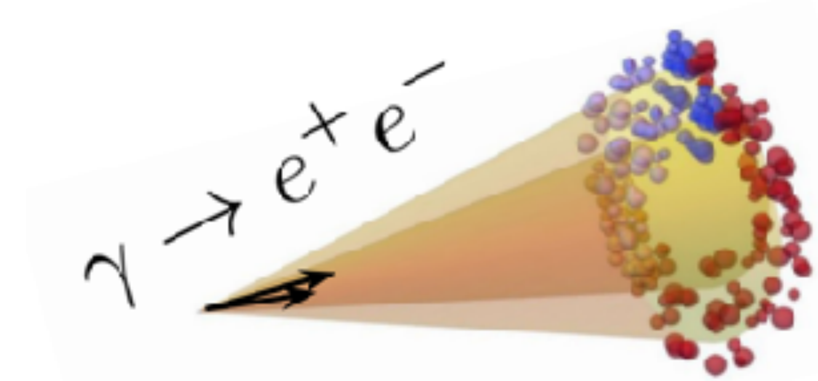
MINIBOONE



- 800-ton mineral oil (CH_2) Cherenkov detector
- Detect Cherenkov ring from **electrons** produced in **ν_e CC scattering** interactions



- However, **photons** produce identical Cherenkov rings



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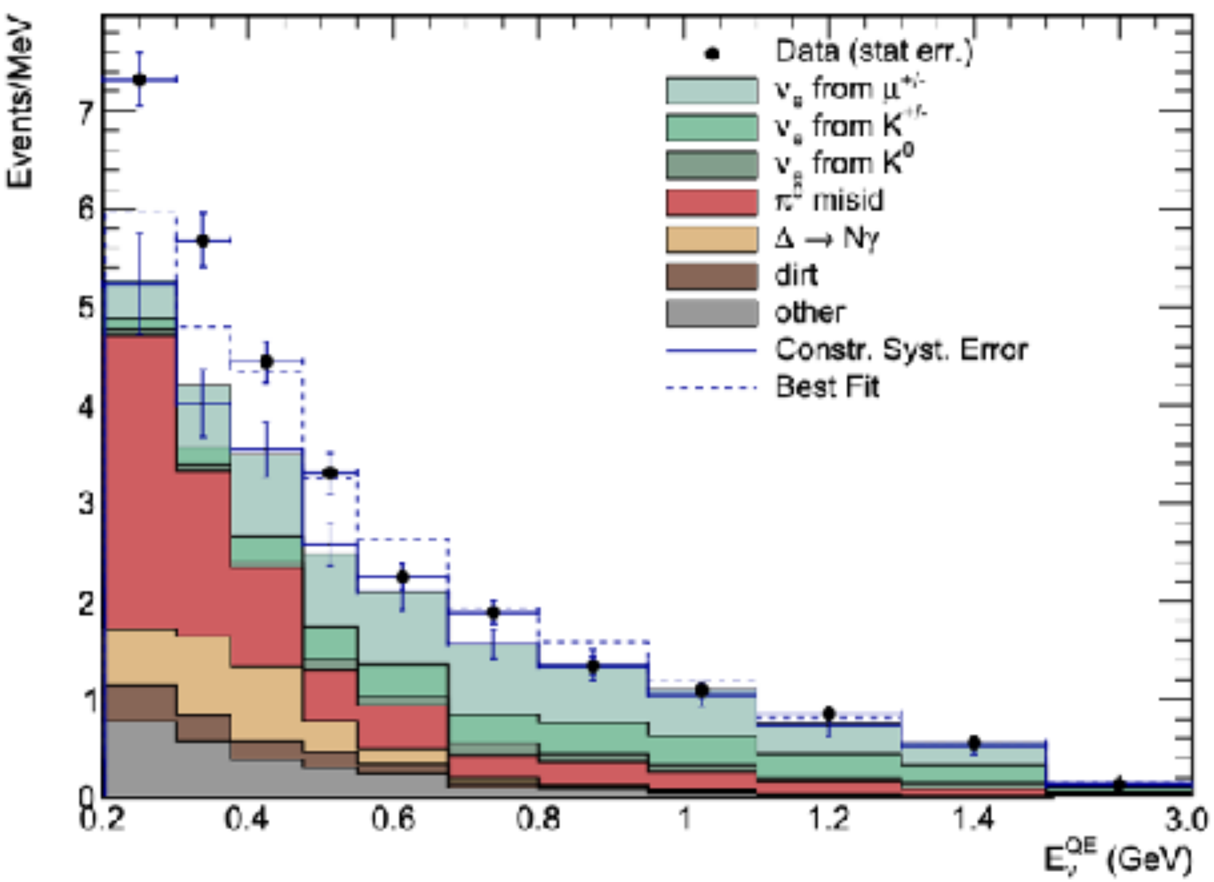
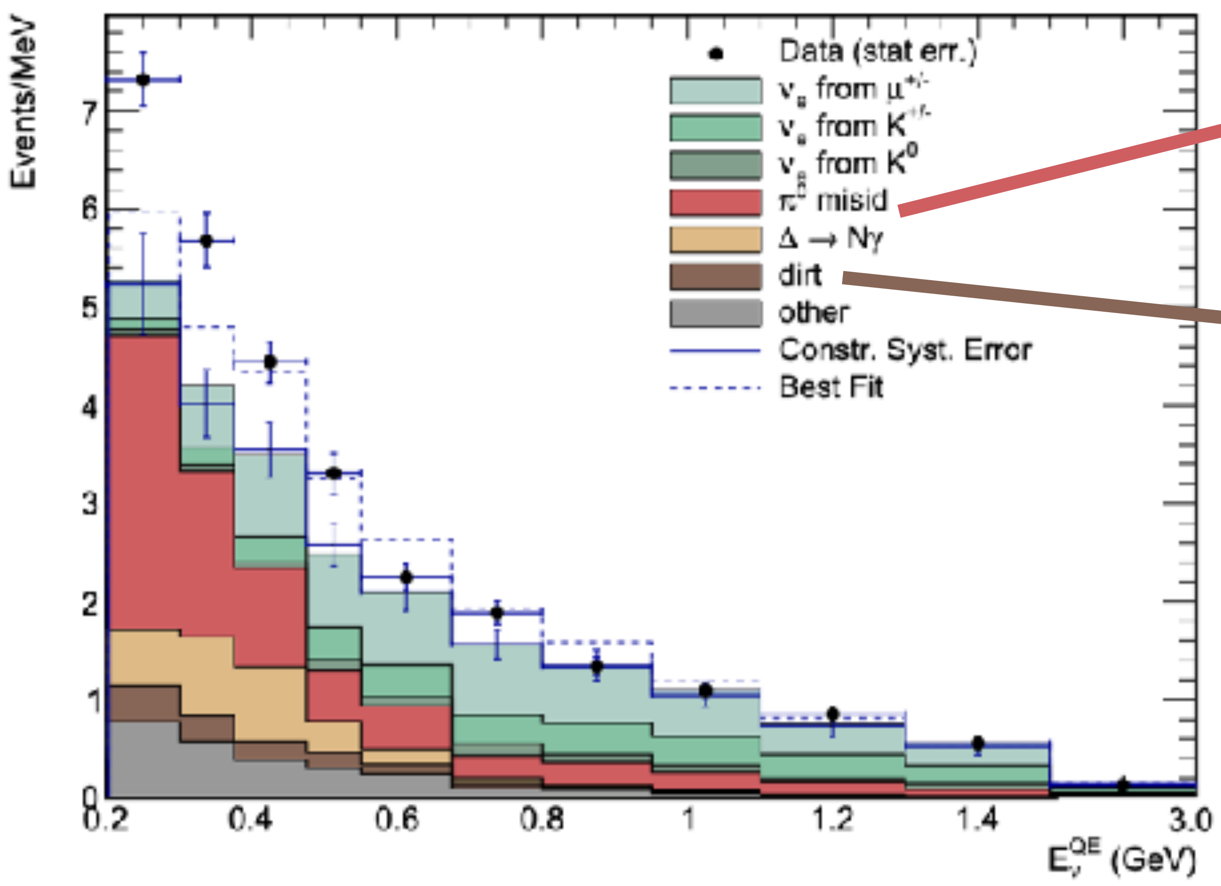


Is the excess electrons?

- Sterile neutrino oscillations → difficult to explain MiniBooNE excess and all other global data
- Best-fit 2-neutrino sterile oscillation appearance spectrum does not predict data well at very low energies
- More complex models can help
  - Mixed oscillations and decay
  - Resonance matter effects
  - Additional sterile neutrinos
  - Non-unitary mixing
  - …and many more!

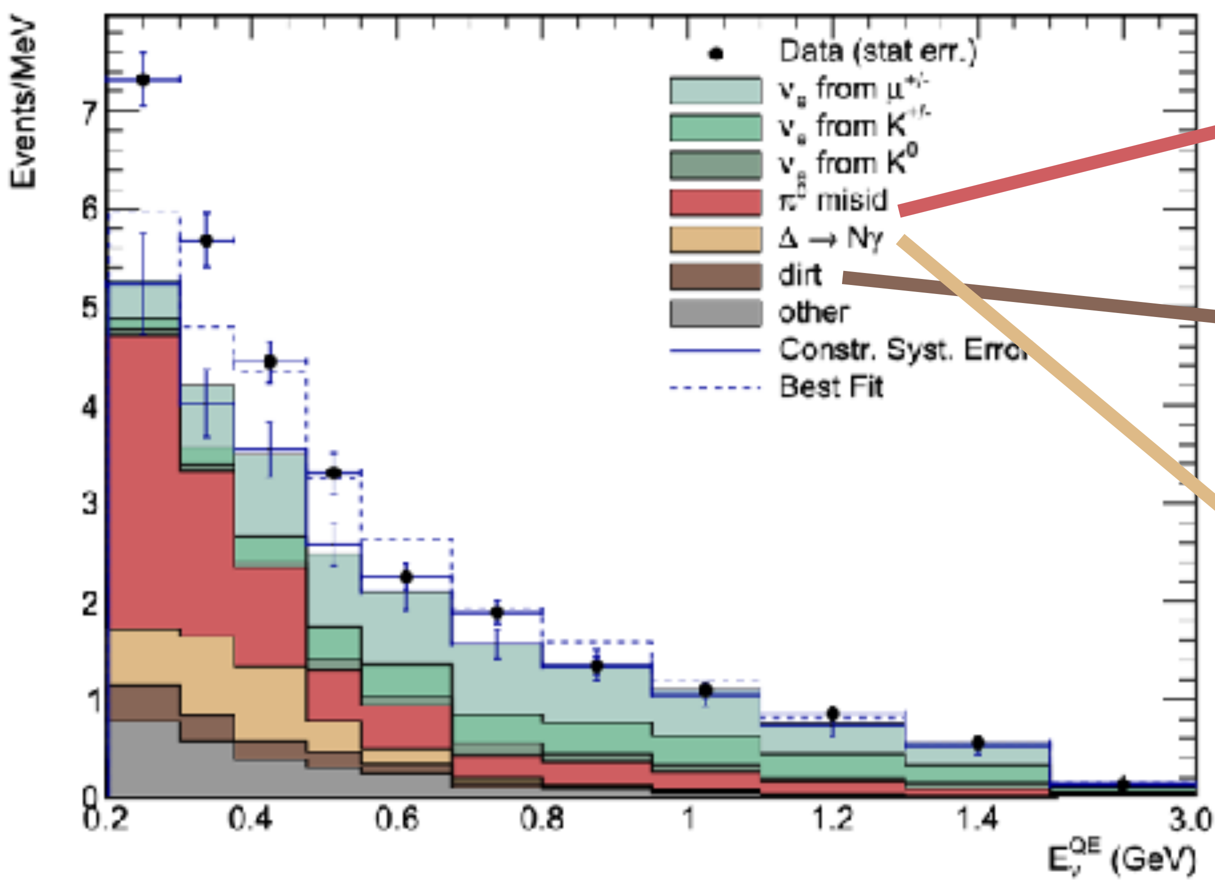
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



Is the excess photons?

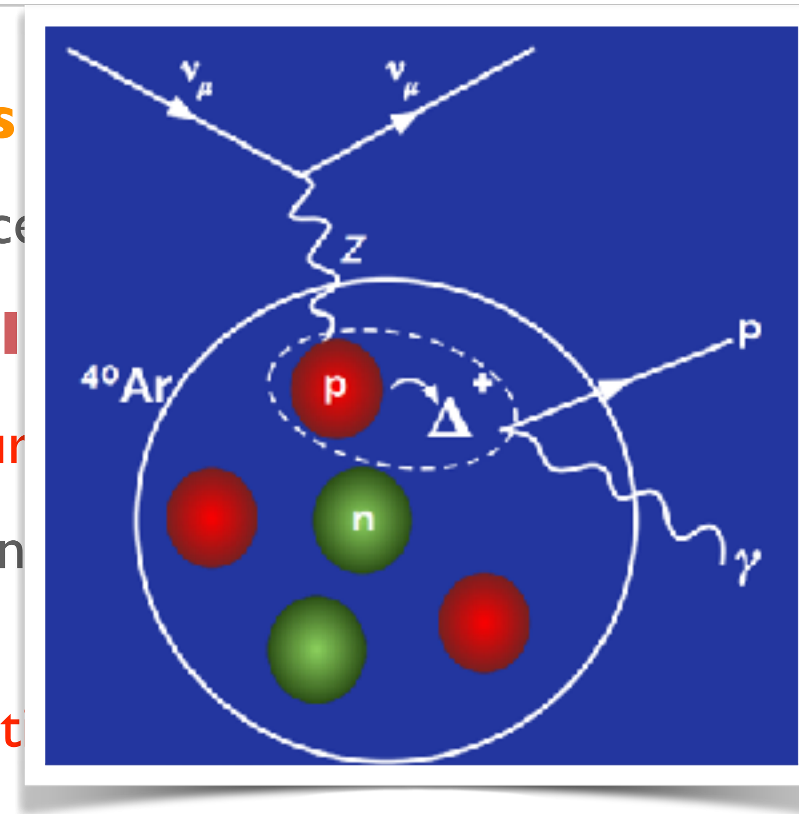
- Several sources of photon backgrounds:
- **NCπ^0 mis-ID**
  - → measured in-situ
- **Dirt** (neutrino interactions outside the detector)
  - → beam timing

THE MINIBOONE LOW-ENERGY EXCESS (LEE)

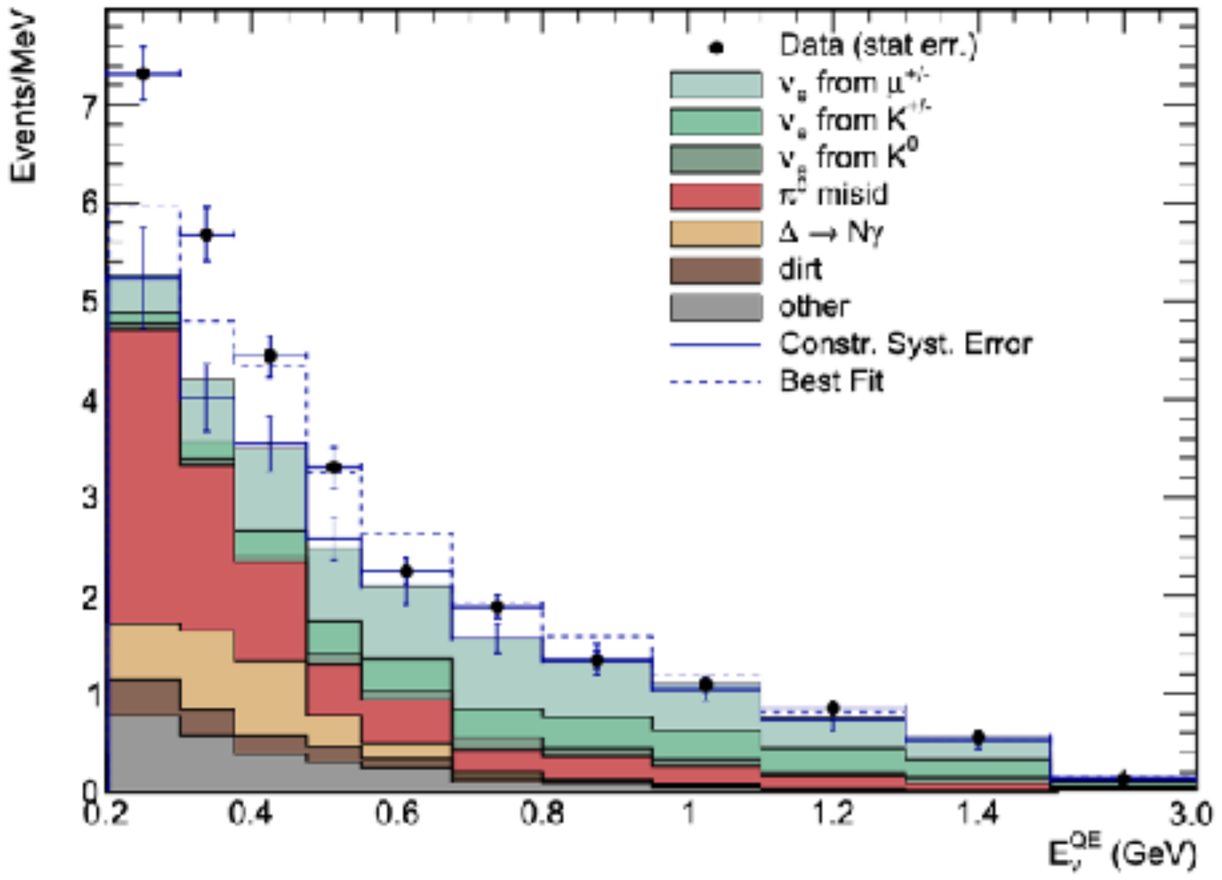


Is the excess

- Several source
  - **NCπ⁰ mis-I**
    - → measur
  - **Dirt** (neutrin detector)
    - → beam t
  - **NC Δ→Nγ**
    - → not constrained directly - predicted from NCπ⁰ rate and theoretical branching fraction
    - Need x3.18 increase to explain excess
    - → to be investigated…



THE MINIBOONE LOW-ENERGY EXCESS (LEE)



Or neither?

- Rich phenomenology developed in recent years
- I'll come back to this!

For now, it's clear that we need more information…

MICROBOONE

MicroBooNE: 170 ton Liquid Argon Time Projection Chamber (LArTPC)

- Stable detector operation 2015-2021: **longest-running LArTPC to date**
  - >95% DAQ uptime
  - 1.52x10^{21} POT collected in total (analyses shown here use subsets, not full POT)

Grateful to Fermilab Accelerator Division, Cryogenics team, Operations team, and Scientific Computing Division!


Rail Station 14

FERMILAB'S NEUTRINO BEAMS

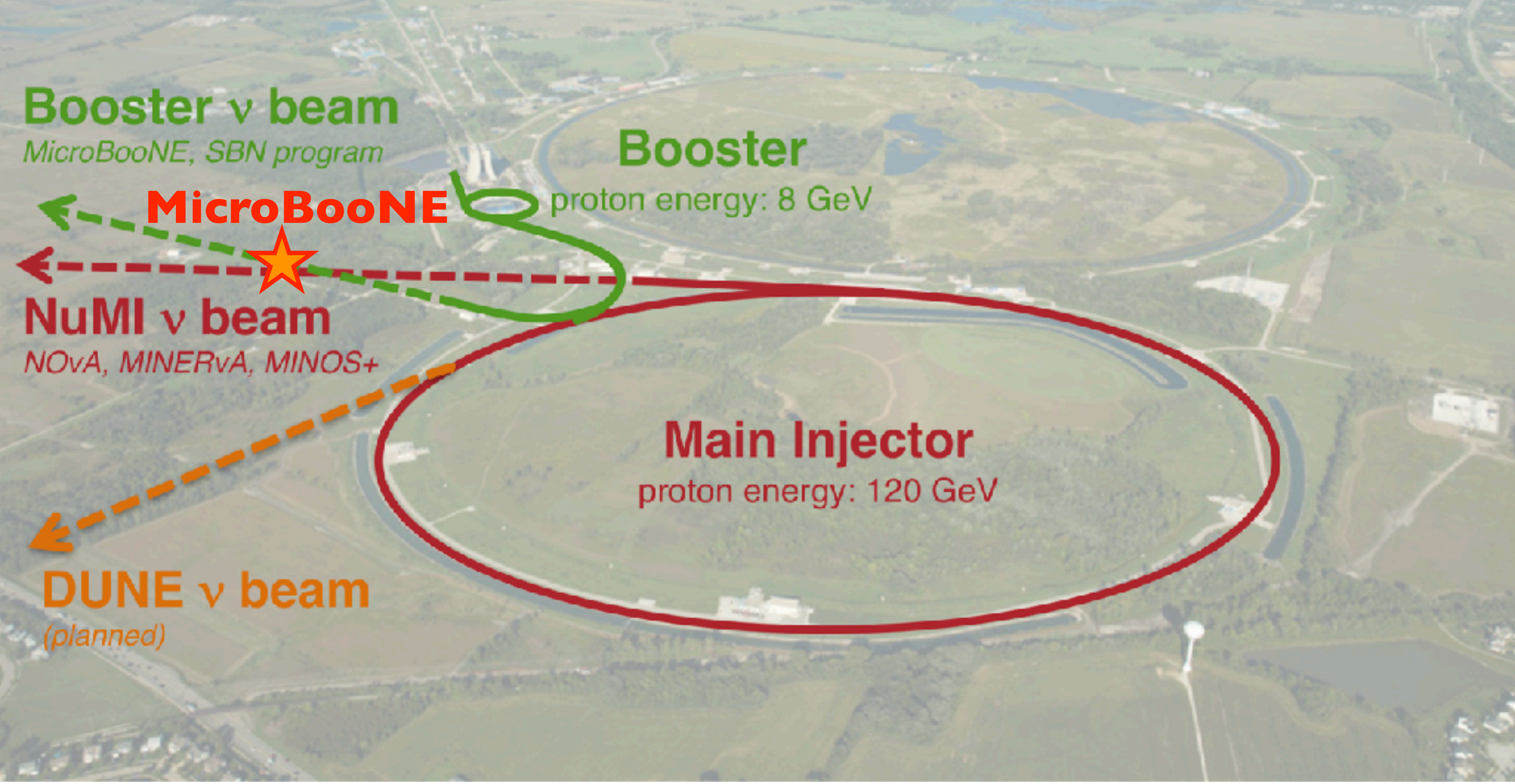
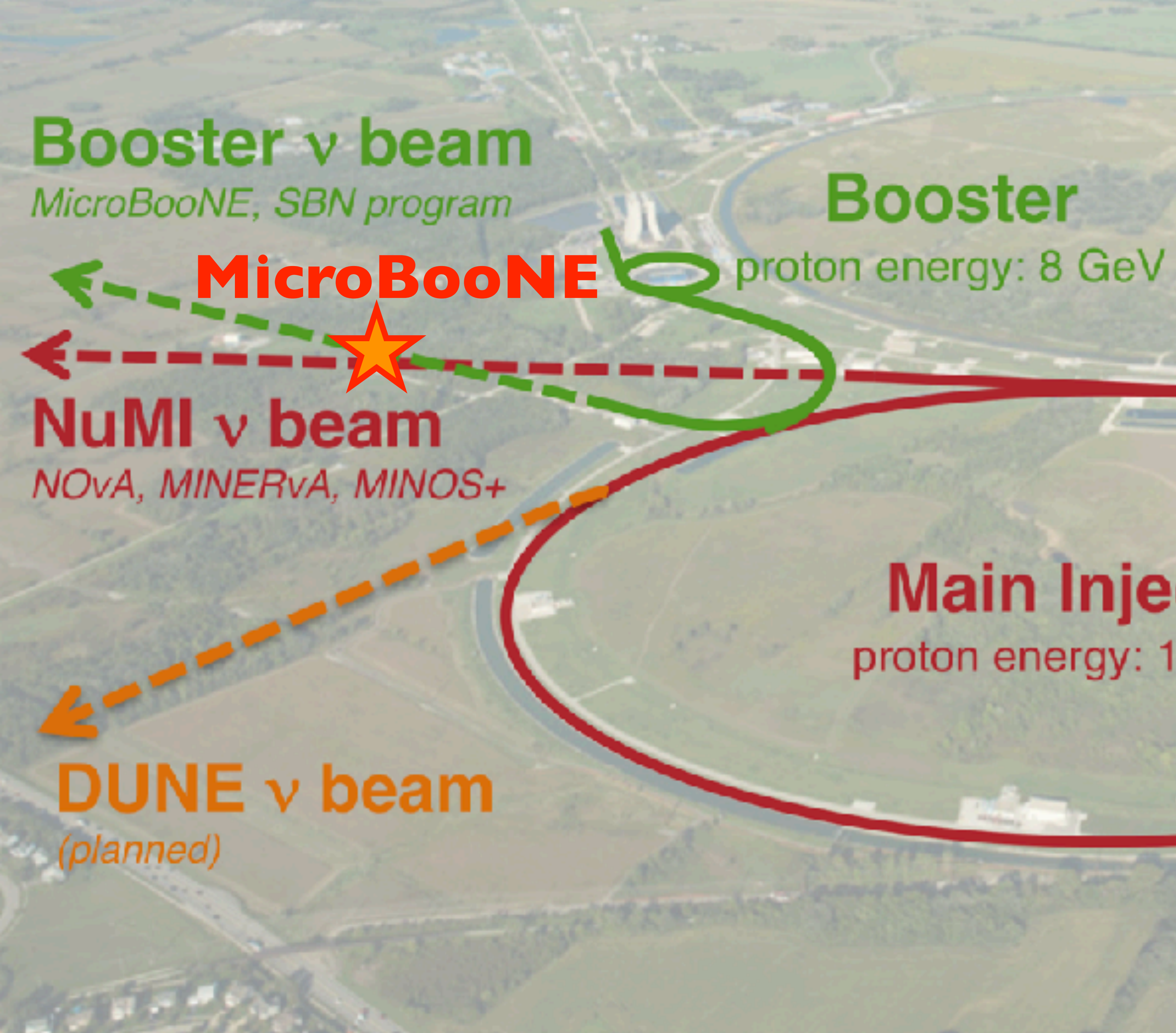


Image: G. Zeller

FERMILAB'S NEUTRINO BEAMS



Booster Neutrino Beam (BNB): 463m

>99% $\nu_\mu/\bar{\nu}_\mu$ at peak

$\langle E_\nu \rangle$ = 850 MeV

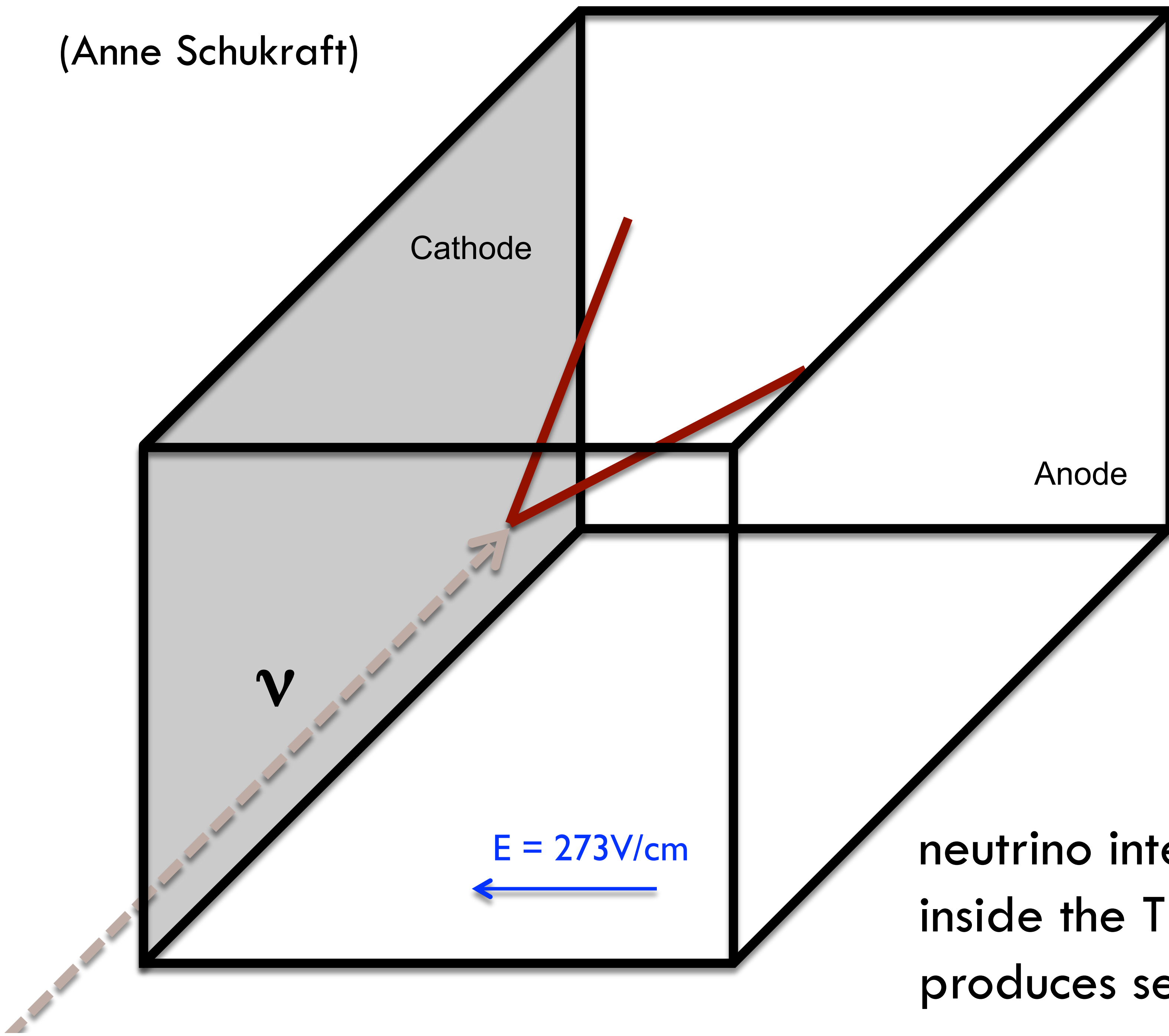
NuMI Neutrino Beam (NuMI): ~680m

8° off axis → 4% ν_e

Image: G. Zeller

LIQUID ARGON TPC

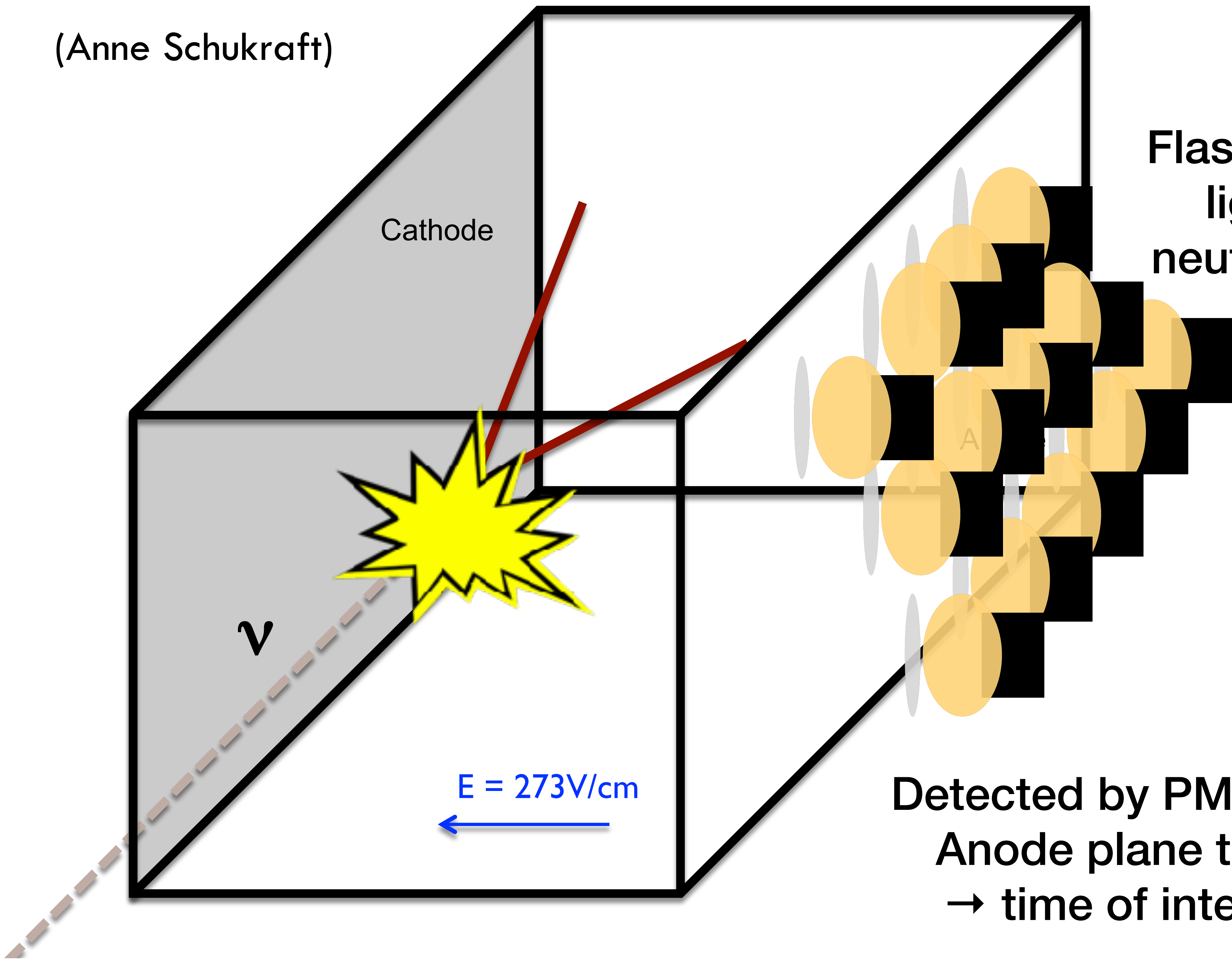
(Anne Schukraft)



neutrino interacts with the argon inside the TPC volume and produces secondary particles

LIQUID ARGON TPC

(Anne Schukraft)

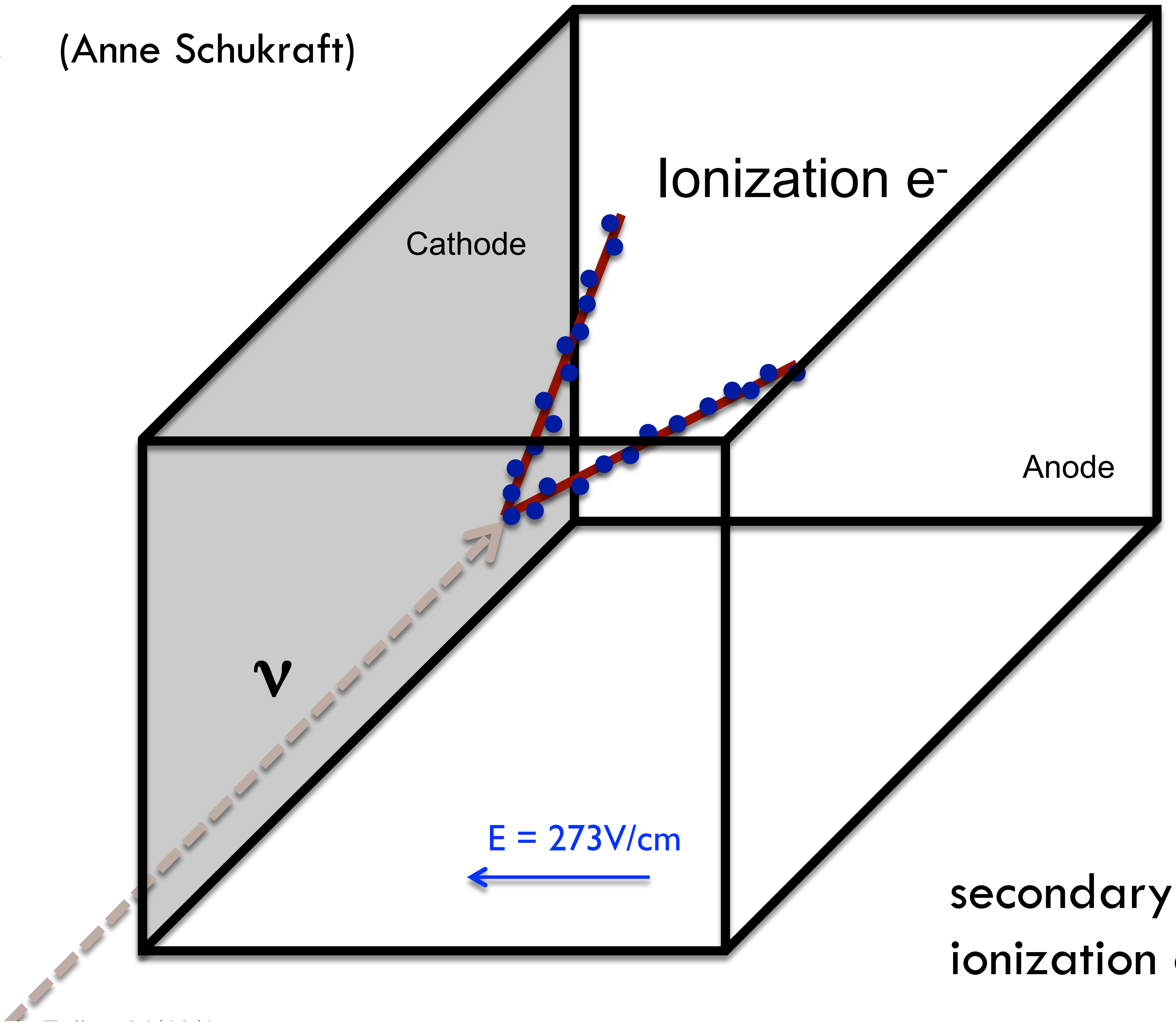


Flash of scintillation light at time of neutrino interaction

Detected by PMTs behind Anode plane to get t0 → time of interaction

LIQUID ARGON TPC

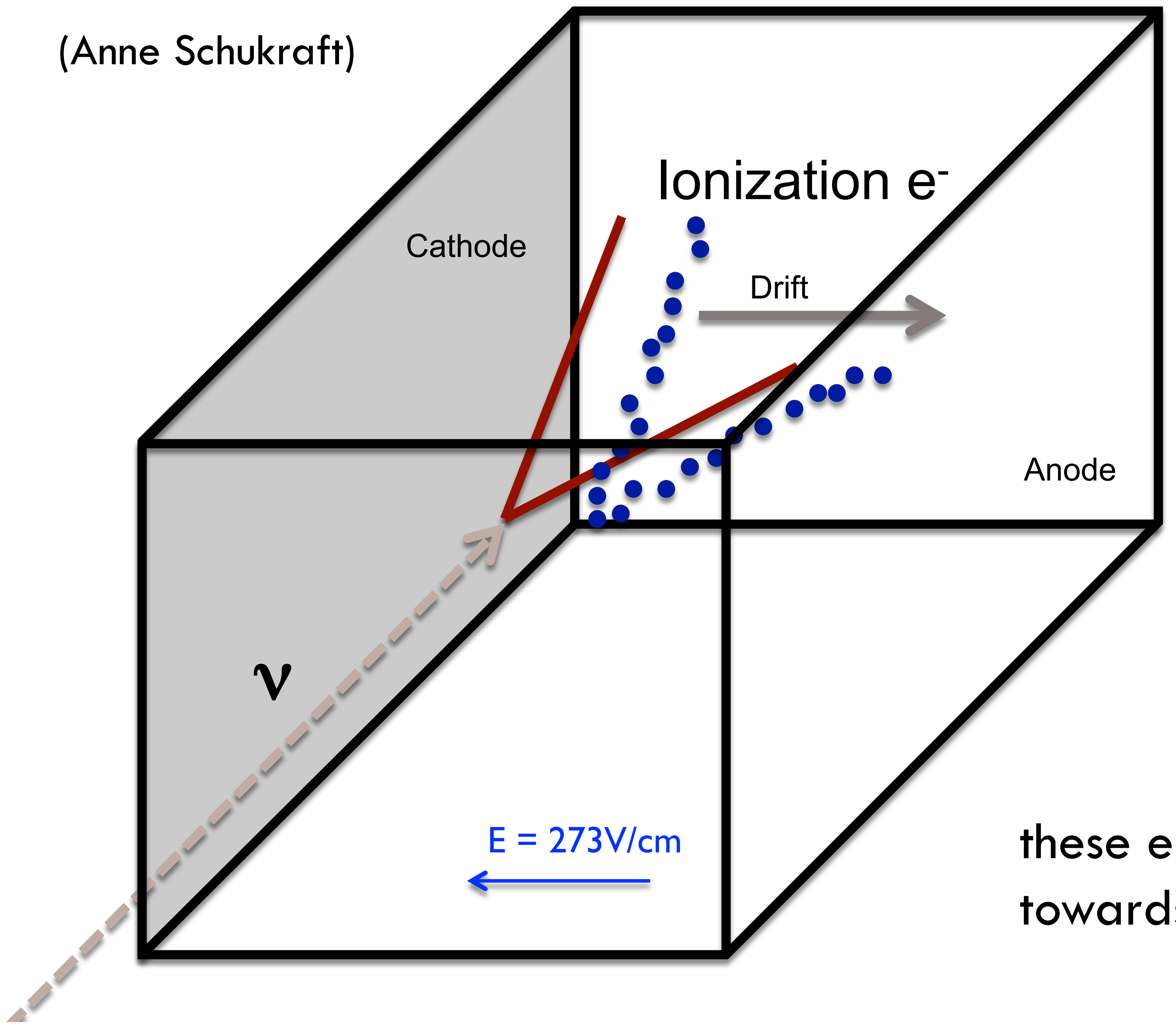
(Anne Schukraft)



secondary particles produce ionization electrons

LIQUID ARGON TPC

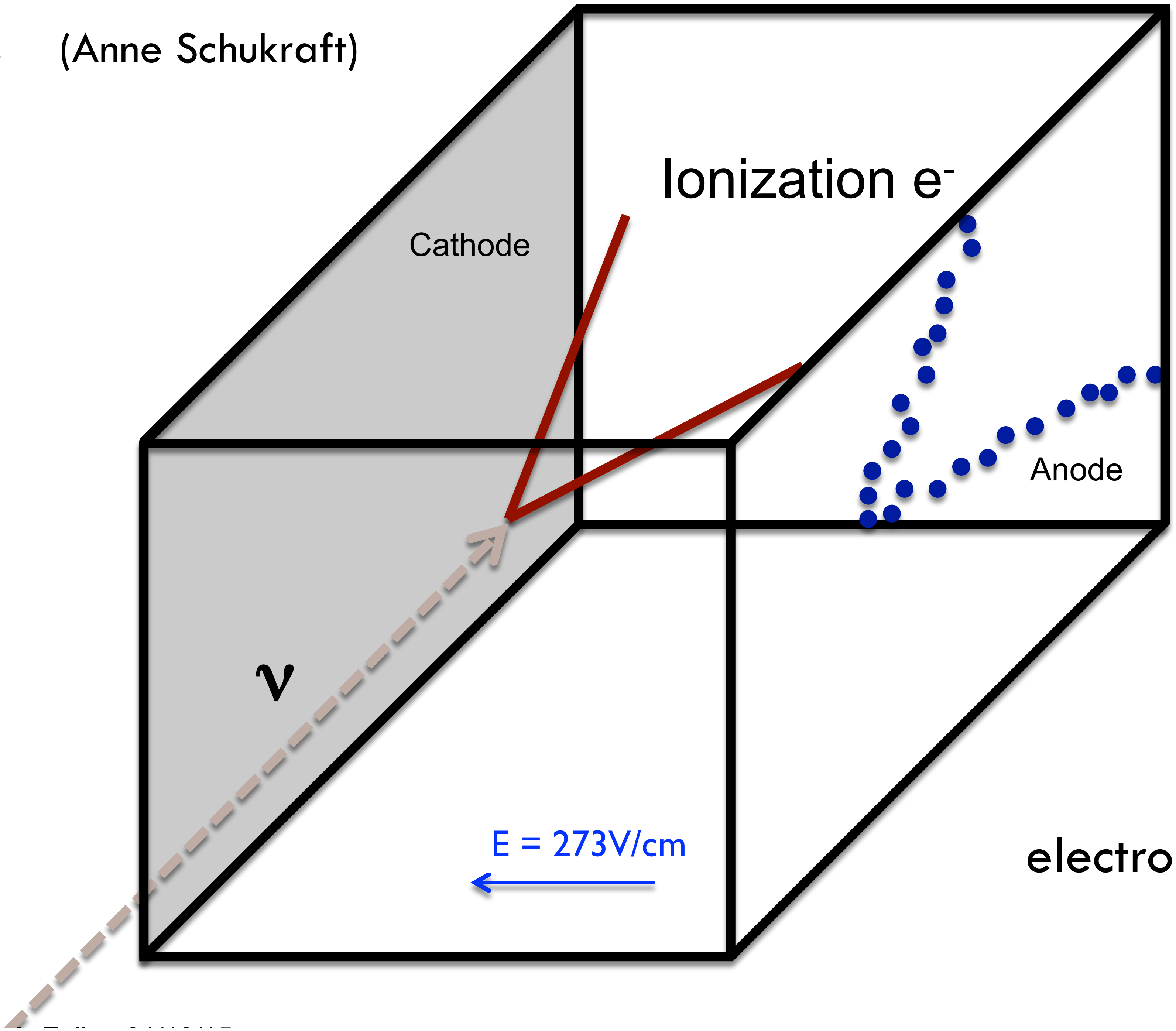
(Anne Schukraft)



these electrons drift towards the anode

LIQUID ARGON TPC

(Anne Schukraft)

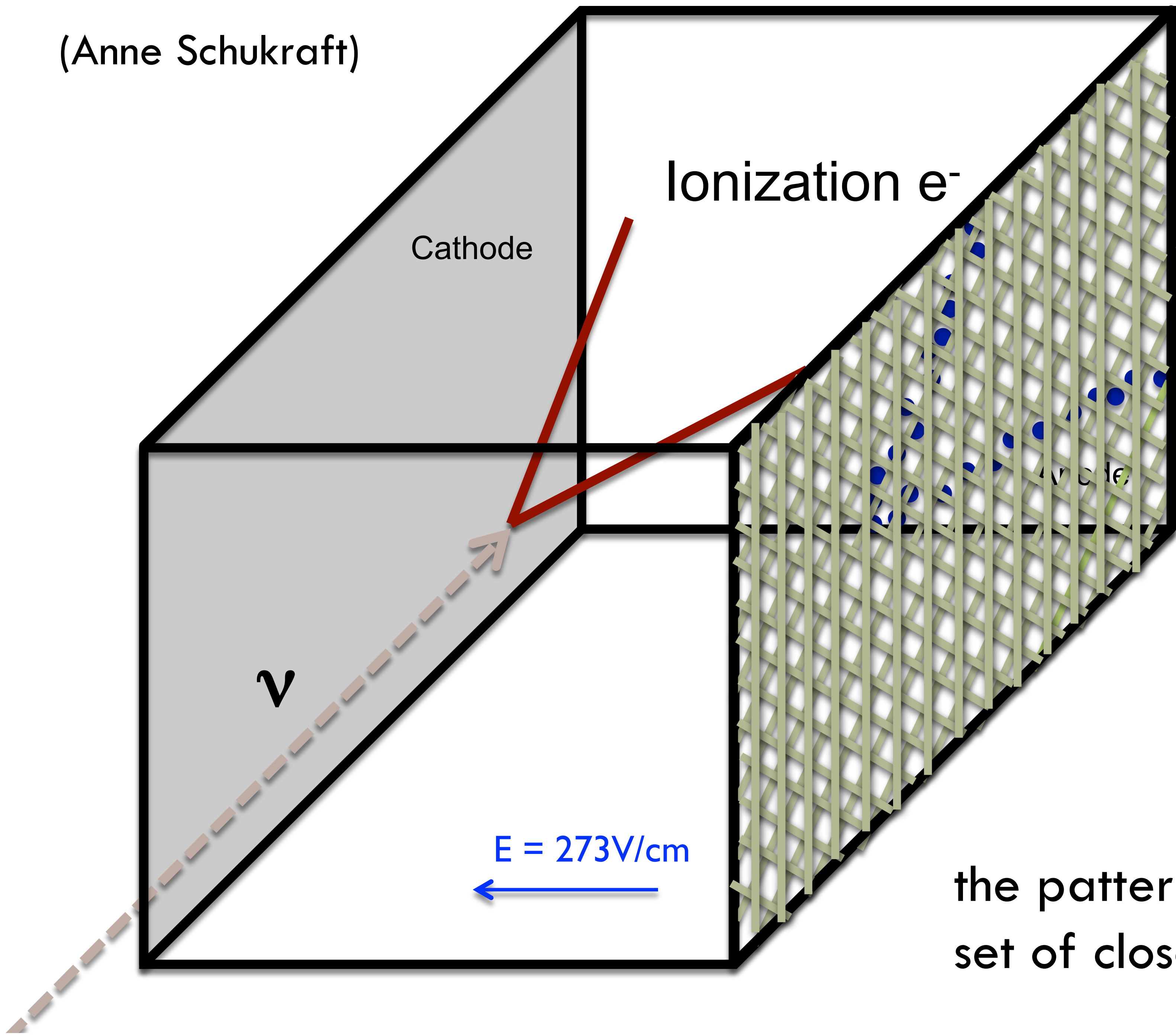


electrons arrive at anode

LIQUID ARGON TPC

(Anne Schukraft)

wire planes

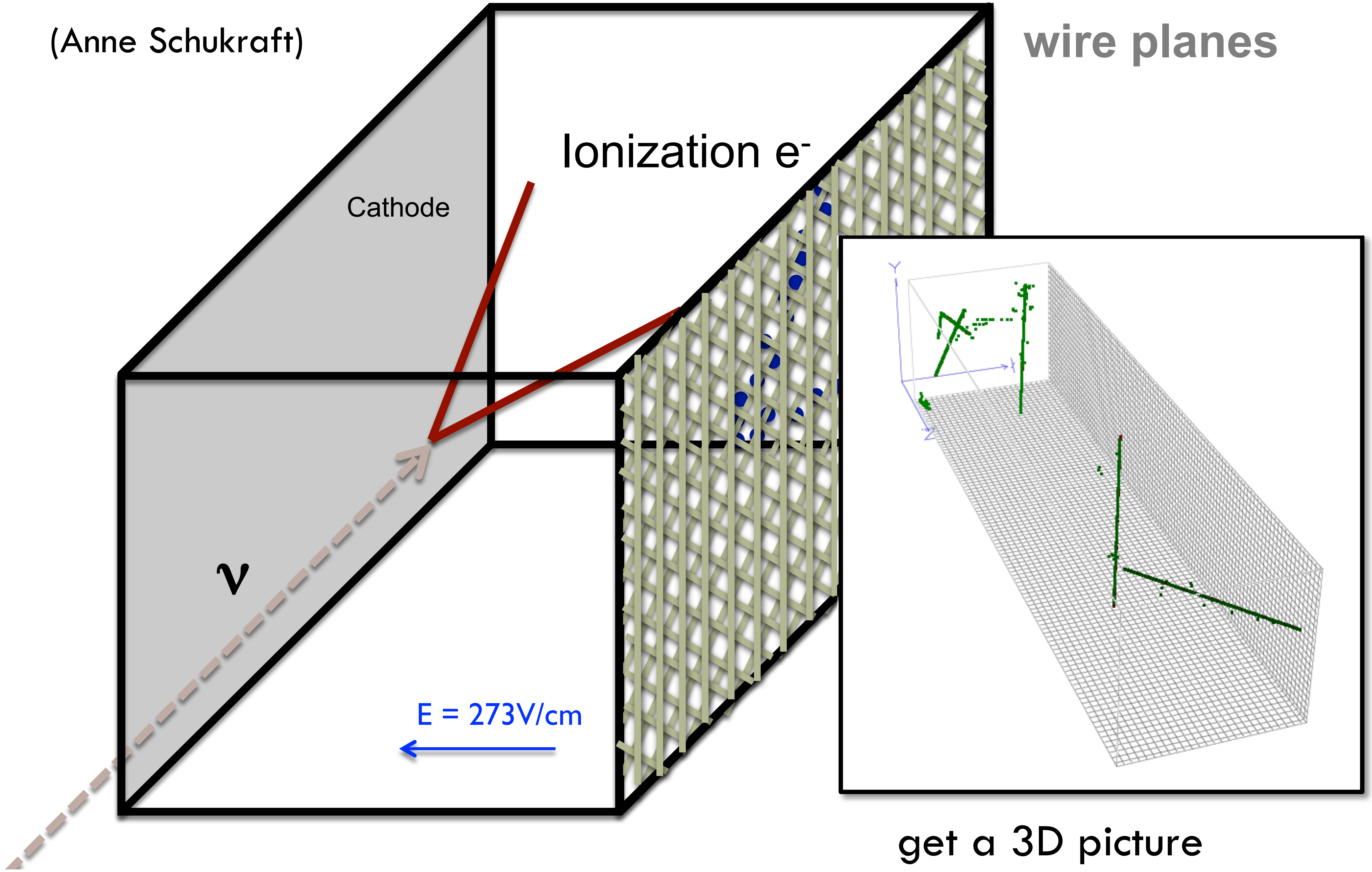


the pattern is recorded on a set of closely spaced wires

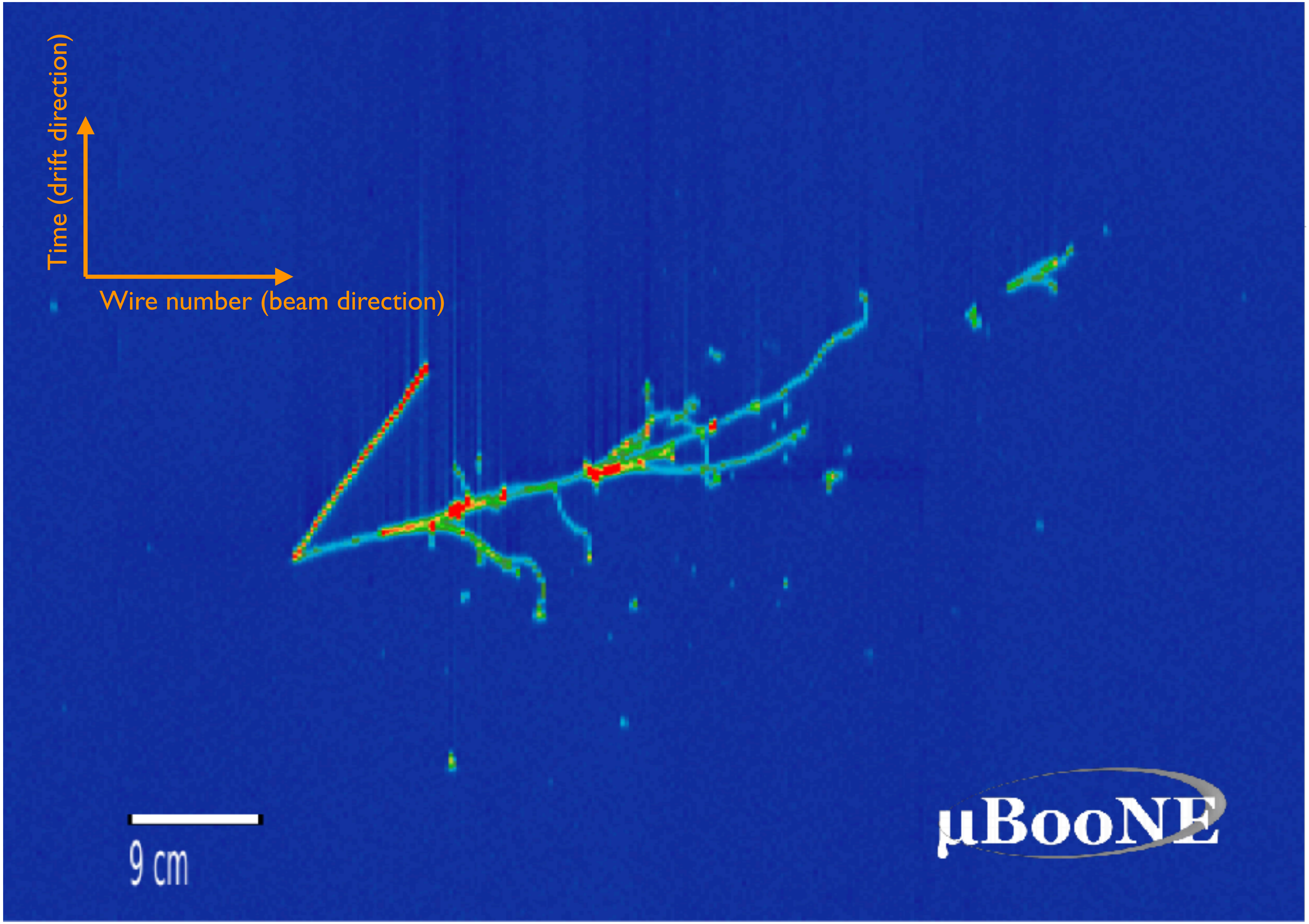
LIQUID ARGON TPC

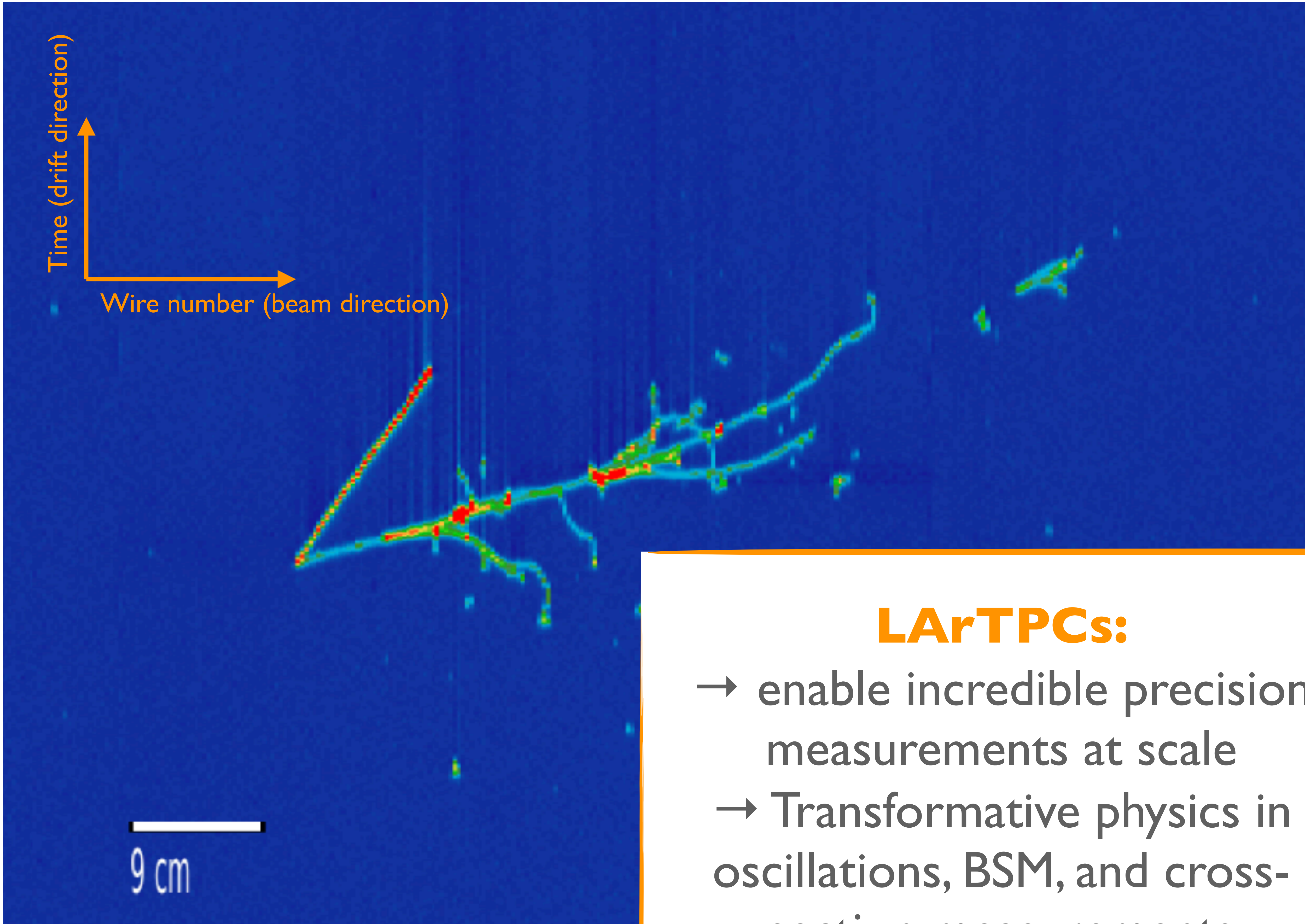
(Anne Schukraft)

wire planes



get a 3D picture


Time (drift direction)
Wire number (beam direction)
9 cm
μBooNE



LArTPCs:

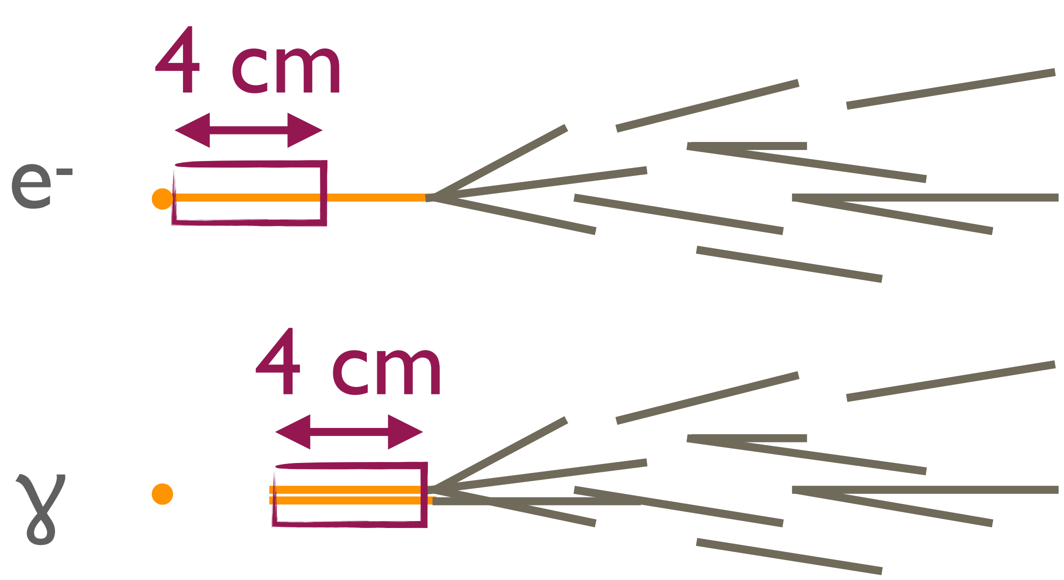
→ enable incredible precision measurements at scale

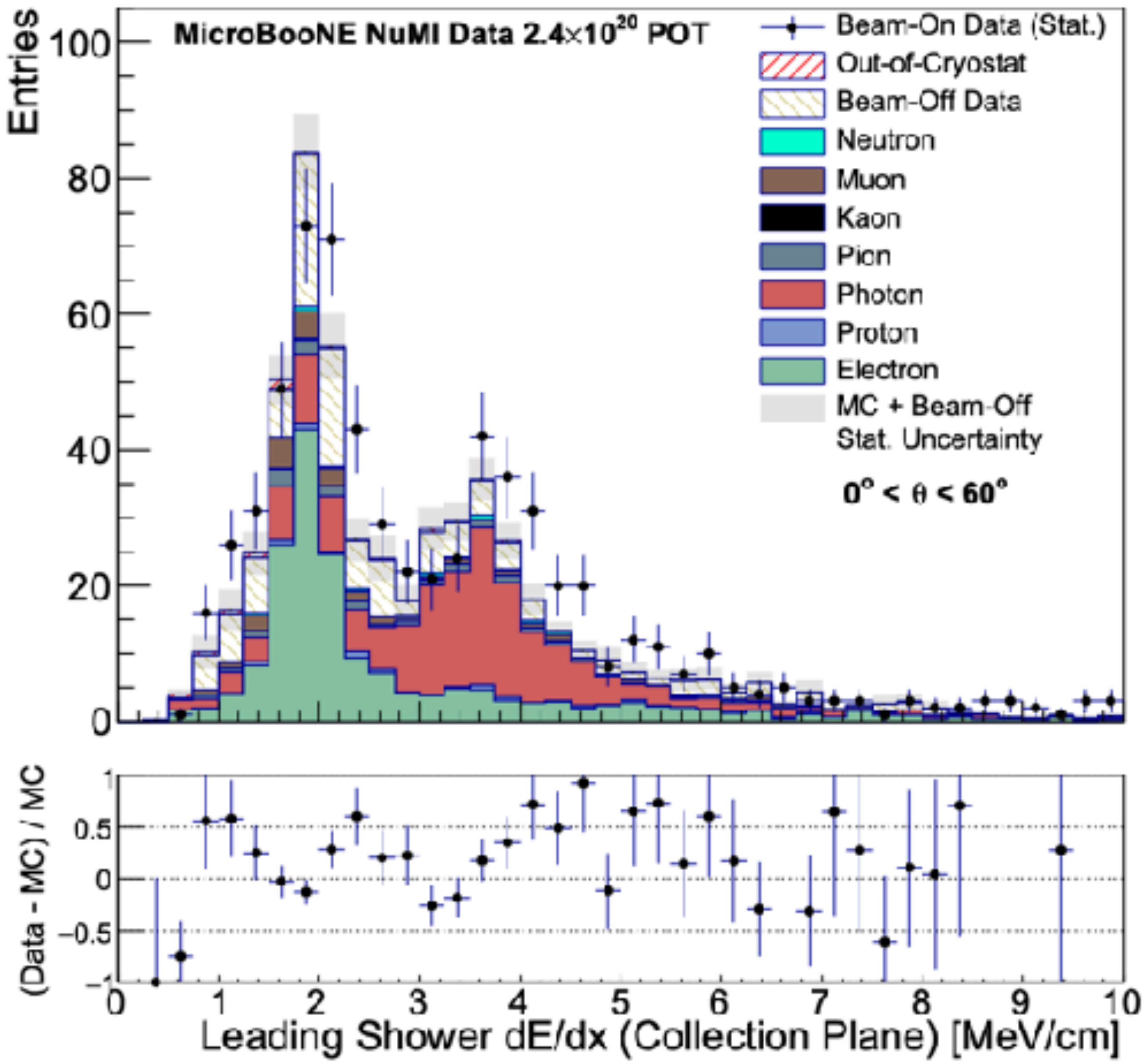
→ Transformative physics in oscillations, BSM, and cross-section measurements

LARTPC STRENGTH: ELECTRONS AND PHOTONS

Phys. Rev. D 104, 052002 (2021)

- **Electrons and photons produce showers in LArTPCs**
- Distinguish using dE/dx at start of shower and start point





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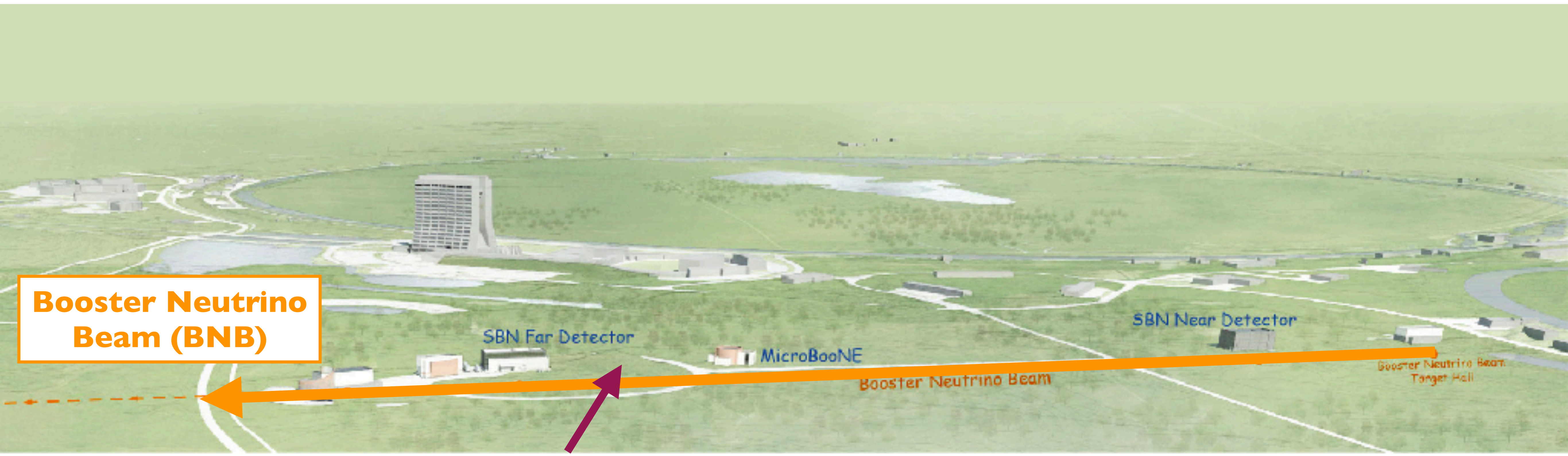
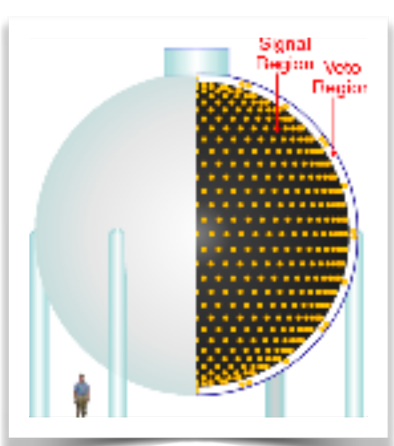
SHORT-BASELINE NEUTRINOS AT FERMILAB



MiniBooNE



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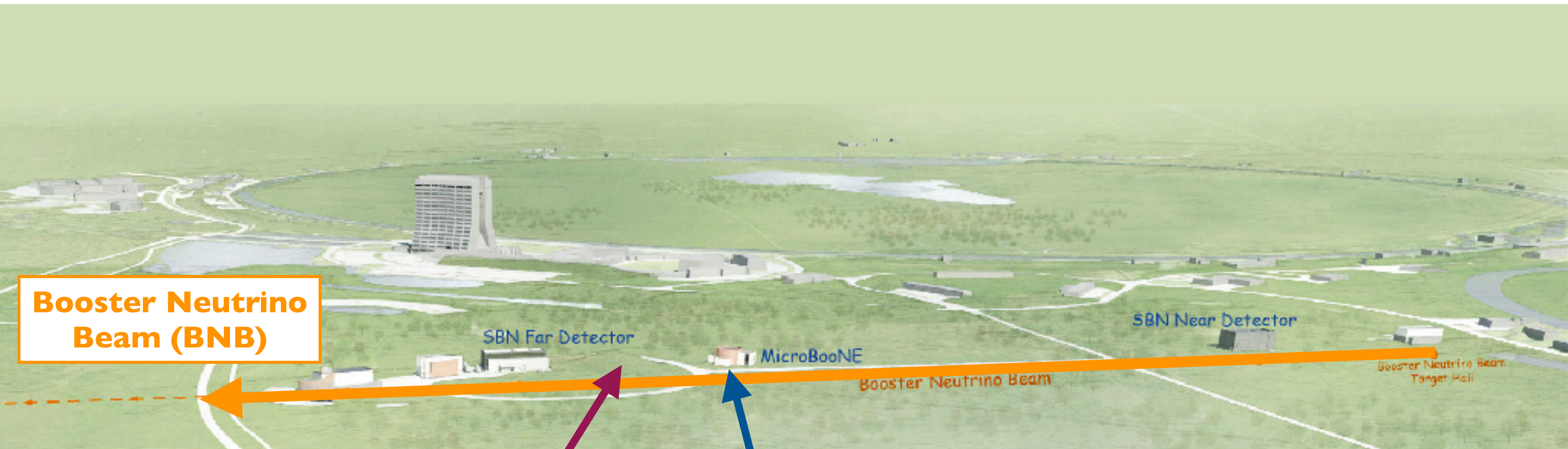
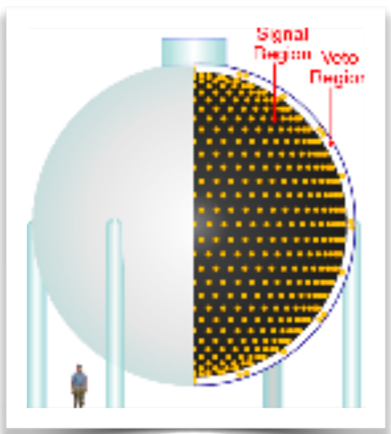


MiniBooNE

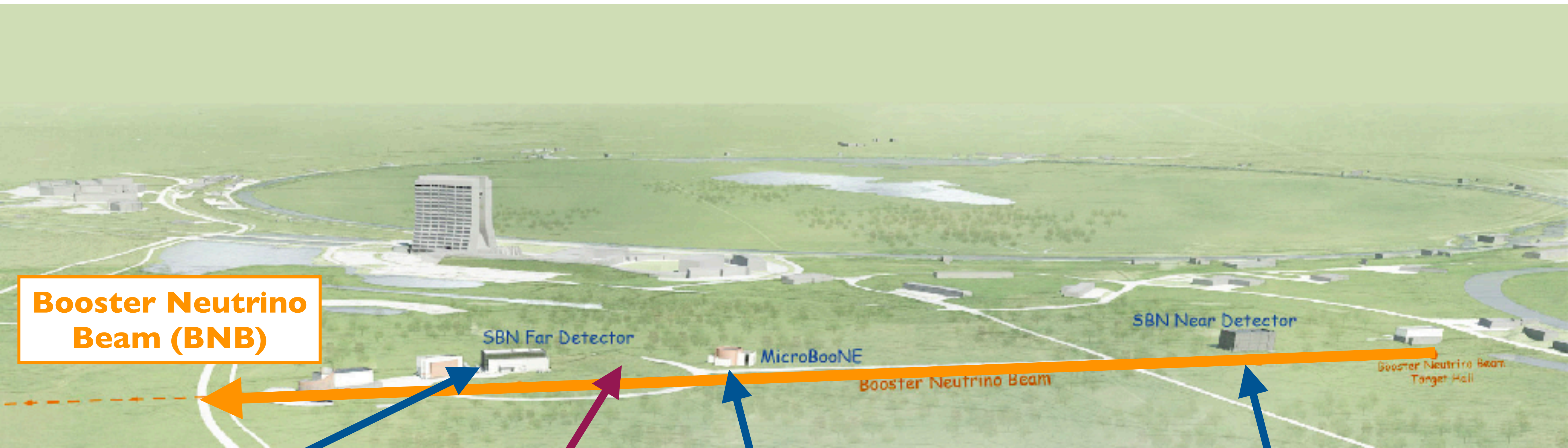
500m



MicroBooNE

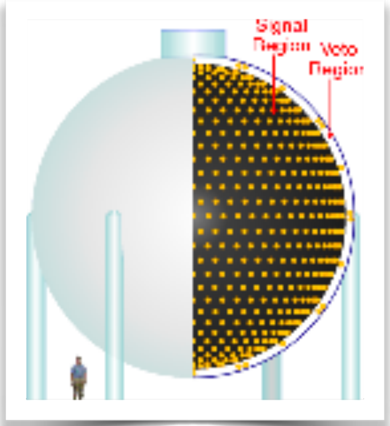
470m

SHORT-BASELINE NEUTRINOS AT FERMILAB



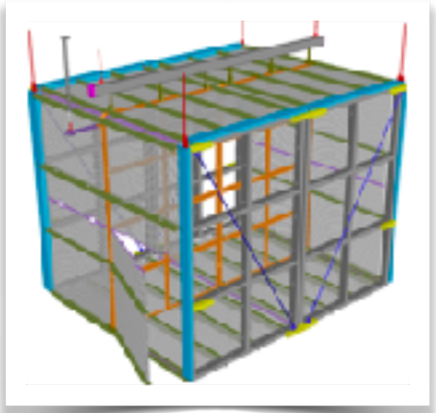
ICARUS

MiniBooNE



MicroBooNE

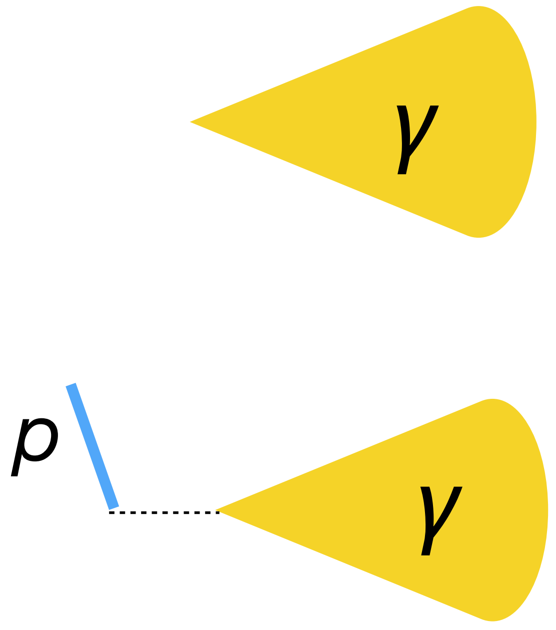
SBND



INVESTIGATING THE MINIBOONE LOW-ENERGY EXCESS

Photon search

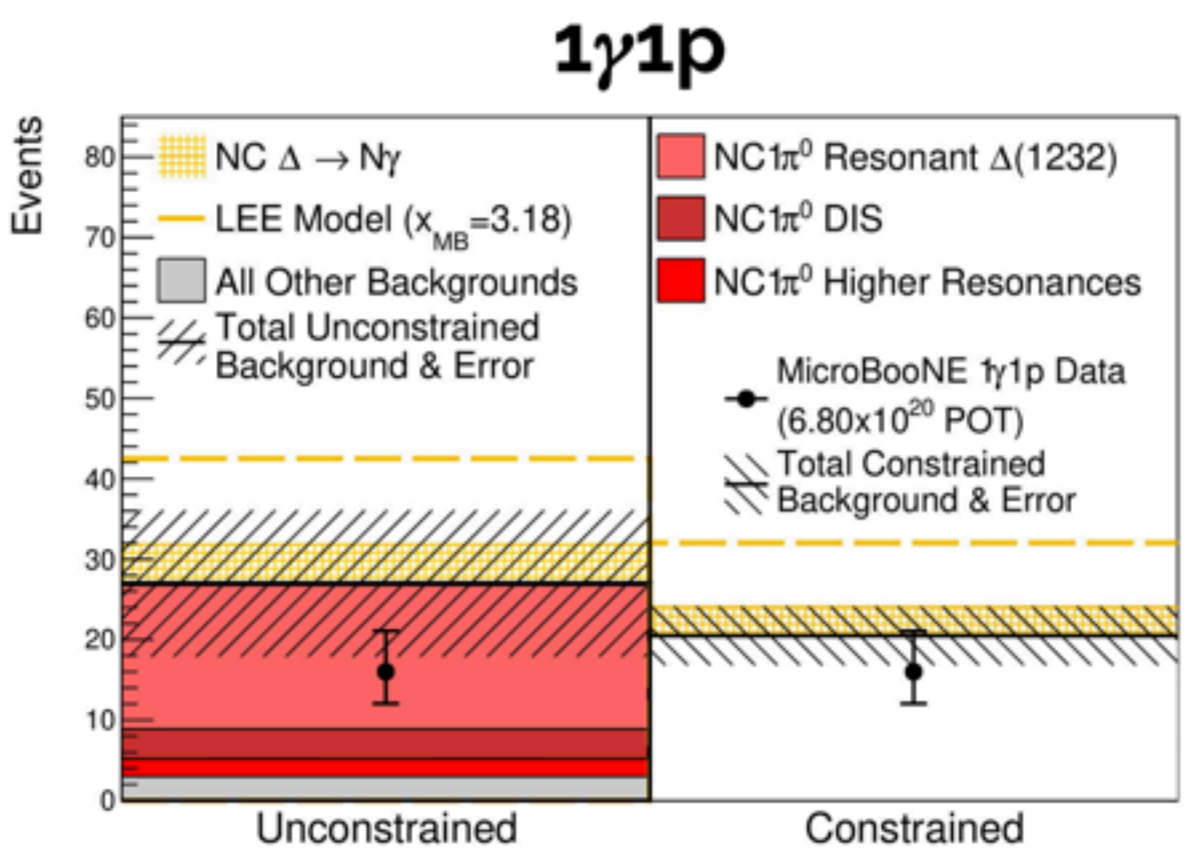
Target $\Delta \rightarrow N\gamma$:
$1\gamma 0p$ and $1\gamma 1p$



arXiv:2110.00409 [hep-ex]

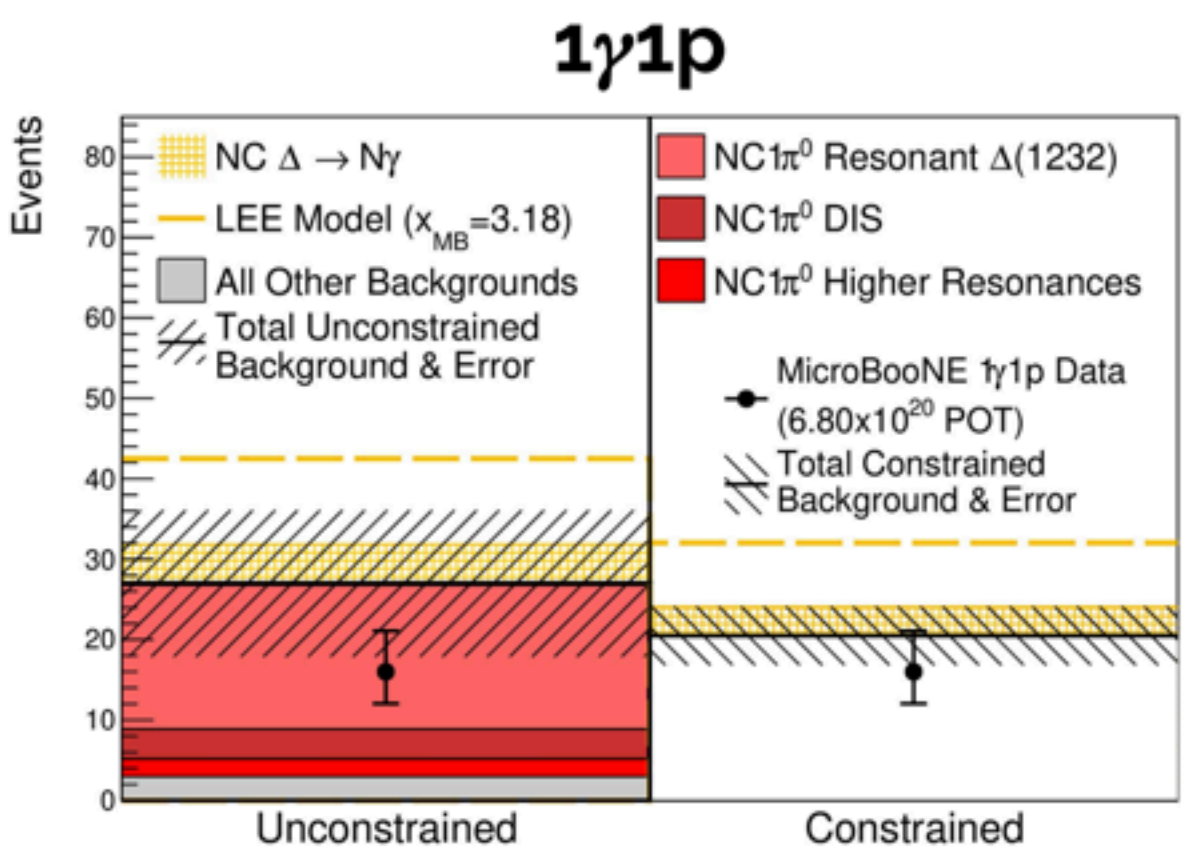
SINGLE PHOTON SEARCH

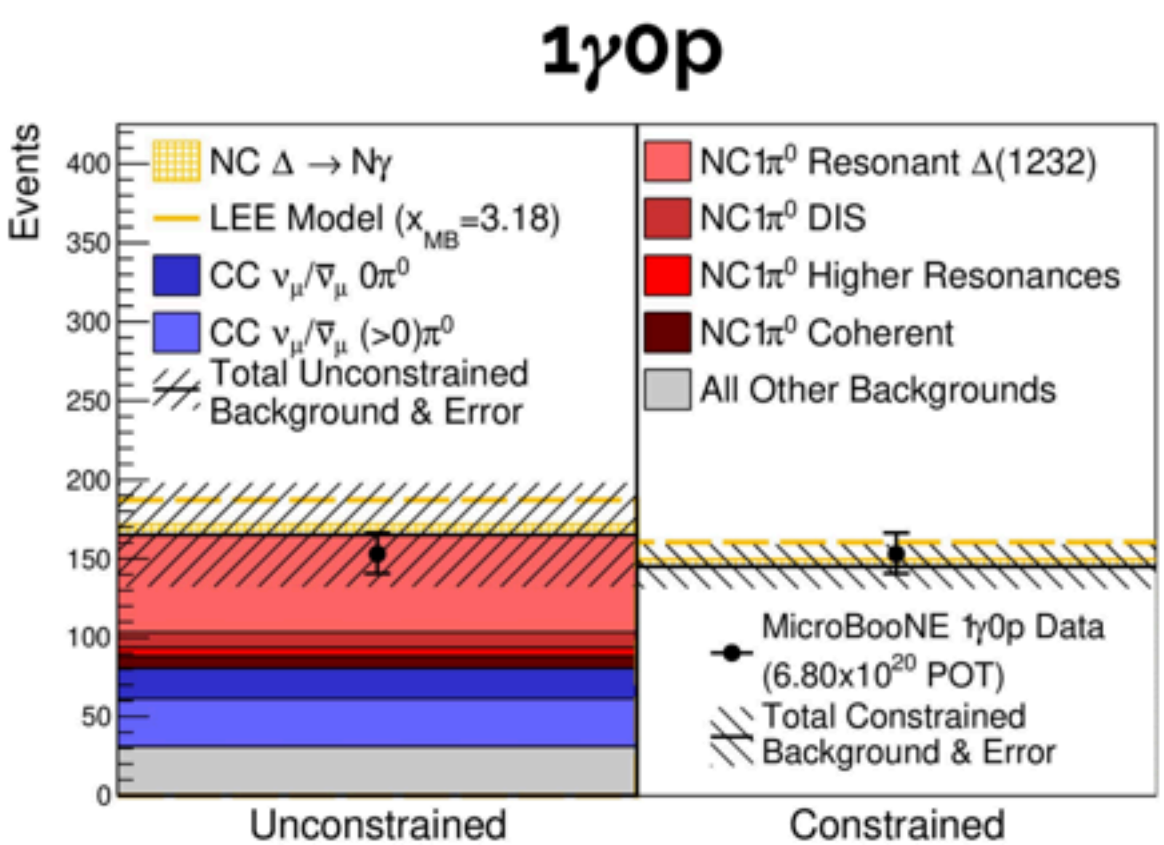
arXiv:2110.00409 [hep-ex]



SINGLE PHOTON SEARCH

arXiv:2110.00409 [hep-ex]



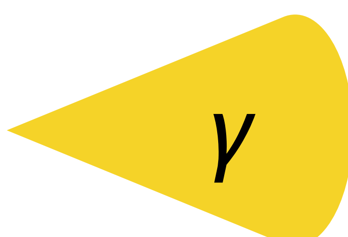


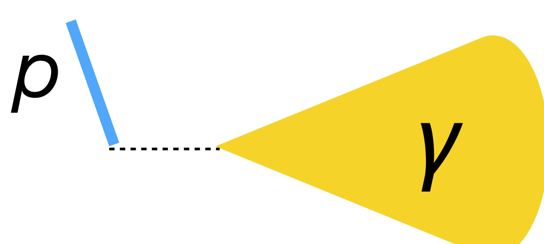
No evidence of an excess in either sample

INVESTIGATING THE MINIBOONE LOW-ENERGY EXCESS

Photon search

Target $\Delta \rightarrow N\gamma$:
$1\gamma0p$ and $1\gamma1p$



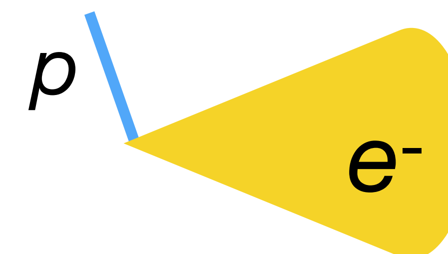


arXiv:2110.00409 [hep-ex]

Electron searches

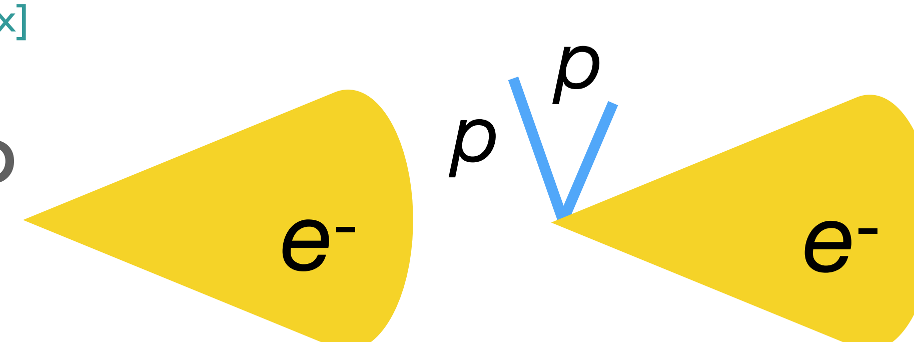
arXiv:2110.14080 [hep-ex]

CCQE-like:
1e1p



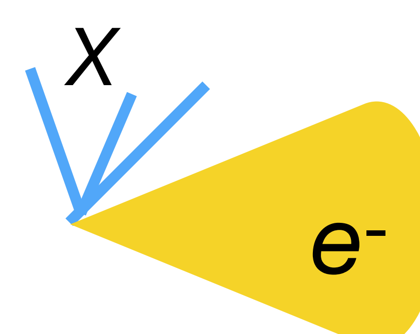
arXiv:2110.14065 [hep-ex]

CC0π: 1e0p
and 1eNp



arXiv:2110.13978 [hep-ex]

Inclusive:
1eX



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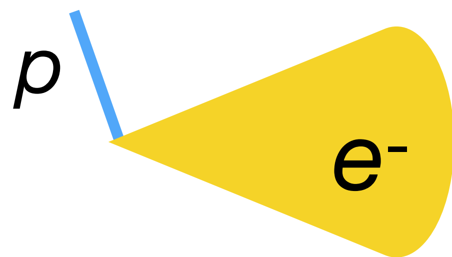
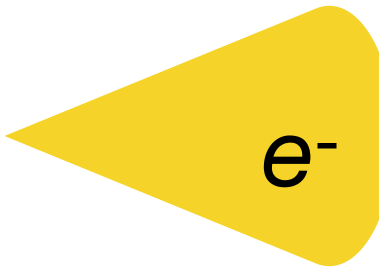
ν_e SEARCH

1e1p



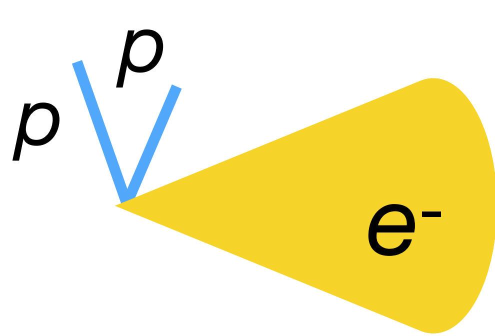
arXiv:2110.14080 [hep-ex]

1e0p



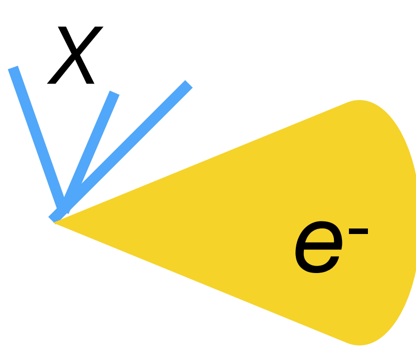
arXiv:2110.14065 [hep-ex]

1eNp



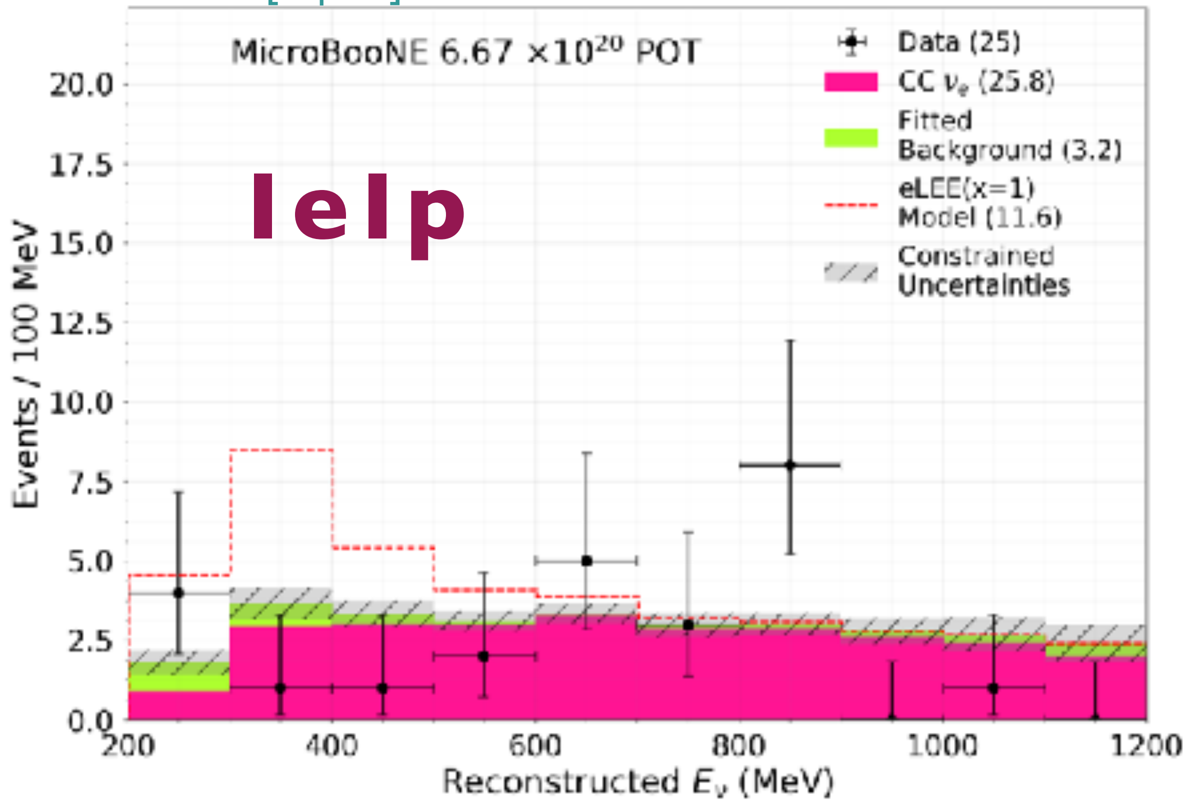
arXiv:2110.14065 [hep-ex]

1eX

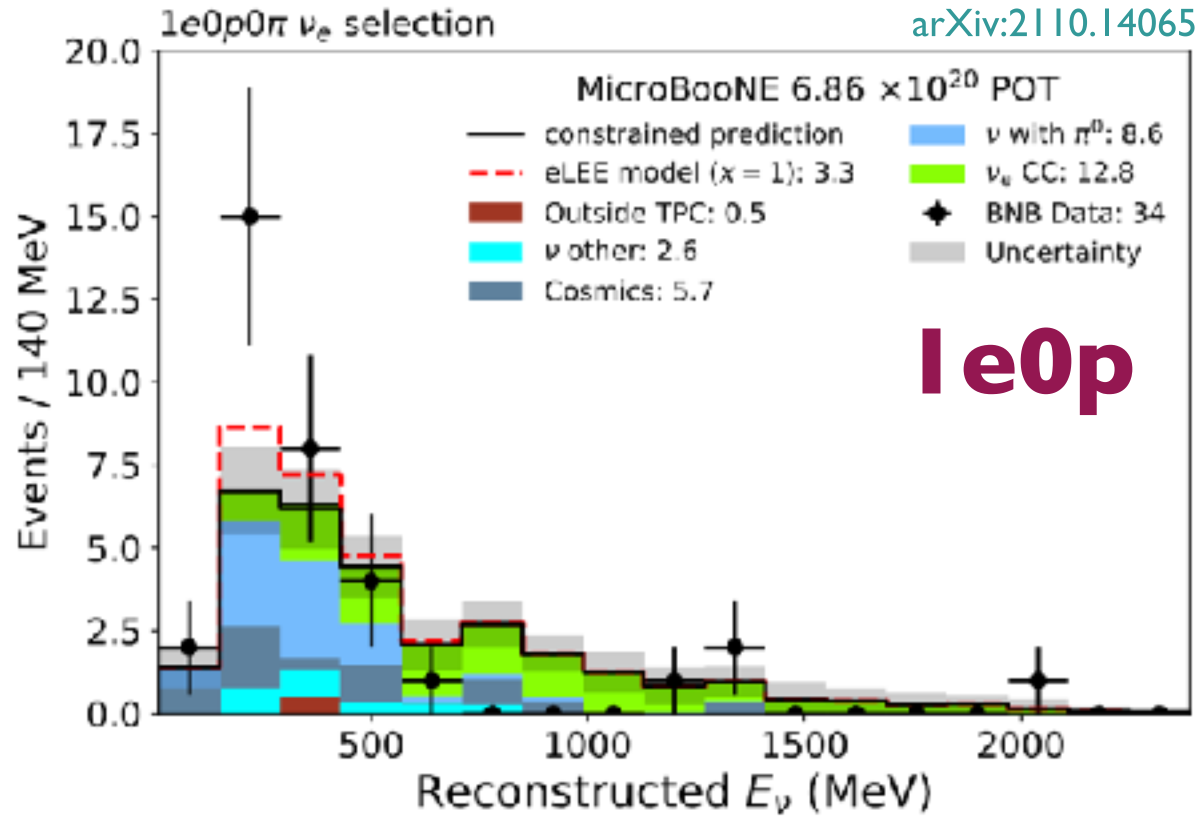


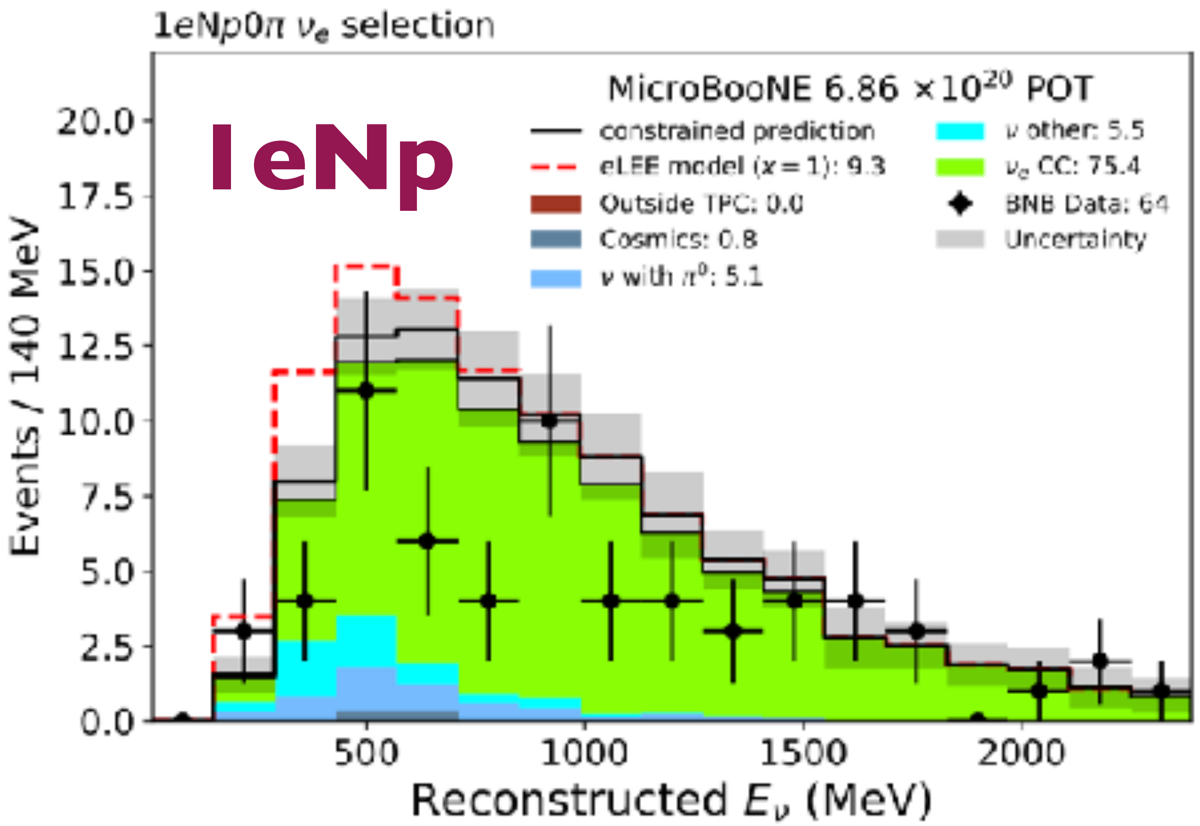
arXiv:2110.13978 [hep-ex]

arXiv:2110.14080 [hep-ex]

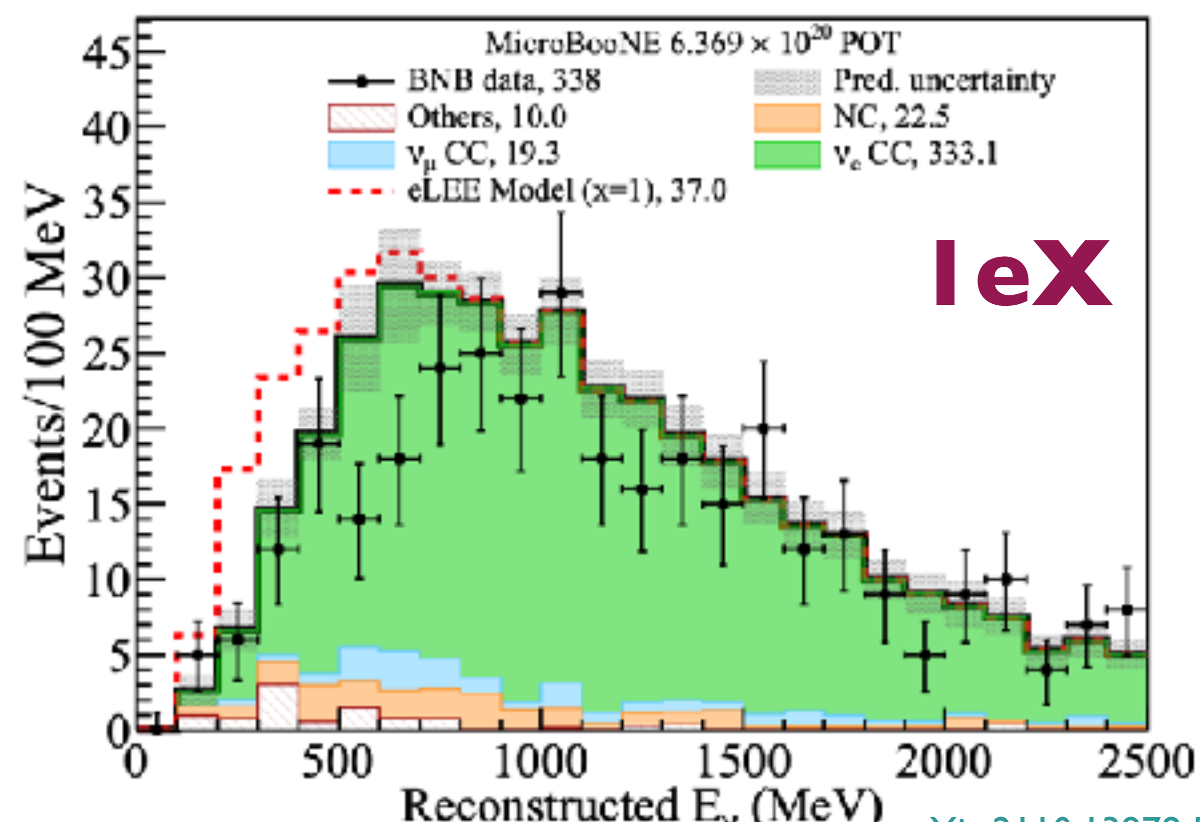


arXiv:2110.14065 [hep-ex]





arXiv:2110.14065 [hep-ex]



arXiv:2110.13978 [hep-ex]

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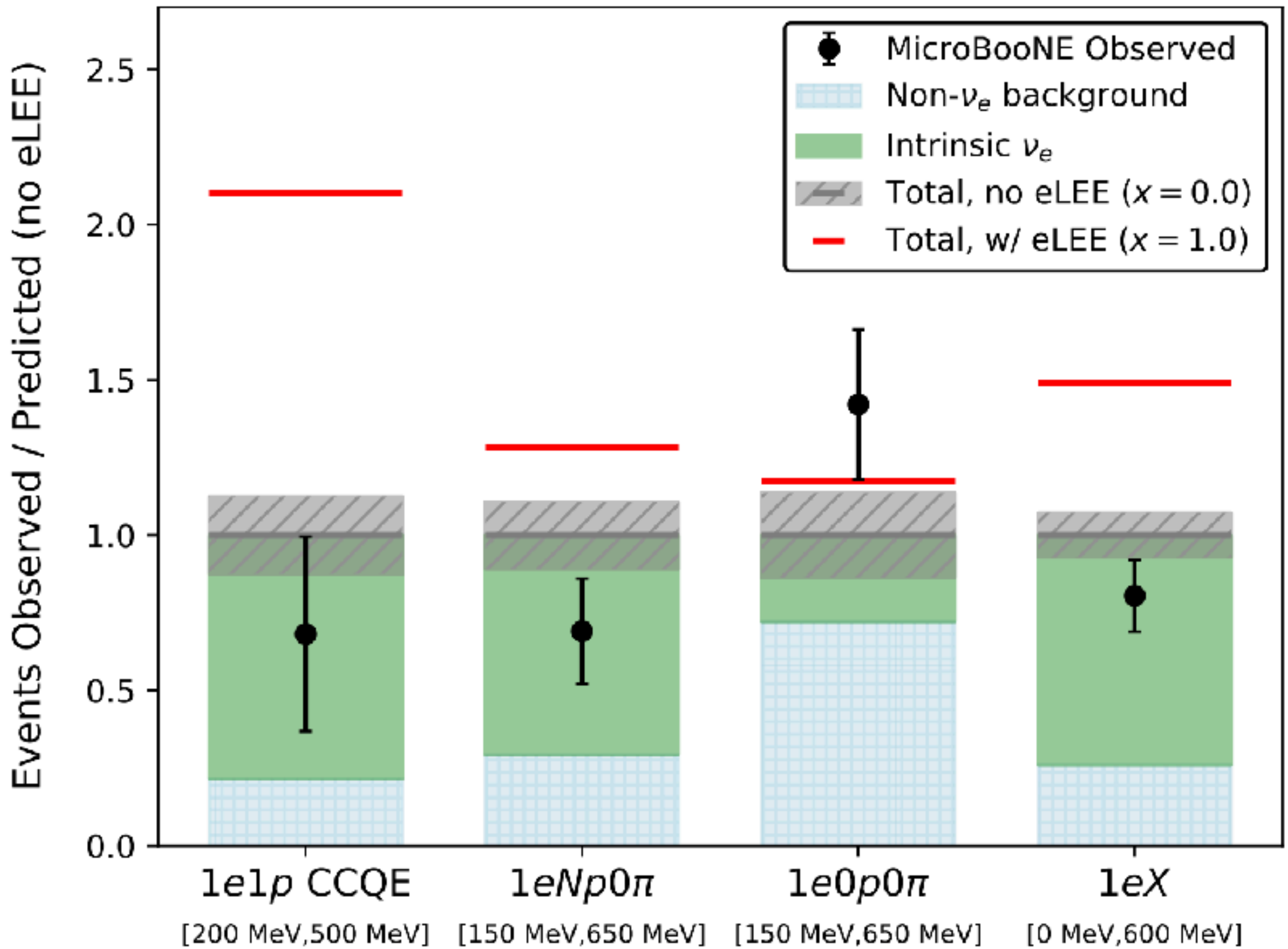


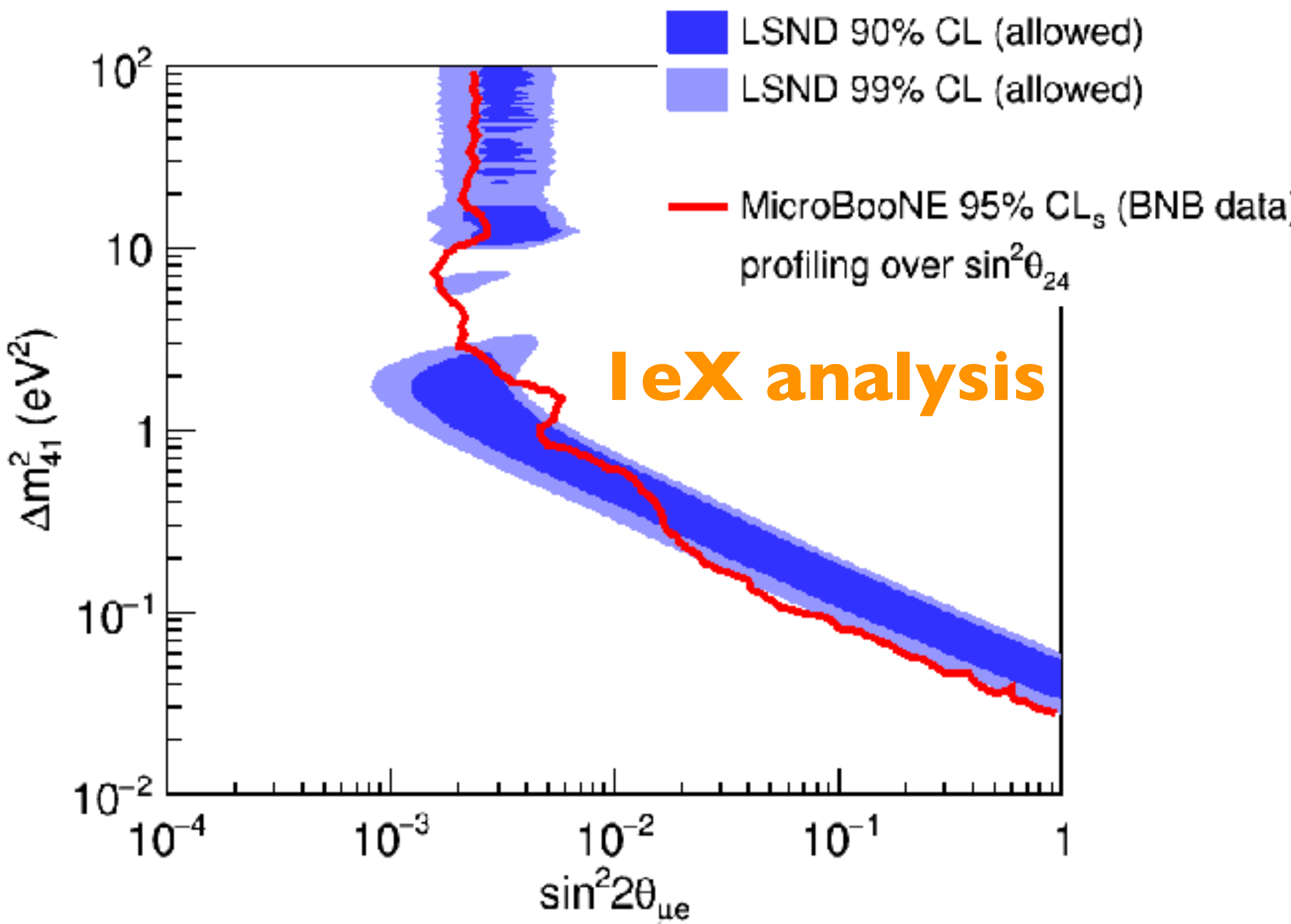
arXiv:2110.14054 [hep-ex]

EXCLUSION CONTOURS

New two weeks ago!

MICROBOONE-NOTE-1116-PUB

- What does this mean for the sterile neutrino hypothesis?
- We haven't seen evidence of an excess → place constraints on oscillation phase space for a new neutrino flavour



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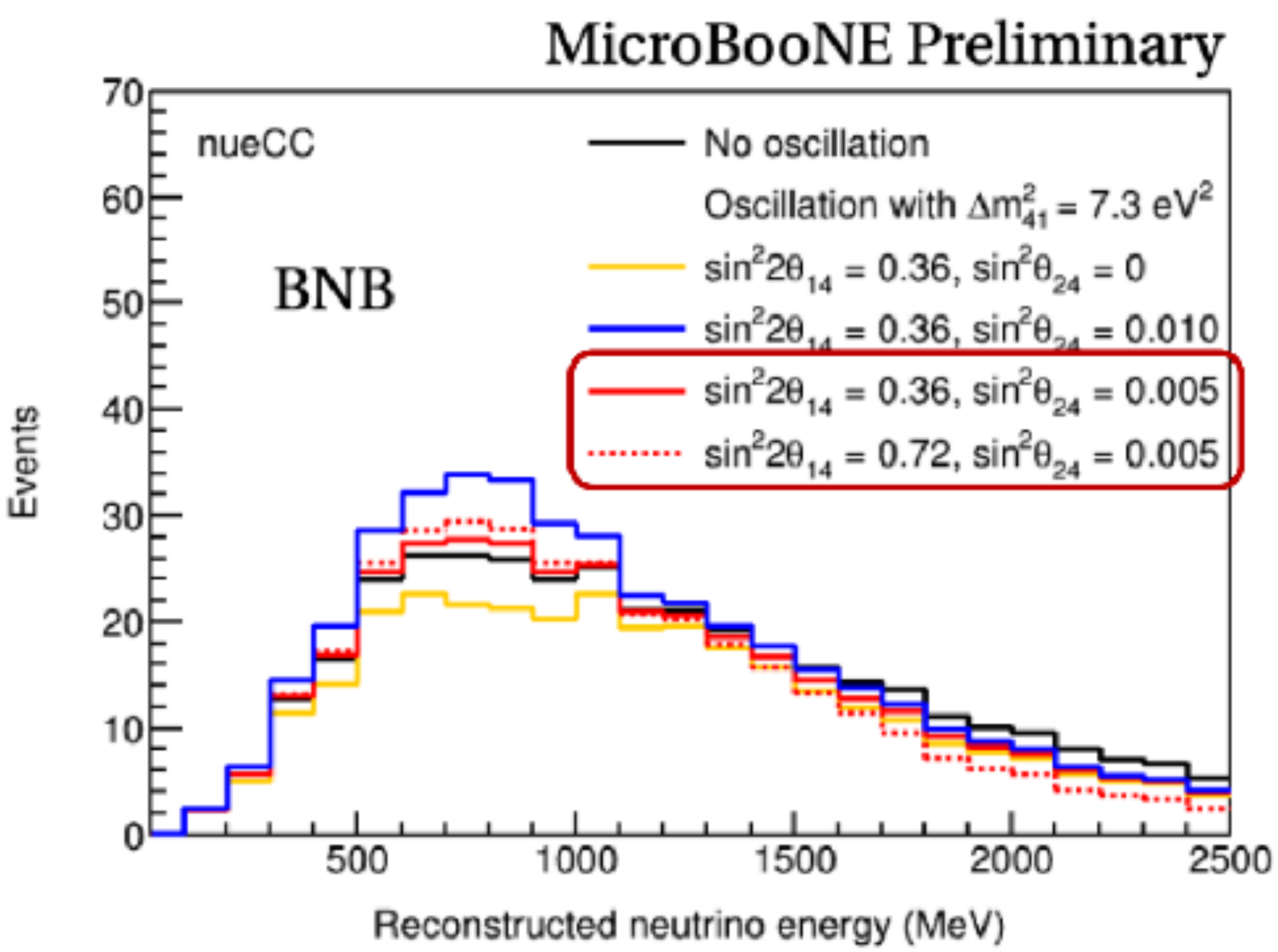
OSCILLATION PARAMETER DEGENERACY

New two weeks ago!

MICROBOONE-NOTE-1116-PUB



ν_e disappearance ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic }\nu_e} P_{\nu_e\to\nu_e} + N_{\text{intrinsic }\nu_\mu} P_{\nu_\mu\to\nu_e}$$

$$= N_{\text{intrinsic }\nu_e}[1 + (R_{\nu_\mu/\nu_e}\sin^2\theta_{24} - 1)\sin^2 2\theta_{14}\sin^2\frac{\Delta m^2_{41}L}{4E}]$$

Cancellation if $\sin^2\theta_{24} = R_{\nu e/\nu\mu}$

(ratio of ν_e to ν_μ in beam)

→ about 0.005 in BNB

→ about 0.04 in NuMI

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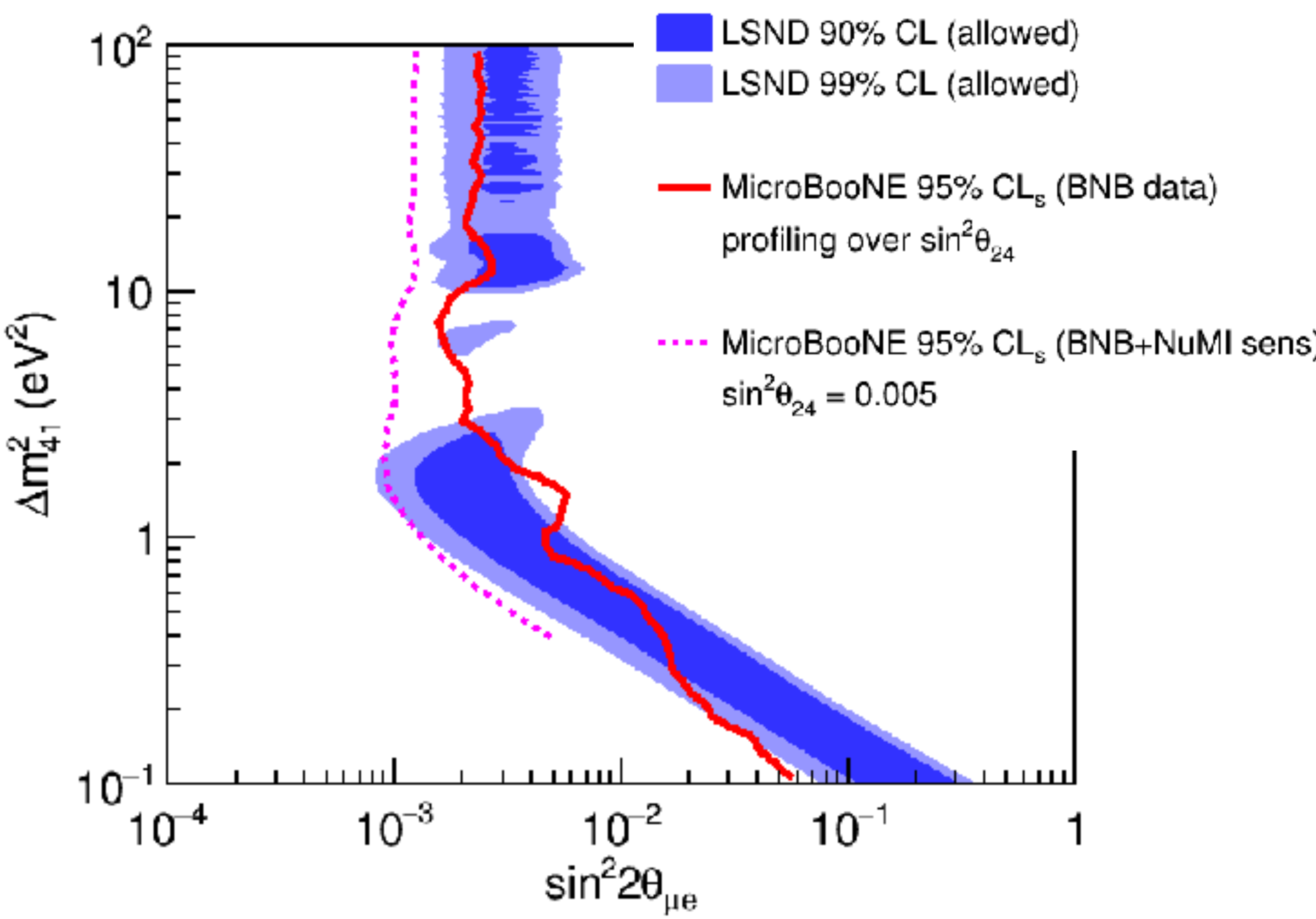
FUTURE PROSPECTS: BNB+NUMI

New two weeks ago!

MICROBOONE-NOTE-1116-PUB

- BNB $R_{\nu e/\nu\mu}$: 0.005
- NuMI $R_{\nu e/\nu\mu}$: 0.04
- Combining both data sets → significantly improved sensitivity
- → Upcoming BNB + NuMI analysis will be sensitive to full LSND allowed regions



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INTERPRETATIONS

These slides heavily inspired by
P. Machado, Fermilab PAC, November 2021

WHAT DOES THIS MEAN?

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

Produces True Electrons (first three items)

Produces True Photons (third and fourth items)

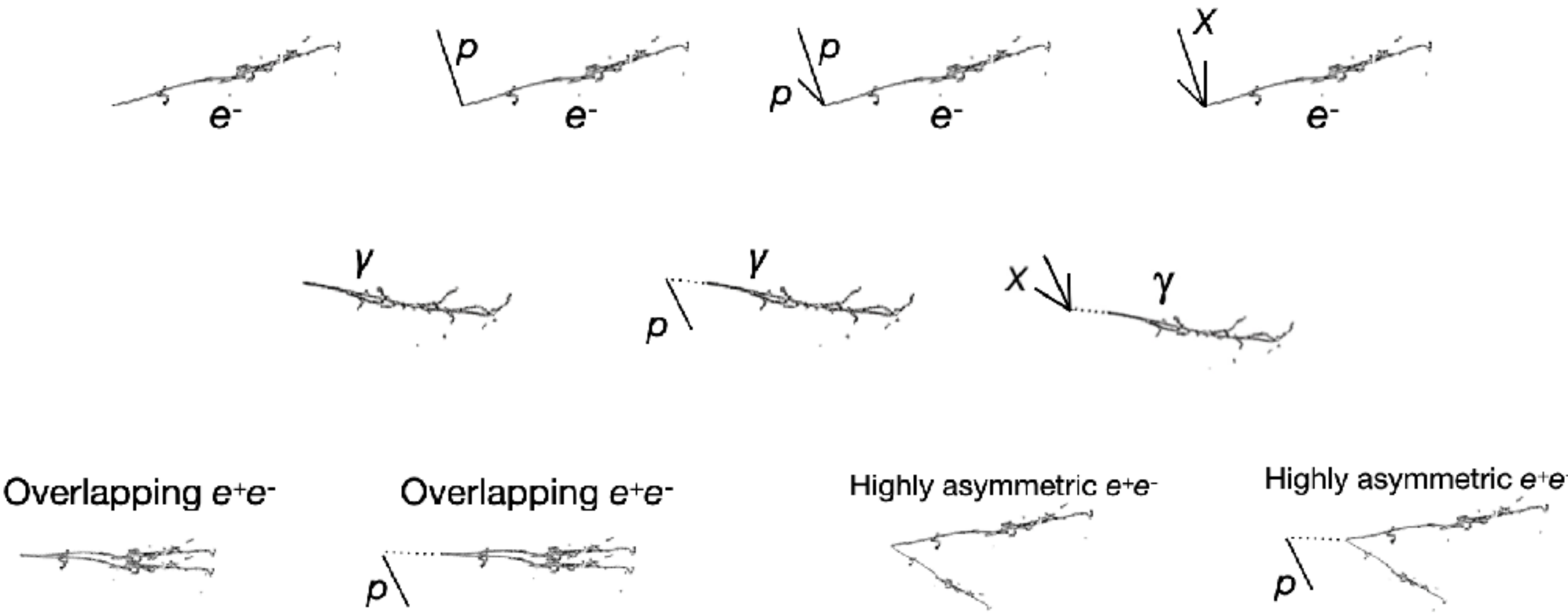
Produces e^+e^- pairs (last three items)

Caution: not an exhaustive list!

This is meant to be representative only

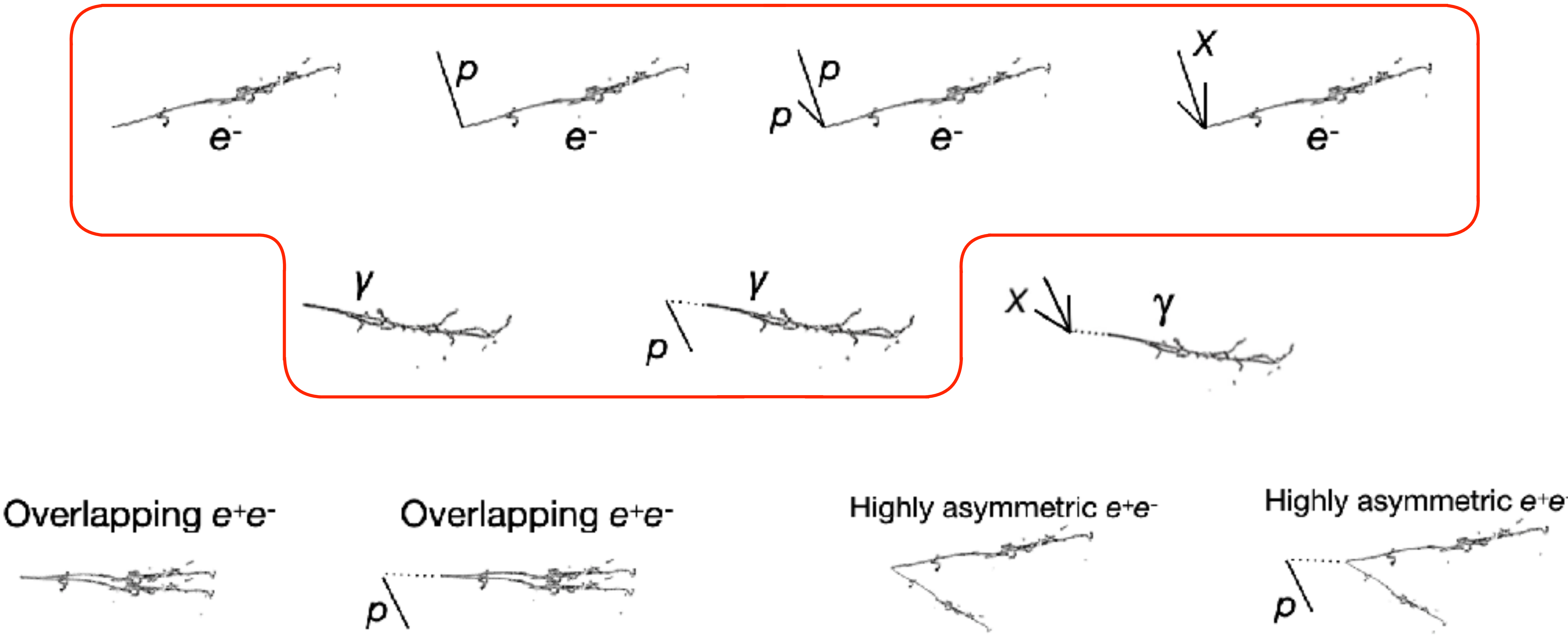
More information: see
P. Machado, Fermilab PAC, November 2021

WHAT DOES THIS MEAN?



WHAT DOES THIS MEAN?

MicroBooNE's first LEE results



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EXPLORATION OF THE MINIBOONE EXCESS

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

Ballett, Pascoli, Ross-Lonergan PRD 2019

Ballett, Hostert, Pascoli PRD 2020

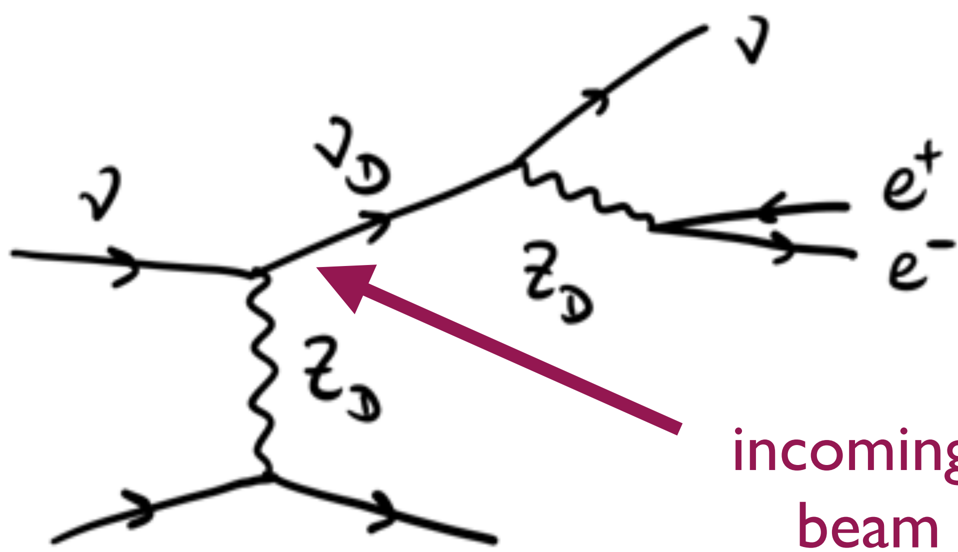
Bertuzzo, Jana, Machado, Zukanovich PRL 2018

Bertuzzo, Jana, Machado, Zukanovich PLB 2019

Arguelles, Hostert, Tsai PRL 2019

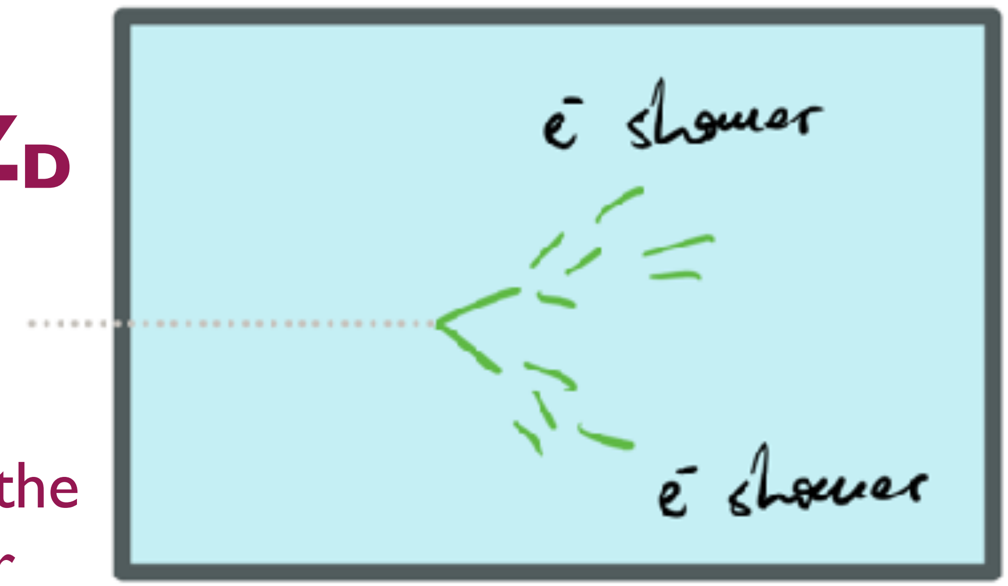
DARK NEUTRINOS

These slides heavily inspired by
P. Machado, Fermilab PAC, November 2021

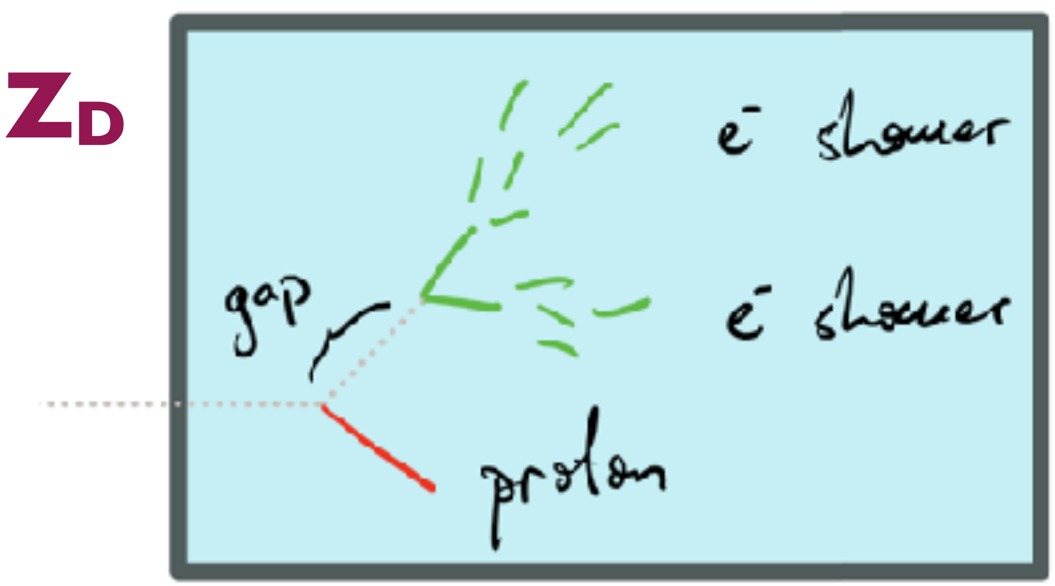


incoming neutrinos from the beam scatter/up-scatter inside the detector

Light Z_D



Heavy Z_D



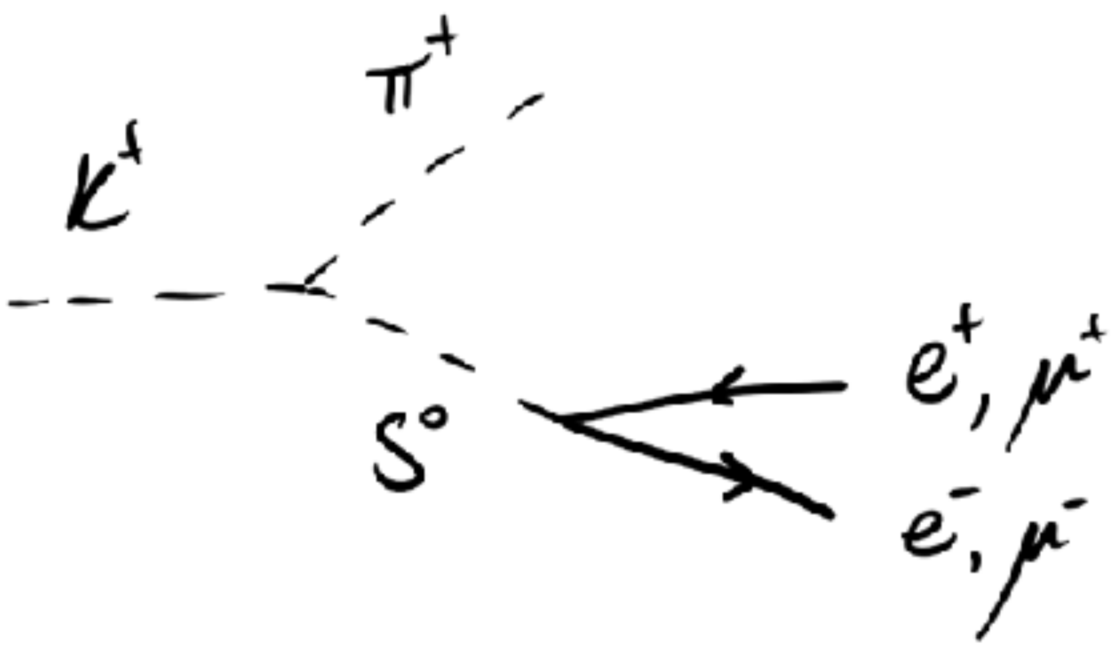
Motivation:

- Origin of neutrino masses
- Dark sector portal
- Fit to MiniBooNE energy and angular spectrum

HIGGS PORTAL SCALARS

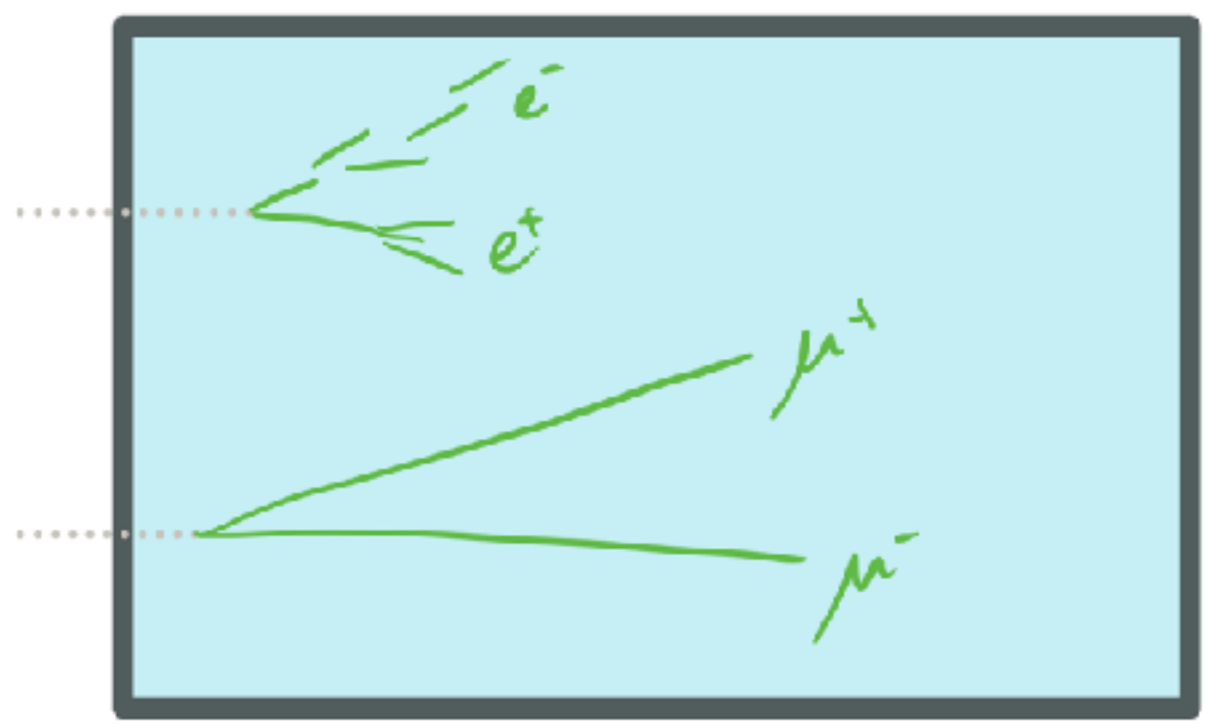
These slides heavily inspired by
P. Machado, Fermilab PAC, November 2021

Batell, Berger, Ismail PRD 2019
Patt, Wilczek 2006



Experimental signature:

- No hadronic activity
- e^+e^- or $\mu^+\mu^-$
- Invariant mass



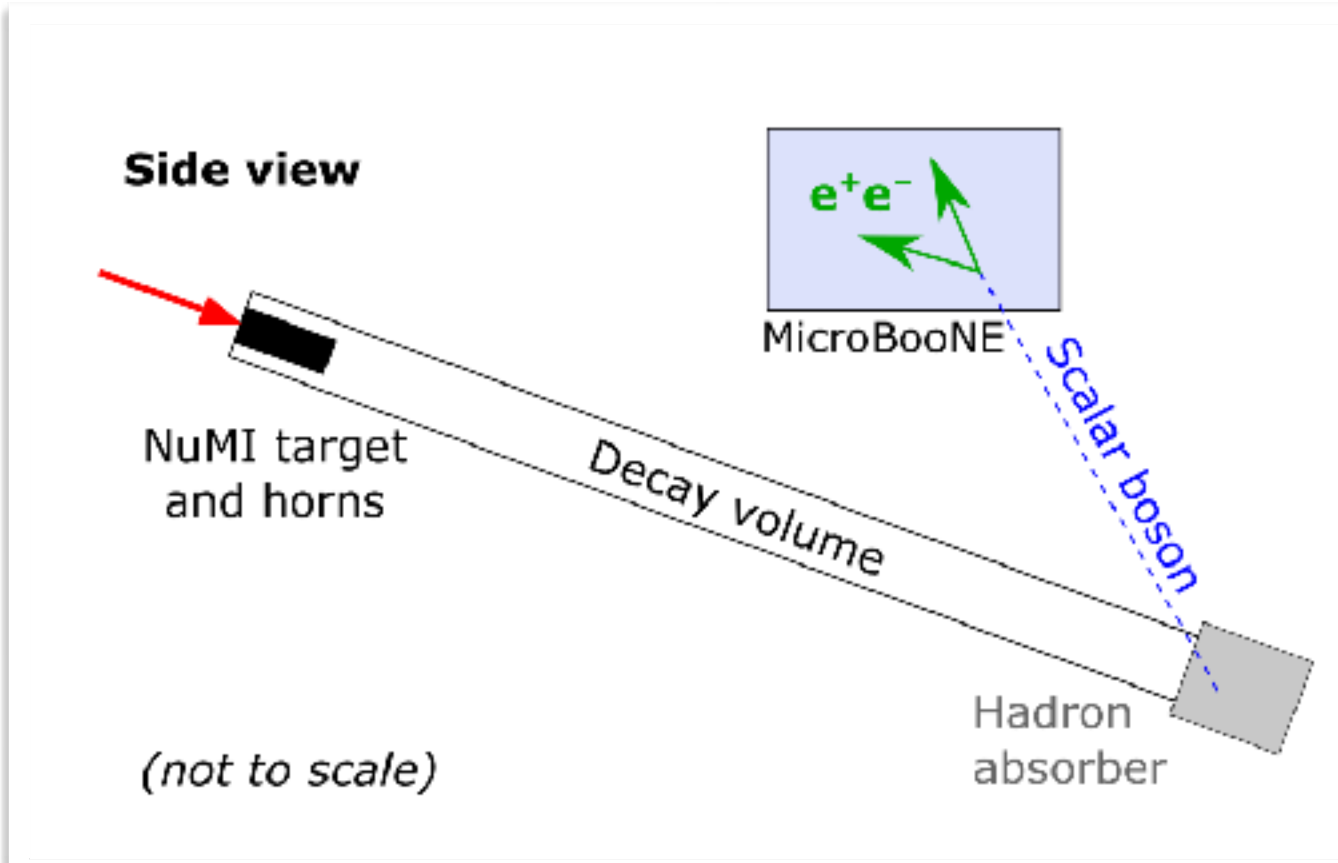
Motivation:

- Portal to dark sector
- Connection to Higgs sector
- Experimental synergy with HNL search

MICROBOONE'S HIGGS PORTAL SCALARS SEARCH

Phys. Rev. Lett. 127, 151803 (2021)

- Search for **e^+e^- decays** from **scalars coming from NuMI hadron absorber**
  - **1 event observed** → 95% C.L. excludes new regions of phase space
- Additional $\mu^-\mu^+$ search coming soon
- e^+e^- techniques applied to LEE search: in progress



MICROBOONE'S HIGGS PORTAL SCALARS SEARCH

Phys. Rev. Lett. 127, 151803 (2021)

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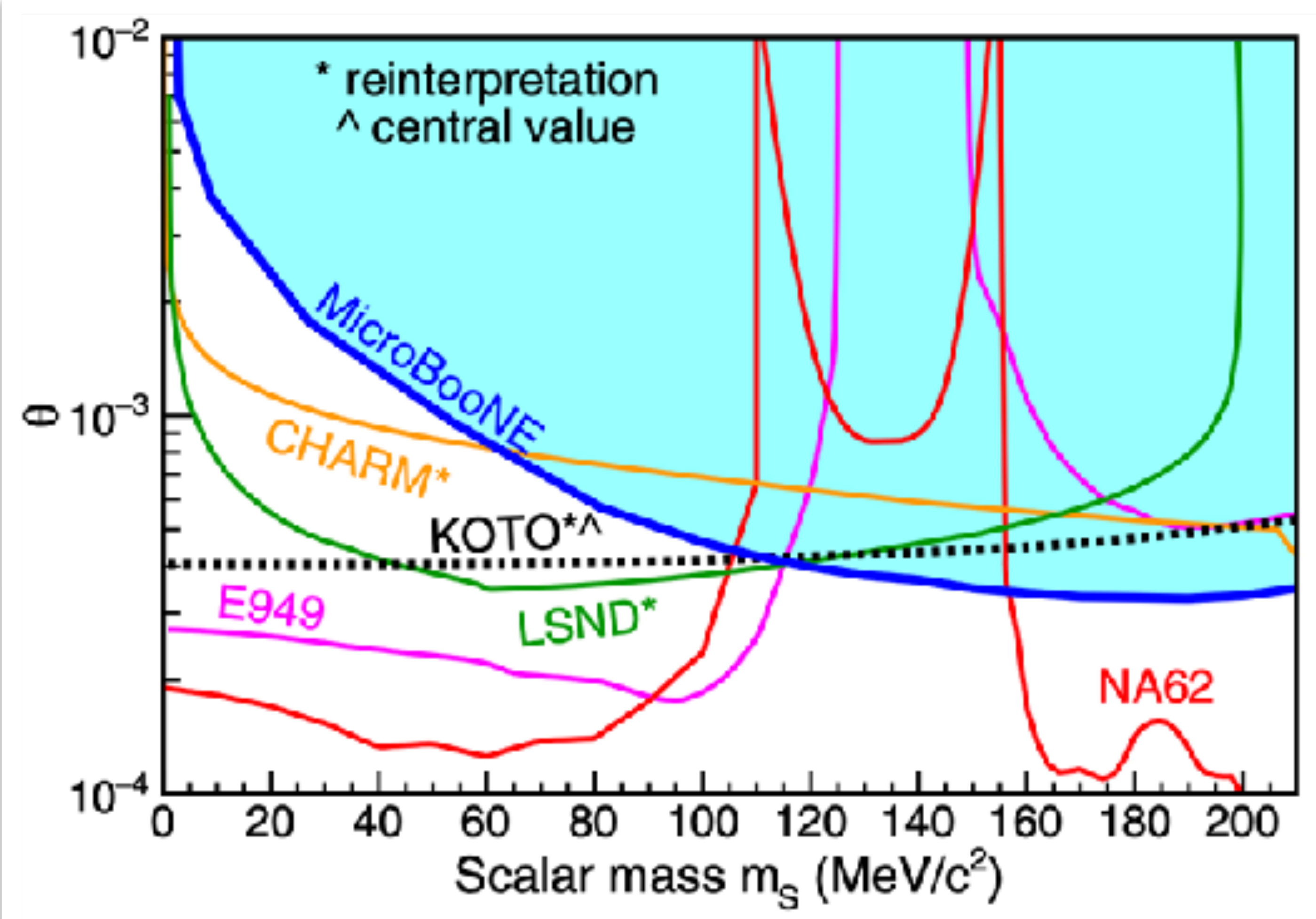


Too many papers to list, but see

Ballett, Pascoli, Ross-Lonergan PRD 2019

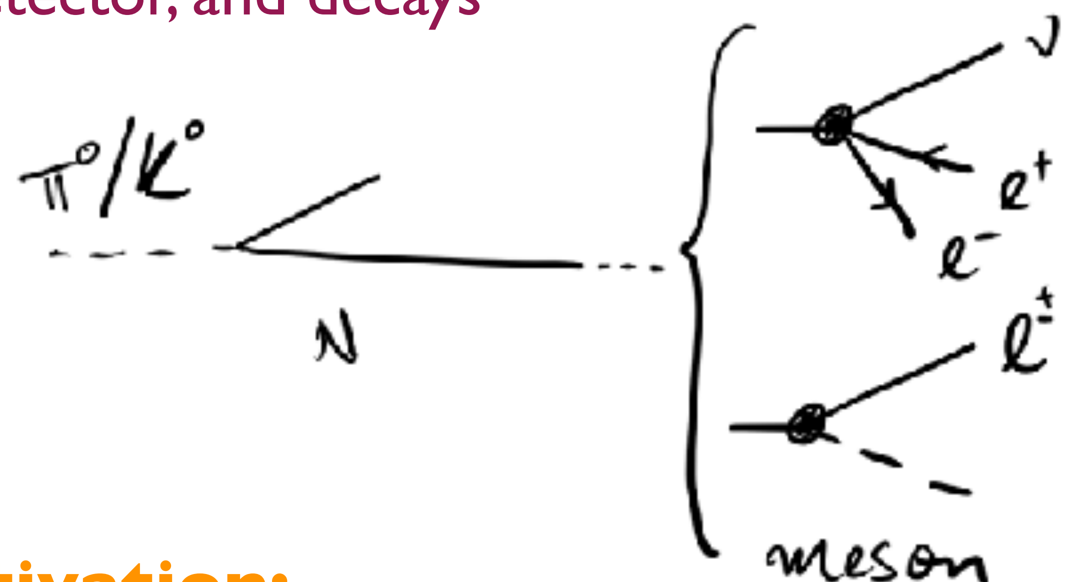
Ballett, Pascoli, Ross-Lonergan JHEP 2017

Kelly, Machado PRD 2021

HEAVY NEUTRAL LEPTONS

These slides heavily inspired by
P. Machado, Fermilab PAC, November 2021

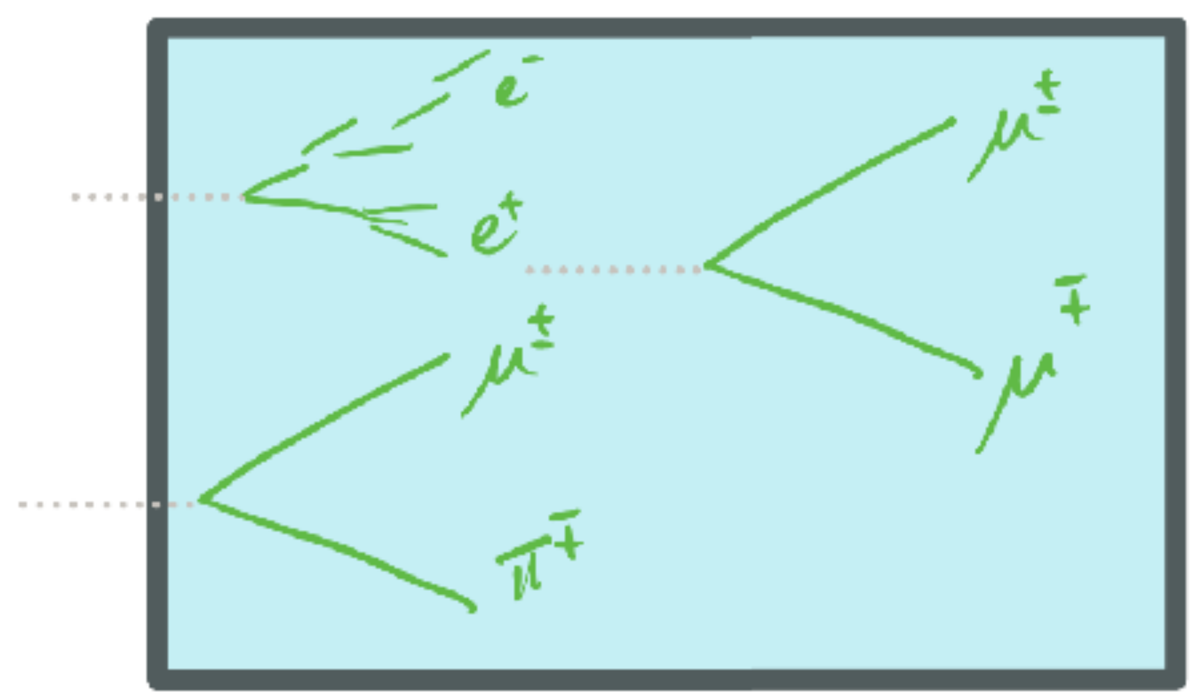
HNL produced in beam decay pipe, propagates to detector, and decays



Experimental signature:

- Several possibilities
- Delayed timing w.r.t. beam neutrinos
- Reconstruct invariant mass?

Less likely/ harder to explain mB anomaly



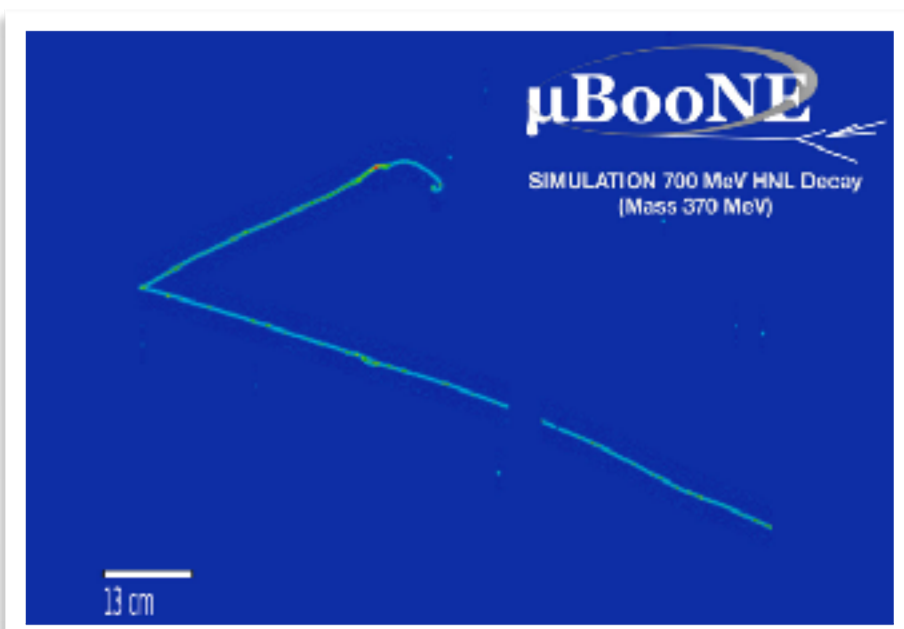
Motivation:

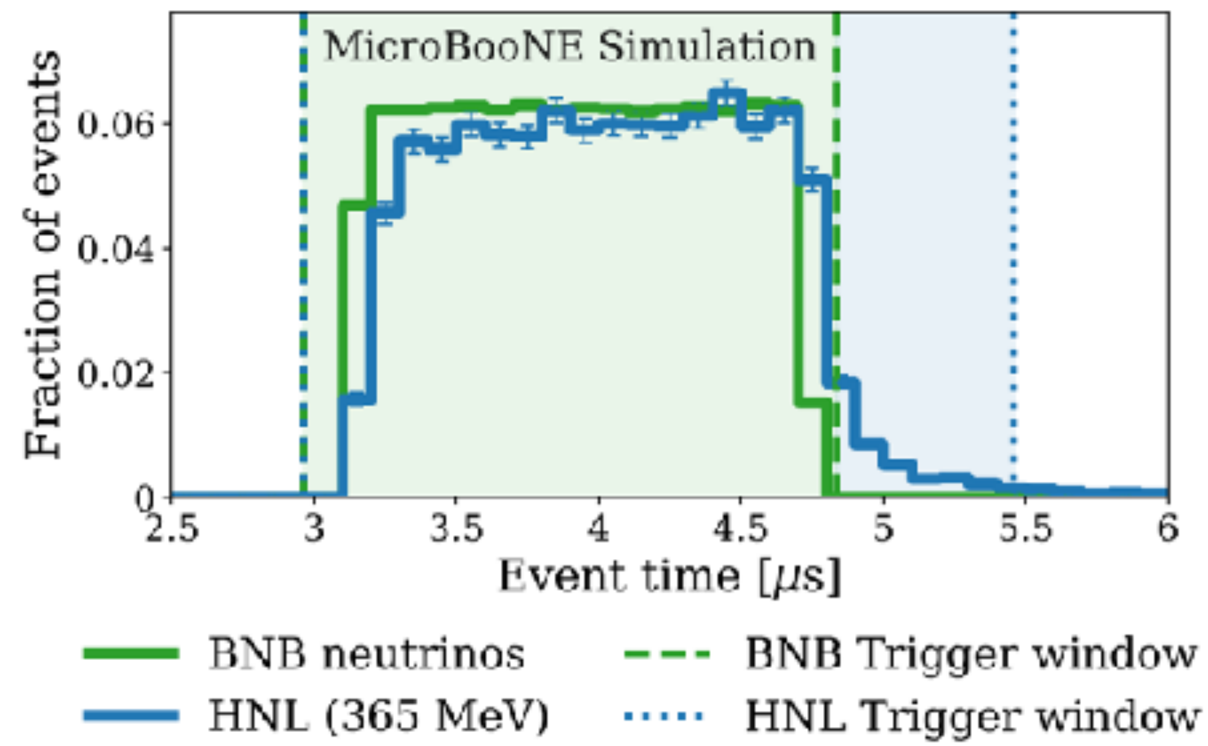
- Possibly related to neutrino mass
- Dirac vs Majorana nature of HNLs can be probed, if discovered

MICROBOONE'S HNL SEARCH

Phys. Rev. D 101, 052001 (2020)

- Search for HNLs decaying to μπ pairs
- Dedicated trigger configuration to detect HNL decays that occur after the neutrino beam spill

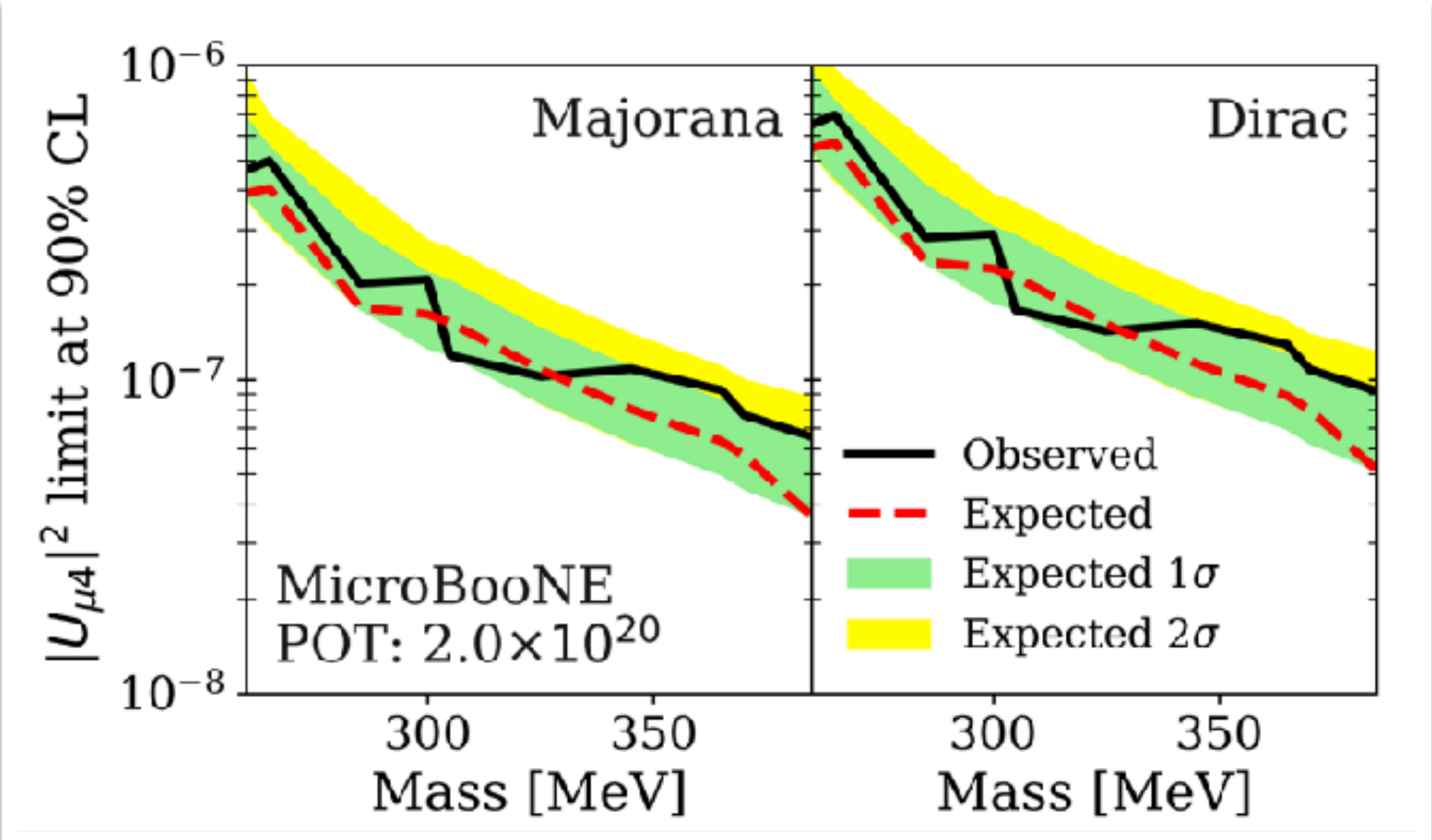




MICROBOONE'S HNL SEARCH

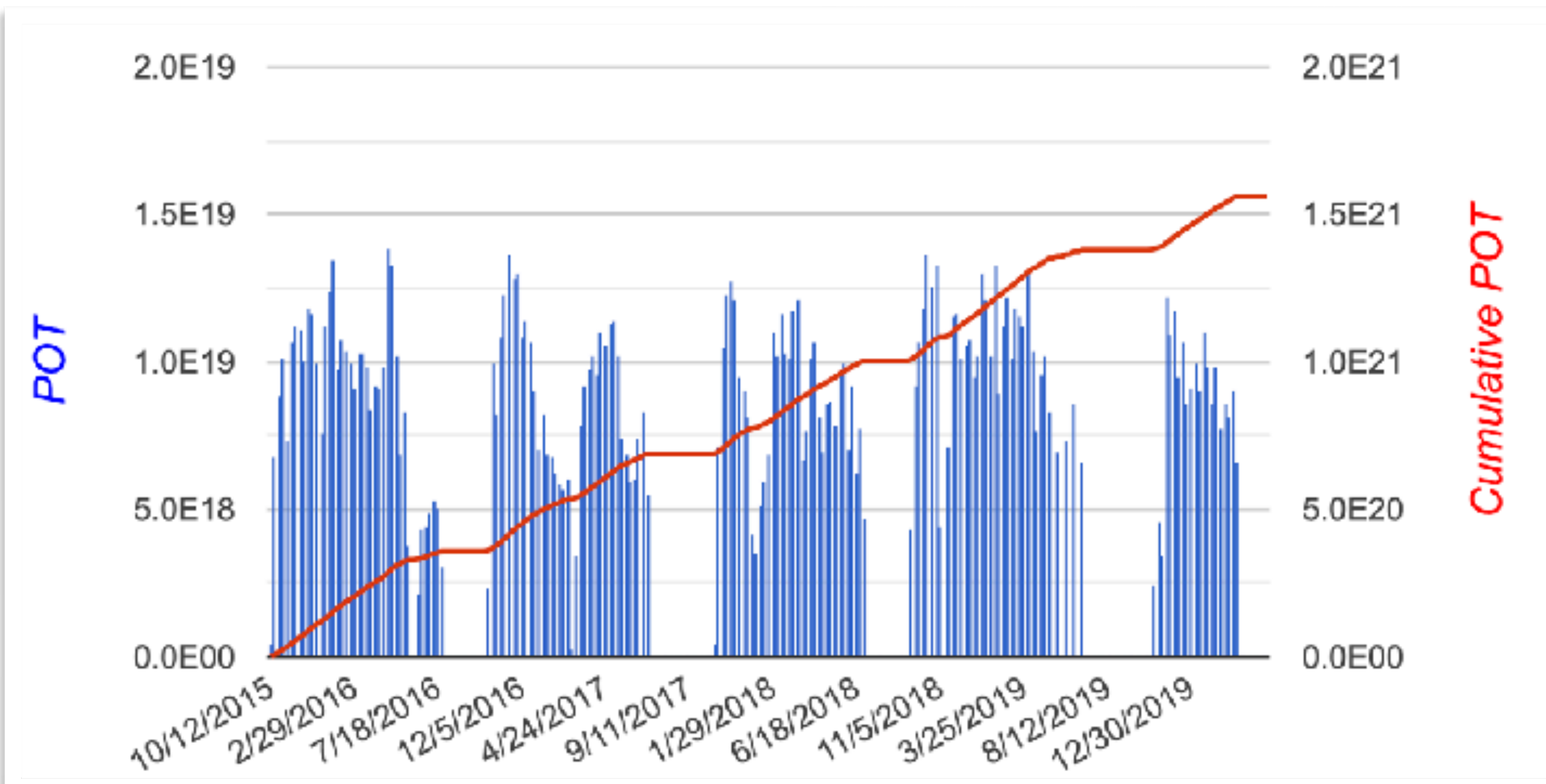
Phys. Rev. D 101, 052001 (2020)

Set upper limits on extended PMNS matrix element $|U_{\mu 4}|^2$ → **most constraining experimental limits at higher masses**. Updated measurement coming soon!



FUTURE INVESTIGATIONS

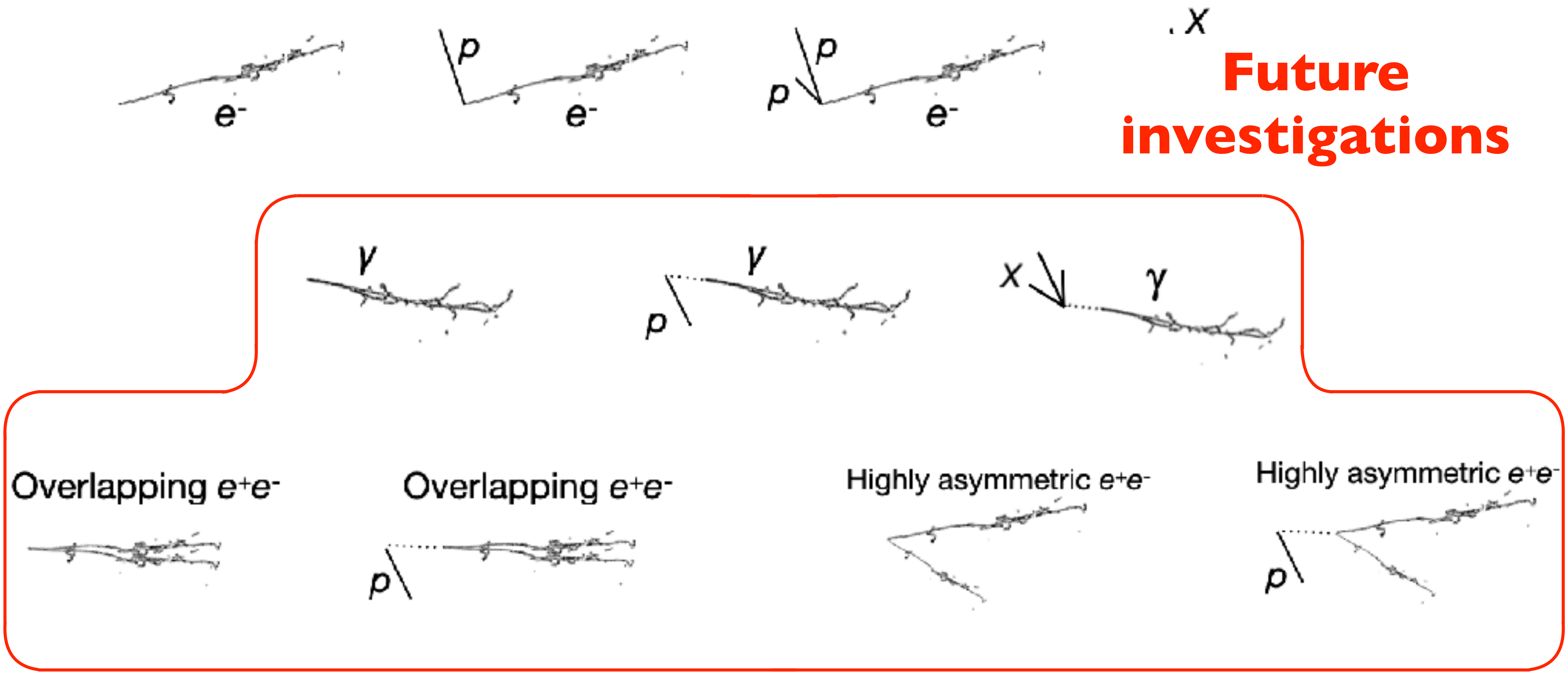
BNB Data collection: Protons on Target (POT)



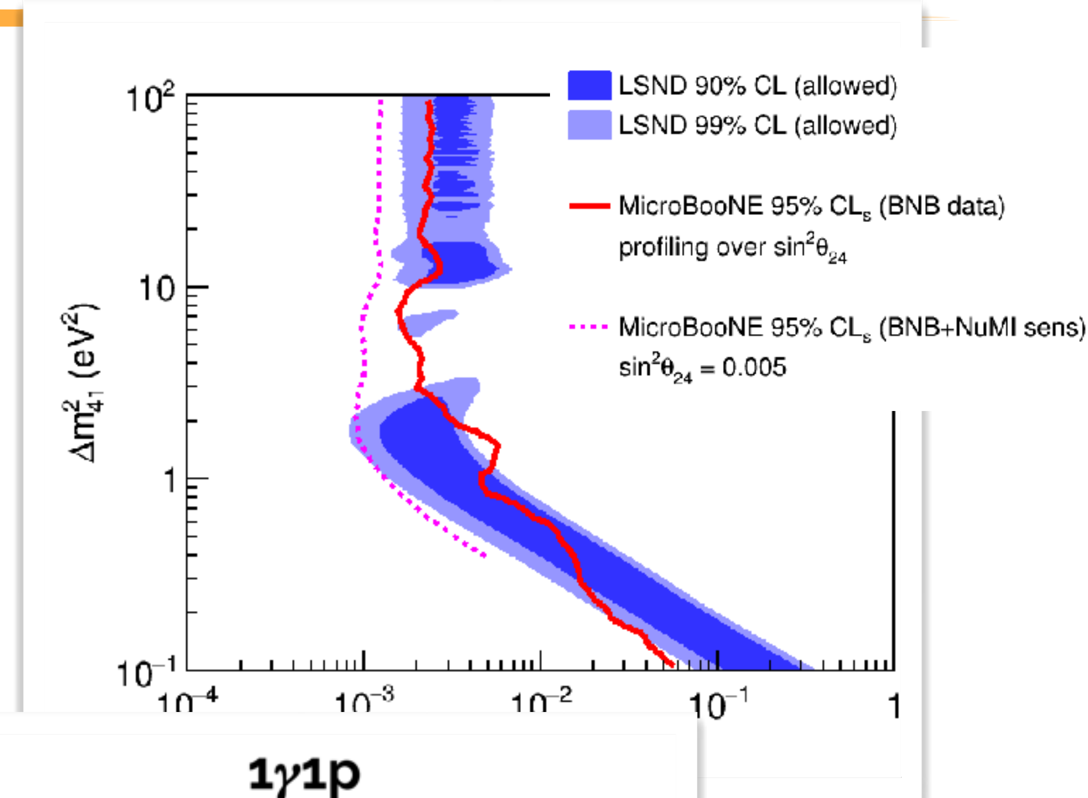
Analysed ~7×10^{20} POT

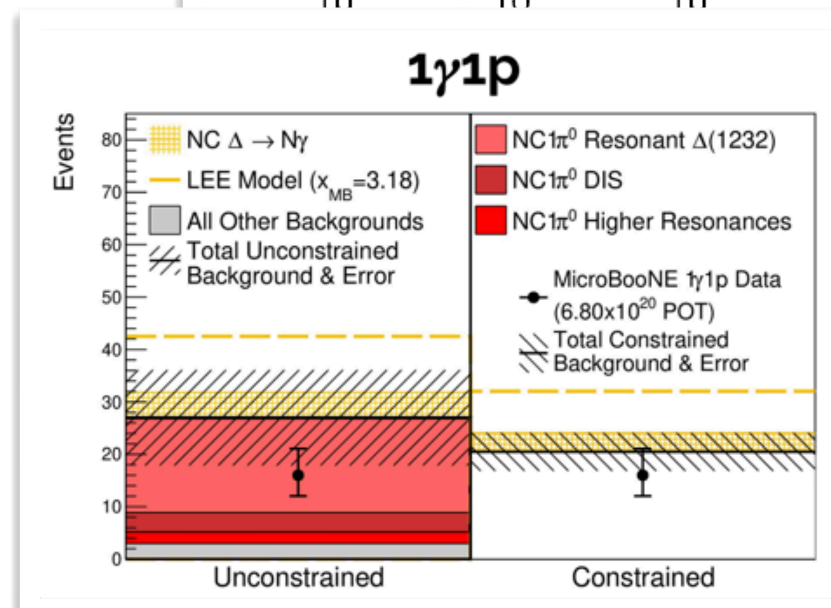
Approximately the same again still to come!

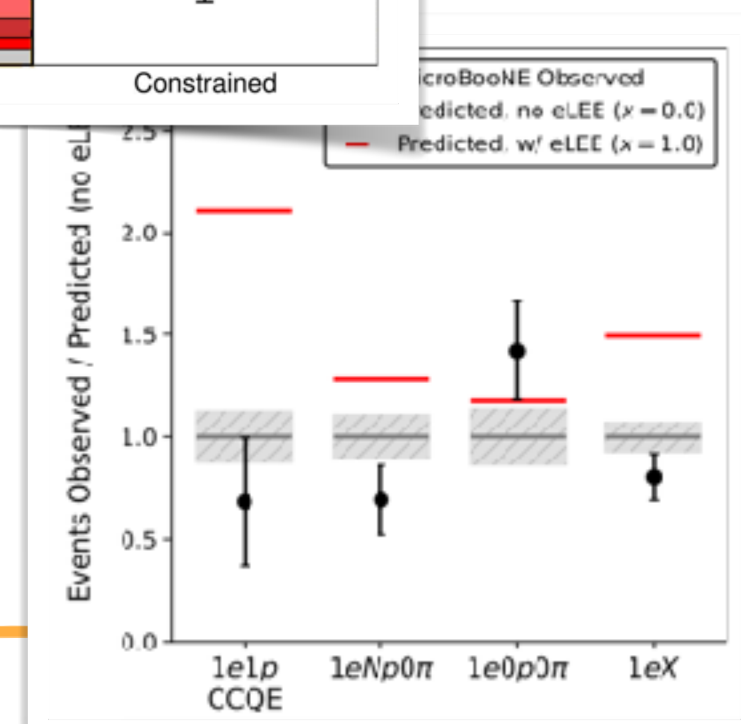
FUTURE INVESTIGATIONS



- Neutrinos are one of the **least-well-understood particles** in the Standard Model
- Neutrino oscillation is **beyond the Standard Model**, and opens the door to **exciting new possibilites**
- However, a lot remains that we **don't understand** (both within the 3-flavour oscillation picture and outside it)
- I present(ed) **new data** from the **MicroBooNE** experiment that sheds light on one of the existing anomalies
- **More data (x2 data statistics), more analyses, and more experiments (SBN) will soon add to this picture**



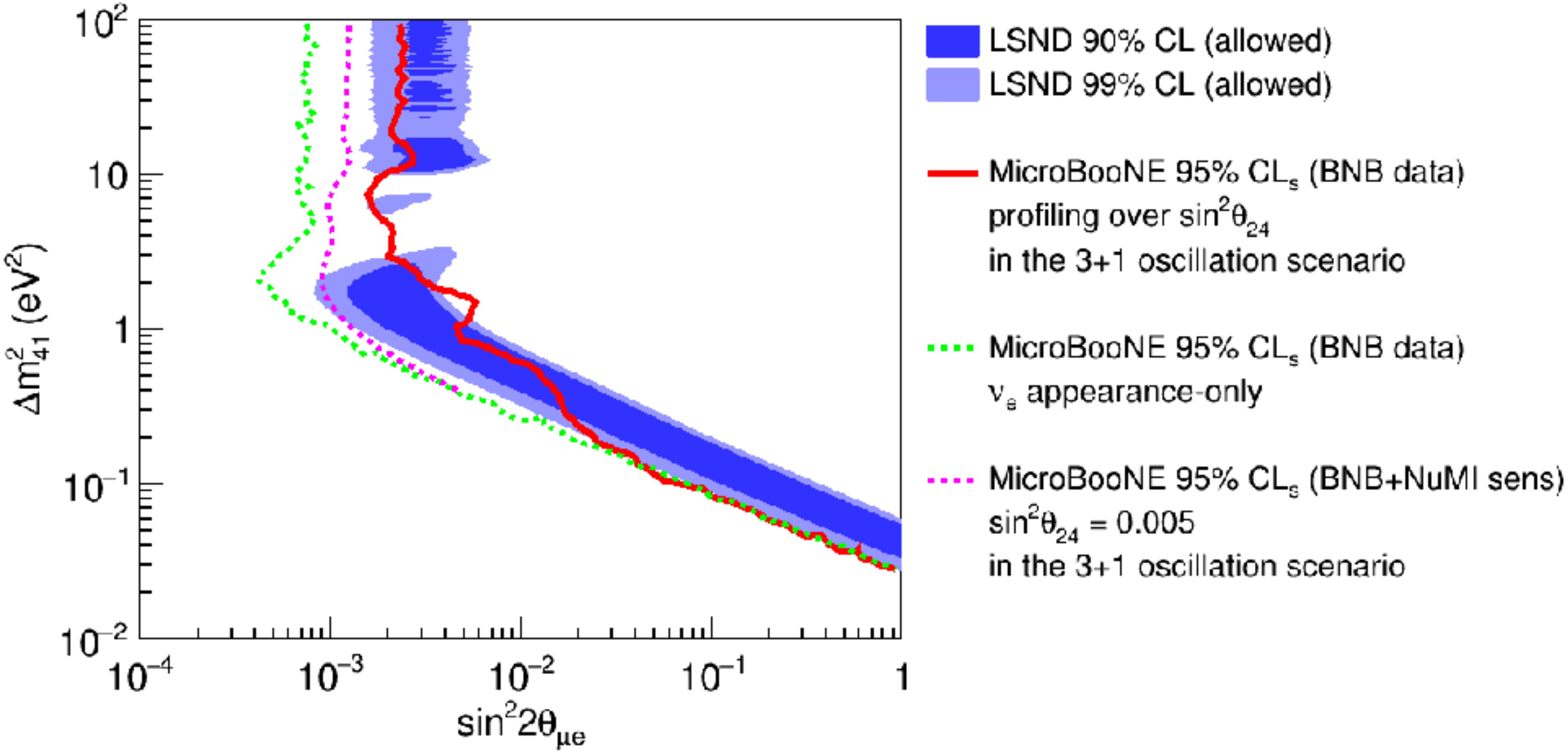




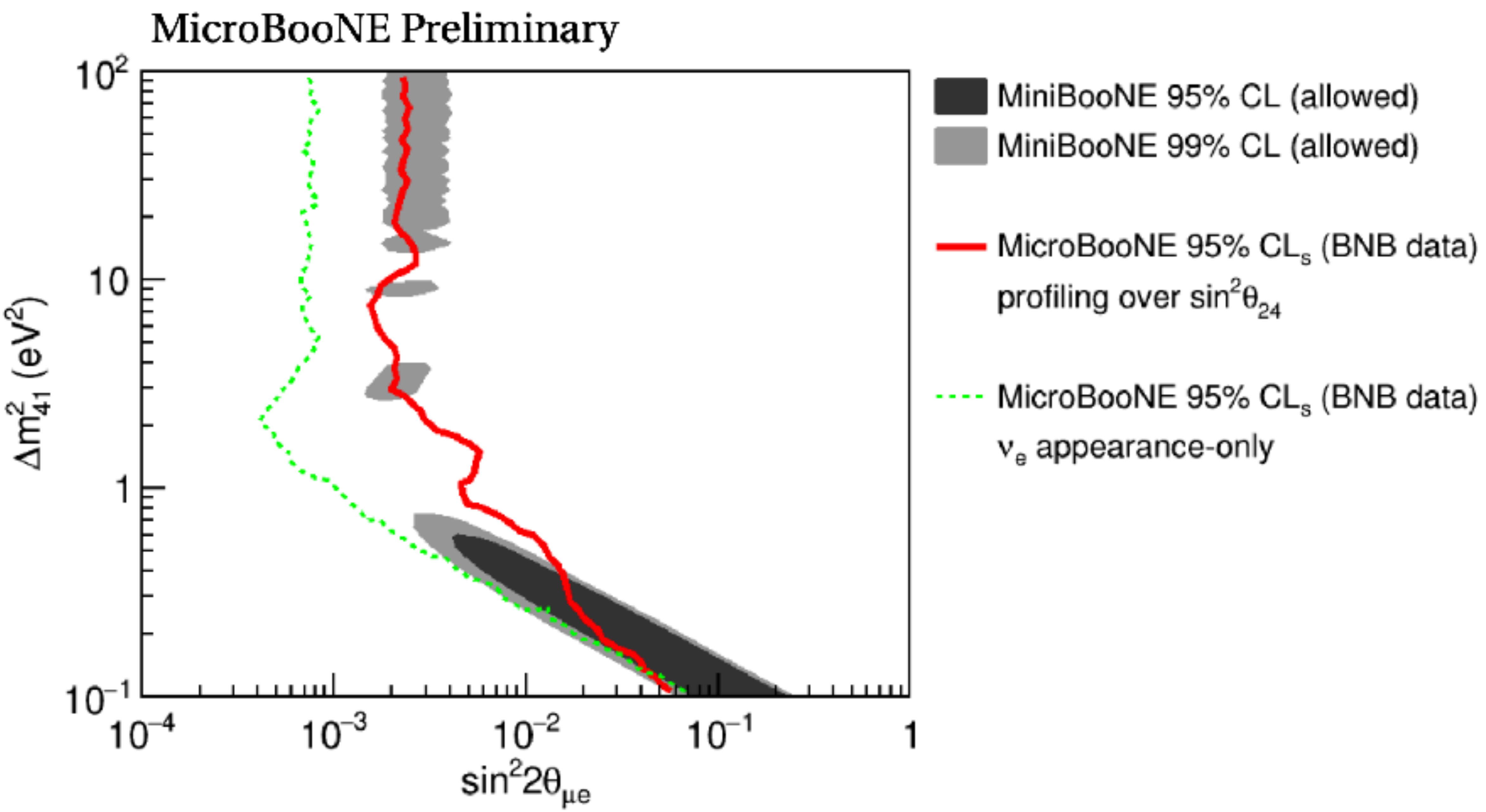
THANK YOU

µBooNE

OSCILLATION PARAMETER DEGENERACY



OSCILLATION PARAMETER DEGENERACY



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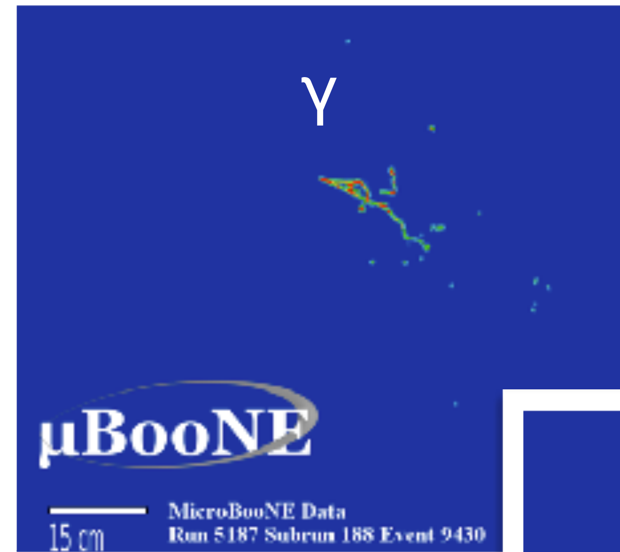
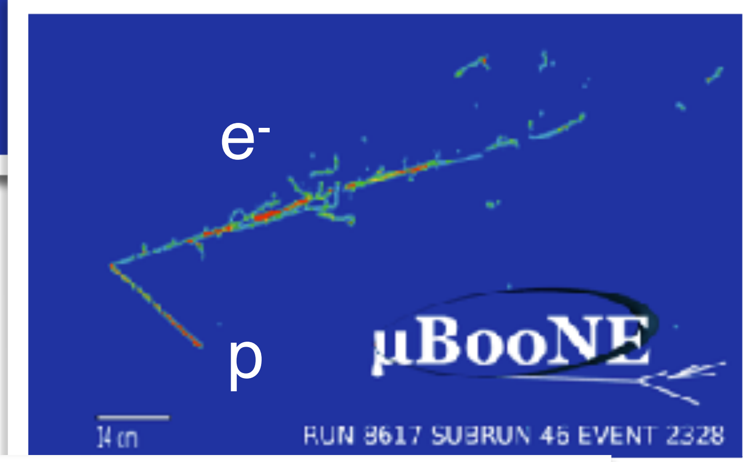
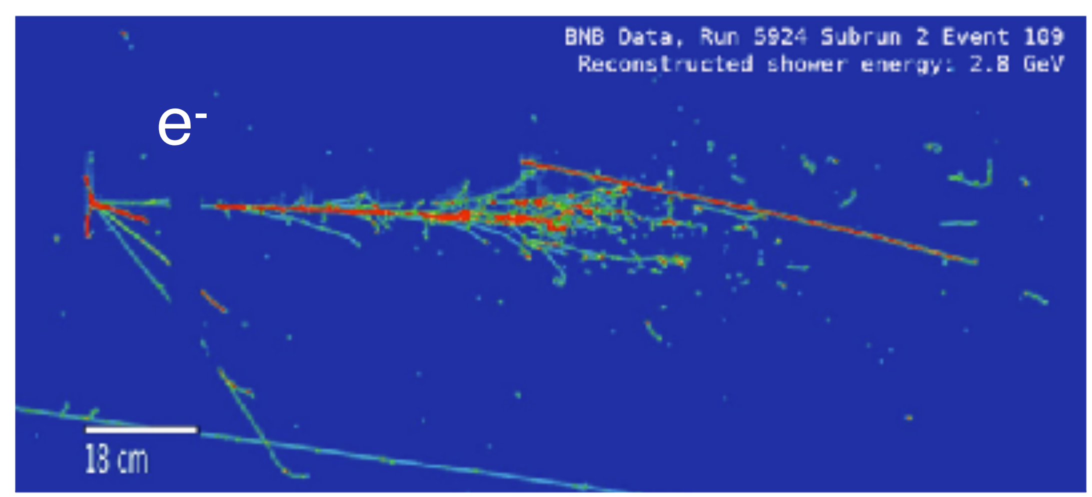
A NOTE ON NEUTRINO ENERGY

- Each analysis selects **different combinations of particles**
- Each analysis uses a **different reconstruction paradigm**
- Electron-search results presented as a function of reconstructed neutrino energy
  - Remember we have to estimate neutrino energy from the particles we measure
  - → reconstructed neutrino energy != true neutrino energy
  - → AND **reco→true mapping is different between analyses**







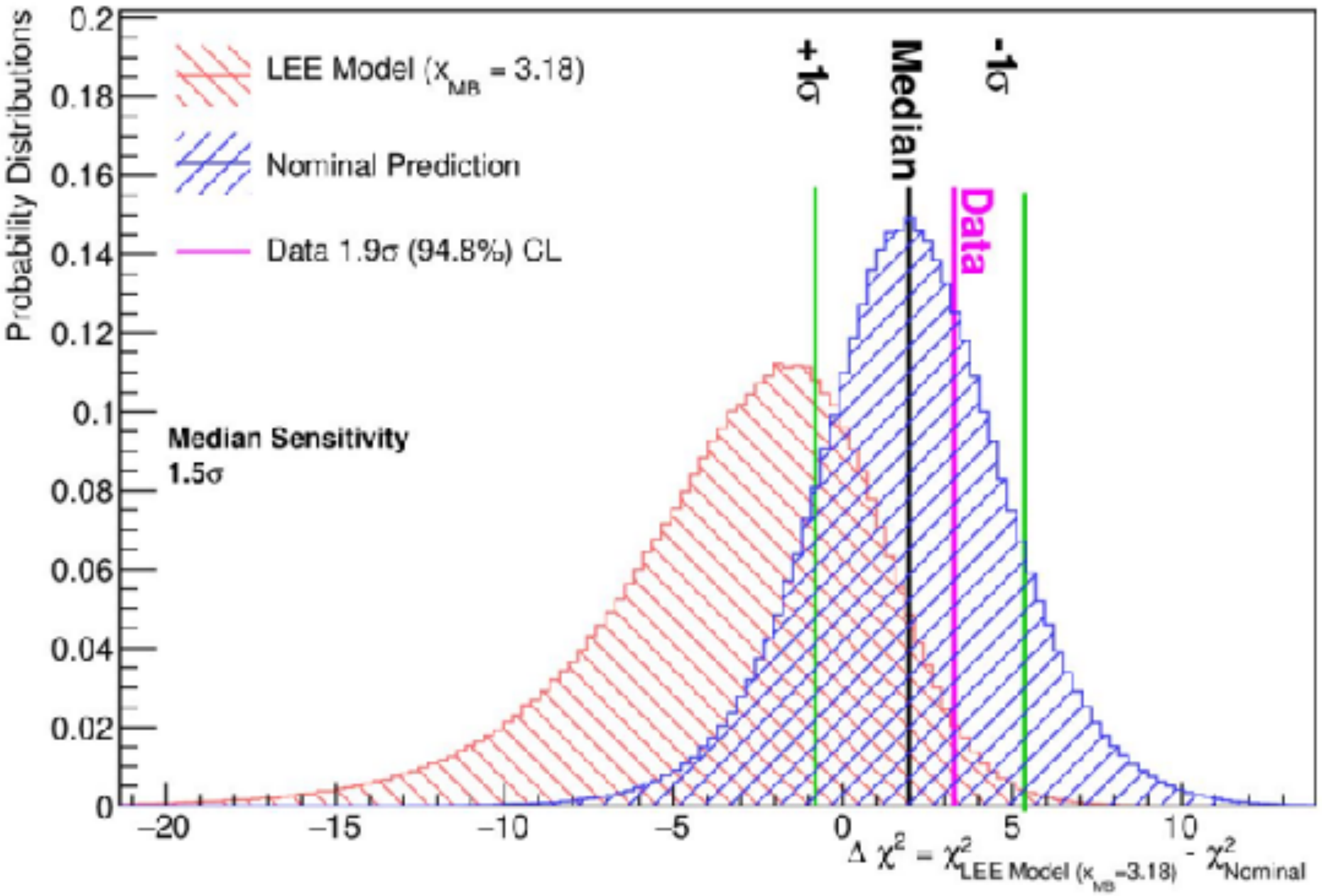
SINGLE PHOTON SEARCH

arXiv:2110.00409 [hep-ex]

- Simple hypothesis test: use combined Neyman-Pearson χ^2 as test statistic

Nucl. Inst. Meth. A 961 (2020) 163677

- Data consistent with nominal $\Delta \to N\gamma$ prediction
- Data **rejects LEE model hypothesis** in favour of nominal prediction at **94.8% CL**



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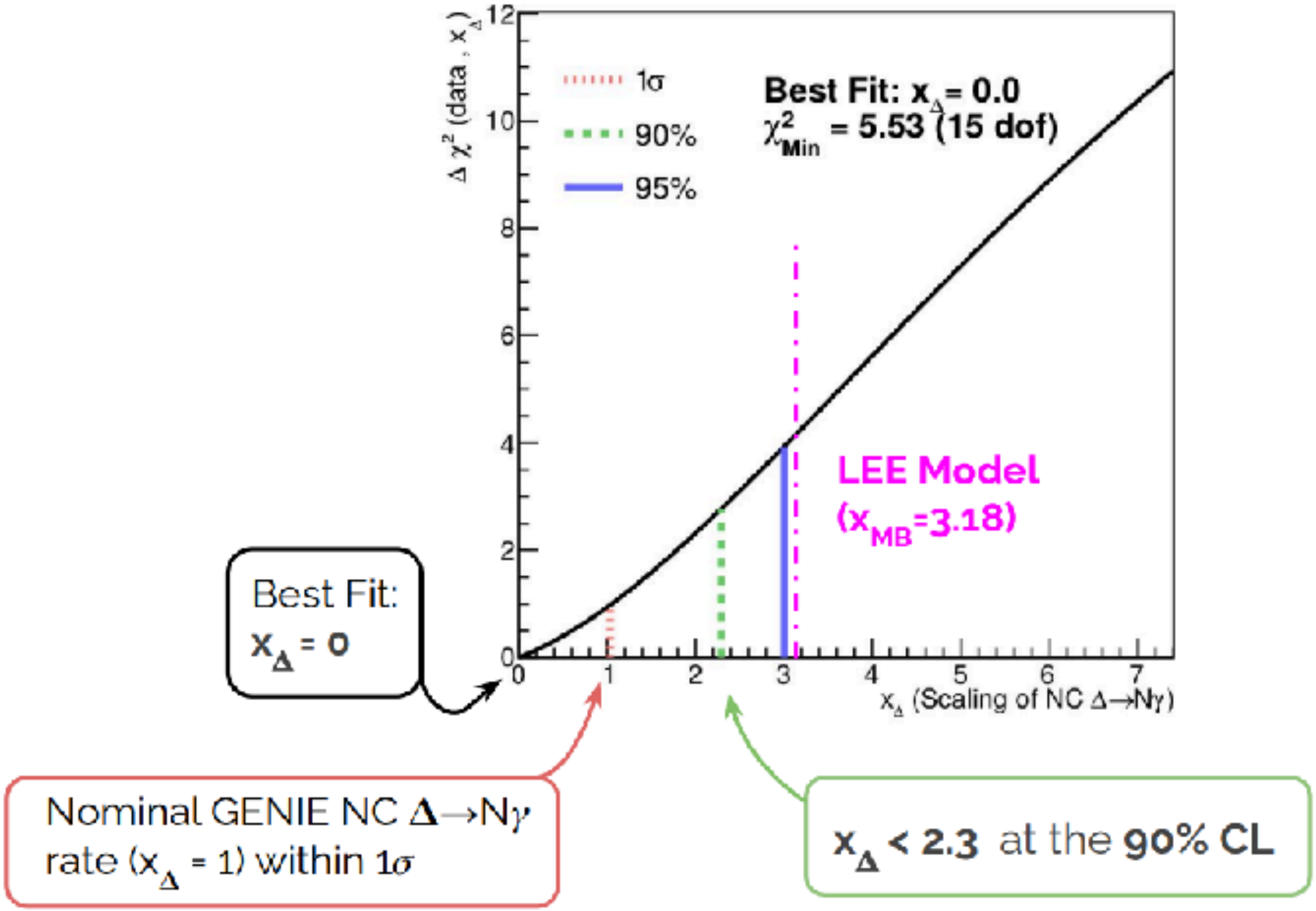
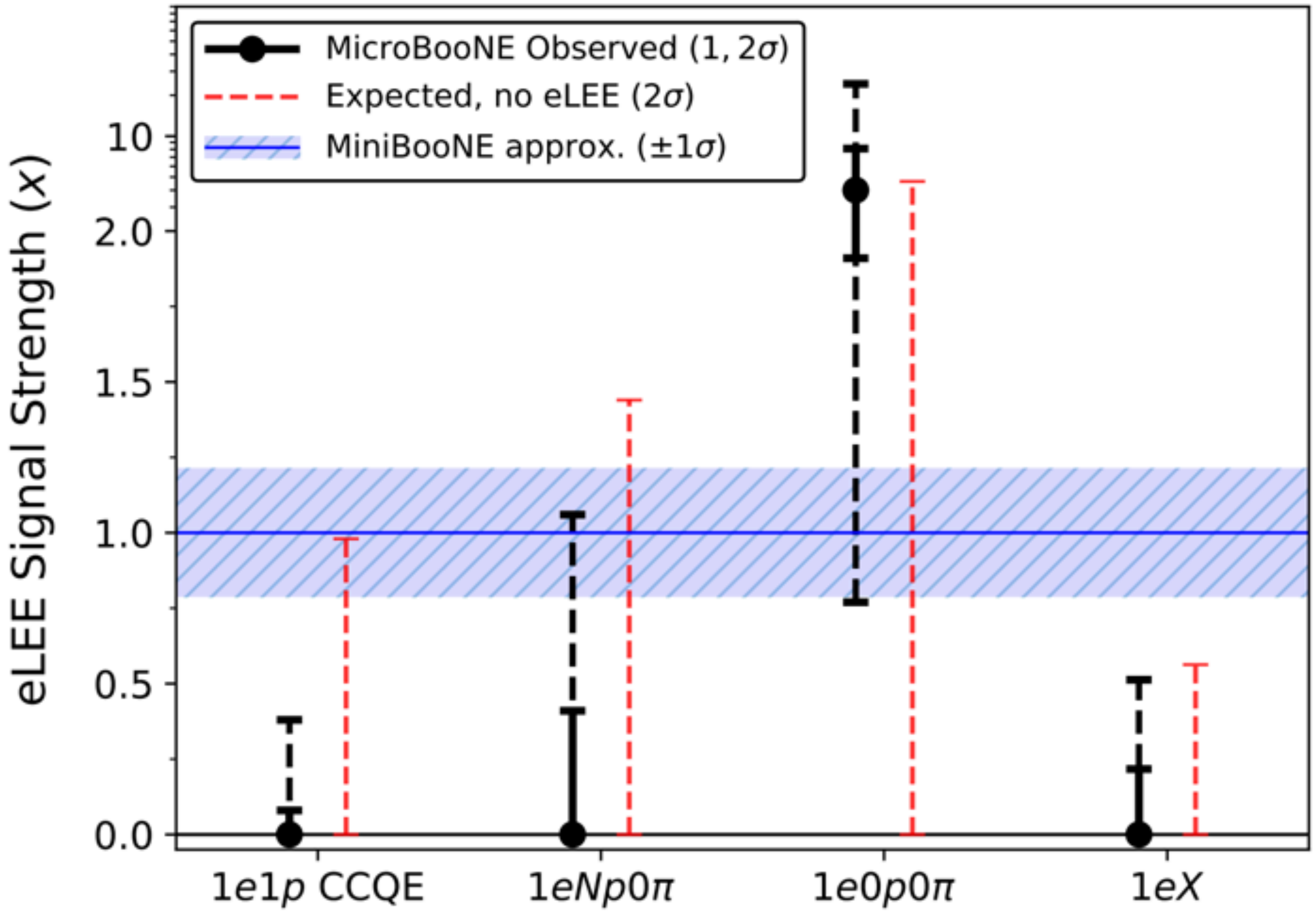
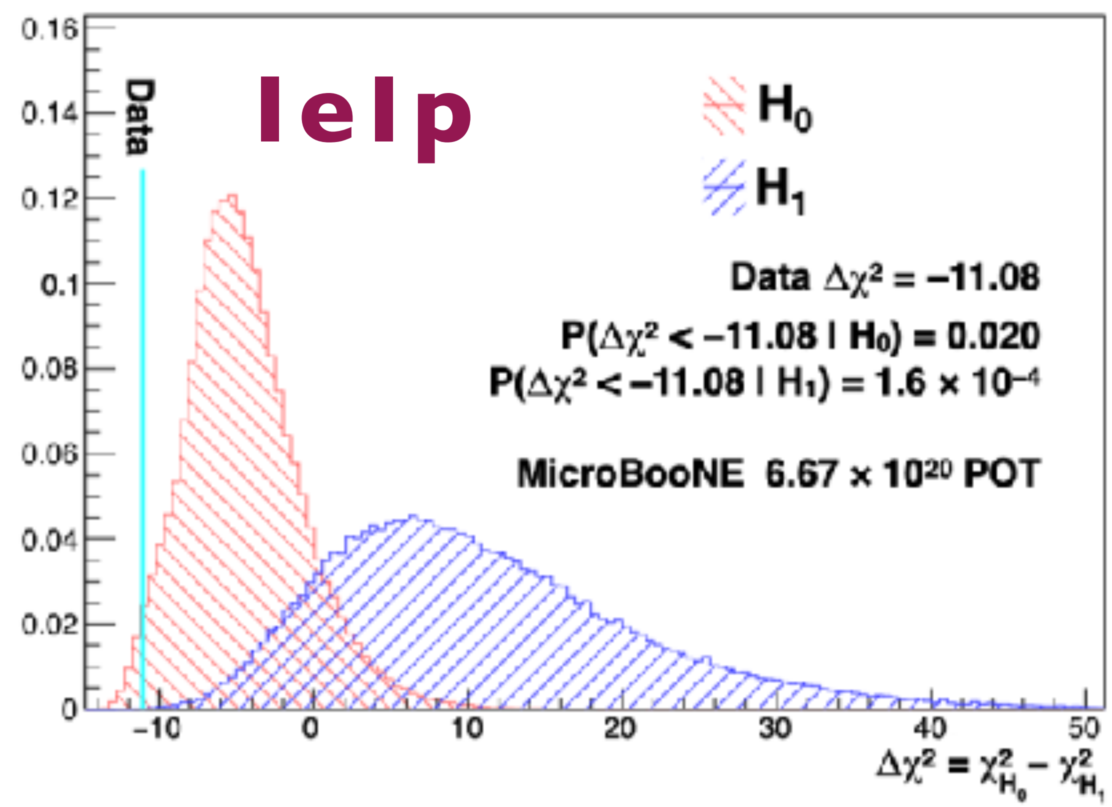
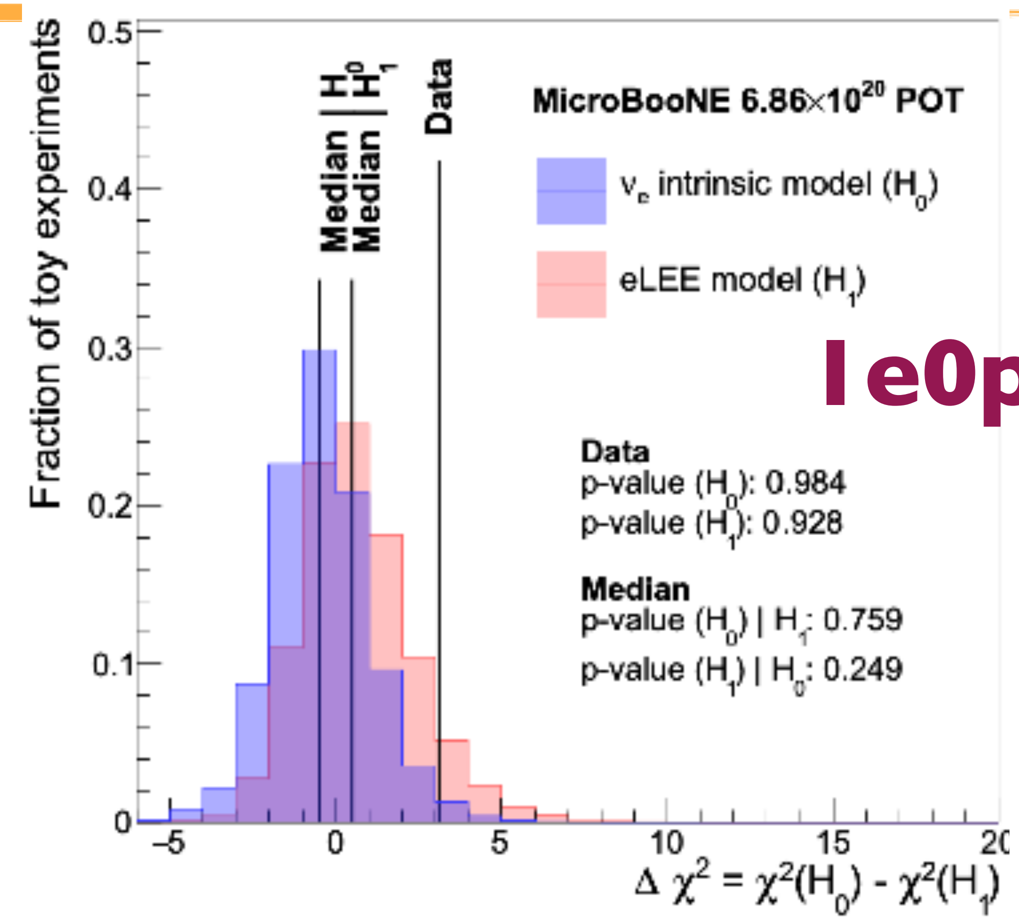
SINGLE PHOTON SEARCH

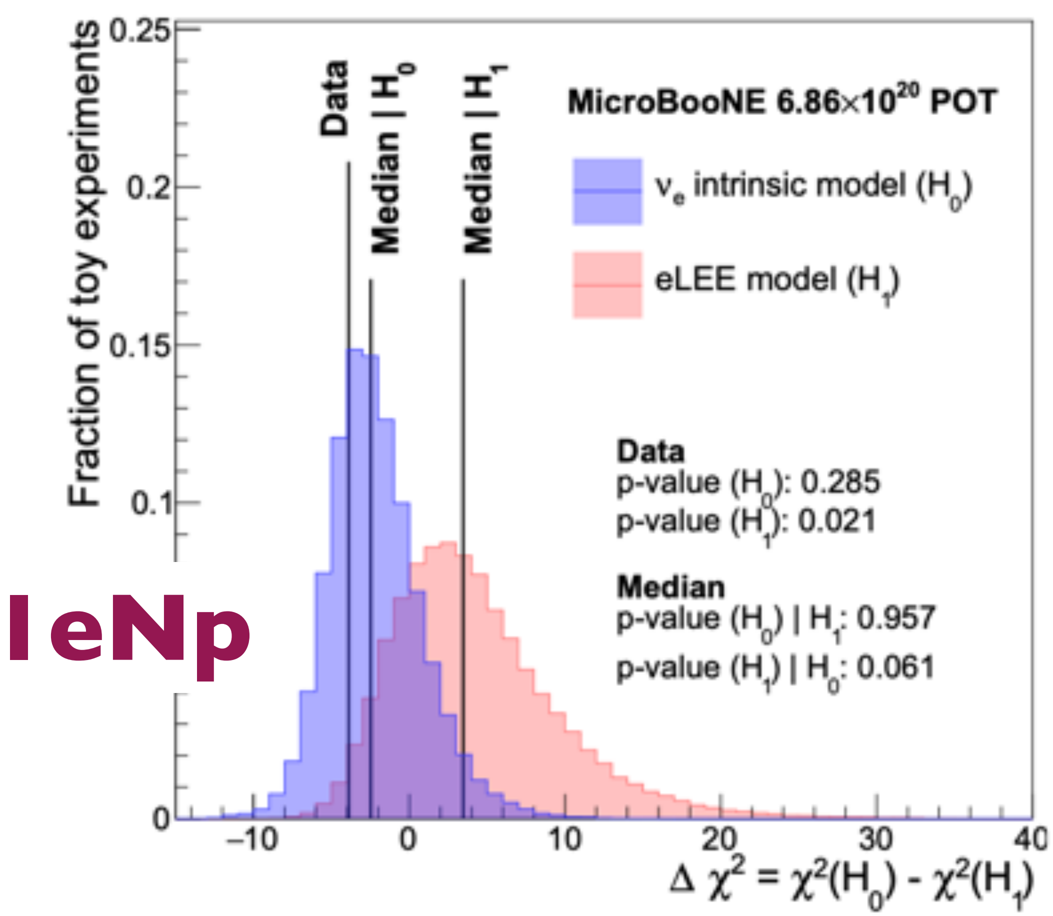


Slide credit: Mark R-L

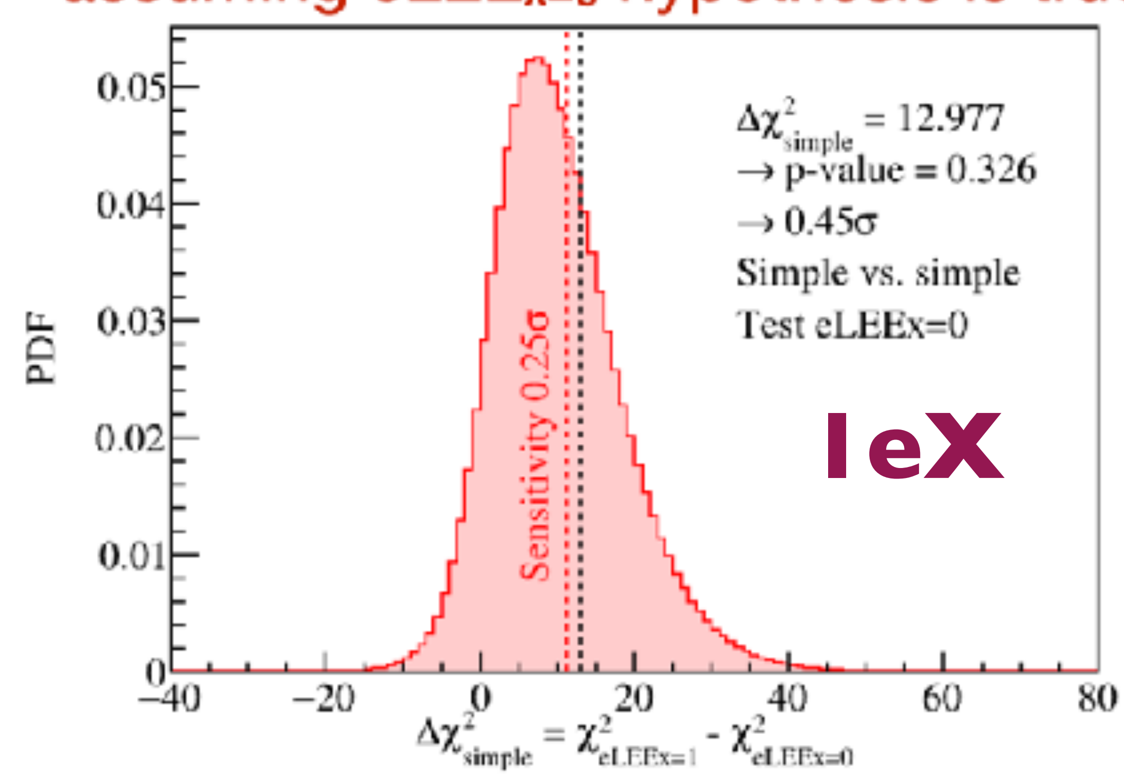

MicroBooNE Observed (1, 2σ)
Expected, no eLEE (2σ)
MiniBooNE approx. (±1σ)
eLEE Signal Strength (x)
10
2.0
1.5
1.0
0.5
0.0
1e1p CCQE
1eNp0π
1e0p0π
1eX





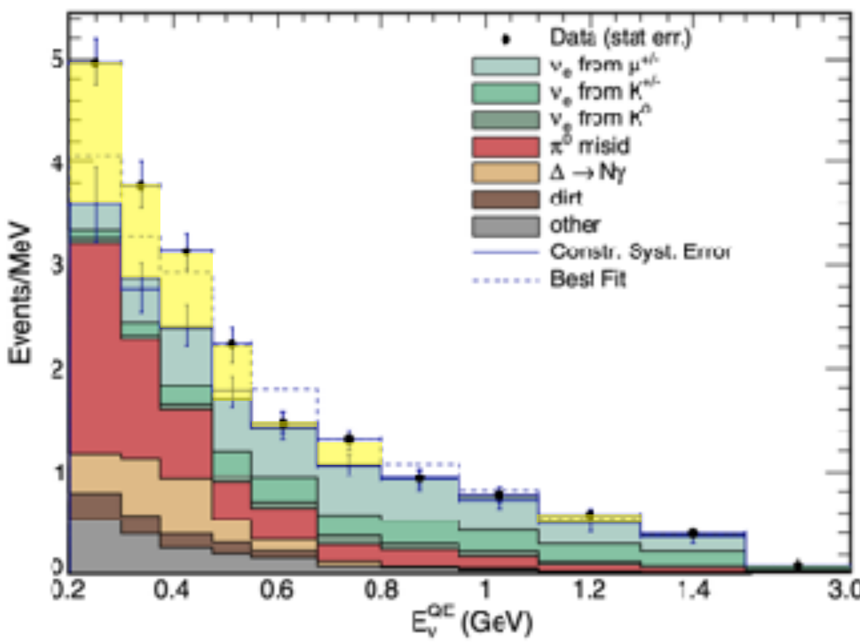


assuming $eLEE_{x=0}$ hypothesis is true



A SIMPLE MODEL OF THE MINIBOONE EXCESS

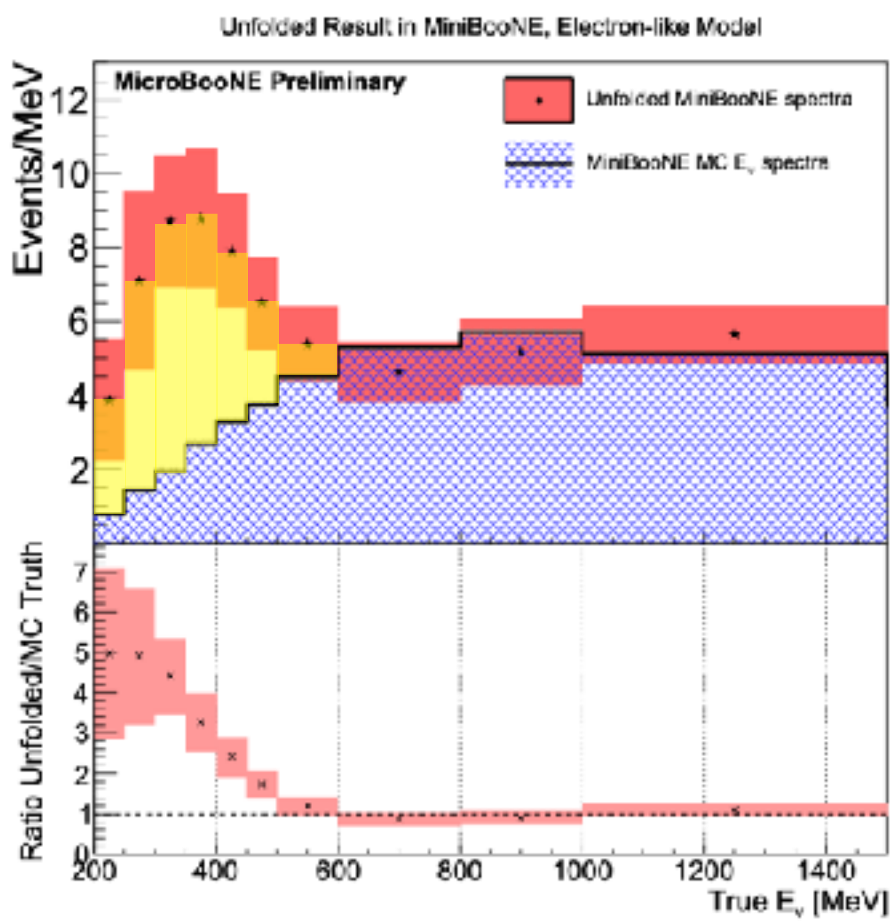
ν_e

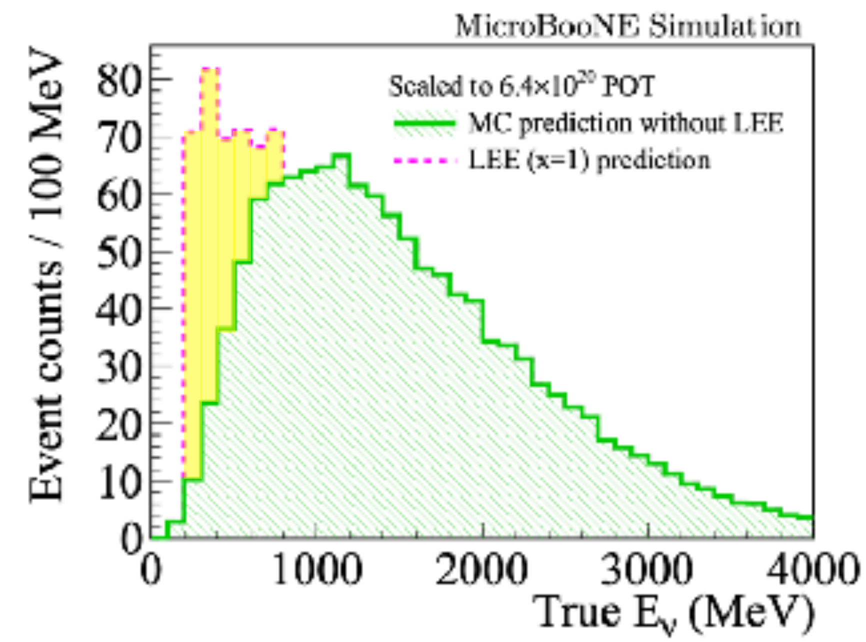


Take **excess** reported in MiniBooNE's 2018 results

Phys. Rev. Lett. 121, 221801

Unfold to true energy, assuming excess is entirely **electron neutrino**



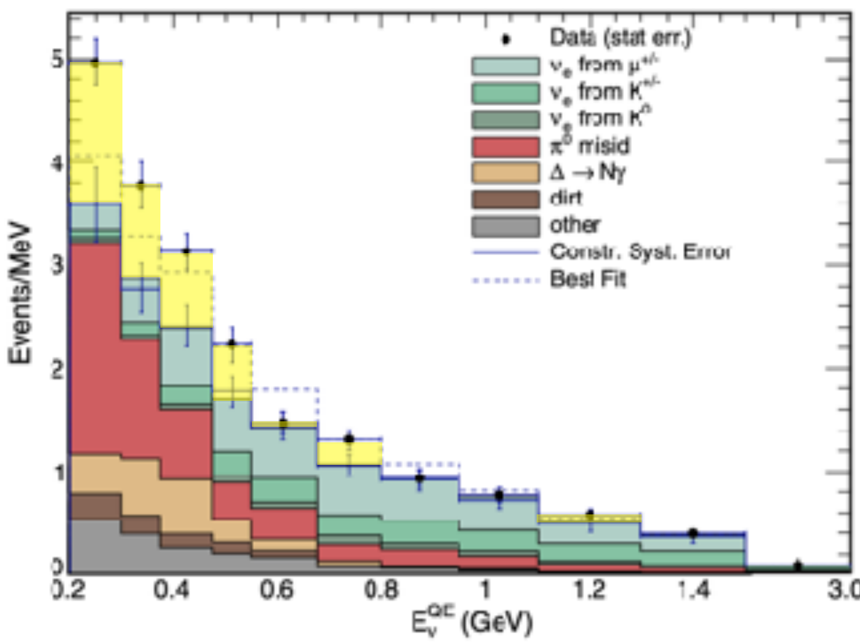


Apply to MicroBooNE to find **expected excess**

Allow normalisation (x) to float

A SIMPLE MODEL OF THE MINIBOONE EXCESS

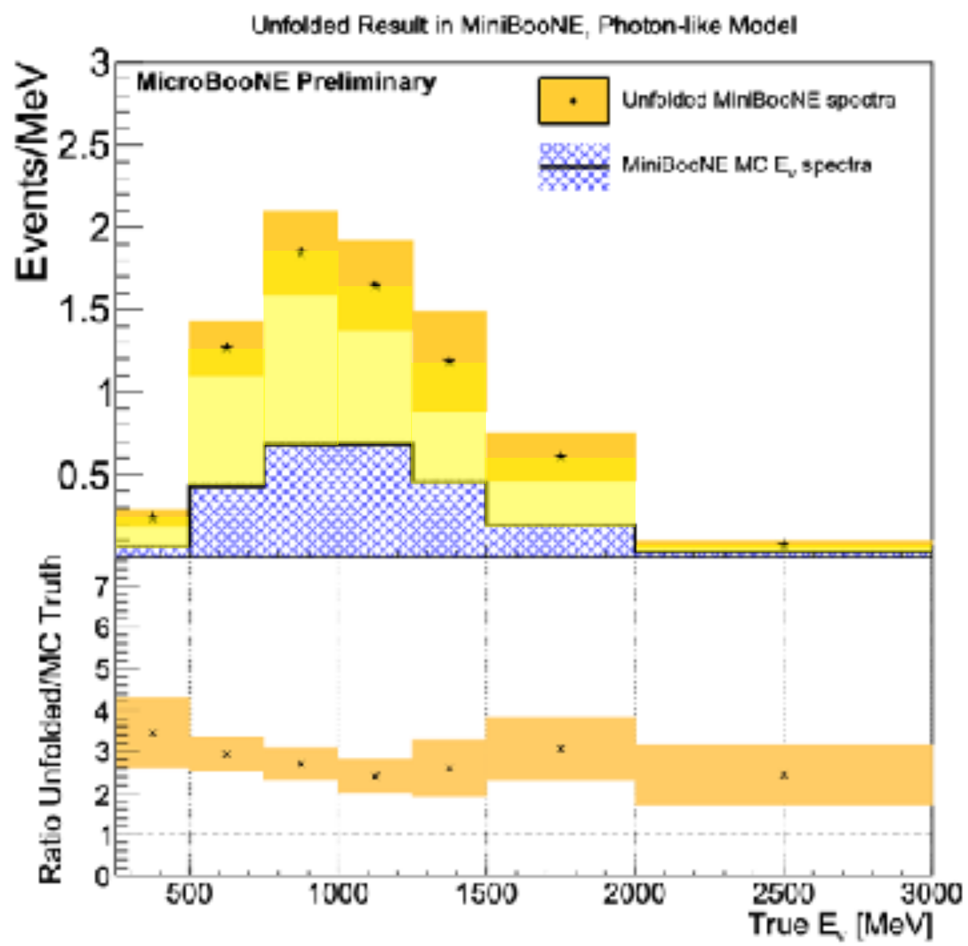
Δ→Nγ

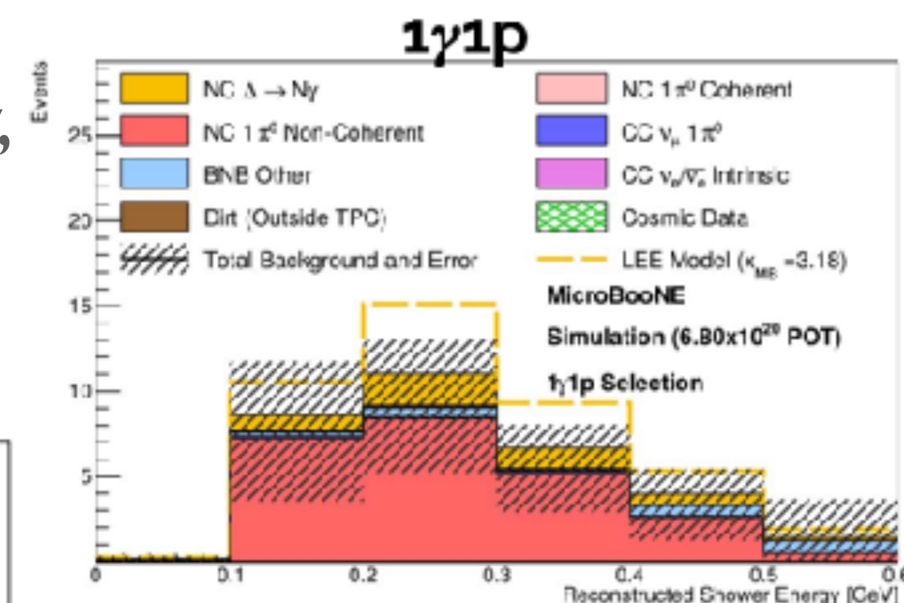


Take **excess** reported in MiniBooNE's 2018 results

Phys. Rev. Lett. 121, 221801

Unfold to true energy, assuming excess is entirely **Δ→Nγ**



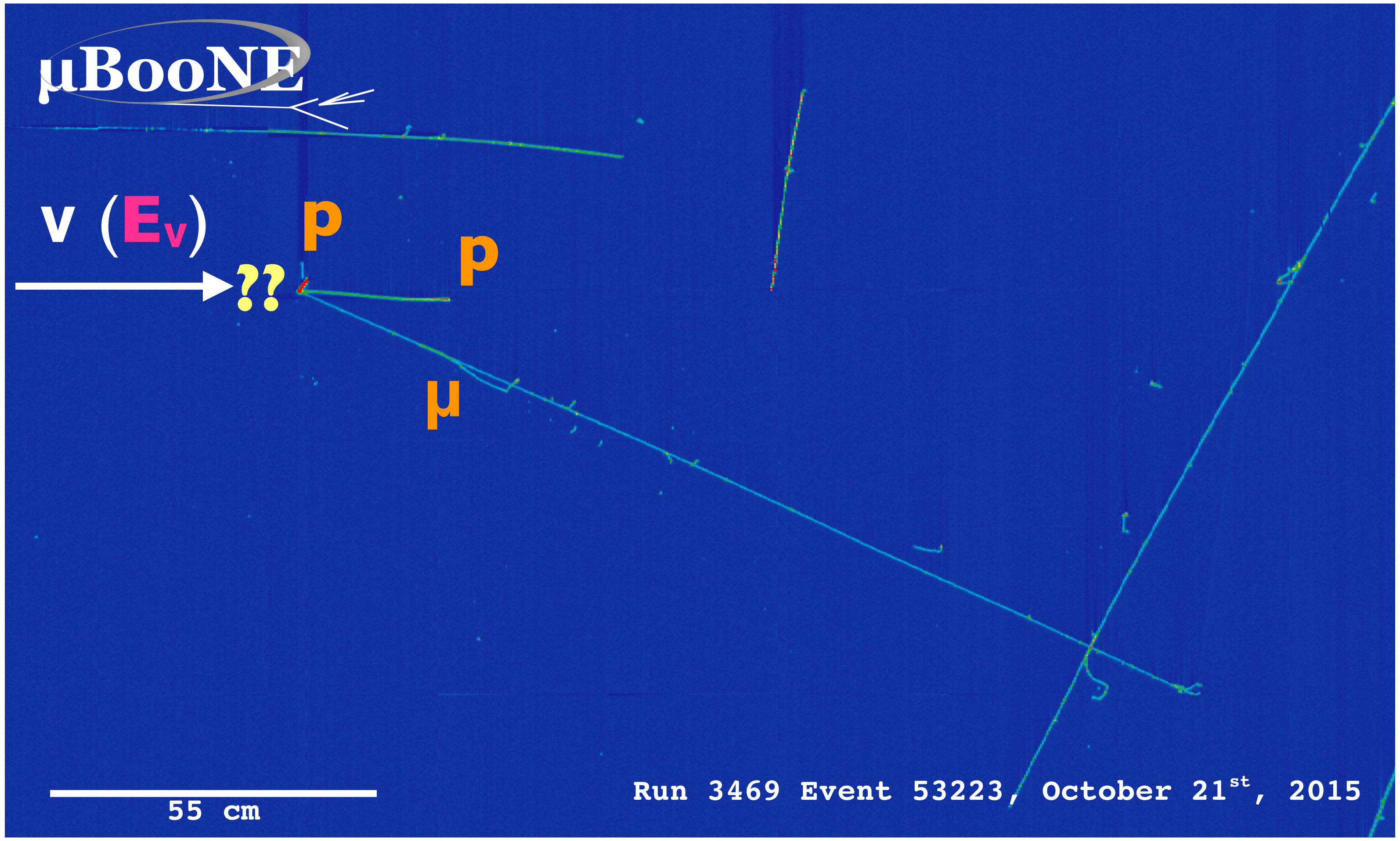


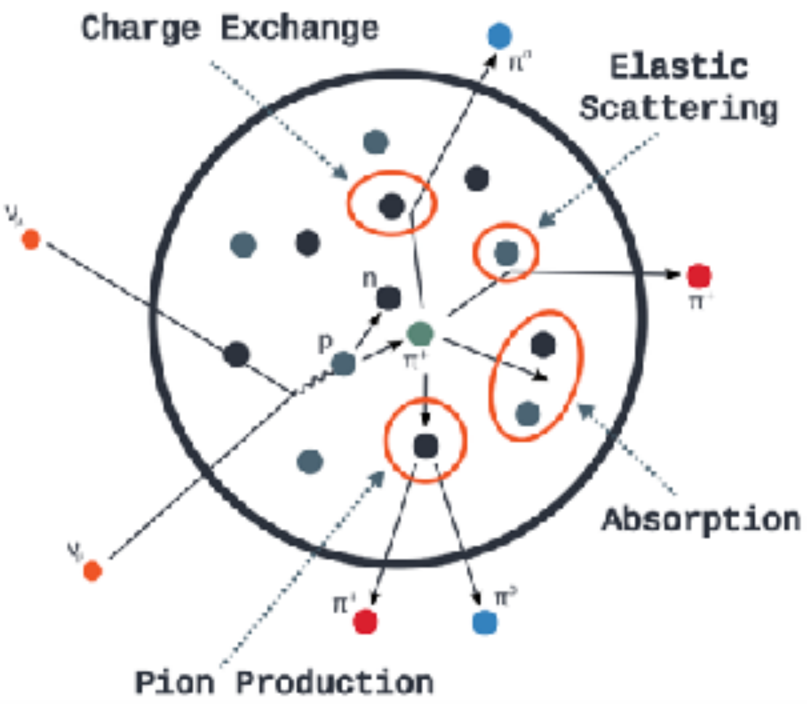
Flat normalisation enhancement of x3.18 could explain excess

Use as model for Δ→Nγ search

DOING THE MEASUREMENT

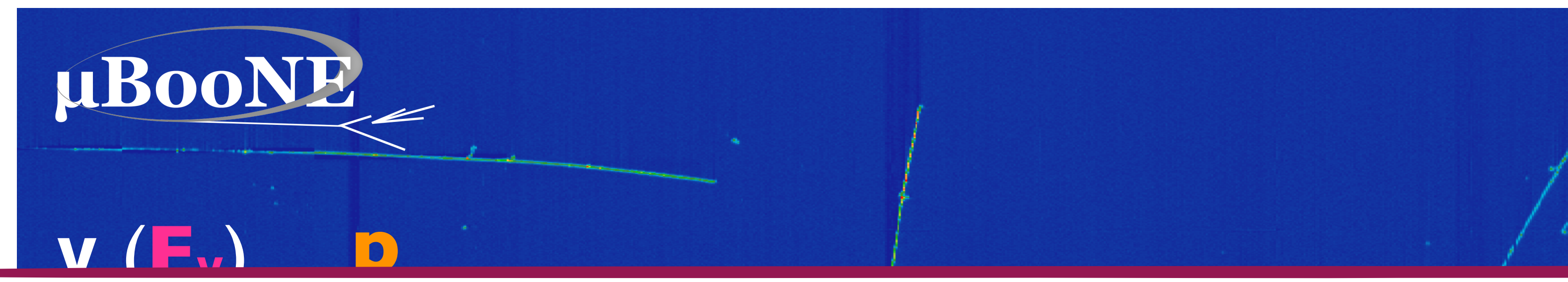
Tune neutrino interaction model to external data





DOING THE MEASUREMENT

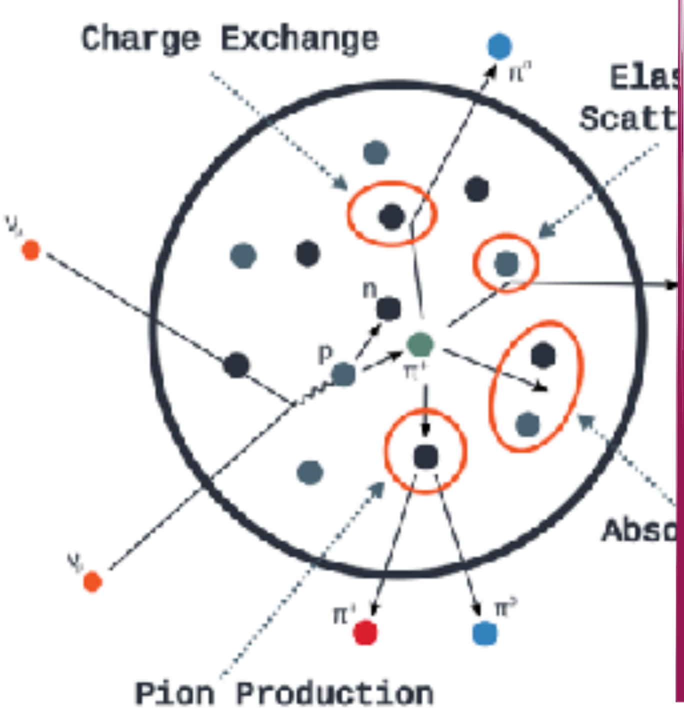
Tune neutrino interaction model to external data



Accurate model required to:

- predict mapping of reconstructed to true neutrino energy
- provide correlations between data samples (see next step of analysis)

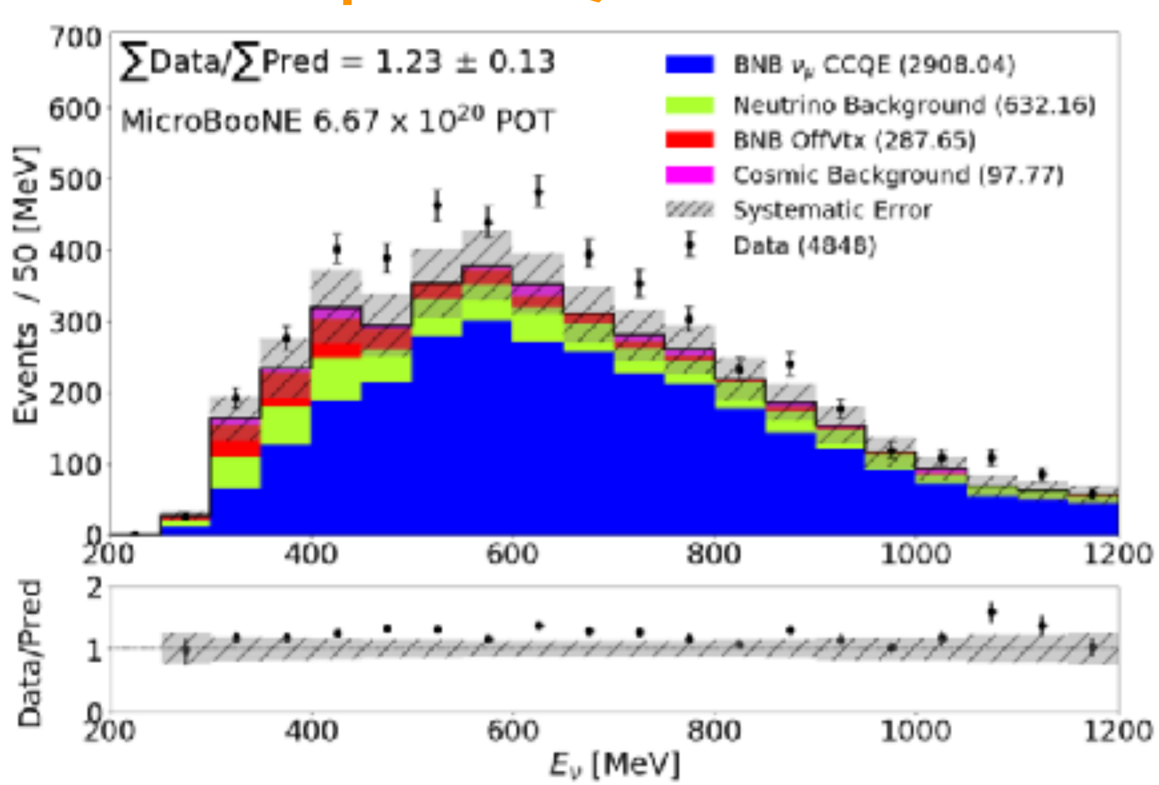
Accurate estimation of uncertainties can be more important than central-value model prediction



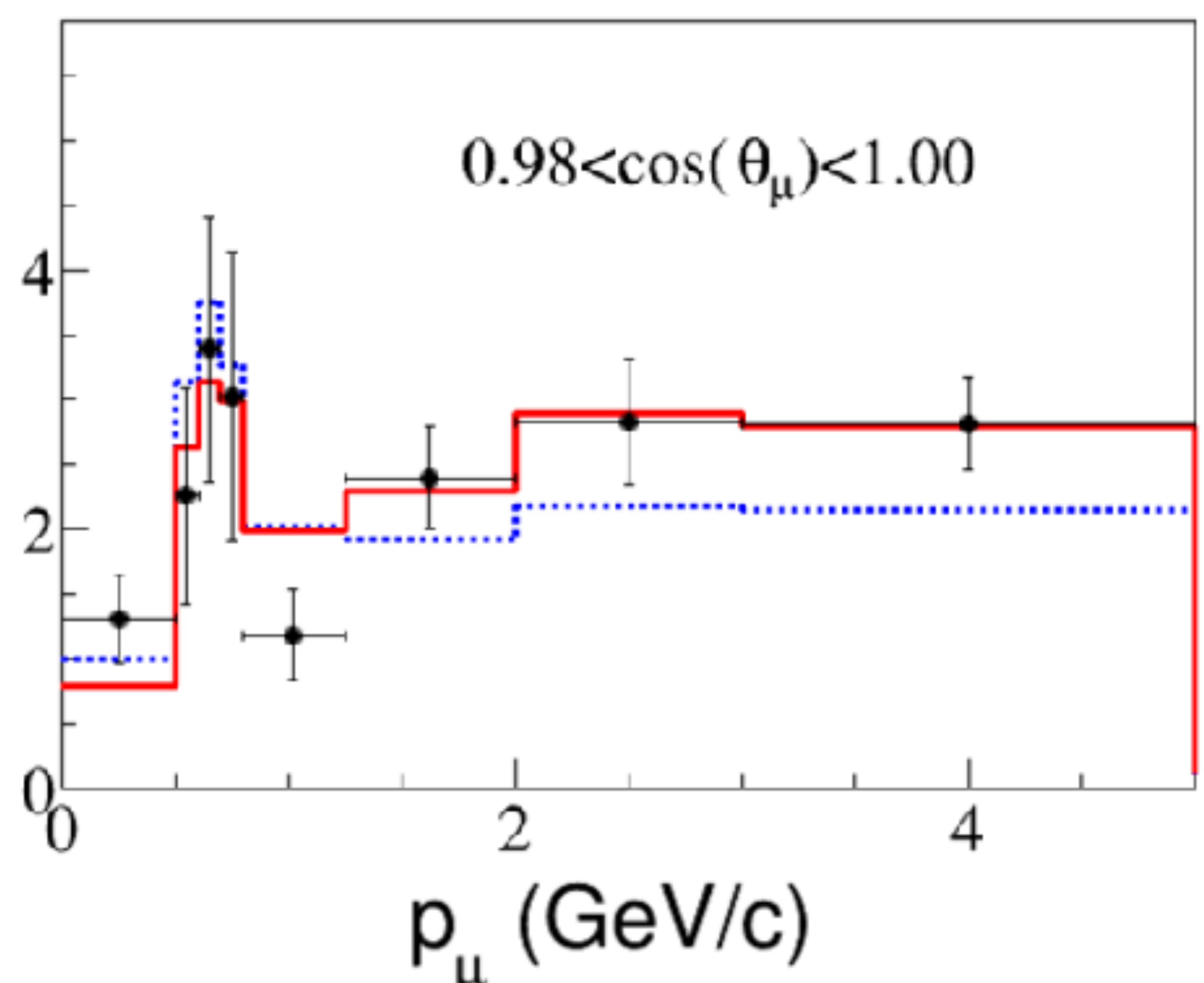
DOING THE MEASUREMENT

Tune neutrino interaction model to external data

ν_μ CCQE-like



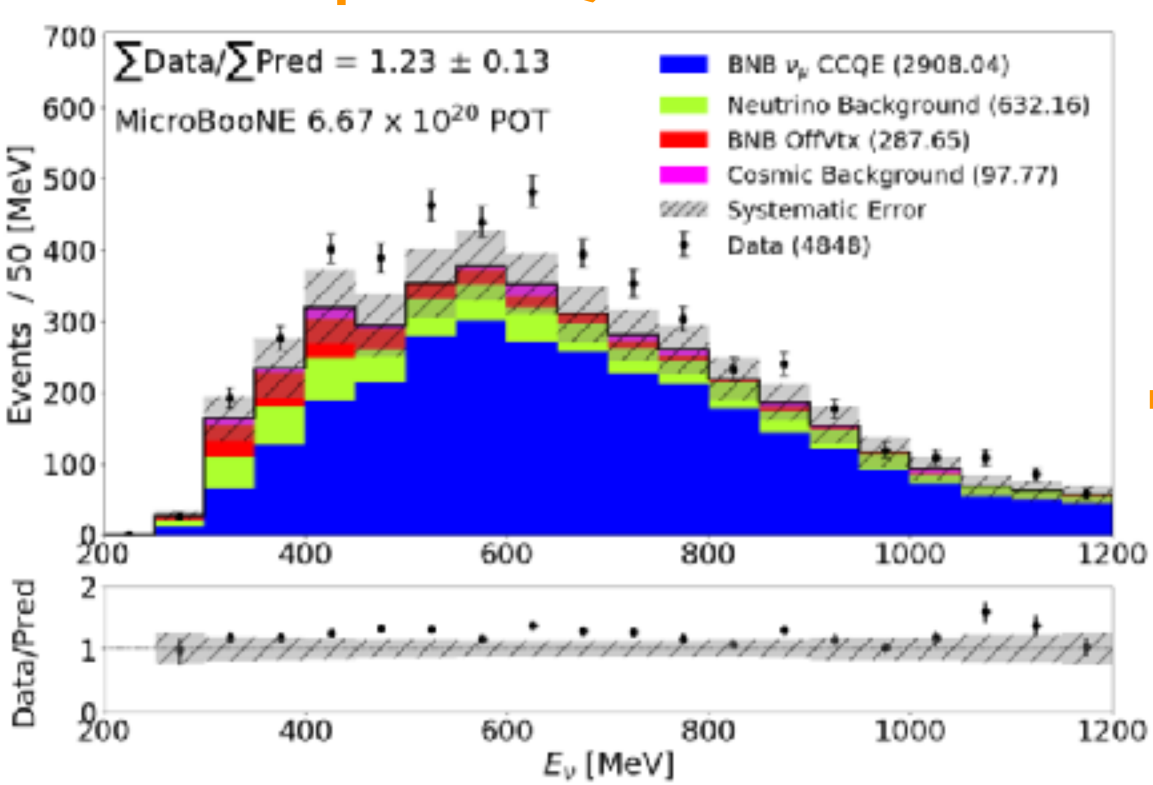
GENIE v3 (untuned) χ^2=115.3/67 bins
MicroBooNE Tune χ^2=63.8/67 bins
T2K Data



DOING THE MEASUREMENT

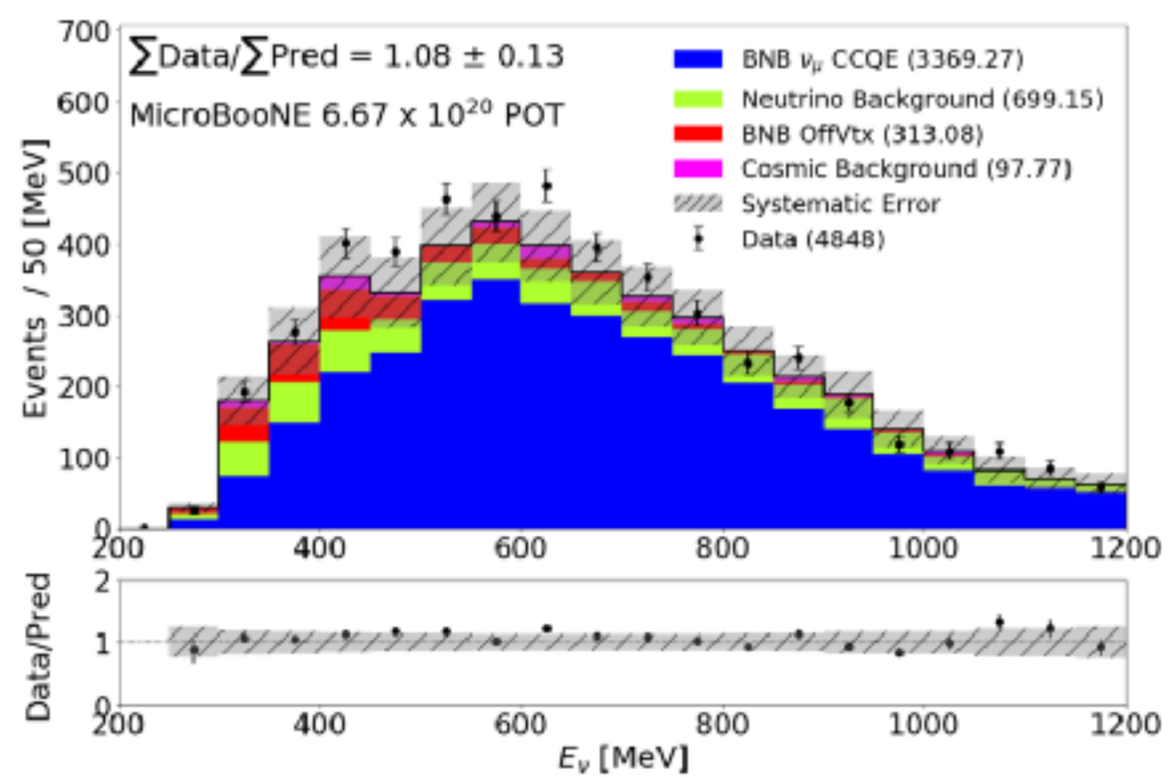
Tune neutrino interaction model to external data

ν_μ CCQE-like



ν_μ CCQE-like

Data/prediction: 1.23 → 1.08



DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

"Sideband" → independent (i.e. non-signal) data sample

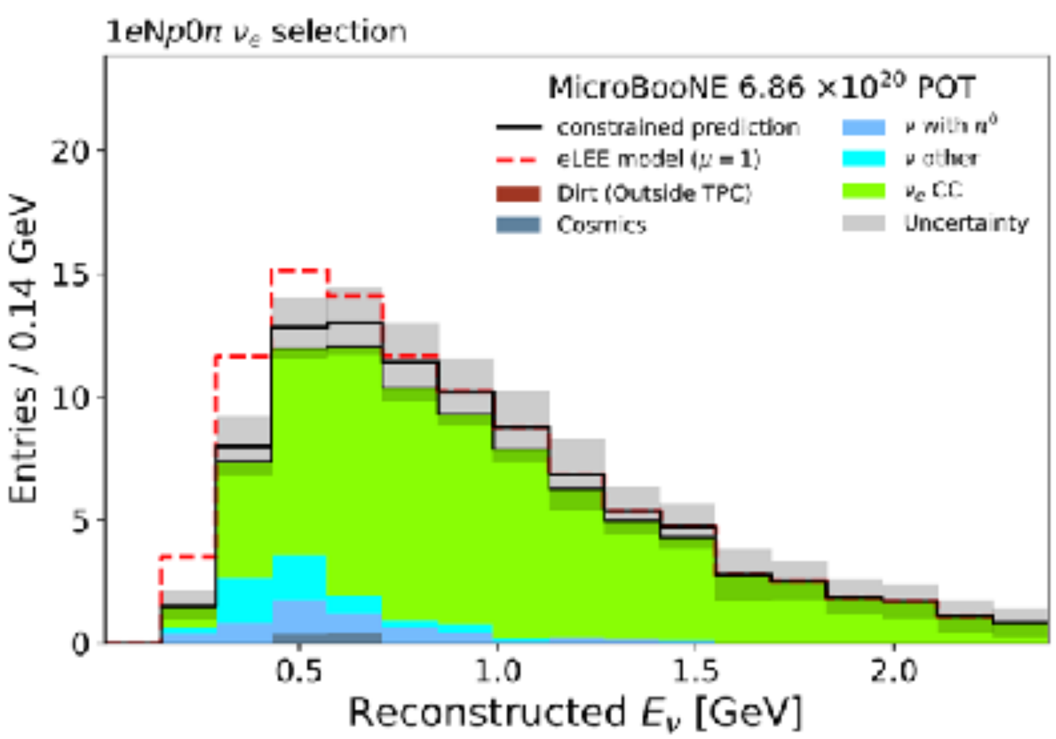
Use to:

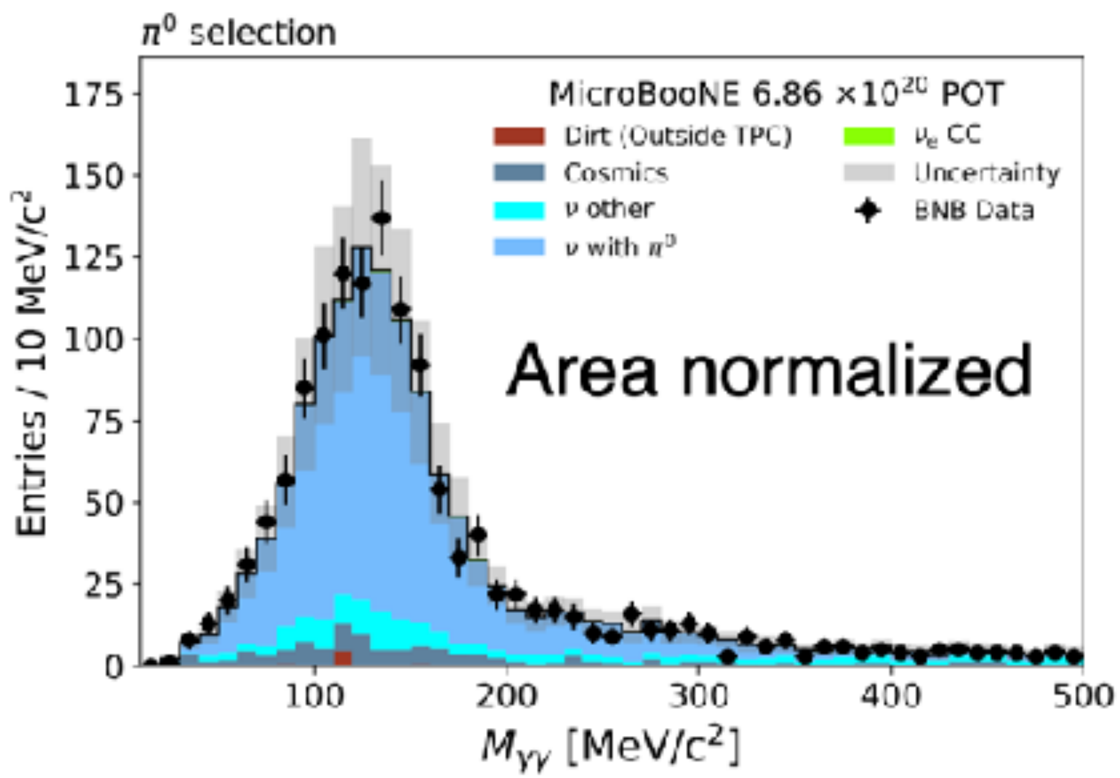
- validate analysis strategy and modelling
- constrain backgrounds in signal sample
- further constrain models to provide data-driven prediction for signal region

DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

ν_e selection sidebands: π^0 and ν_μ

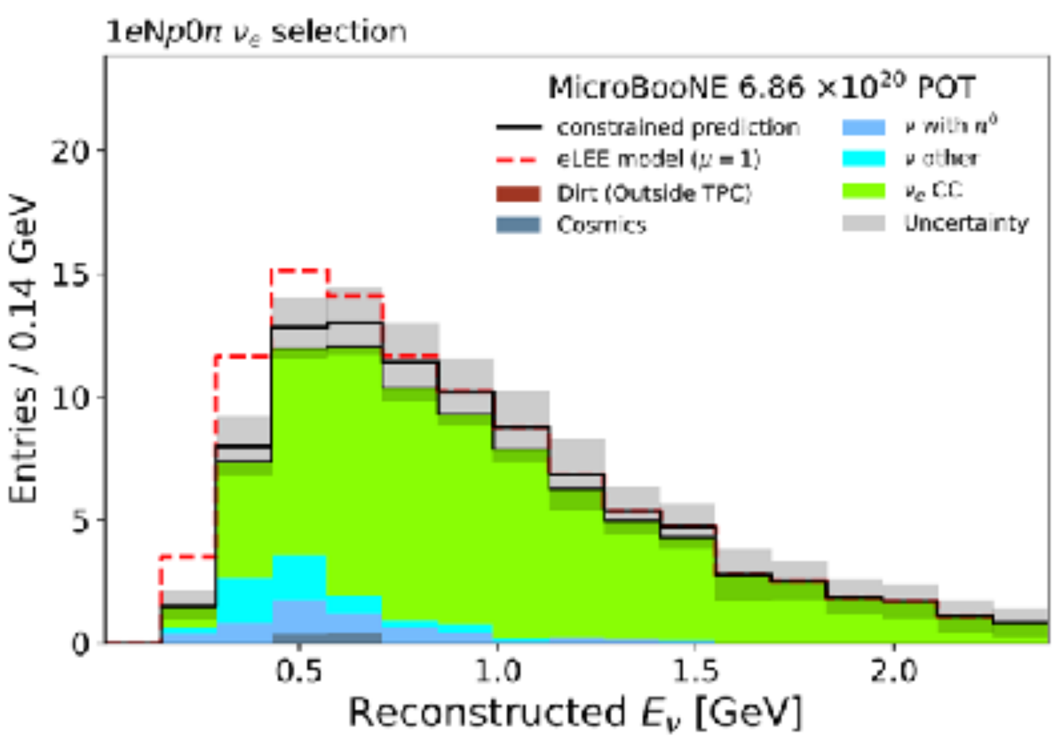


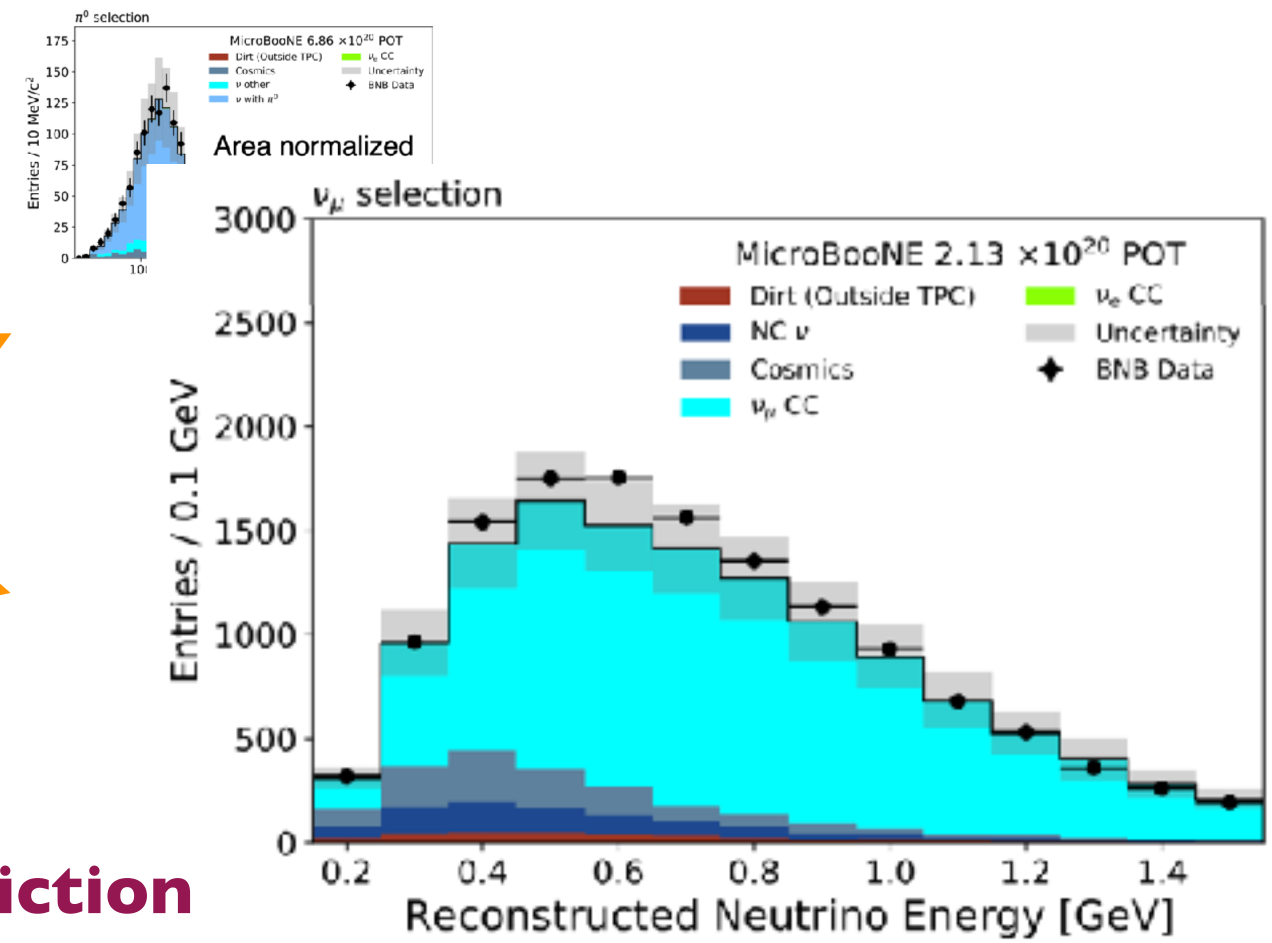


DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

ν_e selection sidebands: π^0 and ν_μ



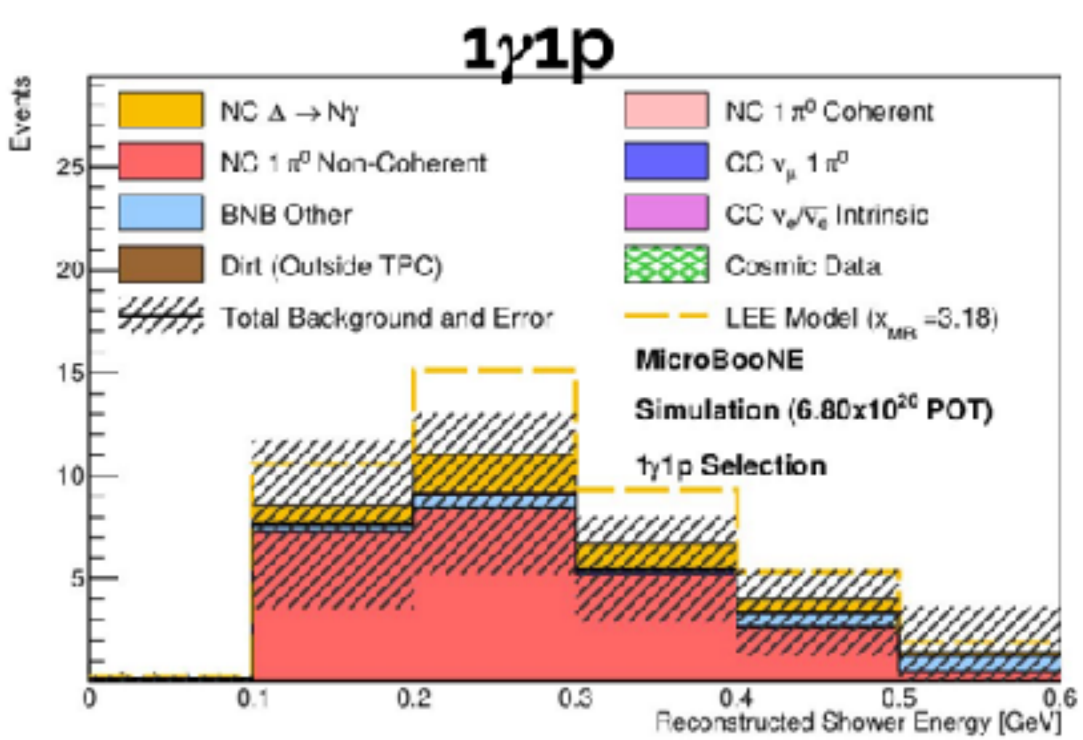


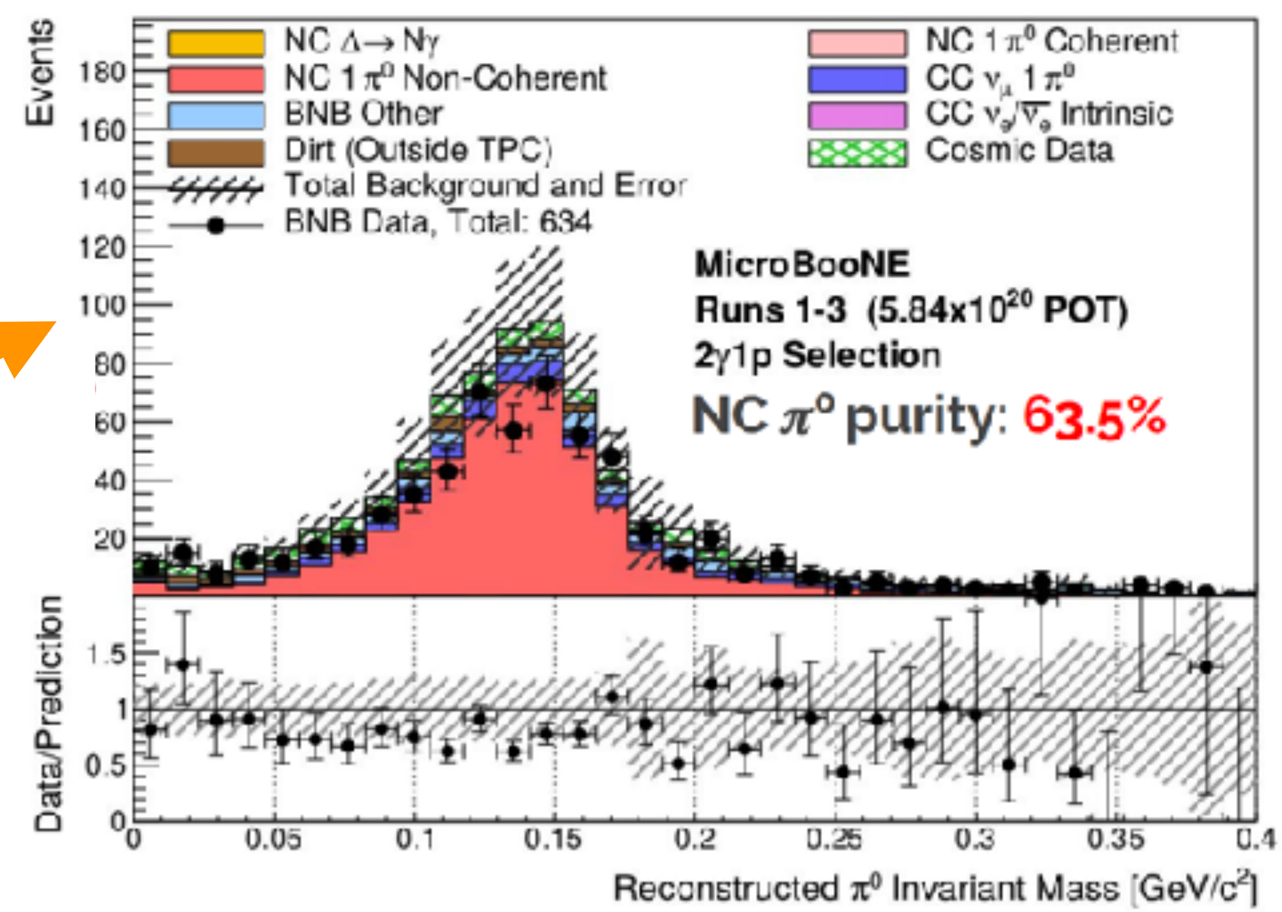
ν_μ measurement constrains ν_e prediction and reduces uncertainty

DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction

Δ→Nγ sideband: NCπ⁰



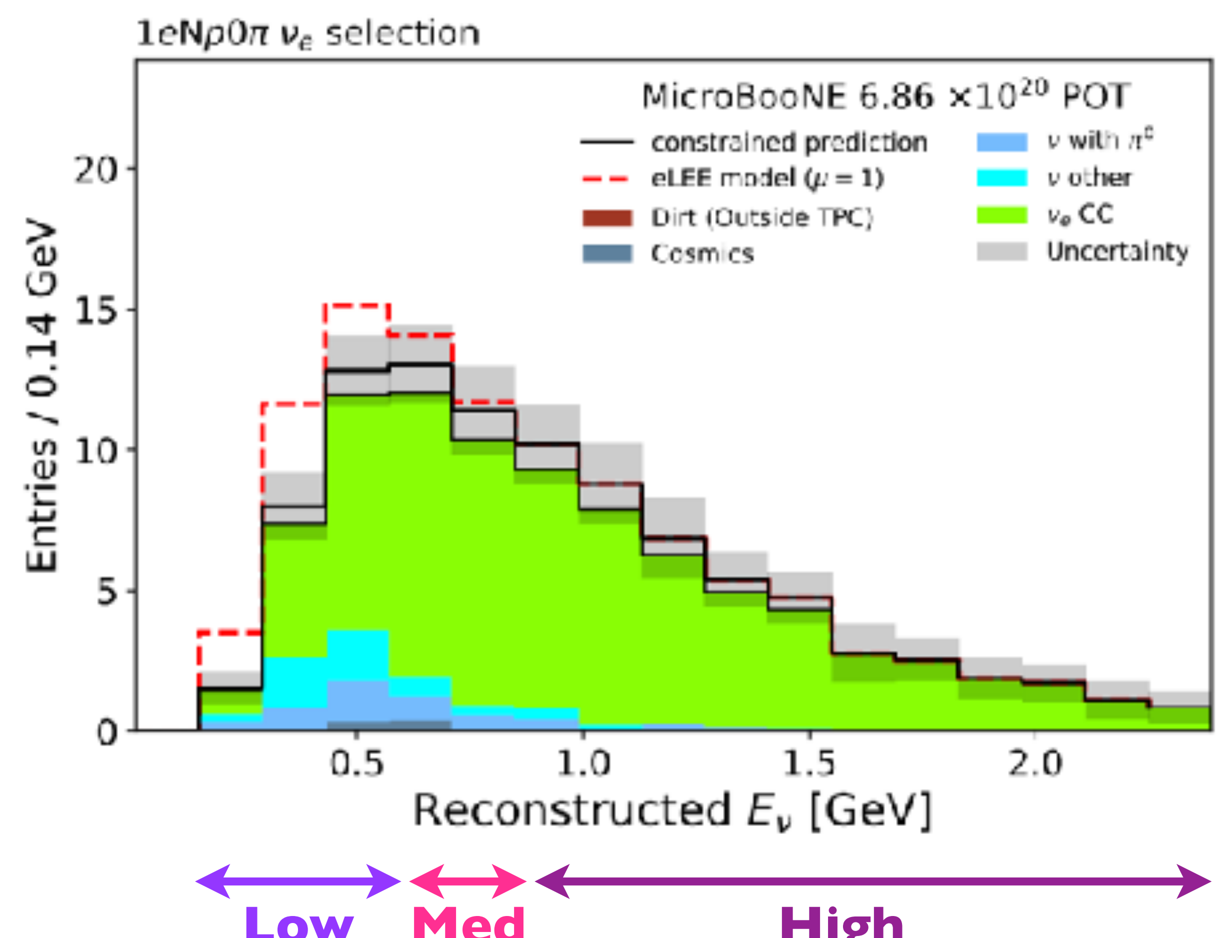


DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction → Staged unblinding

Blind analysis strategy:

- Limited open data sample
- Analysis of sideband data sets
- Blind analysis of fake data sets
- Progressive ν_e unblinding



DOING THE MEASUREMENT

Tune neutrino interaction model to external data → Sideband data sample → data-driven signal prediction → Staged unblinding → Statistical tests

1) Simple hypothesis test

- Does the data prefer the LEE model over the non-LEE model?

2) Signal strength measurement

- Use Feldman-Cousins procedure to measure best-fit signal strength (x) assuming a linear scaling of the LEE model

THE MASS HIERARCHY

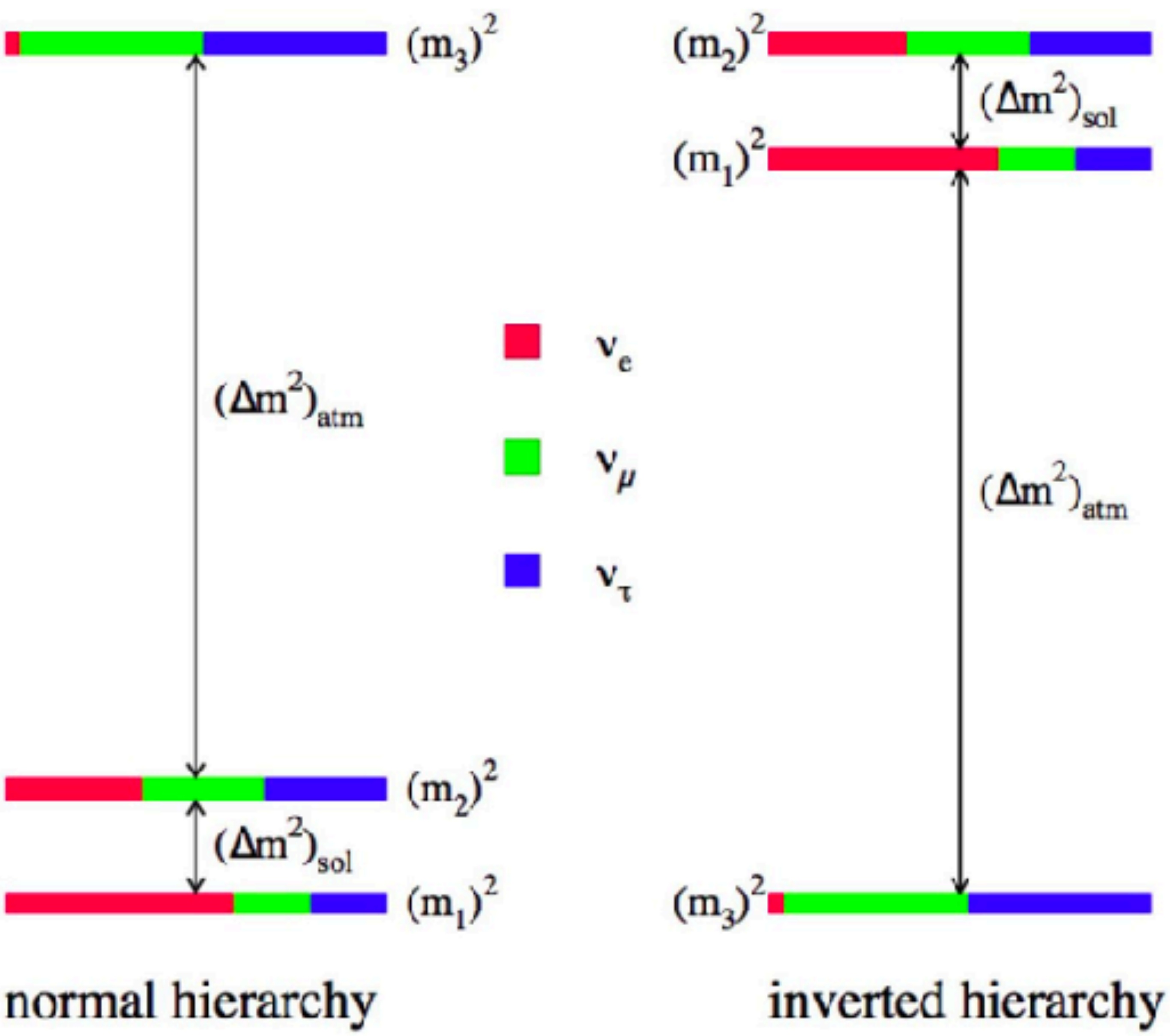
$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

Oscillation is only sensitive to the **size** of Δm^2, not the **sign**

→ We **know the sign of Δm^2_{21}** from solar neutrino measurements

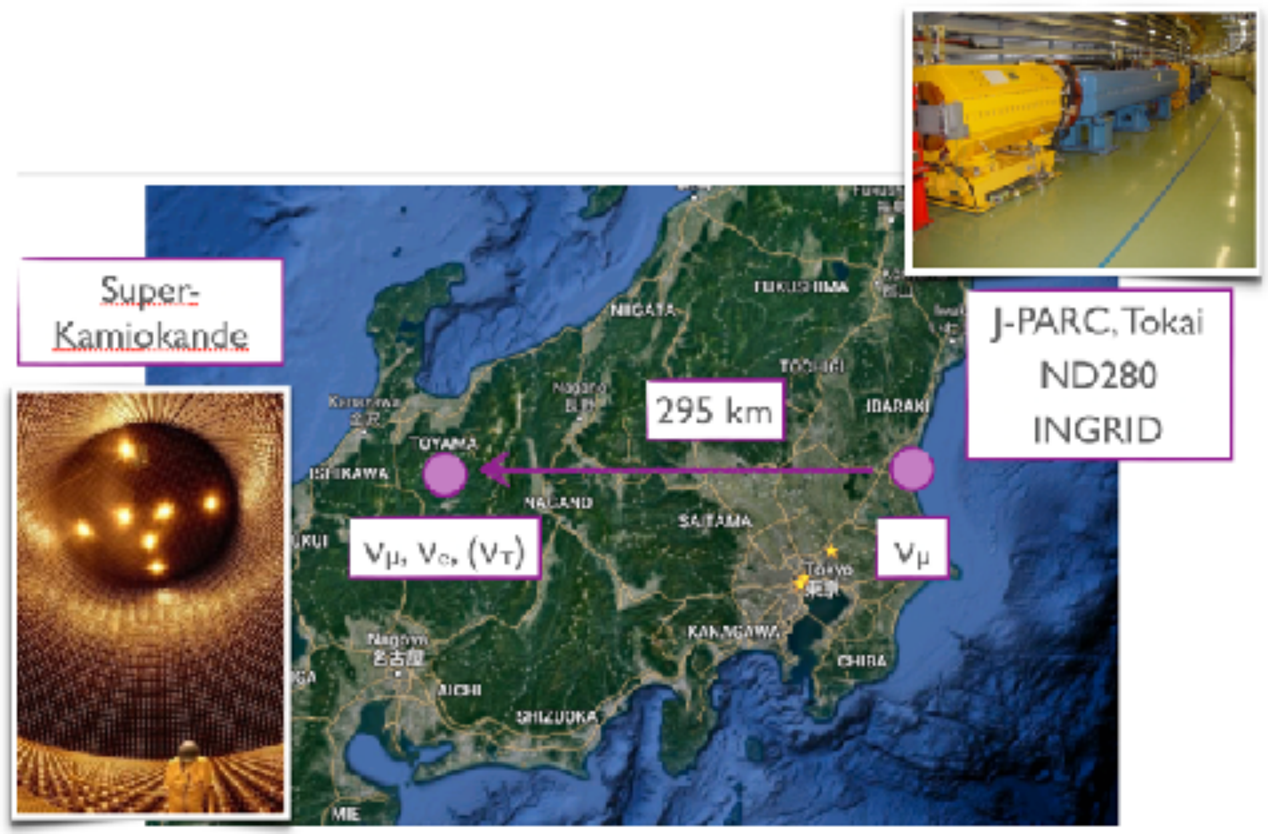
→ We **do not know the sign of $|\Delta m^2_{32}|$**



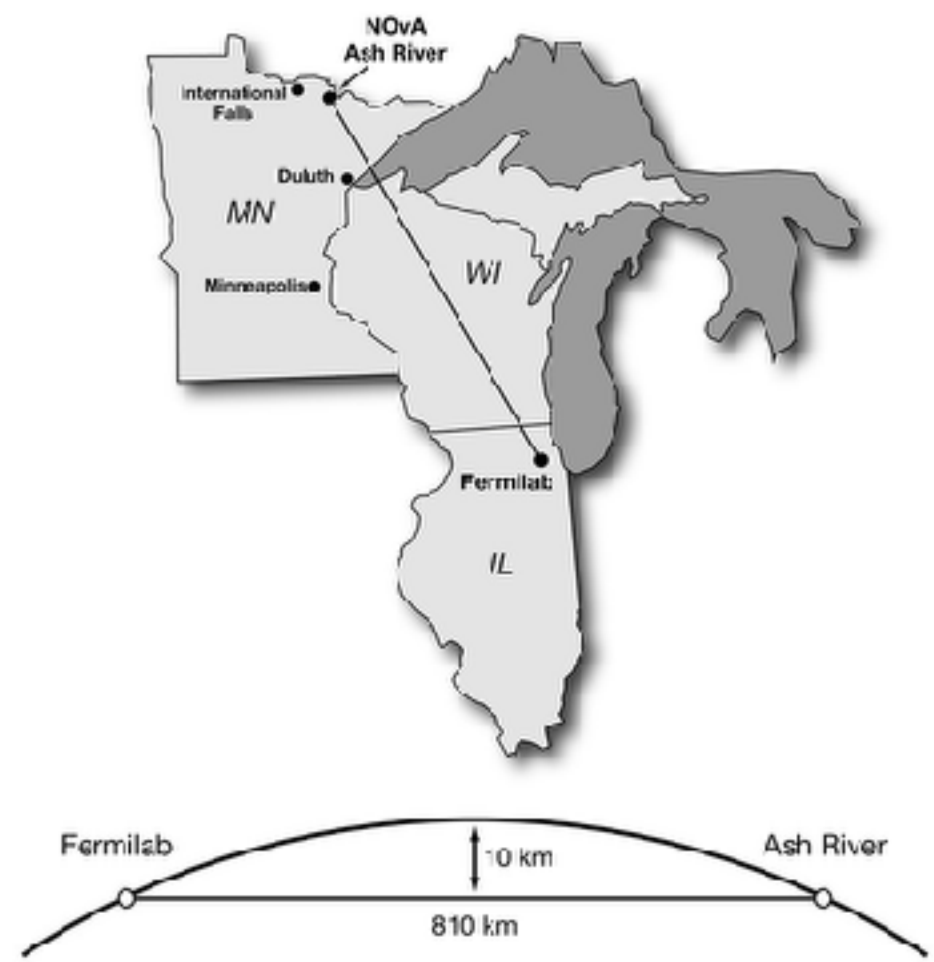
UNIVERSITY OF OXFORD

(TRYING TO) MEASURE CP VIOLATION

T2K
(Tokai to Kamioka)

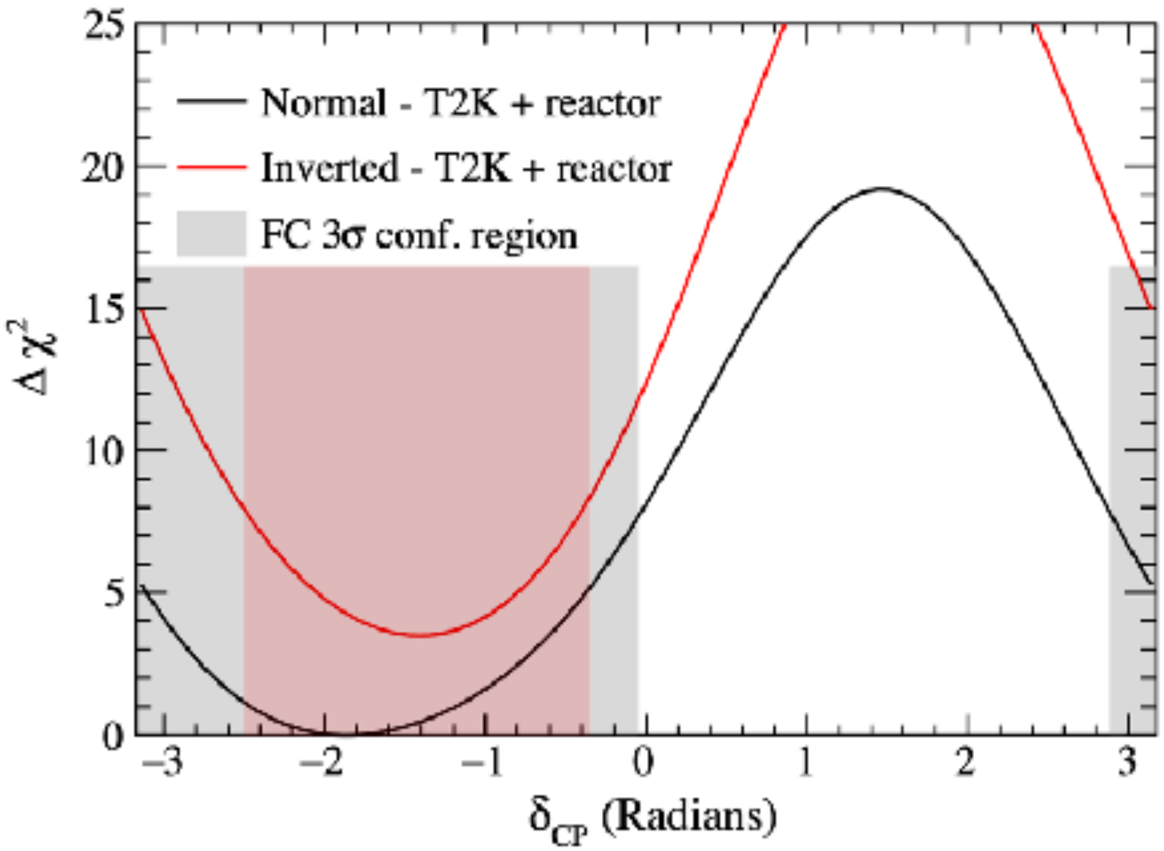


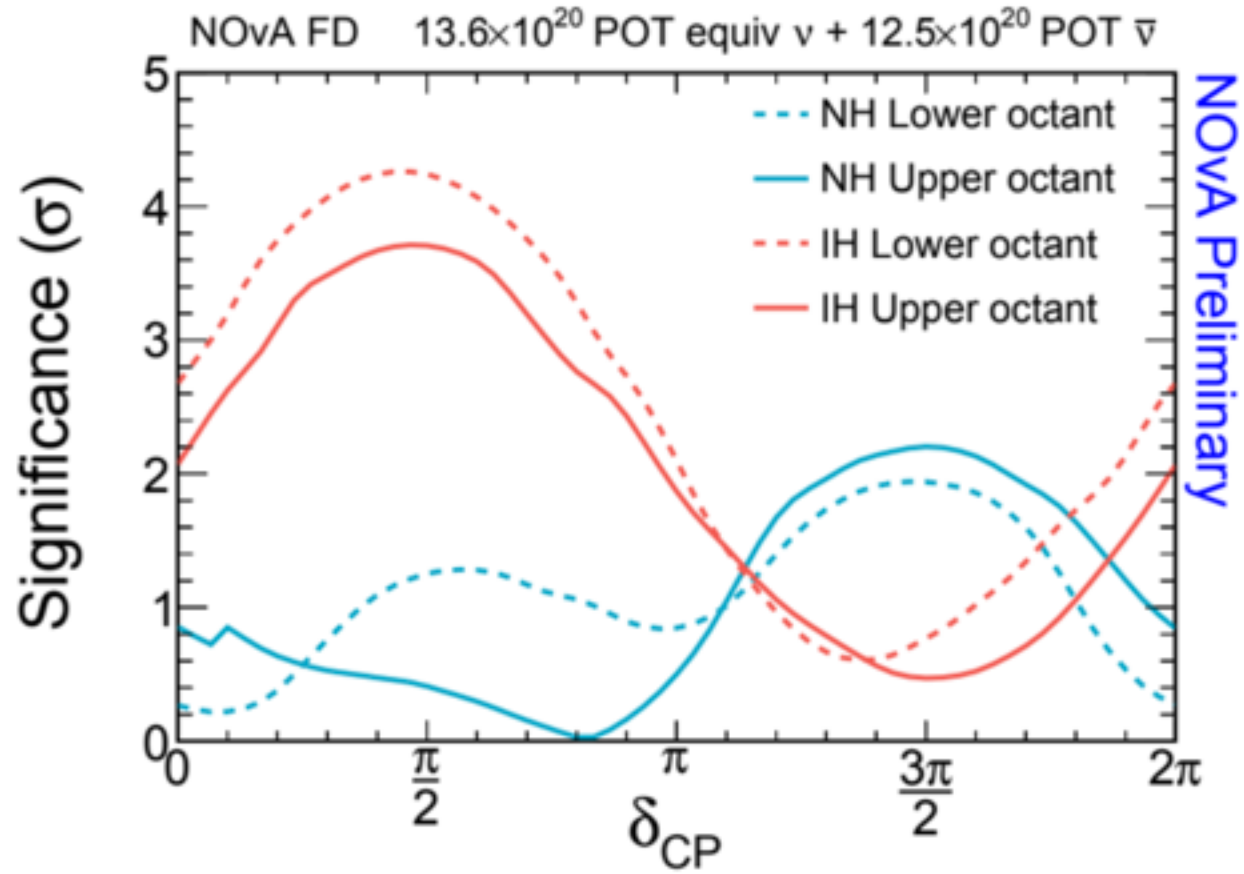
NOvA
(NuMI Off-axis ν_e Appearance)



UNIVERSITY OF OXFORD

(TRYING TO) MEASURE CP VIOLATION



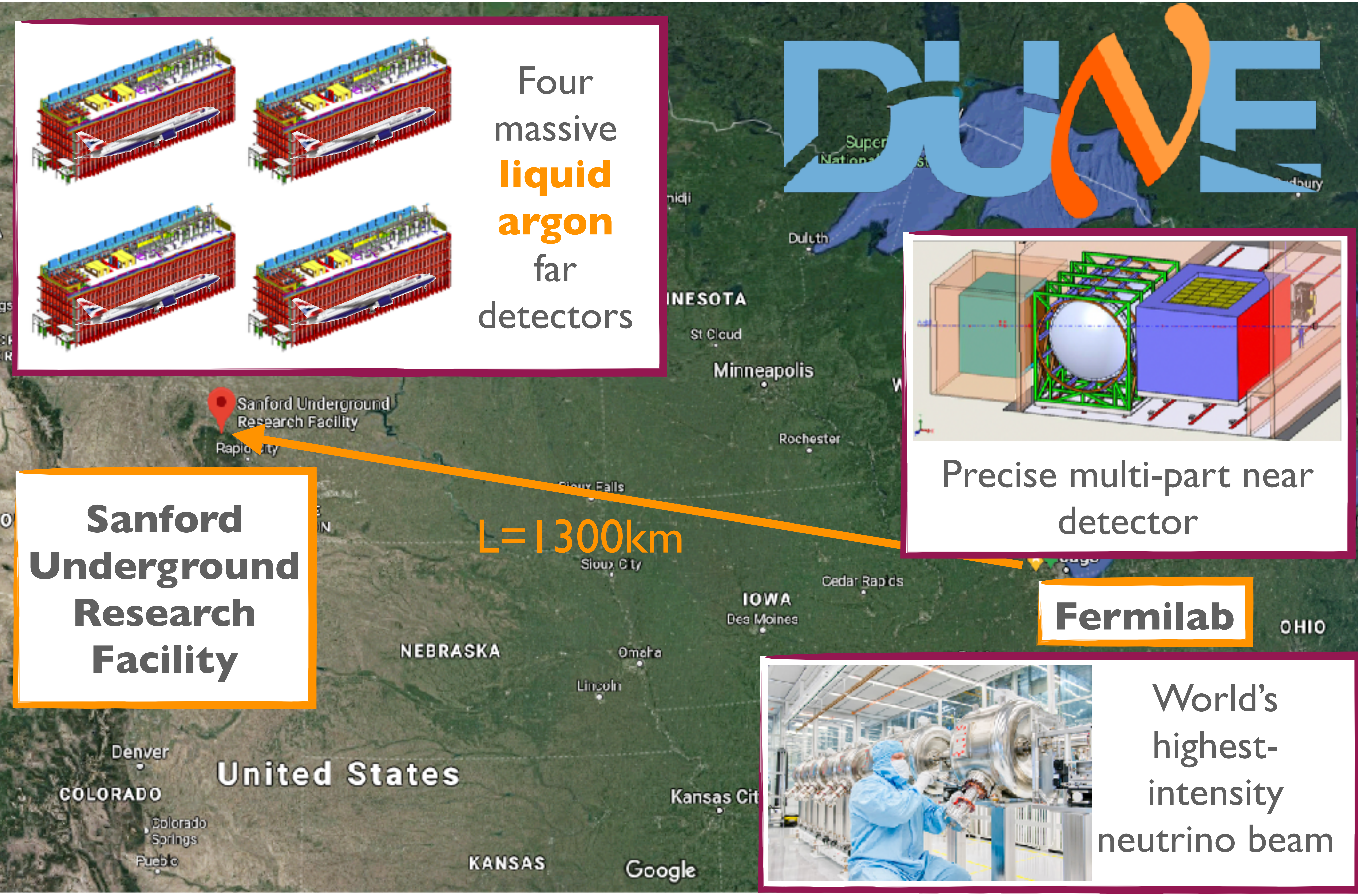


T2K

Favours δ_{CP}=-π/2 in both normal and inverted hierarchy

NOvA

Favours δ_{CP}=-π/2 in inverted hierarchy; δ_{CP}=π/2 in normal



Four massive **liquid argon** far detectors

Precise multi-part near detector

Sanford Underground Research Facility

Fermilab

World's highest-intensity neutrino beam