Status of the MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation Search

APS/DPF – JPS '06

Honolulu, Hawai'i

October 31, 2006

Dave Schmitz

Columbia University

on behalf of the

MiniBooNE Collaboration

Status of the MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation Search

the basic interrogatives of MiniBooNE. . .

- **When** is MiniBooNE going to do it?
- **Who** is MiniBooNE?
- **Where** is MiniBooNE?
- **What** is MiniBooNE trying to do?
- **Why** is MiniBooNE doing it?
- **How** is MiniBooNE going to do it?

When is MiniBooNE going to do it?

So, when are you going to "open the box"?

- For anyone who does not know, MiniBooNE is a **blind analysis** experiment. That is, we cannot look in the potential signal region in the ν_e sample until we are completely satisfied that the analysis is correct, robust and systematic errors are adequately quantified.
- I can tell you that we are presently in the endgame. Many systematic errors are final. Others are very near.
- In fact, this is likely one of few remaining conference talks before there is an oscillation result to present. It is my goal, therefore, to enumerate the components of that analysis.

Who is MiniBooNE?

Y. Liu, D. Perevalov, I. Stancu
University of Alabama, Tuscaloosa, AL 35487

S. Koutsoliotas
Bucknell University, Lewisburg, PA 17837

R. A. Johnson, J. L. Raaf
University of Cincinnati, Cincinnati, OH 45221

T. L. Hart, R. H. Nelson, M. Tzanov, M. J. Wilking, E. D. Zimmerman
University of Colorado, Boulder, CO 80309

A. A. Aguilar-Arevalo, L. Bugel, L. Coney, J. M. Conrad, Z. Djurcic, J. M. Link, K. B. M. Mahn, J. Monroe, D. Schmitz, M. H. Shaevitz, M. Sorel, G. P. Zeller
Columbia University, New York, NY 10027

D. Smith
Embry Riddle Aeronautical University, Prescott, AZ 86301

S. J. Brice, B. C. Brown, D. A. Finley, R. Ford, F. Garcia, P. Kasper, T. Kobilarcik, I. Kourbanis, W. Marsh, P. Martin, F. Mills, C. D. Moore, E. Prebys, A. D. Russell, P. Spentzouris, R. J. Stefanski
Fermi National Accelerator Laboratory, Batavia, IL 60510

D. C. Cox, T. Katori, C. C. Polly, R. Tayloe
Indiana University, Bloomington, IN 47405

G. T. Garvey, A. Green, C. Green, W. C. Louis, G. McGregor, G. B. Mills, H. Ray, V. Sandberg, R. Schirato, R. Van de Water, D. H. White
Los Alamos National Laboratory, Los Alamos, NM 87545

R. Imlay, W. Metcalf, S. Ouedraogo, M. Sung, M. O. Wascko
Louisiana State University, Baton Rouge, LA 70803

J. Cao, Y. Liu, B. P. Roe, H. J. Yang
University of Michigan, Ann Arbor, MI 48109

A. O. Bazarko, P. D. Meyers, R. B. Patterson, F. C. Shoemaker, H. A. Tanaka
Princeton University, Princeton, NJ 08544

P. Nienaber
Saint Mary's University of Minnesota, Rochester, MN 55904

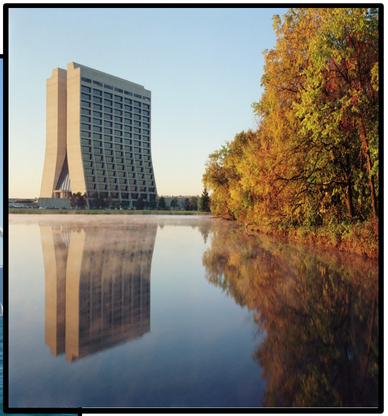
E. Hawker
Western Illinois University, Macomb, IL 61455

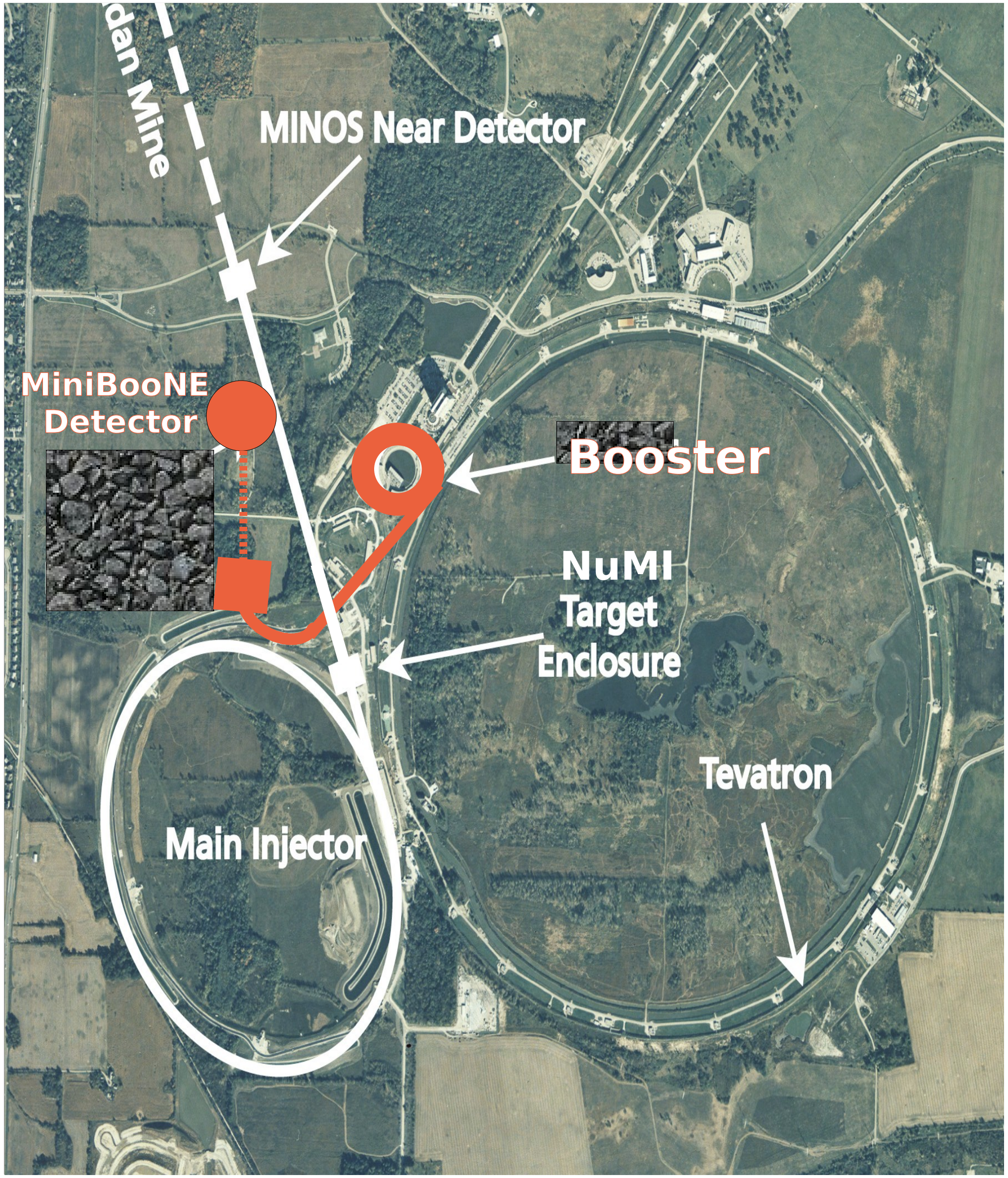
A. Curioni, B. T. Fleming
Yale University, New Haven, CT 06520

MiniBooNE is
72 scientists
from
15 institutions

Where is MiniBooNE?

- MiniBooNE is located on the grounds of the Fermi National Accelerator Laboratory outside of Chicago, IL



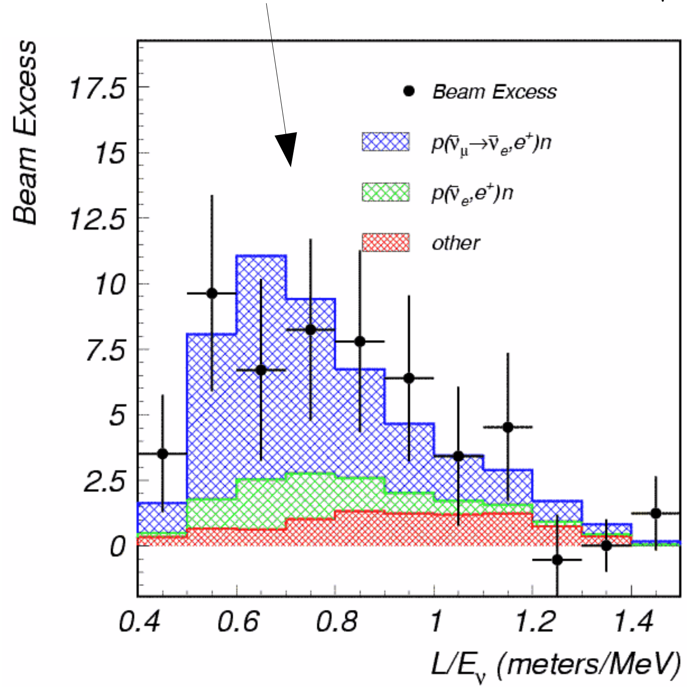


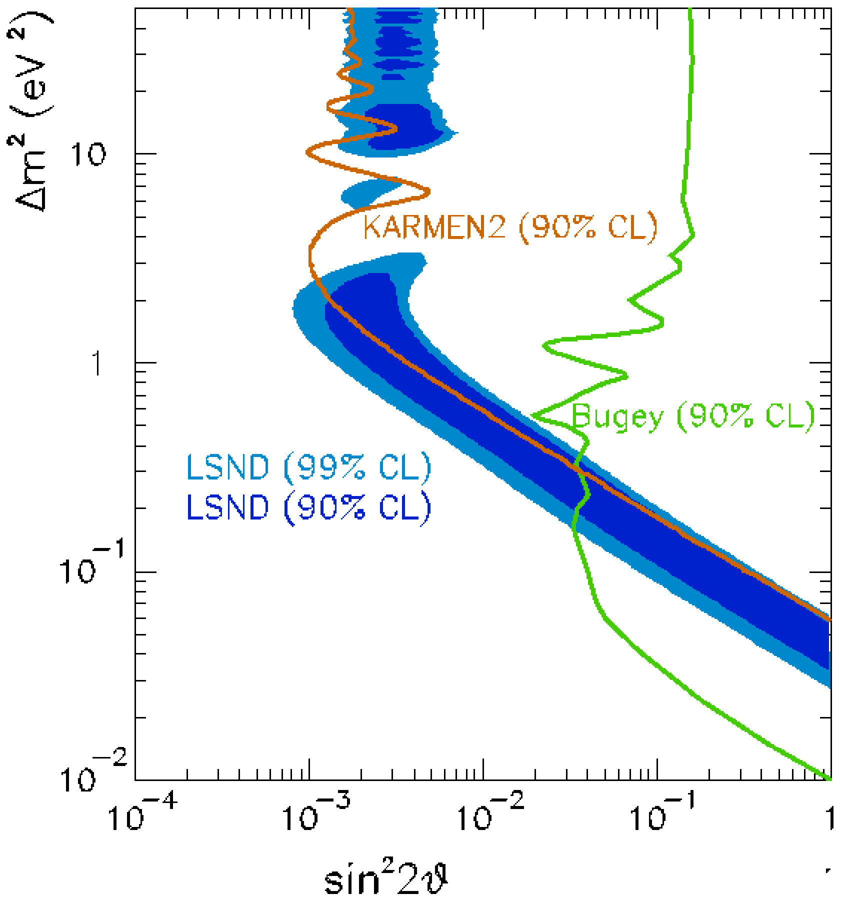
- the protons used to create the neutrino beam are extracted from the Booster accelerator at 8 GeV

What is MiniBooNE trying to do?

- test if the result of LSND is due to $\nu_\mu \rightarrow \nu_e$ **oscillations**
- because the LSND experiment at Los Alamos saw evidence for an unexpected and exciting oscillation signal – which has not been seen elsewhere. . .

LSND saw a 3.8σ excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam





= an oscillation probability of :

(**0.264** +- 0.067 +- 0.045)%

What is MiniBooNE trying to do?

pretty simple actually. . . sort of. . .

- we expect to see both types of neutrinos in the MiniBooNE detector

$$N_{\nu_\mu}(\mathrm{E}) = \Phi_{\nu_\mu}(\mathrm{E}) \times \sigma_{\nu_\mu}(\mathrm{E}) \times \varepsilon_{\nu_\mu}^{det}(\mathrm{E})$$

flux x cross-section x detector response

the observed event rates compared to prediction is where new physics can be found

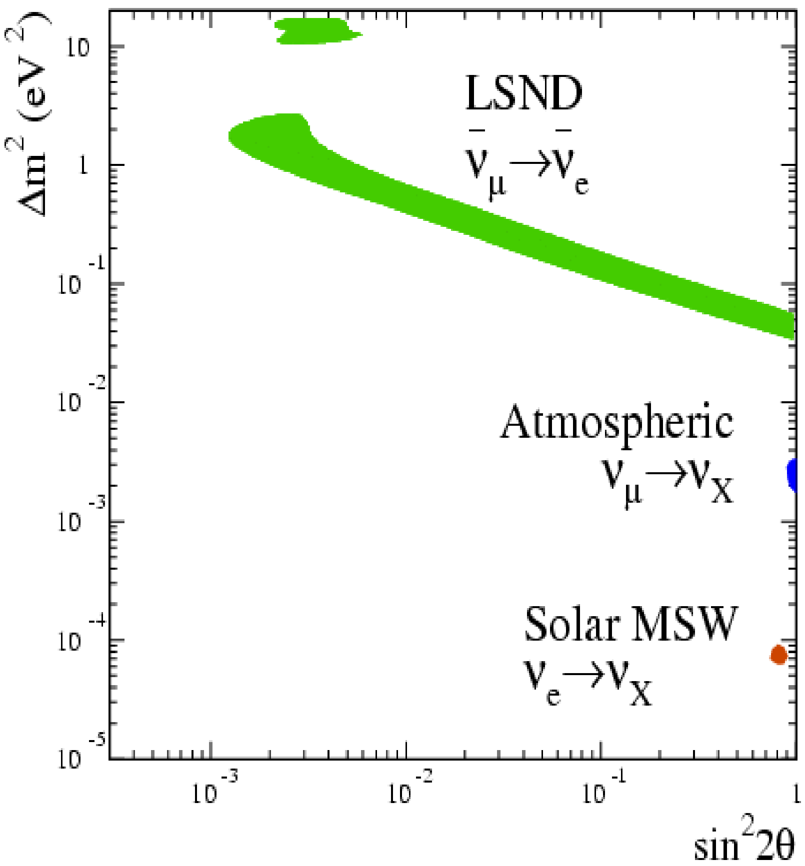
and these components comprise the analysis required to look for it

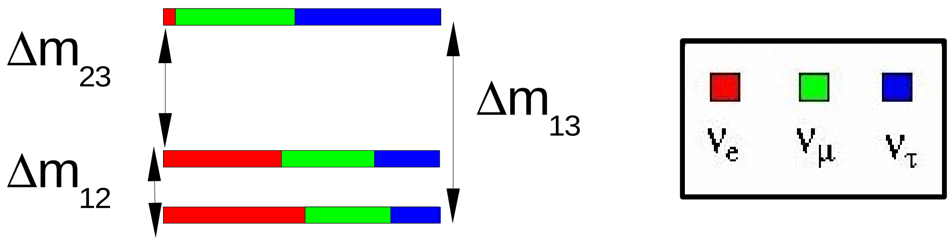
flux x cross-section x detector response

$$N_{\nu_e}(\mathrm{E}) = \Phi_{\nu_e}(\mathrm{E}) \times \sigma_{\nu_e}(\mathrm{E}) \times \varepsilon_{\nu_e}^{det}(\mathrm{E})$$

Why is MiniBooNE doing it?

- the oscillation signal seen by LSND seems to be incompatible with the “atmospheric” and “solar” oscillations and a standard 3 light neutrino model





$$\Delta m_{31} = \Delta m_{21} + \Delta m_{32}$$

$$1 \neq 0.003 + 0.00005$$

confirmation would imply a significant **extension beyond the Standard Model** including, but not limited to, the existence of one or more sterile neutrinos

How is MiniBooNE going to do it?

Some things worth noting first. . .

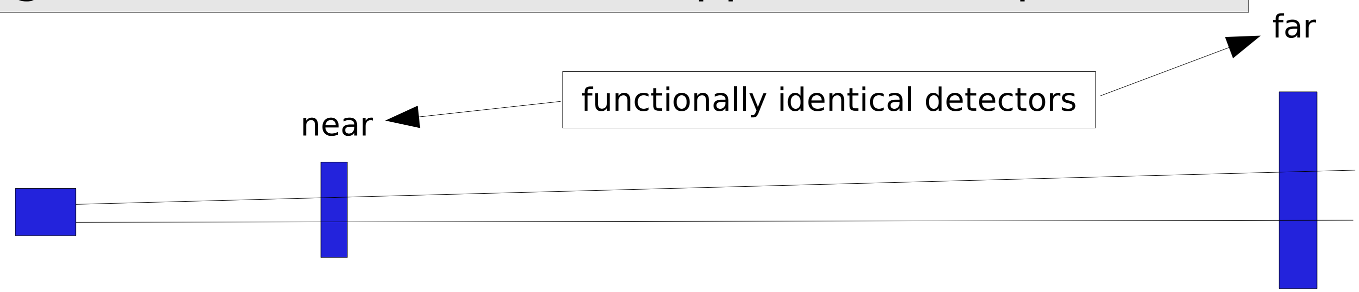
- what makes MiniBooNE different from other accelerator neutrino experiments (K2K, MINOS, etc.)?
  - MiniBooNE is a **short baseline** experiment. The neutrino energies are very similar.
  - The expected **oscillation probability is much much smaller** than the “solar” and “atmospheric” oscillations. **[0.25% vs. maximal !!]**
  - MiniBooNE has only **one detector**, not the standard “near/far” comparison that the long baseline oscillation measurements are based on.

- what effects do these features have on an analysis
  - The baseline is not technically important. It just means we search in a different Δm^2 region. . . and we can walk the neutrinos' path during a lunch break
  - MiniBooNE is an **appearance** experiment. The others, to date, are largely disappearance measurements
  - instead of a “near/far” ratio we tie together the expected rates of ν_μ/ν_e.

How is MiniBooNE going to do it?

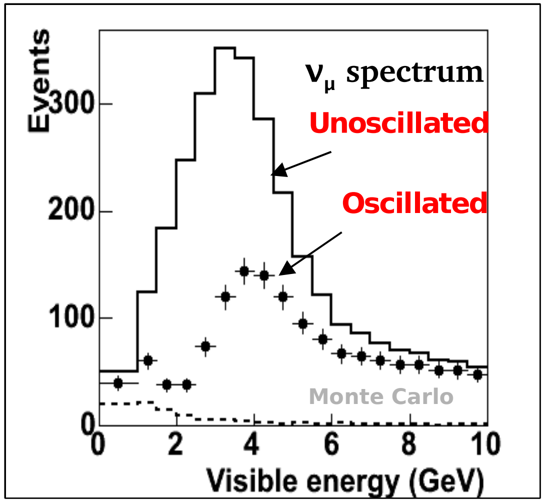
Some things worth noting first. . .

long baseline, two detector disappearance experiment



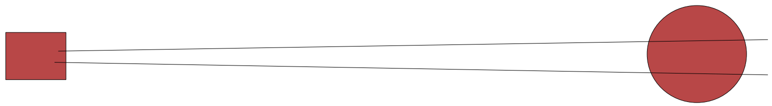
here you see the
unoscillated ν_μ flux

here you see the
oscillated ν_μ flux



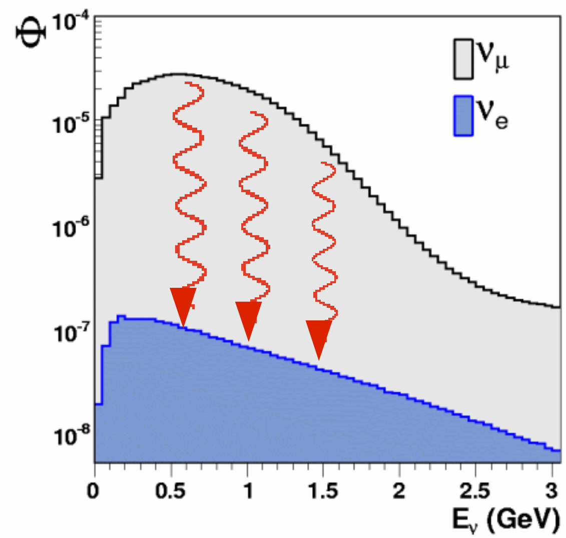
plot shamelessly stolen from MINOS collaboration

short baseline, one detector appearance experiment



here you also see the
oscillated ν_μ flux
appearing as ν_e

here you see a ν_μ flux
that is only 0.25% oscillated
effectively unoscillated ν_μ



How is MiniBooNE going to do it?

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

Generally speaking. . .

flux – MiniBooNE flux prediction is generated using a GEANT4 simulation tied to high precision hadron production measurements made at or near MiniBooNE's exact experimental configuration

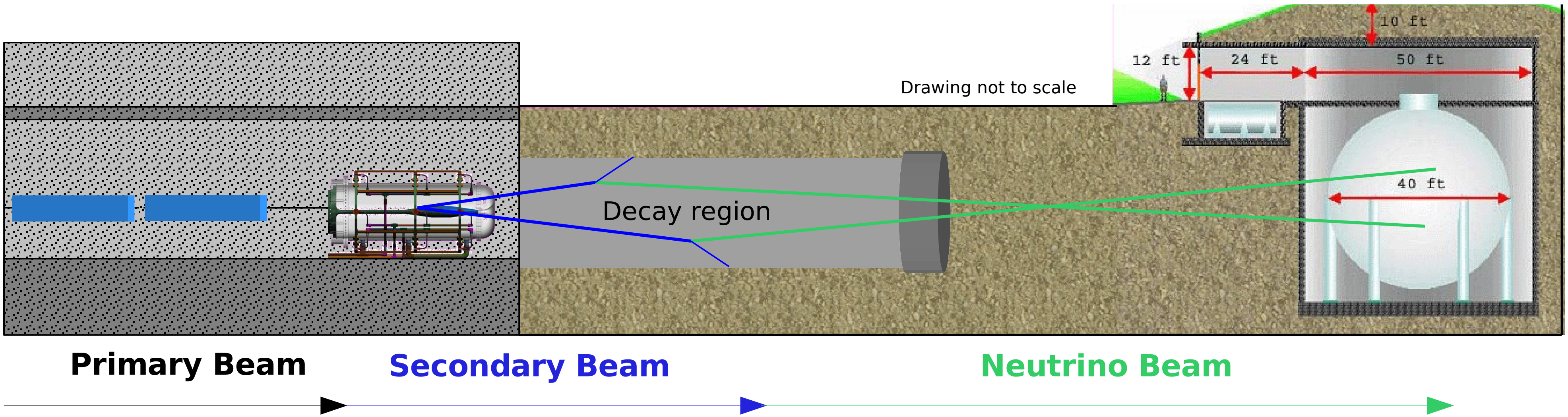
cross-section – model is based on the NUANCE ν event generator package tuned to reproduce our observed event distributions

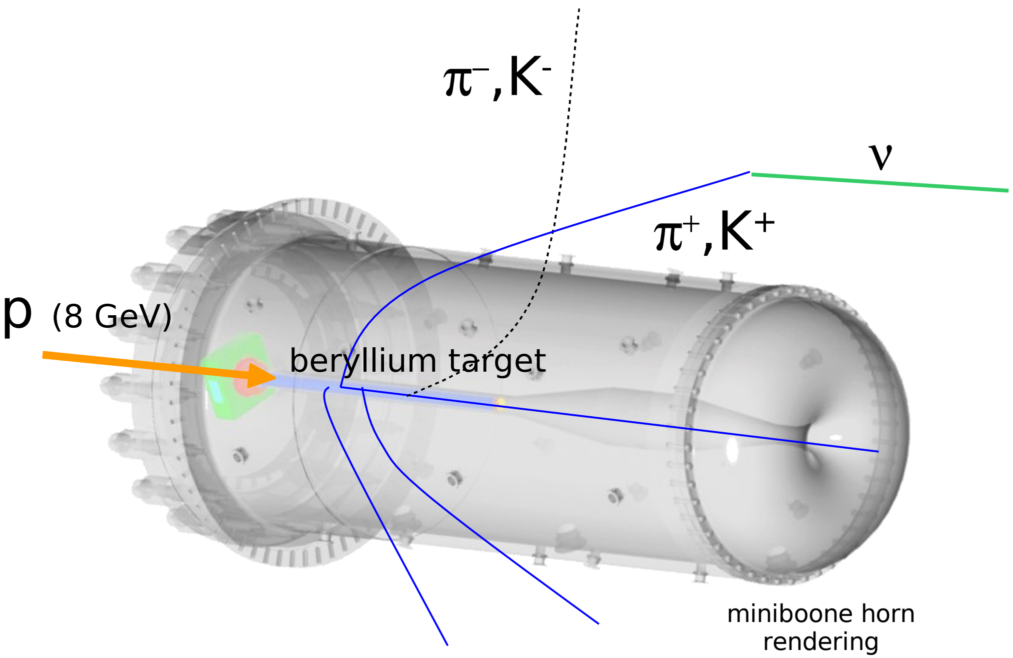
detector response – modeled with GEANT3 simulation expanded to include a 35 parameter optical model to describe our tank's properties.

event classification – higher level algorithms for distinguishing between neutrino types in the detector flux

How is MiniBooNE going to do it?

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$





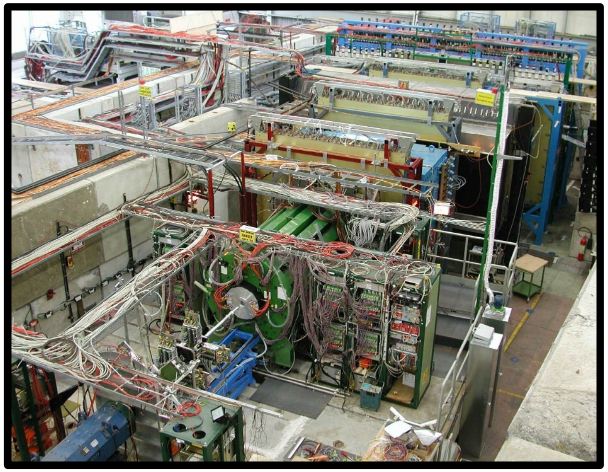
miniboone horn rendering
Bartoszek Engineering

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$K^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^+ \rightarrow \pi^0 + \mu^+ + \nu_\mu$$
$$K^+ \rightarrow \pi^0 + e^+ + \nu_e$$
$$K^0 \rightarrow \pi^\pm + e^\mp + \bar{\nu}_e$$
$$K^0 \rightarrow \pi^\pm + \mu^\mp + \bar{\nu}_\mu$$

ν_μ	~93%
$\bar{\nu}_\mu$	~6%
ν_e	~0.6%
$\bar{\nu}_e$	<0.1%

approximate flux composition

How is MiniBooNE going to do it?

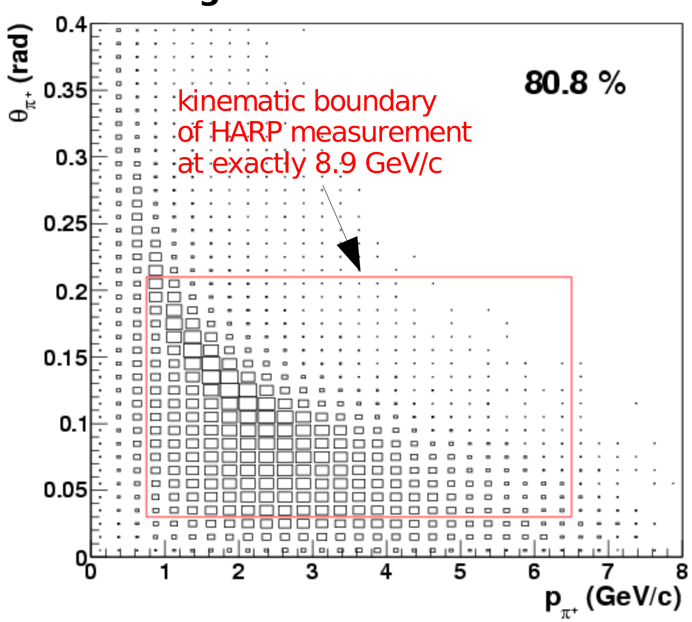


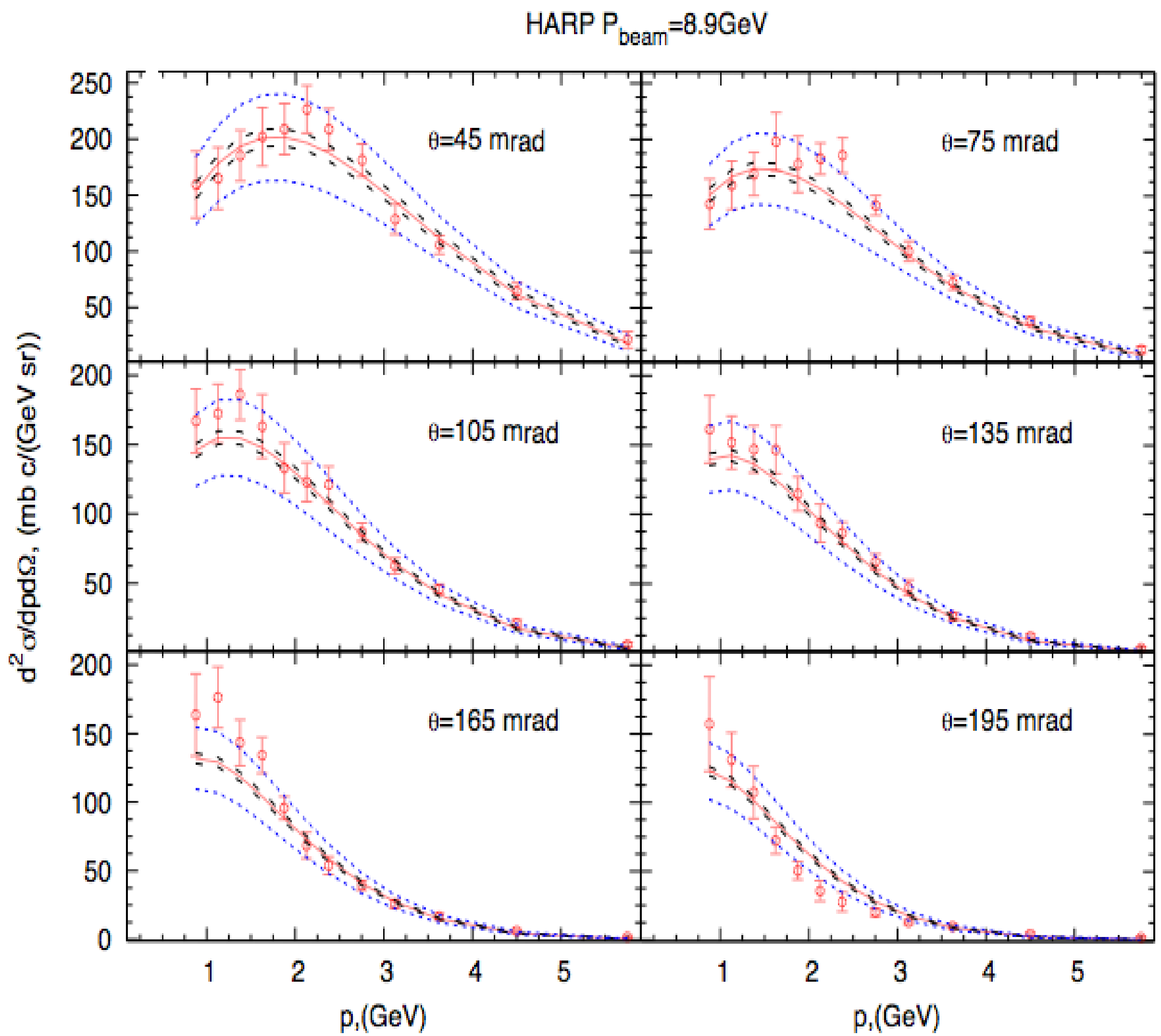
$$N_\nu(\mathrm{E}) = \Phi_\nu(\mathrm{E}) \times \sigma_\nu(\mathrm{E}) \times \varepsilon_{det}(\mathrm{E})$$

$$p + Be \rightarrow \pi^+ \rightarrow \nu_\mu$$

hadron production measurements from the **HARP** and **E910** experiments constrain π^+ and π^- production which yields the muon neutrino fluxes

• black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**





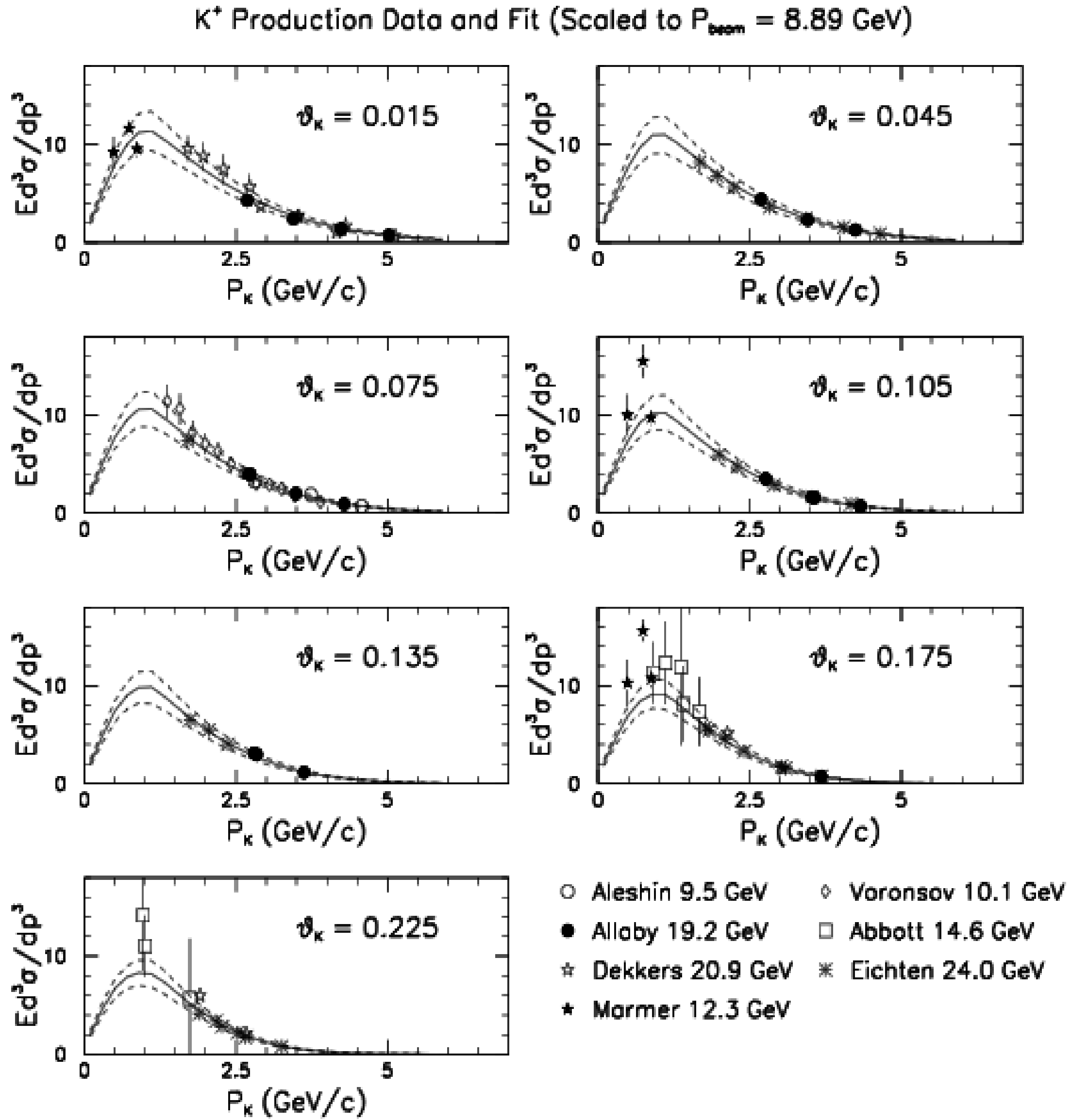
How is MiniBooNE going to do it?

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

- intrinsic electron neutrinos come from **kaon decays** or the decay of muons coming from pions

$$p + Be \rightarrow K^+ \rightarrow \nu_\mu / \nu_e$$

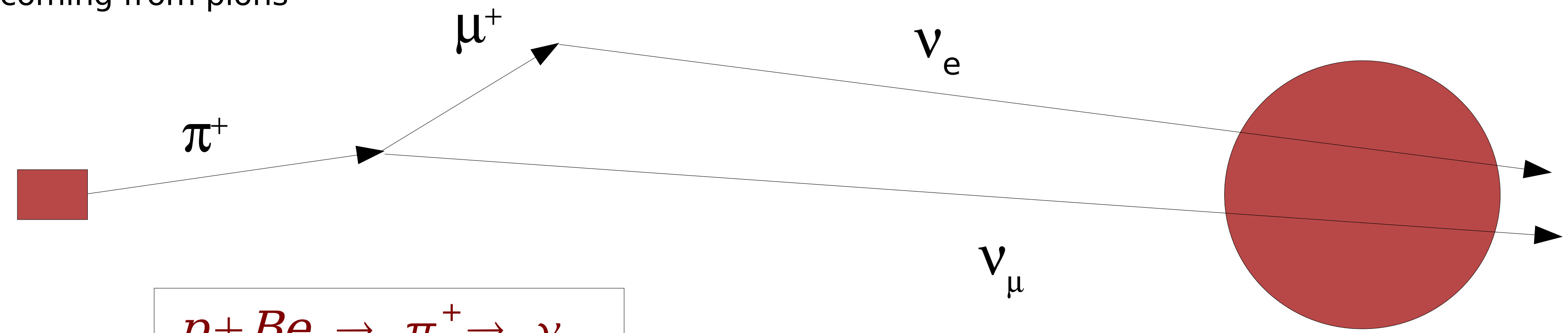
- K^+ data from 10 – 24 GeV/c proton beams
- parameterization based on principles of Feynman scaling developed by MiniBooNE collaborators. Working on a paper.
- plots show data scaled to 8.9 GeV/c beam momentum with parameterization and 1σ excursions
- data will be complemented with kaon measurements from HARP at 8.9 GeV/c
- K^0 also parameterized, but present a much smaller background than K^+



How is MiniBooNE going to do it?

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

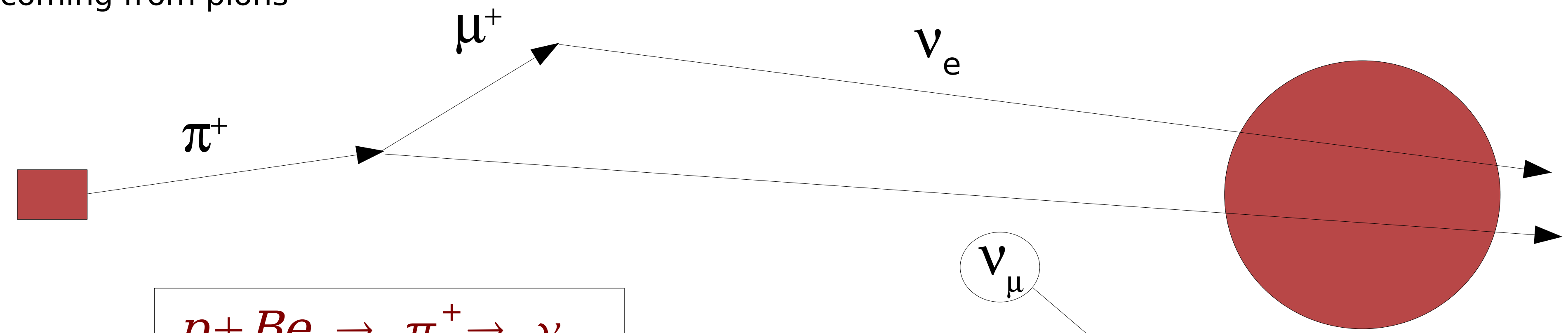
- intrinsic electron neutrinos come from kaon decays or the **decay of muons** coming from pions



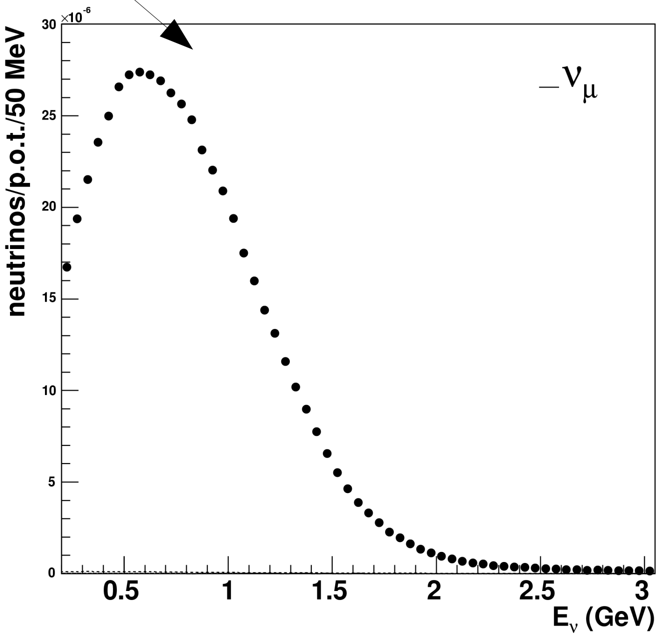
$$p + Be \rightarrow \pi^+ \rightarrow \nu_\mu$$
$$\downarrow$$
$$\mu^+ \rightarrow \nu_e$$

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

- intrinsic electron neutrinos come from kaon decays or the **decay of muons** coming from pions



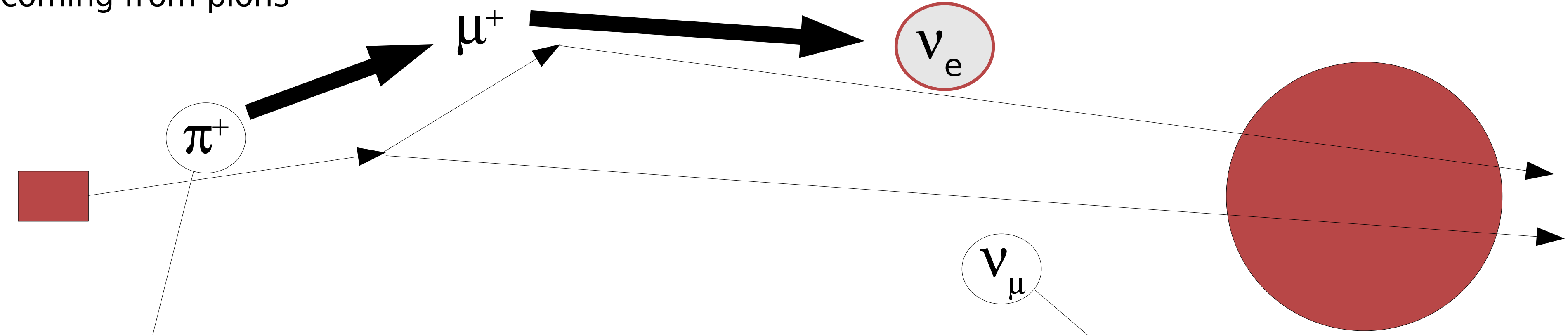
$$p + Be \rightarrow \pi^+ \rightarrow \nu_\mu$$
$$\mu^+ \rightarrow \nu_e$$

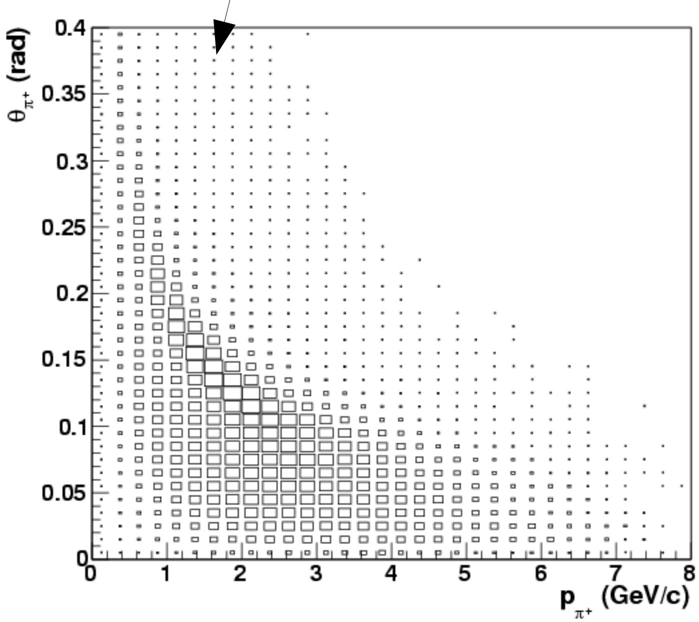


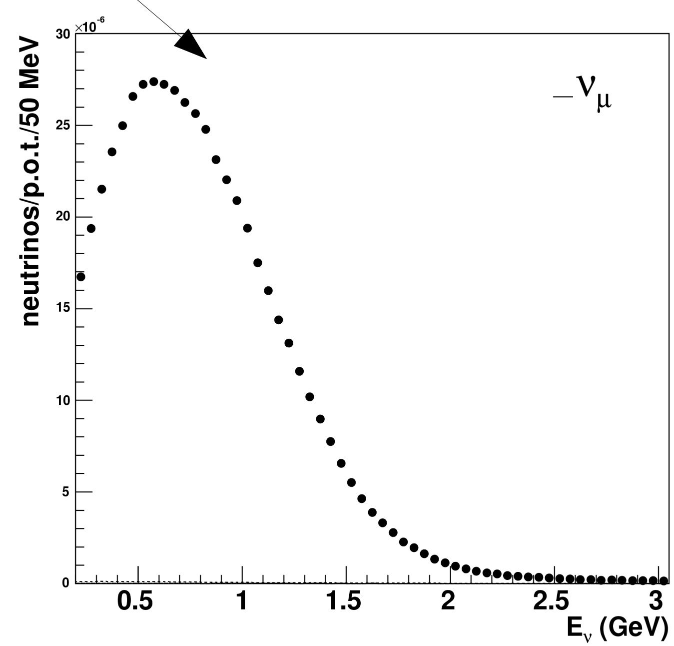
How is MiniBooNE going to do it?

$$N_{\nu}(\mathrm{E})=\Phi_{\nu}(\mathrm{E})\times\sigma_{\nu}(\mathrm{E})\times\varepsilon_{det}(\mathrm{E})$$

- intrinsic electron neutrinos come from kaon decays or the **decay of muons** coming from pions







*note: same technique would apply to tiny signal from $\pi^+ \rightarrow \nu_e$

cross-sections

How is MiniBooNE going to do it?

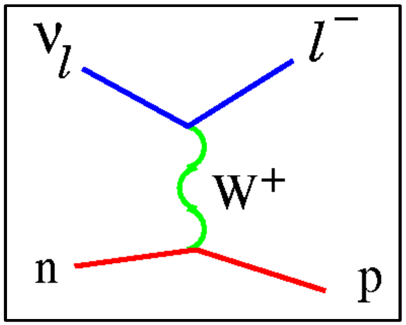
$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

- armed with an input flux, neutrino interactions are simulated using the **NUANCE** neutrino event generator software
- exclusive channels are handled separately and use differing, appropriate models
- total cross-sections are then the sum of all relevant exclusive channels
- nuclear effects of hadrons propagating through the nucleus are considered to give you an expected final state condition
- the most critical exclusive channel for the MiniBooNE oscillation search is the **charged-current quasi-elastic** interaction
- NUANCE models CCQE events using the relativistic Fermi gas model of Smith and Moniz as a framework
- the next most critical exclusive channels are the **NC production of π^0's**
- NUANCE uses the resonant and coherent π^0 production models of Rein and Sehgal

D. Casper, "The nuance Neutrino Physics Simulation, and the Future", Proceedings of NUINT01 workshop (2001)
R.A. Smith, E.J Moniz, "Neutrino Reactions on Nuclear Targets" Nucl.Phys.B43:605 (1972) Erratum-ibid.B101:547 (1975)
D. Rein, L.M. Sehgal, "Coherent pi0 production in neutrino reactions" Nucl.Phys.B223:29 (1983)
D. Rein, L.M. Sehgal, "Neutrino Excitation Of Baryon Resonances And Single Pion Production" Annals.Phys.1333:79 (1980)

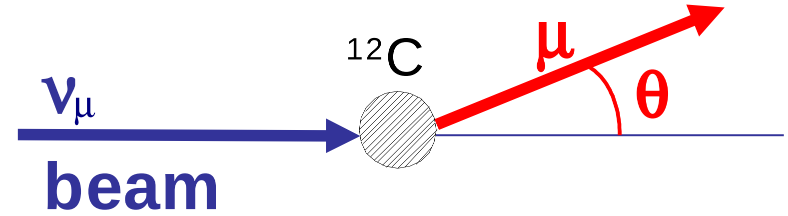
$$N_\nu(\mathrm{E}) = \Phi_\nu(\mathrm{E}) \times \sigma_\nu(\mathrm{E}) \times \varepsilon_{det}(\mathrm{E})$$

CCQE interactions :



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

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



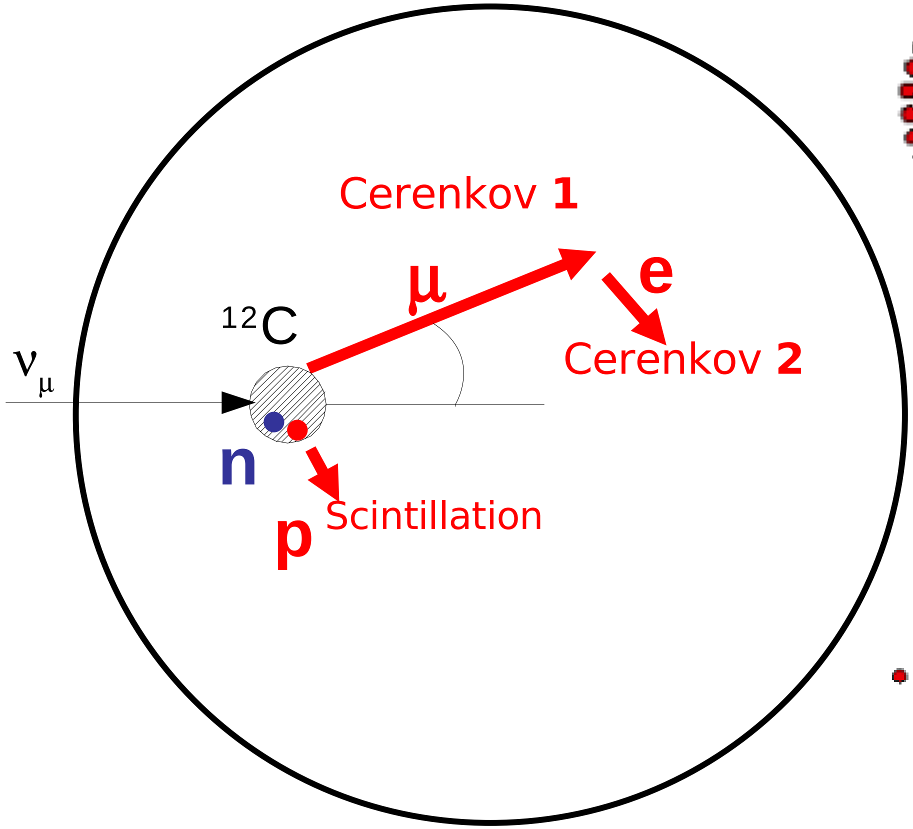
$$E_\nu^{QE} = \frac{1}{2} \frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_l}$$

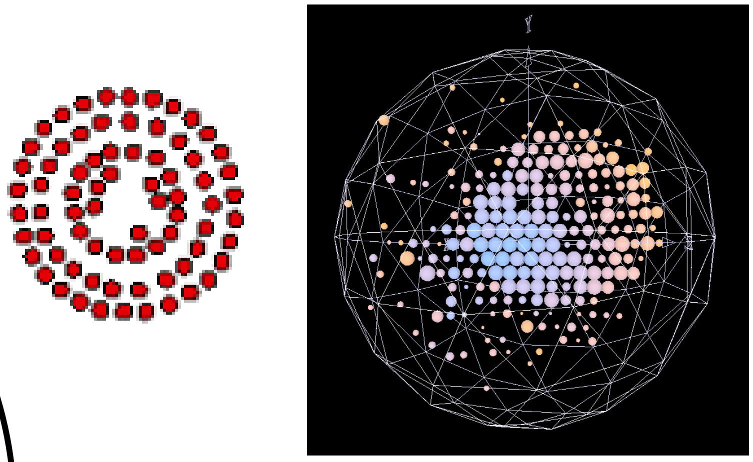
- CCQE events are used because one can use CCQE kinematics to reconstruct the neutrino energy – one can look at **neutrino energy spectra**
- **we will look for an oscillation signal in an E_ν^{QE} distribution of electron events**
- **we can use an E_ν^{QE} distribution of muon events to understand our models**

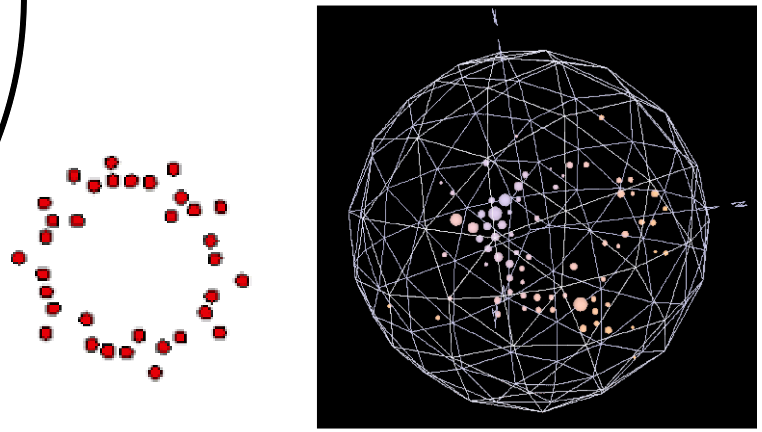
$$N_\nu(\mathrm{E}) = \Phi_\nu(\mathrm{E}) \times \sigma_\nu(\mathrm{E}) \times \varepsilon_{det}(\mathrm{E})$$

Selecting ν_μ CCQE events :

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



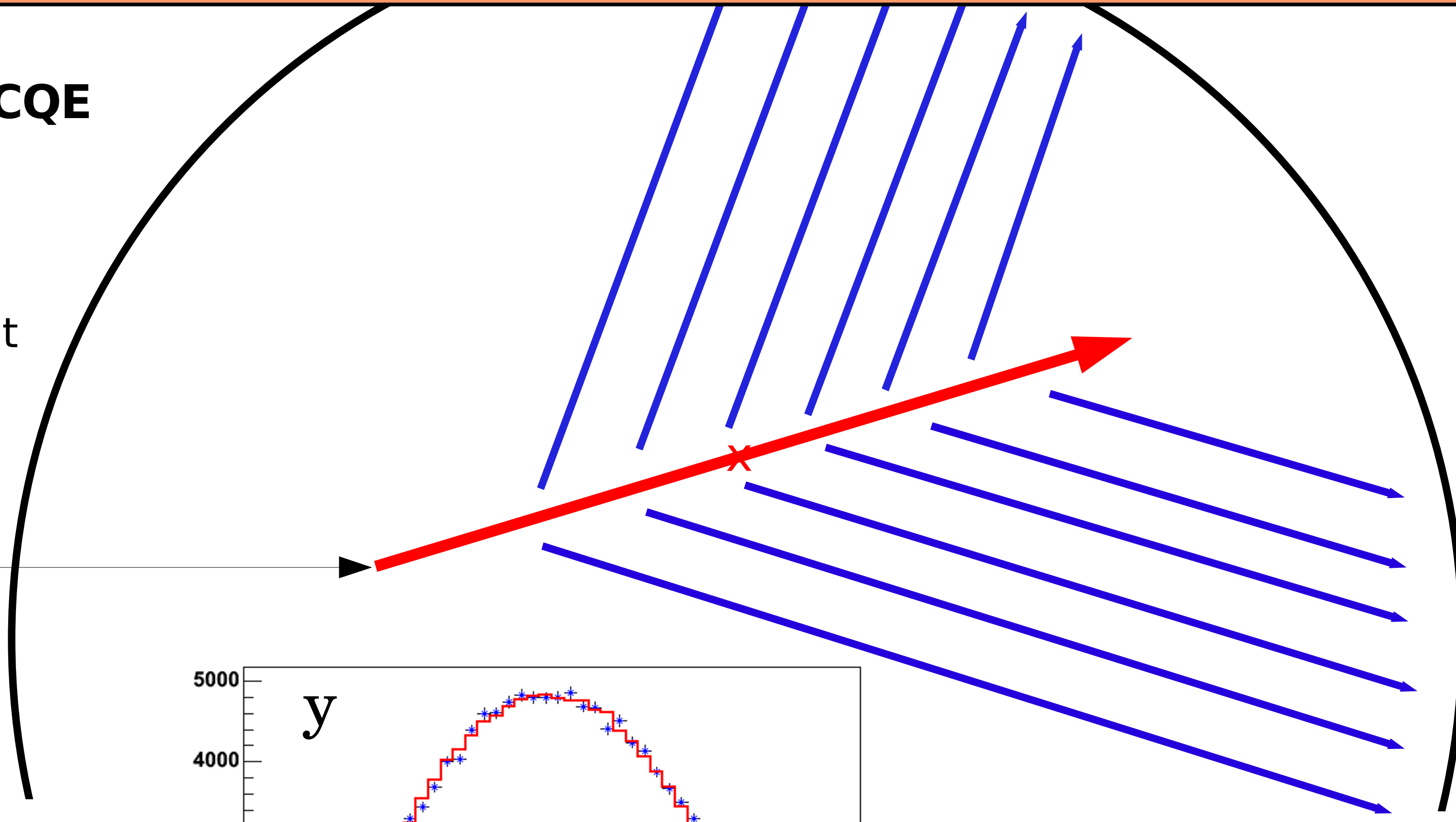


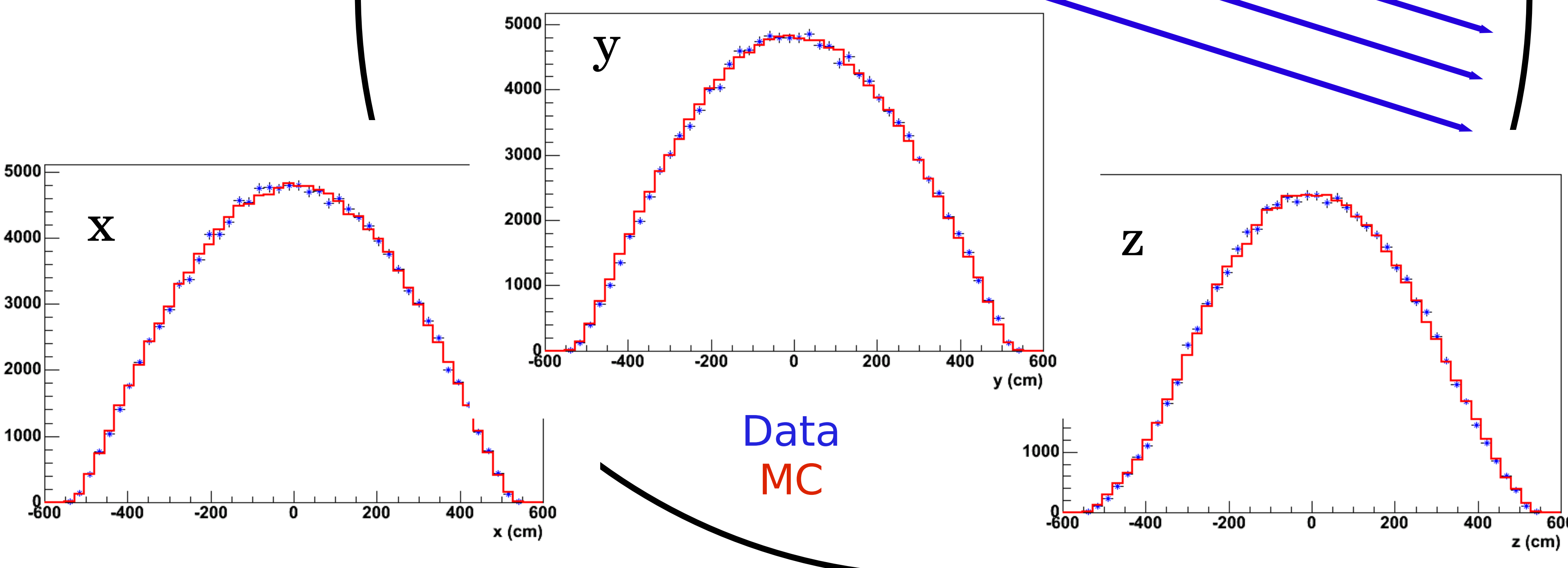


muon-like Cerenkov light followed by electron-like Cerenkov light from the Michel electron are the signature of a ν_μ CCQE event (purity~90%)

Data/MC for ν_μ CCQE events :

start with something not model dependent like a position reconstruction

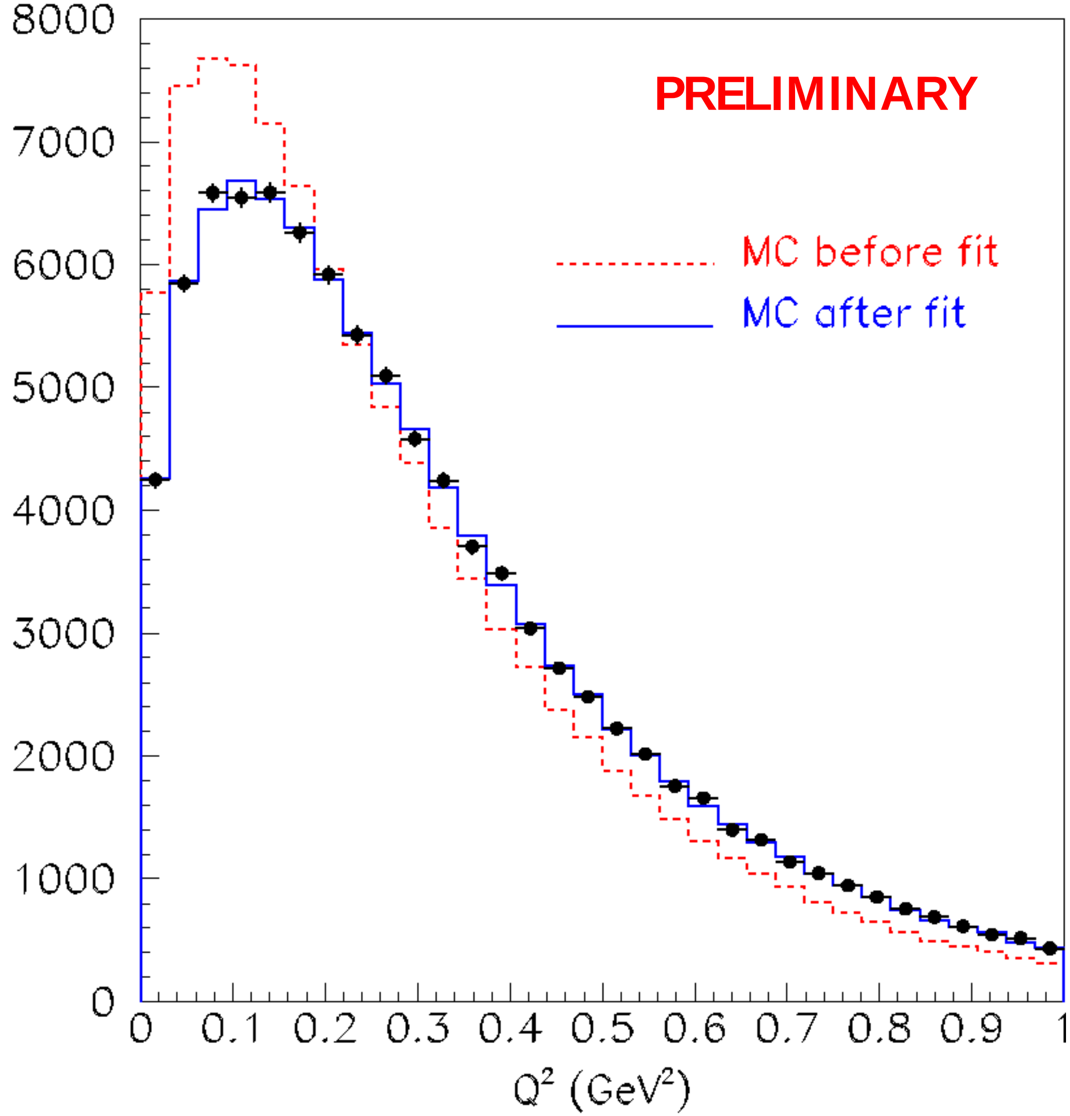




$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

Comparing data to the Smith Moniz model implemented in NUANCE for ν_μ CCQE events :

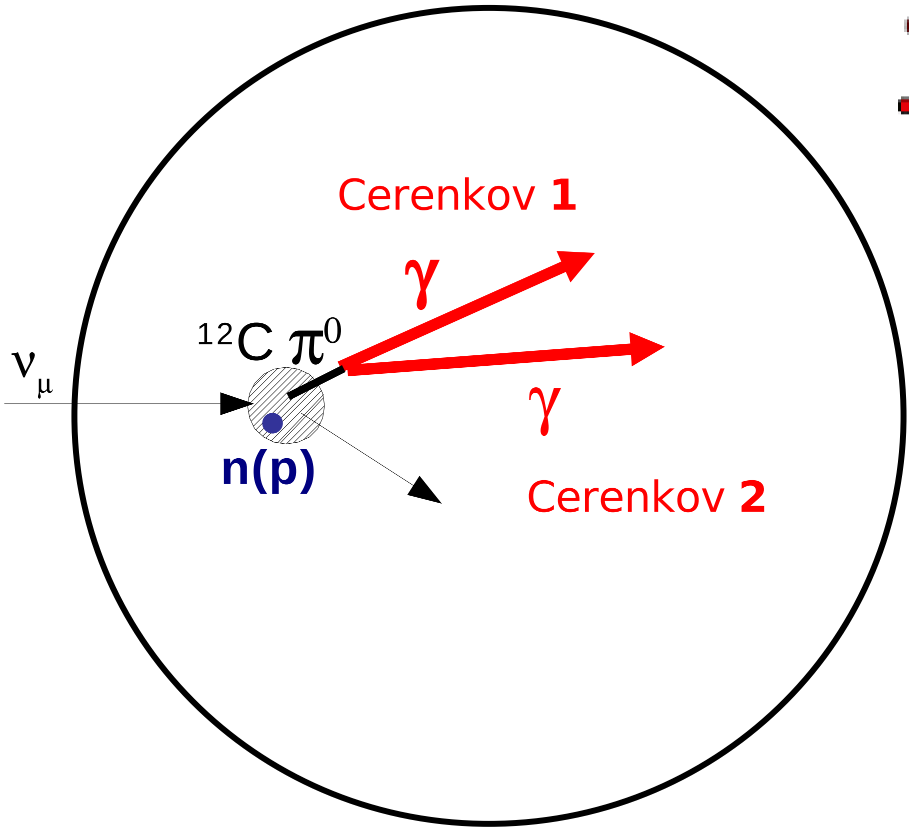
- a deficit is seen in the data for low values of the momentum transfer, Q^2
- similar effects have been seen in other channels and by other experiments
- given the Fermi gas model approximation used one can imagine deficiencies – particularly in the low Q^2 (very forward) kinematic region
- **solution :** use ν_μ data sample to adjust available parameters in present model to reproduce data. only $\nu_\mu - \nu_e$ differences are due to lepton mass effects, m_μ vs. m_e
- outlook : with the high statistics and resolutions attainable at MiniBooNE, the MiniBooNE data will be used in the future to carefully study this and other models of CCQE interactions

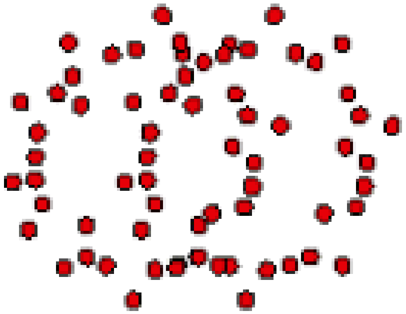


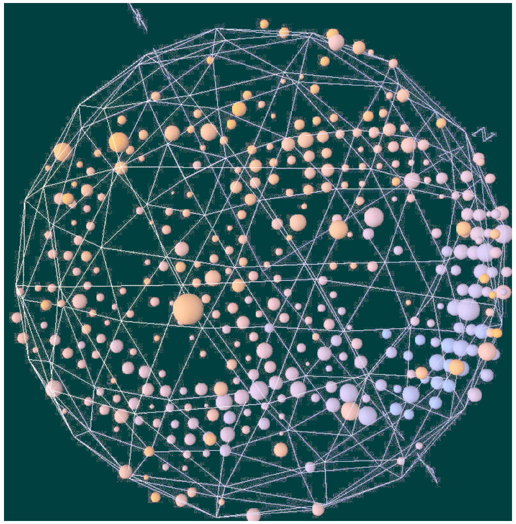
How is MiniBooNE going to do it?

Neutral Current π^0 events :

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$







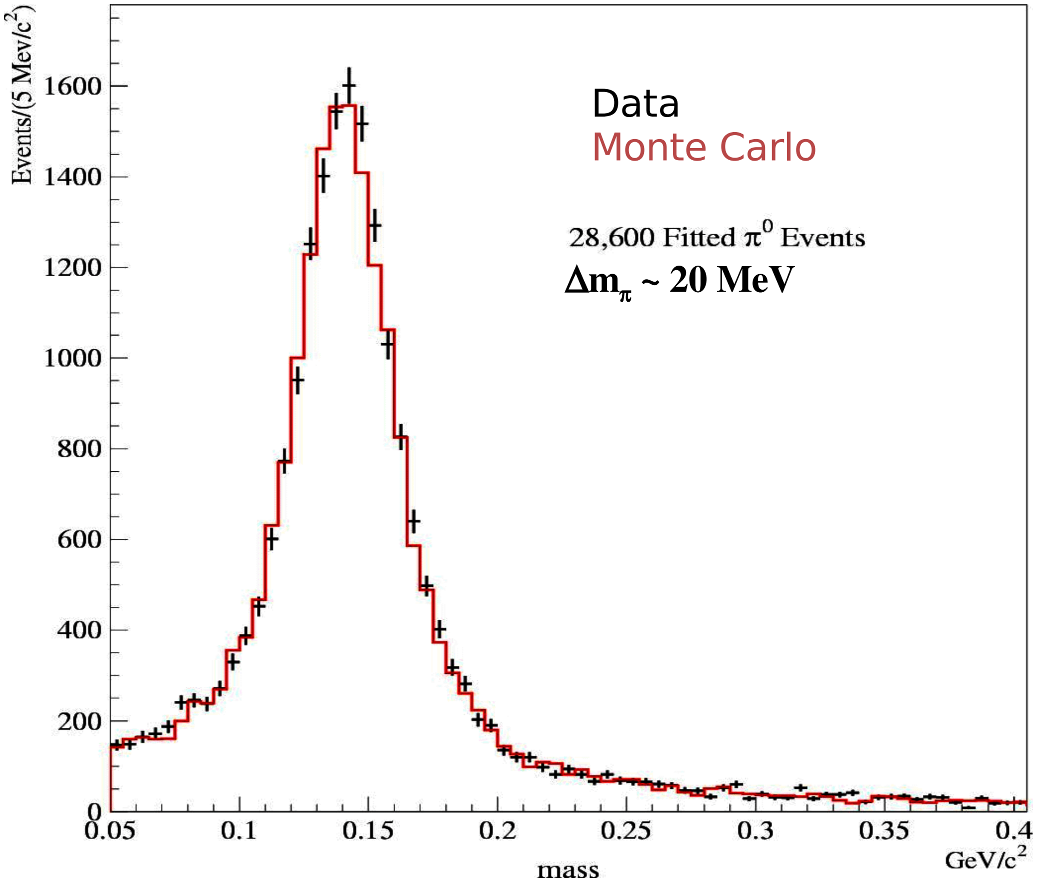
- besides measuring an absolute π^0 production cross-section. . .
- and besides studying the resonant and coherent contributions to the production. . .
- for the oscillation analysis we just care about the **rate of mis-identifying a π^0 as an electron**
- this can occur for very asymmetric decays where one photon is very weak, or for the case where the two photons decay on top of one another and their rings overlap

How is MiniBooNE going to do it?

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

Neutral Current π^0 events :

π^0 mass reconstruction from 2 decay γ's

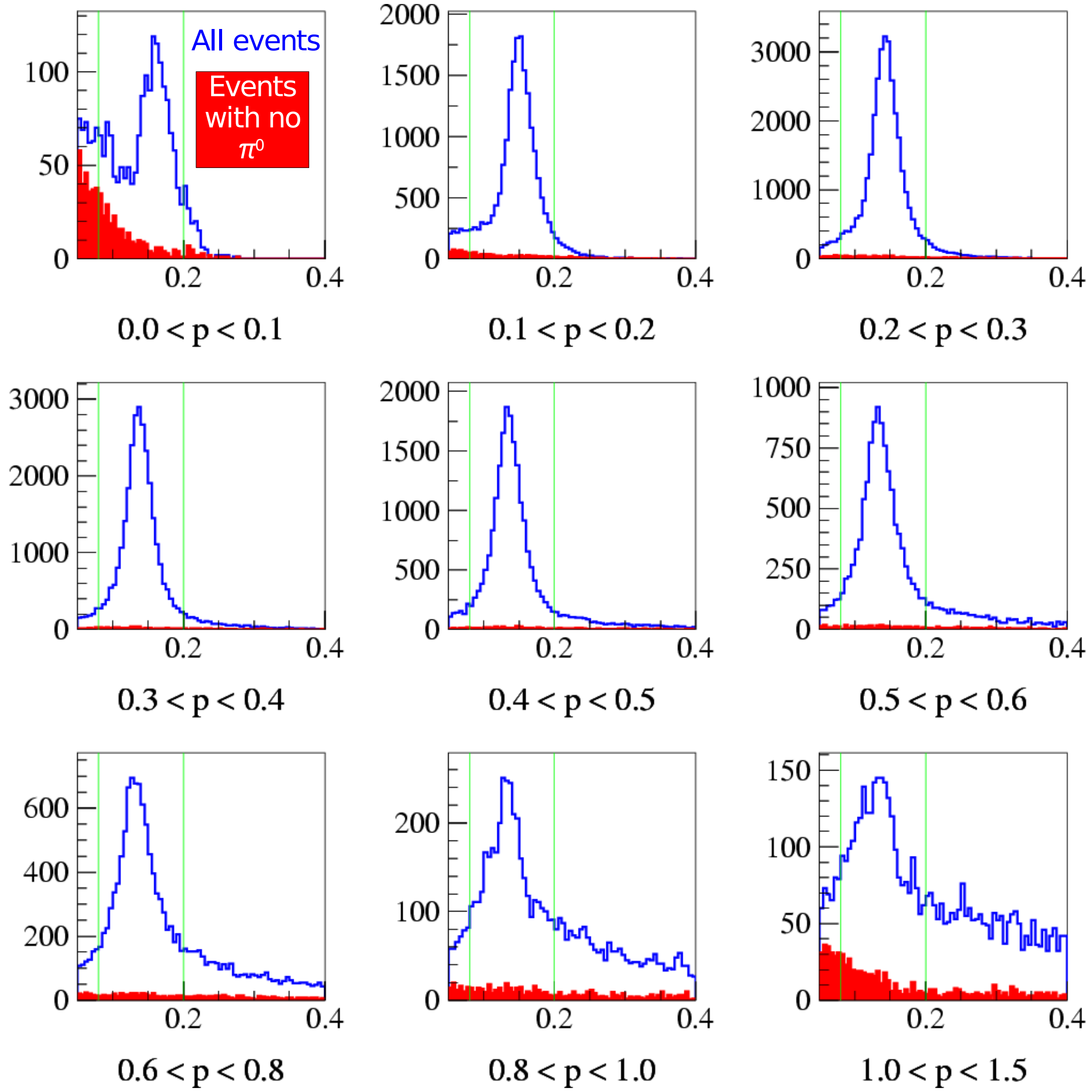


- excellent data/MC agreement in the π^0 mass reconstruction from the 2 γ rings
- excellent mass resolution for a Cerenkov detector

Neutral Current π^0 events :

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

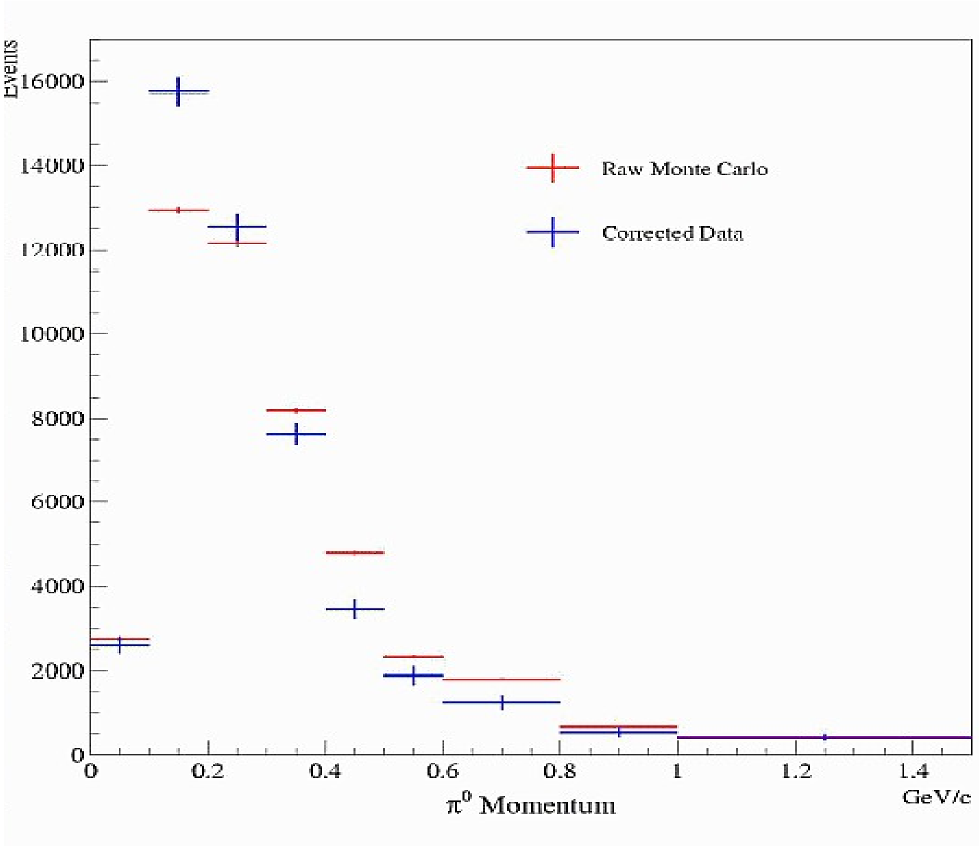
Monte Carlo

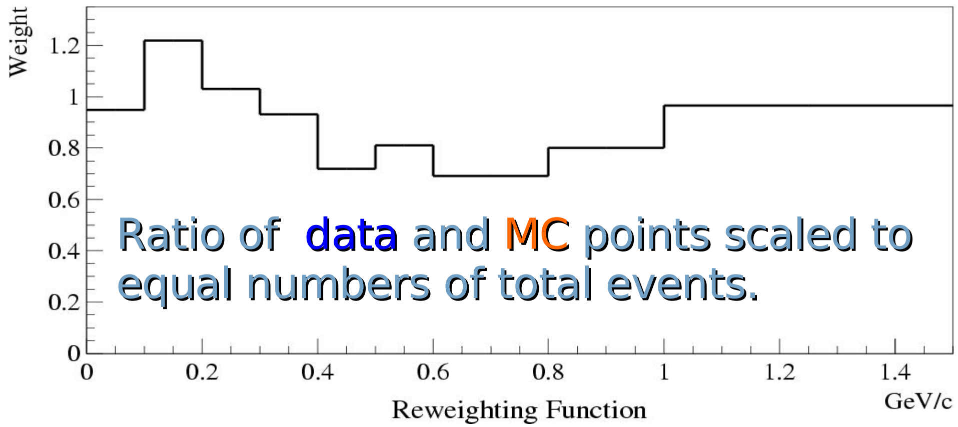


- excellent data/MC agreement in the π^0 mass reconstruction from the 2 γ rings
- excellent mass resolution for a Cerenkov detector
- low background rates predicted by the Monte Carlo in most pion momentum bins
- use MC to determine efficiencies and migrations due to reconstruction with which you can correct data

Neutral Current π^0 events :

$$N_\nu(E)=\Phi_\nu(E)\times\sigma_\nu(E)\times\varepsilon_{det}(E)$$



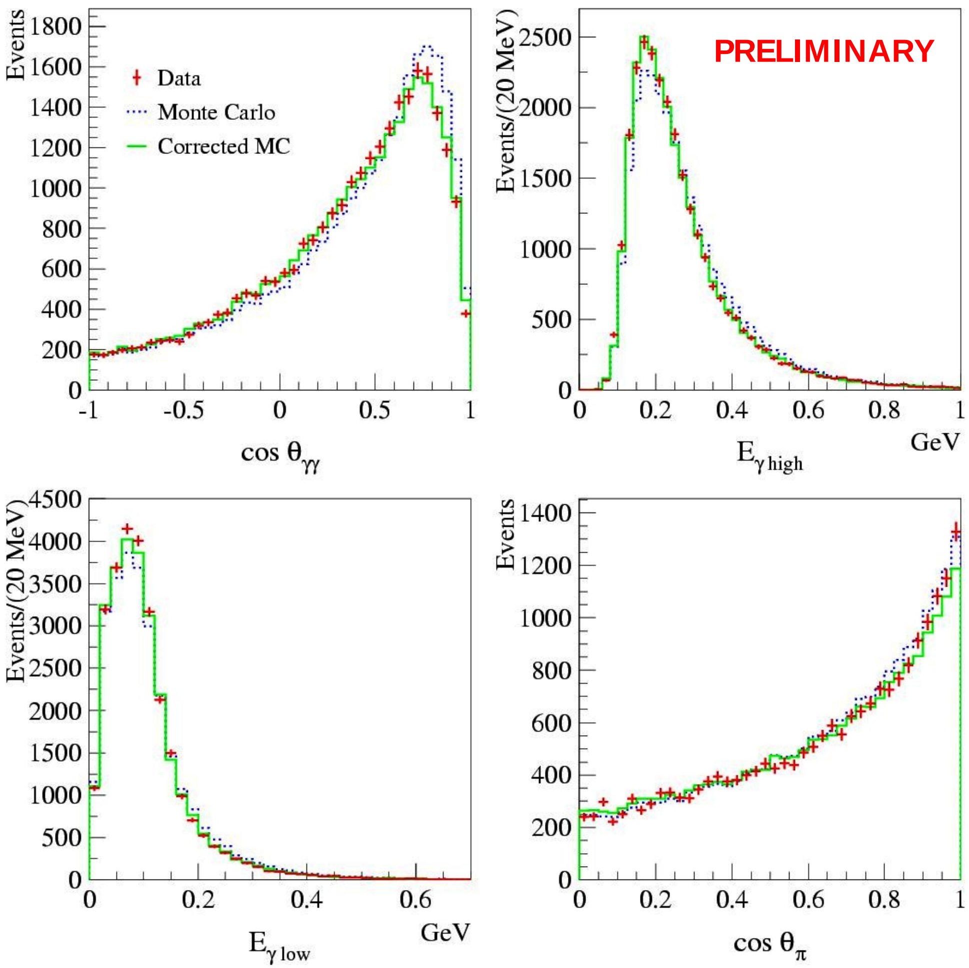


- excellent data/MC agreement in the π^0 mass reconstruction from the 2 γ rings
- excellent mass resolution for a Cerenkov detector
- low background rates predicted by the Monte Carlo in most pion momentum bins
- use MC to determine efficiencies and migrations due to reconstruction with which you can correct data
- compare data/MC π^0 momentum distributions. extract a reweighting function for Monte Carlo

How is MiniBooNE going to do it?

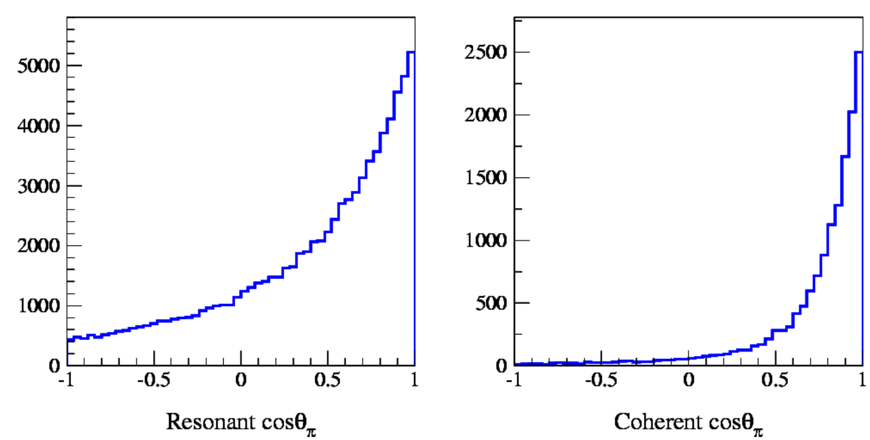
$$N_\nu(E)=\Phi_\nu(E)\times\sigma_\nu(E)\times\varepsilon_{det}(E)$$

Neutral Current π^0 events :



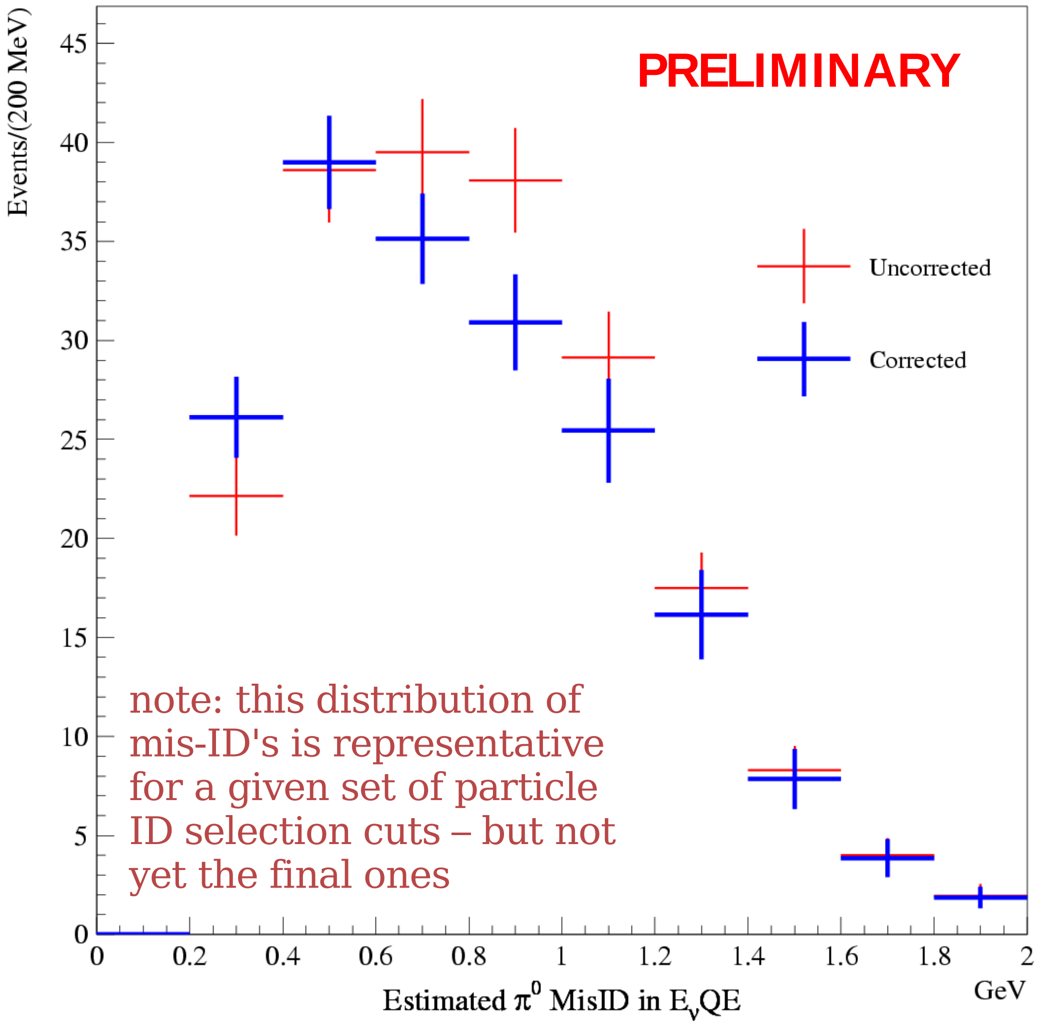
- excellent data/MC agreement in the π^0 mass reconstruction from the 2 γ rings
- excellent mass resolution for a Cerenkov detector
- low background rates predicted by the Monte Carlo in most pion momentum bins
- use MC to determine efficiencies and migrations due to reconstruction with which you can correct data
- compare data/MC π^0 momentum distributions. extract a reweighting function for Monte Carlo
- reweight π^0 momentum distribution in MC

- agreement is much improved in other π^0 variables, except cosθ
- large cosθ discrepancy can be explained by insufficient coherent production in the simulation
- in fact, coherent fraction has been extracted. best fit : 18%



Neutral Current π^0 events :

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$



- excellent data/MC agreement in the π^0 mass reconstruction from the 2 γ rings
- excellent mass resolution for a Cerenkov detector
- low background rates predicted by the Monte Carlo in most pion momentum bins
- use MC to determine efficiencies and migrations due to reconstruction with which you can correct data
- compare data/MC π^0 momentum distributions. extract a reweighting function for Monte Carlo
- reweight π^0 momentum distribution in MC
- apply electron particle ID selection cuts to the π^0 sample in MC
- reconstruct E_ν as if a CCQE electron event
- systematic error on misID yield from this method is below the 10% target

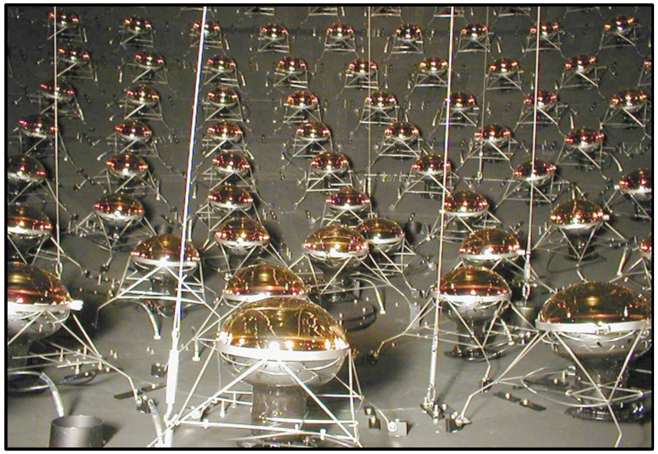
detector response

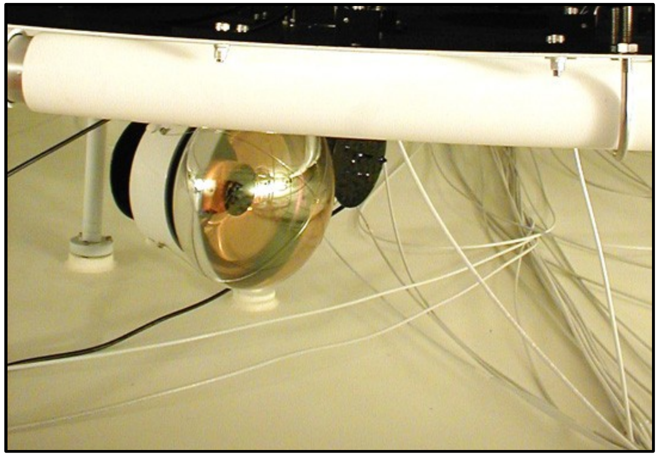
How is MiniBooNE going to do it?

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times \varepsilon_{det}(E)$$

MiniBooNE detector :
- 12 m diameter sphere
- 950,000 liters of mineral oil
- 1280 photomultiplier tubes
- 240 optically isolated tubes in a veto region

tank





veto region

- detector modeled by a GEANT3 simulation with an added 35 parameter “**optical model**” to describe the production, absorption and propagation of light within the tank

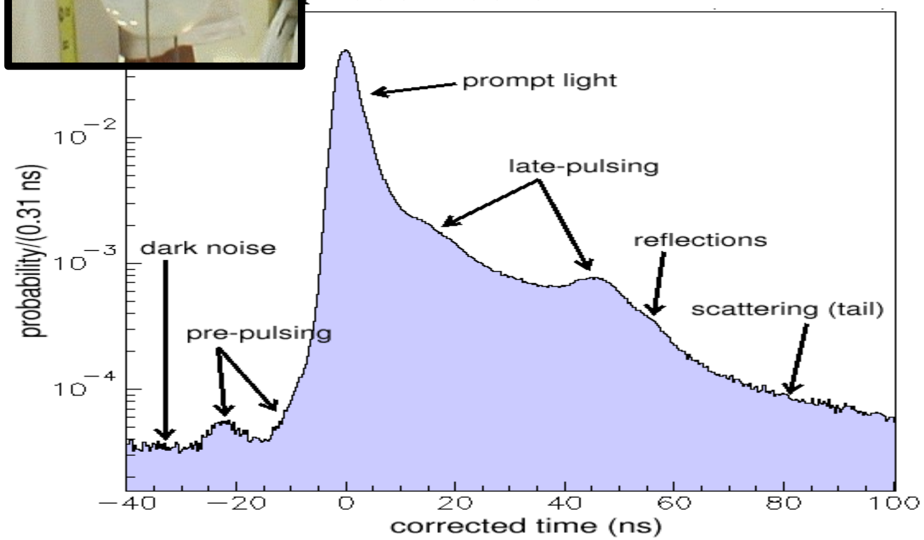
- parameters can be tuned by studying :
  - **external measurements**
  - **Michel electrons in the tank**
  - **cosmic rays in the tank**
  - **NC events in the tank**
  - **calibration lasers inside the tank**

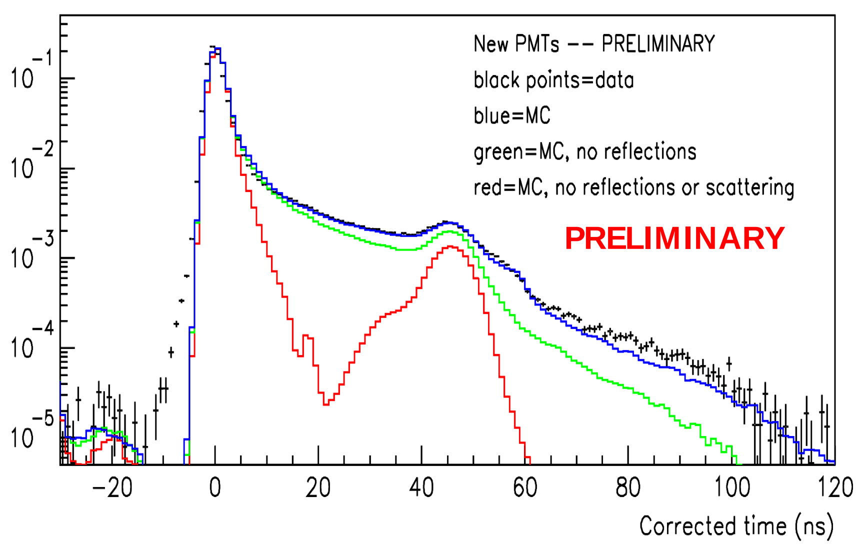
- lacking the ultimate calibration source (i.e. 1 GeV electron gun), we must calibrate the model very carefully with sources we do have to gain confidence we model our signal and background properly

How is MiniBooNE going to do it?

calibration of the detector response :

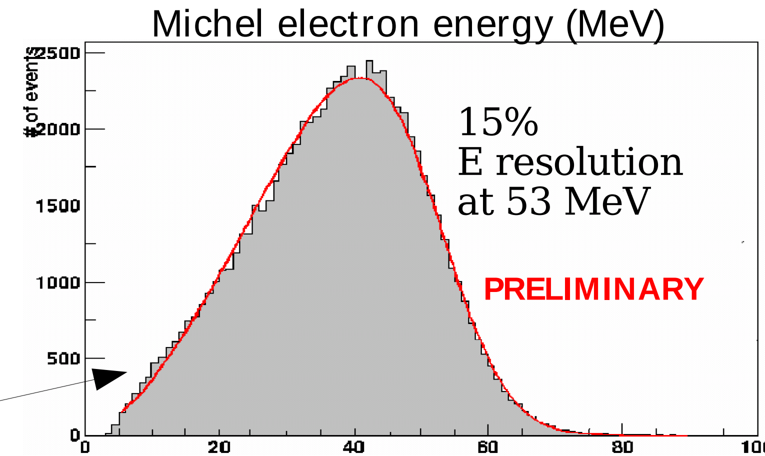
laser flasks



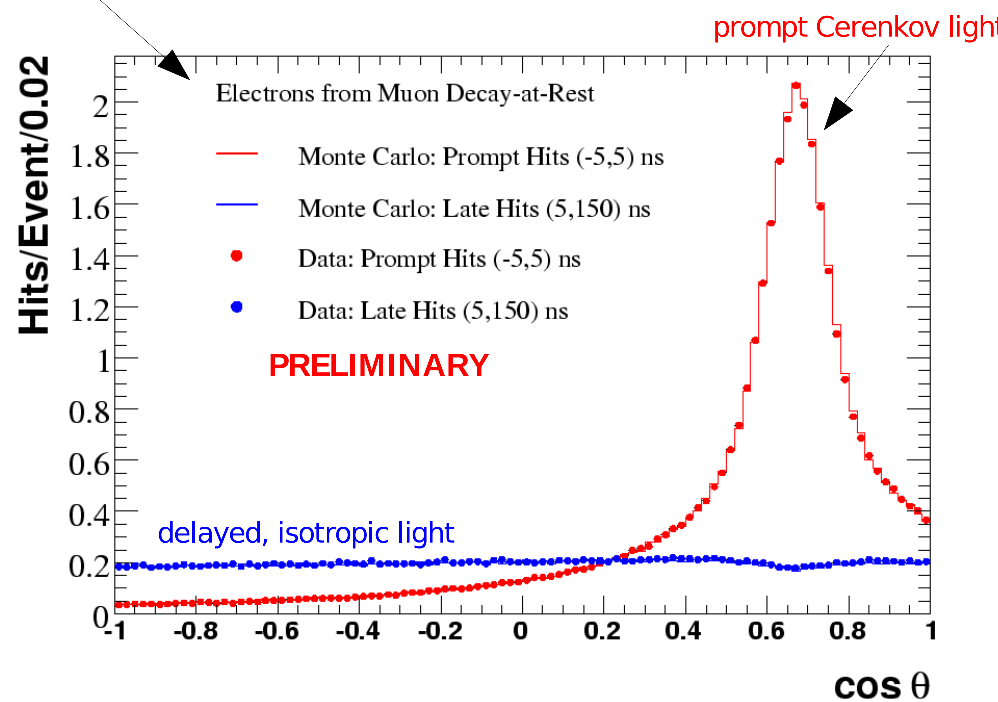


electrons from muon decays

energy



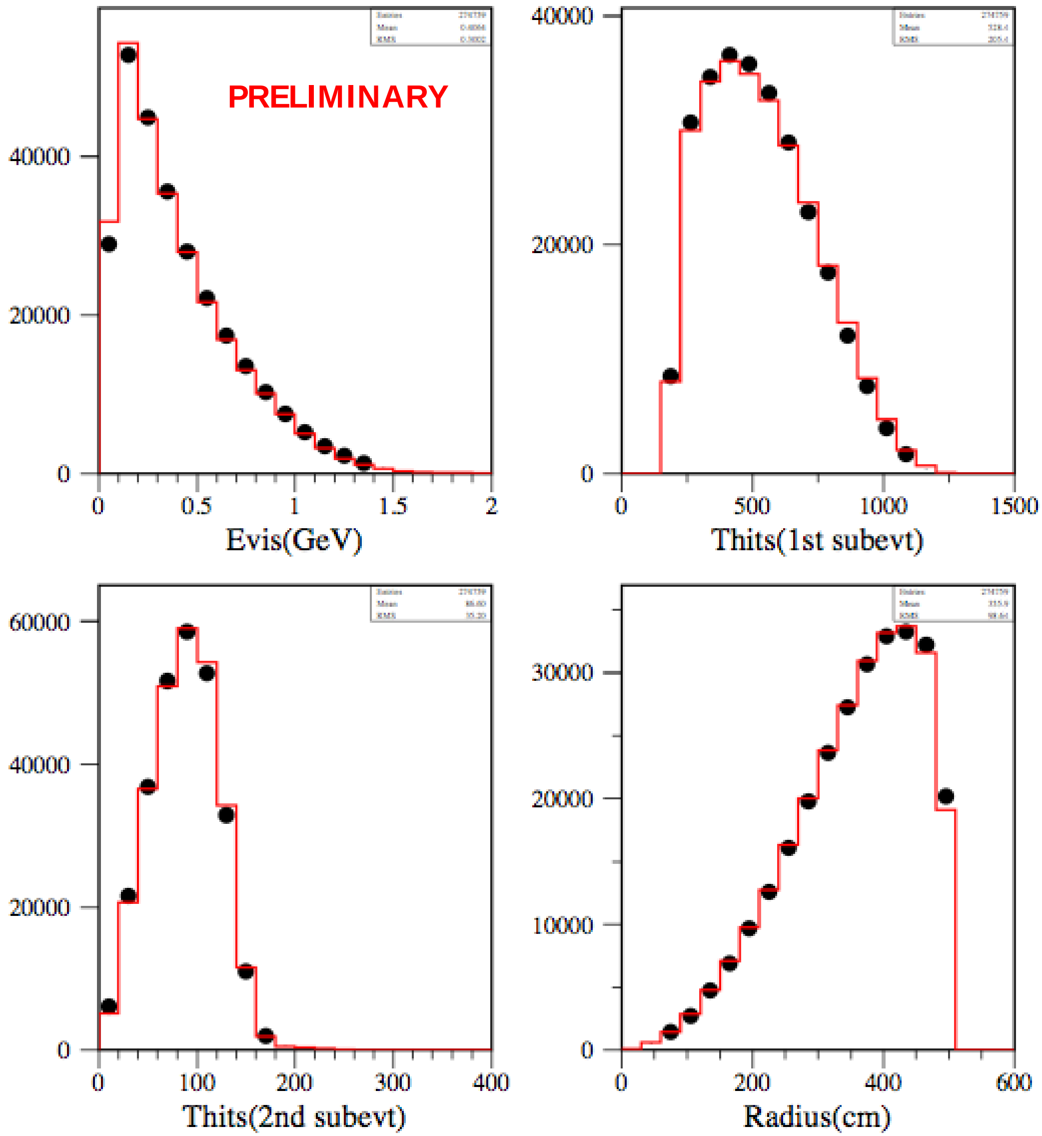
angular distribution of light



How is MiniBooNE going to do it?

$$N_\nu(\mathrm{E}) = \Phi_\nu(\mathrm{E}) \times \sigma_\nu(\mathrm{E}) \times \varepsilon_{det}(\mathrm{E})$$

- an example of higher level variables : an inclusive CC sample
- CC events tagged by a leading muon followed by a decay electron. 2 “sub-events”
- Monte Carlo sample shown includes small amount of “dirt” events generated in area outside of the tank and strobe overlay for noise, cosmics (so just about everything)
- there are many many low and high level variables for which we agonize over data/mc agreement – very important because. . .



event classification

How is MiniBooNE going to do it?

- . . .to generate sensitivity to a 0.25% oscillation signal we need to reject :
  - **99.9% of ν_μ CC interactions**
  - **99% of ν_μ NC π^0 interactions**
  - **maintain ~30-60% efficiency for ν_e interactions**
- to this end we have developed multiple, complimentary event identification methods
  - **likelihood cuts analysis ($L_{e\mu}$,$L_{e\pi}$)**
  - **boosted decision trees**

- . . .to generate sensitivity to a 0.25% oscillation signal we need to reject :
  - **99.9% of ν_μ CC interactions**
  - **99% of ν_μ NC π^0 interactions**
  - **maintain ~30-60% efficiency for ν_e interactions**
- to this end we have developed multiple, complimentary event identification methods
  - **likelihood cuts analysis ($L_{e\mu}$,$L_{e\pi}$)**
  - **boosted decision trees**

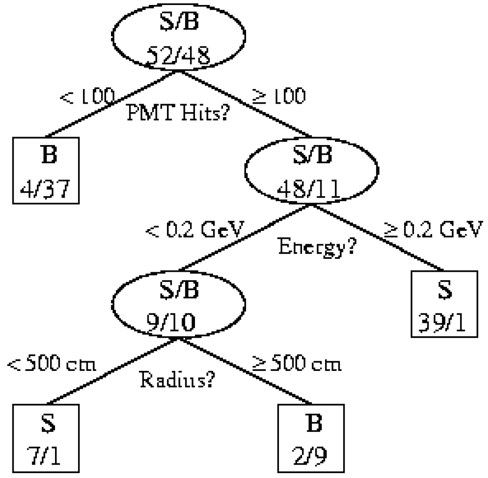
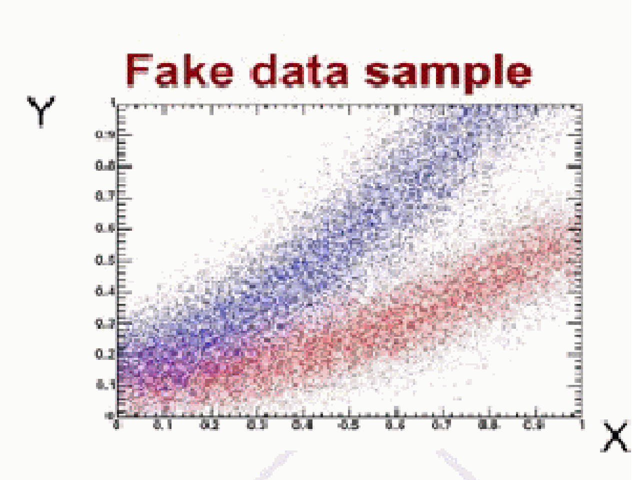


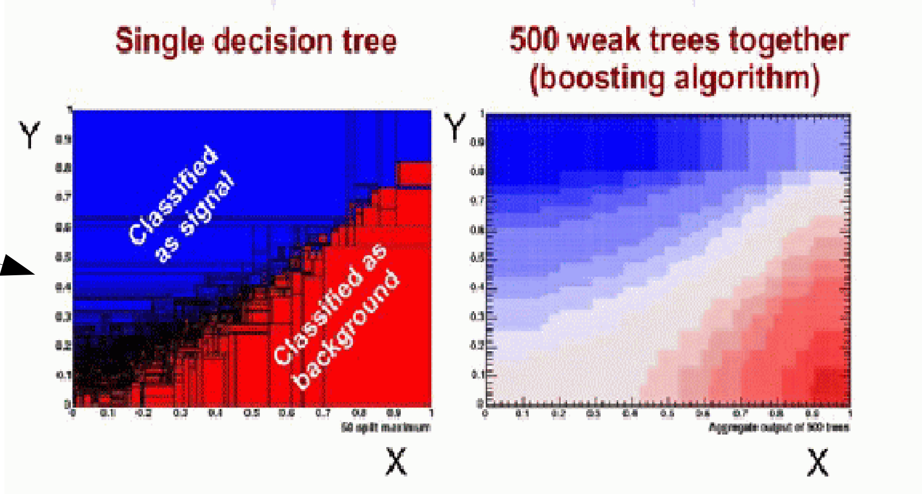
Figure 1: Schematic of a decision tree.

Boosting is a powerful technique involving the weighting and combining of many decision trees into a single output classifier

- . . .to generate sensitivity to a 0.25% oscillation signal we need to reject :
  - **99.9% of ν_μ CC interactions**
  - **99% of ν_μ NC π^0 interactions**
  - **maintain ~30-60% efficiency for ν_e interactions**
- to this end we have developed multiple, complimentary event identification methods
  - **likelihood cuts analysis ($L_{e\mu}$,$L_{e\pi}$)**
  - **boosted decision trees**



Boosting is a powerful technique involving the weighting and combining of many decision trees into a single output classifier

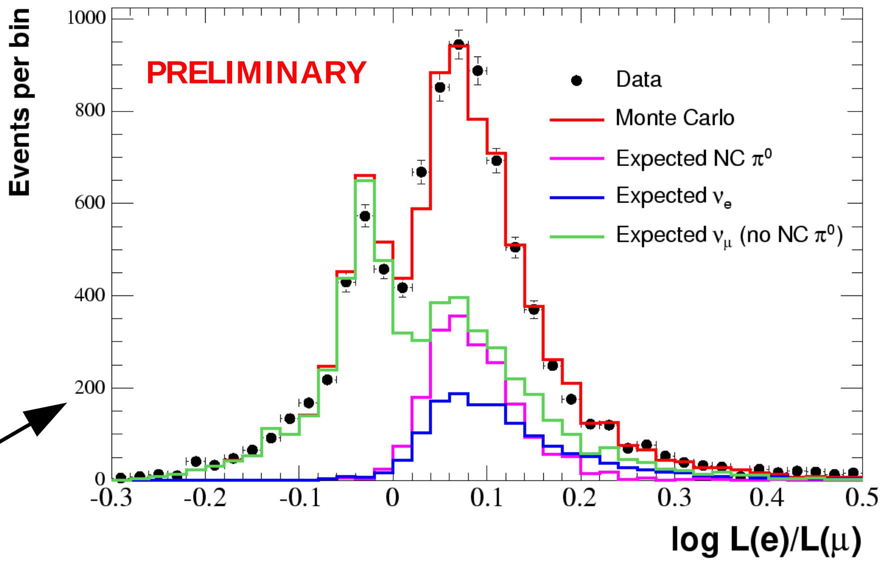


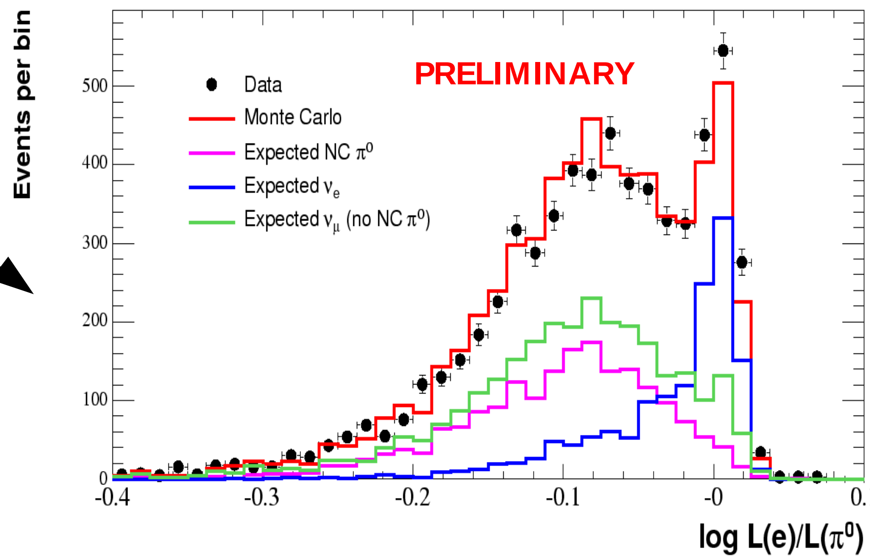
single decision trees prone to "over-training"

See B. Roe *et. al.* papers for a detailed introduction to boosting and comparison to ANN

H. Yang, B. Roe, J. Zhu, "Studies of Boosted Decision Trees for MiniBooNE Particle Identification", Nucl.Instrum.Meth.A555; 370-385 (2005)
B. Roe *et. al.* "Boosted Decision Trees as an Alternative to Artificial Neural Networks for Particle Identification" Nucl.Instrum.Meth.A543; 577-584 (2005)

- . . .to generate sensitivity to a 0.25% oscillation signal we need to reject :
  - **99.9% of ν_μ CC interactions**
  - **99% of ν_μ NC π^0 interactions**
  - **maintain ~30-60% efficiency for ν_e interactions**
- to this end we have developed multiple, complimentary event identification methods
  - **likelihood cuts analysis ($L_{e\mu}$,$L_{e\pi}$)**
  - **boosted decision trees**

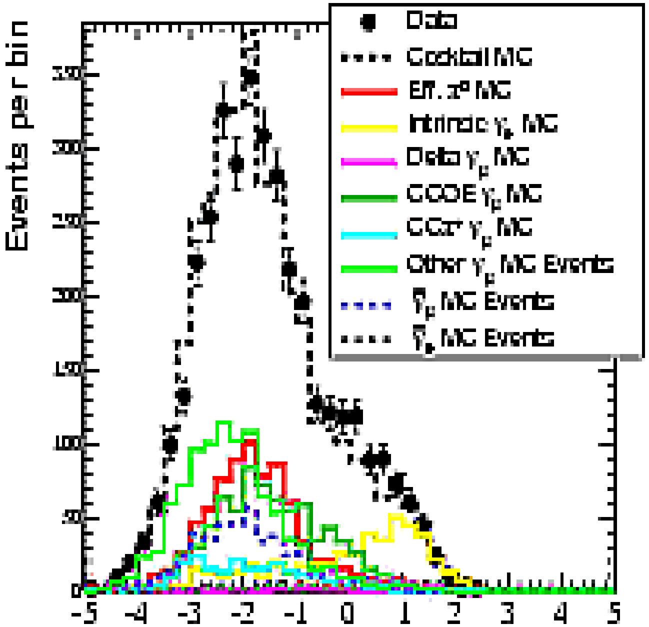


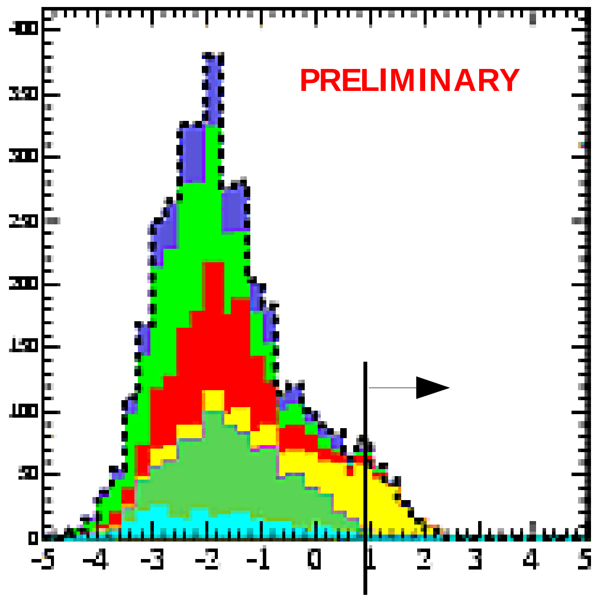


an example of the selection variables performance using neutrinos from the NuMI neutrino beam

NuMI beam contains many ν_e's - an excellent calibration beam for us!

- . . .to generate sensitivity to a 0.25% oscillation signal we need to reject :
  - **99.9% of ν_μ CC interactions**
  - **99% of ν_μ NC π^0 interactions**
  - **maintain ~30-60% efficiency for ν_e interactions**
- to this end we have developed multiple, complimentary event identification methods
  - **likelihood cuts analysis ($L_{e\mu}$,$L_{e\pi}$)**
  - **boosted decision trees**



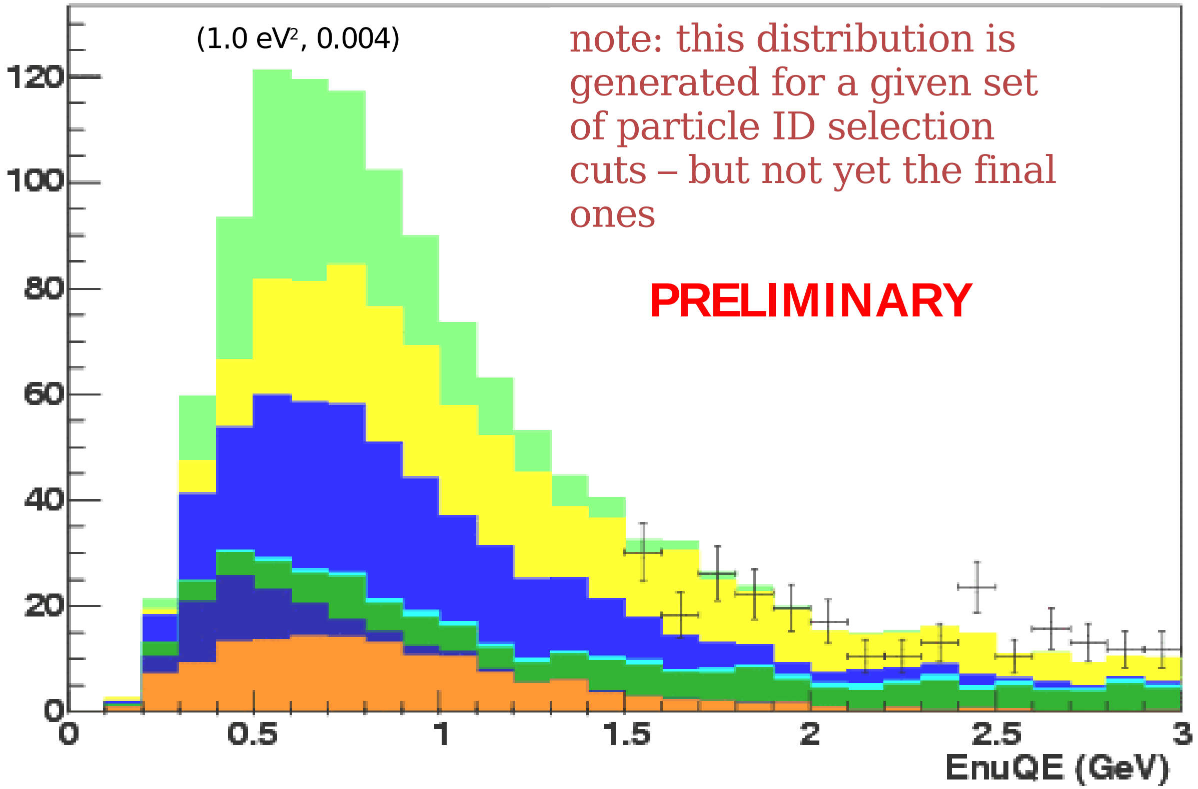


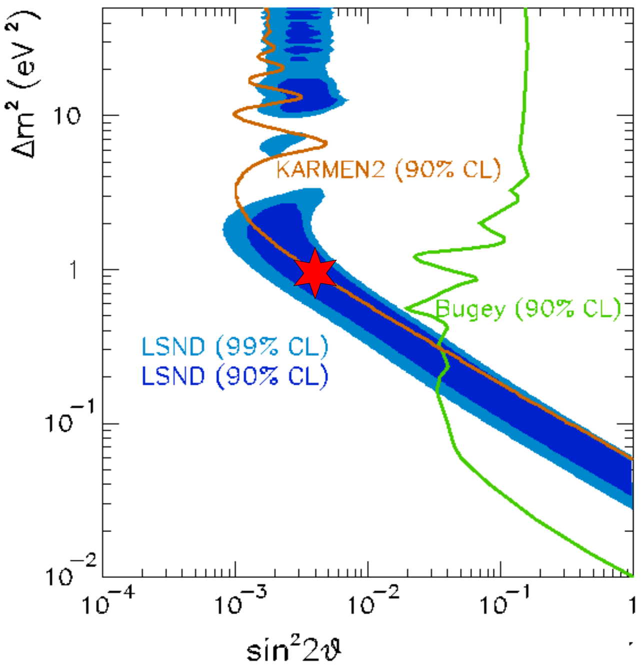
an example of the selection variables performance using neutrinos from the NuMI neutrino beam

NuMI beam contains many ν_e's - an excellent calibration beam for us!

putting it all together. . .

- once all systematic errors and particle ID selection cuts are finalized, a predicted E_ν^{QE} distribution of intrinsic electron and mis-ID electron-like events is compared to a sample in data
- a significant excess implies $\nu_\mu \rightarrow \nu_e$ **oscillations**





oscillation ν_e

ν_e from K decays

ν_e from μ decays

ν_μ NC π^0 events

other misIDs

Summary

- major components of the MiniBooNE oscillation analysis are coming into place
  - flux predictions
    - including ν_μ and ν_e intrinsic backgrounds
  - cross-section models
    - including CCQE and π^0 rates
  - detector "optical model" in great shape
  - particle ID algorithms being finalized
- working to finalize error matrices describing systematic error contributions from flux, cross-section and detector pieces
- working to finalize signal searching software and performing important Monte Carlo fake data tests
- indeed exciting times at the miniature BooNE!

Backups

An aside on the SW parameterization

$$\frac{d^2\sigma(p+A\rightarrow\pi^+ + X)}{dp\,d\Omega}(p,\theta)=c_1 p^{c_2}\left(1-\frac{p}{p_{beam}}\right)\exp\left[-c_3\frac{p^{c_4}}{p_{beam}^{c_5}}-c_6\theta\left(p-c_7 p_{beam}\cos^{c_8}\theta\right)\right]$$

- X : any other final state particle
- p_{beam} : proton beam momentum (GeV/c)
- p, θ : pion lab-frame momentum (GeV/c) and angle (rad)
- $c_1,\ldots, c_8$: empirical fit parameters

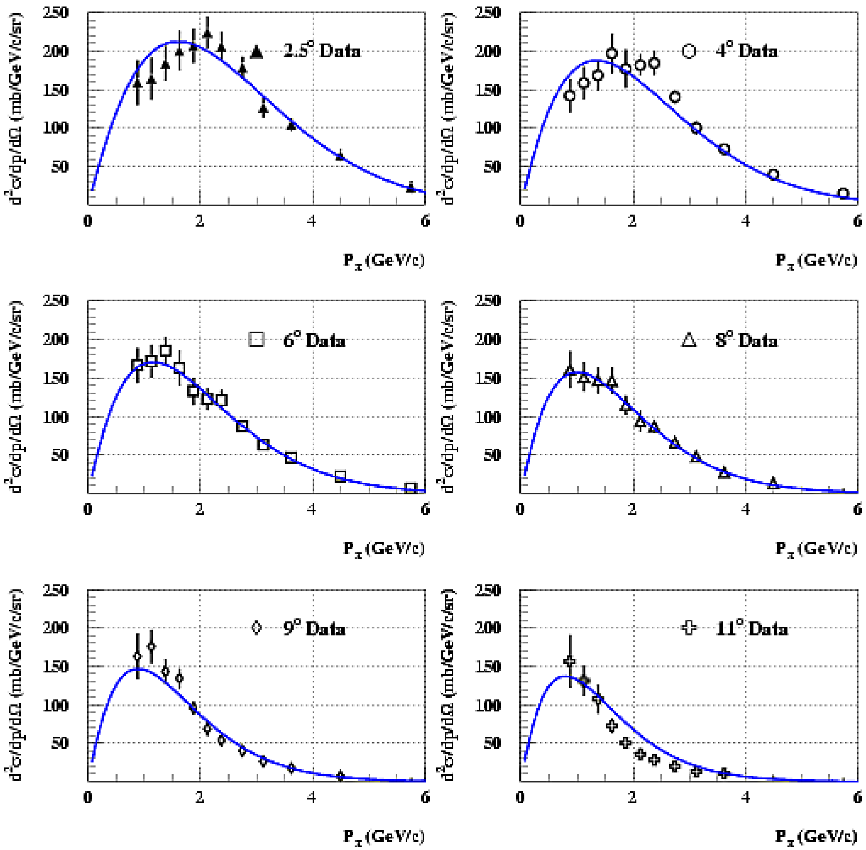
The Sanford-Wang parametrization is useful to:

- combine information from data sets at different beam energies
- input hadron cross-sections into neutrino beam Monte Carlos
- translate pion production uncertainties into neutrino flux uncertainties
- compare results of different experiments in similar energy regions for compatibility

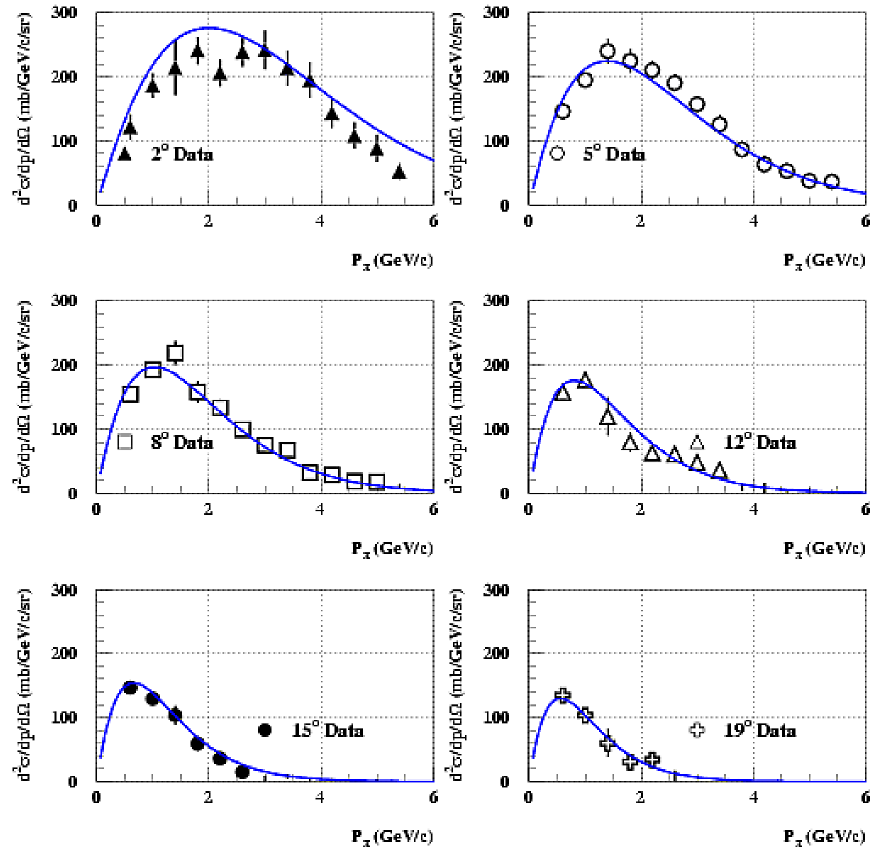
J. R. Sanford and C. L. Wang "Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967) (*unpublished)*

SW fits to HARP and E910 π^+ data

HARP data (8.9 GeV/c)



E910 data (12.3 GeV/c)



- the E910 and HARP data sets are **extremely compatible** in normalization, with some tension in shape

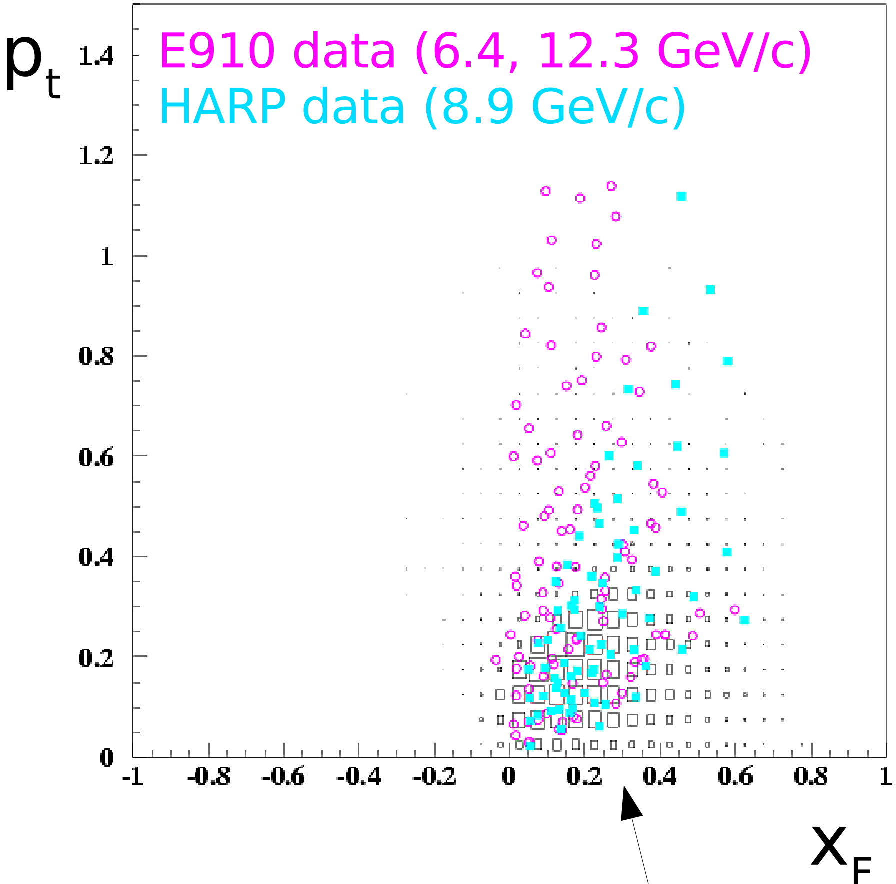
shape only $\chi^2/ndf = 2.23$

total (with norm. penalty term) $\chi^2/ndf = 2.25$

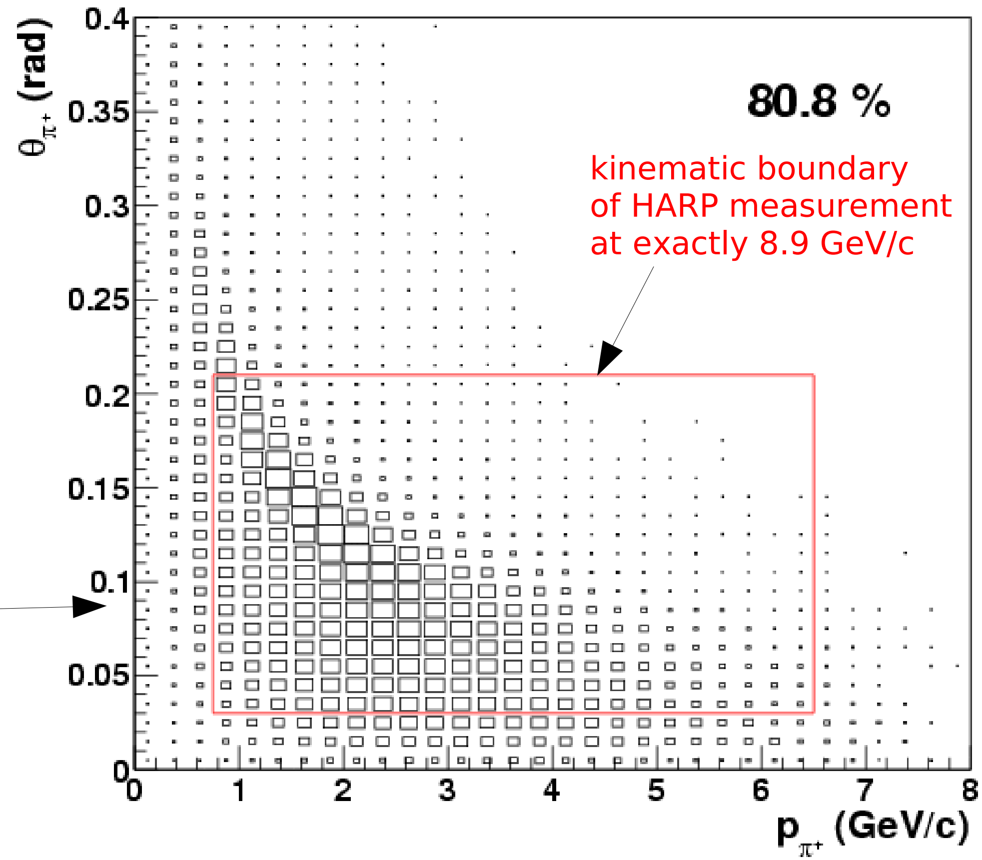
(J. Monroe)

normalization pull term	fit result
n_{HARP}	1.00
$n_{E910\ 6.4}$	1.02 +- 0.06
$n_{E910\ 12.3}$	0.97 +- 0.03

Kinematic coverage of HARP and E910 π^+ data



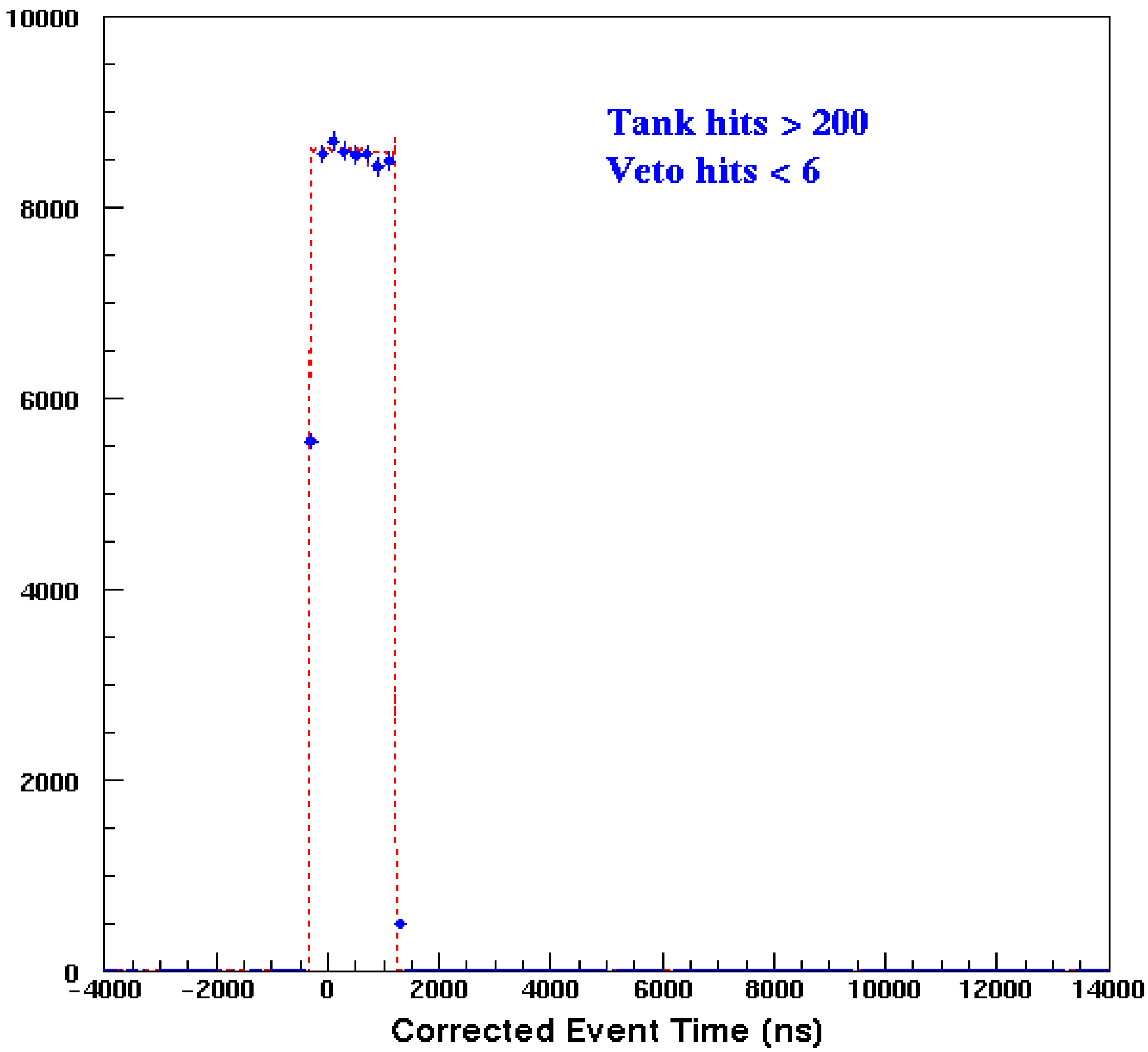
- combining HARP and E910 data gives maximal coverage of the relevant pion phase space for MiniBooNE
- Use the parameterization of Sanford and Wang and fit to both data sets combined



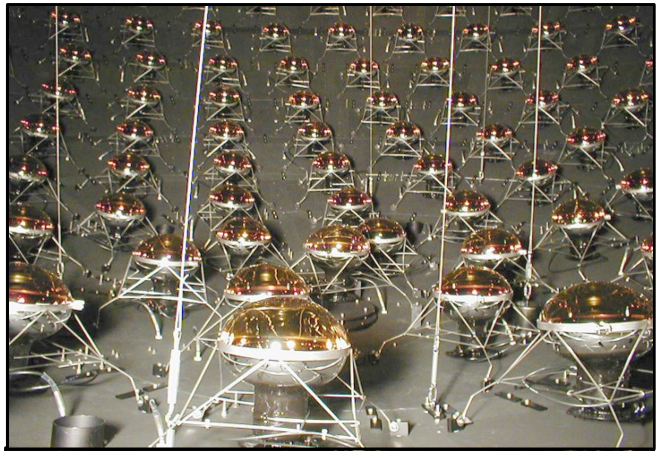
- black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**

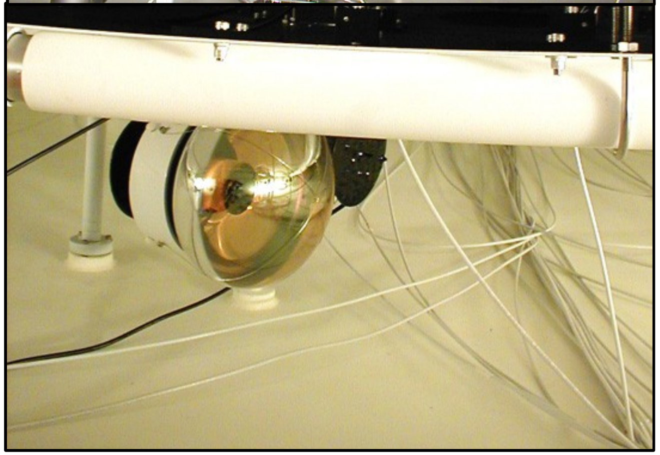
$$p + Be \rightarrow \pi^+ \rightarrow \nu_\mu^{MB}$$

Beam-off background reduced to ~5000:1



tank





veto region