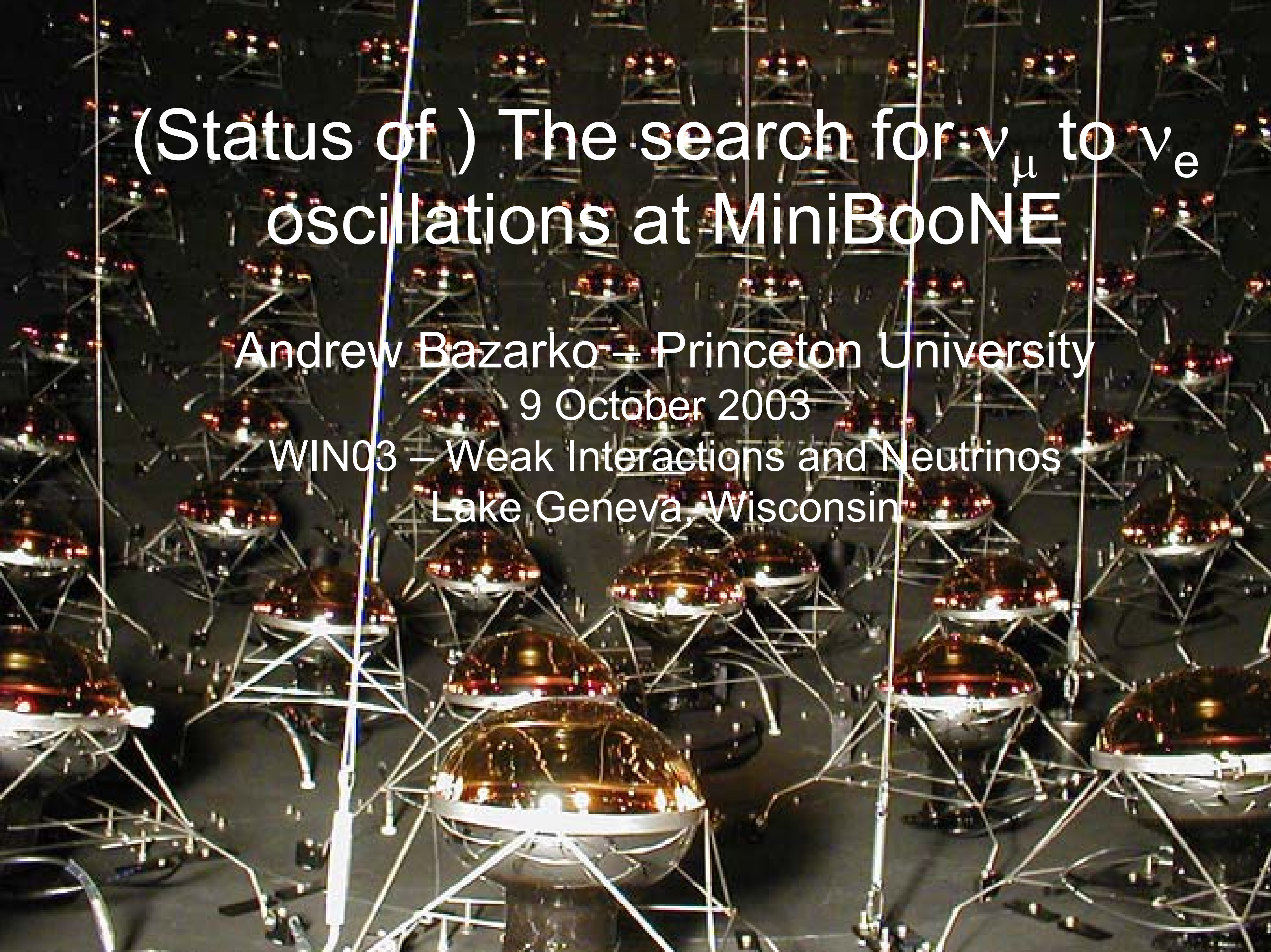


(Status of) The search for ν_μ to ν_e oscillations at MiniBooNE

Andrew Bazarko – Princeton University

9 October 2003

WIN03 – Weak Interactions and Neutrinos

Lake Geneva, Wisconsin

MiniBooNE status snapshot

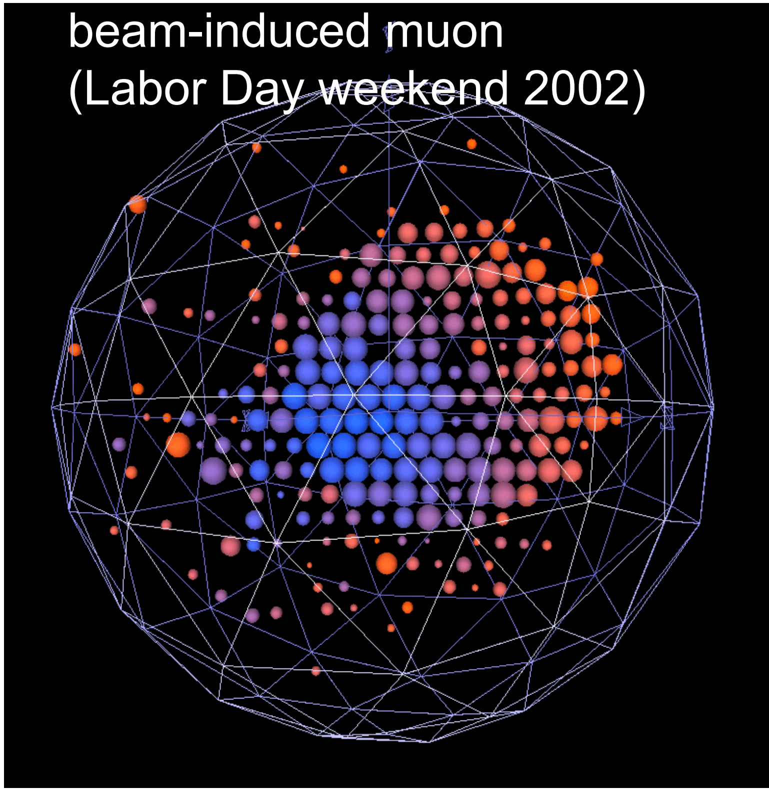
MiniBooNE has been running for 1 year at Fermilab

acquired 15% of goal 10^{21} protons on target

At the moment (Sept – mid Nov) accelerator is shutdown

important accelerator improvements are underway

MiniBooNE's first event:
beam-induced muon
(Labor Day weekend 2002)



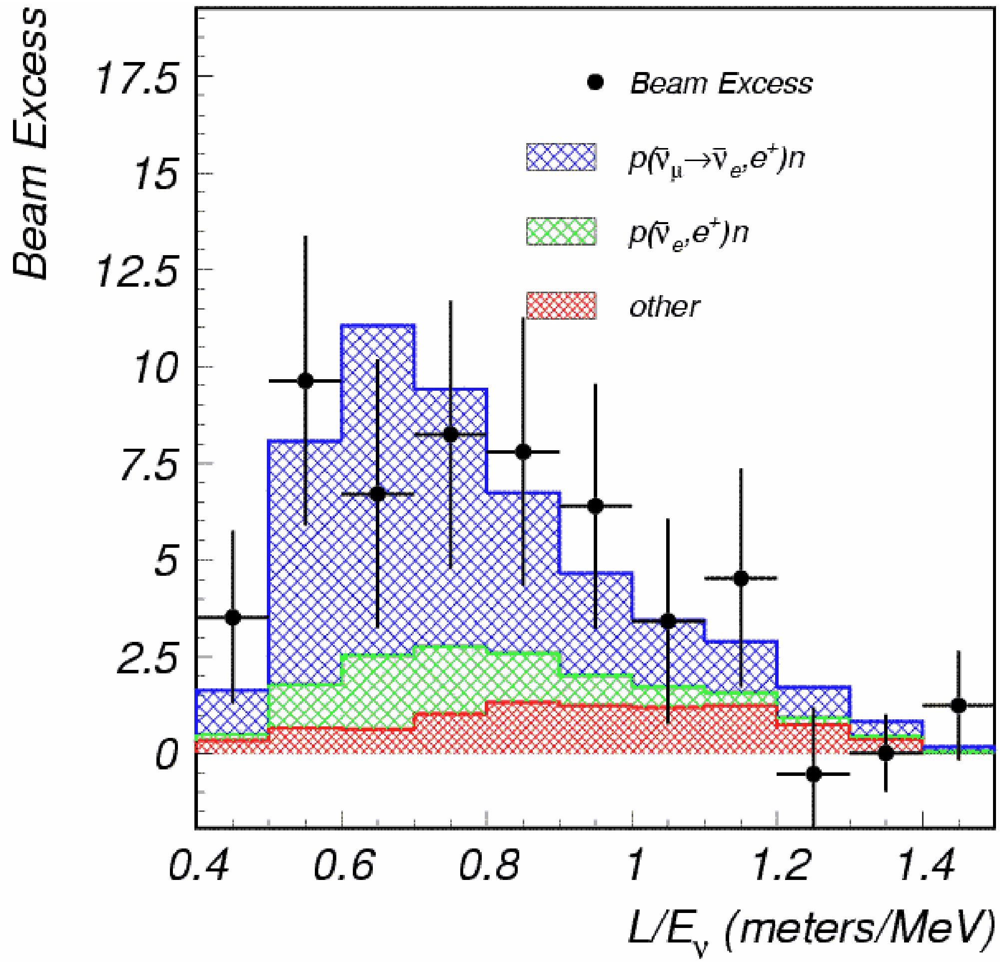
Outline

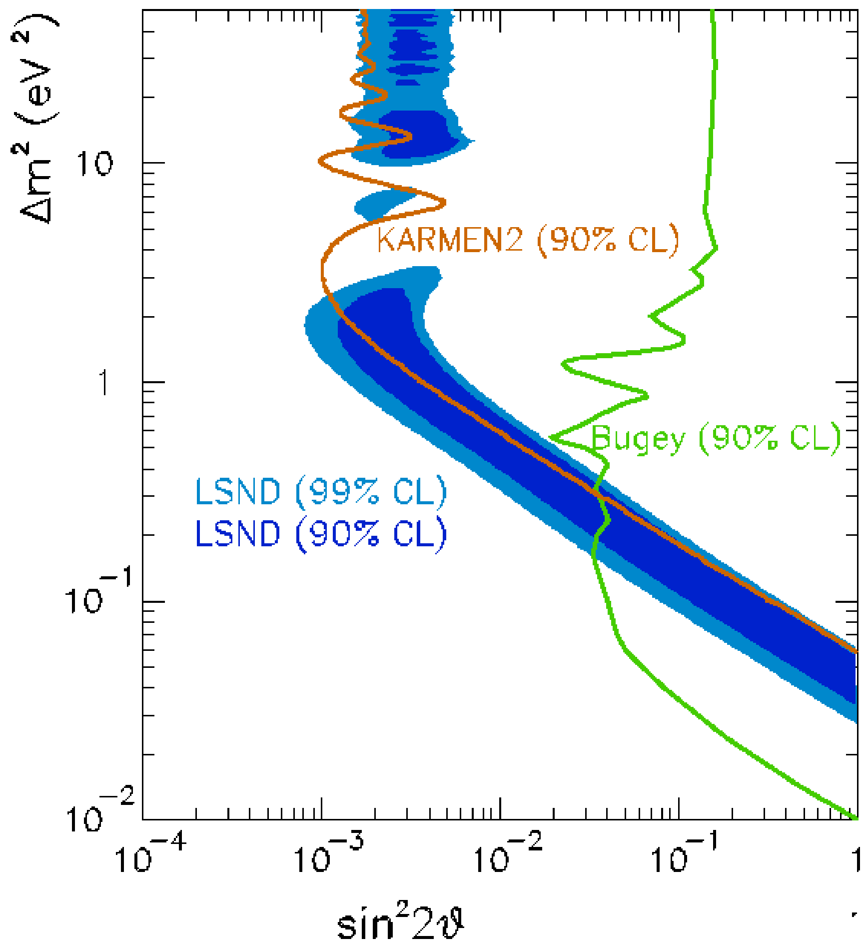
- Overview of the experiment
  - (preview of tomorrow's tour)
- First neutrino events and analysis
- Outlook

LSND:

Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\bar{\nu}_\mu$ beam from μ+ decay at rest
energy 20-53 MeV
baseline 30 m
L/E ~ 1 m/MeV





87.9±22.4±6.0 events

Δm^2~0.2-10 eV^2

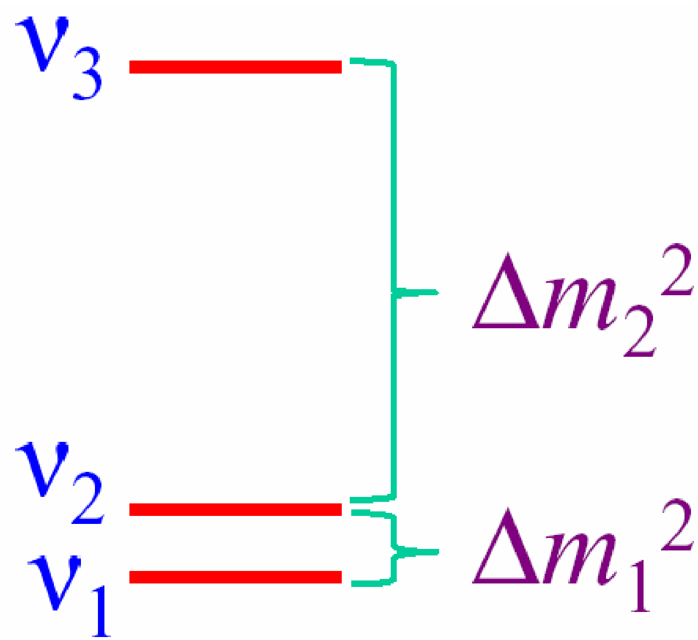
(Bugey is $\bar{\nu}_e$ disappearance)

Too many Δm^2's?

3 light neutrino flavors

Solar (+KamLAND) neutrinos:
- $\Delta m^2 \approx 7\times10^{-5} eV^2$
- mostly $\nu_e \rightarrow \nu_{\mu,\tau}$

Atmospheric (+K2K) neutrinos:
- $\Delta m^2 \approx 2\times10^{-3} eV^2$
- mostly $\nu_\mu \rightarrow \nu_\tau$



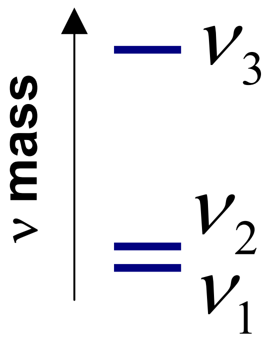
$$\Delta m_3{}^2 = \Delta m_1{}^2 + \Delta m_2{}^2$$

Where does LSND's Δm^2~0.2-10 eV^2
fit in this picture??

ν Oscillation Scenarios:

With current results from solar, atmospheric, and LSND
ν–oscillation searches (3 Δm^2s), we have an interesting situation:

Only 3 active ν:

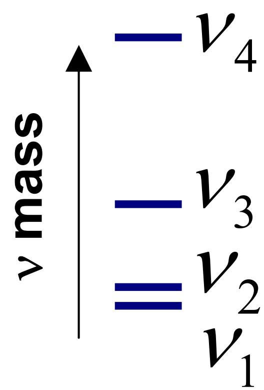


OR...

$$\text{solar}: \nu_e \rightarrow \nu_\mu$$
$$\text{atmos}: \nu_\mu \rightarrow \nu_e, \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \rightarrow \bar{\nu}_e$$

- not a good fit to data

3 active+1 sterile ν:

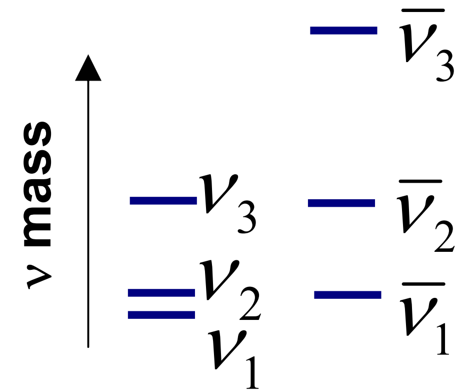


OR...

$$\text{solar}: \nu_e \rightarrow \nu_\mu, \nu_\tau$$
$$\text{atmos}: \nu_\mu \rightarrow \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \rightarrow \bar{\nu}_s \rightarrow \bar{\nu}_e$$

- possible(?)

CPT violation:



OR...

$$\text{solar}: \nu_e \rightarrow \nu_\mu$$
$$\text{atmos}: \nu_\mu \rightarrow \nu_\tau$$
$$\text{LSND}: \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

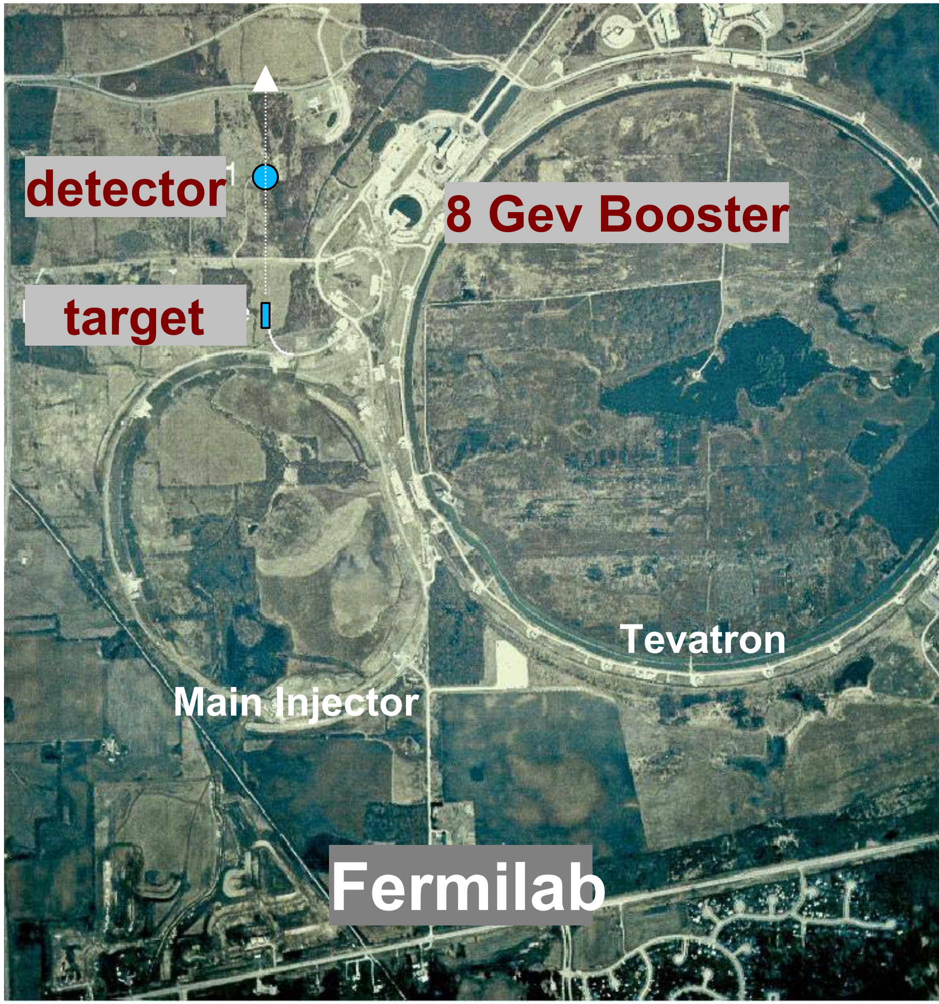
- possible(?)

Need to definitively check the LSND result.

Goal: test LSND with 5-σ sensitivity over whole allowed range

- higher statistics
- different signature
- different backgrounds
- different systematics

MiniBooNE!



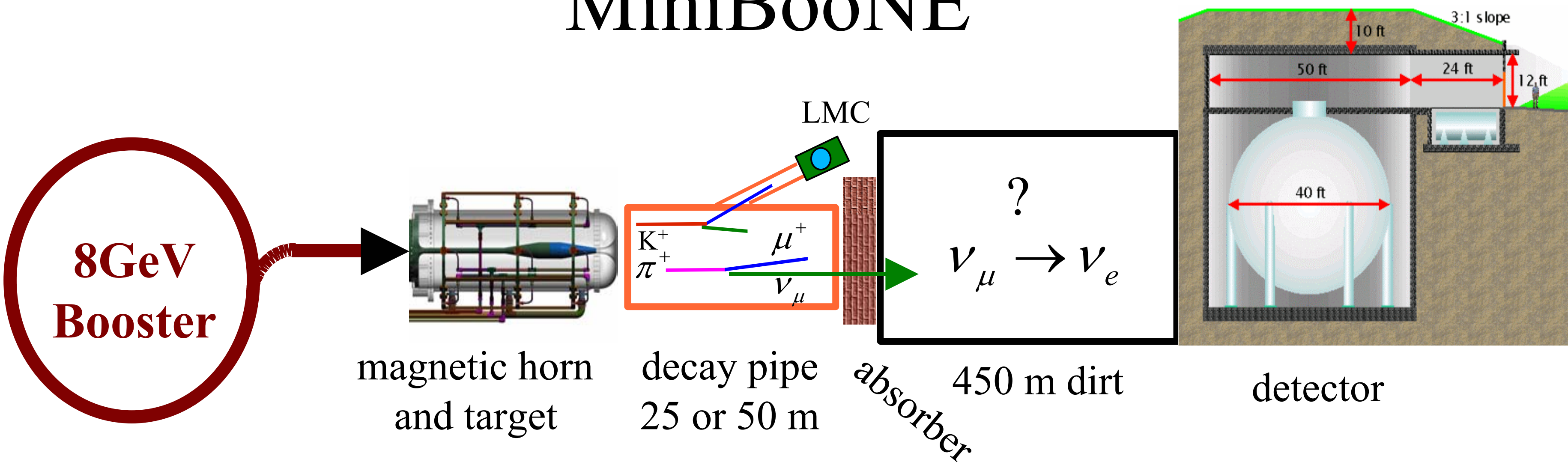
BooNE: Fermilab Booster Neutrino Experiment

First phase: "MiniBooNE"

- Single detector, $\nu_\mu \rightarrow \nu_e$ appearance
- L/E=500 m/500 MeV = 30 m/30 MeV (LSND)

Y. Liu, I. Stancu *Alabama*
S. Koutsoliotas *Bucknell*
E. Hawker, R.A. Johnson, J.L. Raaf *Cincinnati*
T. Hart, E.D. Zimmerman *Colorado*
Aguilar-Arevalo, L.Bugel, J.M. Conrad, J. Formaggio, J. Link, J. Monroe, D. Schmitz, M.H. Shaevitz, M. Sorel, G.P. Zeller *Columbia*
D. Smith *Embry Riddle*
L.Bartoszek, C. Bhat, S J. Brice, B.C. Brown, D.A. Finley, B.T. Fleming, R. Ford, F.G.Garcia, P. Kasper, T. Kobilarcik, I. Kourbanis, A. Malensek, W. Marsh, P. Martin, F. Mills, C. Moore, P. J. Nienaber, E. Prebys, A.D. Russell, P. Spentzouris, R. Stefanski, T. Williams *Fermilab*
D. C. Cox, A. Green, H.-O. Meyer, R. Tayloe *Indiana*
G.T. Garvey, C. Green, W.C. Louis, G.McGregor, S.McKenney, G.B. Mills, V. Sandberg, B. Sapp, R. Schirato, R. Van de Water, D.H. White *Los Alamos*
R. Imlay, W. Metcalf, M. Sung, M.O. Wascko *Louisiana State*
J. Cao, Y. Liu, B.P. Roe *Michigan*
A.O. Bazarko, P.D. Meyers, R.B. Patterson, F.C. Shoemaker, H.A.Tanaka *Princeton*

MiniBooNE



8-GeV protons on Be target →

π^+, K^+,…, focused by horn

decay in 50-m pipe, mostly to ν_μ

all but ν absorbed in steel and dirt

ν's interact in 40-ft tank of mineral oil

charged particles produce light

detected by phototube array

Look for electrons produced by mostly-ν_μ beam

The Booster

8 GeV proton accelerator supplies beam to all Fermilab experiments

It must now run at record intensity

MiniBooNE runs simultaneously with the collider program; goals:

Booster → MiniBooNE: 5×10^{20} p.o.t per year (1×10^{21} total)

Booster → Main Injector →
- antiproton source
- TeVatron
- NuMI
- 120 GeV fixed target

MiniBooNE: negligible impact on collider; improvements to Booster good for NuMI

Booster performance

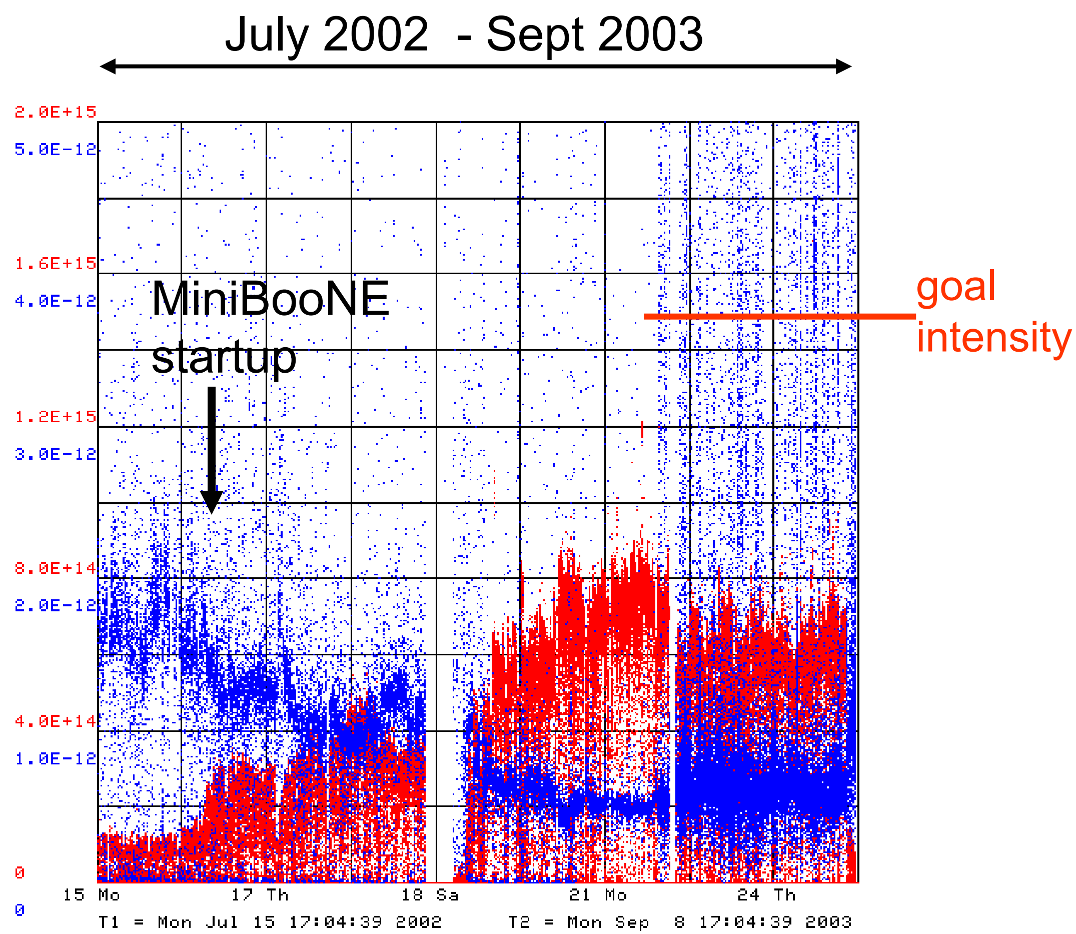
We are pushing the Booster hard

Must limit radiation damage and activation of Booster components:
- increase protons
- but decrease beam loss

~steady improvements
- careful tuning
- understanding optics

need factor of 2-3 to reach goal 10^{21} p.o.t. by early 2005

further improvements coming
- collimator project (now)
- large-aperture RF cavities

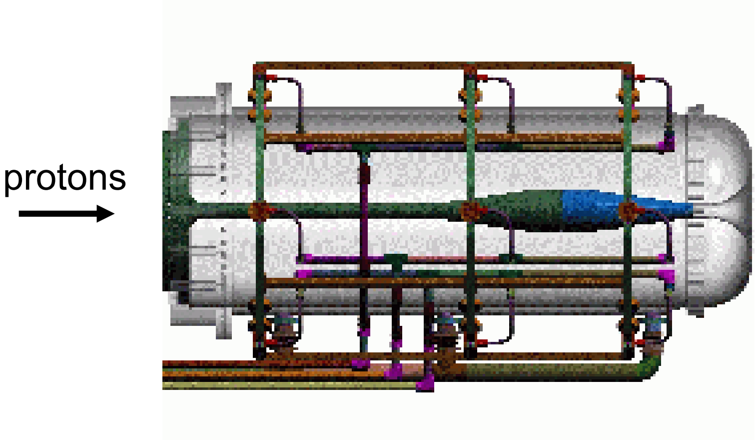


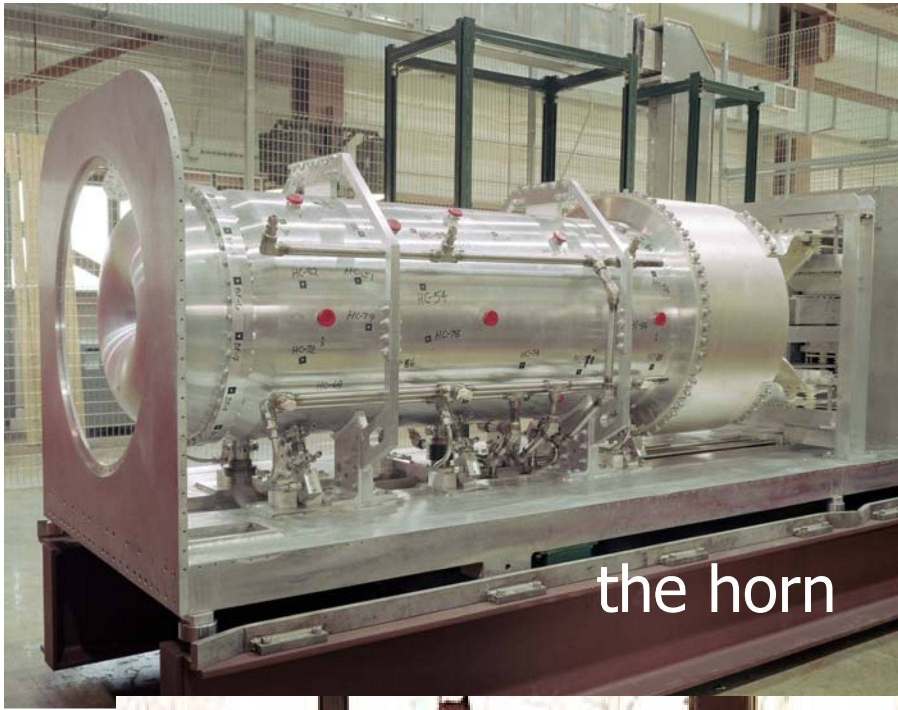
red: Booster output (protons/minute)

blue: energy loss per proton (W-min/proton)

Target and magnetic horn

Increases neutrino intensity by 7x





170 kA in 140 μsec pulses @ 5 Hz

Currently positive particles are being focused, selecting neutrinos $\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$

the horn current can be reversed to select antineutrinos $\pi^{-} \rightarrow \mu^{-} \bar{\nu}_{\mu}$

Prior to run, tested to
11M pulses
has performed flawlessly:
40M pulses in situ

World's longest-lived horn

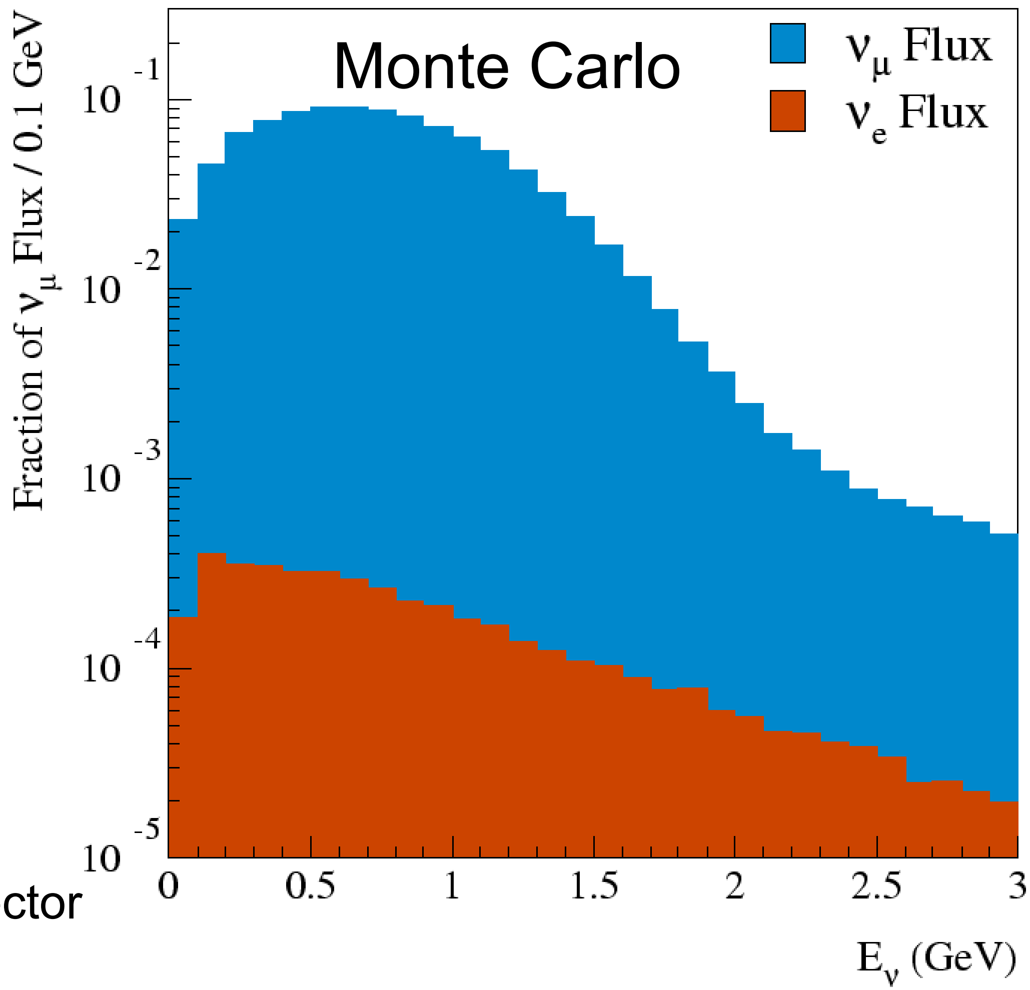
Intrinsic ν_e in the beam

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

$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

$K_L \rightarrow \pi^- e^+ \nu_e$

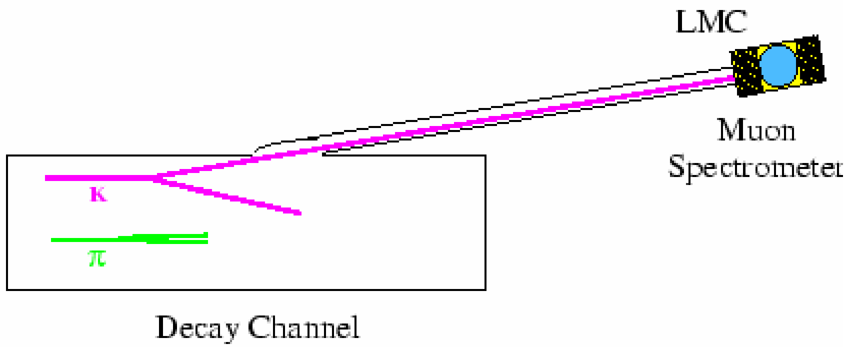


important bkgd to osc search

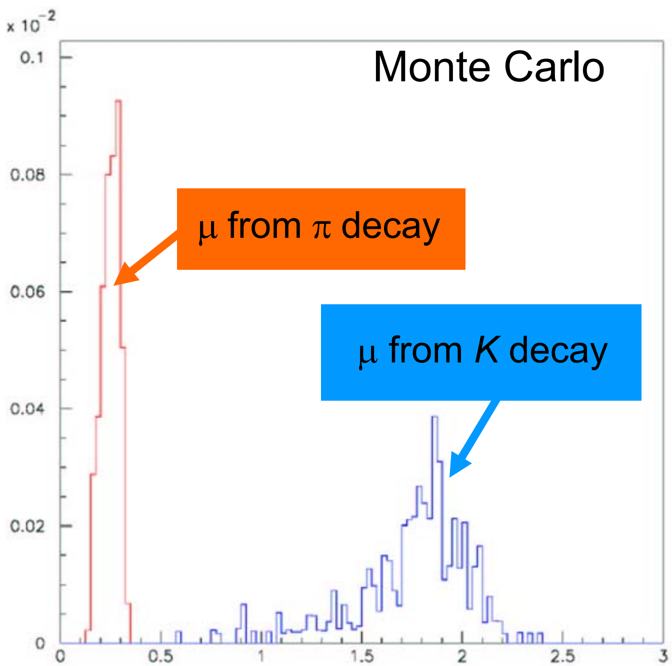
Tackle this background with
- half-million ν_μ interactions in detector
- HARP experiment (CERN)
- E910 (Brookhaven)
- "Little Muon Counter"
- 25 m / 50 m decay length option

Little Muon Counter (LMC)

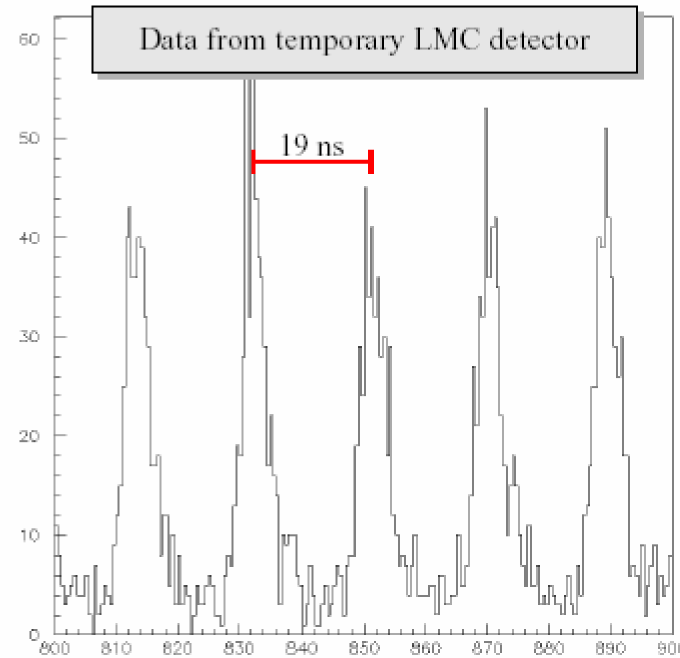
- off-axis (7°) muon spectrometer
- *K* decays produce higher-energy wide-angle muons than π decays
- clean separation of muon parentage
- scintillating fiber tracker



temporary LMC detector (scintillator paddles)
commission data acquisition
53 MHz beam RF structure seen



muon momentum at 7° (GeV)



The MiniBooNE detector

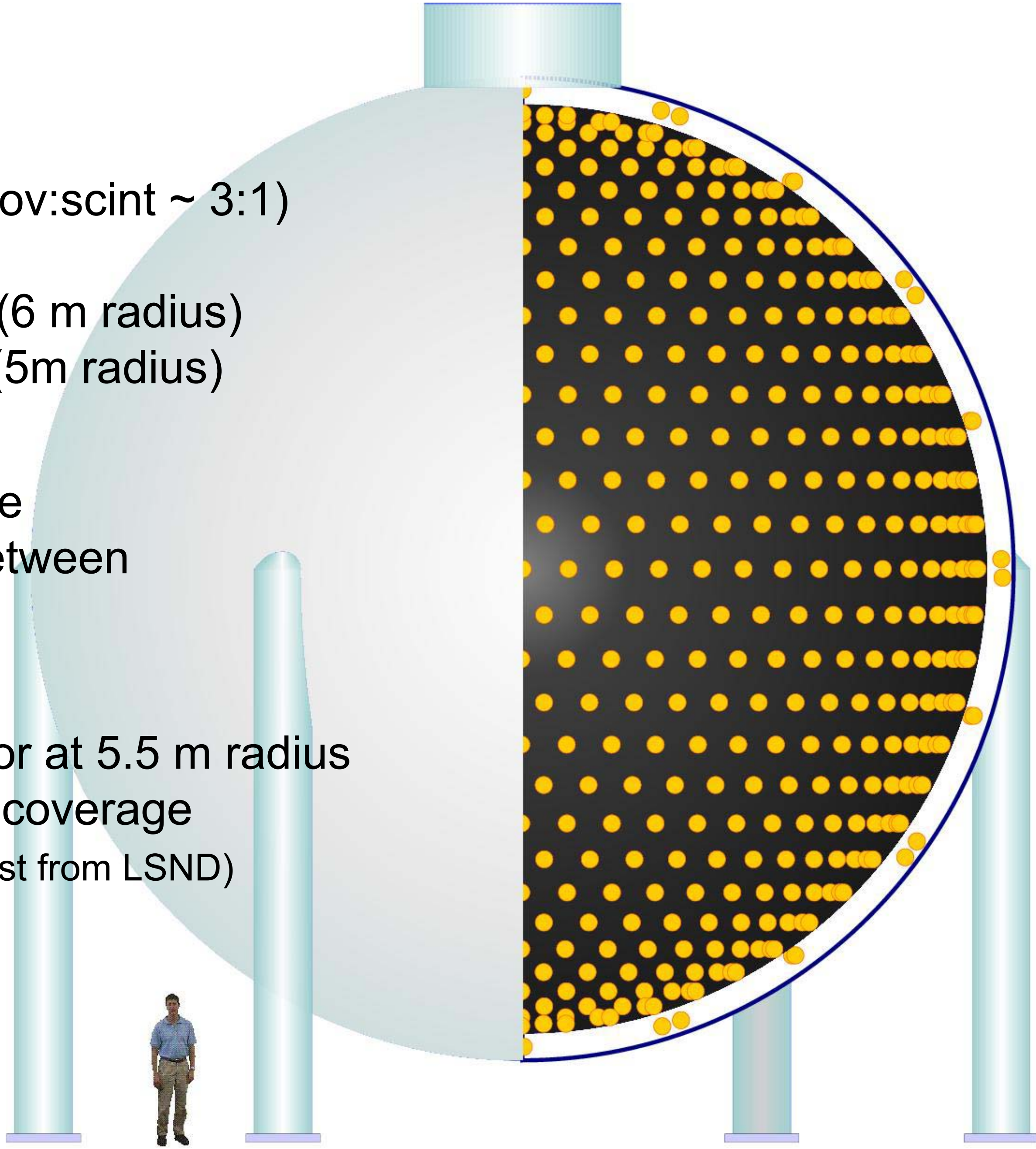
MiniBooNE detector

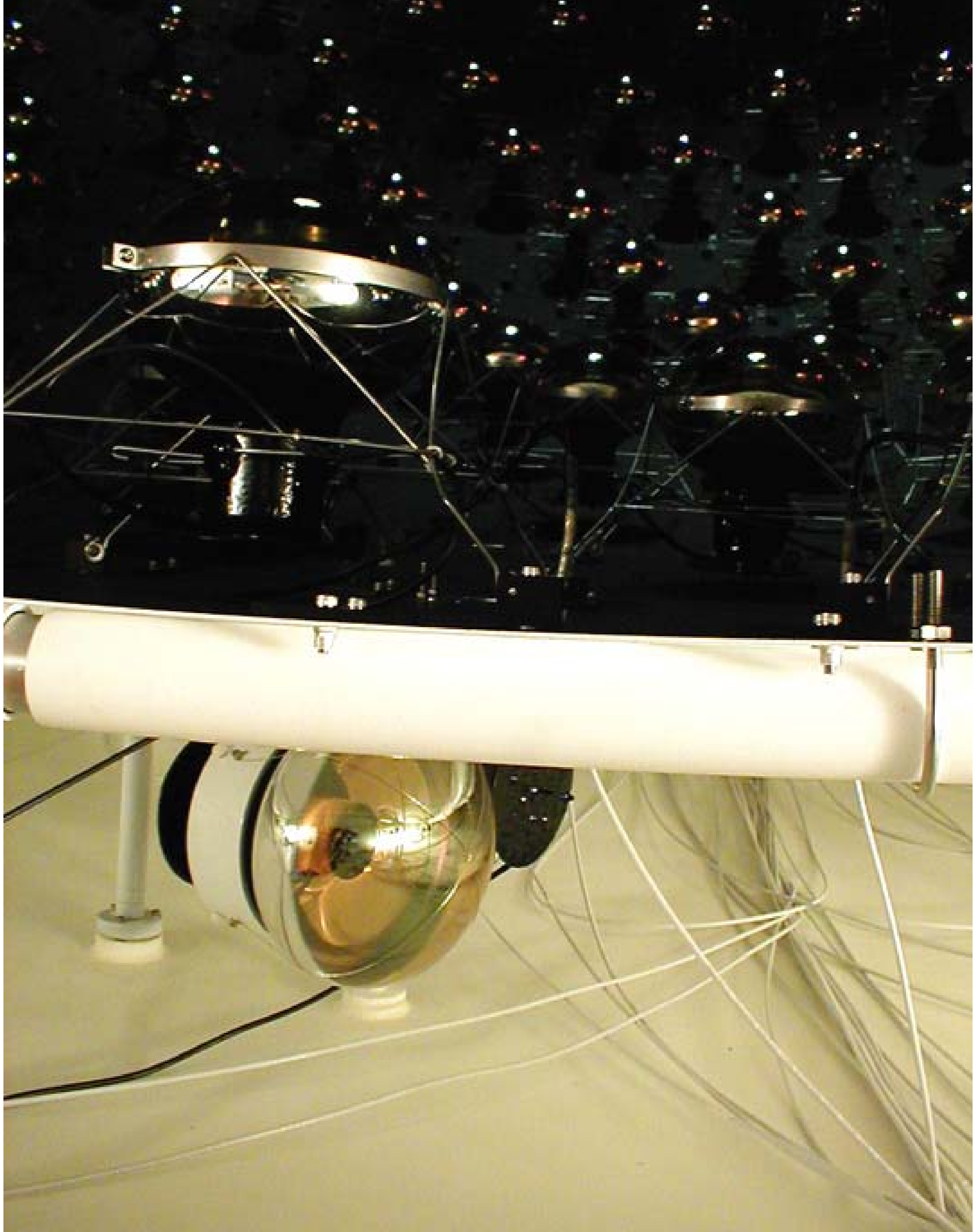
pure mineral oil (Cherenkov:scint ~ 3:1)

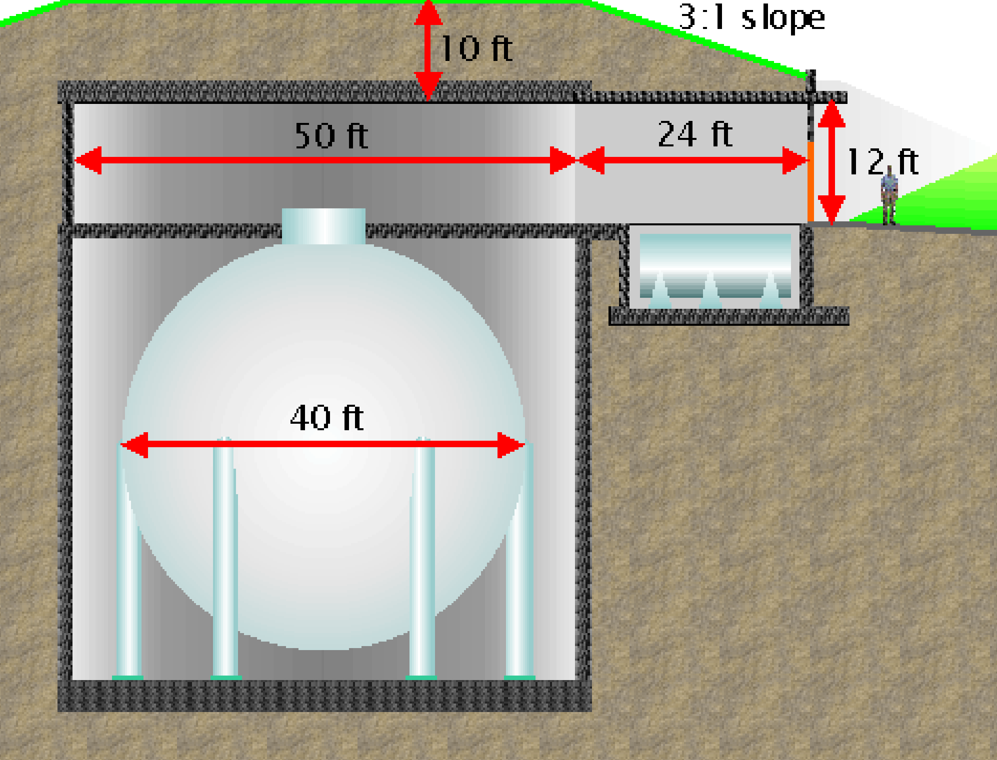
total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)

Phototube support structure
provides opaque barrier between
veto and main volumes

1280 20-cm PMTs in detector at 5.5 m radius
→ 10% photocathode coverage
(330 new tubes, the rest from LSND)
240 PMTs in veto



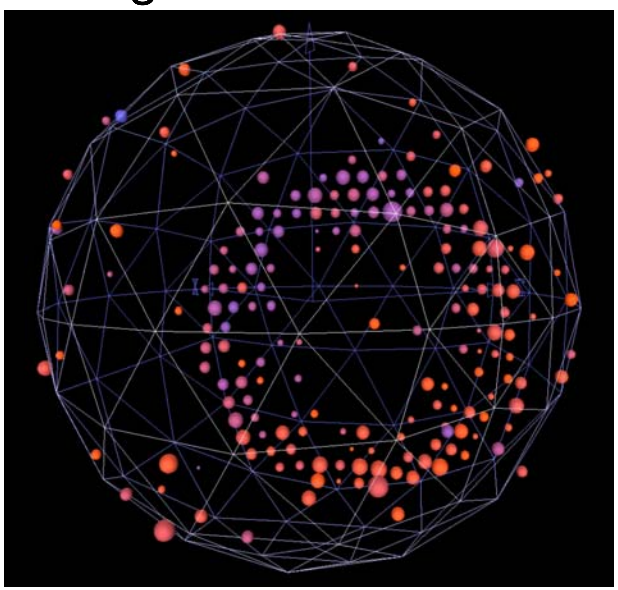



3:1 slope
10 ft
50 ft
24 ft
12 ft
40 ft

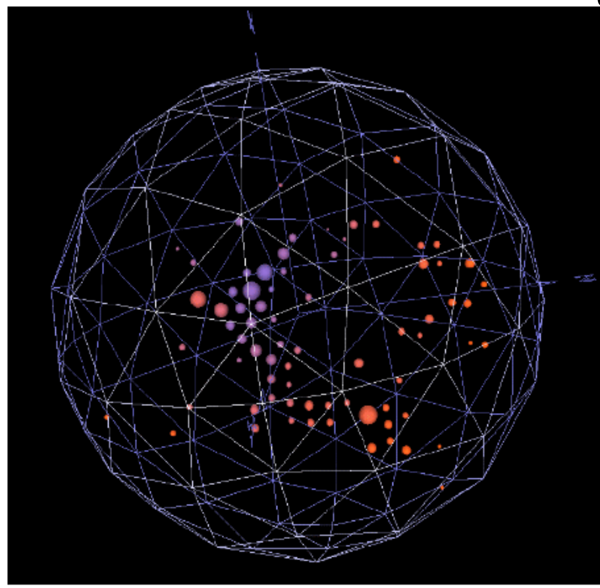

Pattern of hit tubes (with charge and time information) allows reconstruction of track location and direction and separation of different event types.

e.g. candidate events:

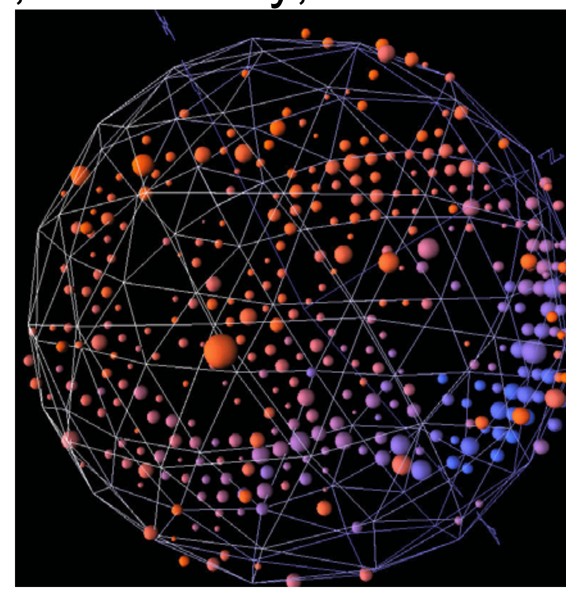
size = charge; red = early, blue = late



muon
from ν_μ interaction

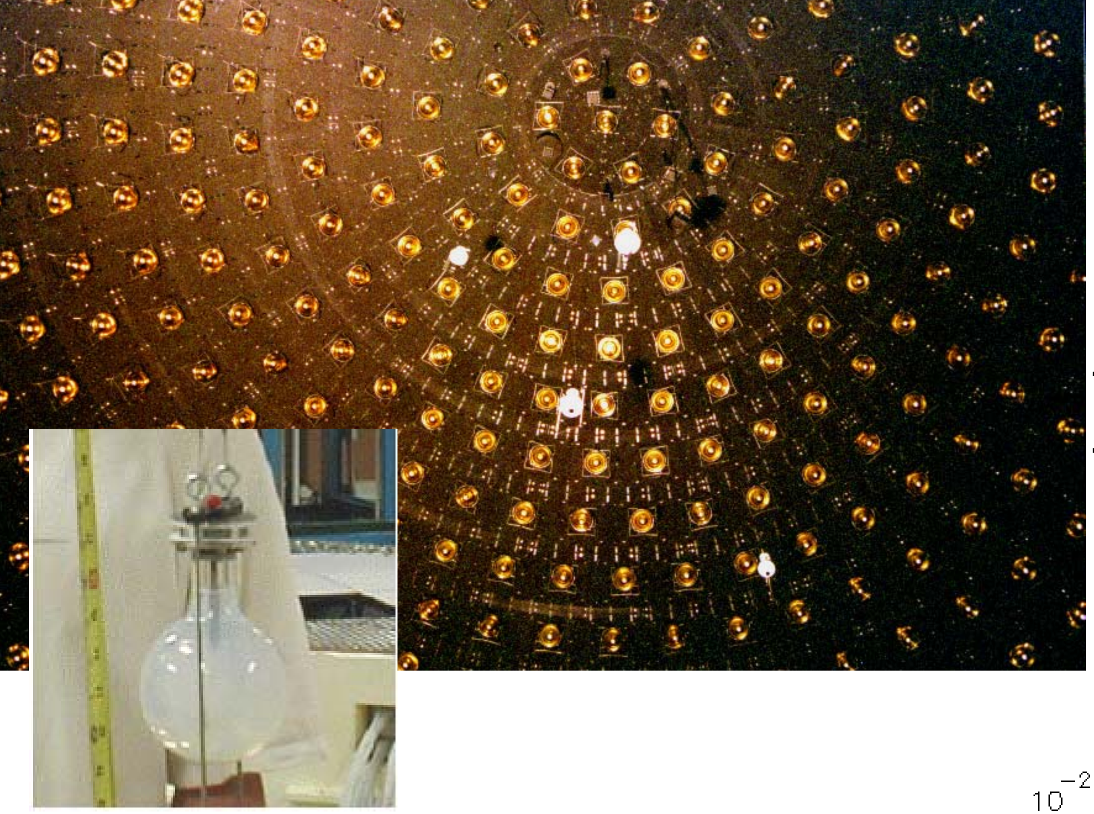


Michel electron
from stopped μ decay
after ν_μ interaction



$\pi^0 \rightarrow$ two photons
from ν_μ interaction

Understanding the detector

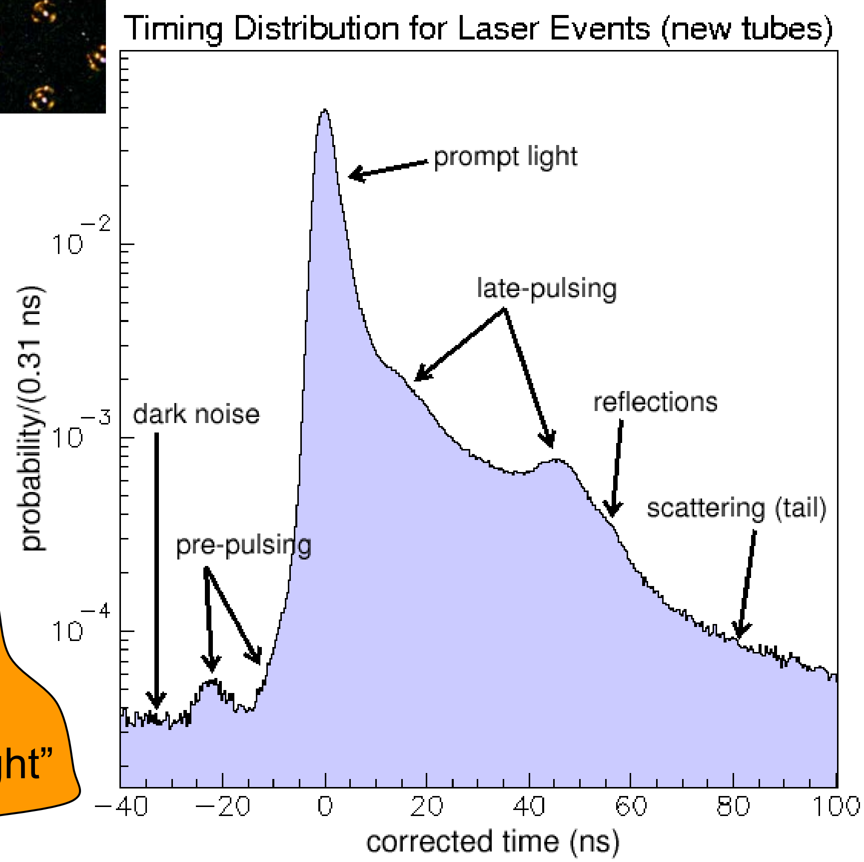


Laser flasks

four Ludox-filled flasks
fed by optical fiber from laser

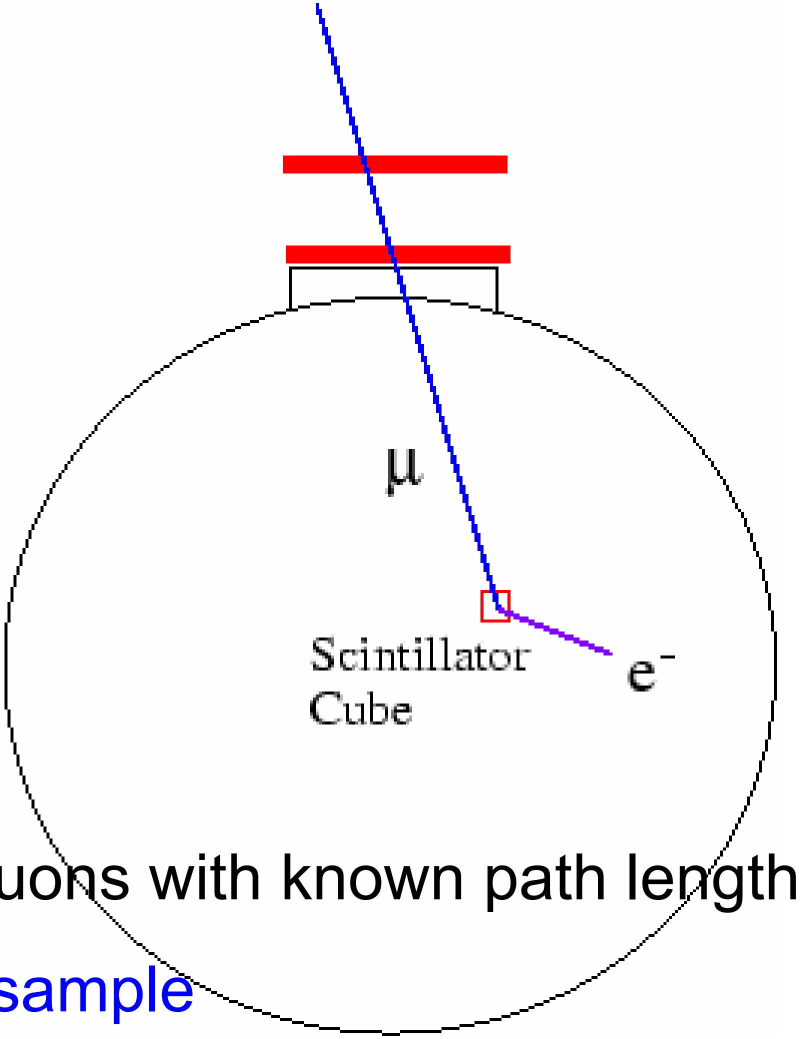
measure:
PMT charge and
time response
and
oil attenuation
length

397 nm laser
(no scintillation!)
modeling other
sources of “late light”



Stopping muon calibration system

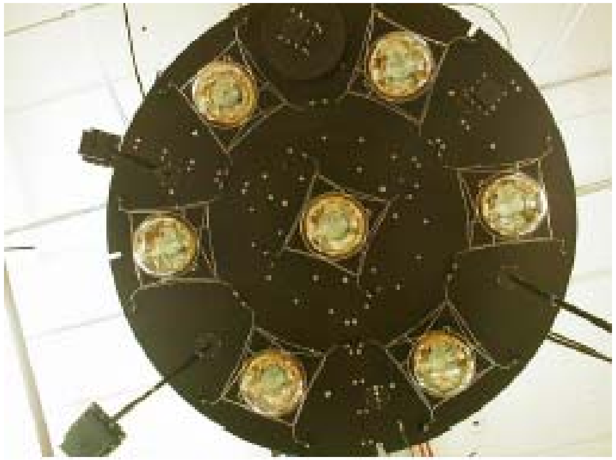
Scintillator tracker above the tank



Optically isolated scintillator cubes in tank:

six 2-inch (5 cm) cubes

one 3-inch cube



stopping muons with known path length

calibration sample of muons up to 700 MeV

Michel electrons

(electrons from the decay of stopped muons)

plentiful source from cosmics
and beam-induced muons

cosmic muon lifetime in oil

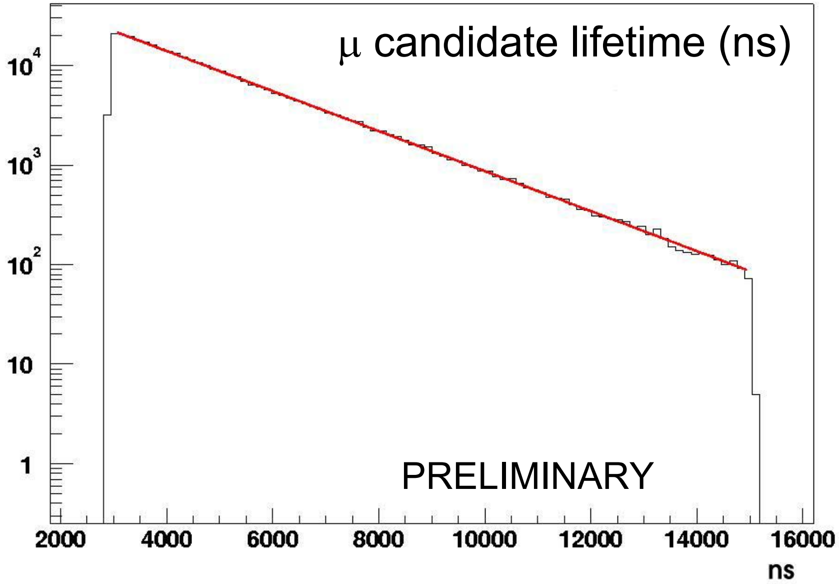
measured: $\tau = 2.15 \pm 0.02\ \mu s$

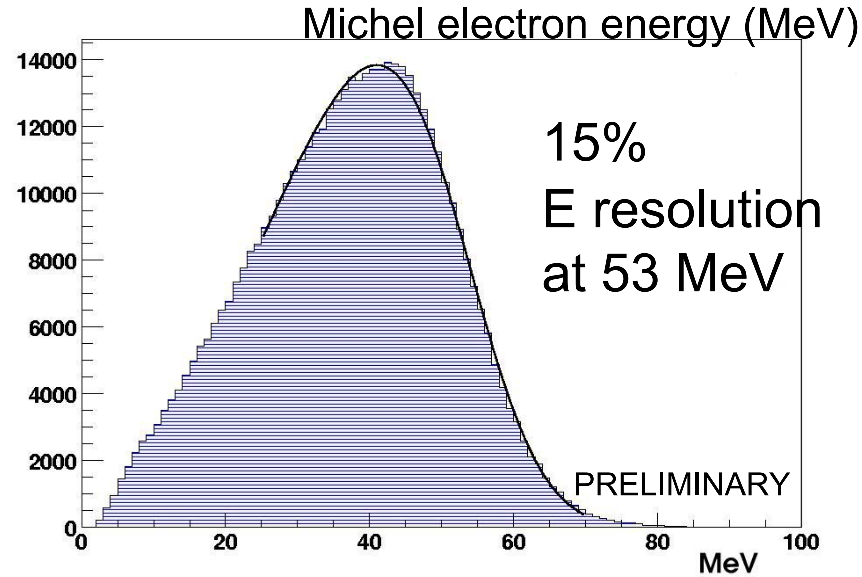
expected: $\tau = 2.13\ \mu s$

(8% μ^- capture)

Energy scale and resolution
at Michel endpoint (53 MeV)

Michel electrons throughout
detector (r<500 cm)





Neutrino events

beam comes in spills @ up to 5 Hz
each spill lasts 1.6 μsec

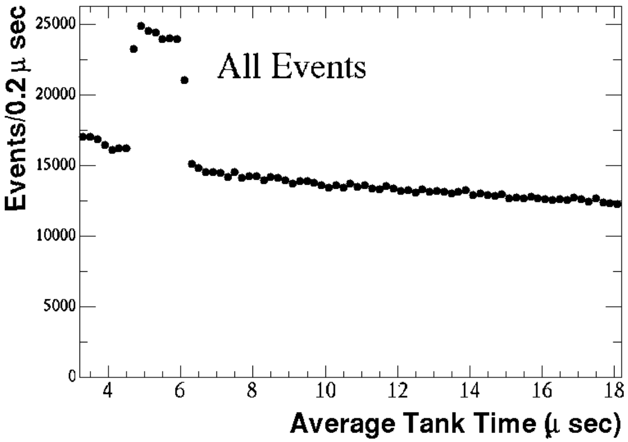
trigger on signal from Booster
read out for 19.2 μsec; beam at [4.6, 6.2] μsec

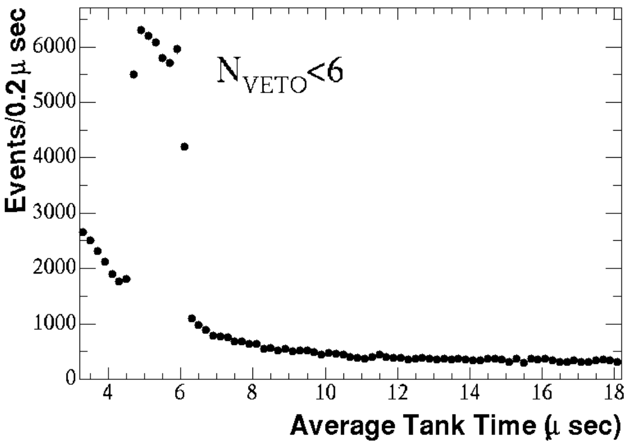
no high level analysis needed to see neutrino events

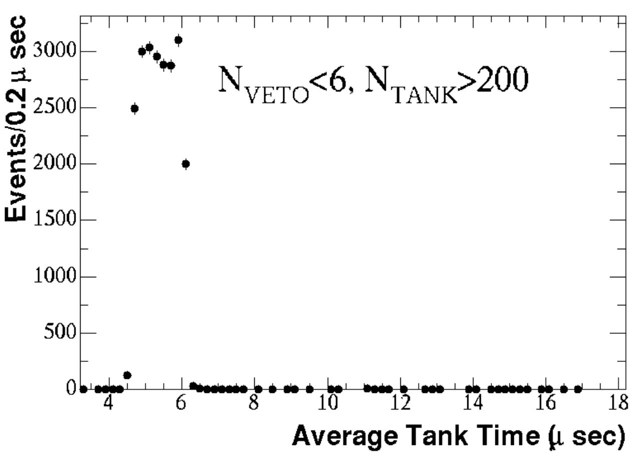
backgrounds: cosmic muons
decay electrons

simple cuts reduce non-beam backgrounds to ~10^{-3}

160k neutrino candidates
in 1.5 x 10^{20} protons on target







The road to $\nu_\mu \rightarrow \nu_e$ appearance analysis

Blind ν_e appearance analysis

you can see all of the info on some events

or

some of the info on all events

but

you cannot see all of the info on all of the events

Early physics: other analyses before $\nu_\mu \rightarrow \nu_e$ appearance

interesting in their own right

relevant to other experiments

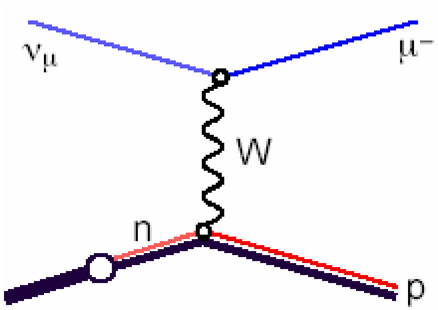
necessary for $\nu_\mu \rightarrow \nu_e$ search

vets data-MC agreement (optical properties, etc.) and reliability of reconstruction algorithms

progress in understanding backgrounds

Early physics

CC quasi-elastic



abundance ~40%
simple topology
one muon-like ring
proton rarely above Č

select “sharp” events
~88% purity

kinematics:
E_μ, θ_μ → E_ν, Q^2
relatively well-known σ:
ν_μ disappearance

NC π^0 production

resonant:

$$\nu + (p/n) \rightarrow \nu + \Delta$$
$$\Delta \rightarrow (p/n) + \pi$$

coherent:

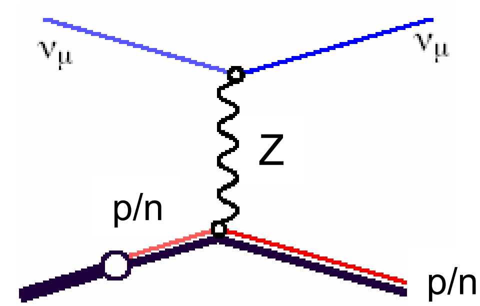
$$\nu + \mathrm{C} \rightarrow \nu + \mathrm{C} + \pi^0$$

abundance ~7%
$\pi^0 \rightarrow \gamma\,\gamma$
two rings
E1, E2 from Č intensities

reconstruct invariant
mass of two photons

background to
ν_e appearance
and
limits on sterile ν

NC elastic

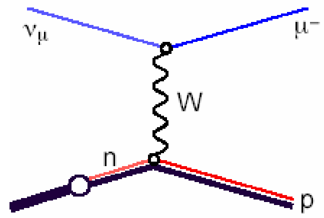


abundance ~15%
usually sub-Č
dominated by
scintillation

low Ntank (pmt hits)
high late light fraction

understanding of
scintillation
sensitive to nucleon
strange spin component

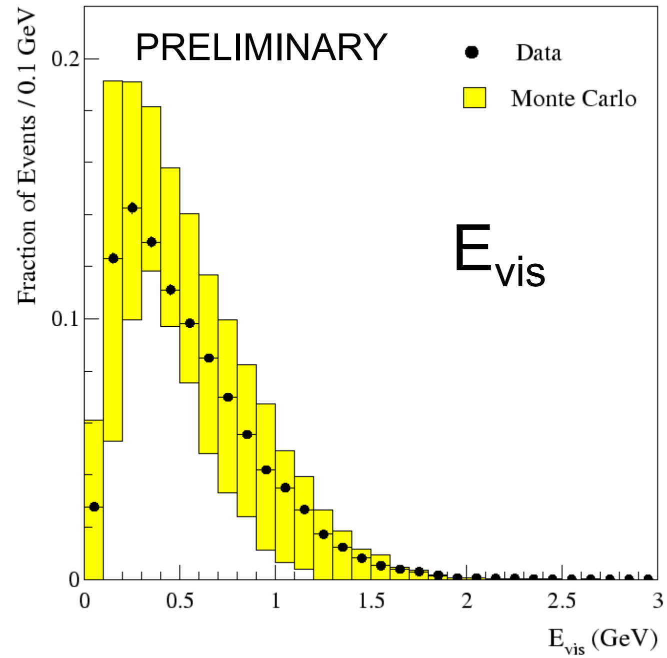
CC ν_μ quasi-elastic events



selection: topology
- ring sharpness
- on- vs. off-ring hits

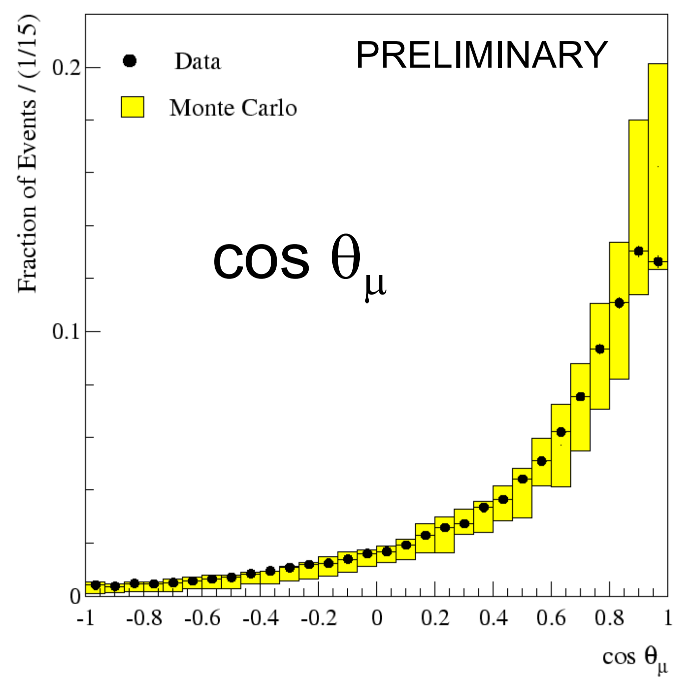
timing
- single μ-like ring
- prompt vs. late light

⇨ variables combined in a Fisher discriminant



data and MC relatively normalized

yellow band: Monte Carlo with current uncertainties from
- flux prediction
- σ_{CCQE}
- optical properties

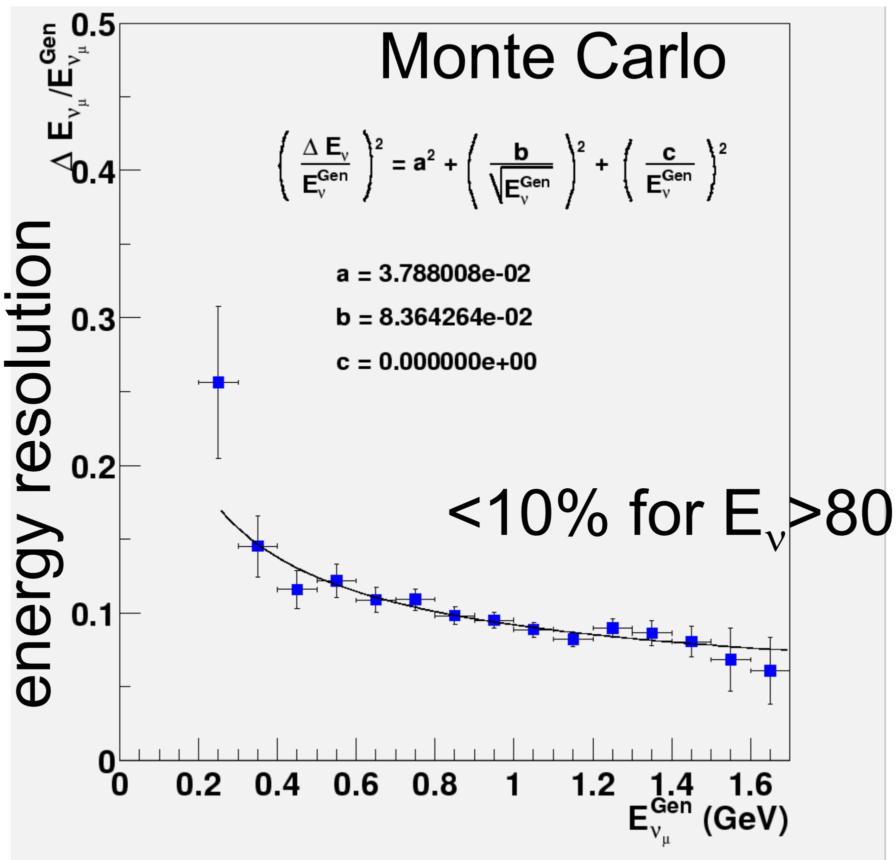


Neutrino energy

kinematic reconstruction:

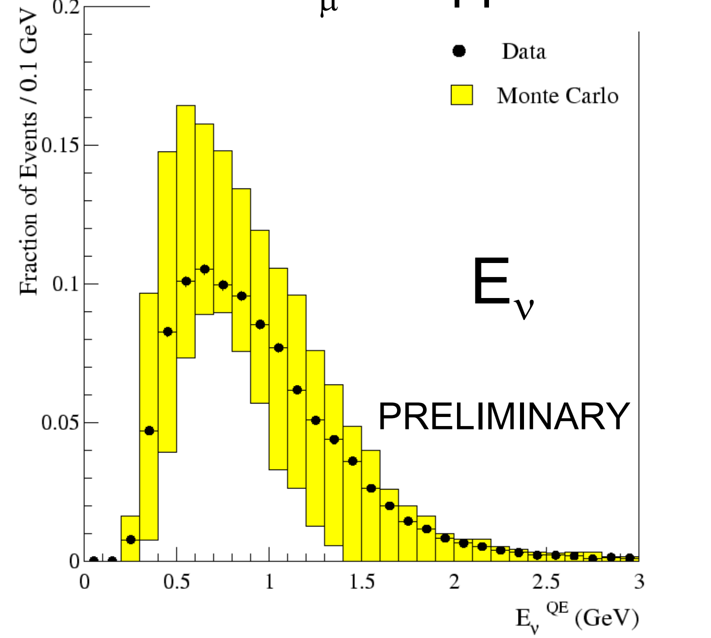
assume $\nu_\mu\, n \rightarrow \mu^-\, p$

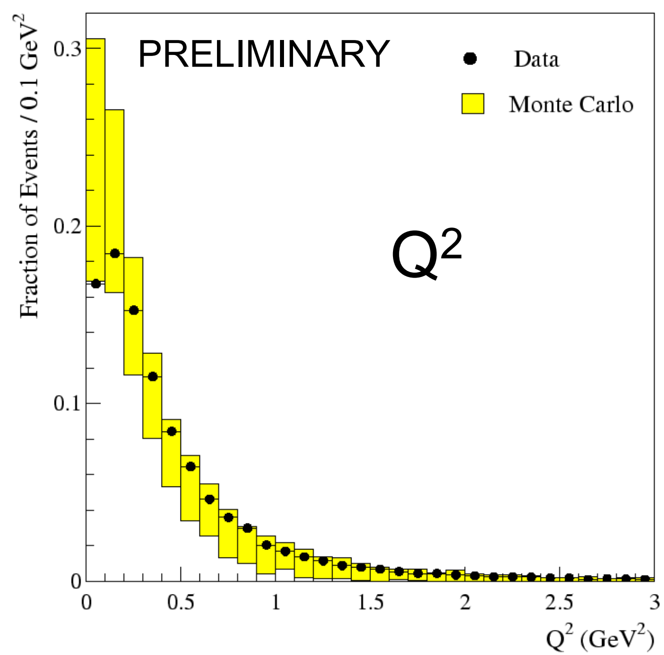
use E_μ, θ_μ to get E_ν



$<10\%$ for $E_\nu > 800$ MeV

sensitive to ν_μ disappearance

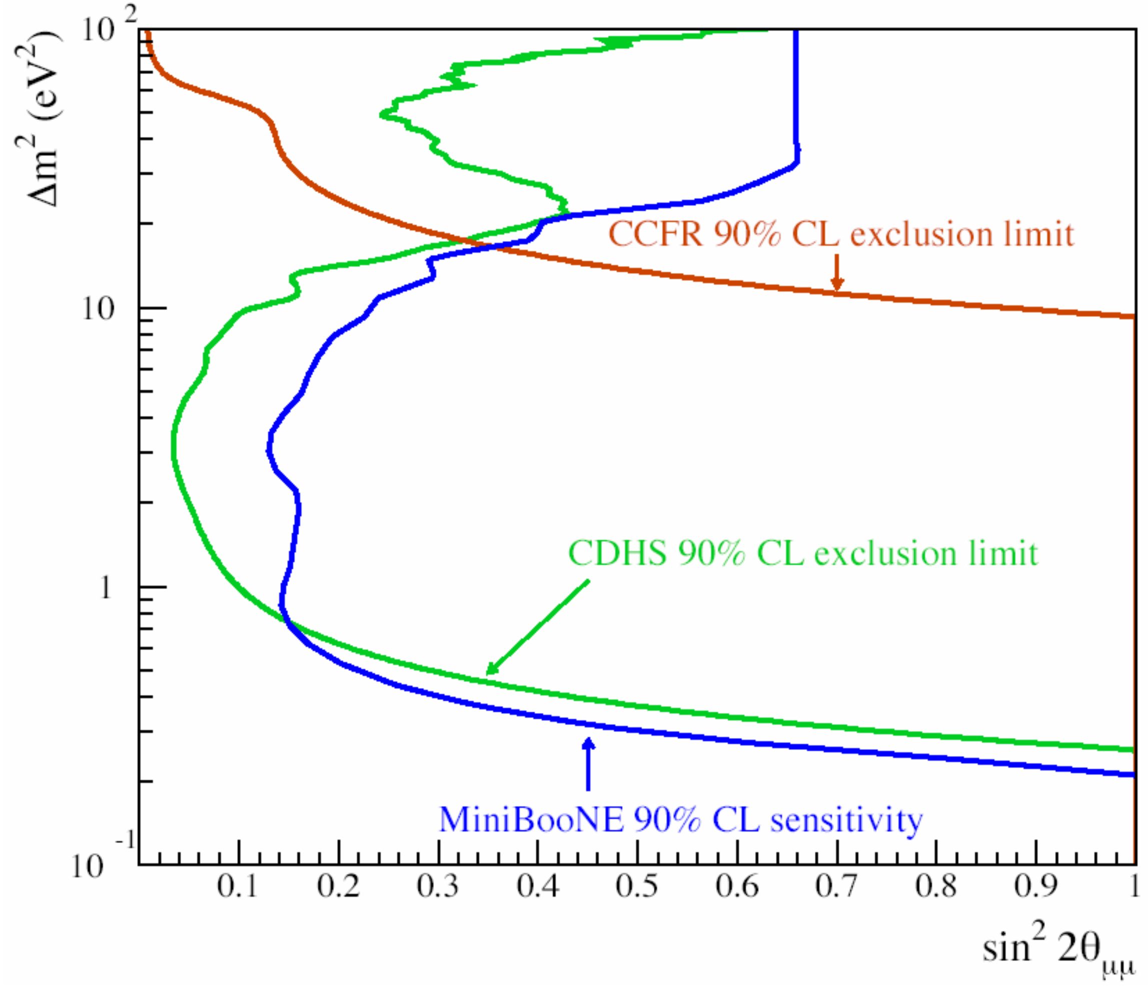




Preliminary ν_μ disappearance sensitivity

systematics
dominated:

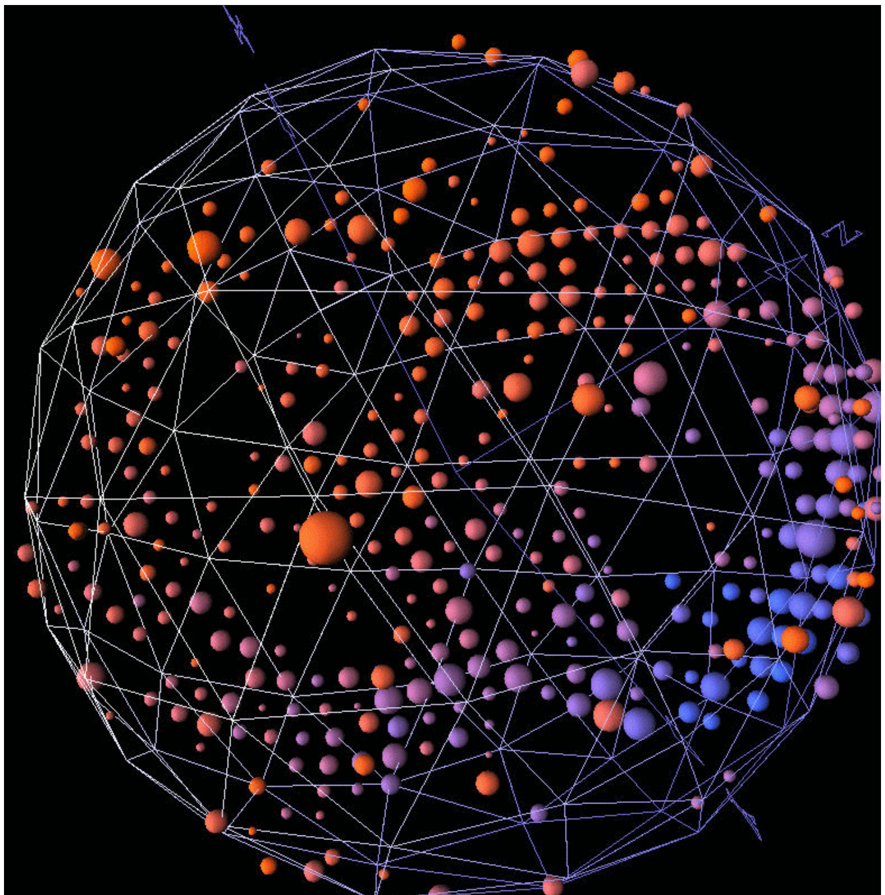
from
uncertainty in flux
prediction

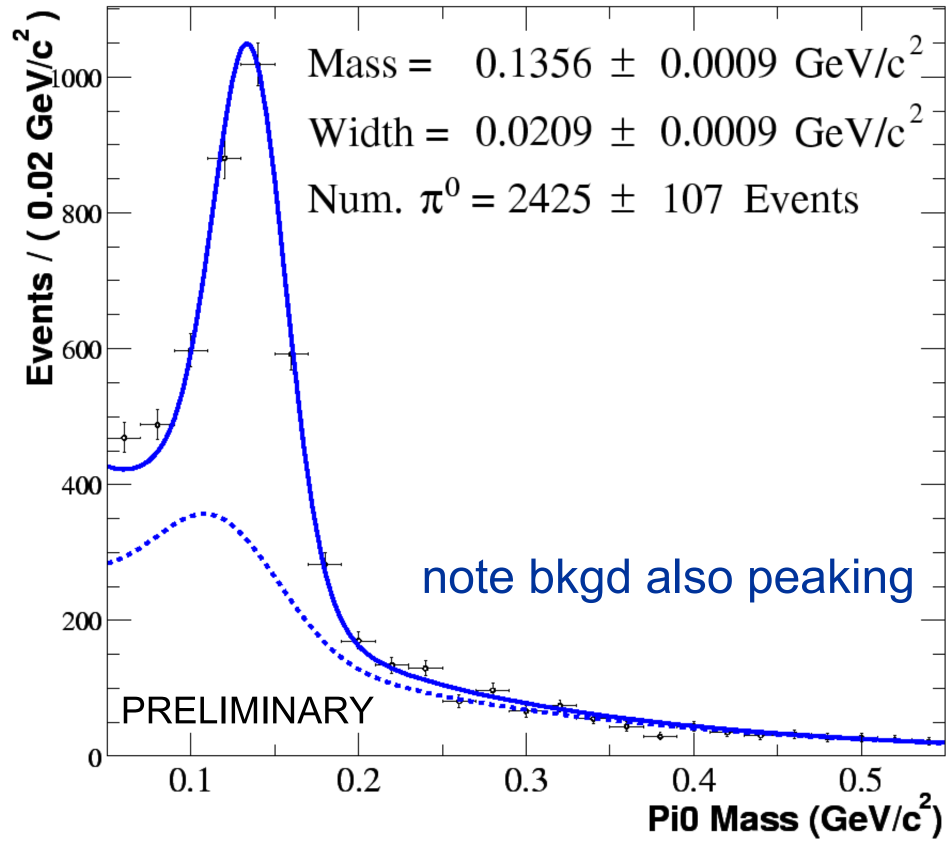


NC π^0 production

$N_{TANK}>200$, $N_{VETO}<6$, no decay electron
perform two ring fit on *all* events
require ring energies E_1, E_2 > 40 MeV

fit mass peak to extract signal yield
including background shape from Monte Carlo

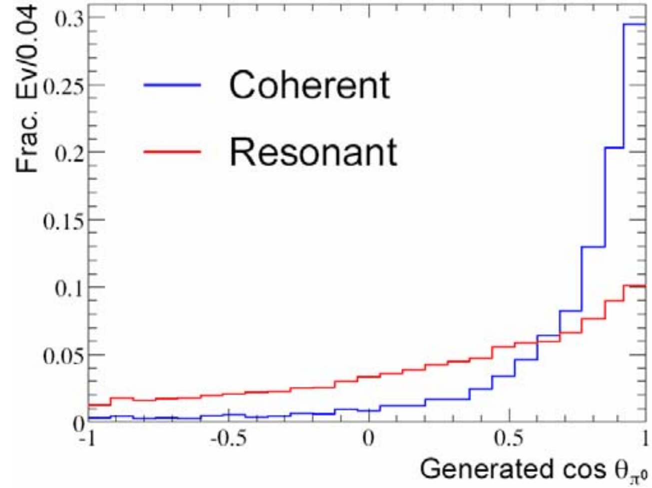




π^0 production angle

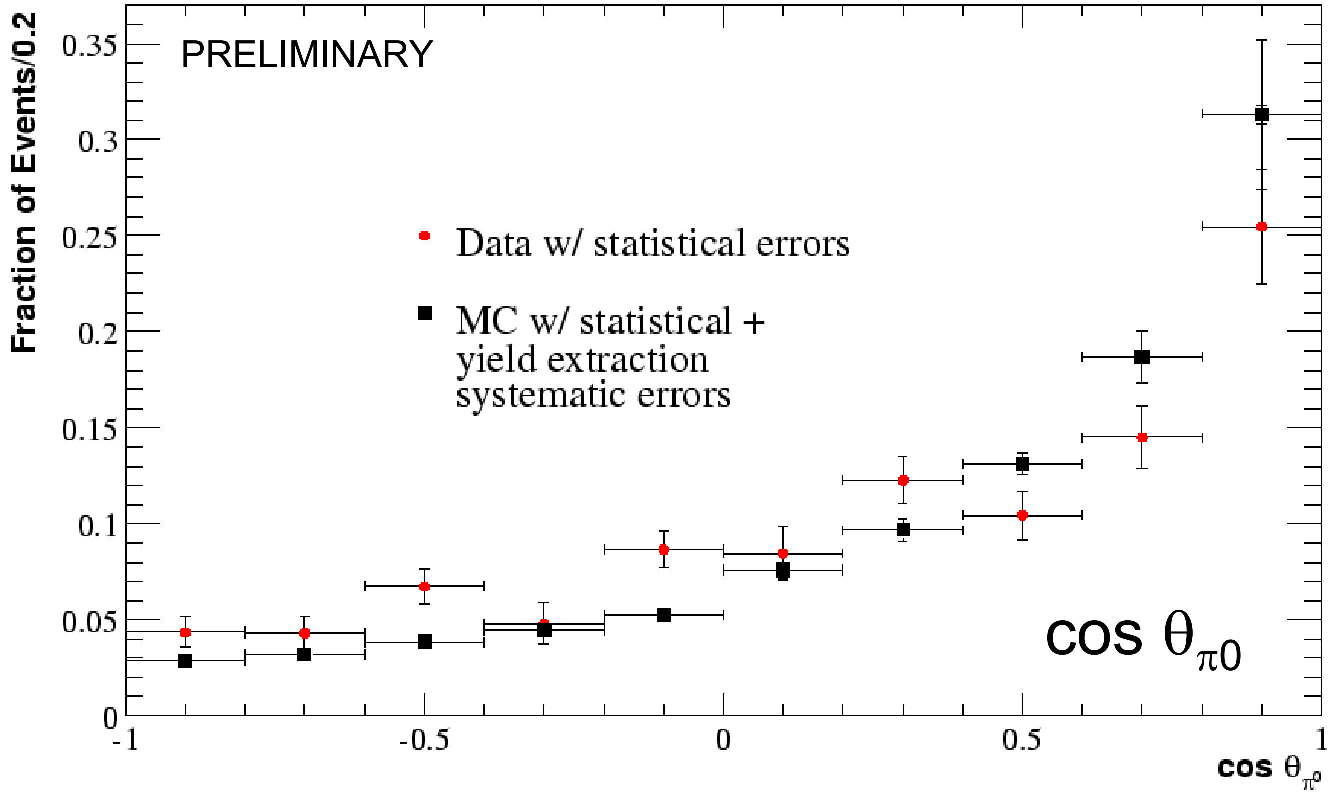
sensitive to production mechanism

coherent is highly forward peaked



data and MC are relatively normalized

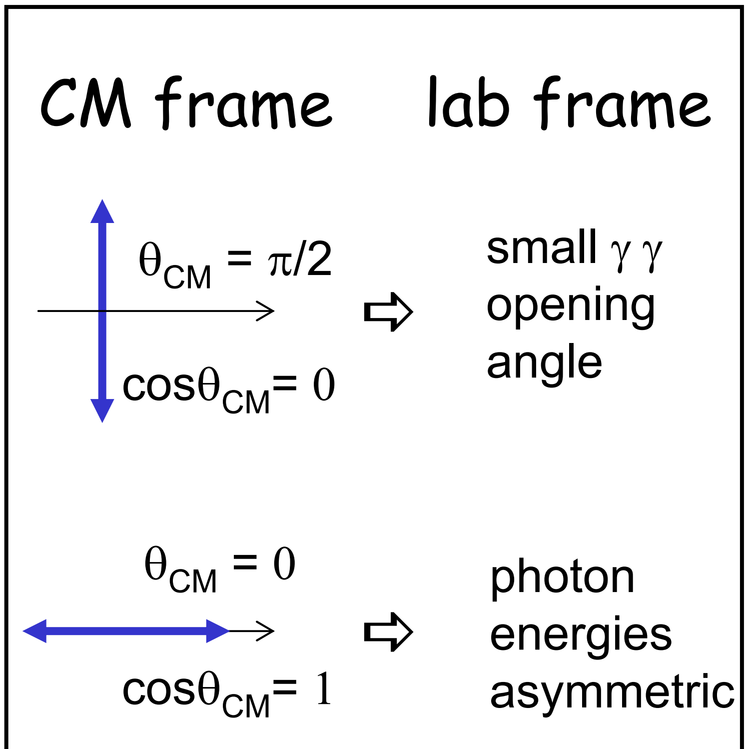
MC shape assumes Rein-Sehgal cross sections

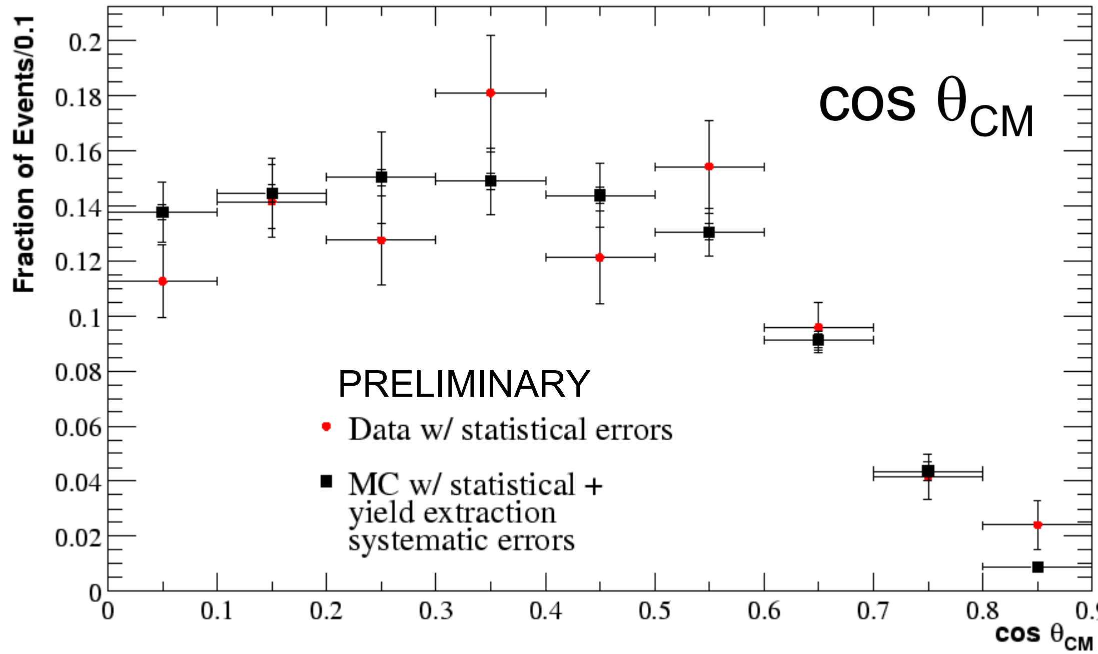


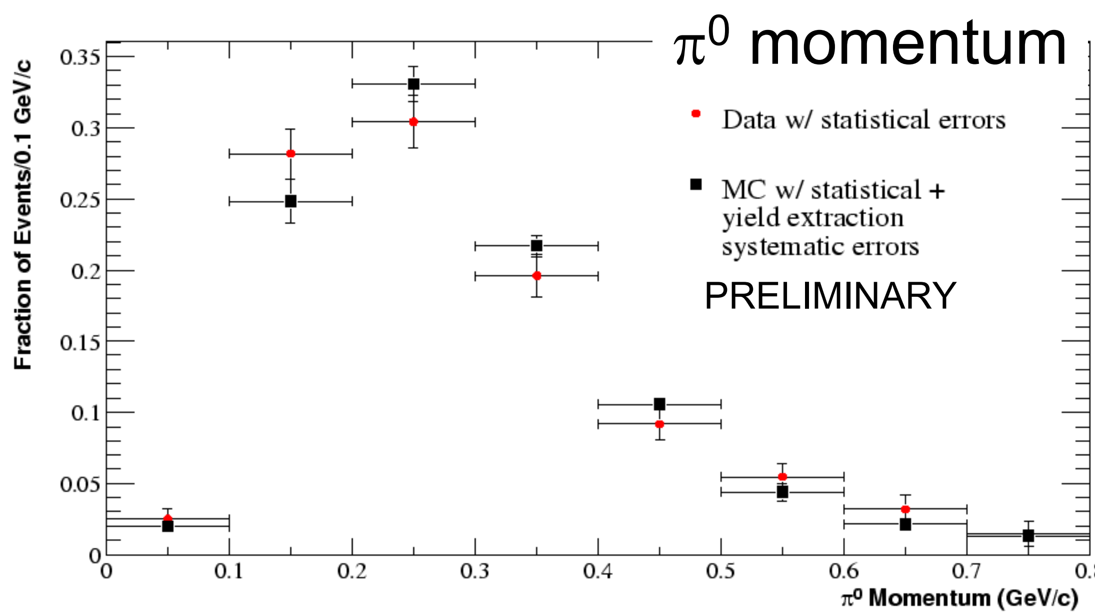
π^0 decay angle

and

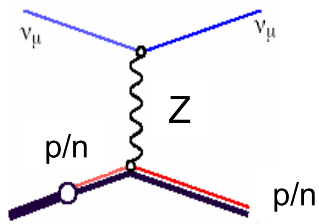
π^0 momentum

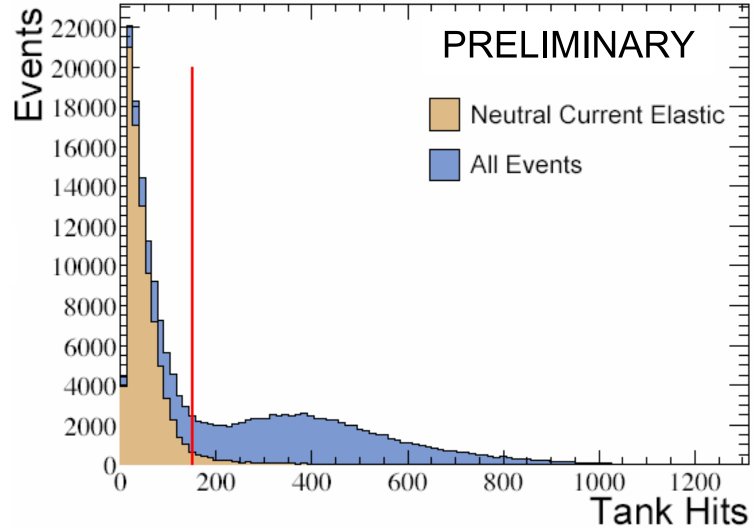






NC elastic scattering





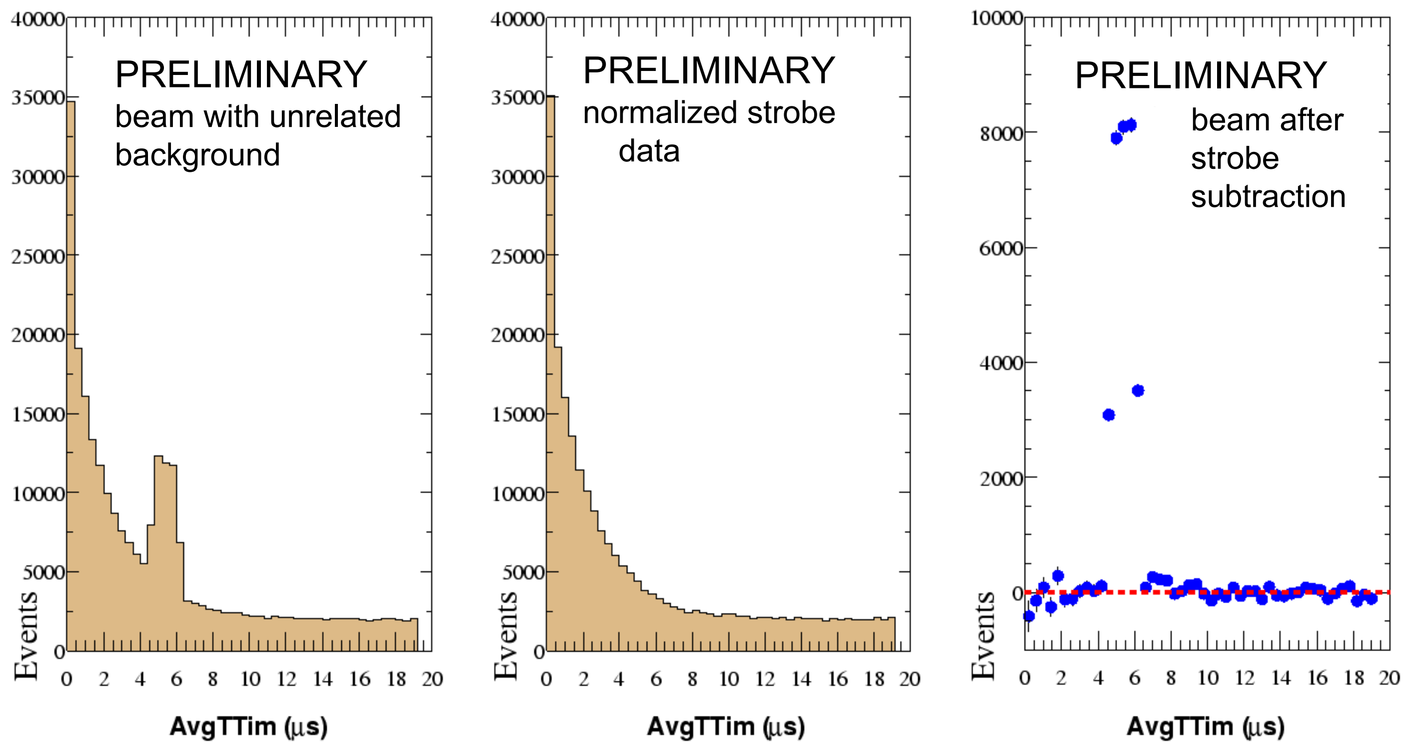
Now select $N_{TANK} < 150$

$N_{VETO} < 6$

Background subtraction

clear beam excess

use random triggers to subtract non-beam background

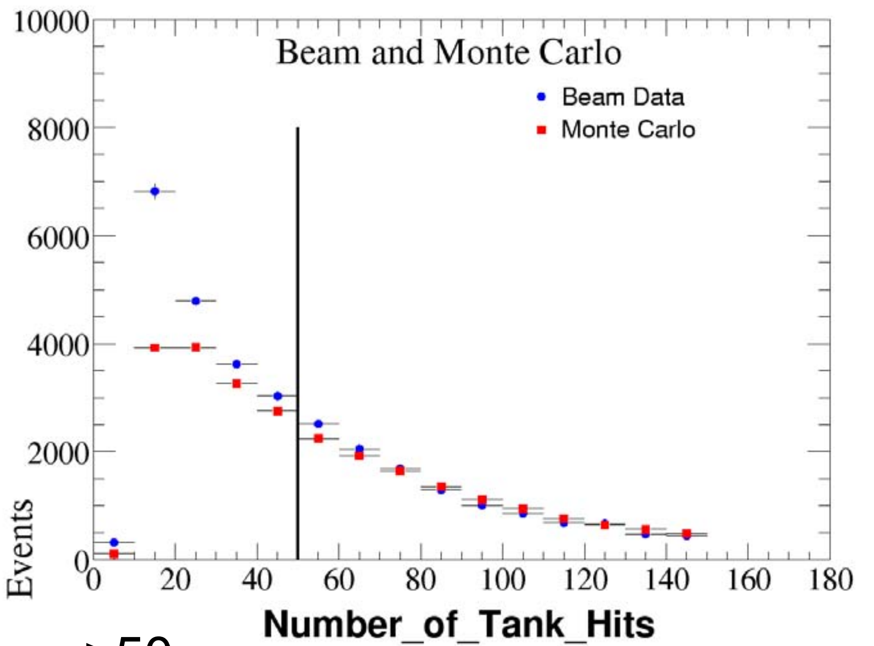


ν_μ NC elastics

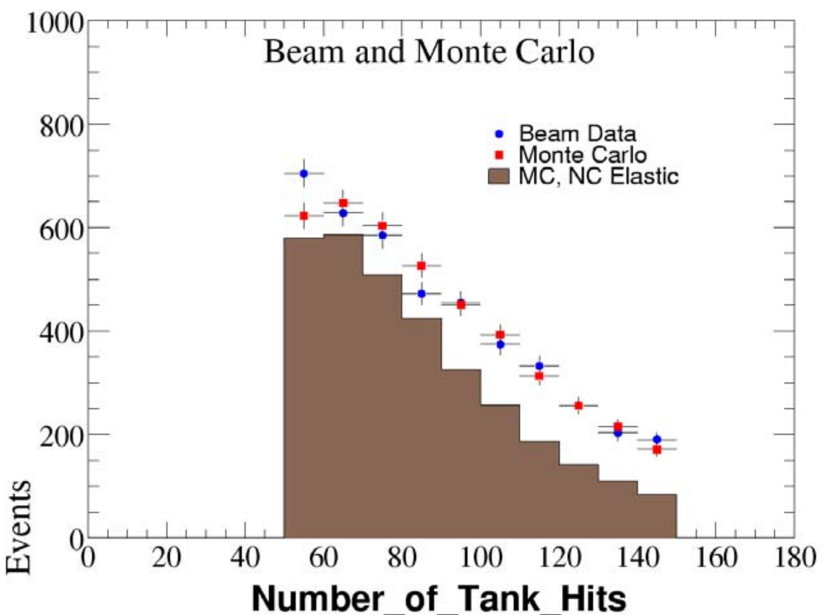
Consider N_{TANK} spectrum

MC and data shapes agree qualitatively for N_{TANK}>50

Unknown component N_{TANK}<30



data and MC relatively normalized for N_{TANK}>50

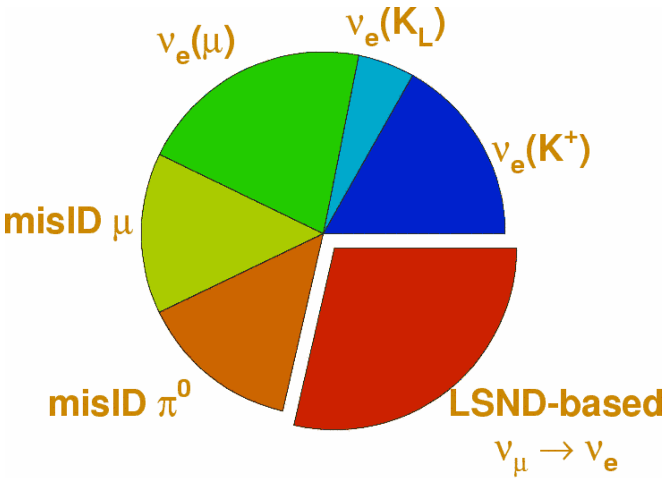


Late light selection:

fit event vertex for N_{TANK}>50
calculate fraction of late hits
select events with significant late light

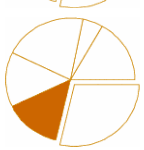
ν_e appearance sensitivity

preliminary estimates,
backgrounds and signal

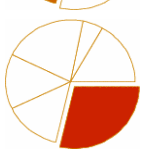


1500 intrinsic ν_e

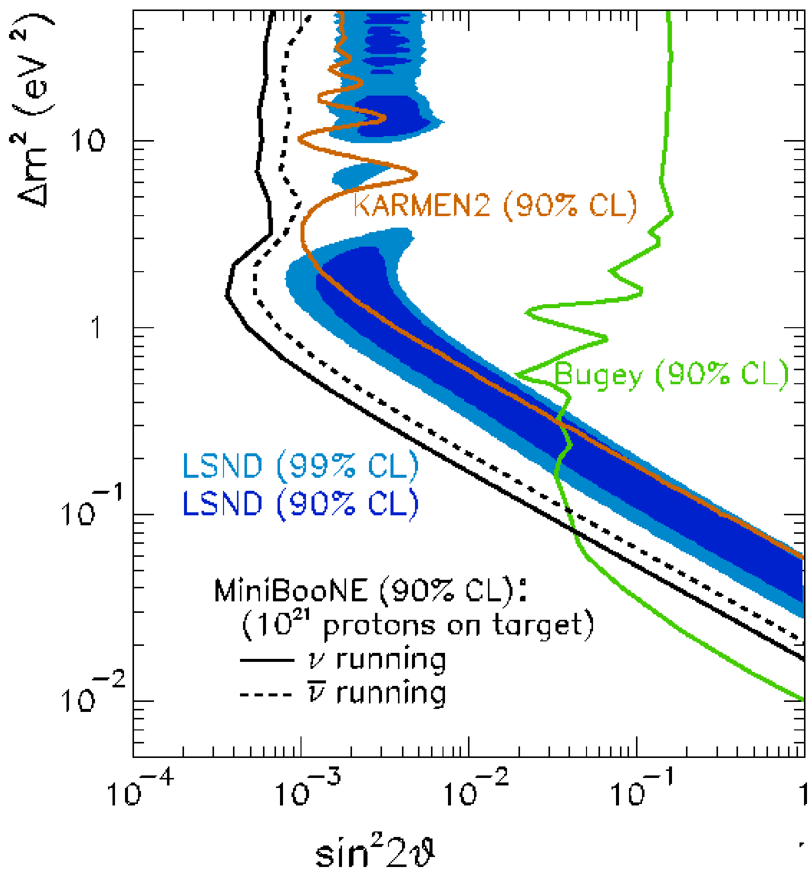
500 μ mis-ID



500 π^0 mis-ID



1000 LSND-based $\nu_\mu \rightarrow \nu_e$



cover LSND allowed region at 5 σ

updated estimates coming

currently expect results in 2005

Conclusions

steadily taking data

currently at 15% of 10^{21} p.o.t

beam is working well, but still need higher intensity

improvements underway (shutdown) will be key

first sample of neutrino physics

detector and reconstruction algorithms are working well