First MiniBooNE $\overline{\nu}_e$ Appearance Results

Georgia Karagiorgi, MIT

FNAL – December 11, 2008

Outline

1. **Motivation for $\bar{\nu}_e$ appearance search**
2. **MiniBooNE Experiment**
3. **MiniBooNE $\bar{\nu}_e$ analysis**
4. **Results**
   - Oscillation fits
   - Implications for low energy excess observed in neutrino mode
5. **Future prospects and conclusions**

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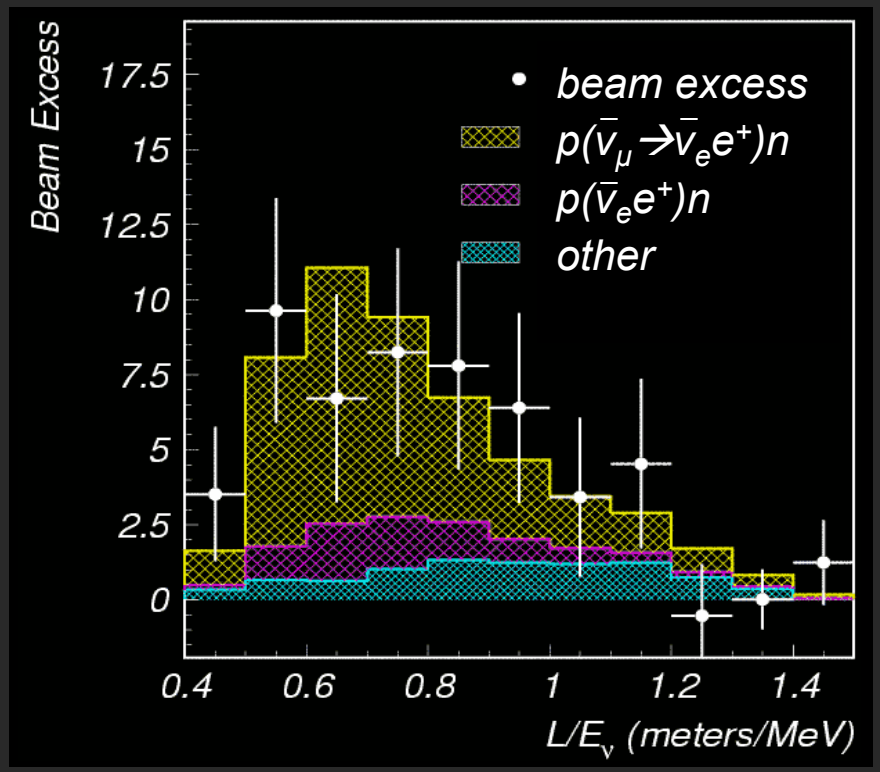
Appearance search @ LSND

- **Collected data from 1993 to 1998**
- **Liquid scintillator (Cherenkov) detector lined with PMT's**
- **Detected $\bar{\nu}_e$ from stopped pion source: $\pi^+ \rightarrow \mu^+ \rightarrow \bar{\nu}_\mu$**

- **observed excess:**
  87.9 ± 22.4 ± 6.0 $\bar{\nu}_e$ events (3.8σ)



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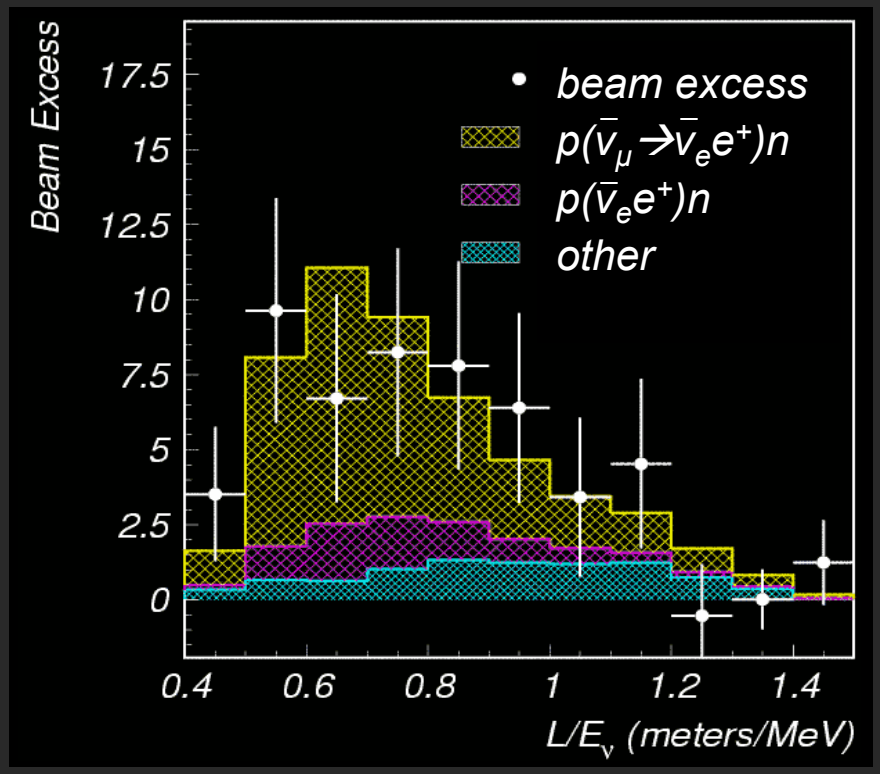
Possible interpretation:

2-neutrino mixing with

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\,\sin^2\left(\frac{1.27\,L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$



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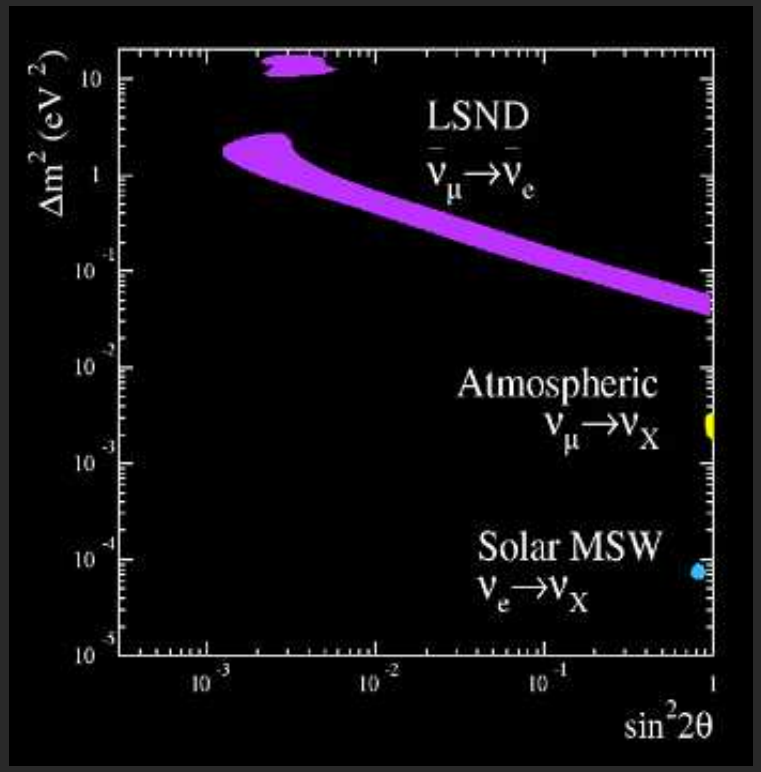
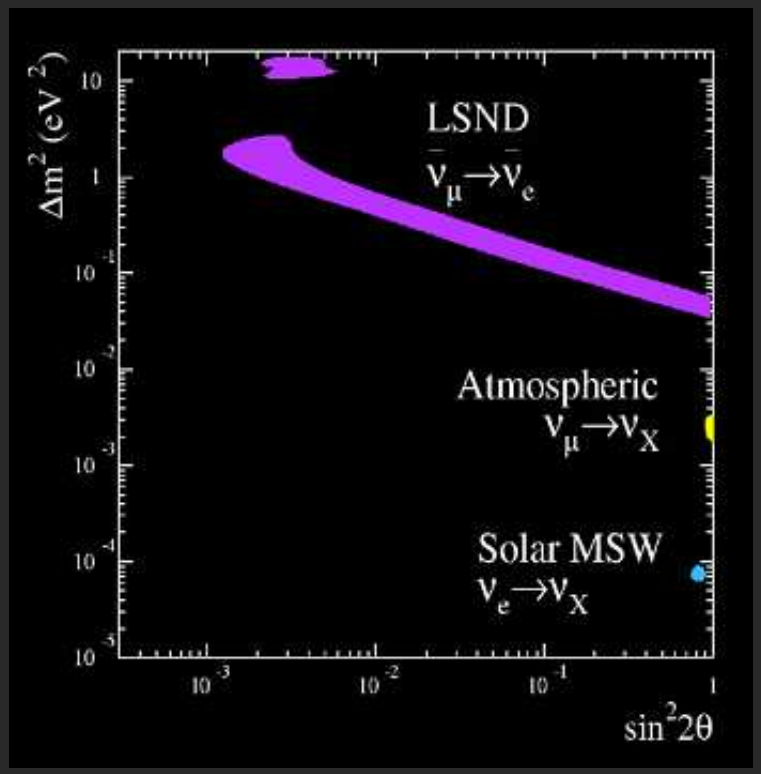


Appearance search @ LSND

However, under this oscillation interpretation:

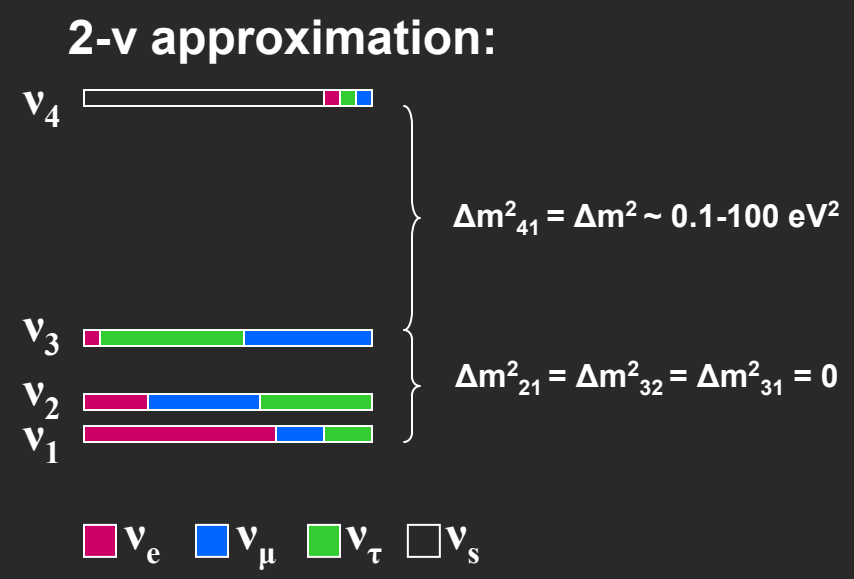
$$\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$$



→ requires new physics beyond the standard three-neutrino mixing scenario

LSND interpretation

- Sterile neutrino models
  - 3+1



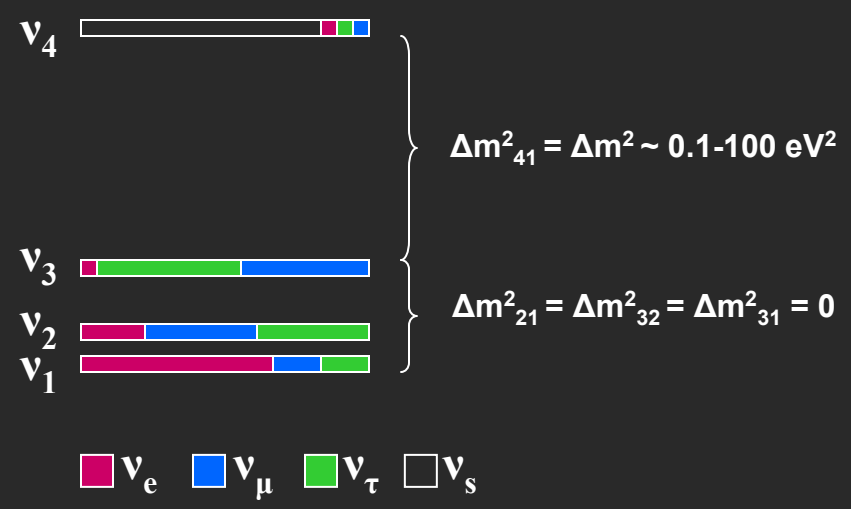
At least 4 mass eigenstates
→at least 4 flavors

But measured $\Gamma(Z \rightarrow \bar{\nu}\,\nu)$ → only 3 different *active* neutrinos
→ 1 *sterile* neutrino

LSND interpretation

- Sterile neutrino models
  - 3+1

2-ν approximation:



Oscillation probability:

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2(1.27\Delta m^2_{41} L/E)$$
$$= \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

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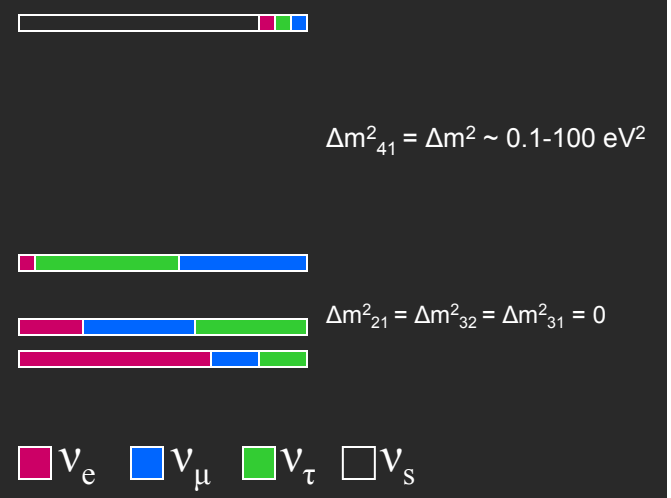
MiniBooNE experiment

- **LSND test: 2-neutrino approximation**
  → **testing simplest interpretation (+1 sterile neutrino)**

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L[m]/E[MeV])$$

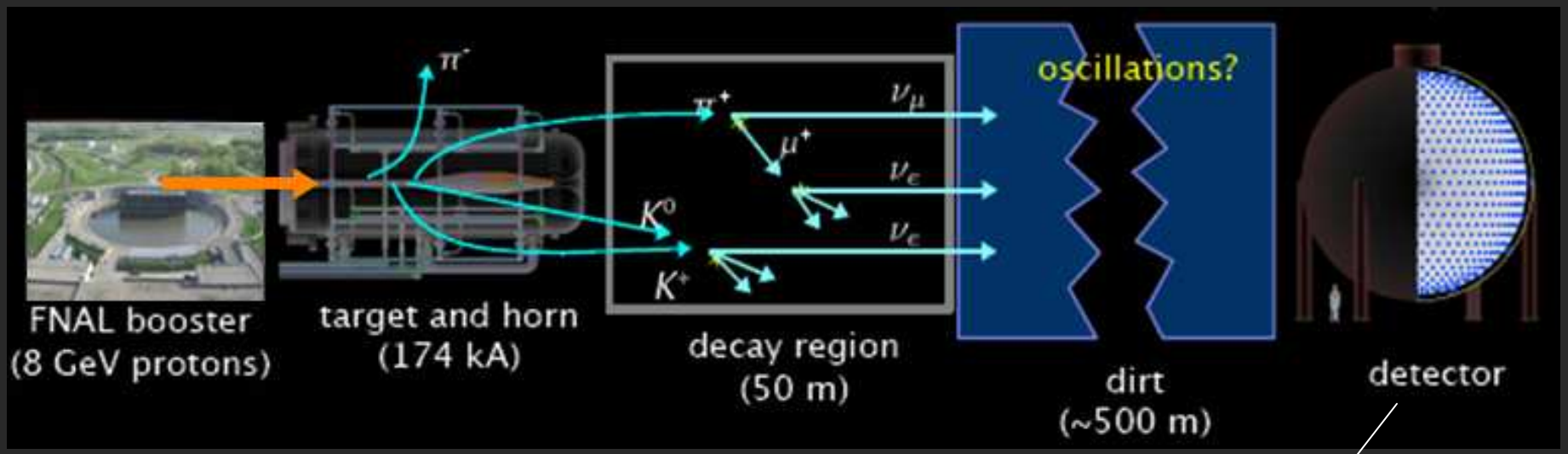


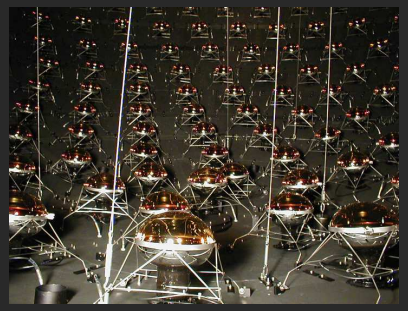
Place detector to preserve LSND L/E:
MiniBooNE: 500 m / 800 MeV
LSND: 30 m / 50 MeV

[Change detection method and systematics]

Run in neutrino mode: incredible statistics!

MiniBooNE experiment



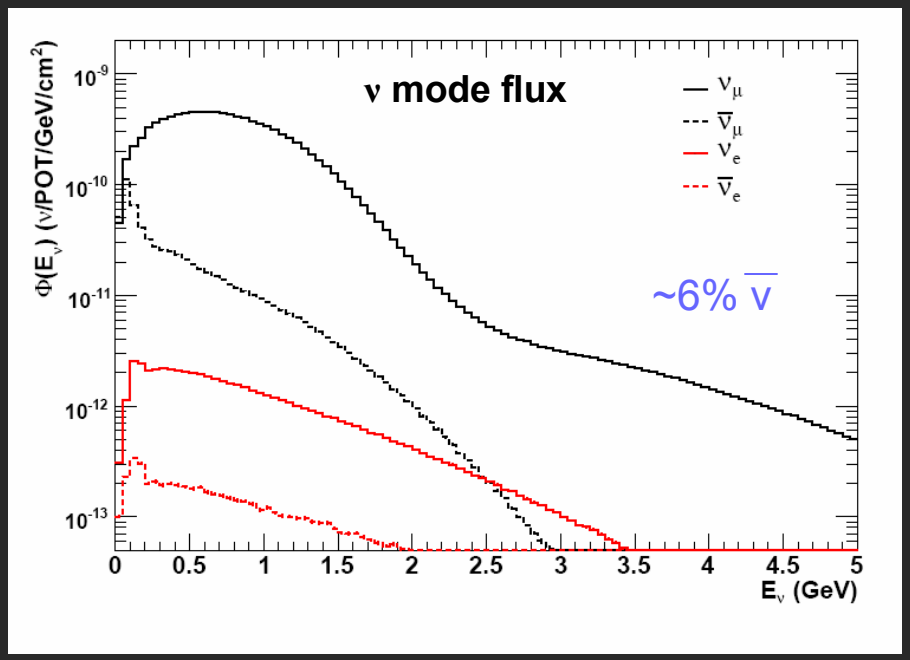


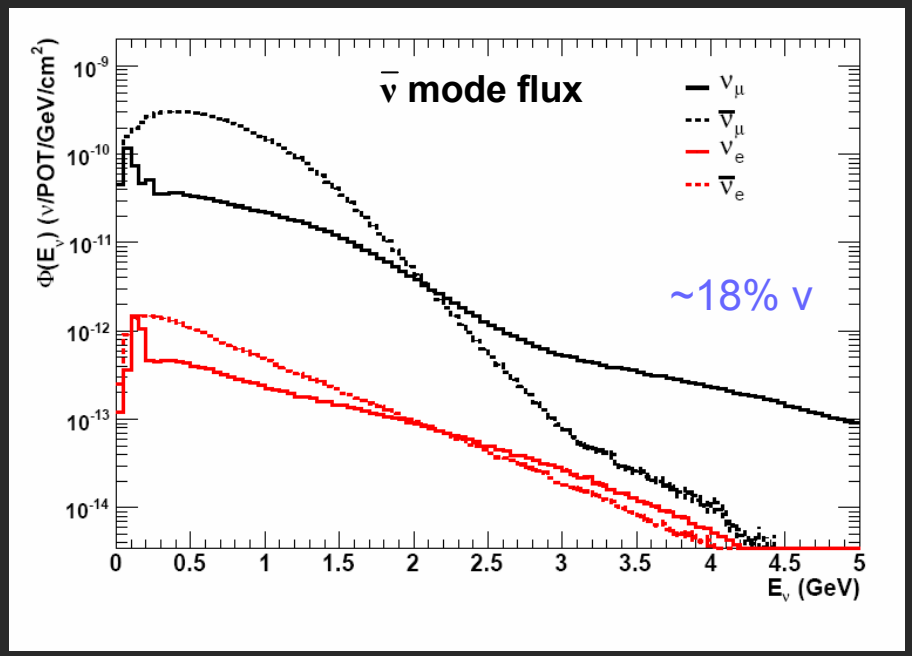
800 ton mineral oil Cherenkov detector
12 m in diameter (450 ton fiducial volume)
lined with 1280 inner PMT's, and 240 outer veto PMT's

[arXiv: 0806.4201[hep-ex], accepted by NIM A]

MiniBooNE experiment

Appearance experiment: it looks for an excess of electron neutrino events in a predominantly muon neutrino beam





neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

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

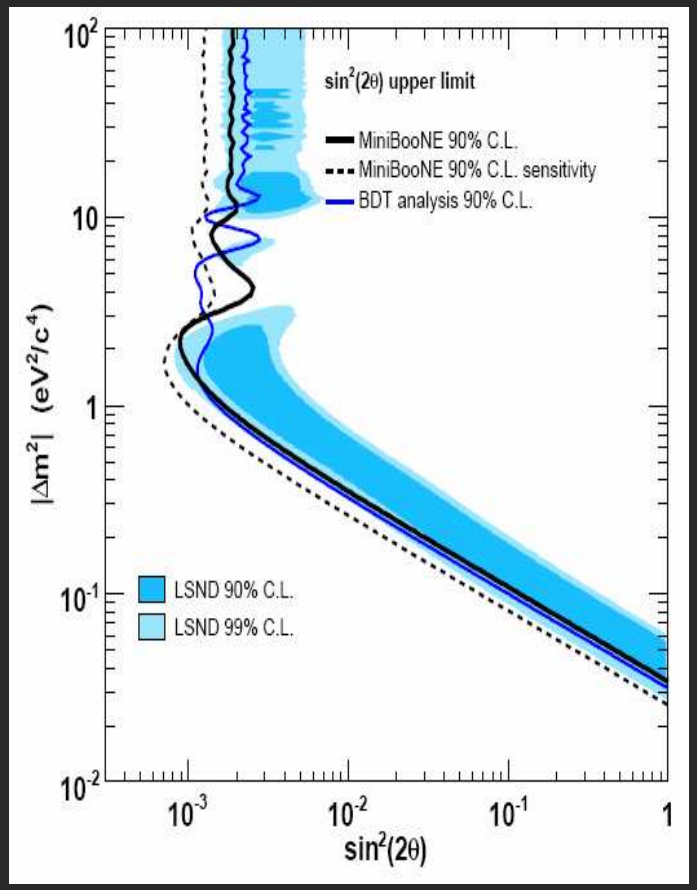
antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

NEW RESULTS!

MiniBooNE ν_e appearance search (ν mode)

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

Sensitivity and limit to $\nu_\mu \rightarrow \nu_e$ oscillations

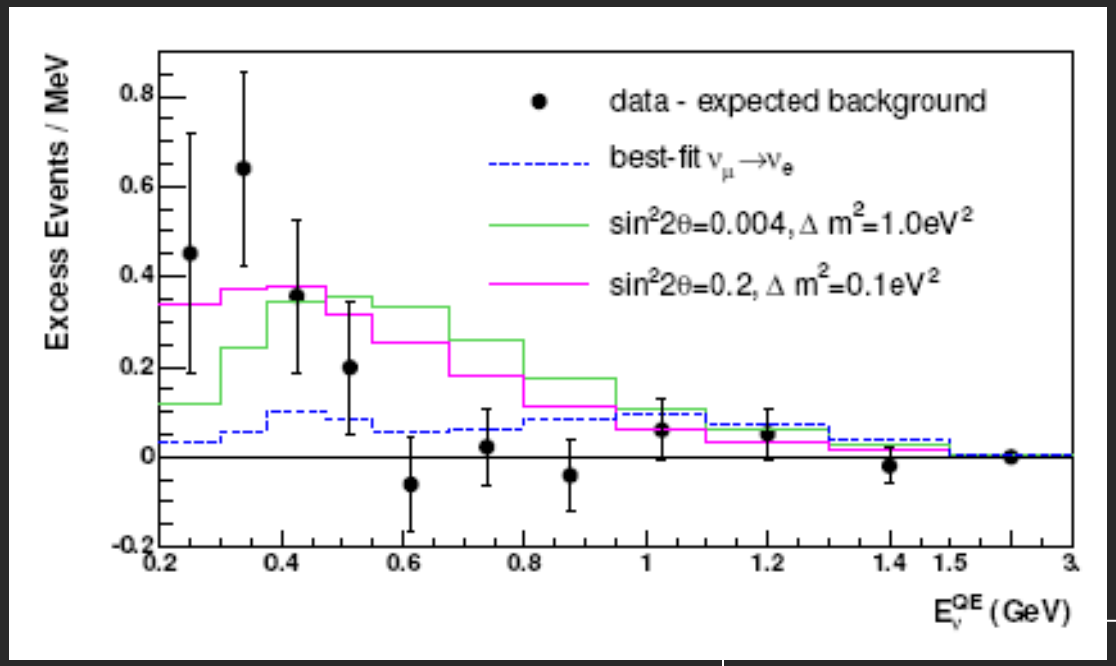


MiniBooNE has ruled out (to 98%CL) the LSND result interpreted as $\nu_\mu \rightarrow \nu_e$ oscillations described with standard L/E dependence, which assumes two-neutrino oscillations, and no CP or CPT violation.

MiniBooNE ν_e appearance search (ν mode)

At the same time, an unexpected excess of ν_e-like events was observed at lower neutrino energies (200 MeV < E_ν^{QE} < 475 MeV)

[See Aug. 1, 2008 W&C talk by C. Polly…]



After thorough investigation, excess still persists at the 3.0σ level, and its source remains unknown…

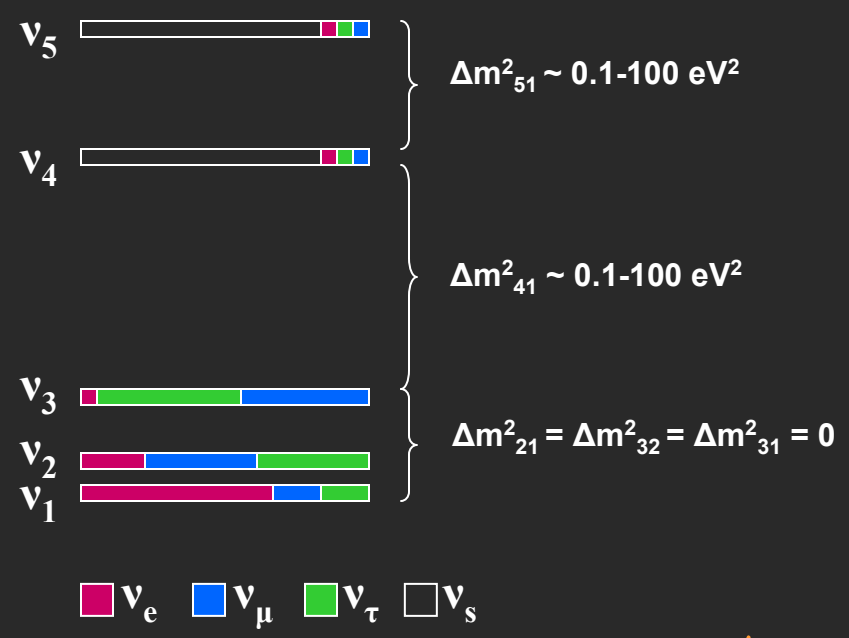
This excess is incompatible with LSND under a two-neutrino oscillation hypothesis.

[paper to be submitted to PRL]

	E>475 MeV	E>200 MeV
Null fit χ^2 (prob):	9.1(91%)	22.0(28%)
Best fit χ^2 (prob):	7.2(93%)	18.3(37%)

LSND interpretation?

- Sterile neutrino models
  - 3+2 → next minimal extension to 3+1 models



2 independent Δm^2
4 mixing parameters
1 Dirac CP phase

Oscillation probability:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2 x_{41} + 4|U_{\mu 5}|^2|U_{e5}|^2 \sin^2 x_{51} + \\ + 8\,|U_{\mu 5}||U_{e5}||U_{\mu 4}||U_{e4}| \sin x_{41} \sin x_{51} \cos(x_{54} \pm \varphi_{45})$$

3+2 models favorable by fits to appearance data, including MiniBooNE neutrino mode result! [hep-ph/0705.0107]

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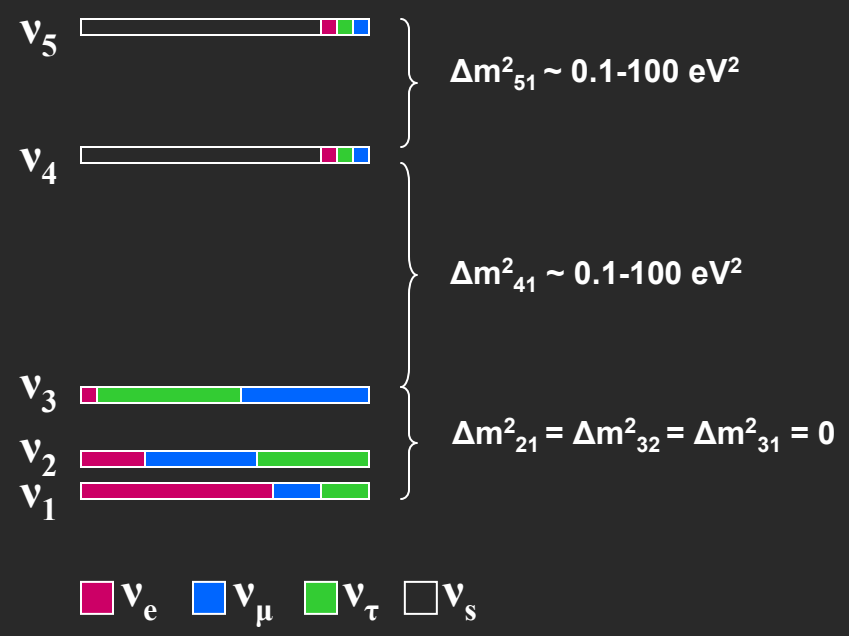

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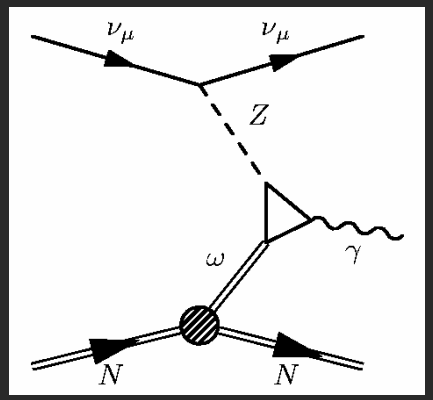
...and appealing due to possibility they offer for CP violation in leptonic sector!

[hep-ph/0305255]

MiniBooNE low energy excess?

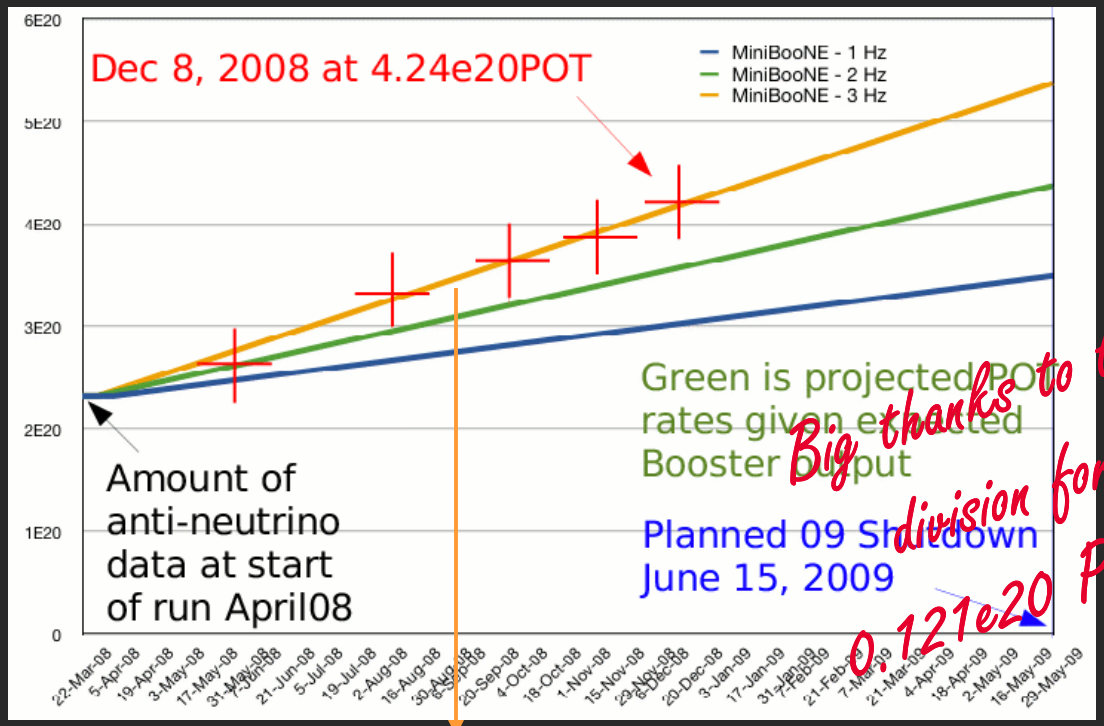
- **Several possible explanations have been put forth by the physics community, attempting to reconcile the MiniBooNE neutrino mode result with LSND and other appearance experiments…**
  - **3+2 with CP violation**
    [Maltoni and Schwetz, hep-ph0705.0107 ; G. K., NuFACT 07 conference]
  - **Anomaly mediated photon production**
    [Harvey, Hill, and Hill, hep-ph0708.1281]
  - **New light gauge boson**
    [Nelson, Walsh, Phys. Rev. D 77, 033001 (2008)]
  - **…**



- **Some of them have fairly concrete predictions for a MiniBooNE antineutrino mode running**

Need a direct test of LSND and another handle on the low energy excess

Fall 2007: approval for extended MiniBooNE antineutrino running to collect data for a total of 5.0e20 POT

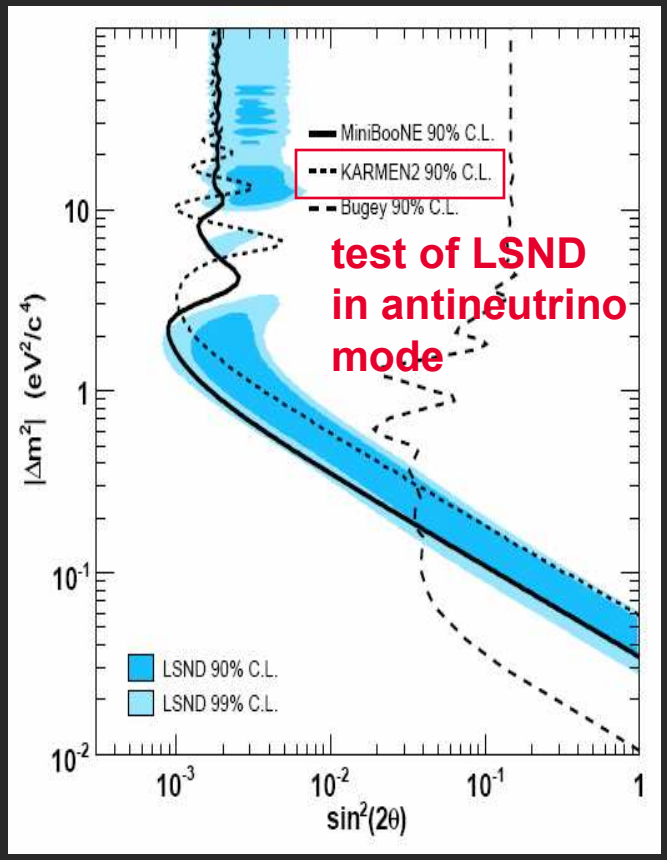


Big thanks to the accelerator division for record-high 0.121e20 POT delivered last week!!!

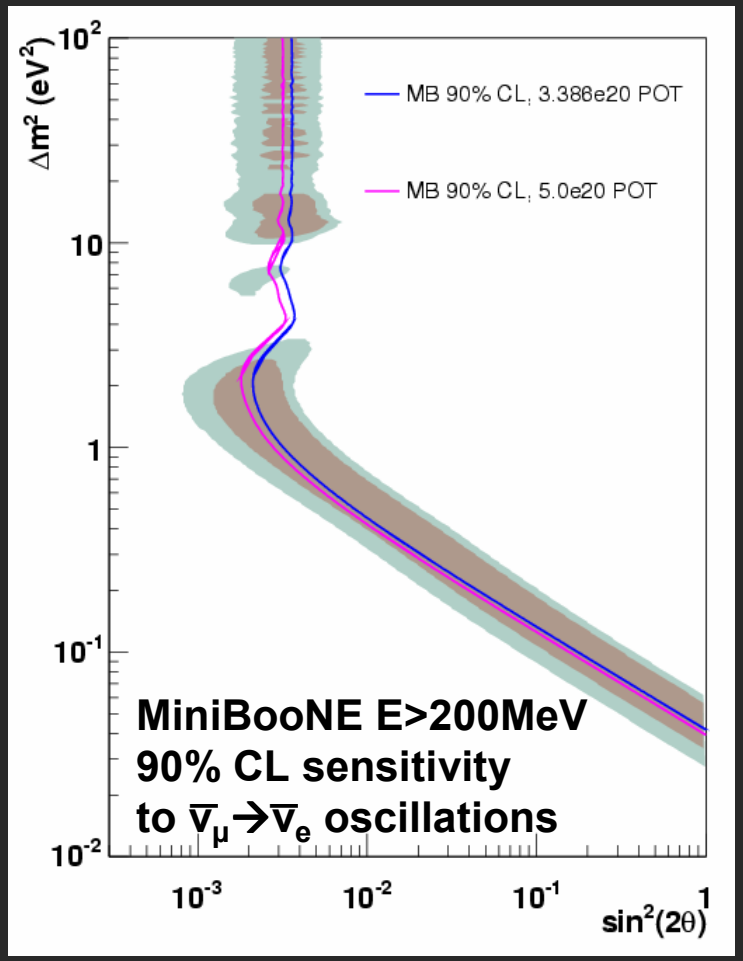
First antineutrino results shown today correspond to 3.386E20 POT !

Need a direct test of LSND and another handle on the low energy excess

Recall, ν mode:



Direct test in antineutrino mode:



MiniBooNE and the νSM

- **Exploring new territories, far beyond the νSM !**
  - **Sterile neutrinos/CP violation** [*hep-ph/0305255*]
  - **Neutrino decay** [*hep-ph/0602083*]
  - **Extra dimensions** [*hep-ph/0504096*]
  - **CPT/Lorentz violation** [*PRD(2006)105009*]

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MiniBooNE $\bar{\nu}_e$ appearance analysis

Same **blind** analysis chain as for neutrino mode…

[*See Aug. 1, 2008 W&C talk by C. Polly…*]

Beam Flux Prediction → **Cross Section Model** → **Optical Model** → **Event Reconstruction** → **Particle Identification** → **Simultaneous Fit to $\bar{\nu}_\mu$ and $\bar{\nu}_e$ events**

Start with a Geant 4 flux prediction for the $\bar{\nu}$ spectrum from π and K produced at the target

Predict $\bar{\nu}$ interactions using the Nuance event generator

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

Use track-based event reconstruction

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

Fit reconstructed energy spectrum for oscillations

…but different background, and different systematics…

MiniBooNE $\bar{\nu}_e$ appearance analysis

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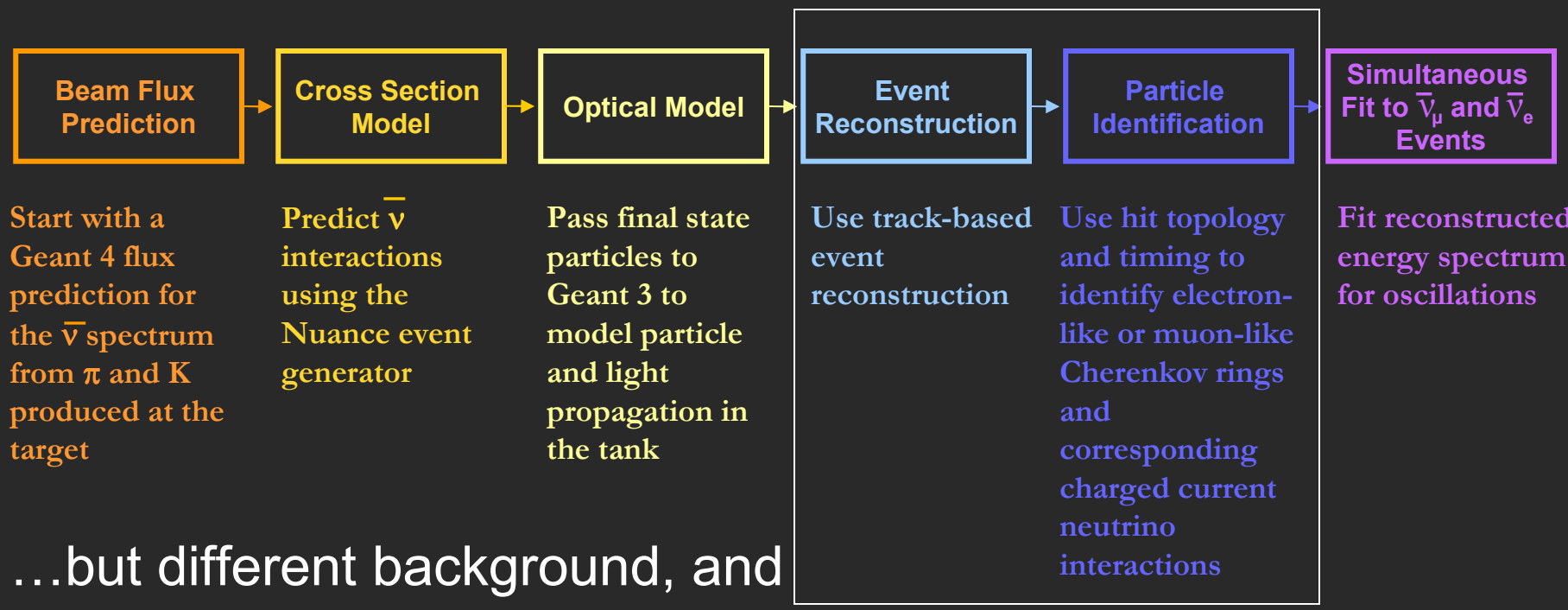

…but different background, and different systematics…

Track-Based Analysis (TBA)

MiniBooNE $\bar{\nu}_e$ appearance analysis

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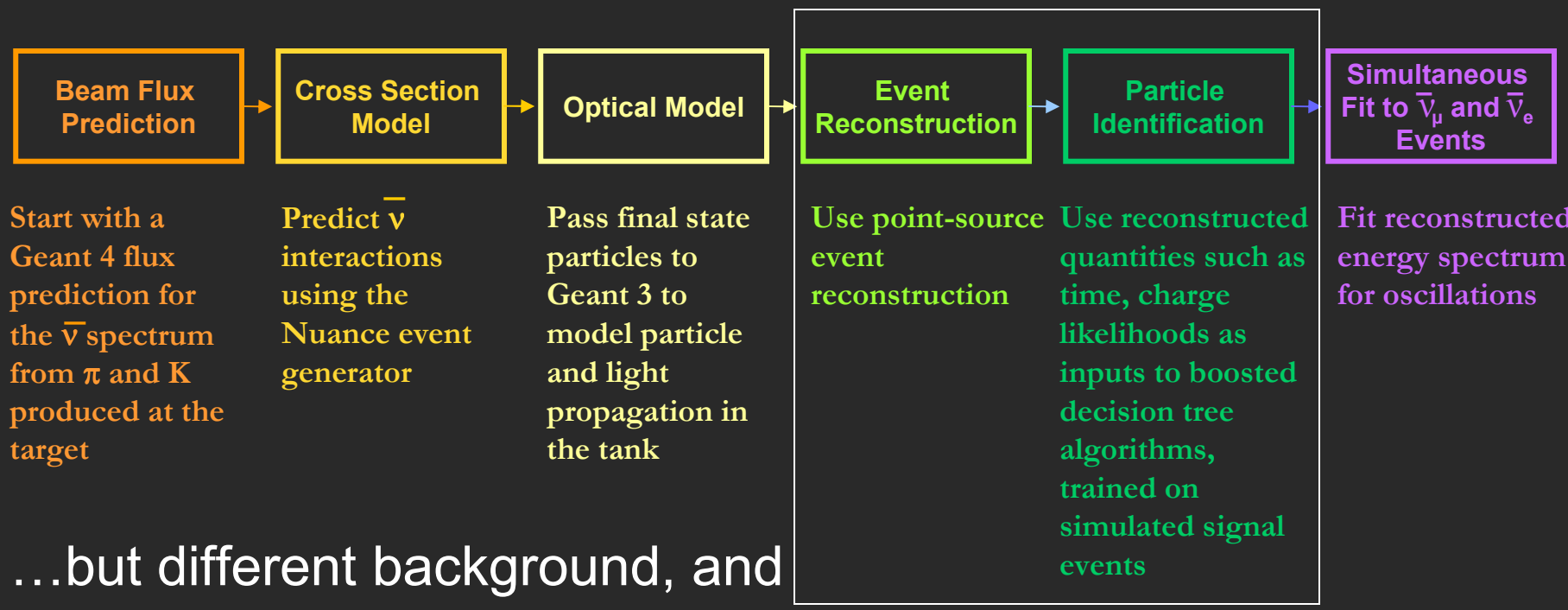
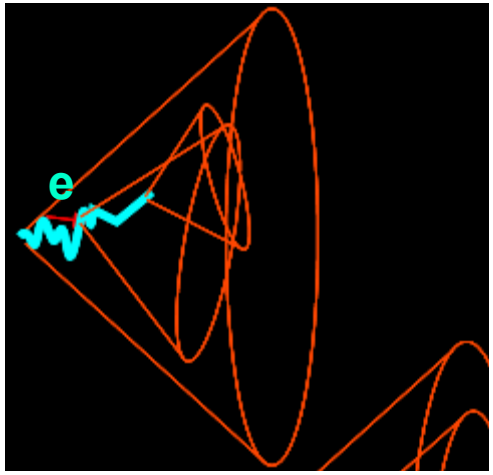
[*See Aug. 1, 2008 W&C talk by C. Polly…*]

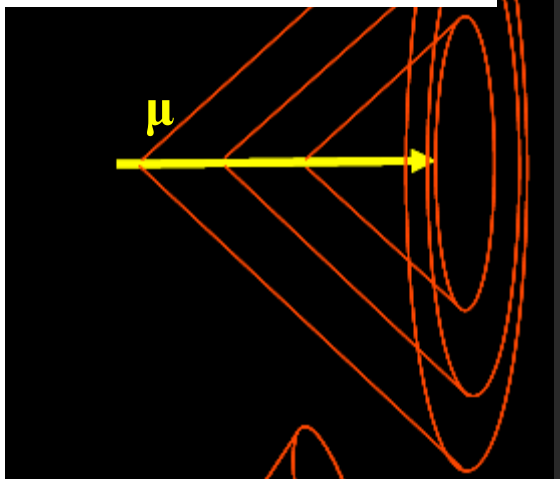


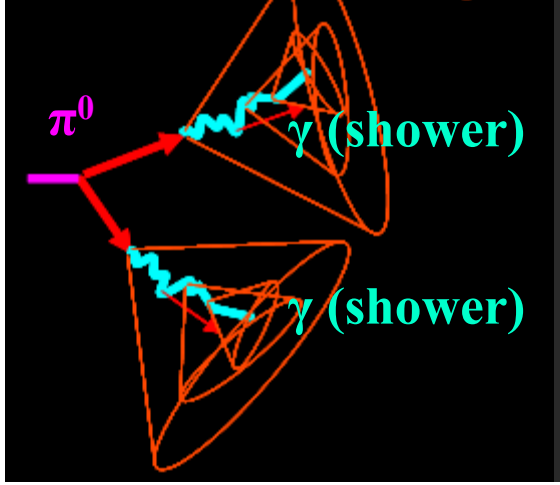
…but different background, and different systematics…

also a Boosted-Decision-Tree analysis (BDT) as a cross-check

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



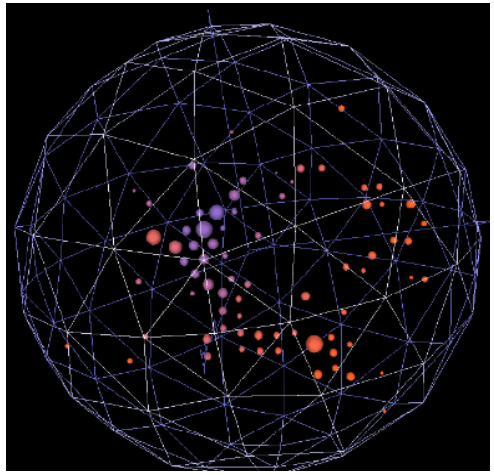


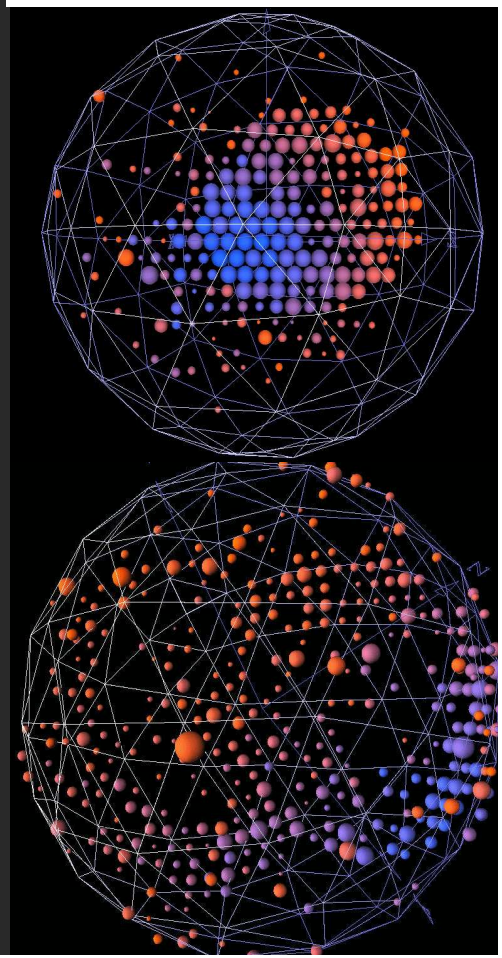


What we want

$\bar{\nu}_e$ **charged-current quasi-elastic events**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$





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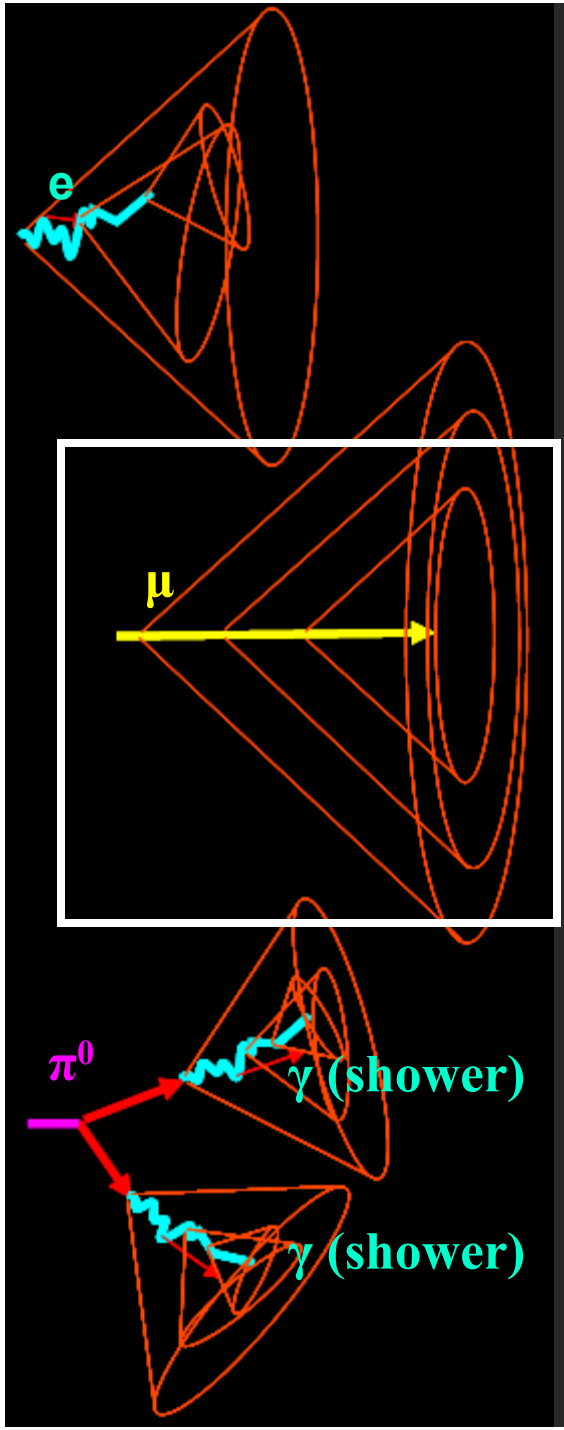
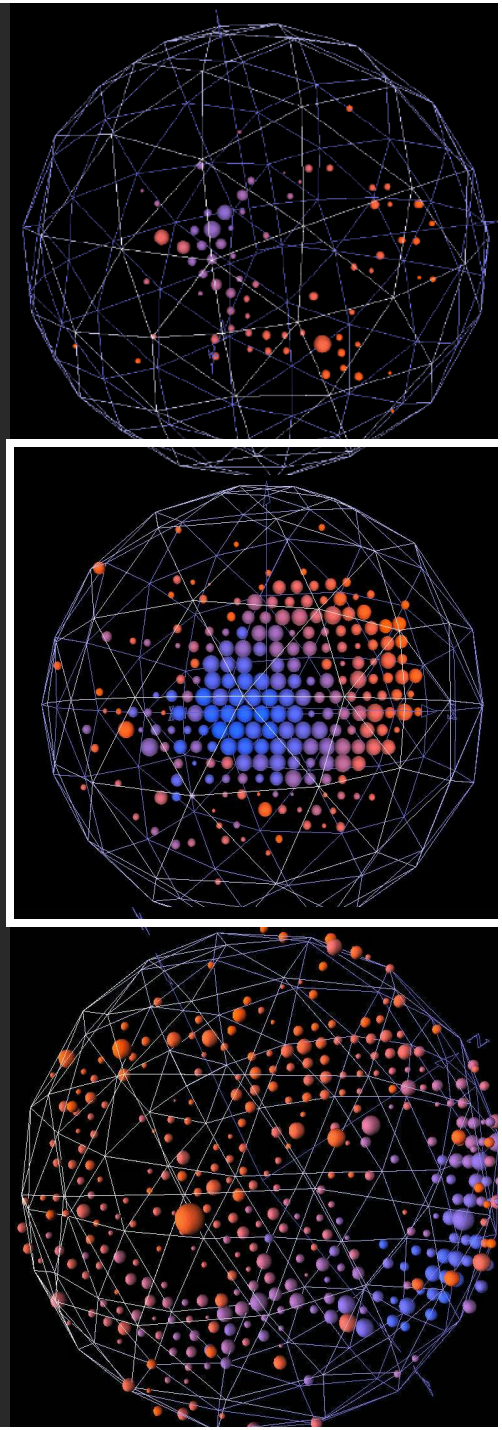
What we don't want



beam dominated by $\bar{\nu}_\mu$ which interact mainly though charged current quasi-elastic (CCQE) channels…

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

(μ decay → second subevent)



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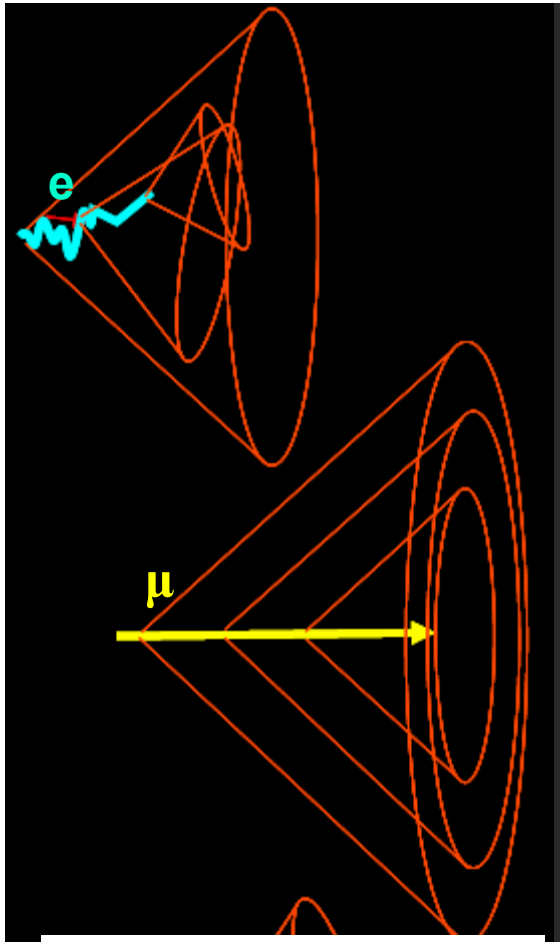


What we don't want

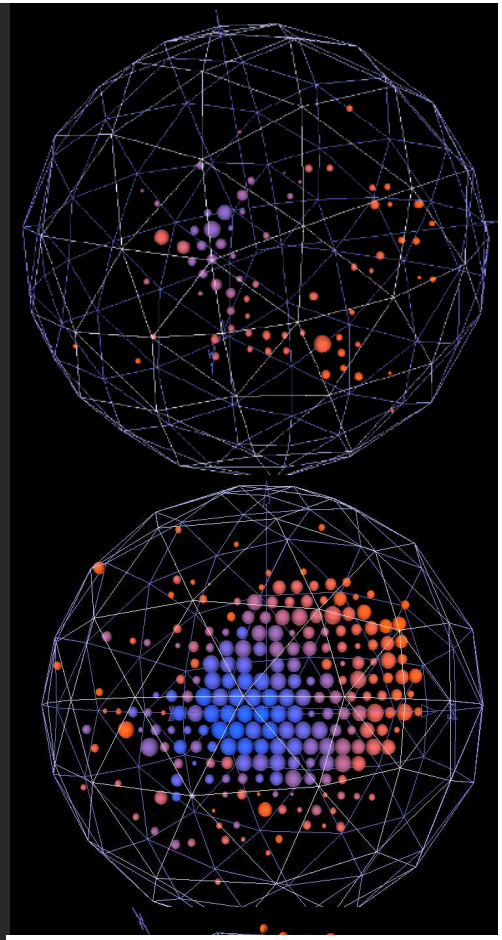
…but some times through neutral current channels, and can therefore be mis-identified as $\bar{\nu}_e$'s…

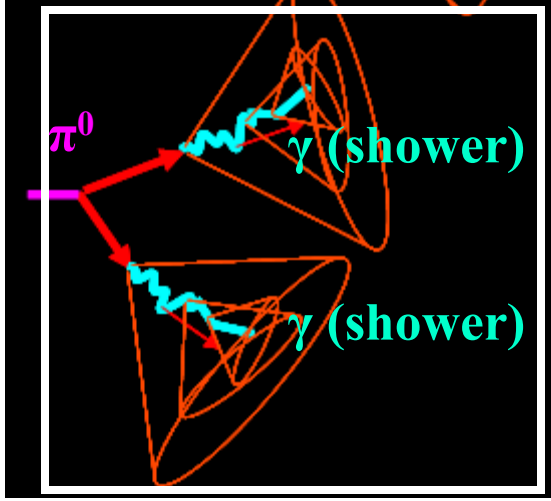
For example, NC π^0:

$$\bar{\nu}_\mu + n/p \rightarrow n/p + \pi^0 + \bar{\nu}_\mu$$

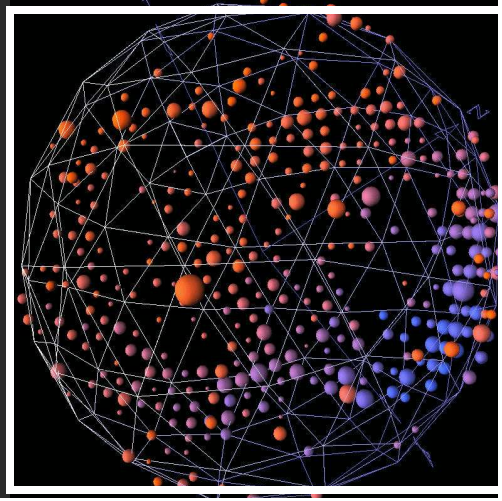
$$\downarrow$$

$$\pi^0 \rightarrow \gamma\gamma$$





…"γ" looks like "e" in a Cherenkov detector



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MiniBooNE $\bar{\nu}_e$ appearance analysis

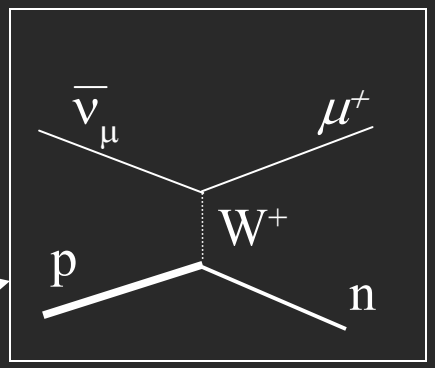
Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

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

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

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



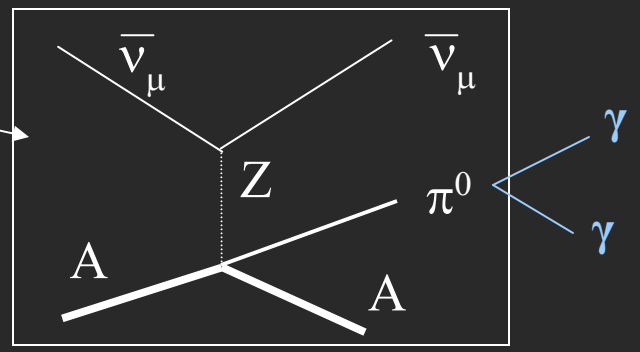
μ^+ can…
…capture on C
…decay too quickly
…have too low energy

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

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

Coherent π^0 production

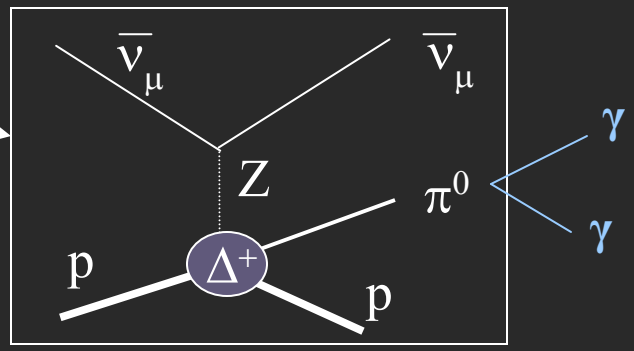


MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

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

Resonant π^0 production

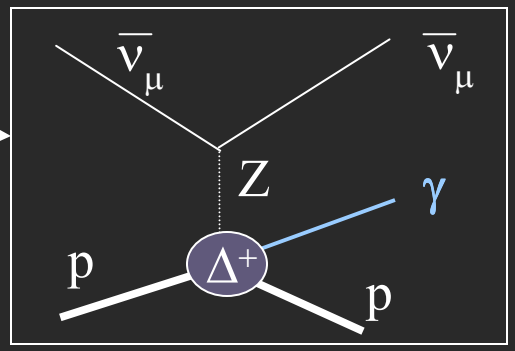


MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

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

…and some times…
Δ radiative decay



MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.74	43.23
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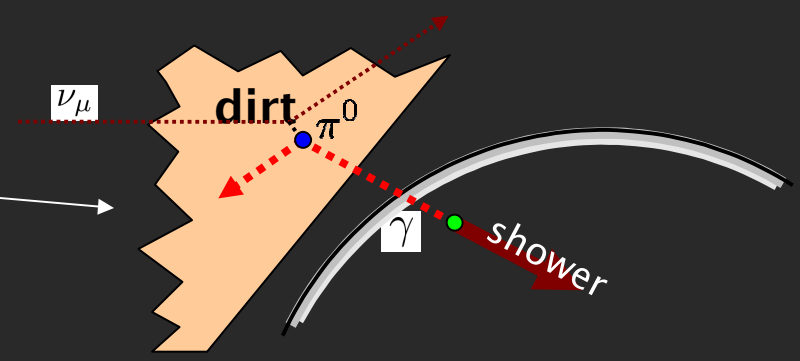
CCQE	2.86	1.24
NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	60.29	57.78
LSND best fit	4.33	12.63

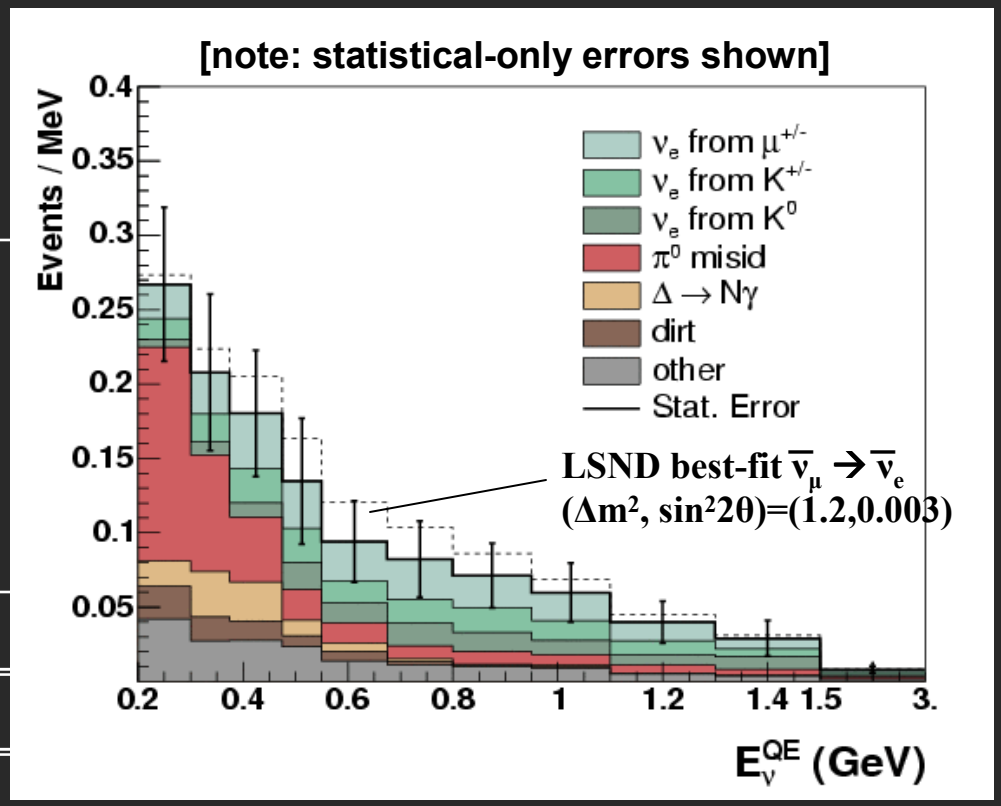


MiniBooNE detector

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

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



MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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*

Come from propagating uncertainties from the HARP experiment using a spline interpolation of the HARP data

[arXiv: 0806.1449 [hep-ex], submitted to PRD]

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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*

Come from propagating uncertainties from Feynman Scaling to the world's K+ production data.

[arXiv: 0806.1449 [hep-ex], submitted to PRD]

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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
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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*

Come from propagating the uncertainties from Sanford Wang to the world K0L production data.

[arXiv: 0806.1449 [hep-ex], submitted to PRD]

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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*

Determined by special runs of the beam Monte Carlo where all the beam uncertainties not coming from meson production by 8 GeV protons are varied one at a time. These variations are treated as 1σ excursions and propagated into a final error matrix.

[arXiv: 0806.1449 [hep-ex], submitted to PRD]

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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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Target and beam models	1.9	3.0	1.3	2.5
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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*

Come from propagating the uncertainties on a number of neutrino cross-section parameters (e.g. M_A)…

…many of which come from fits to (high statistics) MiniBooNE ν_μ data.

See, e.g.,
[Phys. Rev. Lett. 100, 032301 (2008)]

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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*

Come from propagating the error matrix produced by MiniBooNE's π^0 rate measurement.

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

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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
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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*

Come from propagating the uncertainties in a number of hadronic processes, mainly photonuclear interaction final state uncertainties.

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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
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Target and beam models	1.9	3.0	1.3	2.5
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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*

Come from propagating the uncertainty in MiniBooNE's dirt rate measurement.

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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
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NC π^0 yield	1.7	1.6	1.4	1.9
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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*

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

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
E_ν^{QE} range (MeV)	*200-475*	*475-1100*	*200-475*	*475-1100*
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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*

These are uncertainties in our knowledge of the detector. A set of "unisim" variations are run and a matrix results from propagating these variations, treating them as 1σ variations.

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
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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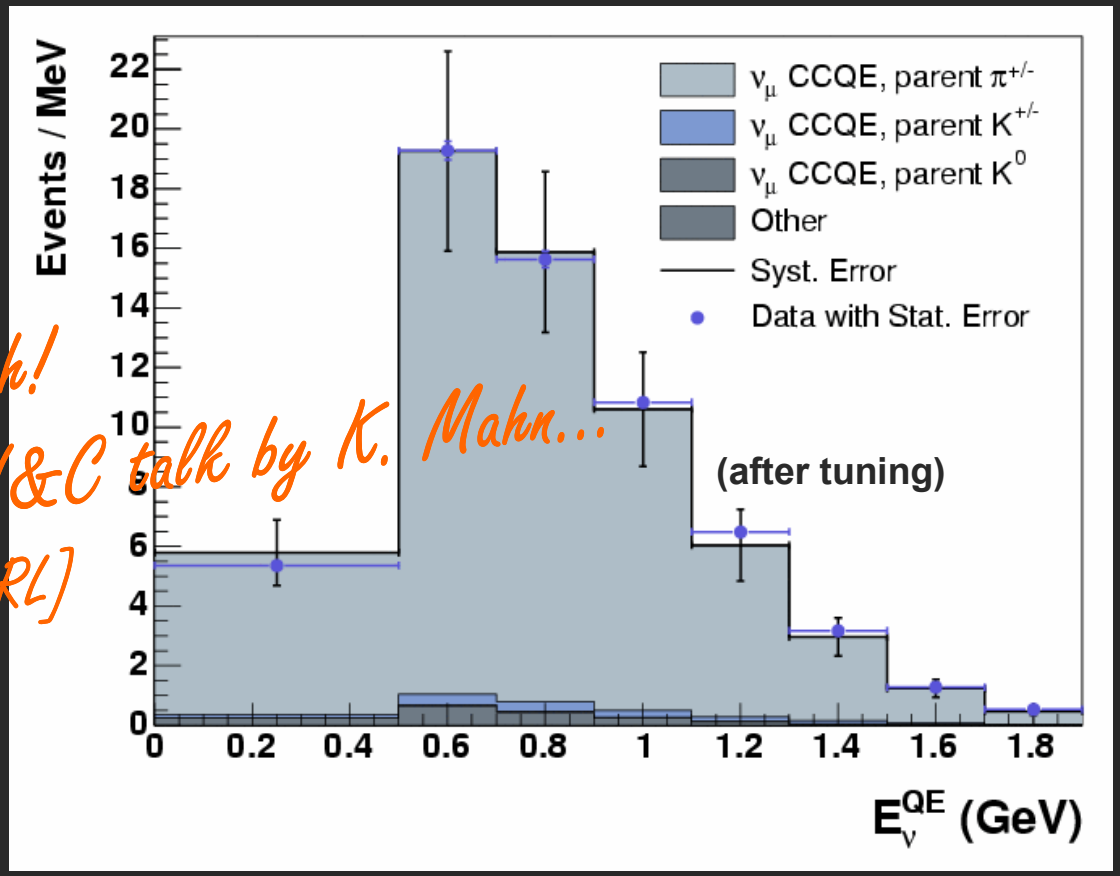
Total (unconstrained)	*16.3*	*16.2*	*12.3*	*14.2*

Similar systematics as for neutrino appearance search, but

ANTINEUTRINO APPEARANCE SEARCH IS MORE STATISTICS LIMITED!

Fit method

The high-statistics $\bar{\nu}_\mu$ CCQE sample (78% $\bar{\nu}_\mu$, 22% ν_μ) is well understood.



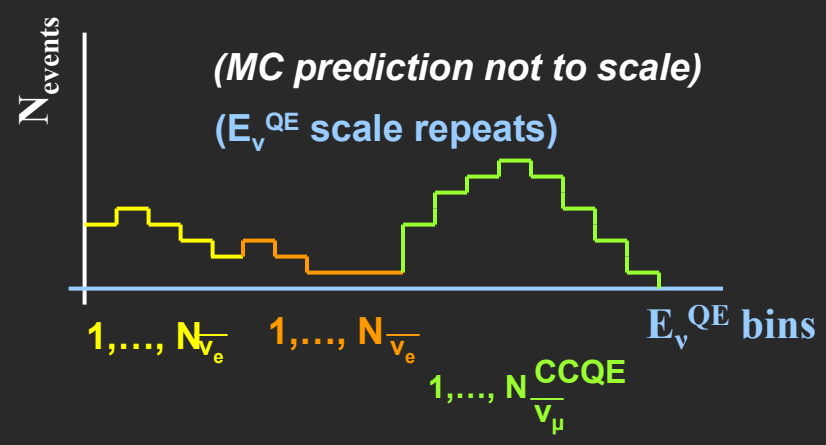
$\bar{\nu}_\mu$ disappearance search!
See Oct. 31, 2008 W&C talk by K. Mahn...
[paper to be submitted to PRL]

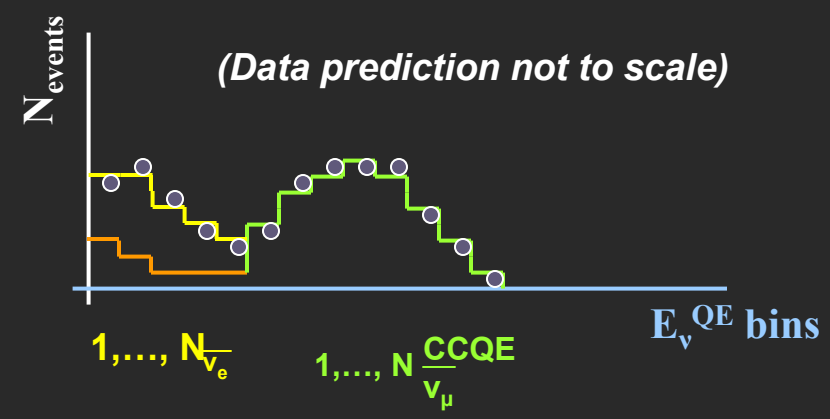
Total number of $\bar{\nu}_\mu$ CCQE data events after selection cuts: 14,193

Fit method

The following three distinct samples are used in the oscillation fits, obtained using the same selection requirements used in neutrino mode analysis:

1. **Background** to $\bar{\nu}_e$ oscillations
2. $\bar{\nu}_e$ **Signal** prediction (dependent on Δm^2, $\sin^2 2\theta$)
3. $\bar{\nu}_\mu$ **CCQE** sample, used to constrain $\bar{\nu}_e$ prediction (signal+background)





Fit method

The following three distinct samples are used in the oscillation fits, obtained using the same selection requirements used in neutrino mode analysis:

1. **Background** to $\bar{\nu}_e$ oscillations
2. $\bar{\nu}_e$ **Signal** prediction (dependent on Δm^2, $\sin^2 2\theta$)
3. $\bar{\nu}_\mu$ **CCQE** sample, used to constrain $\bar{\nu}_e$ prediction (signal+background)

$$\chi^2 = \sum_{i,j}^{N} \left(D_i - \left(B_i + S_i(\sin^2 2\vartheta, \Delta m^2) \right) \right) M_{ij}^{-1} \left(D_j - \left(B_j + S_j(\sin^2 2\vartheta, \Delta m^2) \right) \right)$$

$M_{ij} =$ full syst+stat covariance matrix at best fit prediction

χ^2 calculated using both datasets ($\bar{\nu}_e$ and $\bar{\nu}_\mu$ CCQE), and corresponding covariance matrix

Fit method

Fitting to the $\bar{\nu}_\mu$ CCQE and $\bar{\nu}_e$ spectra simultaneously takes advantage of strong correlations between $\bar{\nu}_e$ signal, background, and the $\bar{\nu}_\mu$ CCQE sample in order to reduce systematic uncertainties and constraining intrinsic $\bar{\nu}_e$ from muon decay

Example:

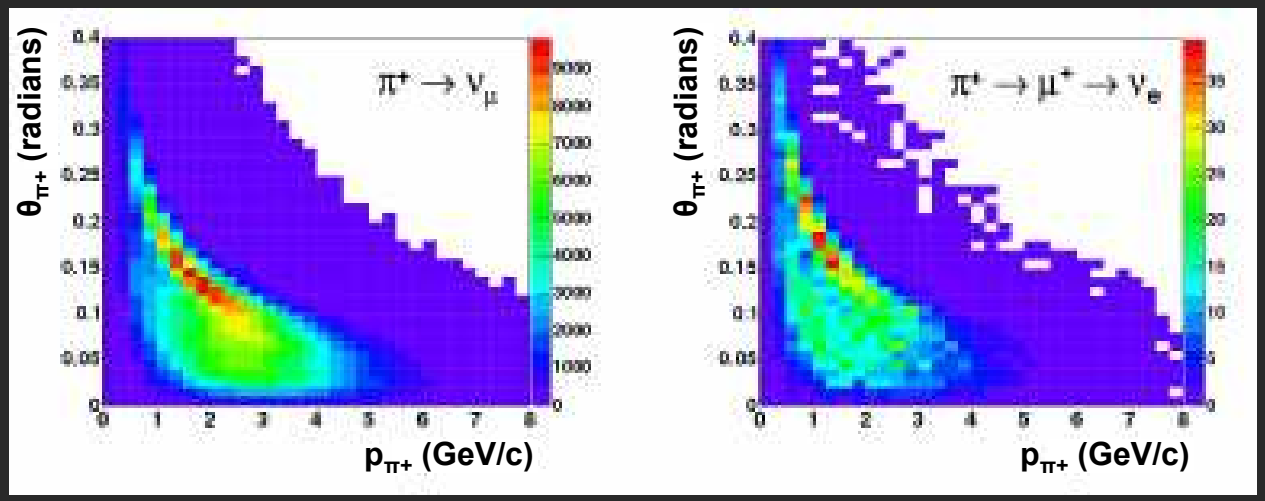
$R(\nu_\mu) = \Phi(\nu_\mu) \times \sigma(\nu_\mu) \times \varepsilon(\nu_\mu)$

$R(\nu_e) = \Phi(\nu_e) \times \sigma(\nu_e) \times \varepsilon(\nu_e)$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$\downarrow$

$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$



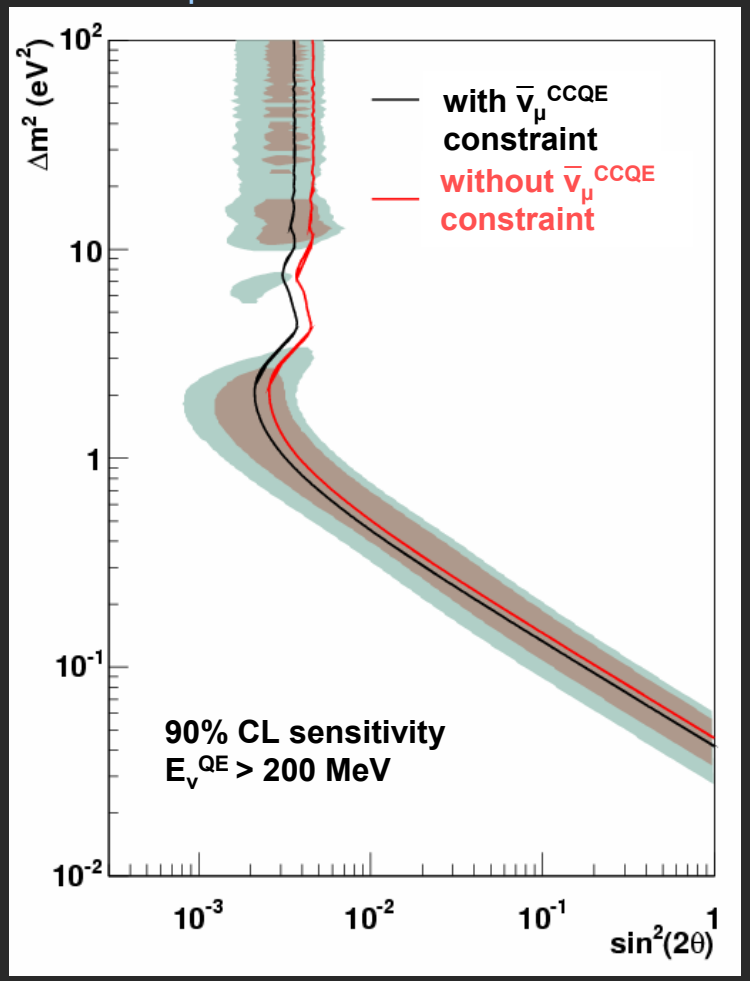
Kinematic distributions of π^+ contributing to ν_μ and ν_e flux (ν mode)

Fit method

Fitting to the $\bar{\nu}_\mu$ CCQE and $\bar{\nu}_e$ spectra simultaneously takes advantage of strong correlations between $\bar{\nu}_e$ signal, background, and the $\bar{\nu}_\mu$ CCQE sample in order to reduce systematic uncertainties and constraining intrinsic $\bar{\nu}_e$ from muon decay

This improves sensitivity and provides a stronger constraint to oscillations →

Effect of $\bar{\nu}_\mu$ CCQE constraint on sensitivity



MiniBooNE sensitivity to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

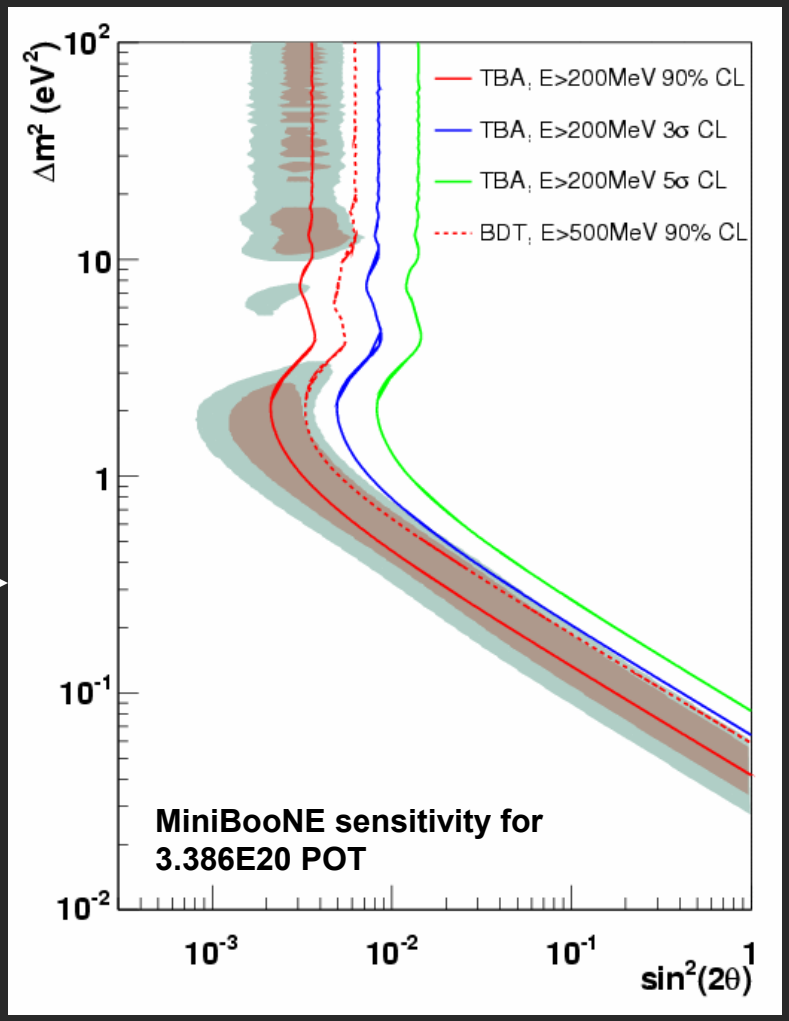
Given neutrino mode results, two fits were considered for $\bar{\nu}_e$ candidate events with TBA:

$E_\nu^{QE} > 475$ MeV

$E_\nu^{QE} > 200$ MeV

For BDT analysis:

$E_\nu^{QE} > 500$ MeV



MiniBooNE sensitivity to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

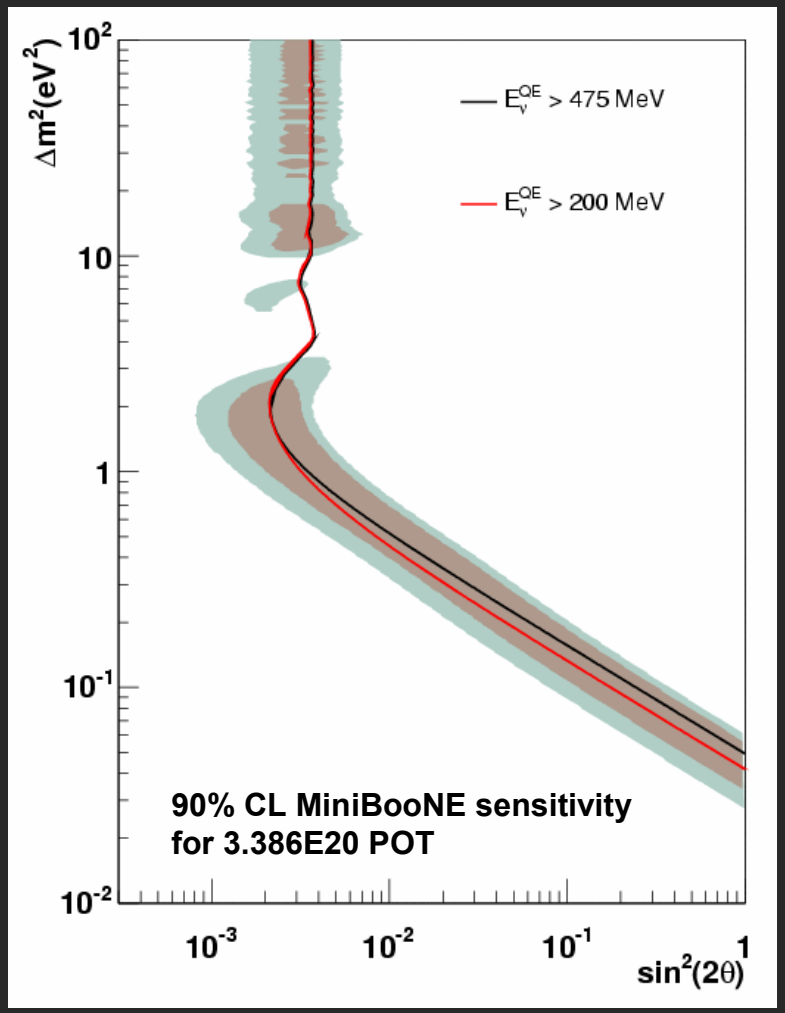
Effect of E_ν^{QE} threshold on sensitivity:

$E_\nu^{QE} > 475$ MeV

$E_\nu^{QE} > 200$ MeV

$$P \sim \sin^2(\underbrace{1.27\ \Delta m^2[\mathrm{eV}^2]\ L[\mathrm{m}] / E[\mathrm{MeV}]}_{\sim \Delta m^2/E \sim 1 \text{ for maximum sensitivity}})$$

→fitting to lower energy increases sensitivity for lower Δm^2



MiniBooNE $\bar{\nu}_e$ appearance analysis

Several cross-checks have been performed:

- **M_A, κ checks, neutrino component in antineutrino (WS) measurement**
- **New π^0 measurement**
- **New dirt fraction extracted**
- **Data quality checks (different periods of running, R/E_{vis} distributions)**
- **BDT analysis**

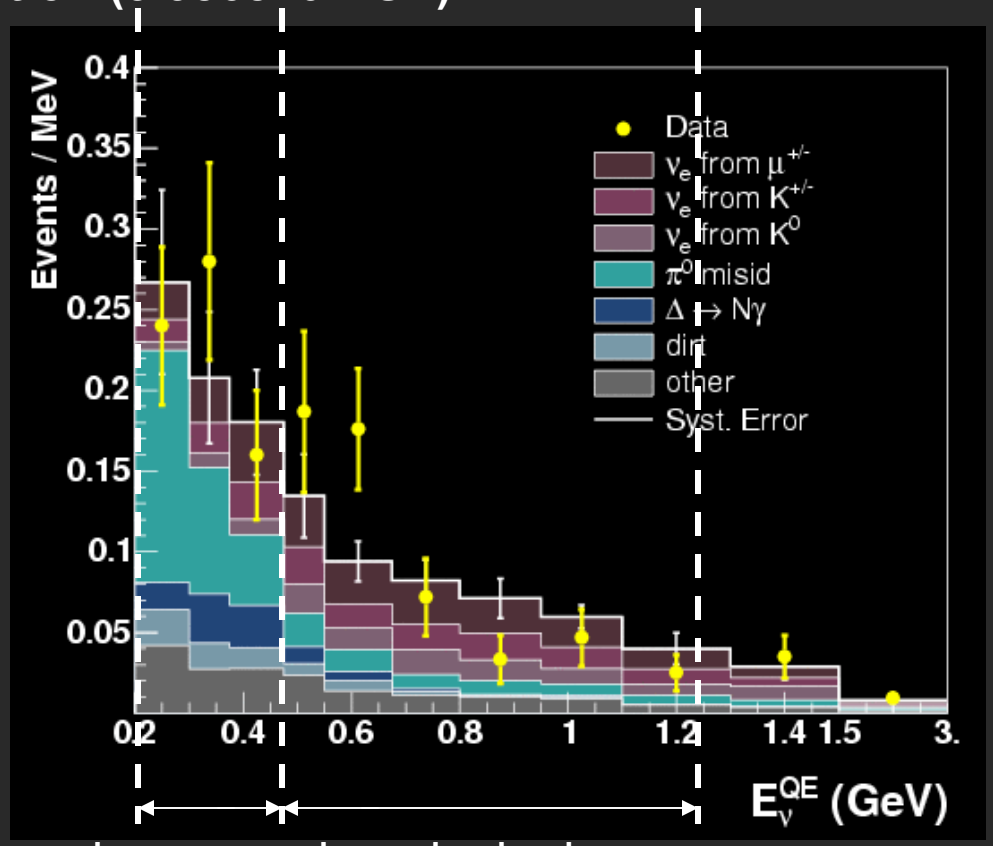
Outline

1. **Motivation for $\bar{\nu}_e$ appearance search**
2. **MiniBooNE Experiment**
3. **MiniBooNE $\bar{\nu}_e$ analysis**
4. **Results**
   - Oscillation fits
   - Implications for low energy excess observed in neutrino mode
5. **Future prospects and conclusions**

Results: Fits to E_ν^{QE} > 200 MeV

$\bar{\nu}_e$ data vs. background distribution (3.386e20 POT):

χ^2_{null}(dof) = 24.51 (19)
χ^2-probability = 17.7%
(calculated using error matrix at null)



low energy region **signal region**

data statistical uncertainty
MC unconstrained systematic uncertainty

Fit summary

E_ν^{QE} fit	χ^2_{null}(dof) χ^2-prob	χ^2_{null}(dof)* χ^2-prob	$\chi^2_{best\text{-}fit}$(dof)* χ^2-prob	$\chi^2_{LSND\ best\text{-}fit}$(dof) χ^2-prob
> 200 MeV	24.51(19) 17.7%	20.18(17) 26.5%	18.18(17) 37.8%	20.14(19) 38.6%
> 475 MeV	22.19(16) 13.7%	17.88(14) 21.2%	15.91(14) 31.9%	17.63(16) 34.6%

(*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)

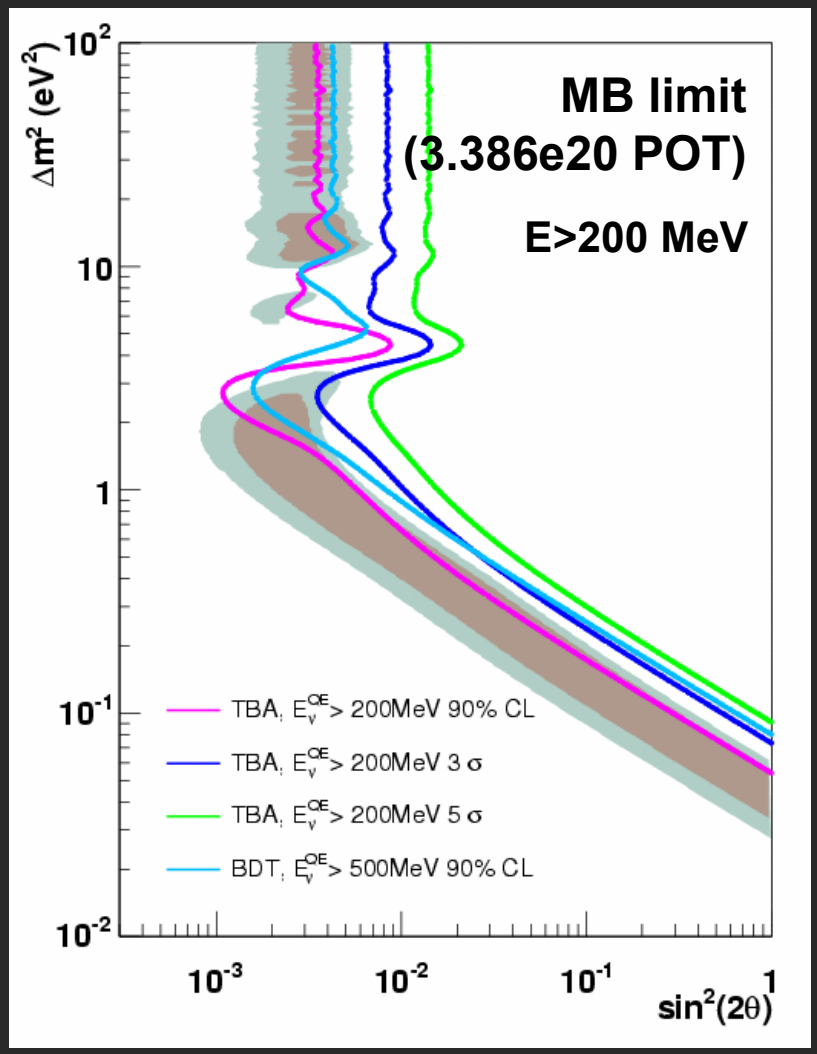
MiniBooNE limit to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

No strong evidence for oscillations →

1-sided raster limit:

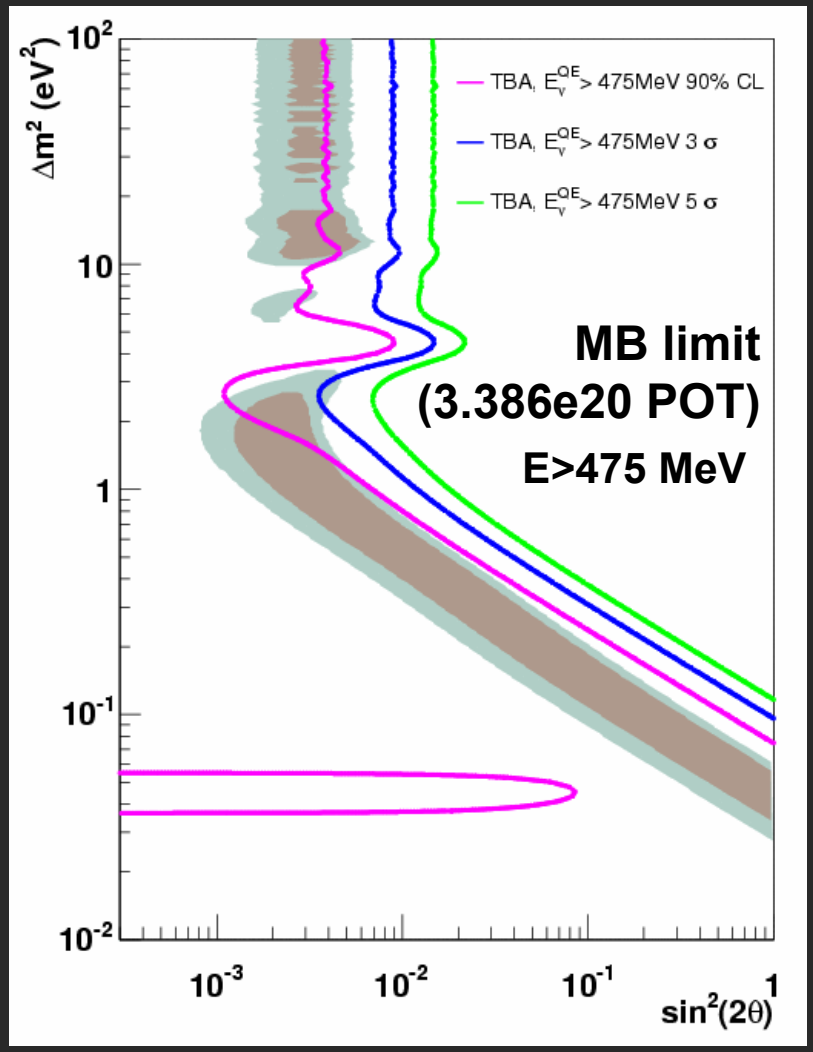
$$\chi^2 = \sum_{i,j}^{N} \left(D_i - \left(B_i + S_i(\sin^2 2\vartheta) \right) \right) M_{ij}^{-1} \left(D_j - \left(B_j + S_j(\sin^2 2\vartheta) \right) \right)$$

M_{ij} = full syst+stat covariance matrix at best fit prediction for each Δm^2



MiniBooNE limit to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

No strong evidence for oscillations →



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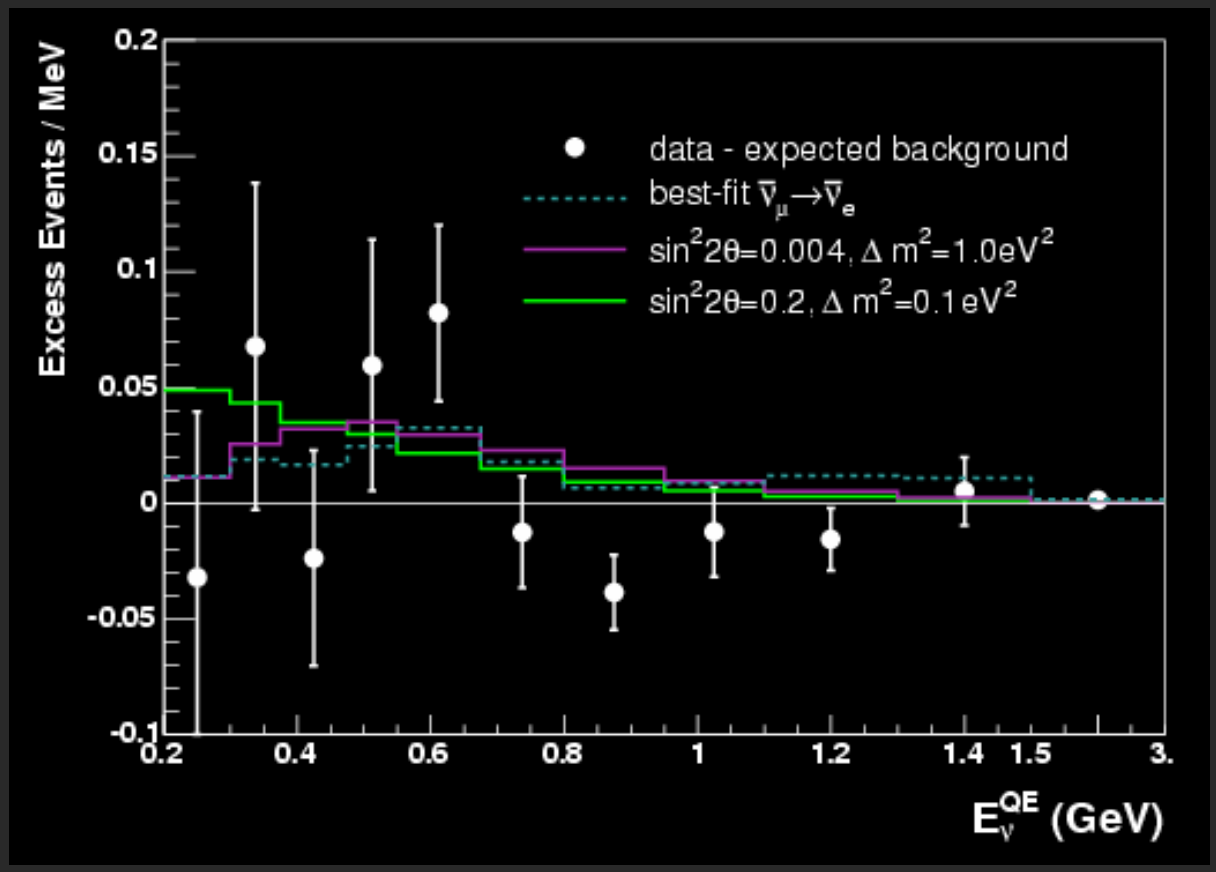
M_{ij} = full syst+stat covariance matrix at best fit prediction for each Δm^2

Oscillation fits to E_ν^{QE} > 200 MeV

Excess distribution and comparison with possible signal predictions:



MiniBooNE best-fit:

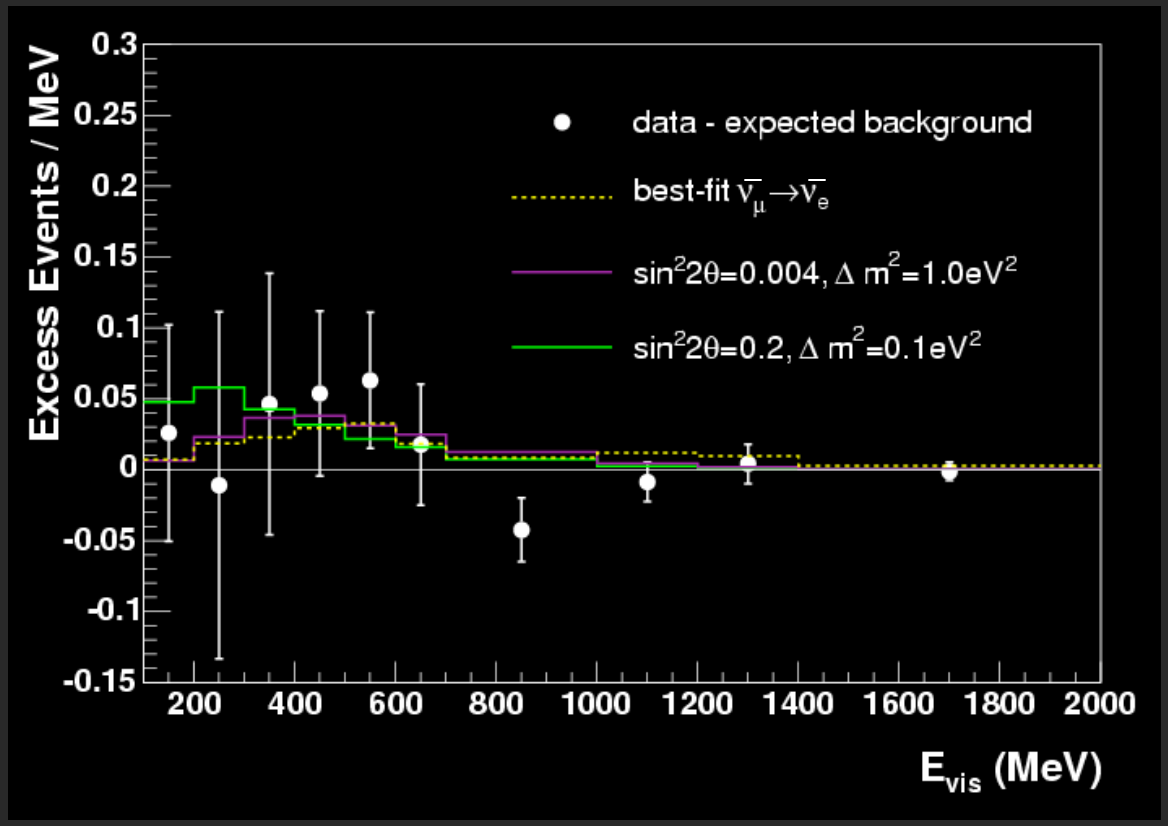
(Δm^2, $\sin^2 2\theta$) = (4.4 eV^2, 0.004)

(E>200MeV)

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

Complementary information: $E_{visible}$

Excess distribution as a function of $E_{visible}$ and comparison with possible signal predictions:



Error bars indicate
data statistical and constrained
bkgd systematic uncertainty

Events summary (constrained syst + stat uncertainty)

[paper to be submitted to PRL]

E_ν^{QE} range (MeV)		$\bar{\nu}$ 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 energy excess

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^0 background**
- **Scales with neutrinos (not antineutrinos)**
- **Scales with background**
- **Scales as the rate of Charged-Current interactions**
- **Scales with Kaon rate at low energy**

Implications for low energy excess

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)*

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

$$\chi^2 = \sum_{i,j} \left(D_i - \left(B_i + S_i\right)\right) M_{ij}^{-1} \left(D_j - \left(B_j + S_j\right)\right)$$

$$i, j = \nu, \bar{\nu} \text{ 200-475MeV bin}$$

The underlying signal for each hypothesis, S, 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**

Implications for low energy excess

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. K^{0L},…)*

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

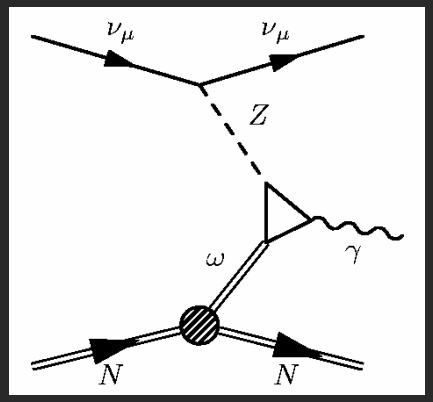
Obviously this should be highly disfavored by the data, but one could imagine a scenario where the neutrino mode observed excess is a fluctuation up from true underlying signal and the antineutrino mode excess is a fluctuation down, yielding a lower χ^2…

Implications for low energy excess

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]

Implications for low energy excess

200-475 MeV	*Data*	*61* $\bar{\nu}$	*544* ν
	MC ± sys+stat (constr.)	*61.5 ± 11.7*	*415.2 ± 43.4*
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Eg.: Scales as π^0 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^0 background?

Or other Neutral-Current process?

For π^0 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^0 event rate to 5%!

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

Implications for low energy excess

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

Implications for low energy 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

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!

The most preferred model is that where the 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!

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Future MiniBooNE Analyses

- **Combined ν_e and $\bar{\nu}_e$ appearance analysis (with CP violation) for stronger constraints on oscillations**

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Future MiniBooNE Analyses

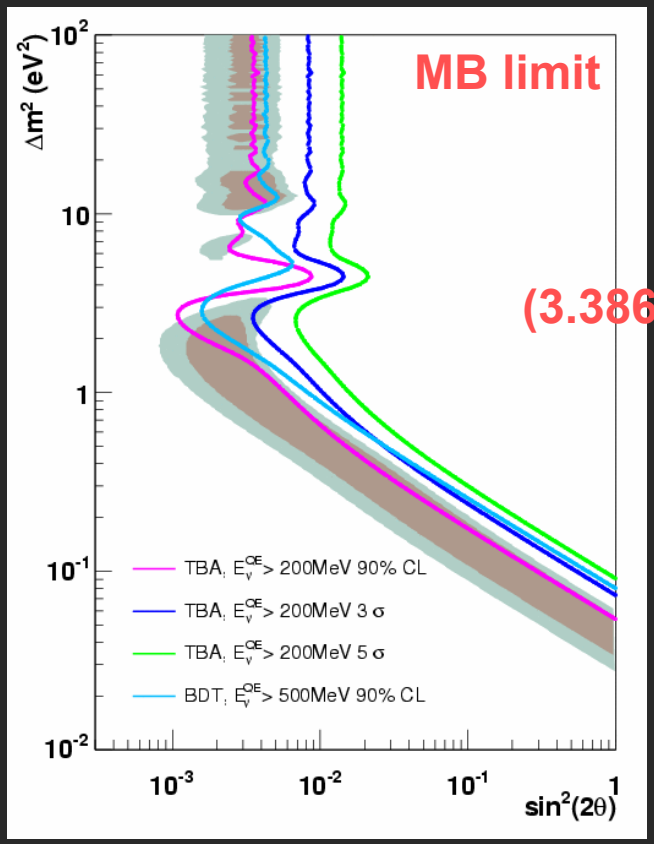
- **Combined ν_e and $\bar{\nu}_e$ appearance analysis (with CP violation) for stronger constraints on oscillations**
- **Combined ν_e and $\bar{\nu}_e$ analysis for low energy events with systematic correlations properly folded in, for testing various low energy excess interpretations**
- **Combined MiniBooNE-NuMI ν_e appearance analysis**

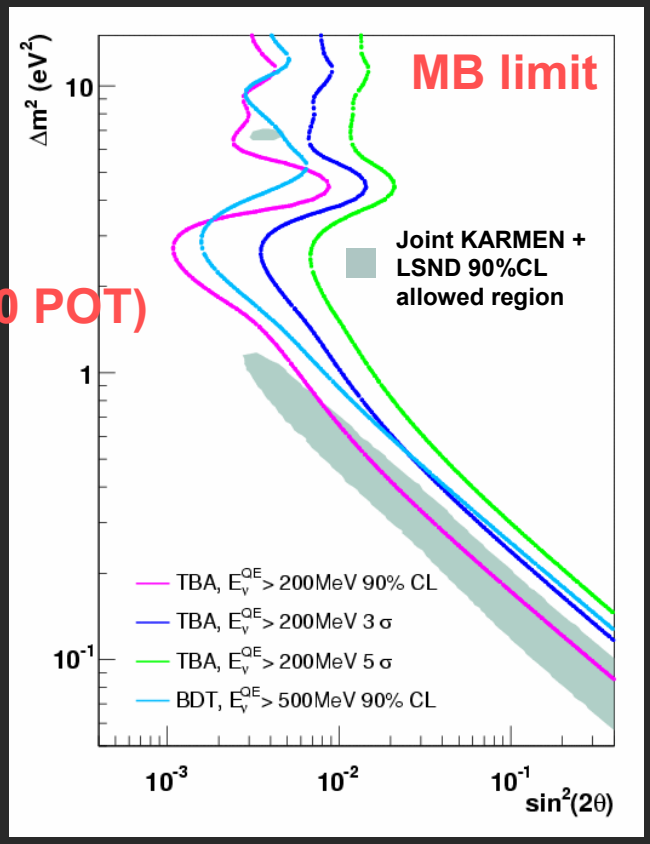
Conclusion

1. We have performed a **blind analysis** to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations: $\bar{\nu}_e$ data in agreement with MonteCarlo background prediction as a function of E_ν^{QE}.

Conclusion

2. So far, no strong evidence for oscillations in antineutrino mode (although currently limited by statistics).





Conclusion

3. Interestingly, no evidence of significant excess at low energy in antineutrino mode. This has already placed constraints to various suggested low energy excess interpretations.

	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%
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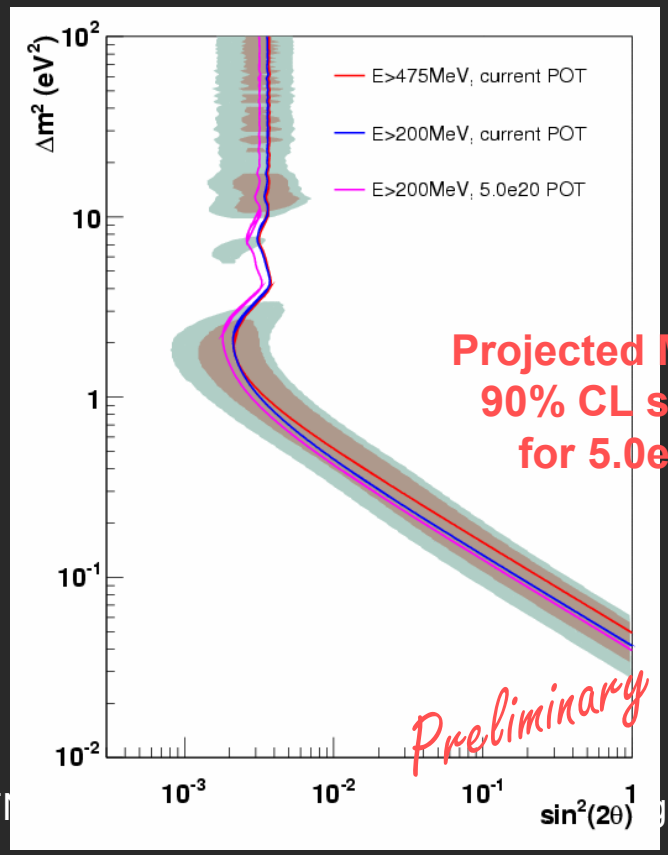
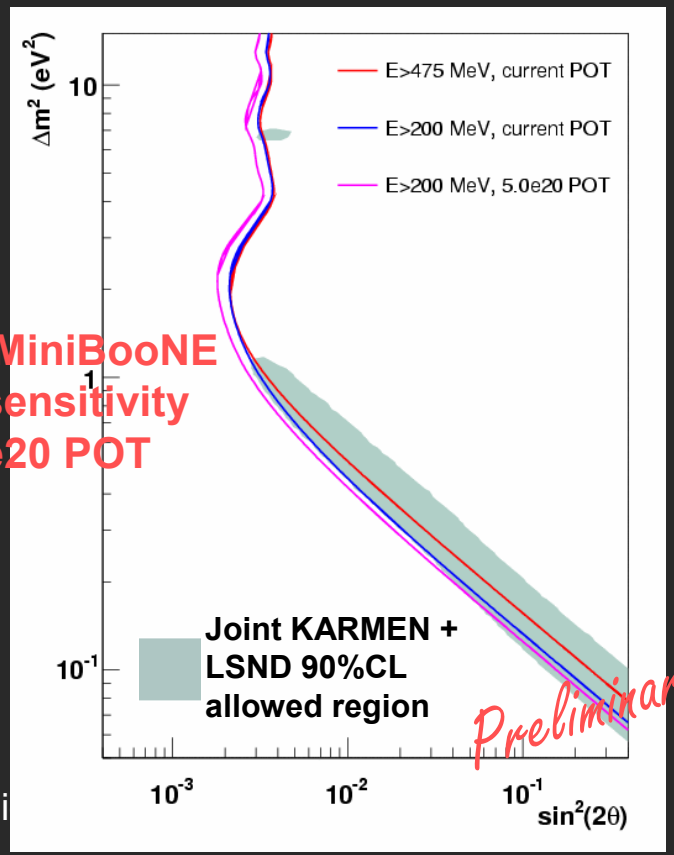
CC scaled	2.9%	5.2%	19.9%
Low-E Kaons	0.1%	0.1%	5.9%
ν scaled	38.4%	51.4%	58.0%

Preliminary

Conclusion

4. In process of **collecting more data** aiming for a total of 5.0e20 POT. This will improve sensitivity to oscillations, and allow further investigation of low energy excess.





Thank you!