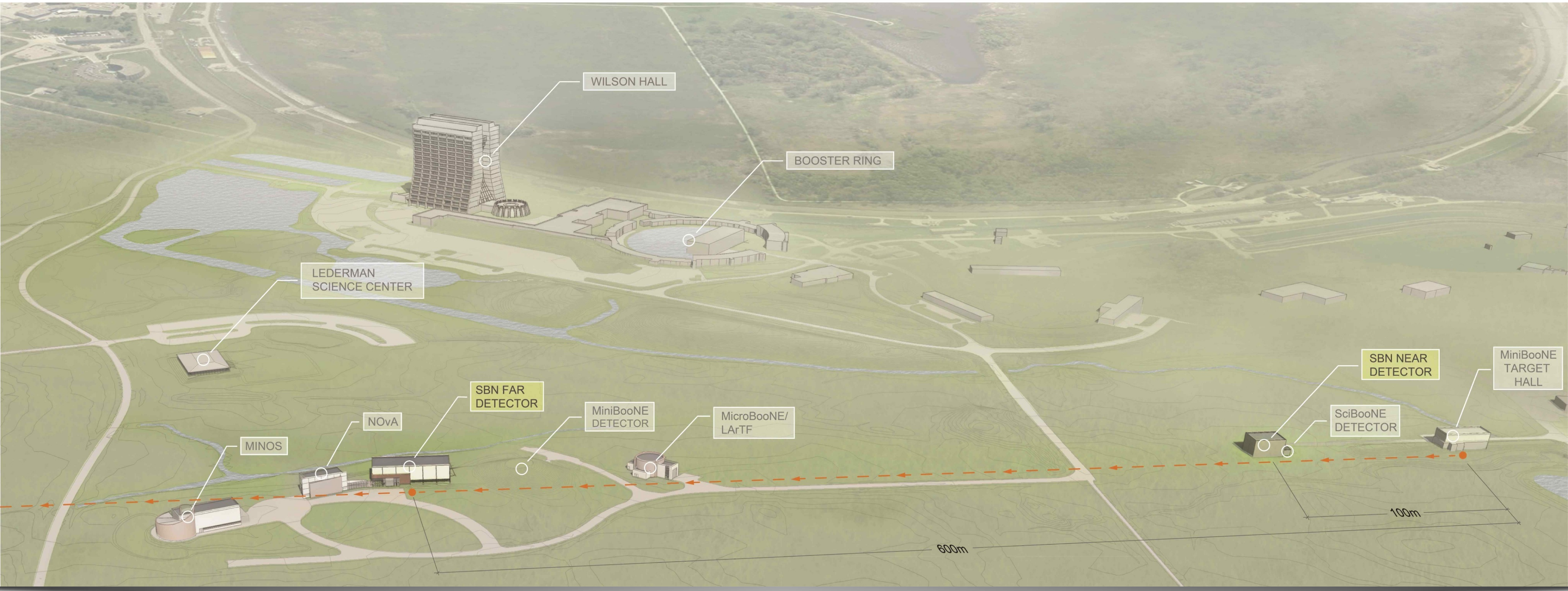
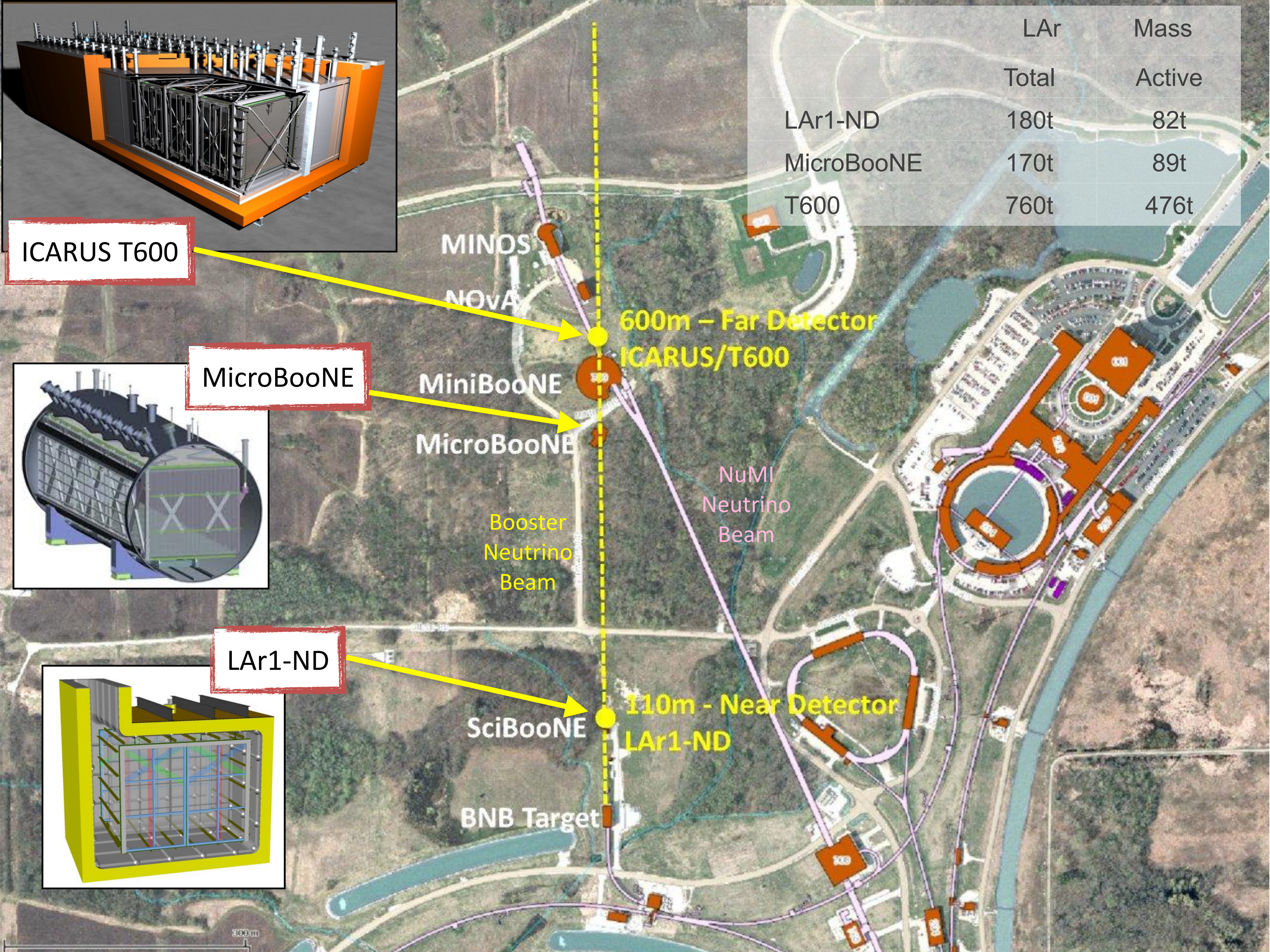
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam

SBN Physics Sensitivities



David Schmitz THE UNIVERSITY OF CHICAGO

for the SBN Task Force and the SBN Collaborations



	LAr	Mass
	Total	Active
LAr1-ND	180t	82t
MicroBooNE	170t	89t
T600	760t	476t

Sensitivity Overview

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- Sensitivity to $\nu_\mu \rightarrow \nu_e$ (ν_e appearance) signals using inclusive ν_e charged-current event samples
  - All known backgrounds included
  - Detailed systematics evaluation, correlations between data sets
  - Some conservative choices & assumptions where future improvement will be possible

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  - Important capability with an accelerator decay-in-flight beam experiment that is complementary to an appearance search for sterile neutrino oscillations
- Appearance (ν_e) and disappearance (ν_μ) analyses currently performed <u>independently</u>
  - Simultaneous analysis of ν_e/ν_μ, including correlations between samples, will greatly improve ability to understand any new physics signals

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For beam events, same simulation used in ALL three detectors, so sample correlations can be evaluated from Monte Carlos

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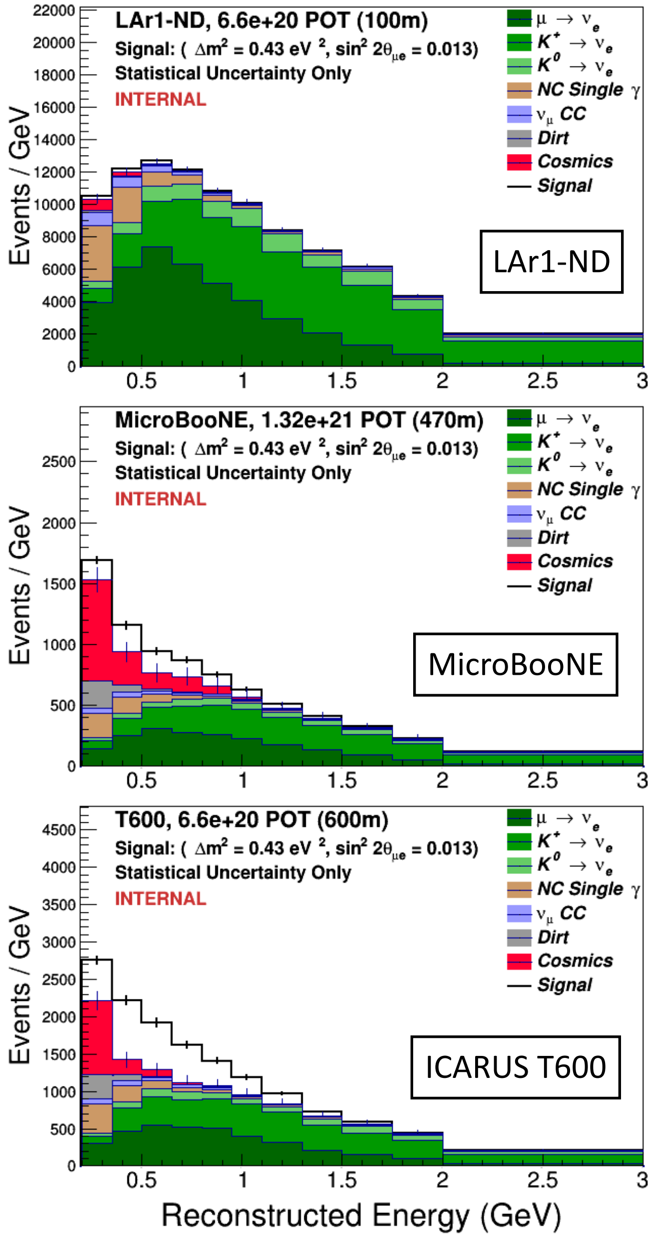
- Observation thresholds are applied based on relevant experience from other detectors (e.g. 21 MeV proton threshold in ArgoNeuT data)

- ‘Reconstructed Neutrino Energy’ is calculated by summing energies of visible final state particles. True energies are smeared according to expected resolutions ($15\%/\sqrt{E}$ for e.m. showers, 5% for hadrons, etc.)

ν_e CC Signal & Background Categories



- **Electron neutrino CC interactions**
  - $\pi \to \mu \to \nu_e$
  - $K^+ \to \nu_e$
  - $K^0 \to \nu_e$

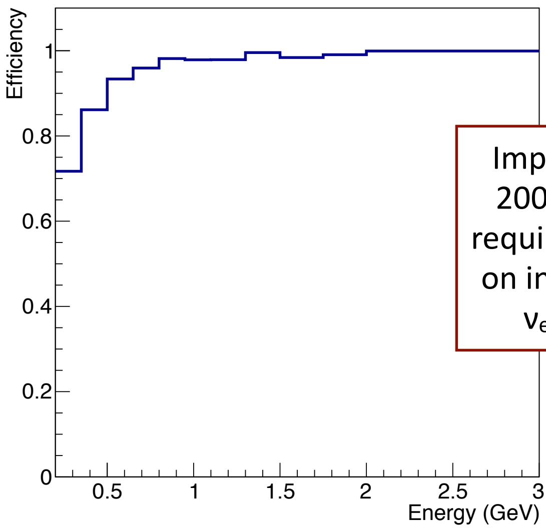
  Intrinsic beam ν_e
  - Sample appearance signal

- **Photon-induced e.m. shower backgrounds**
  - NC misIDs
  - ν_μ CC misIDs
  - "Dirt" Backgrounds: beam-related but out-of-detector interactions
  - Cosmogenic photon sources

Electromagnetic Shower Selection

Electromagnetic Shower Selection

- We require the electromagnetic shower in all selected events to be initiated with $E > 200$ MeV
  - E_e for electron showers
  - E_γ for gamma pair production events
  - E_e for gamma Compton scattering events



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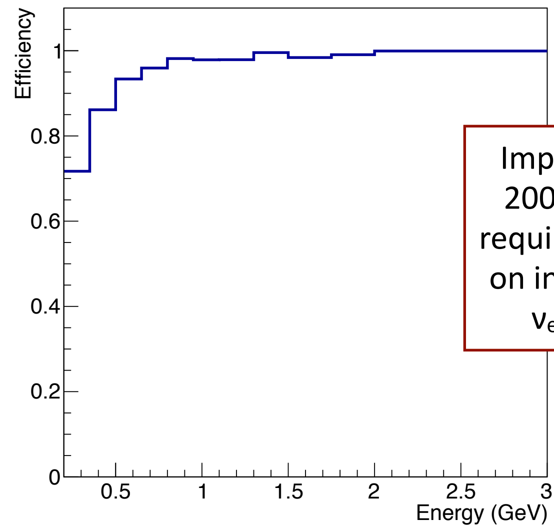

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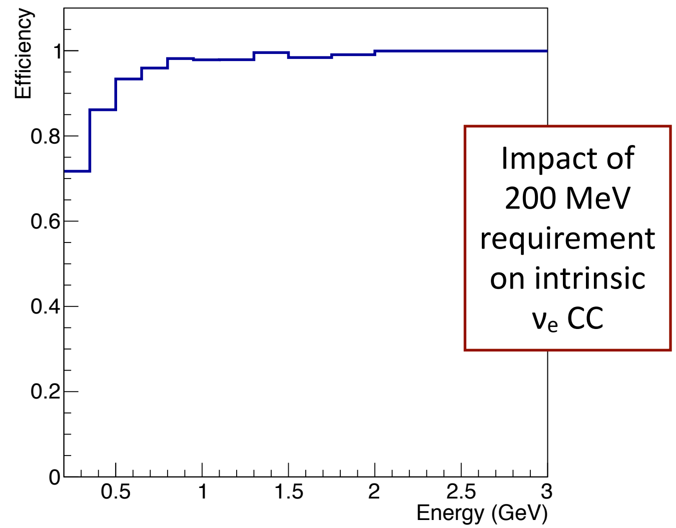
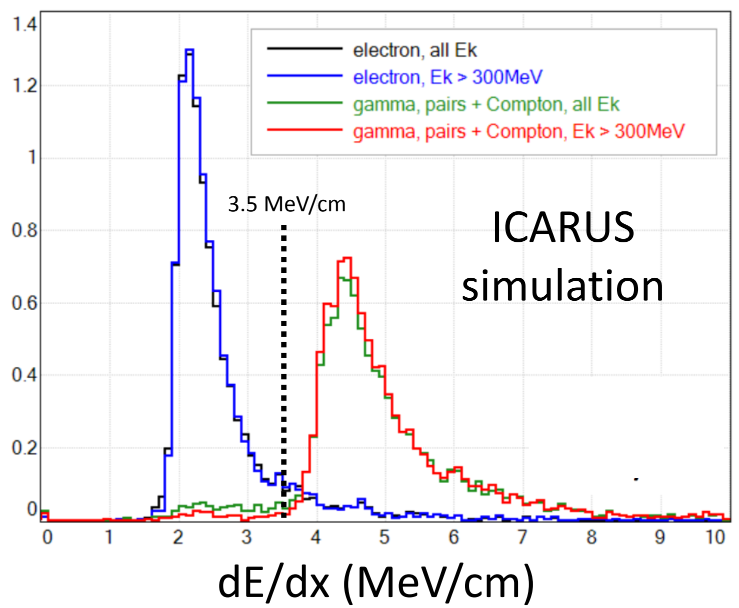


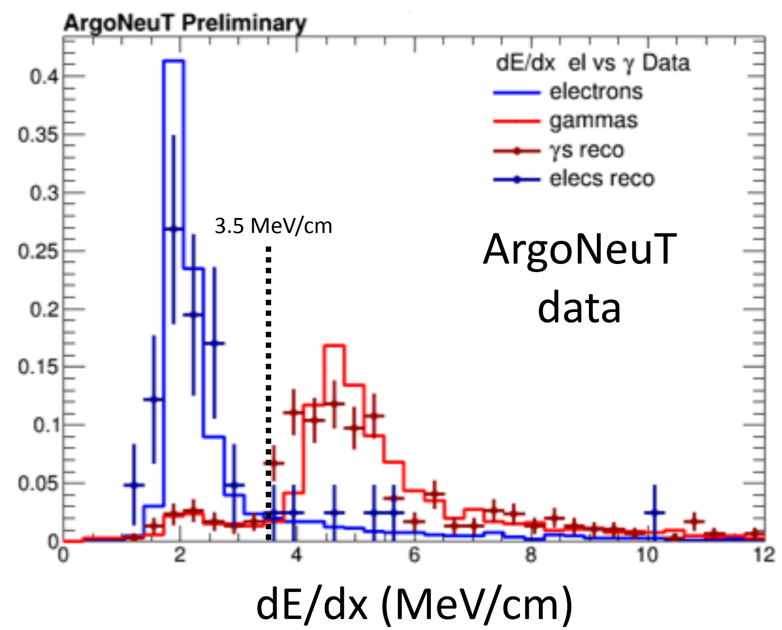
- This minimum shower threshold is applied to help ensure good reconstruction and identification of signal events

- Note the threshold for analysis of events in LAr should be below this and lower energy events will certainly be studied in the SBN experiments, they are just not included here

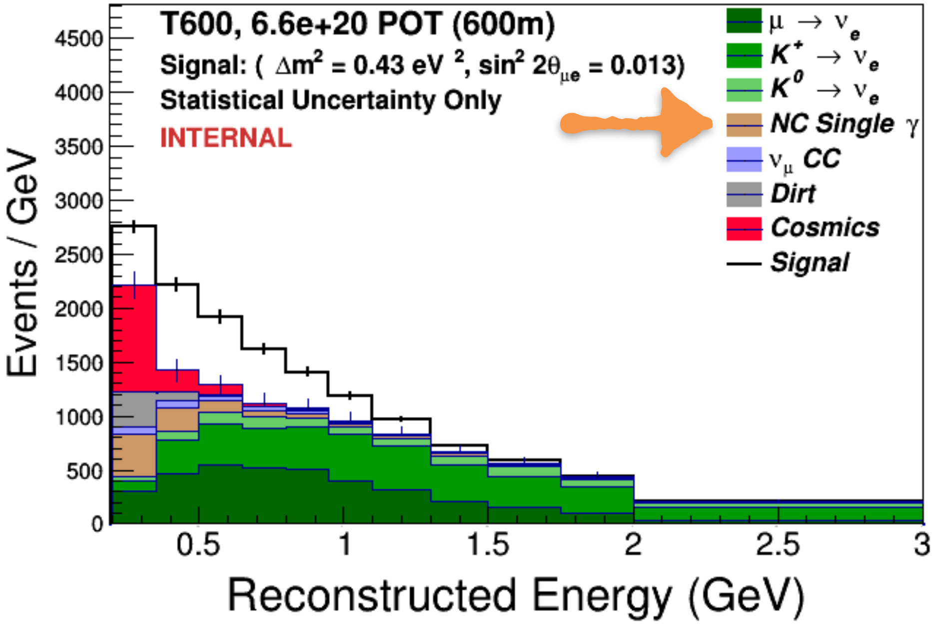
Electromagnetic Shower ID Efficiencies

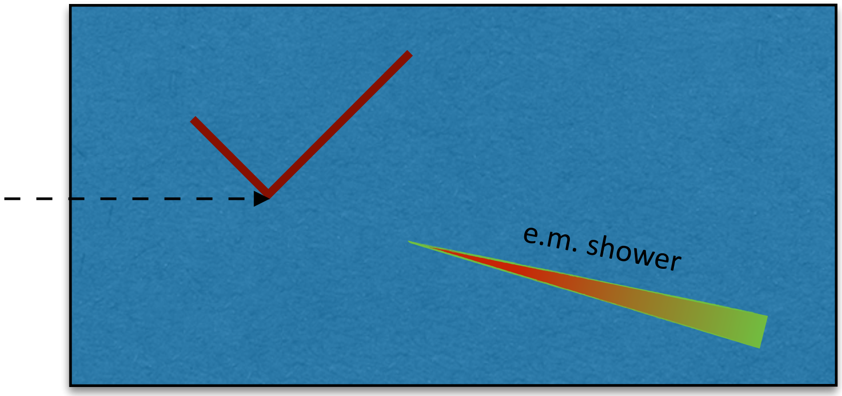
- Electron showers:
  - 80% identification efficiency applied to charged-current inclusive sample for intrinsic and signal electron neutrinos (after 200 MeV requirement)
- Individual photon showers:
  - 94% rejection of single photon pair production showers ($\gamma \rightarrow e^+e^-$) based on expected performance of dE/dx analysis to identify 2 mips at the start of the shower
  - Single photon Compton scatters are retained as an irreducible background





NC Photon Final States





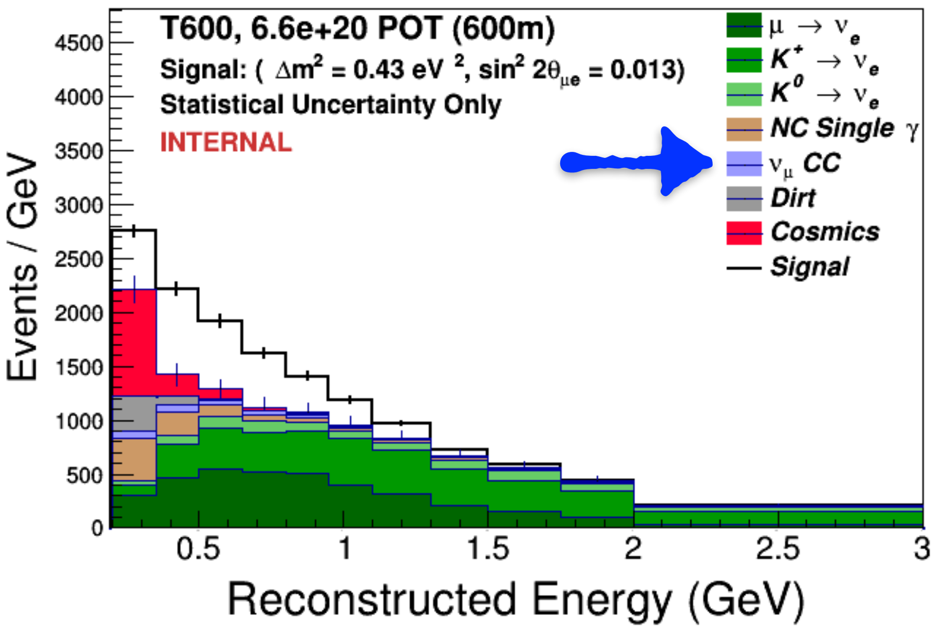
Vertex Requirement: > 50MeV
Gap Requirement > 3cm

- Neutral current $\pi^0 \rightarrow \gamma\gamma$
  - If both photons convert above threshold in TPC volume, can reject
  - If only one converts:
    - Look for a visible event vertex and a gap before the e.m. shower
    - dE/dx cut to reject pair production
- Neutral current single γ final states
  - Look for a visible event vertex and a gap before the e.m. shower
  - dE/dx cut to reject pair production

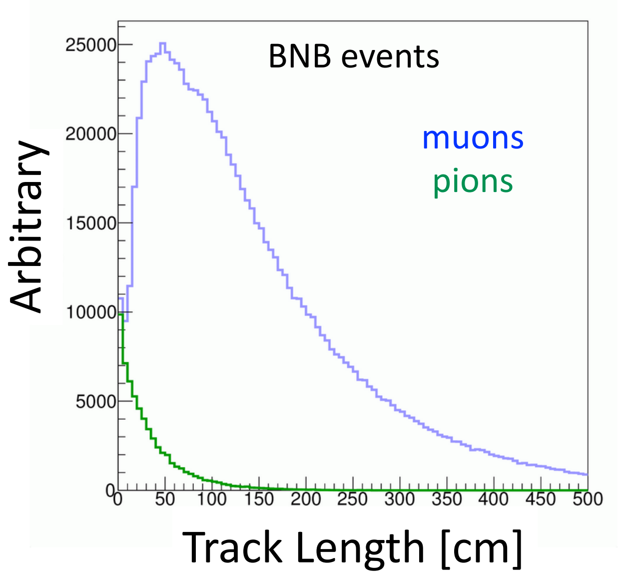
Summary:

Conversion Gap + dE/dx

ν_μ CC Interactions



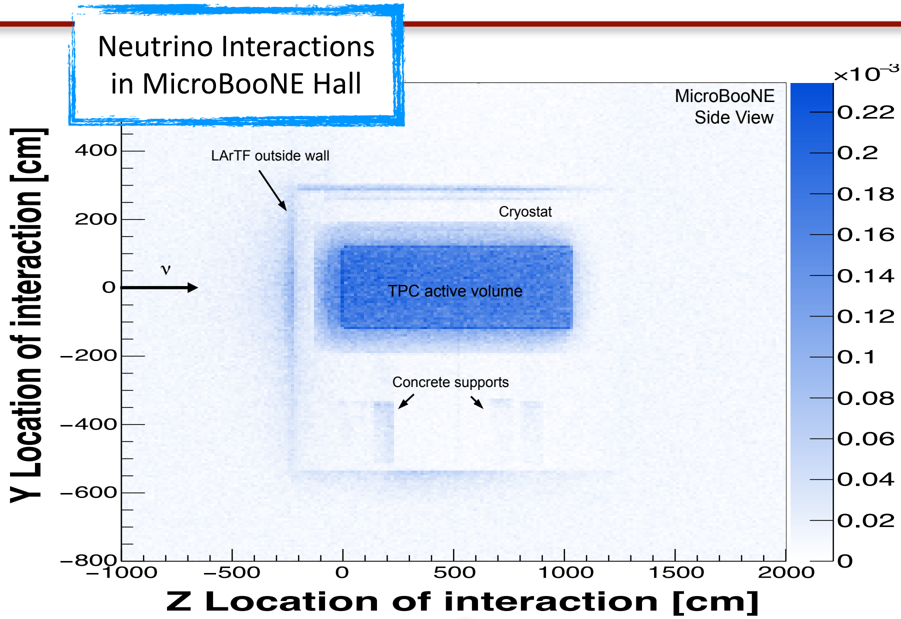
- Minimum ionizing tracks longer than 1m in BNB events are almost all muons
- Events with longest track $\geq$ 1m are rejected as ν_μ CC
- When longest track < 1m and there is an e.m. shower in the final state, the shower is analyzed as in the NC case

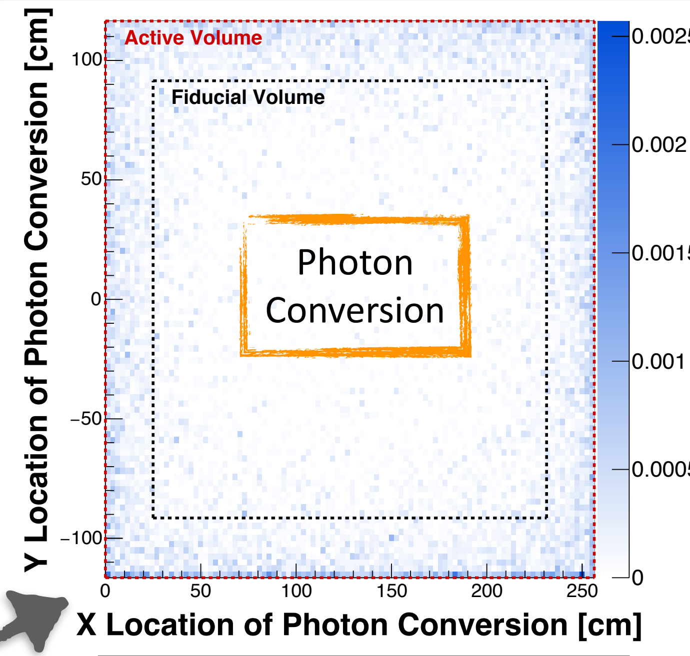


Summary:

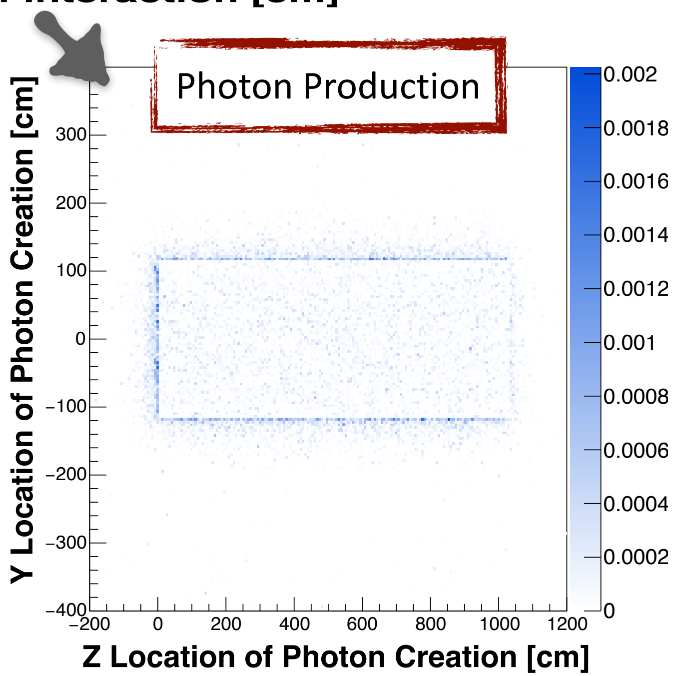
L_{track} + Conversion Gap + dE/dx

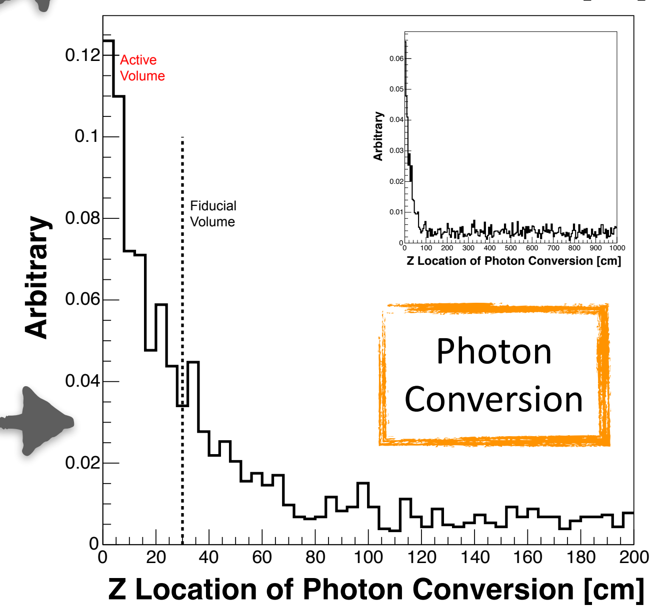
“Dirt” Backgrounds





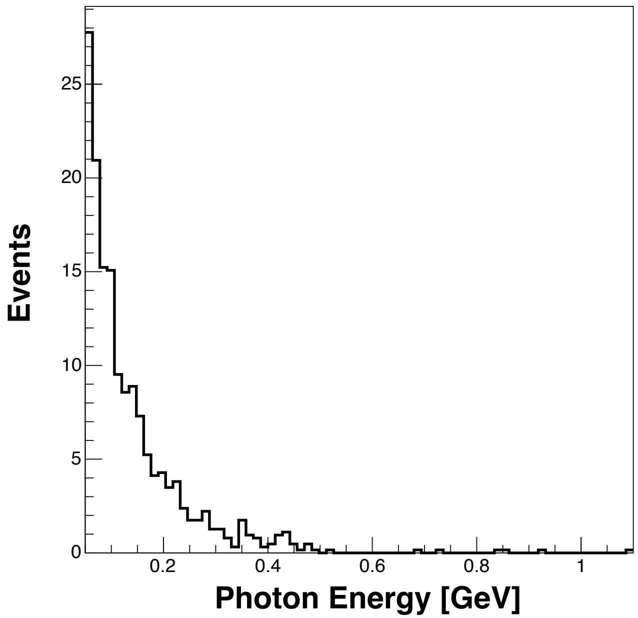
- Single photon entering the detector creates a potential background
- Helped by short radiation length in argon (14 cm)





"Dirt" Backgrounds

Detector	Estimated Dirt Background Events (6.6×10^{20} POT)		
	$z \leq 50\ cm$	$z > 50\ cm$	Total
LAr1-ND	26.2	17.0	43.2
MicroBooNE	2.38	19.5	21.9
ICARUS-T600	5.15	57.0	62.2

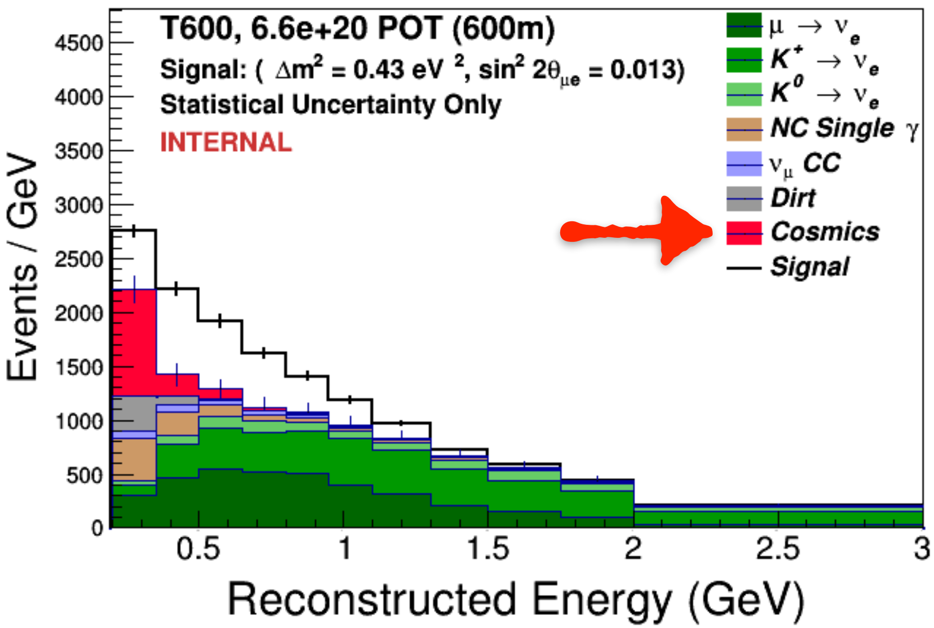


- Chose a very **conservative 25 cm buffer around the fiducial volume** to minimize dirt contamination (also reduce external cosmogenic photons)
- Will be revisited in future to optimize against fiducial volume loss
- Apply more sophisticated external photon ID (e.g. distance to wall in reverse shower direction)

Summary:

dE/dx + Fiducial Volume Buffer

Cosmogenic Backgrounds



- The problem: 1000x longer charge drift time than the beam spill length
  - 1.6 μs beam spill
  - ~1 ms TPC drift time

	Cosmic muons per readout	*Neutrino interaction every N spills*	*Cosmic muon in beam spill every N spills*
LAr1-ND	***2.9***	***25***	***300***
MicroBooNE	***5.0***	***800***	***200***
T300	***5.5***	***500***	***100***

Cosmogenic Backgrounds

- Again, the 14cm radiation length is a help
  - Any primary photons that penetrate the shielding or are produced by other primaries around the detector will convert mostly near the TPC active volume boundaries
- Dominant source of cosmogenic e.m. showers in the TPC are, therefore, muons that <u>also enter the TPC</u>.

	Cosmic photon interaction description	Timing Cat.	Topology Cat.	$E_\gamma > 200$ MeV, Pair prod $E_e > 200$ MeV, Compton LAr1-ND	 μBooNE	 ICARUS
1	γ Compton in spill, primary μ enters AV	A	I	887	206	599
2	γ Pair prod in spill, primary μ enters AV	A	I	52,300	11,600	32,000
3	γ Compton in spill, primary misses AV	A	II	<1	<3	<4
4	γ Pair prod in spill, primary misses AV	A	II	55	82	11
5	γ Compton in drift, primary μ enters AV	B	I	2,550	1,030	3,300
6	γ Pair prod in drift, primary μ enters AV	B	I	150,200	57,950	176,000
7	γ Compton in drift, primary misses AV	B	II	<3	12.4	<4
8	γ Pair prod in drift, primary misses AV	B	II	160	410	60

γ In Spill Time

$\times N_\mu^{\text{drift}}$

γ In Drift (muon in spill)

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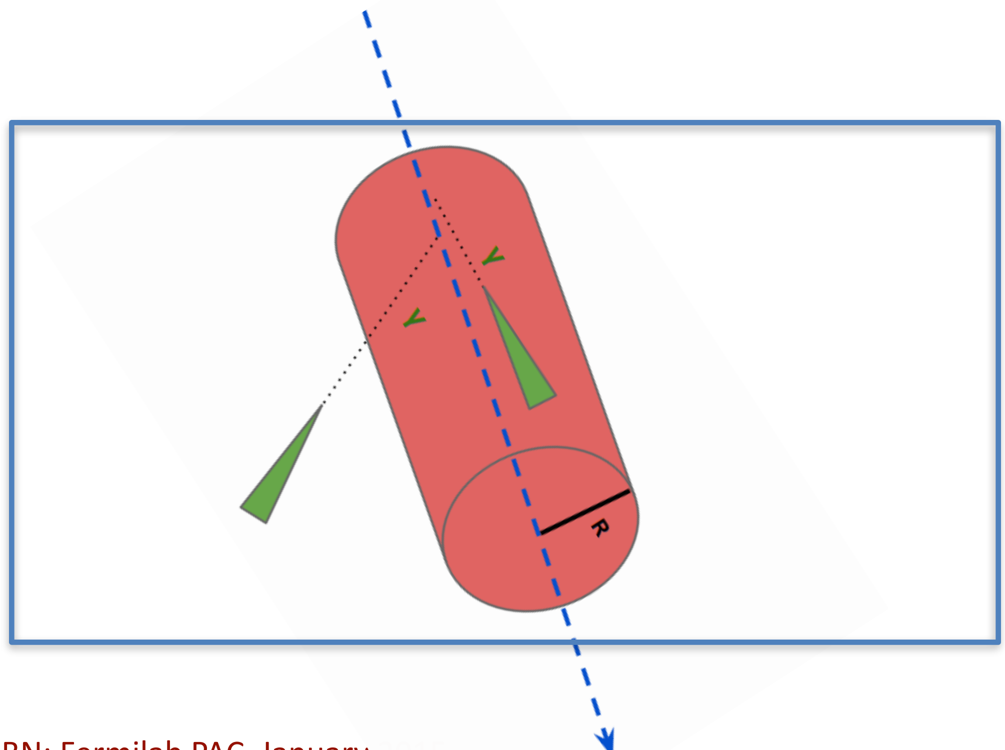
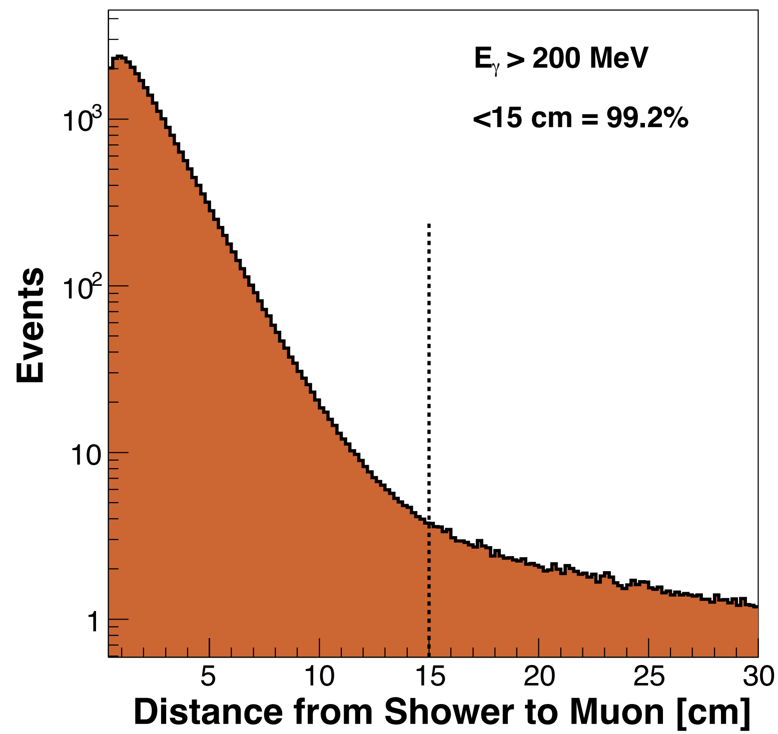




Cosmogenic Backgrounds

- Topology I: parent muon enters the active volume
  - Reject showers within a cylinder around all muon tracks (reject ~99%)
  - dE/dx for pair production showers (reject 94%)
- Topology II: primary photon or parent is not visible
  - dE/dx for pair production showers (reject 94%)

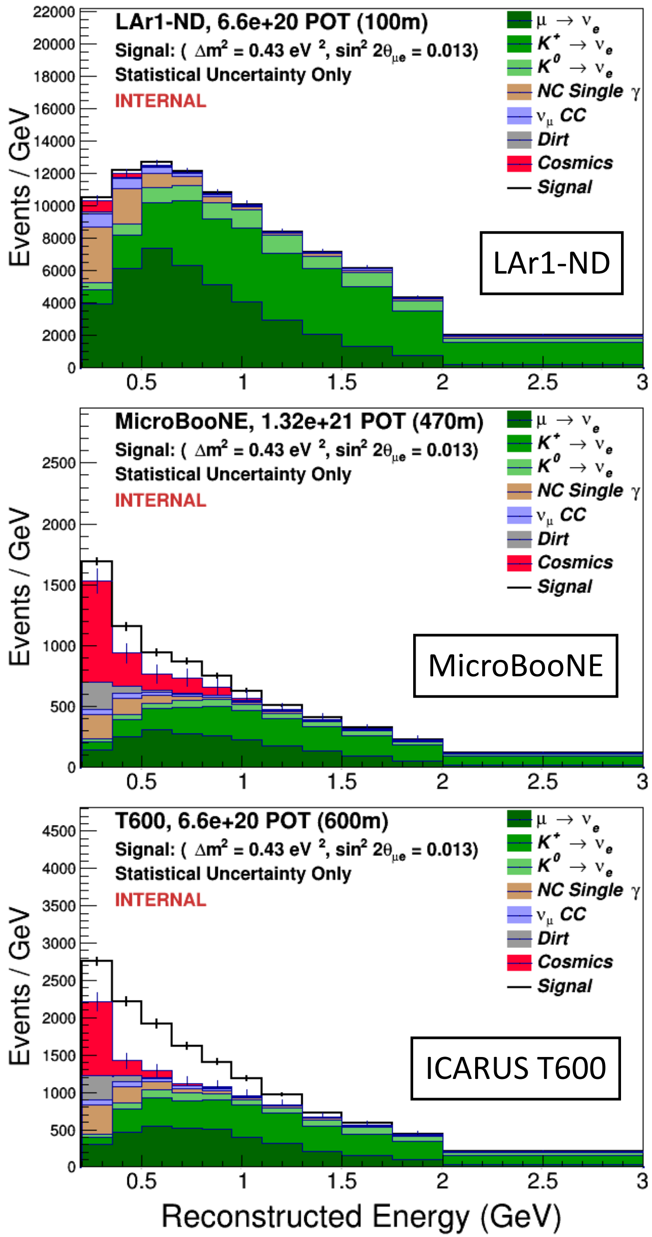
	Interaction description	Timing Cat.	Topology Cat.	$E_\gamma > 200$ MeV, Pair prod $E_e > 200$ MeV, Compton, ν_e LAr1-ND	μBooNE	ICARUS
1	γ Compton in spill, primary μ enters AV	A	I	8	<3	<4
2	γ Pair prod in spill, primary μ enters AV	A	I	26	6	21
3	γ Compton in spill, primary misses AV	A	II	<1	<3	<4
4	γ Pair prod in spill, primary misses AV	A	II	<4	6	<1
5	γ Compton in drift, primary μ enters AV	B	I	22	12	30
6	γ Pair prod in drift, primary μ enters AV	B	I	74	29	113
7	γ Compton in drift, primary misses AV	B	II	<3	12	<4
8	γ Pair prod in drift, primary misses AV	B	II	10	19	<4
	Total Cosmogenic γ backgrounds			146	88	164
	Intrinsic ν_e CC			15,800	413	1,500

γ In Spill Time

$\times N_\mu^{\mathrm{drift}}$

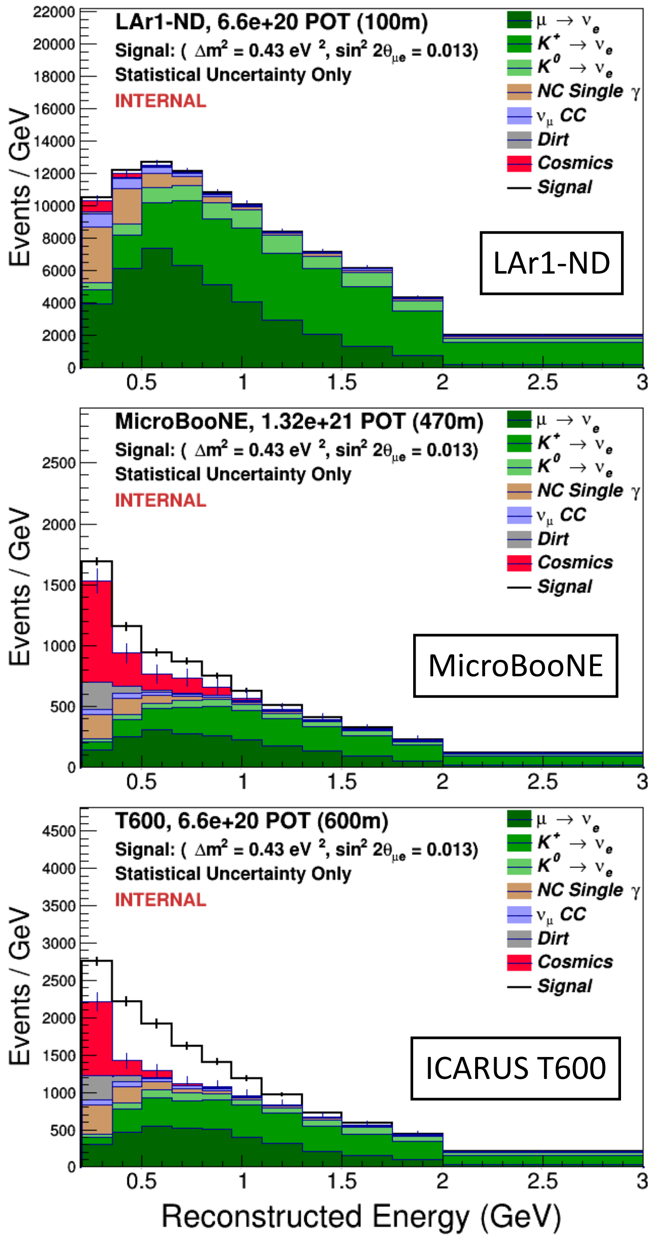
γ In Drift (muon in spill)

ν_e CC Signal & Background Categories



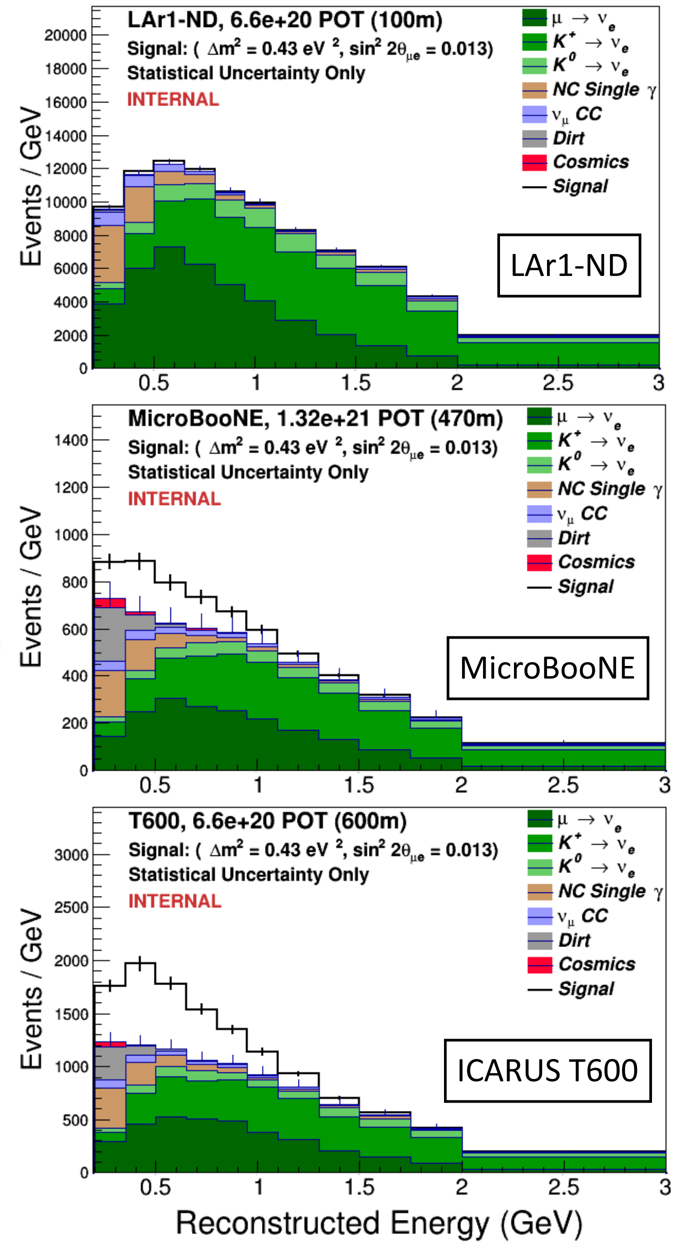
- ❖ Cosmic selection shown to the left relies entirely on proximity to parent muon and dE/dx for photon showers to ID cosmogenic photons
  - ◉ Rate reduced >99% by topological cuts, but remaining background populates at low reconstructed energies
- ❖ Precise timing information can augment the TPC data to reject triggers where the 1.6 μs beam spill time is contaminated by a cosmic event in or near the detector
- ❖ **Combination of internal light signals and an independent external tracking array to ID muons near the detector in the spill time can be used to remove cosmogenic events in the first stages of data analysis**

ν_e CC Signal & Background Categories



Here a combination of information from internal light collection and external cosmic tracking arrays are assumed to identify 95% of beam spills contaminated by a cosmic passing near the detector

small loss of data ~1% of beam triggers are rejected



Analysis Method and Uncertainties

$$\chi^2(\Delta m^2_{41}, \sin^2 2\theta) = \sum_{i,j} \left[N_i^{null} - N_i^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right] (E_{ij})^{-1} \left[N_j^{null} - N_j^{osc}(\Delta m^2_{41}, \sin^2 2\theta)\right]$$

$$E^{total} = E^{\mathrm{stat}} + E^{\mathrm{syst}}$$

$$E^{\mathrm{syst}} = E^{\mathrm{flux}} + E^{\mathrm{cross\ section}} + E^{\mathrm{cosmic\ bkgd}} + E^{\mathrm{dirt\ bkgd}} + E^{\mathrm{detector}}$$

Error matrix

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

Monte Carlo "universes"

Correlation matrix

$$\rho_{ij} = \frac{E_{ij}}{\sqrt{E_{ii}}\sqrt{E_{jj}}} \qquad [-1 \leq \rho \leq 1]$$

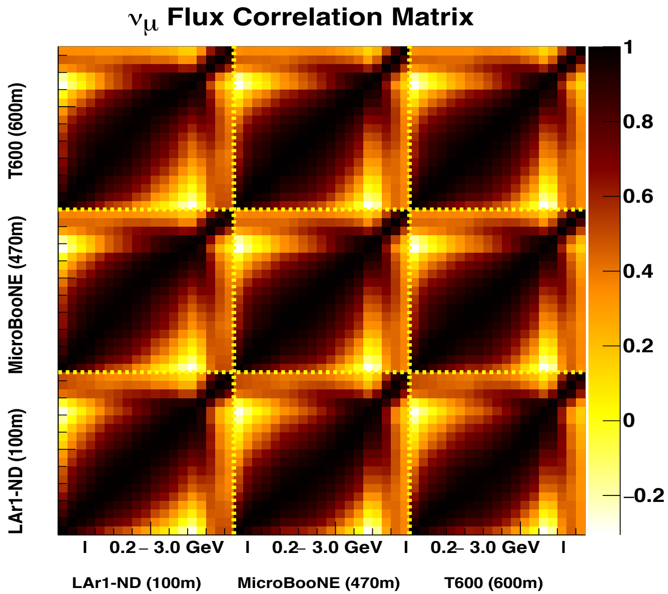
The correlation between samples is encoded into an error matrix in bins of E_{reco} used to calculate the χ^2 statistic

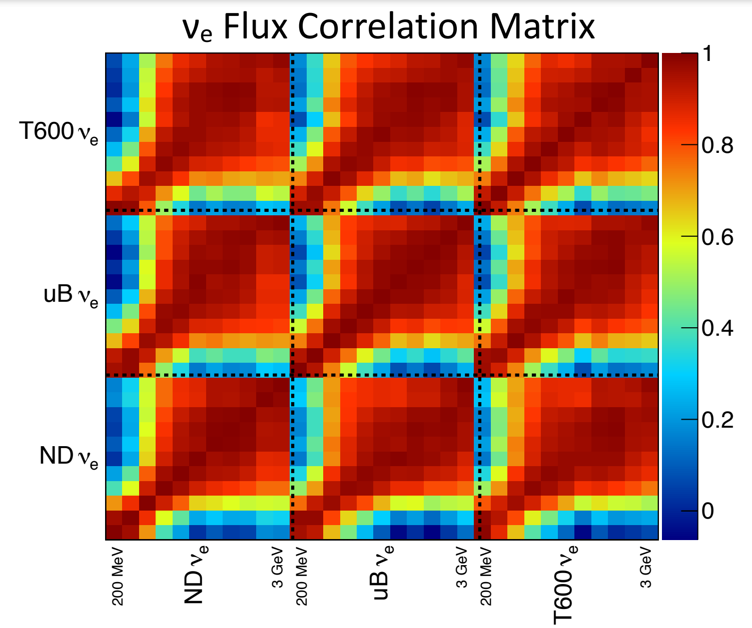
Flux & Cross Section Correlations

Flux Systematic

Evaluated with full BNB G4 Monte Carlo developed by MiniBooNE

Unconstrained uncertainties 5-10%

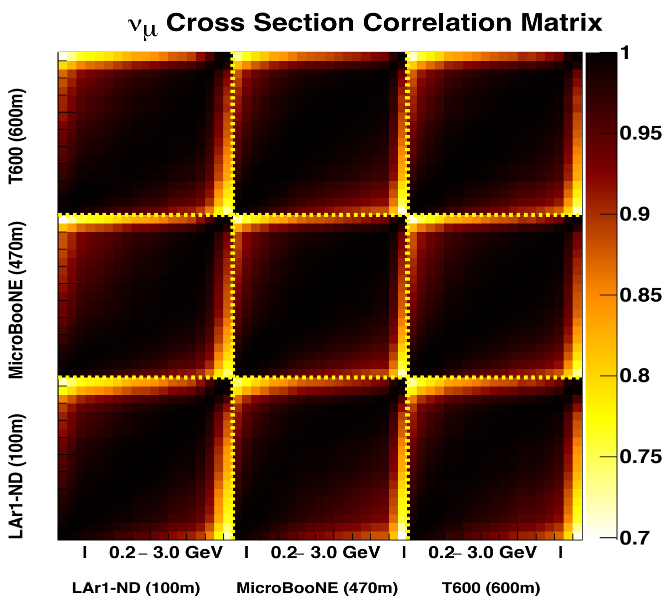


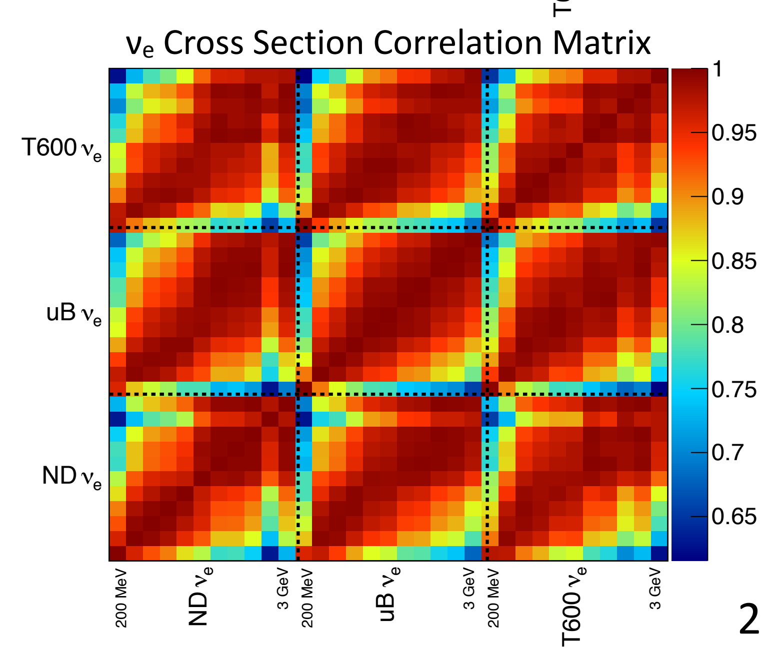


Cross Section Systematics

Evaluated with full GENIE Event Generator simulation

Unconstrained uncertainties 10-30%





Dirt and Cosmic Uncertainties

Dirt and Cosmic Uncertainties

- "Dirt" background level <u>constrained with beam data</u>
  - Study events near the active detector perimeter, with enhanced dirt backgrounds
  - Rate depends on details of detectors and surroundings, so measure in each detector
  - We estimated it can be measured to ~15%, uncorrelated between detectors

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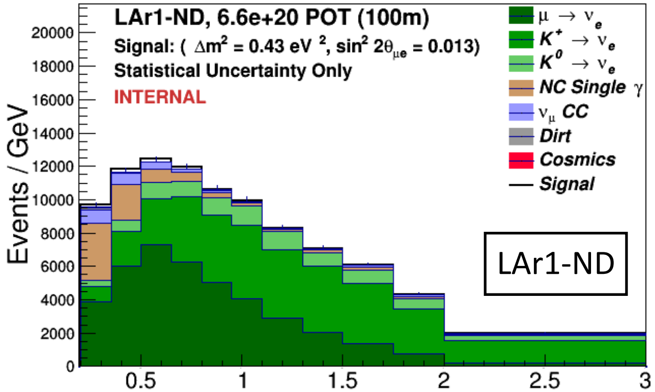
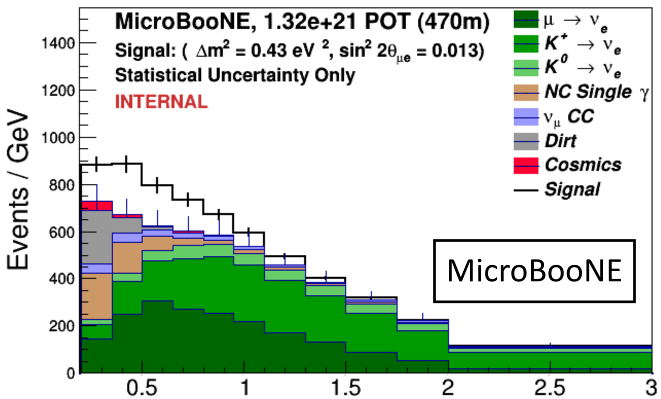
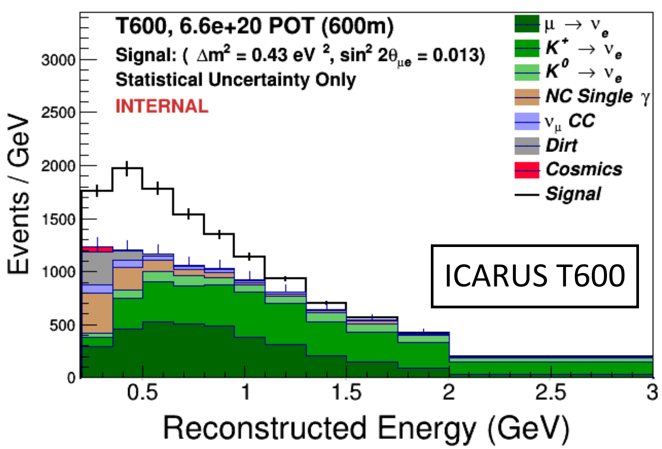
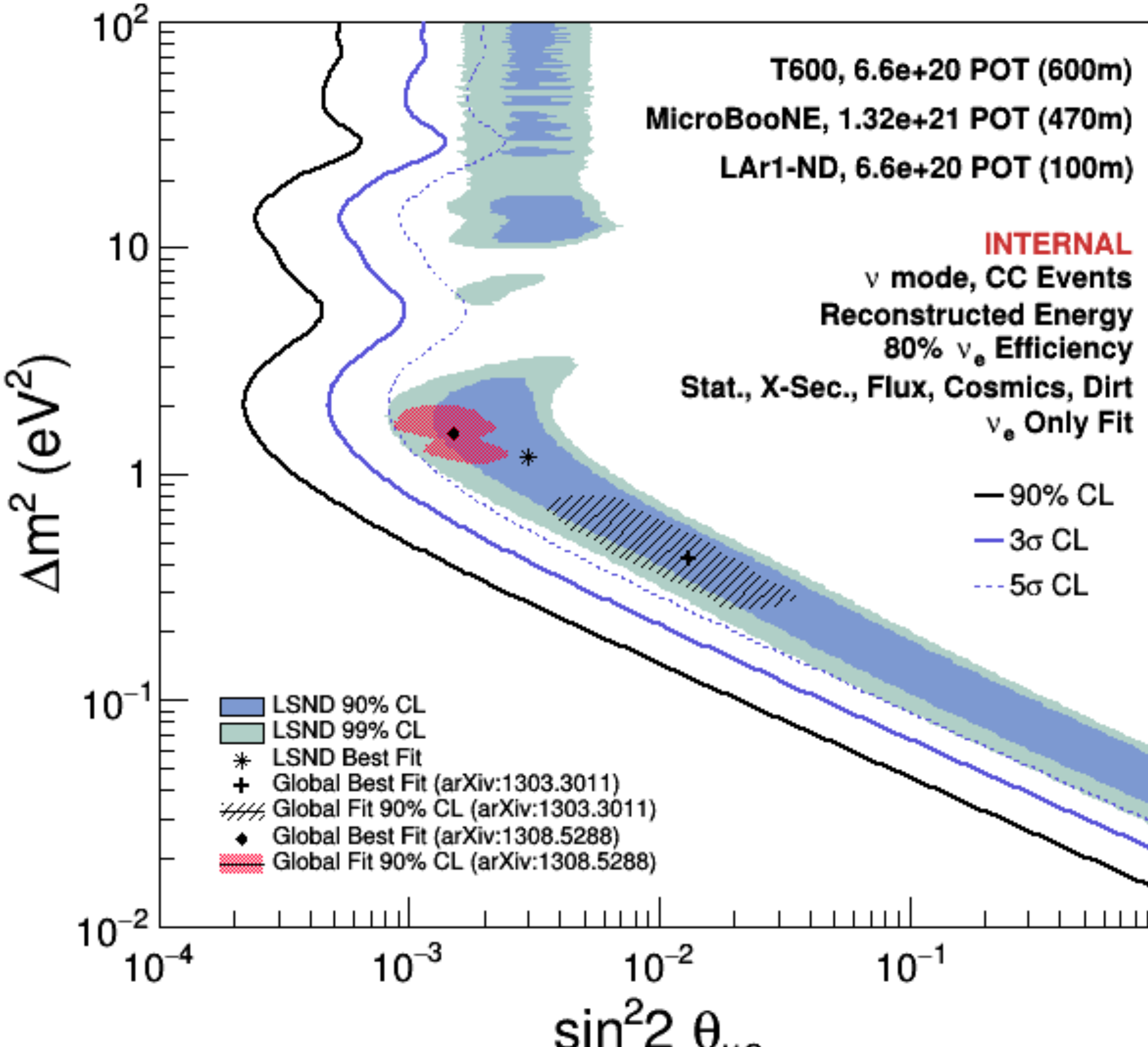
- Cosmic backgrounds <u>constrained with off-beam data</u>
  - It was critical to estimate the rates (as we have done) in order to know that oscillation signals could be observed over the cosmic background
  - The exact rate, however, does <u>not</u> introduce significant systematic uncertainty because it can be measured with high precision using off-beam random event triggers
  - For the sensitivity analysis, we construct the cosmic error matrix to account for the statistical uncertainty on the predicted sample and assume negligible systematics

ν_e Appearance Sensitivity

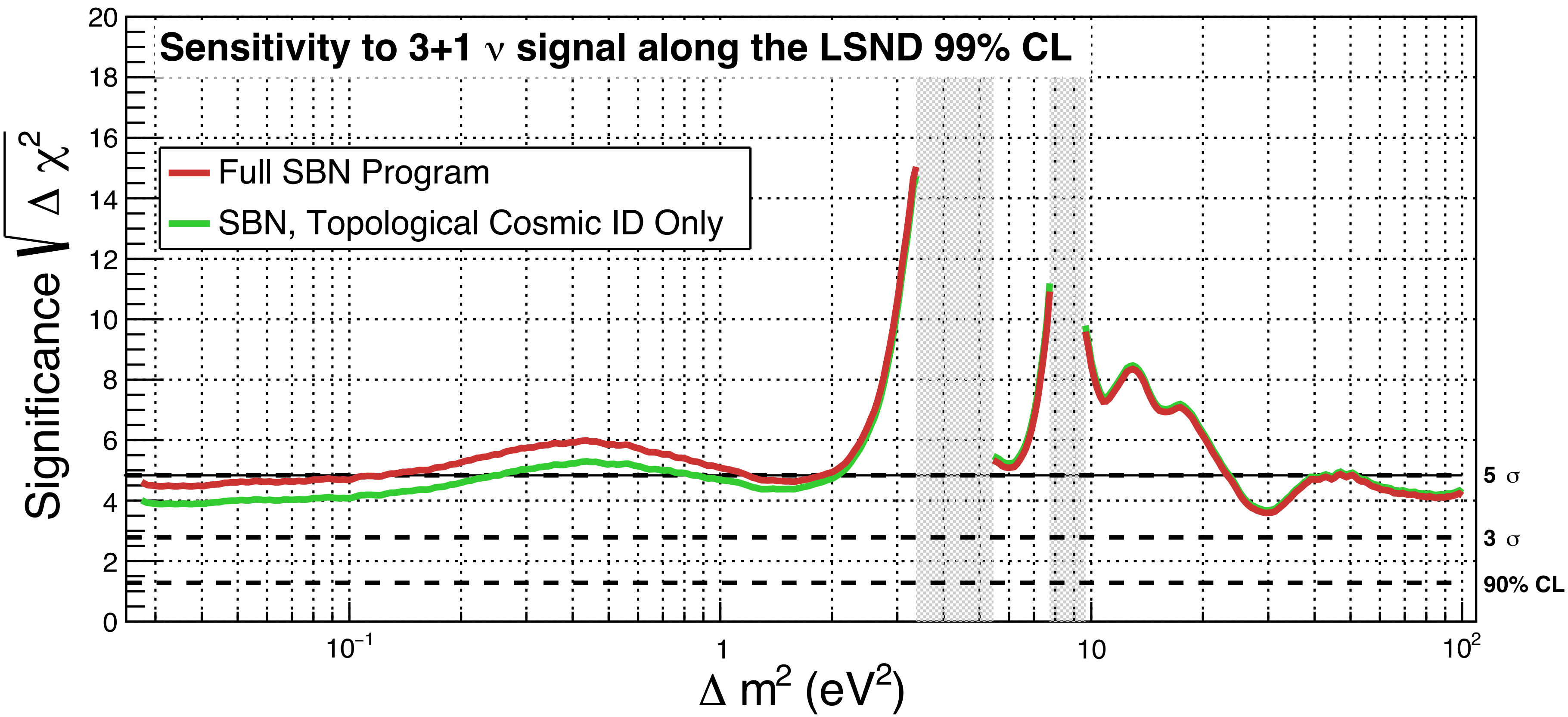








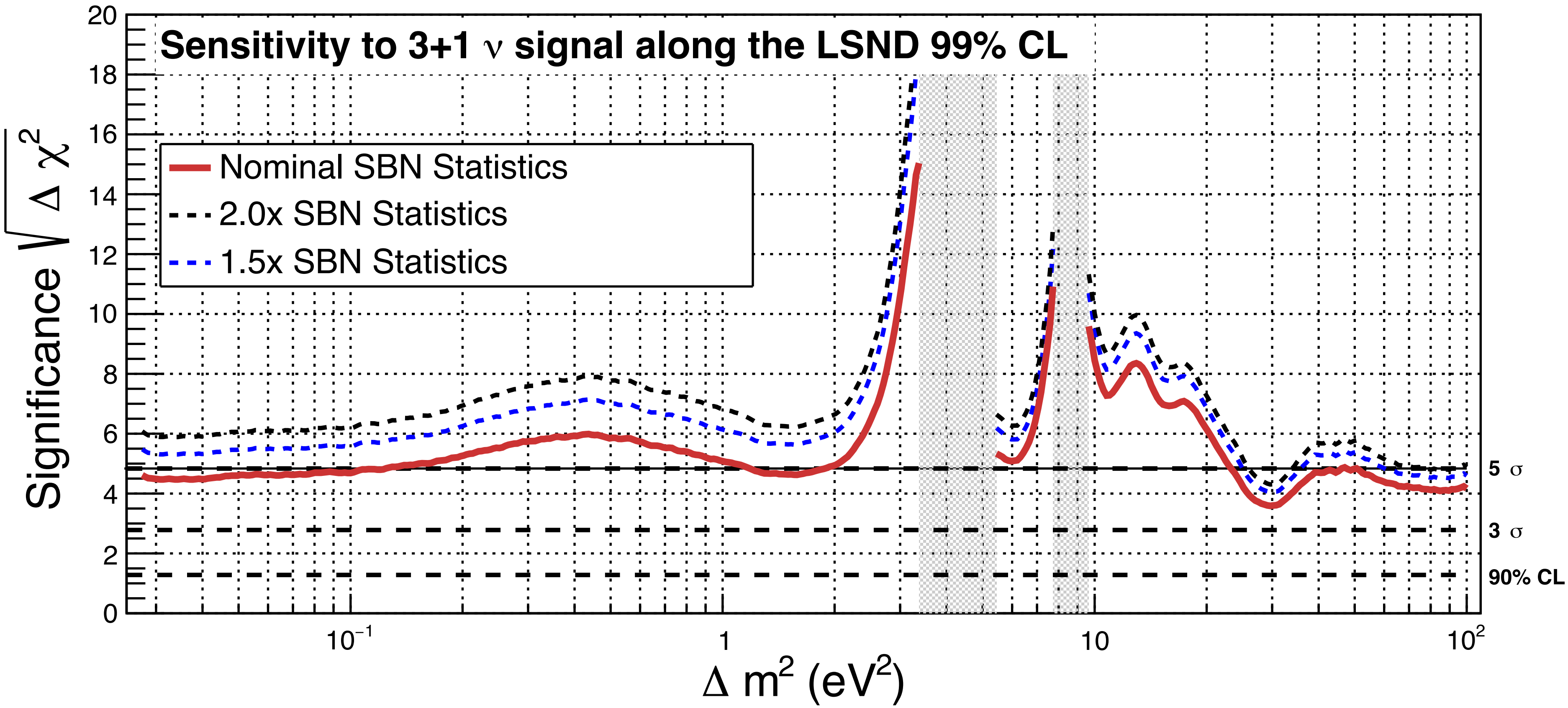
Impact of Cosmic Backgrounds



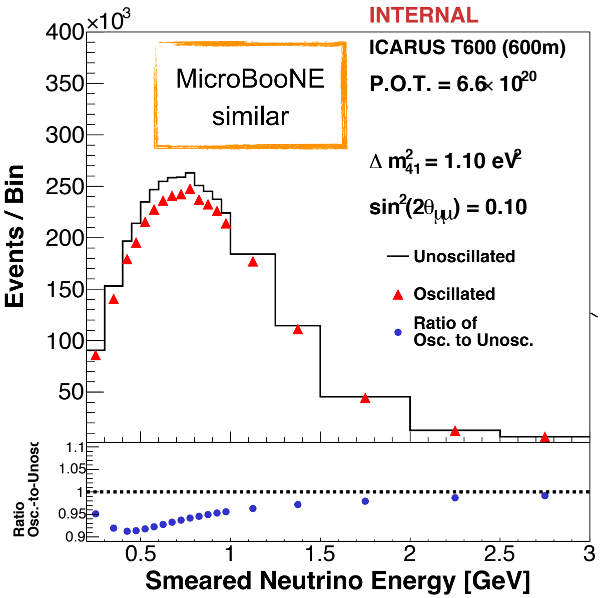
❖ Stronger rejection of cosmic backgrounds through cosmic tagging and timing improves the sensitivity ~0.75σ at low Δm^2

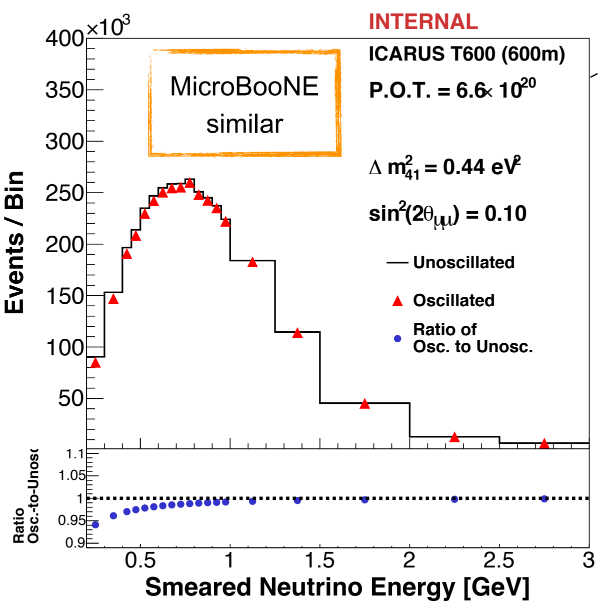
Impact of ν_e Statistics

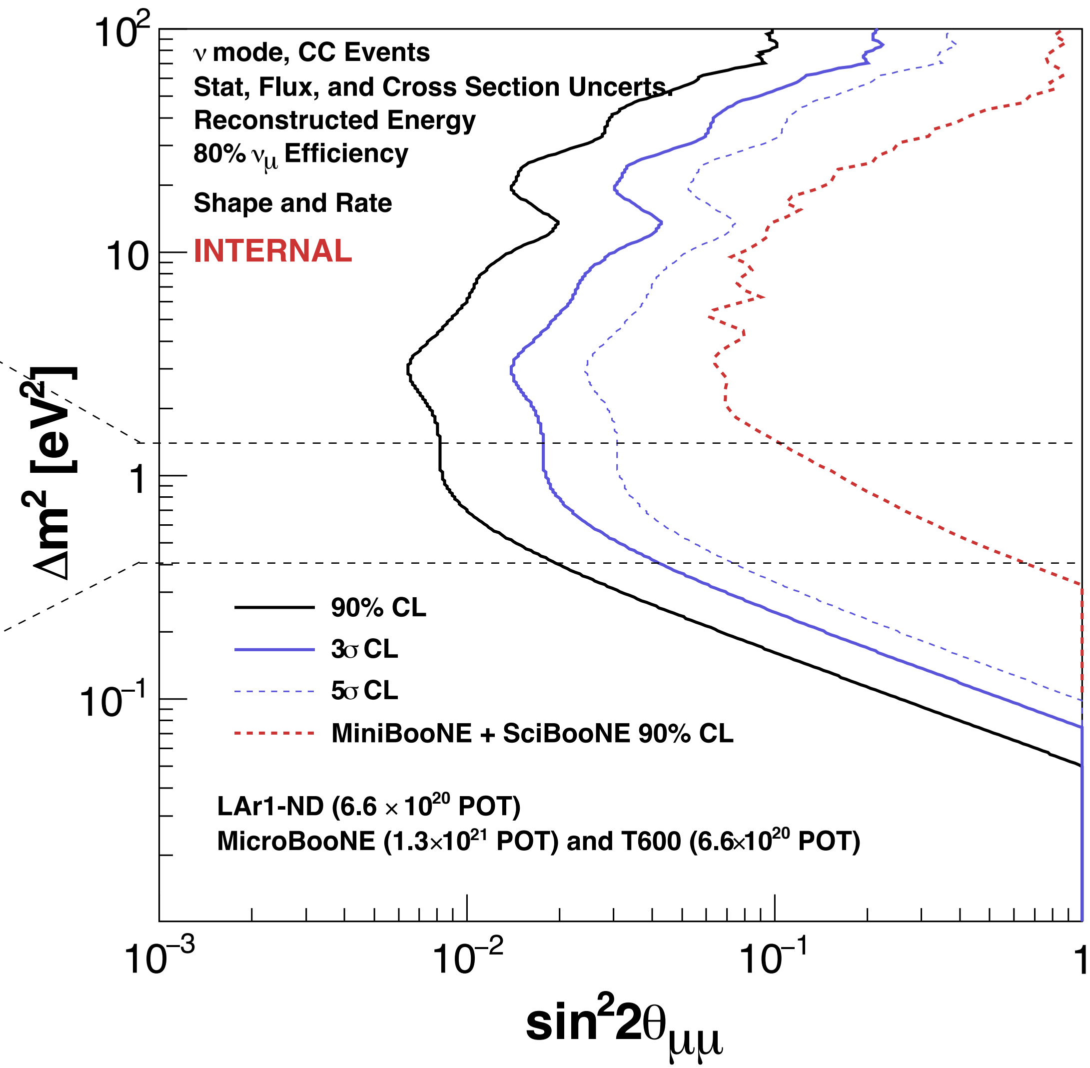
- Increased exposure through, for example, improved BNB performance has a major impact



ν_μ Disappearance Sensitivity







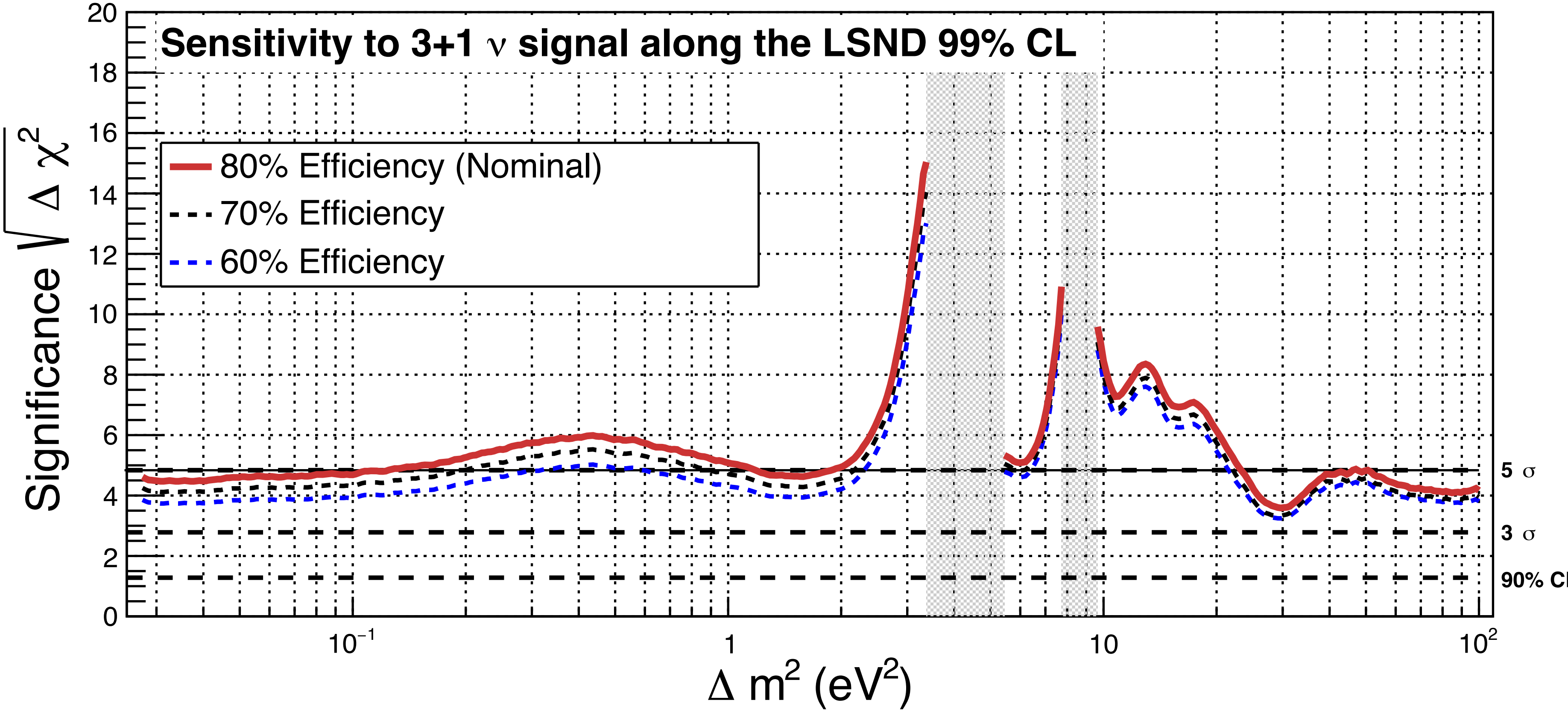
Sensitivity does not detector systematics at this time.
Will be important in this analysis.

Summary

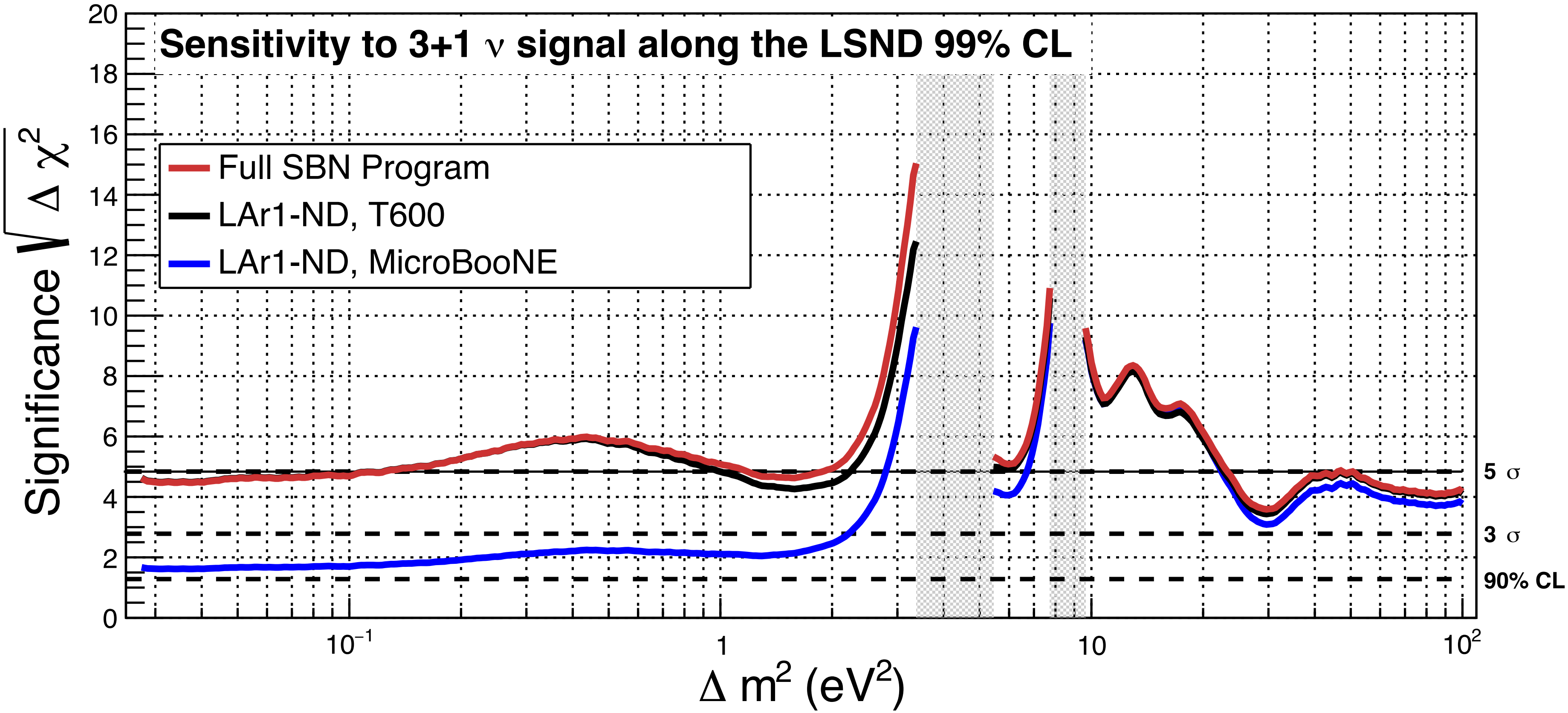
Backups

ν_e Selection Efficiency

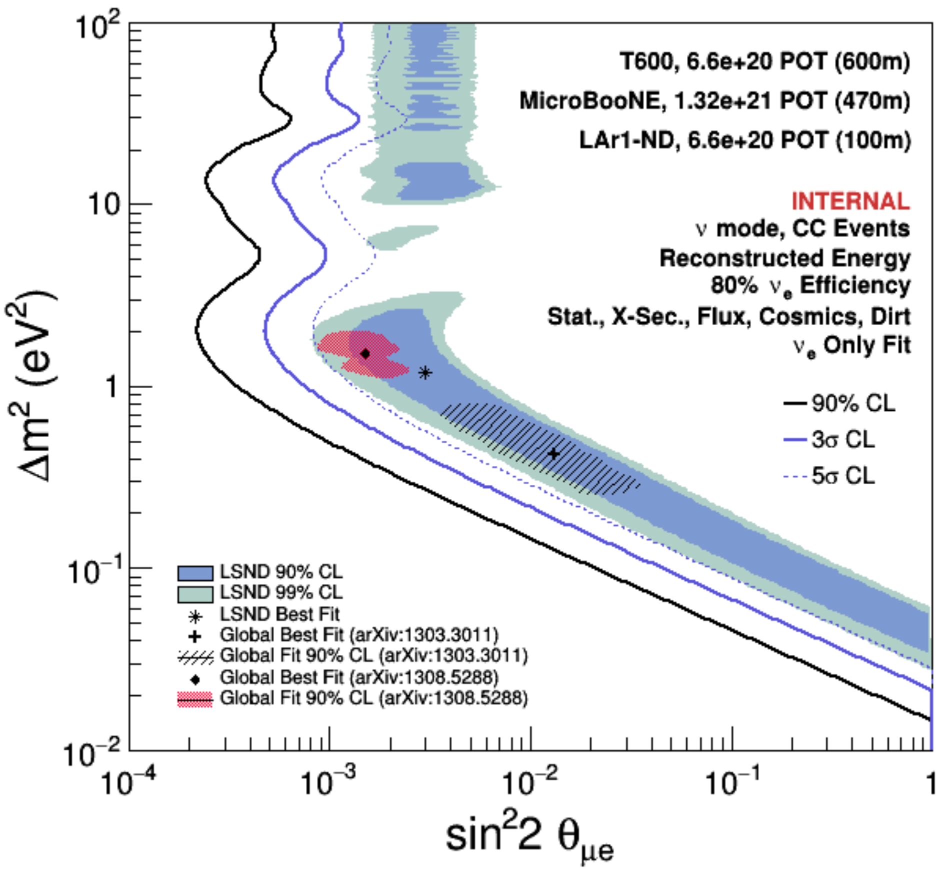
- For fixed exposure time, each 10% reduction in signal efficiency is about 0.5σ in sensitivity

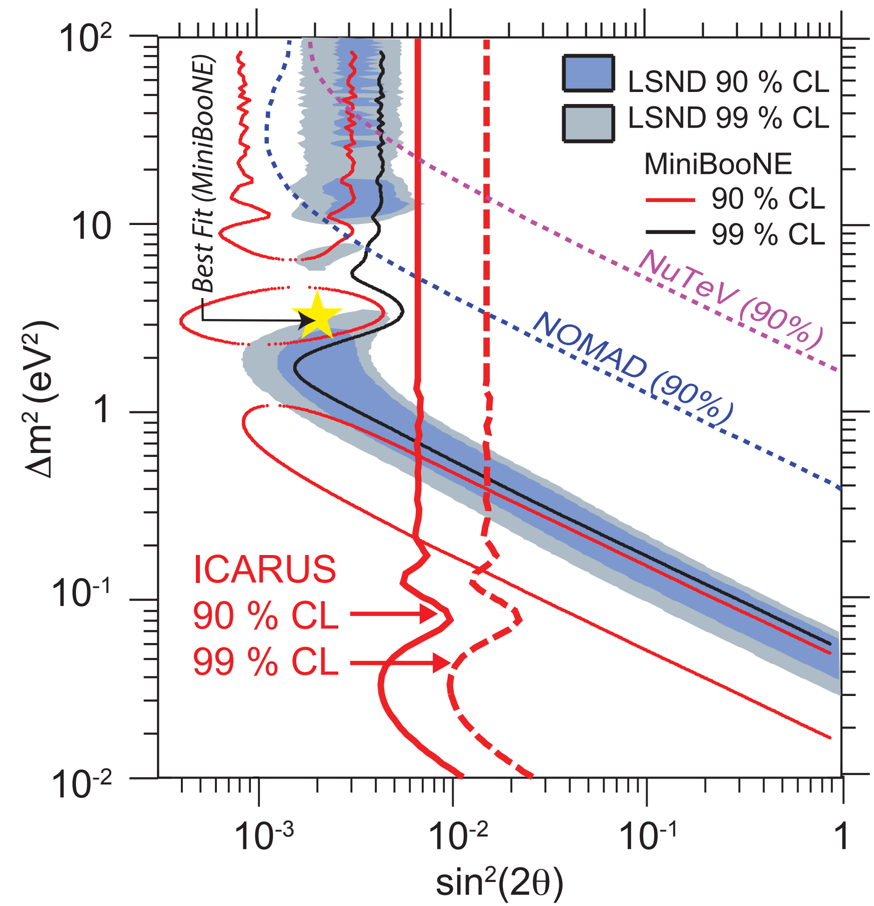


SBN Detectors



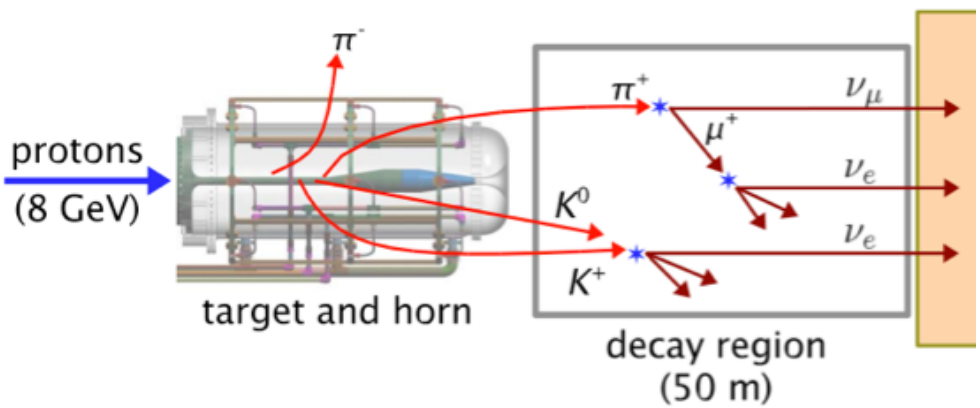
Compare to MiniBooNE Neutrino Mode



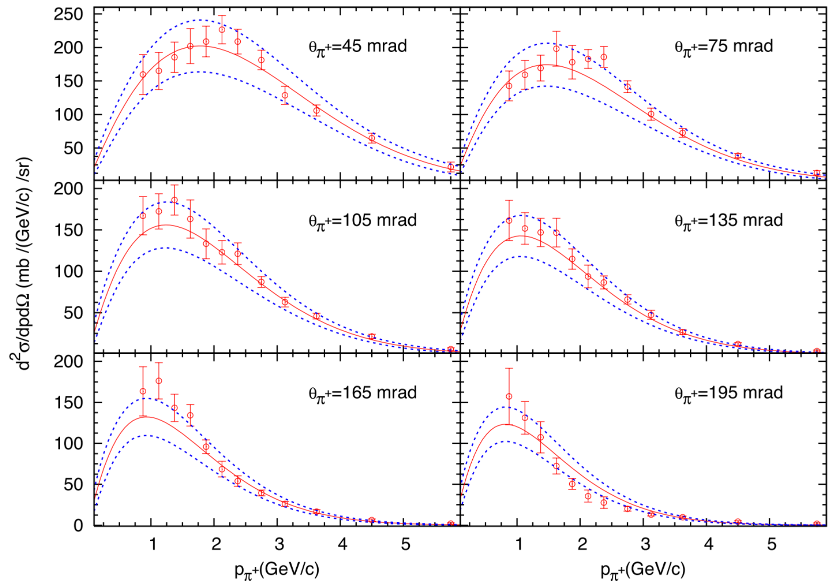


Flux Systematics

- BNB Monte Carlo treats systematic uncertainties related to
  - Primary production of π^+, π^-, K^+, K^-, and K^0 in p+Be collisions at 8 GeV
  - Secondary interactions of p, n, $\pi^\pm$ in the beryllium target and aluminum horn
  - Beam focusing with the magnetic horn



HARP π^+ data



Largest uncertainty (pion production) constrained with dedicated data from HARP experiment.

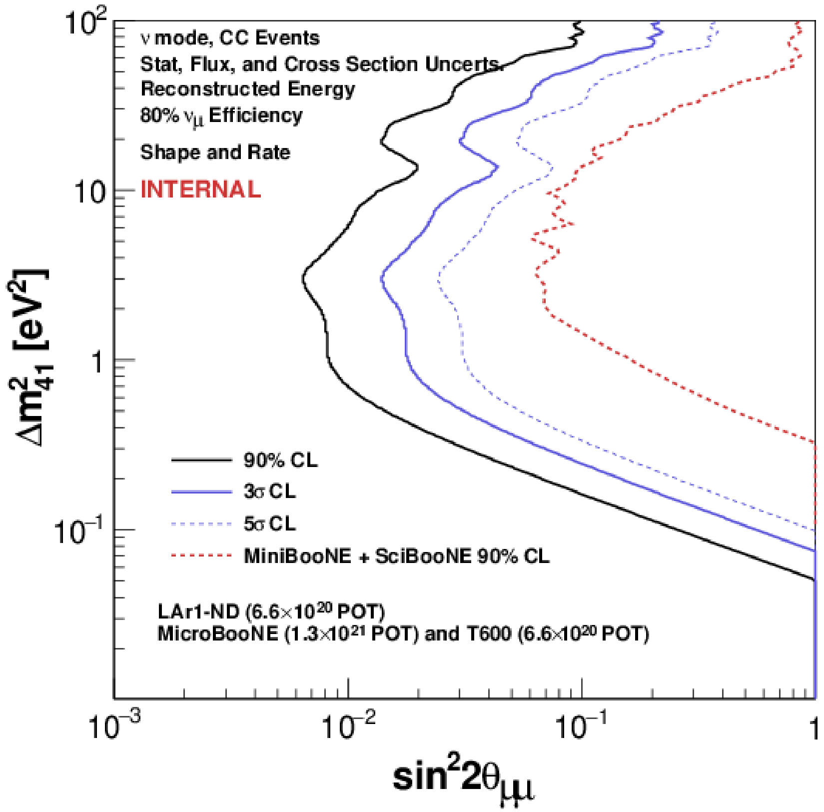
Kaon production constrained with available world data and SciBooNE measurements at high energy.

Cross Section Systematics

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

TABLE IV: *Neutrino interaction model parameters and uncertainties. This information is reproduced here from the GENIE manual Section 8.1 [66] for convenience.*

ν_μ Sensitivity with Detector Systematics



3% uncorrelated detector systematic