Neutrino Oscillation Results from MiniBooNE

Outline:
- motivation, strategy
- experiment
- analysis
- results
- New: further investigations of low-energy region

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XXIII International Symposium
on Lepton and Photon Interactions at High Energy
Aug 13-18, Daegu, Korea

The LSND Result

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

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

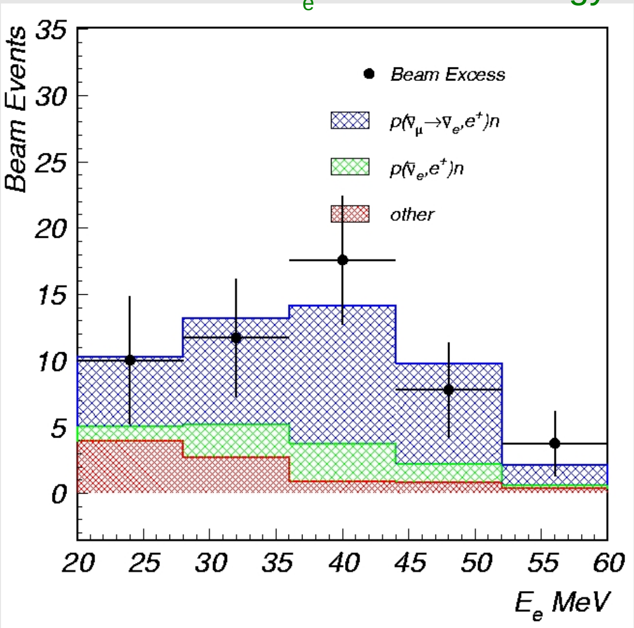
consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

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

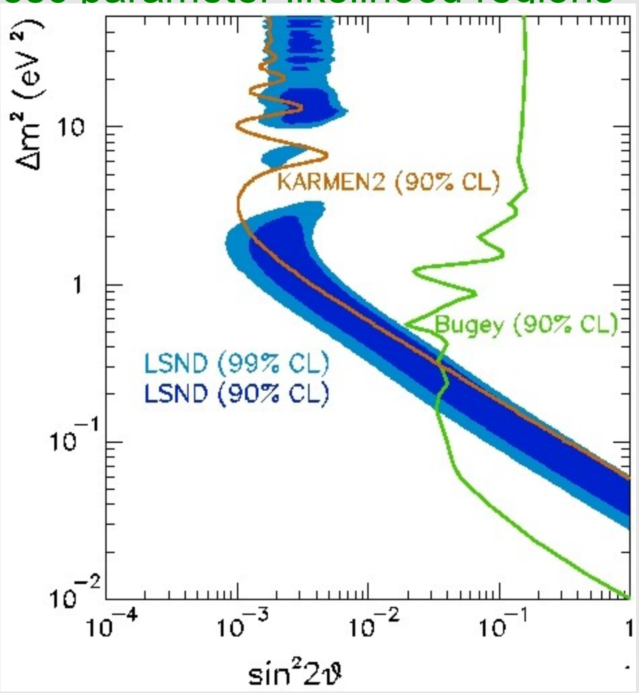
If LSND is correct $\Rightarrow$ new physics.
- additional (sterile) neutrinos
- a different model for oscillations

But LSND had not been tested by another experiment..

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



osc parameter likelihood regions

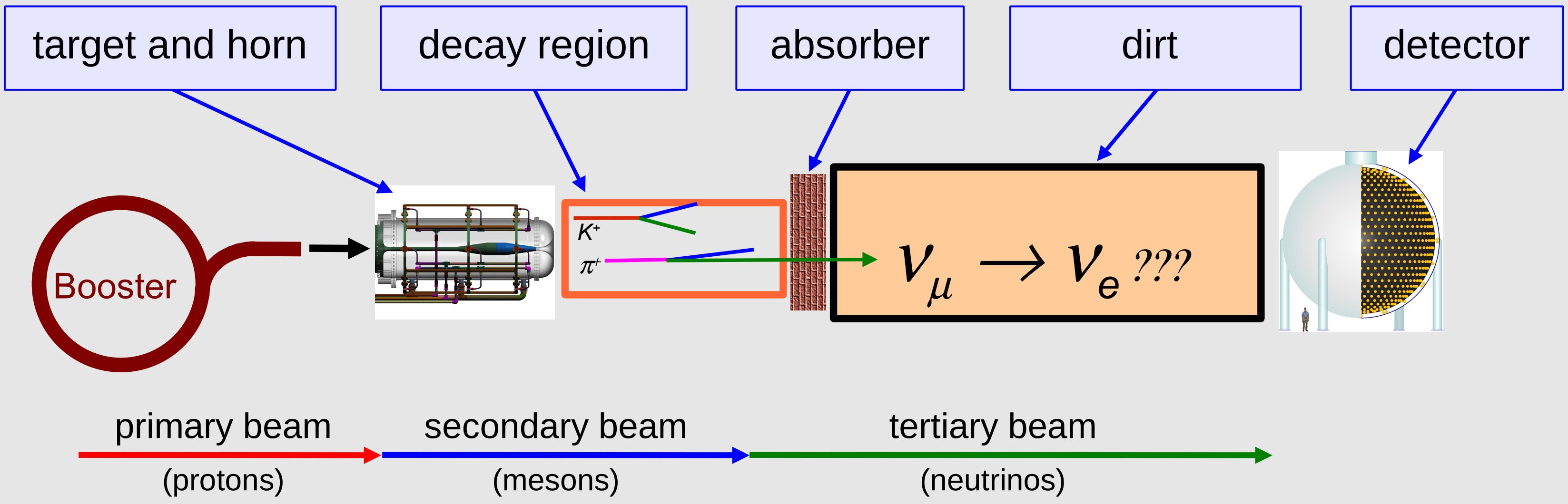


MiniBooNE experimental strategy

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

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

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



MiniBooNE Collaboration

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(The MiniBooNE Collaboration)

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MiniBooNE ν beam

- Fermilab experiment E898

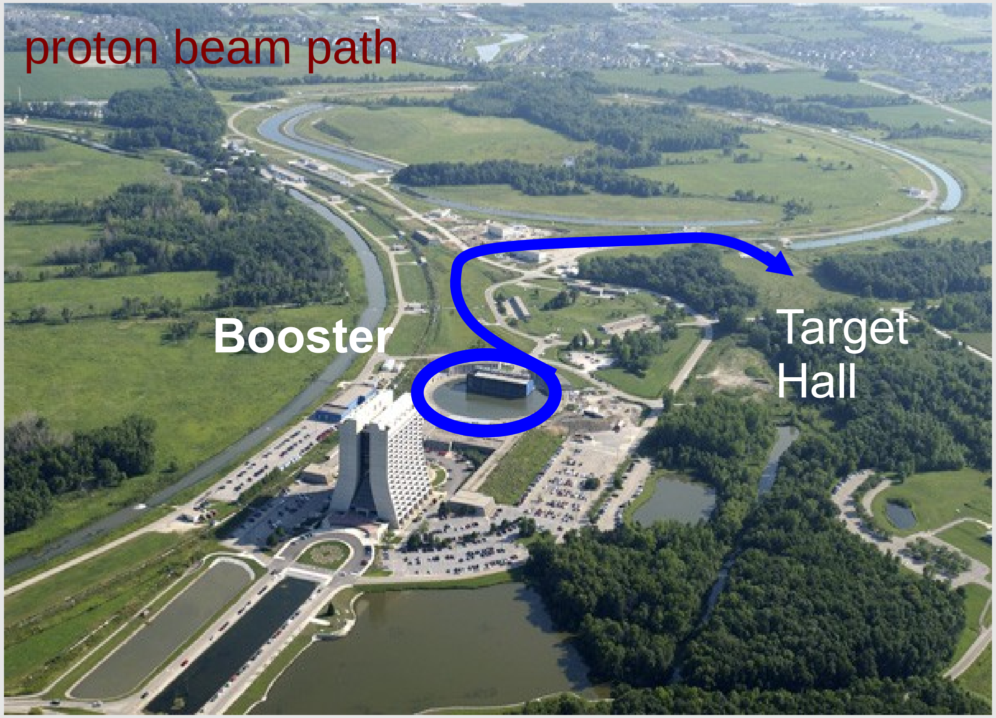
- proton beam from 8 GeV booster accelerator

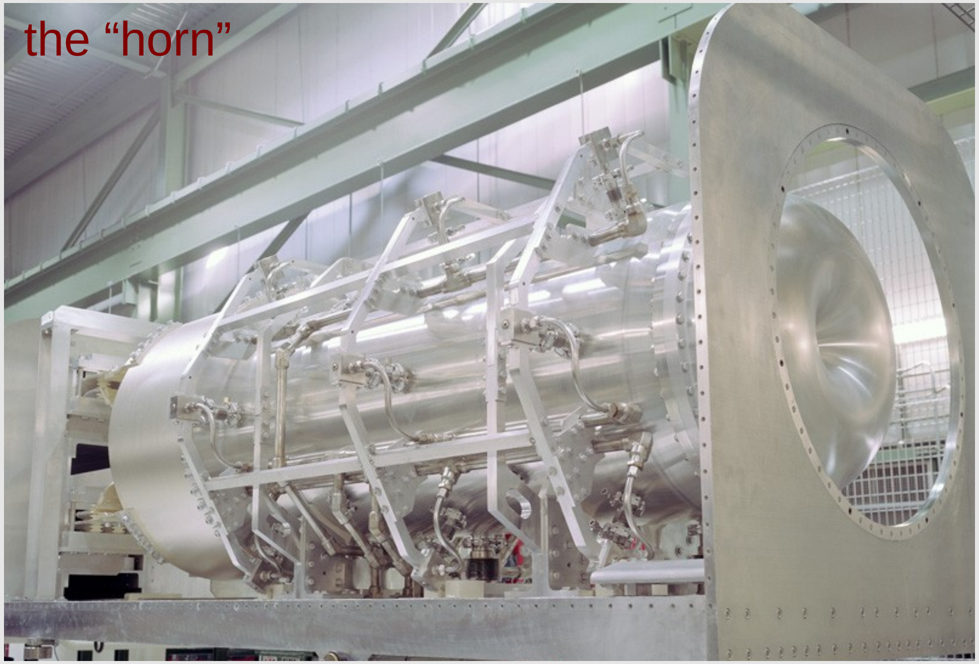
- Delivered to a beryllium target

- within a magnetic horn pulsing with beam spill (current= 170 kA)

- 4×10^{12} protons per 1.6μs beam pulse delivered at ~ 5 Hz.

- Published results use entire neutrino data set:
    - $(5.58 \pm 0.12) \times 10^{20}$ protons
    - Collected 2002-2005



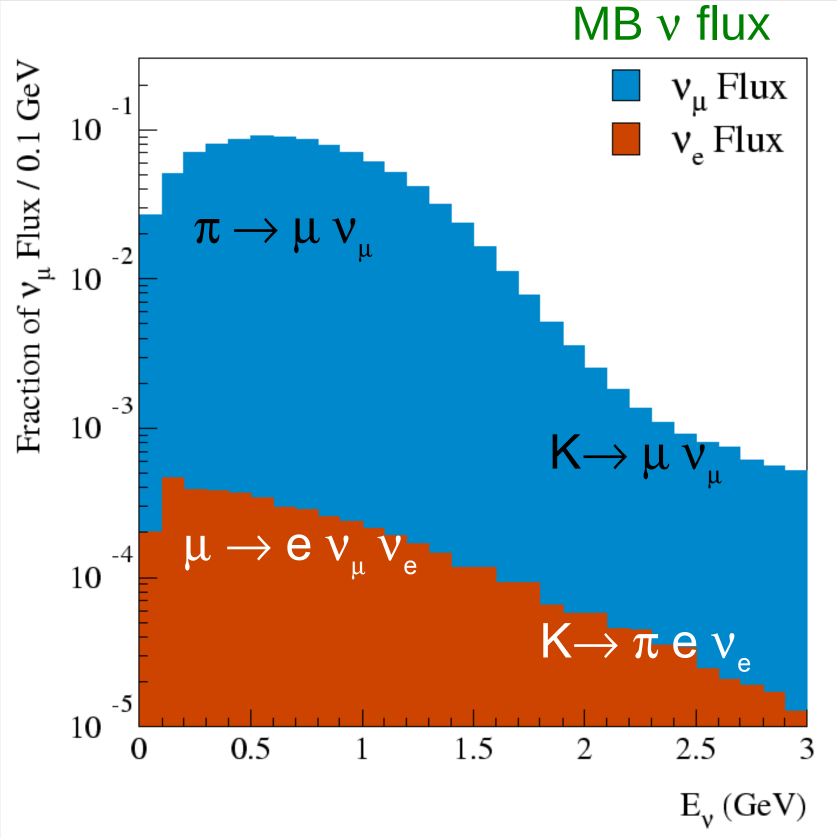


MiniBooNE beam: total ν flux

GEANT4 simulation used to predict flux at detector, includes:

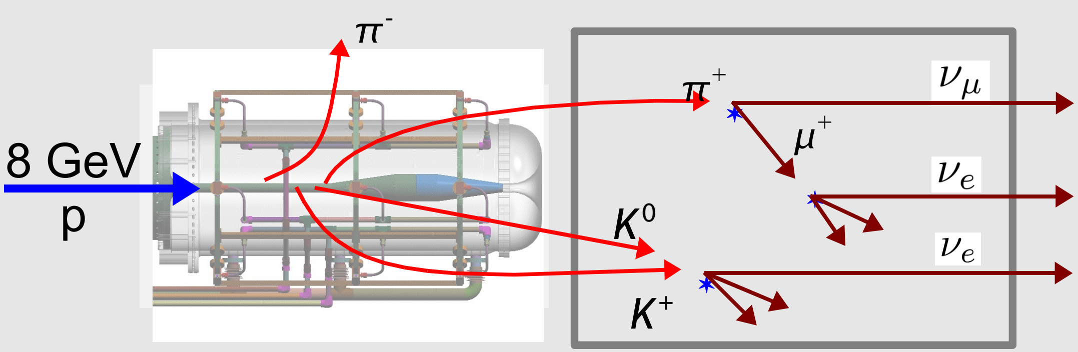
- pi, K production data (from other exps)
- proton interactions (primary, 2ndary)
- horn/decay pipe geometry

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



"Intrinsic" ν_e sources:

$\mu^+ \to e^+\ \bar{\nu}_\mu\, \nu_e$	(52%)
$K^+ \to \pi^0\, e^+\, \nu_e$	(29%)
$K^0 \to \pi^+\, e^-\, \nu_e$	(14%)
Other	(5%)



MiniBooNE Detector

- 541 meters from target

- 12 meter diameter sphere

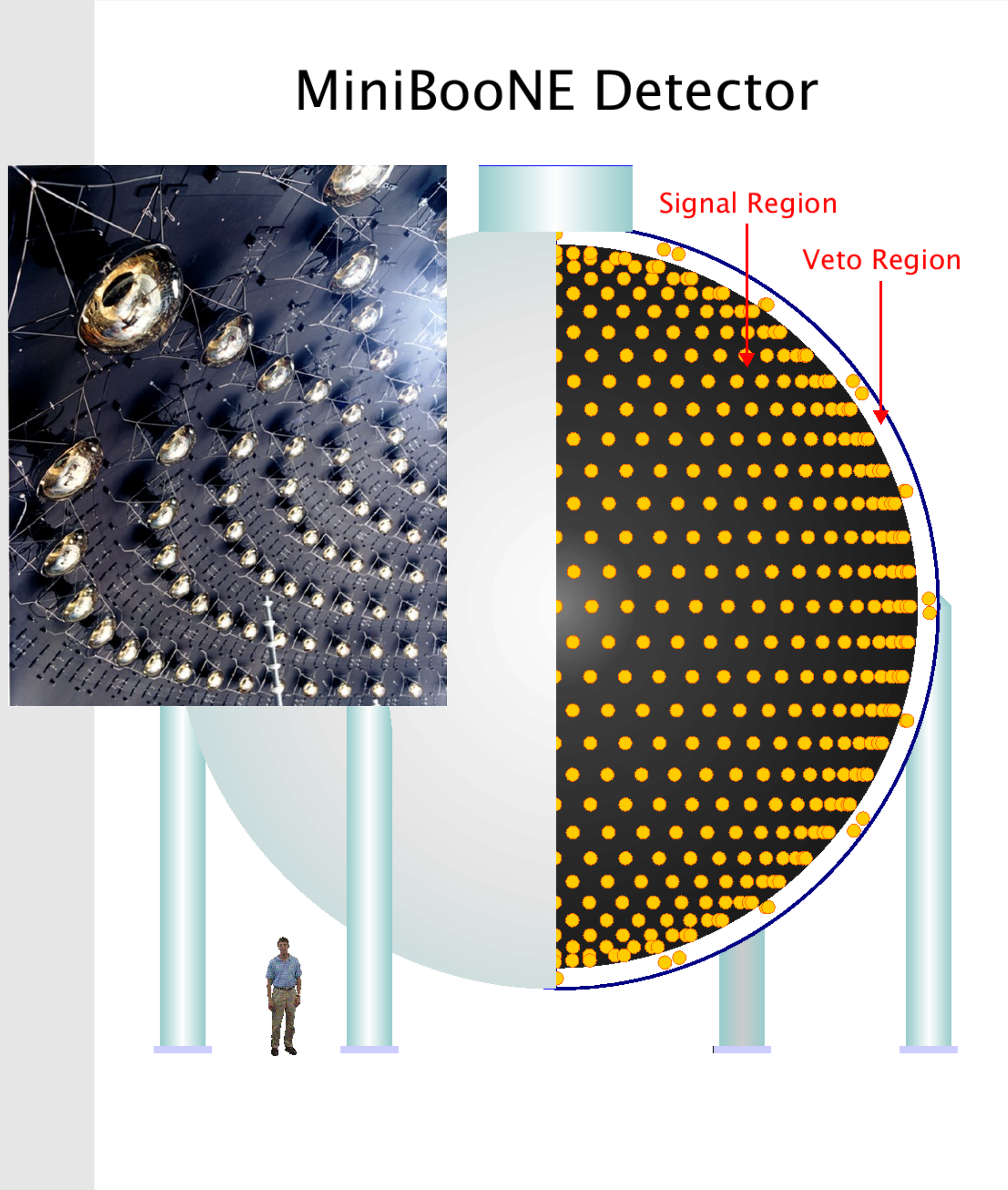
- 800 tons mineral oil (CH_2)

- 3 m overburden

- includes 35 cm “veto region”

- viewed by 1280 8” PMTs (10% coverage) + 240 veto

- Simulated with a GEANT3 Monte Carlo program tuned with external/internal calibration data



ν Events in MiniBooNE

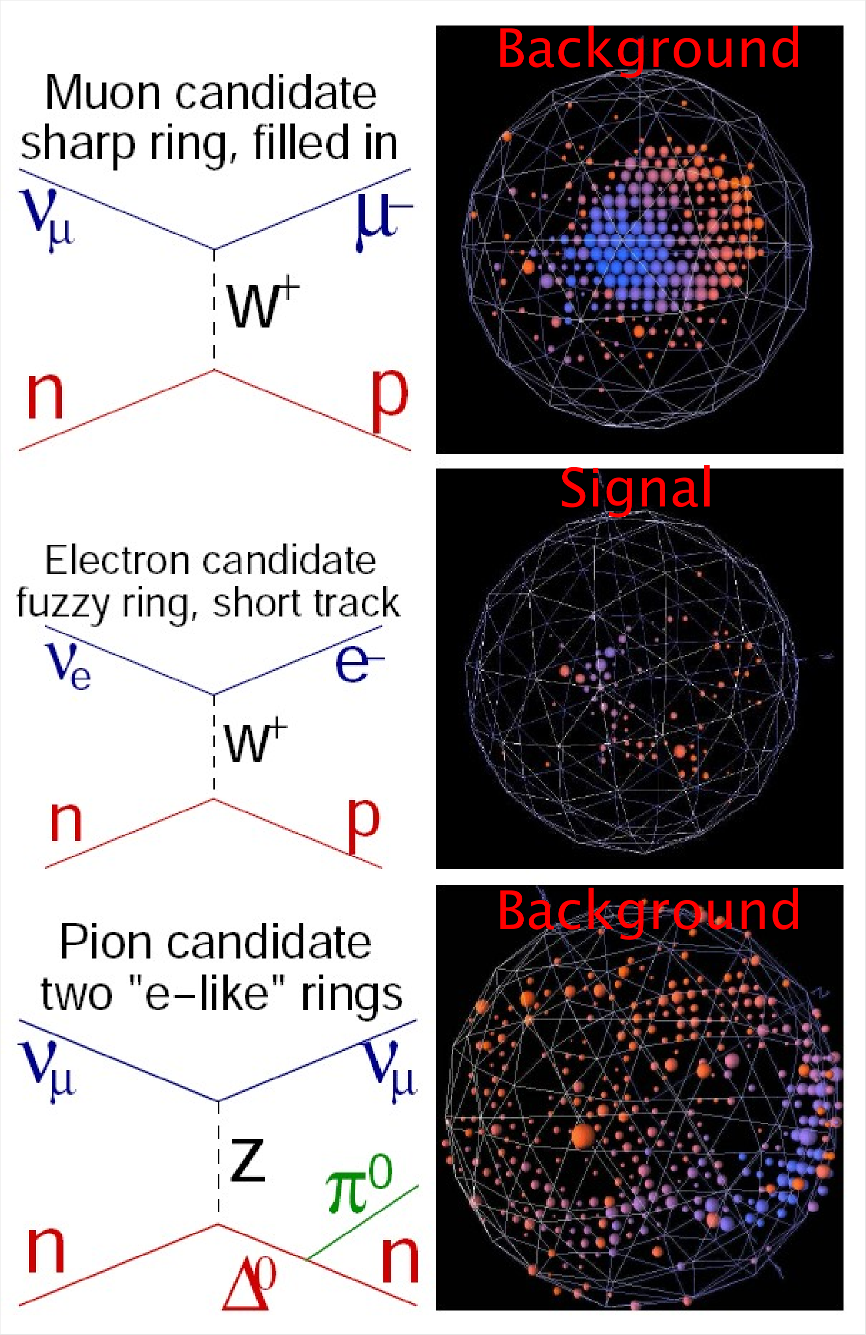
- Recall: search for ν_e in a ν_μ beam

- 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

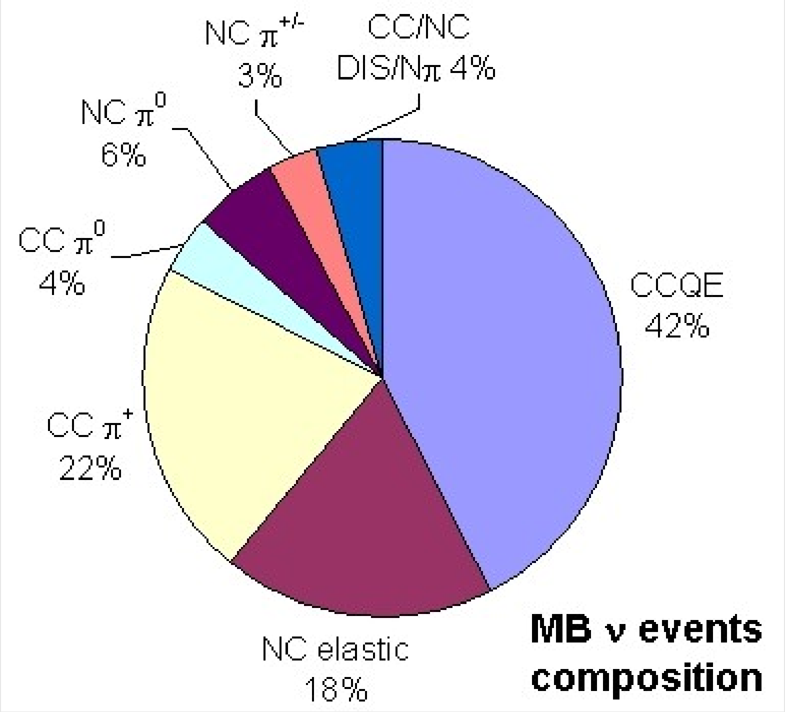
- pattern and timing of the detected light allows for event identification (and position, direction, energy meas.)



ν interactions in detector:

-predicted ν events and fractions from event generator*

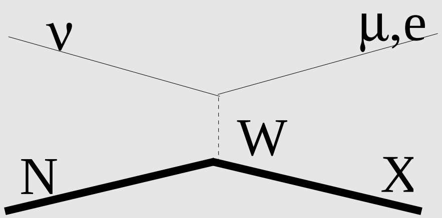
- extensively tuned using MiniBooNE data



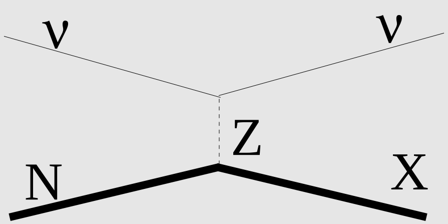
predicted # ν events in data set (no efficiency corrections)

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)

charged-current quasielastic (CCQE) events

CCQE processes:

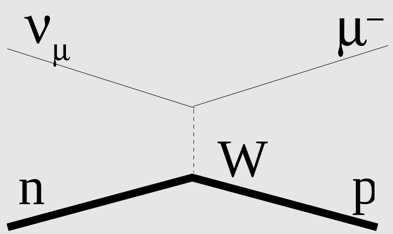
- ν_μ CCQE
  - highest-rate reaction channel
  - provides a measurement of interaction probability (cross section) and a check of the ν_μ flux

- ν_e CCQE
  - is the oscillation signal channel
  - meas. of lepton energy/angle yields ν energy (E_ν) via 2-body quasi-elastic (QE) kinematics:

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

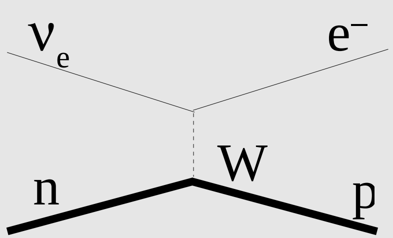
ν_μ CCQE

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



ν_e CCQE

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



CCQE events:

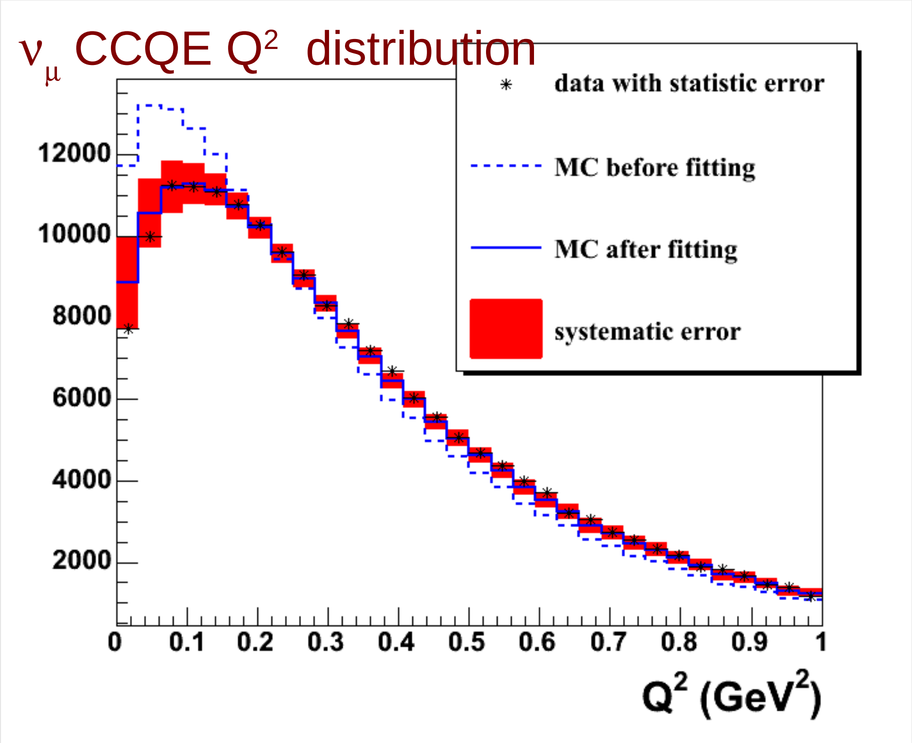
- Excellent description of ν_μ CCQE reaction has been obtained after adjustment of 2 Fermi-gas-model parameters:

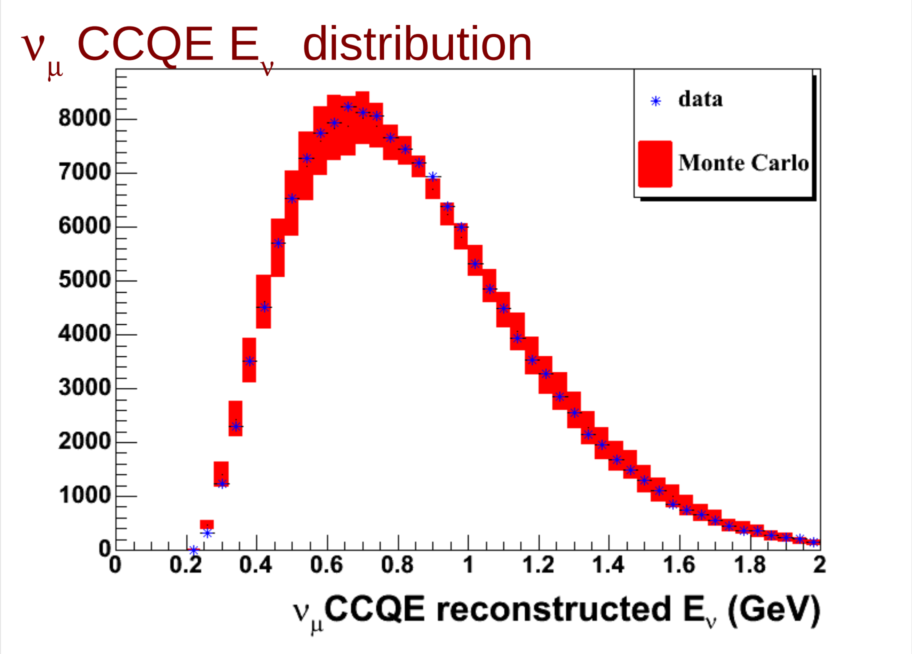
From Q^2 (4-mom. transfer) fits t
ν_μ CCQE data:

M_A^{eff} -- effective axial mass

κ -- Pauli blocking param

- paper on this work:
arXiv:0706.0926 [hep-ex],
submitted for publication

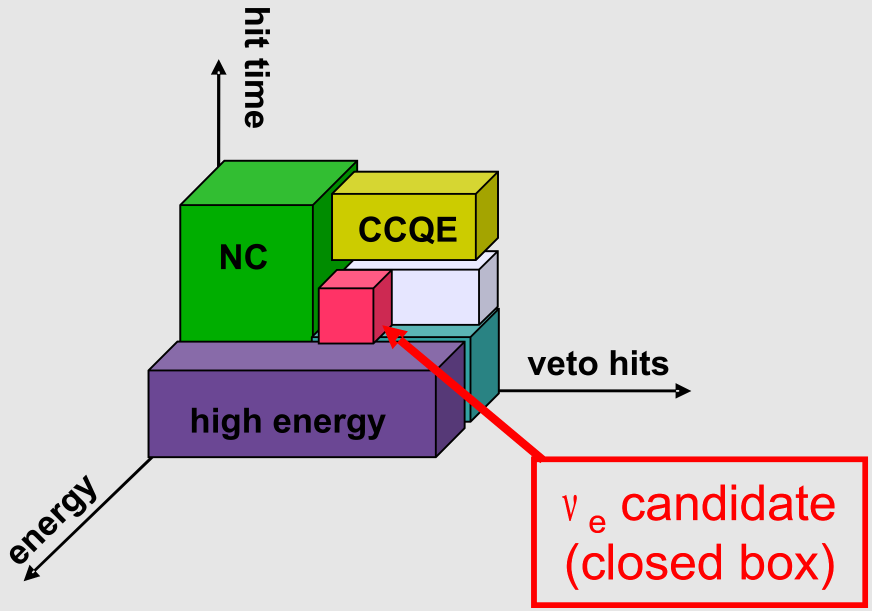




oscillation analysis: strategy

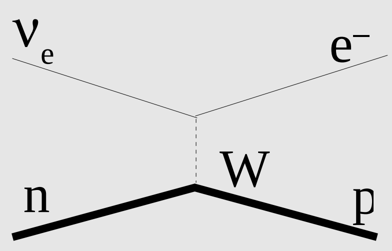
- need accurate, efficient particle identification algorithm to separate (signal) electron-like events from ubiquitous (background) muon, pion events

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



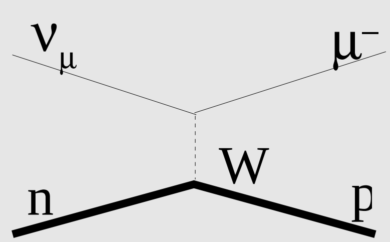
signal reaction:

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



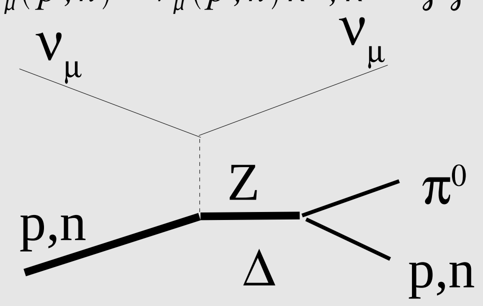
background:

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



background:

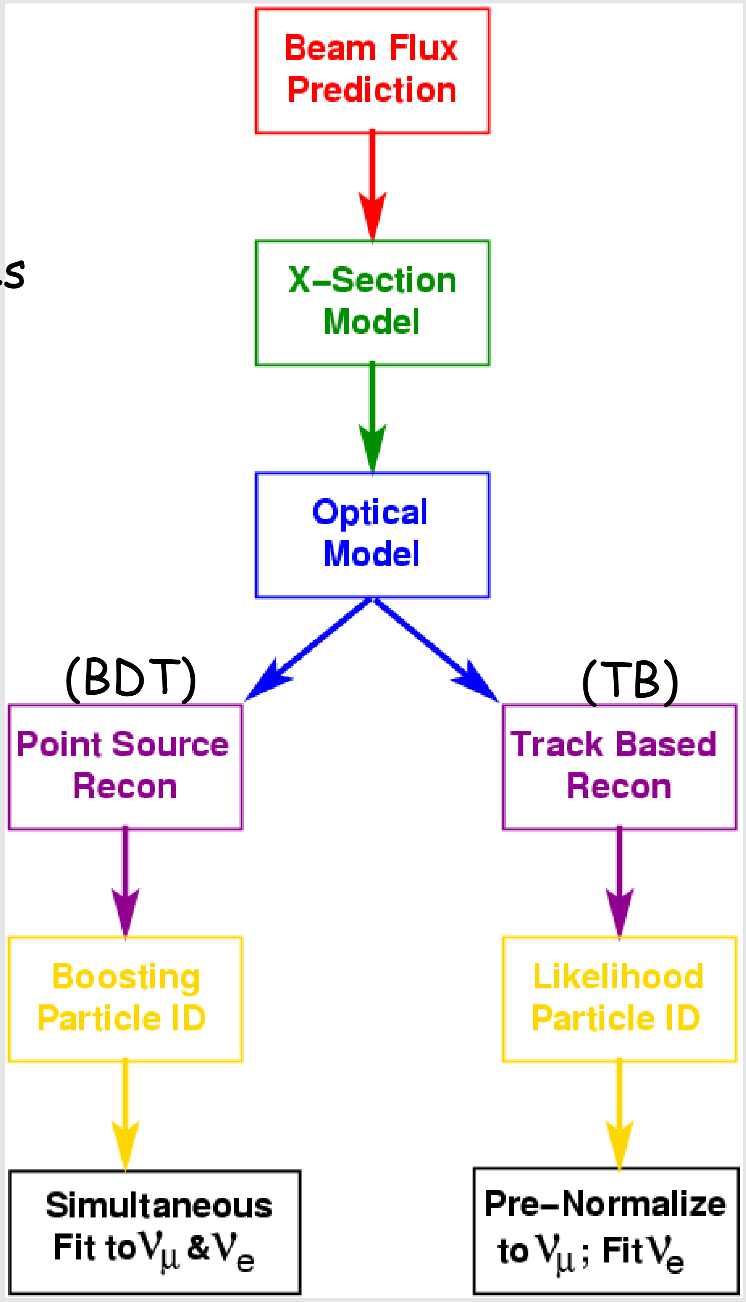
$$\nu_\mu (p,n) \rightarrow \nu_\mu (p,n) \pi^0, \pi^0 \rightarrow \gamma\gamma$$



oscillation analysis: strategy

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"

oscillation analysis: 2 algorithms

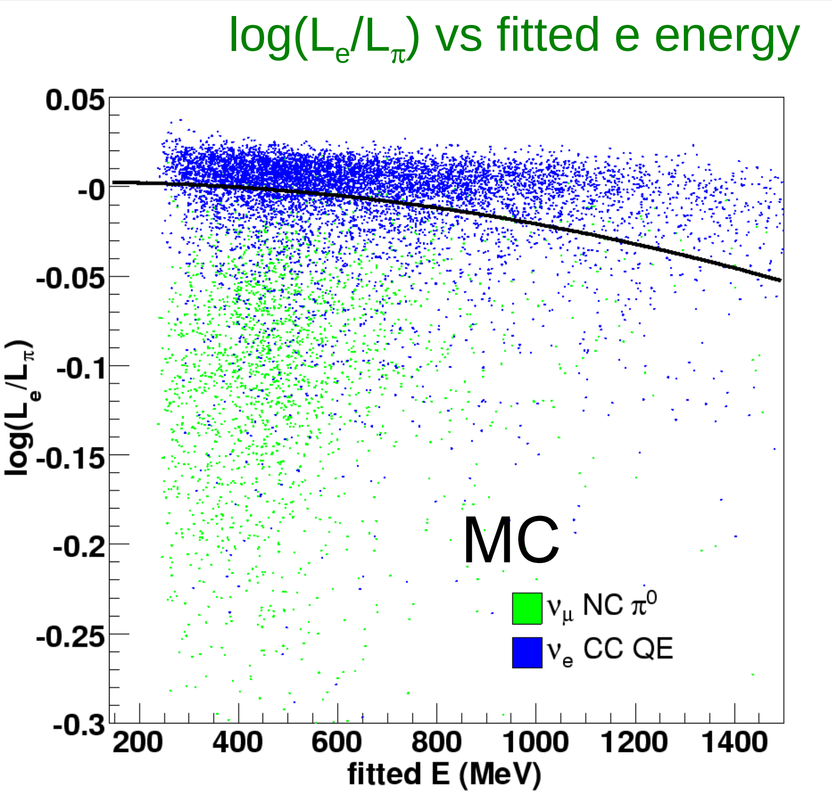
TB event selection:

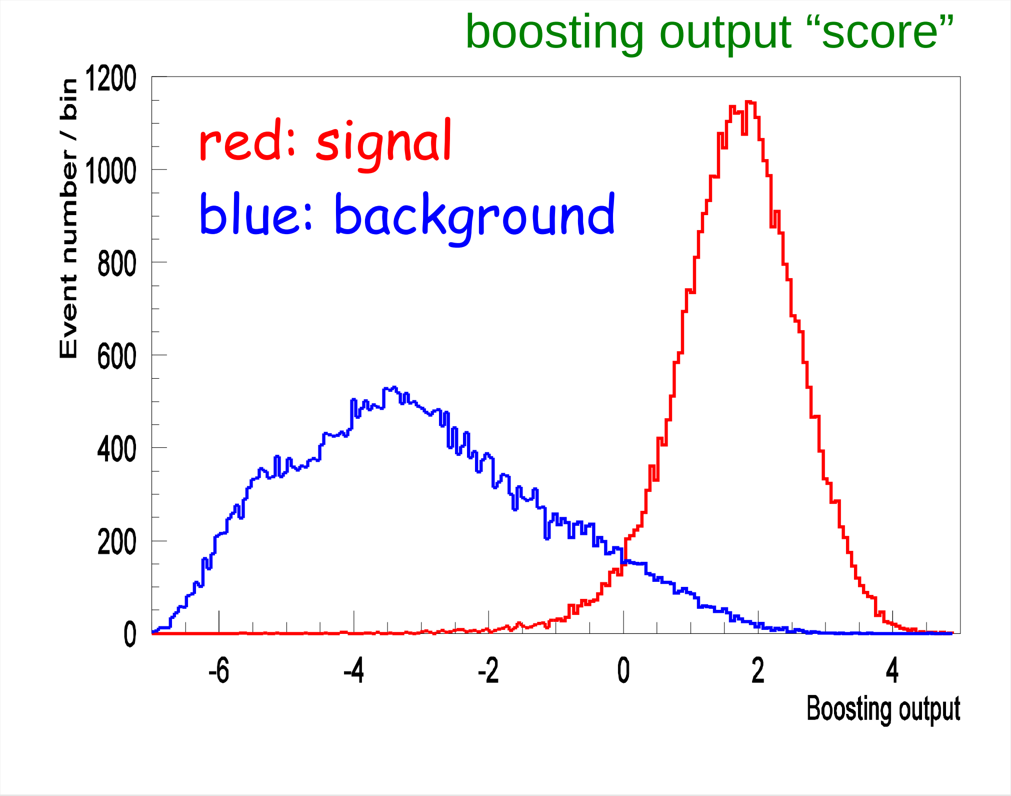
- precuts (# PMT/veto hits, no μ-decay, fiducial volume, etc)
- reject "muon-like" events: $\log(L_e/L_\mu)$
- reject "π^0-like" events: $\log(L_e/L_\pi)$

reconstructed π^0 mass

BDT selection:

- precuts (# PMT/veto hits, no μ-decay, fiducial volume, etc)
- PID "score" from boosting algorithm





oscillation analysis: backgrounds

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

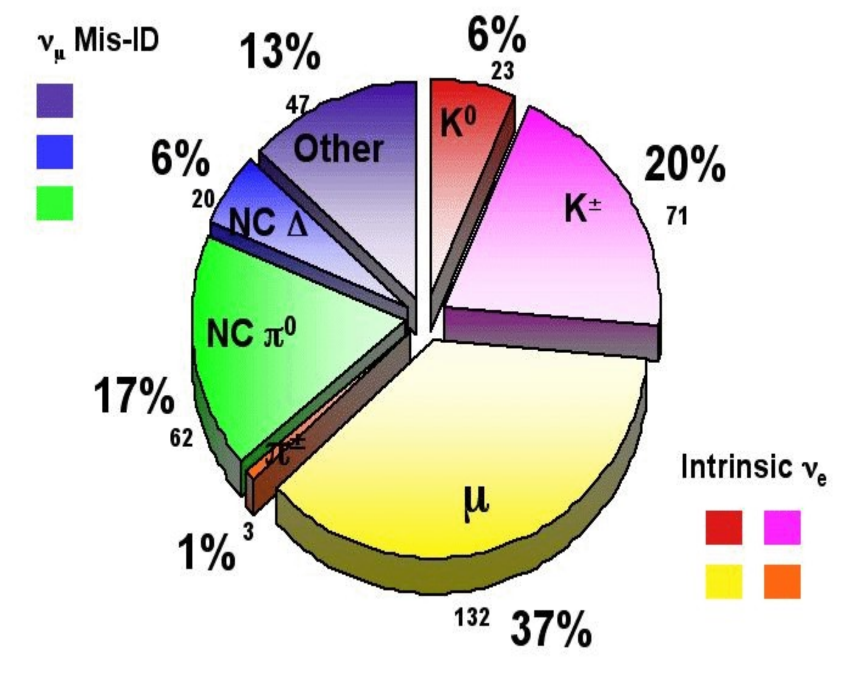
- $\mu \to \nu_e$: (indirectly) measured in ν_μ CCQE events via π-decay chain
- $\pi \to \nu_e$: " " " " " " "
- $K \to \nu_e$: measured in high-energy ν_μ ,ν_eCCQE (from Kaons), extrapolate to low-E

"mis-ID" backgrounds (mainly from ν_μ)

- CC Inclusive: includes CCQE, measured, simulated
- NC π^0: measured, simulated
- NC $\Delta \to N\gamma$: 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



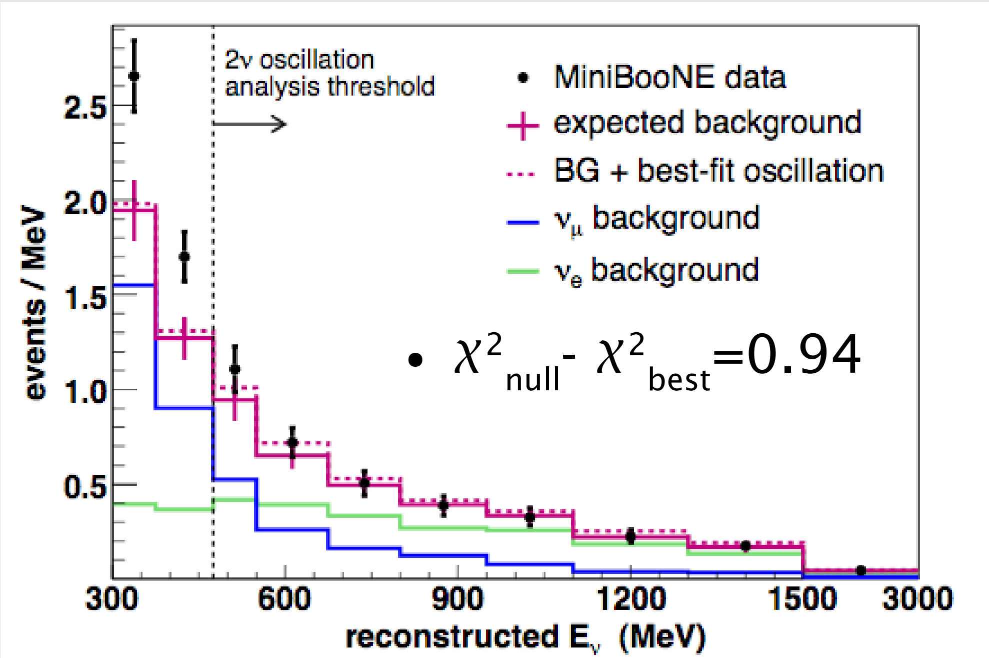
oscillation analysis: box-opening

With...

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

on March 26, 2007

oscillation analysis: results

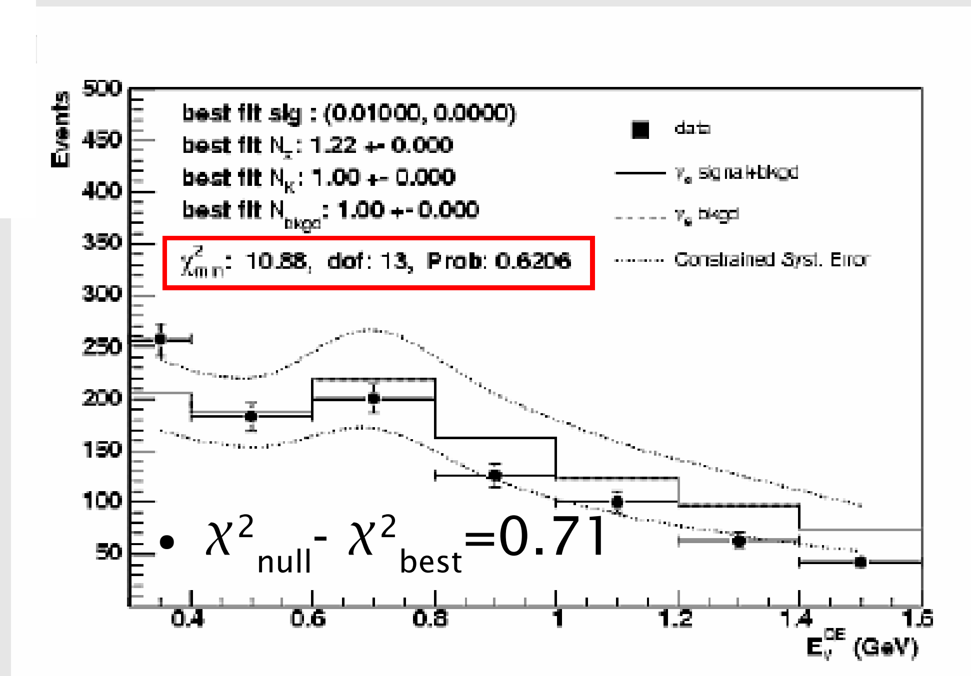


track-based analysis:

- E_ν> 475MeV cut for oscillation analysis region

- no sign of an excess in the analysis region

- visible excess at low E



boosted decision tree analysis:

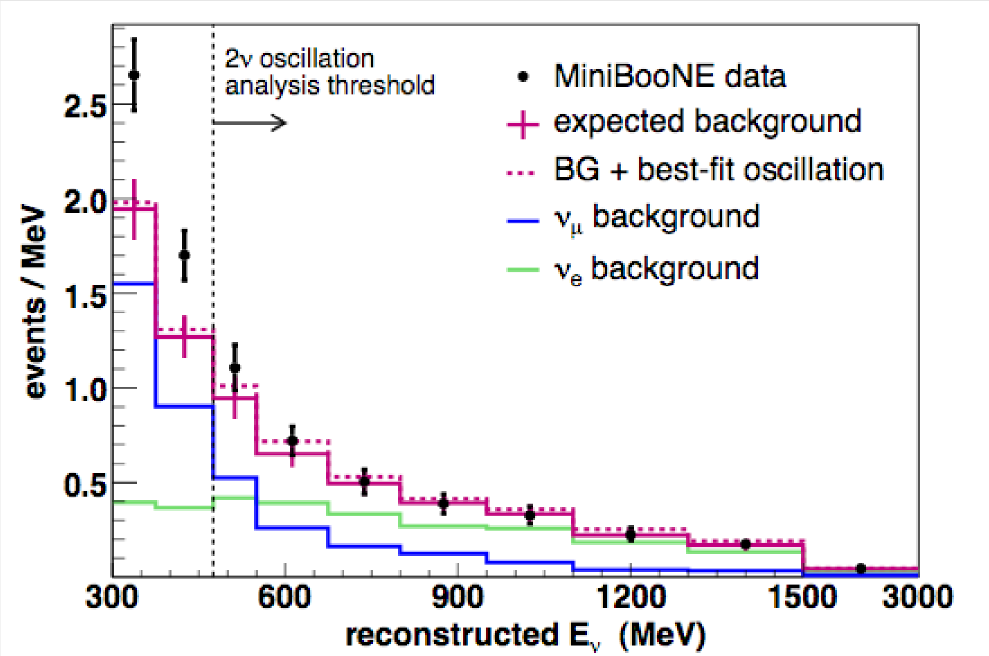
- E_ν> 300MeV cut for oscillation analysis region

- good fit and no significant excess

- Slight excess at lowest E, but larger normalization error weakens significance

Neither analysis shows evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

oscillation analysis: results



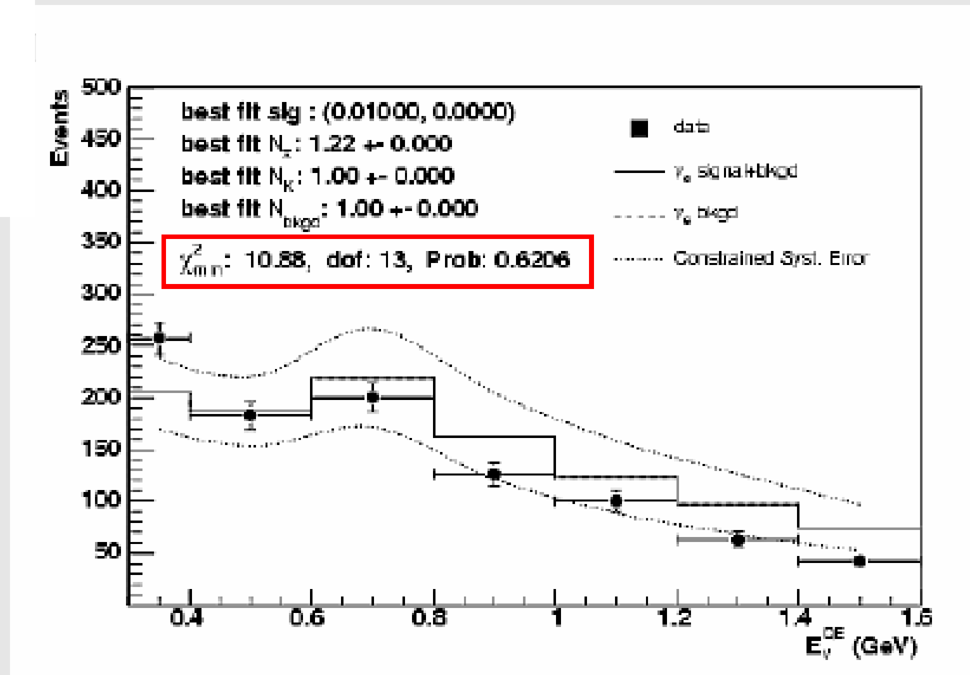
track-based analysis:

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

data: 380 events

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

significance: 0.55 σ



boosted decision tree analysis:

Counting Experiment: $300<E_\nu<1600$ MeV

data: 971 events

expectation: 1070 ±33 (stat) ± 225 (sys)

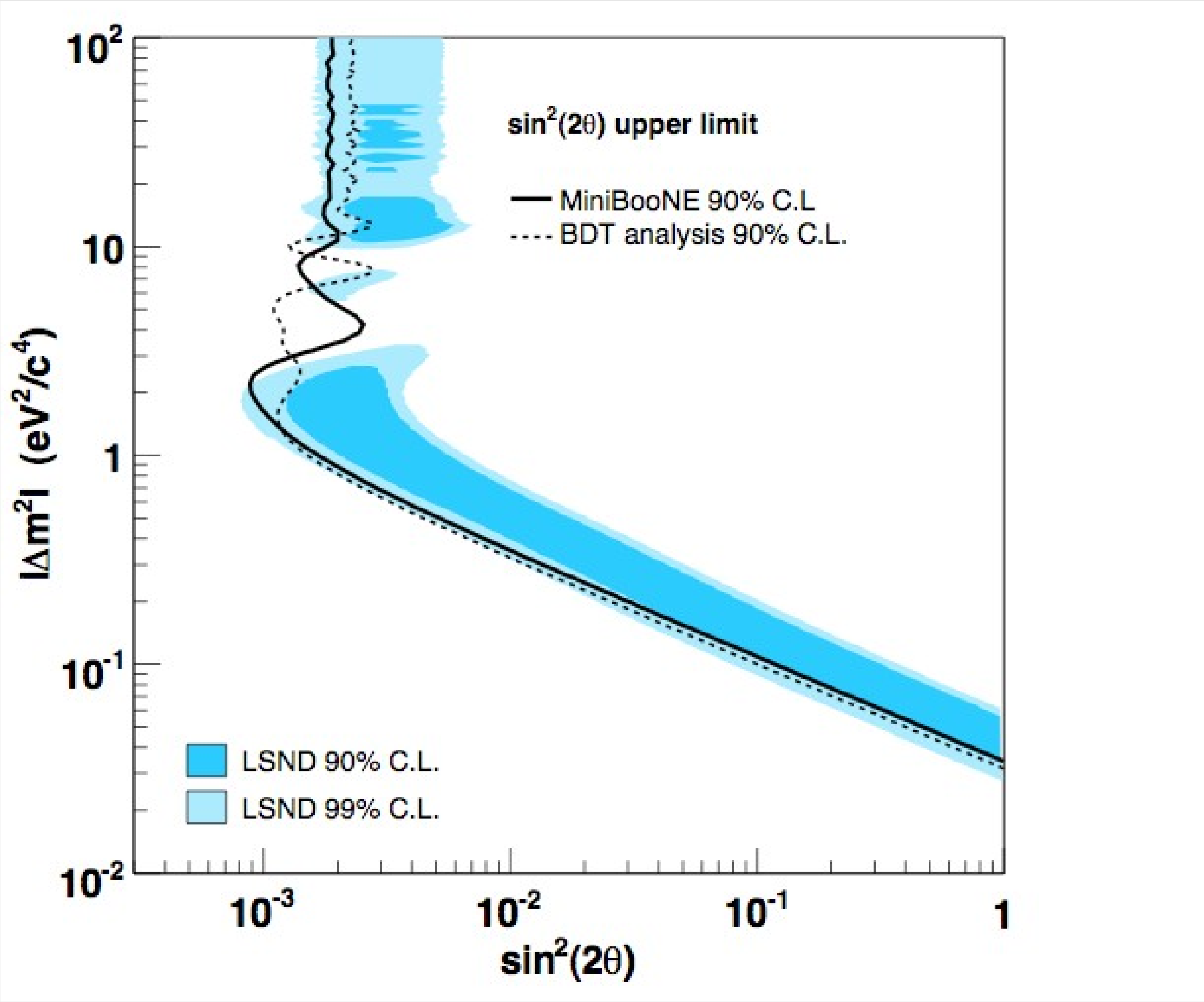
significance: –0.38 σ

Neither analysis shows evidence for
$\nu_\mu \rightarrow \nu_e$ appearance in the analysis region

oscillation analysis: results

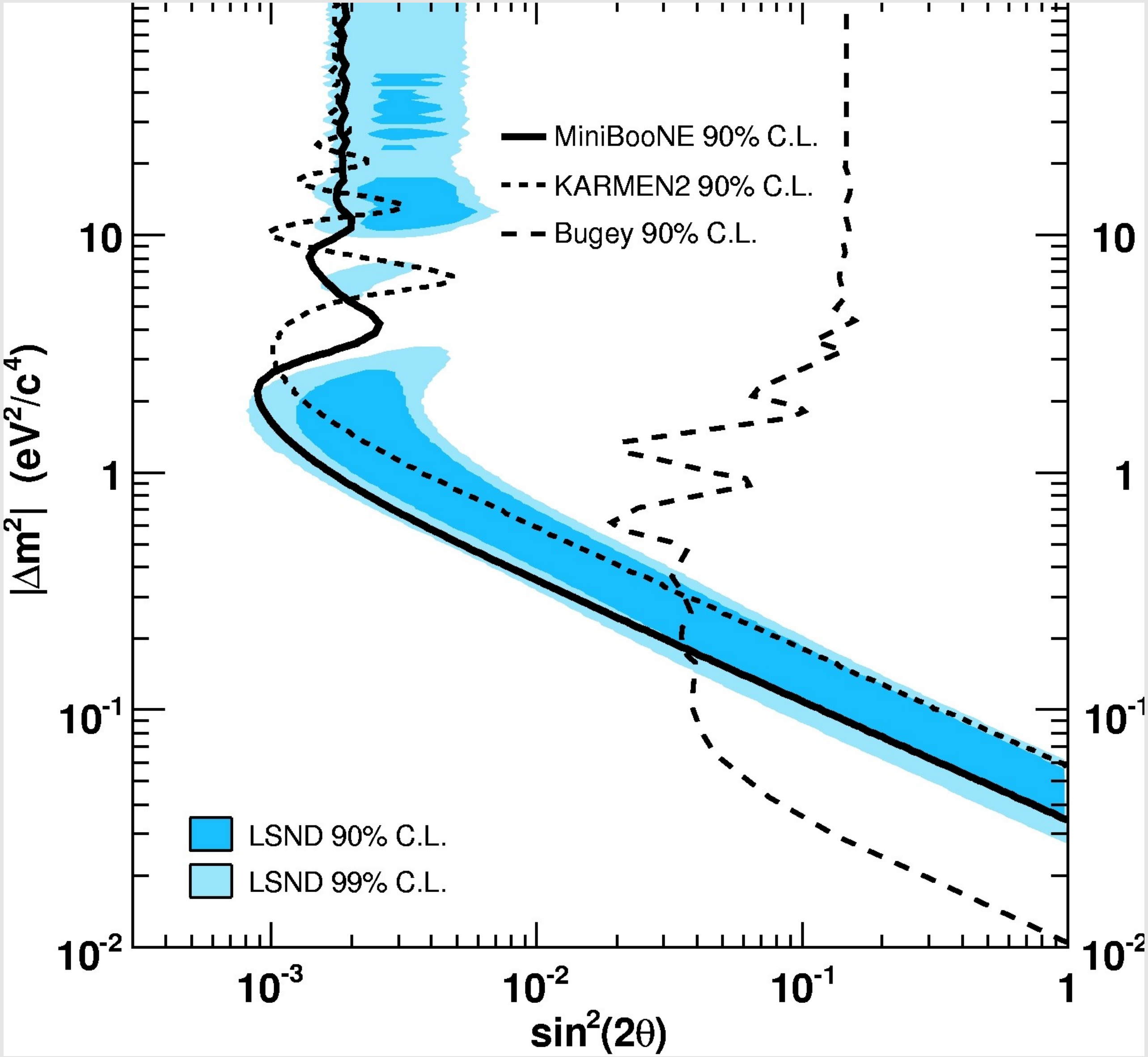
The results from the 2 different analyses are in agreement.

Resulting limit curves:
solid: primary,TB
dashed: BDT



oscillation analysis: results

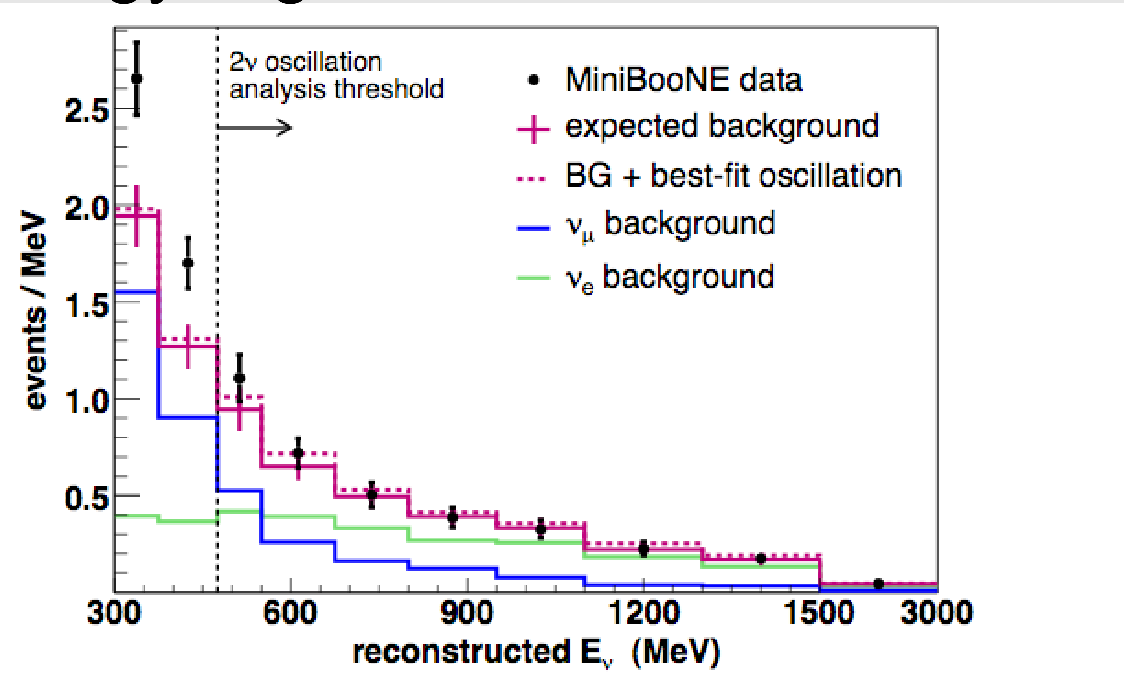
MiniBooNE limit curve together with those from KARMEN2 and Bugey experiments



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

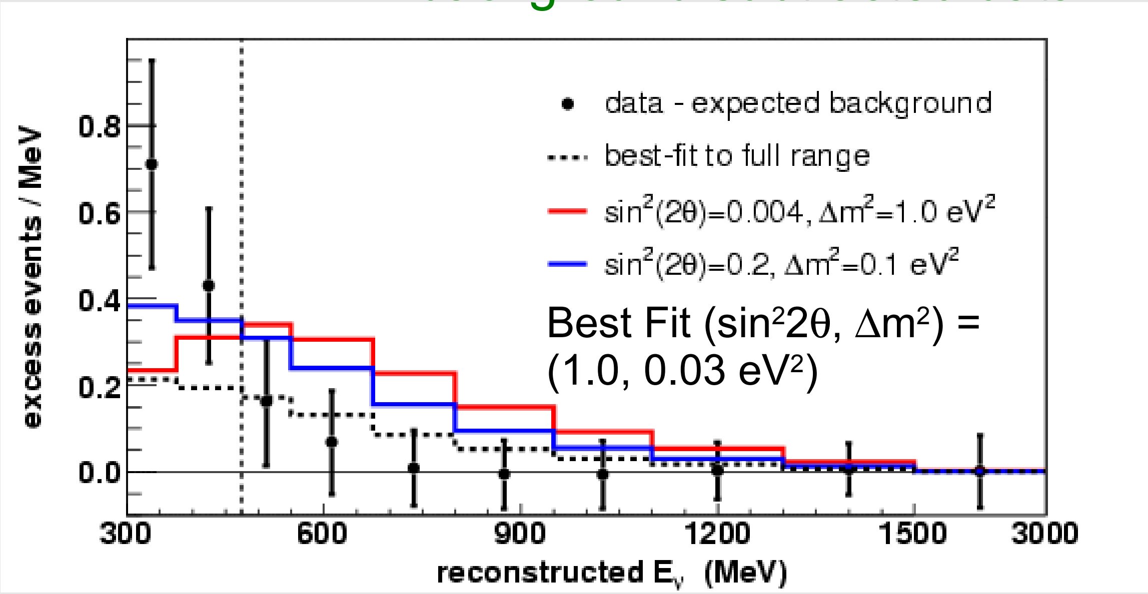
oscillation results: low-energy region

Track-based analysis
E_ν distributions:



For:
$300 < E_\nu < 475$ MeV
96 ± 17 ± 20 events
Excess: 3.7σ

background subtracted data:



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

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

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)

This work includes further tests for

- detector anomalies
- reconstruction problems
- incorrect estimation of calculated backgrounds
- new backgrounds (not considered in original analysis)
- new physics

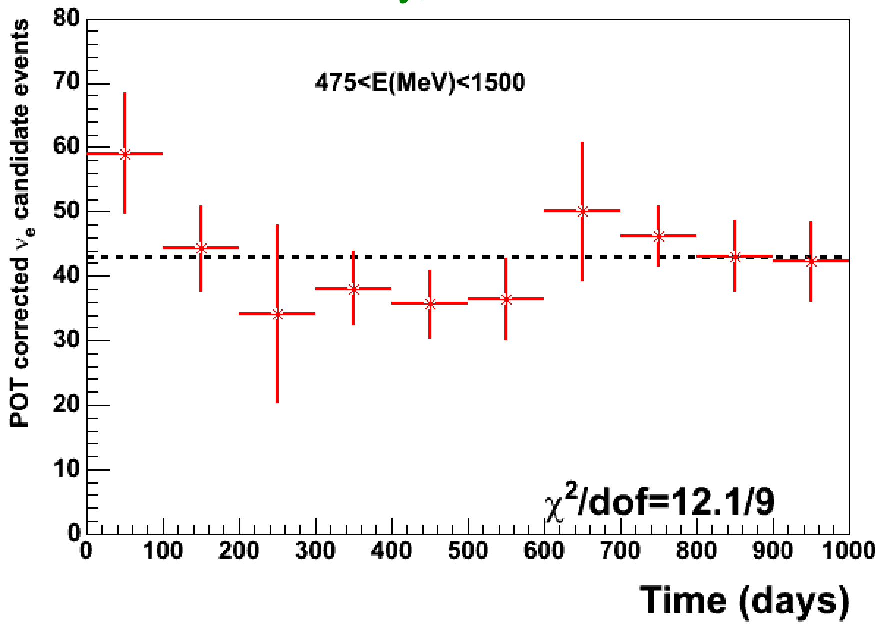
Note: If this is a background it may be relevant for other experiments searching for $\nu_\mu \rightarrow \nu_e$ appearance

MB low-energy events region

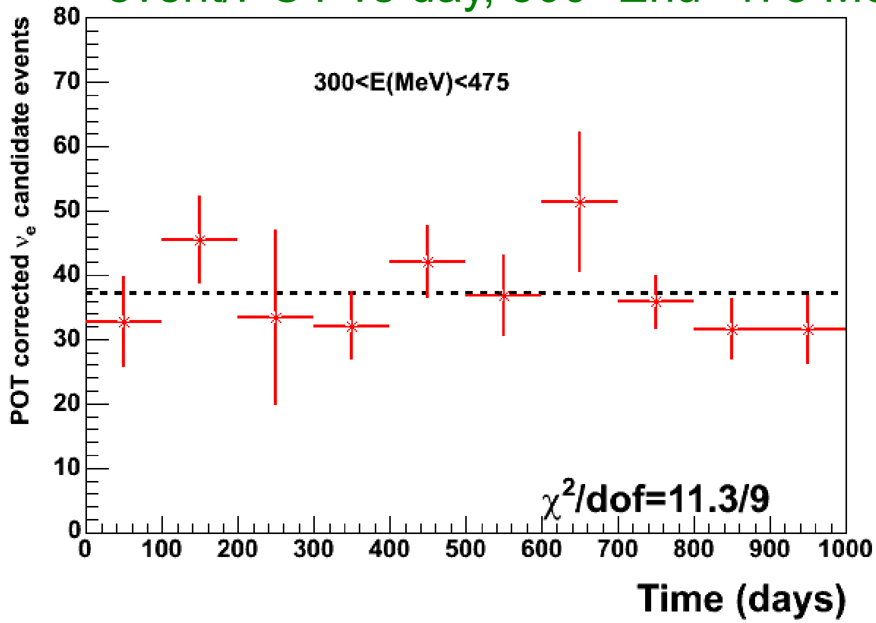
- Detector anomalies? - None found

- For example: rate of electron candidate events is constant (within errors) over course of run

event/POT vs day, 475<Enu<1500 MeV



event/POT vs day, 300<Enu<475 MeV

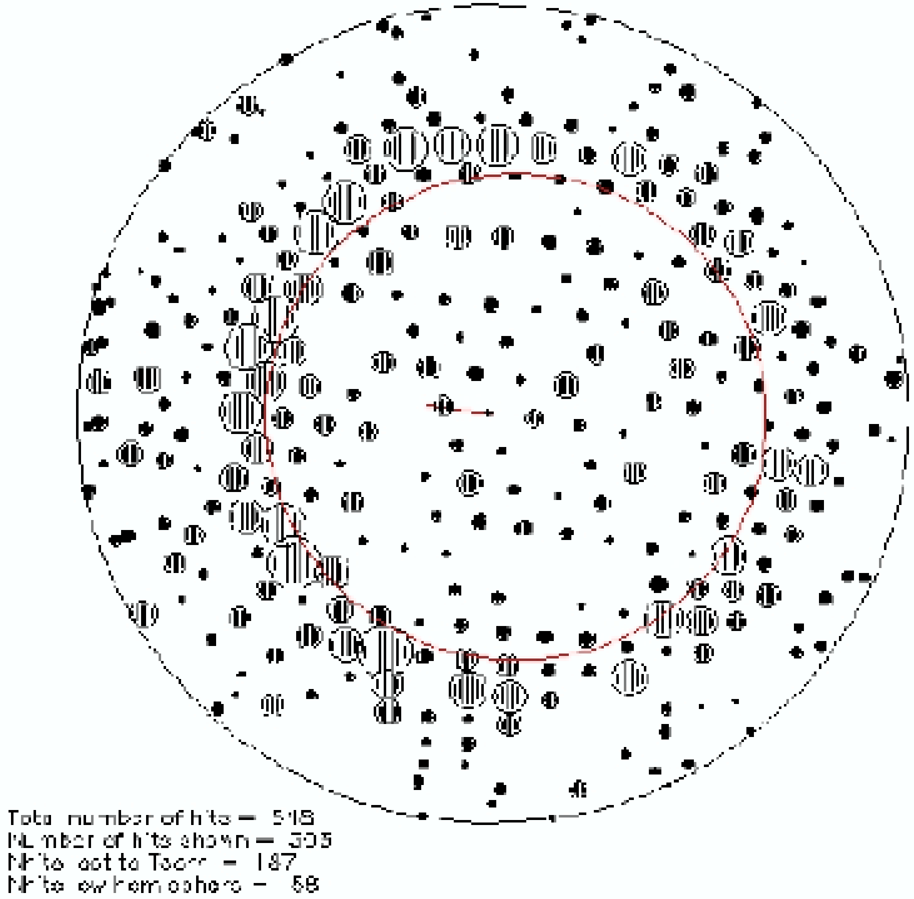


MB low-energy events region

- Reconstruction problems? - None found

- All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

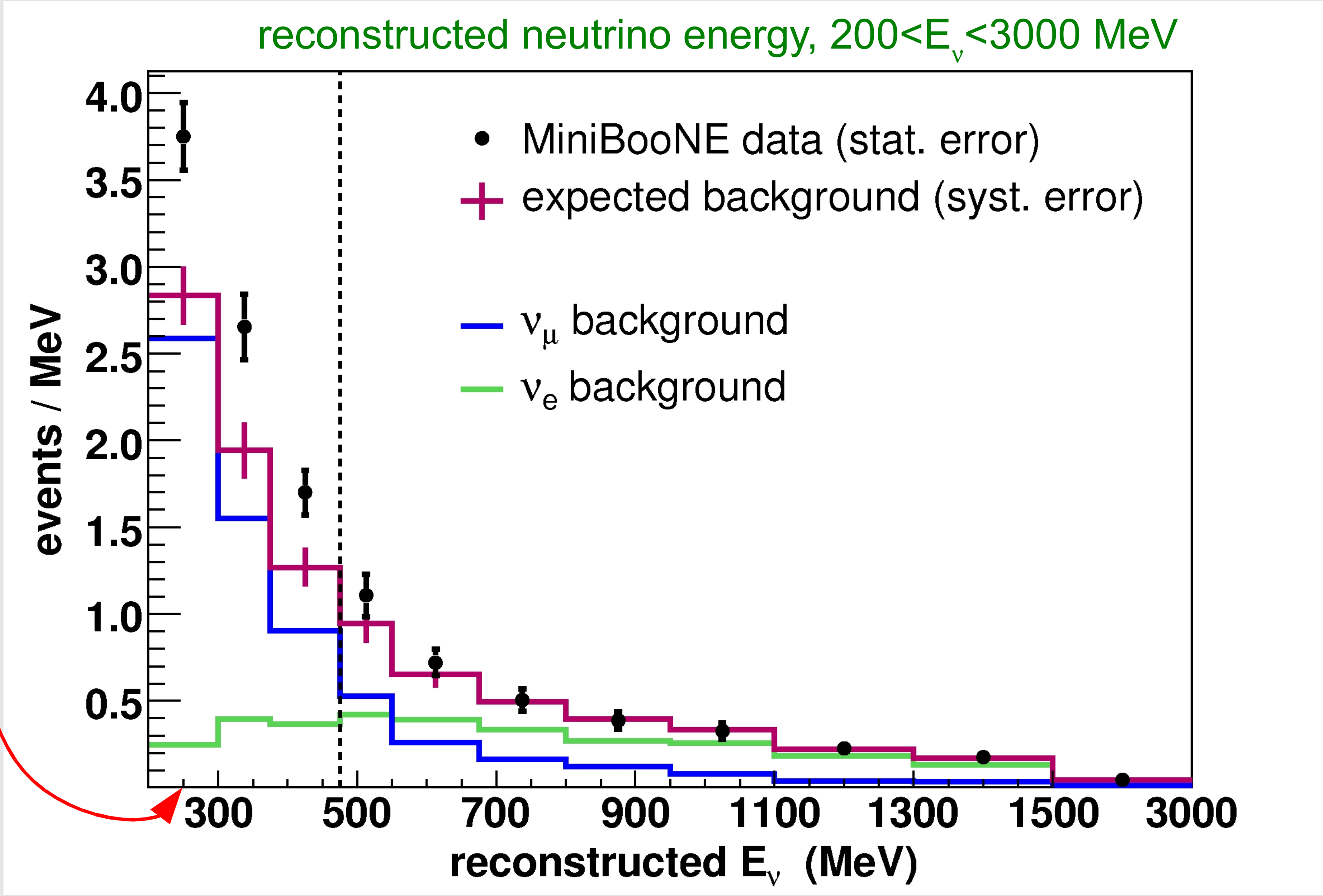
example osc-candidate event display



The "lower"-energy region

- examining lower energy
- excess persists in $200 < E_\nu < 300$ MeV bin

- NEW:
this energy bin



energy/angle distributions

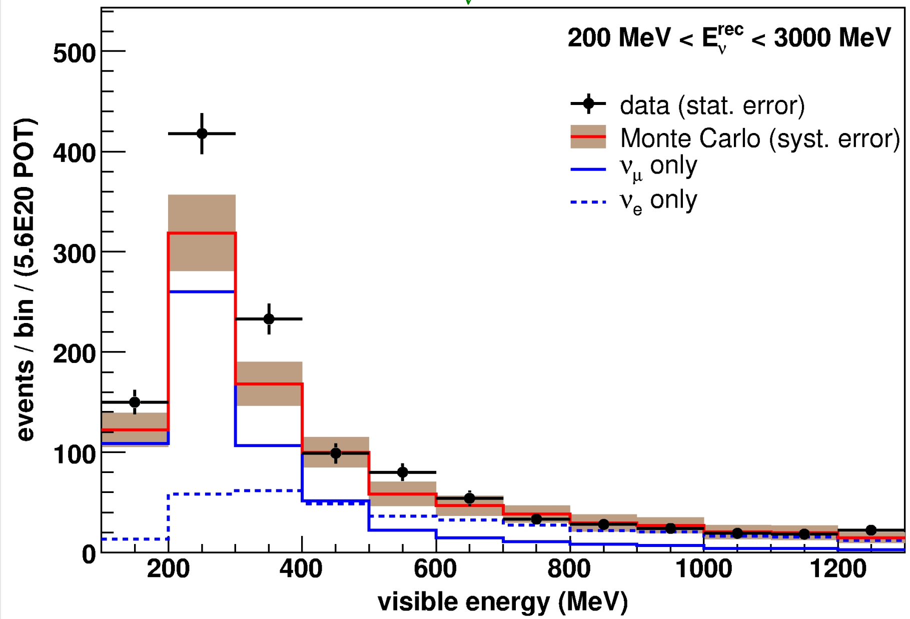
Recall:

- two-body kinematics allow ν energy reconstruction from E_lepton ("visible energy") and lepton angle

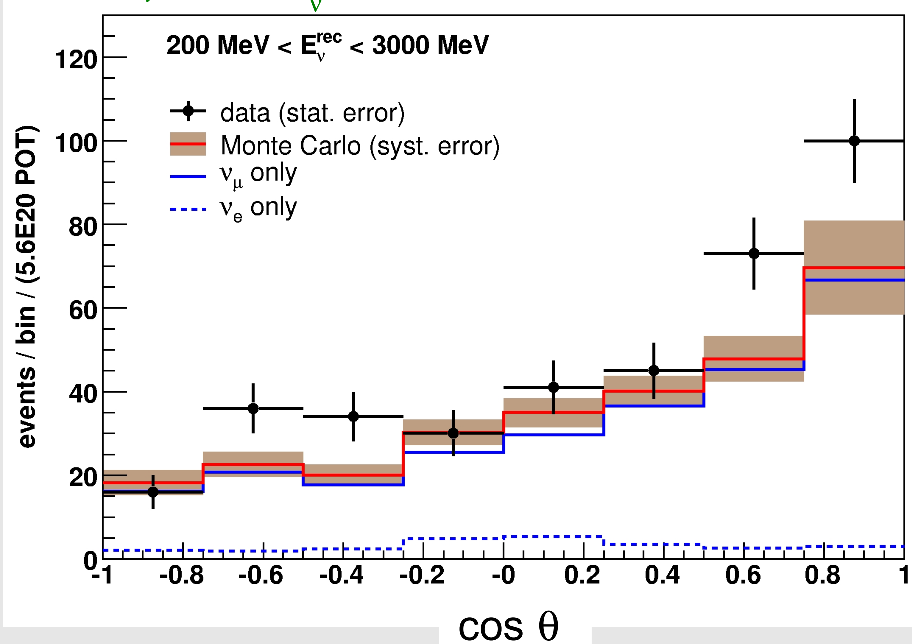
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

- no anomalies in these distributions

visible energy, $200<E_\nu<3000$ MeV



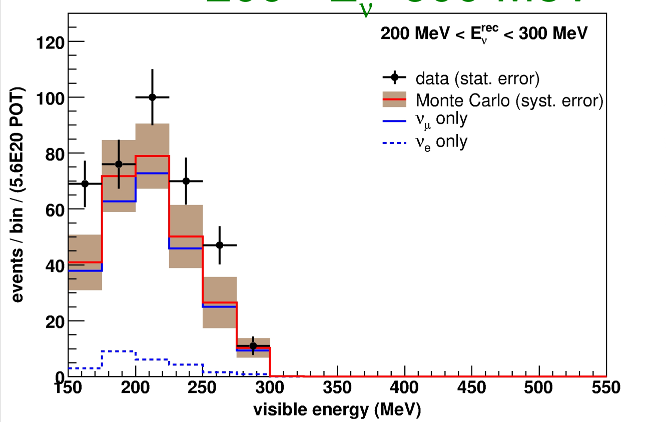
cos θ , $200<E_\nu<3000$ MeV



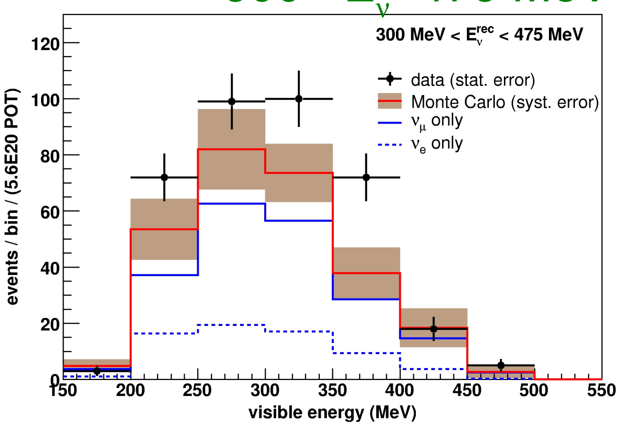
energy/angle distributions in E_ν bins

visible energy distributions:

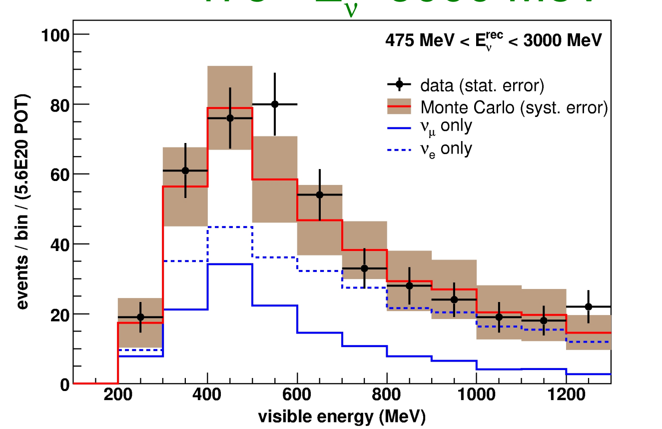
200< E_ν <300 MeV



300 < E_ν <475 MeV

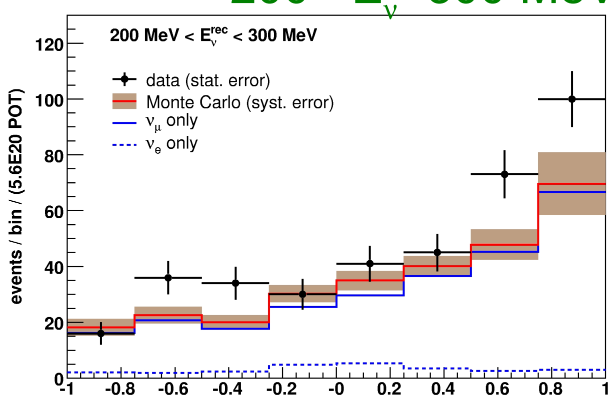


475 < E_ν <3000 MeV



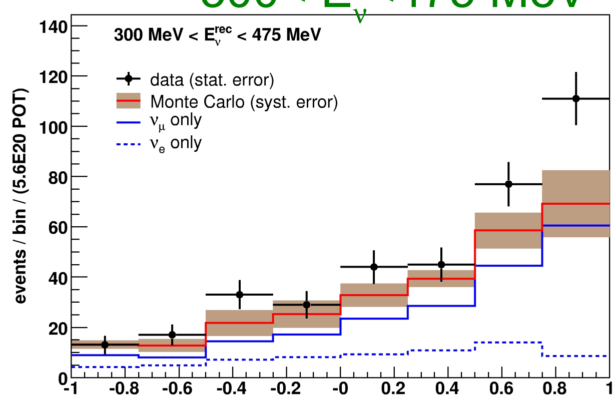
cos θ distributions:

200< E_ν <300 MeV



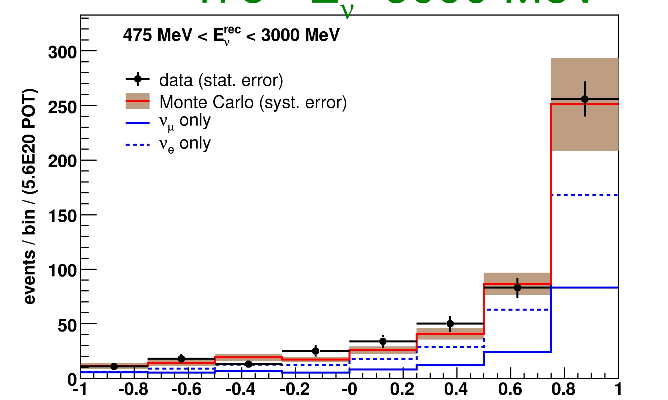
cos θ

300< E_ν <475 MeV



cos θ

475< E_ν <3000 MeV



cos θ

Excess distributed among visible E, cos θ bins

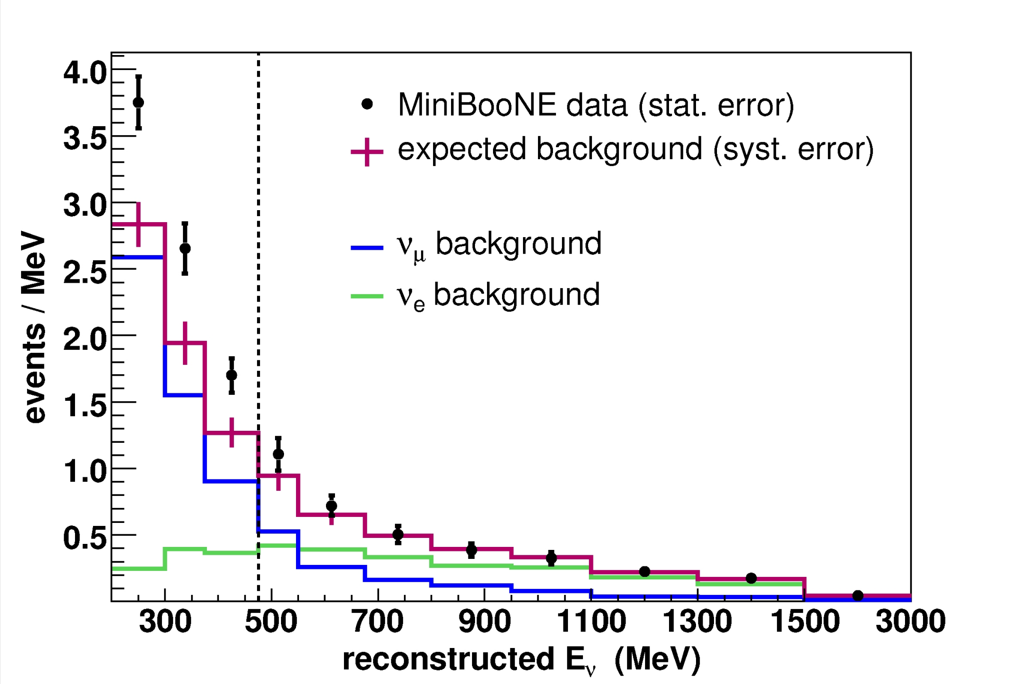
At higher energy, data are well-described by predicted background

Examination of backgrounds

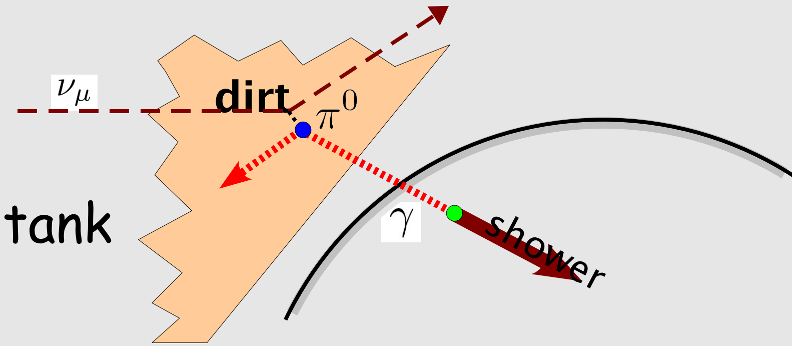
Oscillation candidate summary table:

	reconstructed neutrino energy bin (MeV) 200-300	300-475	475-1250
total background	284±25	274±21	358±35
ν_e intrinsic	26	67	229
ν_μ induced	258	207	129
NC π^0	115	76	62
NC $\Delta \rightarrow N\gamma$	20	51	20
Dirt	99	50	17
other	24	30	30
data	375±19	369±19	380±19

- no significant excess at higher E, where ν_e bkgd dominant
- largest backgrounds at lower E, are ν_μ-induced, in particular:
    - NC π^0
    - NC $\Delta \rightarrow N\gamma$
    - Dirt
- currently scrutinizing these backgrounds

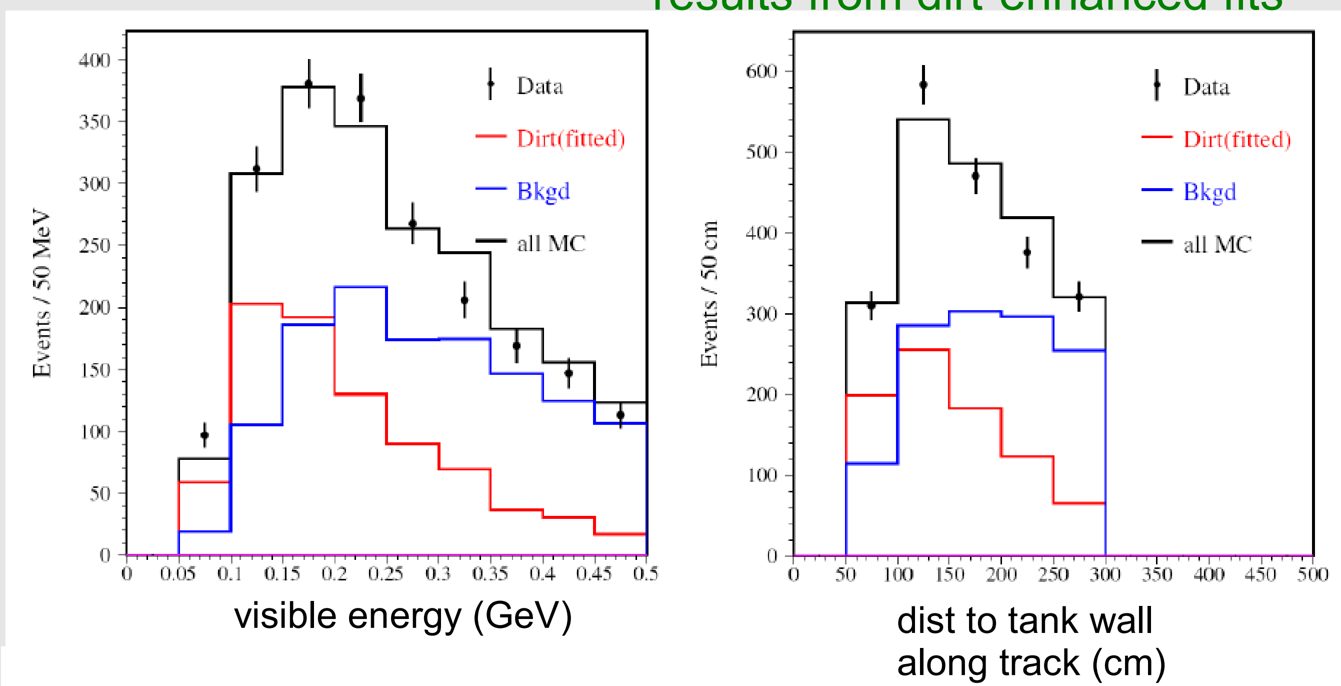


“Dirt” background



- dirt background is due to ν interactions outside detector creating neutrals that enter tank
- measured in “dirt-enhanced” samples:
  - before box-opening, fit predicted: 1.00±0.15
  - in different (open) sample, a fit says that meas/pred is 1.08+-0.12.
- shape of visible E and distance-to-wall distributions are well-described by MC

results from dirt-enhanced fits



Other background explanations

Work in progress to exhaustively check background explanation of excess. Reexamining these (previously estimated and measured!) processes:

- ν_μ-induced NC π^0
- ν_μ-induced NC $\Delta \rightarrow N\gamma$

In addition, new processes being considered:

- ν_μ-induced NC π^0 with photonuclear absorption of π^0 photon
- ν_μ-induced NC photon production (eg: arXiv:0708.1281v1 [hep-ph])

Other data sets in will be available to check signal vs background hypotheses

- ν_e $CC\pi^+$ channel for oscillations
- antineutrinos, taking data since Jan'06
- recently commissioned SciBooNE experiment
- NuMI neutrinos in MB (very soon!)

Summary

- MiniBooNE rules out (to 98%CL) the LSND result interpreted as $\nu_\mu \to \nu_e$ 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:

- $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations with (w/"standard" assumptions of CPT, E-dependence)
- $\bar{\nu}_\mu \to \bar{\nu}_e$ 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*

*e.g.: Sterile neutrinos, *hep-ph/0305255, Phys.Rev.D75:013011,2007.*
Neutrino decay, *hep-ph/0602083, J.Phys.Conf.Ser.39:307-309,2006.*
Extra dimensions, *hep-ph/0504096, Phys.Rev.D72:095017,2005.*
Lorentz Violation: *hep-ph/0606154, Phys.Rev.D74:105009,2006.* ...