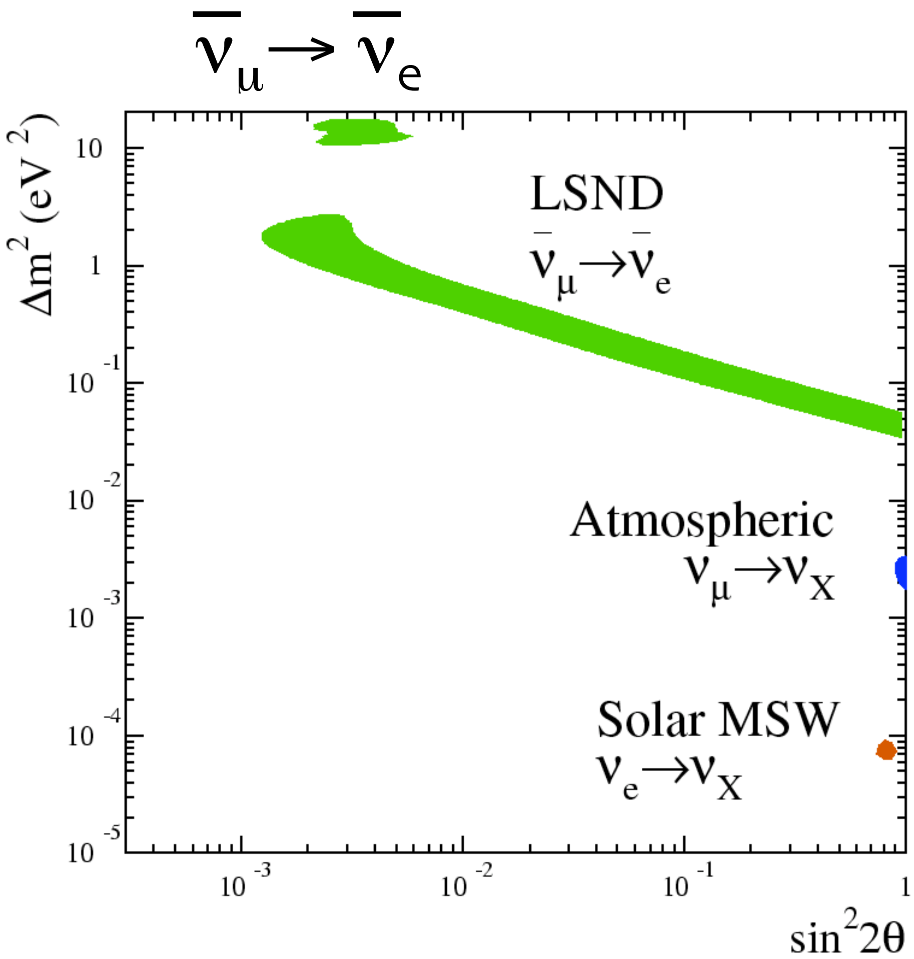
First Anti-neutrino results!

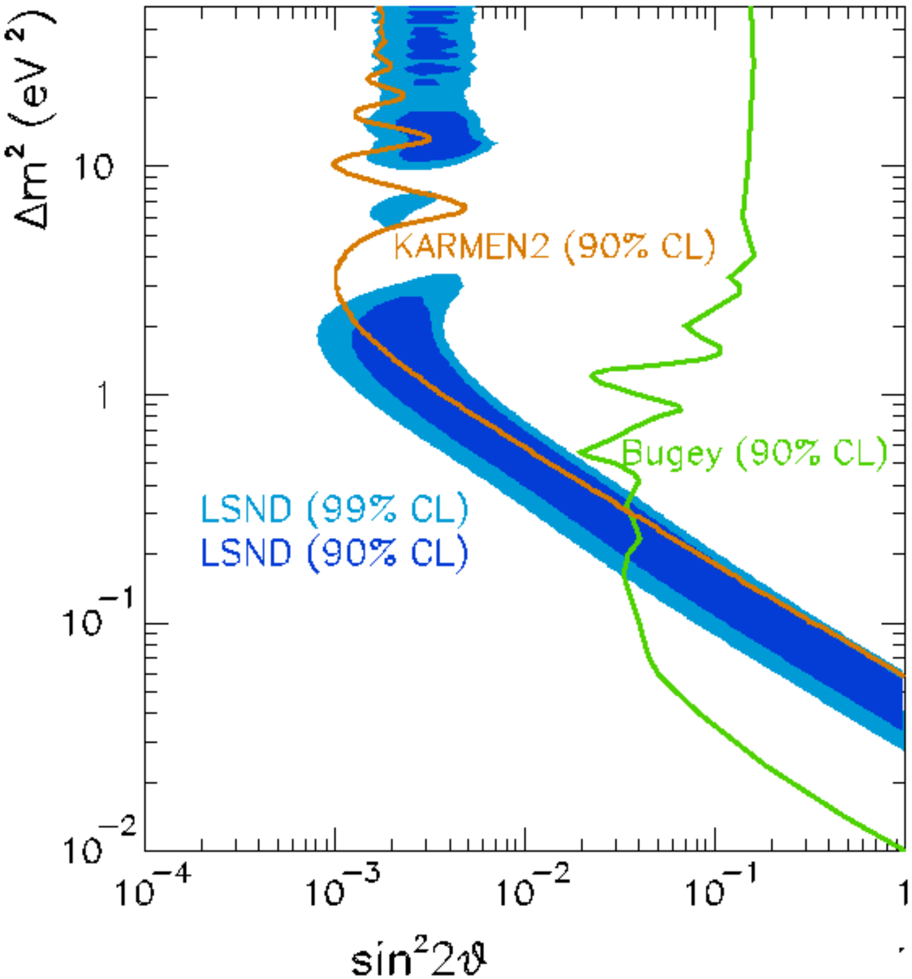
The Notorious LSND Result



- E_ν =20-52.8 MeV
- L =25-35 meters
- 3.8σ excess
- Different from other oscillation signals
- Higher Δm^2
- Smaller mixing angle
- Much smaller probability (very small signal) ~0.3%

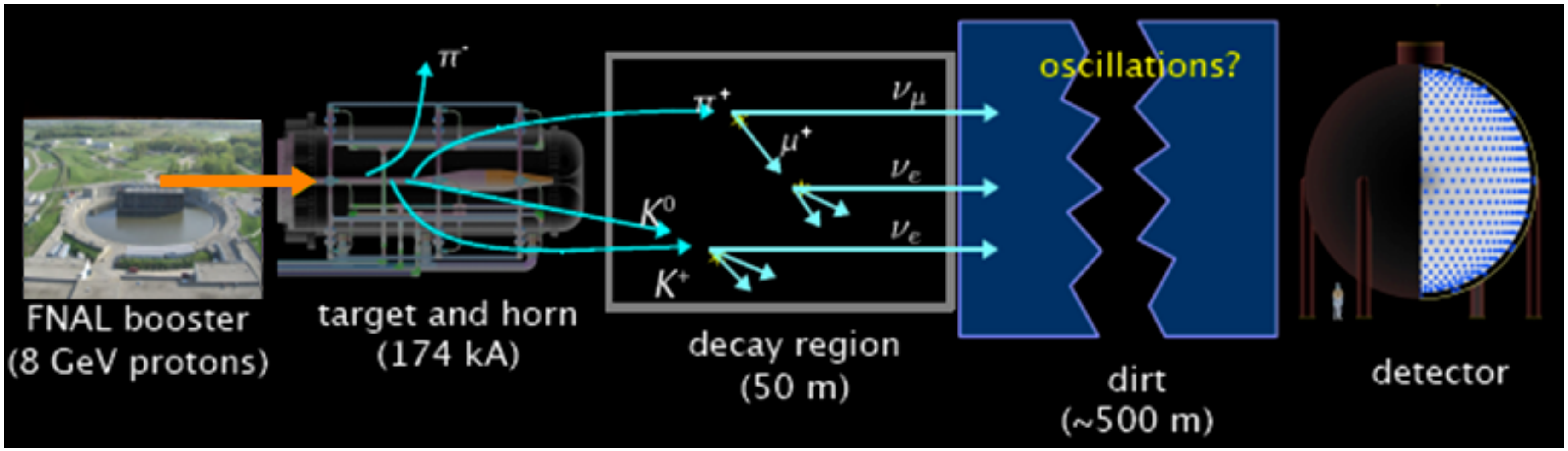
$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\, \Delta m^2\, L}{E}\right)$$

Testing LSND



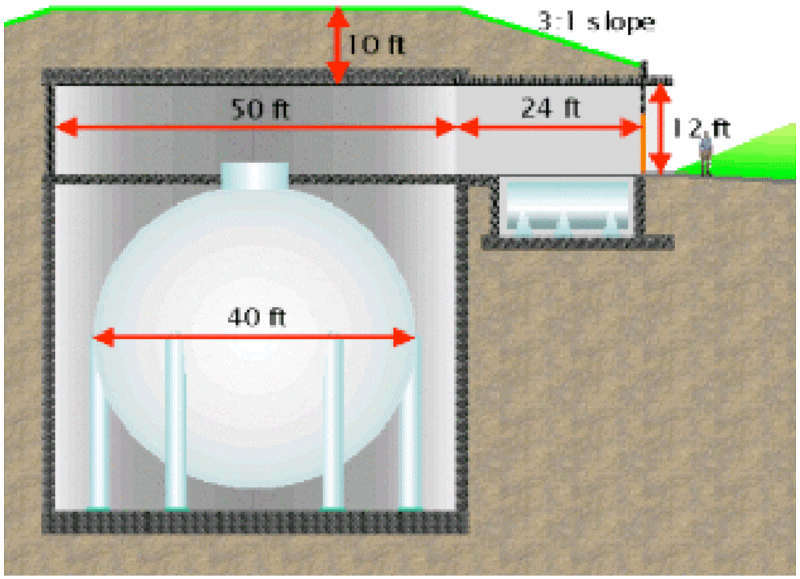
- Want same L/E
- Different detection method
- Different sources of systematic errors
- Test for oscillations using neutrinos, anti-neutrinos

MiniBooNE Neutrino Beam

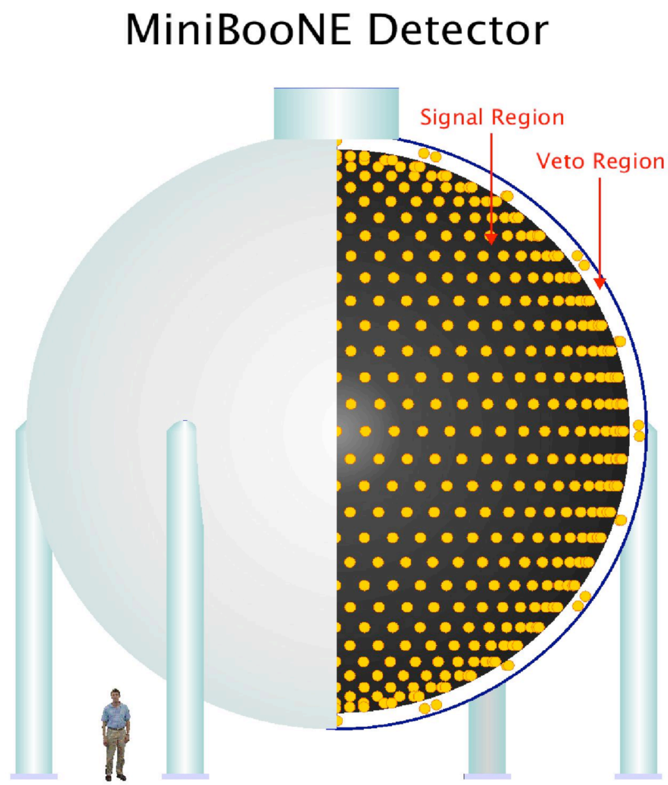


- Mesons decay into the anti-neutrino beam seen by the detector
  - $K^- / \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
    - $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$
- MiniBooNE L/E = 0.5 km / 0.8 GeV (.625)
- LSND L/E = 0.03 km / 0.05 GeV (.6)
- Anti-nu analysis uses 3.386E20 protons on target

MiniBooNE Detector



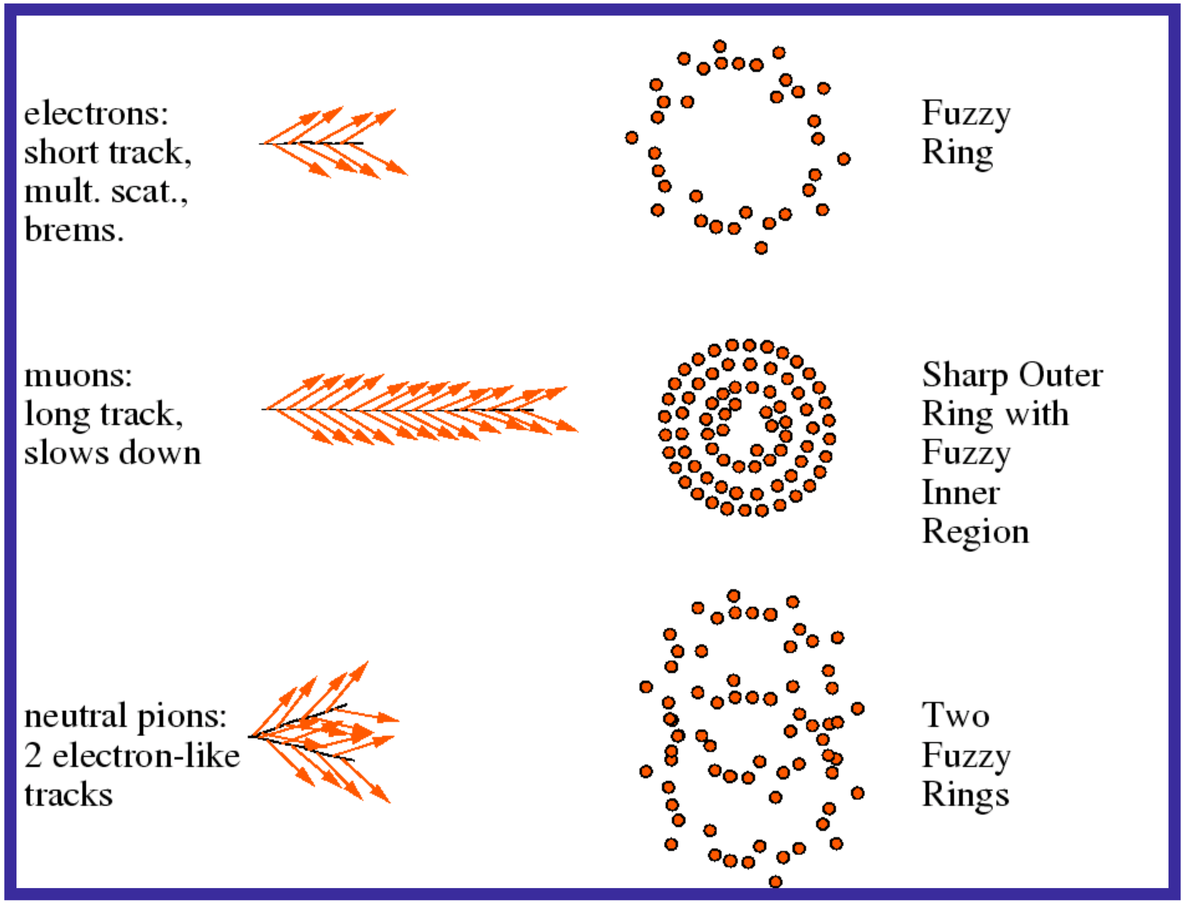
Detector

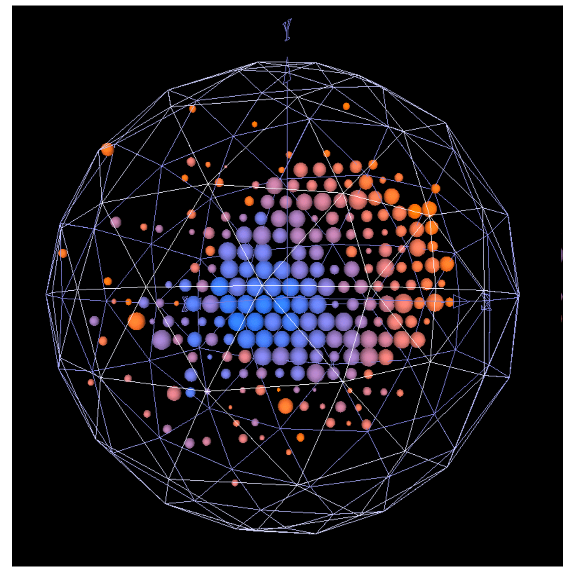


- 12.2 meter diameter sphere
- **Pure** mineral oil
- 2 regions
  - Inner light-tight region, 1280 PMTs (10% coverage)
  - Optically isolated outer veto-region, 240 PMTs

Event Signature

CHARGED-CURRENT QUASI-ELASTIC EVENTS $\bar{\nu}_e\ p \rightarrow e^+\ n$





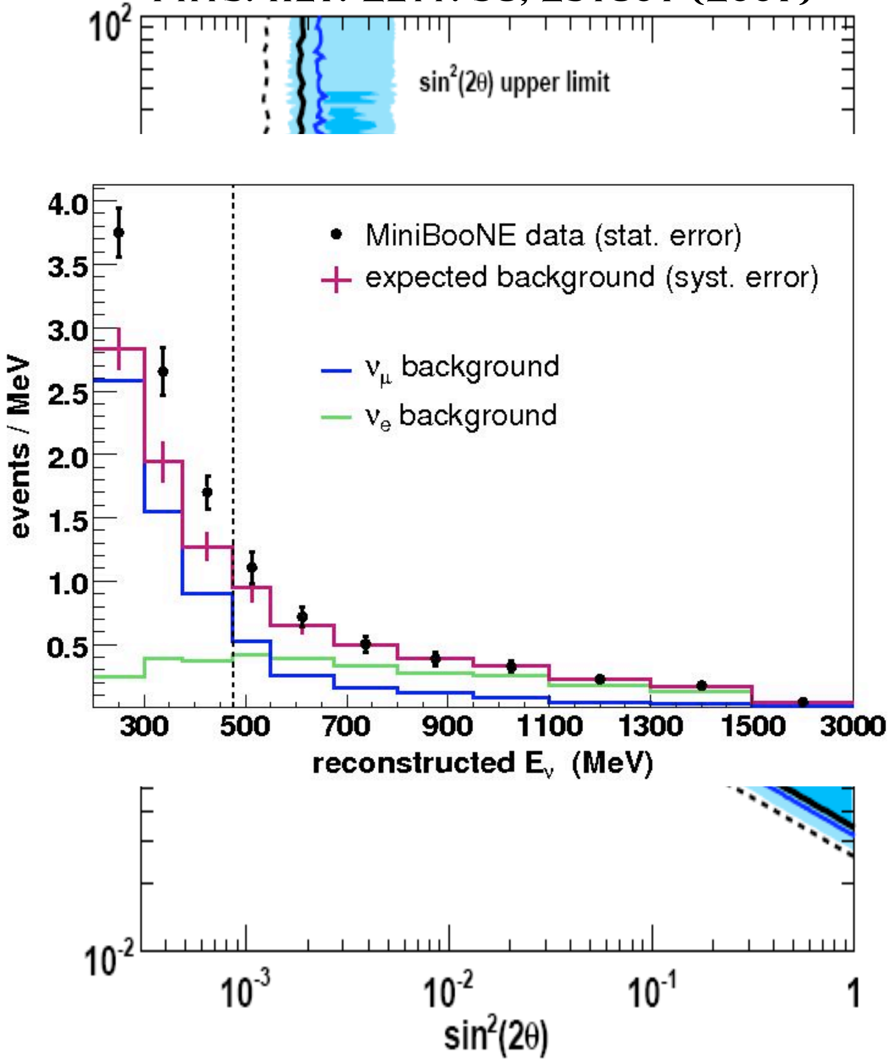
MiniBooNE Analysis

- MiniBooNE is looking for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- MiniBooNE is looking for an excess of $\bar{\nu}_e$ (appearance)

- MiniBooNE performing a blind analysis
  - Some of the info in all of the data
    - Charge per PMT as a function of time
  - All of the info in some of the data
    - ~oscillation free sample to be open for analysis
    - Low-E NC elastic events, $\bar{\nu}_\mu$ CCQE, $\bar{\nu}_\mu$ CCπ^+
  - $\bar{\nu}_e$ candidate events locked away until the analysis 100% complete
  - Same strategy as neutrino mode

Neutrino Mode Result

Phys. Rev. Lett. 98, 231801 (2007)



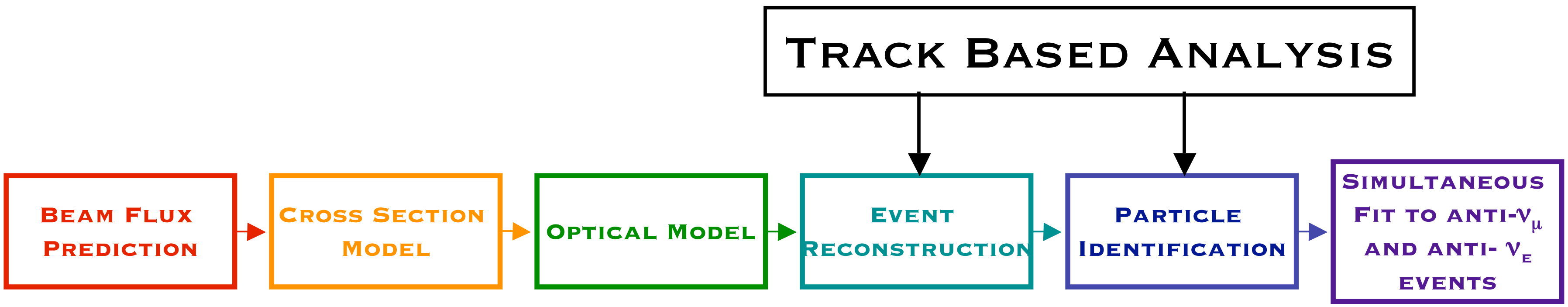
- Used 2 complementary analyses
- ruled out interpretation of LSND as $\nu_\mu \rightarrow \nu_e$ oscillations
  - two-nu oscillations
  - standard L/E depend.
  - no CP, CPT violation
- Unexplained excess of events in low-energy region
  - Excess incompat. With 2-nu LSND-style oscillations

Anti-neutrino Analysis

- Similarities with neutrino mode
  - Using two complementary analyses
  - Using same algorithms
  - Same event selection cuts

- Changes made wrt neutrino mode
  - Added an event selection cut that removes most of the dirt (out of tank) background at low energy
  - Added K^- production systematic error
  - New NC π^0 measurement
  - New dirt fraction extracted

Analysis Chain



Start with a Geant 4 flux prediction for the nu spectrum from π and K produced at the target

Predict nu interactions using the Nuance event generator

Pass final state particles to Geant 3 to model particle, light propagation in the tank

Use track-based event reco

Use hit topology and timing to identify electron-like or muon-like charged current neutrino interactions

Fit reco. energy spectrum for oscillations

Analysis Chain

Boosted Decision tree

Beam Flux Prediction → Cross Section Model → Optical Model → Event Reconstruction → Particle Identification → Simultaneous Fit to anti-ν_μ and anti- ν_e events

Start with a Geant 4 flux prediction for the nu spectrum from π and K produced at the target

Predict nu interactions using the Nuance event generator

Pass final state particles to Geant 3 to model particle, light propagation in the tank

Use point-source event reco

Use boosted decision tree to identify electron-like or muon-like charged current neutrino interactions

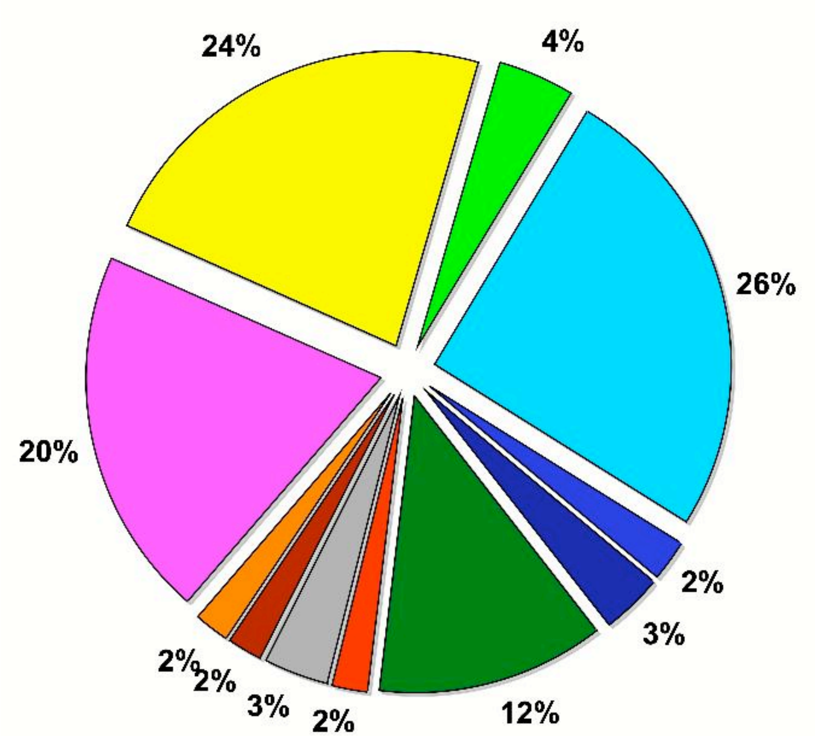
Fit reco. energy spectrum for oscillations

Expected Backgrounds

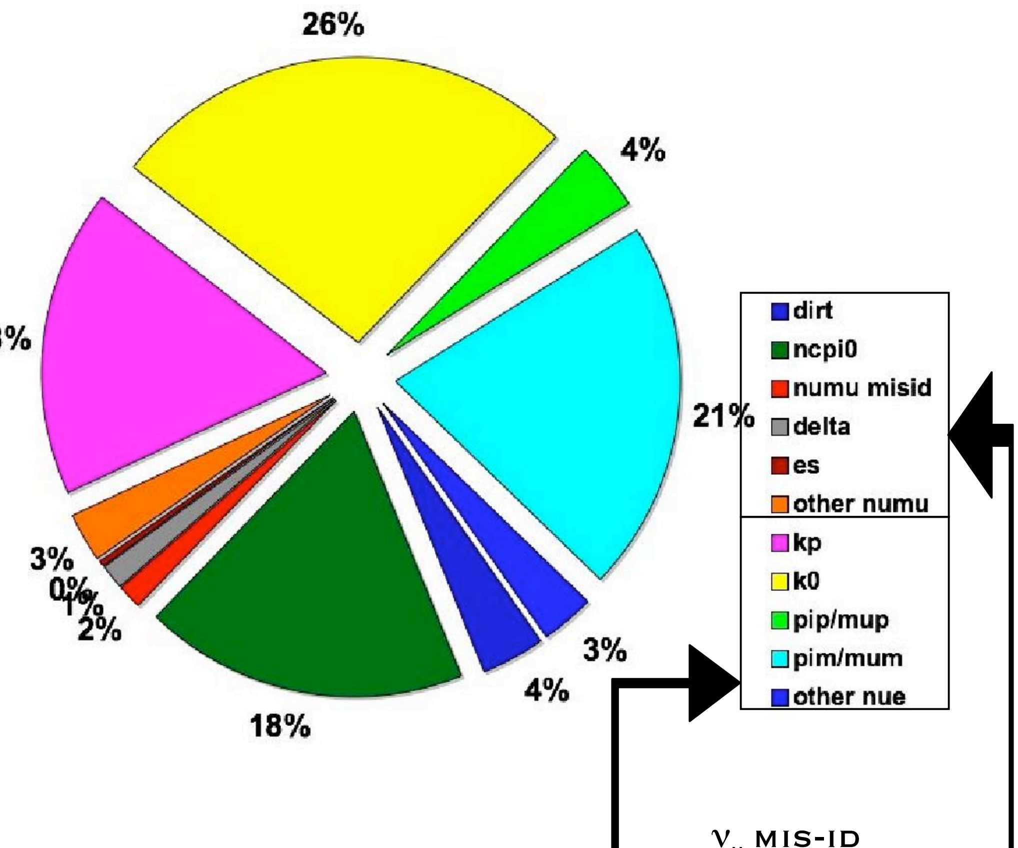
500 MeV < Reconstructed Neutrino Energy < 1.25 GeV

3.386e20 POT

Track Based Analysis



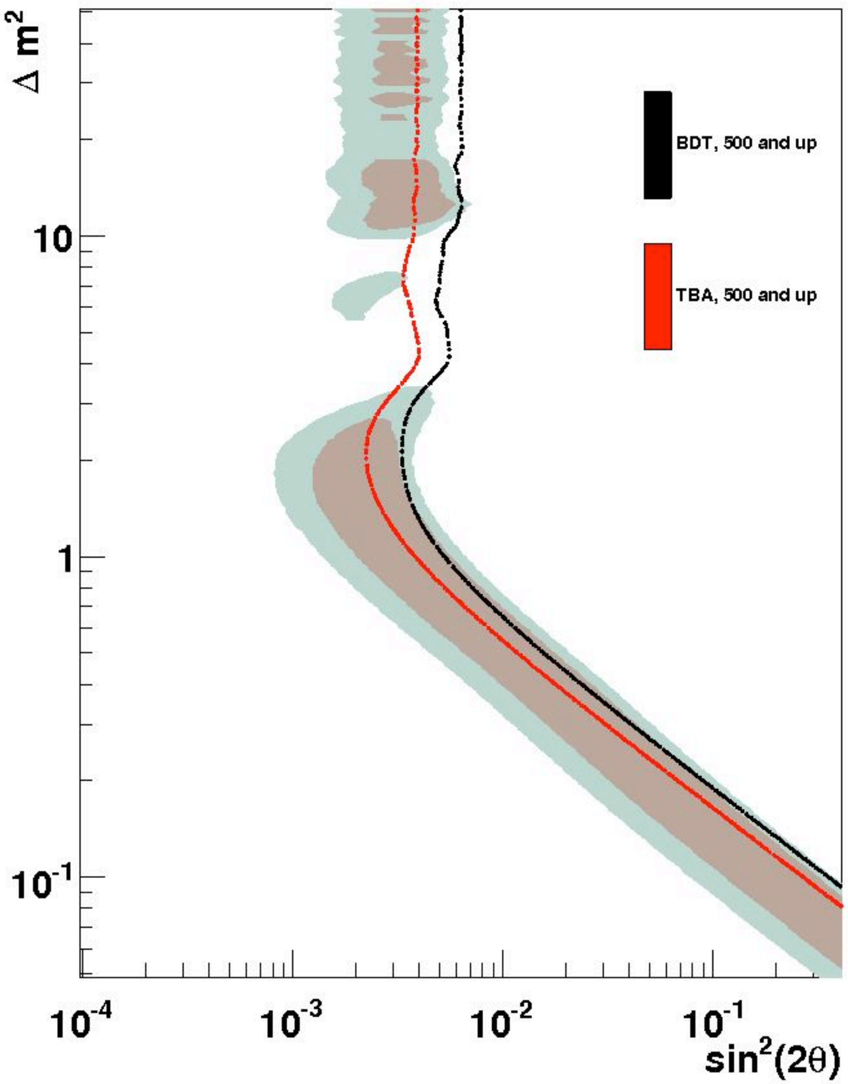
Boosting Analysis



Intrinsic ν_e backgrounds

ν_μ mis-id backgrounds

Expected Sensitivity



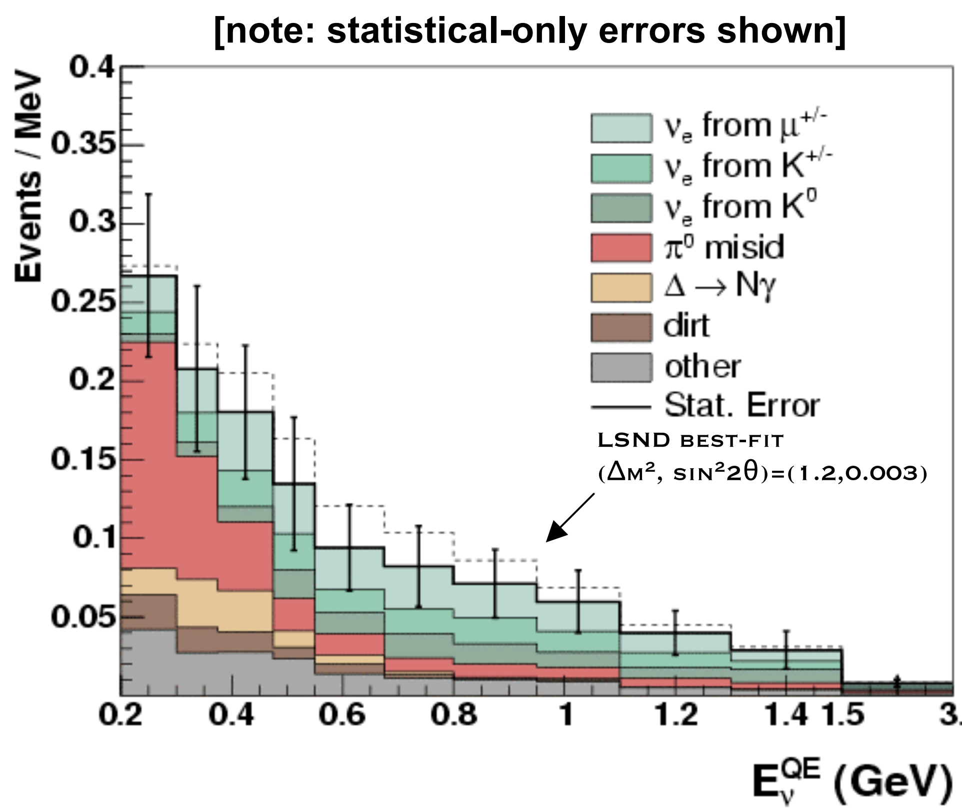
As in neutrino mode, TBA is the more sensitive (default) analysis.

BDT is the cross-check analysis

Expected Background Events

Background composition for TBA analysis (3.386e20 POT)

		200-475 MeV	475-1250 MeV
Intrinsic ν_e	ν_e from $\pi^{\pm}$, $\mu^{\pm}$	8.44	17.14
	ν_e from $K^{\pm,0}$	8.20	24.88
	Other ν_e	1.11	1.21
ν_μ mis-ID	CCQE	2.86	1.24
	NC π^0	24.60	7.17
	Delta Rad	6.58	2.02
	Dirt	4.69	1.92
	Other ν_μ	3.82	2.20
	Total Bgd	60.29	57.78
	LSND Best Fit	4.33	12.63



Systematic Uncertainties

Track Based Analysis

Source	Antinu Mode		Nu Mode	
E_ν^{QE} range (MeV)	200-475	475-1100	200-475	475-1100
Flux from π^+/μ^+ decay	0.4	0.7	1.8	2.2
Flux from π^-/μ^- decay	3.3	2.2	0.1	0.2
Flux from K^+ decay	2.3	4.9	1.4	5.7
Flux from K^- decay	0.5	1.1	-	-
Flux from K^0 decay	1.5	5.7	0.5	1.5
Target and beam models	1.9	3.0	1.3	2.5
ν-cross section	6.4	12.9	5.9	11.9
NC π^0 yield	1.7	1.6	1.4	1.9
Hadronic interactions	0.5	0.6	0.8	0.3
External interactions (dirt)	2.4	1.2	0.8	0.4
Optical model	9.8	2.8	8.9	2.3
Electronics & DAQ model	9.7	3.0	5.0	1.7
Total (unconstrained)	*16.3*	*16.2*	*12.3*	*14.2*

From fits to world's data (HARP, Kaon production)

Systematic Uncertainties

Track Based Analysis

Source	Antinu Mode		Nu Mode	
E_ν^{QE} range (MeV)	200-475	475-1100	200-475	475-1100
Flux from π^+/μ^+ decay	0.4	0.7	1.8	2.2
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Total (unconstrained)	*16.3*	*16.2*	*12.3*	*14.2*

Internal MB measurements

Systematic Uncertainties

Track Based Analysis

Source	Antinu Mode		Nu Mode	
E_ν^{QE} range (MeV)	200-475	475-1100	200-475	475-1100
Flux from π^+/μ^+ decay	0.4	0.7	1.8	2.2
Flux from π^-/μ^- decay	3.3	2.2	0.1	0.2
Flux from K^+ decay	2.3	4.9	1.4	5.7
Flux from K^- decay	0.5	1.1	-	-
Flux from K^0 decay	1.5	5.7	0.5	1.5
Target and beam models	1.9	3.0	1.3	2.5
ν-cross section	6.4	12.9	5.9	11.9
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Electronics & DAQ model	9.7	3.0	5.0	1.7
Total (unconstrained)	*16.3*	*16.2*	*12.3*	*14.2*

Determined by special runs of the beam MC. All beam uncertainties not coming from meson production by 8 GeV protons are varied one at a time. Variations are treated as 1σ excursions, prop into a final error matrix.

Uncert. in a number of hadronic processes, mainly photonuclear interaction final state

Uncertainties in light creation, propagation, and detection in the Tank. Use set of 130 MC "multisims" that have been run where all these parameters are varied according to their input uncertainties.

Systematic Uncertainties

Track Based Analysis

Source	Antinu Mode		Nu Mode	
E_ν^{QE} range (MeV)	200-475	475-1100	200-475	475-1100
Flux from π^+/μ^+ decay	0.4	0.7	1.8	2.2
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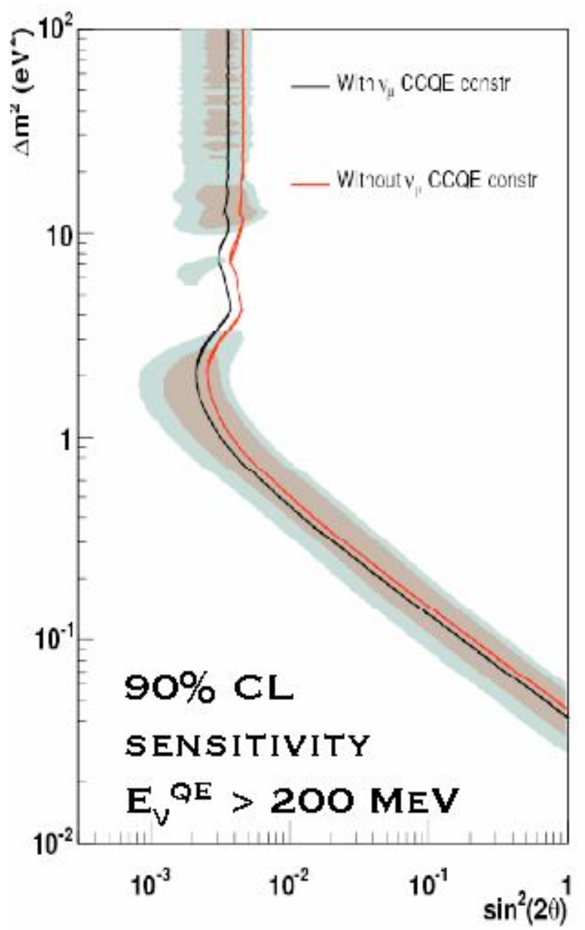
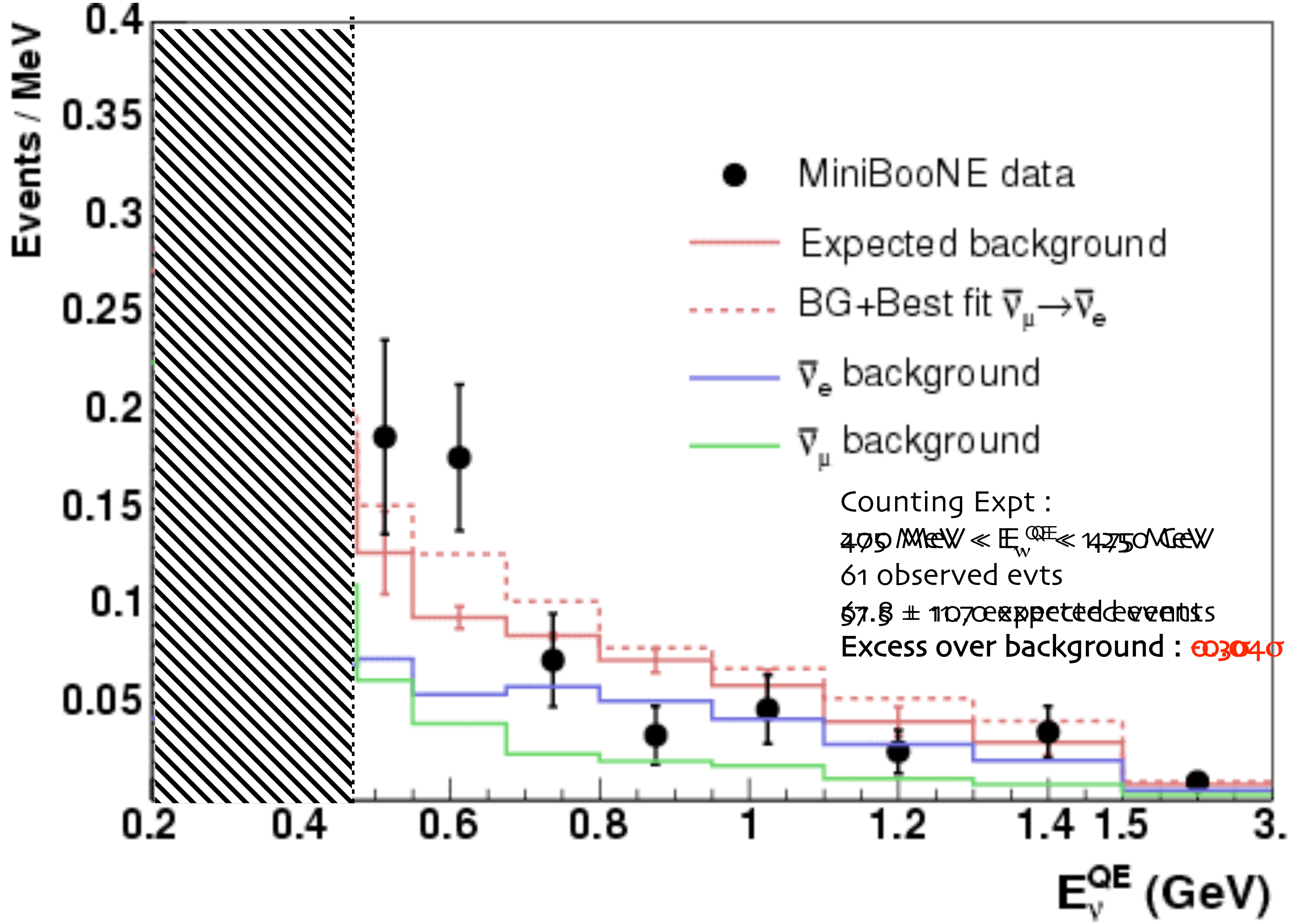
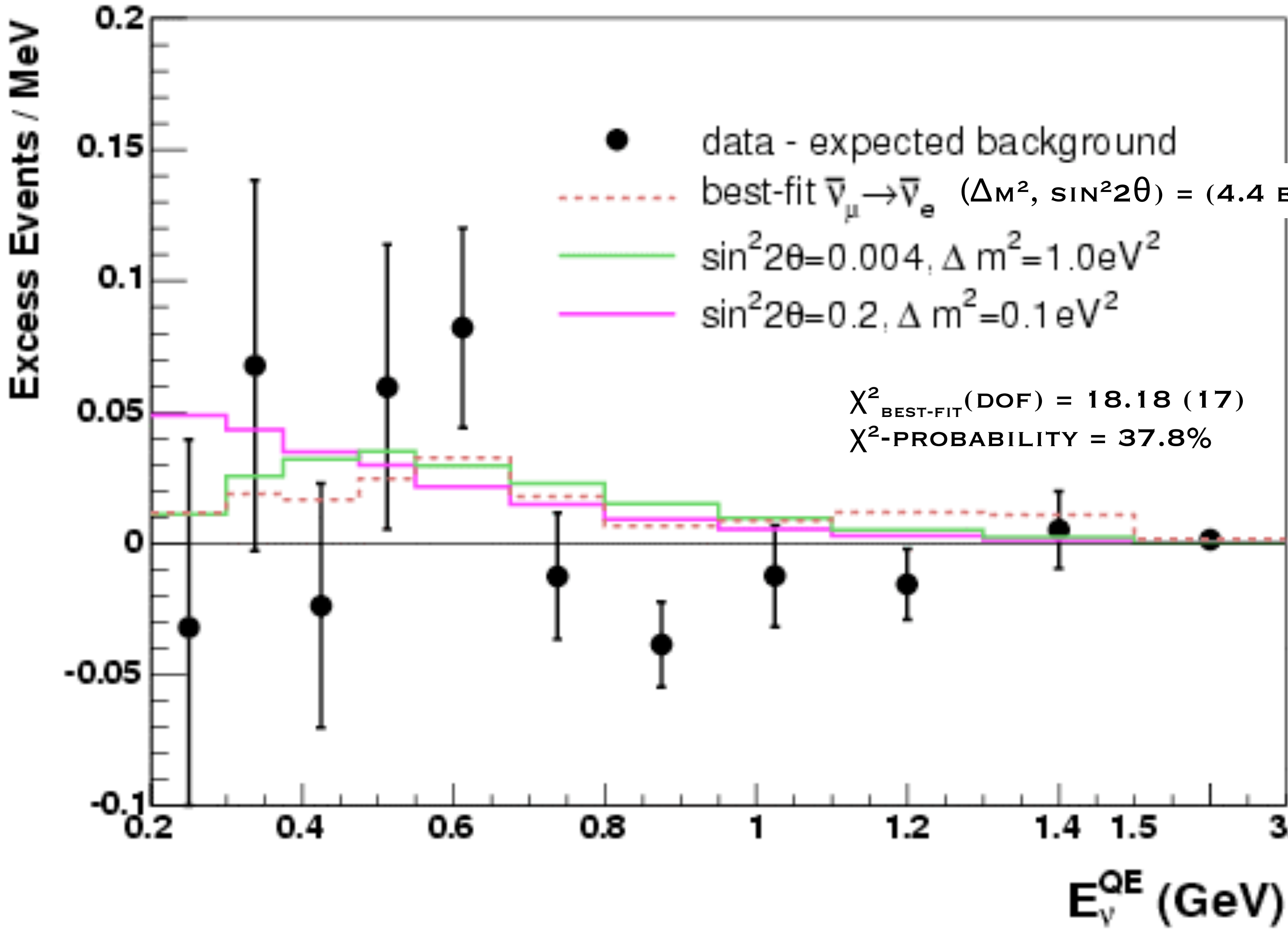


Antineutrino appearance search is statistics limited!

Observed Event Distribution



Excess Distribution



(Δm^2, $\sin^2 2\theta$) = (4.4 eV^2, 0.004)

$\chi^2_{\text{best-fit}}$(dof) = 18.18 (17)
χ^2-probability = 37.8%

Event Summary

arXiv:0812.2243

E_ν^{QE} range (MeV)		anti-ν mode (3.386e20 POT)	ν mode (6.486e20 POT)
200-300	Data	24	232
	MC ± sys+stat (constr.)	27.2 ± 7.4	186.8 ± 26.0
	Excess (σ)	-3.2 ± 7.4 (-0.4σ)	45.2 ± 26.0 (1.7σ)
300-475	Data	37	312
	MC ± sys+stat (constr.)	34.3 ± 7.3	228.3 ± 24.5
	Excess (σ)	2.7 ± 7.3 (0.4σ)	83.7 ± 24.5 (3.4σ)
200-475	Data	61	544
	MC ± sys+stat (constr.)	61.5 ± 11.7	415.2 ± 43.4
	Excess (σ)	-0.5 ± 11.7 (-0.04σ)	128.8 ± 43.4 (3.0σ)
475-1250	Data	61	408
	MC ± sys+stat (constr.)	57.8 ± 10.0	385.9 ± 35.7
	Excess (σ)	3.2 ± 10.0 (0.3σ)	22.1 ± 35.7 (0.6σ)

Excess

Deficit

Implications for Low-E Excess

Maximum χ^2 probability from fits to ν and $\bar{\nu}$ excesses in 200-475 MeV range

	Stat Only	Correlated Syst	Uncorrelated Syst
Same $\nu,\bar{\nu}$ NC	0.1%	0.1%	6.7%
NC π^0 scaled	3.6%	6.4%	21.5%
POT scaled	0.0%	0.0%	1.8%
Bkgd scaled	2.7%	4.7%	19.2%
CC scaled	2.9%	5.2%	19.9%
Low-E Kaons	0.1%	0.1%	5.9%
ν scaled	38.4%	51.4%	58.0%

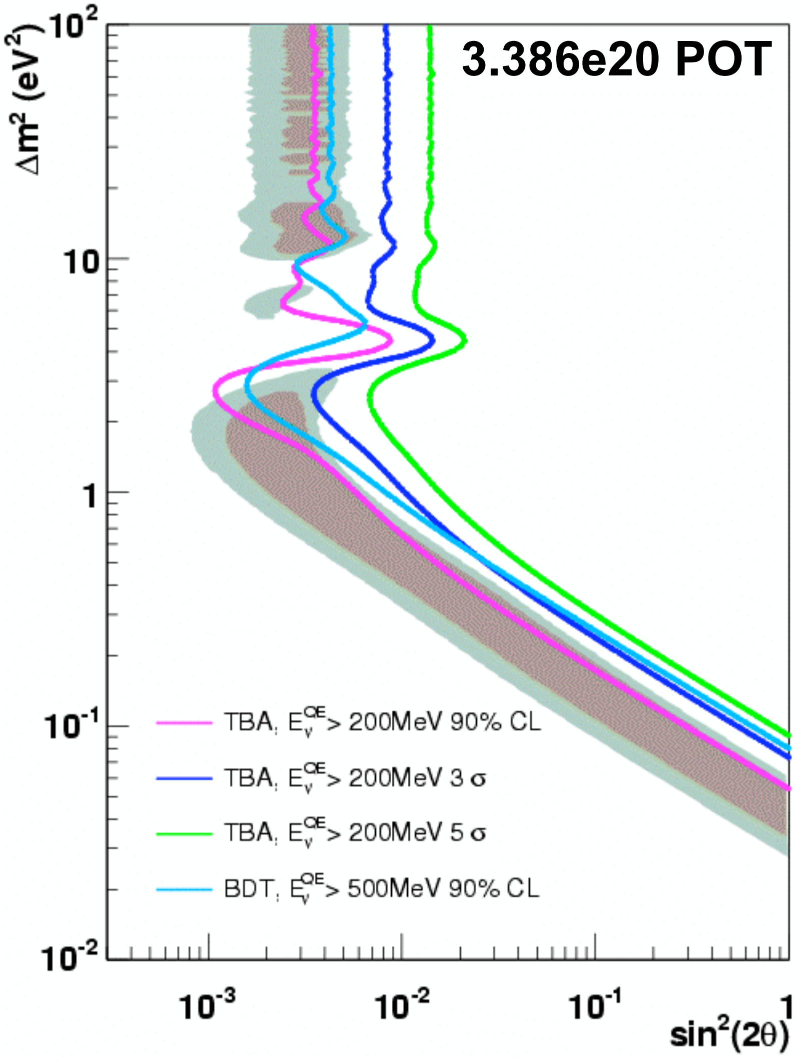
Preliminary
(upper and lower bounds)

Same ν and $\bar{\nu}$ NC cross-section (HHH axial anomaly), POT scaled, Low-E Kaon scaled: strongly disfavored as an explanation of the MiniBooNE low energy excess!

most preferred model: low-energy excess comes from neutrinos in the beam (no contribution from anti-neutrinos)

Currently in process of more careful consideration of correlation of systematics in neutrino and antineutrino mode... results coming soon!

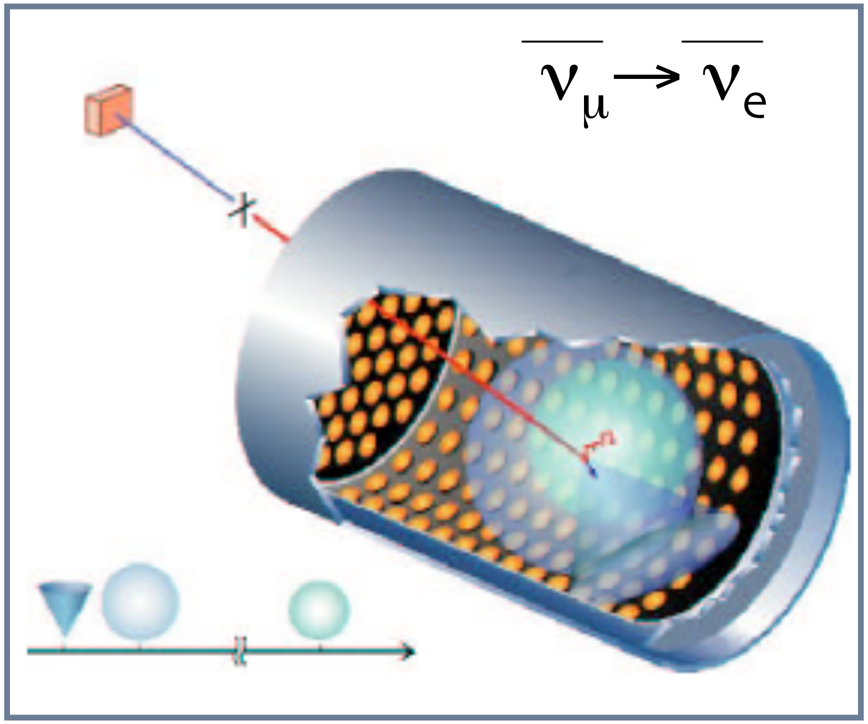
Final Limits



- No strong evidence for oscillations in anti-nu mode
  - Analysis limited by stat
- No evidence of excess at low energy in anti-nu mode
  - Combine nu, anti-nu for low-E analysis
- Data collection continuing through June, 09
- NuMI analysis in 2009!

Backup Slides

The Notorious LSND



- 800 MeV proton beam + H_2O target, Copper beam stop
- 167 ton tank, liquid scintillator, 25% PMT coverage
- E_ν =20-52.8 MeV
- L =25-35 meters

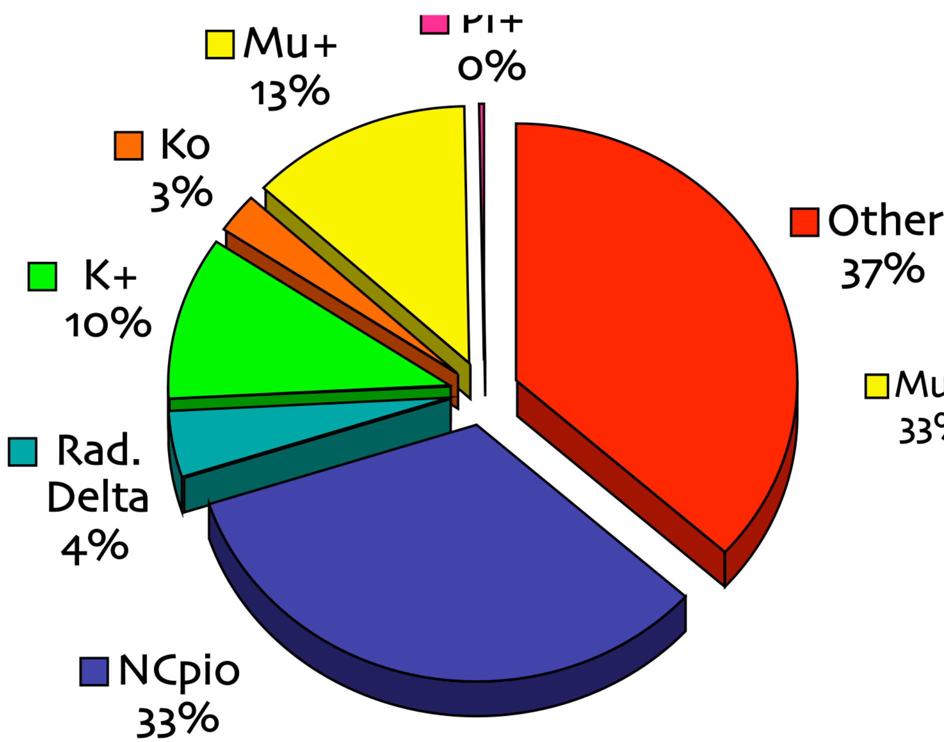
- $\overline{\nu_e} + p \rightarrow e^+ + n$
  - $n + p \rightarrow d + \gamma$ (2.2 MeV)

Neutrino Event Composition

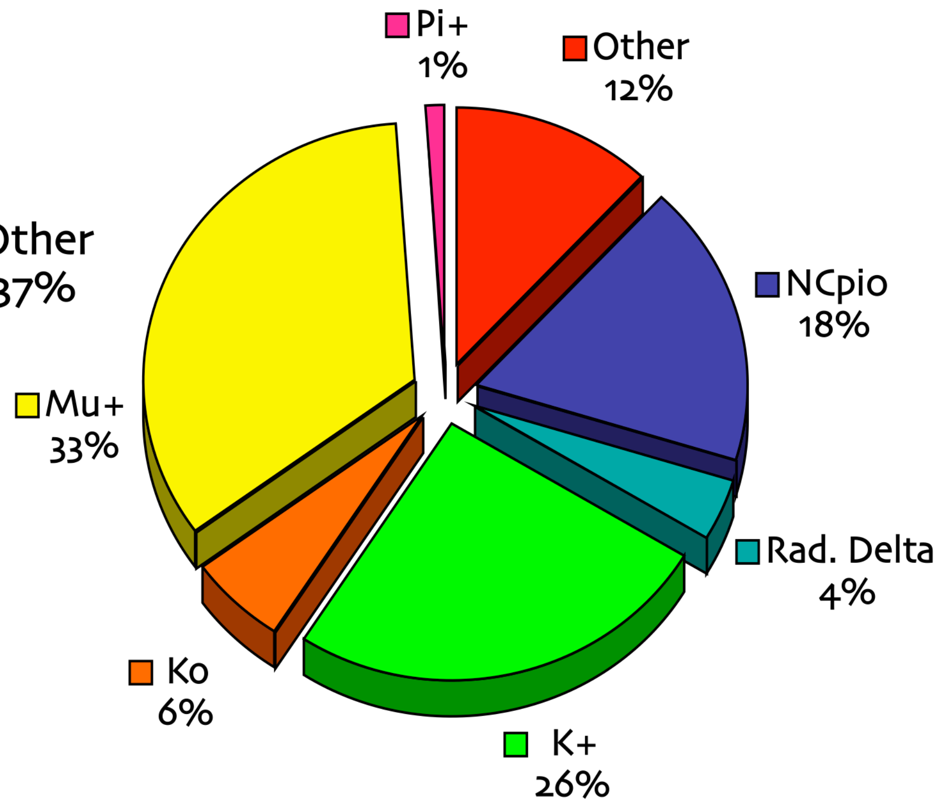
intrinsic ν_e

ν_μ mis-id

Boosting Analysis

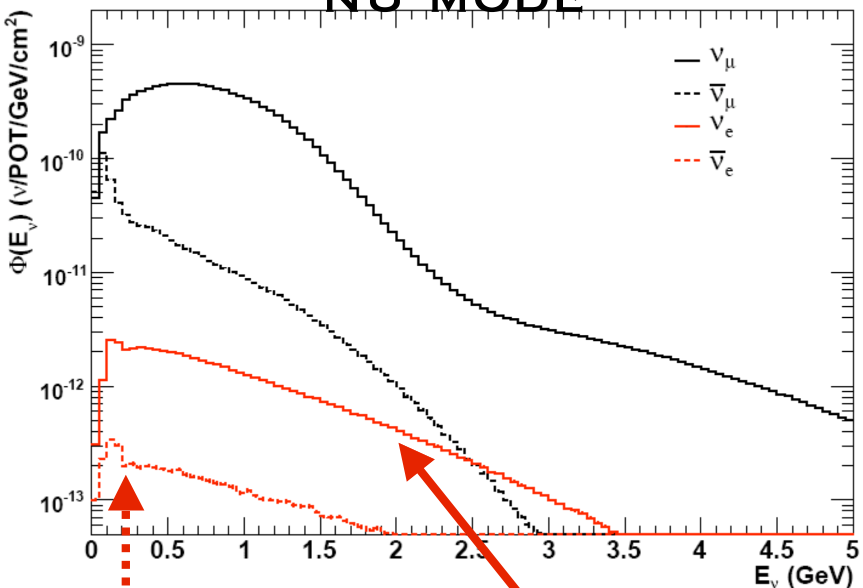


Likelihood Analysis



Flux Prediction

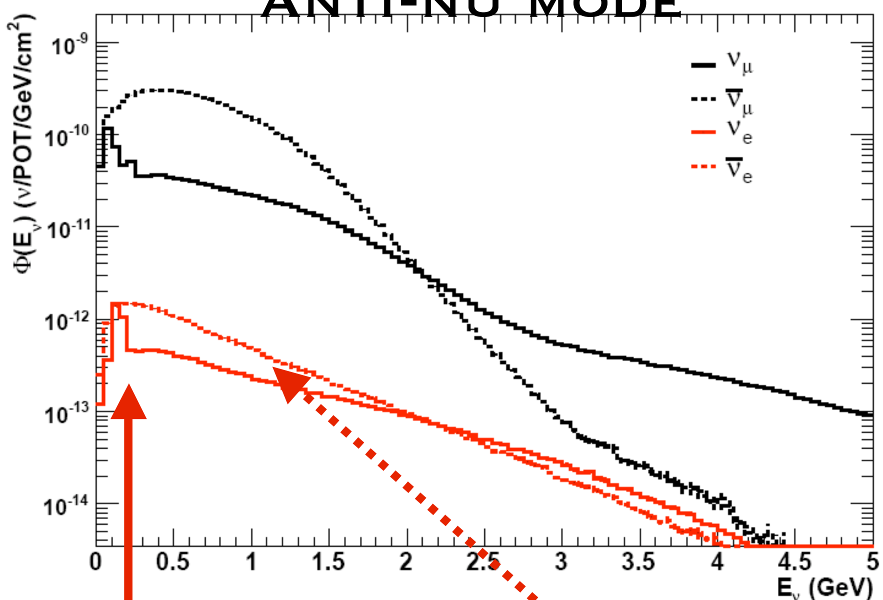
NU MODE



Wrong sign contamination

Intrinsic background to oscillation analysis

ANTI-NU MODE



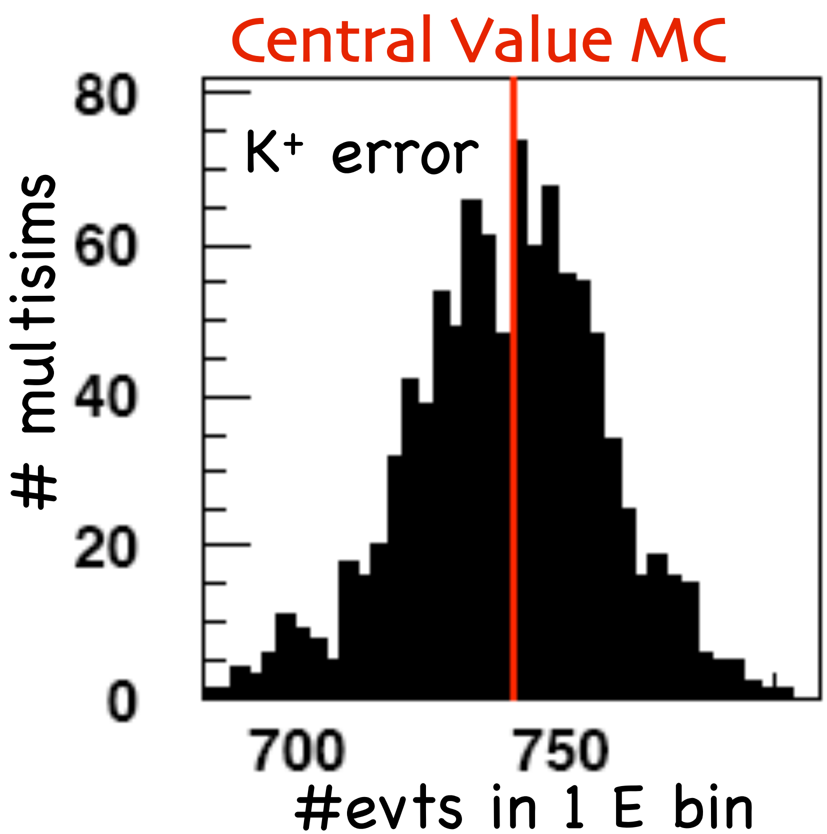
Wrong sign contamination

Intrinsic background to oscillation analysis

- Much larger wrong sign component in anti-neutrino analysis

Systematic Errors

- Use Multisims to calculate systematic errors
- In each MC event vary all parameters at once, according to a full covariance matrix
  - Ex : Feynman scaling of K^+ varies 8 params simultaneously
- Vary full set of parameters many times per event
- OM = 70 multisims. All other errors = 1000
- Use this information to form an error matrix



Systematic Errors

Error	Track vs Boosting (%)	Checked or Constrained by data
DAQ	7.5 / 10.8	☺
Target/Horn	2.8 / 1.3	☺
π^+ Flux	6.2 / 4.3	☺
K^+ Flux	3.3 / 1.0	☺
K^0 Flux	1.5 / 0.4	☺
Dirt	0.8 / 3.4	☺
NC π^0 yield	1.8 / 1.5	☺
Neutrino Xsec	12.3 / 10.5	☺
OM	6.1 / 10.5	☺

Expected background events by source

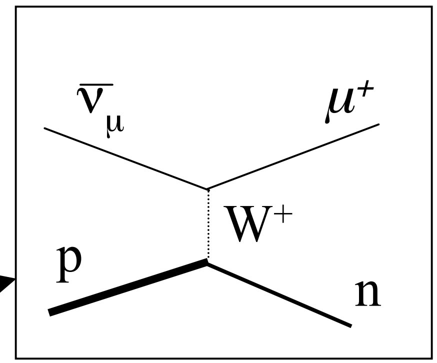
(Track-based analysis)

PROCESS	EVENTS AFTER SELECTION
BEAM UNRELATED	2
DIRT	17
NEUTRAL CURRENT π^0	62
NC RADIATIVE Δ DECAY	20
NC COHERENT AND RADIATIVE	<1
ν_μ QUASIELASTIC	10
NEUTRINO-ELECTRON ELASTIC	7
OTHER ν_μ	13
INTRINSIC ν_e FROM MUONS	132
INTRINSIC ν_e FROM K^+	71
INTRINSIC ν_e FROM K^0	23
INTRINSIC ν_e FROM $\pi^+ \rightarrow e^+ \nu_e$	3
TOTAL BACKGROUND	358 ± 35(syst)
0.26% $\nu_\mu \rightarrow \nu_e$	163

If LSND correct

Expected Event Composition

N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.74	43.23
from $\pi^{\pm}/\mu^{\pm}$	8.44	17.14
from $K^{\pm}$, K^0	8.20	24.88
other ν_e	1.11	1.21
mis-id ν_μ	42.54	14.55
CCQE	2.86	1.24
NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	60.29	57.78
LSND best fit	4.33	12.63



μ^+ can…
…capture on C
…decay too quickly
…have too low energy

Expected Event Composition

N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.74	43.23
from $\pi^{\pm}/\mu^{\pm}$	8.44	17.14
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Dirt	4.69	1.92
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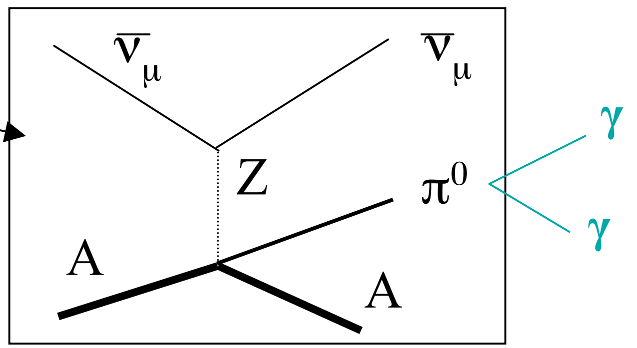
Coherent π^0 production



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NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	60.29	57.78
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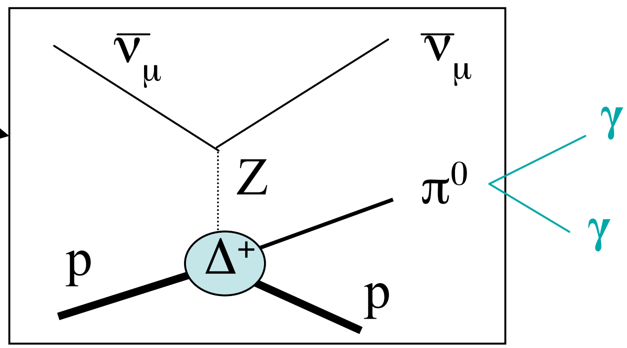
Resonant π^0 production



Expected Event Composition

N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.74	43.23
from $\pi^\pm/\mu^\pm$	8.44	17.14
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other ν_e	1.11	1.21
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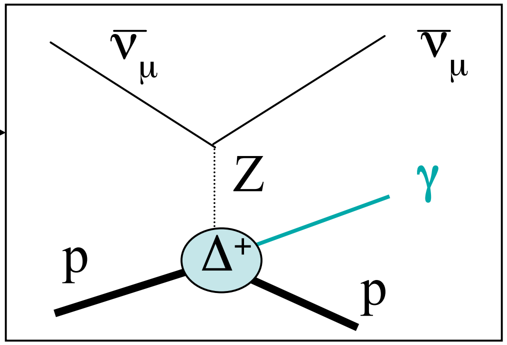
CCQE	2.86	1.24
NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	**60.29**	**57.78**
LSND best fit	**4.33**	**12.63**

…and some times…
Δ radiative decay



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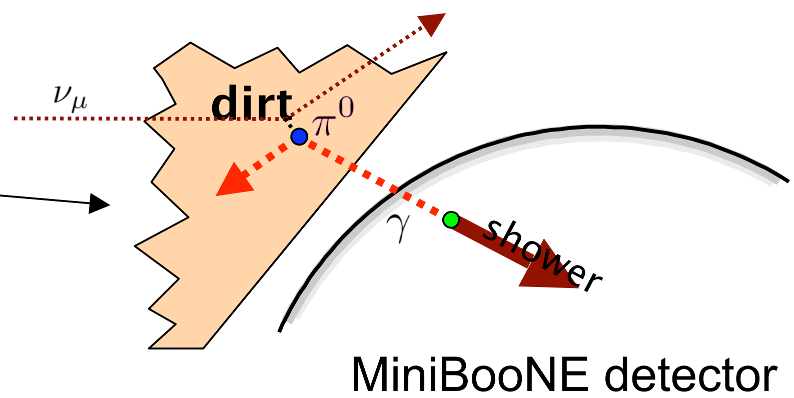
intrinsic ν_e	17.74	43.23
from $\pi^{\pm}/\mu^{\pm}$	8.44	17.14
from $K^{\pm}$, K^0	8.20	24.88
other ν_e	1.11	1.21
mis-id ν_μ	42.54	14.55
CCQE	2.86	1.24
NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	60.29	57.78
LSND best fit	4.33	12.63



200-475 MeV	*Data*	*61*	$\bar{\nu}$	*544*	ν
	MC ± sys+stat (constr.)	*61.5 ± 11.7*		*415.2 ± 43.4*	
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*		*128.8 ± 43.4 (3.0σ)*	

How consistent are excesses in neutrino and antineutrino mode under different underlying hypotheses as the source of the low energy excess in neutrino mode?

- Scales with POT
- Same NC cross section for neutrinos and antineutrinos
- Scales as π^o background
- Scales with neutrinos (not antineutrinos)
- Scales with background
- Scales as the rate of Charged-Current interactions
- Scales with Kaon rate at low energy

			$\bar{\nu}$	ν
200-475 MeV	*Data*	*61*		*544*
	MC ± sys+stat (constr.)	*61.5 ± 11.7*		*415.2 ± 43.4*
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*		*128.8 ± 43.4 (3.0σ)*

- Performed 2-bin χ^2 test for each assumption
- Calculated χ^2 probability assuming 1 DOF

The underlying signal for each hypothesis was allowed to vary (thus accounting for the possibility that the observed signal in neutrino mode was a fluctuation up, and the observed signal in antineutrino mode was a fluctuation down), and an absolute χ^2 minimum was found.

- Three extreme fit scenarios were considered:
  - Statistical-only uncertainties
  - Statistical + fully-correlated systematics
  - Statistical + fully-uncorrelated systematics

200-475 MeV	*Data*	*61*	$\bar{\nu}$	*544*	ν
	MC ± sys+stat (constr.)	*61.5 ± 11.7*		*415.2 ± 43.4*	
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*		*128.8 ± 43.4 (3.0σ)*	

Eg.: scales with POT *(e.g. "paraphotons",...)*

Antineutrino POT: 3.386e20
Neutrino POT: 6.486e20

$$\frac{\text{Antineutrino POT}}{\text{Neutrino POT}} = 0.52$$

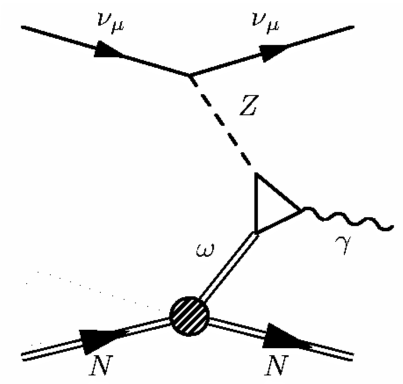
One would expect a $\bar{\nu}$ excess of ~(128.8 events)*0.52 = ~67 events

Obviously this should be highly disfavored by the data, but one could imagine a scenario where the neutrino mode observed excess is a fluctuation up from true underlying signal and the antineutrino mode excess is a fluctuation down, yielding a lower χ^2…

200-475 MeV	*Data*	*61*	$\bar{\nu}$	*544*	ν
	MC ± sys+stat (constr.)	*61.5 ± 11.7*		*415.2 ± 43.4*	
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*		*128.8 ± 43.4 (3.0σ)*	

Eg.: Same NC cross section for neutrinos and antineutrinos *(e.g., HHH axial anomaly)*

Expected rates obtained by integrating flux across all energies for neutrino mode, and antineutrino mode



[Harvey, Hill, and Hill, hep-ph0708.1281]

		$\bar{\nu}$	ν
200-475 MeV	*Data*	*61*	*544*
	MC ± sys+stat (constr.)	*61.5 ± 11.7*	*415.2 ± 43.4*
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*	*128.8 ± 43.4 (3.0σ)*

- Eg.: Scales as π^o background (same NC ν and $\bar{\nu}$ cross-section ratio)

- Expected rates obtained by integrating flux across all energies for neutrino mode, and antineutrino mode

- Mis-estimation of π^o background?
- Or other Neutral-Current process?
  - For π^o background to fully account for MB ν mode excess, it would have to be mis-estimated by a factor of two...
  - ...but we have measured MB π^o event rate to a few percent!

[Phys. Lett. B664, 41 (2008)]

200-475 MeV	*Data*	*61*	$\bar{\nu}$	*544*	ν
	MC ± sys+stat (constr.)	*61.5 ± 11.7*		*415.2 ± 43.4*	
	Excess (σ)	*-0.5 ± 11.7 (-0.04σ)*		*128.8 ± 43.4 (3.0σ)*	

Eg.: Scales with neutrinos (in both running modes)

In neutrino mode, 94% of flux consists of neutrinos

In antineutrino mode, 82% of flux consists of antineutrinos, 18% of flux consists of neutrinos

Predictions are allowed to scale according to neutrino content of the beam

E_ν^{QE} fit	χ^2_{null}(dof)[1] χ^2-prob	$\chi^2_{best\text{-}fit}$(dof)[1] χ^2-prob	$\chi^2_{LSND\ best\text{-}fit}$(dof) χ^2-prob
> 200 MeV	20.18(19) 38.4%	18.18(17) 37.8%	20.14(19) 38.6%
> 475 MeV	17.88(16) 33.1%	15.91(14) 31.9%	17.63(16) 34.6%

([1]Covariance matrix approximated to be the same everywhere by its value at best fit point)

E_ν^{QE} > 200 MeV and E_ν^{QE} > 475 MeV fits are consistent with each other. No strong evidence for oscillations in antineutrino mode. (3.386e20 POT)

2D global fit