A Search for $\nu_\mu \rightarrow \nu_e$ Oscillation with MiniBooNE

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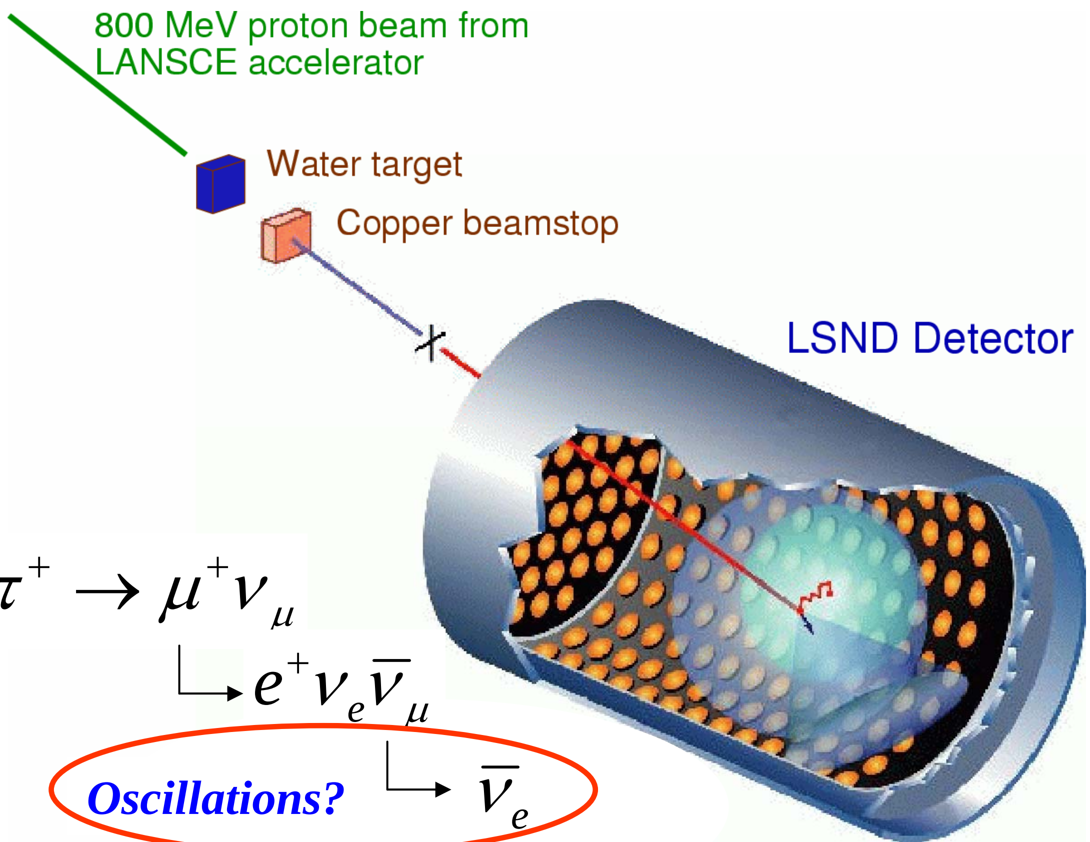
Outline

- ➔Physics Motivation
- ➔The MiniBooNE Experiment
- ➔Neutrino Beam Flux
- ➔Event Reconstruction & Identification
- ➔NuMI / MiniBooNE Data vs. MC
- ➔Measurement of Dirt Events
- ➔Expected Neutrino Oscillation Result

The LSND Experiment



$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\hookrightarrow \bar{\nu}_e$$

Signal: $\bar{\nu}_e \, p \to e^+ n$

$n \, p \to d \, \gamma(2.2\text{MeV})$

LSND took data from 1993-98

Nearly 49000 Coulombs of protons on target

Baseline: 30 meters

Neutrino Energy: 20-55 MeV

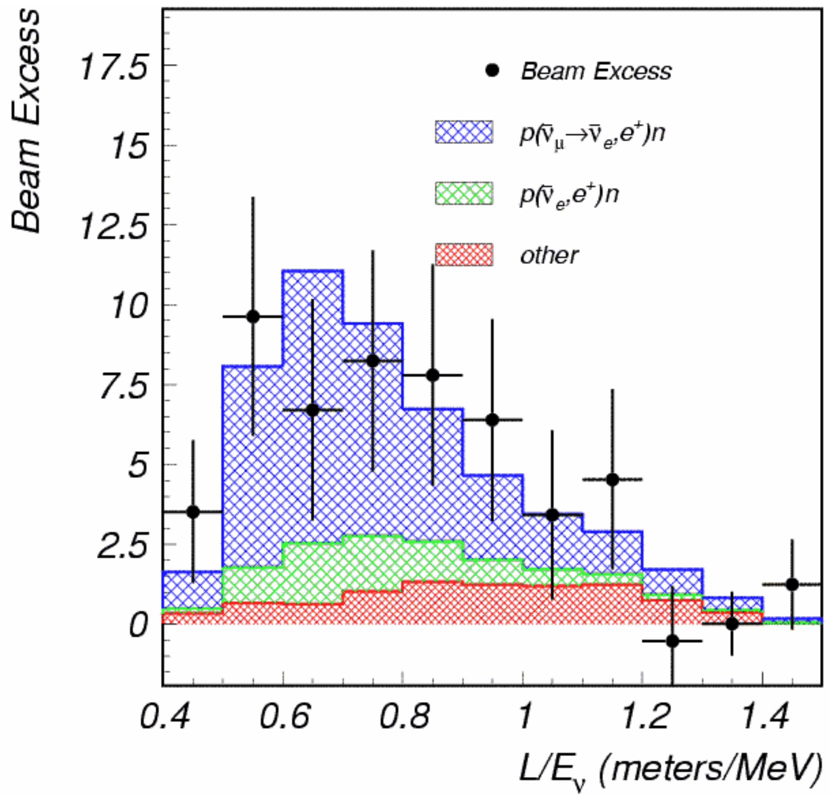
LSND Detector:
-- 1280 phototubes
-- 167 tons Liquid Scintillator

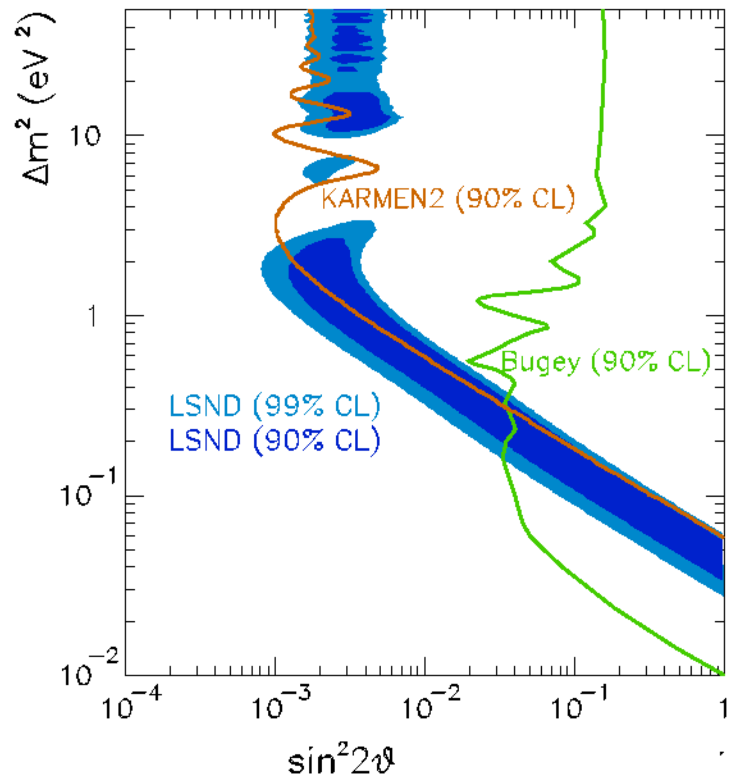
Observe an excess of $\bar{\nu}_e$:
-- 87.9 ± 22.4 ± 6.0 events.

The LSND Experiment

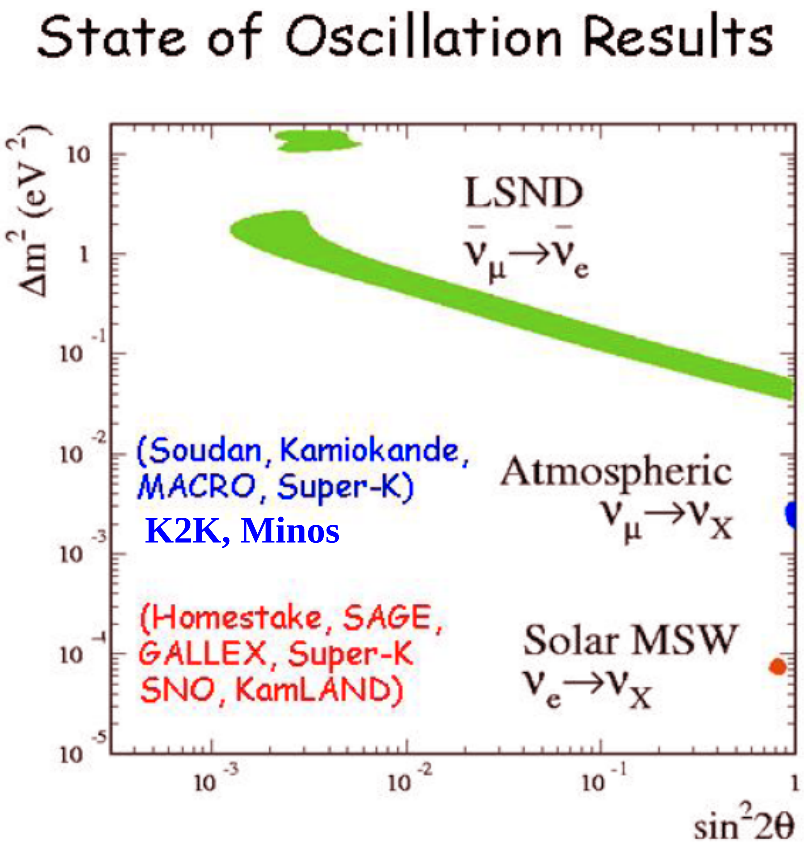
➔ LSND observed a positive signal(~3.8σ), but not confirmed.

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta)\sin^2(\frac{1.27\,L\Delta m^2}{E}) = (0.264 \pm 0.067 \pm 0.045)\%$$





Physics Motivation



- Simplest model has three neutrino mass eigenstates, but…
- Data indicates 3 mass differences
  - $\Delta m^2_{atm} \sim 2\text{-}3\times10^{-3}\ eV^2$
  - $\Delta m^2_{sol} \sim 7\times10^{-5}\ eV^2$
  - $\Delta m^2_{LSND} \sim .1\text{-}10\ eV^2$

$$\Delta m^2_{atm} + \Delta m^2_{sol} \neq \Delta m^2_{lsnd}$$

➔ If the LSND signal does exist, it will imply new physics beyond SM.

➔ The MiniBooNE is designed to confirm or refute LSND oscillation result at $\Delta m^2 \sim 1.0\ eV^2$.

How can there be 3 distinct Δm^2 ?

- **Mass Difference Equation:**

  $$(m_1^2 - m_2^2) + (m_2^2 - m_3^2) = (m_1^2 - m_3^2)$$

1. One of the experimental measurements is wrong
2. One of the experimental measurements is not neutrino oscillations:
   → Neutrino decay
   → Neutrino production from flavor violating decays
3. Additional "sterile" neutrinos involved in oscillation
4. CPT violation or CP violation + sterile ν's allows different mixing for ν's and ν bars.

The MiniBooNE Experiment

- Proposed in summer 1997，operating since 2002
- **The goal of the MiniBooNE Expriment: to confirm or exclude the LSND result and extend the explored oscillation parameter space**
- Similar L/E as LSND
  - Baseline: L = 451 meters, ~ x15 LSND
  - Neutrino Beam Energy: E ~ x(10-20) LSND
- Different systematics: event signatures and backgrounds different from LSND
- High statistics: ~ x5 LSND
- Expected ~ 90% C.L. for most of LSND allowed region

The MiniBooNE Collaboration

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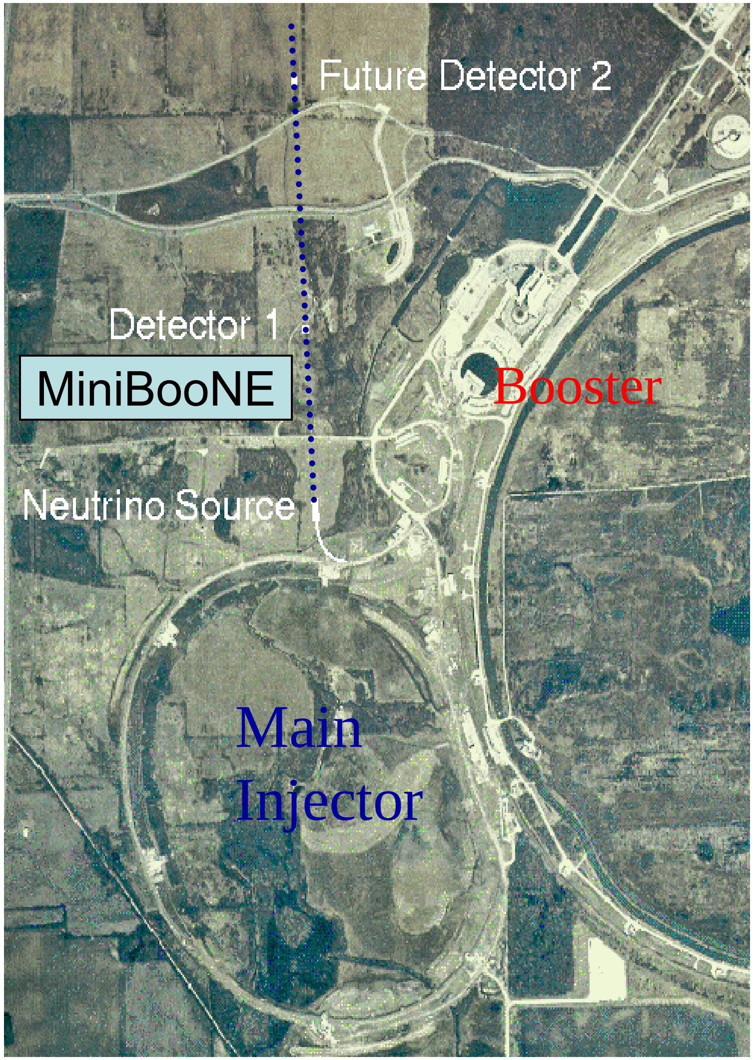
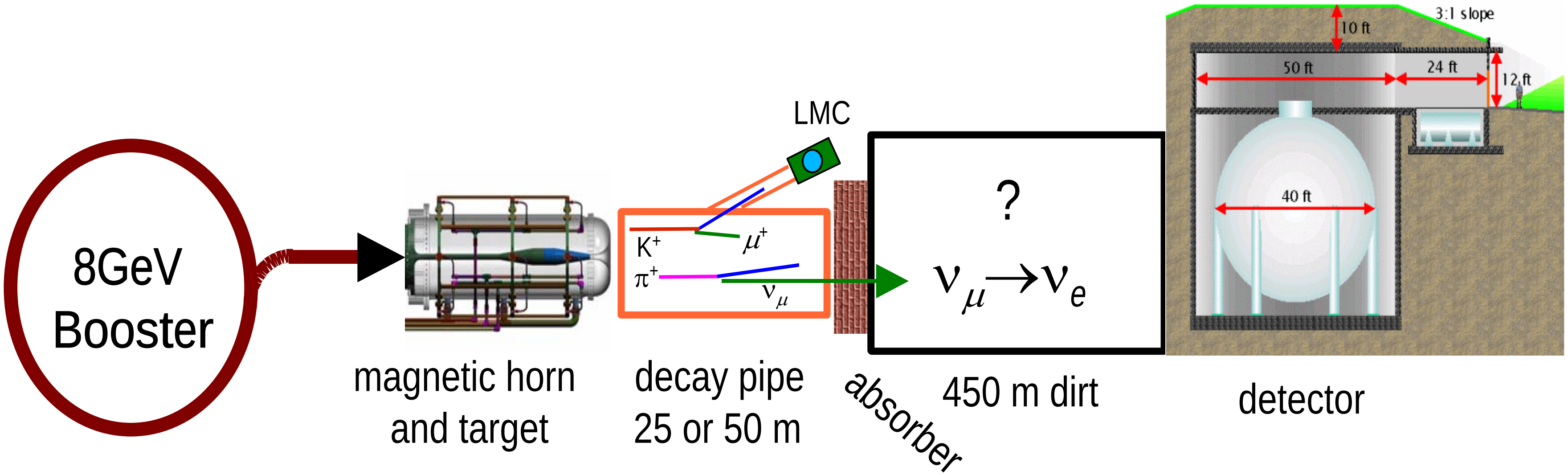
Fermilab Booster



The MiniBooNE Experiment



- The FNAL Booster delivers 8 GeV protons to the MiniBooNE beamline.
- The protons hit a 71cm beryllium target producing pions and kaons.
- The magnetic horn focuses the secondary particles towards the detector.
- The mesons decay into neutrinos, and the neutrinos fly to the detector, all other secondary particles are absorbed by absorber and 450 m dirt.
- 5.579E20 POT for neutrino mode since 2002.
- Switch horn polarity to run anti-neutrino mode since January 2006.

MiniBooNE Flux

8 GeV protons on Be target gives:

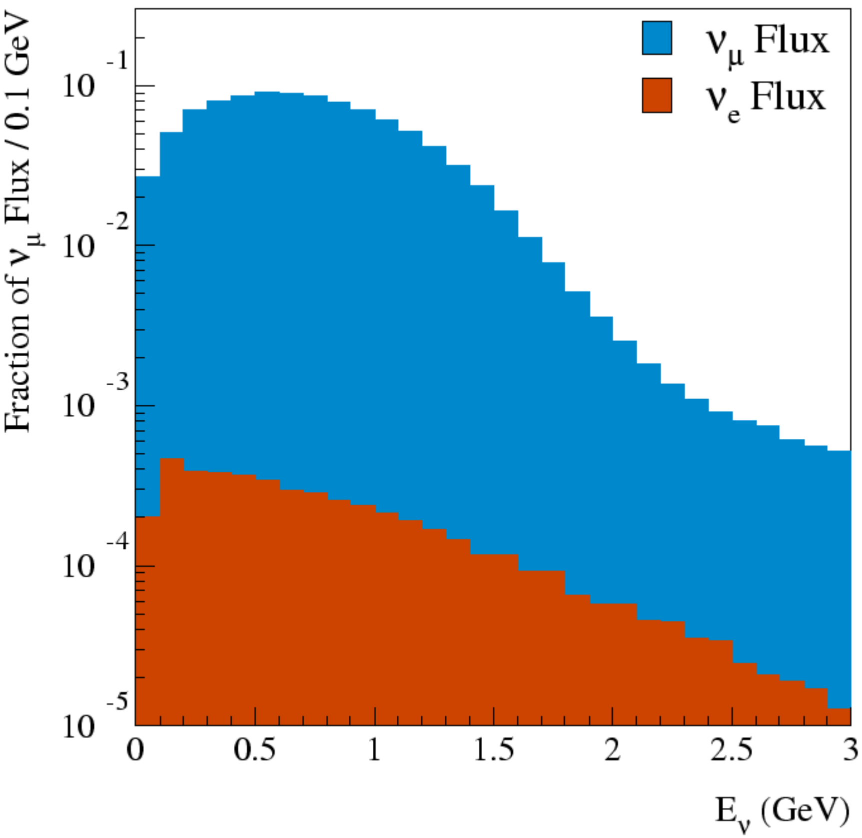
$p + Be \rightarrow \pi^+, K^+, K^0_L$

ν_μ from:

$\pi^+ \rightarrow \mu^+ \nu_\mu \quad K^+ \rightarrow \mu^+ \nu_\mu \quad K^0_L \rightarrow \pi^- \mu^+ \nu_\mu$

Intrinsic ν_e from:

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \quad K^+ \rightarrow \pi^0 e^+ \nu_e \quad K^0_L \rightarrow \pi^- e^+ \nu_e$



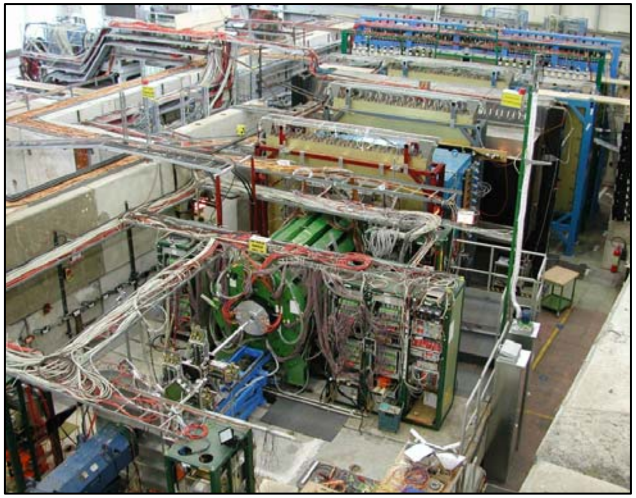
The intrinsic ν_e, ~0.5% of the neutrino flux, are one of the major backgrounds for $\nu_\mu \rightarrow \nu_e$ search.

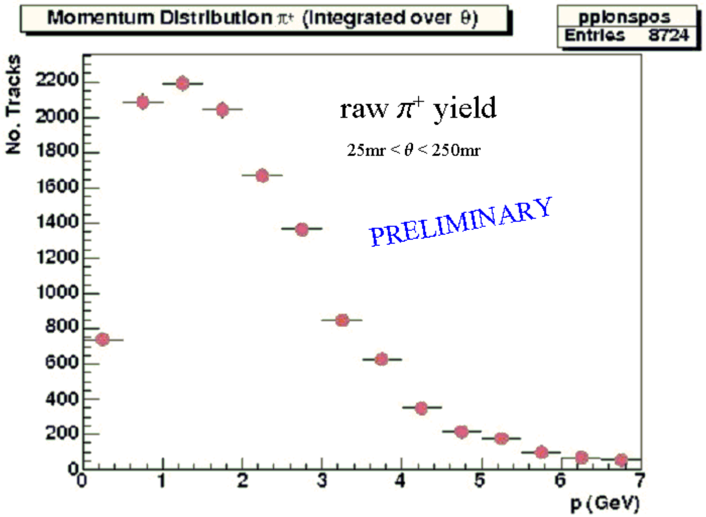
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27 L \Delta m^2}{E}\right)$$

$L(m), E(MeV), \Delta m^2(eV^2)$

Understanding Neutrino Flux (I)

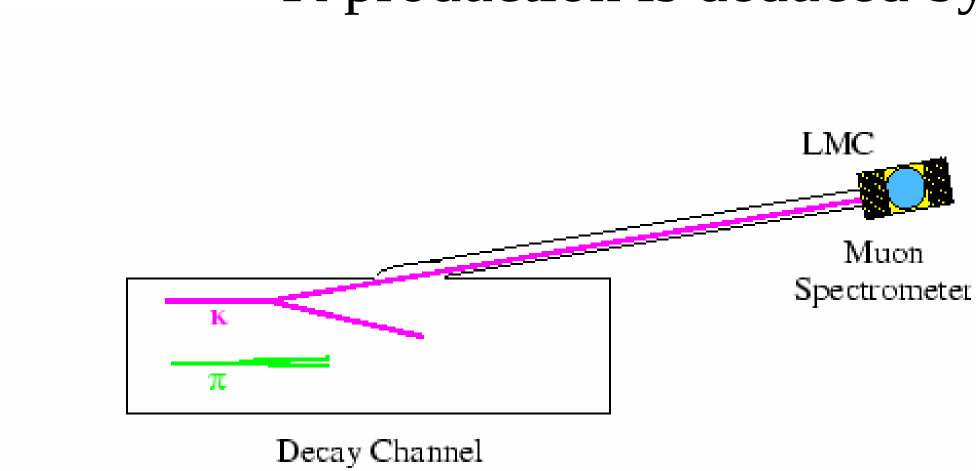
- E910 @ BNL + previous world data fits
  - Basis of current MiniBooNE π production model
- HARP @ CERN, 8 GeV Proton Beam
  - MiniBooNE target slug - thin target (5, 50, 100 % λ)
  - Measure π^+ production

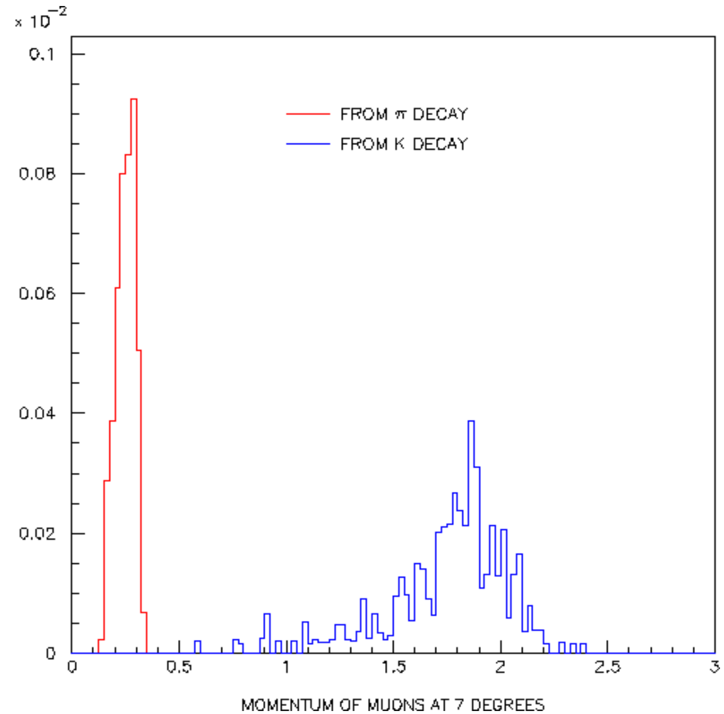




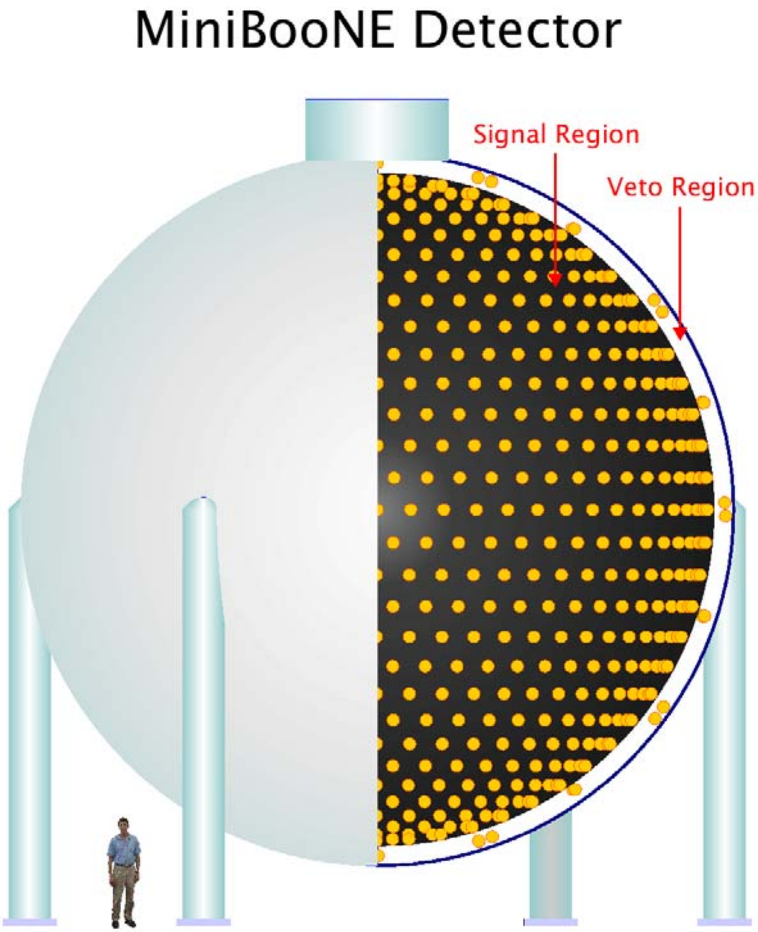
Understanding Neutrino Flux (II)

- Little Muon Counter (LMC)
  - Scintillating fibre tracker 7 degrees off axis
  - K decays produce wider angle μ than π decays
  - K production is deduced by measuring off-axis μ

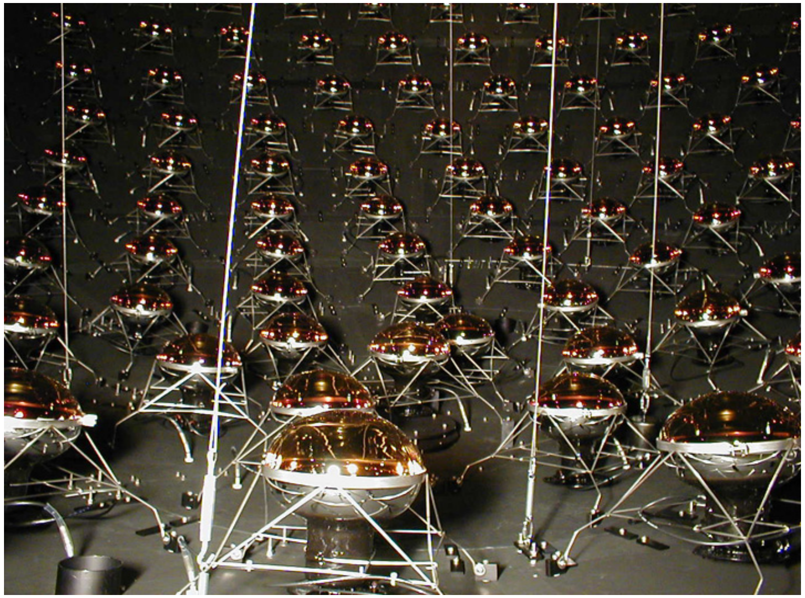




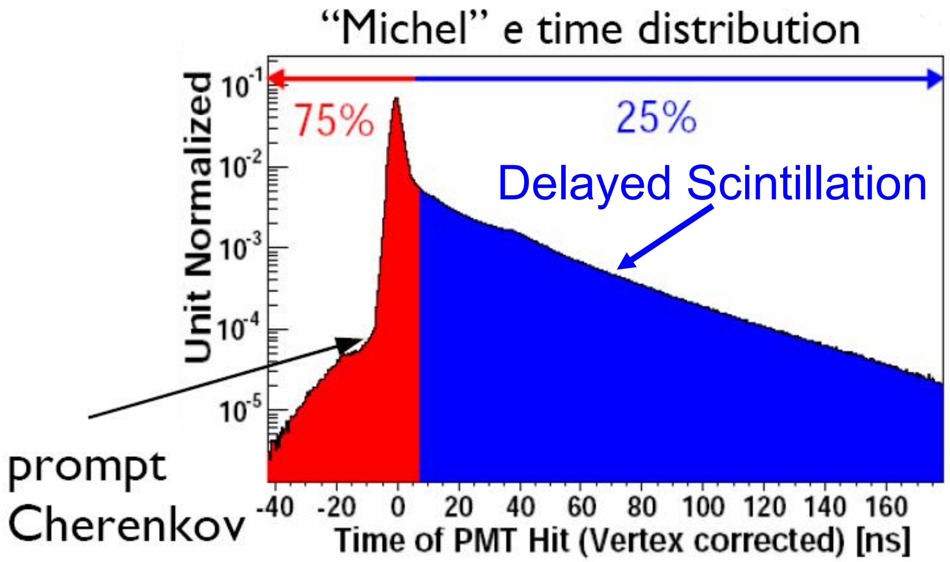
The MiniBooNE Detector



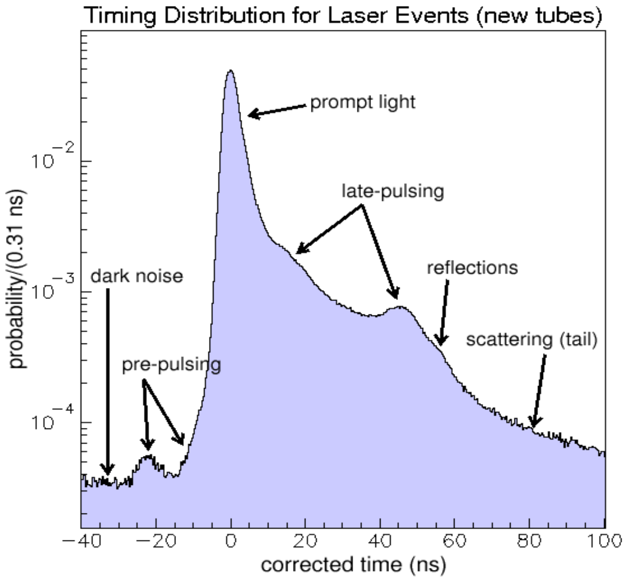
- 12m diameter tank
- Filled with 800 tons of pure mineral oil
- Optically isolated inner region with 1280 PMTs
- Outer veto region with 240 PMTs.



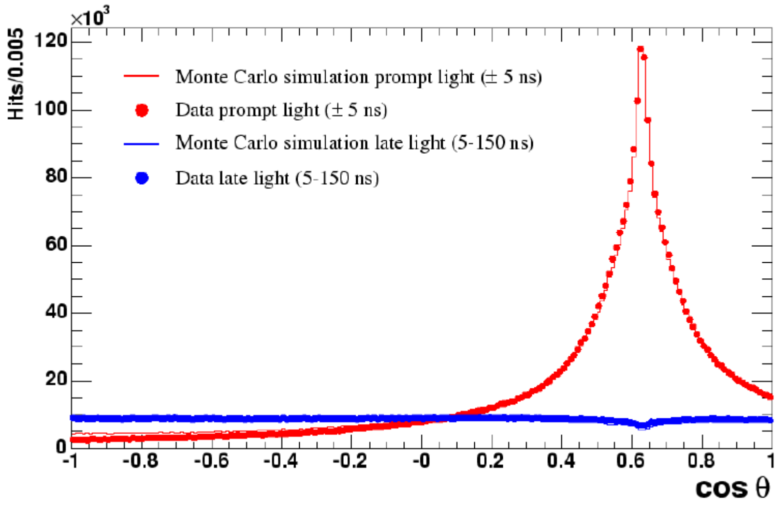
PMT



"Michel" e time distribution
Unit Normalized
75%
25%
Delayed Scintillation
prompt Cherenkov
Time of PMT Hit (Vertex corrected) [ns]



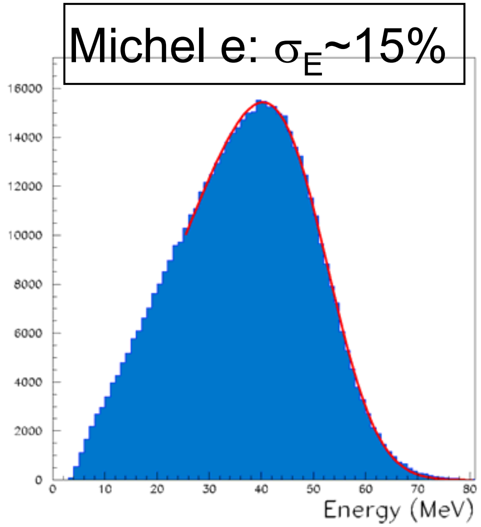
Timing Distribution for Laser Events (new tubes)
probability/(0.31 ns)
prompt light
late-pulsing
reflections
dark noise
pre-pulsing
scattering (tail)
corrected time (ns)

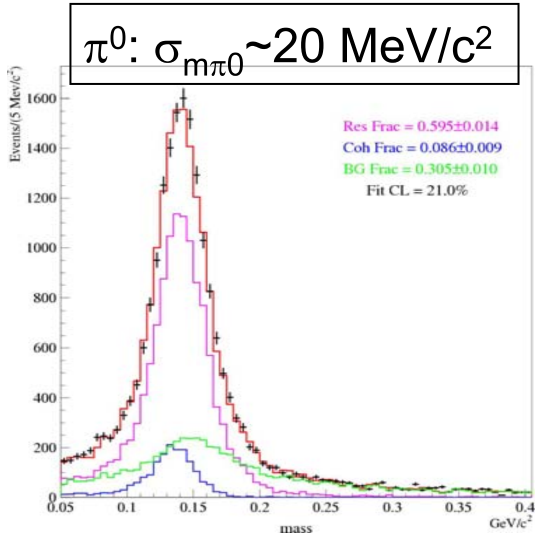


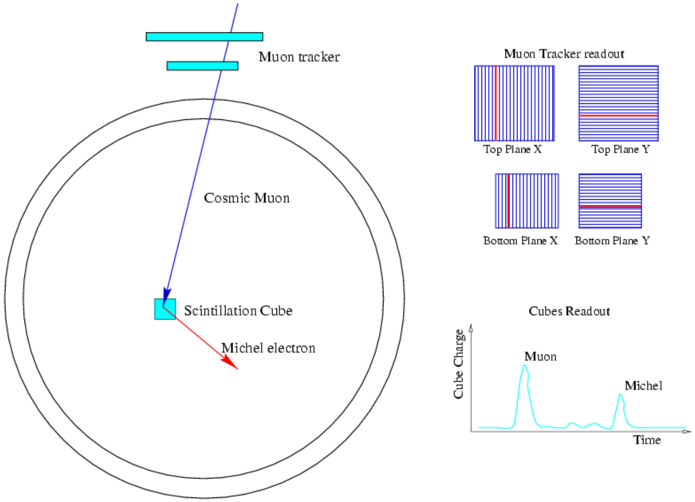
Hits/0.005
Monte Carlo simulation prompt light (± 5 ns)
Data prompt light (± 5 ns)
Monte Carlo simulation late light (5-150 ns)
Data late light (5-150 ns)
cos θ

Energy Calibration

➔ Michel e from μ decay: low energy 52.8 MeV.

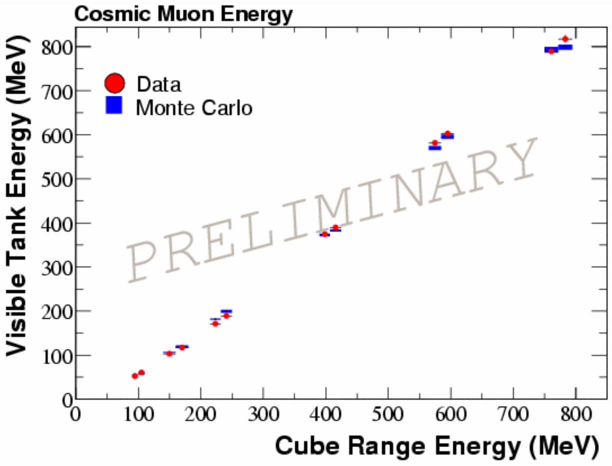






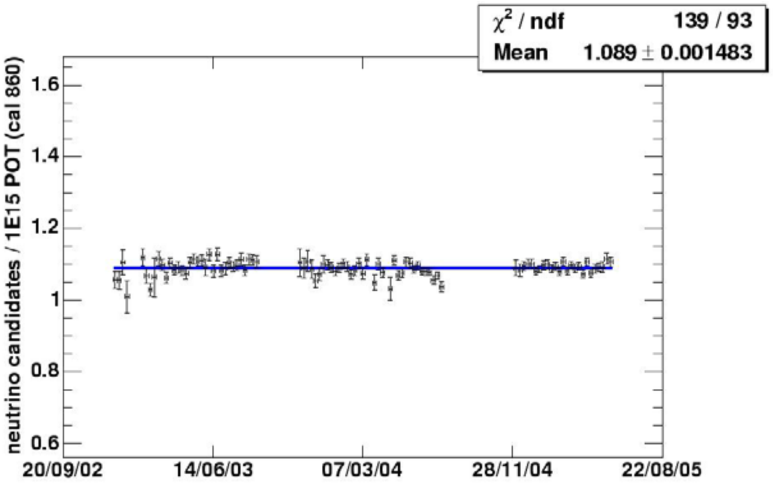
➔ π^0 mass peak: calibrate medium energy, photons decay from π^0 ranging 50 ~ 400 MeV

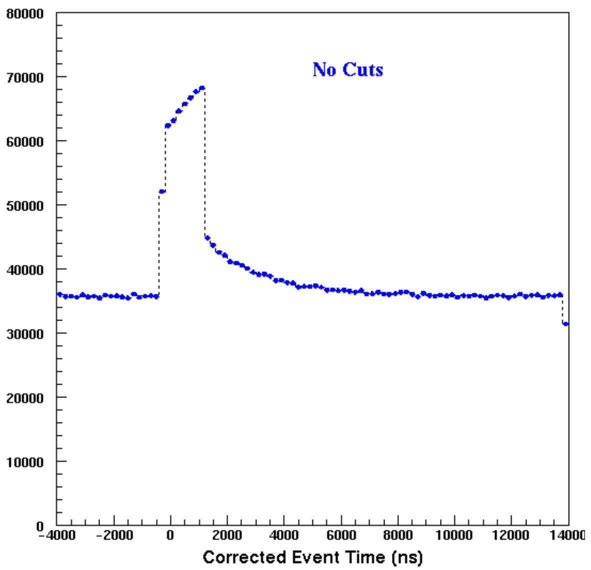
➔ cosmic ray μ + tracker + cubes: calibrate μ energy ranging from 100 ~ 800 MeV

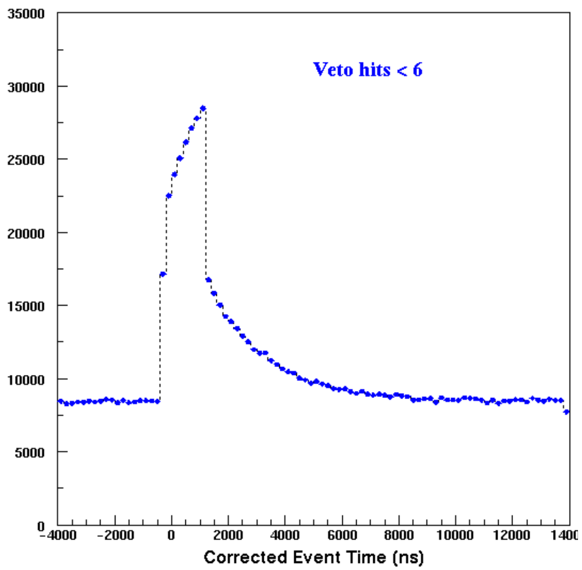


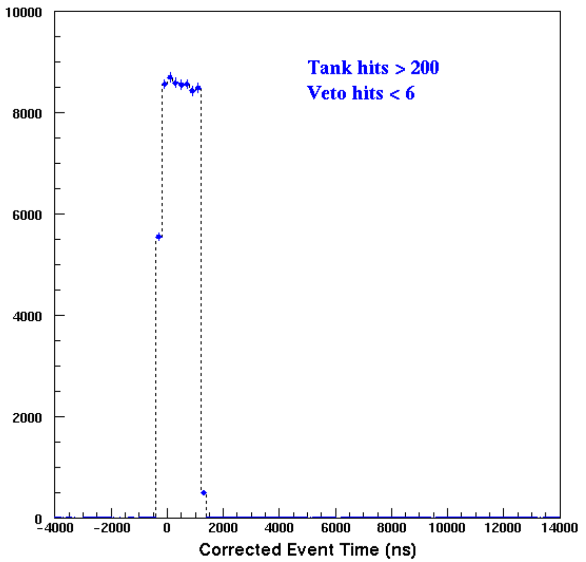
Neutrino Candidates

- DAQ triggered on beam from Booster
- Detector read out for 19.2 μs
- Neutrino pulse through detector lasts 1.6 μs
- 1.09 neutrino candidates / 1E15 POT
- With a few very simple cuts (time window, tank/veto hits) to obtain pure neutrino events.







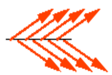


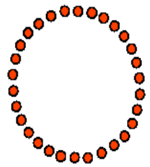
Event Topology

Cerenkov Light...

From side | Ring

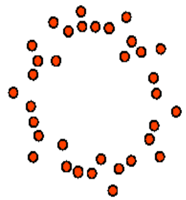
short track, no multiple scattering





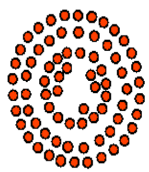
Sharp Ring

electrons: short track, mult. scat., brems.



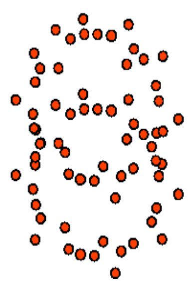
Fuzzy Ring

muons: long track, slows down

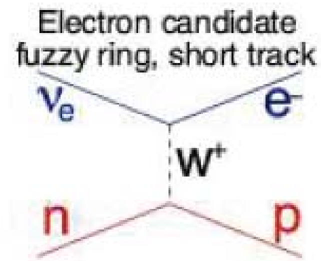


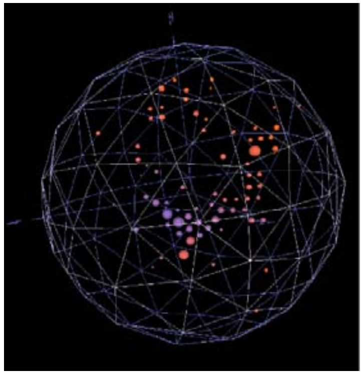
Sharp Outer Ring with Fuzzy Inner Region

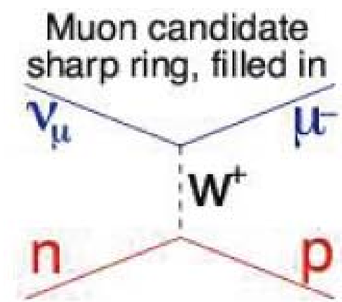
neutral pions: 2 electron-like tracks

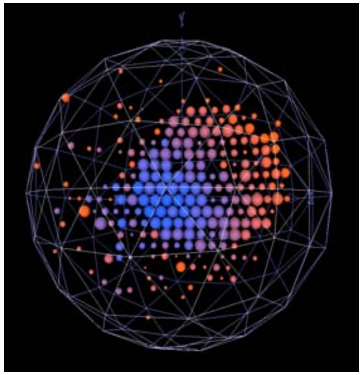


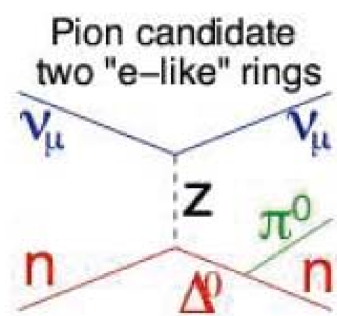
Two Fuzzy Rings

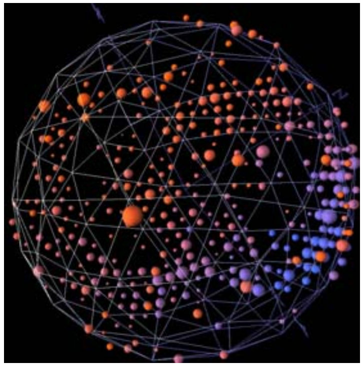












Event Reconstruction

- To reconstruct event position, direction, time, energy and invariant mass etc.
- Cerenkov light – prompt, directional
- Scintillation light – delayed, isotropic
- Using time likelihood and charge likelihood method to determine the optimal event parameters.
- Two parallel reconstruction packages
  - S-Fitter is based on a simple, point-like light source model;
  - P-Fitter differs from S-Fitter by using more 0^{th} approximation tries, adding e/μ tracks with longitudinally varying light source term, wavelength-dependent light propagation and detection, non-point-like PMTs and photon scattering, fluorescence and reflection.

Particle Identification

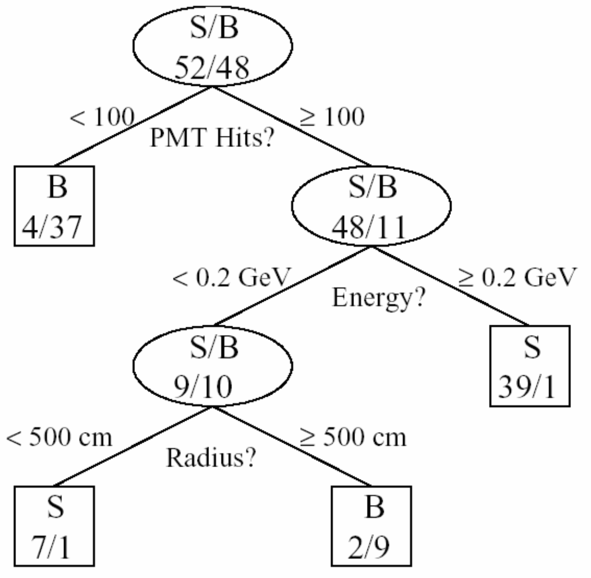
Two complementary and parallel methods:

- Log-likelihood technique:
  - simple to understand, widely used in HEP data analysis
- Boosted Decision Trees:
  - Non-linear combination of input variables
  - Great performance for large number of input variables (about two hundred variables)
  - Powerful and stable by combining many decision trees to make a "majority vote"

Boosted Decision Trees

How to build a decision tree ?

For each node, try to find the best variable and splitting point which gives the best separation based on Gini index.
Gini_node = Weight_total*P*(1-P), P is weighted purity
Criterion = Gini_father – Gini_left_son – Gini_right_son
Variable is selected as splitter by maximizing the criterion.

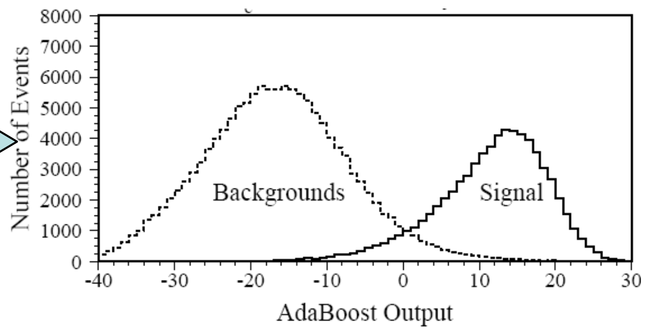


How to boost the decision trees?

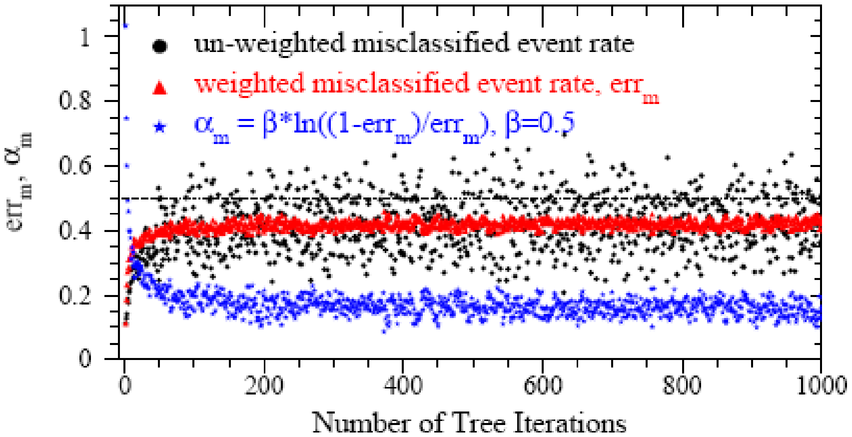
Weights of misclassified events in current tree are increased, the next tree is built using the same events but with new weights, Typically, one may build few hundred to thousand trees.

How to calculate the event score ?

For a given event, if it lands on the signal leaf in one tree, it is given a score of 1, otherwise, -1. The sum (probably weighted) of scores from all trees is the final score of the event.

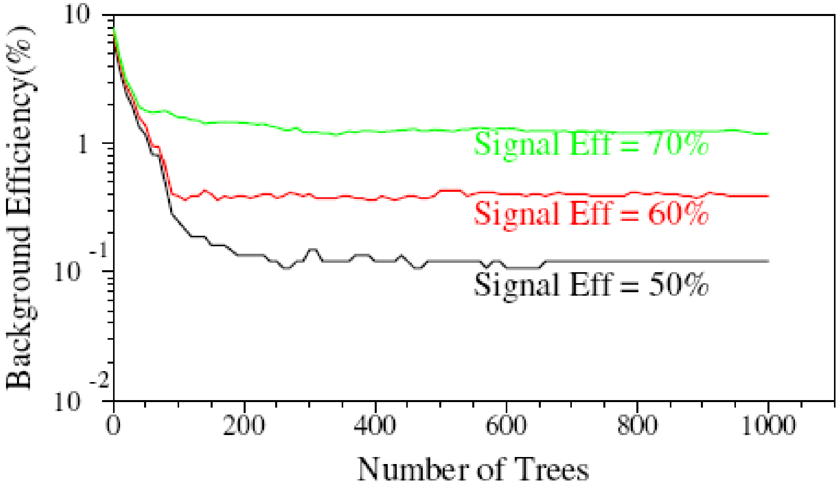


Performance vs Number of Trees



➔ Boosted decision trees focus on the misclassified events which usually have high weights after hundreds of tree iterations. An individual tree has a very weak discriminating power; the weighted misclassified event rate err_m is about 0.4-0.45.

➔The advantage of using boosted decision trees is that it combines many decision trees, “weak” classifiers, to make a powerful classifier. The performance of boosted decision trees is stable after a few hundred tree iterations.



Ref1: H.J.Yang, B.P. Roe, J. Zhu, “Studies of Boosted Decision Trees for MiniBooNE Particle Identification”, Physics/0508045, Nucl. Instrum. & Meth. A 555(2005) 370-385.
Ref2: B.P. Roe, H.J. Yang, J. Zhu, Y. Liu, I. Stancu, G. McGregor, ”Boosted decision trees as an alternative to artificial neural networks for particle identification”, physics/0408124, NIMA 543 (2005) 577-584.

Blindness Analysis

- We do not look into the data region where the ν_e oscillation candidates are expected.
- We are allowed to use part sample to check the goodness of Monte Carlo modeling
  - Some of the information in all of the data
  - All of the information in some of the data

➔To use NuMI sample as an useful cross check

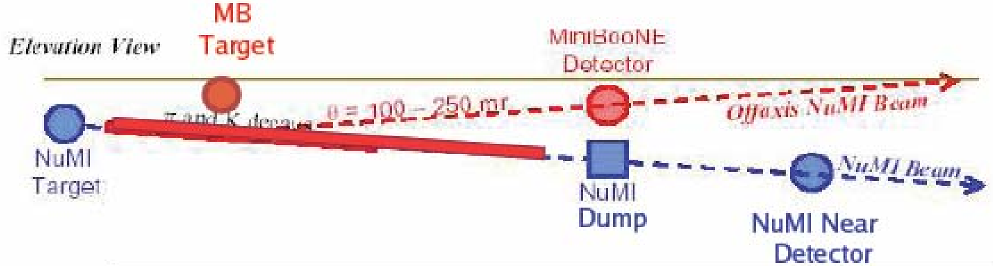
➔To use ν_μ background events to study the agreement of Data and Monte Carlo events.

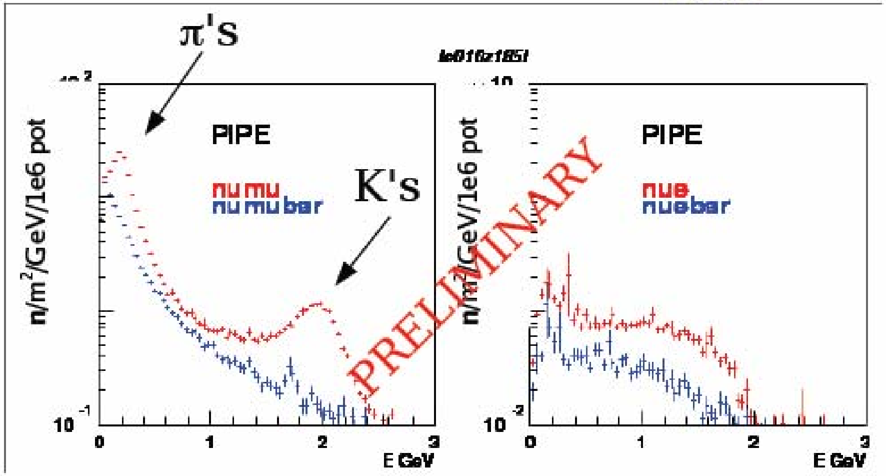
NuMI Sample

Use NuMI beam as a cross check for analysis → Event Classification

MiniBooNE sees TWO neutrino beams

(World's 1st off axis ν detector!)

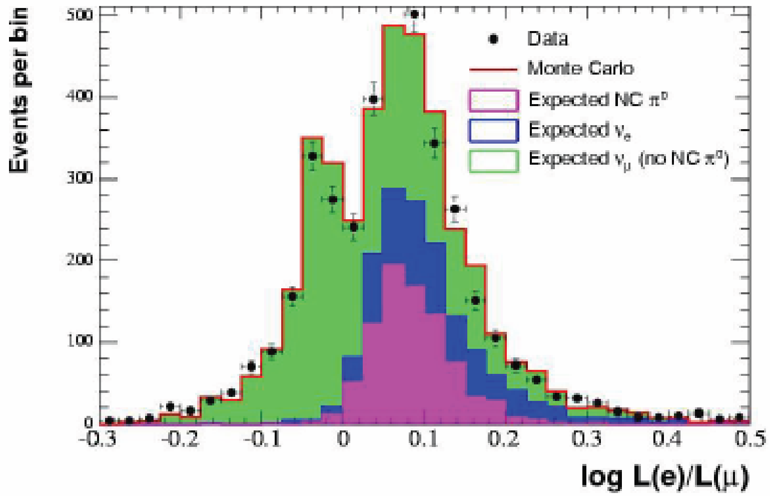


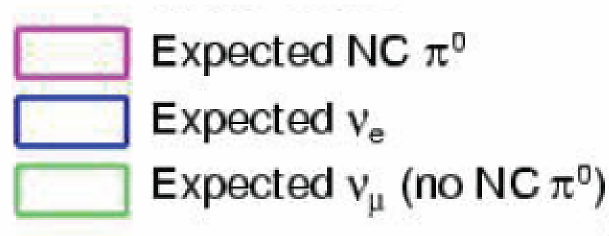


Thesis project: Alexis A. Aguilar-Arévalo

NuMI Sample

NuMI Event Classification: Likelihood analysis

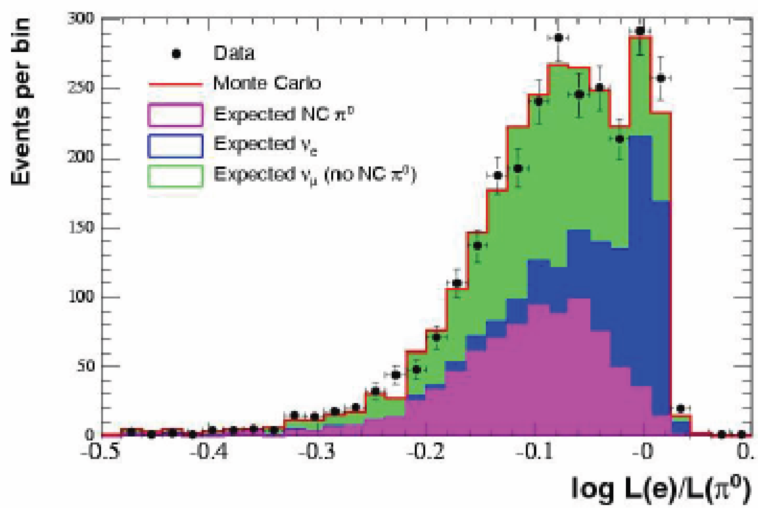




relatively normalized data/MC

↓

good agreement

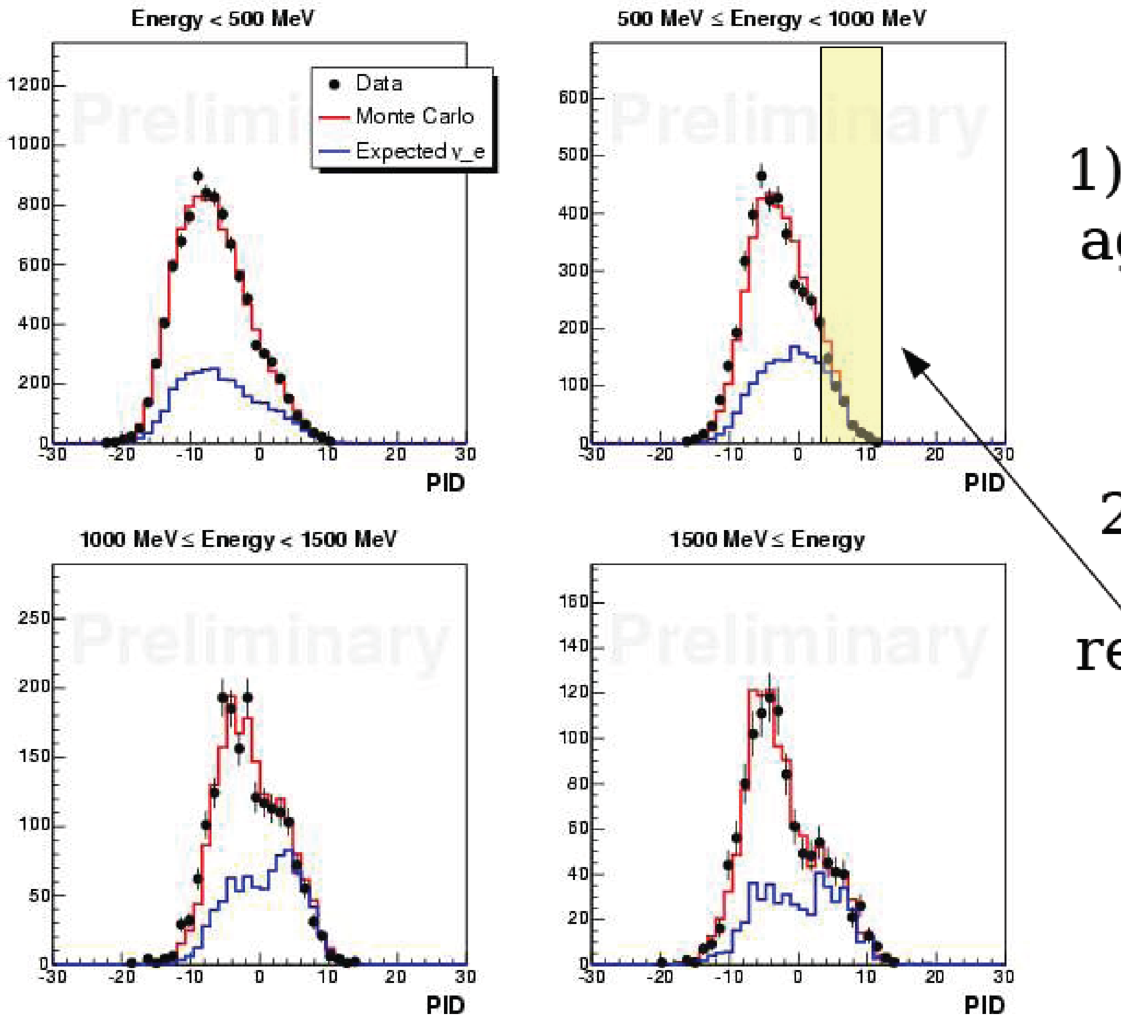


Cut on log L(e)/L(μ)>0.02

resolving power in log L(e)/L(π°)

NuMI Sample

NuMI Event Classification: Boosted Decision Trees

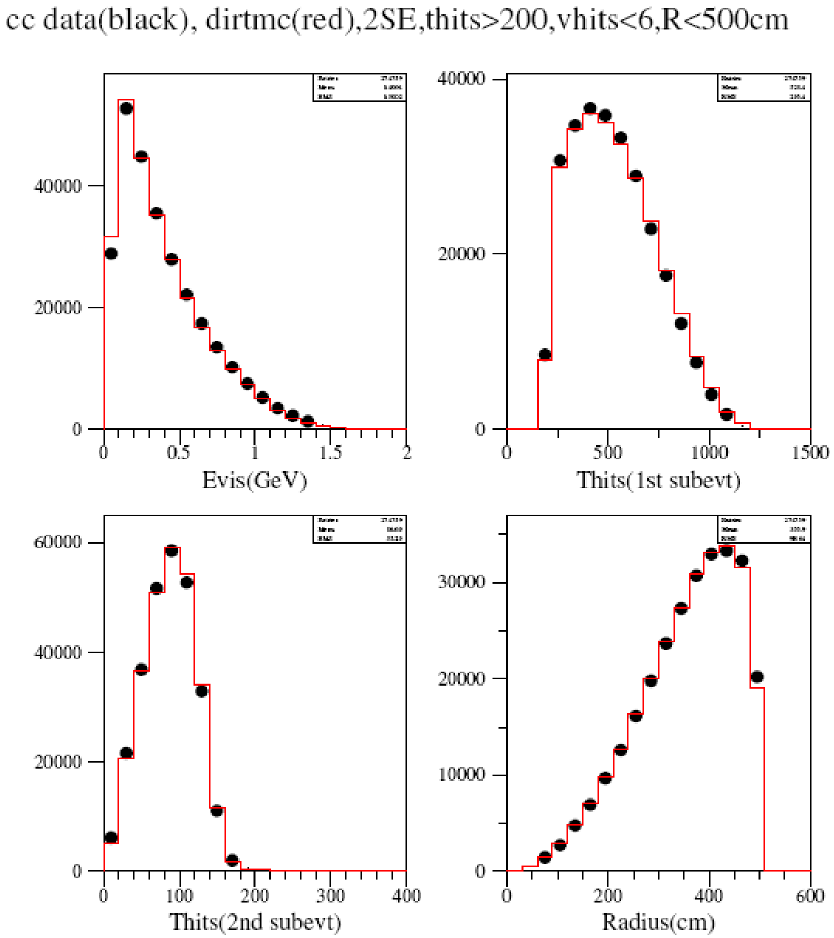


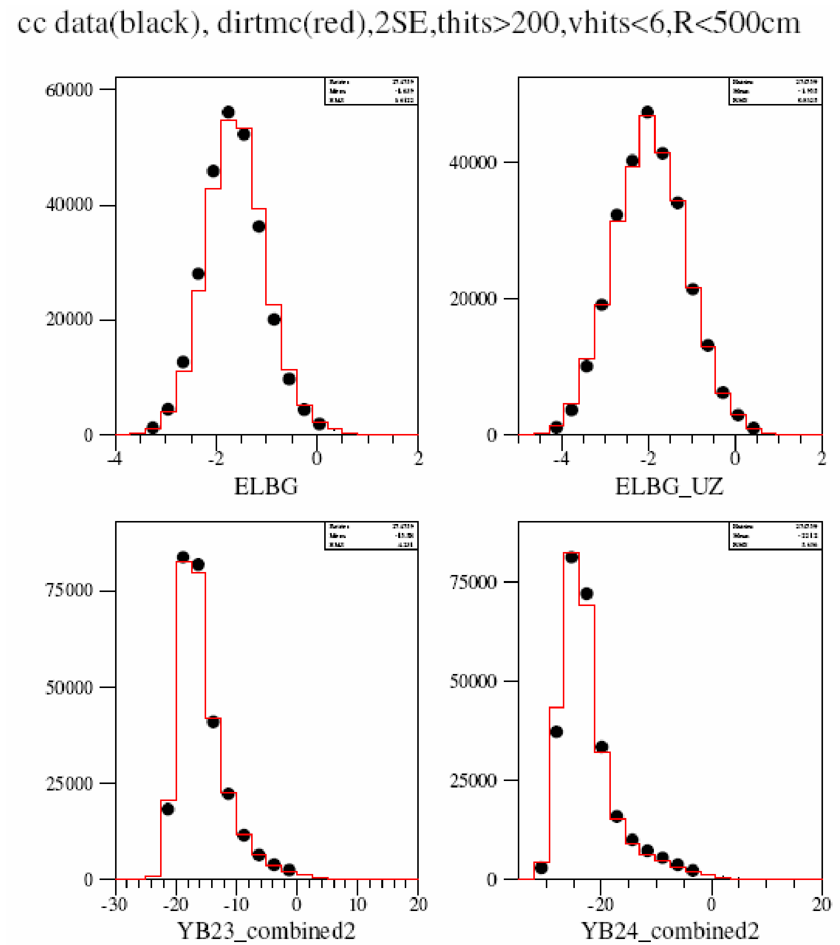
1) good data/MC agreement over range of energies

2) Use regions of greatest resolving power to study

e's vs background

MiniBooNE Data VS. Monte Carlo





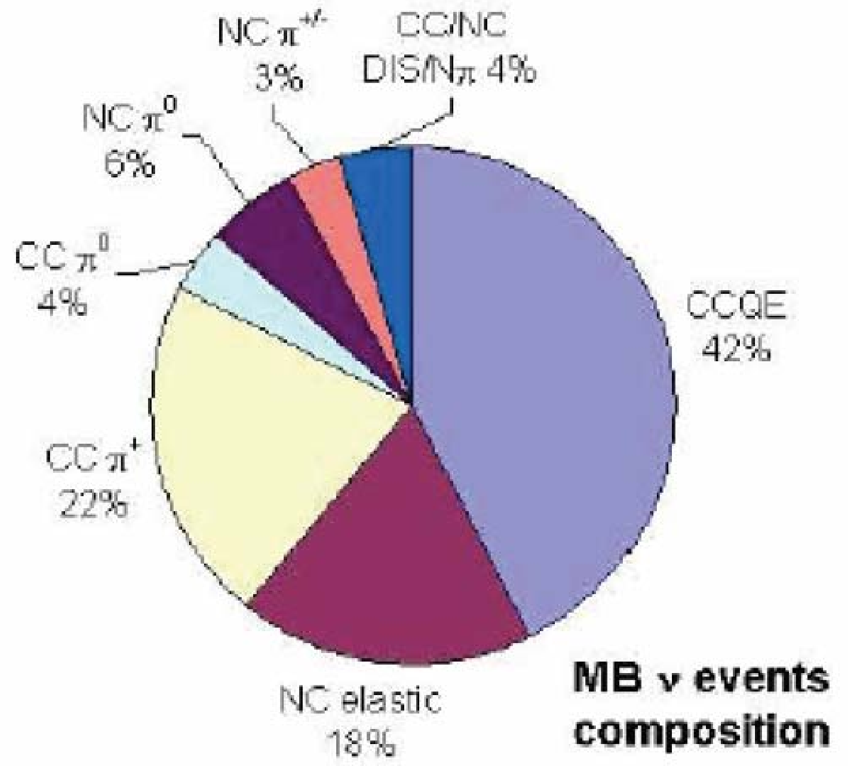
Visible Energy, Tank Hits, Radius

Outputs of Boosted Decision Trees

MiniBooNE Event Rates

➔ ν events currently "on-tape"
5.6E20 protons-on-target (POT)

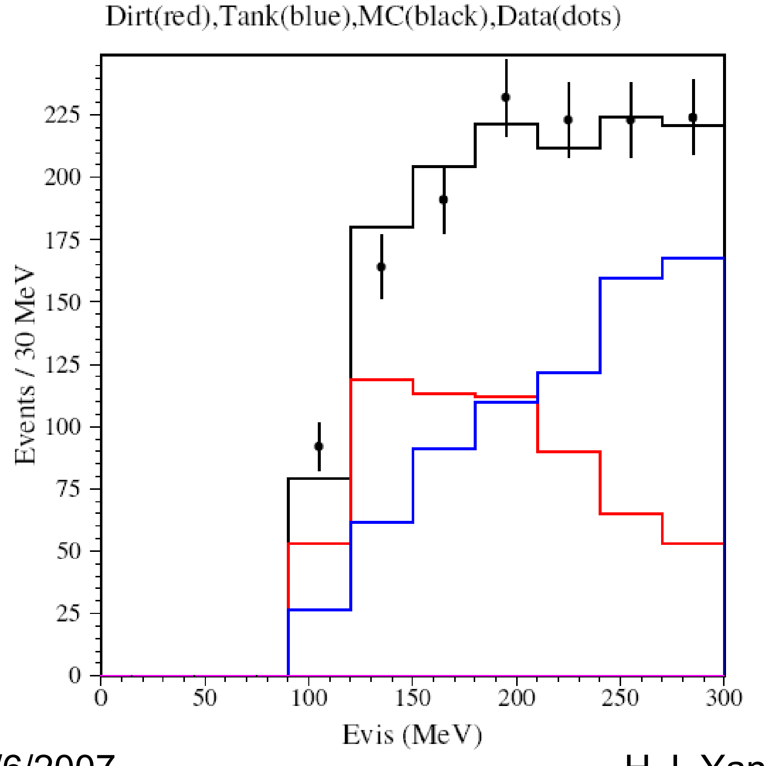
"CC" = charged current
"NC" = neutral current



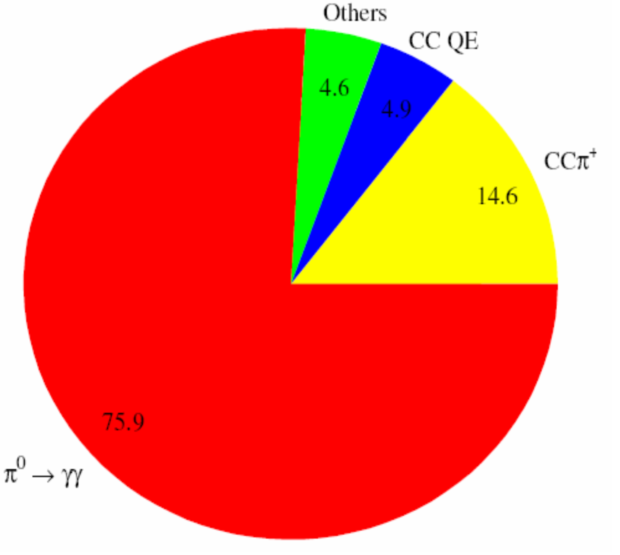
ν channel	events
all channels	810k
CC quasielastic	340k
NC elastic	150k
CC π^+	180k
CC π^0	30k
NC π^0	48k
NC $\pi^{+/-}$	27k
CC/NC DIS, multi-π	35k

Measurement of Dirt Events

➔Neutrino beam interacts with dirt outside of tank, the high energy photons (100 ~ 300 MeV) sneak into the tank to produce electron-like Cerenkov ring.
➔N_dirt_measured / N_dirt_expected = 0.99 ± 0.15
➔Dirt events contribute ~10% of background for oscillation nue search.

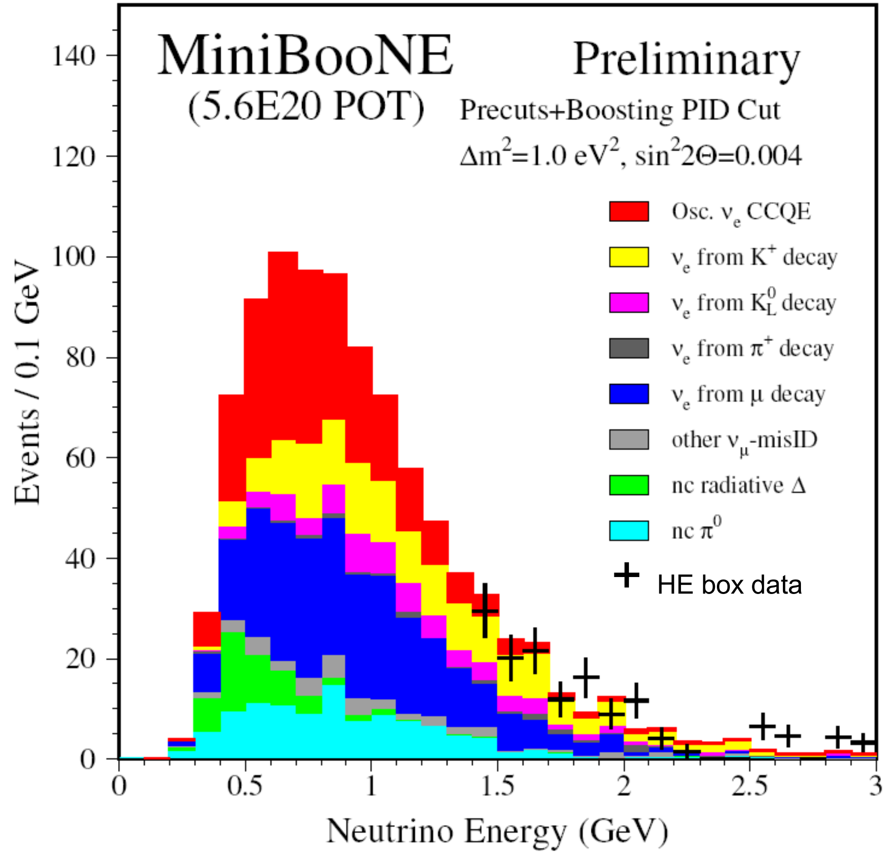


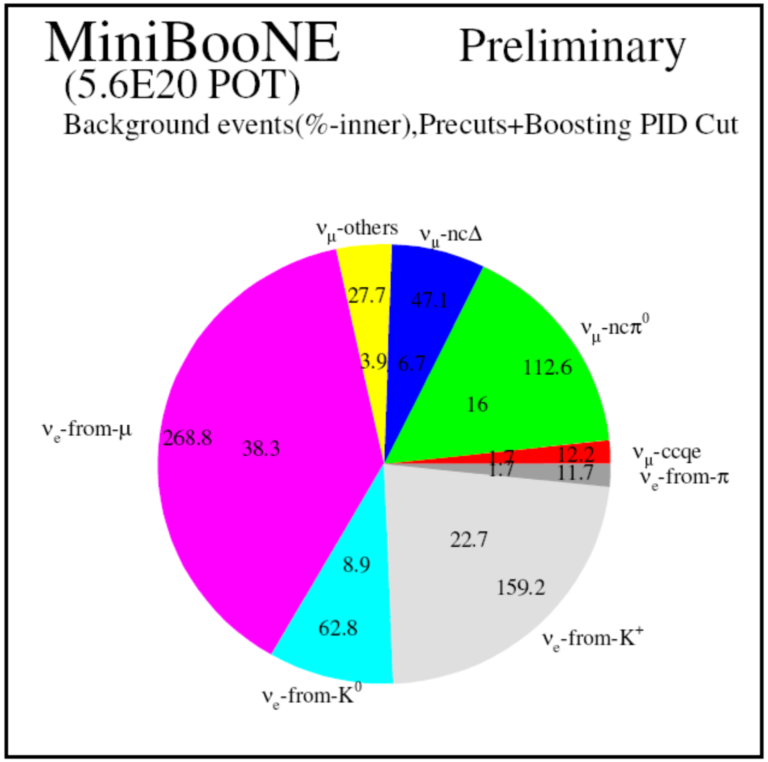
Event Type of Dirt after PID cuts



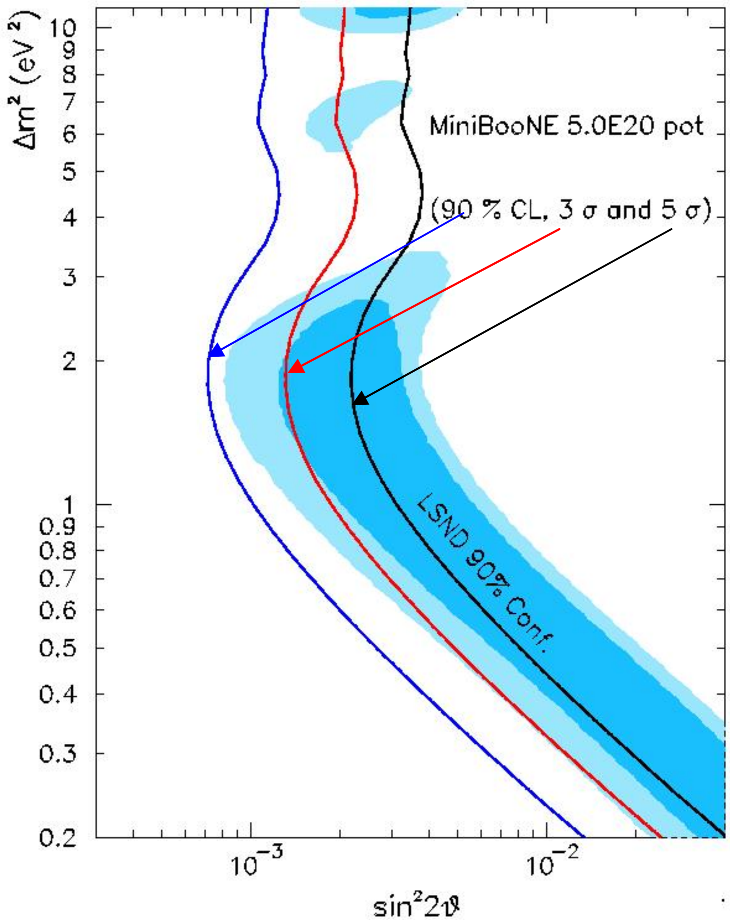
Expected Nue Oscillation Events

N_oscnue ~ 239 (Δm^2=1.0 eV^2, $\sin^2 2\Theta$=0.004), N_background ~ 702, N_dirt ~ 80





Nue Oscillation Sensitivity



- ➔ MiniBooNE aims to cover most of LSND allowed region at 90% CL.
- ➔ We are currently finalizing systematic error matrix from beam flux, cross sections, detector modeling, optical modeling etc.
- ➔ We are finalizing analysis program.
- ➔ We anticipate to open box shortly.