Neutrino Interactions Systematics and the Fermilab Short-Baseline Neutrino Program

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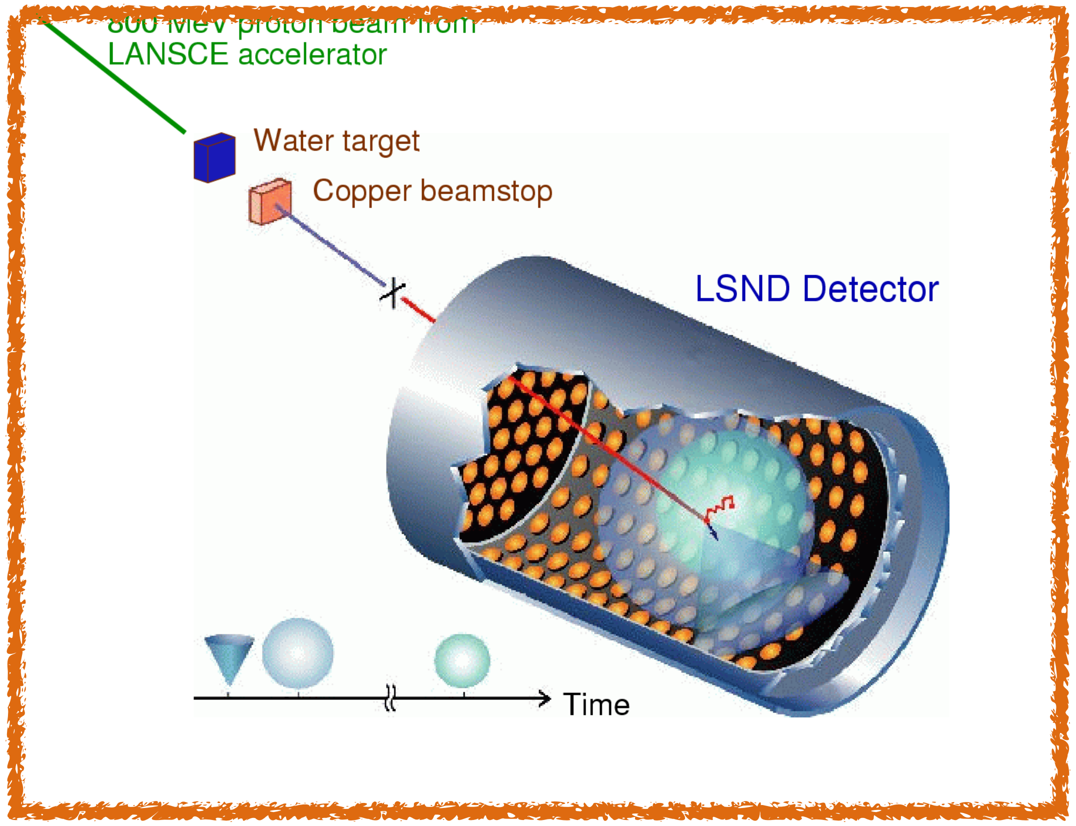
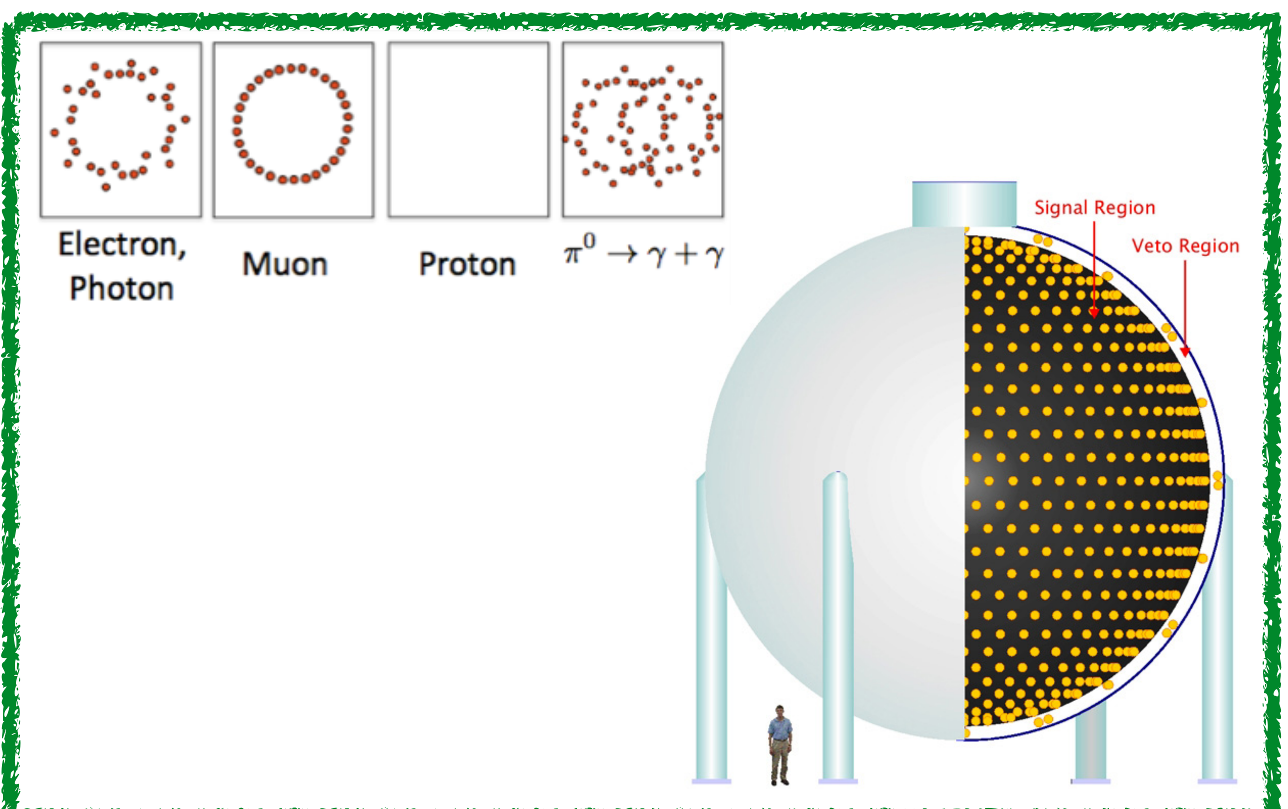
THE UNIVERSITY OF CHICAGO

Sterile Neutrino Physics





- We have many hints for additional neutrino states from a variety of experiments

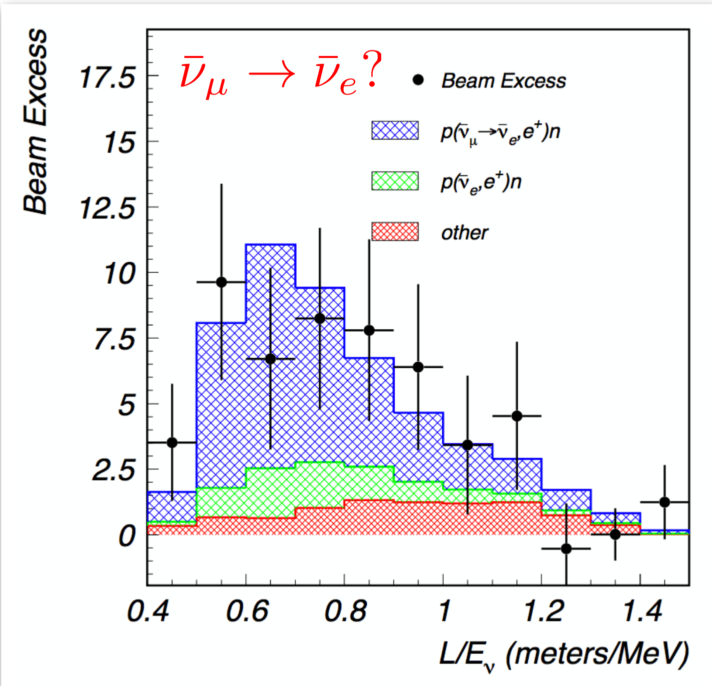
- Two accelerator based experiments have inspired the Short-Baseline Neutrino program

  - **LSND**, scintillator detector experiment at the Los Alamos LANSCE accelerator in the 90's

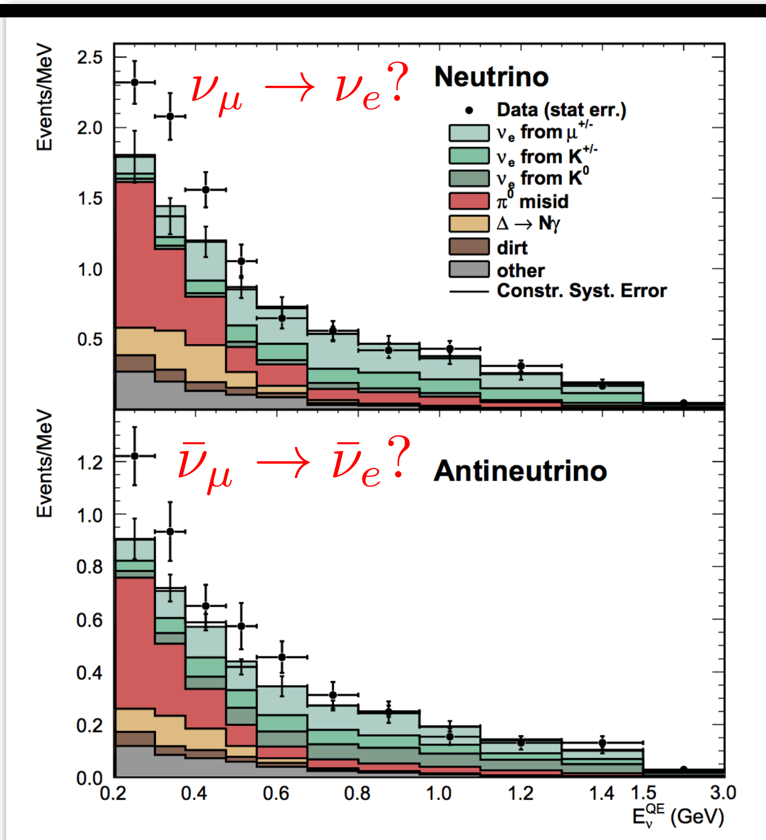
  - **MiniBooNE**, Designed to follow up on LSND using a different baseline and energy but same L/E

Sterile Neutrino Physics

Phys.Rev. D64 (2001) 112007



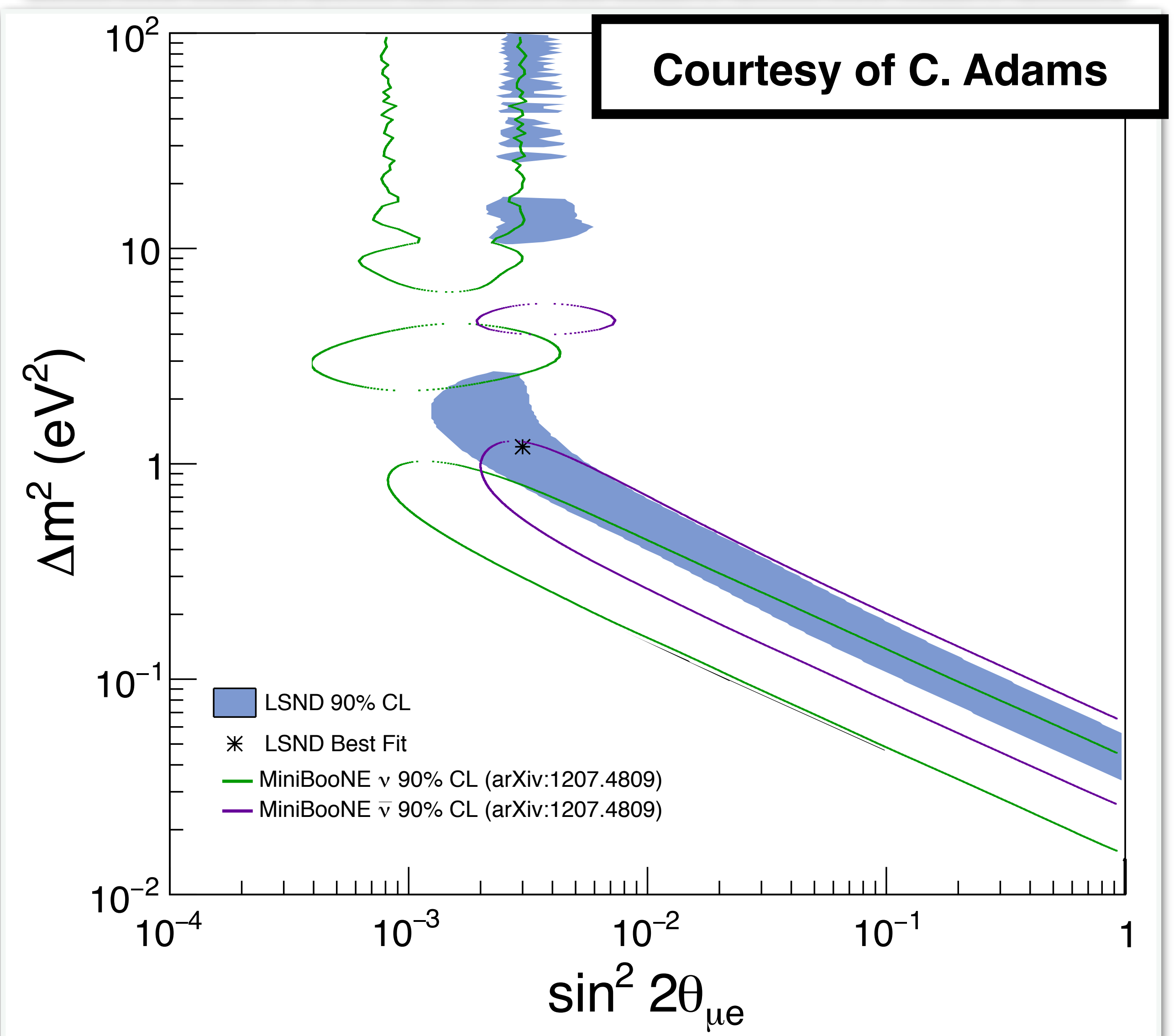
Phys.Rev.Lett. 110 (2013) 161801



- Both of these experiments found excesses of electron-like neutrino interactions in beams composed mostly on muon neutrinos
- They had very different systematics
  - LSND relied on inverse beta decay and used a stopped-pion neutrino source
  - MiniBooNE studied "CCQE" events using a pion-decay-in-flight beam with a peak energy of 800 MeV

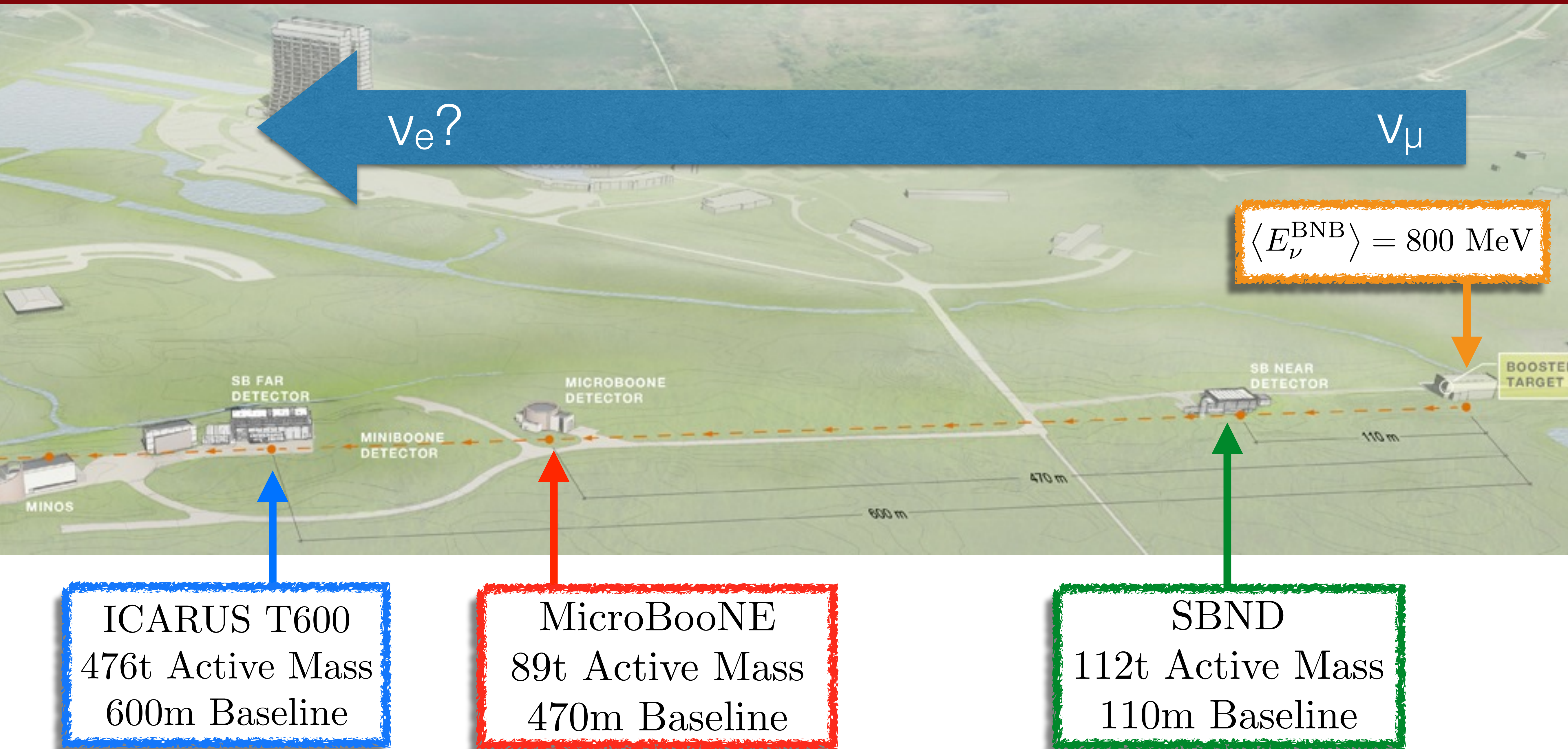
Sterile Neutrino Physics

$$P^{3+1}_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \frac{\Delta m^2_{41} L}{4E}$$



- Can be interpreted as oscillations by including one additional neutrino with a mass around 1 eV
  - LSND and MiniBooNE both have significances around 3σ for this interpretation
- This interpretation of the data leaves a fairly large amount of parameter space to explore

Short-Baseline Neutrino Program



- We hope to provide a definitive answer to the question of sterile neutrinos with masses around 1 eV

elin Program

Atmospheric Neutrino Mixing Scale

$L/E \approx 500 \text{ km/GeV}$

Solar Neutrino Mixing Scale

$L/E \approx 15,000 \text{ km/GeV}$

Sterile Neutrino Mixing Scale

$$L/E \approx 1 \text{ km/GeV}$$

$\langle E_\nu^{\text{BNB}} \rangle = 800 \text{ MeV}$

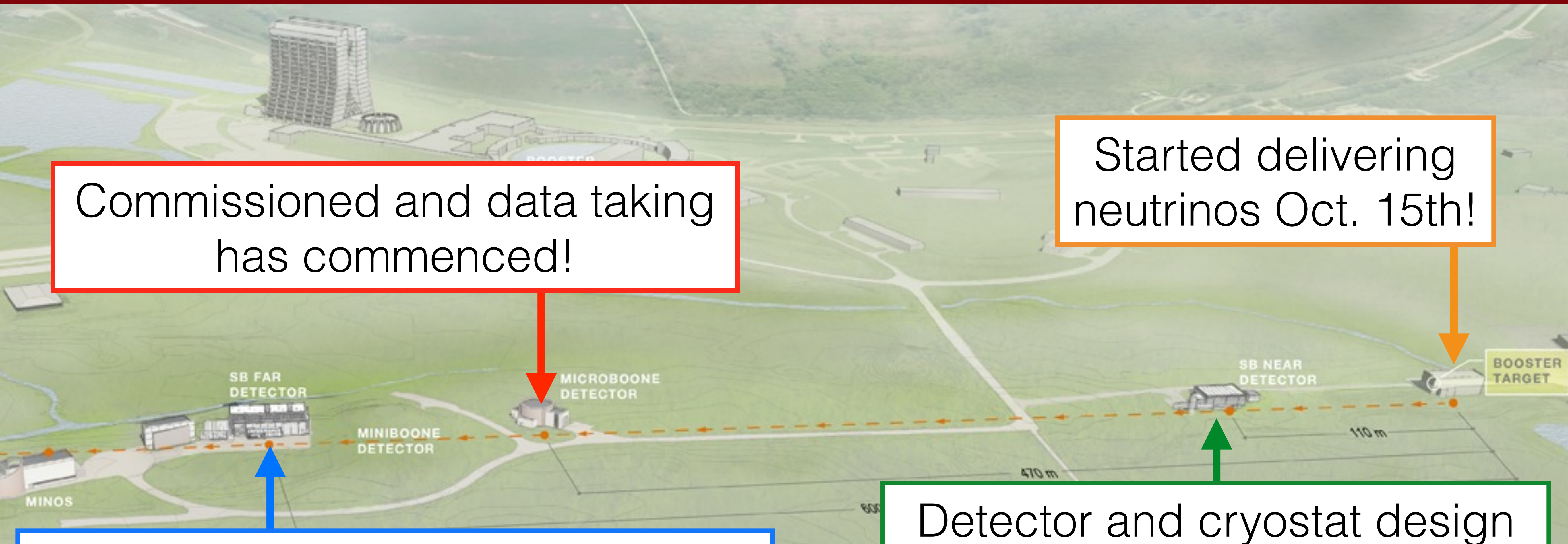
ICARUS T600
476t Active Mass
600m Baseline

MicroBooNE
89t Active Mass
470m Baseline

SBND
112t Active Mass
110m Baseline

- Thanks to this large mass splitting we can situate three similar detectors along a short-baseline and decouple ourselves from standard three neutrino oscillations

Short-Baseline Neutrino Program Status

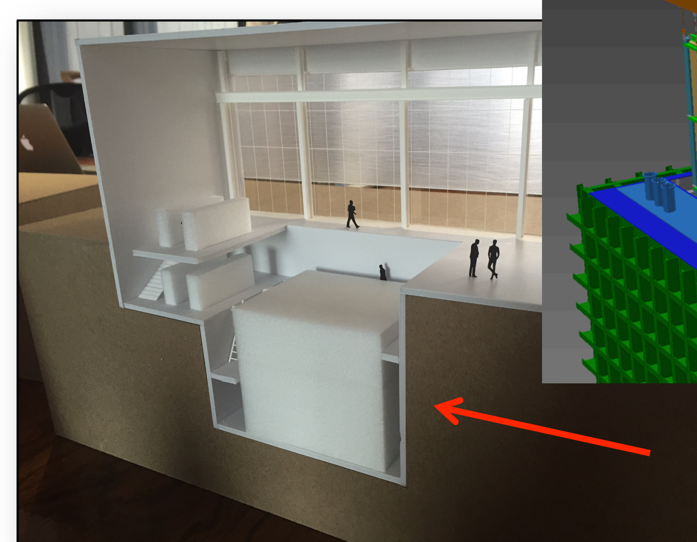


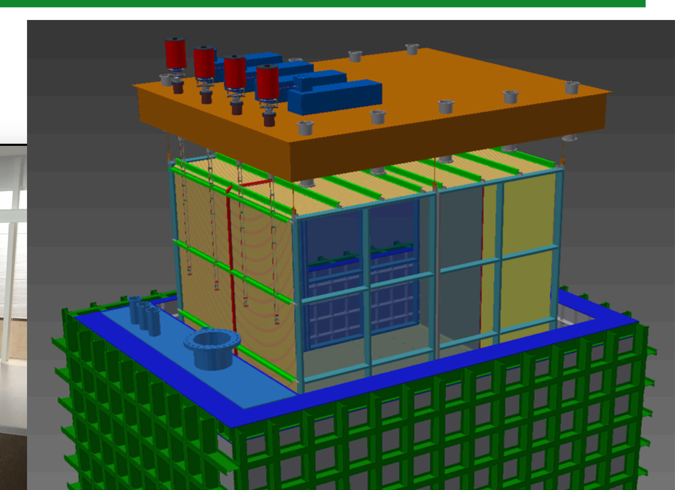
Commissioned and data taking has commenced!

Started delivering neutrinos Oct. 15th!

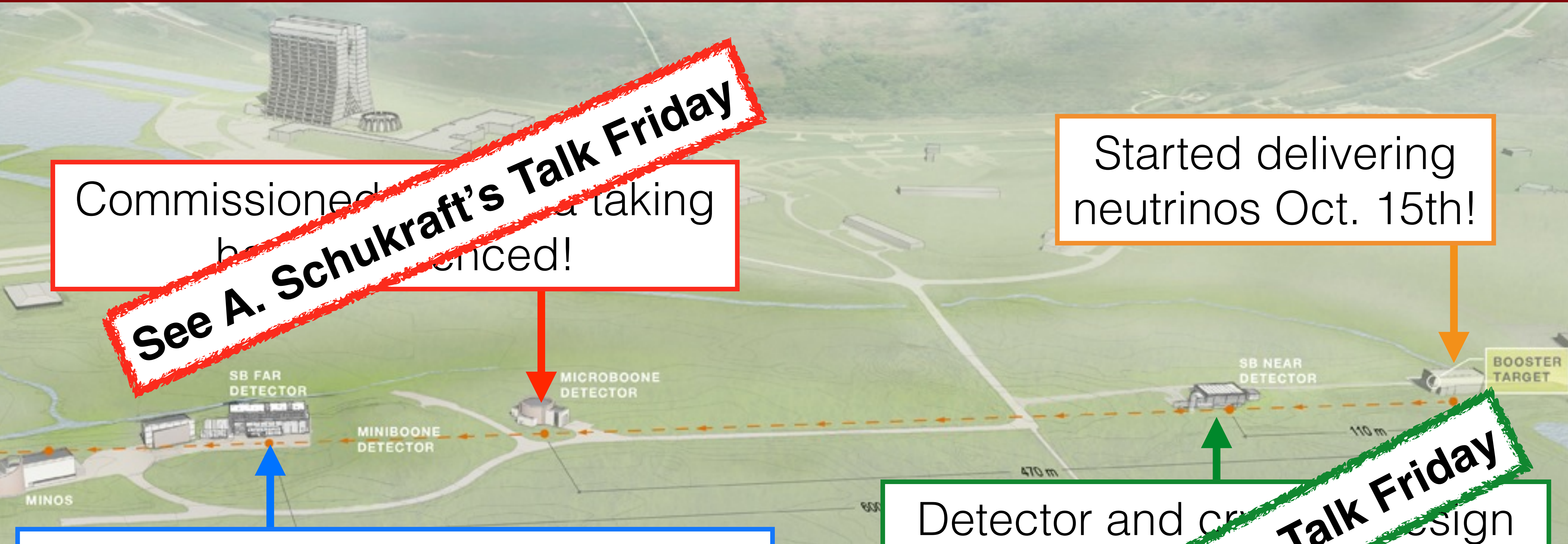
Building construction and detector refurbishment are fast underway!

Detector and cryostat design are quickly maturing with large international collaboration





Short-Baseline Neutrino Program Status



Commissioned … taking … h… …enced!

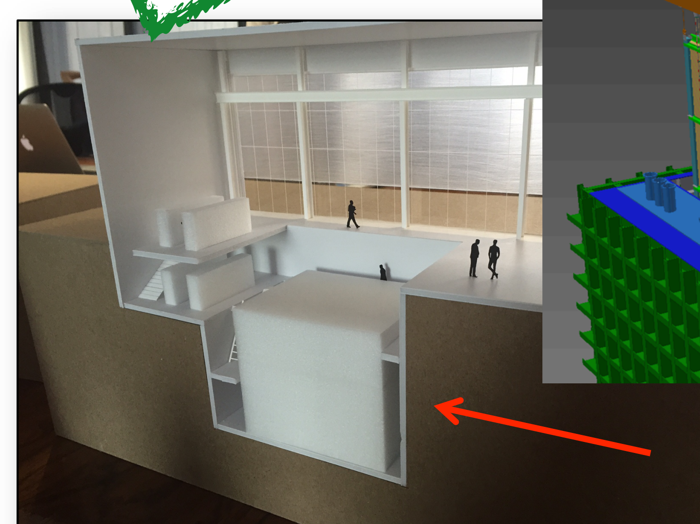
See A. Schukraft's Talk Friday

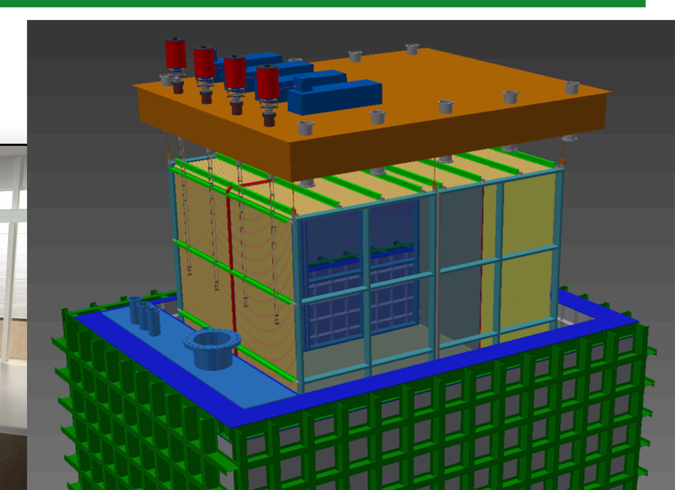
Started delivering neutrinos Oct. 15th!

Building construction and detector refurbishment are fast underway!

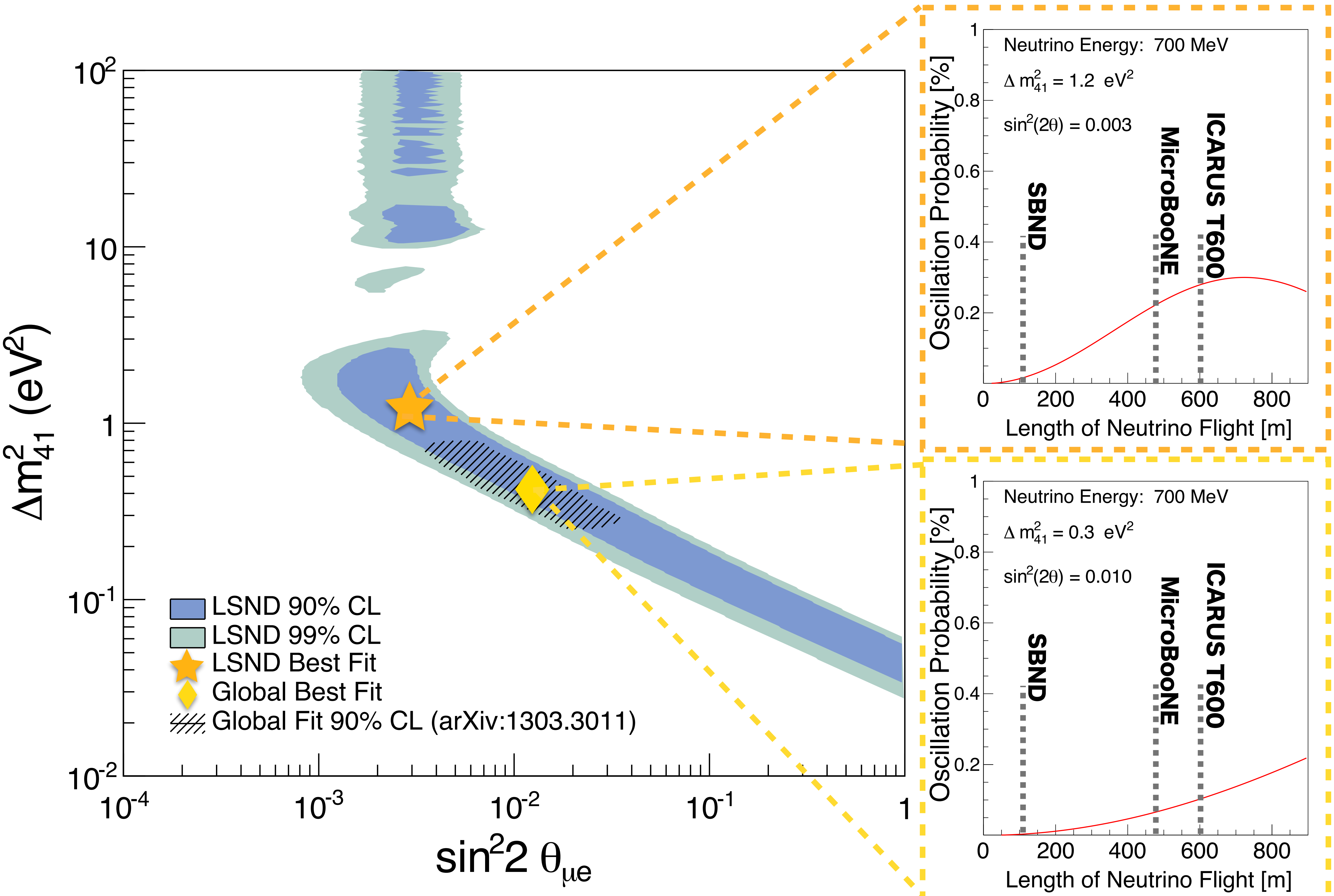
Detector and cr… …esign are quick… …ing with large i… …nal collaboration

See C. Adams's Talk Friday

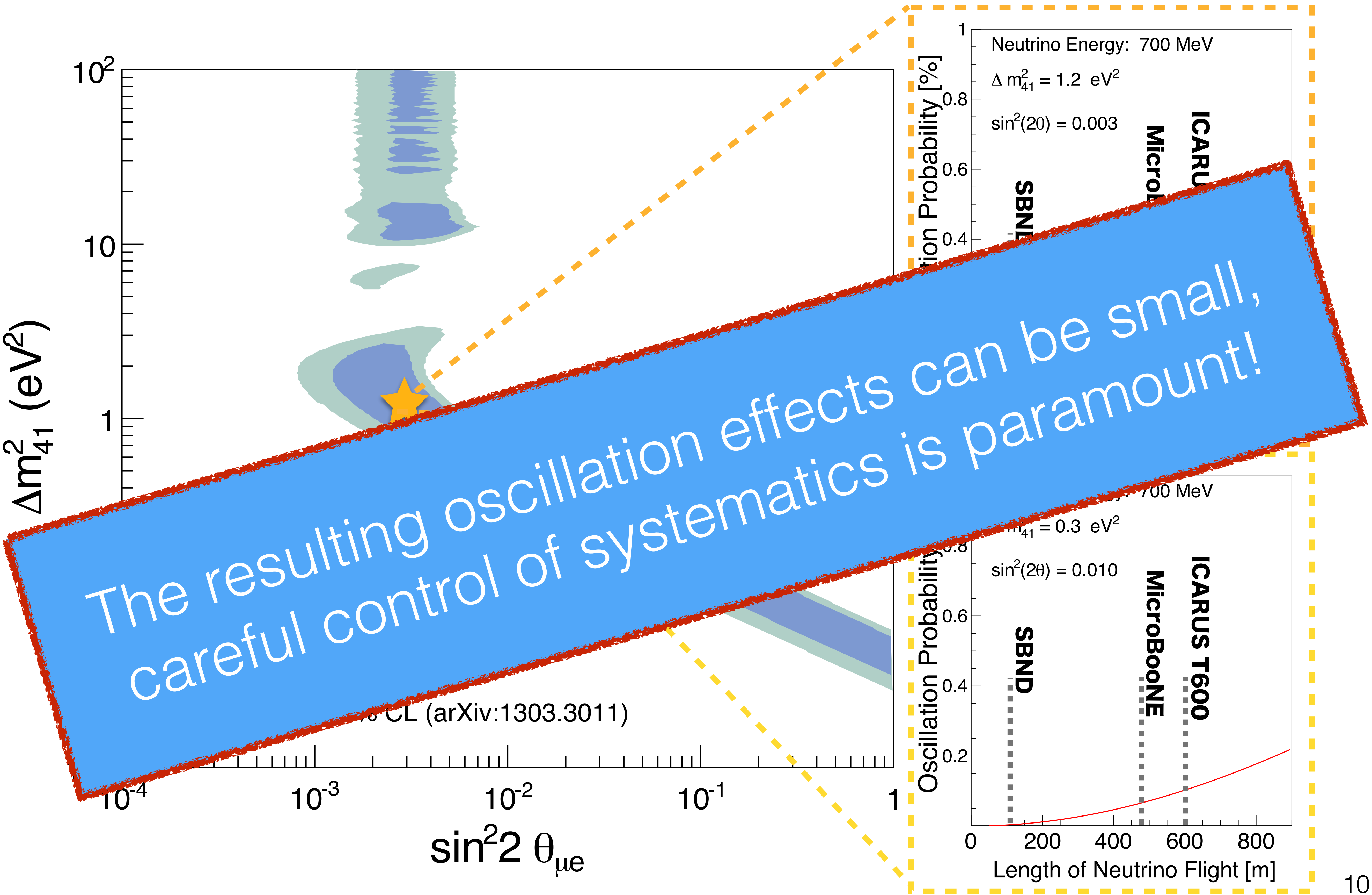




Sterile Neutrino Physics



Sterile Neutrino Physics

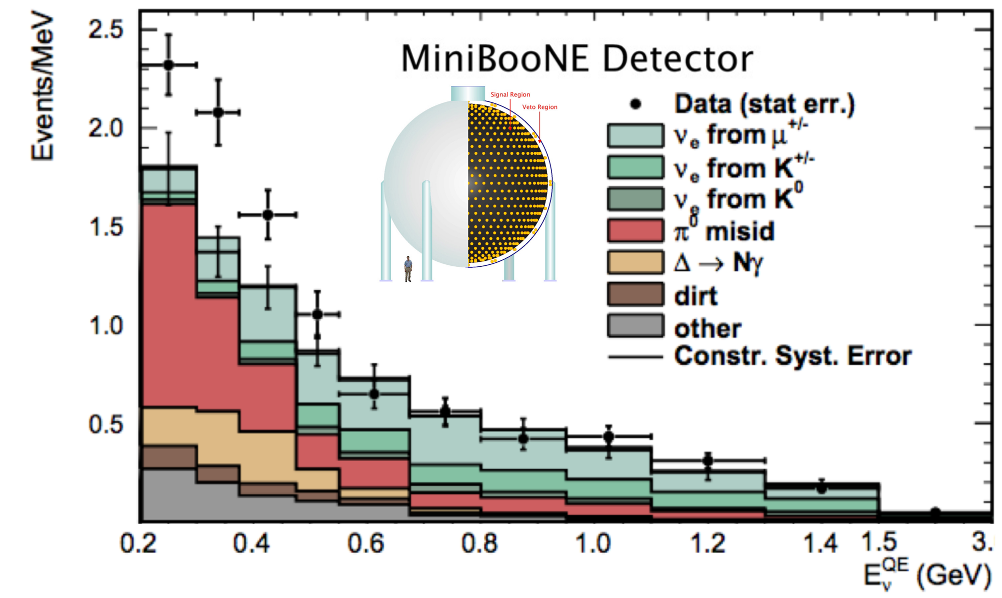


The resulting oscillation effects can be small, careful control of systematics is paramount!

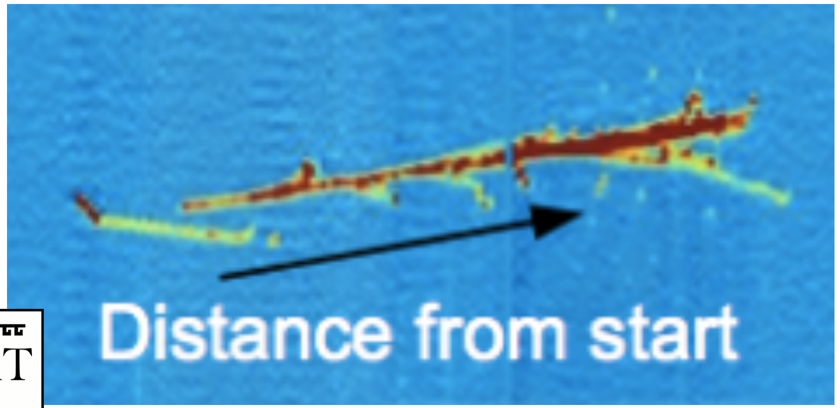
Issue with Electron Appearance

- One issue that plagues appearance measurements are electromagnetic backgrounds not coming from electron-neutrino interactions
  - BNB energies: $\pi^0 \rightarrow \gamma\gamma$ or $\Delta \rightarrow N\gamma$
- LArTPCs provide two handles to suppress these backgrounds
- Thanks to the spatial resolution of the detectors we will be able to resolve the small gaps between vertices and photon shower

The Problem…

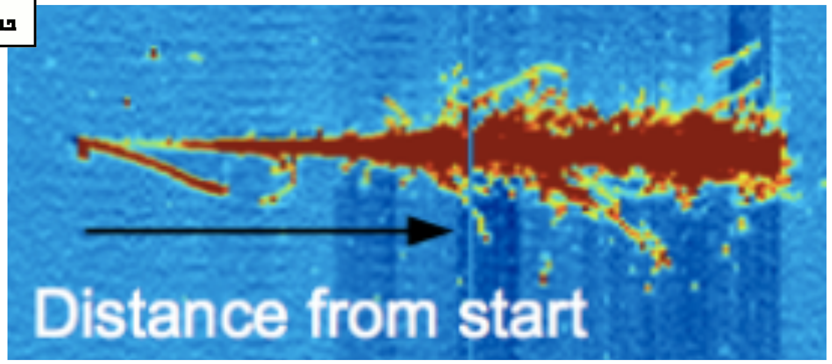


Data NC Candidate



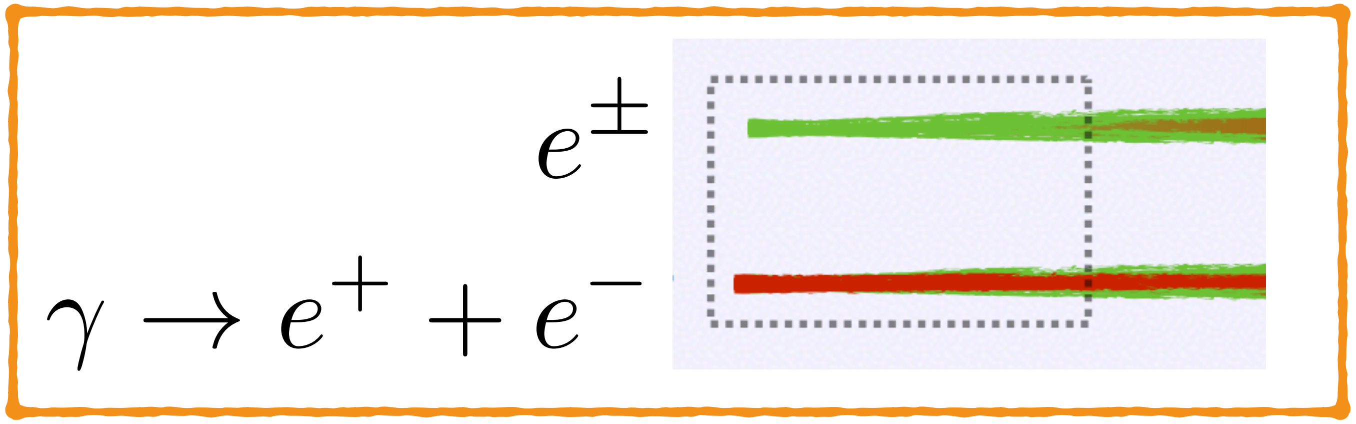
ArgoNeuT

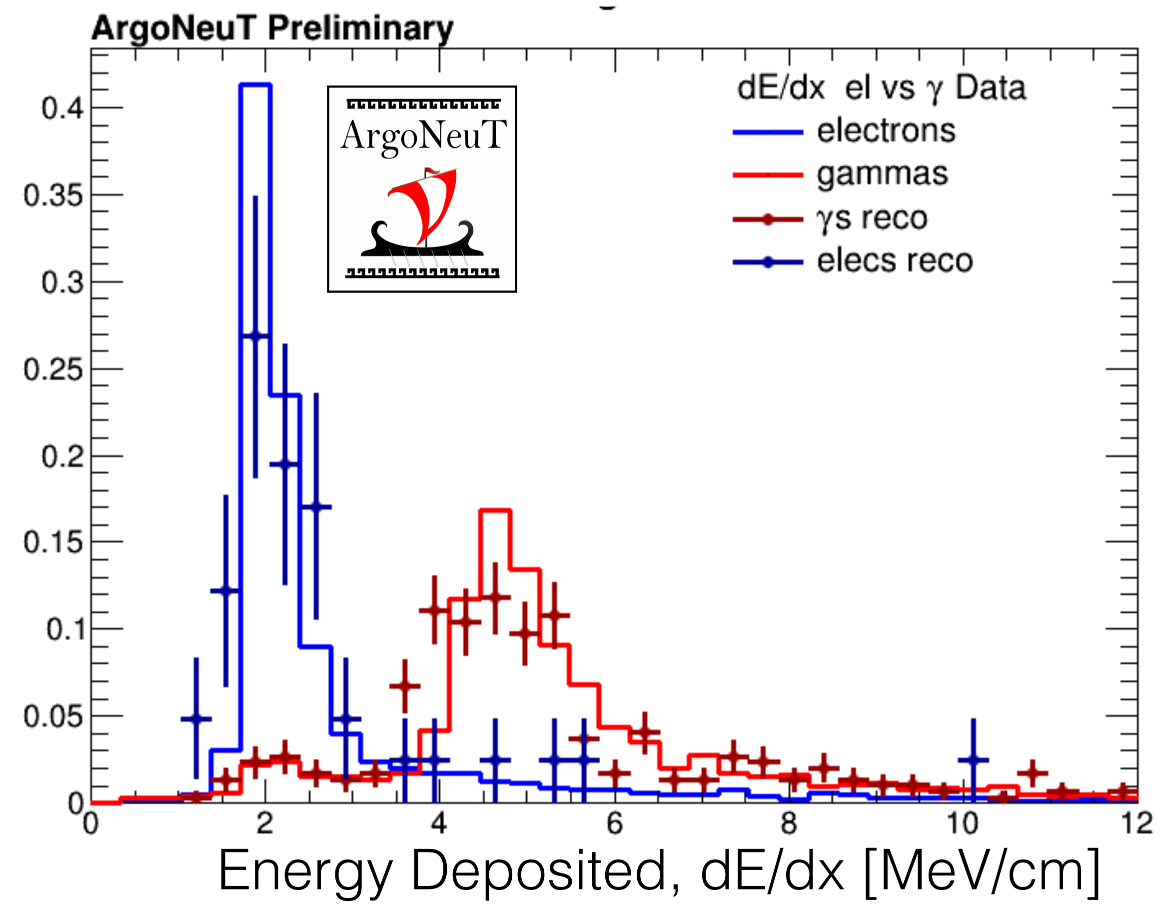
Data ν_e CC Candidate



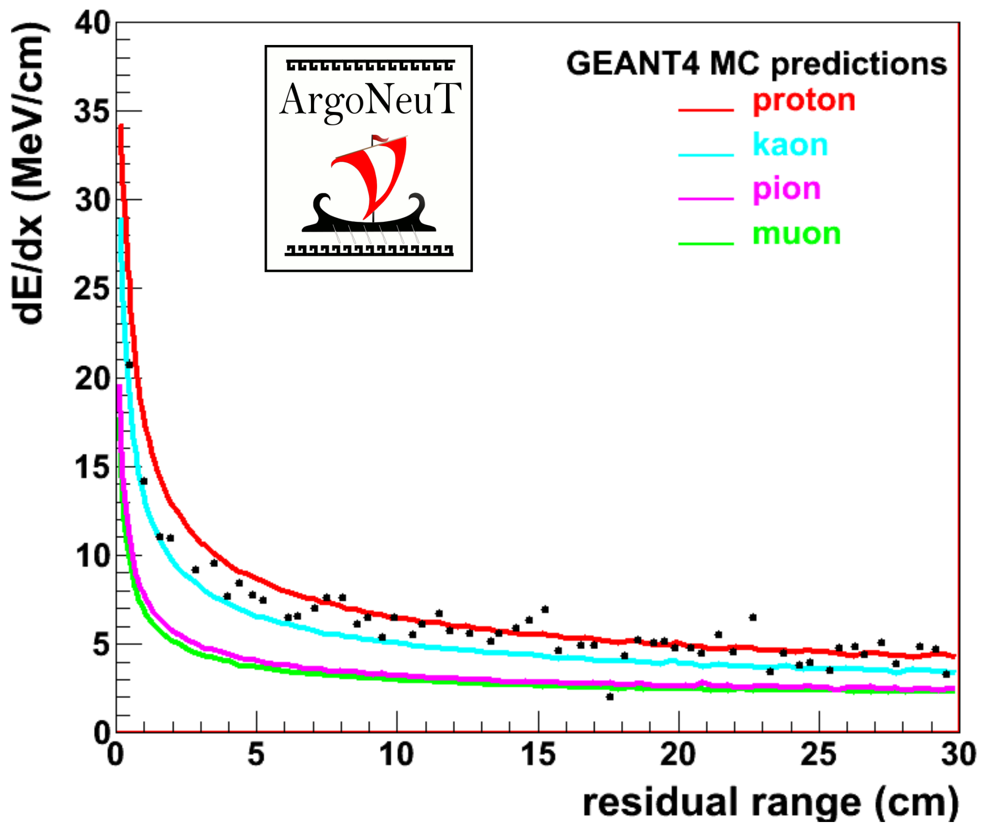
Liquid Argon Time Projection Chambers

- An additional handle for electron-photon separation comes from the calorimetric information of the shower



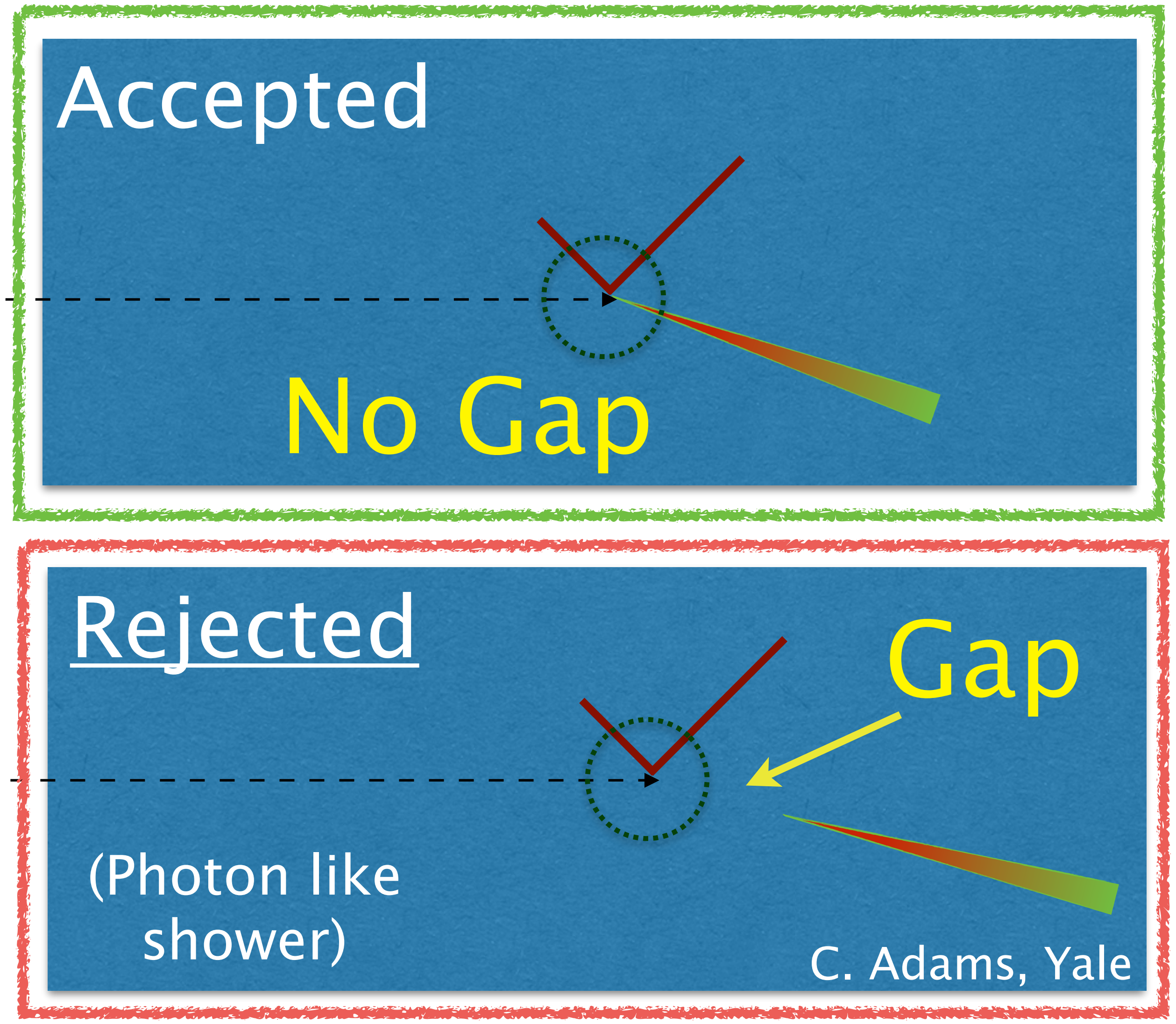


- Thanks to this calorimetric information LArTPCs also have powerful PID capabilities
  - This allows us to carefully characterize the hadronic final state

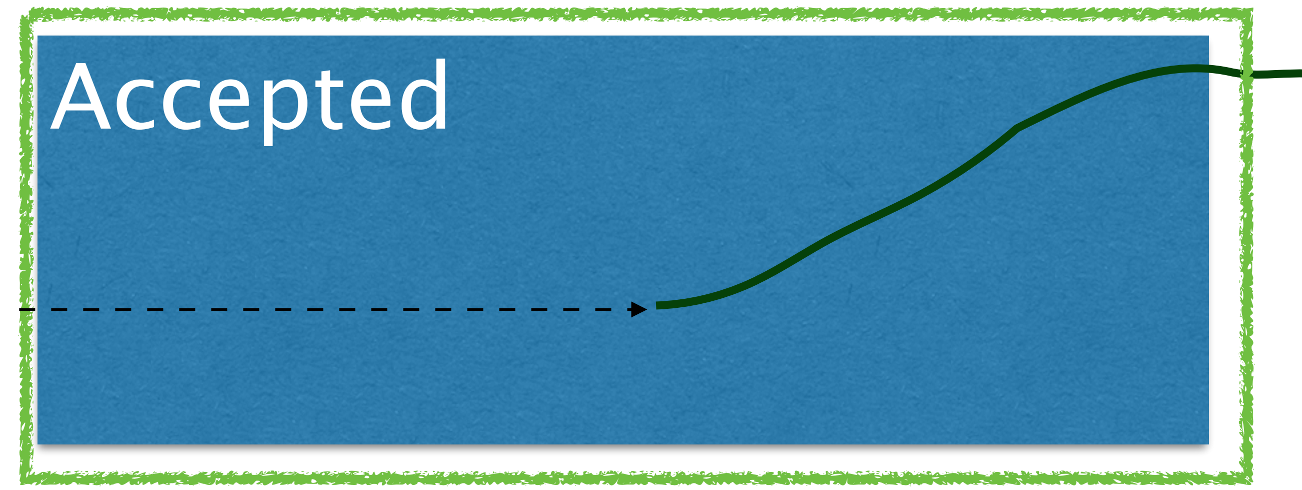


Searching For Oscillations

Electron Appearance

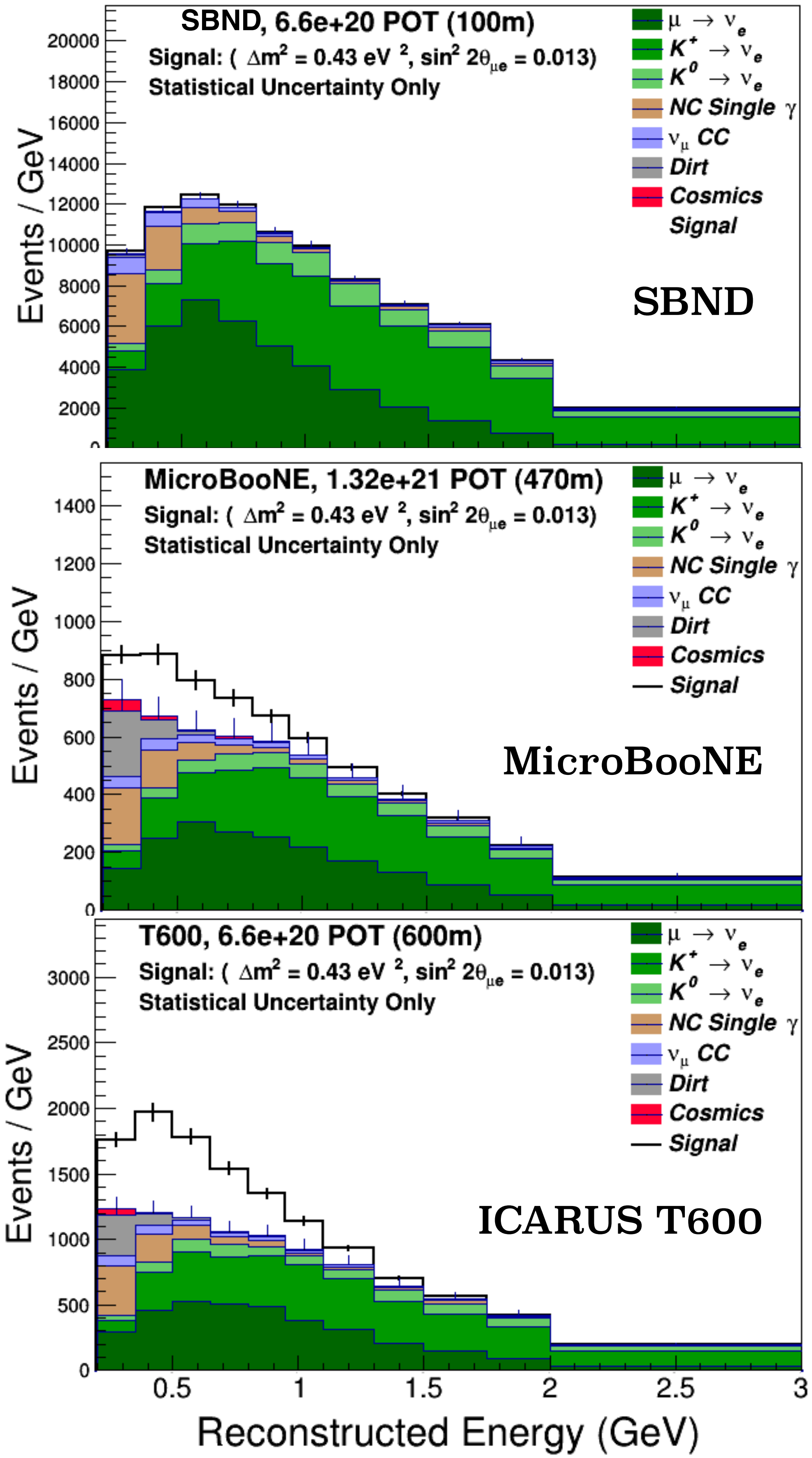


Muon Disappearance



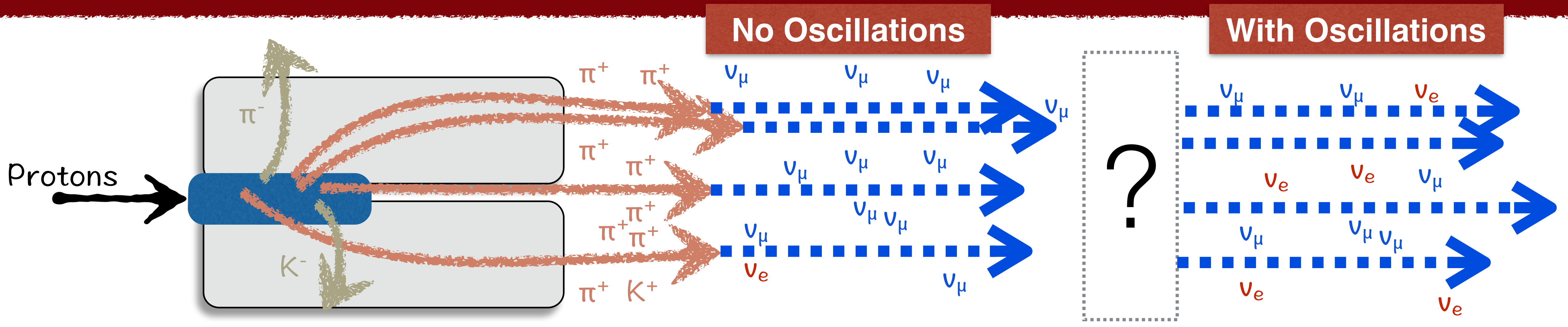
- When we select events we do so on a topological basis
  - For example, relying on gaps between showers and vertices to suppress photon induced backgrounds

Searching For Oscillations

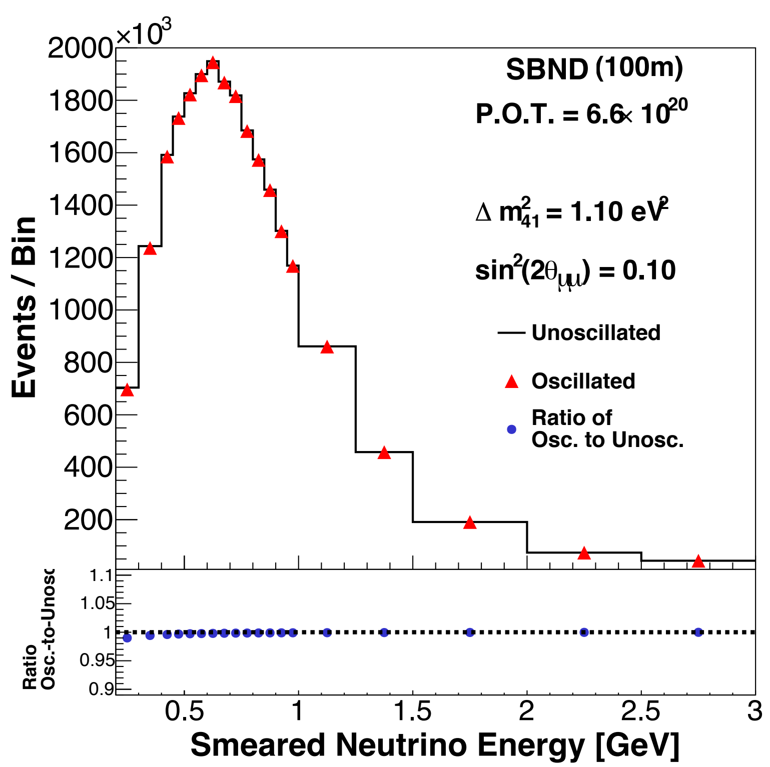


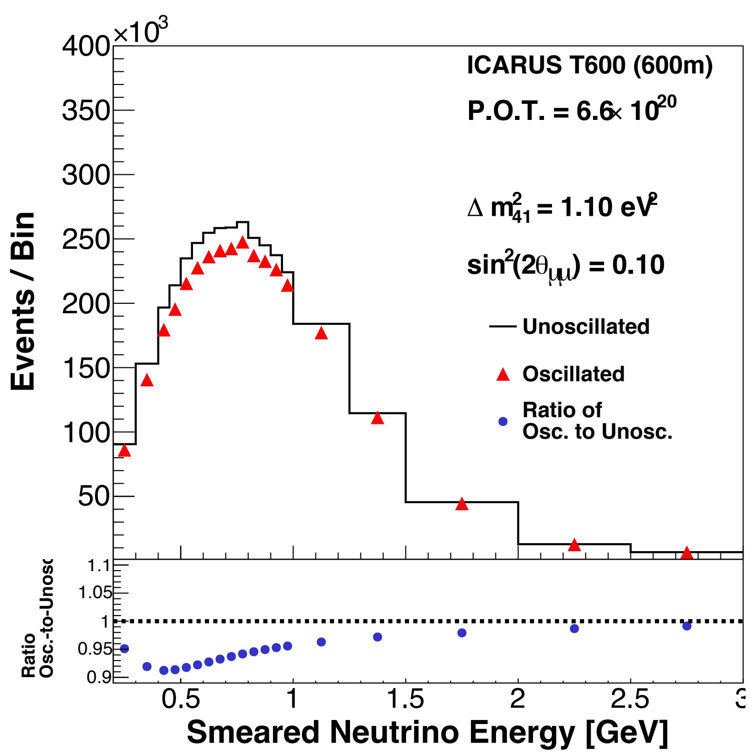
- Thanks to the LArTPC technology you can see that our dominant background in the appearance search is beam intrinsic electron neutrinos
- For comparison the “Kopp Global” (arXiv:1303.3011) best fit signal is placed onto the backgrounds, demonstrating how well it will be observed in the three detectors

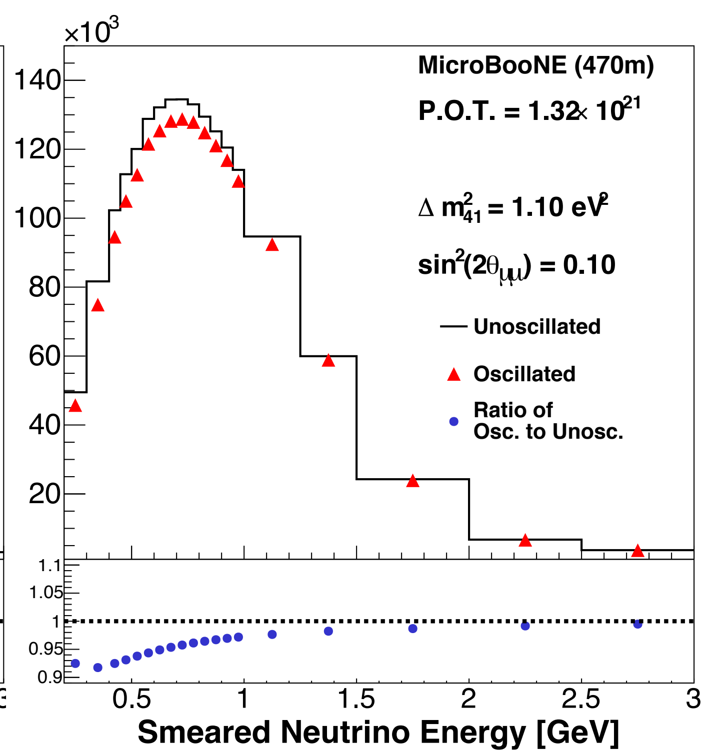
Searching For Oscillations



- To interpret any appearance signal as oscillations we should also be able to observe muon neutrino disappearance
  - Fairly background free but oscillation effects can be small







Systematics

We need to address a host of systematic uncertainties before we can address how confident we are in observing any signal

- **Background Systematics**
    - Beam induced, detector external - highly detector specific
    - Cosmic Induced - surface detectors, so we can measure this background to high accuracy

- **Flux Uncertainties**
    - Dominated by hadron production uncertainties, also includes focusing effects and secondary interactions
- **Cross Section Uncertainties**
    - Study systematic variations of neutrino interaction models

Estimating Systematics

- **Flux Uncertainties**

Phys. Rev. D79 072002 (2009)

  - Relied on the MiniBooNE flux uncertainty framework to help us accurately account for these systematic variations

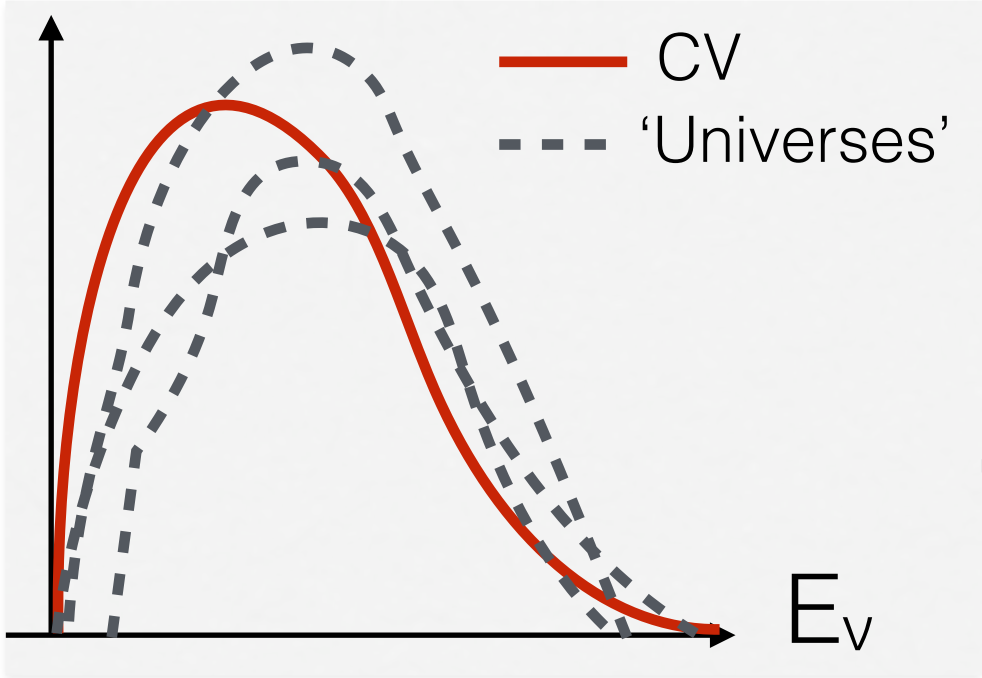
- **Cross Section Uncertainties**
  - Used GENIE event reweighing package to vary the normalization systematics that would most affect our class of events

Parameter	Description	1σ Uncertainty (%)
M_A^{CCQE}	Axial mass for CC quasi-elastic	-15%+25%
M_A^{CCRES}	Axial mass for CC resonance neutrino production	±20%
M_A^{NCRES}	Axial mass for NC resonance neutrino production	±20%
$R_{bkg}^{\nu p,CC1\pi}$	Non-resonance background in $\nu p, CC$ 1π reactions.	±50%
$R_{bkg}^{\nu p,CC2\pi}$	Non-resonance background in $\nu p, CC$ 2π reactions.	±50%
$R_{bkg}^{\nu n,CC1\pi}$	Non-resonance background in $\nu n, CC$ 1π reactions.	±50%
$R_{bkg}^{\nu n,CC2\pi}$	Non-resonance background in $\nu n, CC$ 2π reactions.	±50%
$R_{bkg}^{\nu p,NC1\pi}$	Non-resonance background in $\nu p, NC$ 1π reactions.	±50%
$R_{bkg}^{\nu p,NC2\pi}$	Non-resonance background in $\nu p, NC$ 2π reactions.	±50%
$R_{bkg}^{\nu n,NC1\pi}$	Non-resonance background in $\nu n, NC$ 1π reactions.	±50%
$R_{bkg}^{\nu n,NC2\pi}$	Non-resonance background in $\nu n, NC$ 2π reactions.	±50%
NC	Neutral current normalization	±25%
DIS-NuclMod	DIS, nuclear model	Model switch

How to Estimate Impact of Systematics

- Create a large number of “universes” by randomly drawing a variation for each of the systematic variables from a gaussian centered at the mean for each parameter with a width of 1σ

- Using these universes we can then estimate the overall uncertainties and in the end estimate our sensitivity



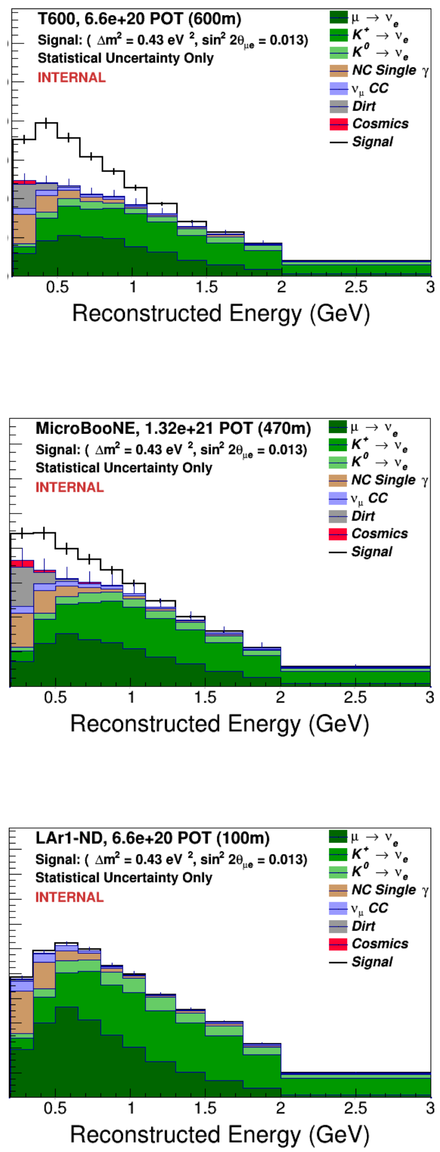
Error Matrix Definition

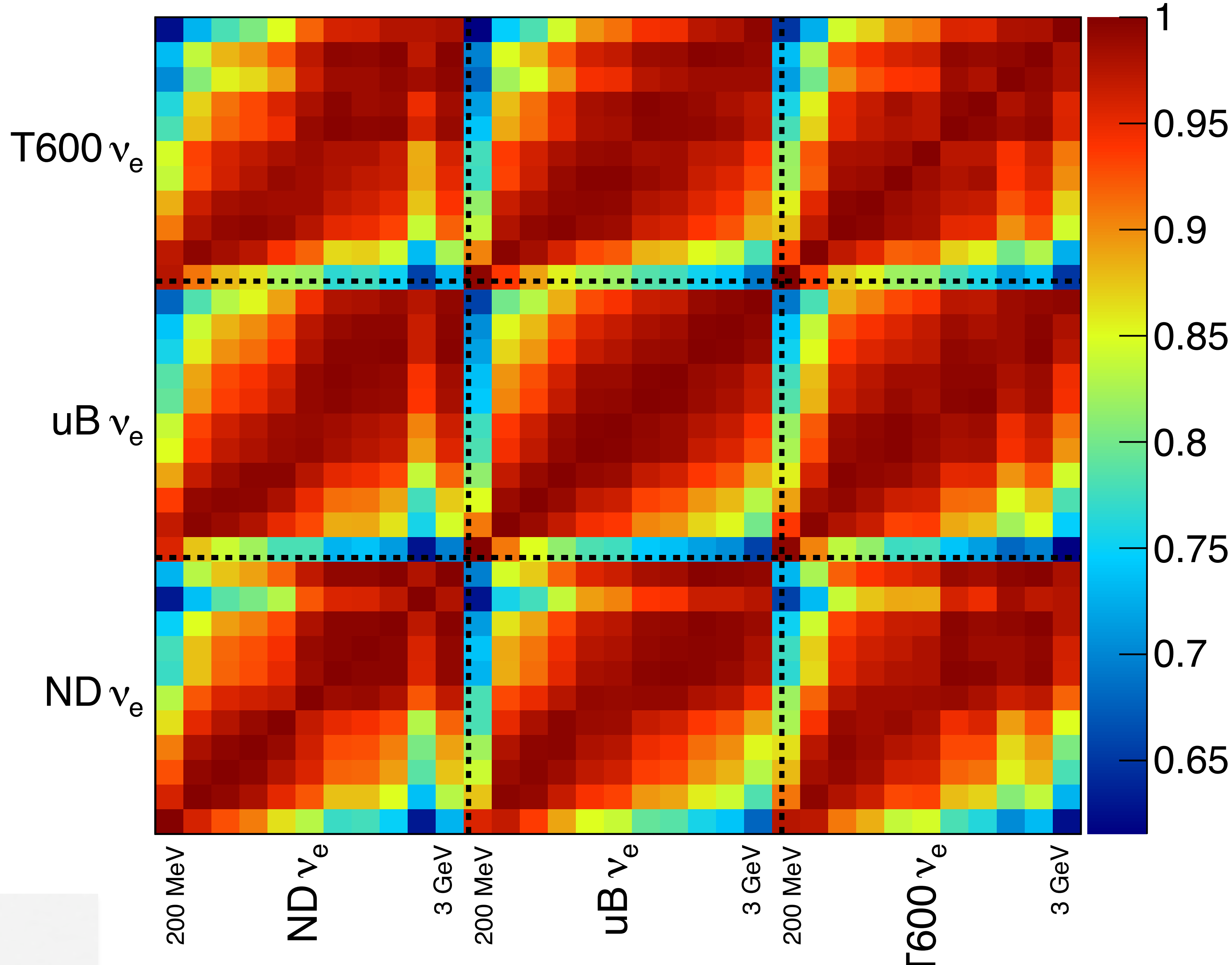
$$E_{ij} = \frac{1}{n}\sum_{m=1}^{n}\left[N^i_{CV} - N^i_m\right] \times \left[N^j_{CV} - N^j_m\right]$$

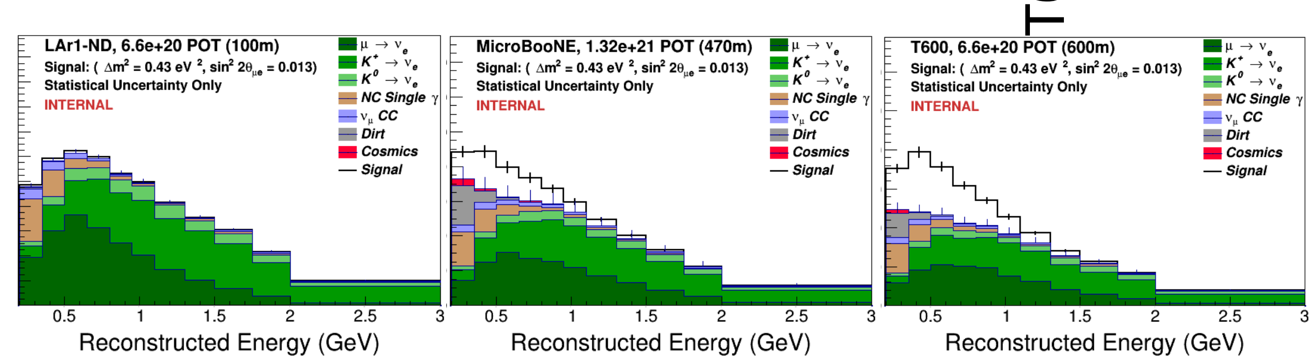
$$\chi^2 = \sum_{i,j}\left[N_i^{null} - N_i^{osc}\right]\left(E_{ij}\right)^{-1}\left[N_j^{null} - N_j^{osc}\right]$$

Sensitivity Surface Definition

Correlation Matrices

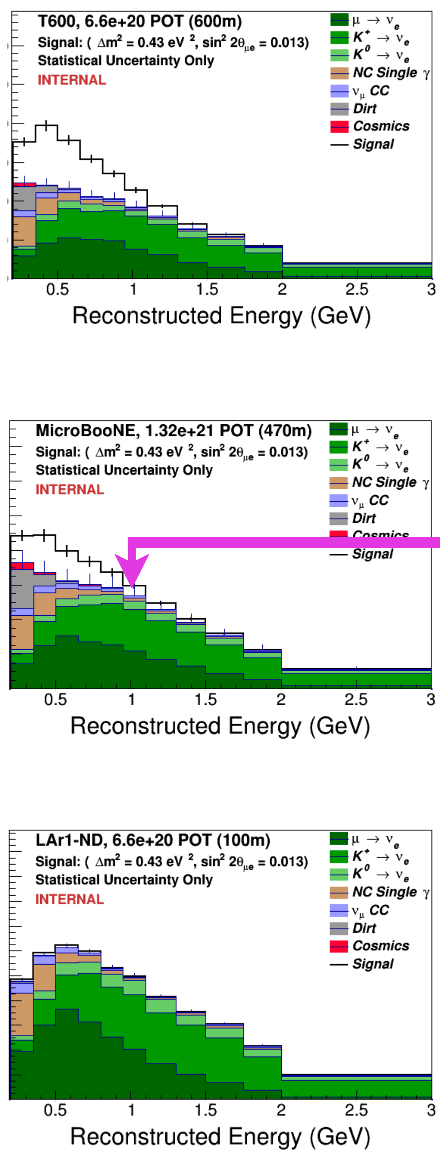


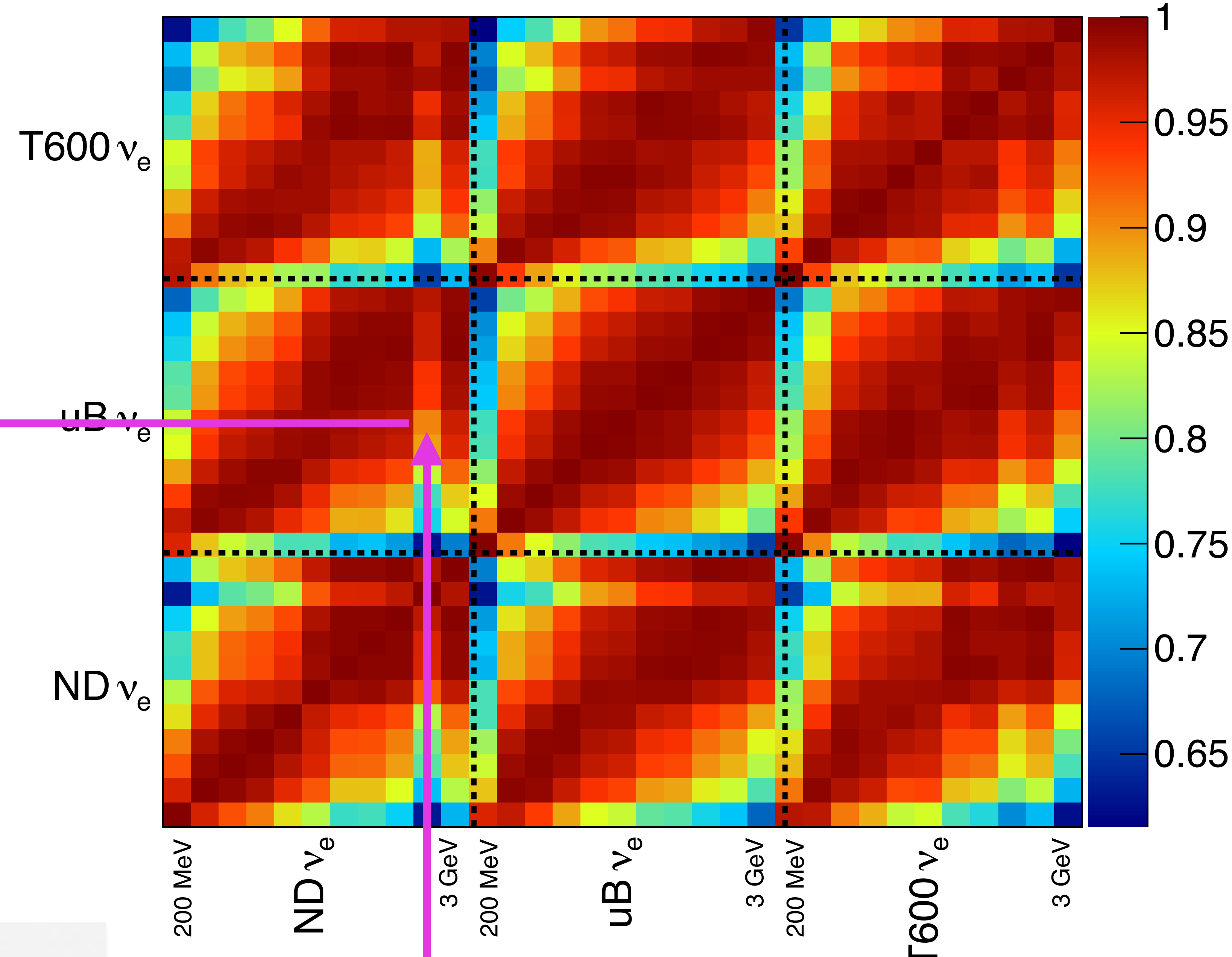


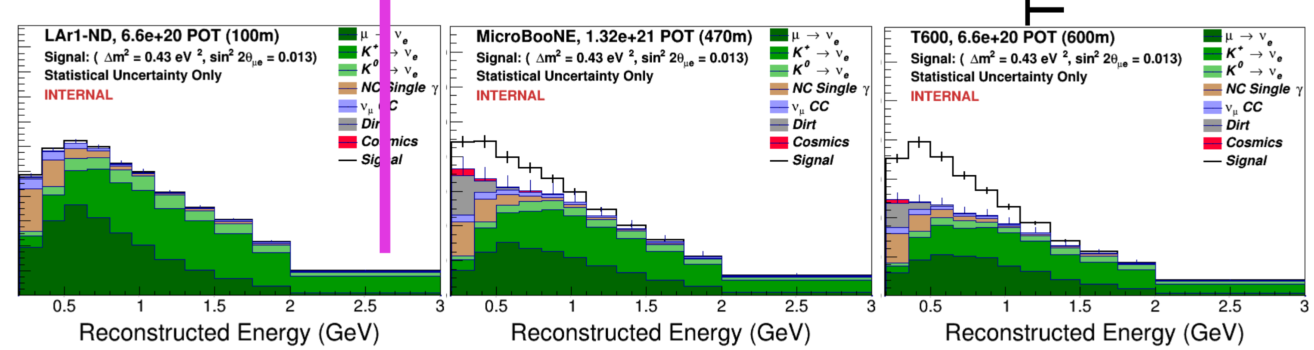


$$\rho_{ij} = \frac{E_{ij}}{\sqrt{E_{ii}}\sqrt{E_{jj}}}$$

Correlation Matrices

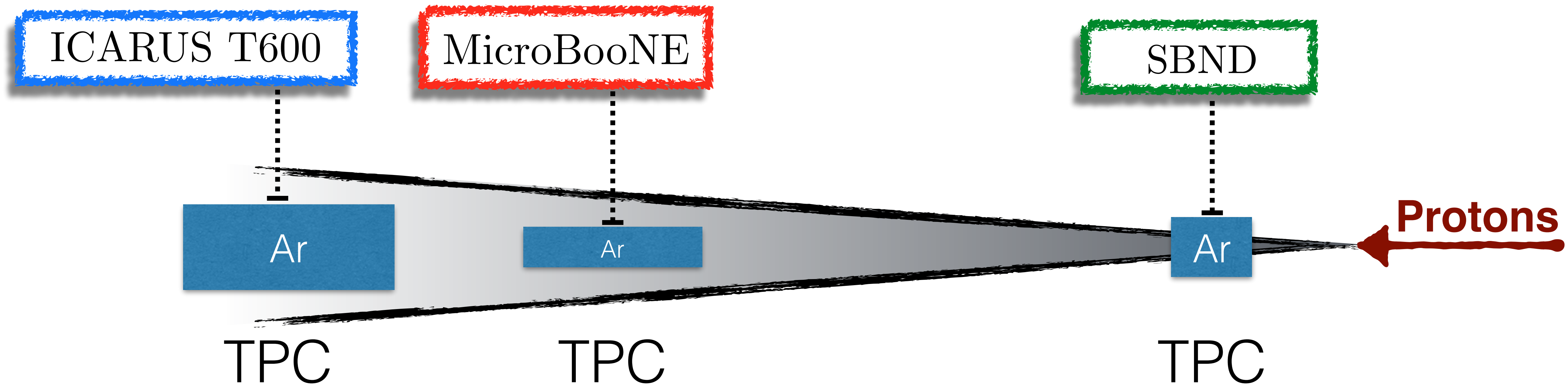


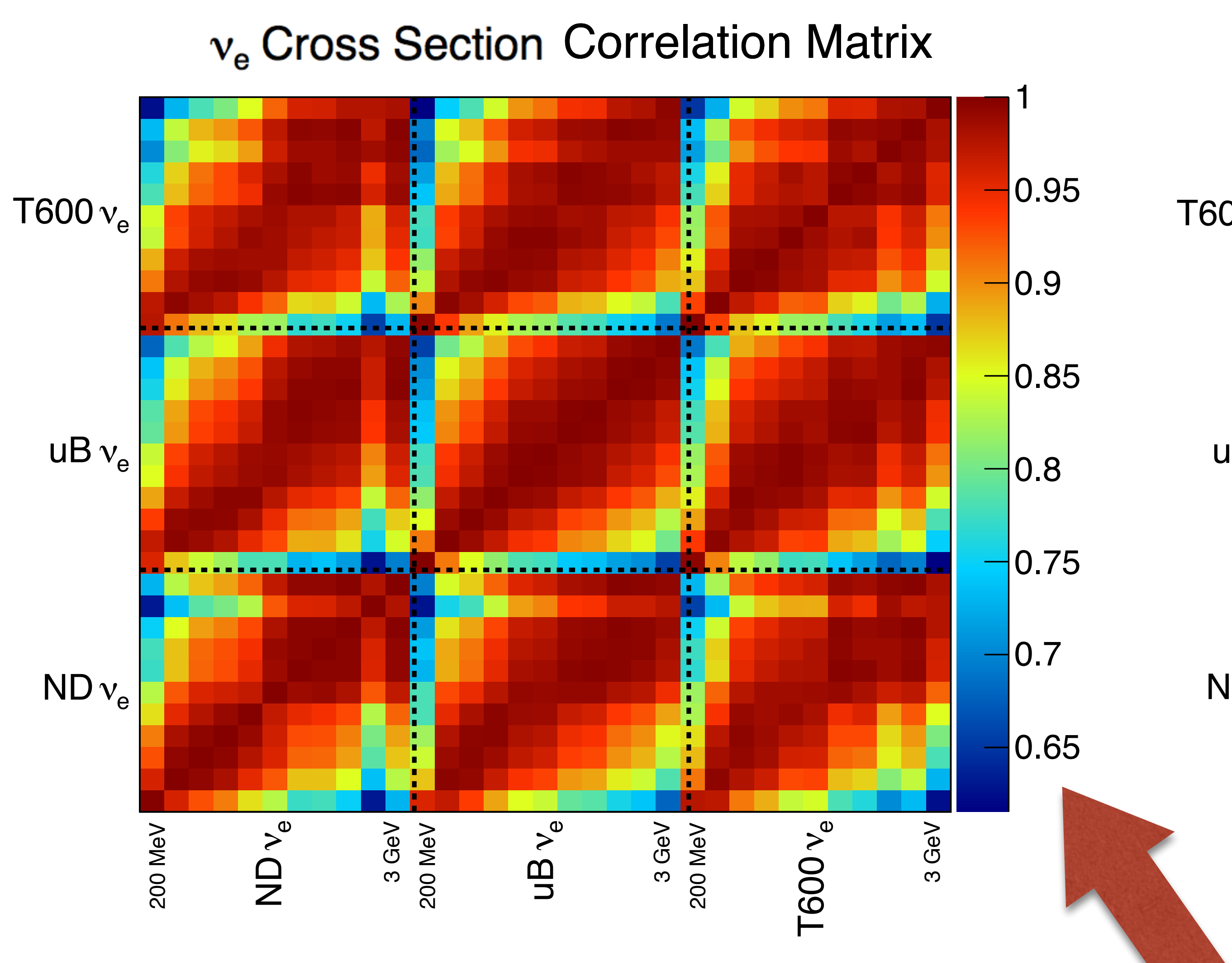


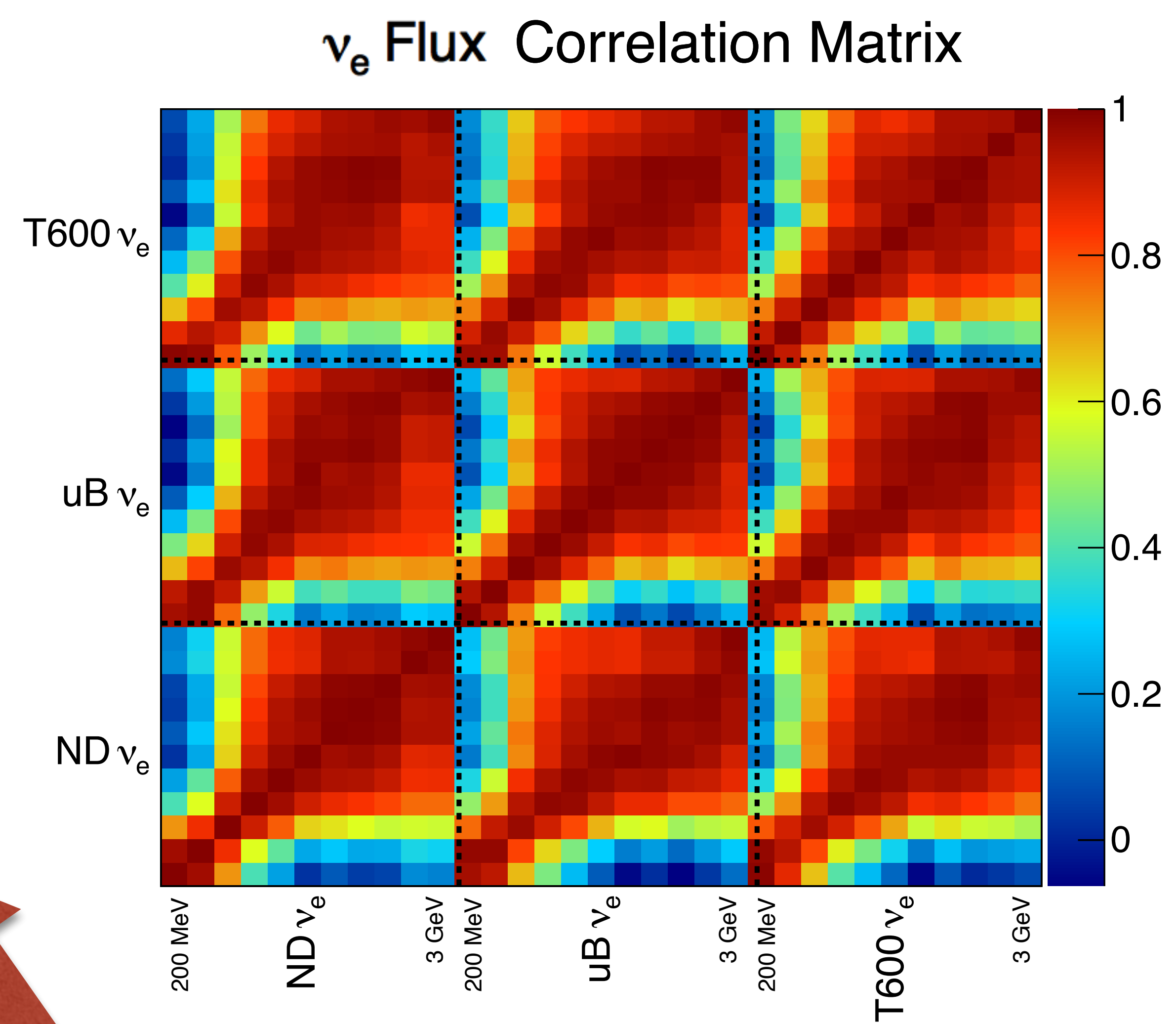


The amount of change expected in **bin *j*** if you measure a deviation in **bin *i***

Flux and Cross Section Correlation Matrices

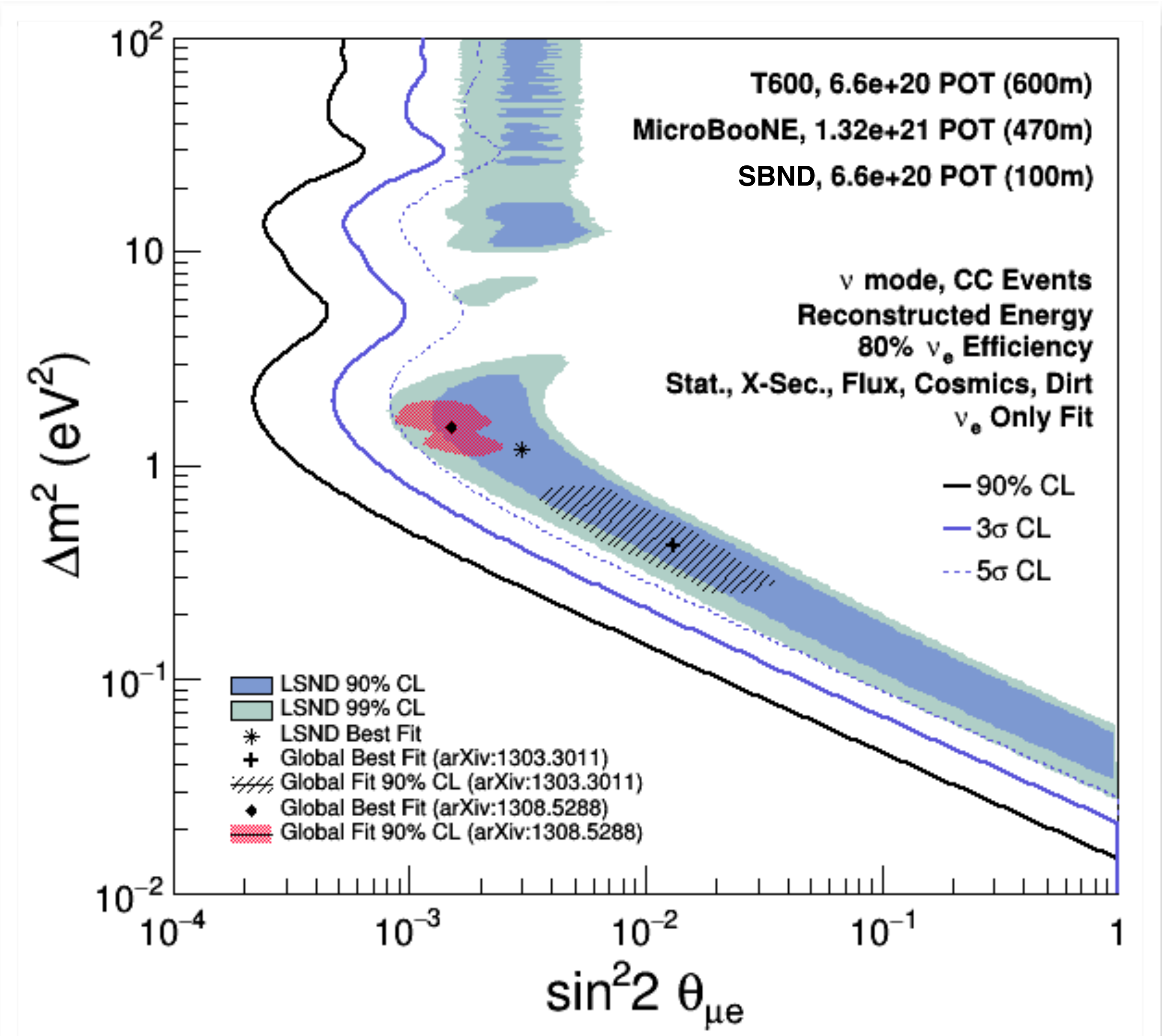




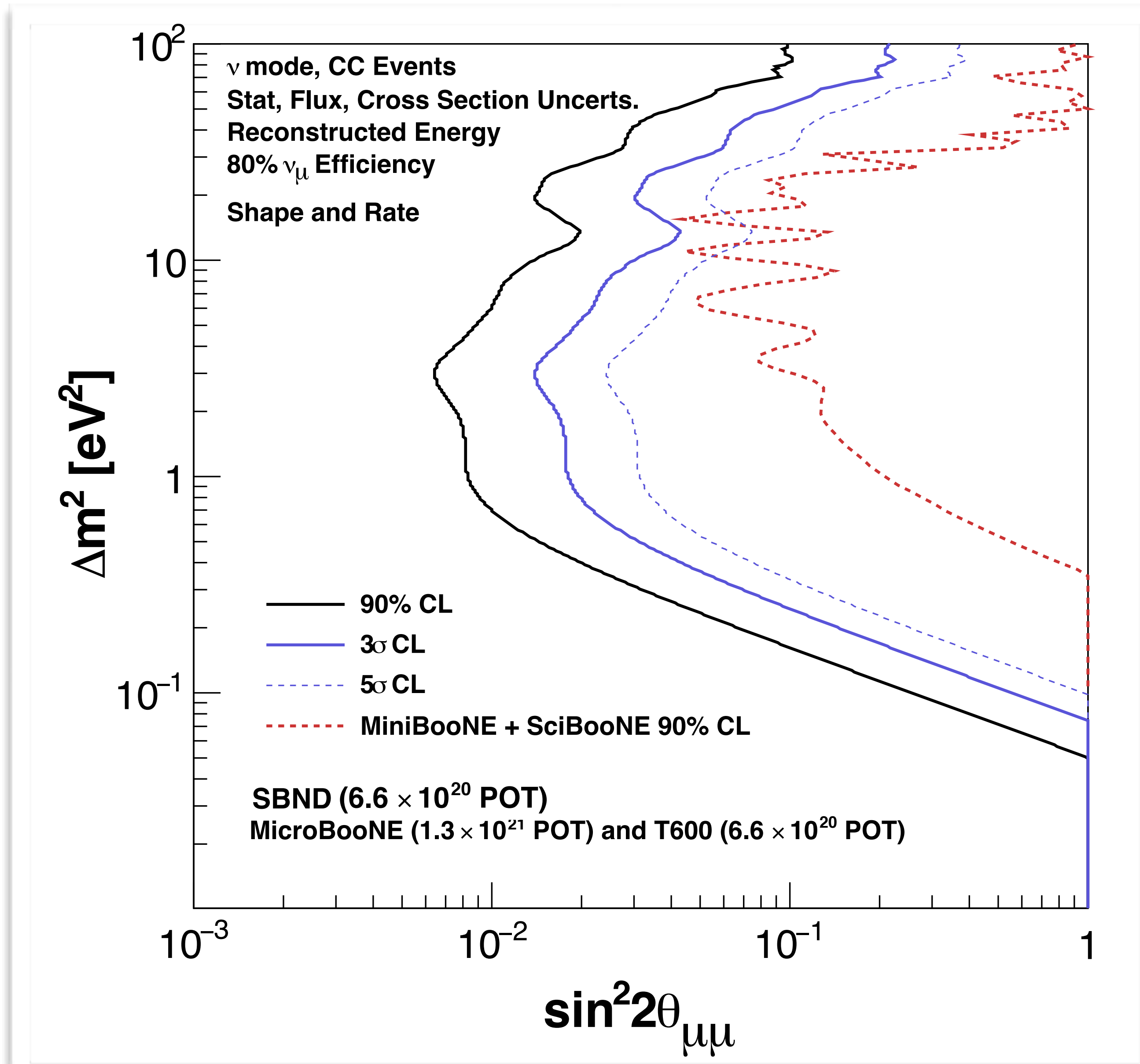


Oscillation Sensitivities

Electron Appearance



Muon Disappearance



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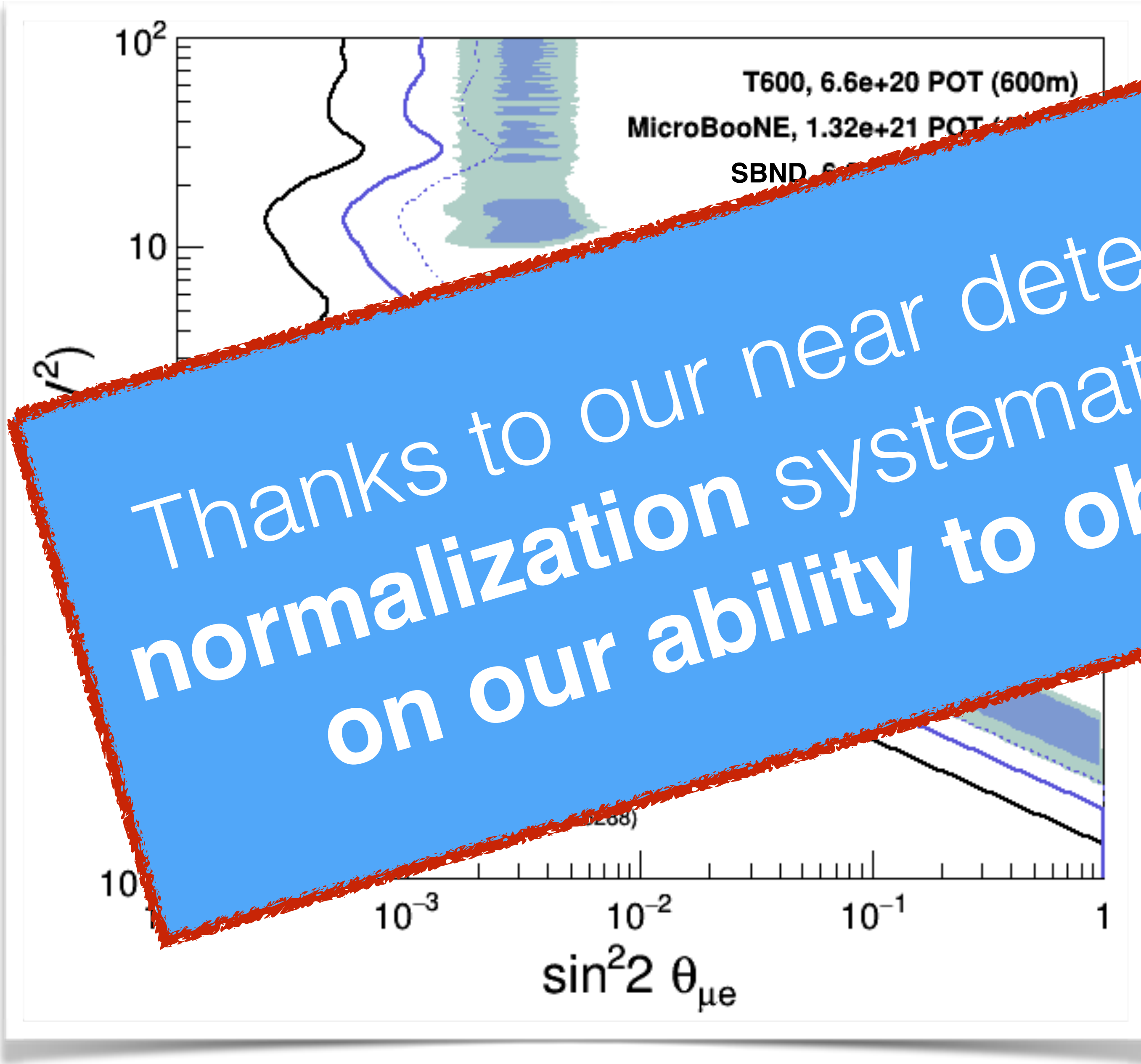
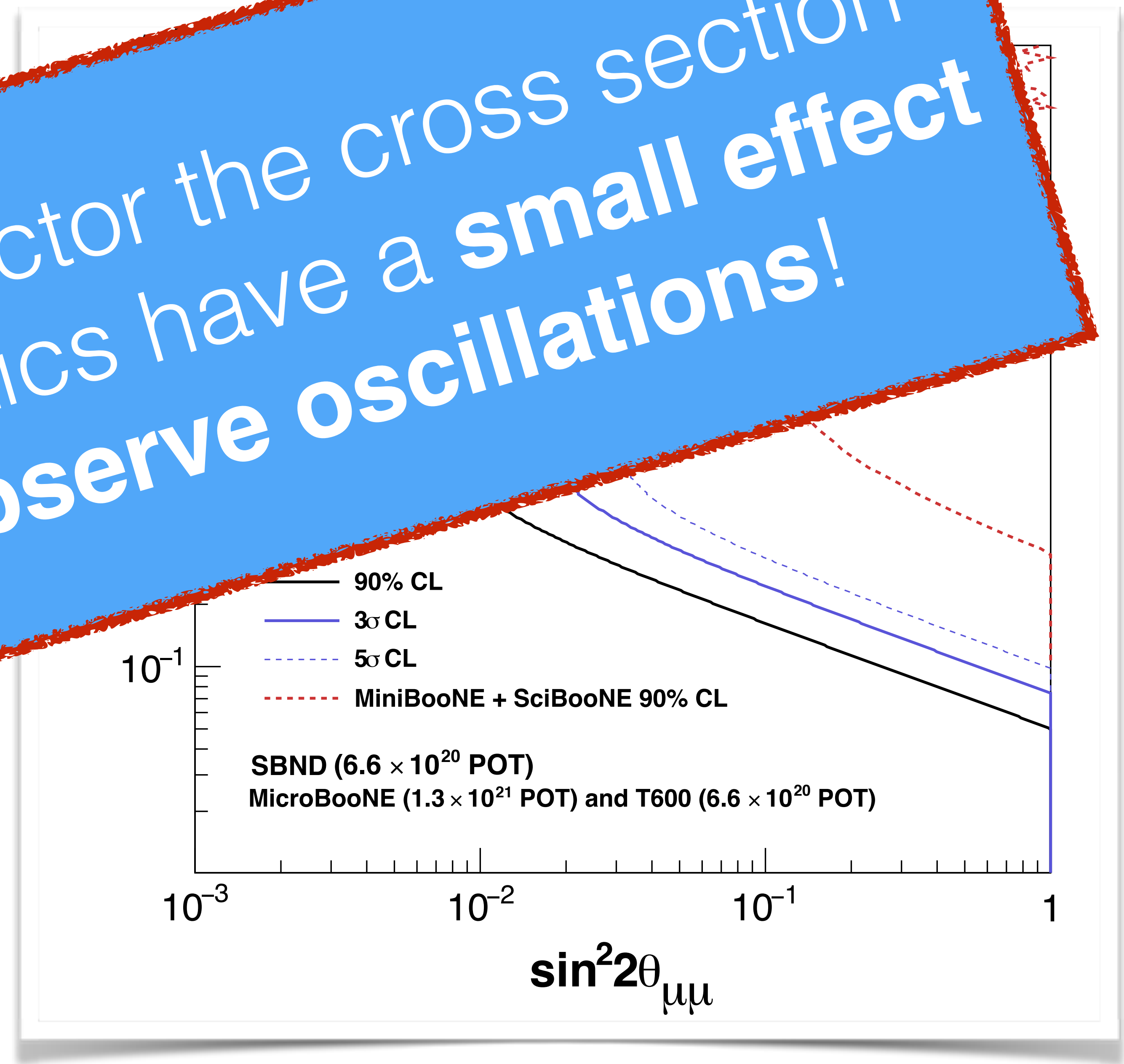


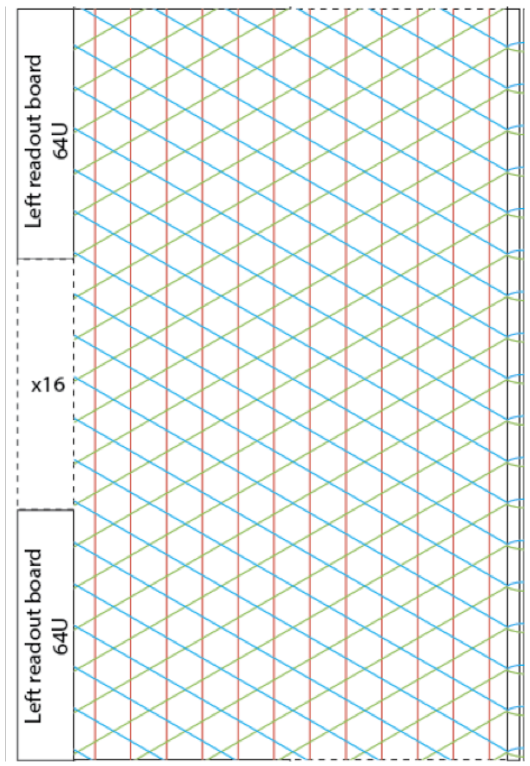


Thanks to our near detector the cross section **normalization** systematics have a **small effect on our ability to observe oscillations**!

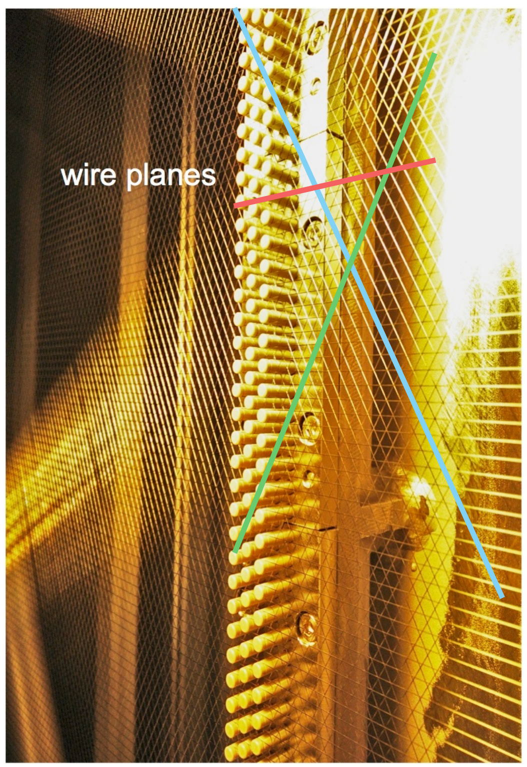
Detector Systematics

- One uncertainty that was not addressed is the detector-to-detector differences
  - All three are LArTPCs but can have differences in wire-orientation, electric fields, etc which can introduce uncorrelated uncertainties
- We need to keep detector systematics at the 2-3% range otherwise they will degrade our sensitivities

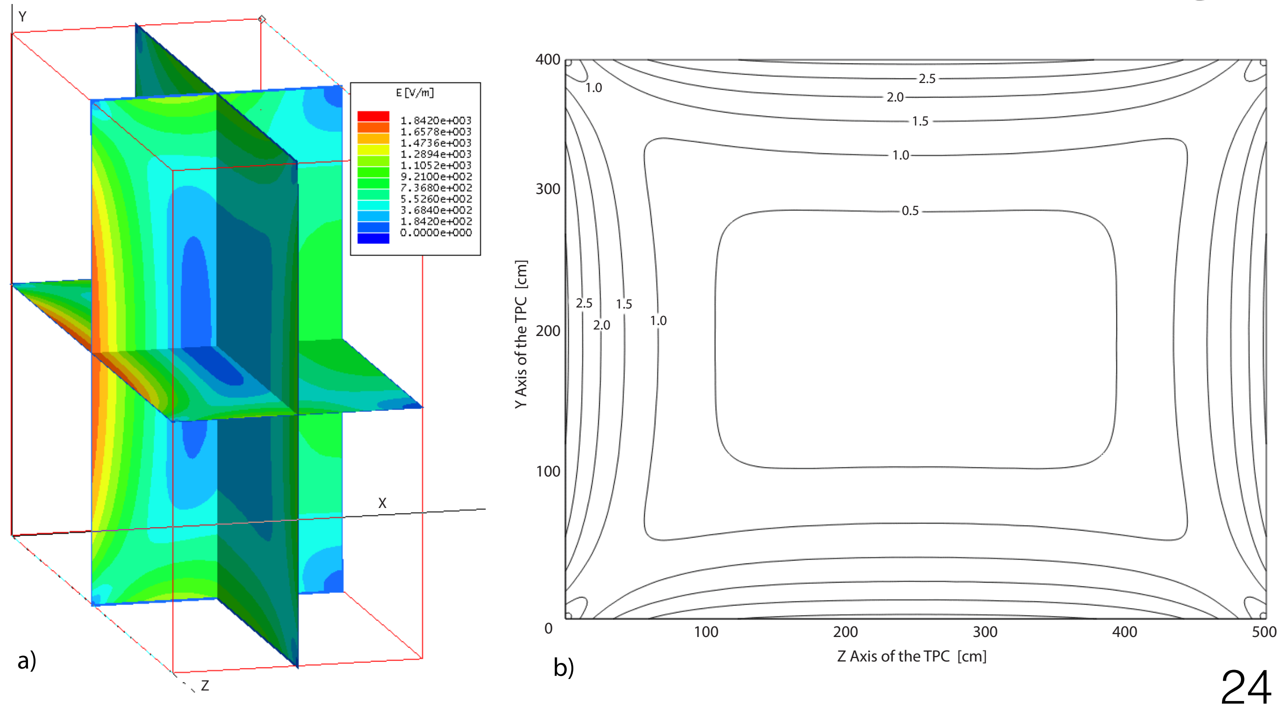
SBND Wires



ICARUS Wires

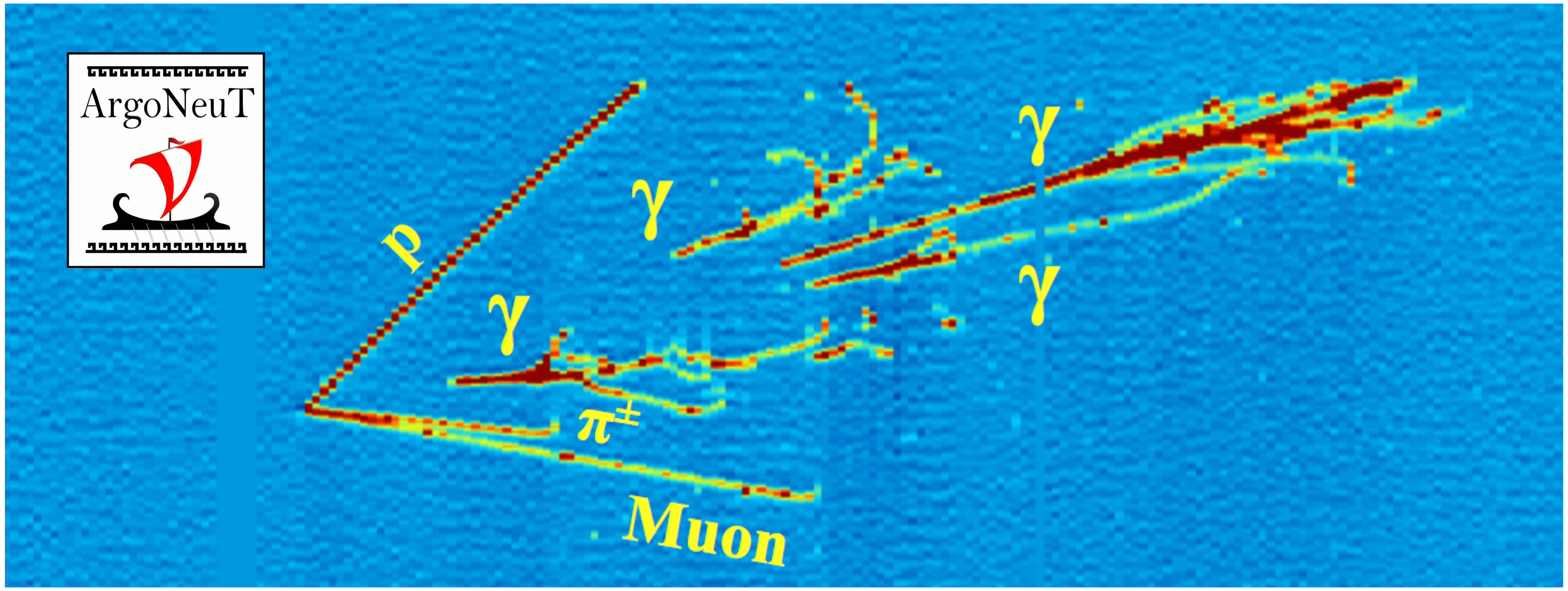


Estimated SBND Space Charge



Additional Systematic Effects

- We have shown that cross section normalization uncertainties will not hamper our ability to resolve an oscillation signal
- If we find a signal we will want to interpret it within the oscillation parameter space
  - Systematics which affect our neutrino energy reconstruction will bias our measurement of these parameters
- All SBN detectors are on the surface so associating neutron scatters with the primary neutrino interaction could be difficult



Neutrino Energy Reconstruction

- LArTPCs enable the use of multiple E_ν definitions
- Each definition of the neutrino energy will be sensitive to different systematics

CCQE-Assumption

$$E_\nu^{QE} = \frac{m_N E_\mu - \frac{m_\mu^2}{2}}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

Calorimetric Method

$$E_\nu^{calo} = E_\mu + \sum T_p$$

Calorimetric Method with Missing pT

Phys.Rev.D90, (2014)

$$E_\nu^{calo+\not{p}_T} = E_\mu + \sum T_p + E_{sep} + \sqrt{\not{p}_T{}^2 - M_{A-np}^2} - M_{A-np}$$

Unaffected

Slightly Biased

Highly Biased

Neutrino Energy Reconstruction

- LArTPCs enable the use of multiple E_ν definitions
- Each definition of the neutrino energy will be sensitive to different systematics

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Calorimetric Method

$$E_\nu^{calo} = E_\mu + \sum T_p$$

Calorimetric Method ... pT

Phys.Rev.D90, (2014)

$$E_\nu^{calo+\not{p}_T} = E \ldots E_{sep} + \sqrt{\not{p}_T{}^2 - M_{A-np}^2} - M_{A-np}$$

See O. Palamara's Talk After Lunch

Unaffected

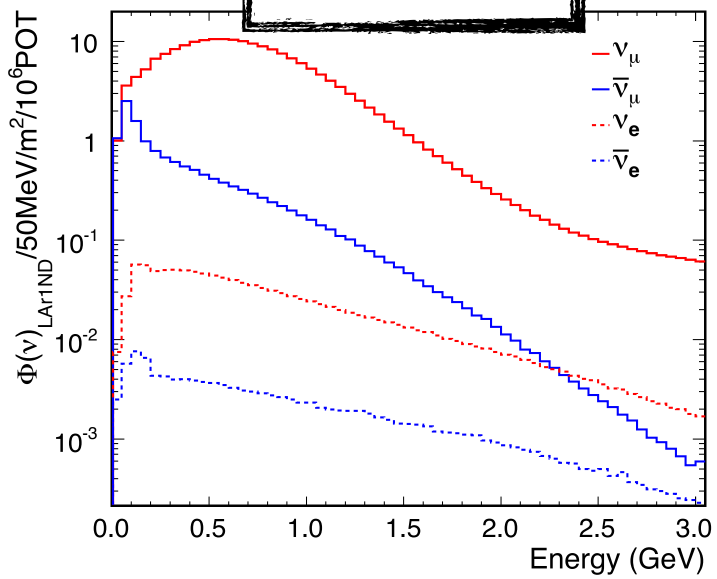
Slightly Biased

Highly Biased

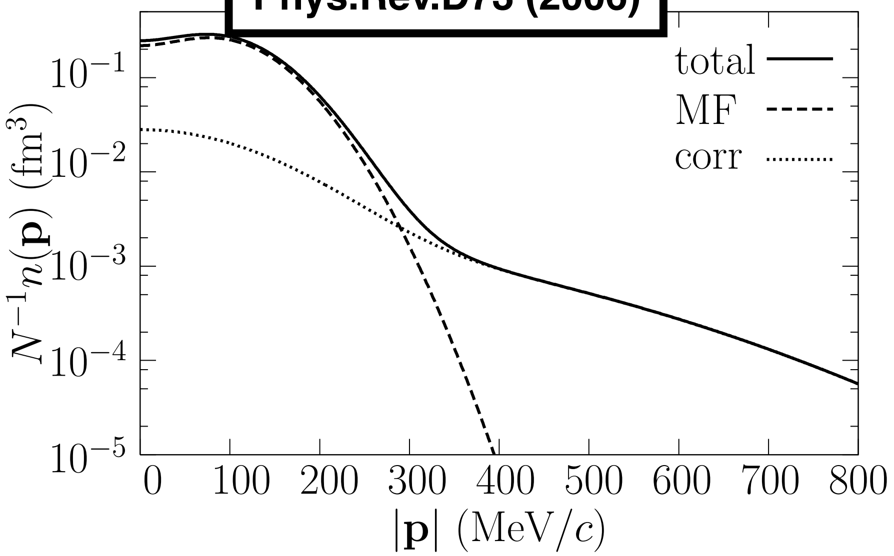
Initial Nucleon Momentum

- The BNB produces fairly low energy neutrinos, with a peak energy of ~800 MeV
- If the nucleon we scatter off has a sizable local momentum it can bias the energy calculation

BNB Flux



F. Berruto, *et al.* Phys.Rev.D73 (2006)



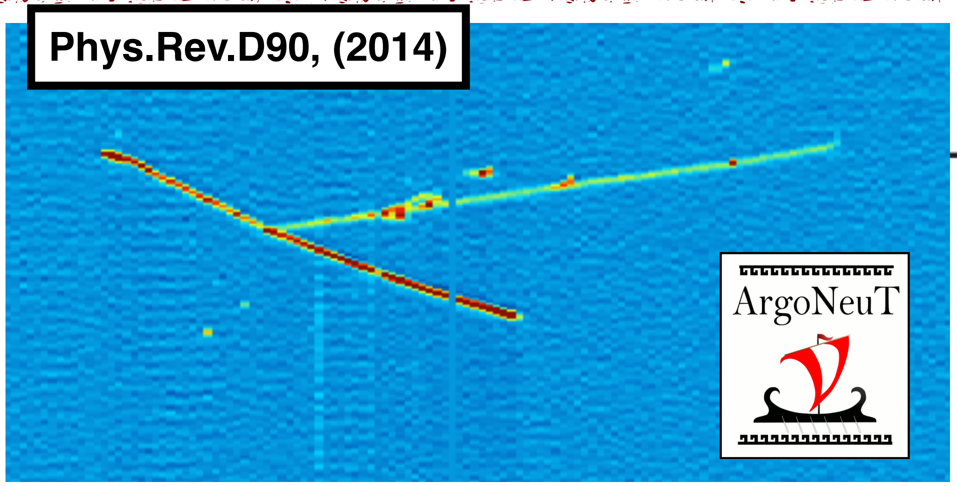
$E_\nu^{calo+\not{p}_T}$ — *Takes into account momentum imbalance*

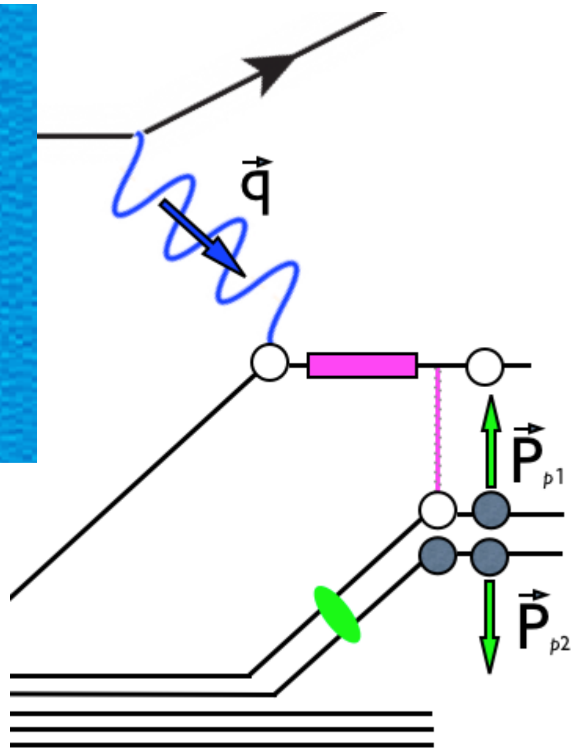
E_ν^{calo} — *Introduce or reduce energy from the system*

E_ν^{QE} — *Assumes stationary nucleons for QE*

Multi-nucleon correlations

- Multi-nucleon correlations will change the final state composition and introduce additional final state energy





- Large sample of neutrino interactions in SBND to estimate the magnitude of this effect
  - Understanding which observables are most sensitive will allow us to constrain them better

$$E_\nu^{calo+\not{p}_T}$$

By correcting for the missing p_T these event will be balanced

$$E_\nu^{calo}$$

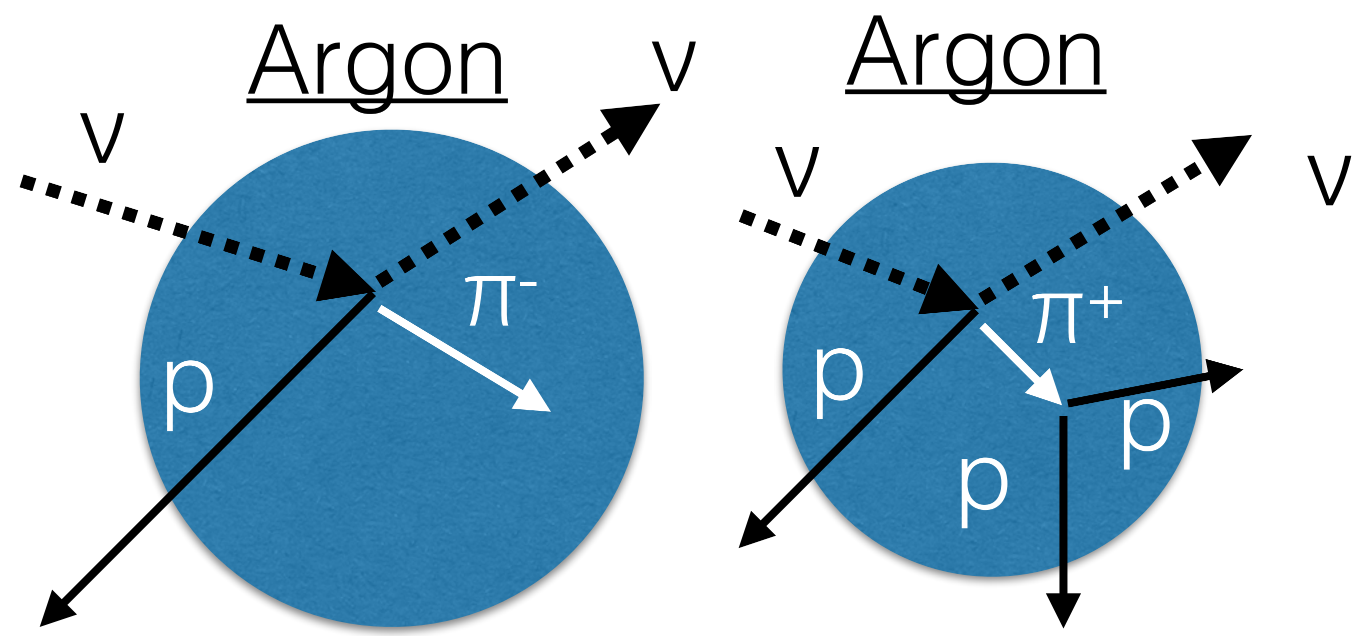
The introduction of energy not due to the neutrino will introduce a bias

$$E_\nu^{QE}$$

Assumes scattering of single nucleon

Final State Interactions

- Final state interactions will play two important roles in our measurement
  - It will modulate the energy of the hadronic side of the interaction
  - Modify the shape and composition of the backgrounds that we expect to see
- LArIAT will measure these effects, scaling can then be applied to move the interaction into the nuclear medium



$E_{\nu}^{calo+\not{p}_T}$

Missing energy creates a bias but missing p_T correction reduces impact

E_{ν}^{calo}

No missing p_T correction so full impact on missing energy

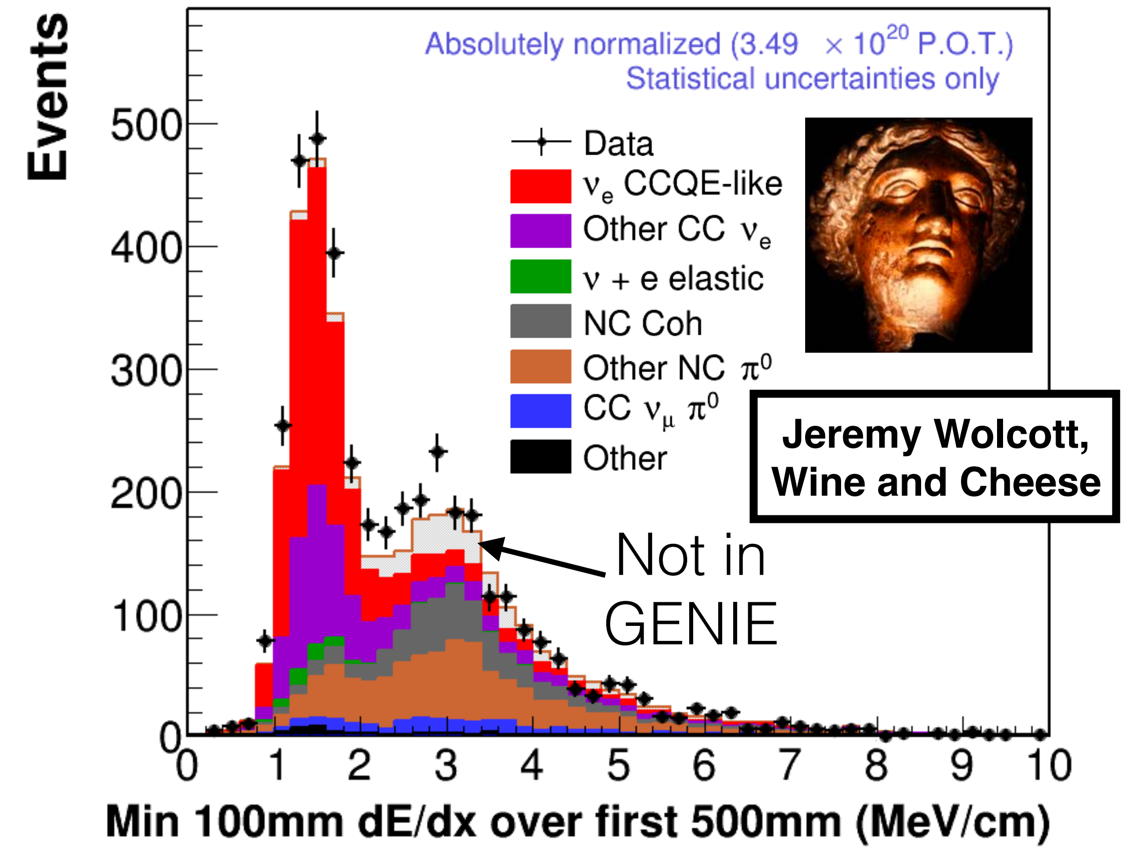
E_{ν}^{QE}

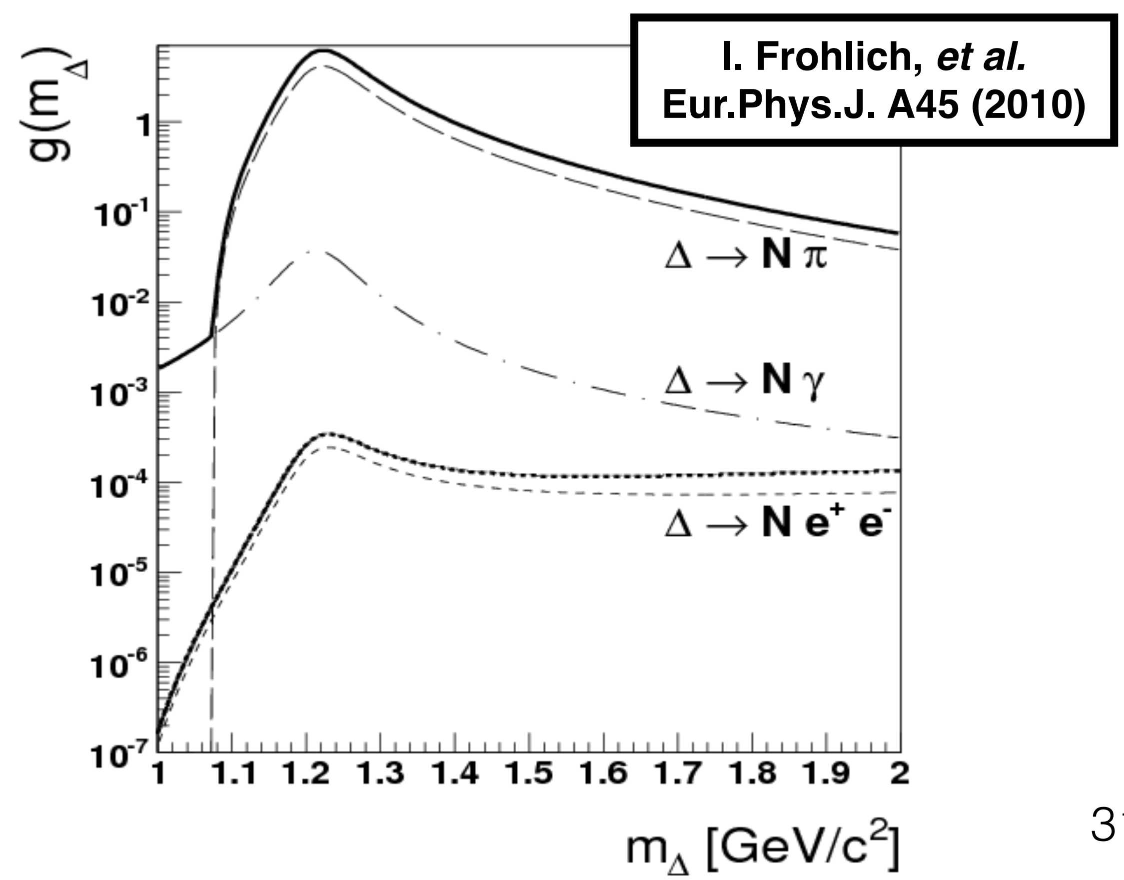
If the event is truly CCQE then only the lepton matters but could hide true topology

Background Modeling

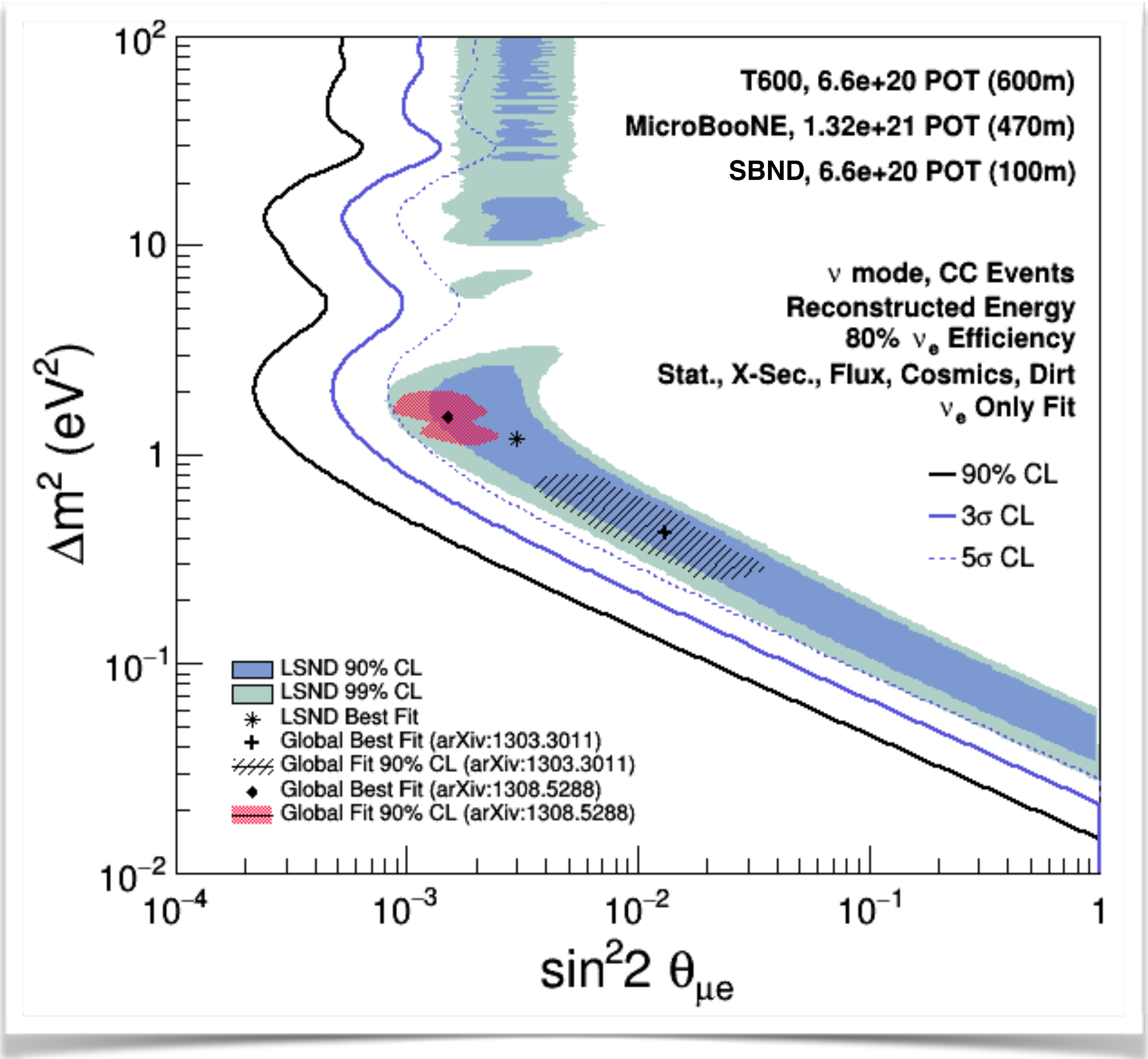
- While we will have a large data sample to validate all of our background predictions having a robust and mature estimate of those backgrounds will be hugely important

- This includes having the various backgrounds included in our generators with realistic branching ratios of the resulting hadrons





Conclusions



- The near detector allows us to constrain many of the interaction systematics and allows high statistics measurements of background channels
- Thanks to the LArTPC technology we can rely on a variety of neutrino energy reconstruction methods

Understanding impact of systematics associated with E_ν biases are essential to properly interpret any observed oscillation signal

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Back-up Slides

Effect of More Statistics