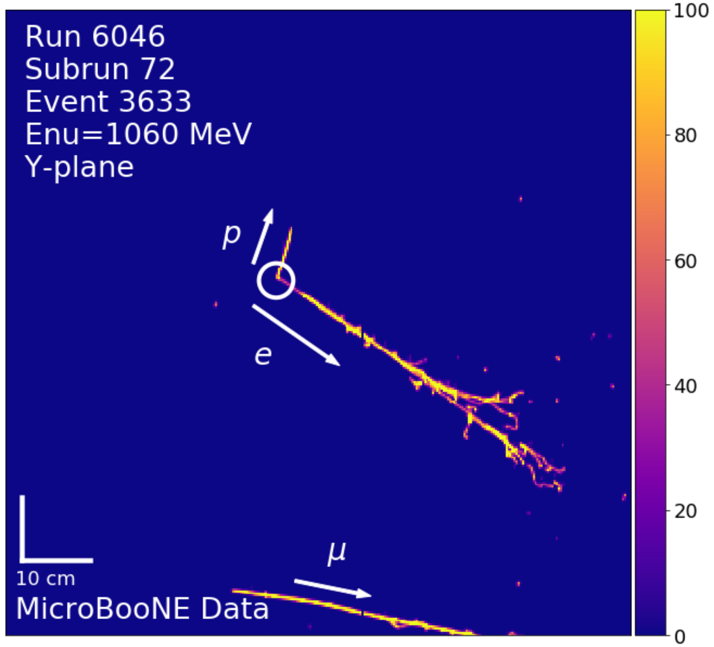
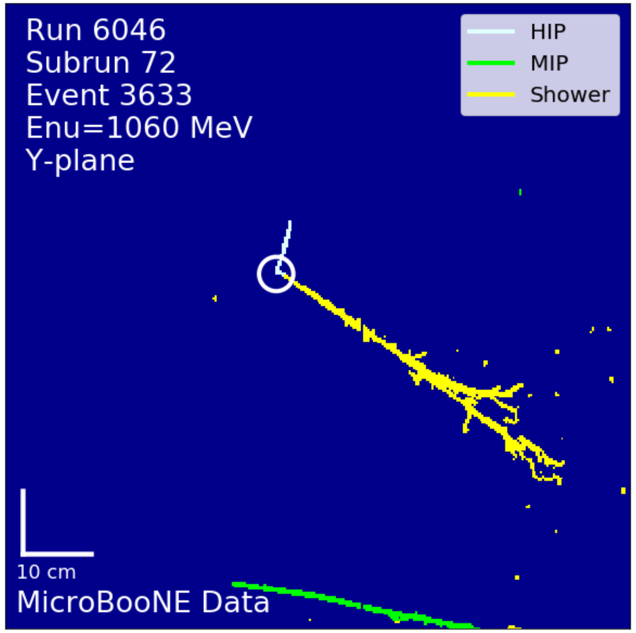
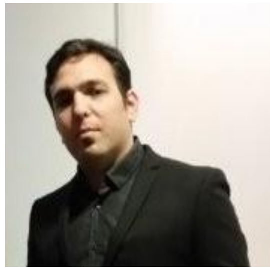
MicroBooNE's new results from the 2-body CCQE DL-based search for an electron neutrino excess





Ran Itay

On behalf of MicroBooNE

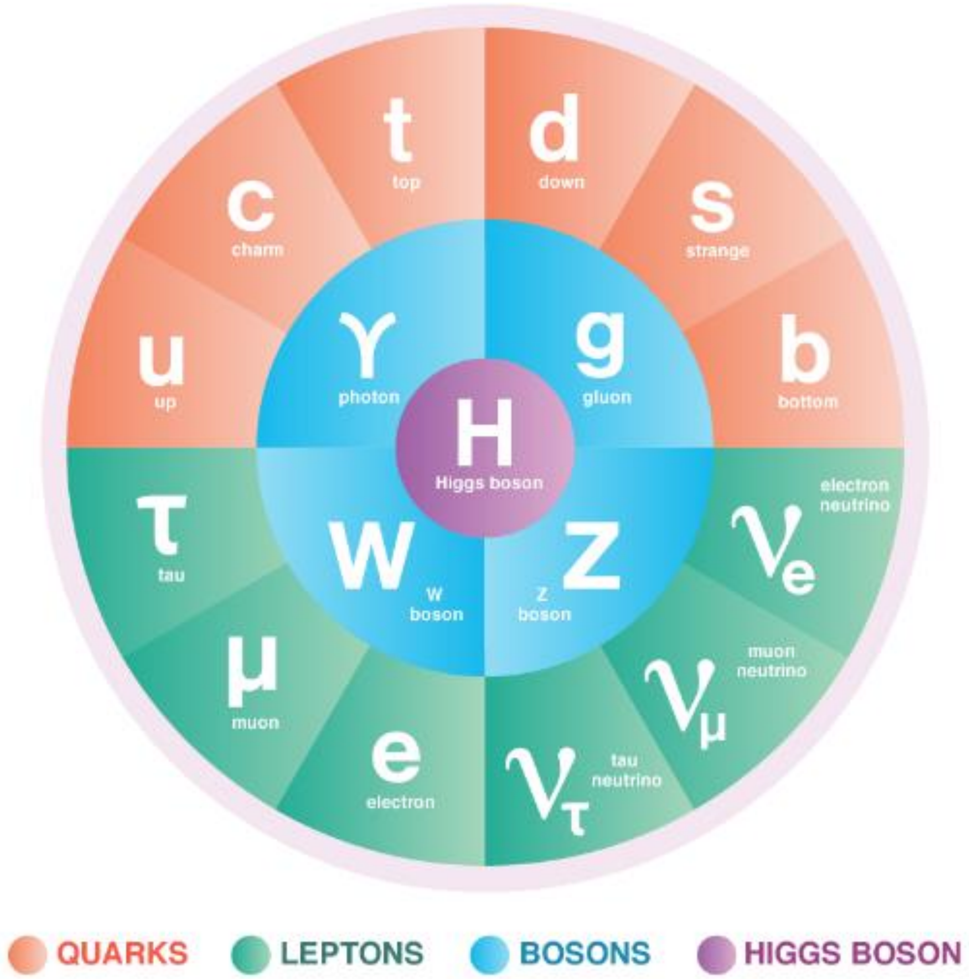


SLAC

November, 2021

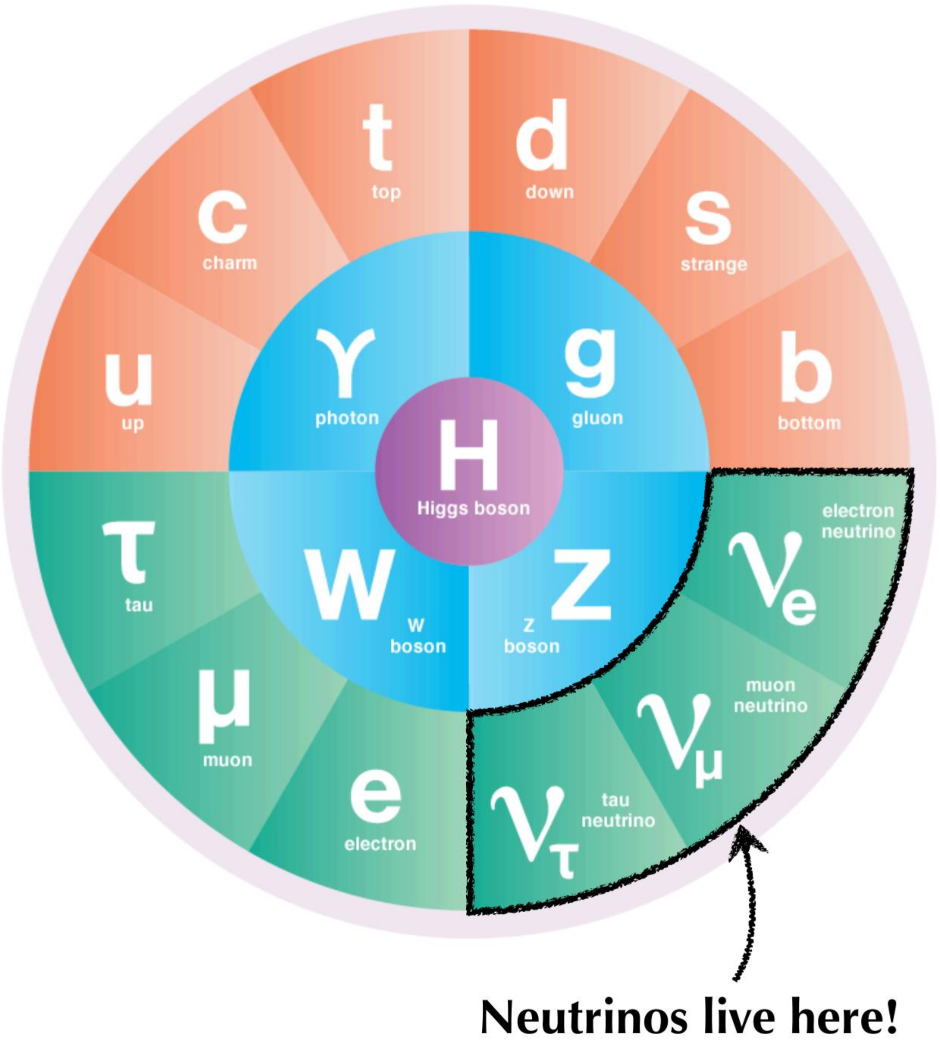
Overview

- The standard model of particle physics
  - Particle content
  - Forces
- Although describes well much of phenomenology, we know it is only an approximate theory.
- DM, Gravity, g-2, and more…
- Many question arising specifically from the neutrino sector.



Overview

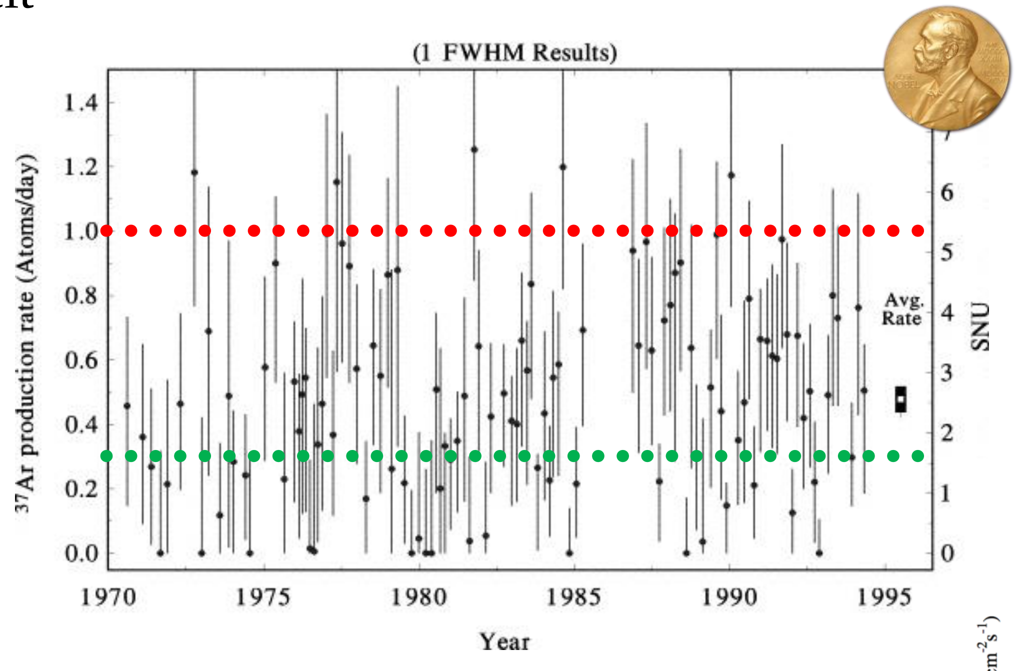
- Neutrinos are the most abundant massive particle in the Universe.
- Electrically neutral
- Very small cross section.
- Present many anomalies which cannot be explained within the SM (e.g., mass).



Overview

- Experiments sensitive to only one flavor observed a deficit (Homestake late 60's)
- Later confirmed by SNO & SK
- This deficit depends on the distance from source.
- This phenomenon is best explained via **neutrino oscillation**

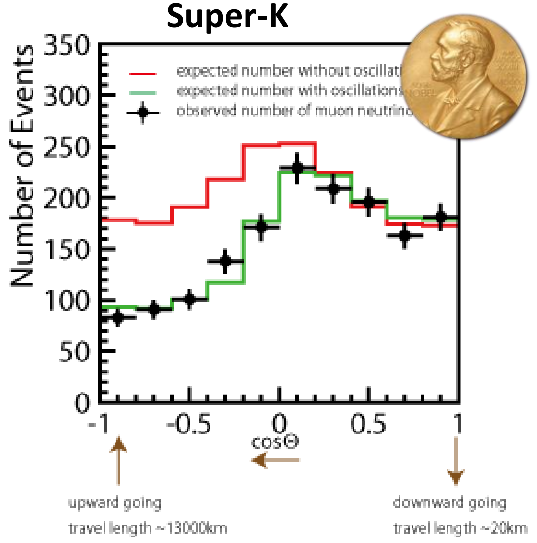
Homestake Experiment



Solar

Cosmic

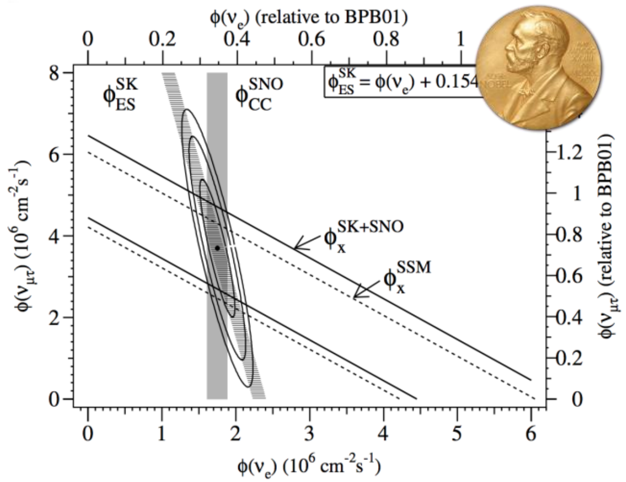
Super-K



No Osc
With Osc
Data

Solar

SNO



Overview

- Neutrino oscillation is a quantum mechanical effect, occurring on macroscopic scales
- First predicted in 1957 by Pontecorvo
- Neutrinos are produced in interaction eigenstate (ν_e , ν_μ , ν_τ), but propagate in mass eigenstate (ν_1 , ν_2 , ν_3)

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

$$P_{\alpha\to\beta} = \left|\langle \nu_\beta(L)|\nu_\alpha(0)\rangle\right|^2$$

$$p_{\alpha\to\beta} = \left|\sum U_{\alpha i}^* U_{\beta i} e^{-\frac{i(m^2 L)}{2E}}\right|^2$$

L- baseline
E_{ν}- neutrino energy

Overview

- Neutrino oscillation is a quantum mechanical effect, occurring on macroscopic scales
- Neutrinos are produced in interaction eigenstate (ν_e , ν_μ , ν_τ), but propagate in mass eigenstate (ν_1 , ν_2 , ν_3)
- We can probe only Δm^2
- **Simple example 2 neutrino case**

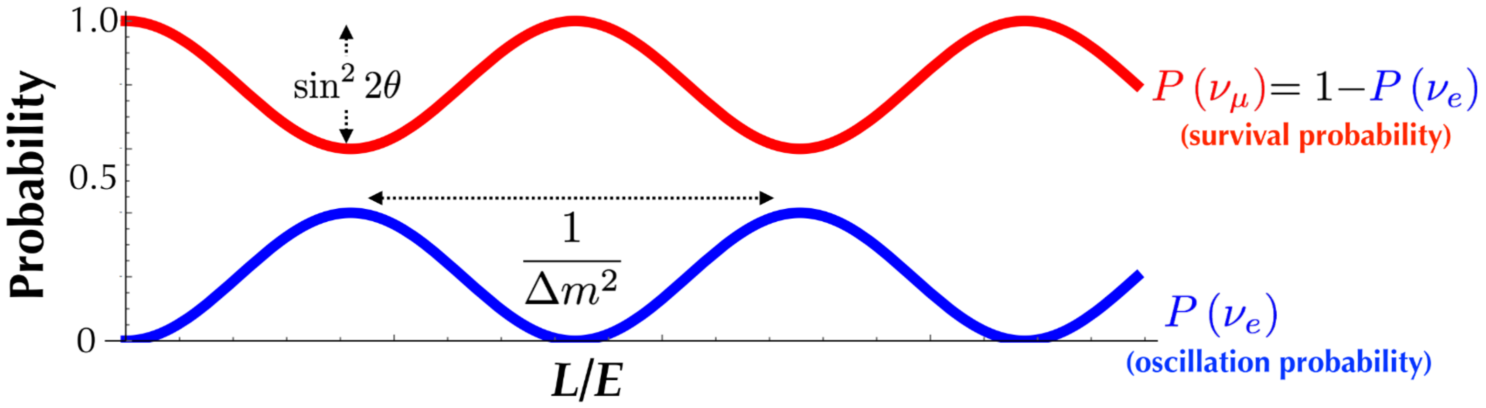
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$p_{osc} = \sin^2(2\theta) \cdot \sin^2\left(1.27 \cdot \frac{\Delta m_{12}^2 L}{E_\nu}\right)$$

L- baseline

E_{ν}- neutrino energy

$$\Delta m_{12}^2 \equiv m_1^2 - m_2^2$$

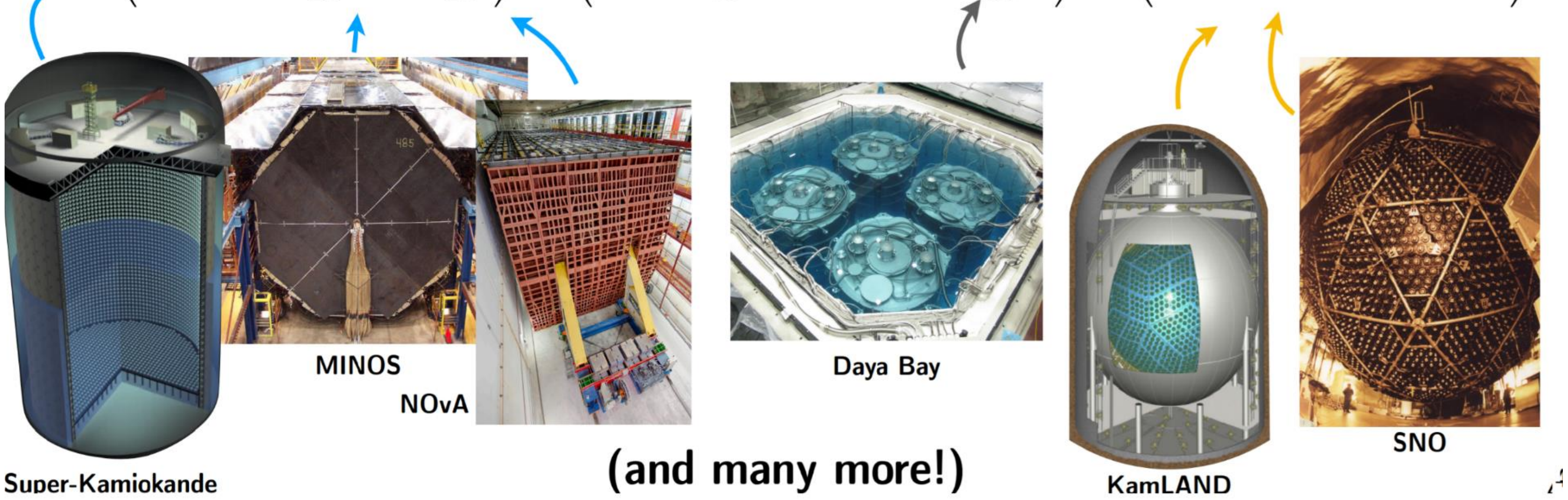


Overview

- SM case 3 flavors
- PMNS matrix has
  - 3 mixing angles
  - 1 CP violating phase
- Different L/E probe different mixing angles

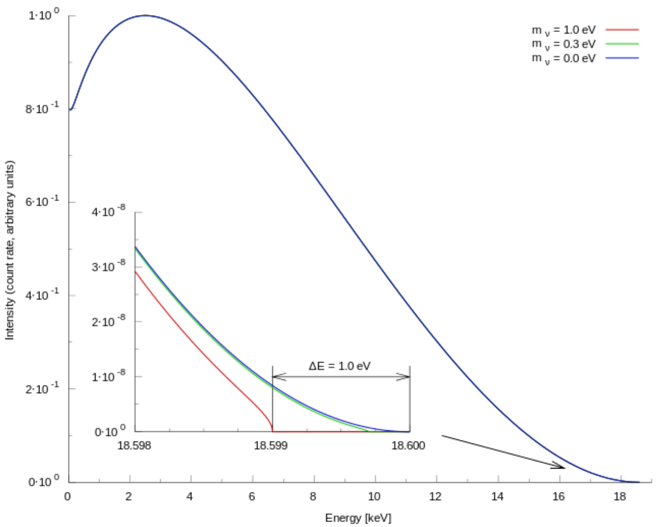
Atmospheric & Accelerator   Reactor   Solar & KamLAND

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

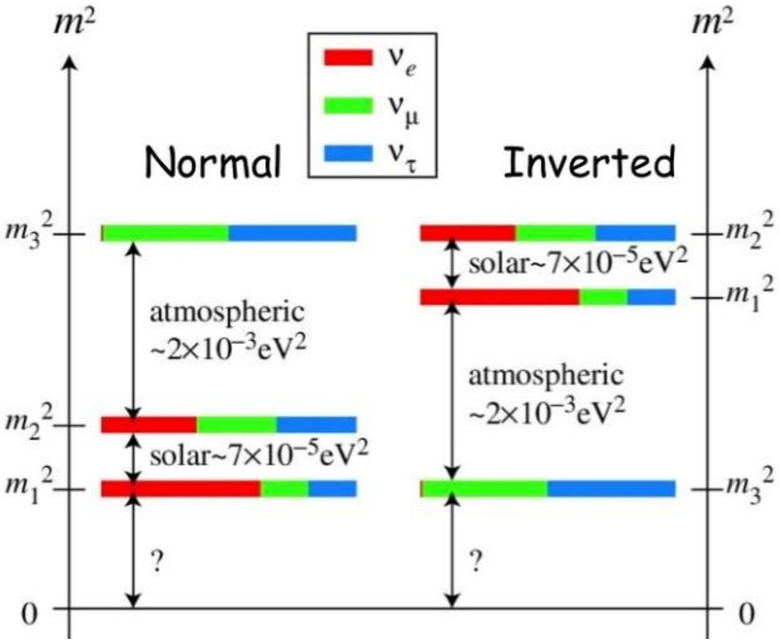


Overview

What is the neutrino absolute mass ?

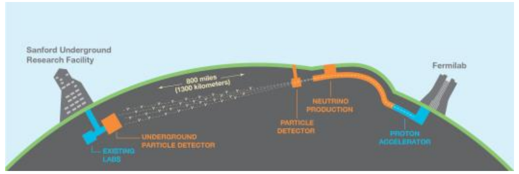


Mass Hierarchy?



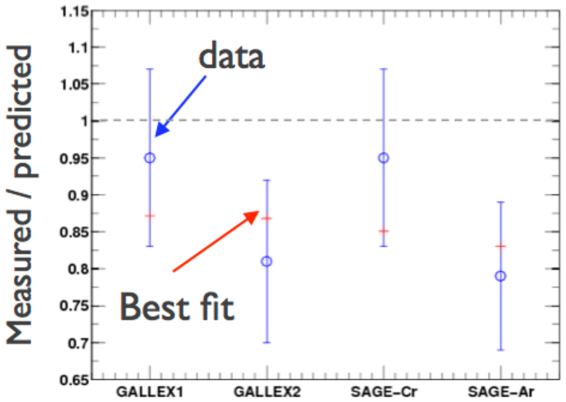
Is the neutrino Majorana / Dirac ?

Do neutrino violate CP

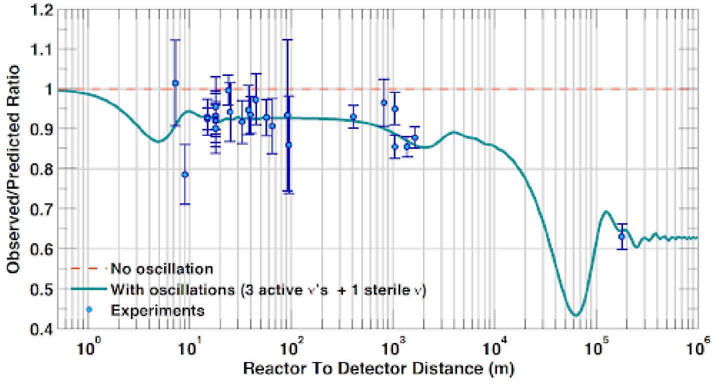


Motivation

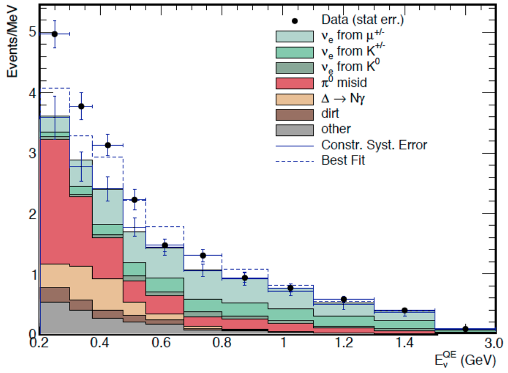
Gallium Anomaly



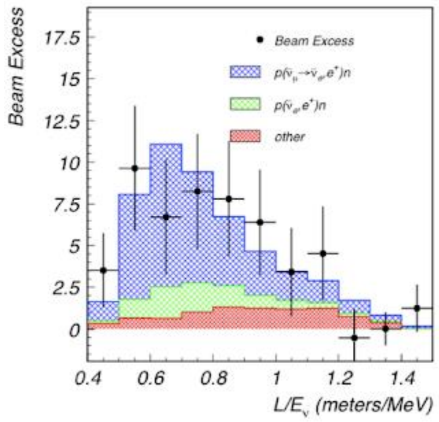
Reactor Anomaly



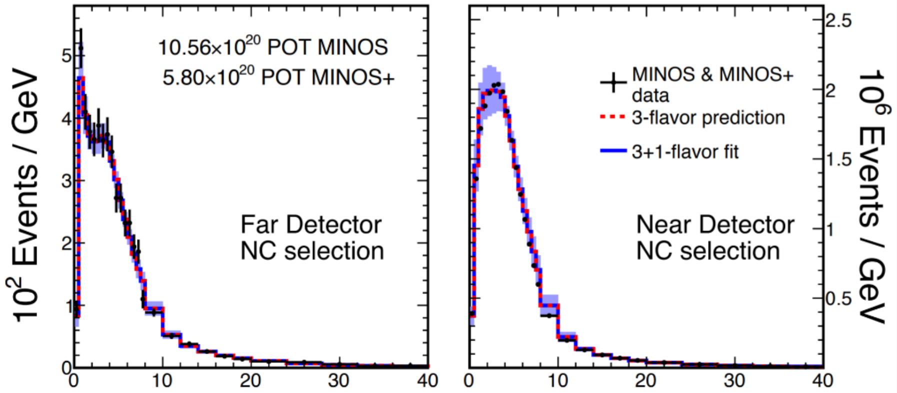
MiniBooNE



LSND



No evidence for disapperance

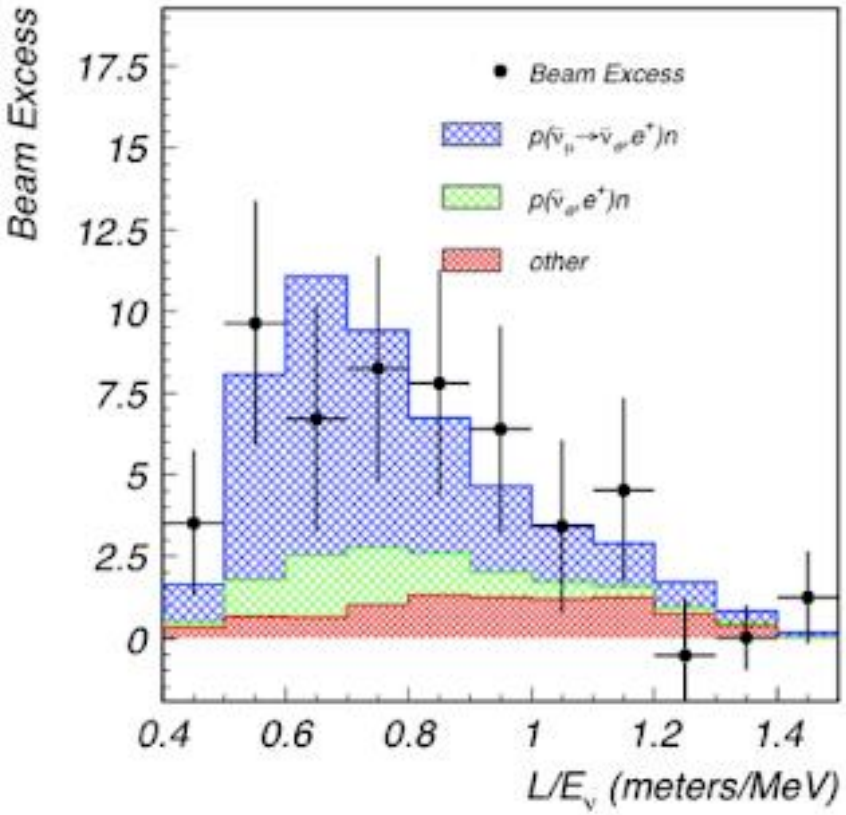


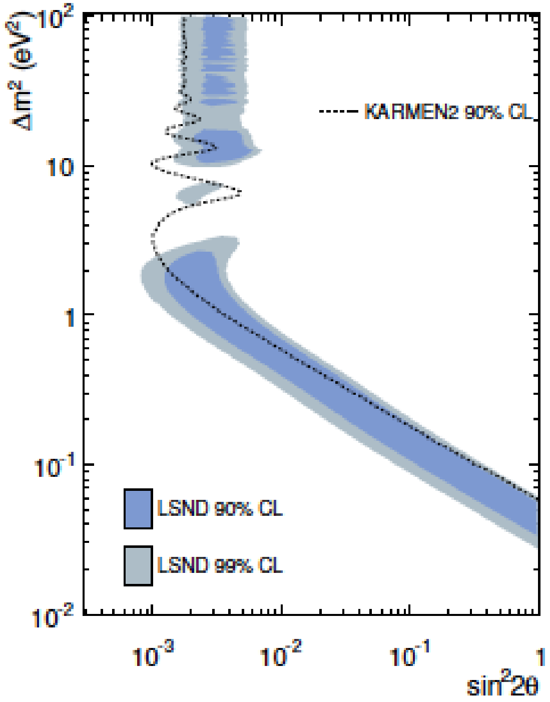
Motivation

Major Anomalies

1. LSND

- Operating at Los Alamos
- via IBD
- 3.8σ excess





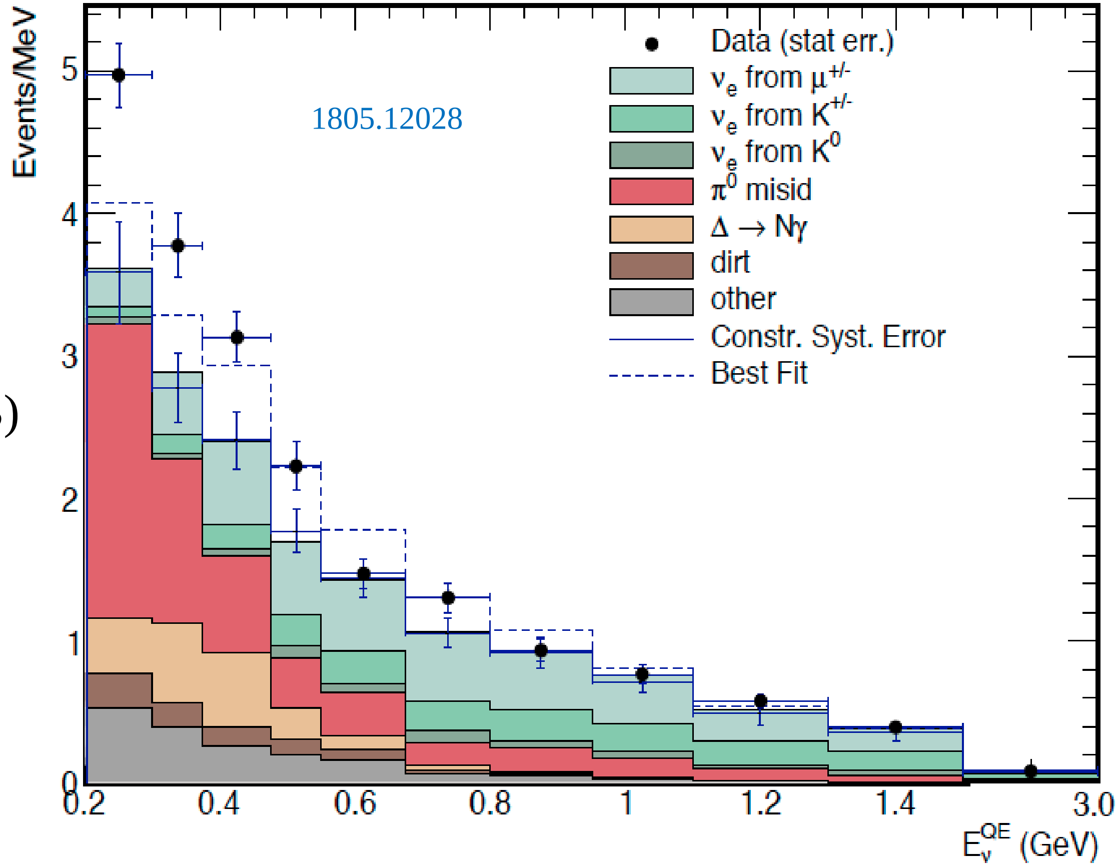
PRD 64,112007 (2001)

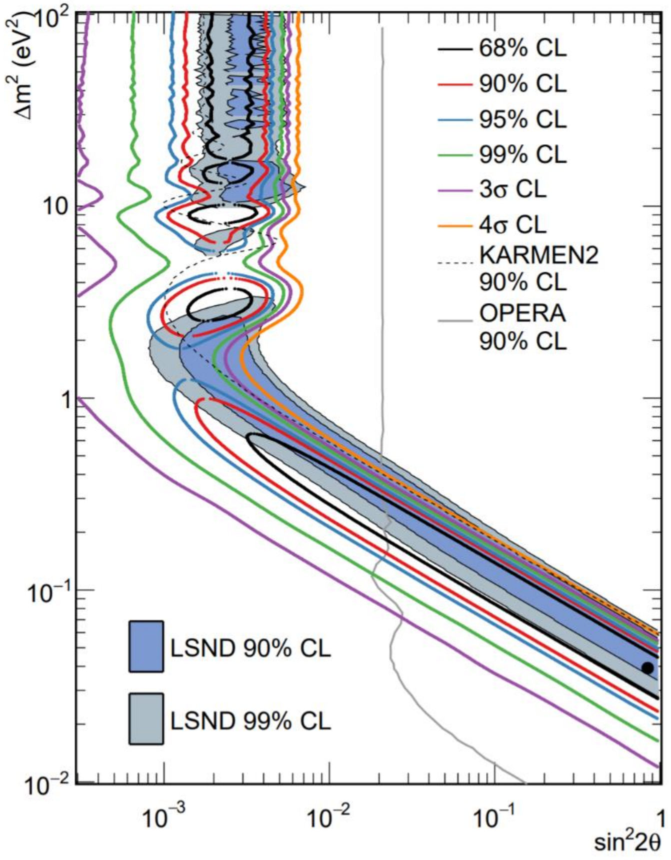
Motivation

Major Anomalies

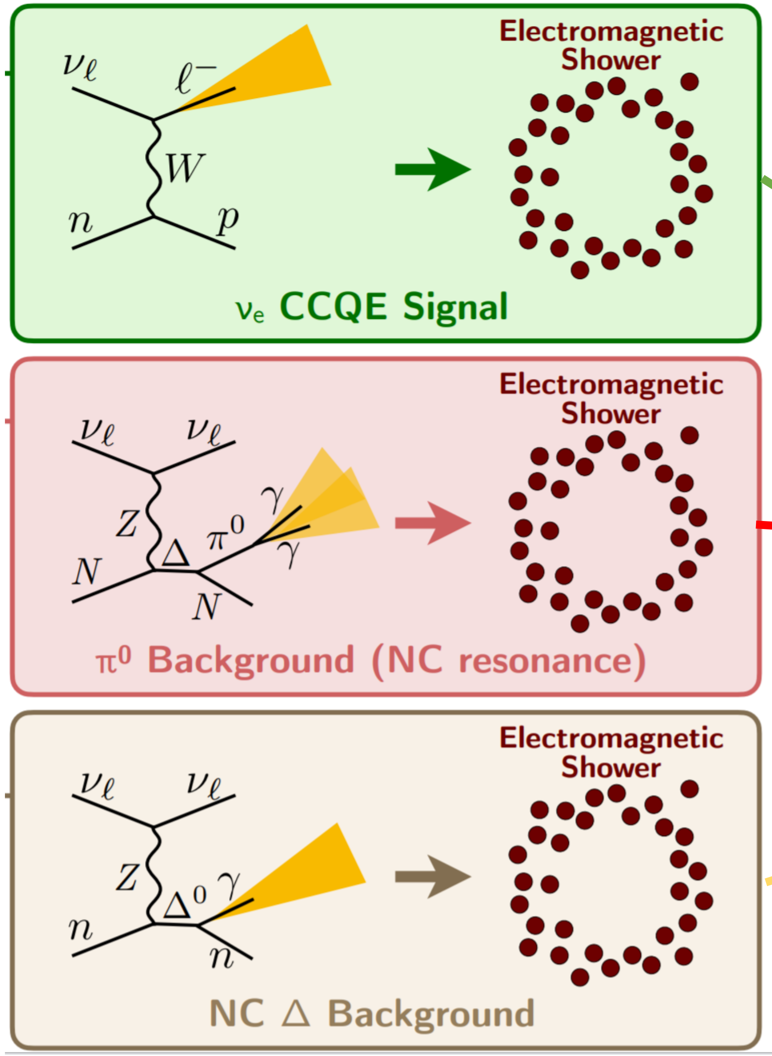
2. MiniBooNE

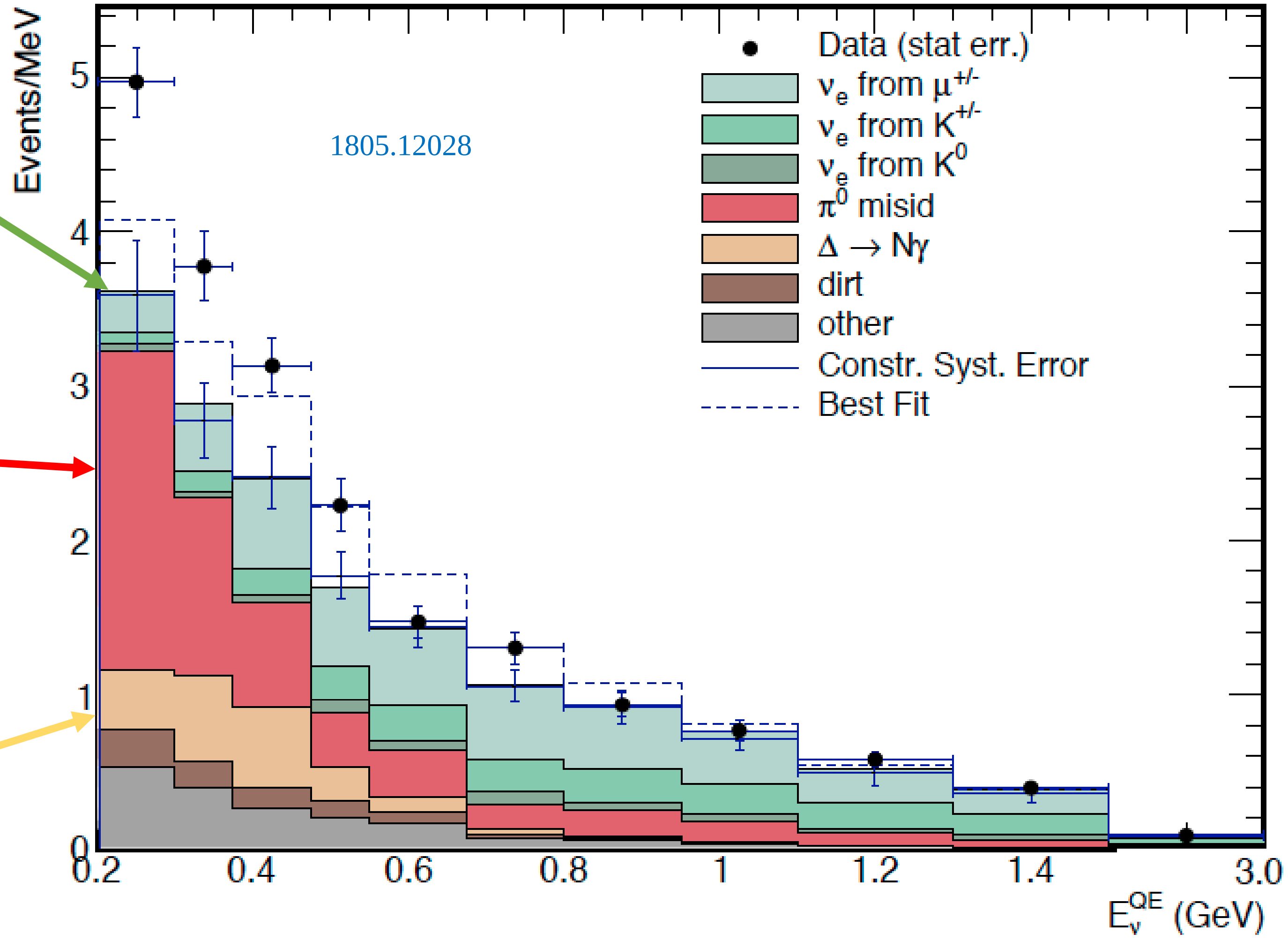
- Operating at FNAL (BNB)
- Similar L/E ~ 1m/MeV
- Mineral Oil Cherenkov
- 4.5 σ (ν_e) / 4.7σ ($\overline{\nu_e}$) excess (LEE)



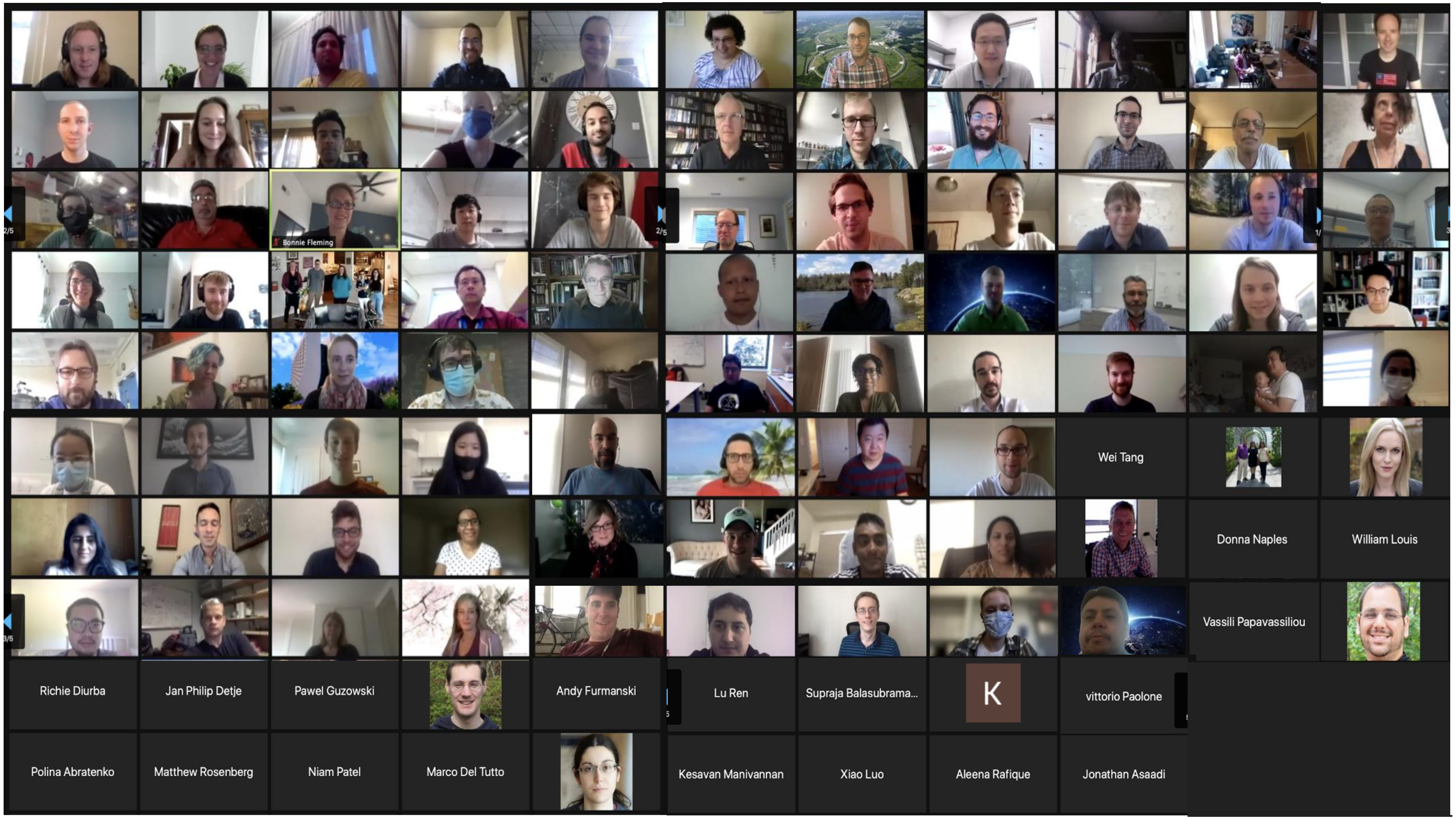


Motivation


Electromagnetic Shower
W
n
p
νe CCQE Signal
Electromagnetic Shower
Z
N
Δ
π0
γ
N
π0 Background (NC resonance)
Electromagnetic Shower
Z
n
Δ0
γ
n
NC Δ Background


Events/MeV
1805.12028
Data (stat err.)
νe from μ+/-
νe from K+/-
νe from K0
π0 misid
Δ → Nγ
dirt
other
Constr. Syst. Error
Best Fit
0
1
2
3
4
5
0.2
0.4
0.6
0.8
1
1.2
1.4
3.0
EνQE (GeV)

MicroBooNE



180 collaborators

40 postdocs

60 grad students (40% international students)

36 institutions

5 countries

MicroBooNE

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36 institutions

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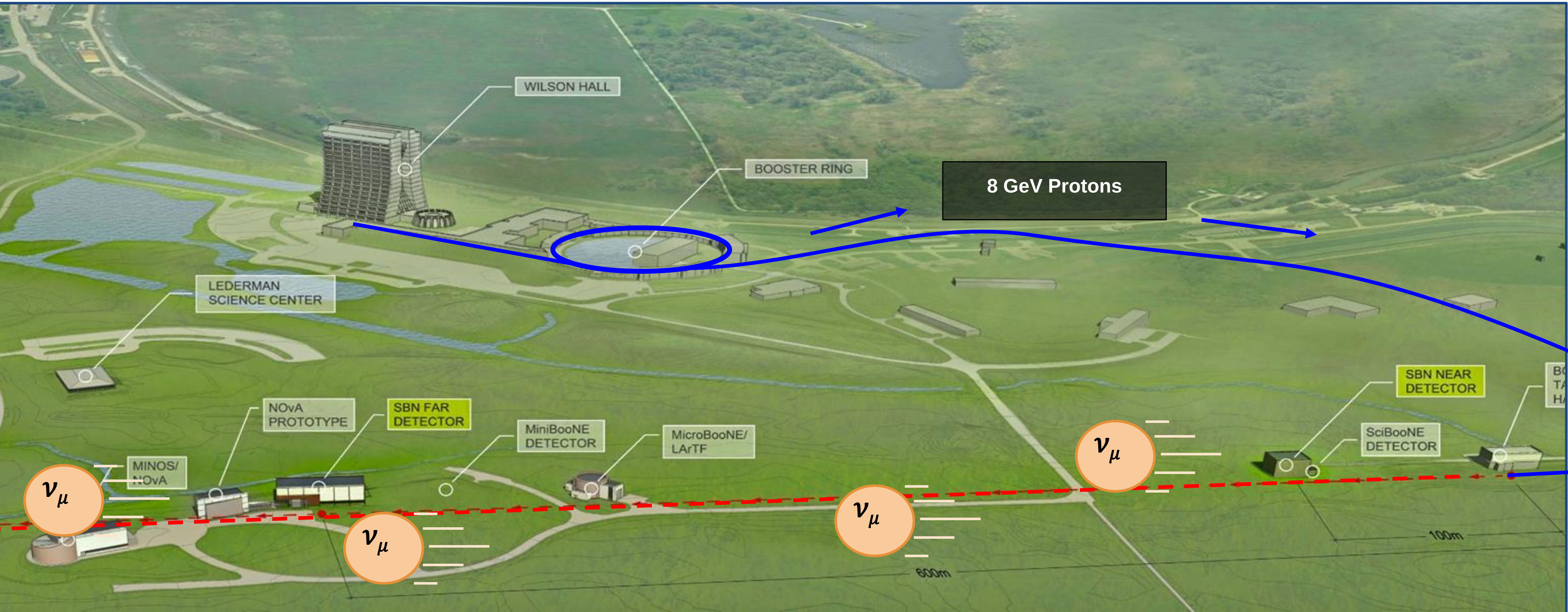
MicroBooNE

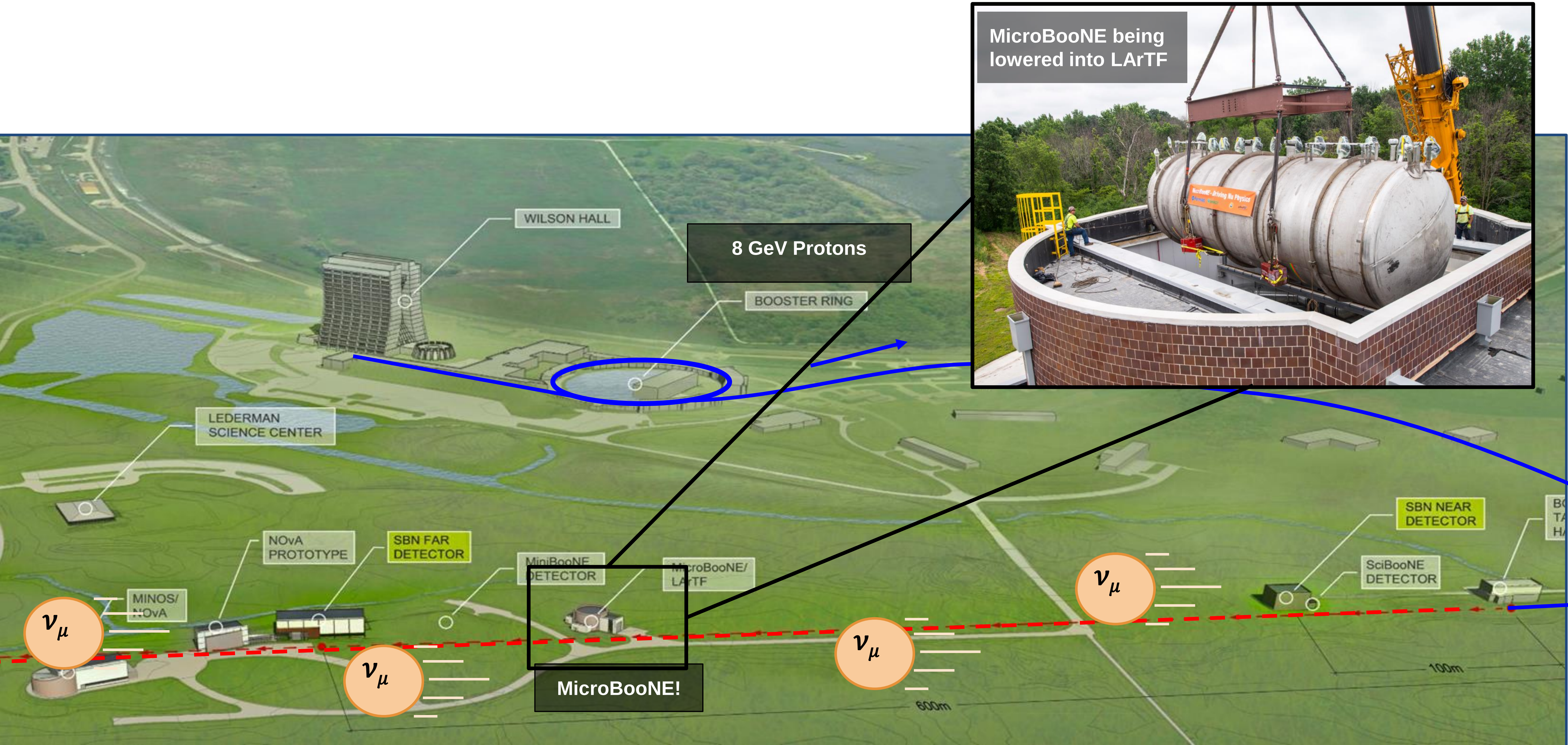
SLAC ubooners:

- Ran Itay
- Yun-Tse Tsai
- Tracy Usher
- Mark Convery
- Kazu Terao

MicroBooNE


WILSON HALL
BOOSTER RING
8 GeV Protons
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
ν_μ
ν_μ
ν_μ
ν_μ
100m
600m

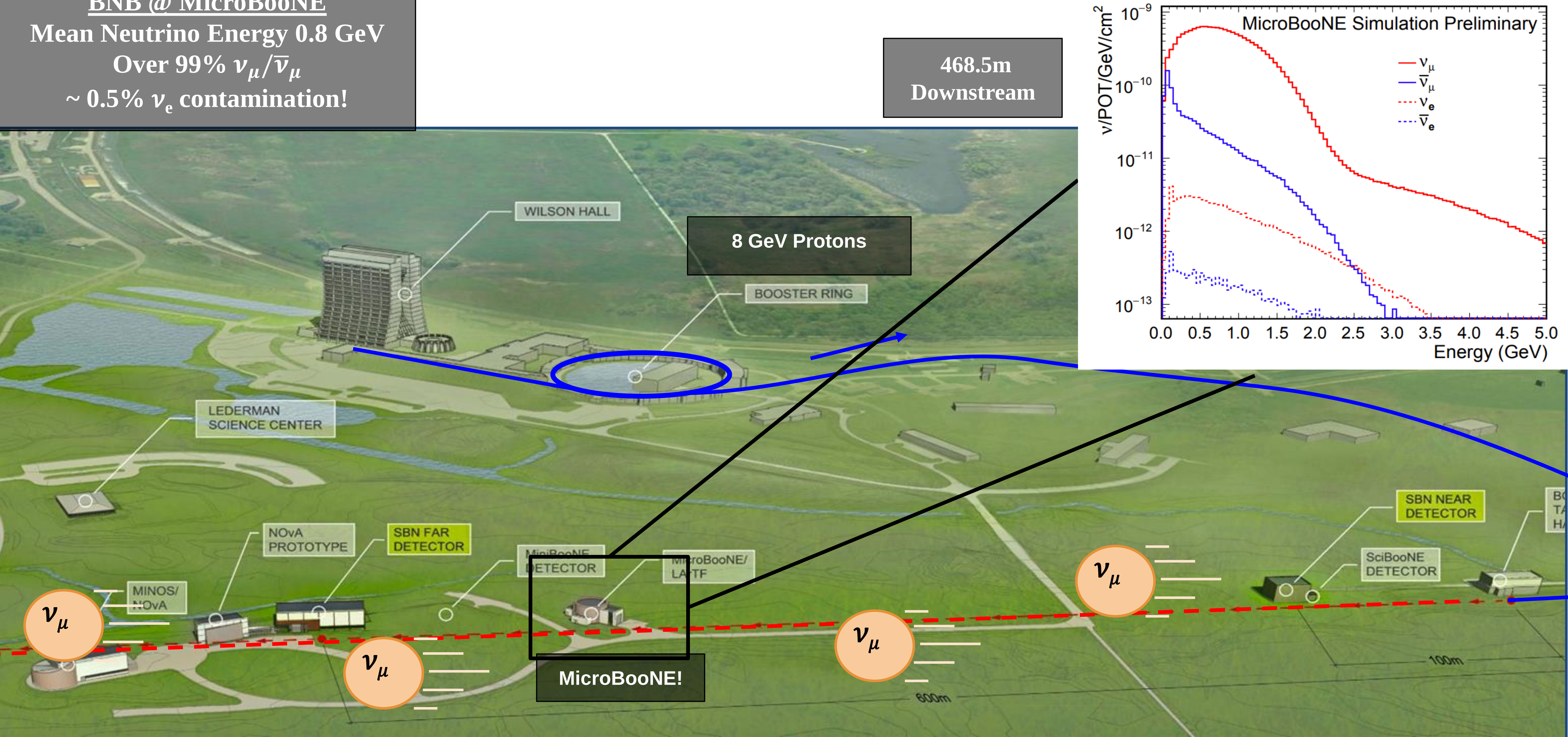
MicroBooNE


MicroBooNE being lowered into LArTF
8 GeV Protons
WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS/ NOvA
SBN NEAR DETECTOR
SciBooNE DETECTOR
ν_μ
ν_μ
ν_μ
ν_μ
MicroBooNE!
100m
600m

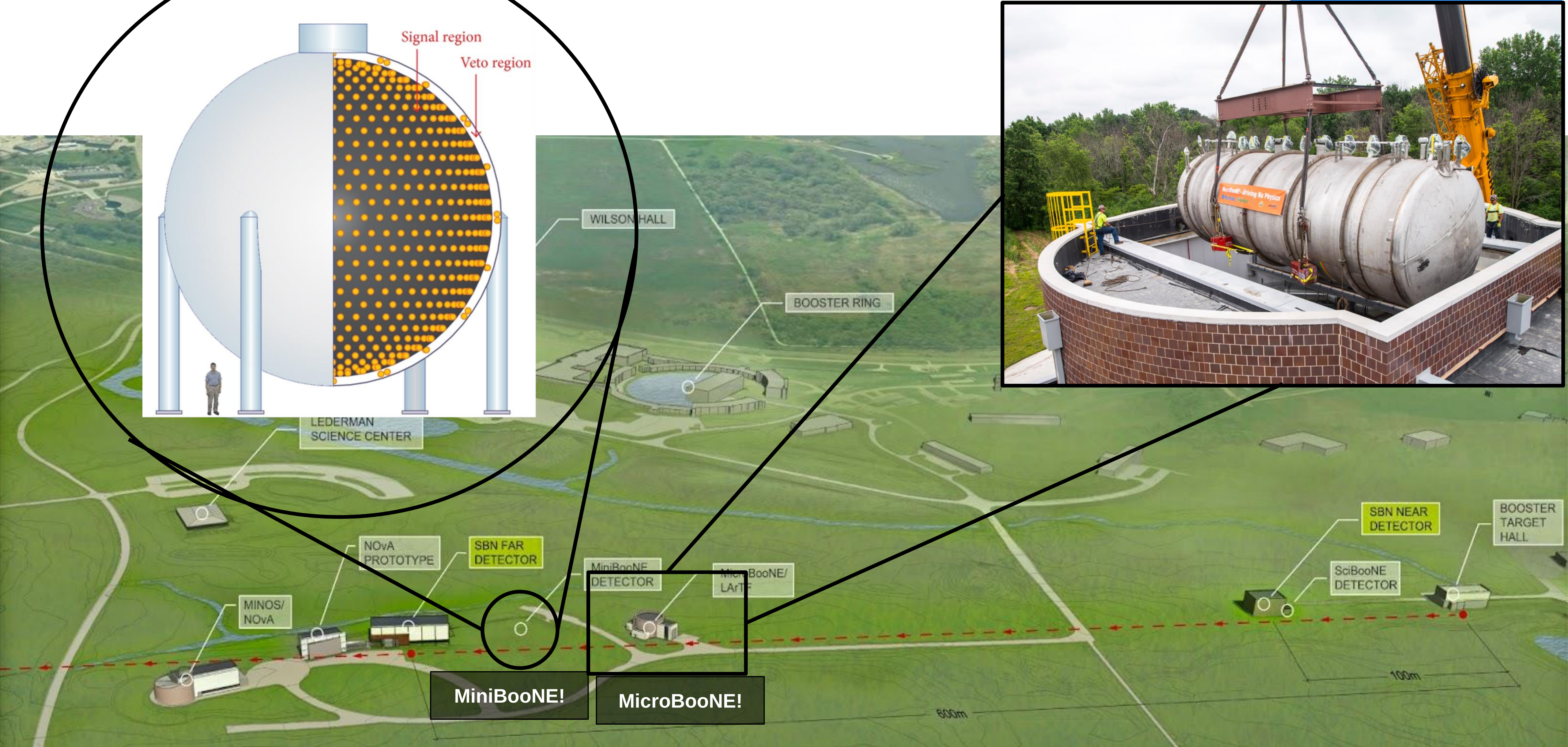
MicroBooNE

BNB @ MicroBooNE
Mean Neutrino Energy 0.8 GeV
Over 99% $\nu_\mu/\bar{\nu}_\mu$
~ 0.5% ν_e contamination!

468.5m Downstream



MicroBooNE


Signal region
Veto region
WILSON HALL
BOOSTER RING
LEDERMAN SCIENCE CENTER
NOvA PROTOTYPE
SBN FAR DETECTOR
MINOS/ NOvA
MiniBooNE DETECTOR
MicroBooNE/ LArTF
SBN NEAR DETECTOR
SciBooNE DETECTOR
BOOSTER TARGET HALL
100m
600m
MiniBooNE!
MicroBooNE!

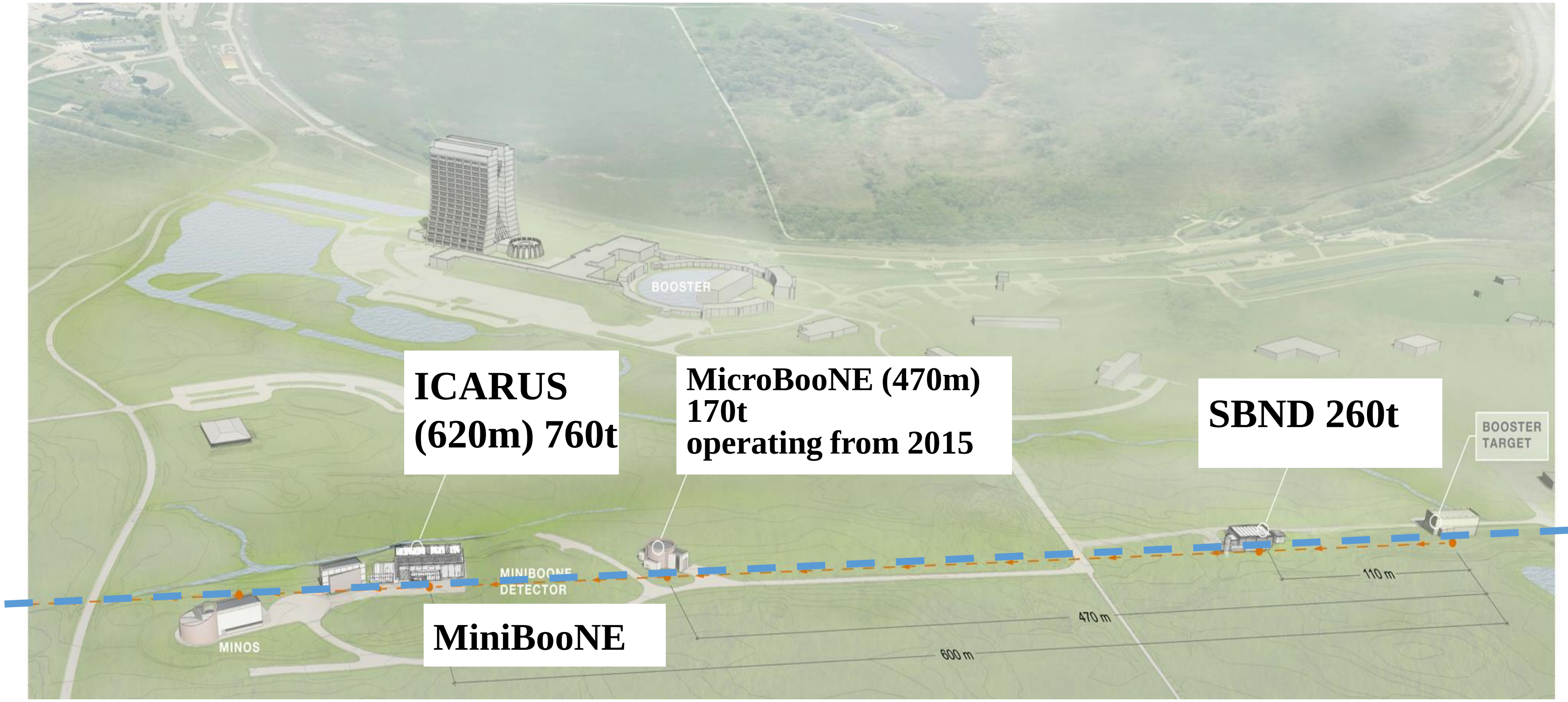
MicroBooNE

Short Baseline Neutrino (SBN) program

- SBND
- ICARUS

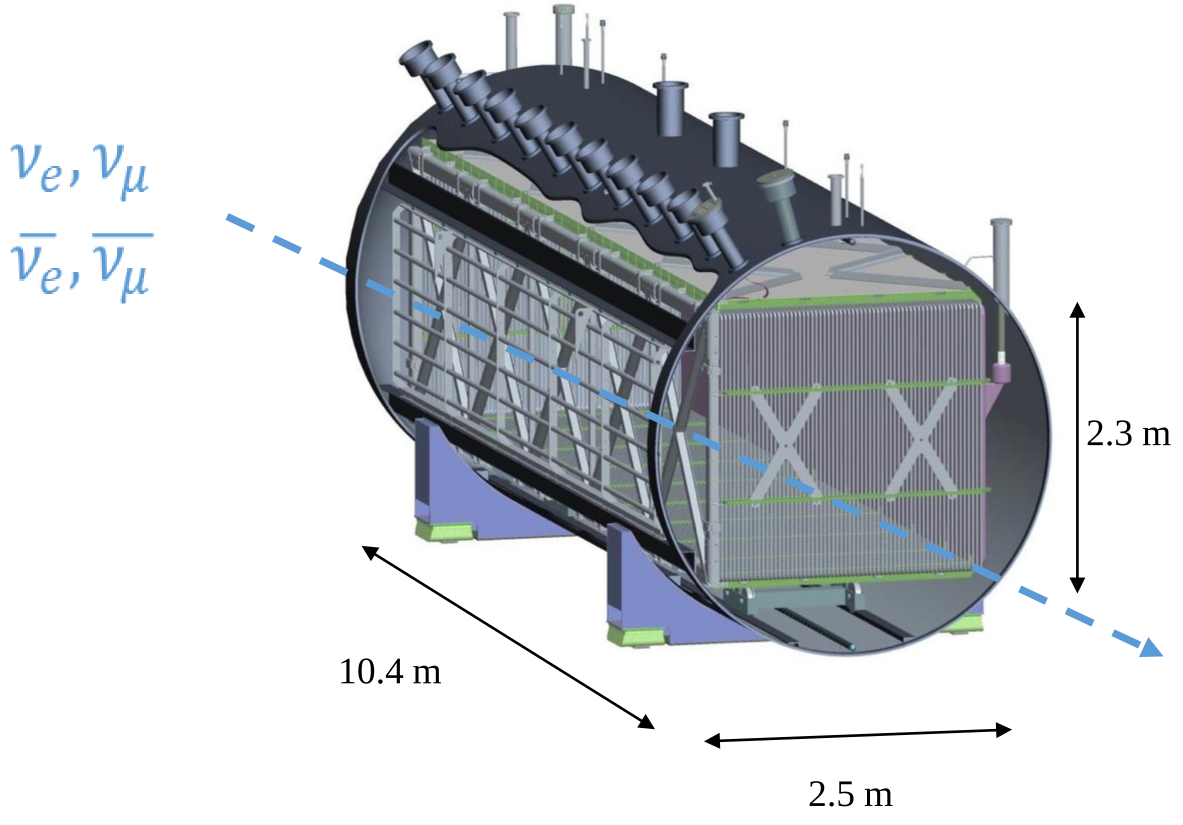
MicroBooNE

- Same beam
- Similar baseline
- using LArTPC to better distinguish e/γ



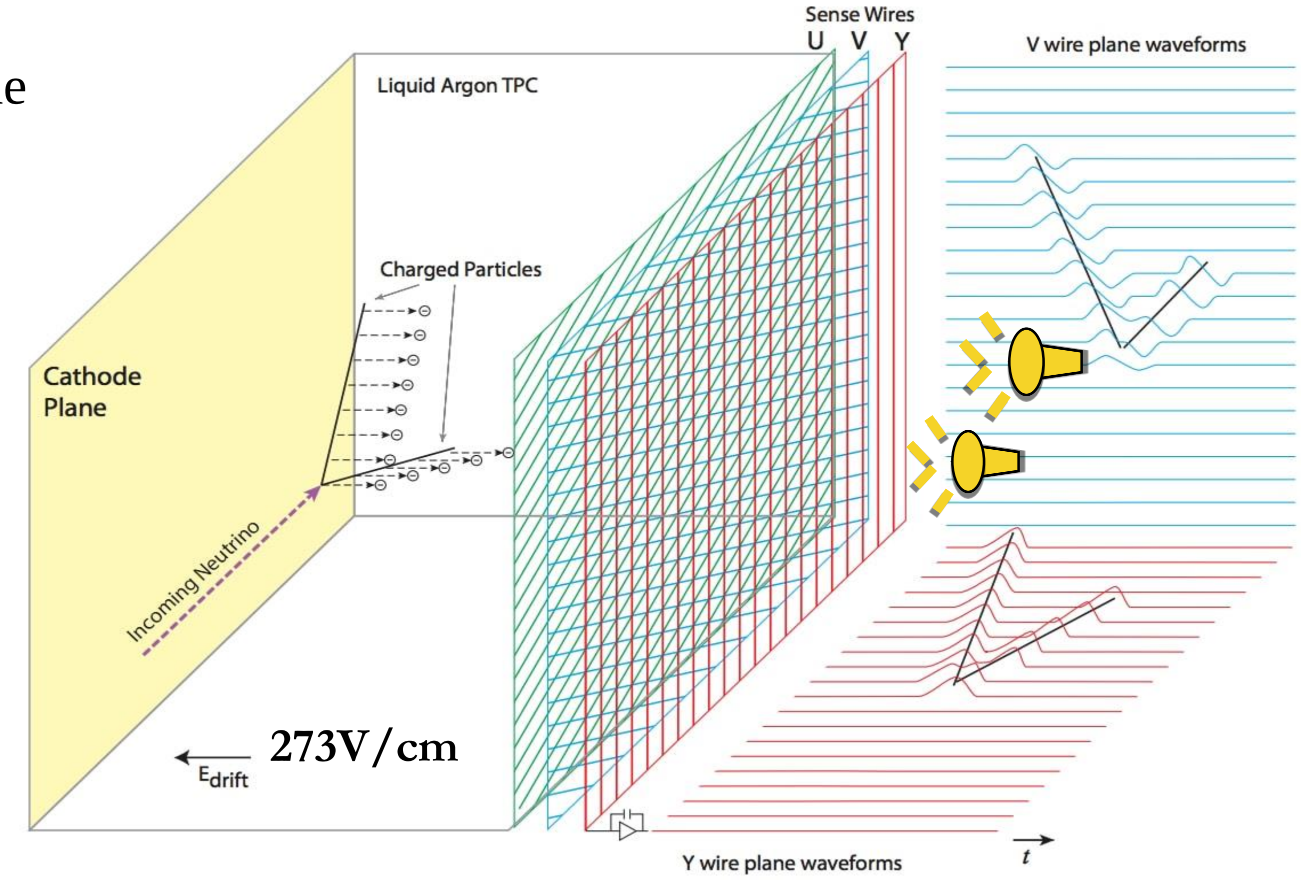
MicroBooNE

- **Micro Boo**ster **N**eutrino **E**xperiment
  - First large scale LAr TPC constructed in the U.S.
  - 85 ton Liquid Argon (LAr) TPC (active mass)
  - Operating since 2015
  - Longest Running LArTPC ~500k neutrinos collected
  - Surface detector (~5 kHz cosmics)
- **Goals**
  - LEE search
  - Cross-section measurements
  - R&D for DUNE



MicroBooNE

- Three wire planes
  - 2 induction planes (2,400 wires each).
  - 1 collection plane (3,456 wires).
  - 3mm wire pitch.
- 32 8” PMT



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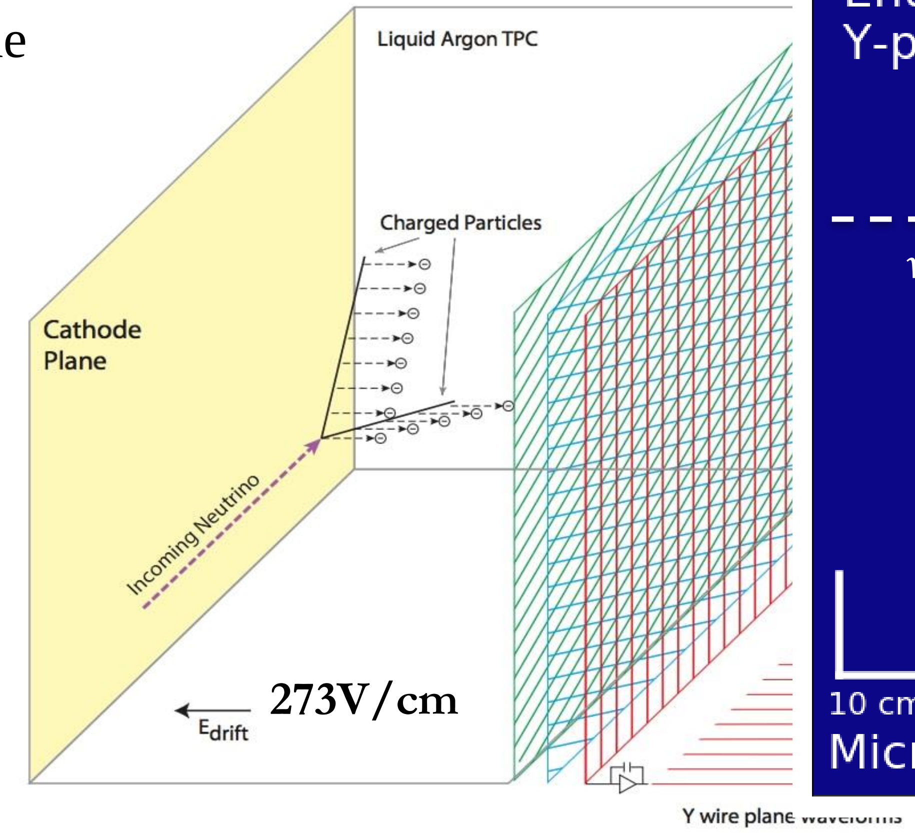
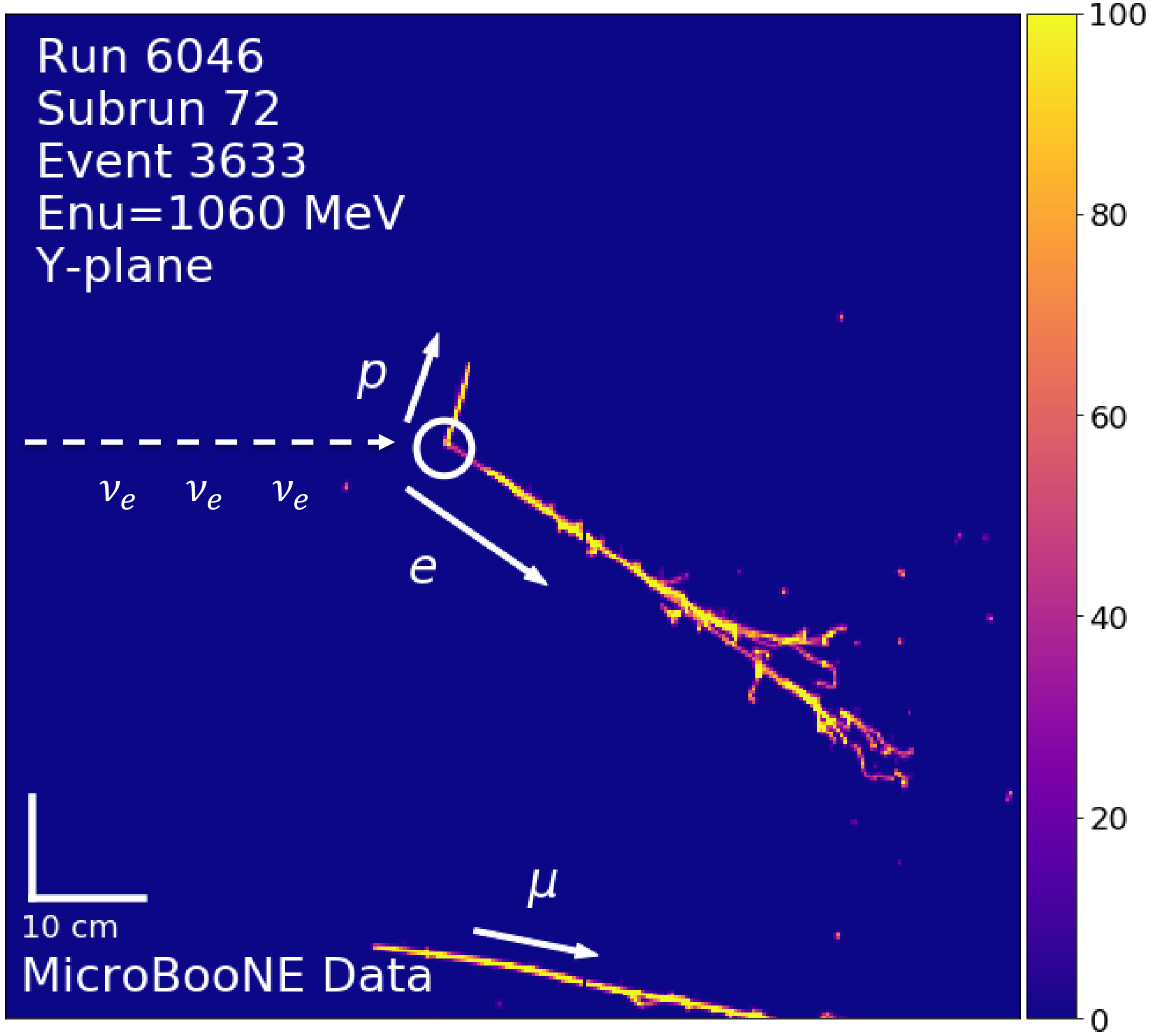
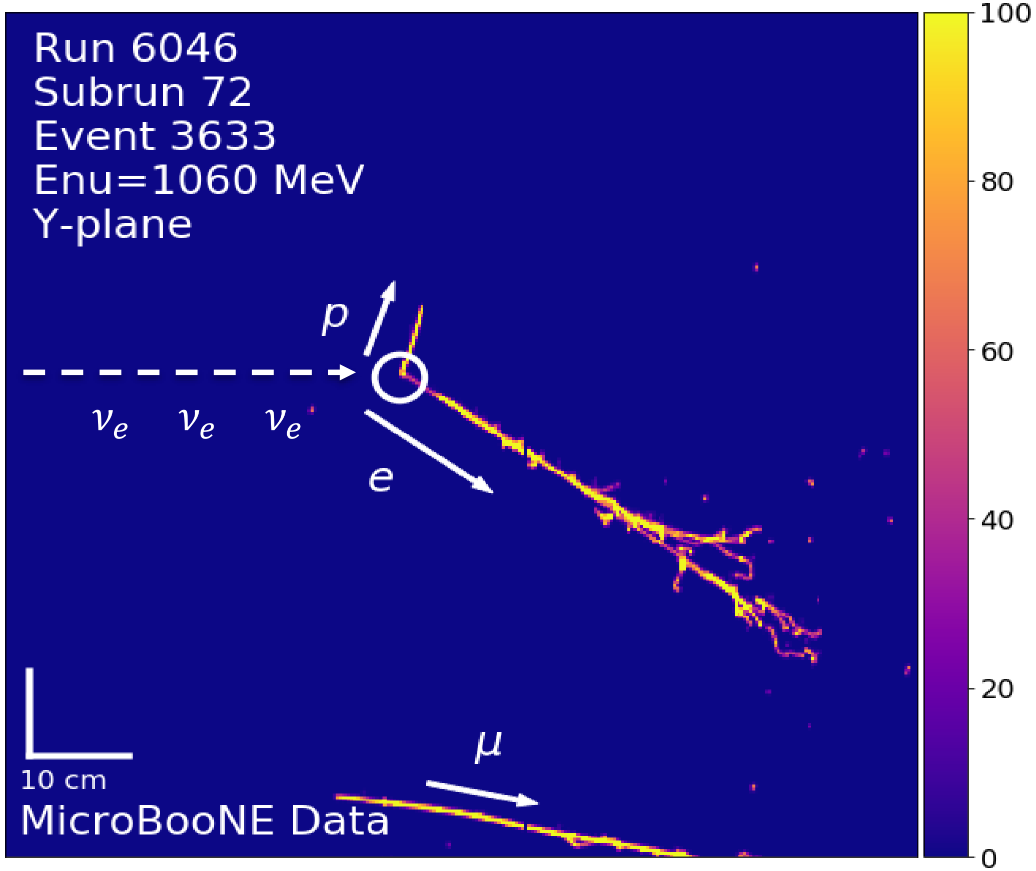
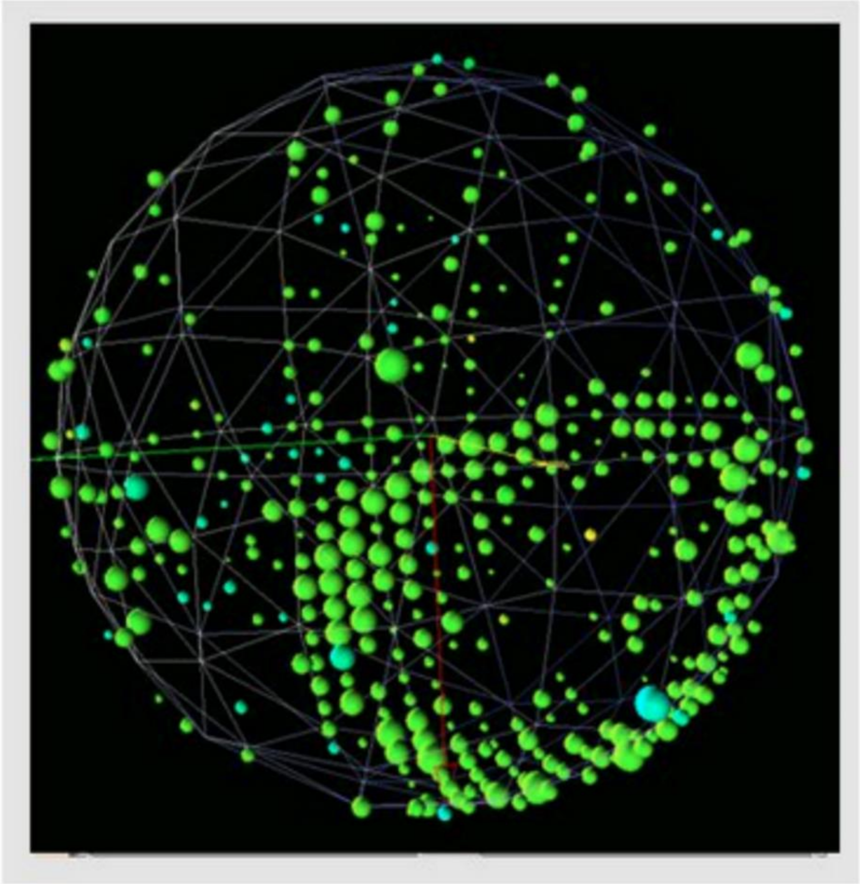




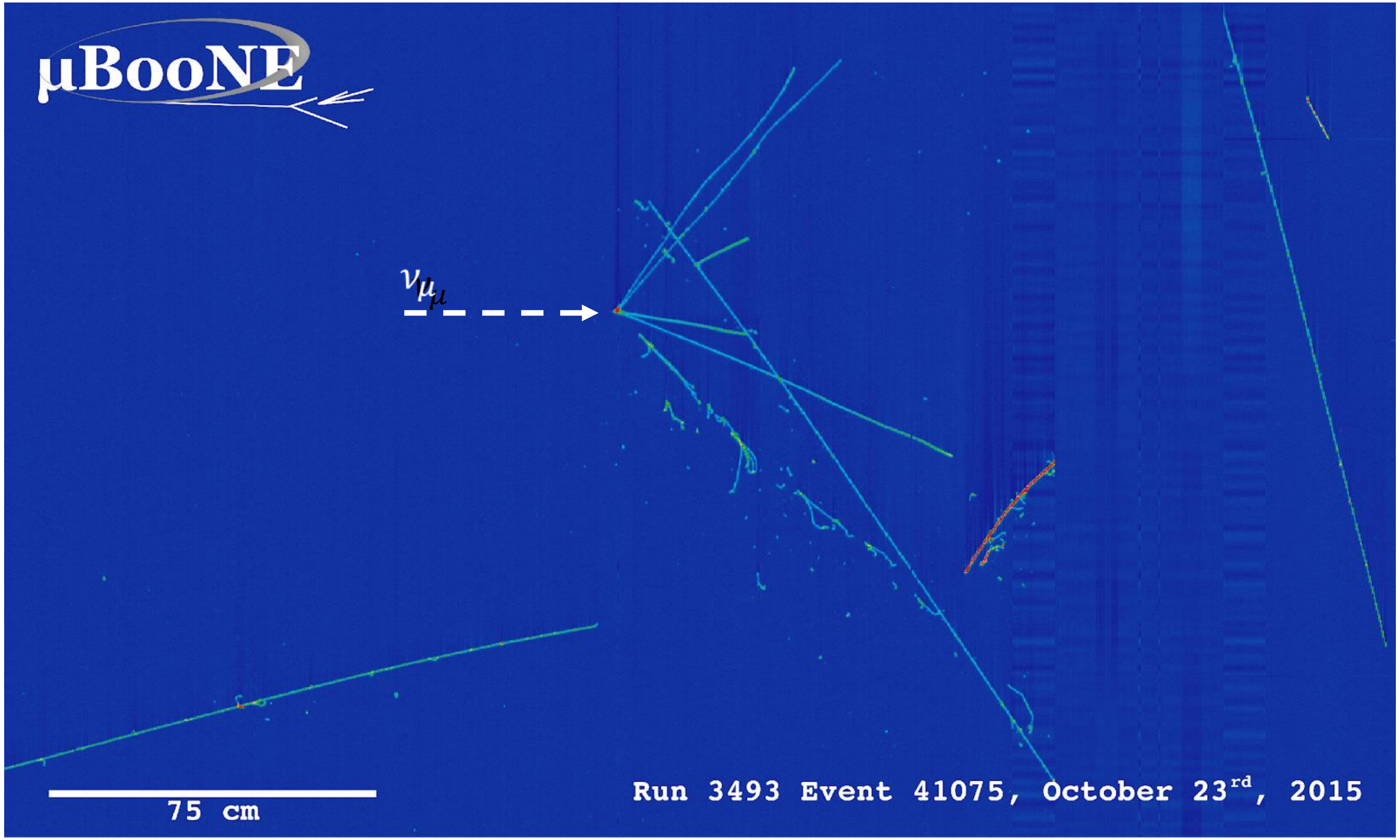
MicroBooNE



Vs.

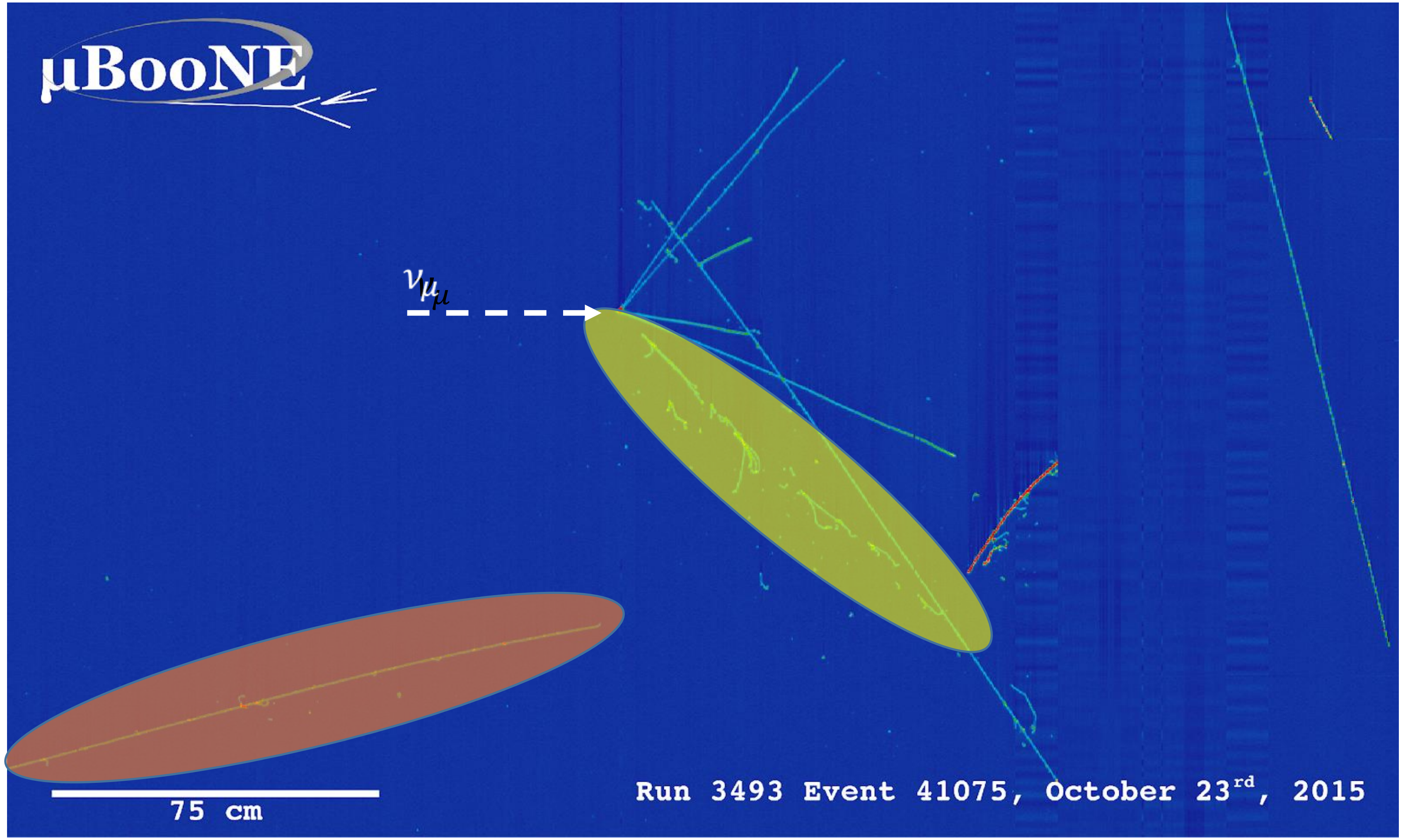


MicroBooNE



MicroBooNE

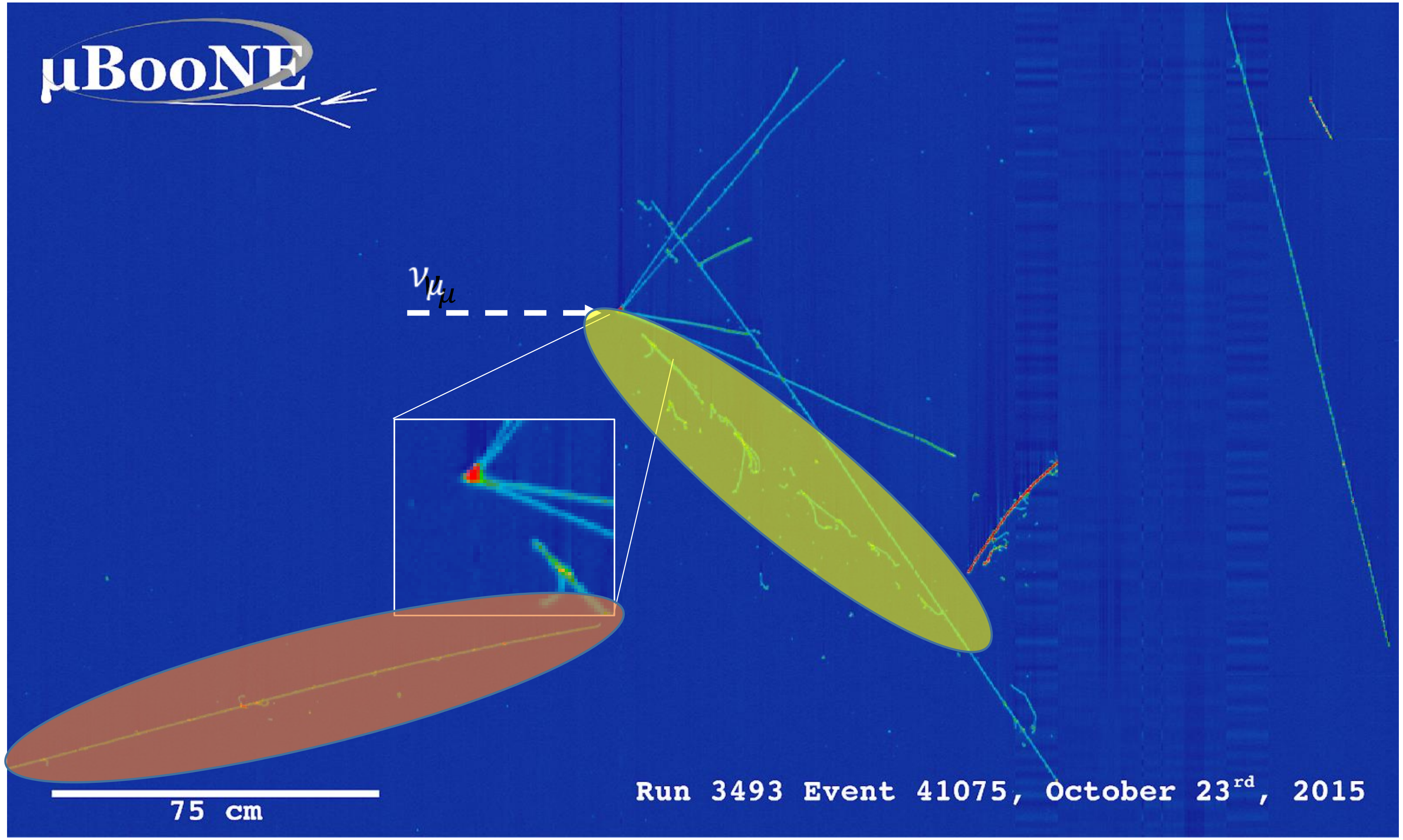
- **Shower Vs Track**
  distinct topologies



MicroBooNE

- **Shower Vs Track**
  distinct topologies

- **γ Vs e**
  Gap from vertex



MicroBooNE

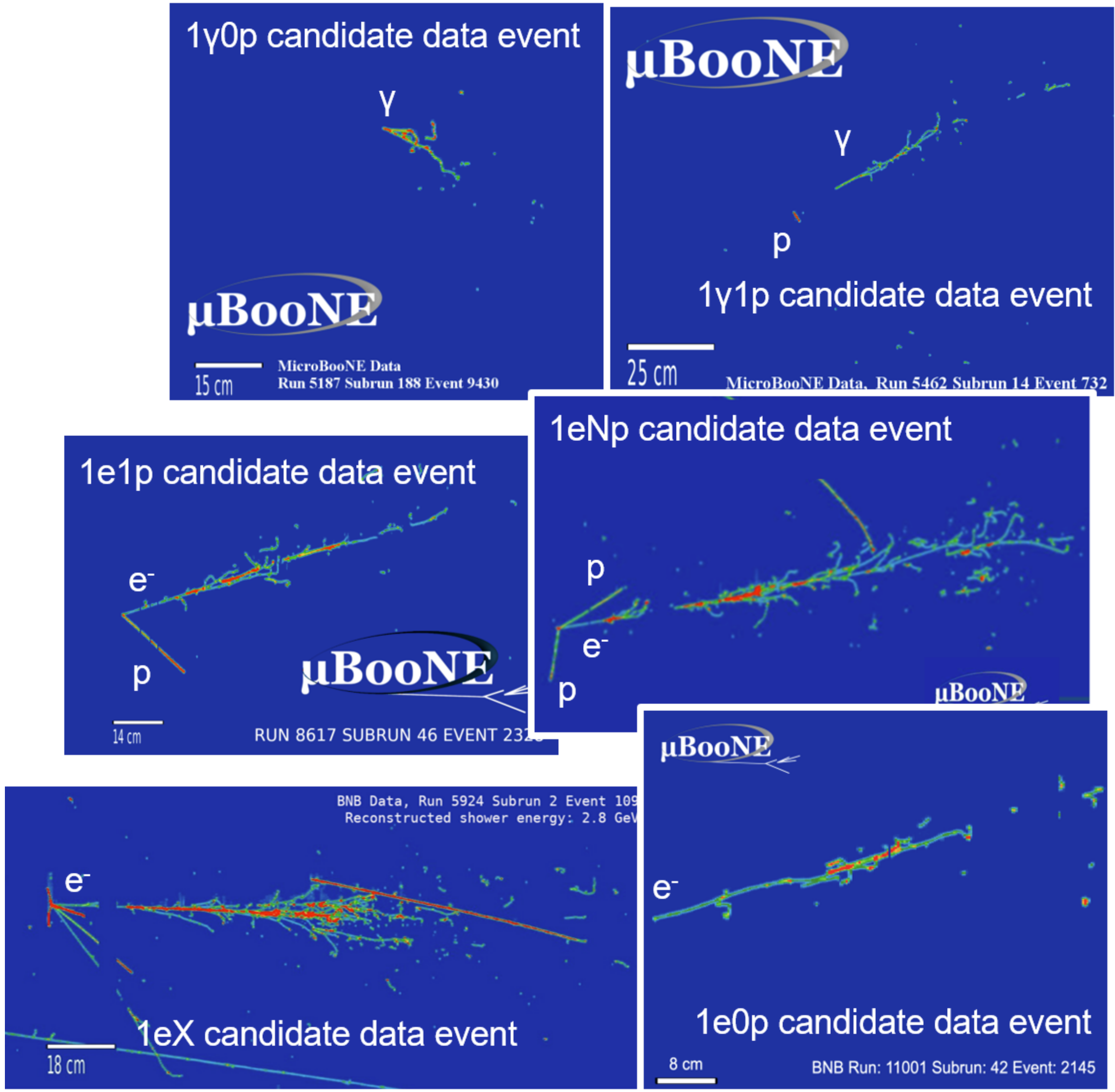
- Four independent analyses targeting different final states, hence probing different theoretical models

- Single photon analysis

  1. Targeting NC Δ —> Nγ hypothesis **(1γ0p, 1γ1p)**

- Analyses searching for a ν_e rate excess

  2. Restricting to quasi-elastic kinematics **(1e1p)**
  3. MiniBooNE-like final states **(1eNp, 1e0p)**
  4. All ν_e final states **(1eX)**



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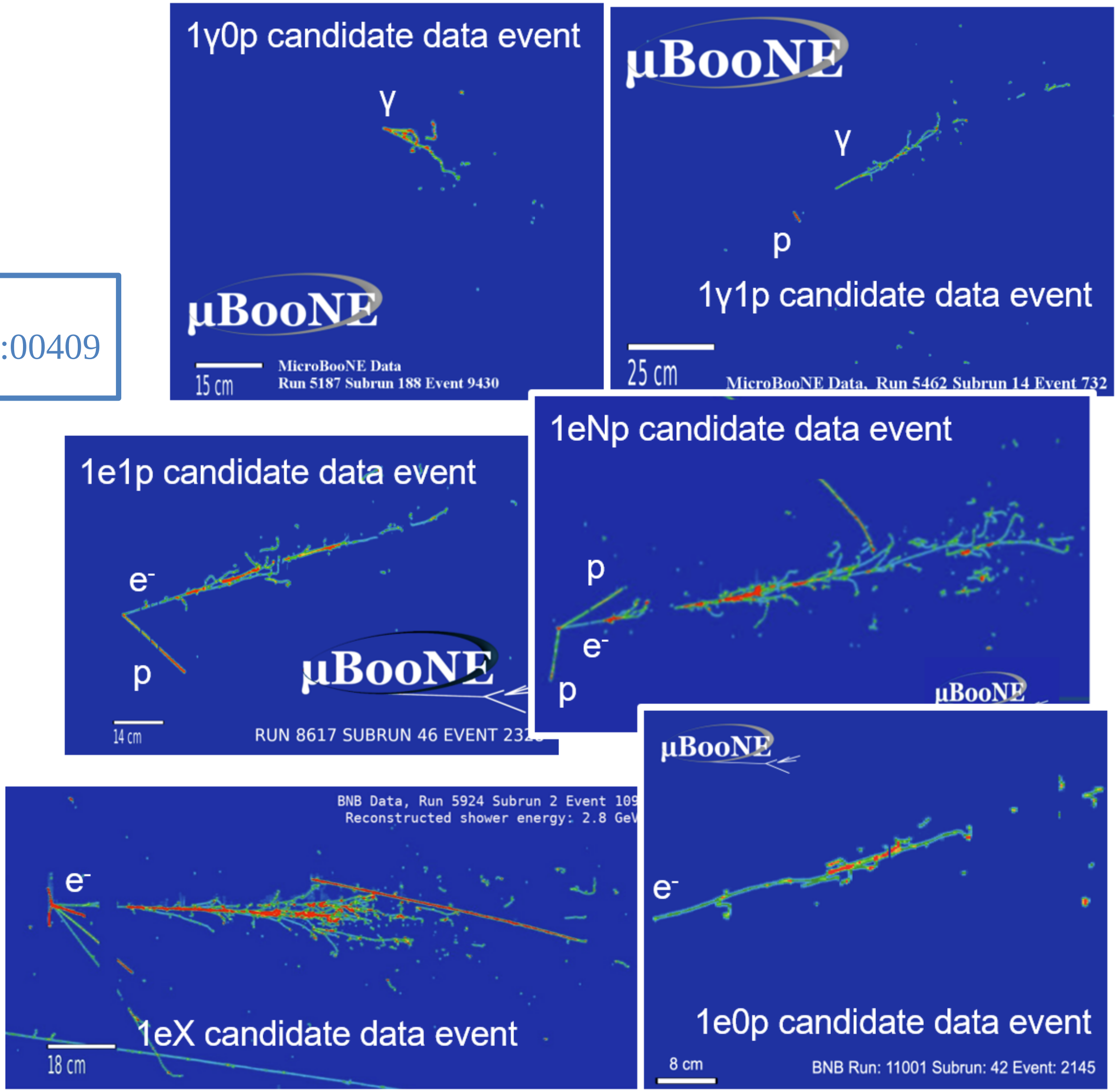
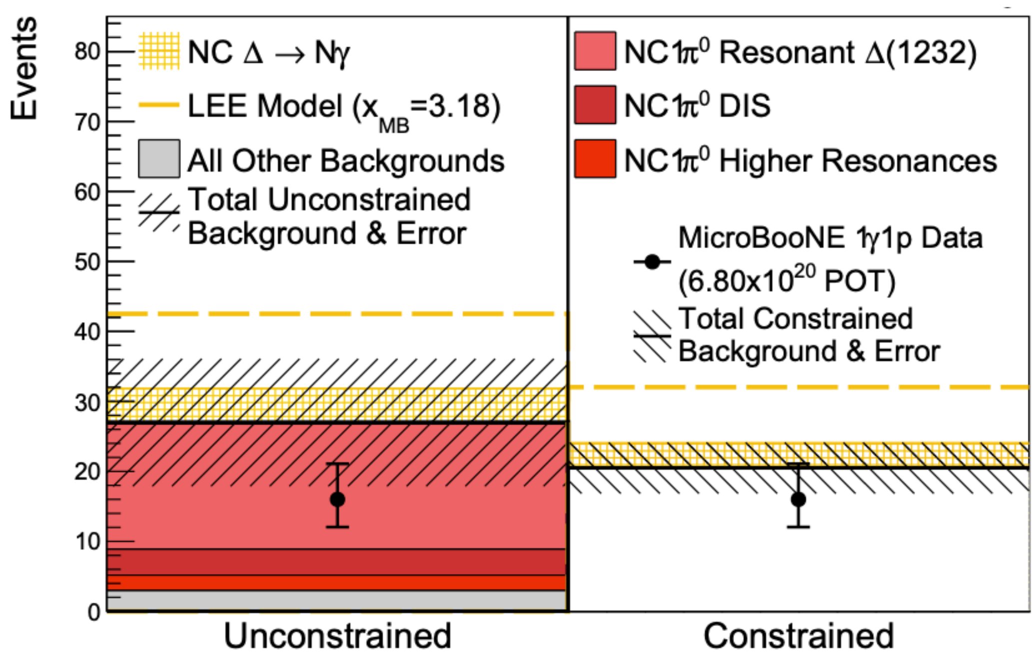
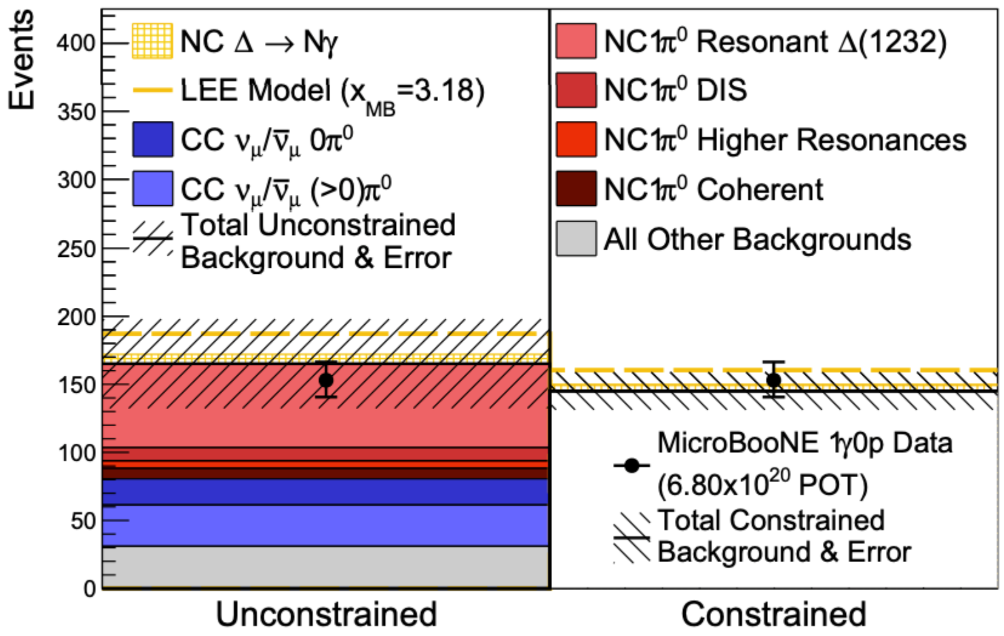
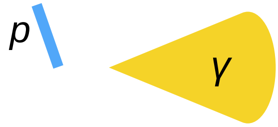
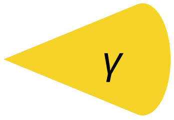


MicroBooNE









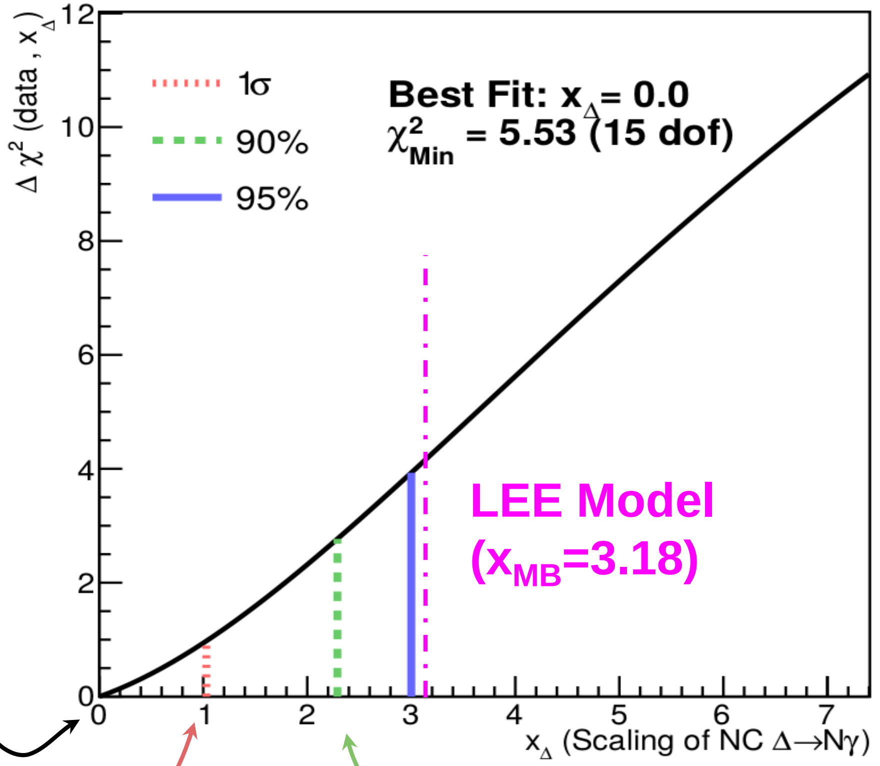
No evidence for enhance rate of single photons from NC **Δ**→Nγ decay

Disfavor the interpretation of the MiniBooNE anomalous excess as a factor of 3.18 enhancement to the rate NC **Δ**→Nγ, in favor of the nominal prediction at 94.8% CL

MicroBooNE

Elevate this normalization **scaling to a continuous parameter, x_Δ,** and perform a fit to extract the best fit and classical confidence intervals, via the Feldman-Cousins procedure

Small under fluctuation results in best fit x_Δ = 1, SM is within 1 sigma



Best Fit:
x_Δ = 0

Nominal GENIE NC **Δ**→Nγ rate (x_Δ = 1) within 1σ

x_Δ < 2.3 at the **90% CL**

MicroBooNE

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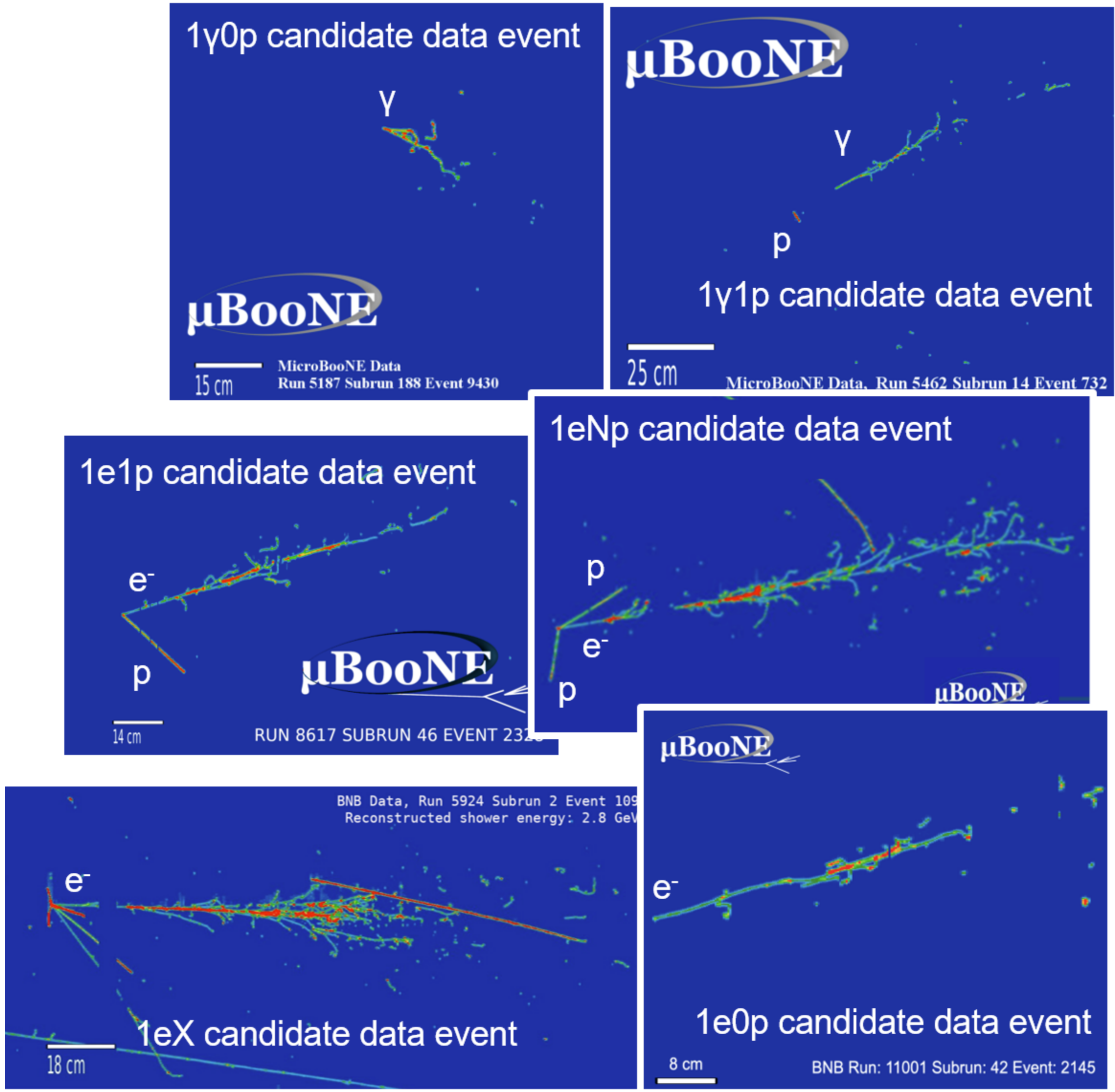
  4. All ν_e final states **(1eX)**

  arXiv: 2110.14054 ; arXiv: 2110.14080 ; arXiv: 2110.14065 ; arXiv: 2110.13978

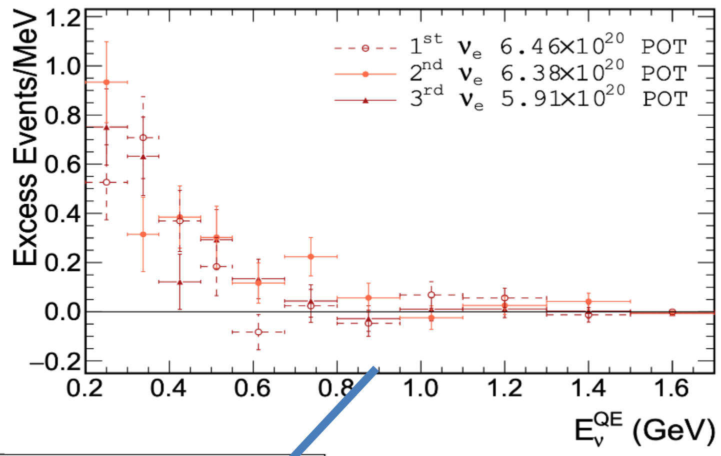
http://ubdllee.org

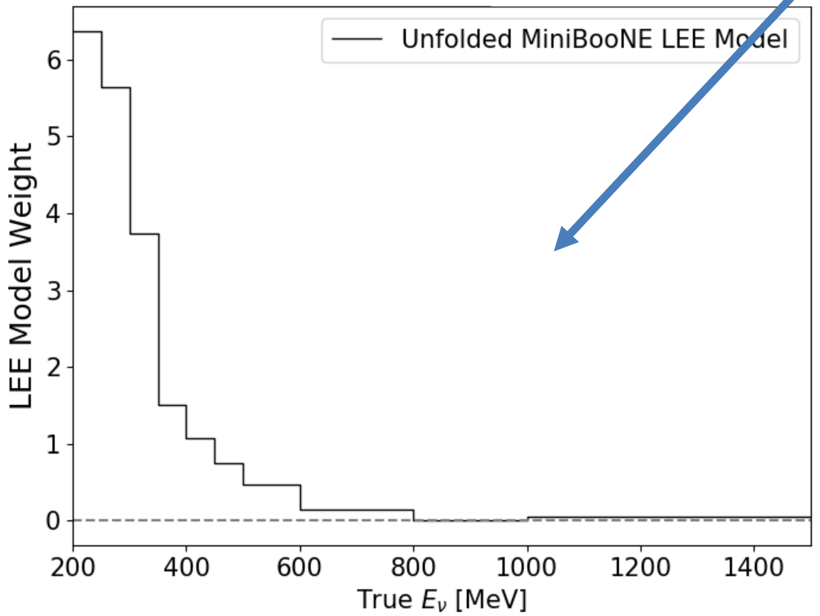


MicroBooNE

- Unfold 2018 MiniBooNE excess under ν_e hypothesis
  - **Considers only E_ν dependence**
- Derive scaling template to model enhancement of intrinsic ν_e rate in the Booster Neutrino Beam
- Does the data prefer the ν_e prediction or this simple "eLEE" model?
  - $\Delta\chi^2$ hypothesis testing

Phys. Rev. D 103, 052002 (2021)

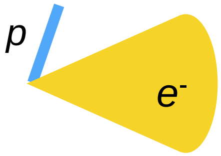




MicroBooNE

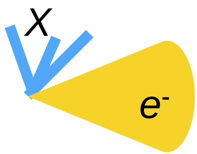
Three independent searches across multiple single electron final states

- Exclusive two-body charged-current quasi-elastic (CCQE) ν_e scattering [1e1p]



- Semi-inclusive ν_e scattering without final state pions [1eNp0π (N≥1) + 1e0p0π]

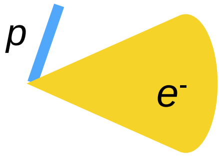
- Inclusive ν_e scattering [1eX]



MicroBooNE

Three independent searches across multiple single electron final states

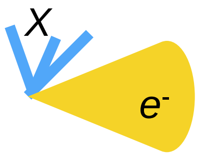
- Exclusive two-body charged-current quasi-elastic (CCQE) ν_e scattering [1e1p]



Today's talk will focus on this analysis, with results from all other at the end

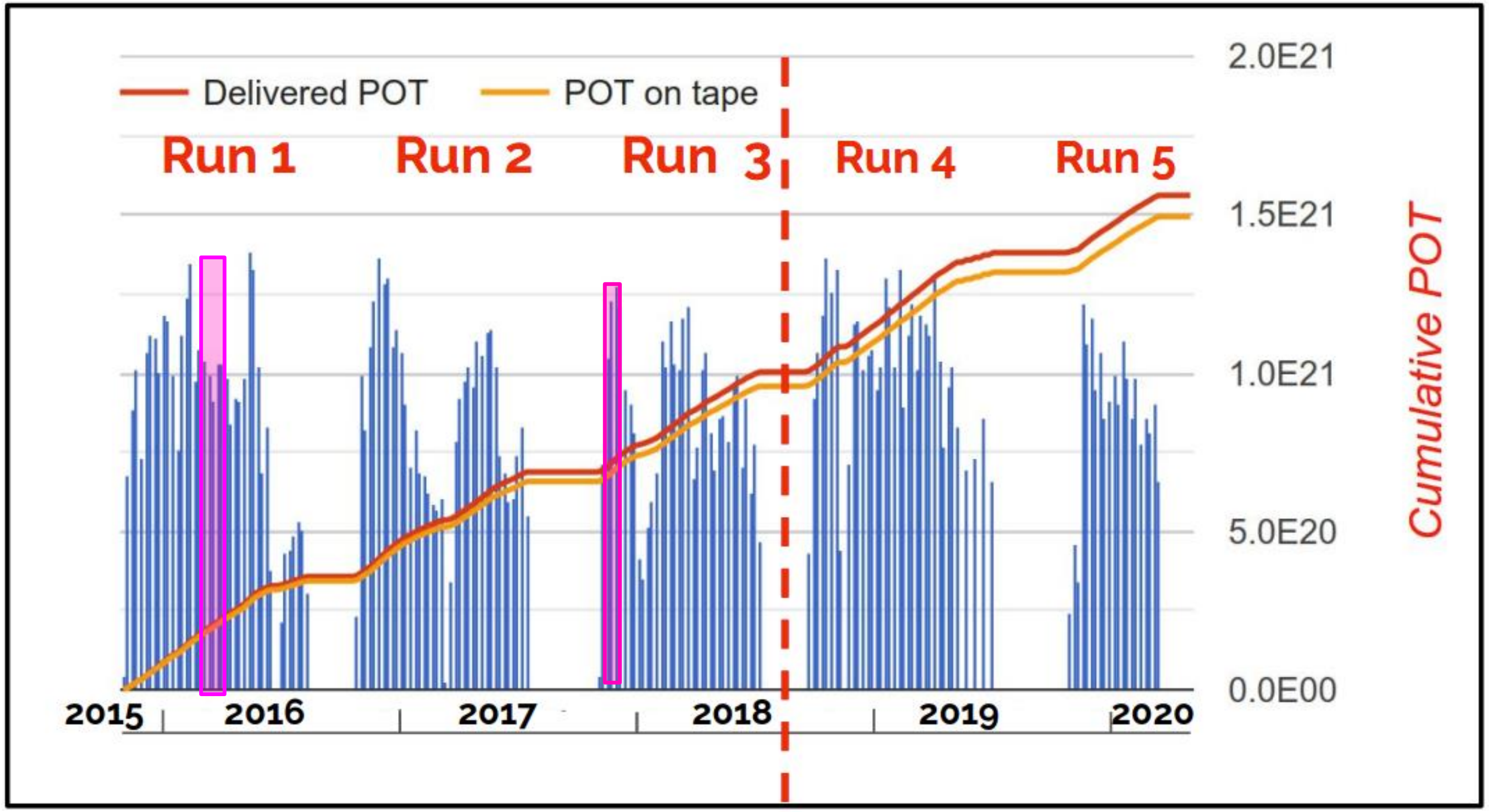
- Semi-inclusive ν_e scattering without final state pions [1eNp0π (N≥1) + 1e0p0π]

- Inclusive ν_e scattering [1eX]

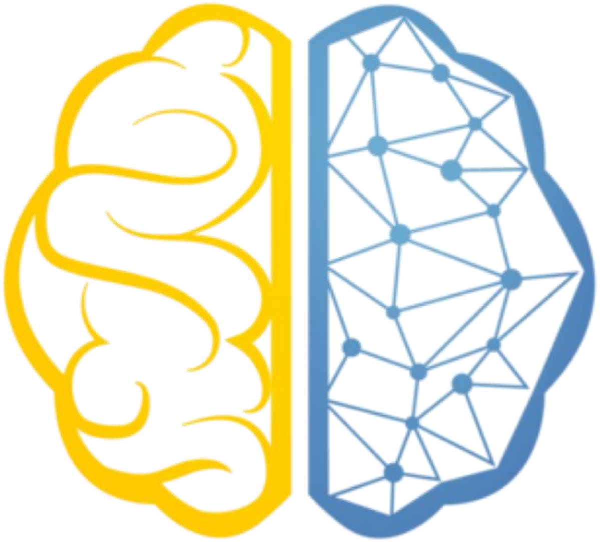


MicroBooNE

- In today's talk I will be presenting results based on **~6.67x10^{20} (DL specific) protons-on-target (POT)** from **Runs 1-3**
- These were **blind analyses,** so all **development** and **validation** took place first using a small unblinded **0.4x10^{20} POT** from Run 1 sample (~1/17th the size) and **0.1x10^{20} POT** from Run 3 sample
- Sequential unblinding
  - 700-1200 MeV
  - 500- 700 MeV
  - 200- 500 MeV



DL-LEE

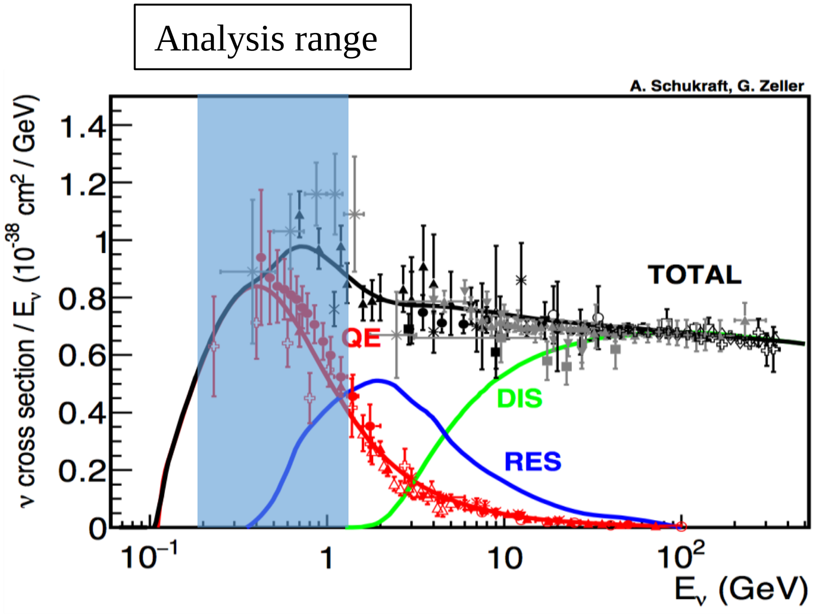


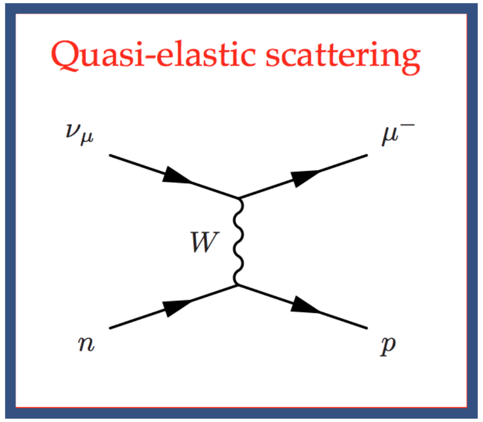
The Exclusive analysis, looking only for CCQE two-body topologies using deep-learning-based reconstruction

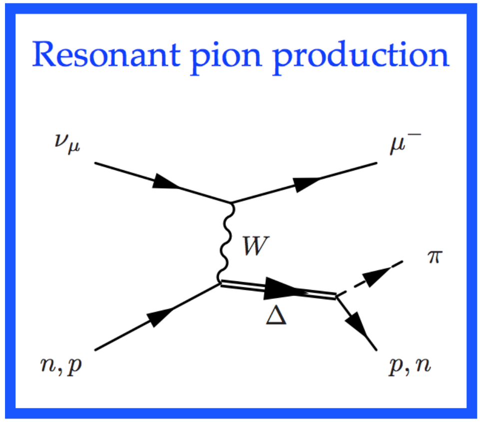
The DL Analysis

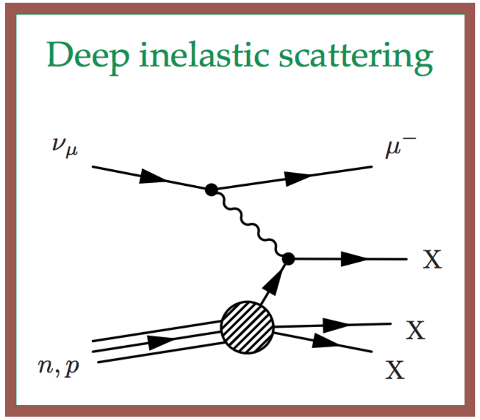
Exclusive analysis, looking only for CCQE two-body topologies (1ℓ1p).

- Expected signal peaks at low energies (200-500) MeV.
- The dominant cross section in these energies is QE.
- QE interactions are better understood.





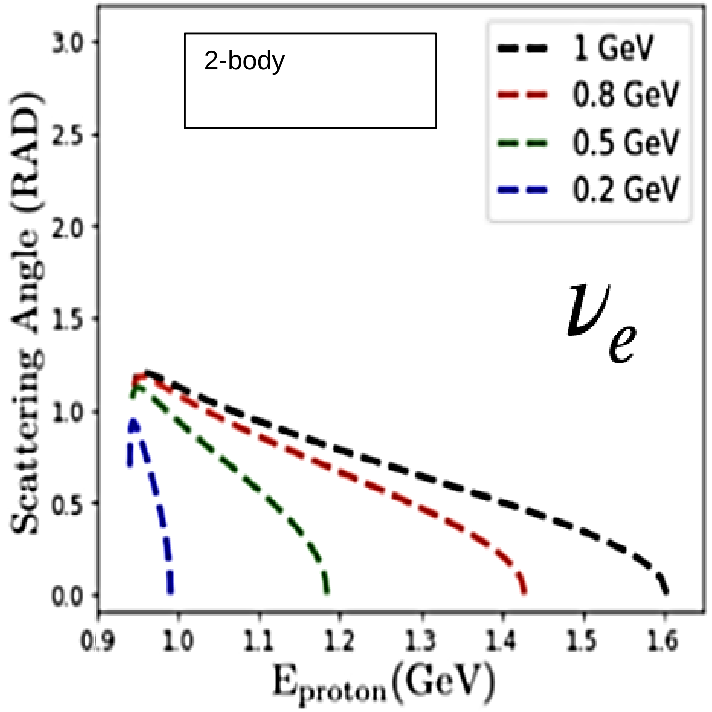


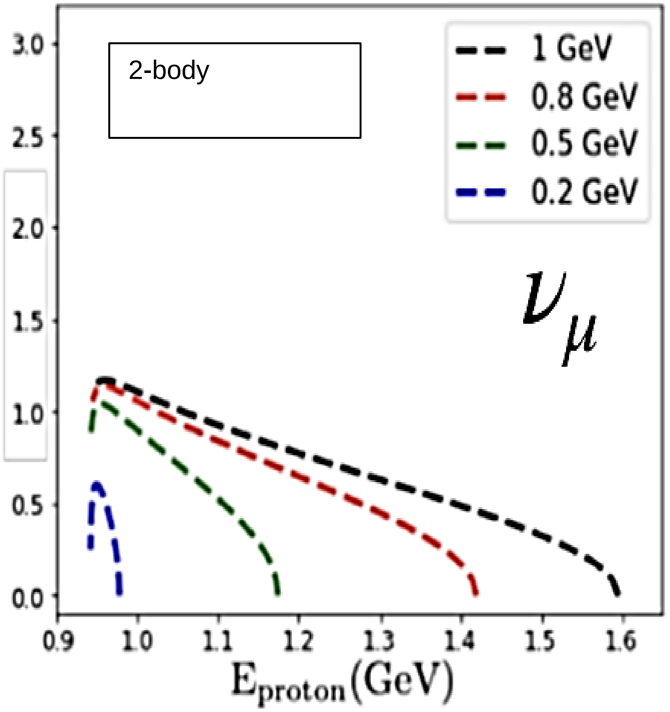


The DL Analysis

Exclusive analysis, looking only for CCQE two-body topologies (1ℓ1p).

E_ν^{range} *	$E_p + E_\ell - (m_n - E_b)$
E_ν^{QE-p}	$\frac{E_p(m_n - E_b) + \frac{1}{2}(m_\ell^2 - (m_n - E_b)^2 - m_p^2)}{(m_n - E_b) + \lvert\vec{p}_p\rvert cos\theta_p - E_p}$
$E_\nu^{QE-\ell}$	$\frac{E_\ell(m_n - E_b) + \frac{1}{2}(m_p^2 - (m_n - E_b)^2 - m_\ell^2)}{(m_n - E_b) + \lvert\vec{p}_\ell\rvert cos\theta_\ell - E_\ell}$
Δ^{QE}	$\sqrt{(E_\nu^{QE-p} - E_\nu^{QE-\ell})^2 + (E_\nu^{QE-p} - E_\nu^{range})^2 + (E_\nu^{QE-\ell} - E_\nu^{range})^2}$



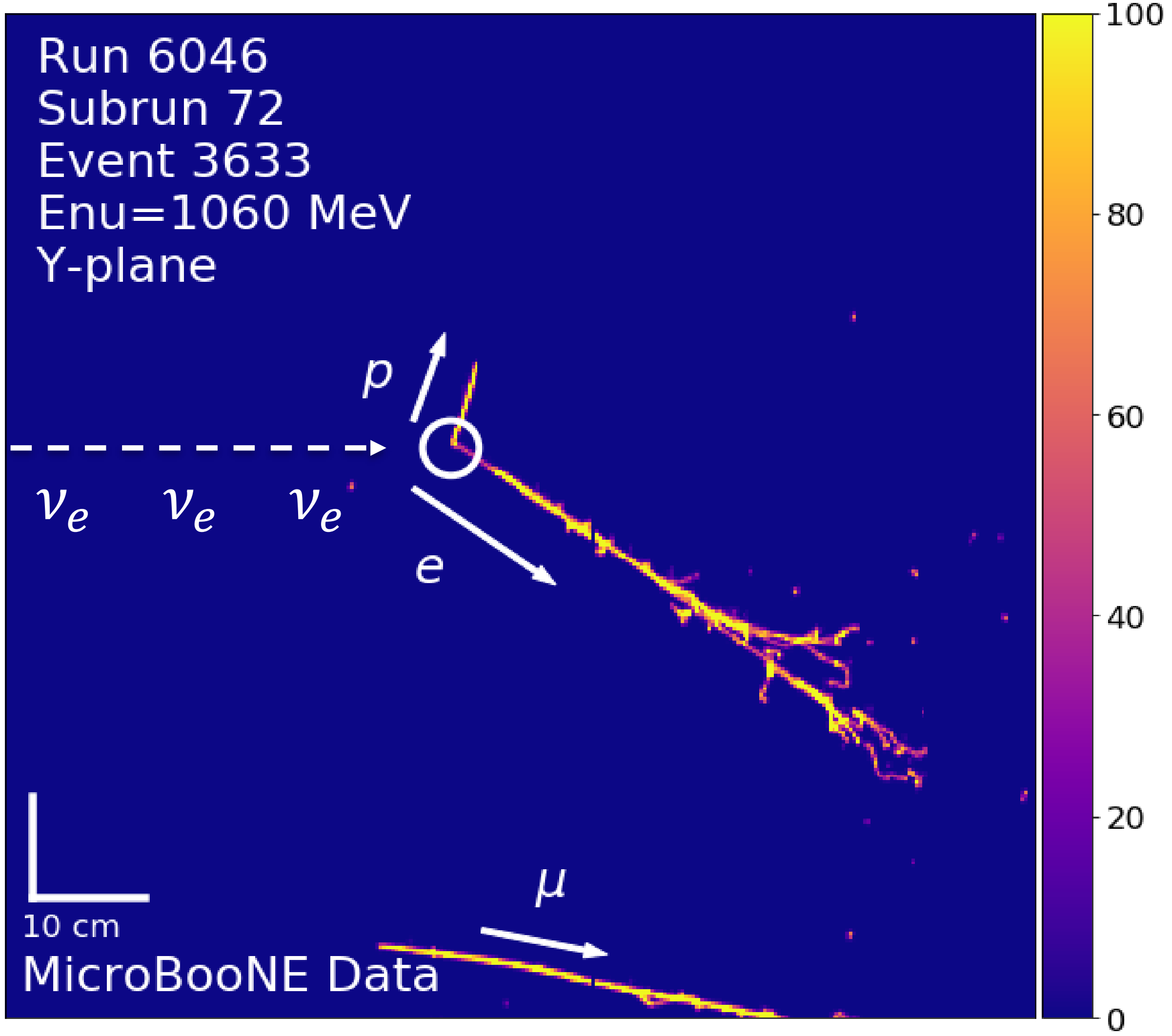


- Selected events, are kinematically consistent with two-body scattering.
- purely physics-based separation, e.g.,
  - forward going protons.
  - reconstructed energy consistent with CCQE.
  - near unity Bjorken-X.
- Not many background interactions pass these requirements.

The DL Analysis

Deep-learning-based reconstruction

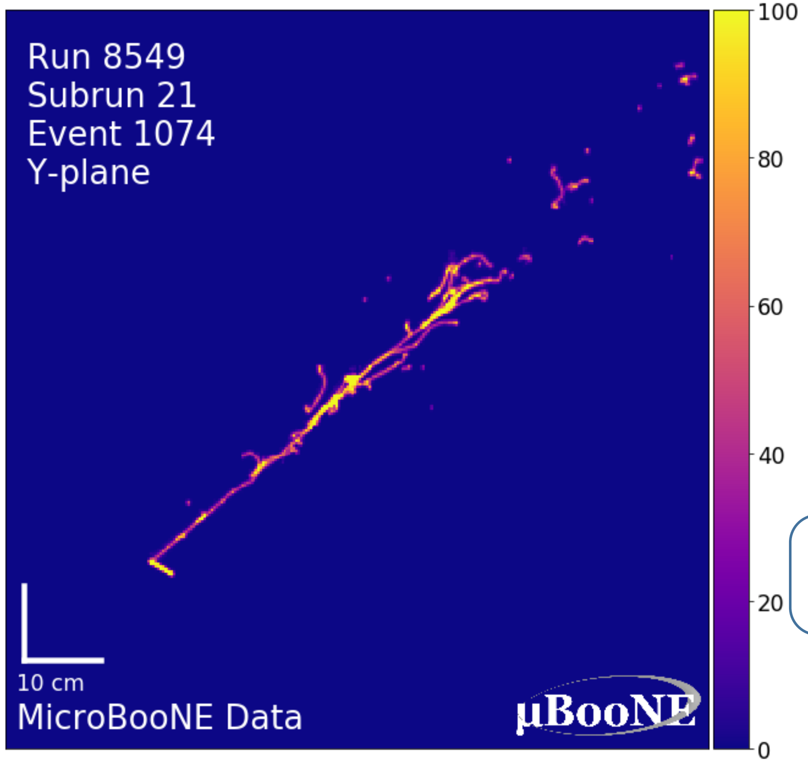
- Treating our data as sets of images.
- An example 90 × 90 cm^2 image, cropped around interaction.
- Allows utilizing the great capabilities of deep learning algorithms.
- Pixel intensity – integrated signal over 6 time-ticks.
- Pixel resolution is 3 × 3.3 mm.



The DL Analysis

Classify pixels into tracks/ shower

Before



Semantic Segmentation Using SparseSSNet

Cosmic Tagging

Vertex and Track / Shower Reconstruction

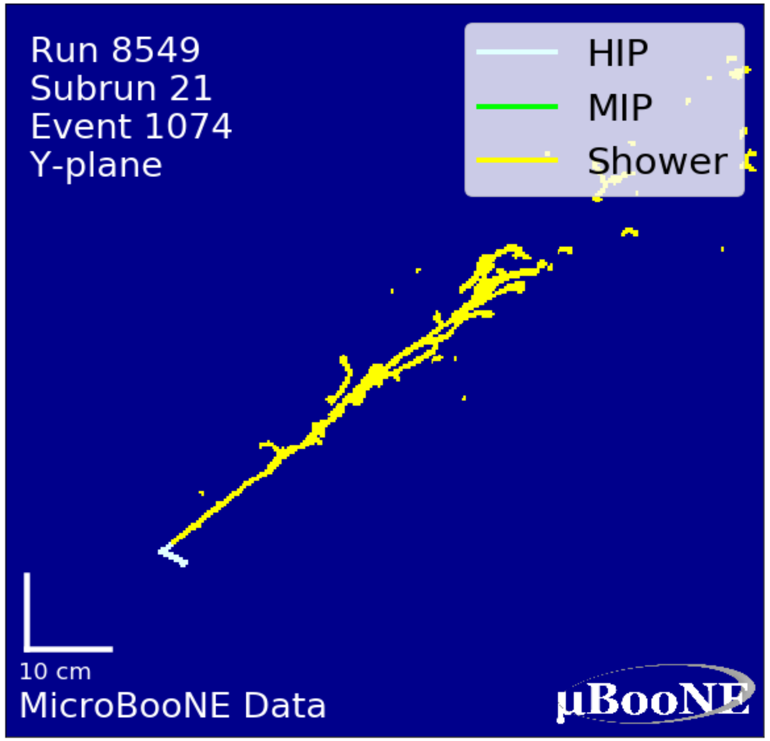
MPID

1e1p sample | π^0 | 1μ1p sample

Systematics Results

10.1103/PhysRevD.103.052012

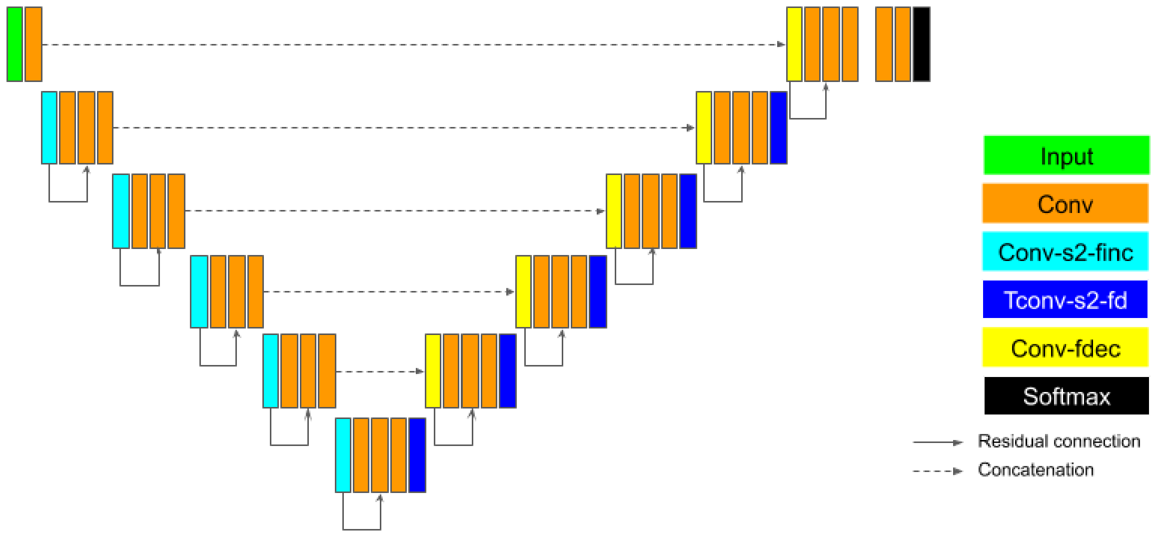
After



The DL Analysis

- Use of SSCN, more efficient for our sparse data (<0.5% important pixels)
  cvpr:2018 ; arxiv:1706.01307

- UResNet – a hybrid of Unet & ResNet



- Single hot labels
  Highly Ionizing Particles (protons)
  Minimum Ionizing Particles (μ , $\pi^{\pm}$) } Track
  shower (e, γ),
  delta (knock-on electron),
  Michel electrons (decay of muons) } Shower

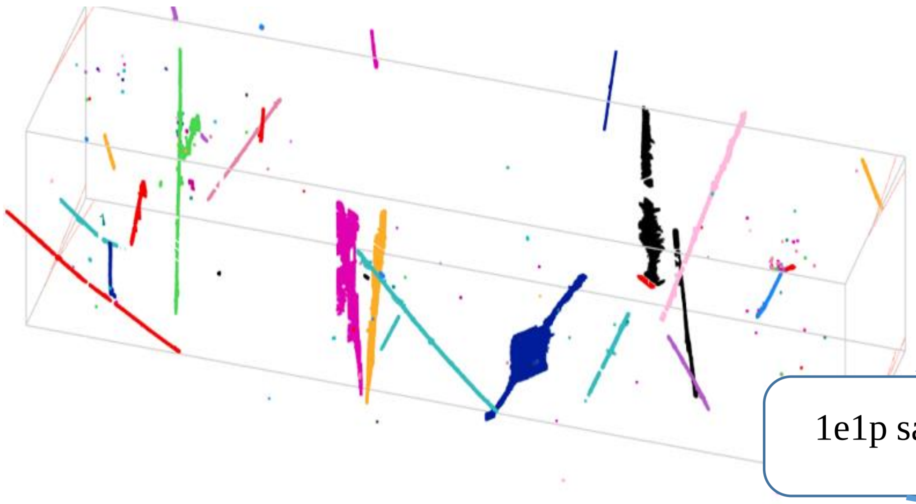
- Predictions in 2D – different network per plane

	Test	Enhanced ν_e sample	BNB sample
Track	0.992	0.992	0.998
Shower	0.996	0.859	0.823

The DL Analysis

Remove Cosmics

Before



Semantic Segmentation Using SparseSSNet

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Vertex and Track / Shower Reconstruction

MPID

1e1p sample

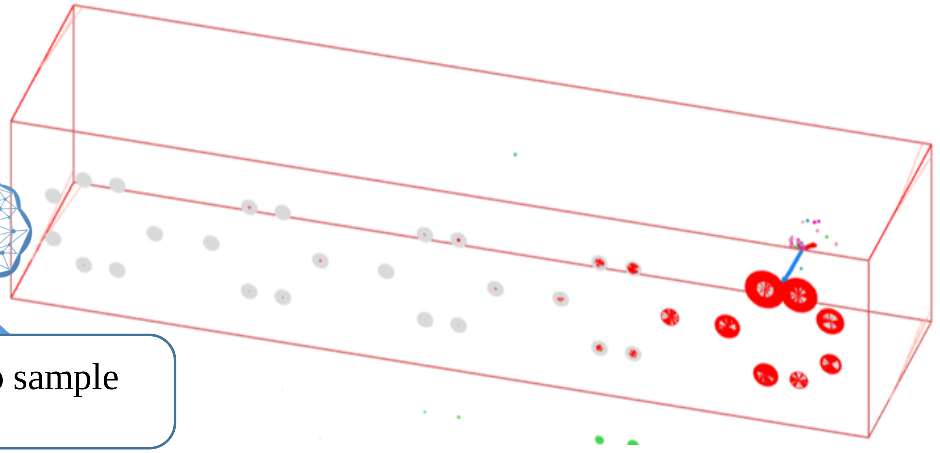
π^0

1μ1p sample

Systematics Results

10.1103/PhysRevApplied.15.064071

After

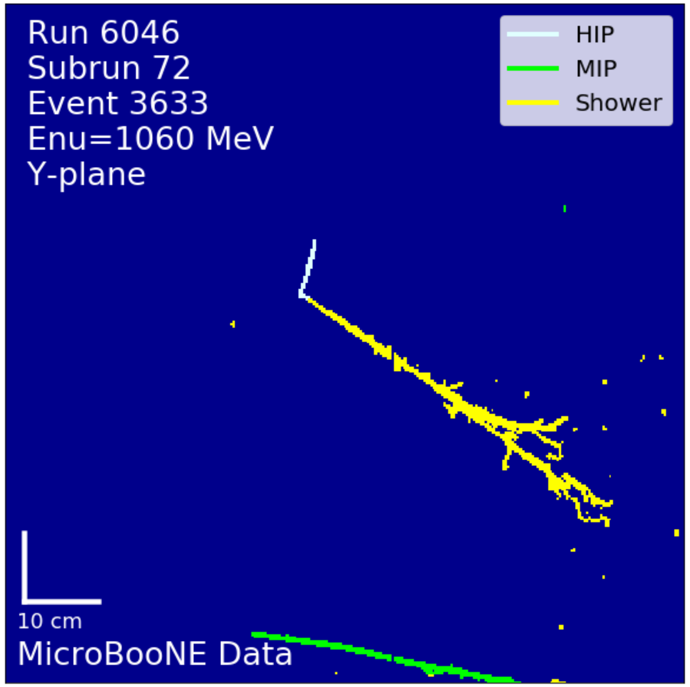


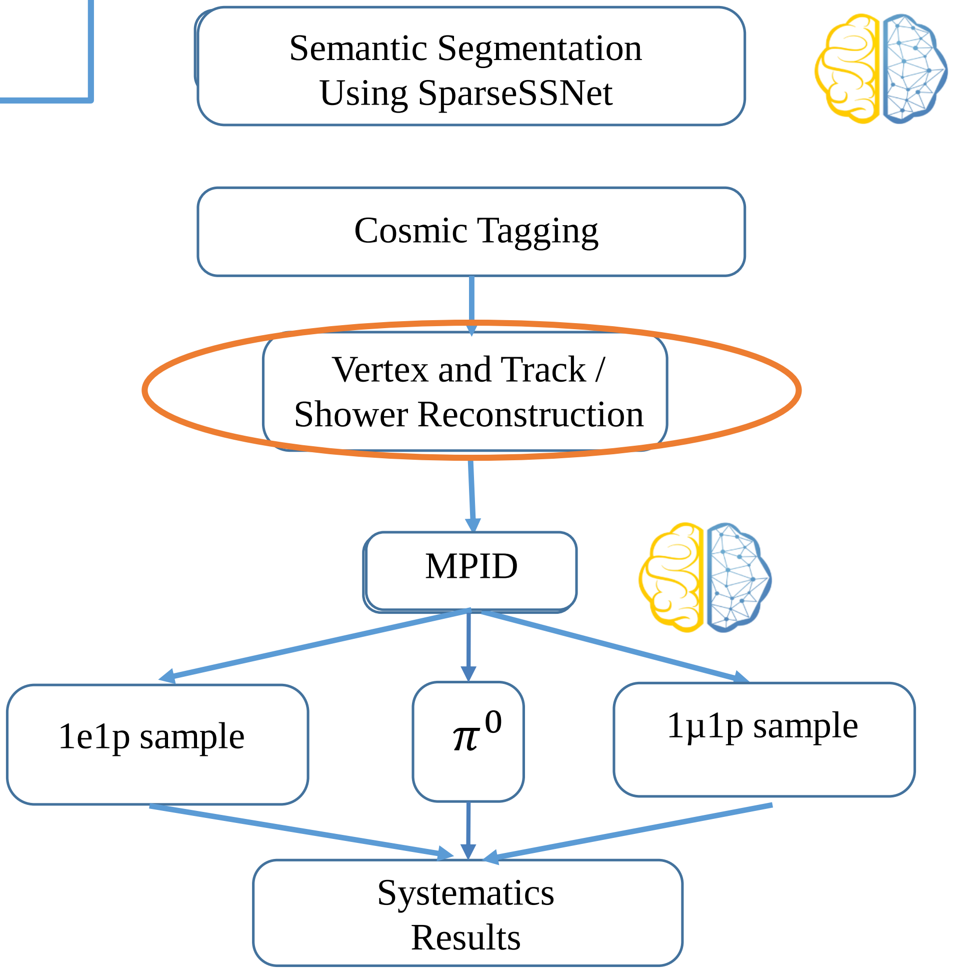
The DL Analysis

Cleaner image
Identify vertex, cluster showers and tracks
Relies on labels from SparseSSNet

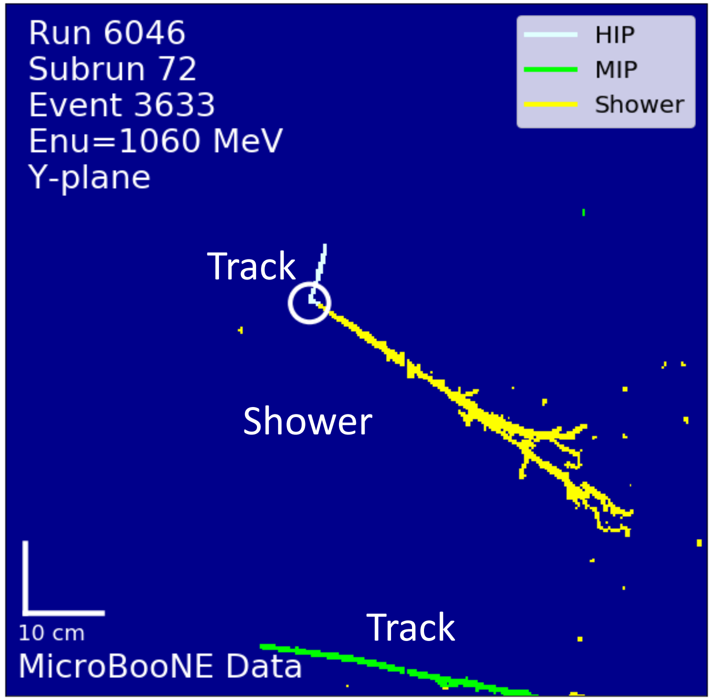
arXiv: 2110.11874
10.1088/1748-0221/16/02/P02017 JINST

Before





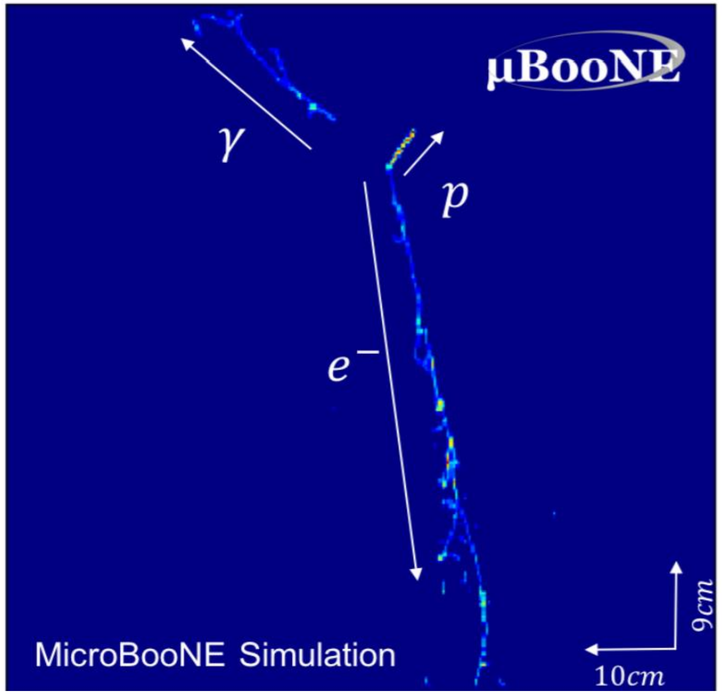
After

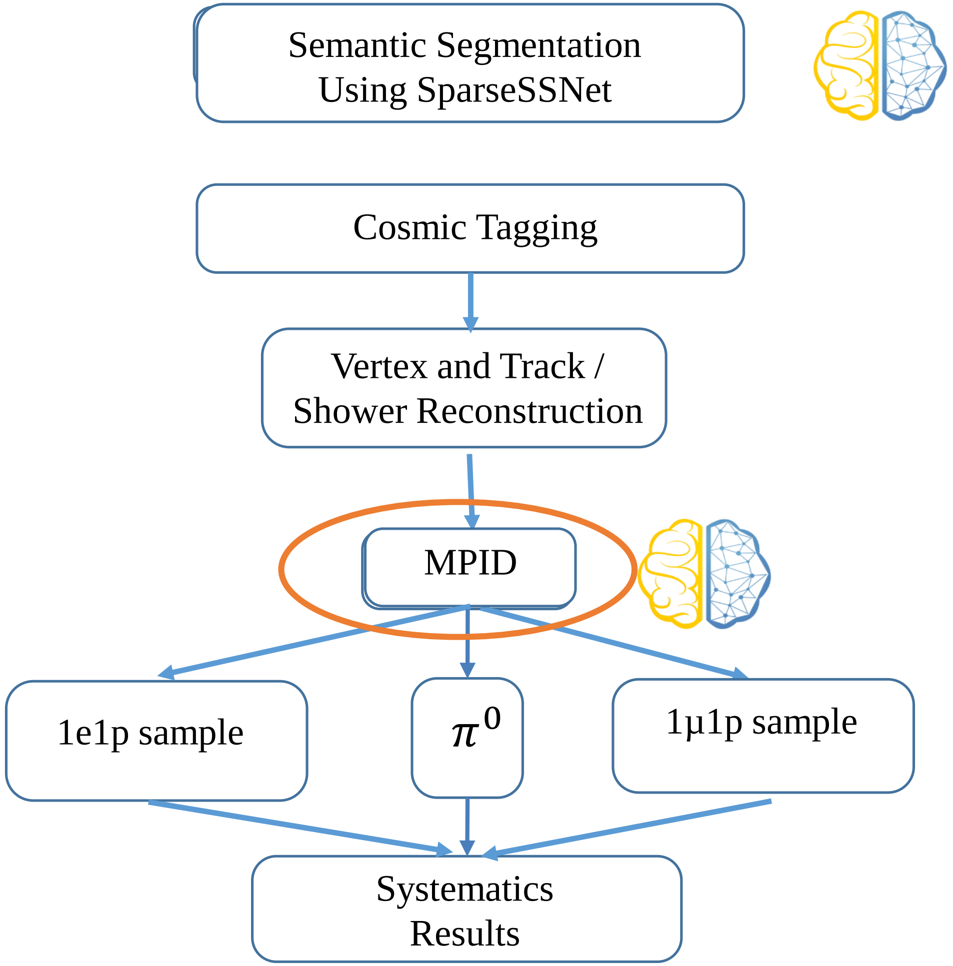


The DL Analysis

Identify particle content

Before





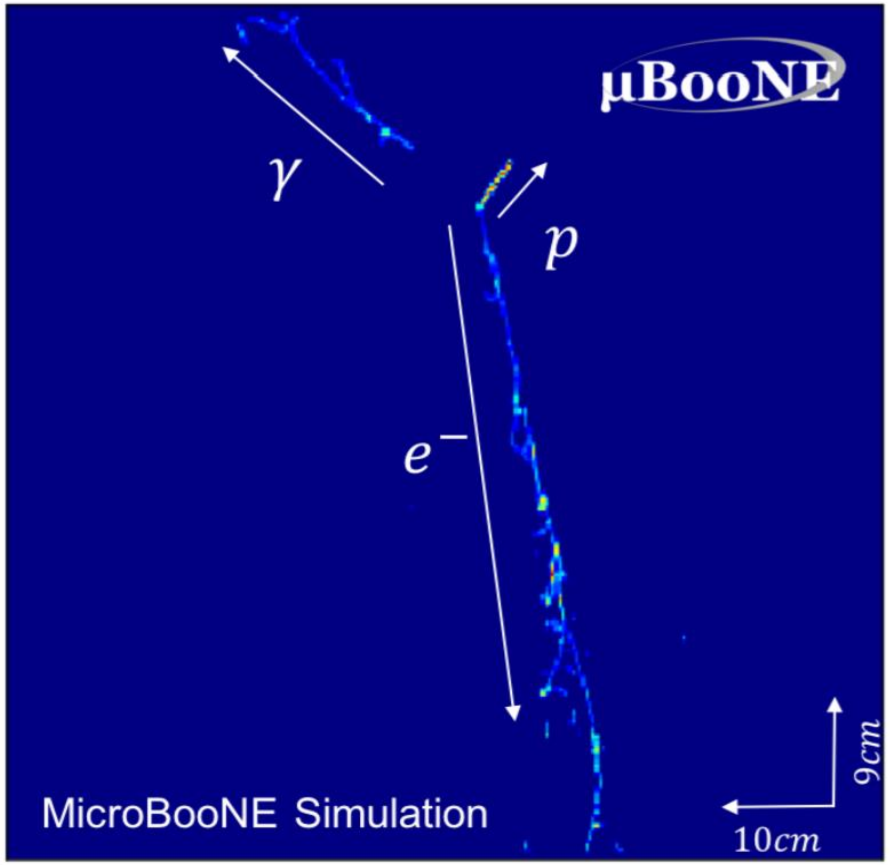
10.1103/PhysRevD.103.092003

After

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

The DL Analysis

- Multiple Particle IDentification
- Image based identification CNN
- For each event gives 5 scores (p, e, γ, μ, π)



	p	e^-	γ	μ^-	$\pi^\pm$
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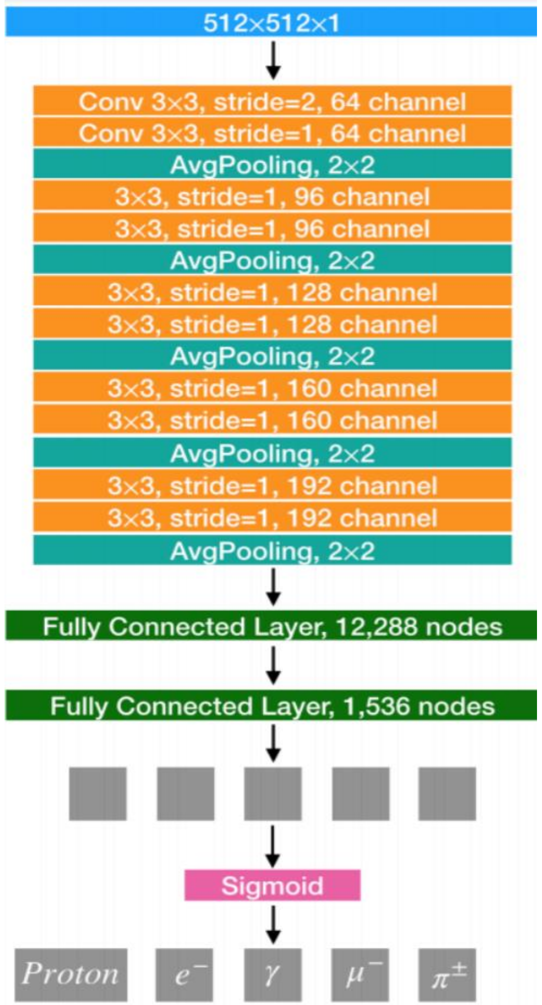
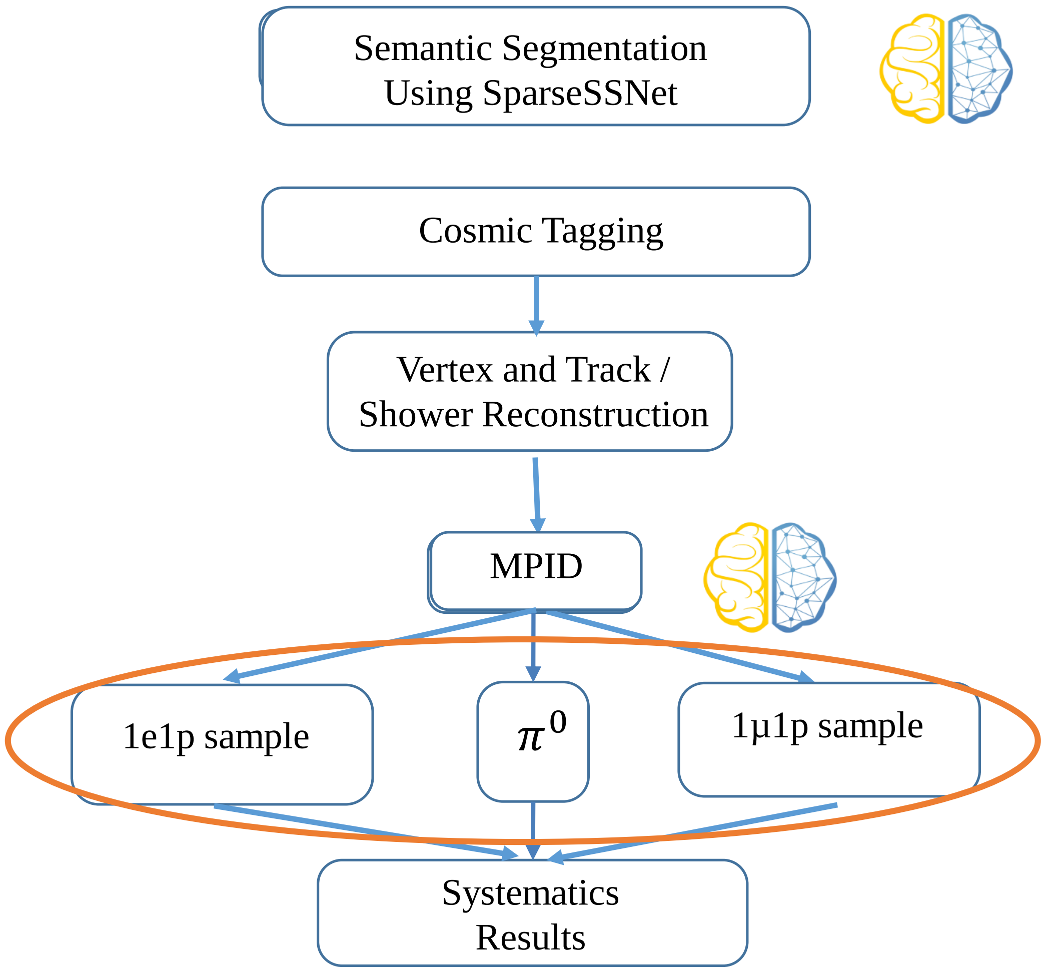


The DL Analysis

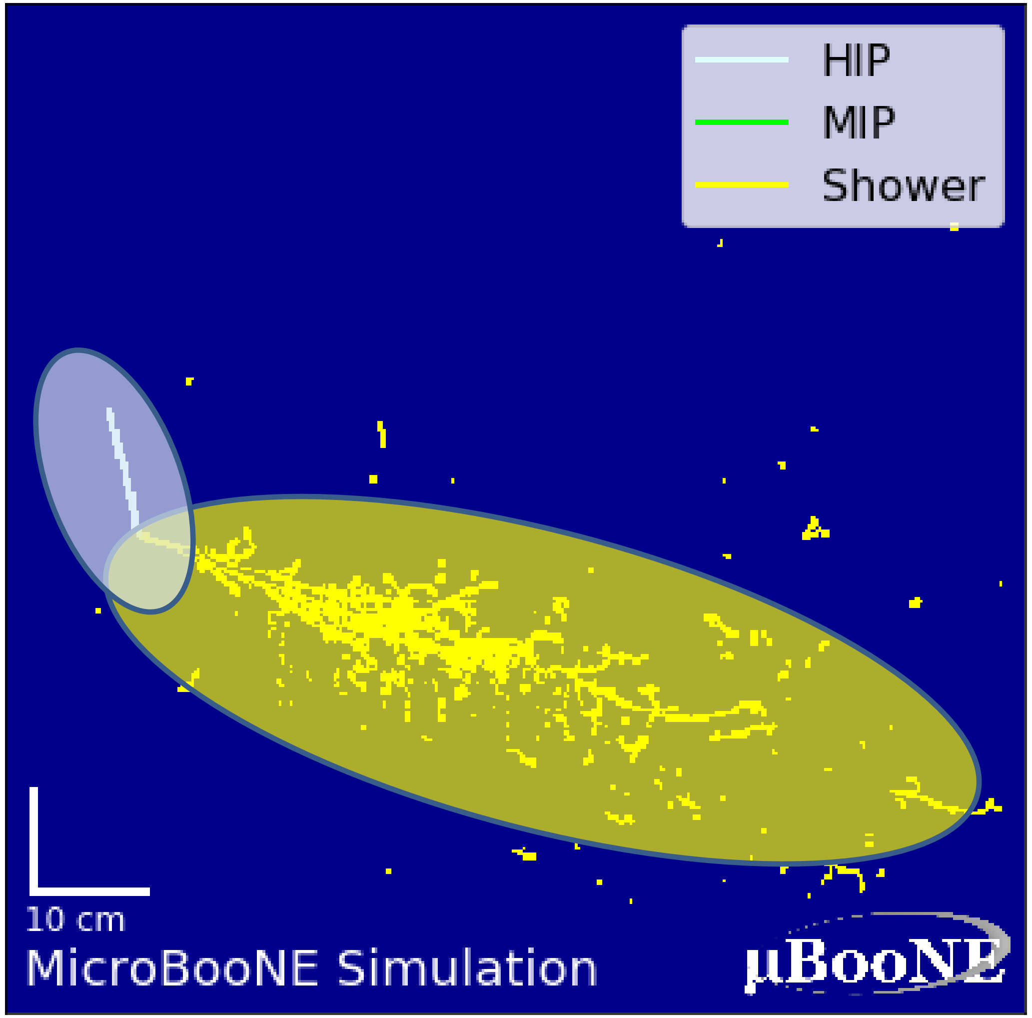
Knowledge about particle content and clusters

Divide into the various samples



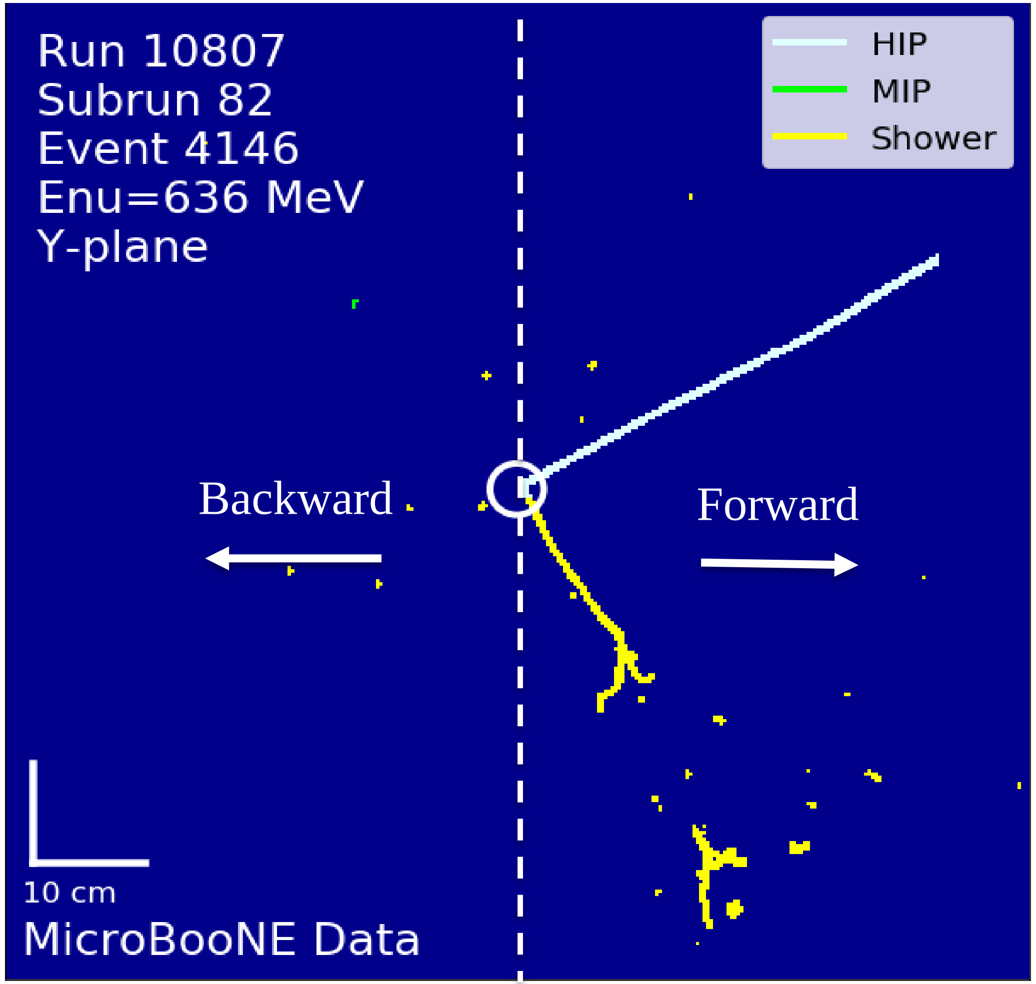
The DL Analysis

- **Orthogonality Cut (1e1p or 1μ1p candidates)**
  Shower fraction in most shower-like cluster.
  - **> 0.2 → $1e1p$ candidate.**
  - **<= 0.2 → $1\mu1p$ candidate.**



The DL Analysis

- Broad data quality selection.
  - E.g., forward going proton
- Variation of "Random BDT Forest" taking the average score. Reduces bias and variation. Especially important for low statistics event samples.
  - 19 kinematic variables (e.g., QE consistency)
  - 4 ionization variables (e.g., shower labeled pixel fraction)
- Particle content criteria.
  - MPID
  - π^0rejection



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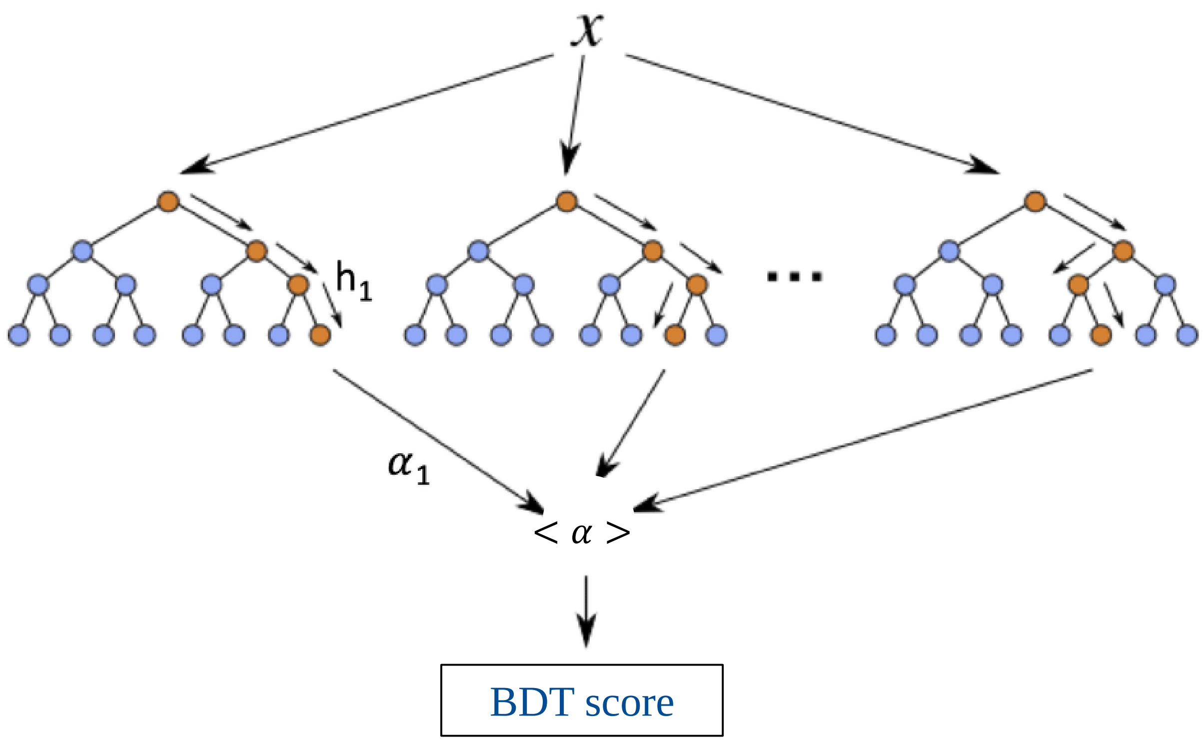

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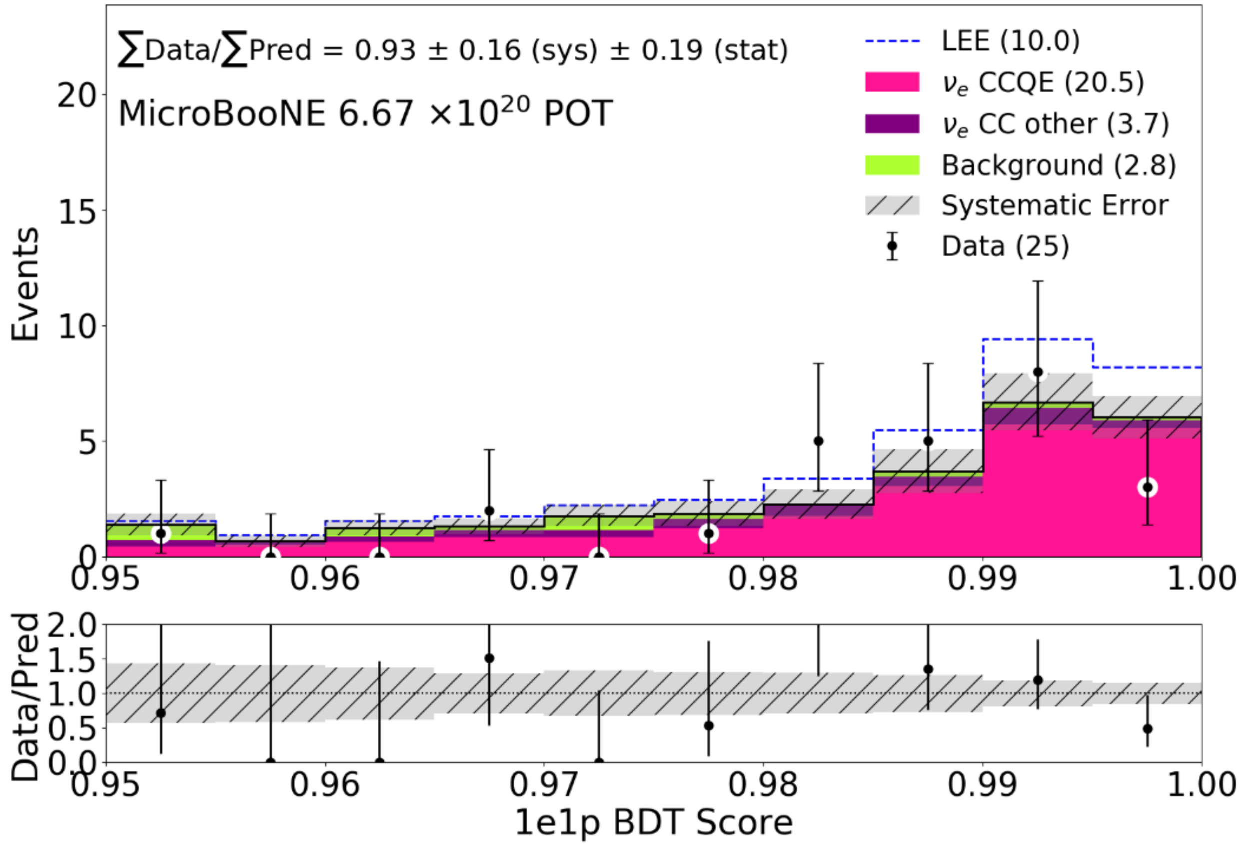
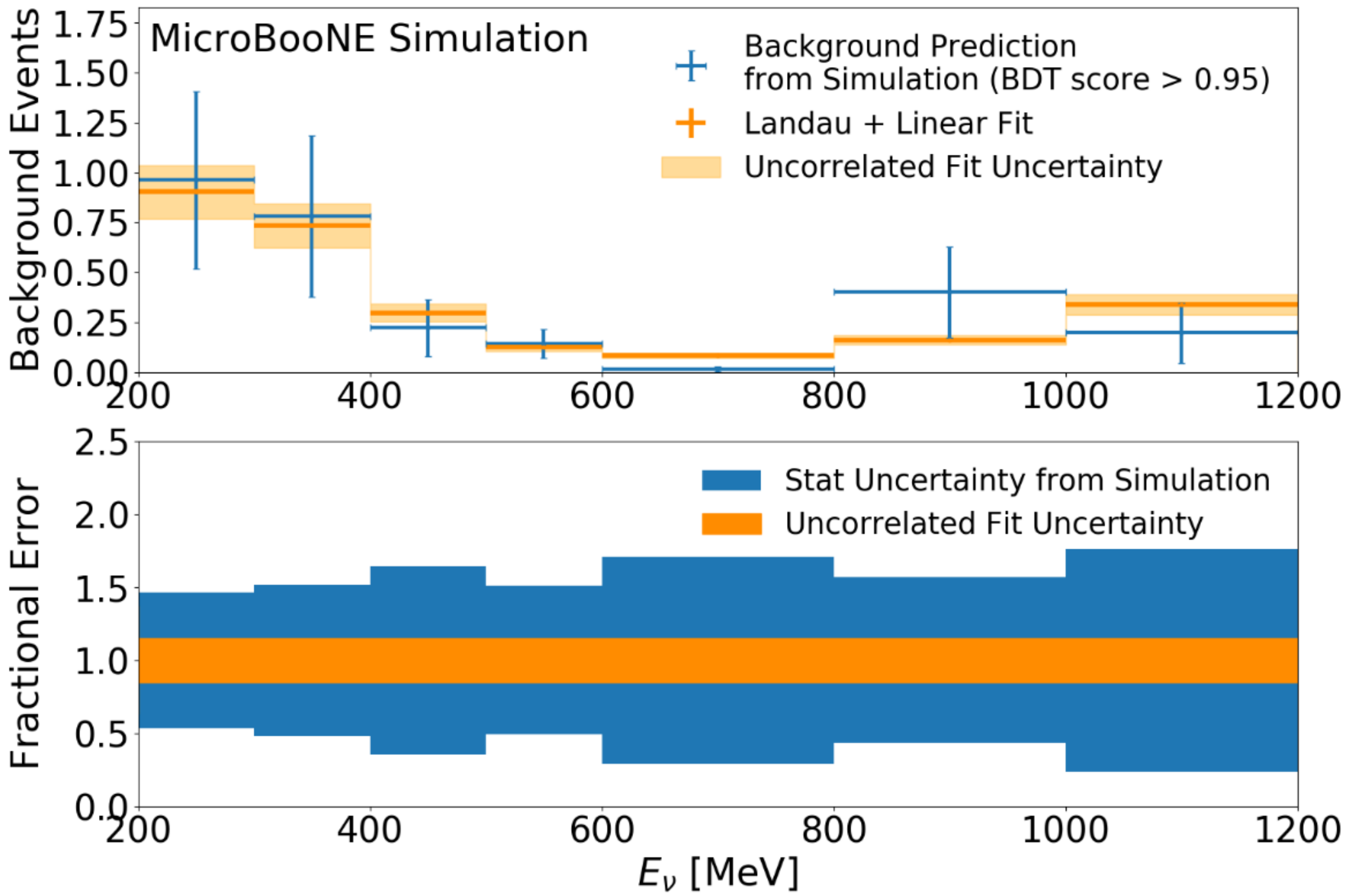


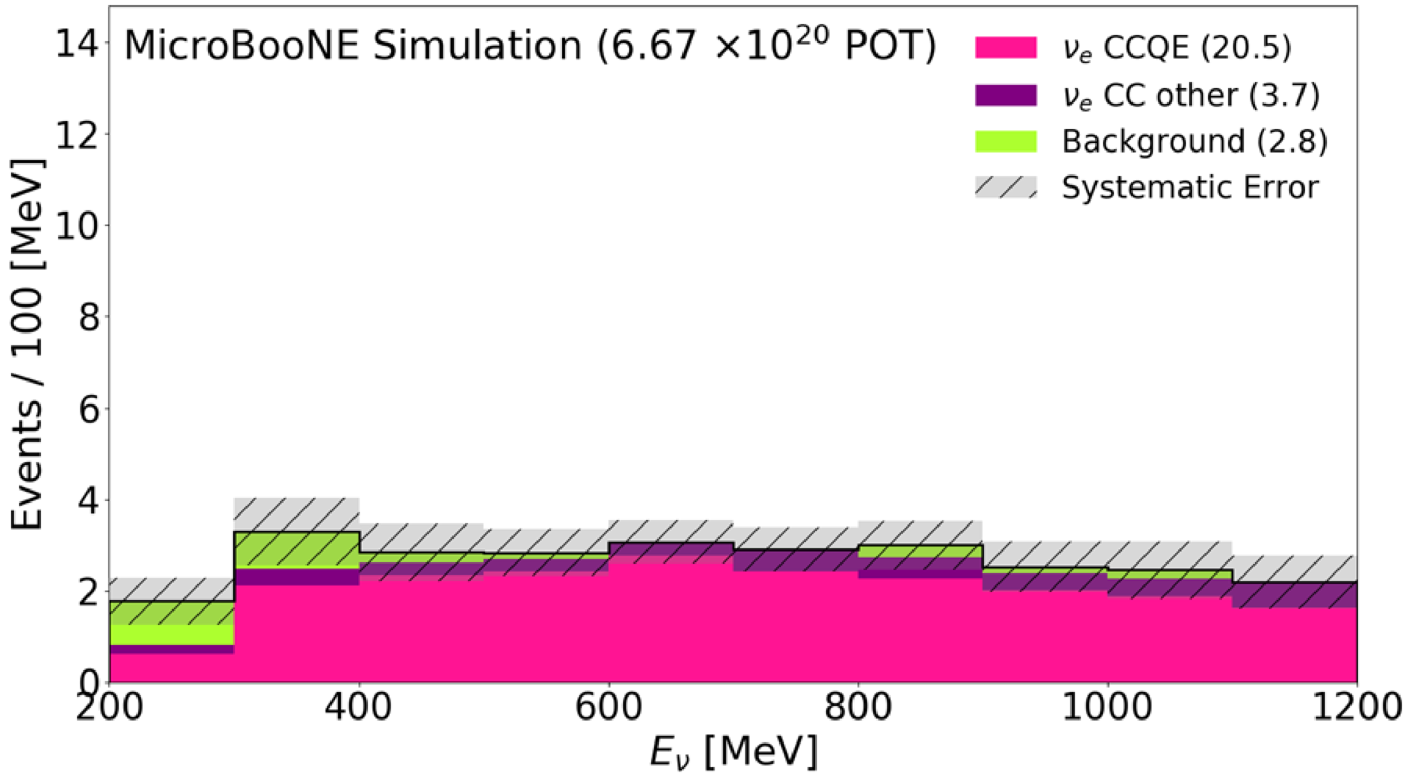
The DL Analysis

- The selected background ν_μ simulation sample suffers from low statistics.
- We use an empirical fit to the simulation and produce background predictions (reducing uncertainties from MC size)



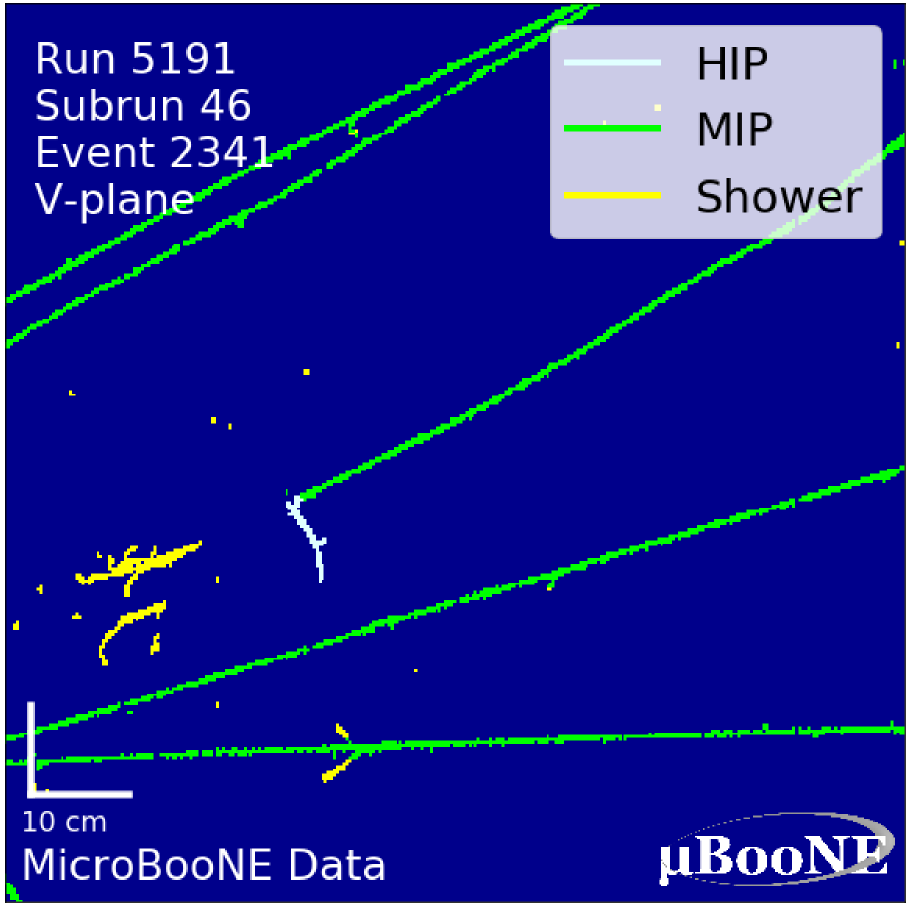
The DL Analysis

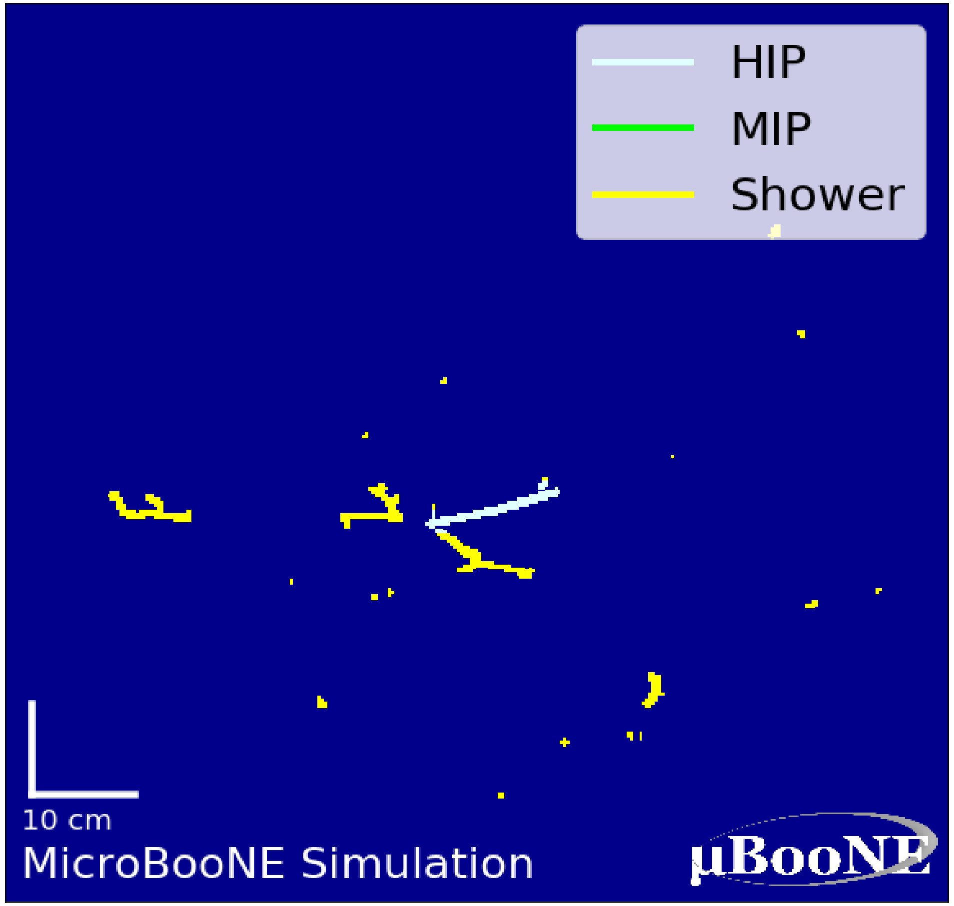
- Final selection (MC)
  - Purity - 75% (all CCQE events)
  - Efficiency – 6.6% (all CCQE events)
- Compromising efficiency for high purity.



The DL Analysis

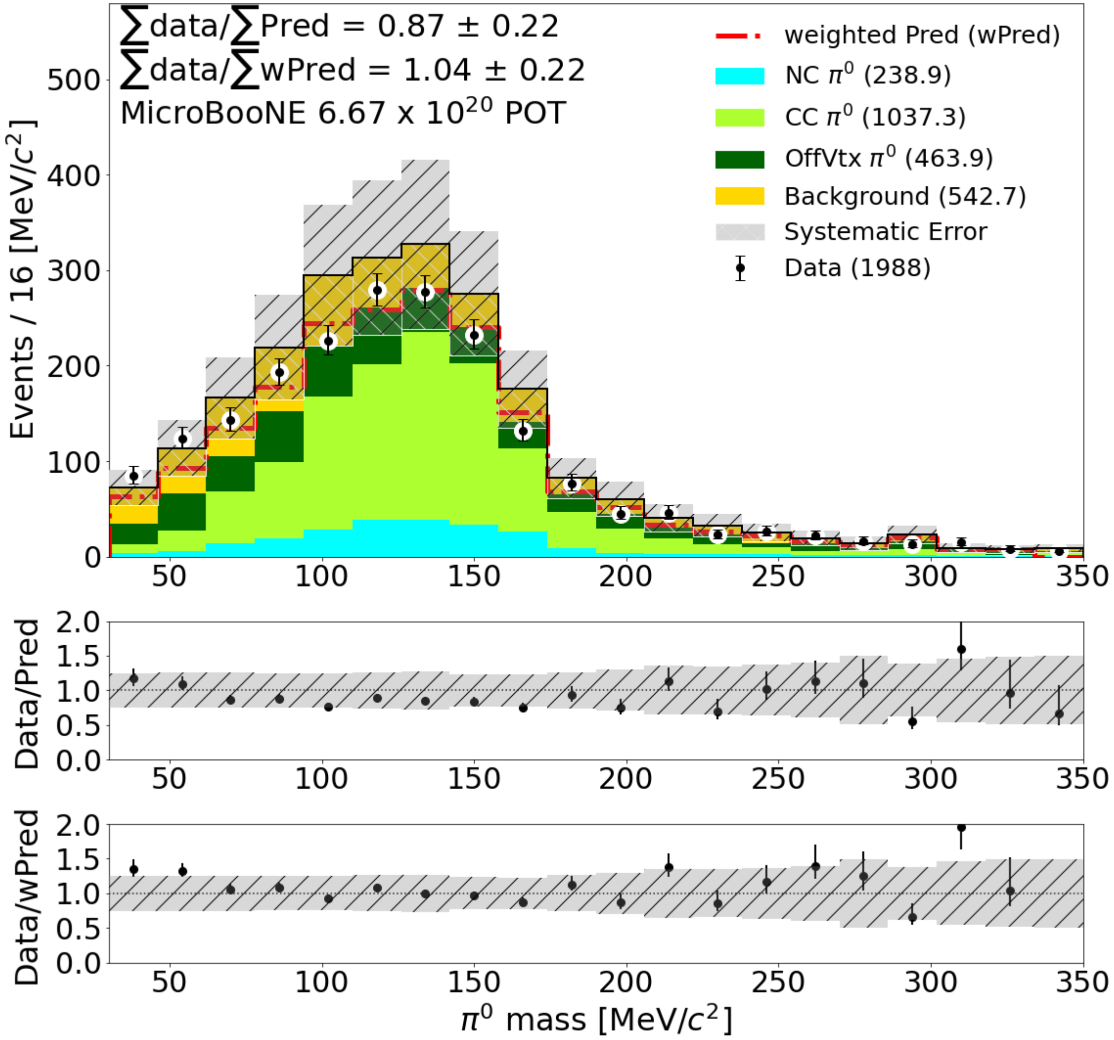
- We use dedicated π^0samples to measure our dominant background.





The DL Analysis

- A small (within systematic) deficit is obsereved.
- We use a data-driven method to re-weight the MC.
- All simulations with π^0at the final state, are then re-scaled (for the 1e1p and 1μ1p)
- Also serves as a standard candle for our reconstruction.

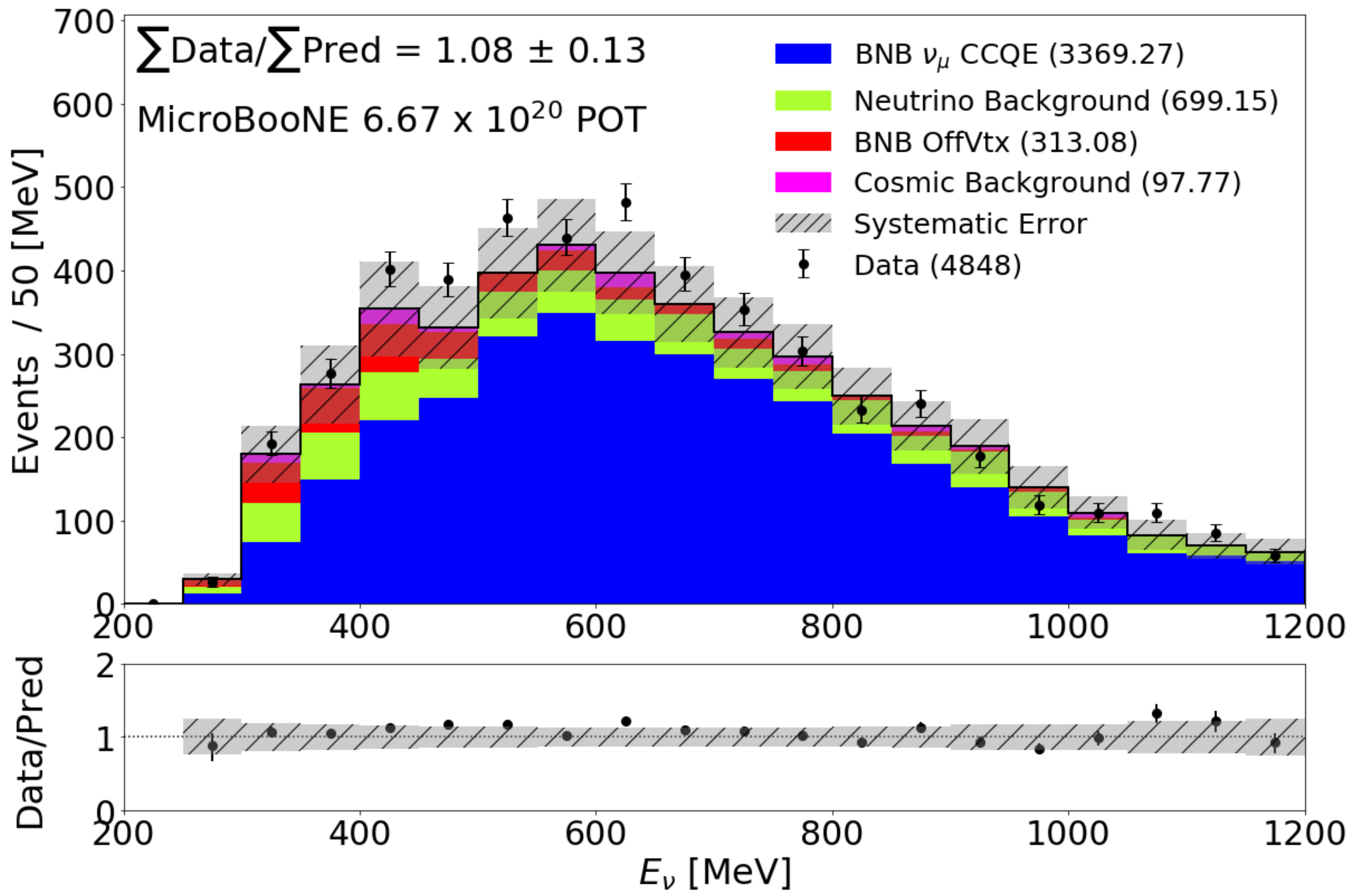


arXiv: 2110.11874

The DL Analysis

We use the $1\mu1p$ sample to constrain.

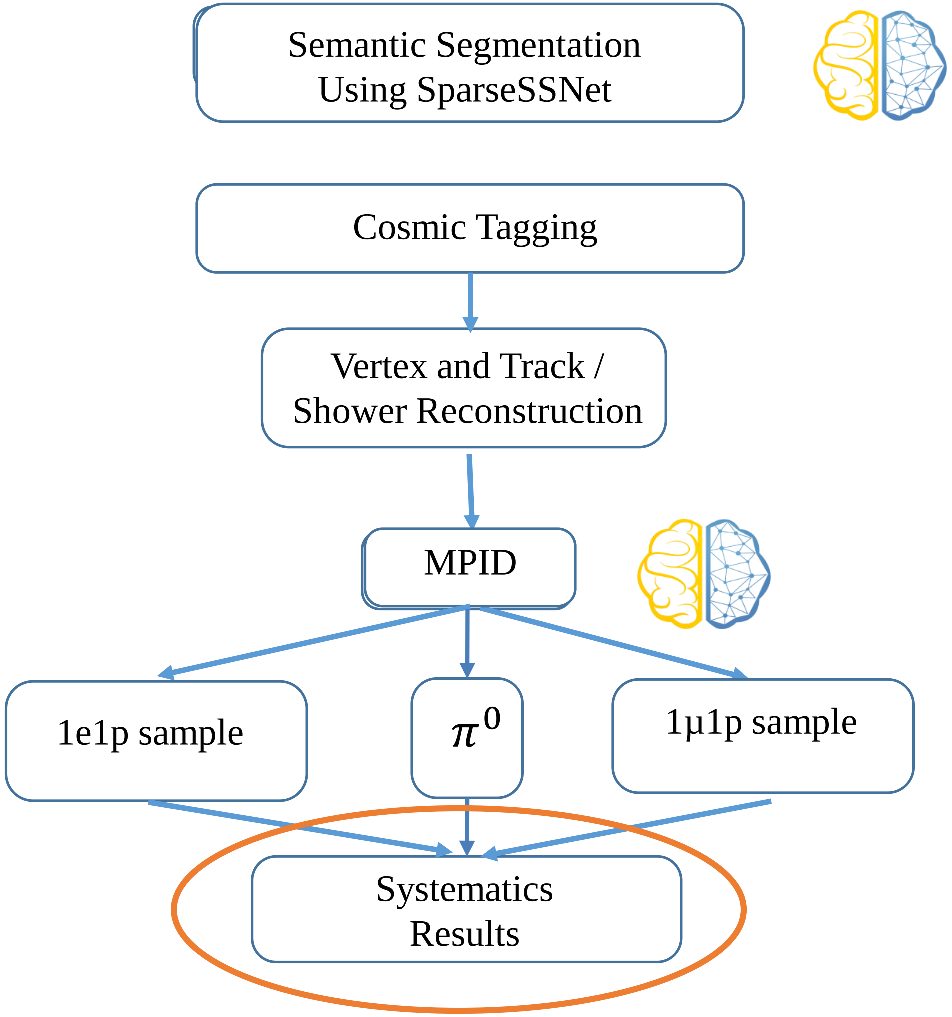
- Broad data quality selections
- Variation of "Random BDT Forest" taking the average score.
- MPID proton score > 0.9 – rejecting cosmic rays
- Final selection:
  - Purity of 77.3% (all CCQE events)
  - Efficiency of 4.3% (all CCQE events)



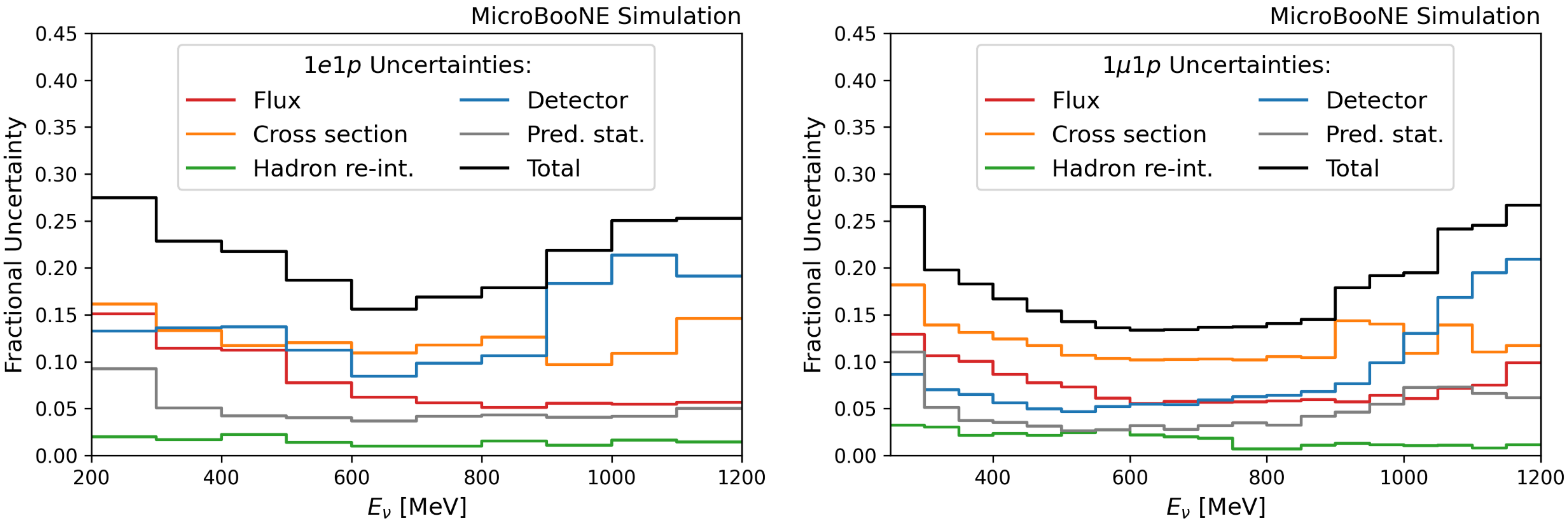
The DL Analysis

All Information is there

Get Results

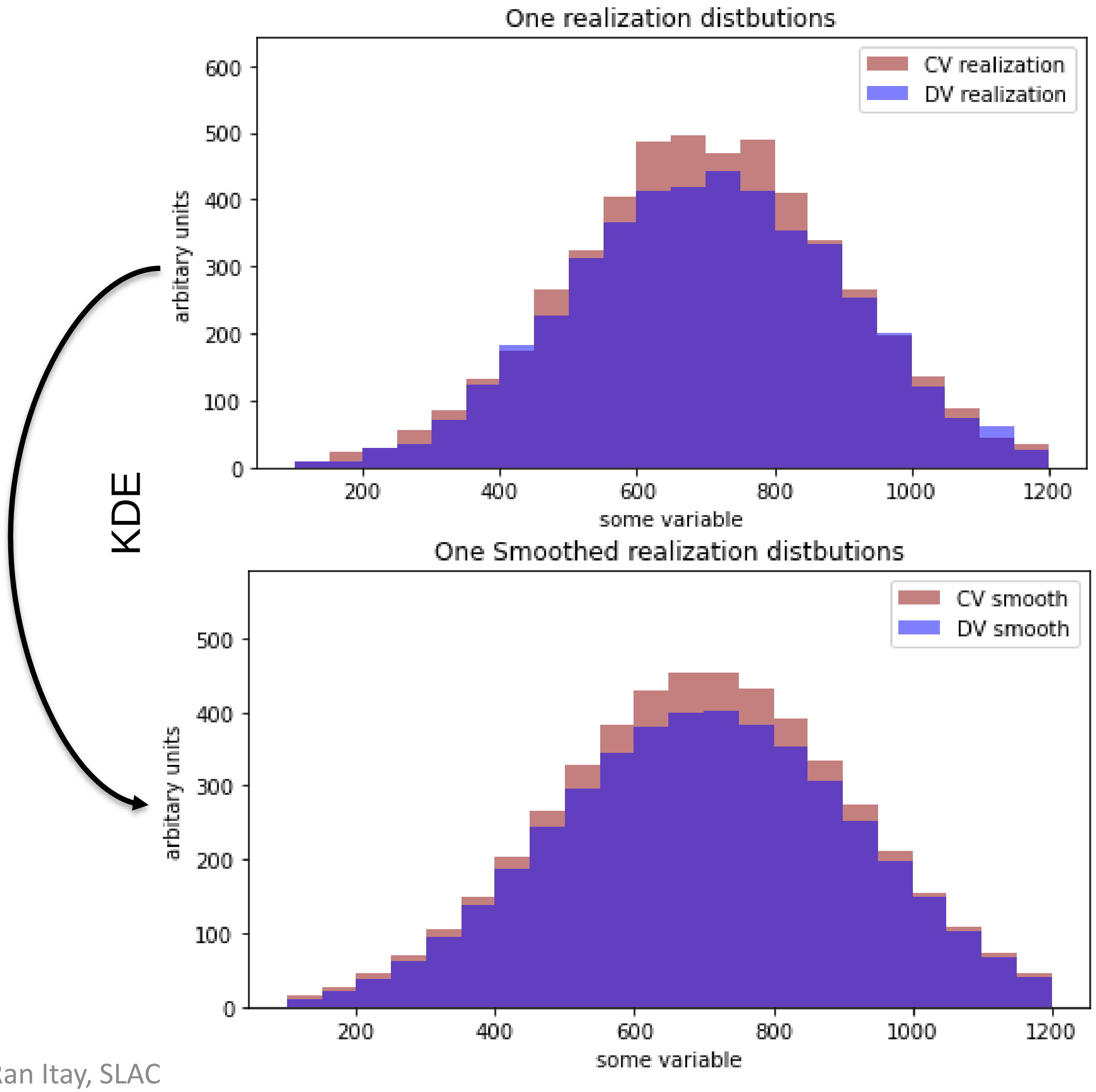


The DL Analysis



The DL Analysis

- Detector systematic uncertaies are evaluated by comparing the detector variation to the central value MC [MicroBooNE Pub-note 1075]
- Detector systematics MC samples suffer from large statistical fluctuations.
- We mitigate that by smoothing the MC spectra using a **KDE** algorithm



The DL Analysis

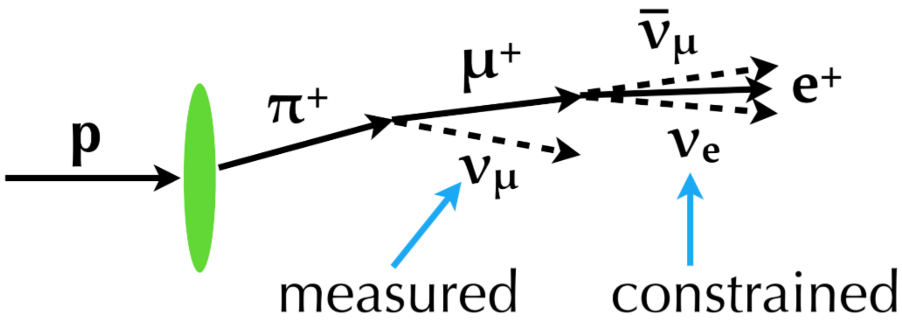
- Applying the constraint procedure gives the final systematic uncertainty budget.
- Allows comparison to data and not to GENIE model

$$\Sigma = \begin{pmatrix} \Sigma^{ee} \Sigma^{e\mu} \\ \Sigma^{\mu e} \Sigma^{\mu\mu} \end{pmatrix}$$

$$\mu^{e,\text{ constr.}} = \mu^{e} + \Sigma^{e\mu} \left(\Sigma^{\mu\mu}\right)^{-1} \left(x^{\mu} - \mu^{\mu}\right)$$

$$\Sigma^{ee,\text{ constr.}} = \Sigma^{ee} - \Sigma^{e\mu} \left(\Sigma^{\mu\mu}\right)^{-1} \Sigma^{\mu e}$$

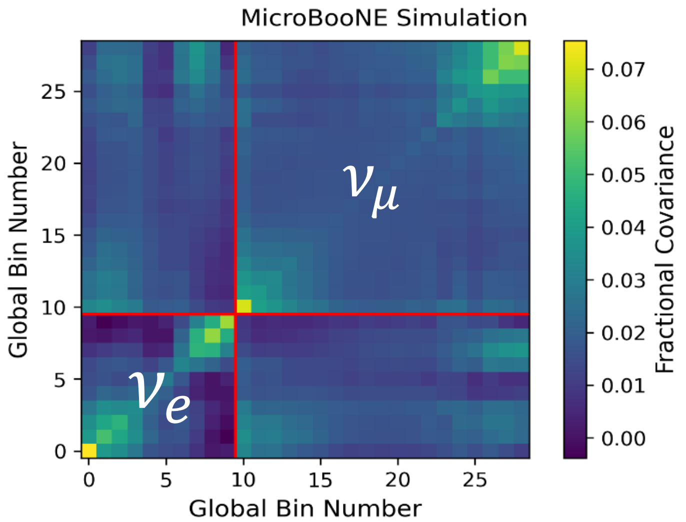
where x^{μ} is the 1μ1p observation,
and μ^{μ} (μ^{e}) is the 1μ1p (1e1p) prediction

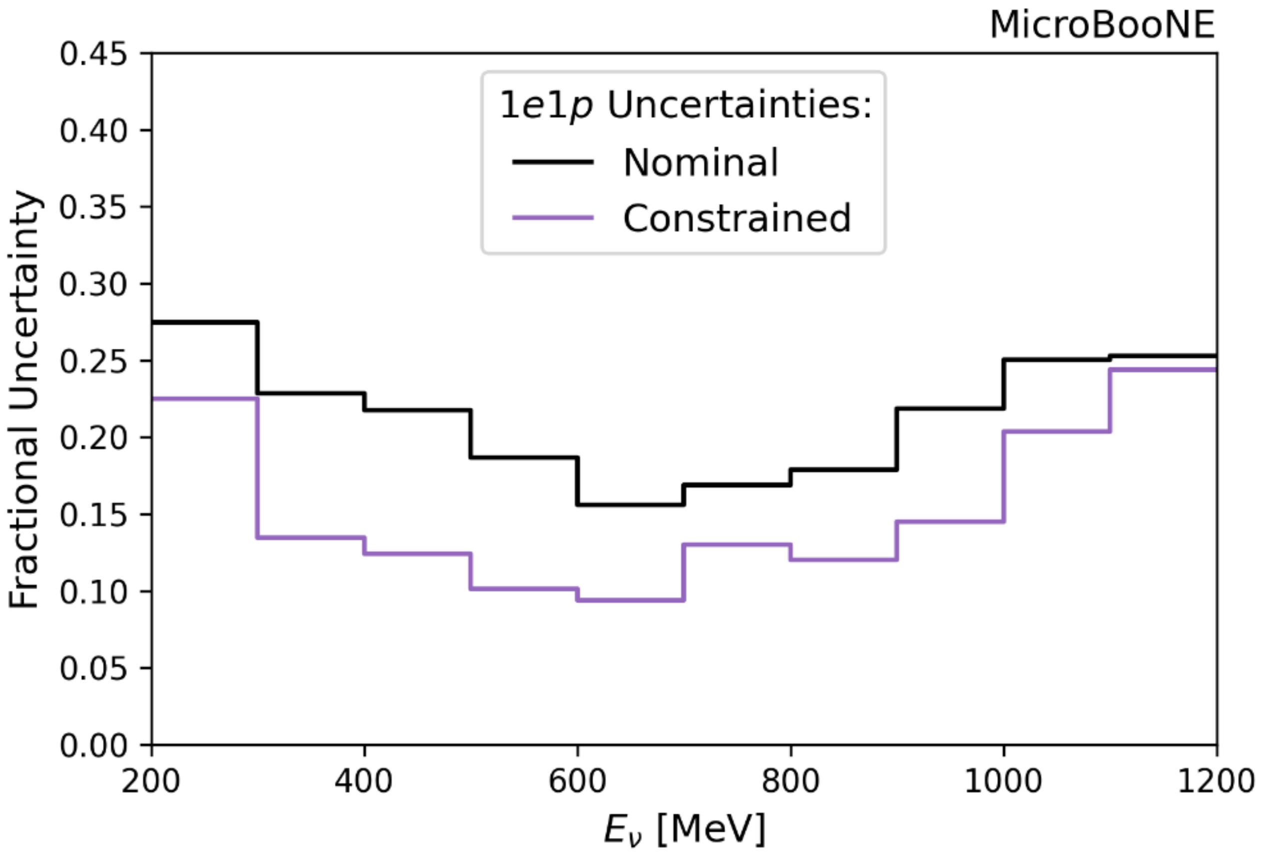


The DL Analysis

- Applying the constraint procedure gives the final systematic uncertainty budget.

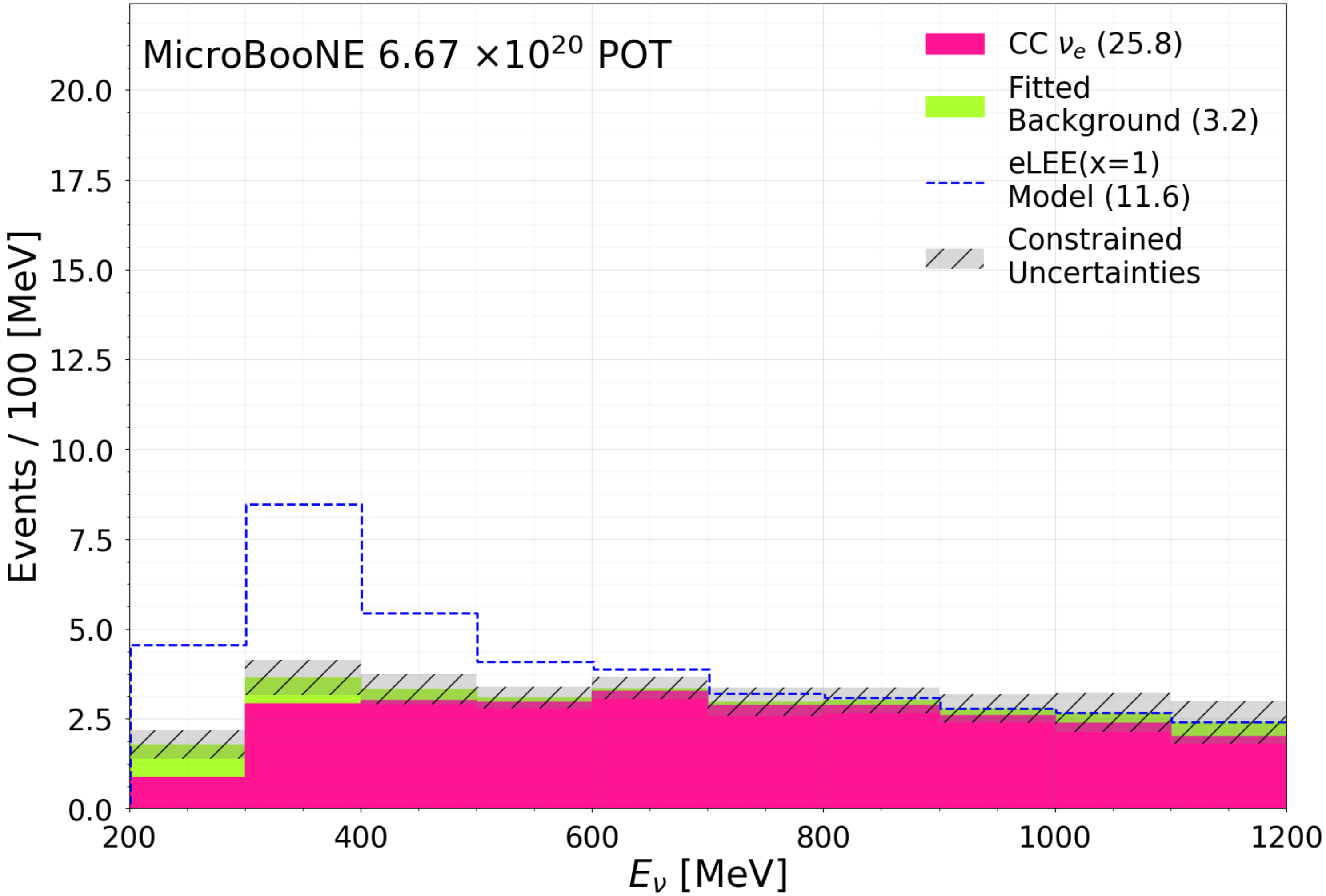
- Notice constraint results in reduction of systematic uncertainty.



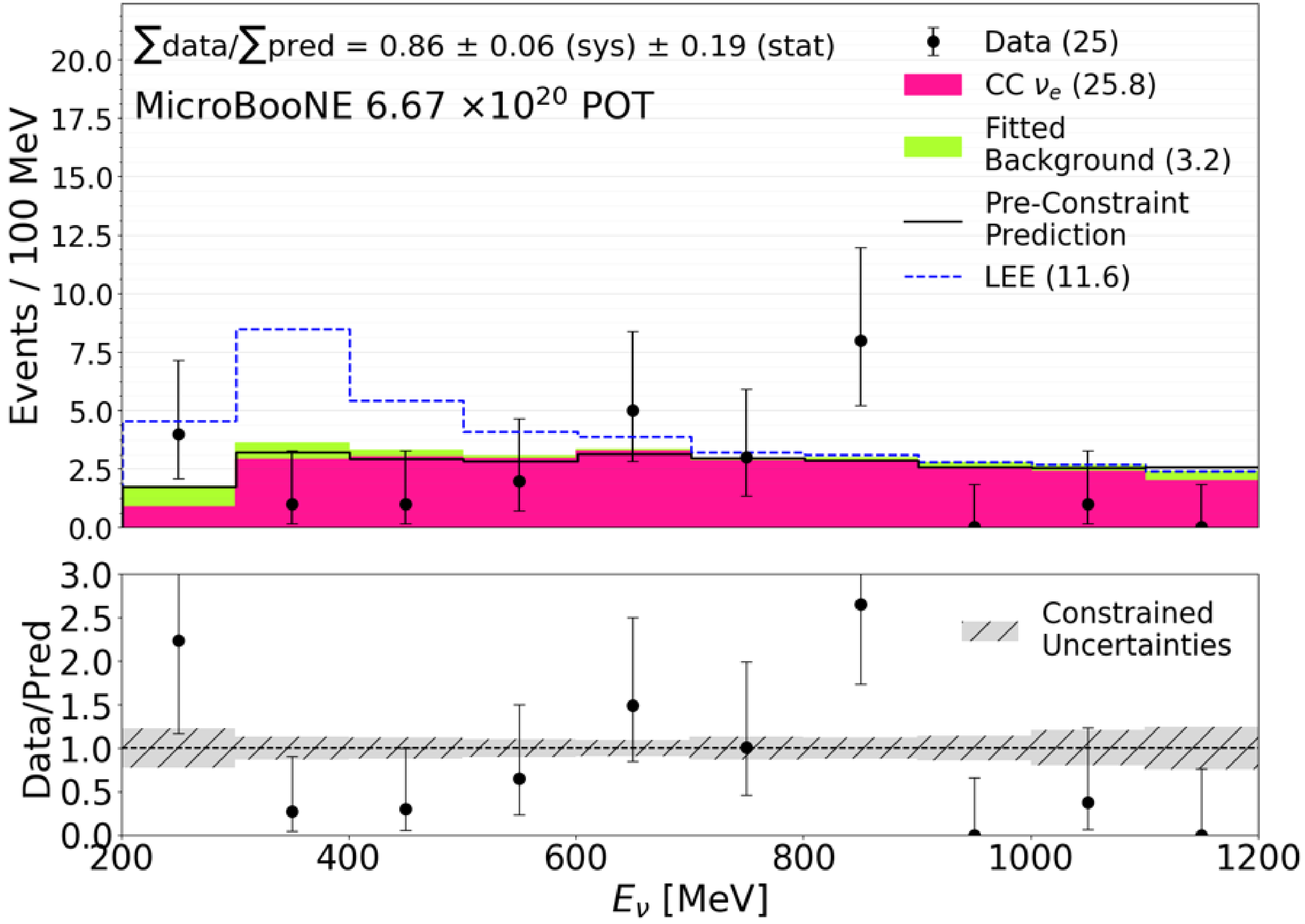


Results

Results


MicroBooNE 6.67 ×10^20 POT
CC ν_e (25.8)
Fitted Background (3.2)
eLEE(x=1) Model (11.6)
Constrained Uncertainties
Events / 100 [MeV]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
200
400
600
800
1000
1200
E_ν [MeV]

Results


∑data/∑pred = 0.86 ± 0.06 (sys) ± 0.19 (stat)
MicroBooNE 6.67 ×10^20 POT
Data (25)
CC ν_e (25.8)
Fitted Background (3.2)
Pre-Constraint Prediction
LEE (11.6)
Events / 100 MeV
Constrained Uncertainties
Data/Pred
E_ν [MeV]

Results

First looking at the data to MC agreement

- H_0 – MB=0
- H_1 – MB=1

- 200-1200 – full analysis range
- 200-500 – LEE enhanced range

- P-value are calculated using **frequentist** approach

Nominal Predictions

Range	H_0		H_1	
	$\chi^2_{\mathrm{CNP}}/\mathrm{dof}$	p-value	$\chi^2_{\mathrm{CNP}}/\mathrm{dof}$	p-value
200–500 MeV	6.06/3	0.138	8.30/3	0.053
200–1200 MeV	23.02/10	0.024	25.37/10	0.014

Constrained Predictions

Range	H_0		H_1	
	$\chi^2_{\mathrm{CNP}}/\mathrm{dof}$	p-value	$\chi^2_{\mathrm{CNP}}/\mathrm{dof}$	p-value
200–500 MeV	7.91/3	0.075	17.3/3	0.002
200–1200 MeV	25.28/10	0.014	36.35/10	5.0×10^{-4}

Results

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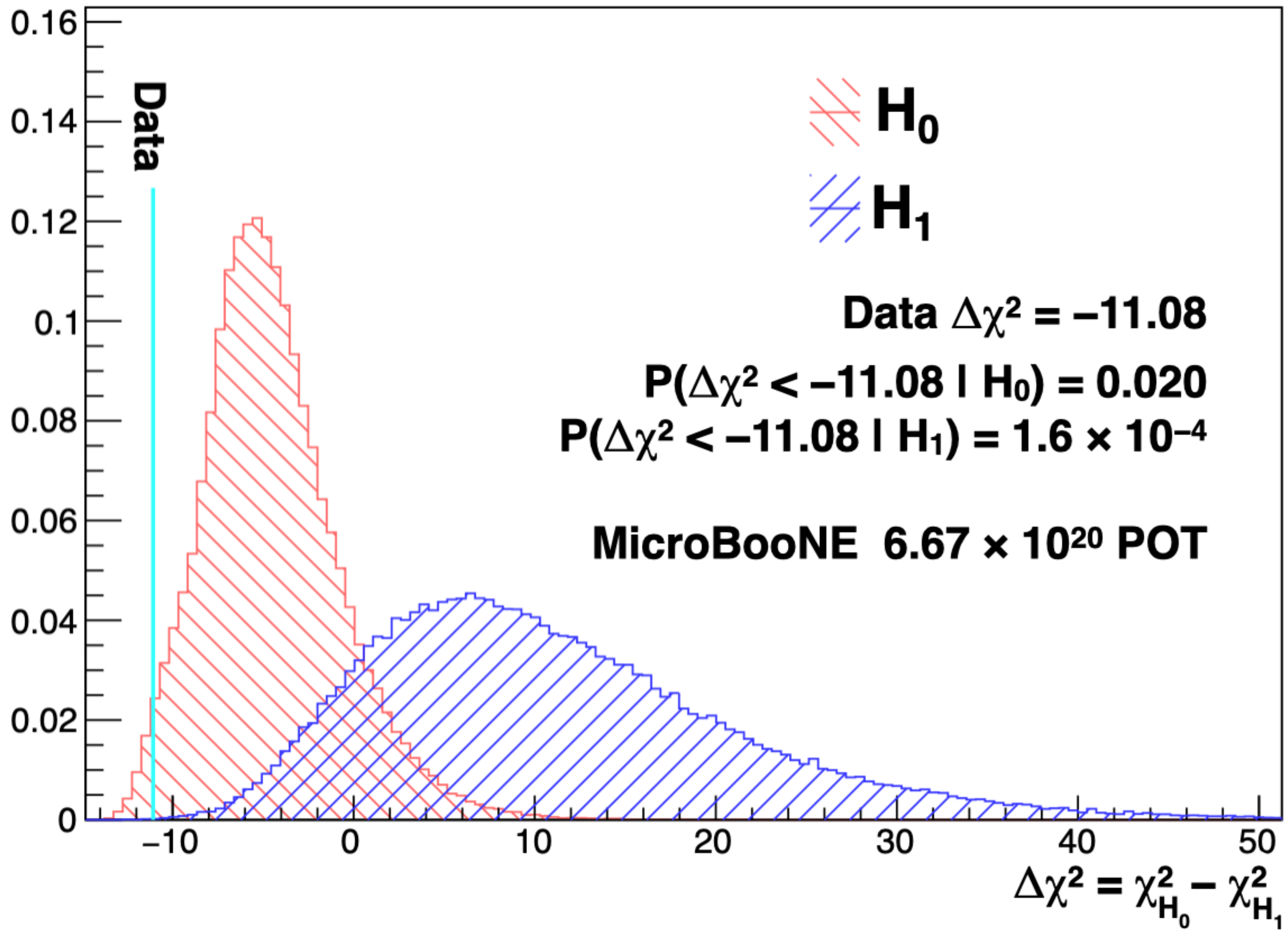
Results

Second Comparing the two hypothesis using a $\Delta\chi^2$ formalisem

- H_0 – LEE (x=0)
- H_1 – LEE (x=1)

- Rejecting H_1 with **3.6σ**
- Using **CLs** to mitigate under-fluctuation results in a reduced significance of **2.4σ**

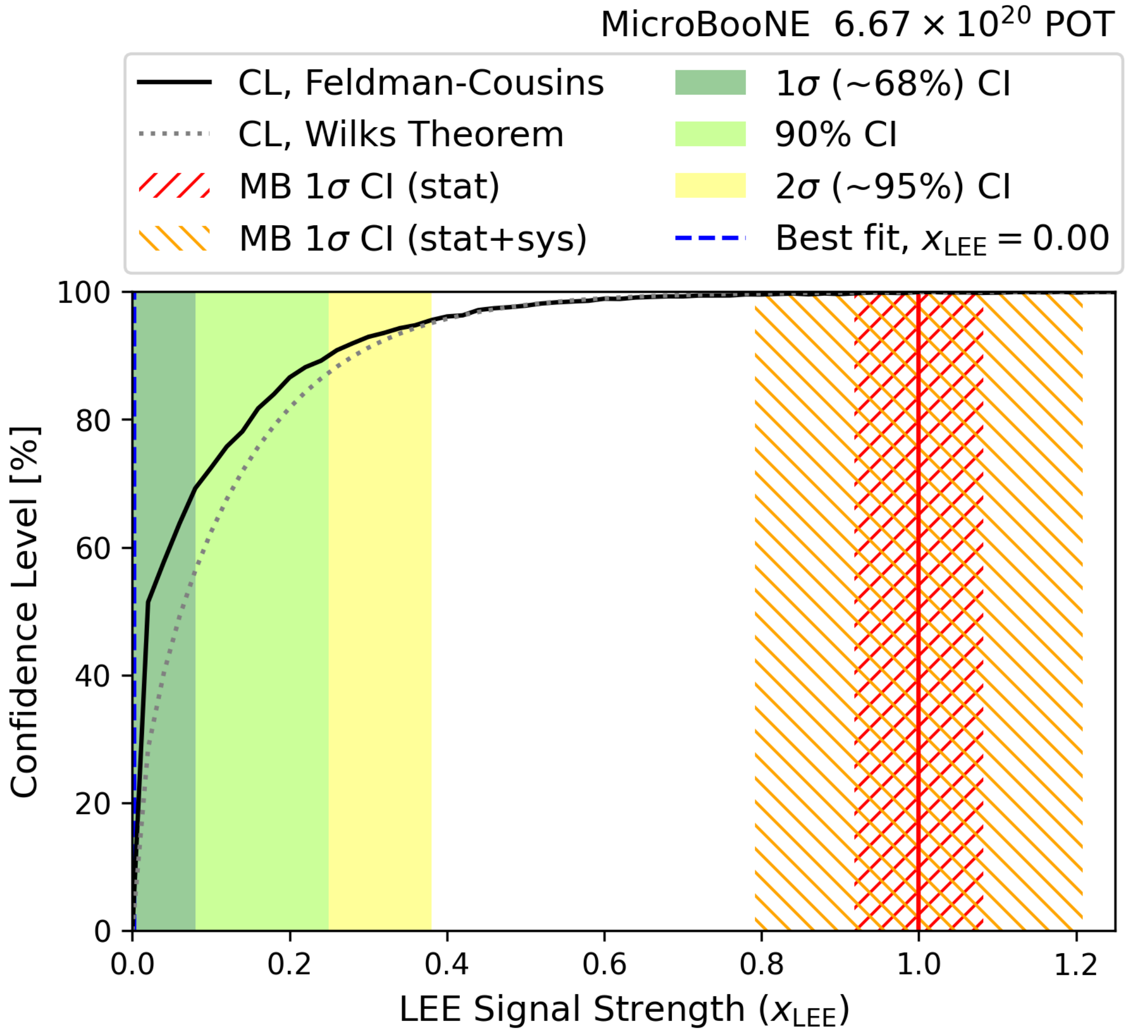


Results

Finally, signal strength.

- Best fit LEE(x=0)
- We reject LEE(x=0.25) with 90% C.L.

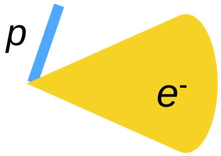
In conclusion, the analysis reported in this paper is inconsistent with observation of an excess of ν_e events in the signal range. Hence, these results disfavor explanations of the MiniBooNE low energy excess based purely on ν_e interactions.



Results

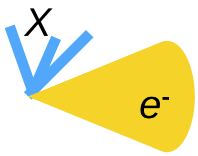
Three independent searches across multiple single electron final states

- Exclusive two-body charged-current quasi-elastic (CCQE) ν_e scattering [1e1p]

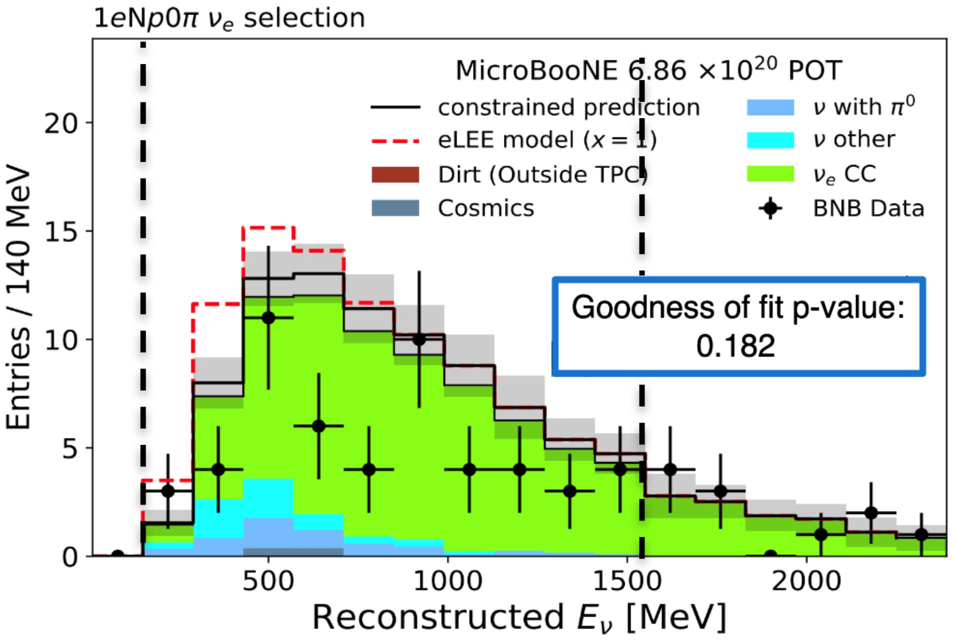


- Semi-inclusive ν_e scattering without final state pions [1eNp0π (N≥1) + 1e0p0π]

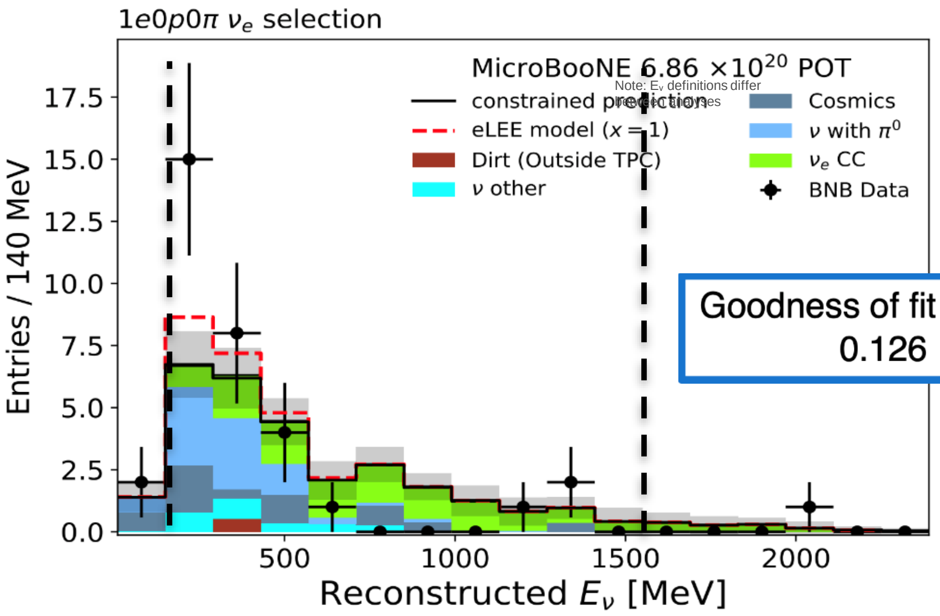
- Inclusive ν_e scattering [1eX]



Results



Goodness of fit p-value: 0.182



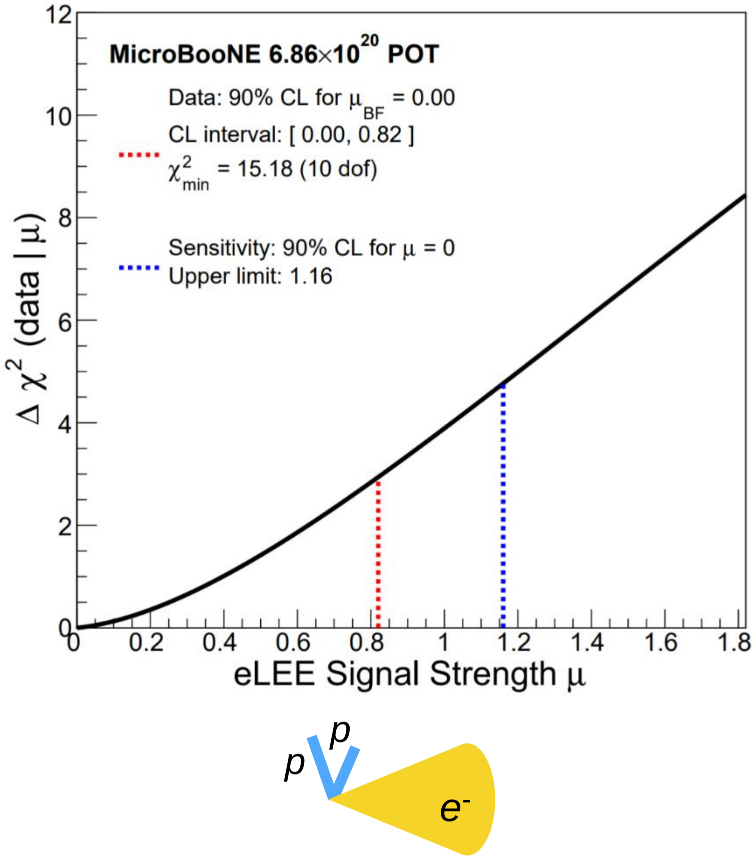
Goodness of fit p-value: 0.126

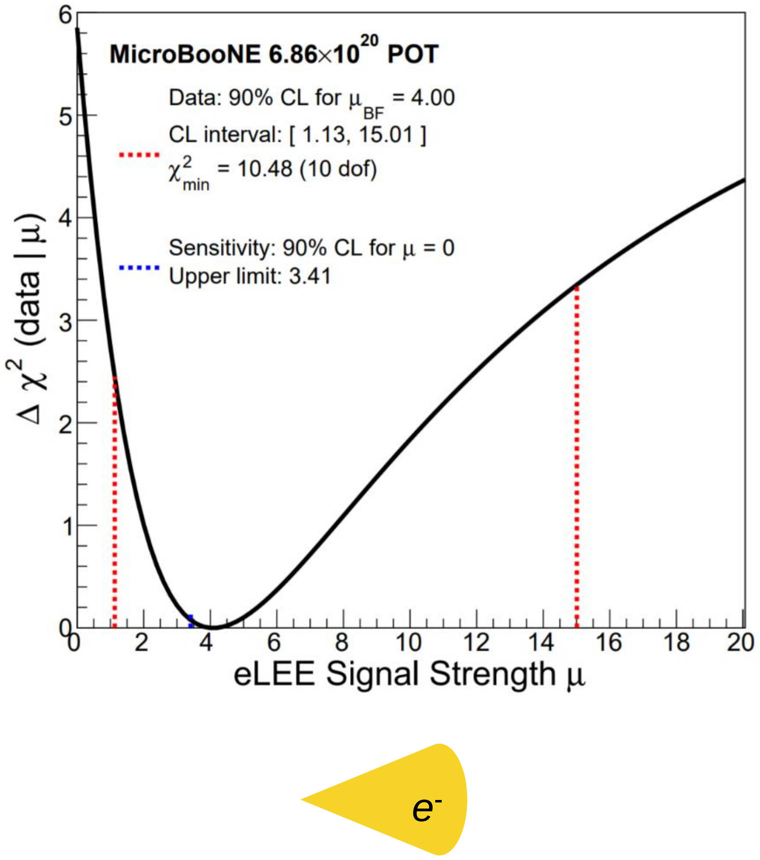
Combined p-value: 0.098

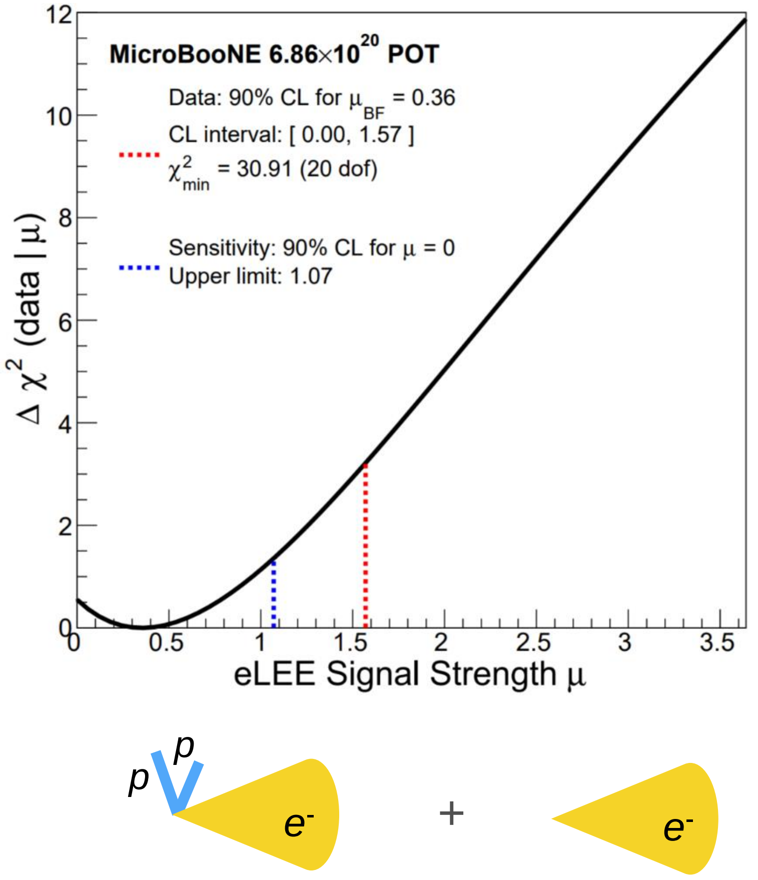
Excludes eLEE model at 97.9% level

Low sensitivity, prefers eLEE model over nominal ν_e model

Results


MicroBooNE 6.86×10^20 POT
Data: 90% CL for μ_BF = 0.00
CL interval: [0.00, 0.82]
χ²_min = 15.18 (10 dof)
Sensitivity: 90% CL for μ = 0
Upper limit: 1.16
Δ χ² (data | μ)
eLEE Signal Strength μ
p
p
e-

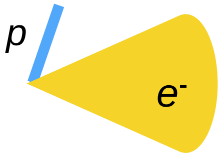

MicroBooNE 6.86×10^20 POT
Data: 90% CL for μ_BF = 4.00
CL interval: [1.13, 15.01]
χ²_min = 10.48 (10 dof)
Sensitivity: 90% CL for μ = 0
Upper limit: 3.41
Δ χ² (data | μ)
eLEE Signal Strength μ
e-


MicroBooNE 6.86×10^20 POT
Data: 90% CL for μ_BF = 0.36
CL interval: [0.00, 1.57]
χ²_min = 30.91 (20 dof)
Sensitivity: 90% CL for μ = 0
Upper limit: 1.07
Δ χ² (data | μ)
eLEE Signal Strength μ
p
p
e-
+
e-

Results

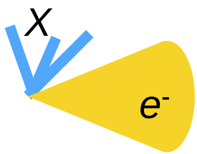
Three independent searches across multiple single electron final states

- Exclusive two-body charged-current quasi-elastic (CCQE) ν_e scattering [1e1p]

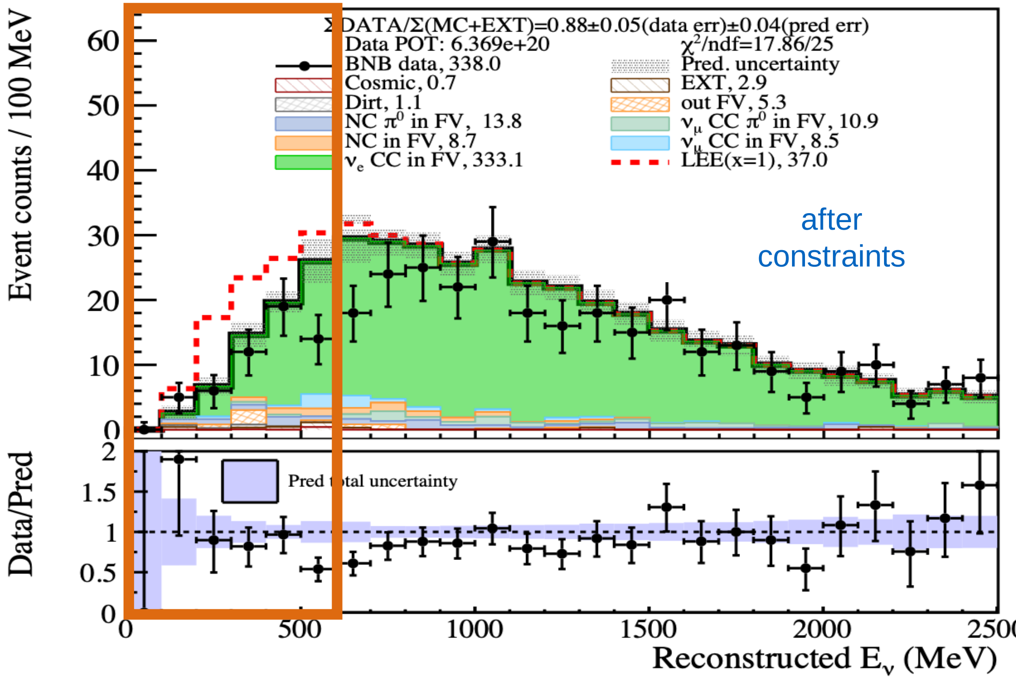


- Semi-inclusive ν_e scattering without final state pions [1eNp0π (N≥1) + 1e0p0π]

- Inclusive ν_e scattering [1eX]



Results



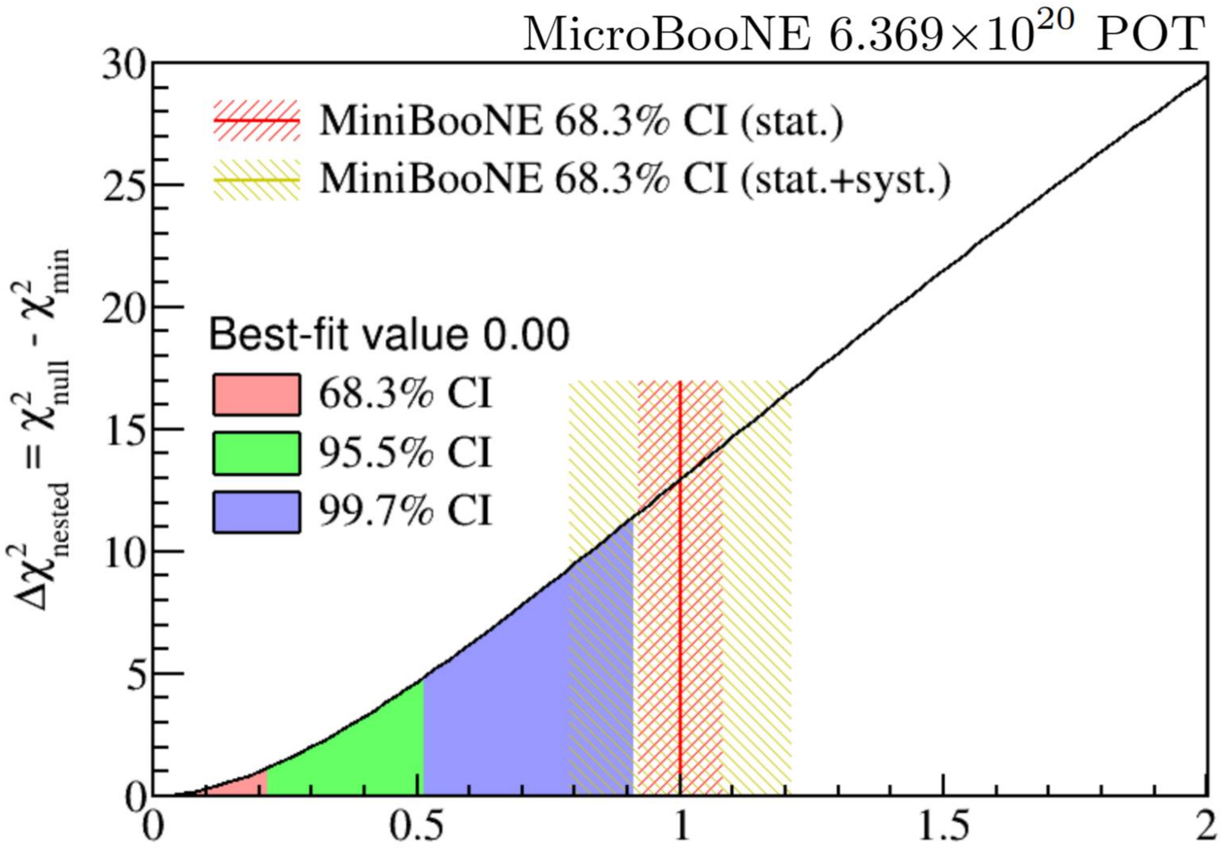
χ^2/ndf, $\mathrm{eLEE}_{x=0}$		
Energy region	w/o constr.	w/ constr.
(0, 2500) MeV	12.55/25 $p_{\mathrm{val}} = 0.982$	17.86/25 $p_{\mathrm{val}} = 0.848$
(0, 600) MeV	4.25/6 $p_{\mathrm{val}} = 0.643$	5.78/6 $p_{\mathrm{val}} = 0.448$
χ^2/ndf, $\mathrm{eLEE}_{x=1}$		
Energy region	w/o constr.	w/ constr.
(0, 2500) MeV	13.02/25 $p_{\mathrm{val}} = 0.976$	28.24/25 $p_{\mathrm{val}} = 0.297$
(0, 600) MeV	4.23/6 $p_{\mathrm{val}} = 0.646$	15.73/6 $p_{\mathrm{val}} = 0.015$

Inclusive ν_e scattering [1eX]

Results

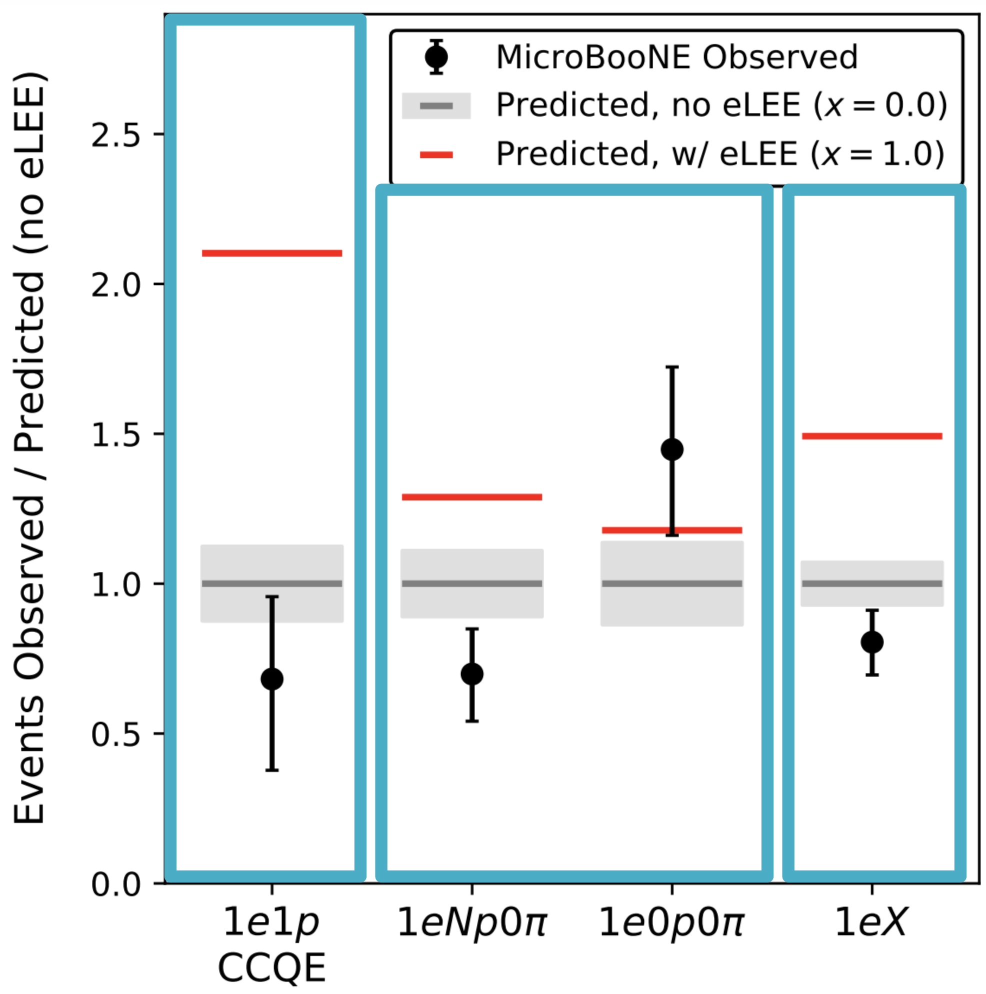
Finally, signal strength.

- Best fit LEE(x=0)
- We reject LEE(x=0.5) with 95.5% C.L.



Results

- ν_e prediction adequately describes the data across many different kinematic quantities
- Observe ν_e candidate event rates in general agreement **with or below** the predicted rates
- Results from LEE enhanced region



Summary

Summary

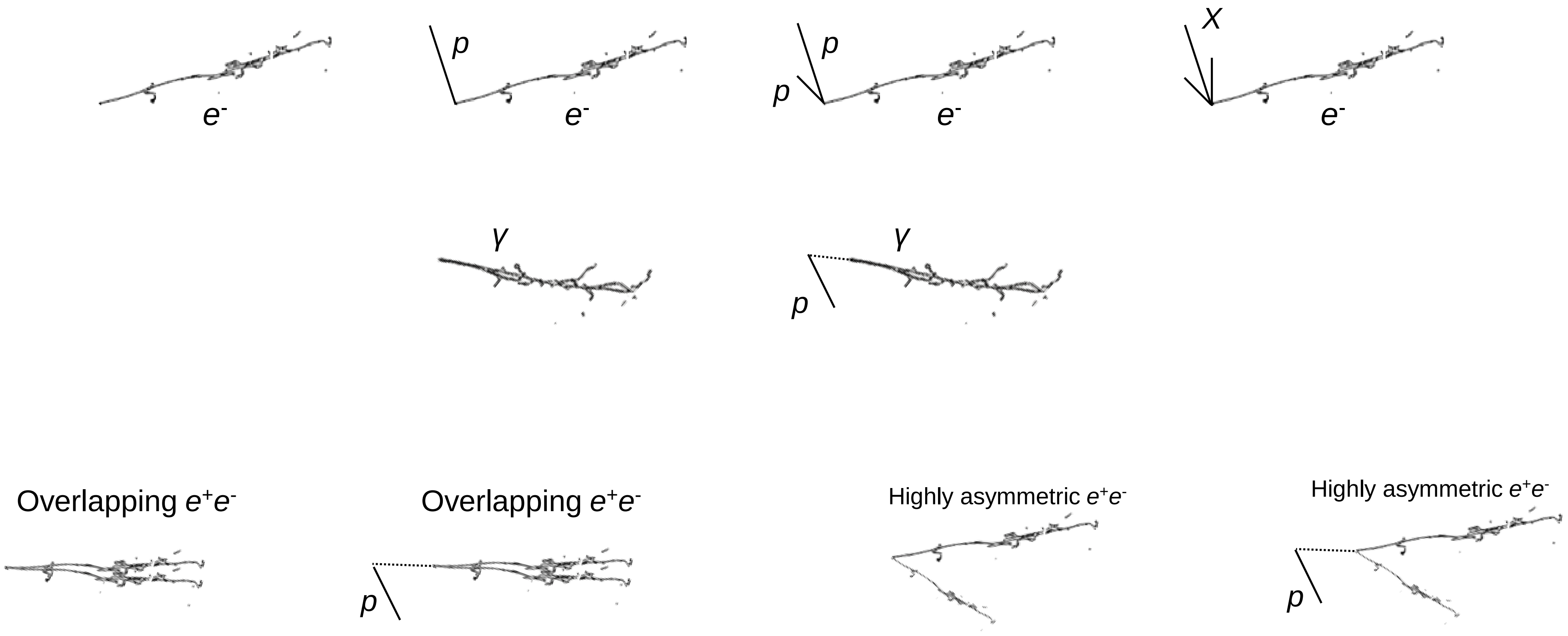
- First eLEE searches, sets limits on many theoretical models
- Only ½ of the data procesed

First series of results (1/2 the MicroBooNE data set) [spans 1e0p – 1γ0p]

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma0p$	$1\gamma1p$	$1\gamma X$
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							✔	✔	✔

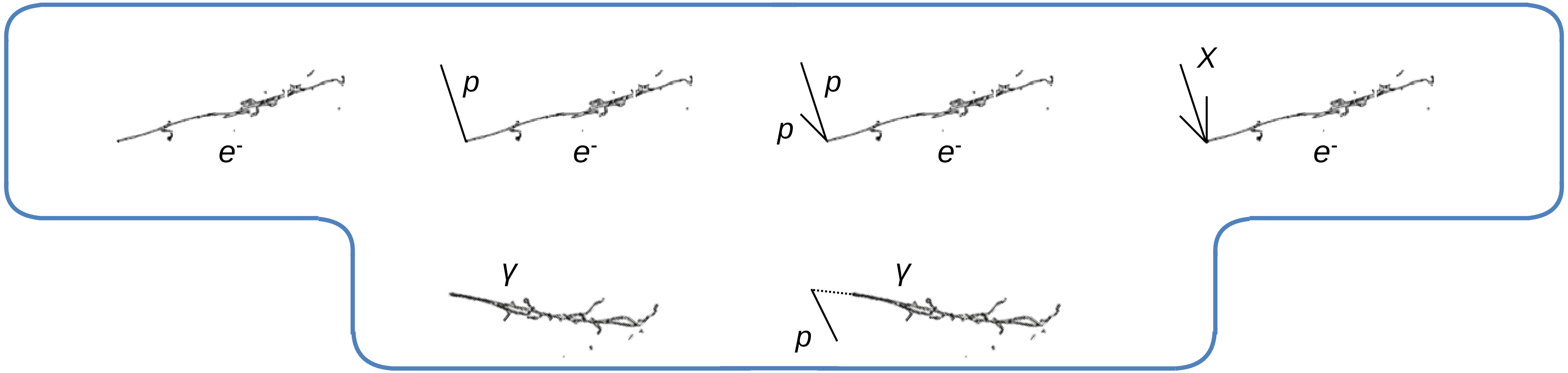
Summary

What's next?

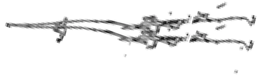


Summary

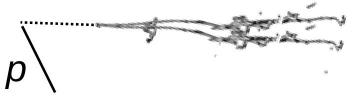
First results



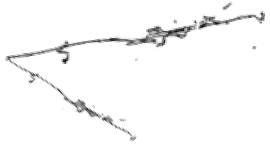
Overlapping e^+e^-



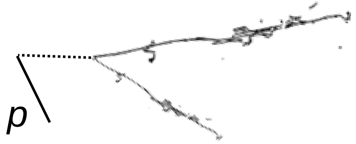
Overlapping e^+e^-



Highly asymmetric e^+e^-

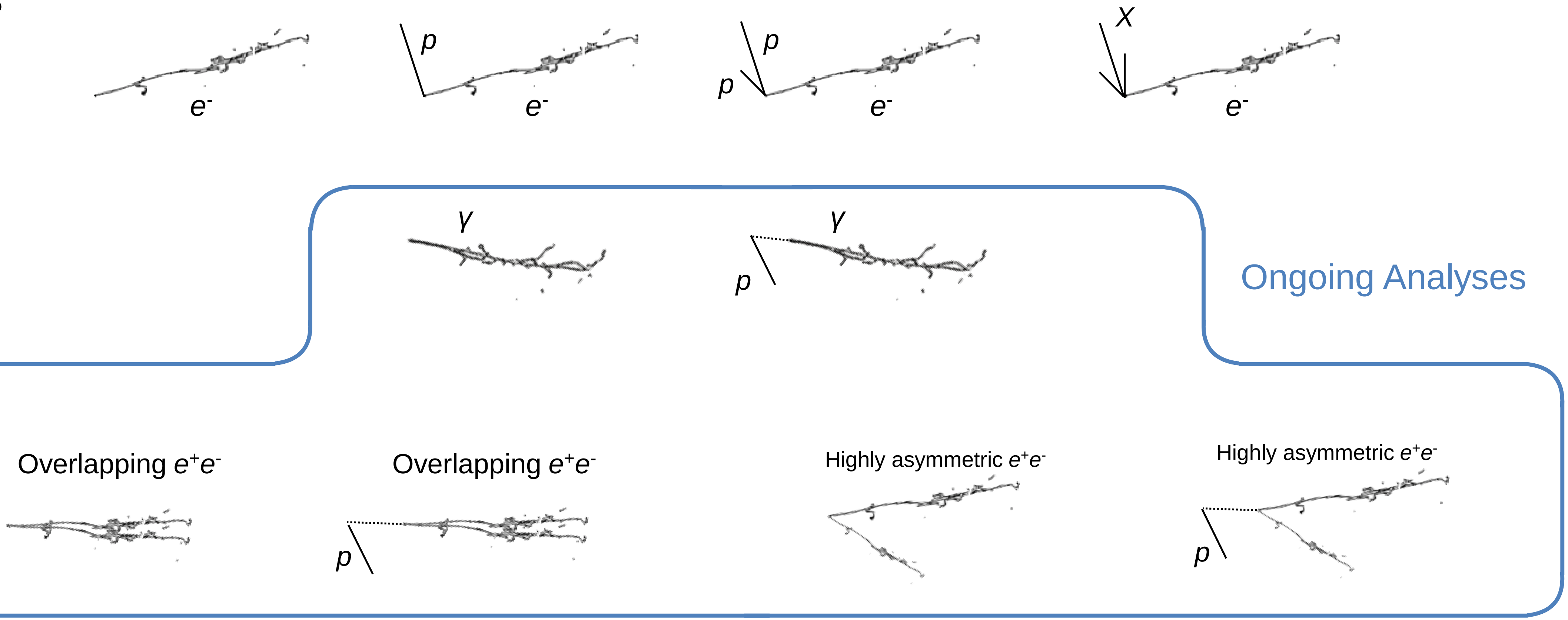


Highly asymmetric e^+e^-



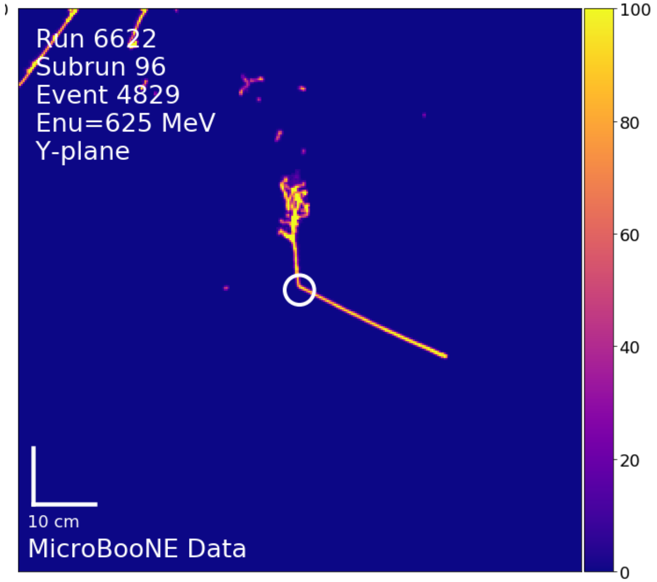
Summary

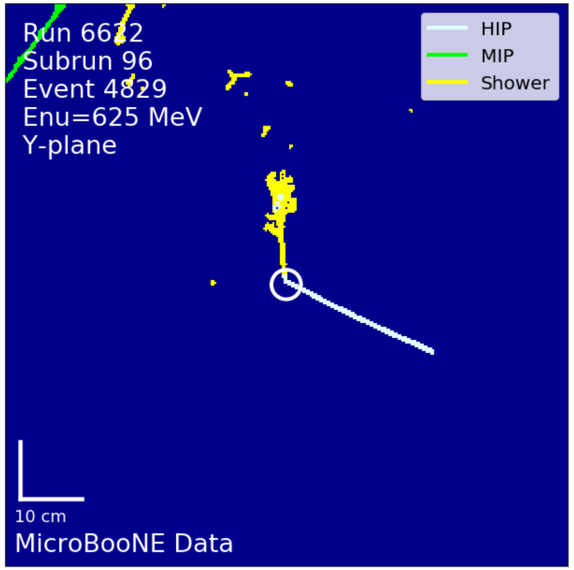
What's next?



Summary

- Our results are found to be consistent with the nominal ν_e expectations. **No excess of ν_e events is observed**
- Best fit with simple MiniBooNE e model, on ¾ analyses is at 0
- Reject simple eLEE model of the MiniBooNE low energy excess at >97% for both exclusive and inclusive event classes
- We disfavor the interpretation of MiniBooNE LEE as a x3.18 enhancement of NC $\Delta \rightarrow N\gamma$ rate at 94.8% CL
- Paper on arxiv, and submitted to PRD+PRL.





Questions