Results from MiniBooNE

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for the MiniBooNE Collaboration

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Les Rencontres de Physique de la Vallée d'Aoste

Outline

The MiniBooNE Collaboration

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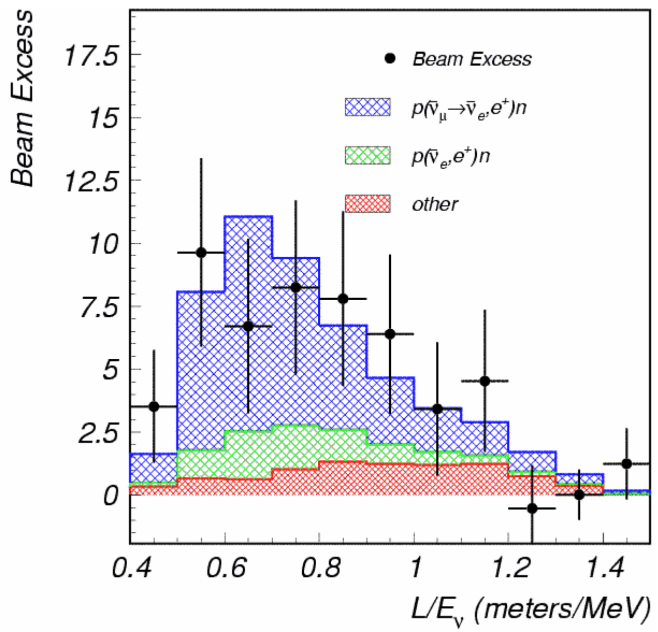
Indiana University

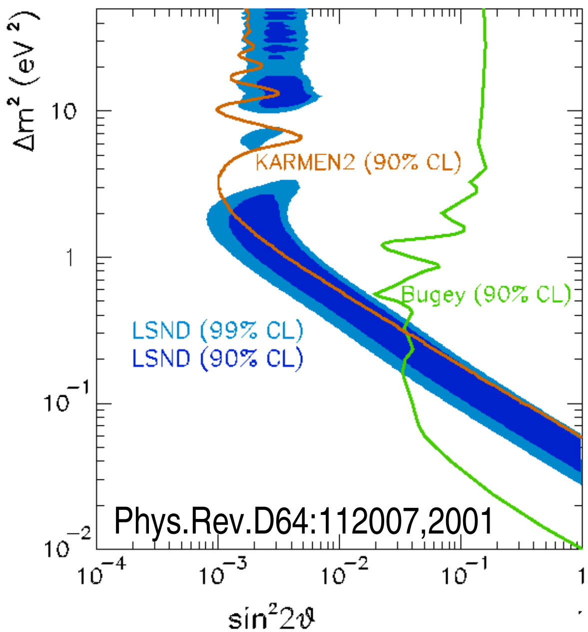
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

MiniBooNE was Prompted by the Positive LSND Result

LSND observed a (~3.8σ) excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam: 87.9 ± 22.4 ± 6.0 events

Oscillation probability $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$





The Karmen Exp. did not confirm the LSND oscillations but had a smaller distance.

LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν's.

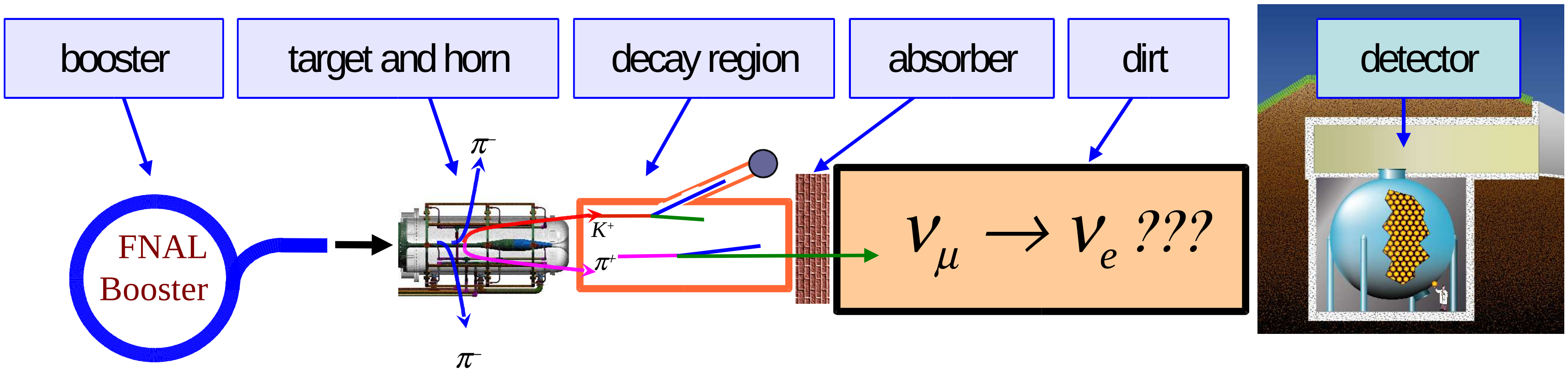
⇒ Models developed with 2 sterile ν's

or

Maybe one of the experiments is wrong.

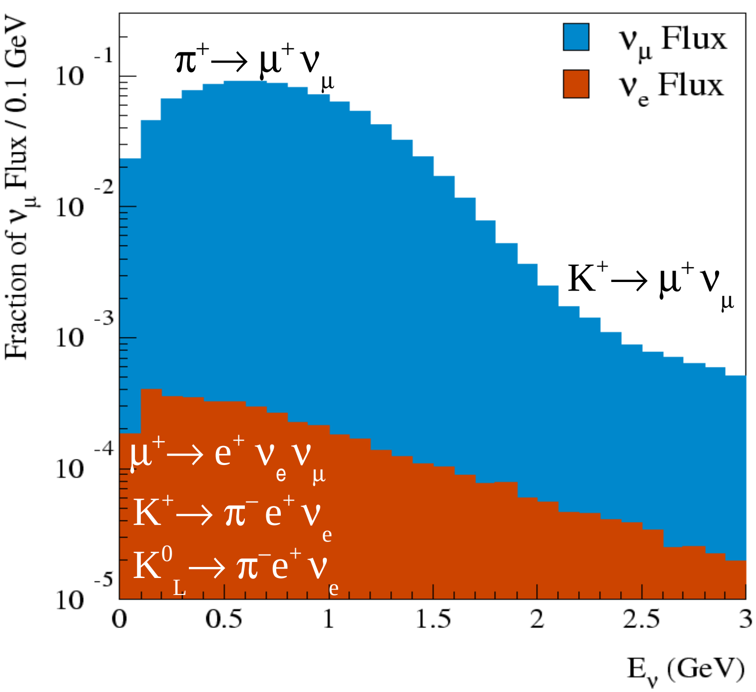
MiniBooNE's task:
Confirm or refute LSND.

The MiniBooNE Experiment



Look for $\nu_\mu \to \nu_e$ oscillations in the LSND region with different systematics

- Longer baseline: L ~ 500 m
- Higher ν energy: E ~ 600 MeV



Detector:

Sphere (D=12 m) filled with mineral oil, lined with PMTs.
Optically isolated veto, instrumented with PMTs.

Detector requirements:

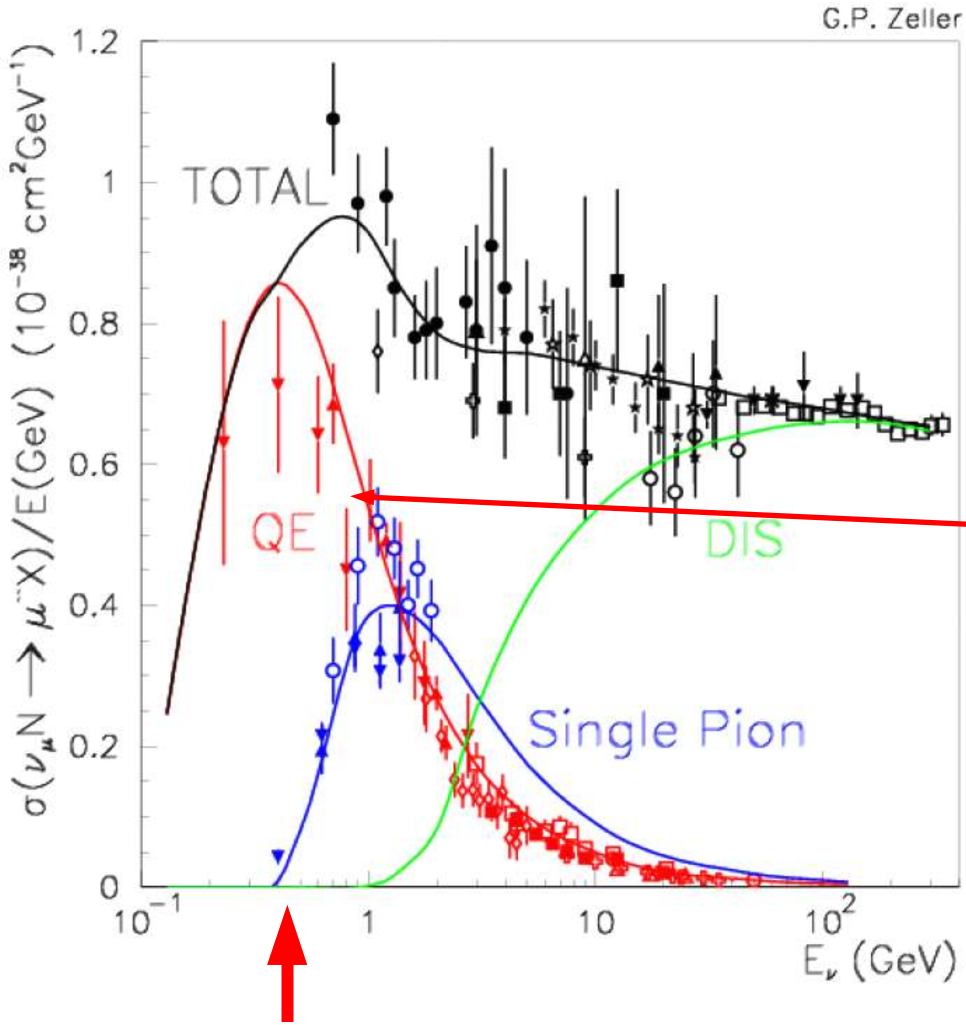
-Reconstruct events: *x,y,z,t, E,* etc.

- Able to distinguish ν_μ from ν_e

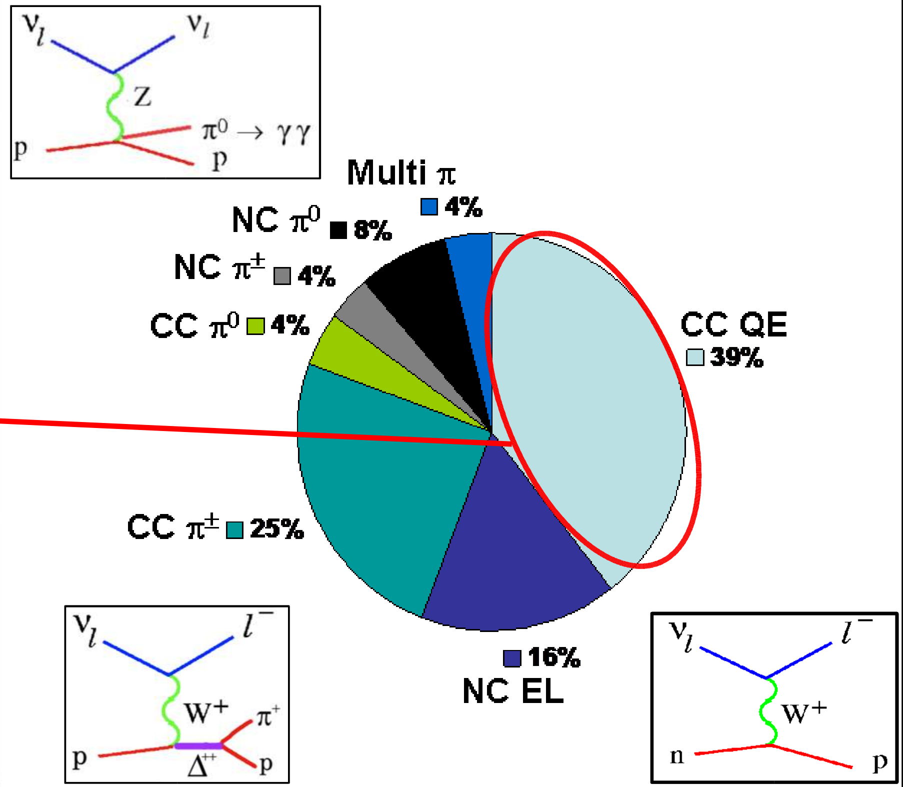
$\Rightarrow \nu_e / \nu_\mu \approx$ **0.5%**

Look for ν_e excess over expectations.

Neutrino Interactions

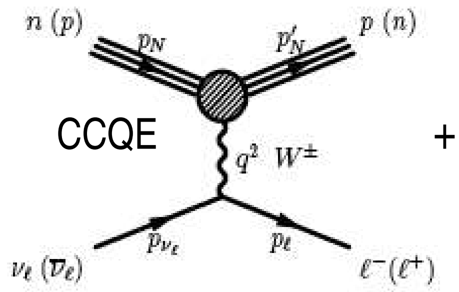


MiniBooNE typical ν energy

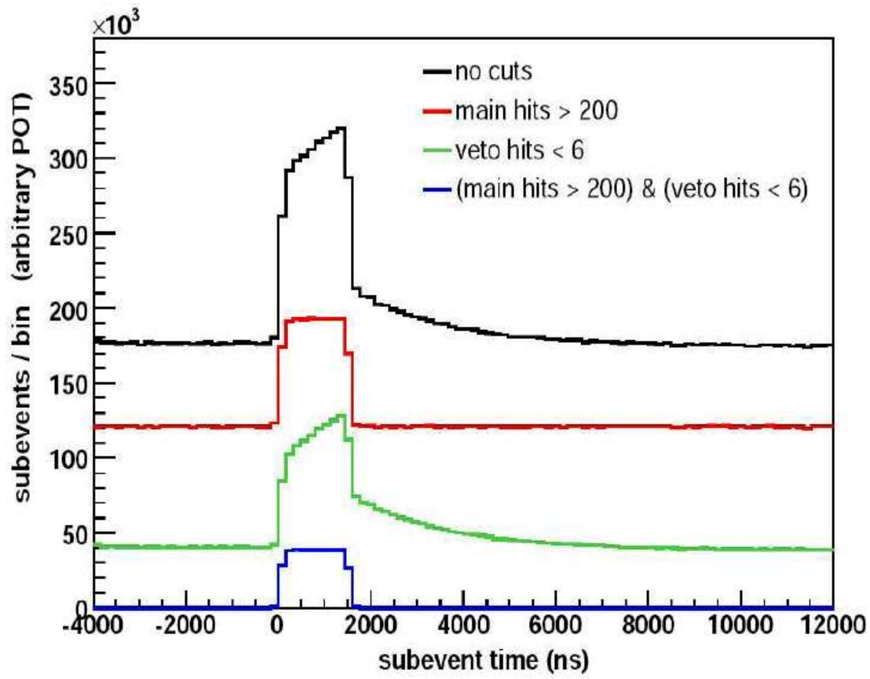


ν events in the detector

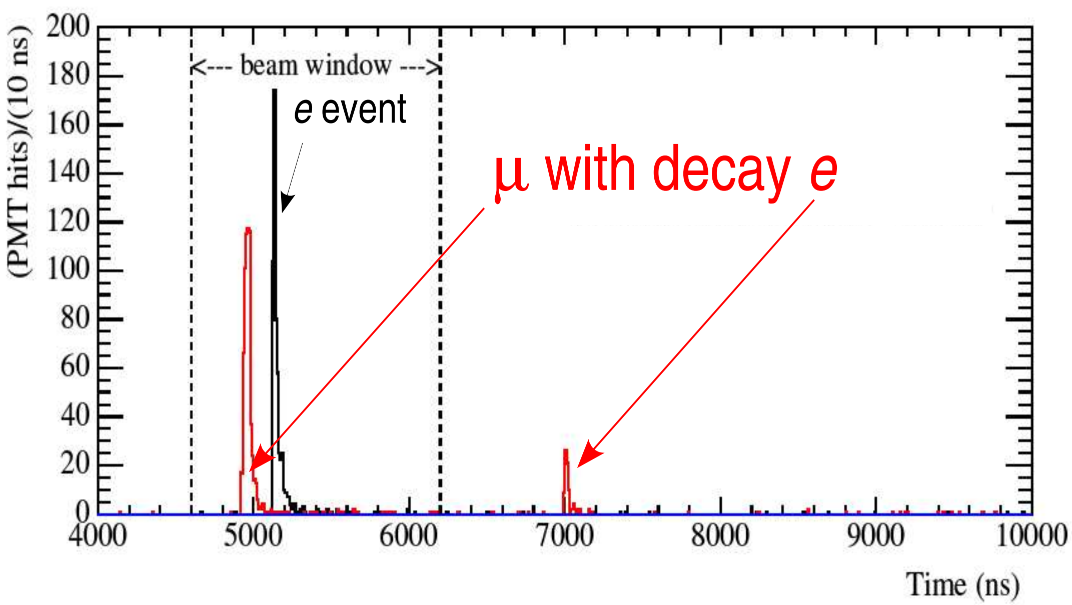
- Cosmic μ rejected with low veto activity cut.
- Exponential decay: *e* from μ decay: Rejected with minimum tank hits cut.



+ Others ...



Sub-events:

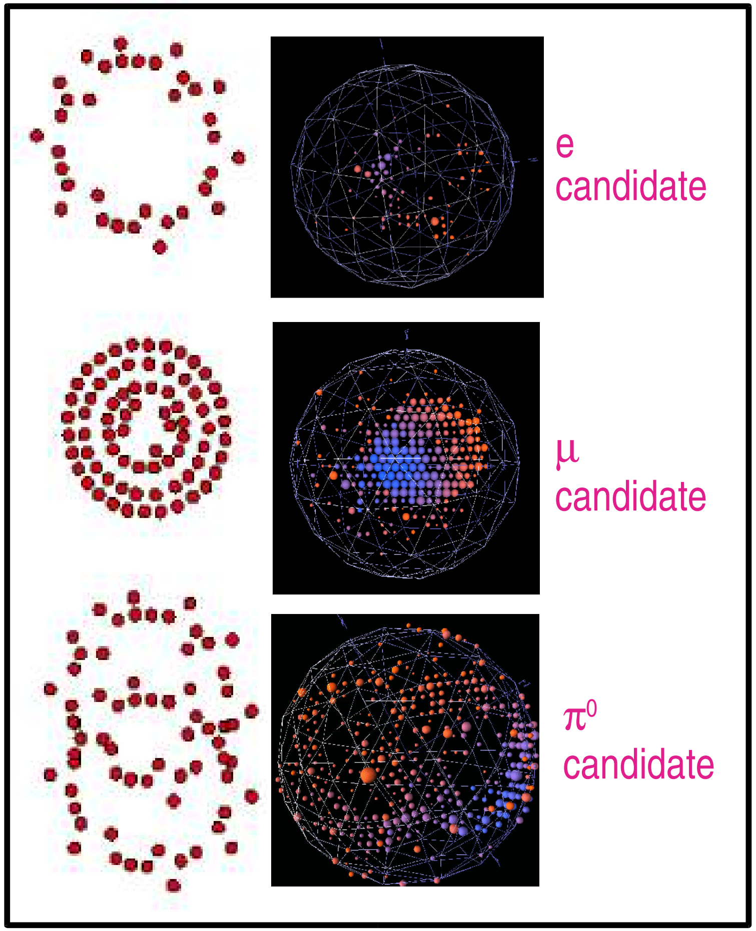


- μ from ν_μ CCQE interactions have typically two sub-events.
- ν_e CCQE interactions, typically one sub-event.

Particle ID Algorithms

- Identify ν_μ from delayed μ-decay electron signature (92% non-capture probability)

- Identify events using
  - hit topology



- PID Variables
  - Reconstructed physical observables
    - Track length, particle production angle relative to beam direction
  - Auxiliary quantities
    - Timing, charge related : early/prompt/late hit fractions, charge likelihood
  - Geometric quantities
    - Distance to wall

- Two PID algorithms used for Oscillation Analyses:
  1. *A **Likelihood*** based analysis: e/μ and e/π^0
  2. A "***boosted decision tree***" algorithm to separate e, μ, π^0 *(See B. Roe et al. NIM A543 (2005))*

Structure of oscillations analysis

1. Use meson production data to determine the ν flux (target simulated in GEANT4)

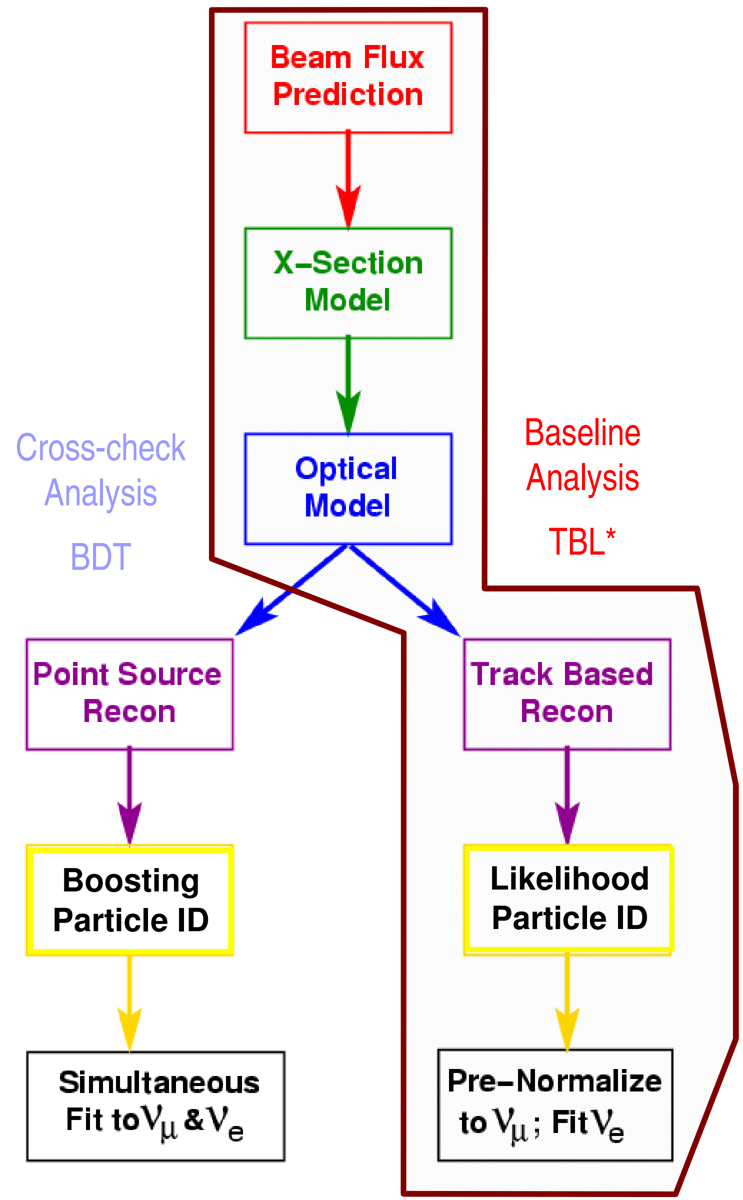
2. Use NUANCE cross-section model to predict ν interaction rates and final states

3. Final state particles are passed to a GEANT3 simulation of the detector to model particle and light propagation in the tank

4. Starting with event reconstruction, two independent analyses follow:
   (1) Track Based Likelihood (TBL*)
   (2) Boosted Decision Tree (BDT)

5. Develop particle-ID cuts to separate signal from background

6. Fit reconstructed E_ν^{QE} distribution in the data for 2ν oscillations



Oscillation Signal
$\Rightarrow$ An Excess of "ν_e" Events over Expectation

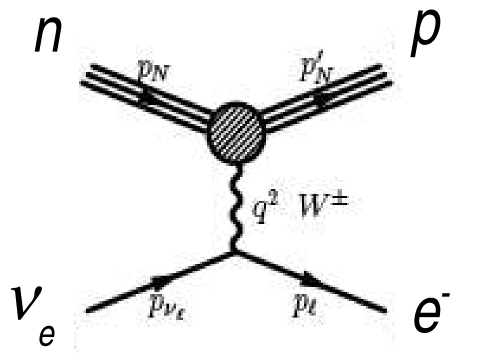
All the major backgrounds for the oscillation search can be constrained directly from measurements using MiniBooNE data

- **NC π production:**
  Largest mis-ID background, where one of the decay photons is missed. Rate constrained from dedicated NC π sample. Also constrains radiative Δ decays: $\Delta \rightarrow N\gamma$.
- **External events (Dirt):**
  Backgrounds from interactions with material outside of the detector. Rate constrained from dedicated sample.
- **Intrinsic kaon decay ν_e's:**
  Partially constrained by observed ν_e events at high energy where there are no oscillation events.
- **Intrinsic muon decay ν_e's:**
  Largest intrinsic ν_e background. Highly constrained by the observed ν_μ events. The constraint can applied by using the combined ν_e/ ν_μ oscillation fit.

BDT and TBL ν_e sample pre-selection:

Similar for the two oscillations analyses: **BDT** and **TBL**.

We ultimately want to isolate ν_e CCQE events: $\nu_e + n \rightarrow p + e^-$

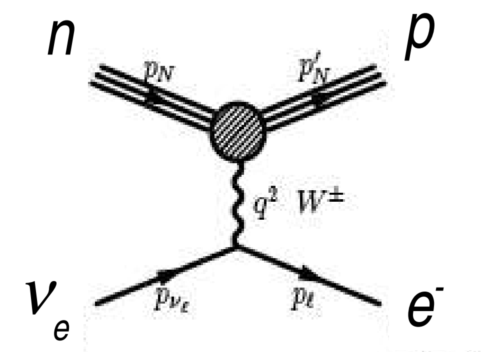


Veto hits < 6 Tank hits > 200	Reject cosmic μ, Michel decay *e*.
Only 1 sub-event	Keep electron-like events.
Radius < 500 cm	Fiducial volume (algorithm dependent).

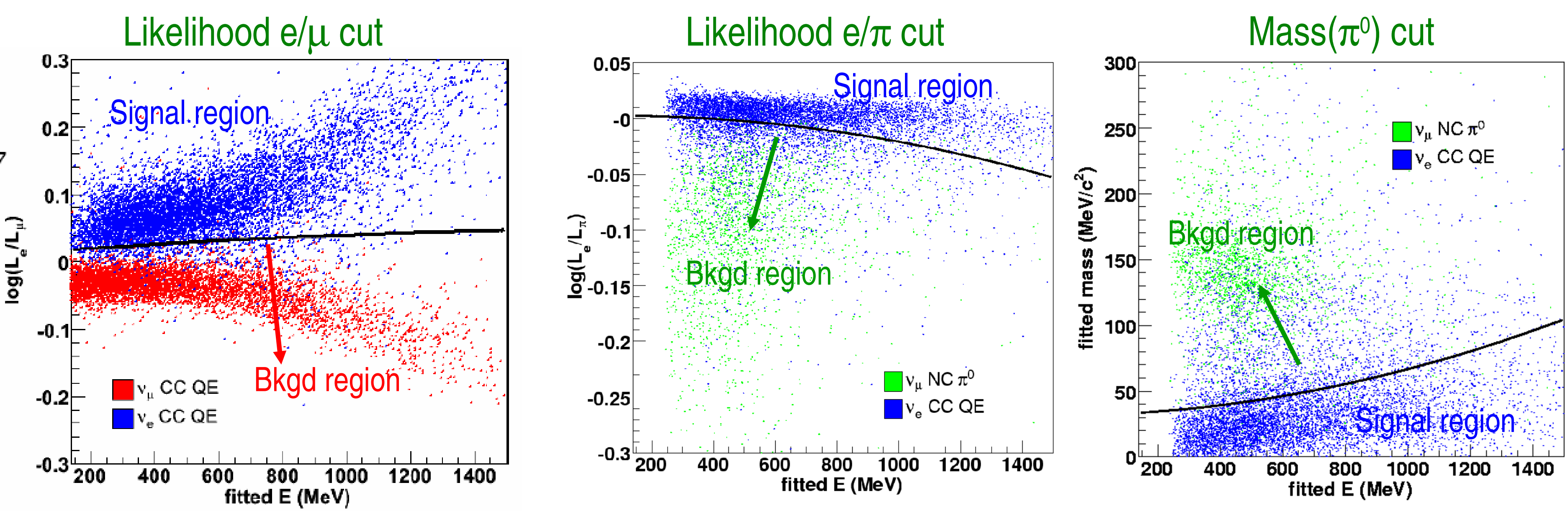
TBL Analysis: Cuts Used to Separate ν_μ events from ν_e events

Fit the observed light distributions to three hypotheses:

Use the fit likelihoods as discriminators:
- single electron track L_e
- single muon track L_μ
- two electron-like rings (π^0 event hypothesis) L_π, and M_π



Combine three cuts to accomplish the separation: $L_{e\mu}$, $L_{e\pi}$, and 2-track mass



Blue points are signal ν_e events

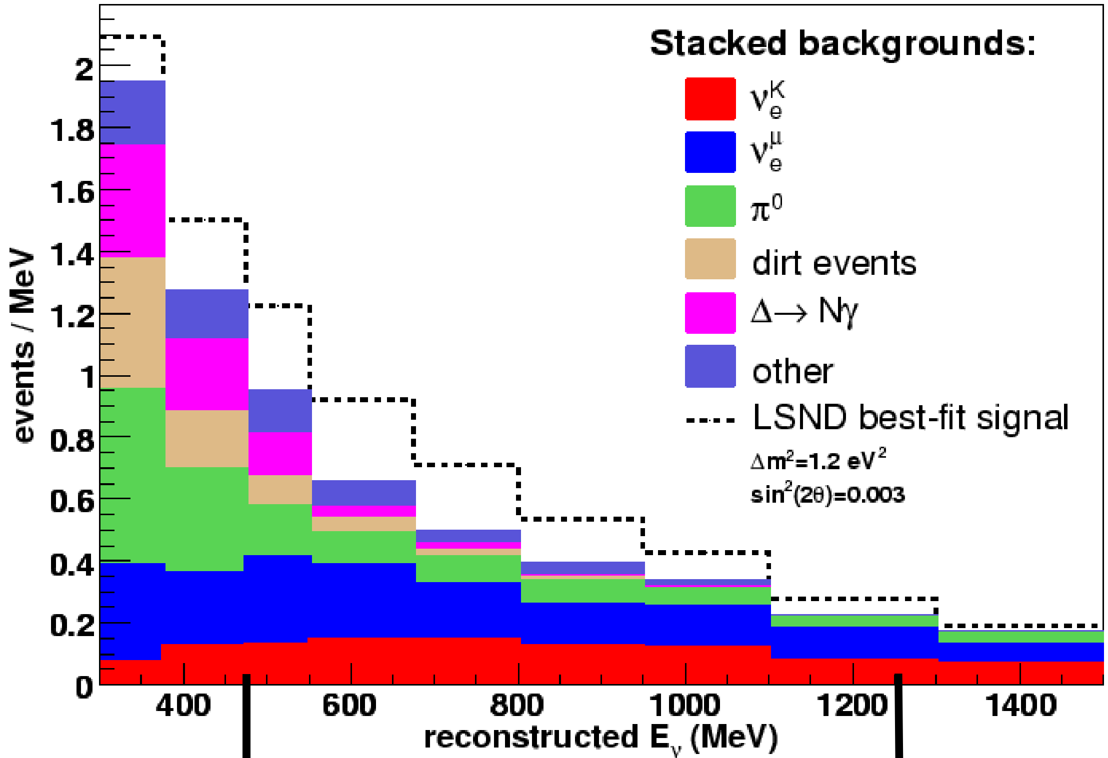
Red points are background ν_μCC QE events

Green points are background ν_μ NC π^0 events

TBL Analysis: expected events

Using the graphical cuts shown in previous slides, select ν_e candidate sample

Composition shown below:



Counting experiment range

Counting experiment

475 MeV – 1250 MeV	
ν_e^K	94 ± 27
ν_e^μ	132 ±10
NC π^0	62 ±10
Dirt	17 ± 3
$\Delta \rightarrow N\gamma$	20 ± 4
Other	33 ± 6
Total	358 ± 35
LSND best fit $\nu_\mu \rightarrow \nu_e$	126 ± 21

Sig/√Bkgd = 6.8

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

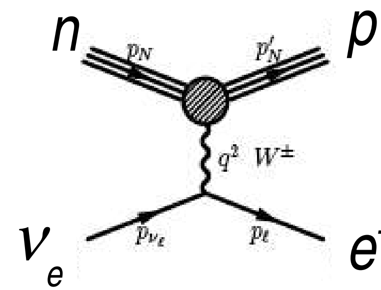
Systematic uncertainties -TBL based-

Source of uncertainty on ν_e background	TBL Uncertainty (%)
Flux from $\pi^+/\mu+$ decay	6.2
Flux from K^+ decay	3.3
Flux from K^0_L decay	1.5
Target and beam models	2.8
ν-cross sections	12.3
NC π^0 yield	1.8
External interactions ("Dirt")	0.8
Optical model	6.1
DAQ electronics model	7.5
Constrained Total *	9.6

* Total is not the quadrature sum. Errors are further constrained from ν_μ data.

ν_μ and ν_e data use consistent track-based reconstruction and energy estimator.

BDT specific ν_e selection cuts:



Decision tree: Sequential series of cuts based on a MC study.

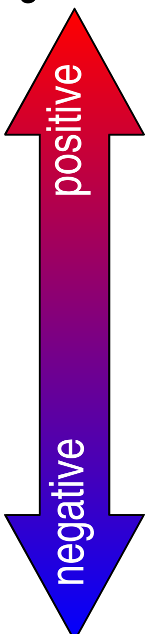
Boosted Decision Tree:

Weight of misclassified events is increased to find a new set of sequential cuts.

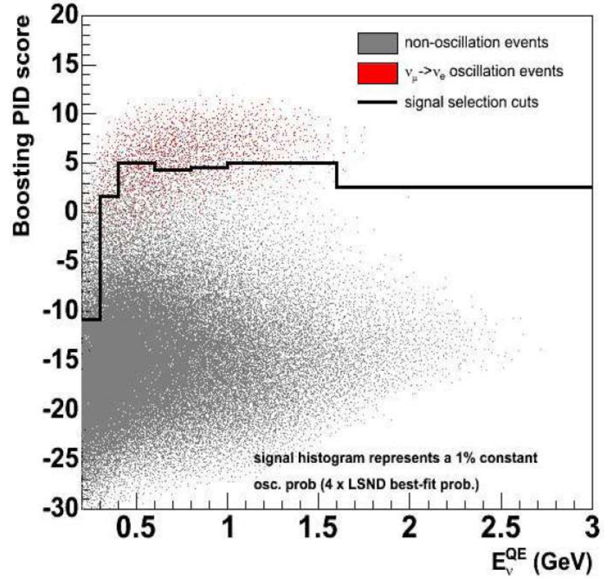
Make many decision trees,
each re-weighting the events to enhance identification of backgrounds misidentified by earlier trees **("boosting").**

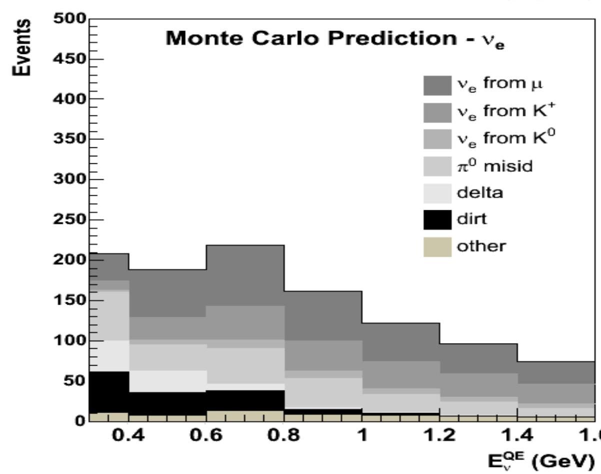
For each tree, the data event is assigned
+1 if it is identified as signal,
-1 if it is identified as background.
The sum from all trees is combined into a "**score**".

signal-like



Background -like

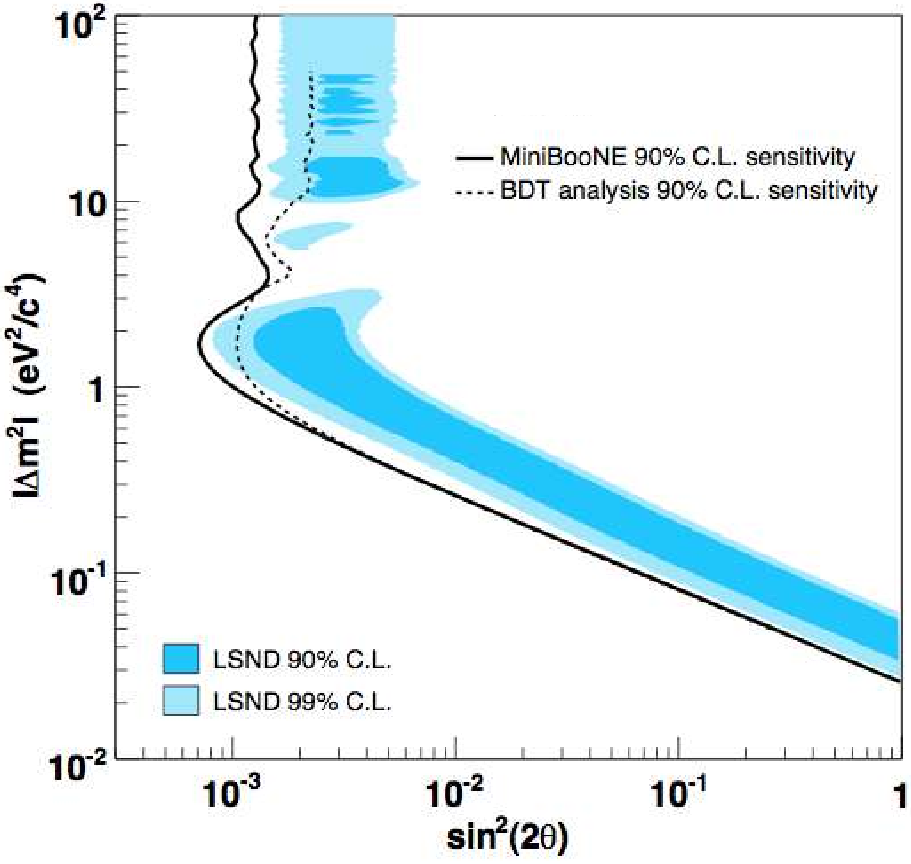




The BDT cut as a function of E_ν^{QE} is optimized to give maximum sensitivity to oscillations.

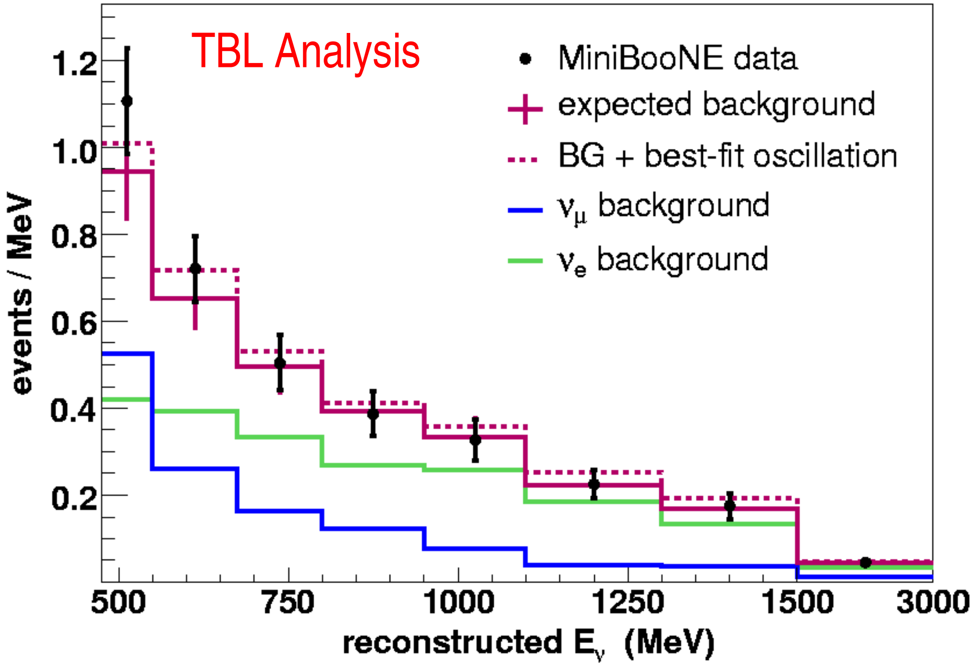
Comparing the sensitivities: BDT vs TBL

Determined from simulation only



- TBL analysis (solid) has higher sensitivity. **Chosen as the primary analysis on this basis**
- Decision made previous to un-blinding
- 90% C.L. determined with $\Delta\chi^2 = 1.64$

MiniBooNE First Results (April, 2007)



Oscillation Search Region
$475 < E_\nu < 1250$ MeV

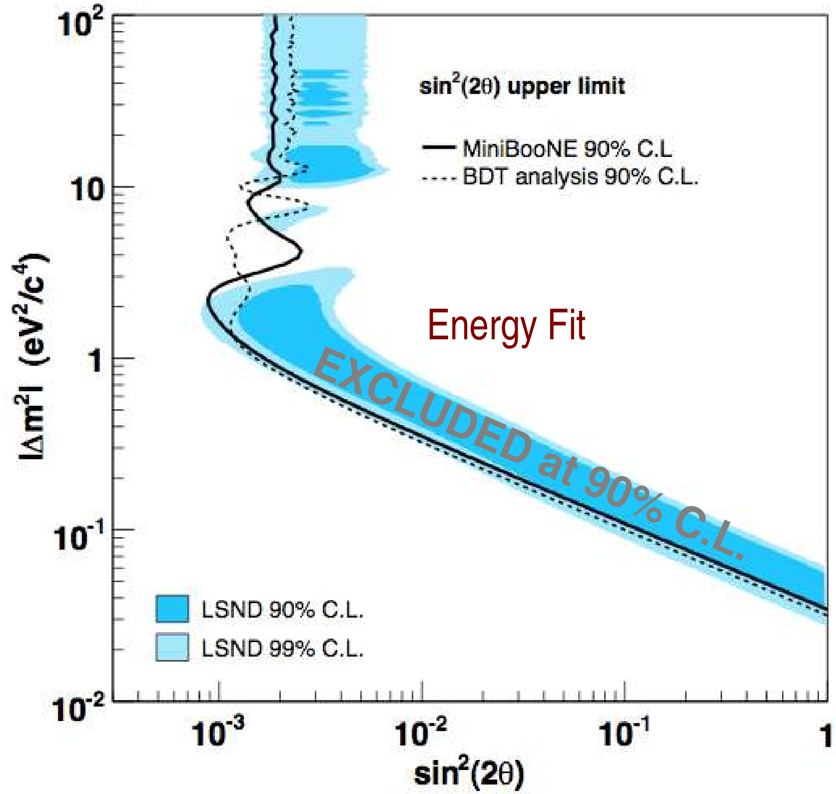
data: 380 ± 19 (stat) events
expectation: 358 ± 35 (sys) events
significance: 0.55 σ

Best Fit (dashed):
$(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ eV^2)$

Probability of Null Fit: 93%
Probability of Best Fit: 99%

Data consistent with expected background
$\Rightarrow$ Inconsistent with a $\nu_\mu \rightarrow \nu_e$ oscillations

Exclude region in parameter space:



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

A Combined ν_eBDT, ν_eTBL, ν_μCCQE Oscillations Fit

Do oscillation fit to the observed and ν_eBDT, ν_eTBL, and ν_μCCQE energy distributions by minimizing the following χ^2 statistic:

$$\chi^2 = \begin{pmatrix} \Delta_i^{\nu_e \mathrm{BDT}} & \Delta_i^{\nu_e \mathrm{TBL}} & \Delta_i^{\nu_\mu \mathrm{CCQE}} \end{pmatrix} \begin{pmatrix} M_{ij}^{\nu_e \mathrm{BDT}, \nu_e \mathrm{BDT}} & M_{ij}^{\nu_e \mathrm{BDT}, \nu_e \mathrm{TBL}} & M_{ij}^{\nu_e \mathrm{BDT}, \nu_\mu \mathrm{CCQE}} \\ M_{ij}^{\nu_e \mathrm{TBL}, \nu_e \mathrm{BDT}} & M_{ij}^{\nu_e \mathrm{TBL}, \nu_e \mathrm{TBL}} & M_{ij}^{\nu_e \mathrm{TBL}, \nu_\mu \mathrm{CCQE}} \\ M_{ij}^{\nu_\mu \mathrm{CCQE}, \nu_e \mathrm{BDT}} & M_{ij}^{\nu_\mu \mathrm{CCQE}, \nu_e \mathrm{TBL}} & M_{ij}^{\nu_\mu \mathrm{CCQE}, \nu_\mu \mathrm{CCQE}} \end{pmatrix}^{-1} \begin{pmatrix} \Delta_j^{\nu_e \mathrm{BDT}} \\ \Delta_j^{\nu_e \mathrm{TBL}} \\ \Delta_j^{\nu_\mu \mathrm{CCQE}} \end{pmatrix}$$

where $\Delta_i^{\nu_e \mathrm{BDT/TBL}} = \mathrm{Data}_i^{\nu_e \mathrm{BDT/TBL}} - \mathrm{Pred}_i^{\nu_e \mathrm{BDT/TBL}}(\Delta m^2, \sin^2 2\theta)$, and $\Delta_j^{\nu_\mu \mathrm{CCQE}} = \mathrm{Data}_i^{\nu_\mu \mathrm{CCQE}} - \mathrm{Pred}_i^{\nu_\mu \mathrm{CCQE}}$

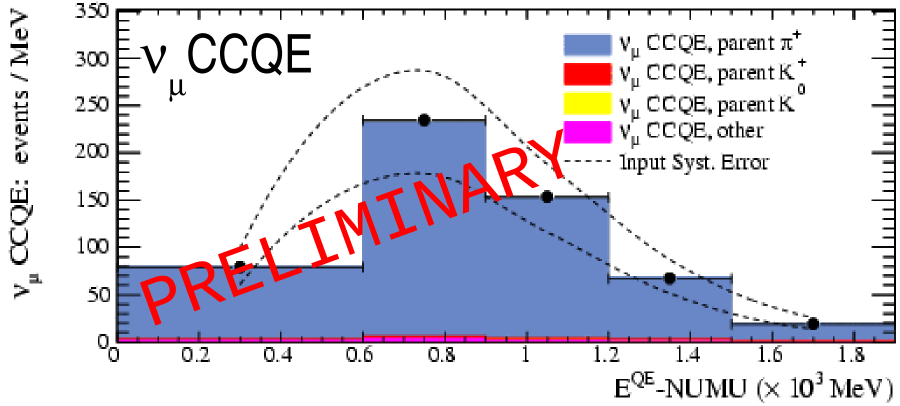
Systematic (and statistical) uncertainties are included in $(M_{ij})^{-1}$ matrix

- Covariance matrix includes correlations between ν_e and ν_μ events.
- Statistical error component takes care of event overlap in ν_e samples.
- 68% of TBL ν_e's are also BDT ν_e's ⇒ improvement is expected.

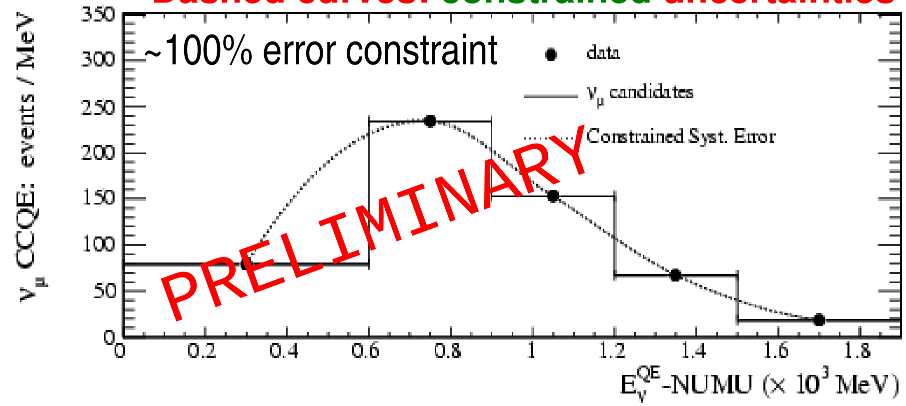
Need to define which ν_μCCQE sample to use. In this calculation we use the ν_μCCQE sample of the BDT analysis in the combination. This causes a loss of sensitivity in the TBL component (not identical to first result).

Comparison of the three distributions before and after fit

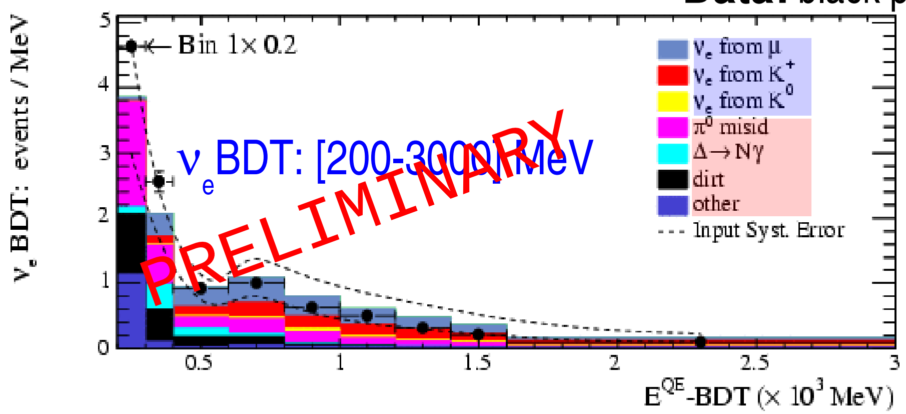
Dashed curves: unconstrained uncertainties

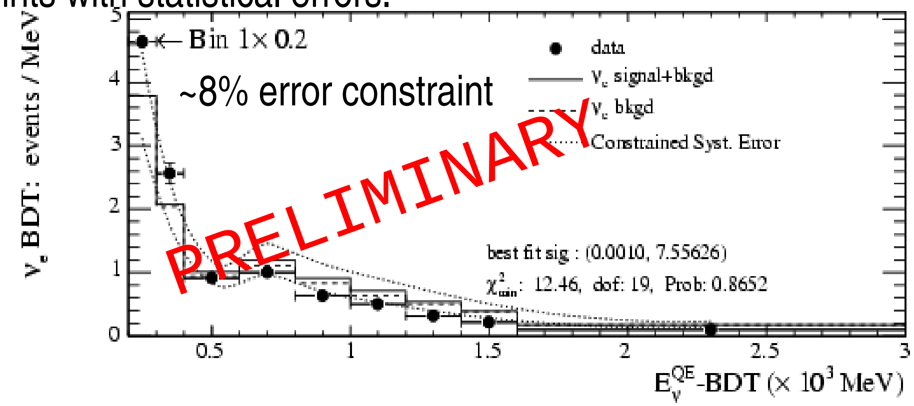


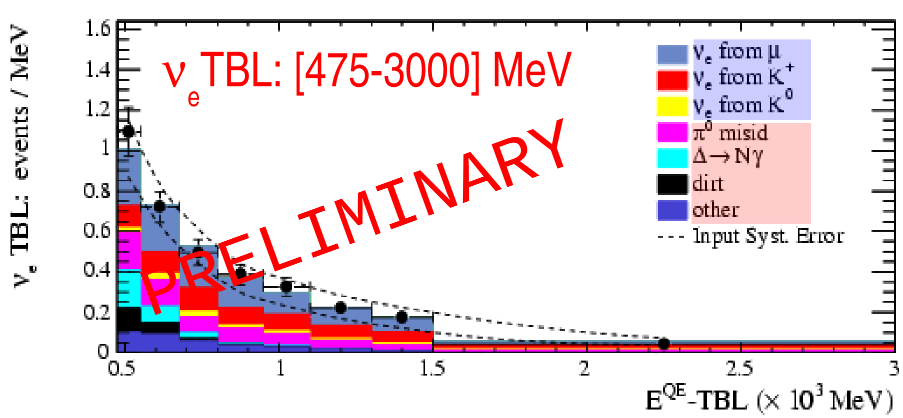
Dashed curves: constrained uncertainties

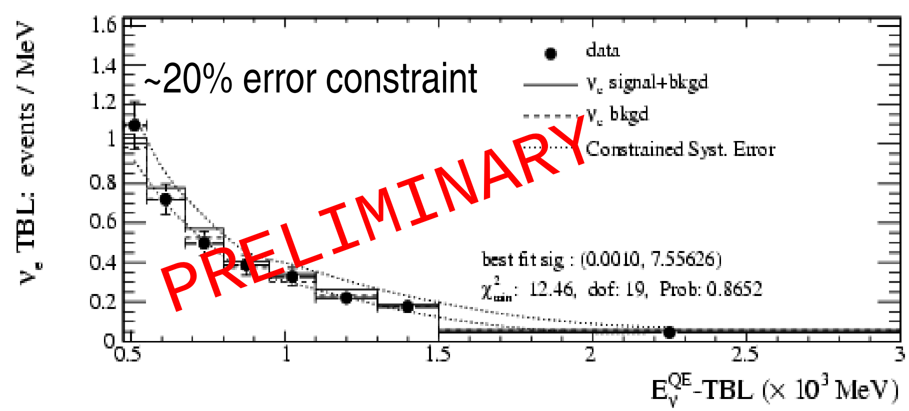


Data: black points with statistical errors.









The ν_eBDT + ν_eTBL + ν_μCCQE results:

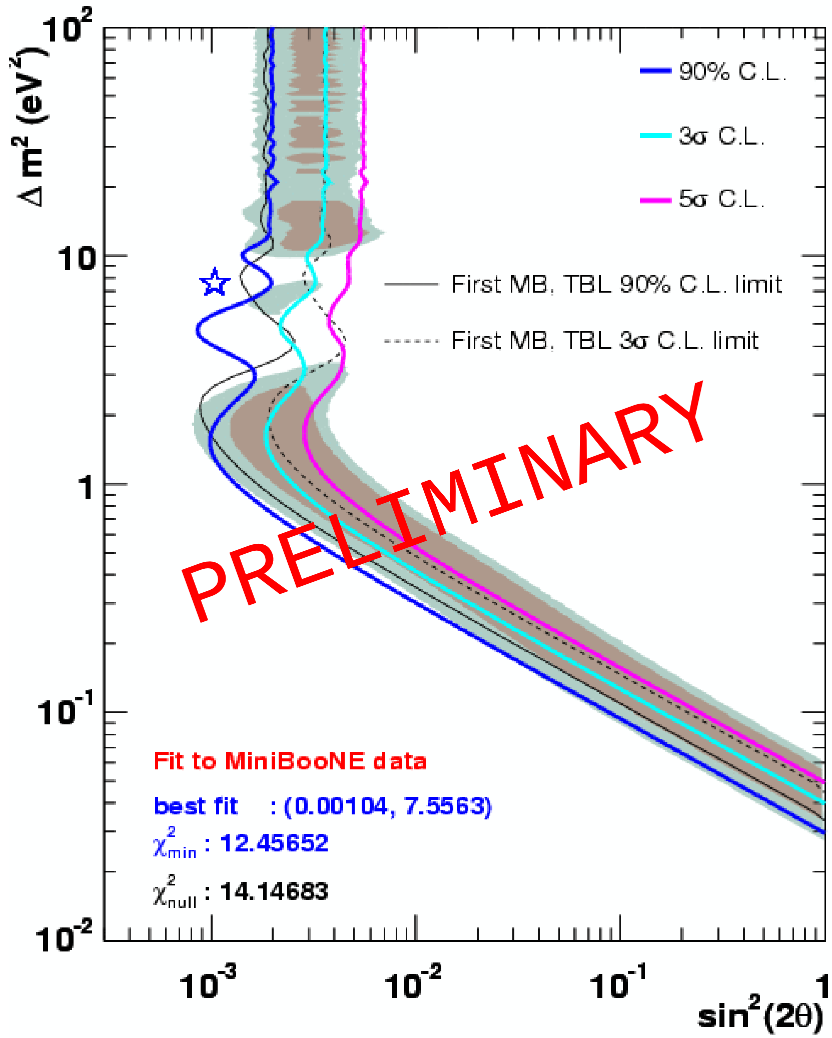
The combination of the three samples gives a significant increase in coverage in the region $\Delta m^2 < 1$ eV^2.

Differences in the details are due to the specific fluctuations in the three data samples and the interplay with correlations among them.

3σ and 5σ limits improve significantly: 5σ is comparable to previous 3σ at low Δm^2.

The combination yields a consistent result.

Limits from fits to open data



10%-30% improvement in 90% C.L. limit below ~1eV^2.

What does this mean?

With the blind analysis we asked the specific question:

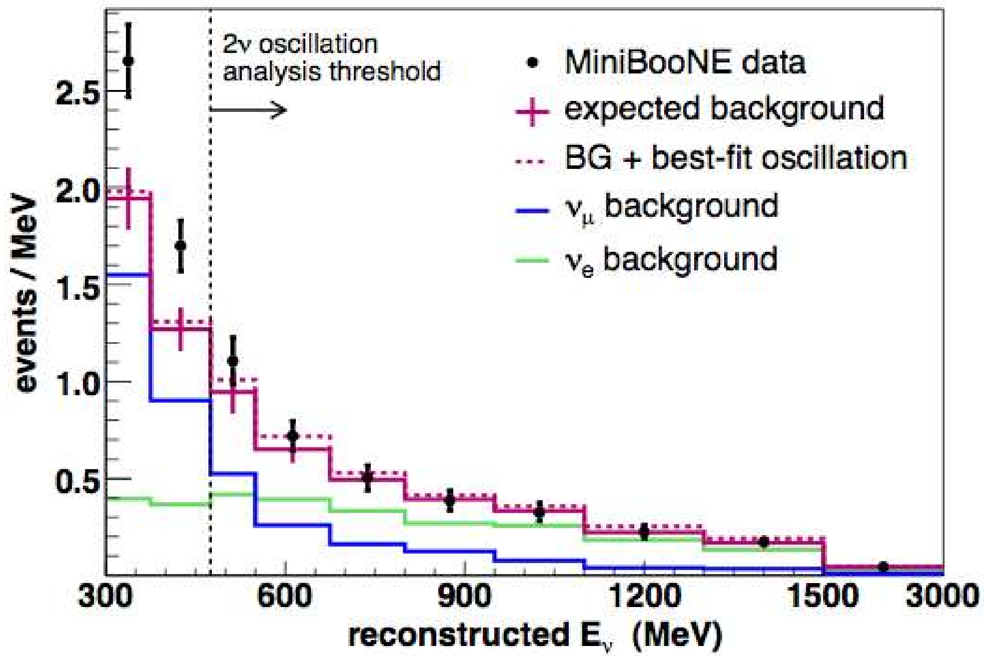
Do ν_μ oscillate directly into ν_e with $\Delta m^2 \sim 1\ eV^2$, as suggested by LSND?

We have a clear answer:

NO.

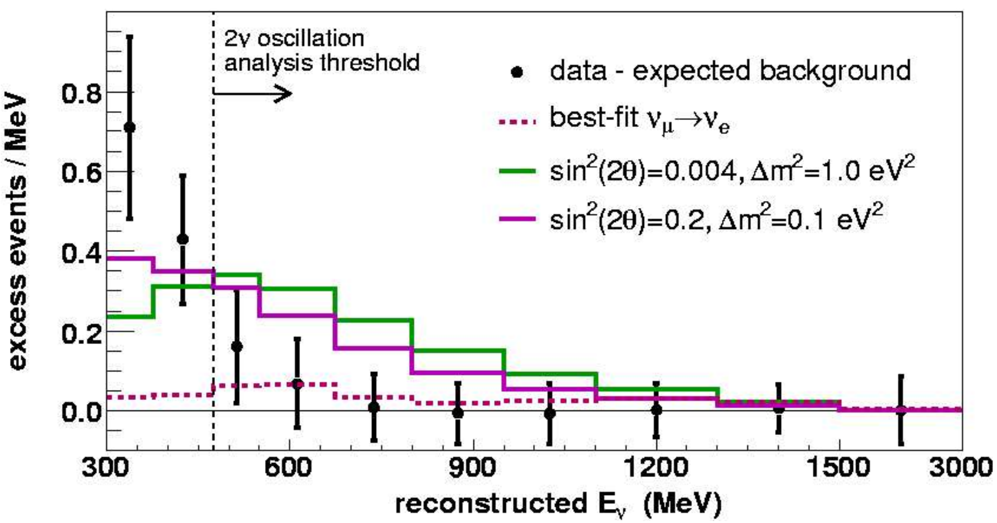
But there is more work to do ...

We observe an Excess of Events below 475 MeV:
We use the official TBL result to study it.



96 ± 17 ± 20 events above background, for 300< E_ν^{QE} <475MeV

Deviation: 3.7 σ

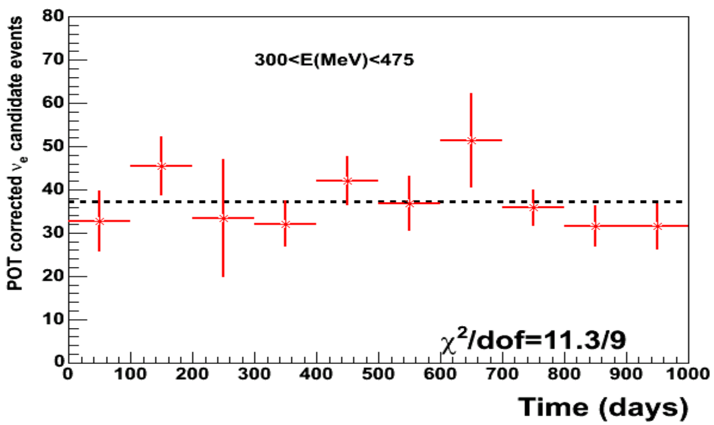


Excess Distribution is inconsistent with a simple two-neutrino oscillation model

Investigating the low E excess (E_ν < 475 MeV)

No Detector anomalies found

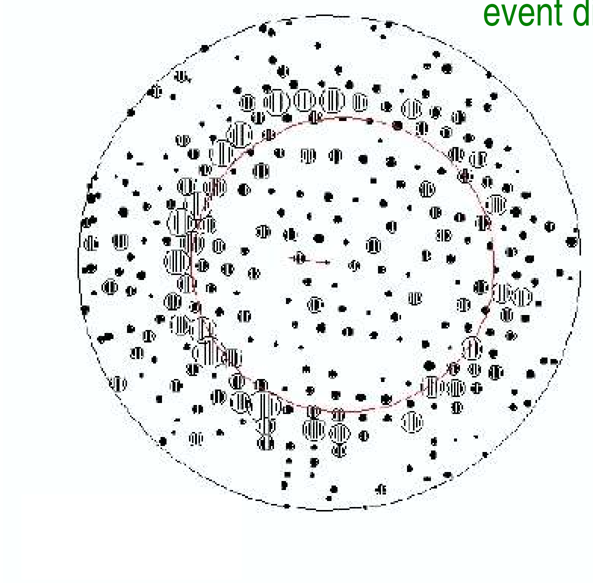
Example: rate of electron candidate events is constant (within errors) over course of run



No Reconstruction problems found

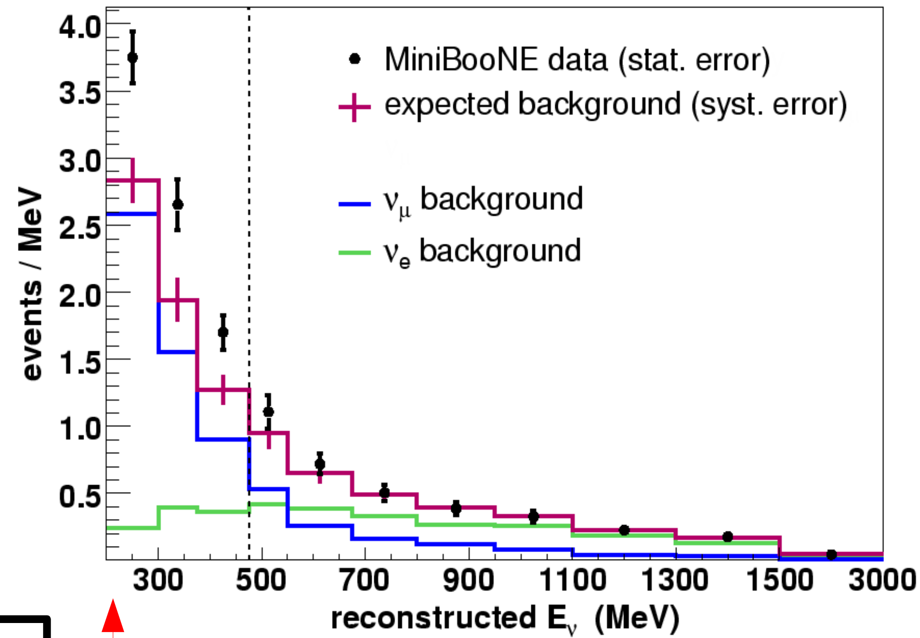
All low-E electron candidate events have been examined via event displays, consistent with 1-ring events.

Could be electrons or photons.



Going further down in energy ...

- Opened bin from 200-300 MeV.
- Calculate full systematic errors.
- Excess persists below 300 MeV



New Bin

	Reconstructed ν energy bin (MeV) 200-300	300-475	475-1250
total BG	**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**

- ν_μ mis-ID BG dominates the new bin even more.

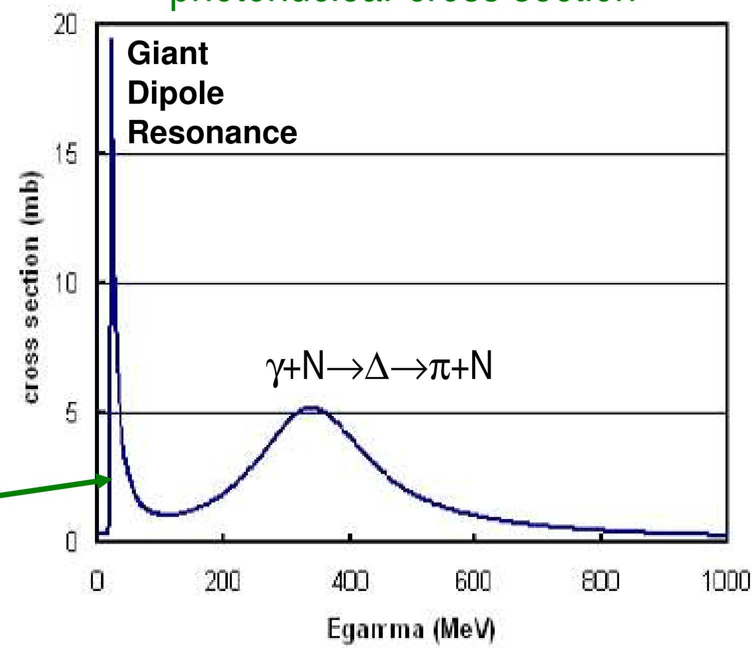
Possible Sources of Single Gamma Backgrounds

MiniBooNE cannot tell an electron from a single gamma.

Processes that remove/absorb one of the gammas from a ν_μ induced NC $\pi^0 \rightarrow \gamma\gamma$

- Should be in the GEANT detector Monte Carlo. Might be exceptions or inaccurate rates.
  - Example: photo-nuclear absorption

photonuclear cross section

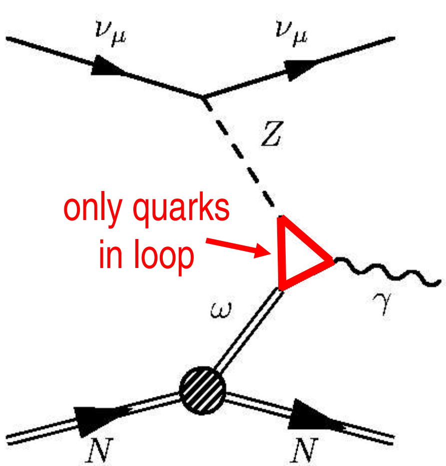


$\Rightarrow$ Under active investigation

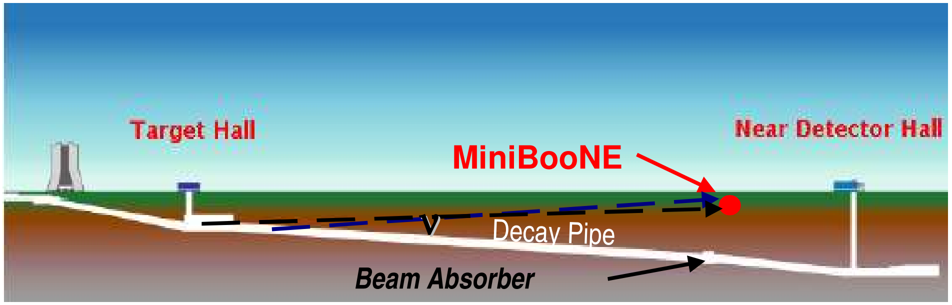
ν processes that produce a final state single gamma

- Example: Anomaly mediated photon production (Harvey, Hill, and Hill, arXiv:0708.1281[hep-ex])

$\Rightarrow$ Under active investigation



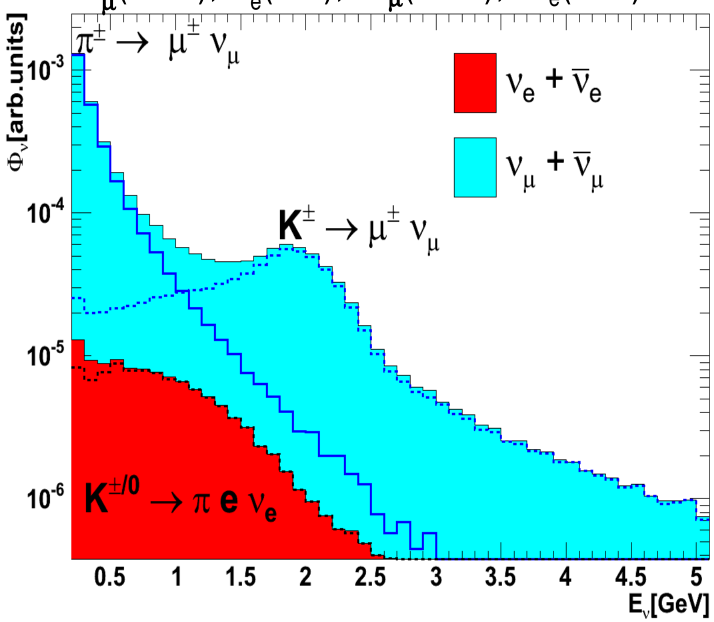
Check with neighboring neutrino source: NuMI → MINOS



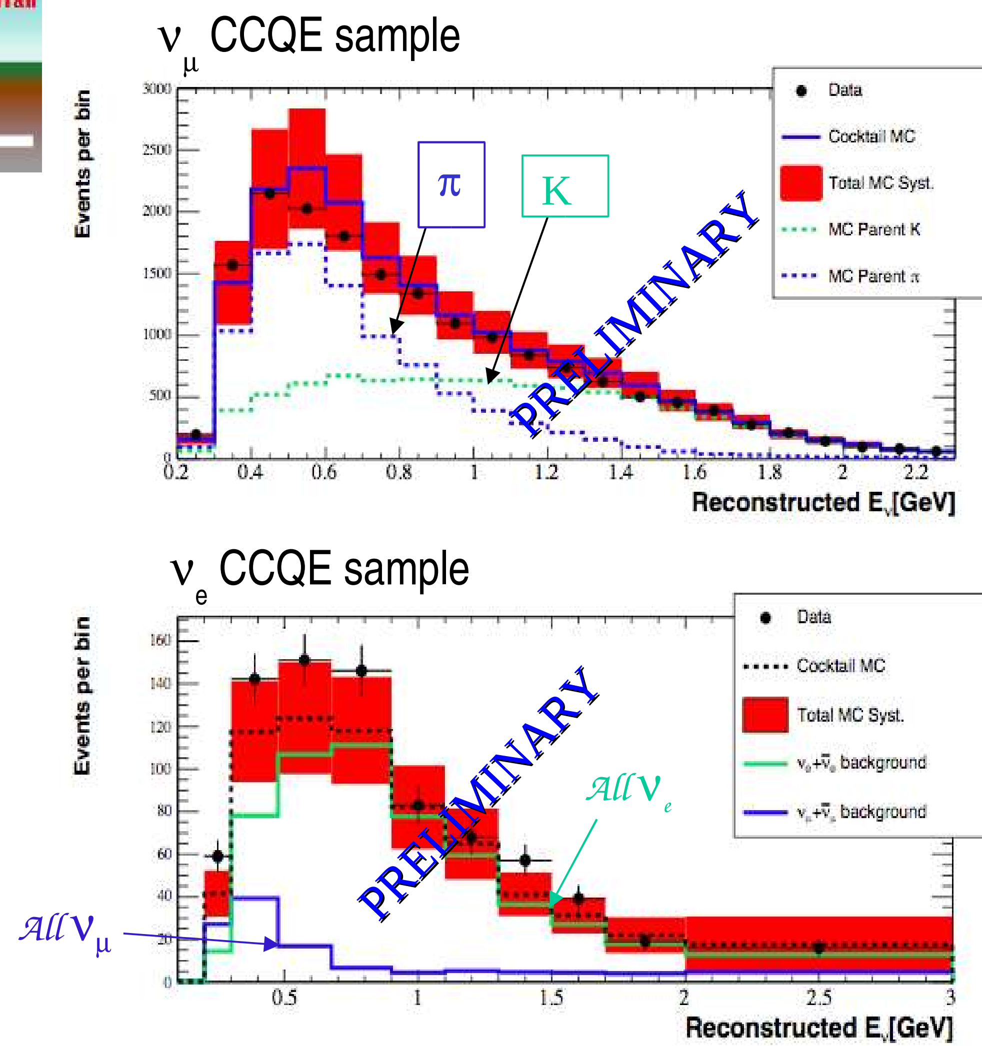
First results presented at Fermilab: Z. Djurcic, Joint Exp. Theor. Phys. Seminar Dec. 11, 2007

NuMI flux composition:

ν_μ(66%), ν_e(2%), $\bar{\nu}_\mu$(31%), $\bar{\nu}_e$(1%)



Enhanced in ν_e from K decay because of the off-axis position (~111 mrad off axis).



Future plans

- Run MiniBooNE in anti-neutrinos for several more years to make oscillations search in anti-neutrino mode.
  - Statistics are less but background are smaller and somewhat different.
  - Provides another low *E* data set and directly checks LSND.

- Constrain further the systematic errors in the analysis of NuMI beam events. This tests properties if the detector with a different beam.

- SciBooNE experiment can test properties of the Booster neutrino beam with different detector. Will provide new data on ν cross sections.

- Study exotic scenarios (*e.g.* extra dimensions – Päs, Pakvasa, Weiler, Phys.Rev. D72 095017, 2005-) that could explain low E excess.

- MicroBooNE
  - New proposed experiment to put a 70 ton Liquid Argon detector near MiniBooNE
    - High ν_e efficiency down to low energies
    - ***Can tell electron from gamma events***
    - Nearly free of background from misidentified particles

Summary

- MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ 2ν oscillations.
- Incompatible with LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations signal at 98% C.L.
- Low energy excess under active investigation.
- More analysis of more data in progress.