Results from the MiniBooNE Experiment

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for the MiniBooNE Collaboration

June 3, 2008, PASCOS '08

Outline

The experiment and the oscillations result

NC π^0 rate measurement

Combining analyses

Compatibility of high Δm^2 experiments

Event excess below oscillations analysis threshold

Data from the NuMI beam at MiniBooNE

Summary

The MiniBooNE Collaboration

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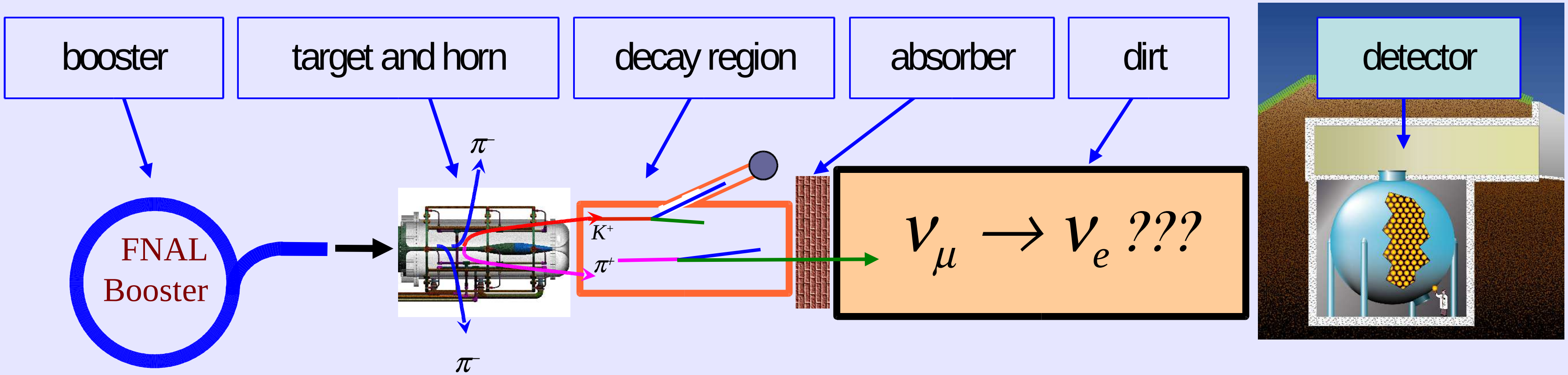
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

The MiniBooNE Strategy

Test the LSND indication of anti-electron neutrino oscillations
keep same *L/E*, change beam energy and systematic errors

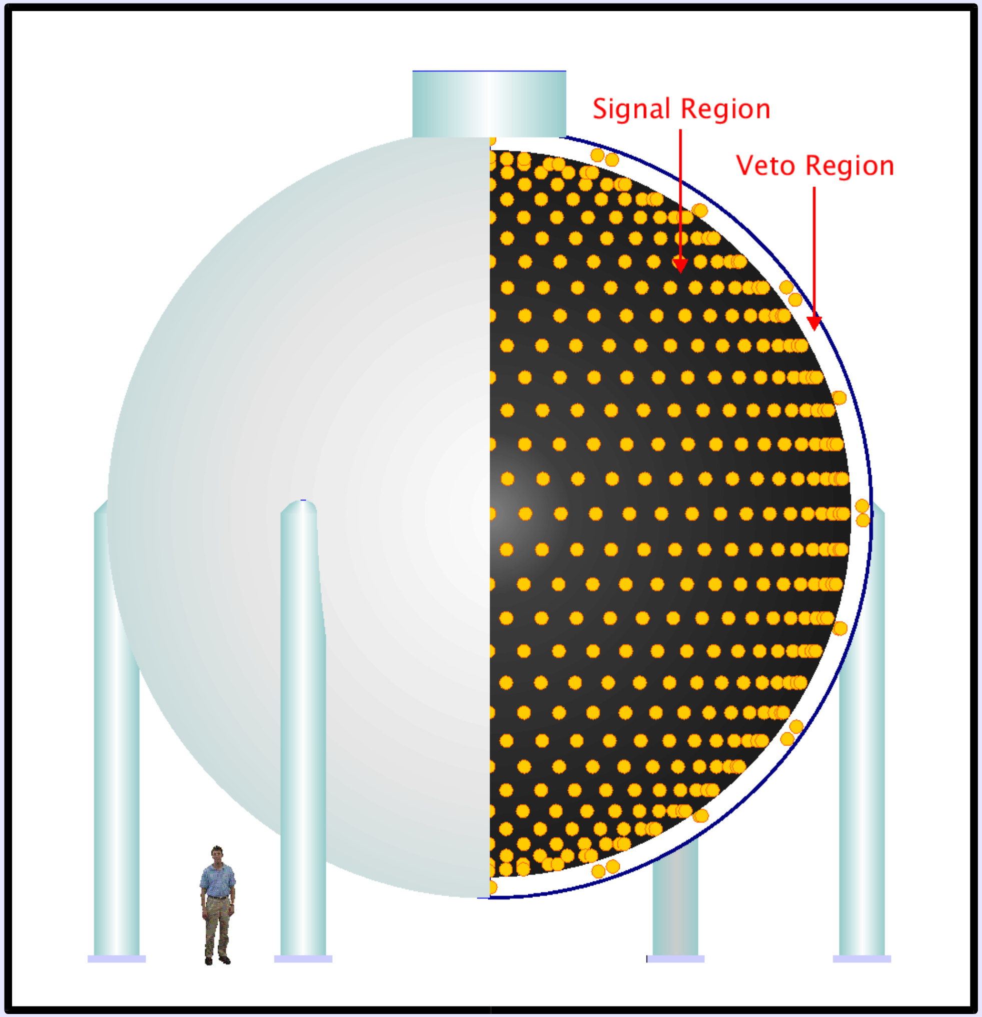
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

Neutrino Energy (E):		Baseline (L):	
MiniBooNE:	~600 MeV	MiniBooNE:	~540 m
LSND:	~30 MeV	LSND:	~30 m



Integrated Fluxes: ν_μ = 93.8%, ν_e = 0.5%, $\bar{\nu}_\mu$ = 5.7%, $\bar{\nu}_e$ = 0.08%

The MiniBooNE Detector



541 meters downstream of target

3 meter overburden of dirt

12 meter diameter sphere

Filled with 800 t of pure mineral oil
(CH_2 -- density 0.845 gr/cm^3, n=1.47)

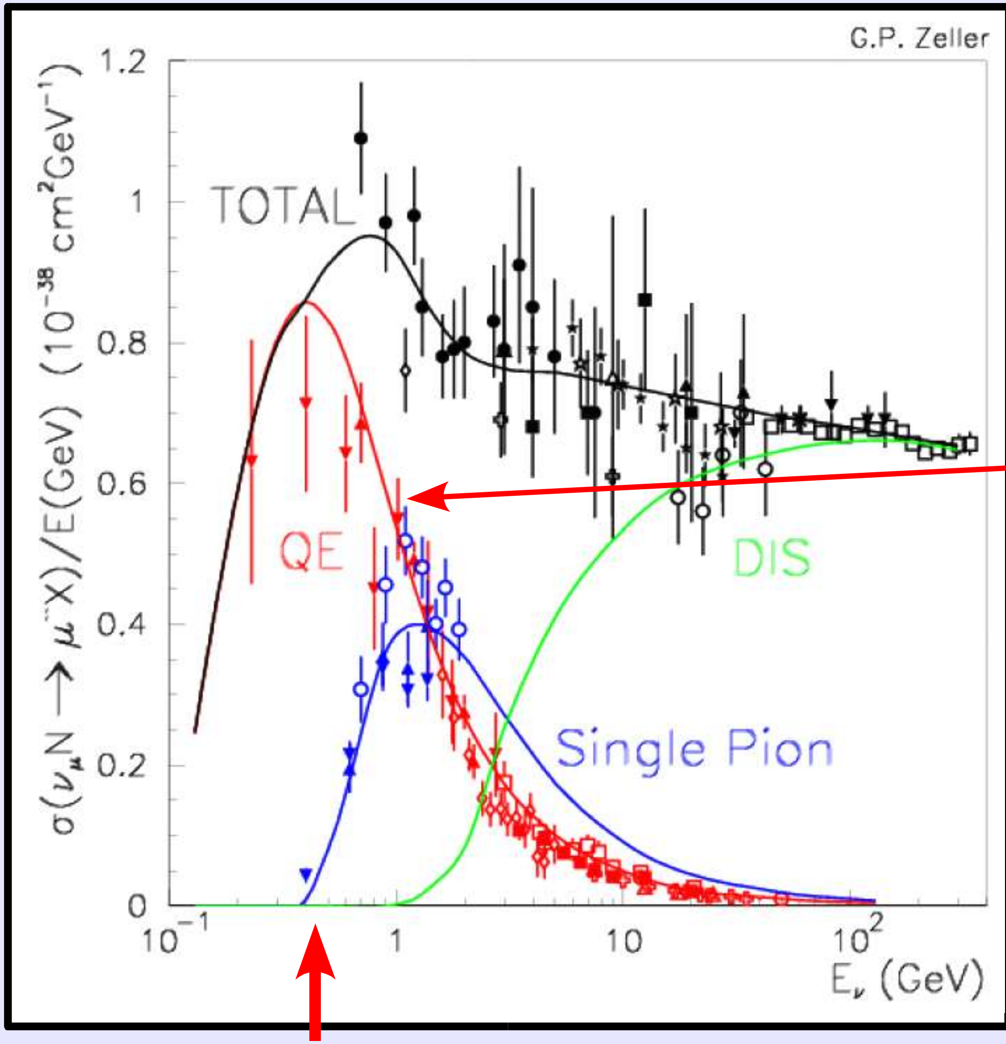
Fiducial volume 450 t

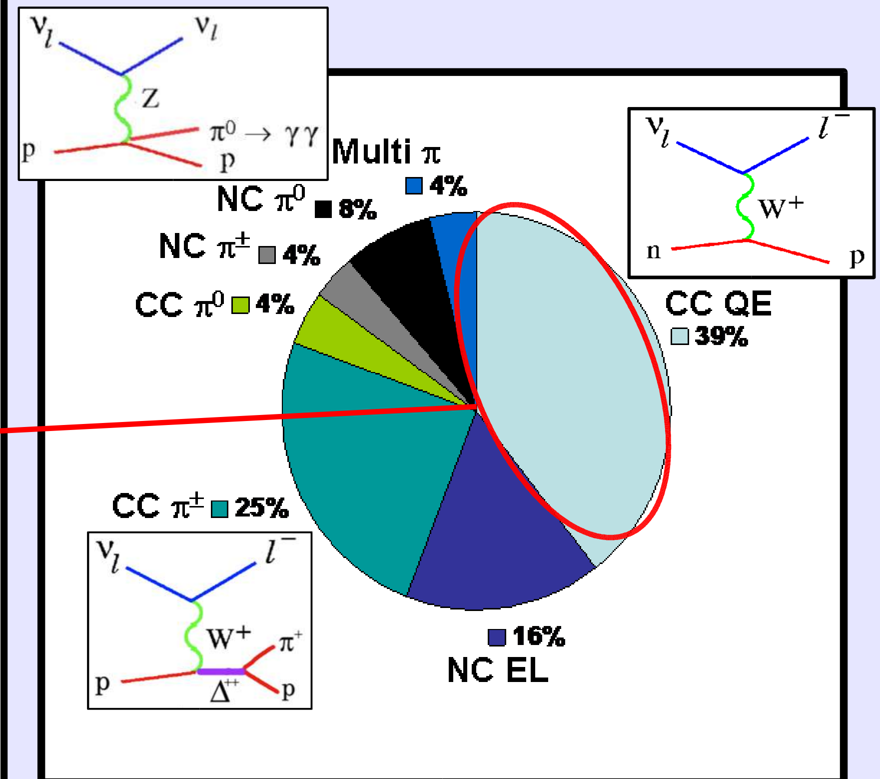
1280 inner 8” phototubes – 10% coverage

240 veto phototubes

Less than 2% tubes failed during run

Neutrino Interactions





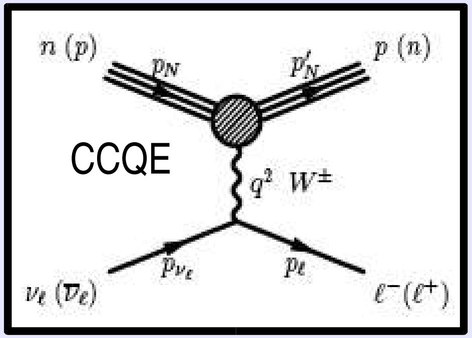
MiniBooNE typical ν energy

- 5.6×10^{20} POT in neutrino mode (10/02-12/05).
- 193,709 ν_μ CCQE interaction candidates

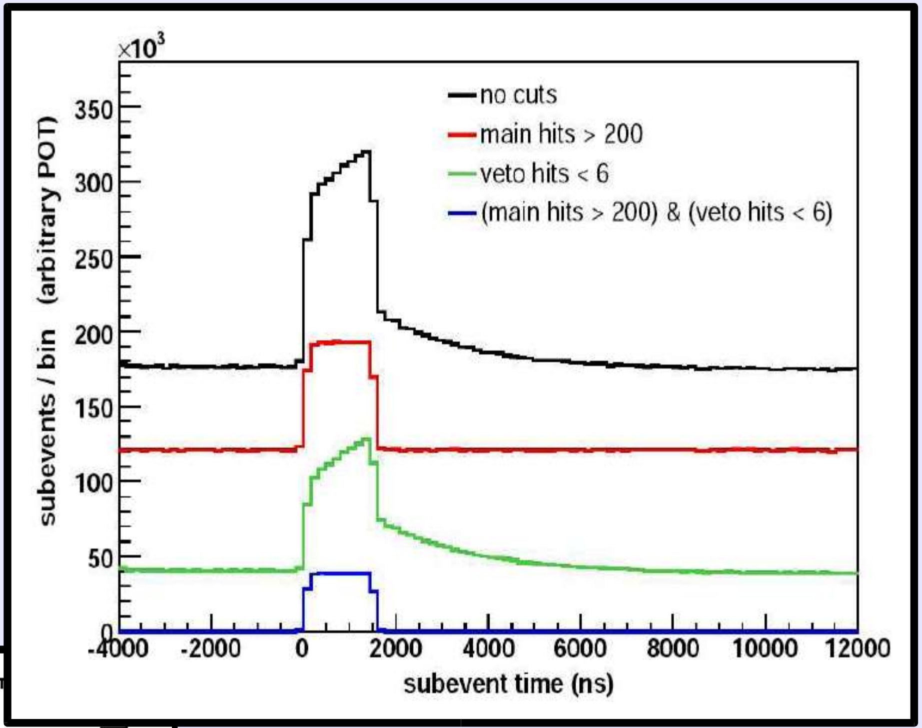
  Phys. Rev. Lett. 98, 231801 (2007).

ν events in the detector

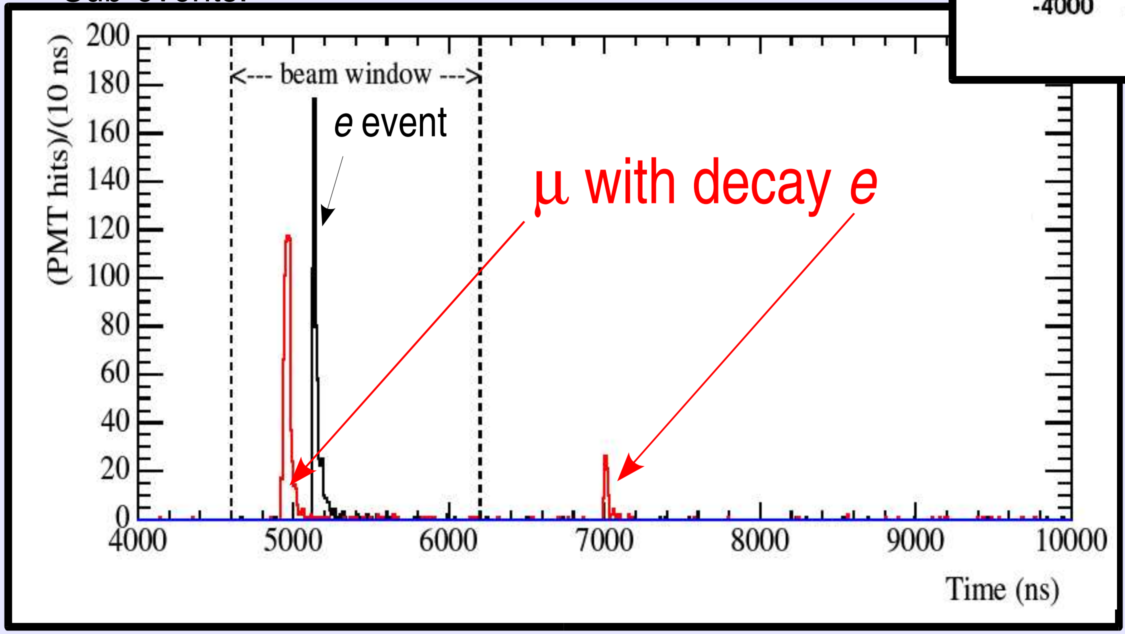
- Cosmic μ rejected with low veto activity cut.
- Exponential decay: *e* from μ decay: Rejected with minimum tank hits cut.



+ Others ...



Sub-events:



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

Oscillation analysis structure

Two algorithms used:

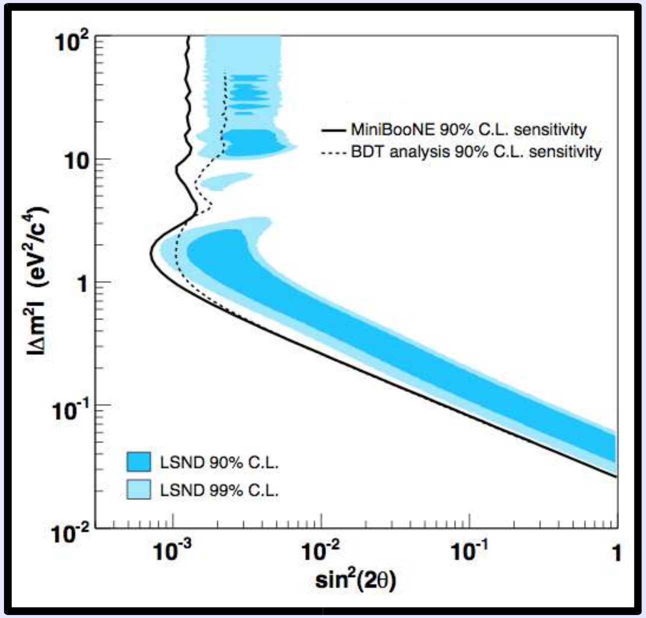
(1) Track Based Likelihood (TBL*)

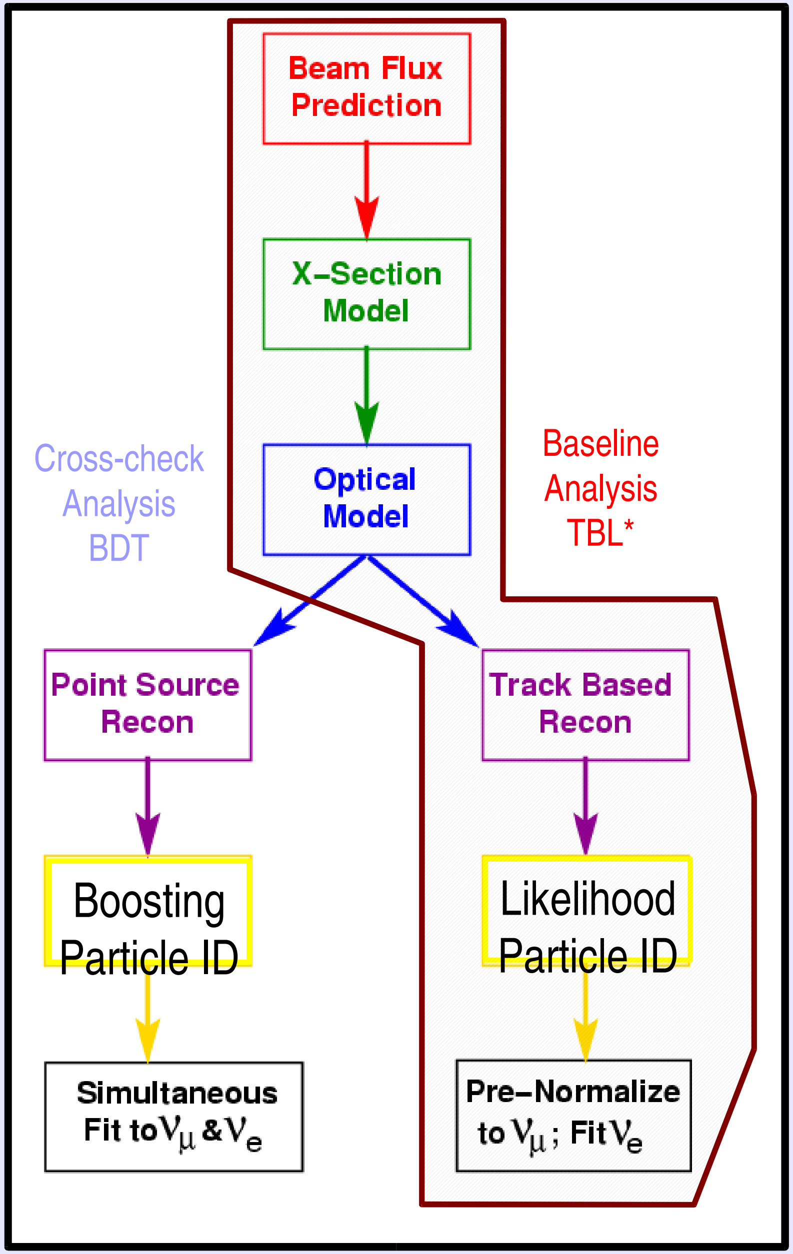
Uses direct reconstruction of particle types and likelihood ratios for PID.

(2) Boosted Decision Tree (BDT)

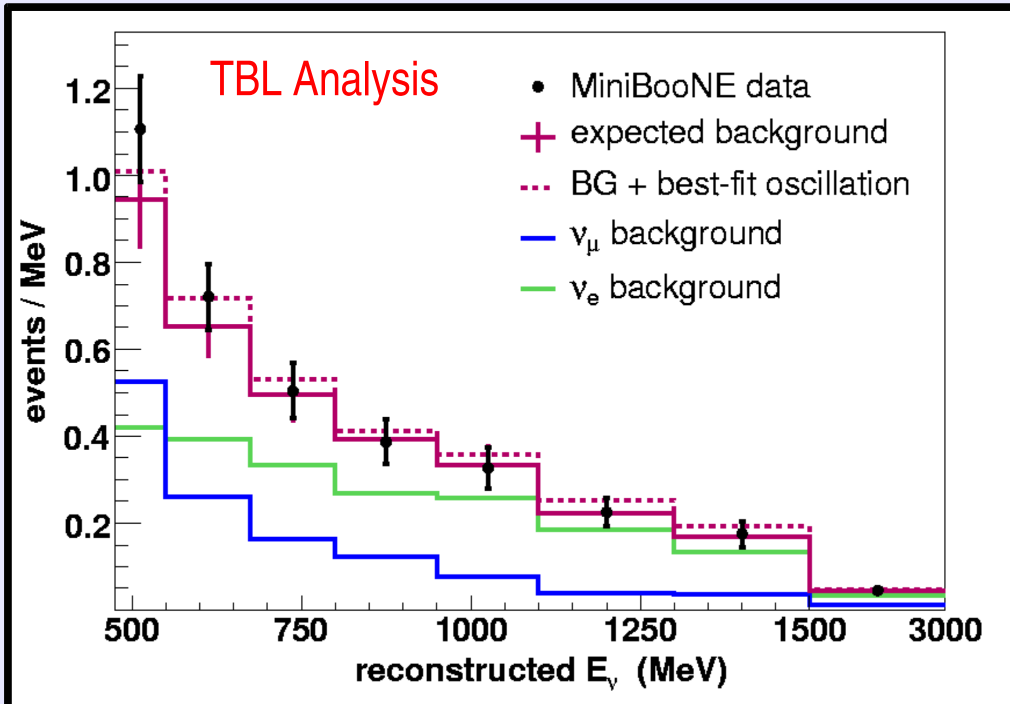
Uses less detailed reconstruction, and a set of "low level" variables combined in BDT algorithm into a PID *score*.

The TBL analysis had higher sensitivity to oscillations, hence was chosen for primary results.





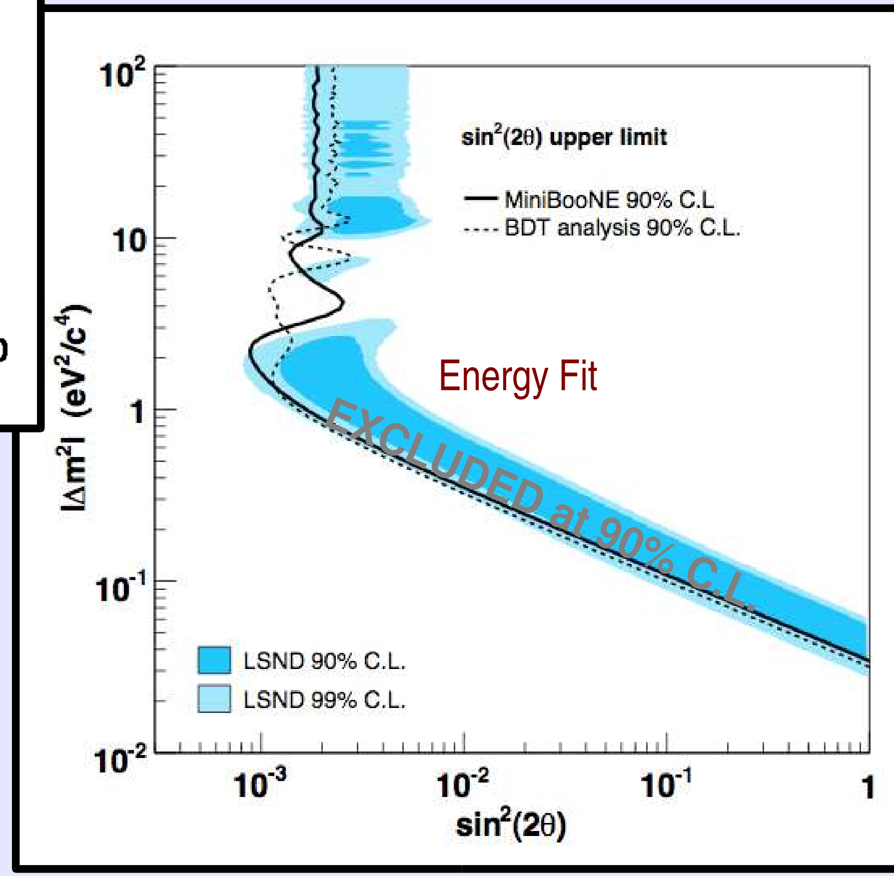
MiniBooNE First Results (April, 2007)



Data consistent with expected background

⇒ Inconsistent with a $\nu_\mu \rightarrow \nu_e$ oscillations

Exclude region in parameter space:



Oscillation Search Region

$475 < E_\nu < 1250$ MeV

data: 380 ± 19 (stat) events

expectation: 358 ± 35 (sys) events

significance: $0.55\ \sigma$

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%

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

Oscillation Signal

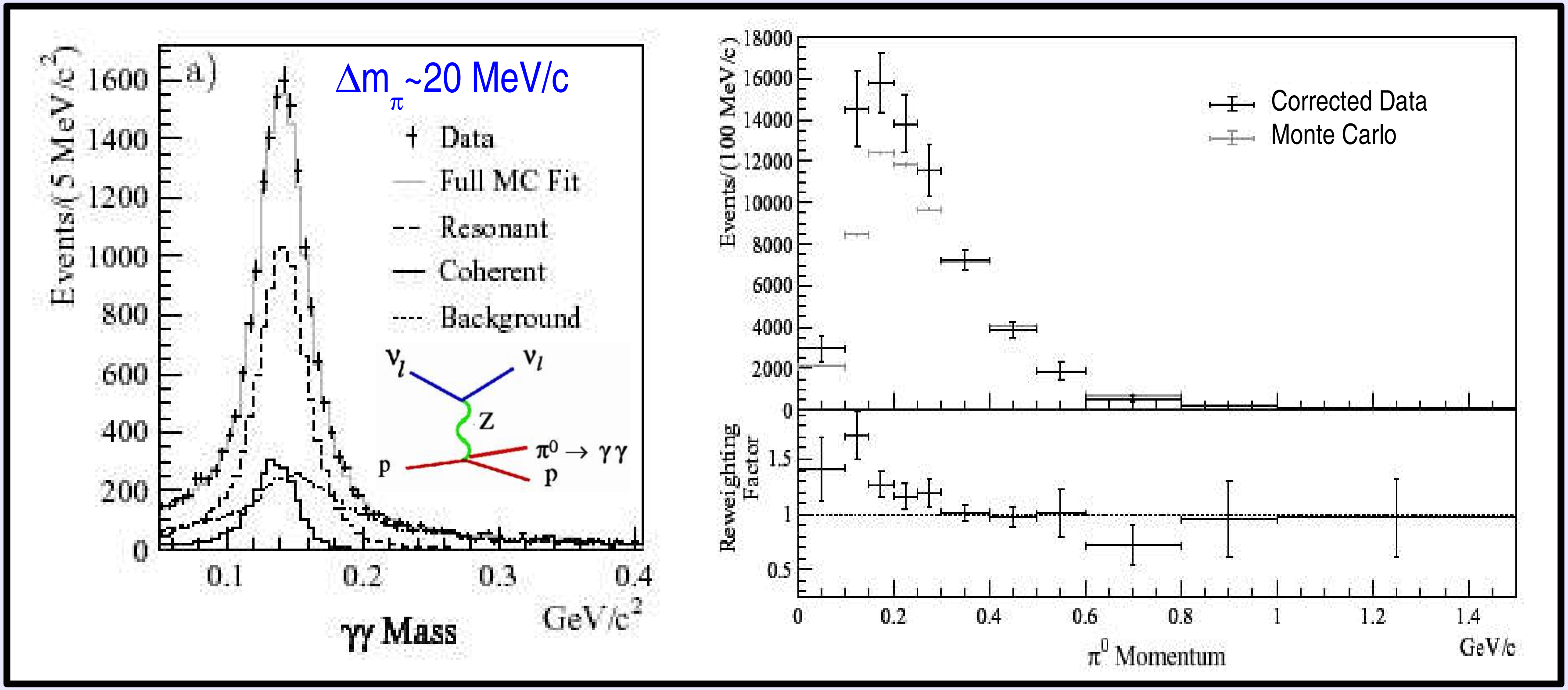
$\Rightarrow$ An Excess of "ν_e" Events over Expectation

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

- **NC π^0 production:** (arXiv:0803.3423, accepted for publication by Phys. Rev. Lett.)
  Largest mis-ID background, where one of the decay photons is missed.
  MiniBooNE cannot distinguish electrons from single gammas.
  Rate constrained from dedicated NC π^0 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.

Measurement of ν_e NC π^0 Rate and constraint of ν_e of Mis-IDs

Largest NC π^0 sample ever collected (28,600 π^0 events)



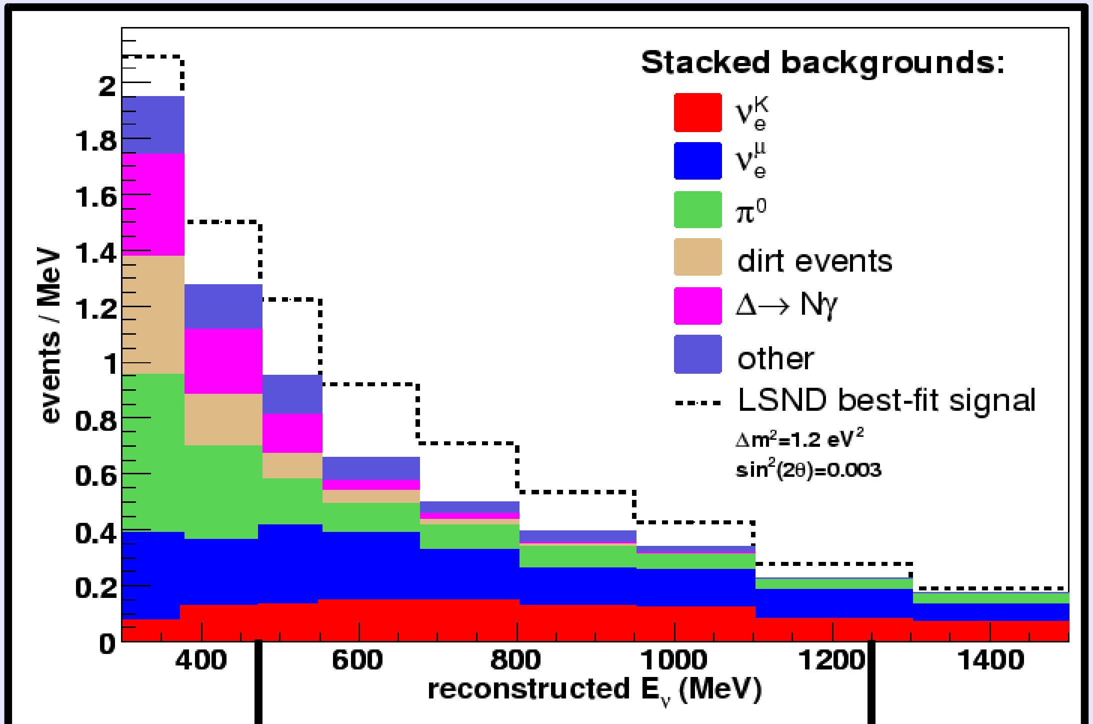
- π^0 rate measured to a few percent.
- Critical to oscillation analysis → without π^0 rate errors would be ~25%

- First measurement of coherent NC π^0 production off ^{12}C below 2 GeV (19.5±2.7 %) .

arXiv: 0803.3423, accepted by Phys. Lett. B

TBL Analysis: expected events

ν_e candidate sample composition shown below:



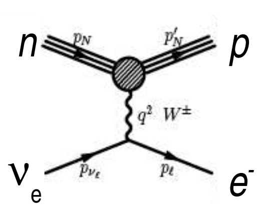
Counting experiment range

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

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



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).

The ν_eBDT + ν_eTBL + ν_μCCQE results:

Paper at draft stage

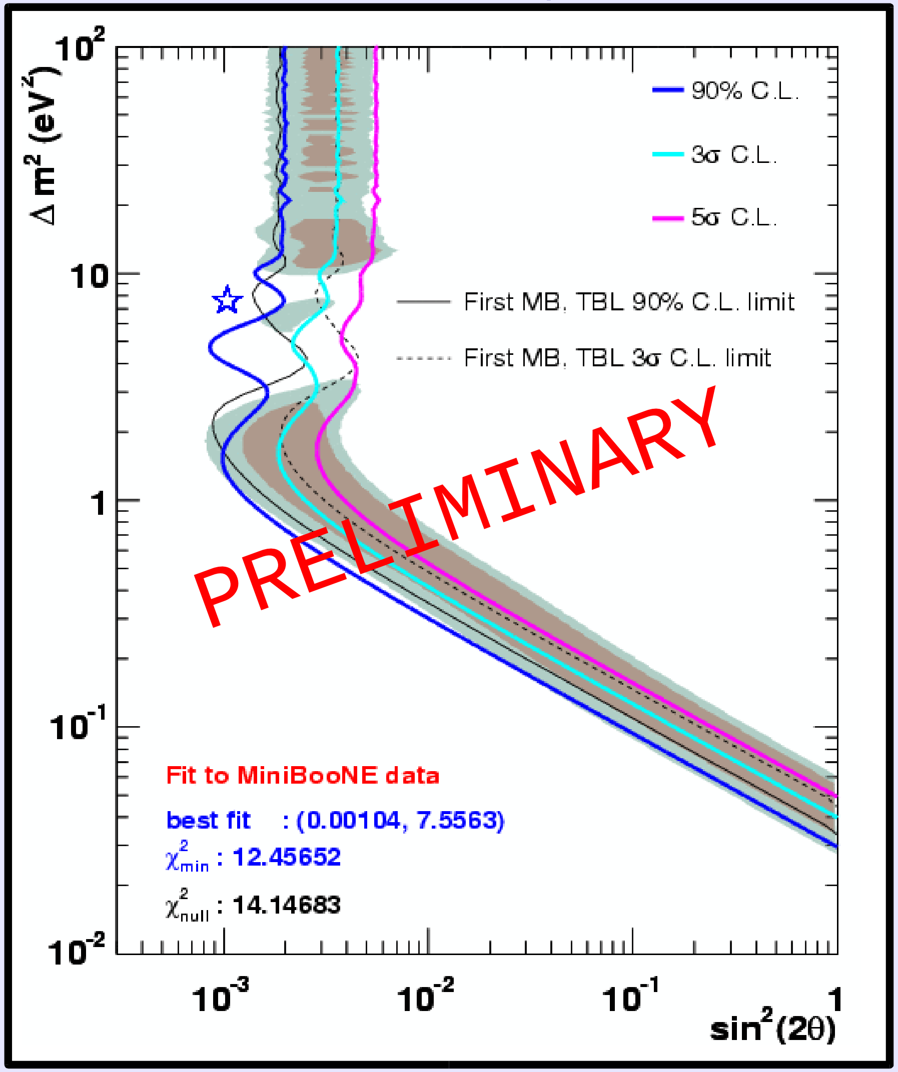
The combination of the three samples gives a significant increase in coverage in the region $\Delta m^2 < 1$ eV^2.

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.

Global data analysis

Combine results of MiniBooNE, LSND, KARMEN2, and Bugey.

Compatibility:

- How probable is it that all experimental results come from the same underlying 2-ν oscillation hypothesis?
- Assessed by combining the $\Delta\chi^2$ surface of each experiment.

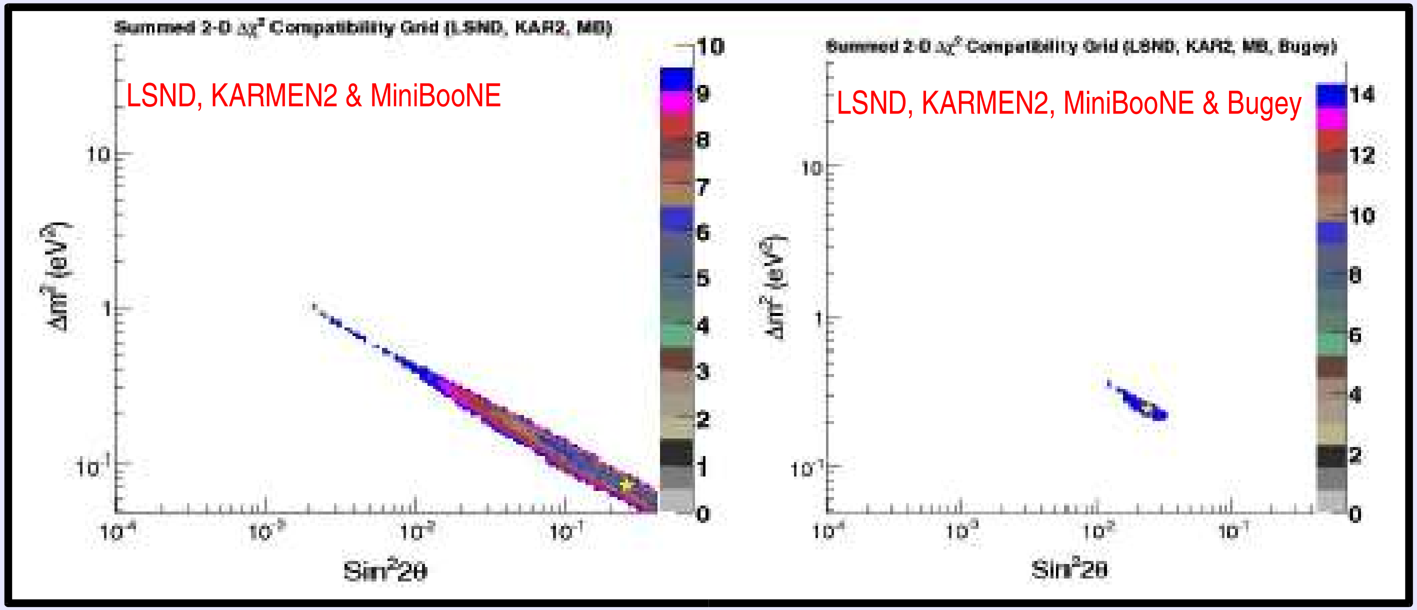
LSND	KARMEN2	MB	Bugey	Max. Comp. (%)	Δm^2 (eV^2)	$\sin^2 2\theta$
✓	✓	✓		25.36	0.072	0.256
✓	✓	✓	✓	3.94	0.242	0.023
✓		✓		16.00	0.072	0.256
✓		✓	✓	2.14	0.253	0.023
	✓	✓		73.44	0.052	0.147
	✓	✓	✓	27.37	0.221	0.012

arXiv: 0805.1764[hep-ex], submitted to Phys. Rev. D

Global data analysis, Allowed regions

Allowed Regions:

- Indicate where oscillation parameters would lie, at a given CL, assuming all experimental results can arise in a framework of 2-ν oscillations.
- The compatibility is the measure of this assumption.



LSND, KARMEN2 & MiniBooNE:

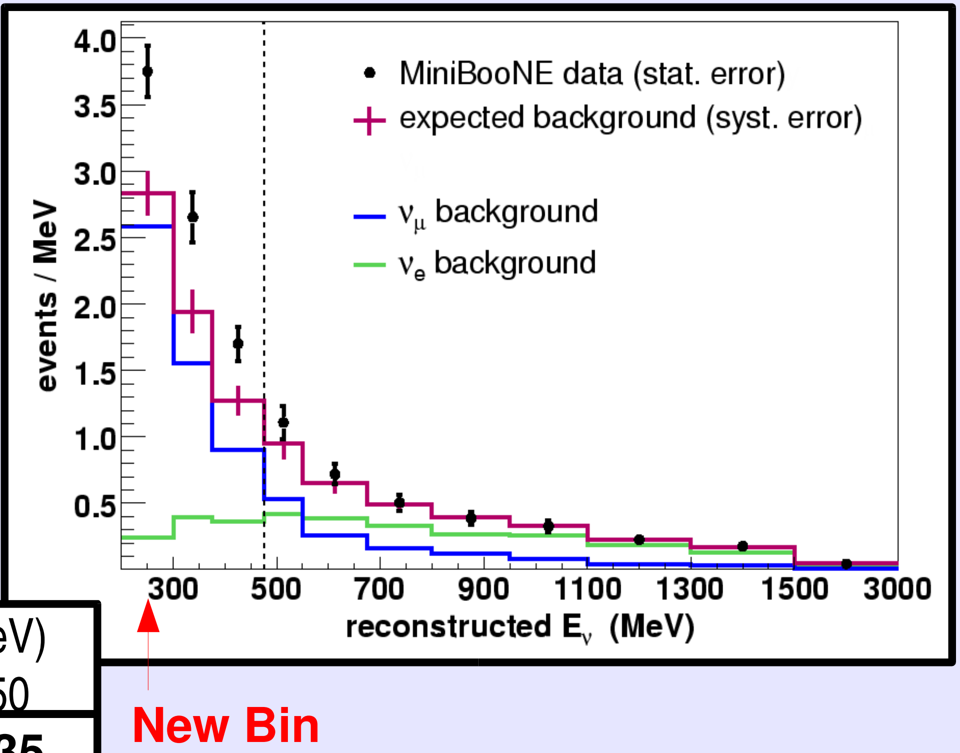
- 25.36% compatibility at $\Delta m^2 = 0.072\ eV^2$, $\sin^2 2\theta = 0.256$.

LSND, KARMEN2, MiniBooNE & Bugey:

- 3.94% compatibility at $\Delta m^2 = 0.242\ eV^2$, $\sin^2 2\theta = 0.023$.

We observe an excess of events below 475 MeV

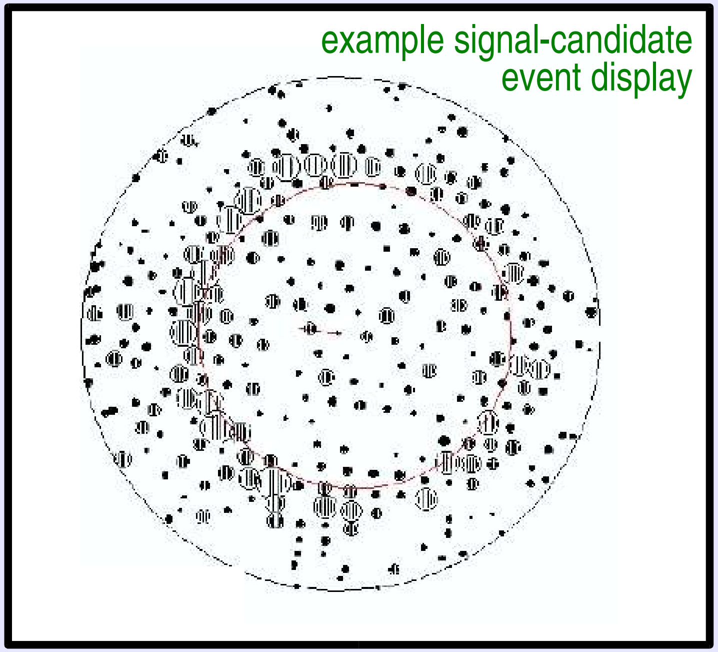
- 96 ± 17 ± 20 evts. above background for $300 < E_\nu^{QE} < 475$MeV.
- Opened bin from 200-300 MeV.
- Calculated full systematic errors.
- Excess persists below 300 MeV



	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.

Investigating the low E excess (E_ν < 475 MeV)

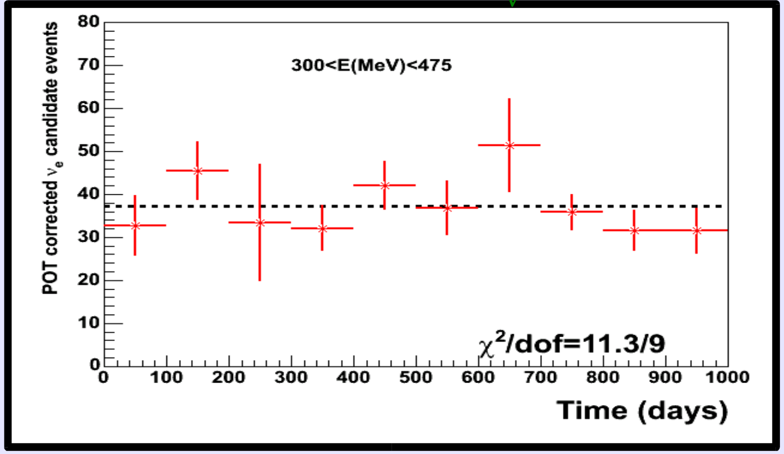


No Reconstruction problems found

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

Could be electrons or photons.

event/POT vs day, $300<E_\nu<475$ MeV



No Detector anomalies found

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

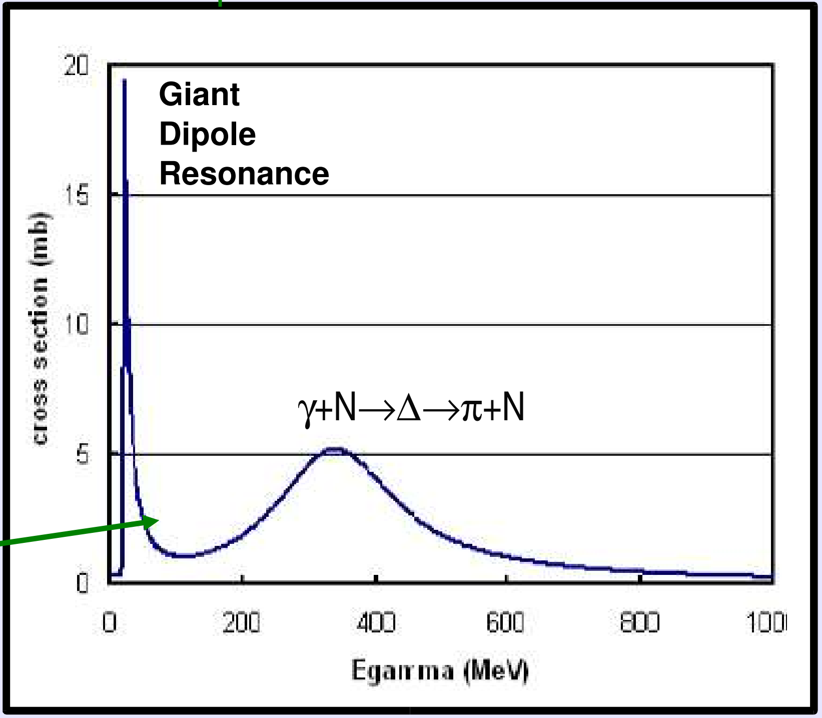
Possible Sources of Single Gamma Backgrounds

MiniBooNE cannot tell an electron from a single gamma.

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

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

photo nuclear cross section

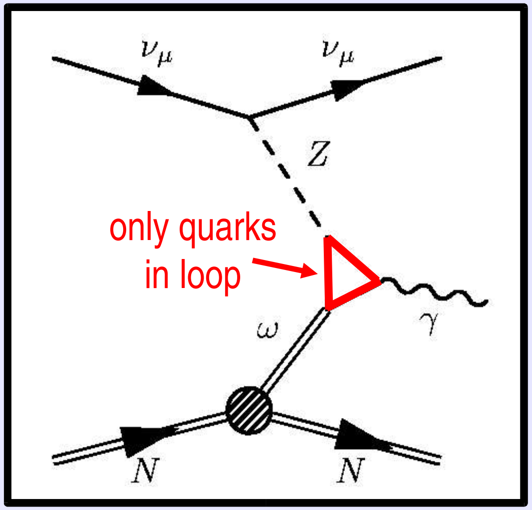


$\Rightarrow$ Under active investigation

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

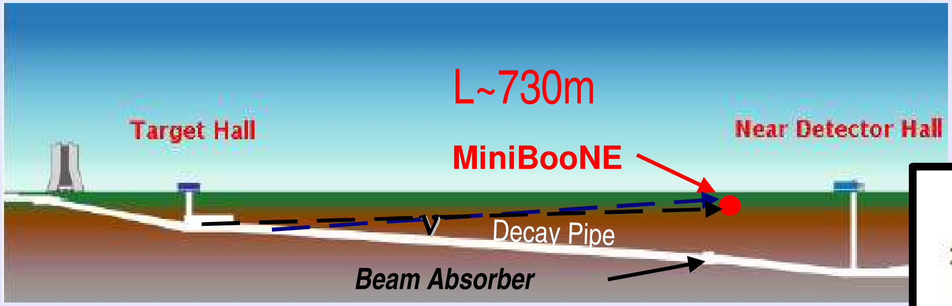


Advances in understanding the Low Energy excess:

- Included photo-nuclear effect (reduces excess)
  - Absent from GEANT3 – creates background from π^0's
- More comprehensive hadronic errors.
  - e.g. uncertainties from final states in photo-nuclear interactions
- Better handling of beam π^+ production uncertainties
  - Errors propagated in a model-independent way
- Improved measurement of ν induced π^0's (increases excess)
  - e.g. finer momentum binning
- Incorporation of MiniBooNE π^0 coherent/resonant measurement (increases excess)
  - No longer rely on more uncertain past results
- Better handling of radiative decay of Δ resonance (reduces excess)
  - As inferred from the measured π^0 rate.

Nearing a the end of a comprehensive review of the ν_e appearance backgrounds and uncertainties. Not ready for release yet.

Check with neighboring neutrino source: NuMI → MINOS

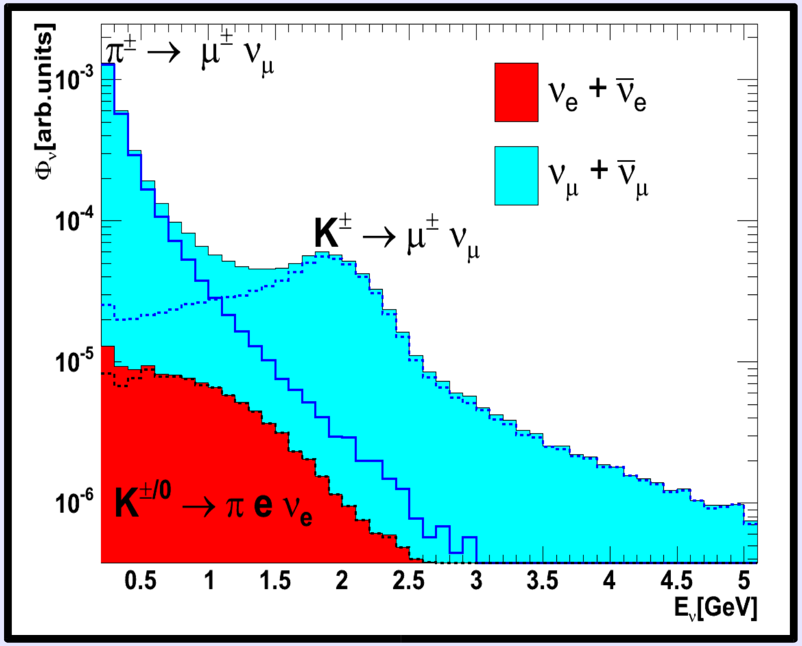


Test of principle of a horn-focused off-axis beam.

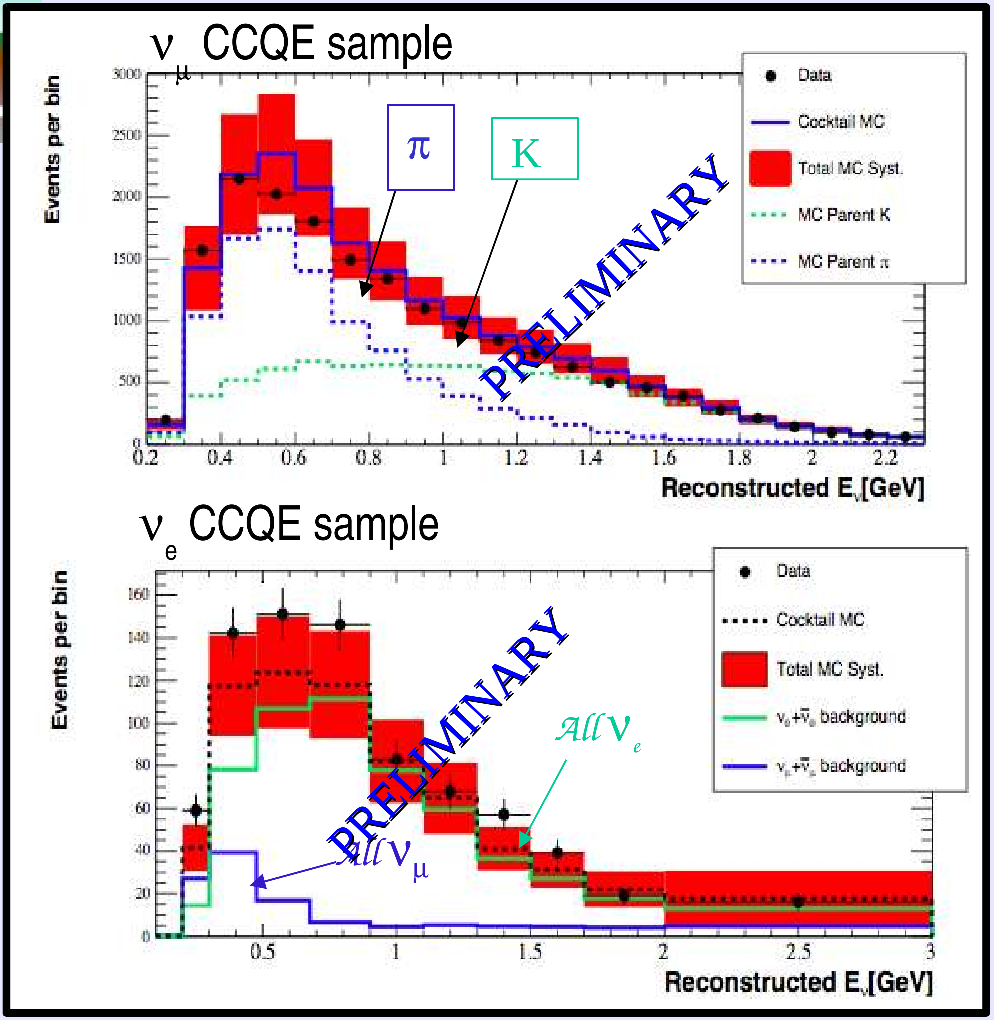
Joint Exp. Theor. Phys. Seminar Dec. 11, 2007

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).



MiniBooNE Present and Future

- Collected ~6.6 x 10^{20} POT in neutrino mode.
  - Making various cross section measurements.
  - Searching for various neutrino oscillations.
  - Publications being produced.

- Collected ~2.5 x 10^{20} POT in anti-neutrino mode.
  - Making various cross section measurements.
  - Searching for $\bar{\nu}_\mu$ disappearance.

- In Nov 2007 request for extra running in anti-neutrino mode granted.
  - LSND was an indication of $\bar{\nu}_e$ appearance.
  - Extra ~2.5 x10^{20} for a grand total of ~5 x10^{20} POT.
  - Will take data during FY2008 and FY2009.

Summary

- MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ 2ν oscillations.
- Combined BDT and TBL analysis sets tighter limit below $\Delta m^2 < 1\ eV^2$.
- High Δm^2 experiments (LSND, KARMEN2, MB & Bugey) compatible only at the 3.94% level.
- Low energy excess under active investigation. Expect full update this summer.
- NuMI beam data is complementary to MiniBooNE flux. Only a small significance excess in the ν_e sample is seen with current uncertainties (will constrain them using ν_μ sample as done with booster beam data).
- More analysis of more data in progress.

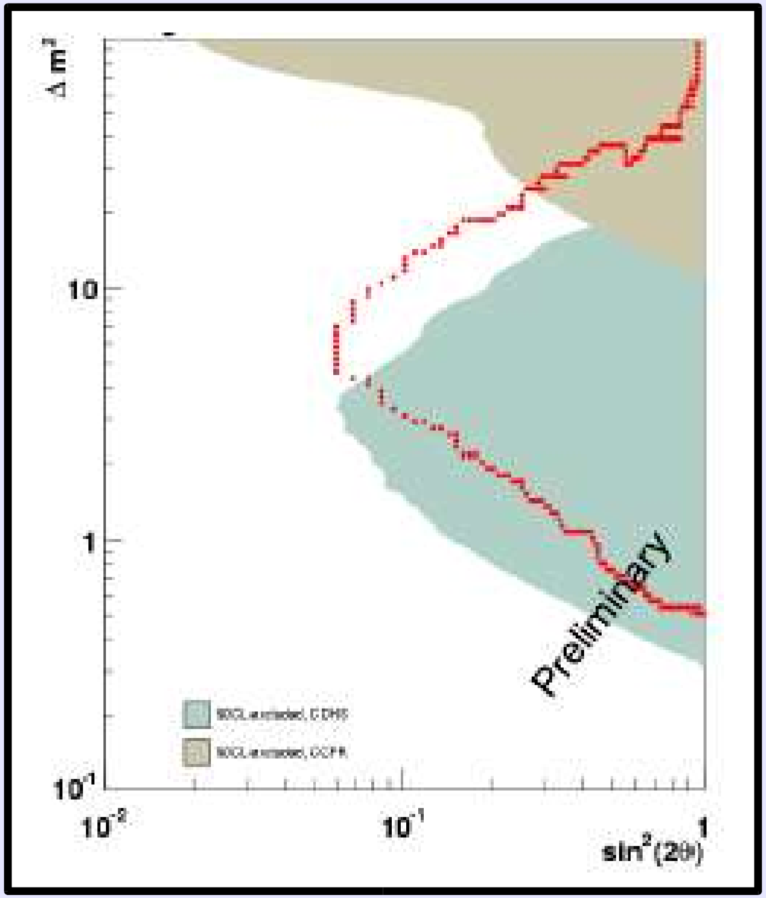
Backups

MiniBooNE ν_μ disappearance sensitivity

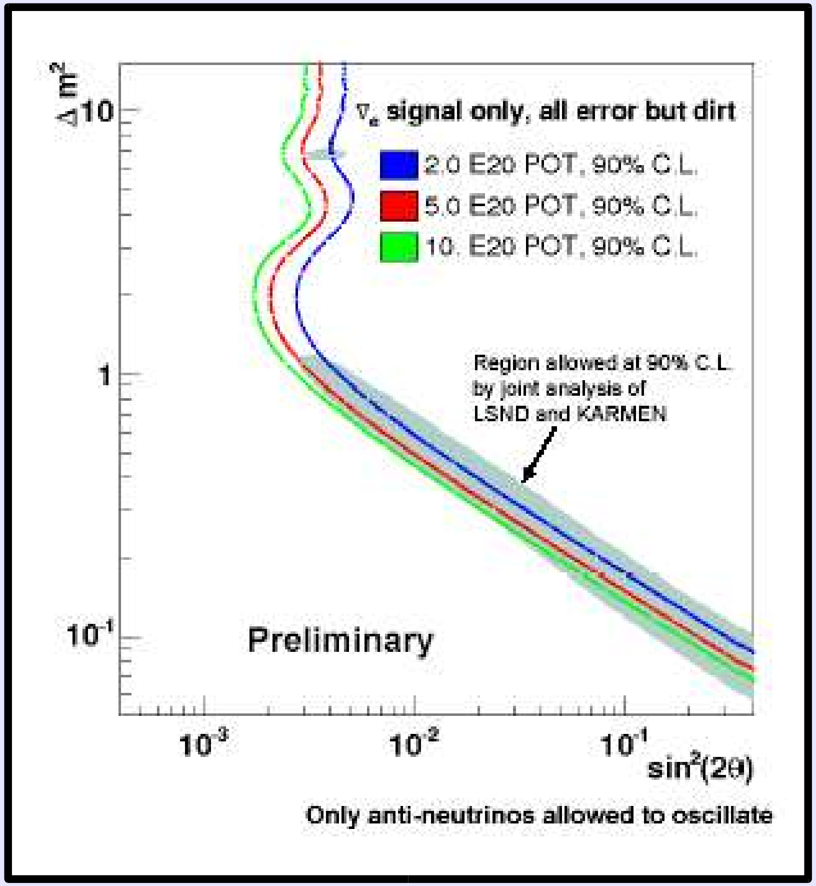
MiniBooNE 90% C.L. sensitivity with full suite of systematic uncertainties.

CDHS and CCFR 90% CL shown for comparison.

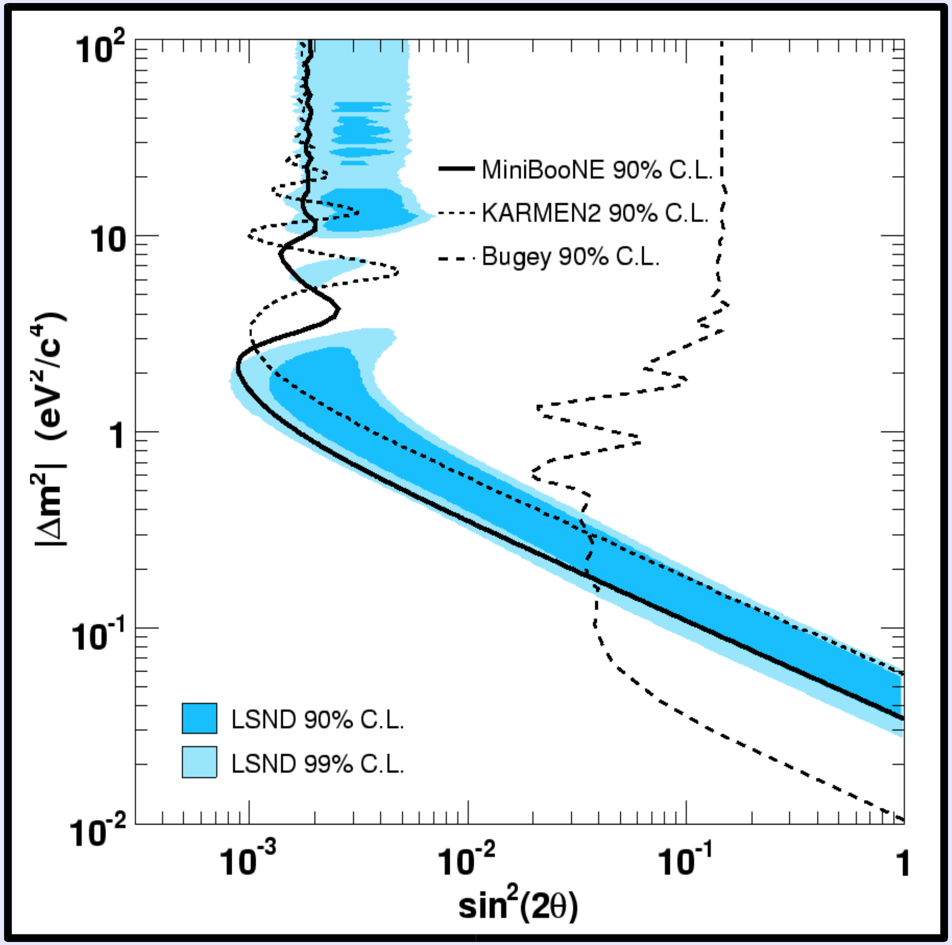
A combined analysis with SciBooNE data will significantly improve sensitivity.



MiniBooNE anti-nue appearance sensitivity



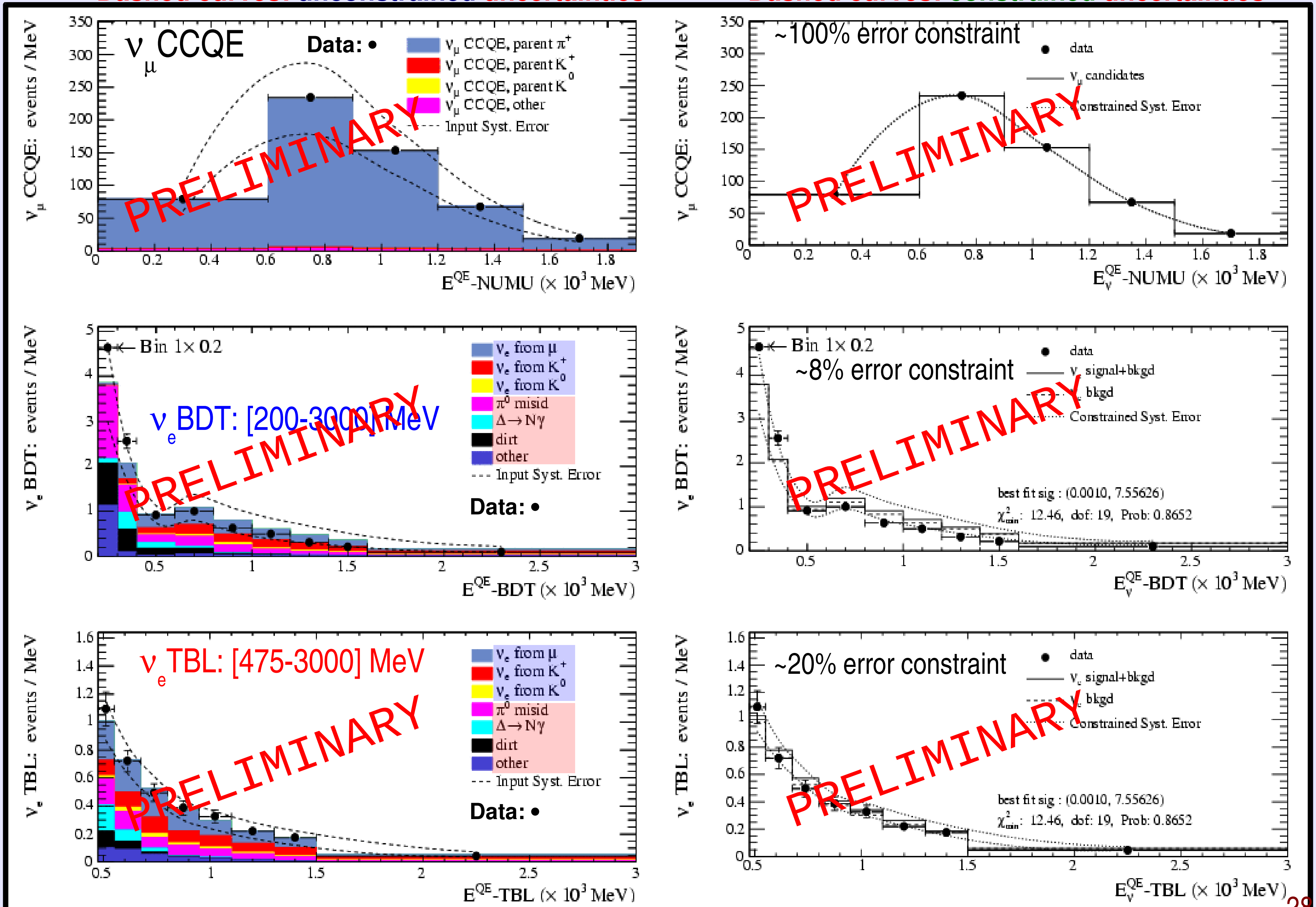
MiniBooNE, KARMEN2, Bugey



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

Comparison of the three distributions before and after fit

Dashed curves: unconstrained uncertainties — Dashed curves: constrained uncertainties



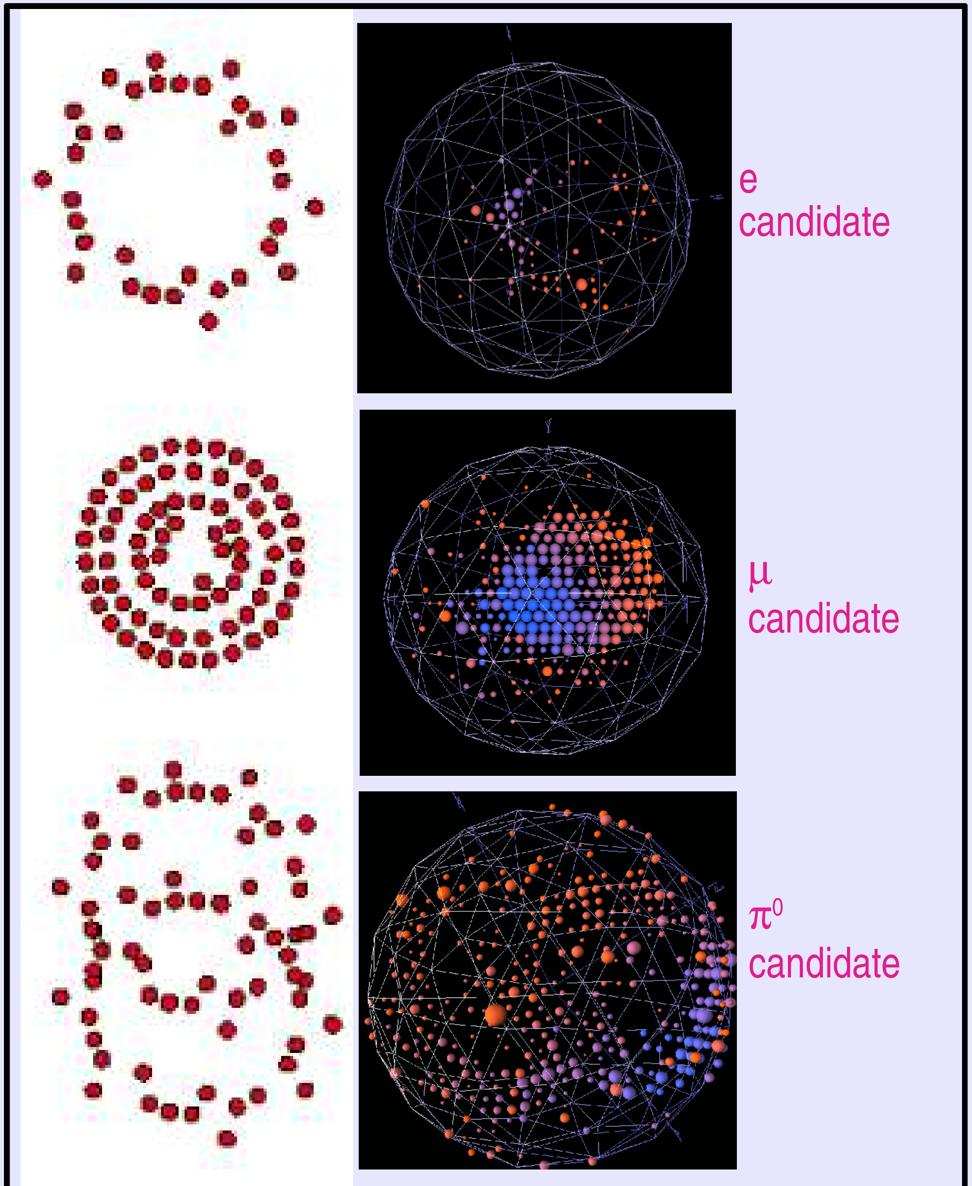
Systematic uncertainties -TBL based-

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.

Particles in the detector

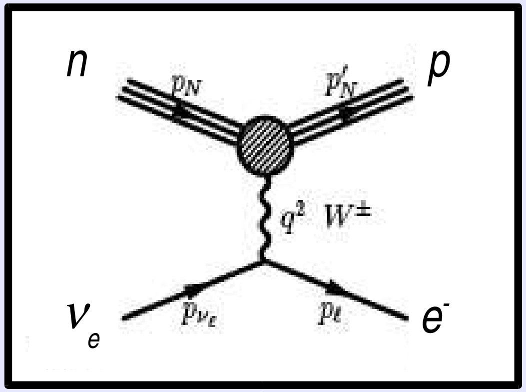


TBL Analysis: Cuts Used to Separate ν_μ events from ν_e events

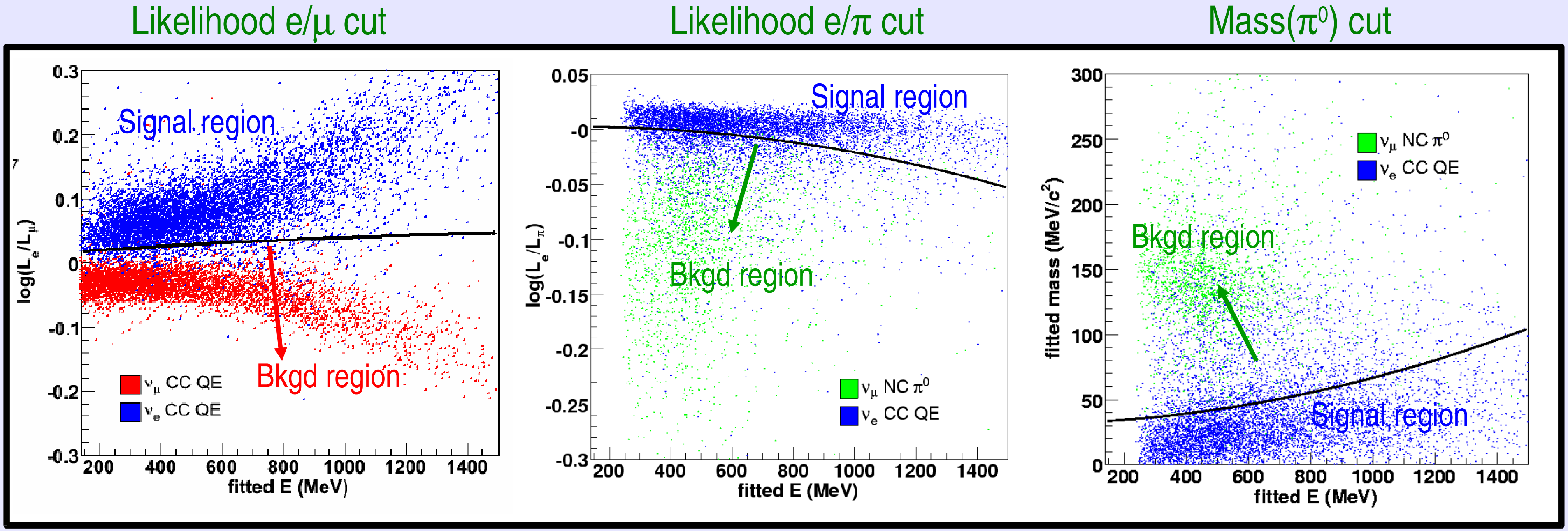
Fit the observed light distributions to three hypotheses:

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

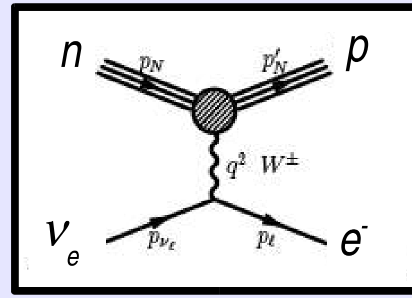


Blue points are signal ν_e events

Red points are background ν_μCC QE events

Green points are background ν_μ NC π^0 events

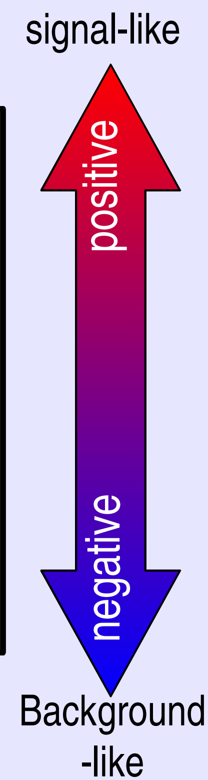
BDT specific ν_e selection cuts:

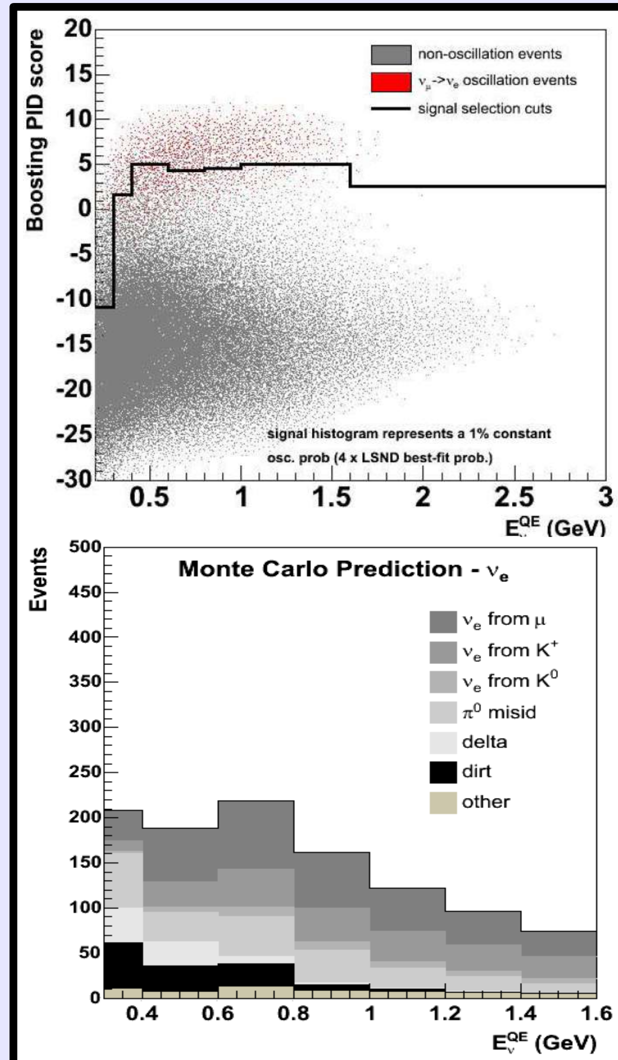


Decision tree: Sequential series of cuts based on a MC study.

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"**.

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