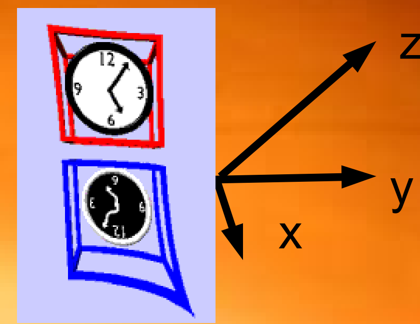
Neutrino Oscillations and and Lorentz Violation Results from MiniBooNE

Outline:
- LSND
    - signal for ν oscillations
    - sidereal analysis and LV
- Tandem Model
- MiniBooNE
    - experiment, analysis, ν results
    - LV results



R. Tayloe,
Indiana University
CPT 2007

The LSND Result

The LSND experiment observed an excess of $\bar{\nu}_e$ event s in beam of $\bar{\nu}_\mu$

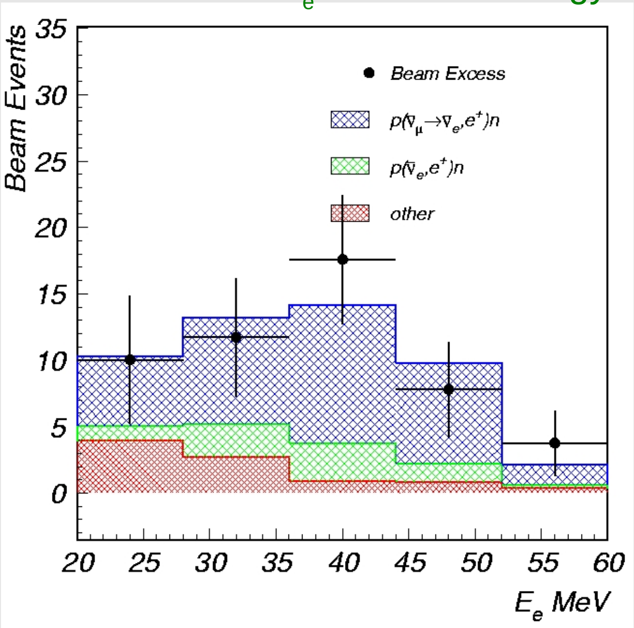
$87.9 \pm 22.4 \pm 6.0 \ (4\sigma)$

consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

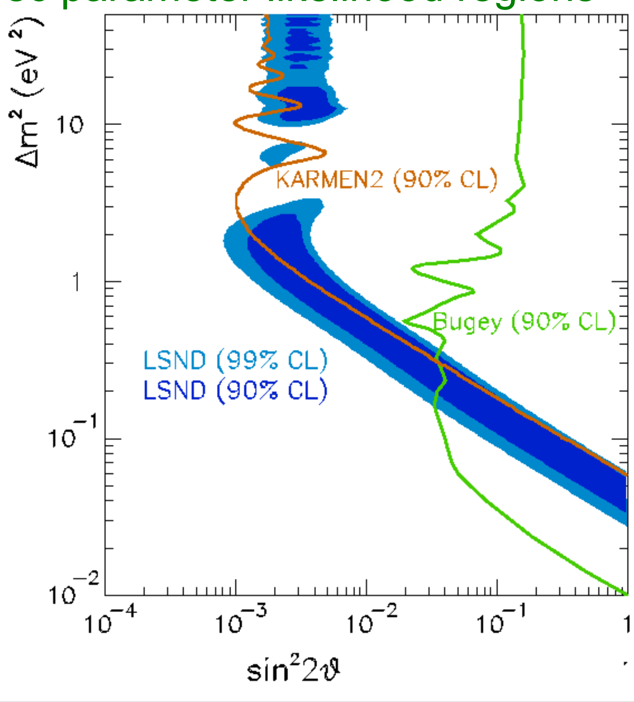
However, this result, with large Δm^2 ,does not fit in a 3 generation neutrino model (given results from other oscillation experiments) since $\Delta m_{12}^2 + \Delta m_{13}^2 + \Delta m_{23}^2 = 0$

If LSND is correct $\Rightarrow$ new physics.
- additional (sterile) neutrinos
- a different model for oscillations

$\bar{\nu}_e$ events vs energy



osc parameter likelihood regions



Review: Sidereal variation in the LSND signal

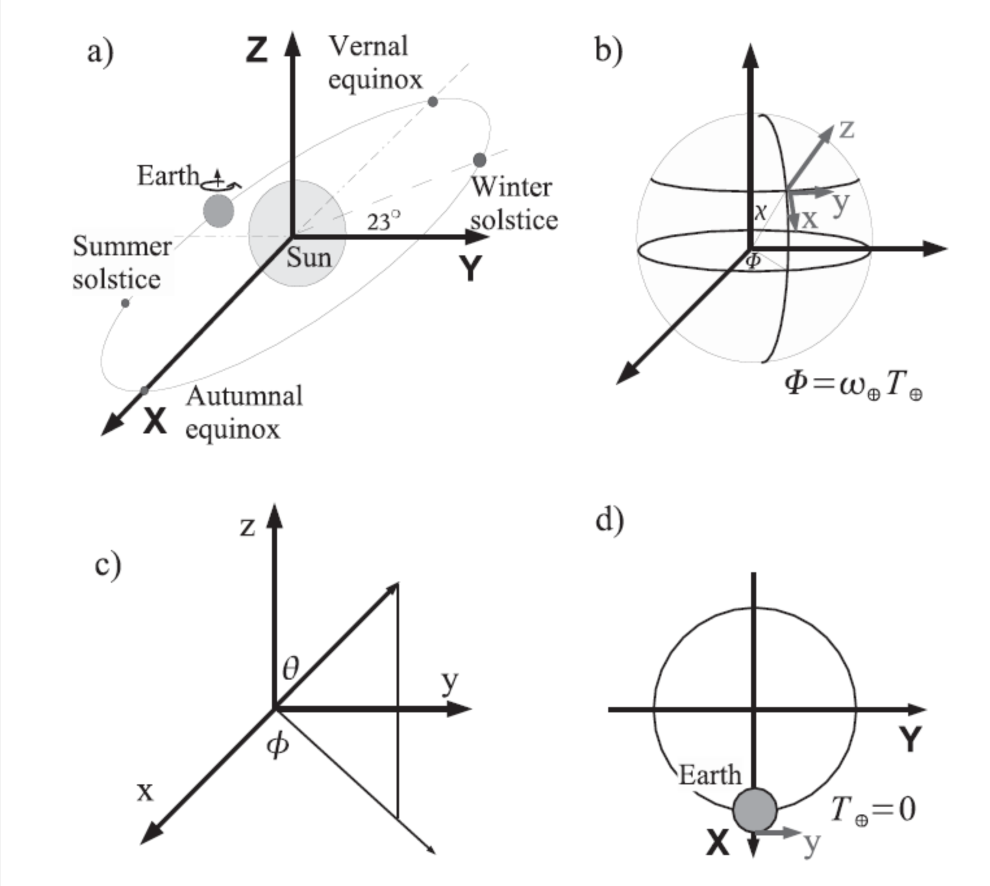
- In AK, MM, PRD**70**, 076002, a short-baseline approximation for neutrino oscillations (allowing for sidereal variation) was developed.
- In PRD**72**, 076004 we (with LSND collaboration) reported the results of a search for sidereal variation in the LSND signal...

$$(h_{\text{eff}})_{ab} = |\vec{p}|\delta_{ab} + \frac{(\tilde{m}^2)^*_{ab}}{2|\vec{p}|} + \frac{1}{|\vec{p}|}[-(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu]^*_{ab}.$$

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \simeq \frac{|(h_{\text{eff}})_{\bar{e}\bar{\mu}}|^2 L^2}{(\hbar c)^2}.$$

$$P_{\bar{\nu}_\mu \to \bar{\nu}_e} \simeq \frac{L^2}{(\hbar c)^2} |(\mathcal{C})_{\bar{e}\bar{\mu}} + (\mathcal{A}_s)_{\bar{e}\bar{\mu}} \sin\omega_\oplus T_\oplus + (\mathcal{A}_c)_{\bar{e}\bar{\mu}} \cos\omega_\oplus T_\oplus + (\mathcal{B}_s)_{\bar{e}\bar{\mu}} \sin 2\omega_\oplus T_\oplus + (\mathcal{B}_c)_{\bar{e}\bar{\mu}} \cos 2\omega_\oplus T_\oplus|^2,$$

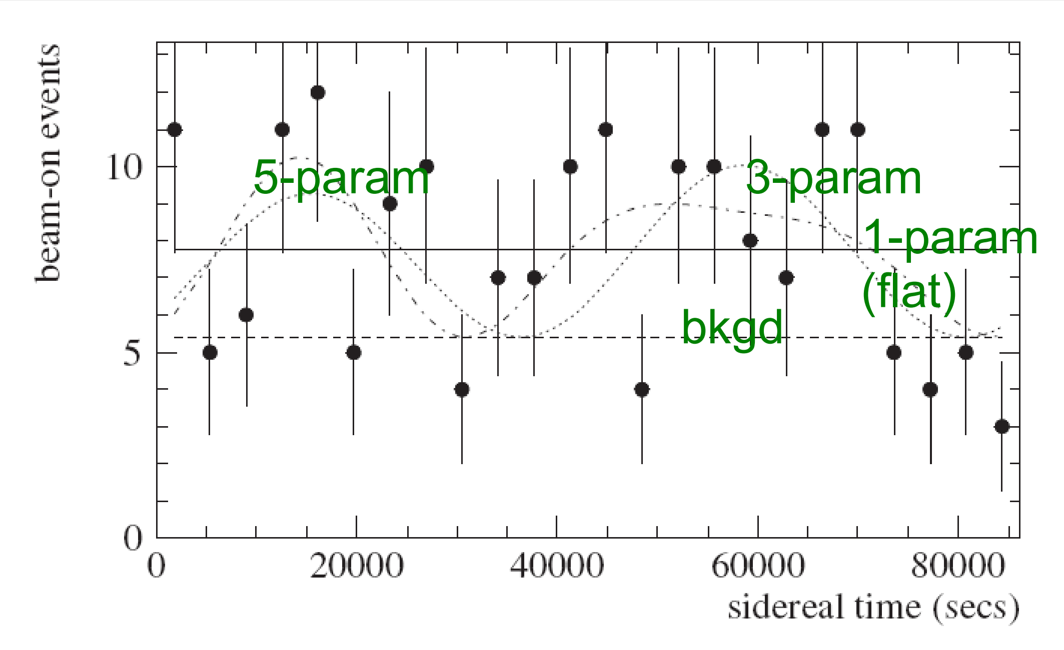
all are f(a_L, c_L and ν beam direction in sun-centered frame)



Sidereal variation in the LSND signal

- LSND sidereal variation, results:

consistent with no sidereal variation...



Null hypothesis tests				
	beam-on		beam-off	
	sidereal	GM	sidereal	GM
# of events	186		1656	
Pearson's χ^2:				
N_{bins}	37	37	37	37
χ^2	44.8	27.6	29.6	40.3
$P(\chi^2)$	0.15	0.84	0.77	0.29
Kolmogorov-Smirnov:				
D_n	0.076	0.066	0.019	0.040
P(KS)	0.234	0.386	0.604	0.010

Beam-on/beam-off tests		
	sidereal	GM
D_n	0.067	0.046
P(KS)	0.432	0.864

Sidereal variation in the LSND signal

- LSND sidereal variation, results:
extraction of SME parameter combinations.

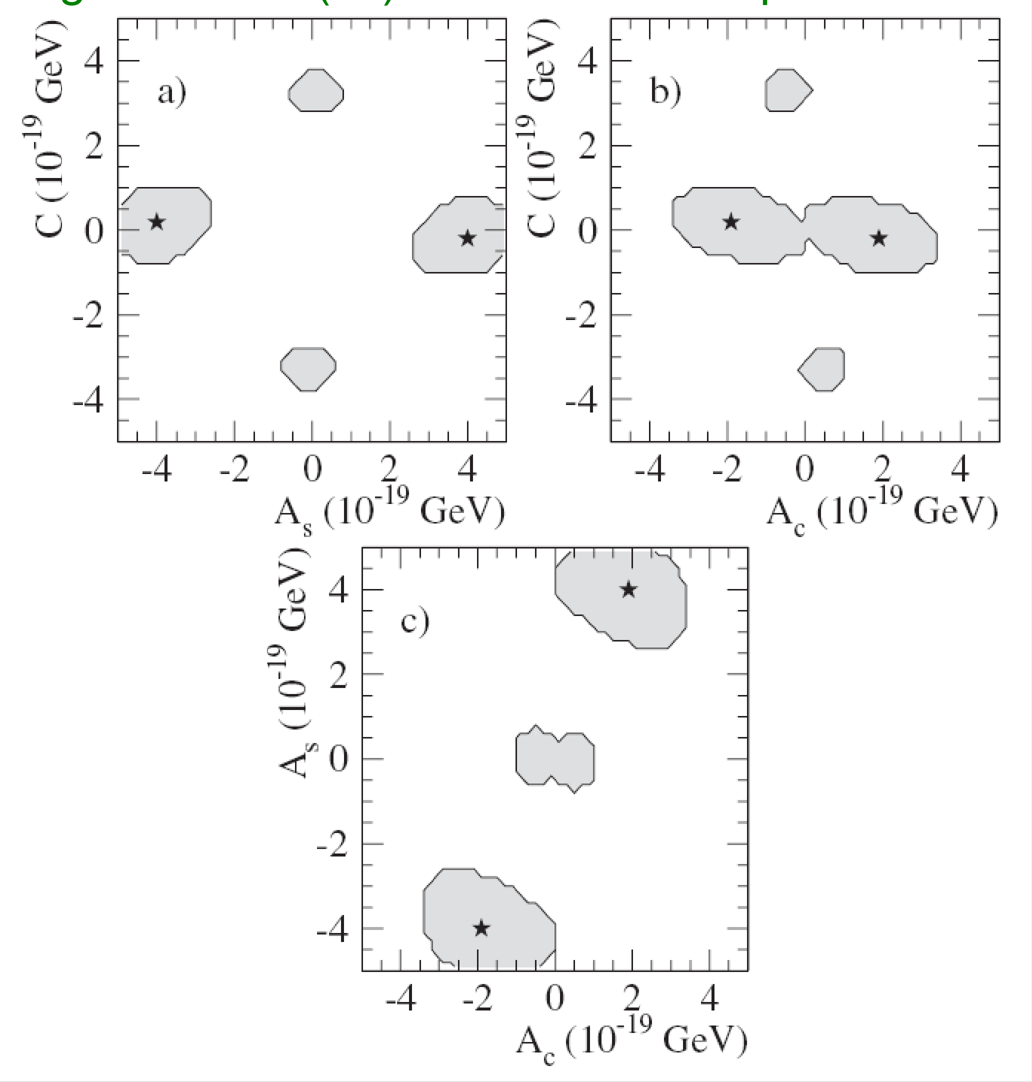
- allowed regions include sidereal variations (non-zero A_s, A_c)

- extracted parameter square-sum:

$$|(C)_{\bar{e}\bar{\mu}}|^2 + \frac{1}{2}|(\mathcal{A}_s)_{\bar{e}\bar{\mu}}|^2 + \frac{1}{2}|(\mathcal{A}_c)_{\bar{e}\bar{\mu}}|^2 = 9.9 \pm 2.3 \pm 1.4\,(10^{-19}\ \mathrm{GeV})^2,$$

- (noted by AK,MM before this analysis)
- regardless of sidereal variation, if the SME is used to explain LSND then, a_L or E x c_L ~10^{-19} GeV
(~ expected Planck-scale effects)

Log-likelihood (1s) contours from 3-parameter fit



A "global model" of ν oscillations (with the SME)

- The biggest challenge in constructing a global model of ν oscillations within the SME is the E-dependence. SK-atmospheric and KAMLAND report an L/E dependence... How to model with with E^0 and E^1 terms?

$$h_{\text{eff}} = \frac{1}{E}[(a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu].$$

- AK, MM noted that the mixed energy dependence in the coeffs can lead to a LV "see-saw" mechanism that occurs in certain energy ranges ("pseudomass")

- the "bicycle-model"

$$\left(h_{bicycle}\right)_{ab} \rightarrow \begin{pmatrix} \breve{c}E & \breve{a} & \breve{a} \\ \breve{a} & 0 & 0 \\ \breve{a} & 0 & 0 \end{pmatrix}$$

The "tandem model"

- T. Katori, V. A. Kosteleck`y,
R. Tayloe, Phys.Rev.D74:105009,2006.

- start with bicycle model

- add additional m^2 term which generates a 2nd seesaw...

- 3 parameters, rotationally invariant

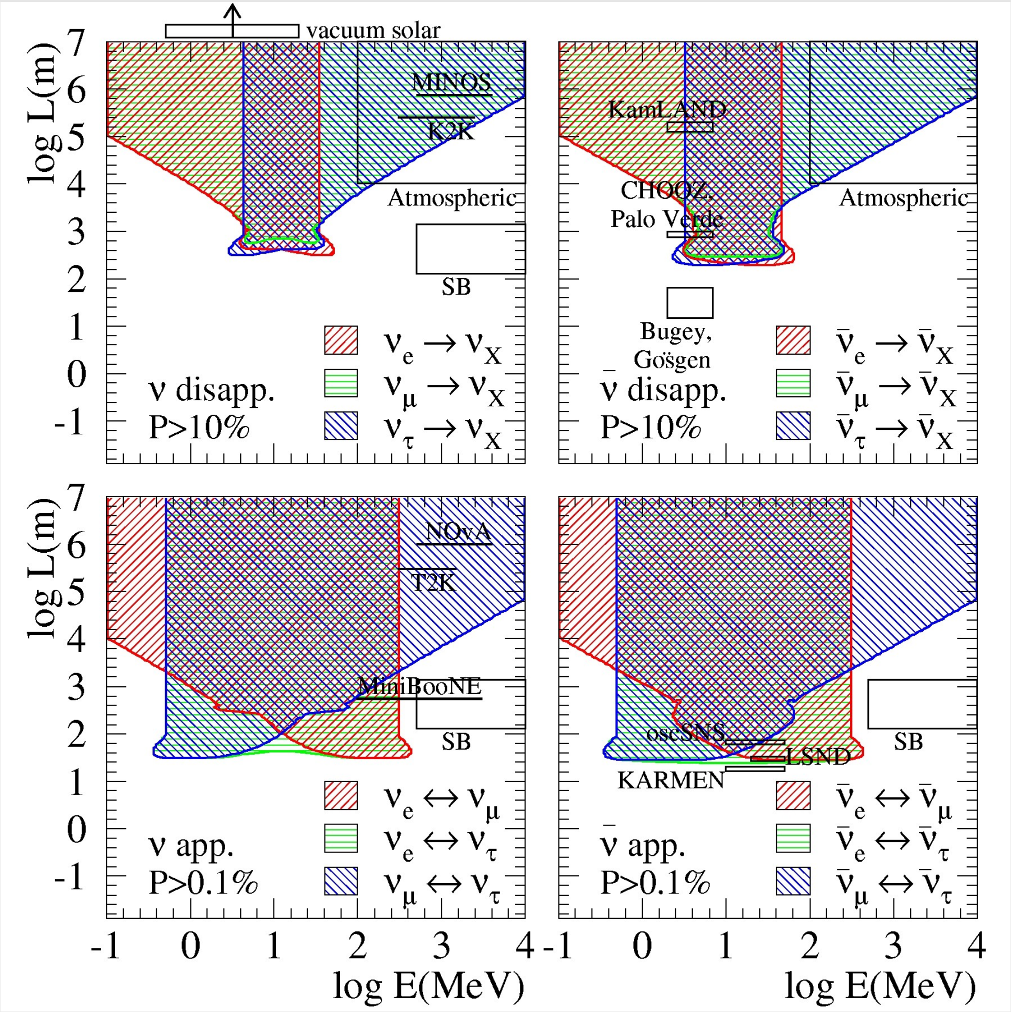
- explain solar, atmospheric, KamLAND, LSND

- only 3 parameters (remember, standard 3ν has 4-6)

- no MSW needed for solar

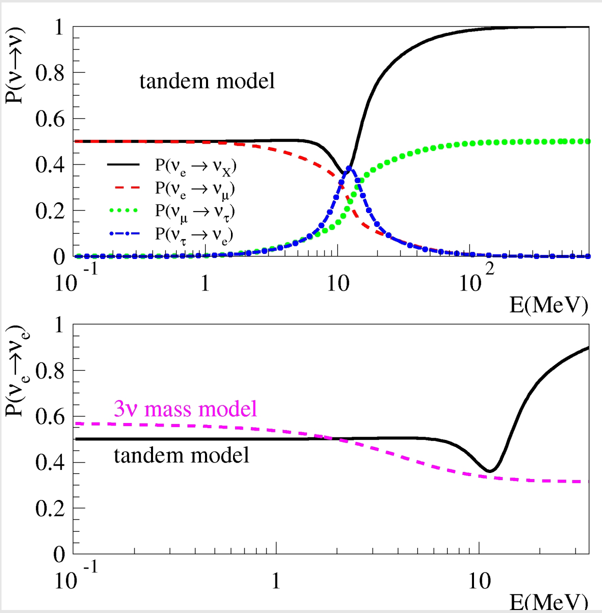
- prediction for MiniBooNE (among others)

global oscillation probabilities

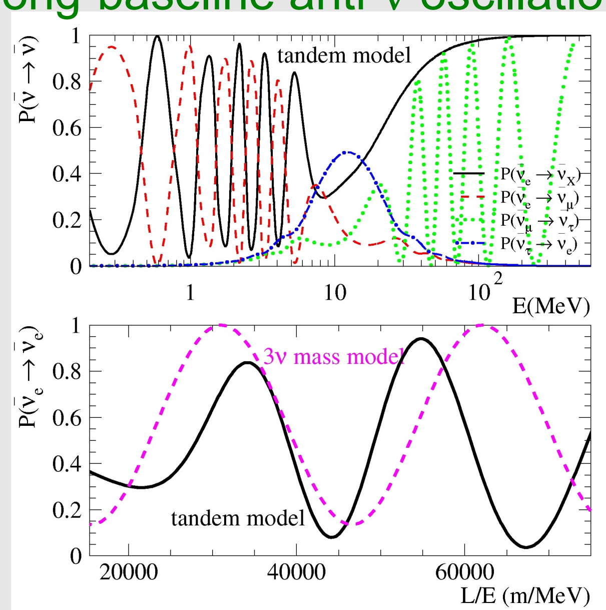


oscillation probabilities

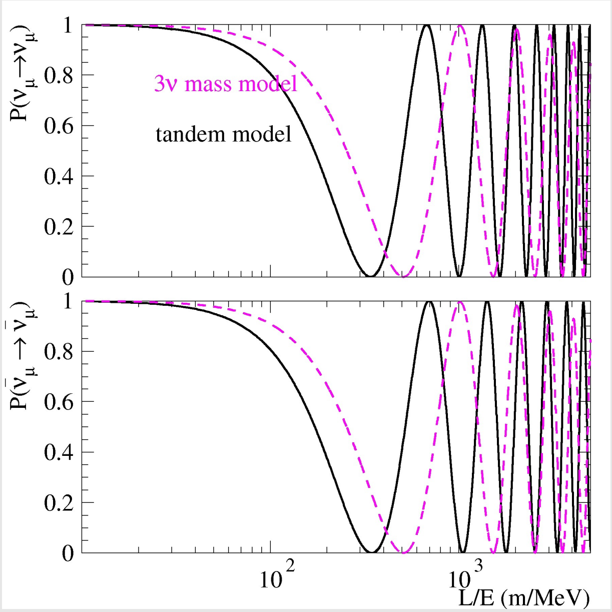
solar neutrino oscillations



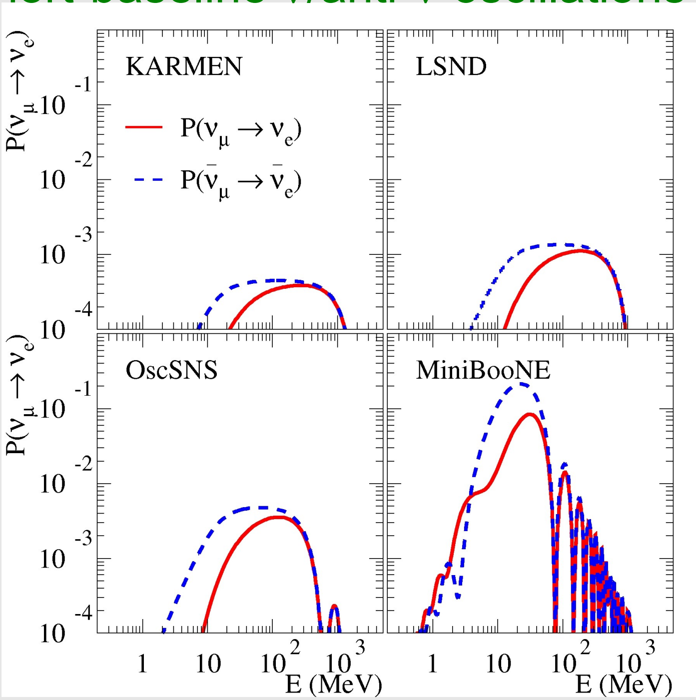
long-baseline anti-ν oscillations



atmos. ν/anti-ν oscillations



short-baseline ν/anti-ν oscillations



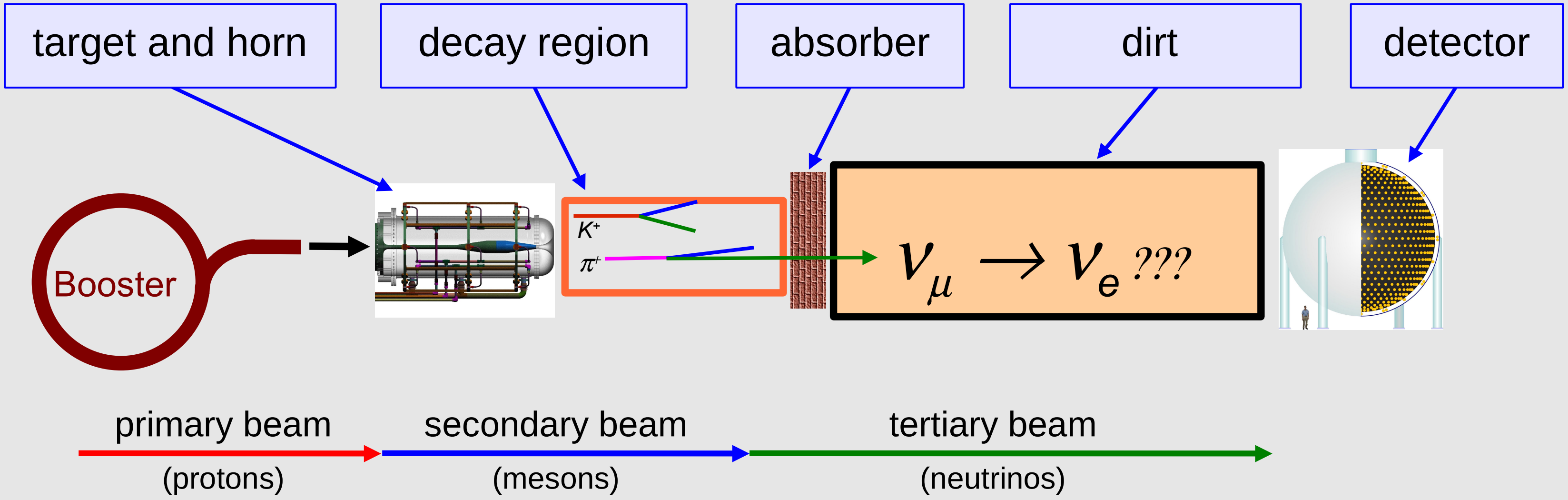
MiniBooNE experimental strategy

- Test the LSND observation via $\nu_\mu \to \nu_e$ appearance.
- Keep L/E same, change beam, energy, and systematic errors

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

neutrino energy (E):
MiniBooNE: ~500 MeV
LSND: ~30 MeV

baseline (L):
MiniBooNE: ~500 m
LSND: ~30 m



MiniBooNE Collaboration

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(The MiniBooNE Collaboration)

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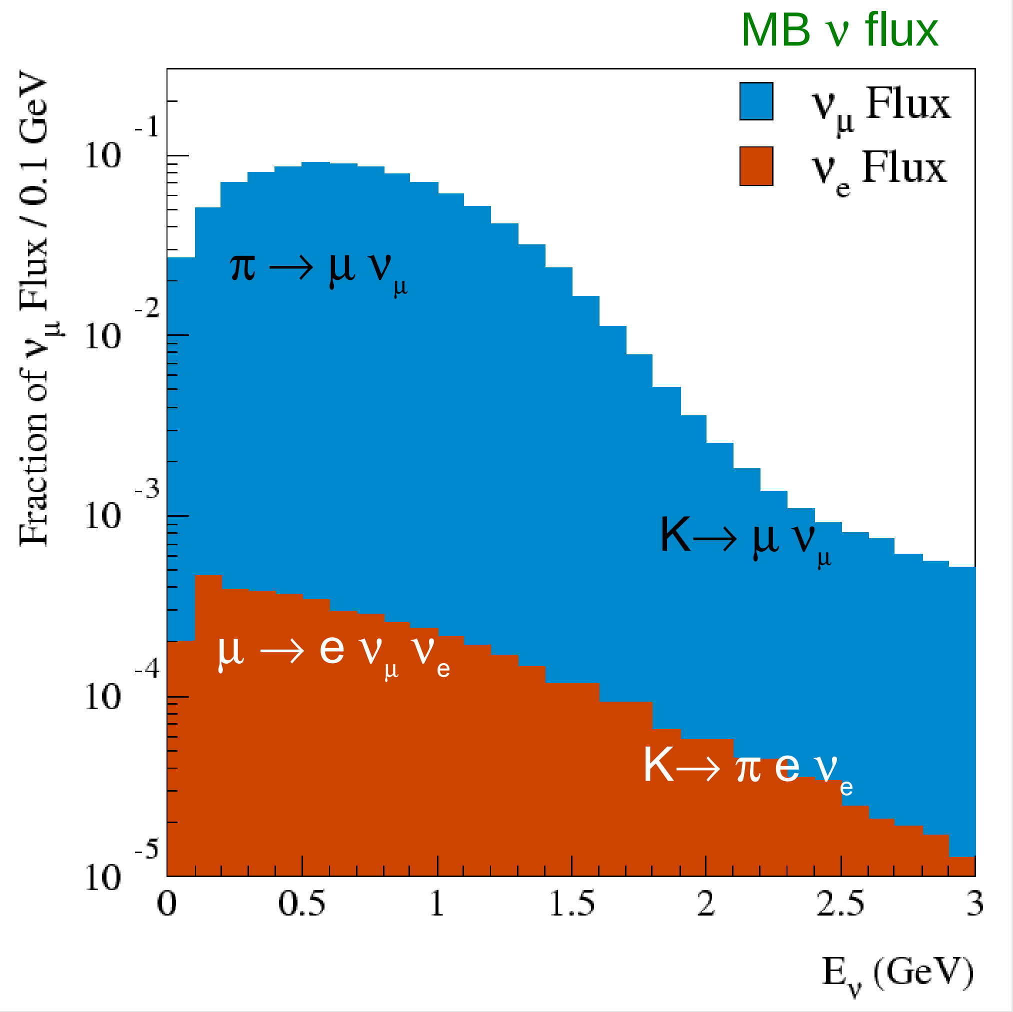
[16] *Yale University, New Haven; CT 06520*

MiniBooNE beam: total ν flux

- mean energy ~800MeV
- ν_e/ν_μ = 0.5%



ν Events in MiniBooNE

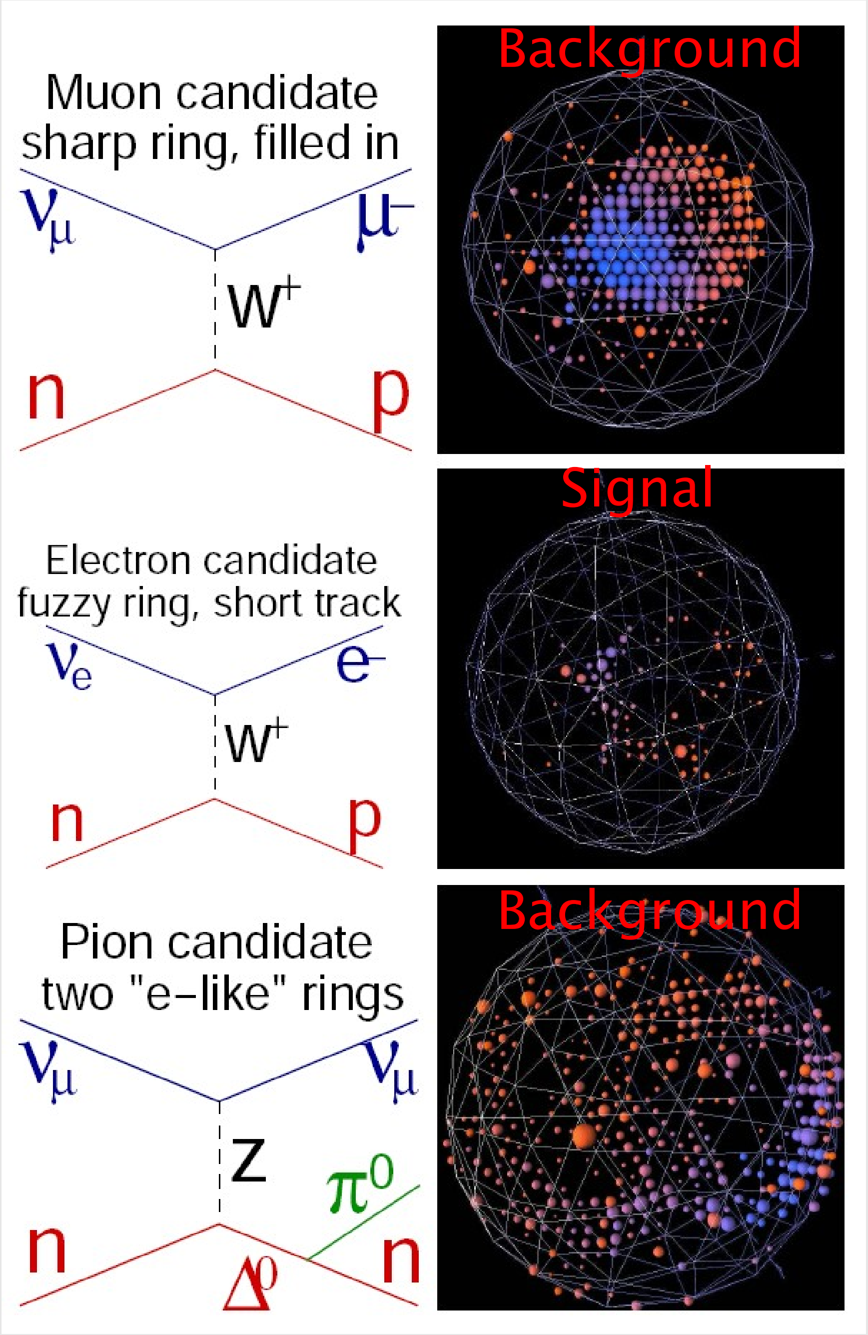
- Recall: search for ν_e in a ν_μ beam

- signature of a ν_e reaction (signal):
  electron

- need to distinguish from backgrounds (due to ν_μ reactions) that consist of a muon or π^0

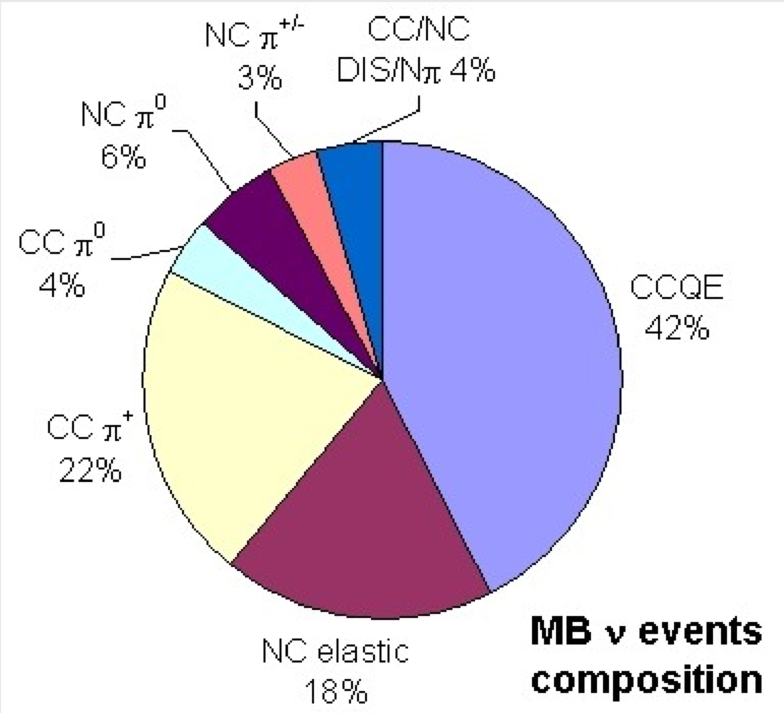
- ν interaction products create (directed, prompt) Cerenkov light and (isotropic, delayed) scintillation light

- pattern and timing of the detected light allows for event identification (and position, direction, energy meas.)



ν interactions in detector:

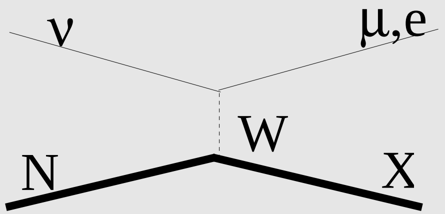
-predicted ν events and fractions
 from event generator*
- extensively tuned using MiniBooNE data



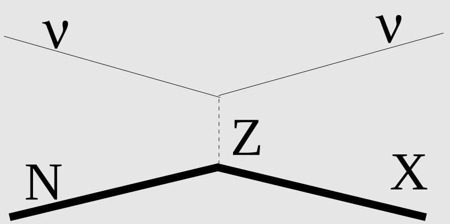
predicted # ν events in data set
(no efficiency corrections)

CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k
NC π^0	48k
NC $\pi^{+/-}$	27k
CC/NC DIS, multi-π	35k
all channels	810k
ν osc. events	~1k

"CC":
charged-
current



"NC":
neutral-
current



*NUANCE (D. Casper, NPS, 112 (2002) 161)

oscillation analysis: strategy

- need accurate, efficient particle identification algorithm to separate (signal) electron-like events from ubiquitous (background) muon, pion events

- To avoid experimenter bias, this was done with "blind" procedure, signal data set kept in "box" until algorithms set.

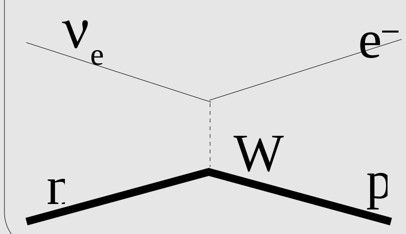
Two algorithms were used:

- "track-based" (TB)
  Uses direct reconstruction of particle types and likelihood ratios for particle-ID
- "boosted decision trees" (BDT)
  Set of low-level variables combined with BDT algorithm -> PID "score"

- In the end, the TB analysis had slightly better sensitivity, so is used for primary results.
BDT analysis is a powerful "double-check"

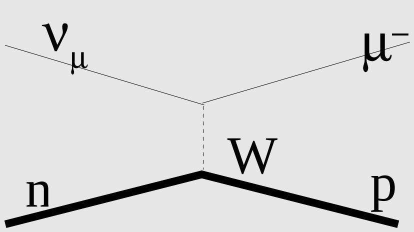
signal reaction:

$$\nu_e n \rightarrow e^- p$$



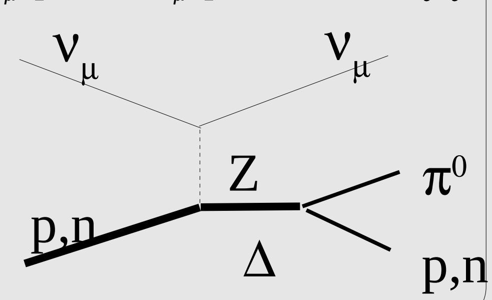
background:

$$\nu_\mu n \rightarrow \mu^- p$$



background:

$$\nu_\mu (p,n) \rightarrow \nu_\mu (p,n) \pi^0, \pi^0 \rightarrow \gamma\gamma$$



oscillation analysis: backgrounds

intrinsic-ν_e backgrounds (from ν_e produced at ν source)

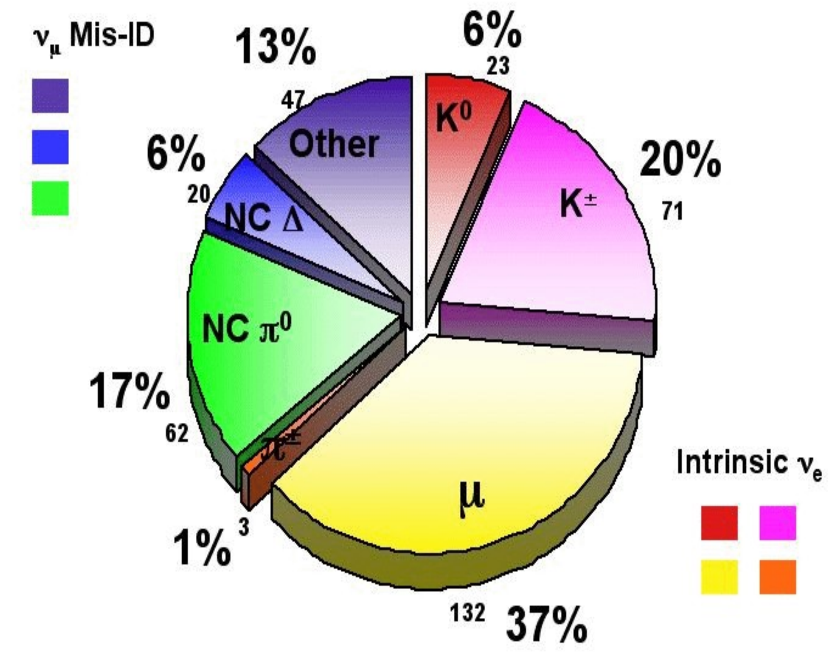
- $\mu \rightarrow \nu_e$: (indirectly) measured in ν_μ CCQE events via π-decay chain
- $\pi \rightarrow \nu_e$: " " " " " " "
- $K \rightarrow \nu_e$: measured in high-energy ν_μ ,ν_eCCQE (from Kaons), extrapolate to low-E

"mis-ID" backgrounds (mainly from ν_μ)

- CC Inclusive: includes CCQE, measured, simulated
- NC π^0: measured, simulated
- NC $\Delta \rightarrow N\gamma$: constrained in data, simulated
- NC coherent, radiative γ: calculated, negligible
- Dirt: ν interactions outside tank, simulated, measured
- beam-unrelated events, measured, very small

correlated errors on all backgrounds are considered

TB analysis predicted backgrounds



oscillation analysis: box-opening

With...

- algorithms finalized,
- cuts determined,
- backgrounds predicted,
- the neutrino oscillation box was opened

on March 26, 2007

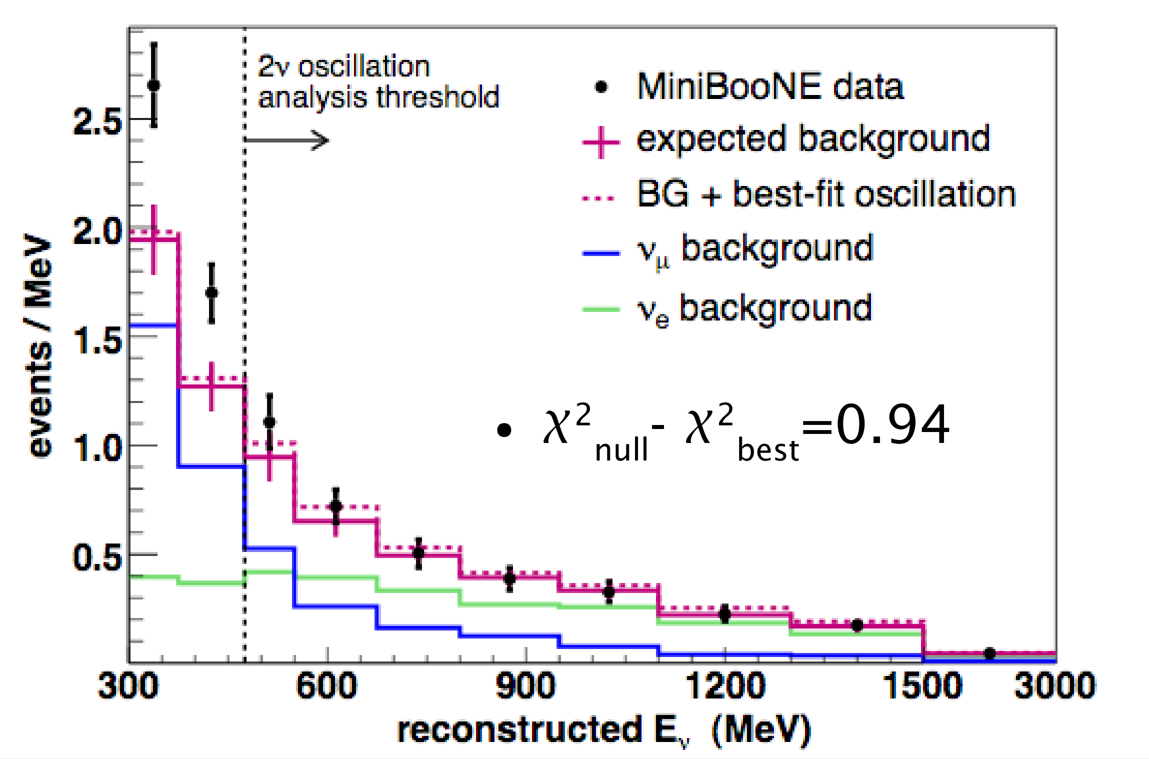
oscillation analysis: results

track-based analysis:

- E_ν> 475MeV cut for oscillation analysis region

- no sign of an excess in the analysis region

- visible excess at low E



No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

oscillation analysis: results

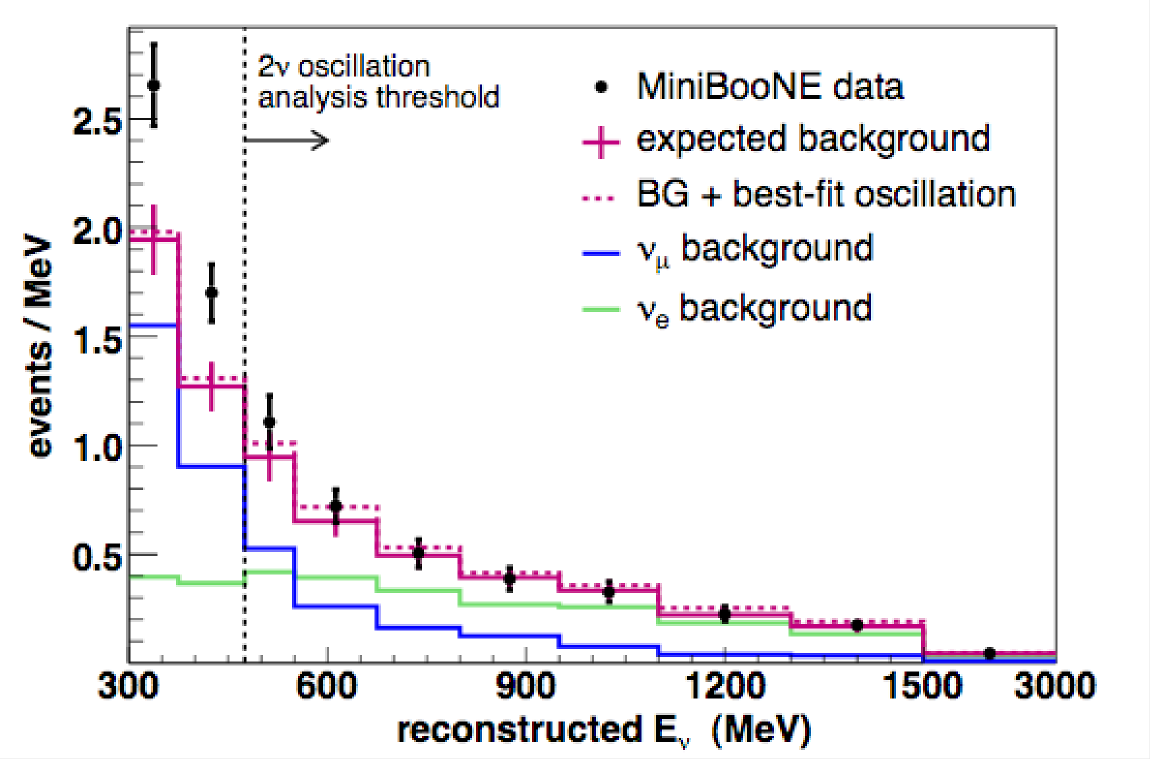
track-based analysis:

Counting Experiment: $475 < E_\nu < 1250$ MeV

data: 380 events

expectation: 358 ±19 (stat) ± 35 (sys)

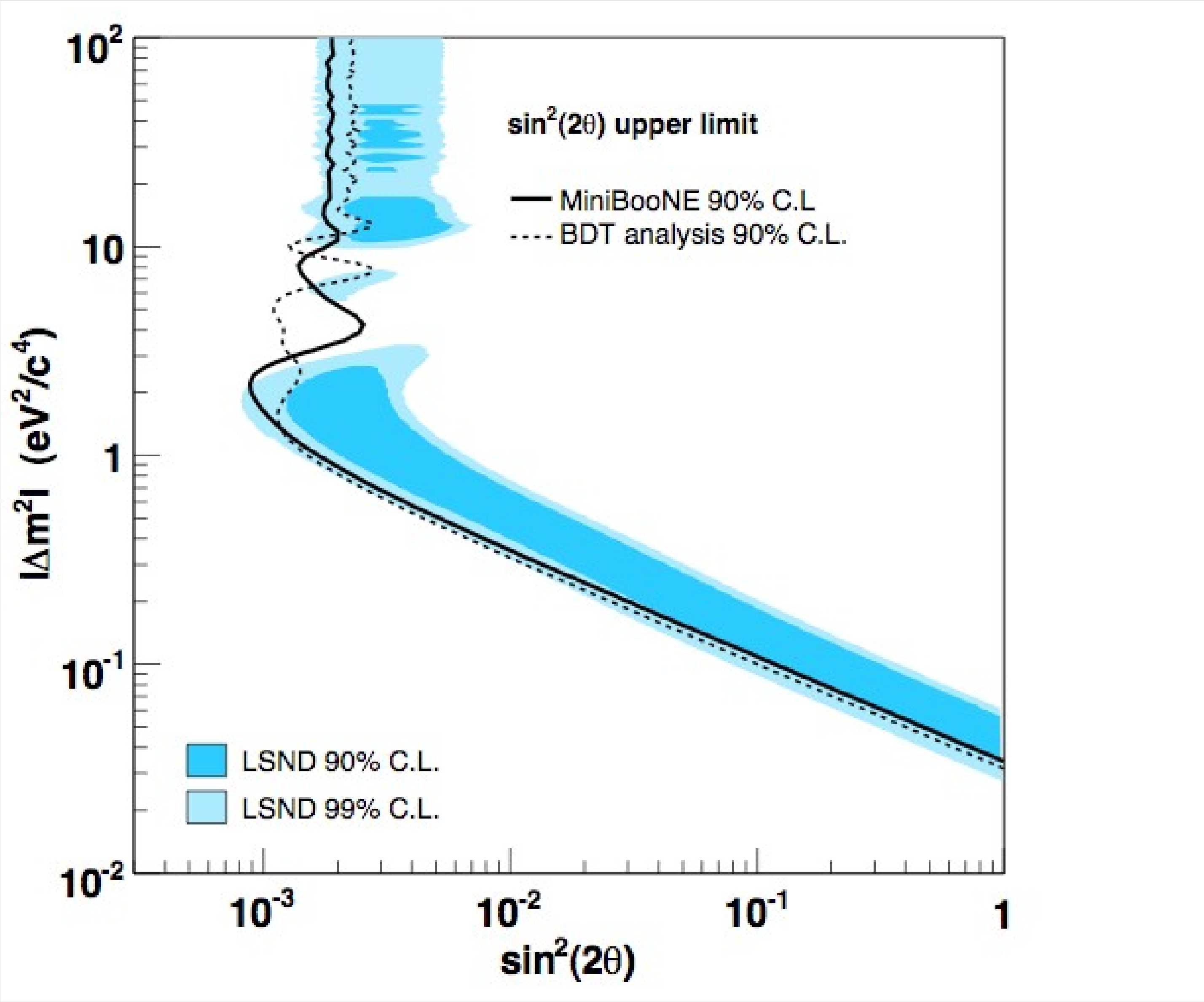
significance: 0.55 σ



No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

oscillation analysis: results

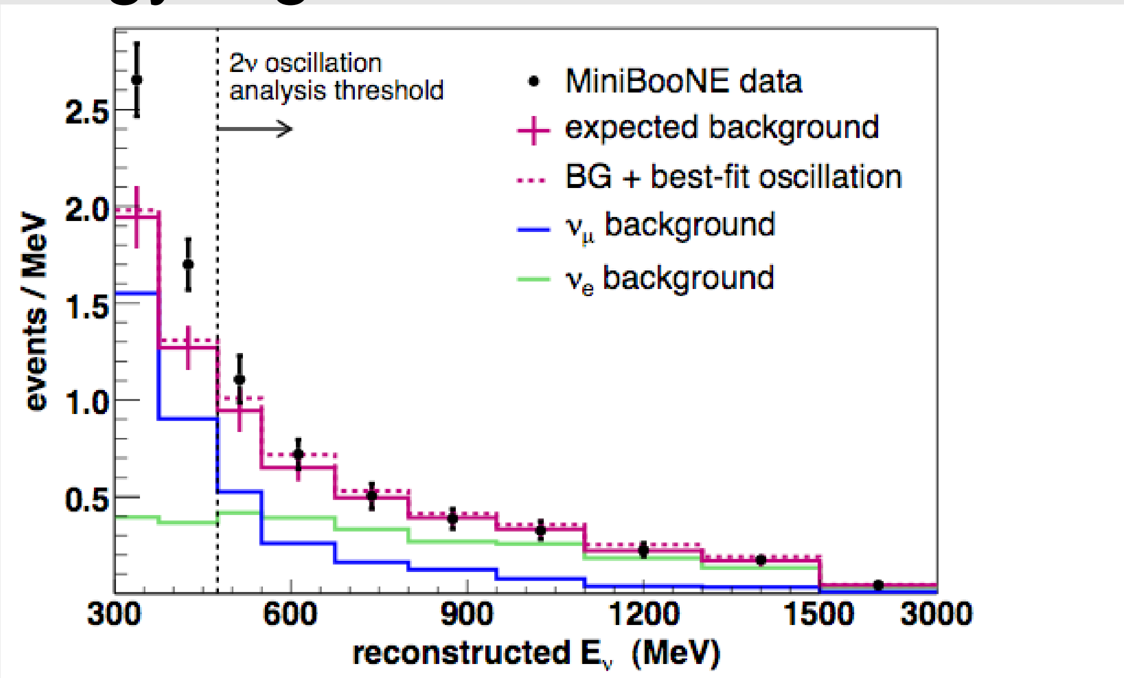
Limit curves:
solid: TB,
primary result
dashed: BDT



- MiniBooNE and LSND incompatible at a 98% CL for all Δm^2 under a 2ν mixing hypothesis

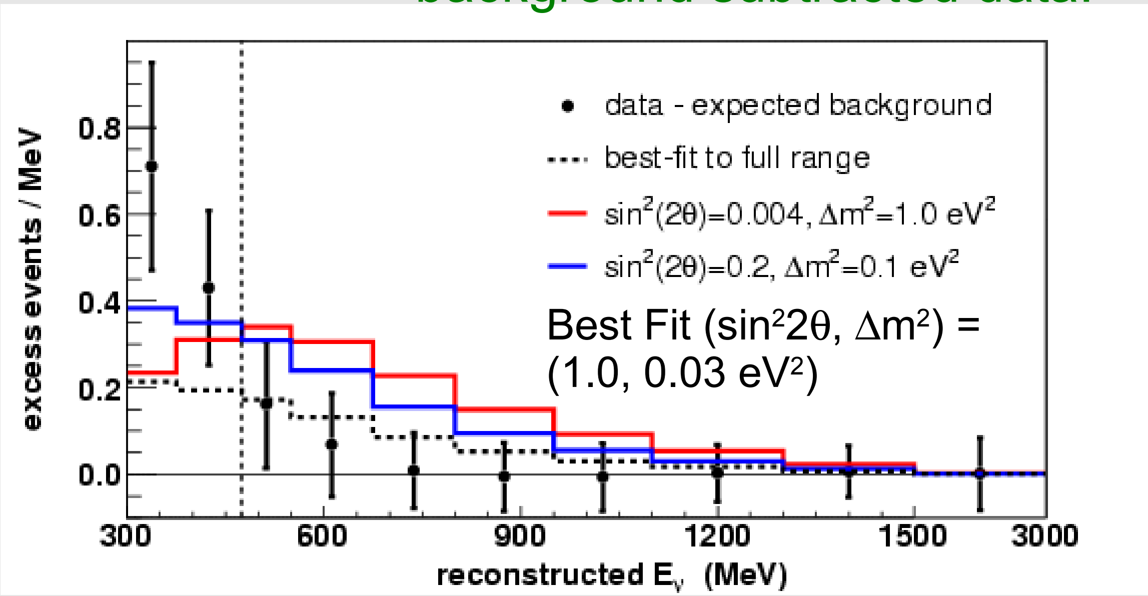
oscillation results: low-energy region

Track-based analysis
E_ν distributions:



For:
300<E_ν<475 MeV
96 ± 17 ± 20 events
Excess: 3.7σ

background subtracted data:



The energy-dependence of excess is not consistent with $\nu_\mu \rightarrow \nu_e$ appearance assuming standard energy dependence

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

Continuing work to understand low-energy region

- We continue to work to characterize and to determine the source of the event excess in the low-energy region (E_ν<475MeV)

It may be...

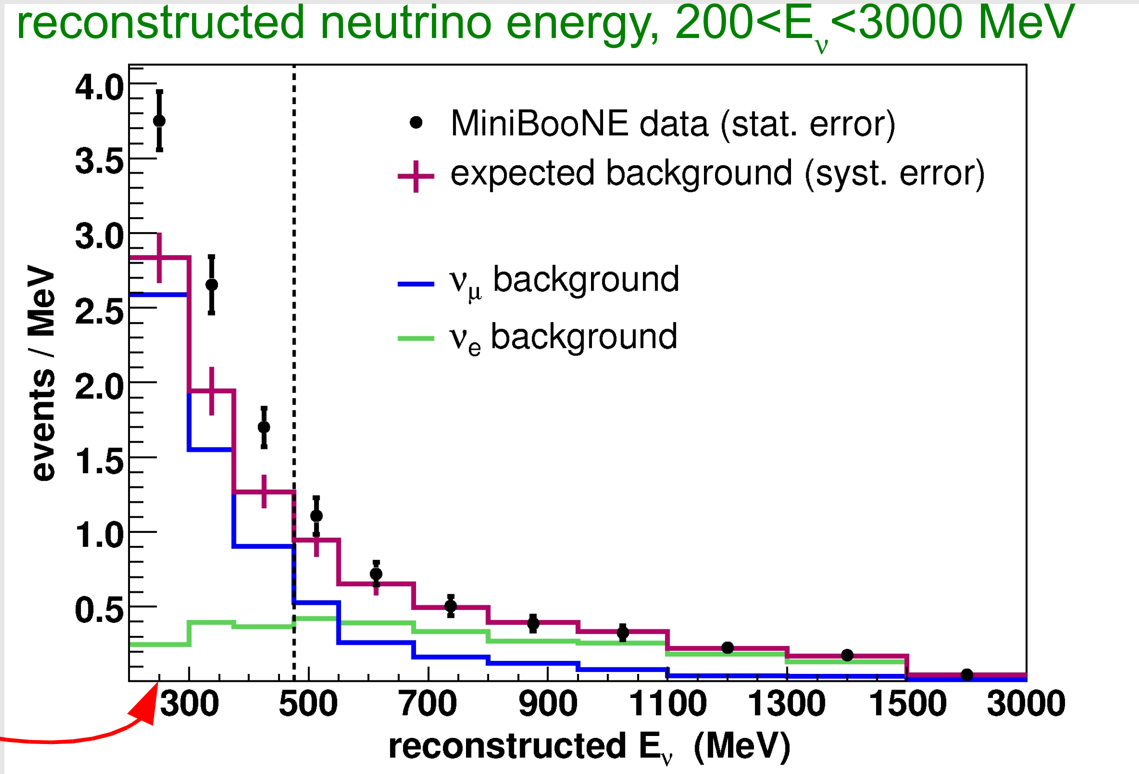
- detector or analysis problems
- a background (and of importance for other experiments searching for $\nu_\mu \rightarrow \nu_e$ appearance)
- new physics

Working on all of these...

new results soon

- NEW!

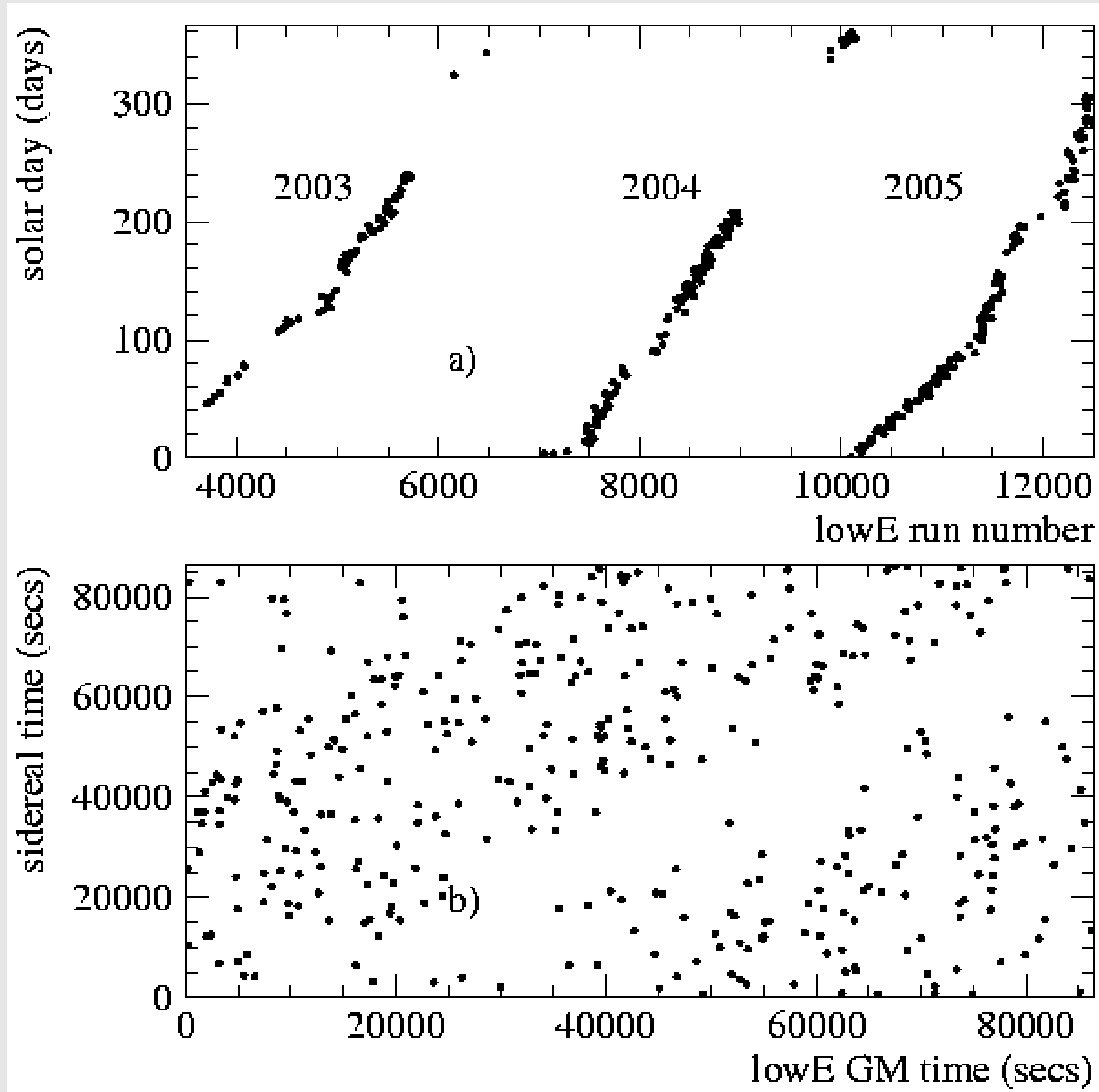
this energy bin



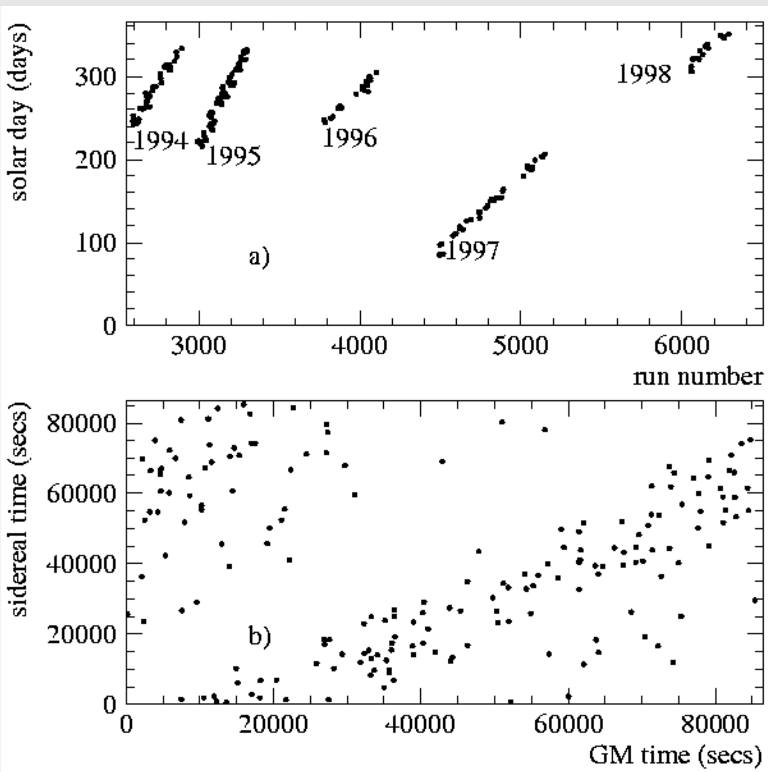
Sidereal Analysis of MiniBooNE data

- Proceeding analogously to LSND sidereal analysis…
- better "coverage" than LSND data of sidereal day

$300<E_\nu<475$MeV MiniBooNE data



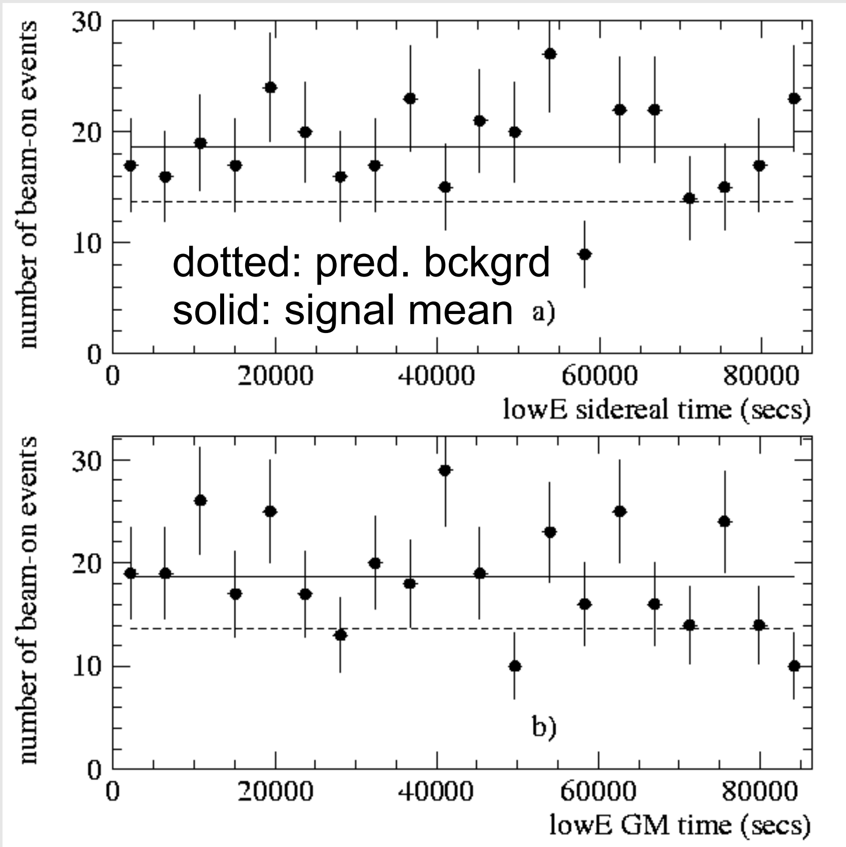
LSND data



Sidereal Analysis, Preliminary results

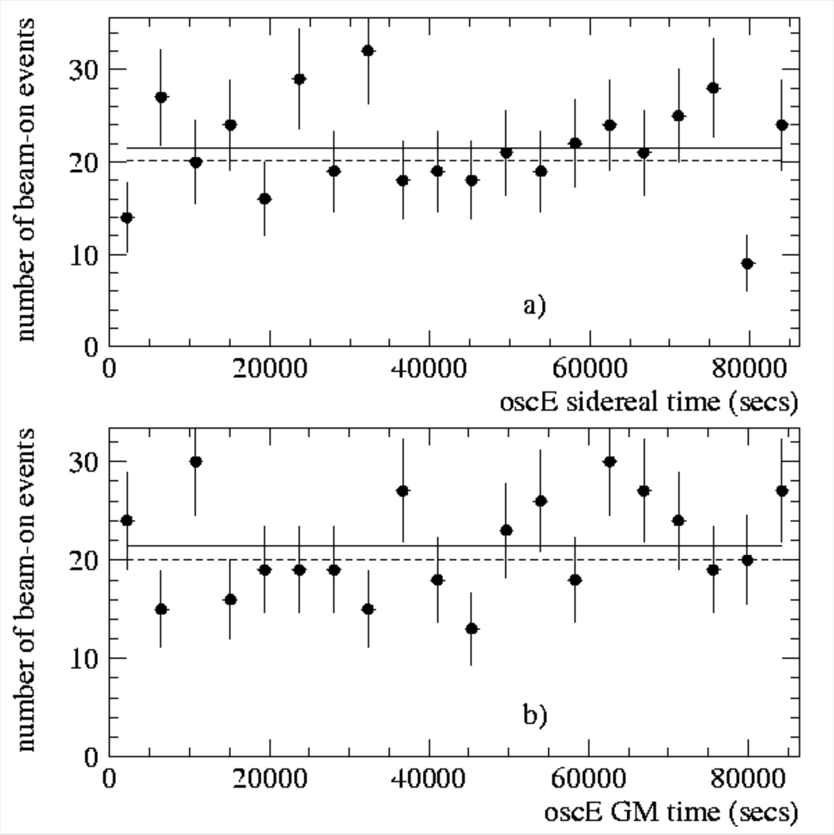
300<E_ν<475MeV:

sidereal:Pearson's χ^2 = 79.5/73 (P=0.28)
GM: Pearson's χ^2 = 72.8/73 (P=0.49)



475<E_ν<1250MeV:

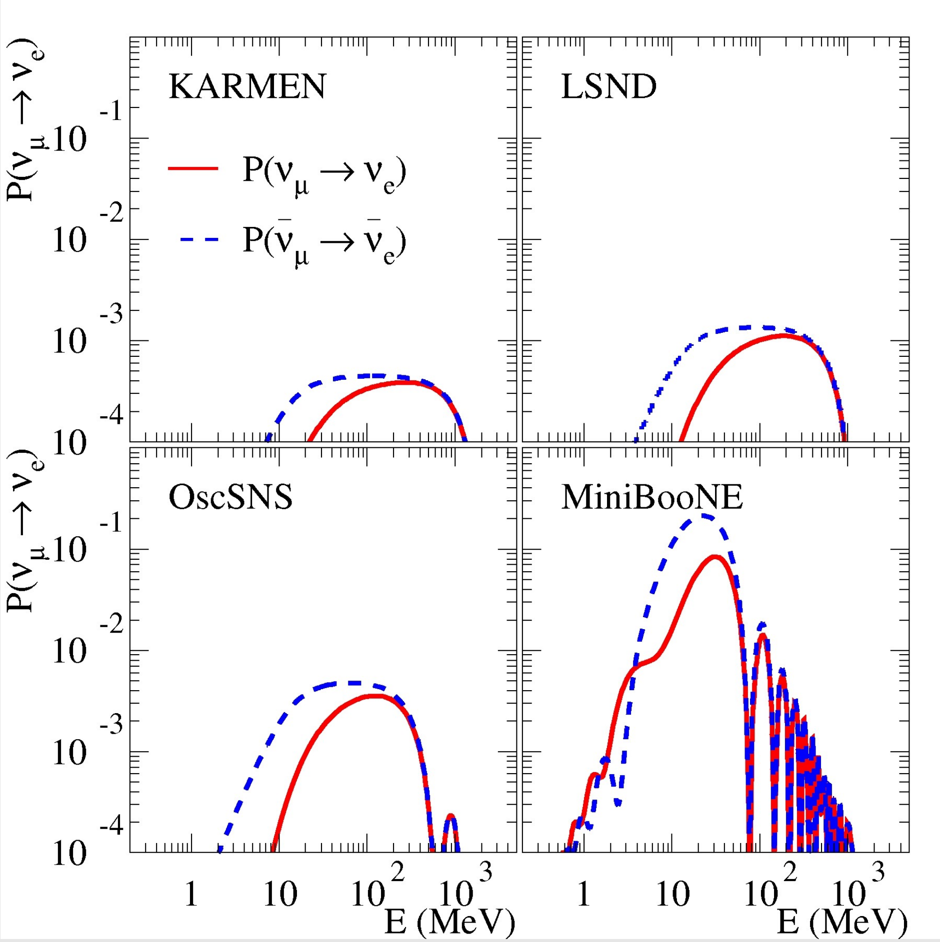
sidereal:Pearson's χ^2 = 77.2/84 (P=0.69)
GM: Pearson's χ^2 = 76.4/84 (P=0.71)



- actual chi2 tests performed with more bins (~5 events bin)
- final sidereal analysis will extract allowed regions or limits on SME parameters

Tandem model prediction

- Using MiniBooNE (public) data that includes detector efficiency effects, we calculated oscillation signal as predicted by tandem model. Recall prediction:



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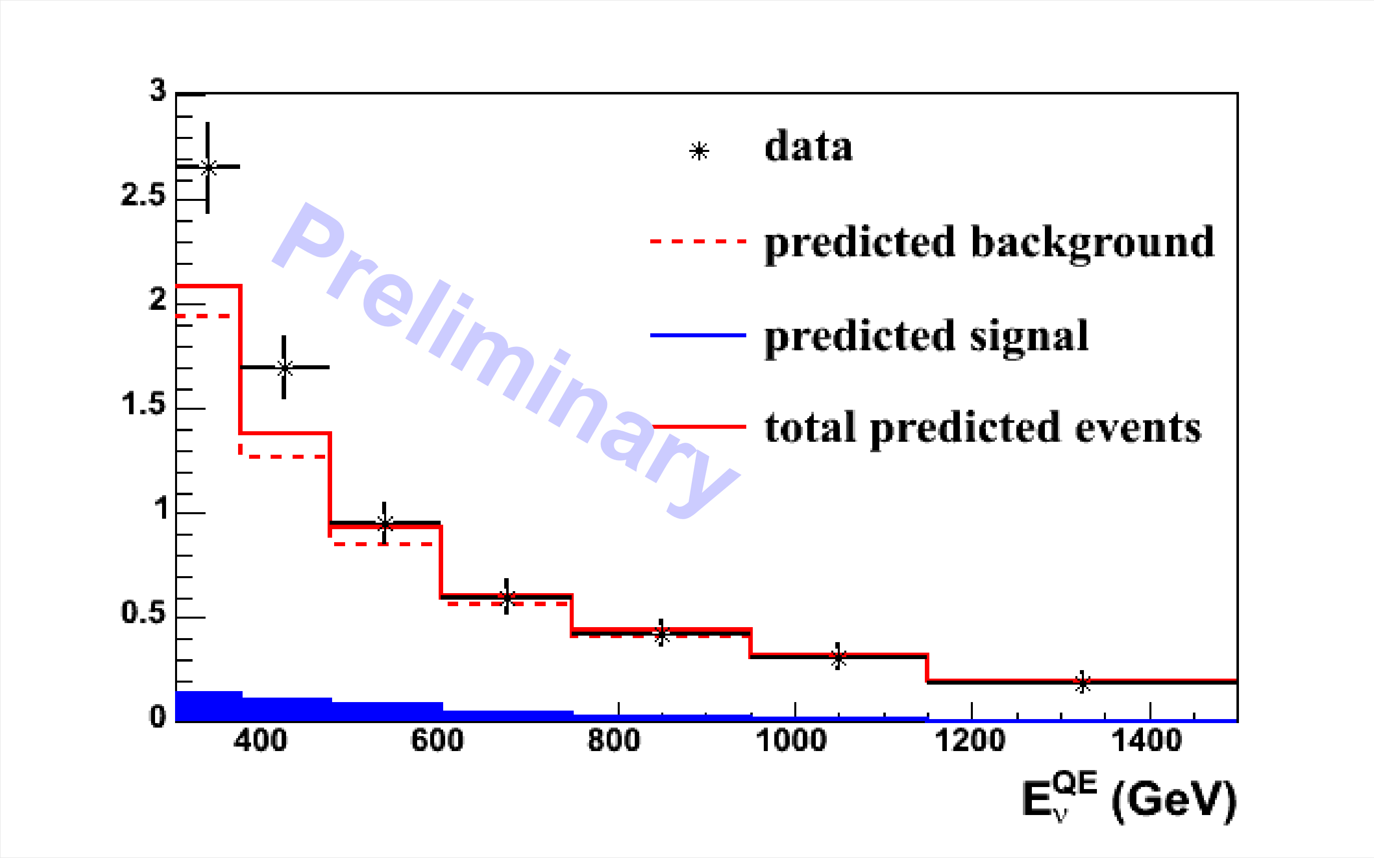

Summary

- MiniBooNE rules out (to 98%CL) the LSND result interpreted as $\nu_\mu \rightarrow \nu_e$ oscillations described with standard L/E dependence
(Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])

This eliminates the following interpretations of LSND:

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with (w/"standard" assumptions of CPT, E-dependence)
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ via a single sterile neutrino (" ")

- The as-yet-unexplained deviation of MiniBooNE data from prediction at low-energy could be a background ... Currently working on this with very high priority.

... Or perhaps, new physics
- final sidereal analysis to come
- more work on tandem model

Summary

- MiniBooNE rules out (to 98%CL) the LSND result interpreted as $\nu_\mu \rightarrow \nu_e$ oscillations described with standard L/E dependence
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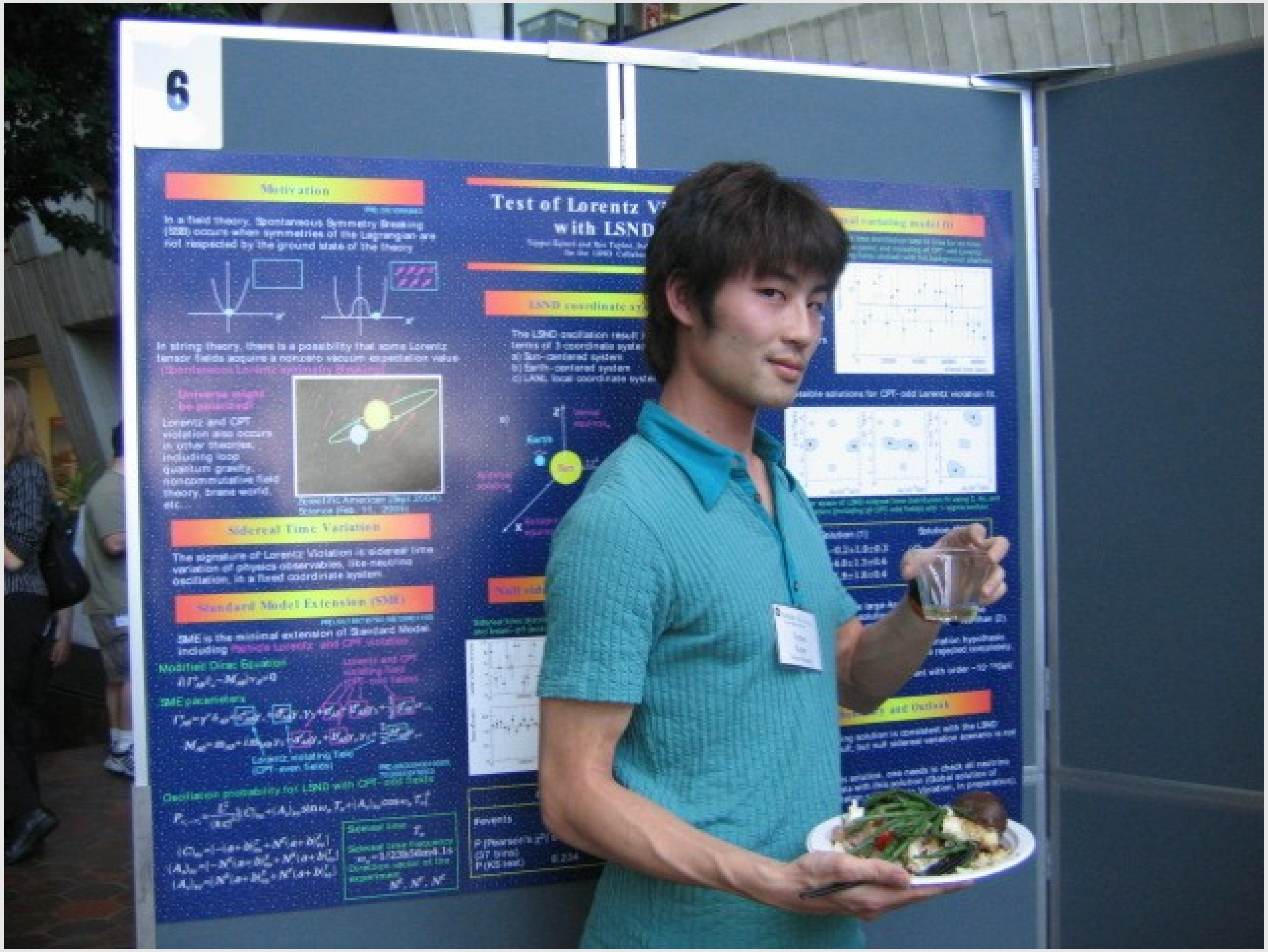
- Thanks to AK for workshop and collaboration!

Summary



- Much credit due to Teppei Katori, please see his poster this evening!

Summary

- MiniBooNE rules out (to 98%CL) the LSND result interpreted as $\nu_\mu \rightarrow \nu_e$ oscillations described with standard L/E dependence
(Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])

This eliminates the following interpretations of LSND:

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with (w/"standard" assumptions of CPT, E-dependence)
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ via a single sterile neutrino (" ")

- The as-yet-unexplained deviation of MiniBooNE data from prediction at low-energy could be a background ... Currently working on this with very high priority.

... Or perhaps, new physics
- final sidereal analysis to come
- more work on tandem model