

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

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Seminar at Brookhaven National Laboratory

MiniBooNE status snapshot

We are running at Fermilab, now in our third year

running since September 2002

goal 10^{21} protons on target and a 2 year run

first year: got 1.5 x 10^{20} p.o.t.

second year: reached 3.7 x 10^{20}

We'll reach 5 x 10^{20} in April

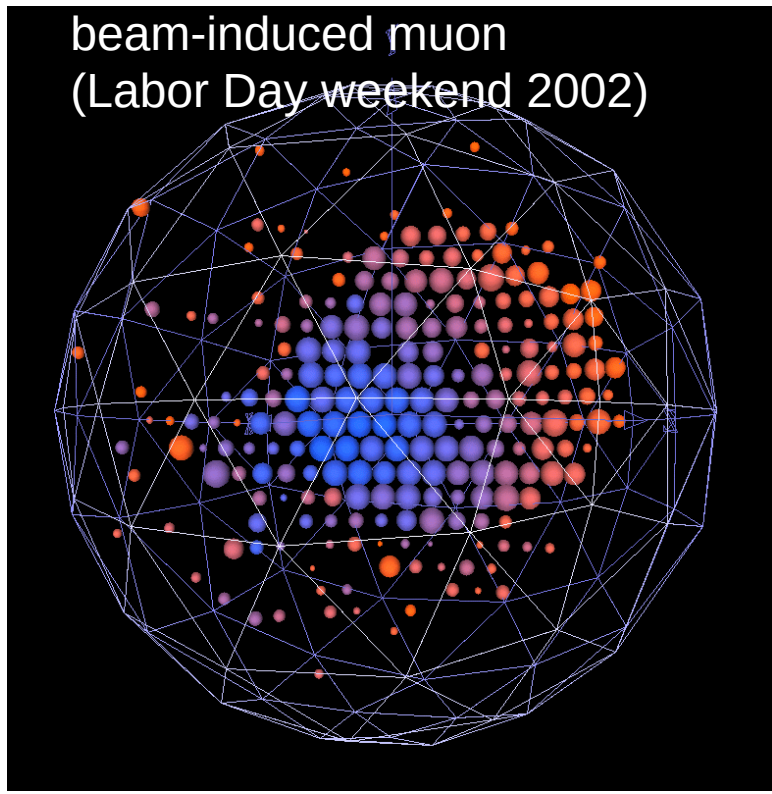
→ compete with NuMI for protons

We are collecting data
and
preparing the analysis

Outline

- Overview of the experiment
- First neutrino events and analysis
- Outlook

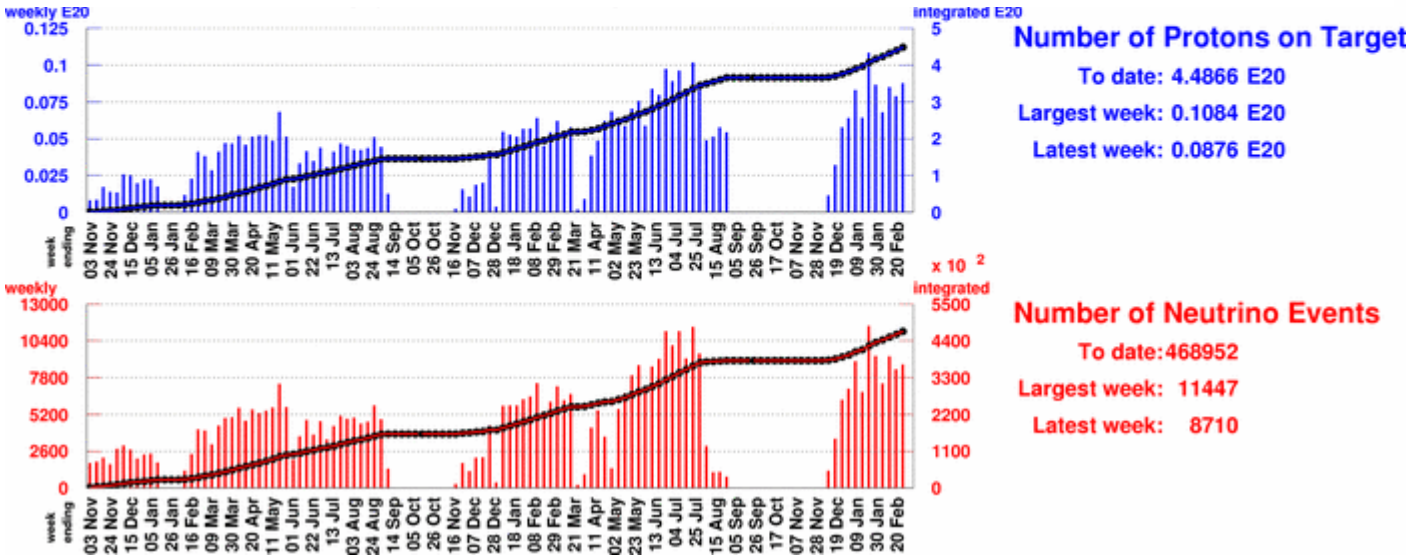
MiniBooNE's first event:



MiniBooNE run progress

Currently running at about 2/3 of goal intensity

~steady improvement



Nov 2002

intentional horn-off run

Feb 2005

horn ground fault

NuMI high-rep running to start March 14

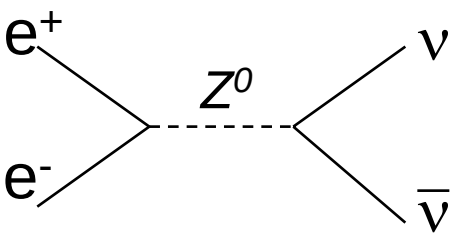
Neutrinos in the Standard Model

no EM or strong interactions
only weak interactions
grouped in left-handed doublets
no right-handed singlet → massless

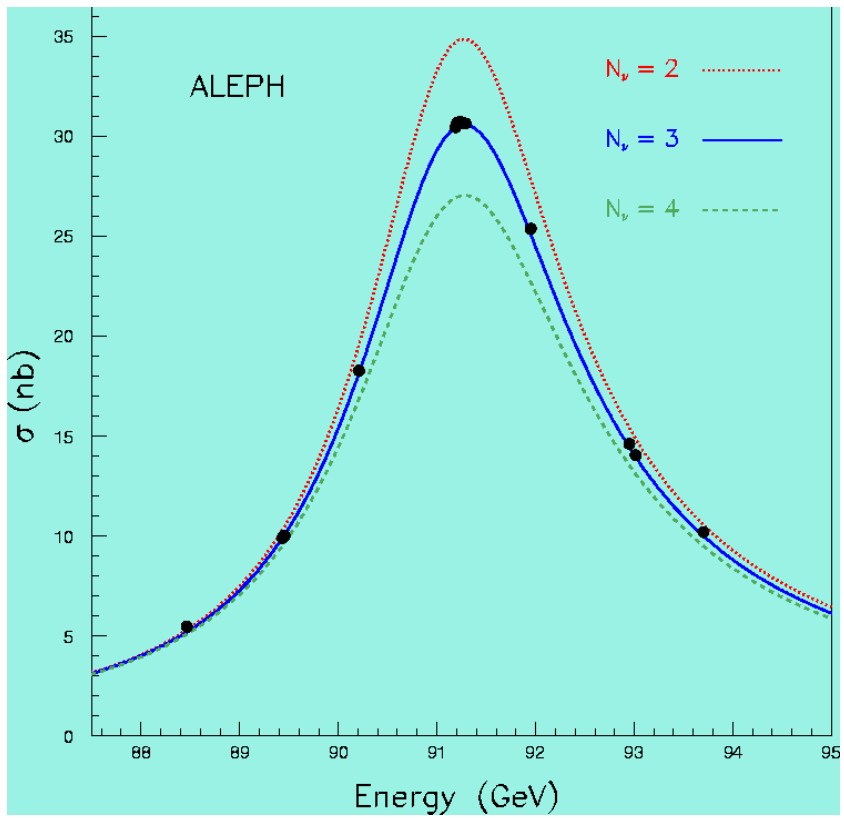
$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

The number of light neutrino flavors
SLC and LEP 1989

Z^0 lineshape



Answer: 3

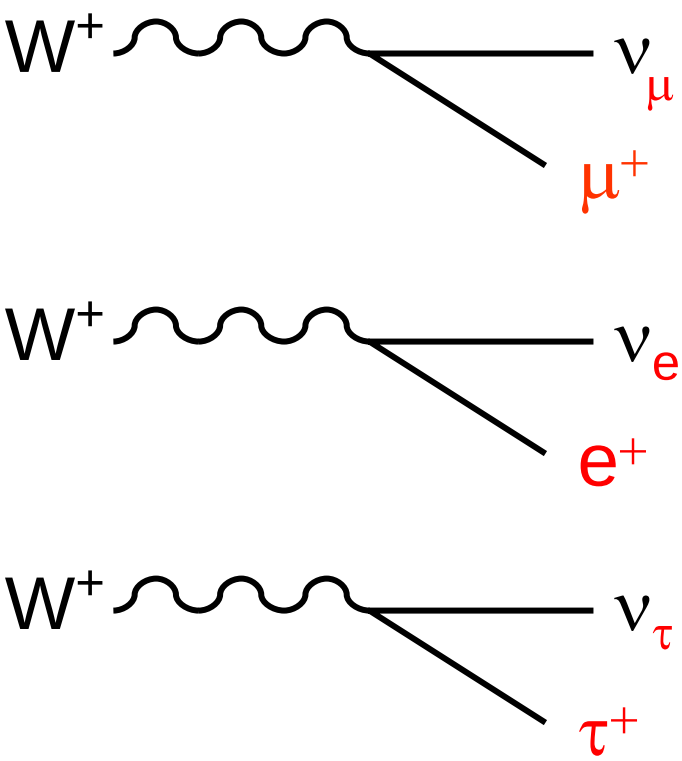


Knowing the flavor

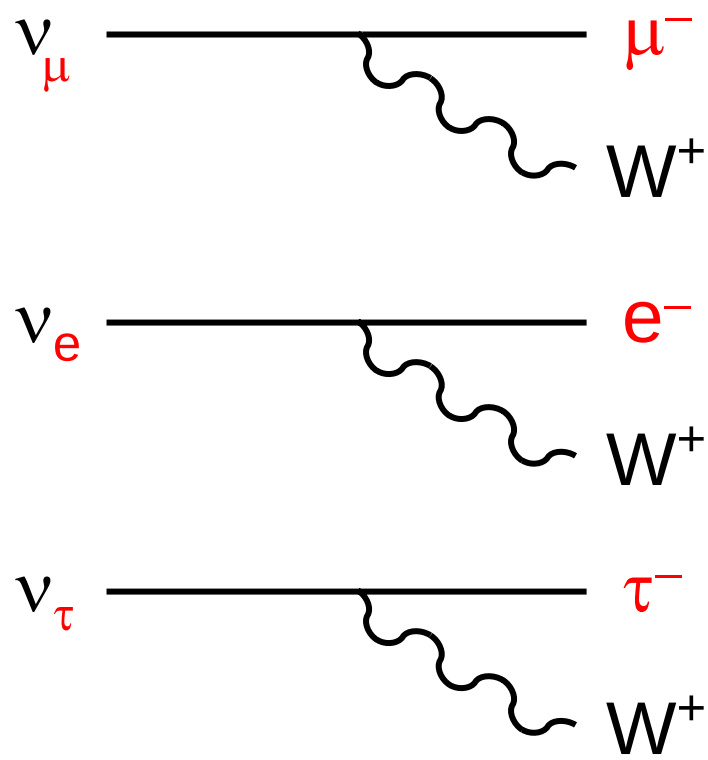
Weak Interactions: conserve lepton flavor

neutrino is produced/detected in association with a charged lepton

neutrino birth



neutrino demise



Neutrino mixing

Assume that a neutrino of definite flavor is a mixture of mass states:

flavor states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

MNS mixing matrix

mass states

e.g. $|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$

The mass states determine the free particle evolution

$$|\nu_i(x)\rangle = e^{-ip\cdot x}|\nu_i(0)\rangle$$

Consider the trivial cases:

U = 1

degenerate m_i $\longrightarrow$ $|\nu_l\rangle$ remains unchanged as a function of time/position

Neutrino oscillations

If $U \neq 1$ and m_i are not degenerate:
$|\nu_l\rangle$ will evolve non-trivially with time

Start with flavor α and observe flavor β after some time/distance

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2[1.27\Delta m^2_{ij}(L/E)] + 2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin[2.54\Delta m^2_{ij}(L/E)]$$

disappearance: start with known amount of ν_α, find less ν_α later
appearance: start with ν_α, find some ν_β later

two flavor oscillations,
characterized by θ, Δm^2

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

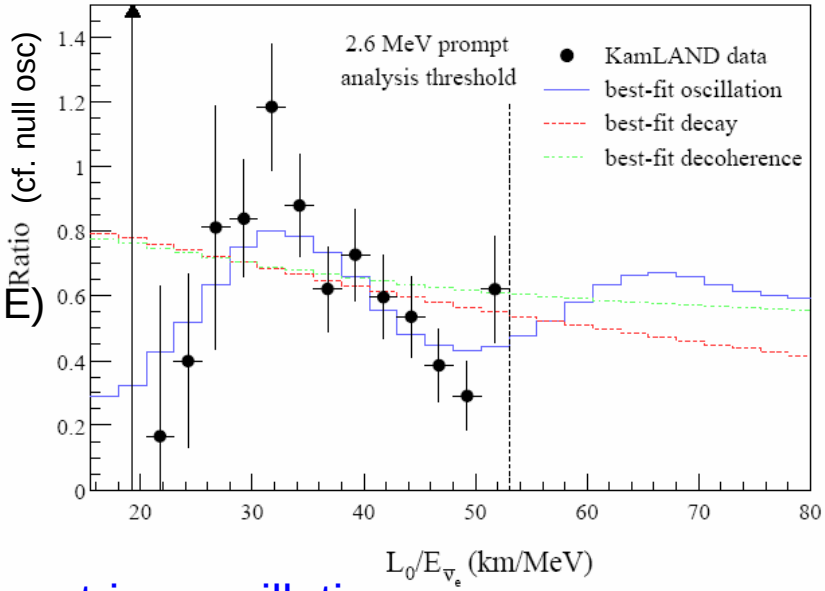
Current situation

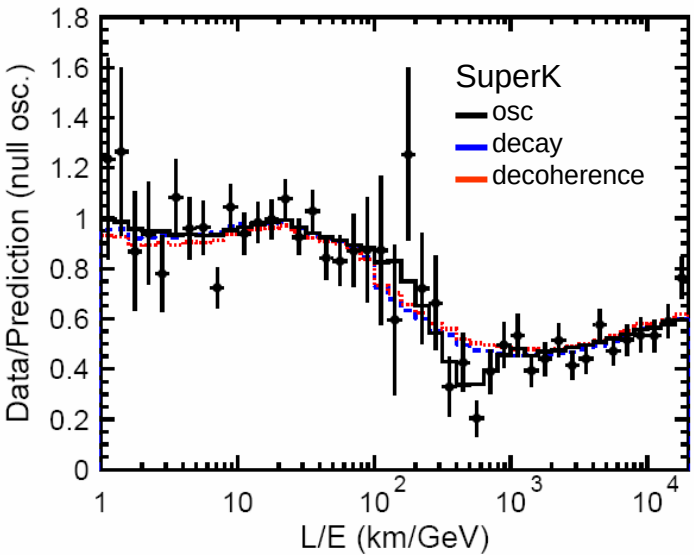
solar neutrino oscillations

deficit of ν_e observed from the sun

Cl (Homestake), H_20 (K,SuperK), Ga (GALLEX, SAGE)

confirmed by SNO, KamLAND (reactor ν_e)



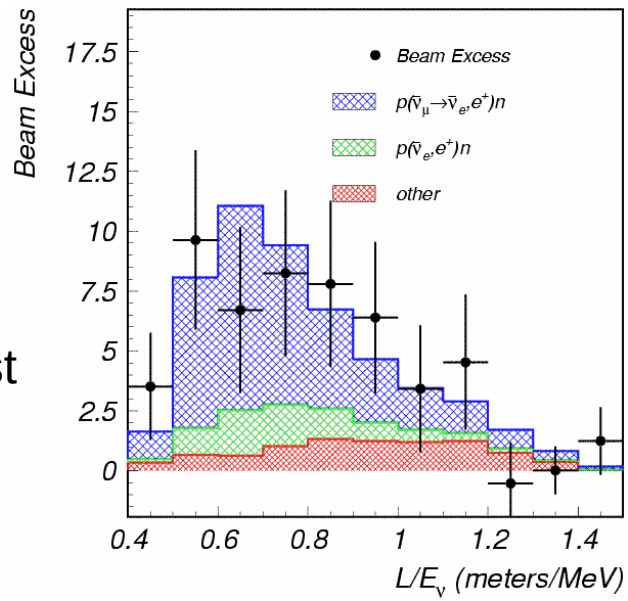


atmospheric neutrino oscillations

zenith angle dependent deficit of ν_μ

Kamiokande, SuperK, Soudan, MACRO

confirmed by K2K (accelerator), MINOS to come



LSND neutrino oscillations

appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam from μ^+ decay at rest

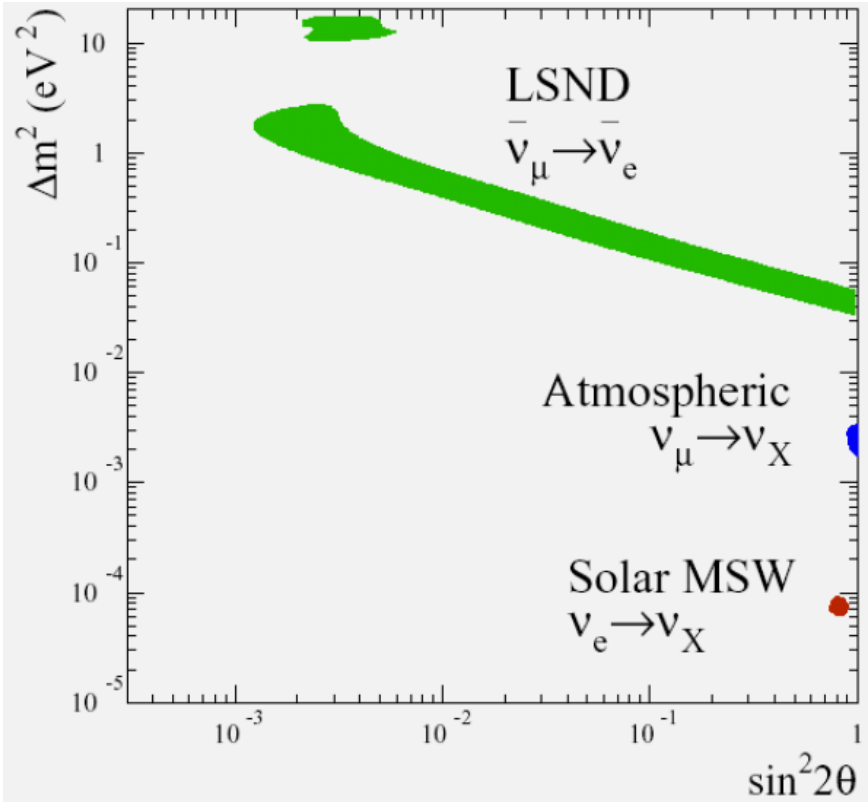
unconfirmed, but not excluded either

Oscillation Evidence

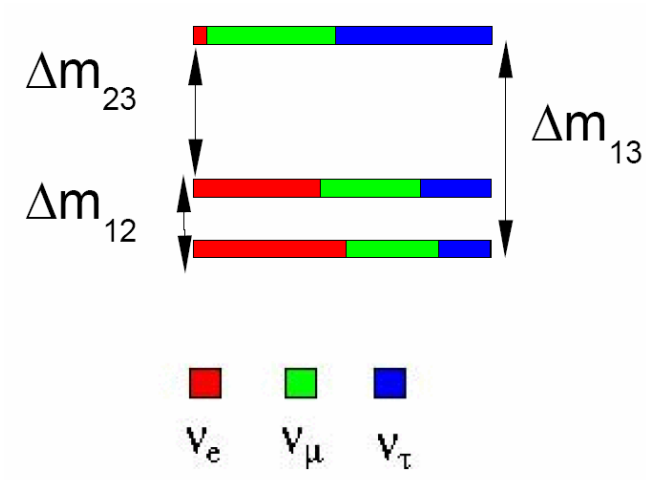
LSND
Δm^2 = 0.2 – 10 eV^2, small mixing

atmospheric
Δm^2 = 2.5 x 10^{-3} eV^2, large mixing

solar
Δm^2 = 8 x 10^{-5} eV^2, large mixing



$$\Delta m^2_{\odot} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$$



For three neutrinos expect

$$\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$$

How can there be three distinct Δm^2's?

One of the measurements is wrong

LSND has performed internal checks, need MiniBooNE

One of the measurements is not neutrino oscillations

neutrino decay → limited by global fits

neutrino production from flavor violating decay → KARMEN restricts

Additional sterile neutrinos involved in oscillations

possible, but probably need (3+2) model

CPT violation or CP violation and sterile ν's

allows different mixing for neutrinos and antineutrinos

possible

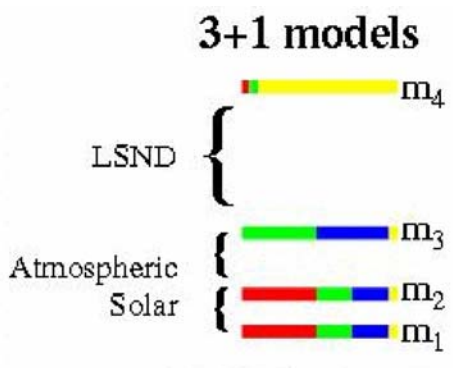
Experimental situation:

Tension between LSND and the null short baseline experiments

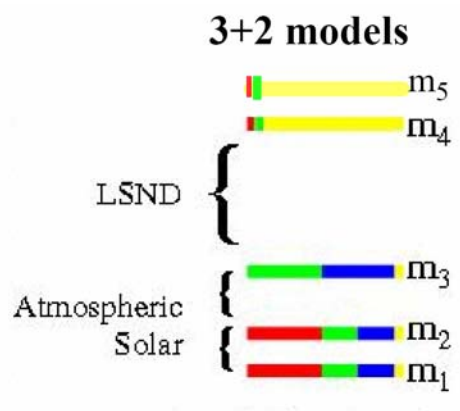
global fits to (3+1), (3+2): Sorel, Conrad, Shaevitz. Phys Rev D70 (2004) 073004

Is LSND compatible with limits on active to sterile mixing from other short-baseline experiments?

Channel	Experiment	Lowest Δm^2 Reach (90% CL)	$\sin^2 2\theta$ Constraint (90% CL) High Δm^2	Optimal Δm^2
$\nu_\mu \to \nu_e$	LSND	$3 \cdot 10^{-2}$	$> 2.5 \cdot 10^{-3}$	$> 1.2 \cdot 10^{-3}$
	KARMEN	$6 \cdot 10^{-2}$	$< 1.7 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
	NOMAD	$4 \cdot 10^{-1}$	$< 1.4 \cdot 10^{-3}$	$< 1.0 \cdot 10^{-3}$
$\nu_e \to \nu_{\not e}$	Bugey	$1 \cdot 10^{-2}$	$< 1.4 \cdot 10^{-1}$	$< 1.3 \cdot 10^{-2}$
	CHOOZ	$7 \cdot 10^{-4}$	$< 1.0 \cdot 10^{-1}$	$< 5 \cdot 10^{-2}$
$\nu_\mu \to \nu_{\not\mu}$	CCFR84	$6 \cdot 10^{0}$	none	$< 2 \cdot 10^{-1}$
	CDHS	$3 \cdot 10^{-1}$	none	$< 5.3 \cdot 10^{-1}$
$\nu_\mu \to \nu_\tau$	NOMAD	$7 \cdot 10^{-1}$	$< 3.3 \cdot 10^{-4}$	$< 2.5 \cdot 10^{-4}$
	CHORUS	$5 \cdot 10^{-1}$	$< 6.8 \cdot 10^{-4}$	$< 4.5 \cdot 10^{-4}$
$\nu_e \to \nu_\tau$	NOMAD	$6 \cdot 10^{0}$	$< 1.5 \cdot 10^{-2}$	$< 1.1 \cdot 10^{-2}$
	CHORUS	$7 \cdot 10^{0}$	$< 5.1 \cdot 10^{-2}$	$< 4 \cdot 10^{-2}$



Best fit:
$\Delta m^2 = 0.92$ eV^2
$U_{e4} = 0.136$,
$U_{\mu 4} = 0.205$
with
Compatibility
Level = 3.6%

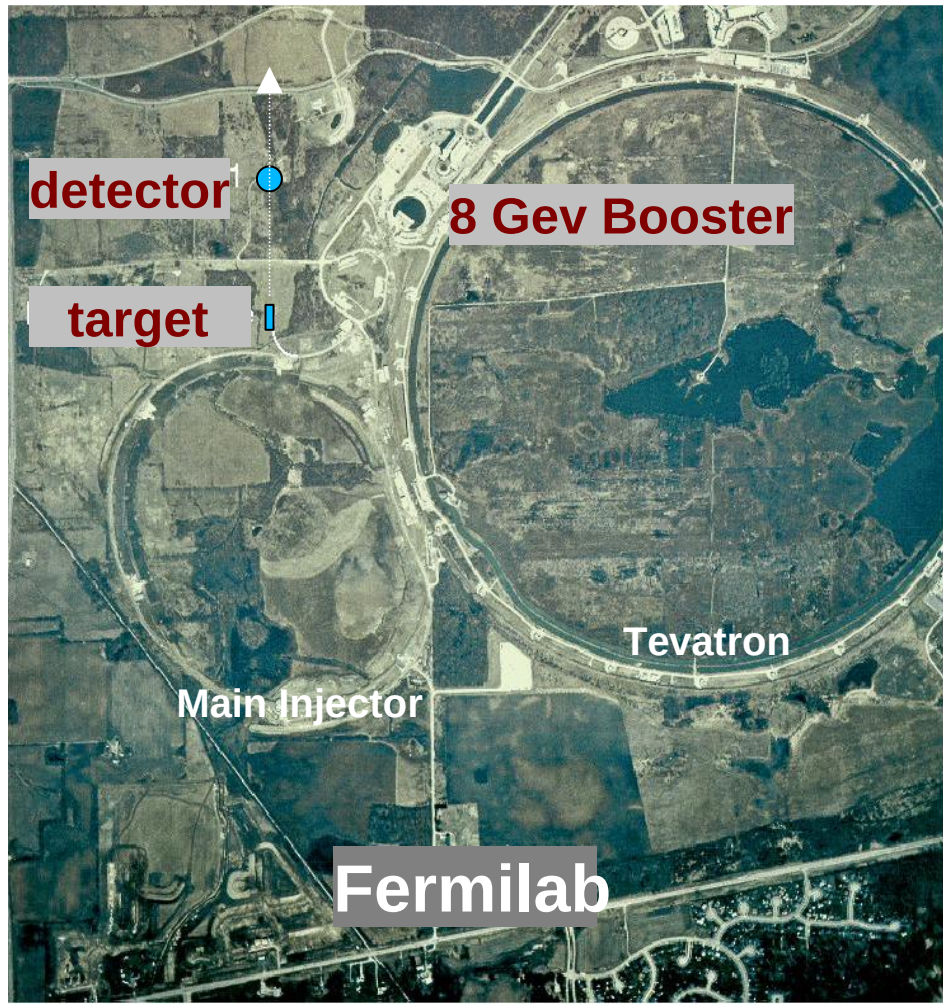


Best Fit:
$\Delta m_{41}^2 = 0.92$ eV^2
$U_{e4} = 0.121$, $U_{\mu 4} = 0.204$
$\Delta m_{51}^2 = 22$ eV^2
$U_{e5} = 0.036$, $U_{\mu 4} = 0.224$
with
Compatibility
Level = 30%

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

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

MiniBooNE!



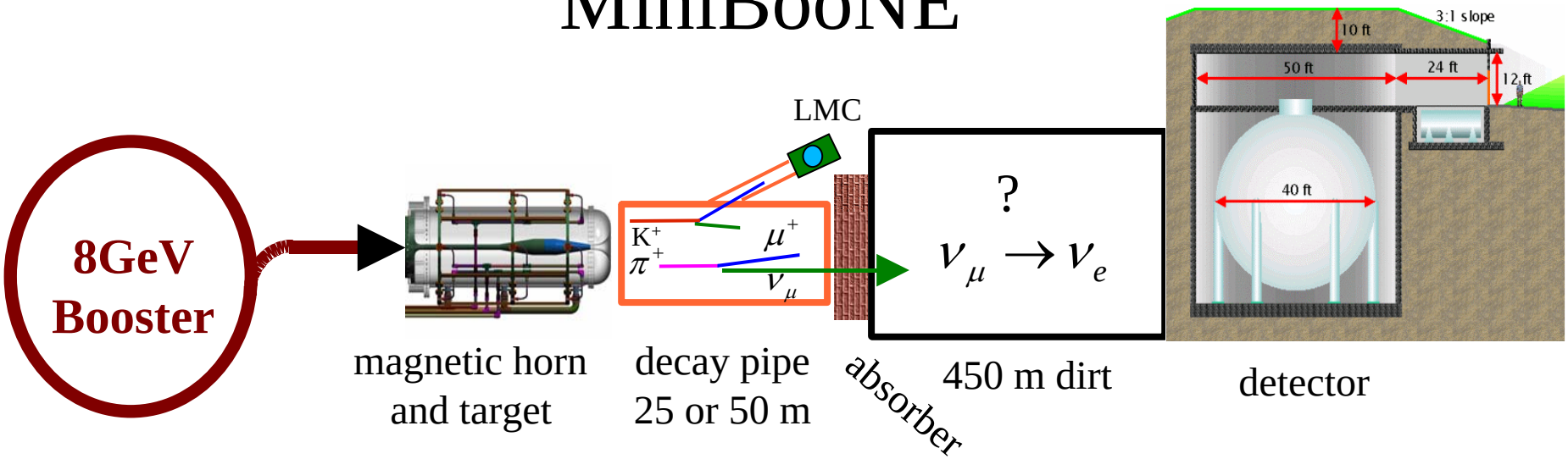
BooNE: Fermilab Booster Neutrino Experiment

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

LSND vs. MiniBooNE experimental scheme

LSND:

μ^+ decay at rest $\longrightarrow \bar{\nu}_\mu \cdots\cdots\rightarrow \bar{\nu}_e$

$\bar{\nu}_e\, p \longrightarrow e^+ n$

- $e^+ n \longrightarrow$ capture on $p \longrightarrow$ 2.2 MeV γ
- E_e~40 MeV

Most backgrounds have accidental neutron or low-E γ

BooNE:

π^+ decay in flight $\longrightarrow \nu_\mu \cdots\cdots\rightarrow \nu_e$

$\nu_e\, n \longrightarrow e^- p$

- E_e~300 MeV

Backgrounds: beam ν_e

$\nu_\mu n \longrightarrow \mu^- p$, mis-ID μ as e

$\nu_\mu n \longrightarrow \nu_\mu n \pi^0$, mis-ID π^0 as e

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)

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

Booster → Main Injector:
- antiproton source
- TeVatron
- NuMI ← competition for protons
- 120 GeV fixed target

Booster performance

We are pushing the Booster hard

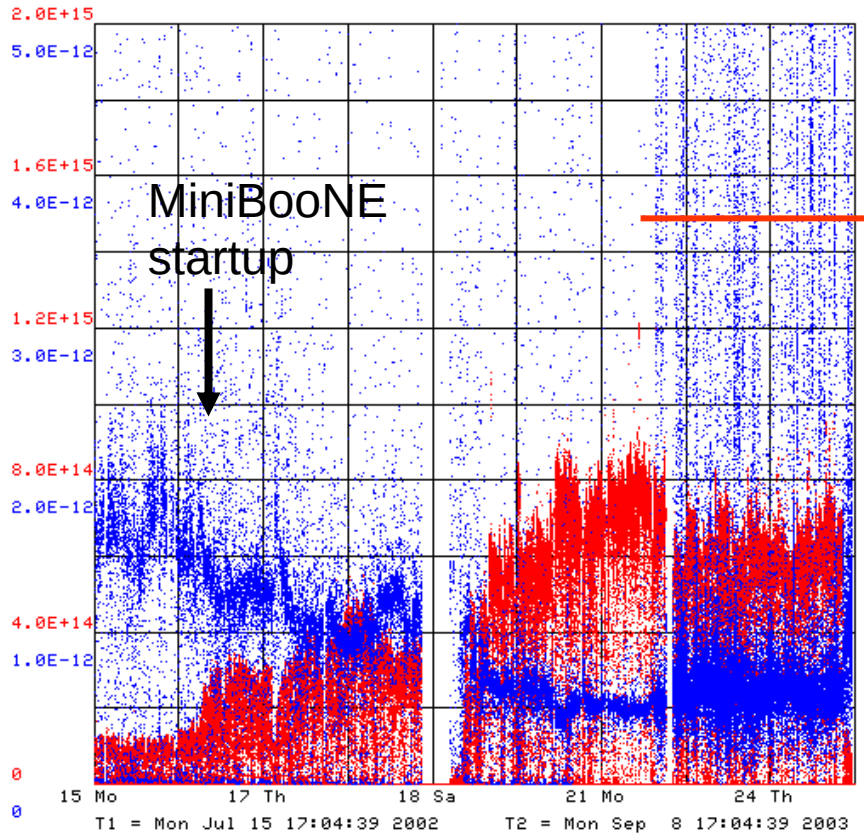
Must limit radiation damage and activation of Booster components:
- increase protons
- but decrease beam loss

~steady improvements
- careful tuning
- understanding optics

further improvements:
- new Booster collimators
- large-aperture RF cavities

Now reach 80% of goal intensity
→ 5x10^{20} p.o.t. by early 2005

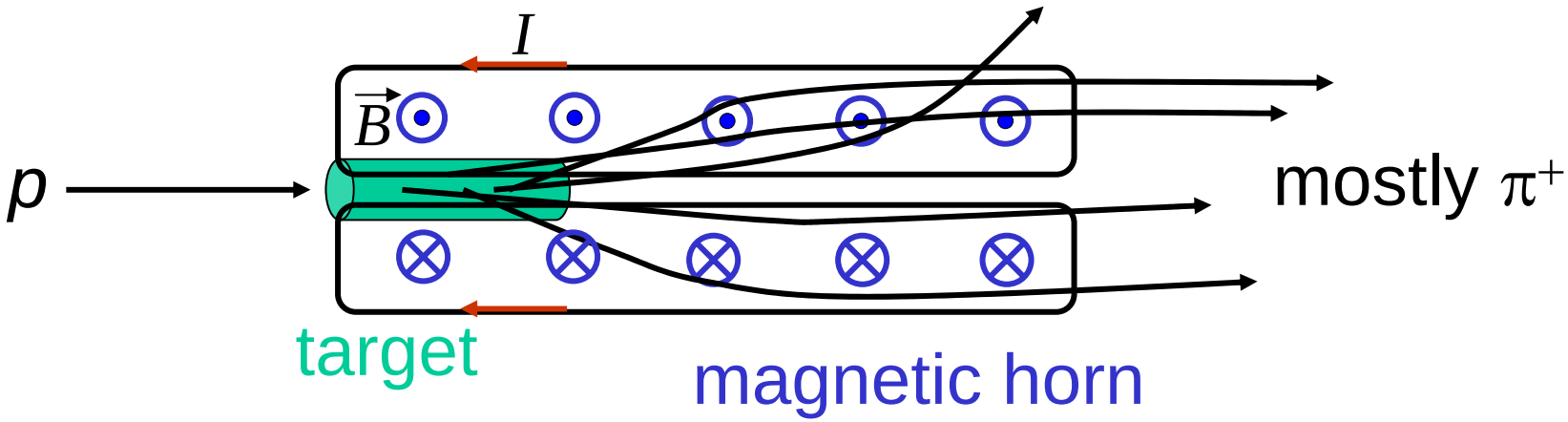
our first year:
July 2002 - Sept 2003



red: Booster output (protons/minute)

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

A flavor-selected ν beam



We want a beam of ν_μ, *not* ν_e, $\overline{\nu}_\mu$, or $\overline{\nu}_e$ – seems hard, but…

$\pi^+ \rightarrow \mu^+ \nu_\mu$ 99.99% of the time!

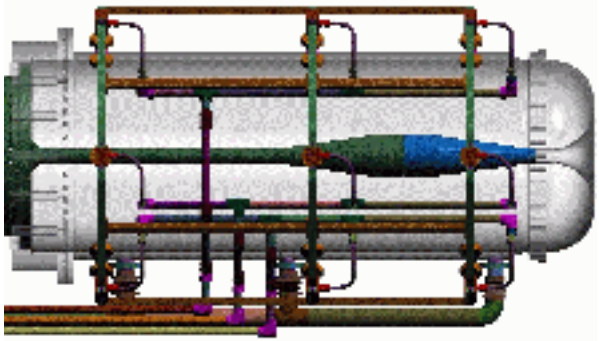
not ν_e, $\overline{\nu}_\mu$, or $\overline{\nu}_e$

takes advantage of Helicity Suppression
(discussion of loopholes to come)

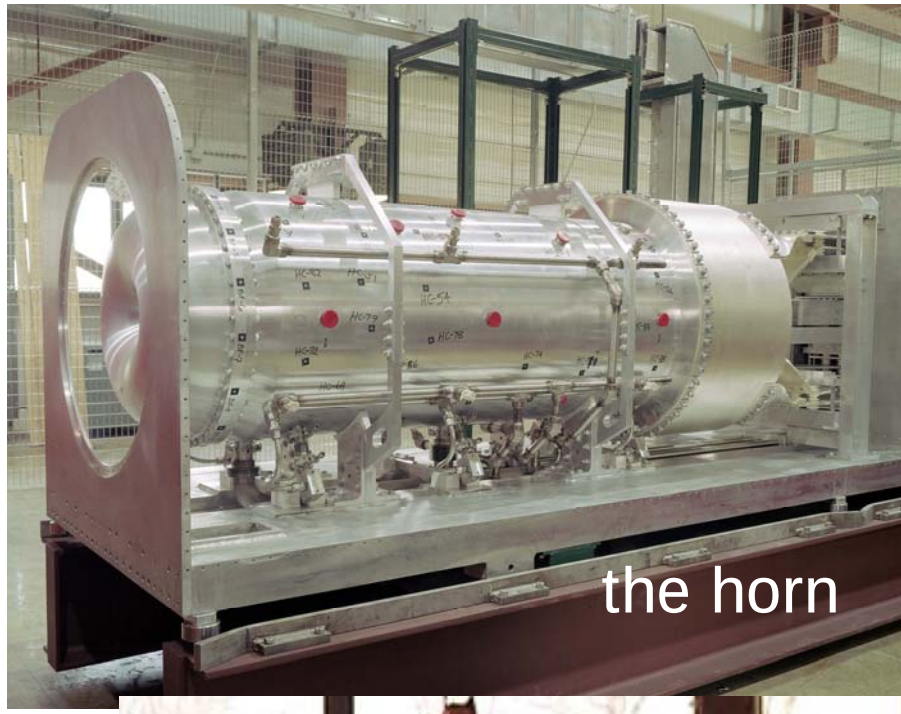
Target and magnetic horn

Increases neutrino intensity by 6x

protons →



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
first horn reached
100M pulses

World's longest-lived horn



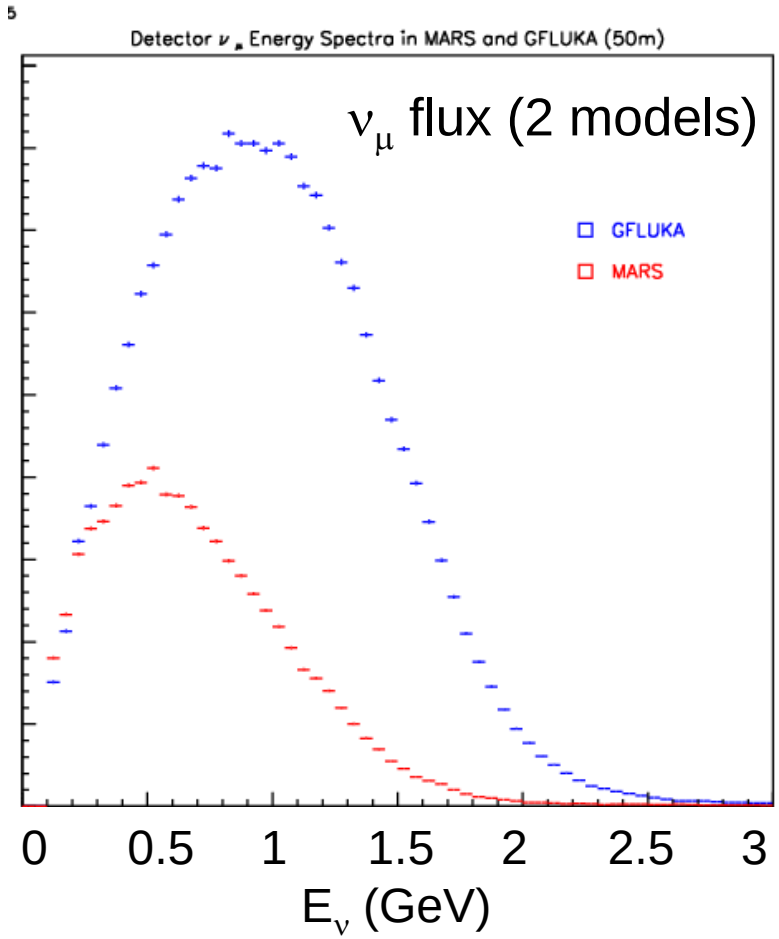


Intrinsic ν_e in the beam

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

Beam background tactics

- need constraints on bkgds
- simulations vary (a lot!)



We must *measure* them:

$\pi \rightarrow \mu \rightarrow \nu_e$

- ν_μ spectrum
- 25 m / 50 m decay length option

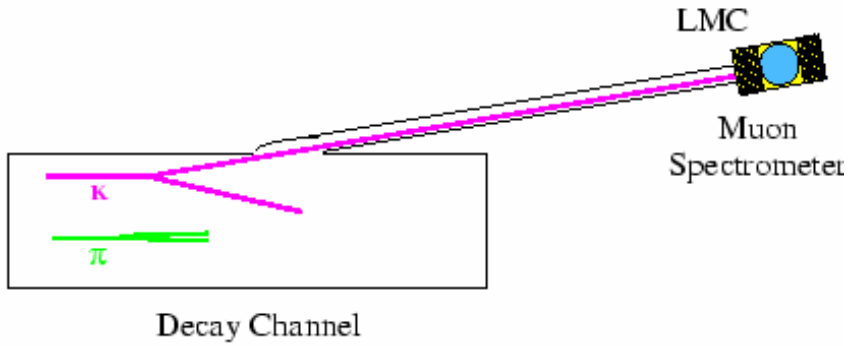
K^+, $K_L \rightarrow \nu_e$

- "Little muon counter"
- high-energy ν_μ events

All

- HARP, CERN experiment dedicated to measuring secondary particle production by protons

LMC: Little Muon Counter



a secondary beam kaon monitor

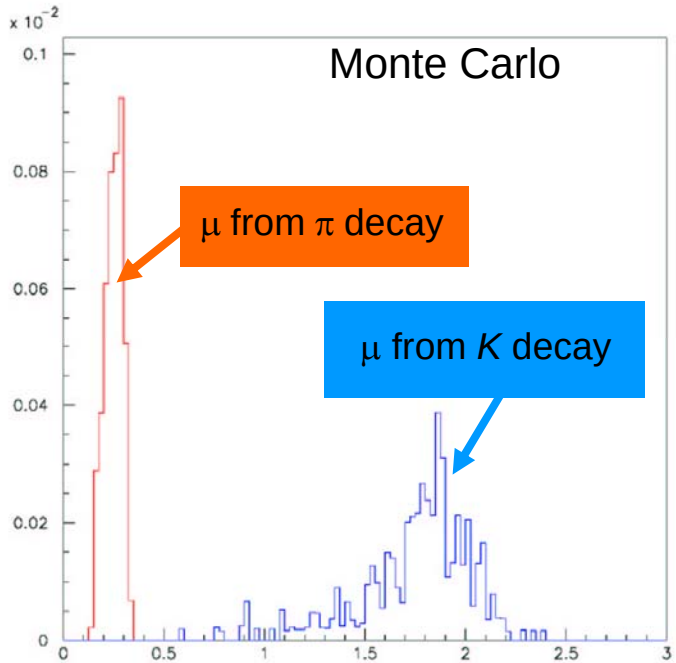
→ an off-axis muon beam

principle: larger p_T available in kaon vs. pion decay

observe muons at wide angle (7 degrees)

K decays produce higher-energy wide-angle muons than π decays

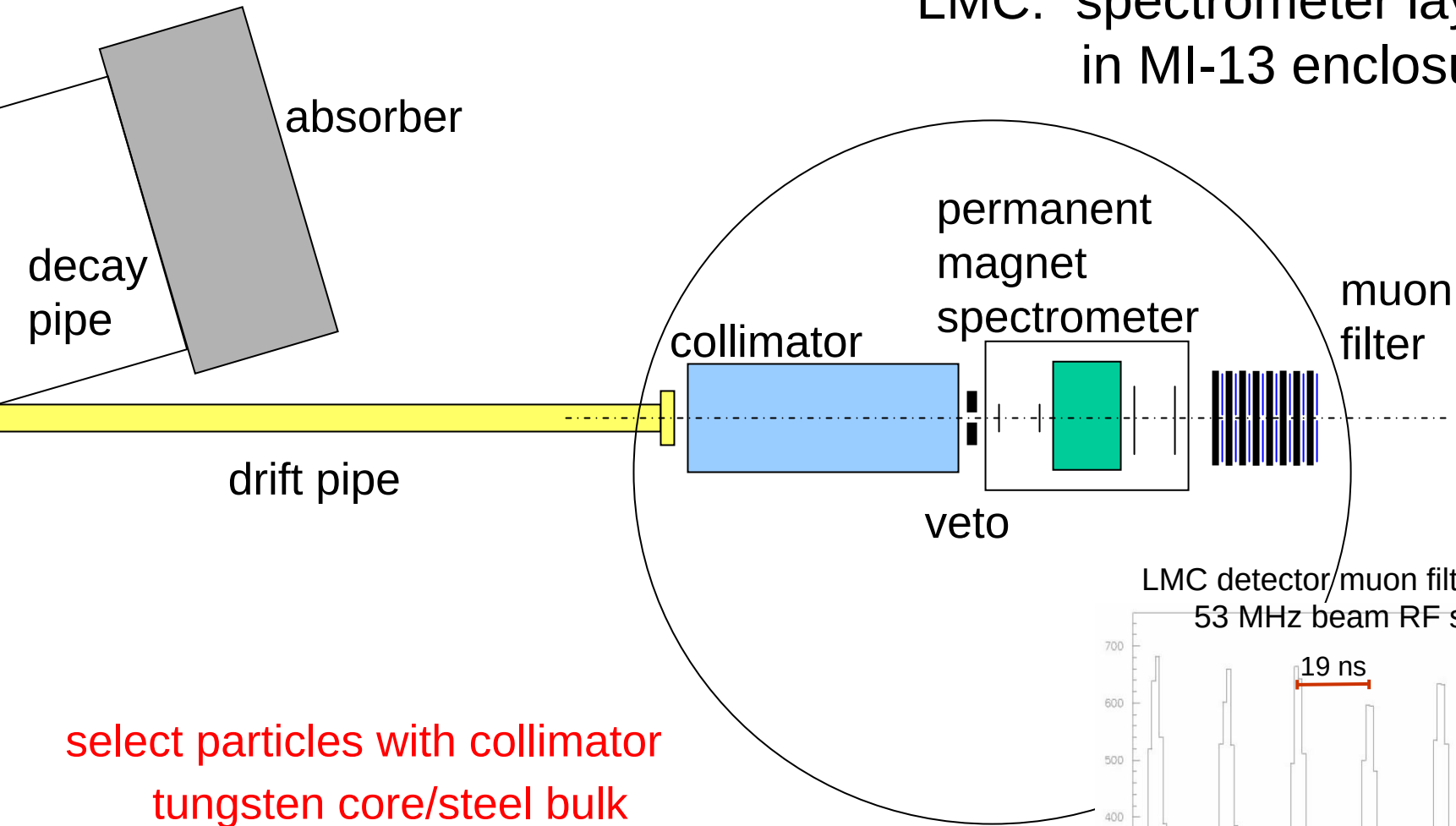
muons from pions and kaons clearly seperated in energy



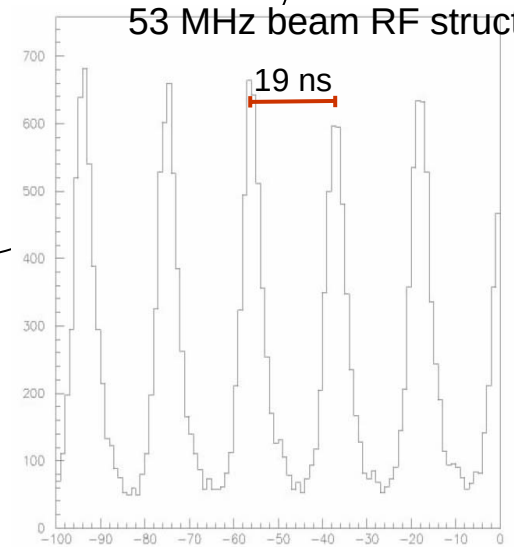
muon momentum at 7° (GeV)



LMC: spectrometer layout in MI-13 enclosure



LMC detector/muon filter
53 MHz beam RF structure



PMT time – beam-on-target time (ns)

select particles with collimator

tungsten core/steel bulk

measure trajectories w/ scintillating fibers

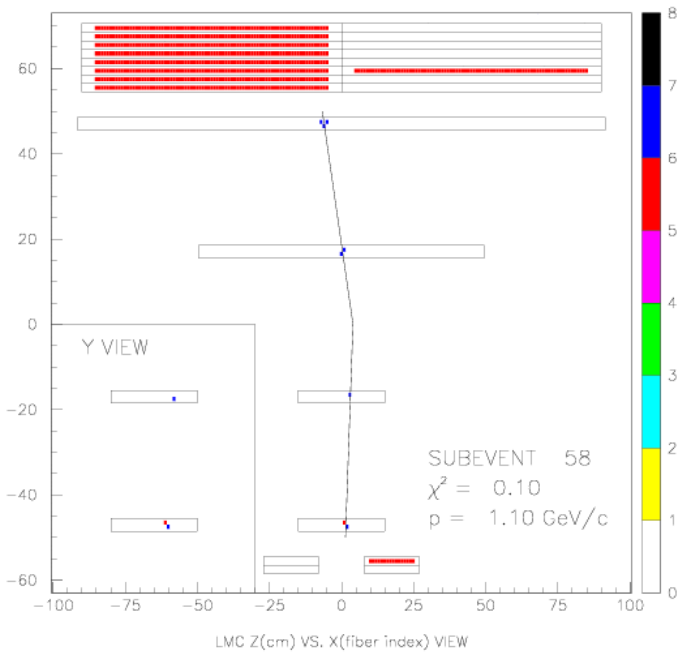
2.3 kgauss-23 cm permanent dipole

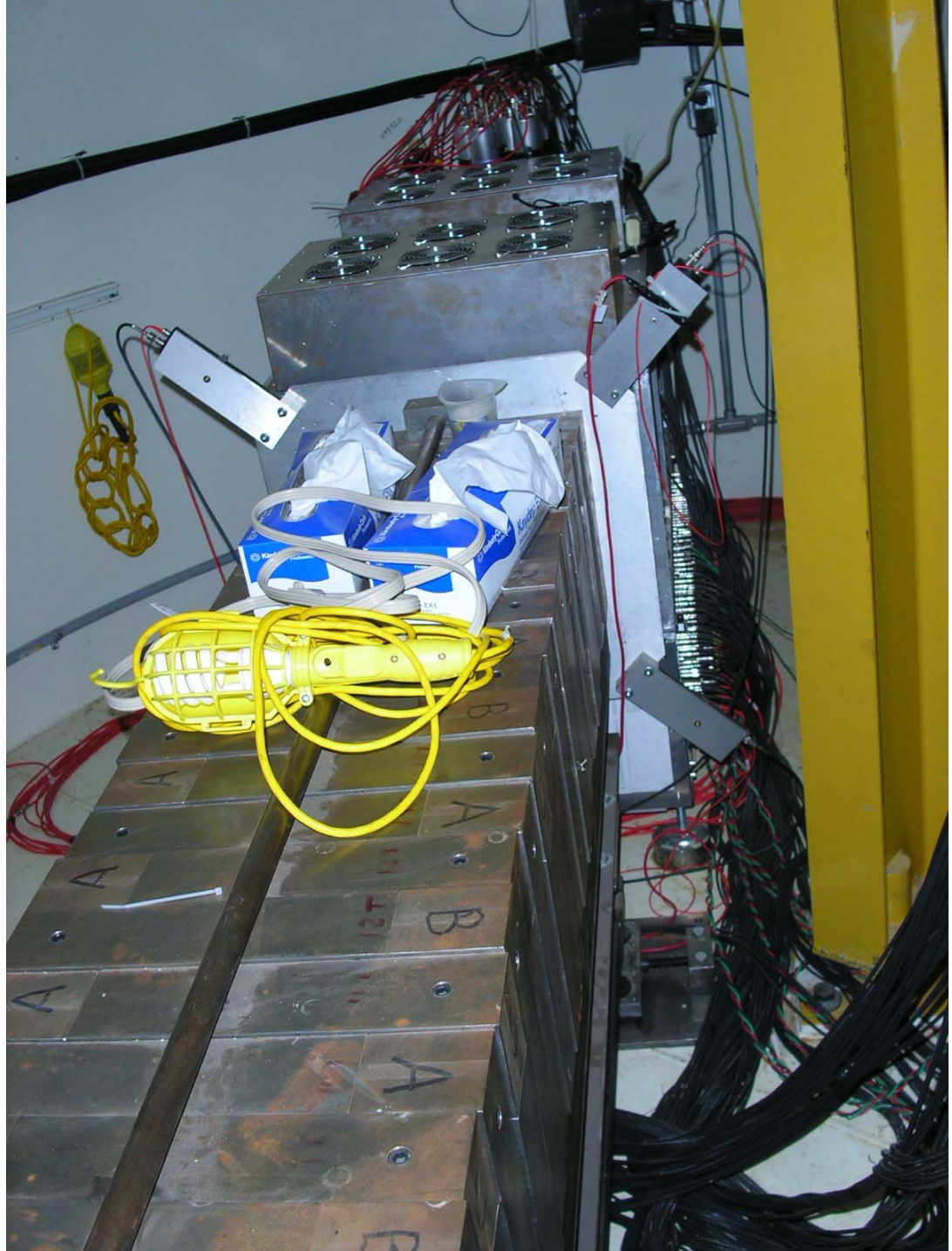
pion-muon separation with muon filter range stack

8 layers, 5 cm-tungsten-scintillator

we are trying to demonstrate this new technique

goal is to provide a meaningful constraint on the kaon-induced ν_e background





The MiniBooNE detector



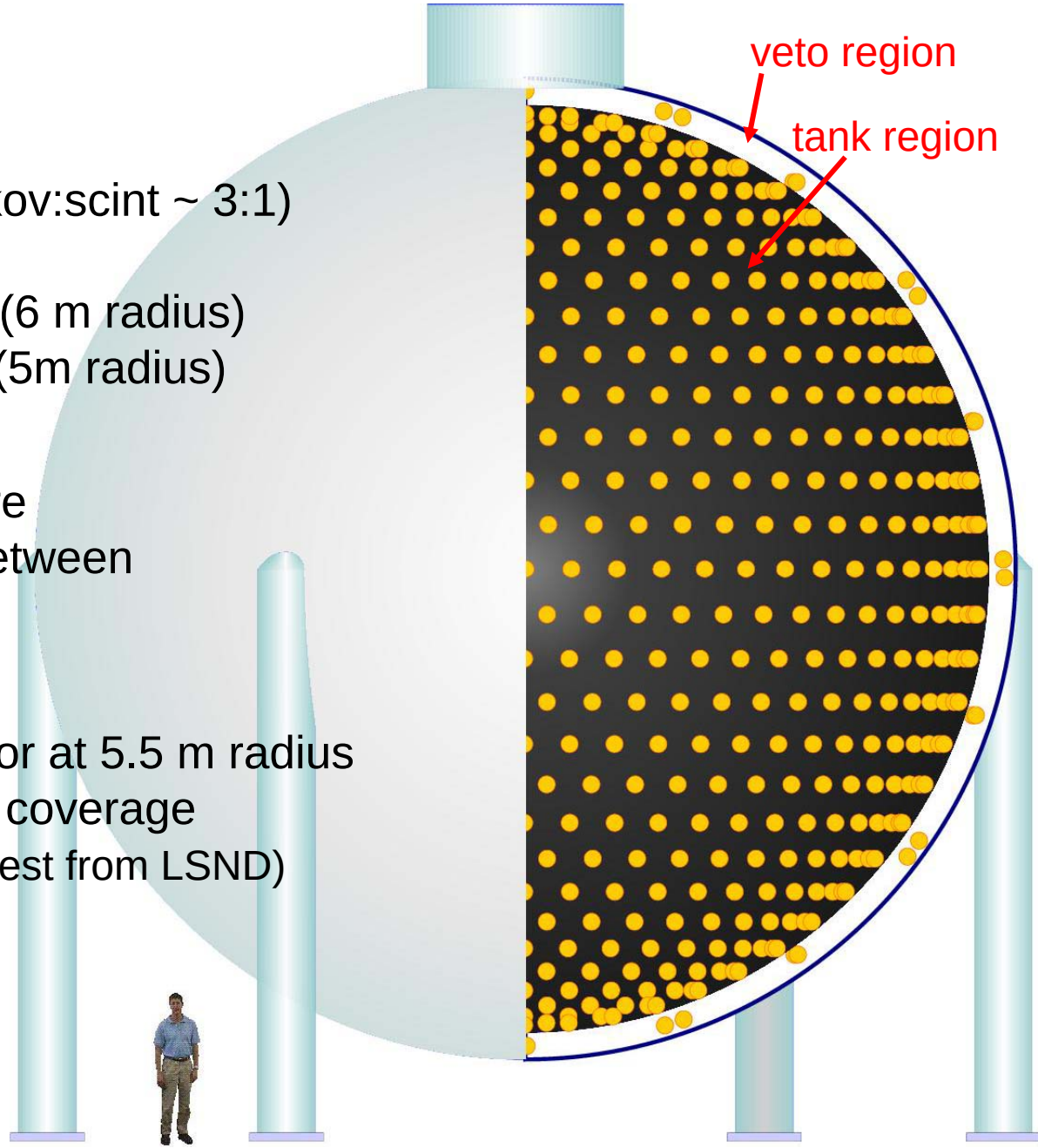
MiniBooNE detector

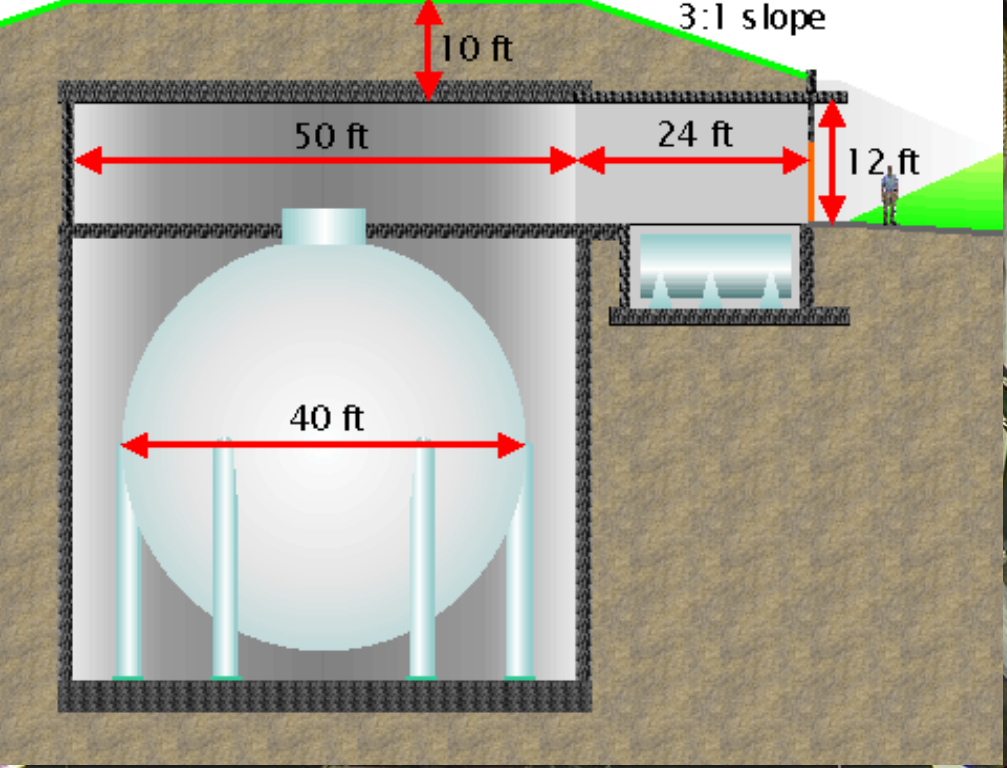
pure mineral oil (Cherenkov:scint ~ 3:1)

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

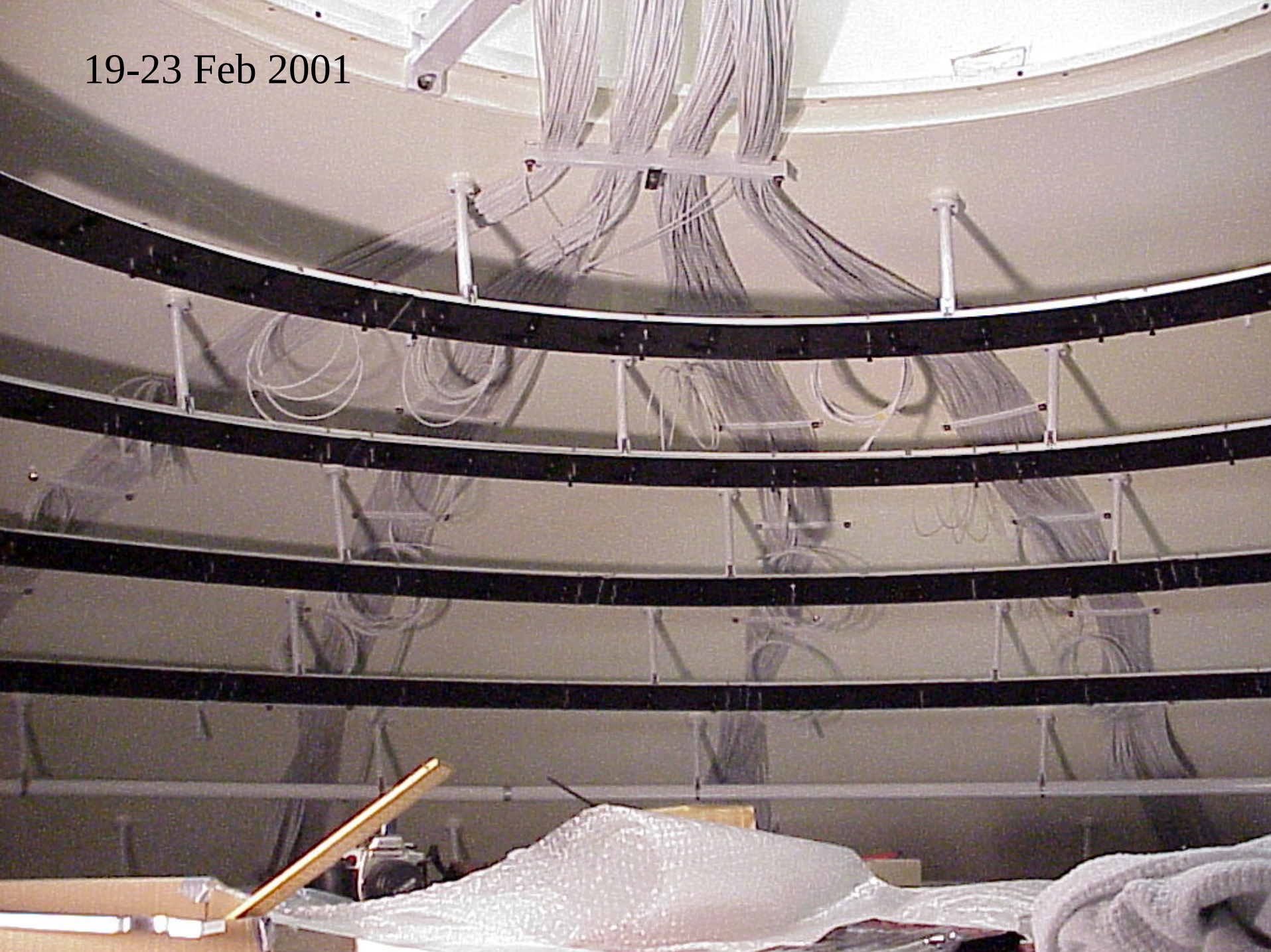

January 2001

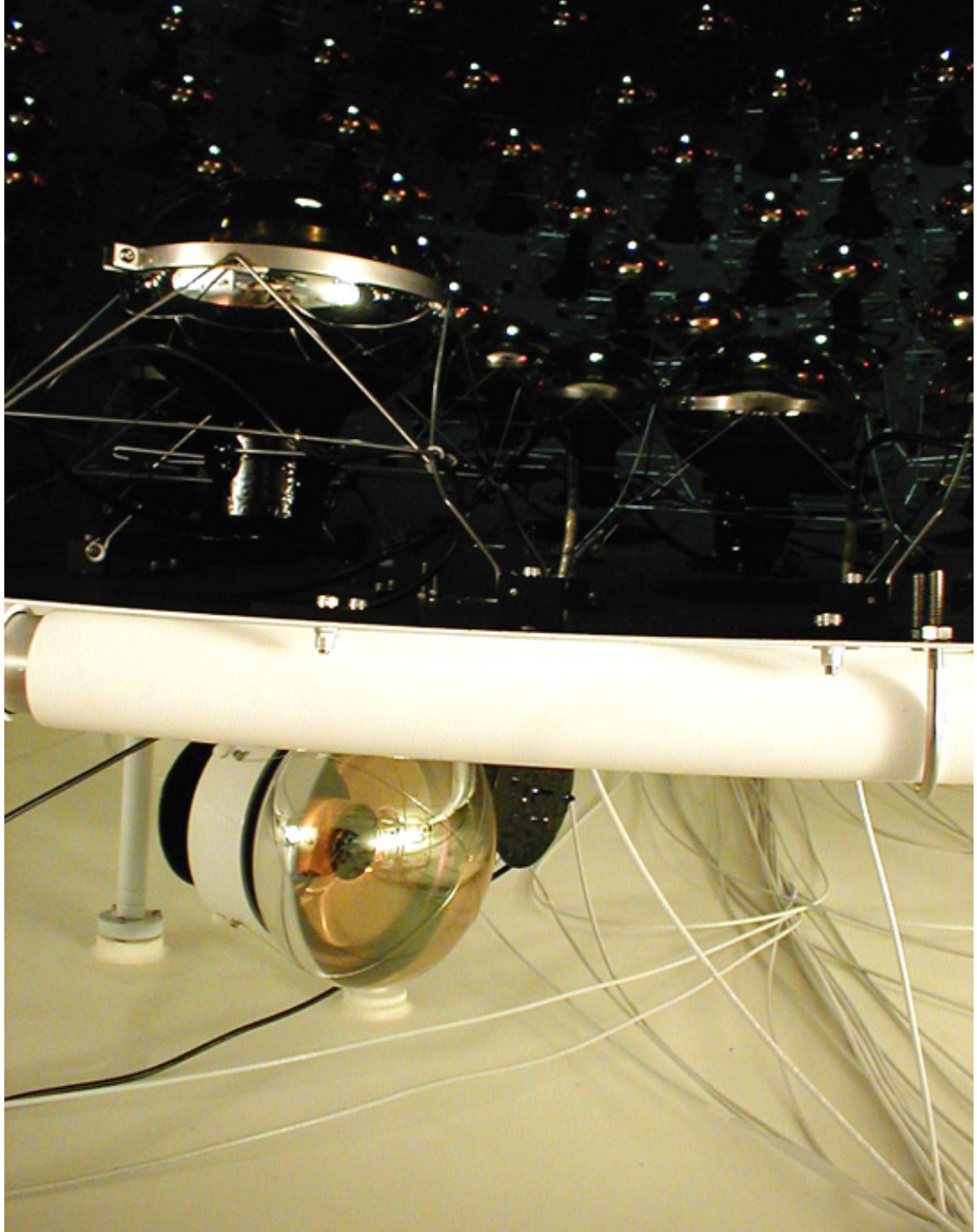






16 Feb 2001


19-23 Feb 2001



Neutrino events

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

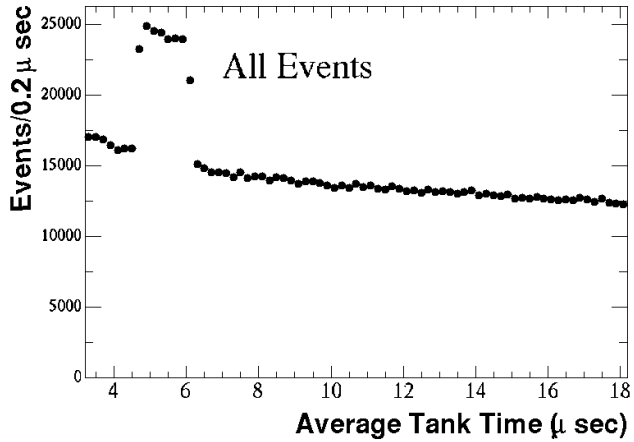
trigger on signal from Booster
read out for 19.2 μsec; beam at [4.6, 6.2] μsec

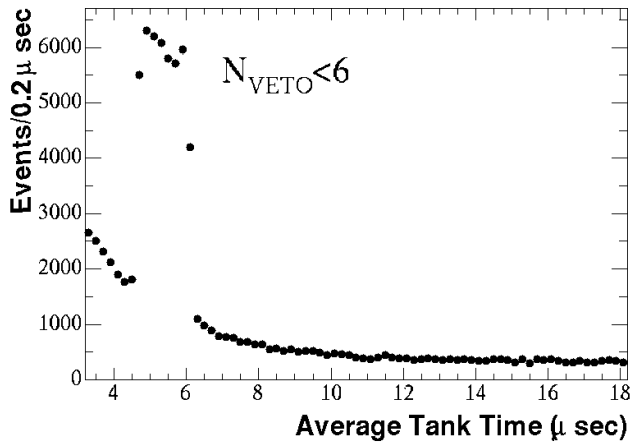
no high level analysis needed to see neutrino events

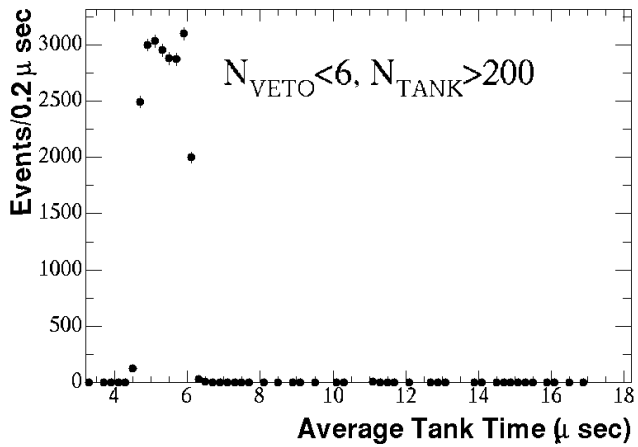
backgrounds: cosmic muons
decay electrons

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

current collected data:
470k neutrino candidates
for 4.5 x 10^{20} protons on target

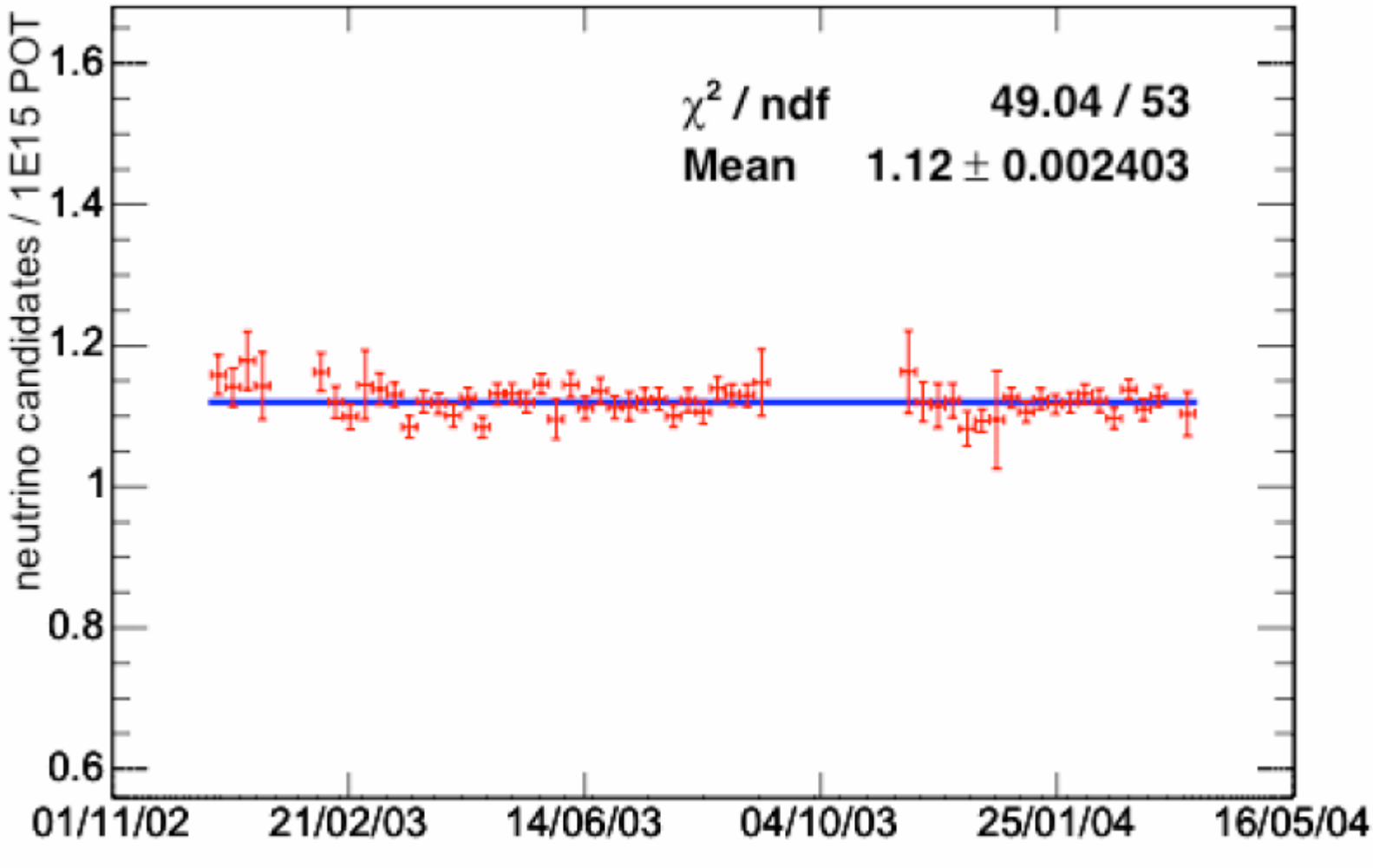






1.12 ν events / 10^{15} p.o.t.

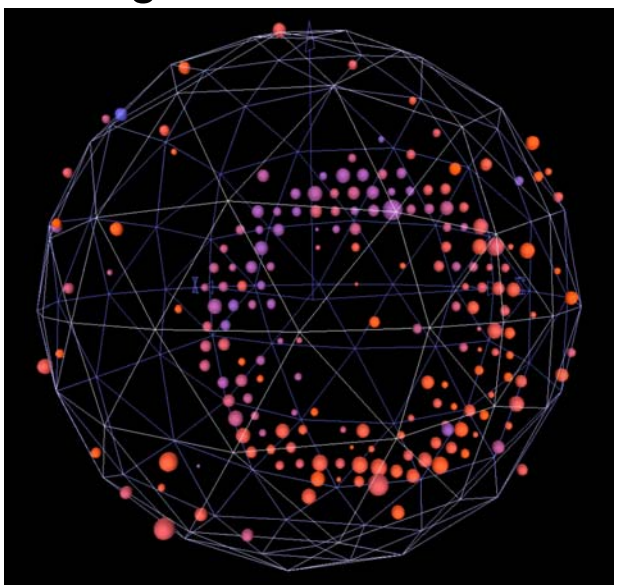
ν event every 1.5 minutes



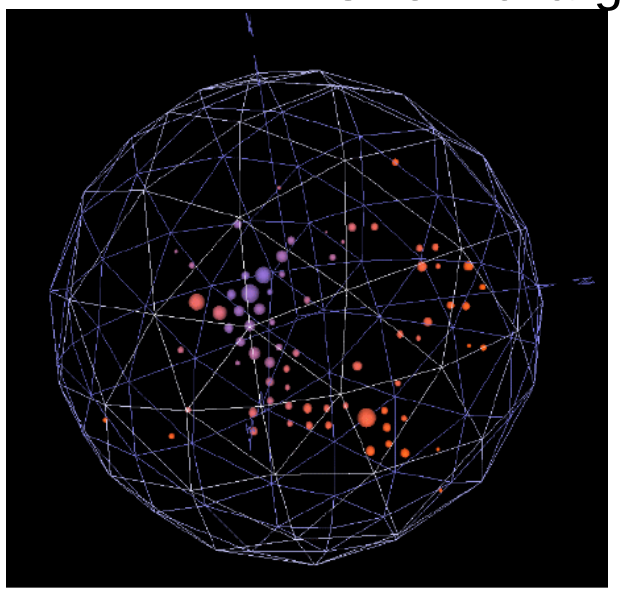
Pattern of hit tubes (with charge and time information)
allows reconstruction of track location and direction
and separation of different event types.

e.g. candidate events:

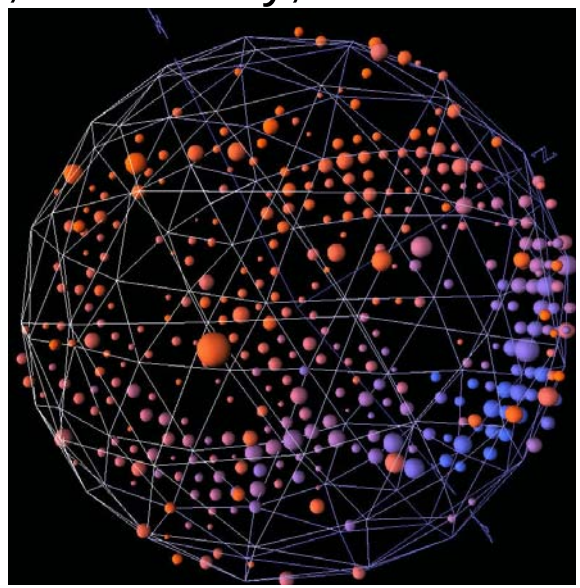
size = charge; red = early, blue = late



muon
from ν_μ interaction



Michel electron
from stopped μ decay
after ν_μ interaction



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

Detection and Reconstruction of Events

Charged particles in the mineral oil emit

Cherenkov radiation
- prompt
- in cone (θ_c=47.4^o for β~1)
- $\propto$ path above threshold

Scintillation light
- emission time constant ~ 20 ns
- isotropic
- $\propto$ kinetic energy

Fuzzy vs. sharp Cherenkov ring

particle ID

Ratio of prompt to late light

In pure mineral oil, Cherenkov:scint ~ 3:1

Photon propagation in mineral oil

Event reconstruction is sensitive to optical model

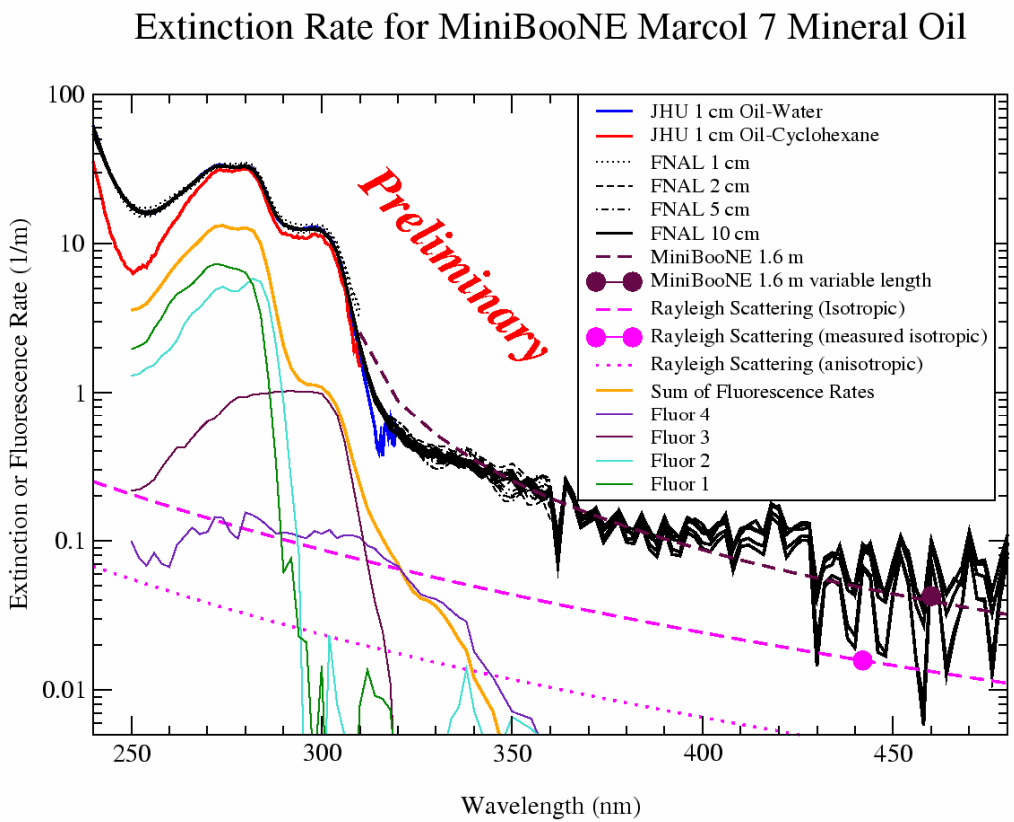
primary: Cherenkov and scintillation light

optical properties change dramatically over wavelength range

- absorption ⇨ photon disappears (thermal dissipation)
- Rayleigh scattering ⇨ density perturbations
  prompt, no λ shift
- Raman scattering ⇨ excite vibrational modes
  prompt, with λ shift
- flourescence ⇨ excite molecular states
  delayed emission, with λ shift

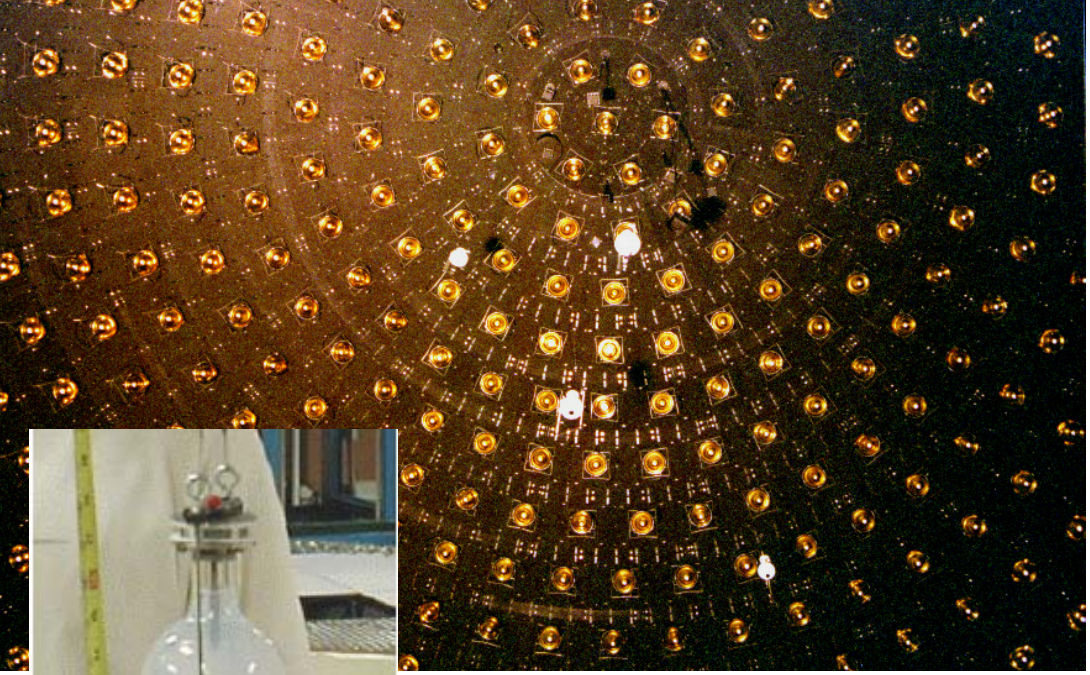
Summary of optical model processes

measurements of
- index of refraction
- Rayleigh/Raman
- Flourescence
  - time resolved
  - steady state
- extinction
- scintillation



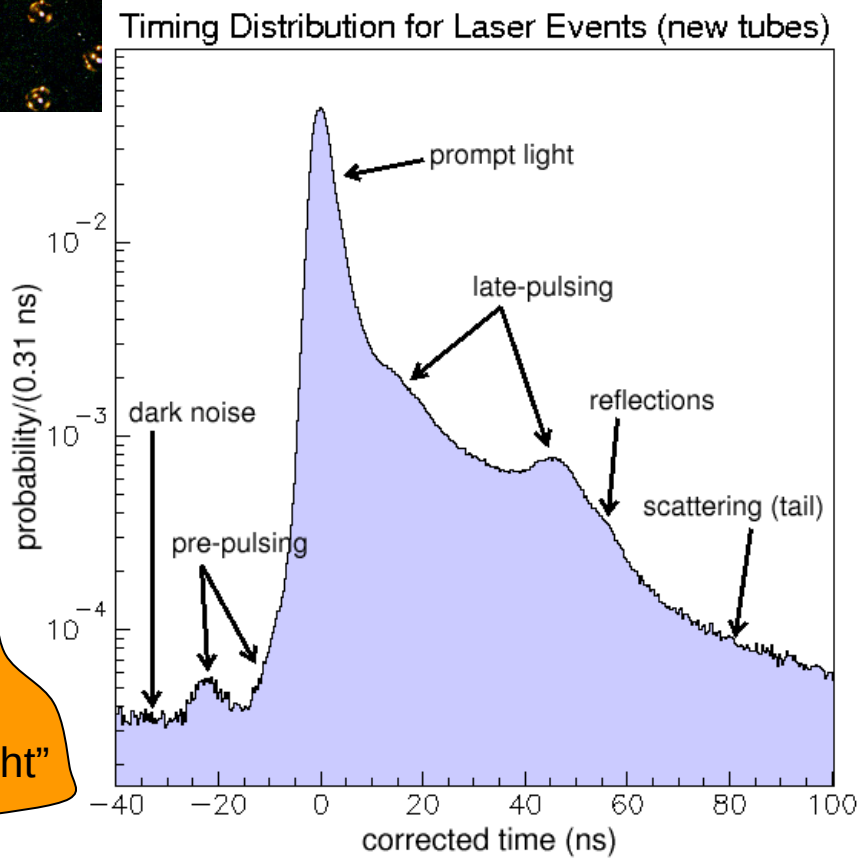
These bench measurements complement *in situ* calibrations

Understanding the detector



Laser flasks

four Ludox (colloidal silica)-filled flasks
fed by optical fiber from laser



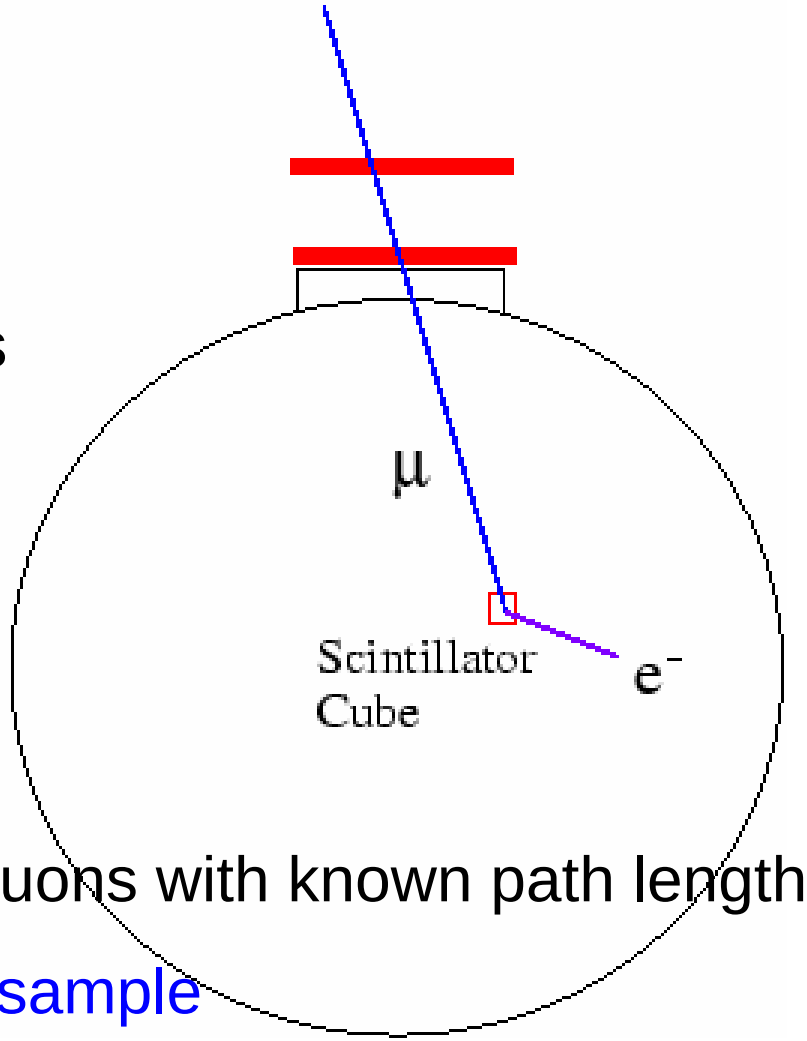
measure:
PMT charge and time response
and
oil attenuation length

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

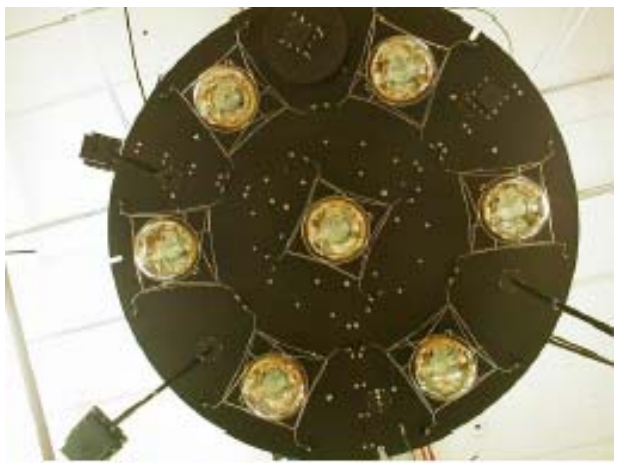


Stopping muon calibration system

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 800 MeV

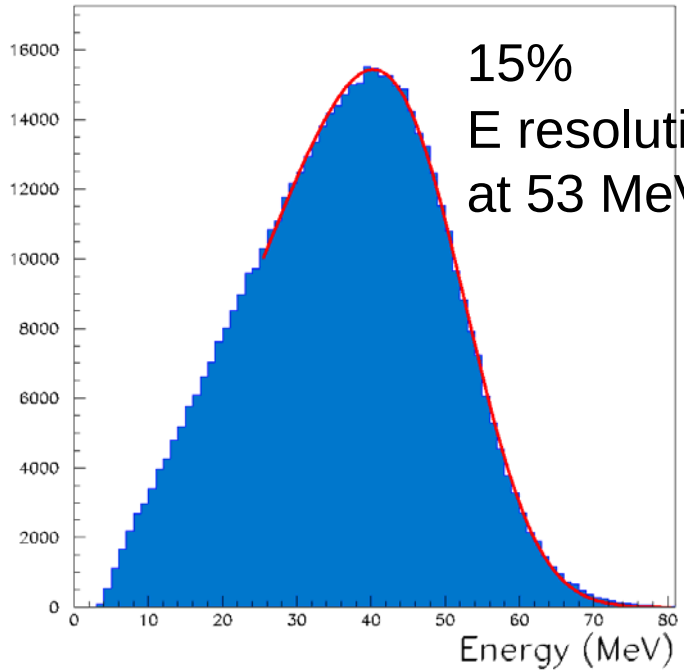
Calibration systems

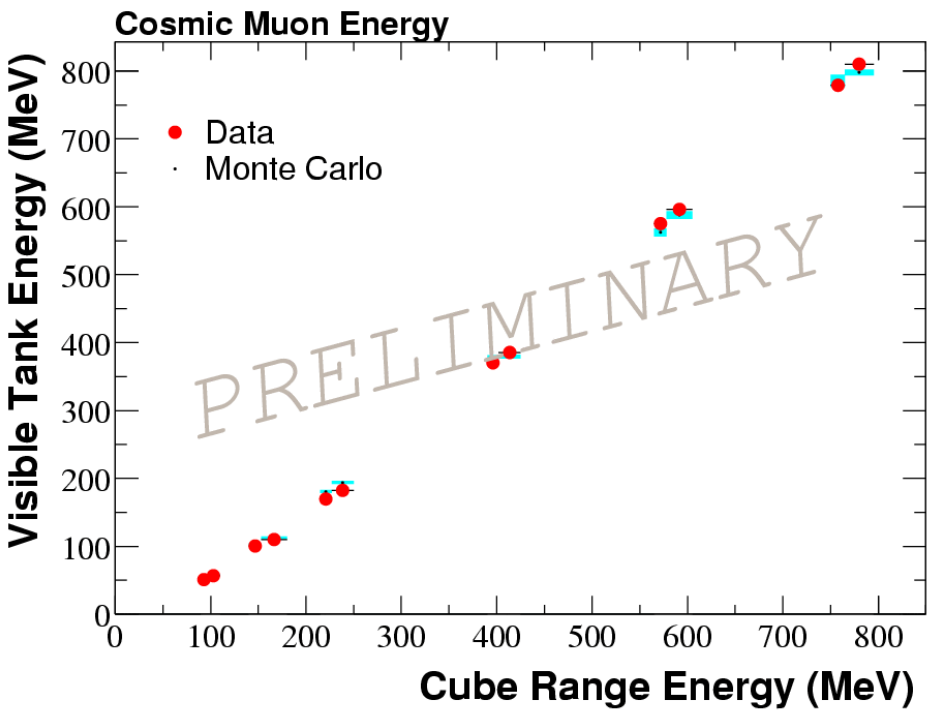
Michel electrons

decay of stopped muons

Energy scale and resolution
at Michel endpoint (53 MeV)

Michel electrons throughout
detector (r<500 cm)



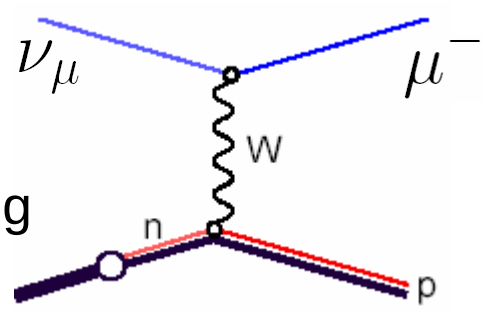


Tracker/cube
reconstructed muons

compared known range
with reconstructed energy

Neutrino interactions at O(1 GeV)

Charged current
quasi-elastic scattering



Neutral current
π^0 production

resonant:

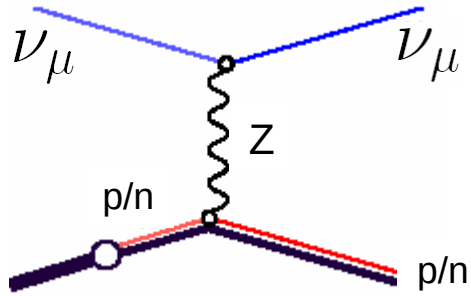
$$\nu_\mu\ (p/n) \rightarrow \nu_\mu\ \Delta$$
$$\Delta \rightarrow (p/n)\ \pi^0$$

coherent:

$$\nu_\mu\ C \rightarrow \nu_\mu\ C\ \pi^0$$



Neutral current
elastic scattering



other (e.g. multipion production)

Charged pion production
e.g. $\nu_\mu\ p \rightarrow \mu^-\ p\ \pi^+$

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

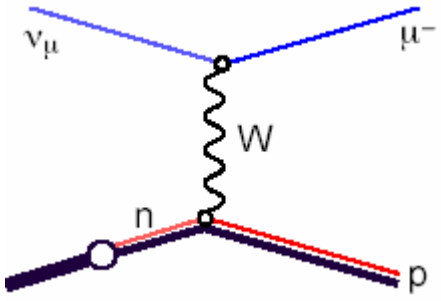
necessary for $\nu_\mu \rightarrow \nu_e$ search

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

progress in understanding backgrounds

Early physics

CC quasi-elastic



NC π^0 production

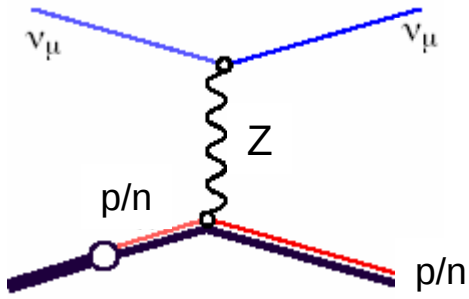
resonant:

$$\nu_\mu\,(p/n) \;\rightarrow\; \nu_\mu\,\Delta$$
$$\Delta \;\rightarrow\; (p/n)\,\pi^0$$

coherent:

$$\nu_\mu\,C \rightarrow \nu_\mu\,C\,\pi^0$$

NC elastic



why relevant to $\nu_\mu \rightarrow \nu_e$ search

kinematics:
E_μ, $\theta_\mu \rightarrow$ E_ν
measure ν_μ flux

ν_e appearance in QE channel

$\pi^0 \rightarrow \gamma\,\gamma$
important background

dominated by scintillation understanding of proton recoil

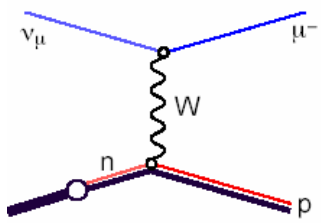
what other interest

using predicted flux:
ν_μ disappearance

better measurement of π^0 cross section
→ limits on sterile ν

sensitive to nucleon strange quark spin component

CC ν_μ quasi-elastic events



~40% of the events are $\nu_\mu\, n \longrightarrow \mu^-\, p$

much of the rest are messy

selection: N_{TANK}>200, N_{VETO}<6

topology

ring sharpness

on- vs. off-ring hits

timing

single μ-like ring

prompt vs. late light

⇨ variables combined in a Fisher discriminant

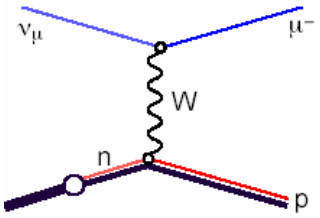
selection:

~90% purity

~60% efficiency

for events inside the fiducial volume

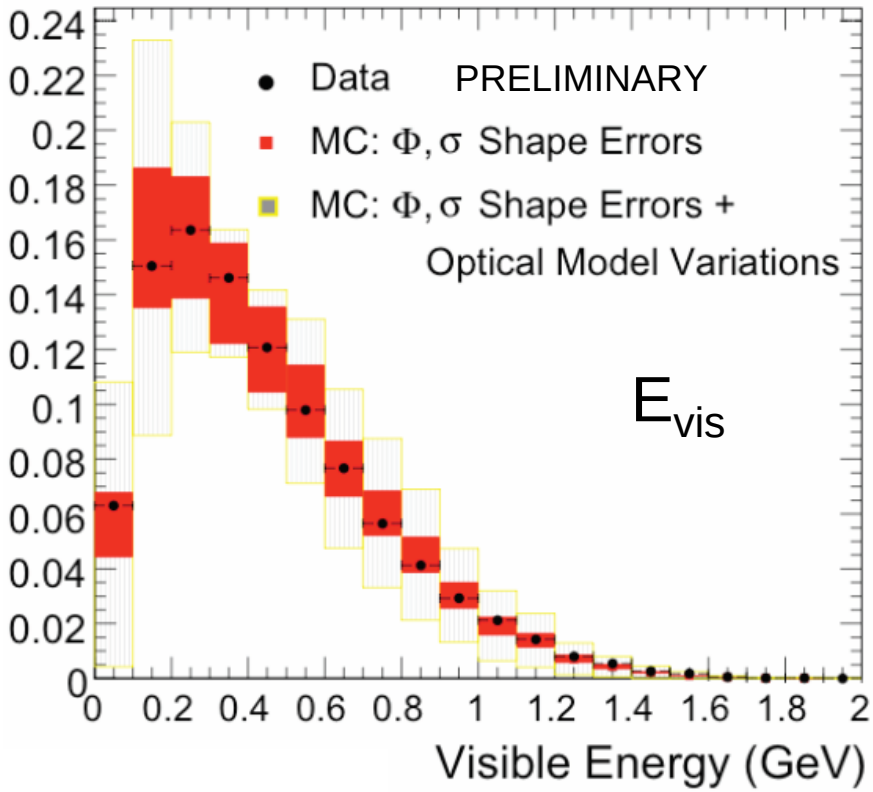
CC ν_μ quasi-elastic events

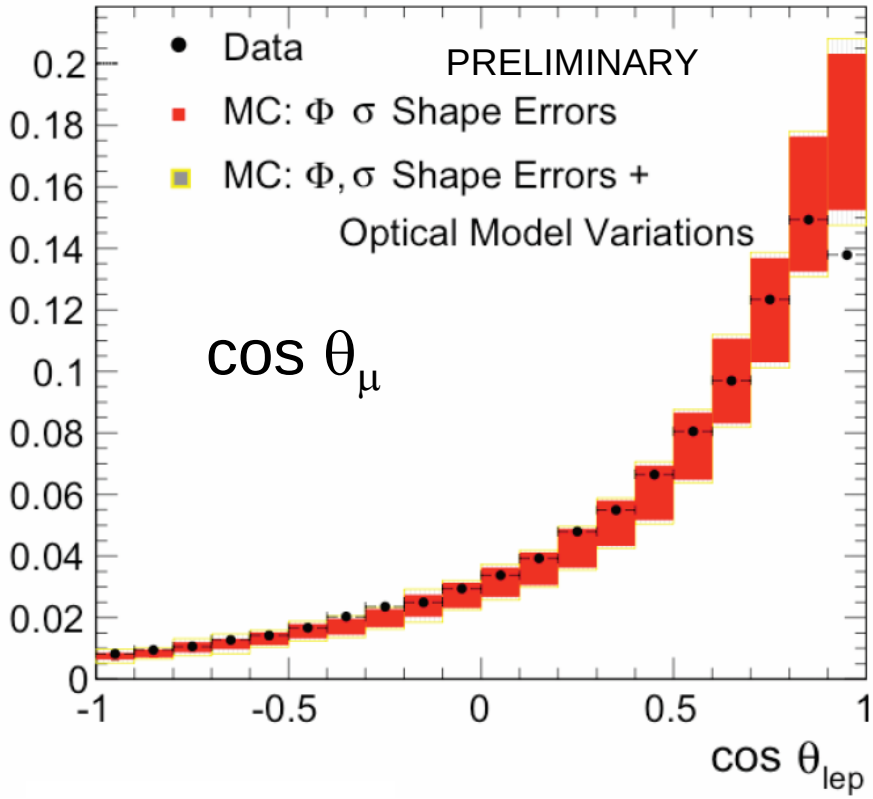


uncertainty bands: Monte Carlo with variations from

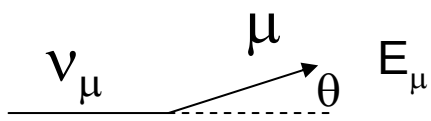
- flux prediction
- σ_{CCQE}
- optical properties

data and MC relatively normalized





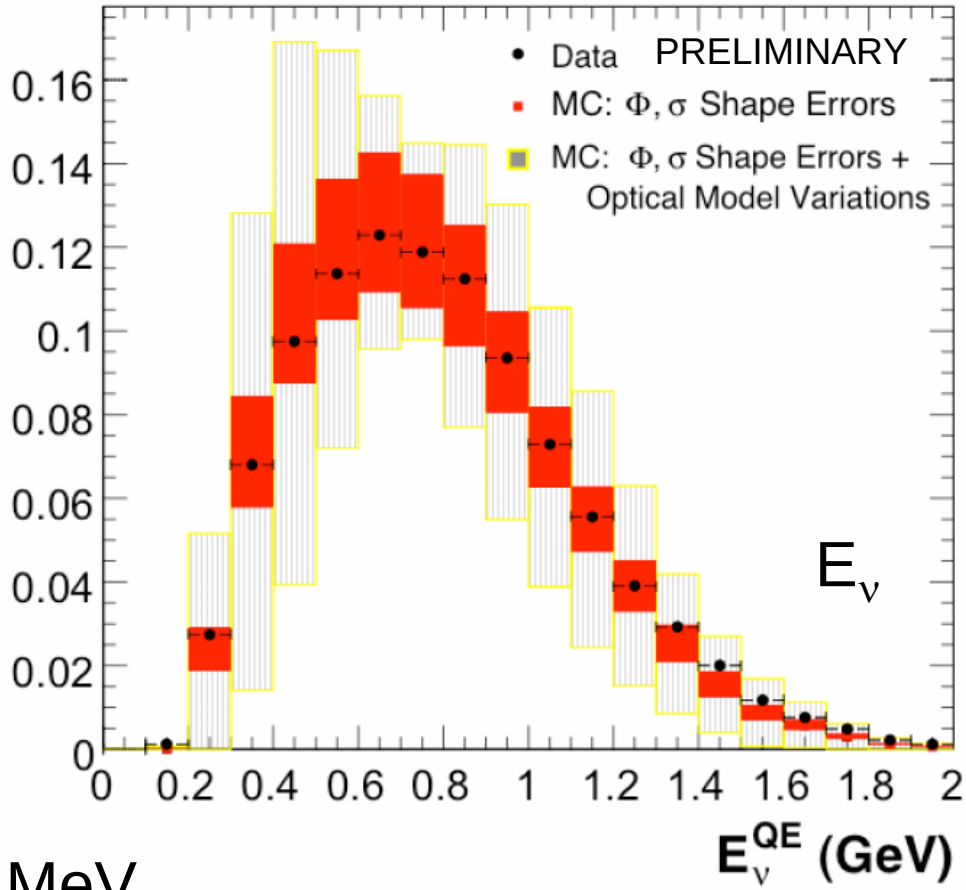
Neutrino energy

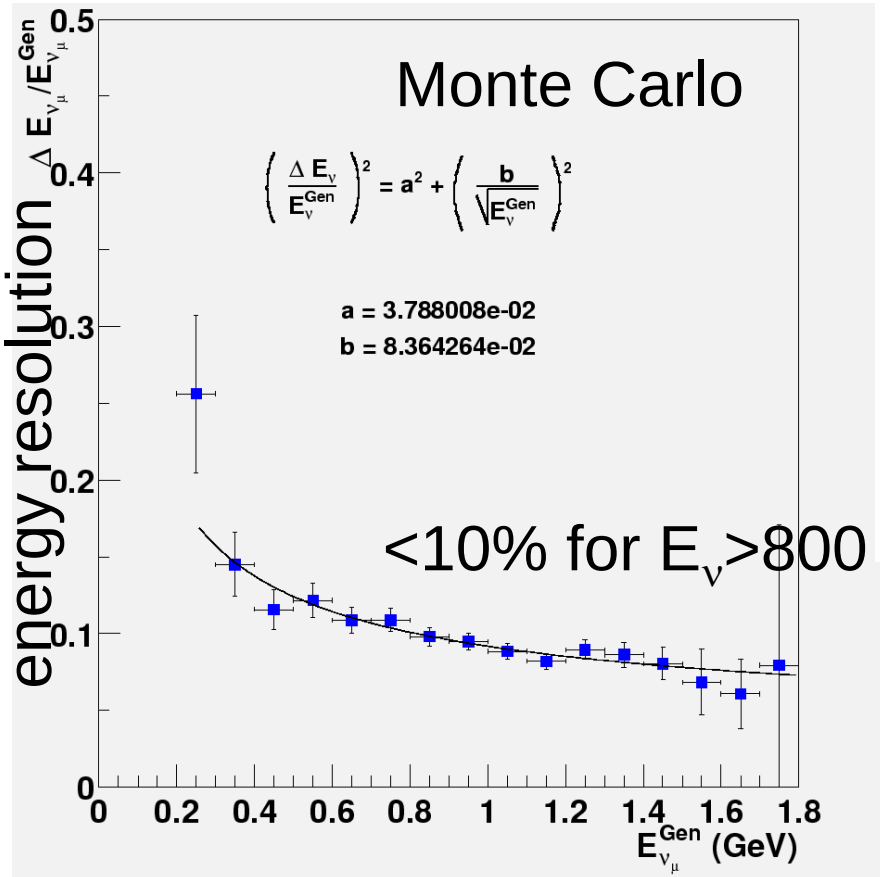


kinematic reconstruction:

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

use E_μ, θ_μ to get E_ν



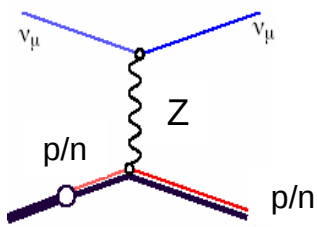


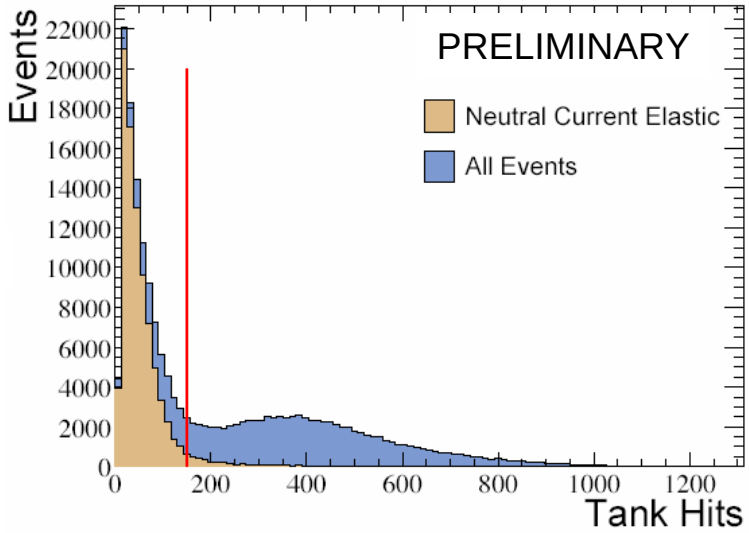
<10% for E_ν>800 MeV

compare to reliable flux prediction

→ ν_μ disappearance analysis

NC elastic scattering



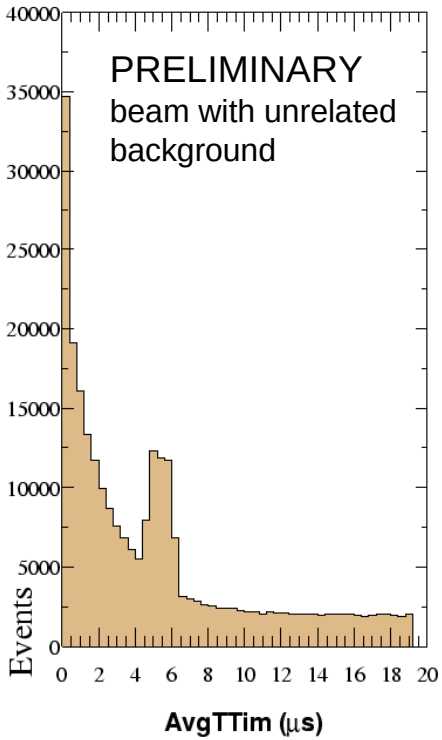


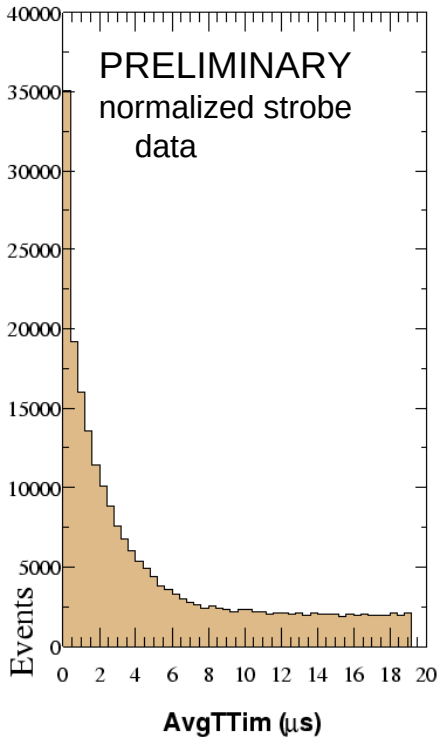
Now select $N_{TANK} < 150$
$N_{VETO} < 6$

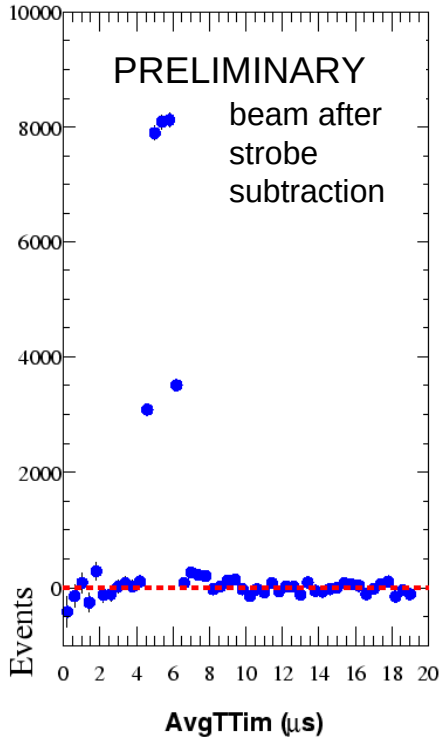
beam-off background subtraction

clear beam excess

challenges: beam-on bkgd, neutrons, etc.



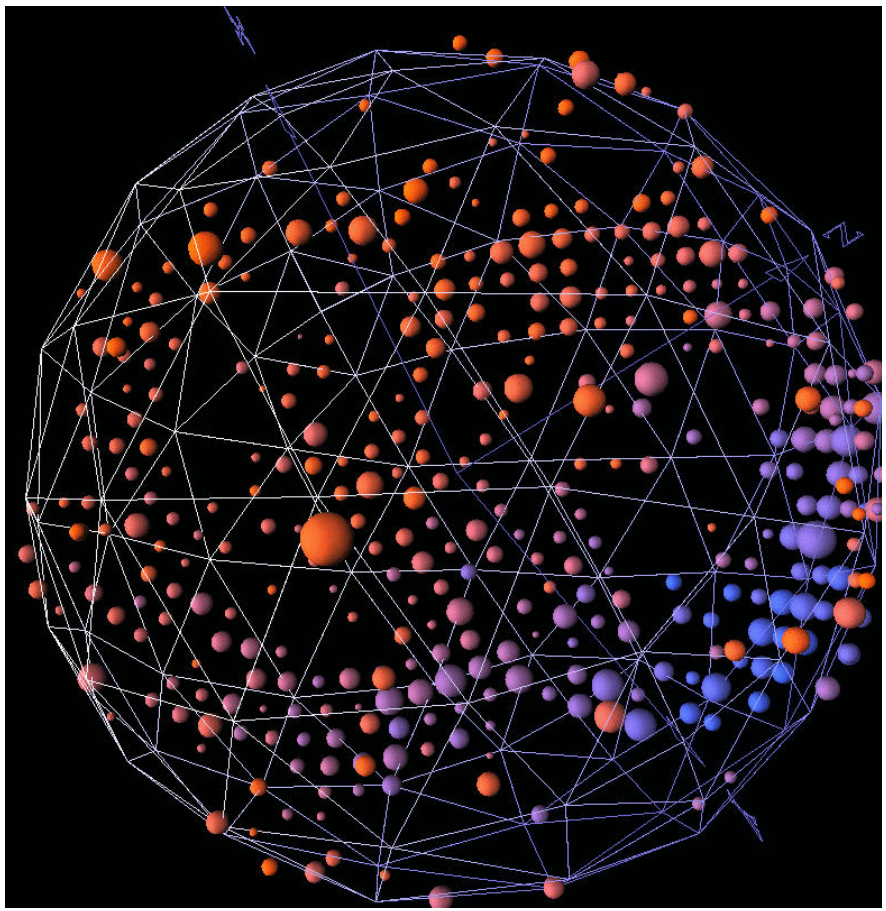


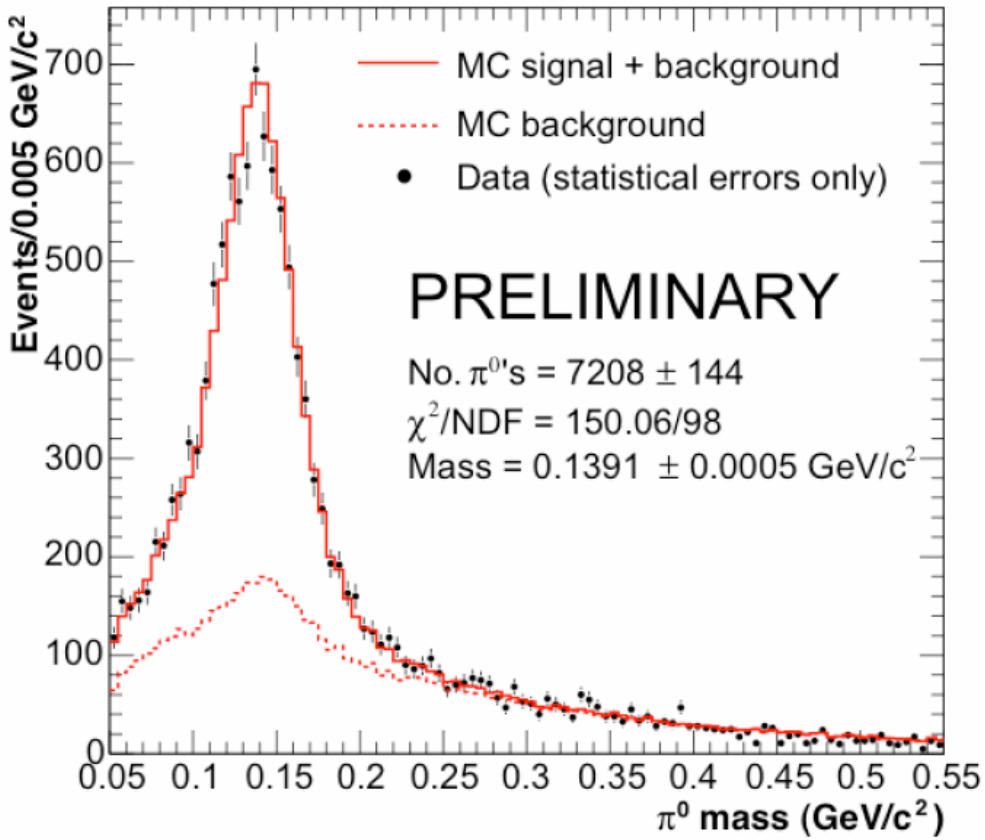


NC π^0 production

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

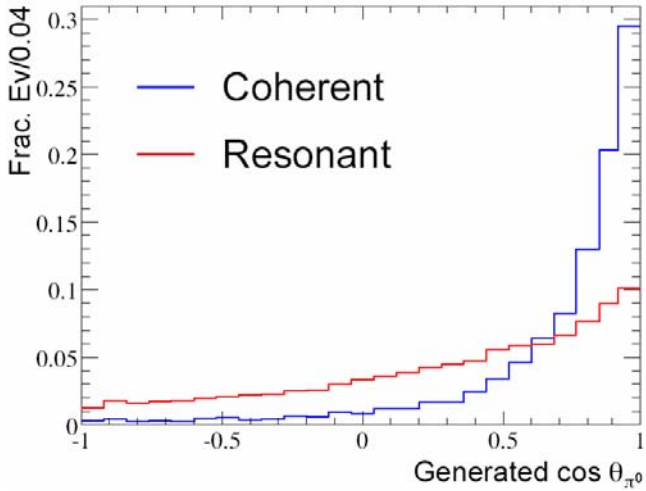




π^0 production angle

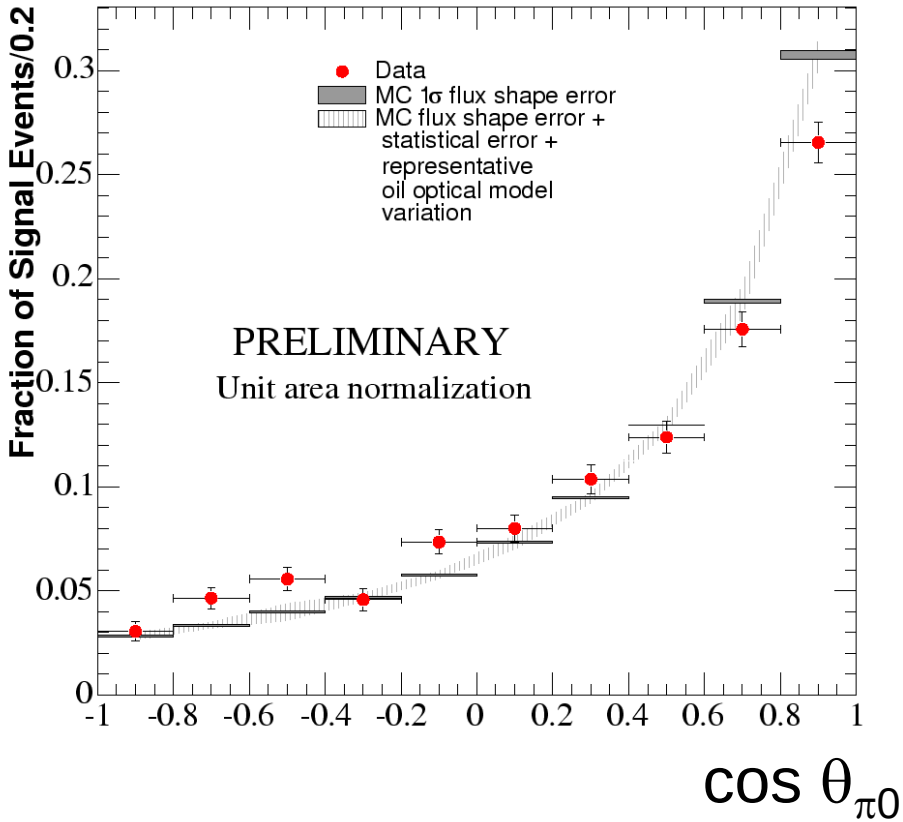
sensitive to production mechanism

coherent is highly forward peaked



data and MC are relatively normalized

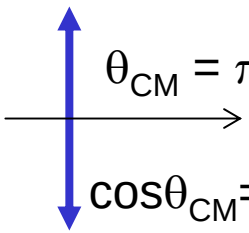
MC shape assumes Rein-Sehgal cross sections

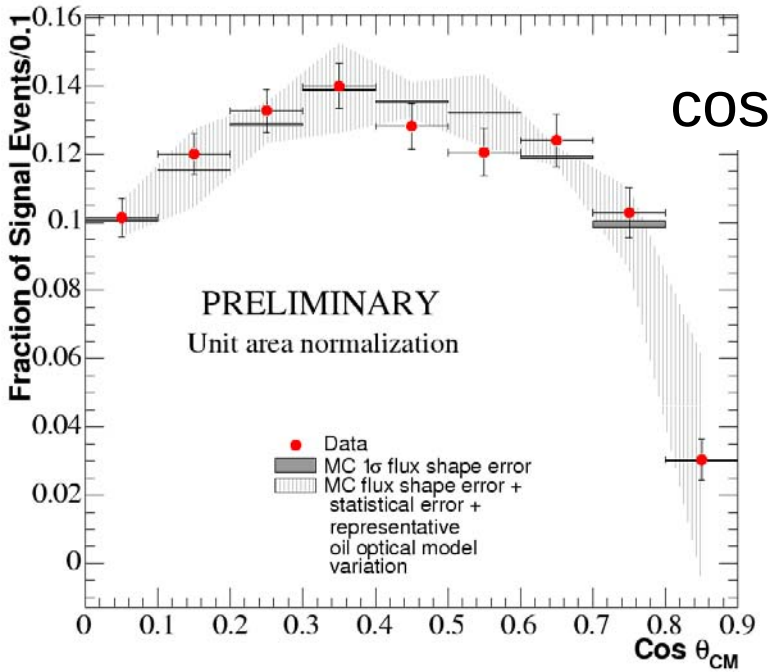


π^0 CM decay angle

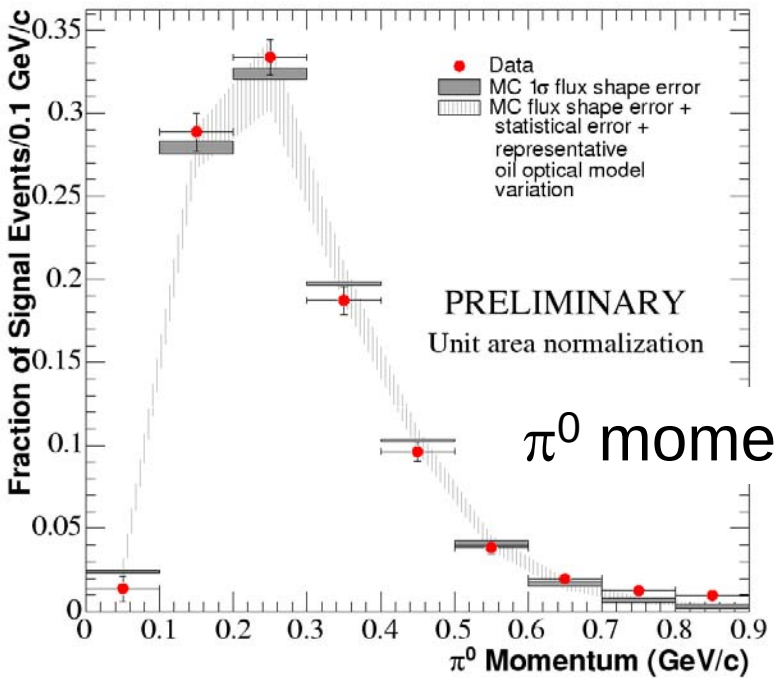
and

π^0 lab momentum

CM frame	lab frame
$\theta_{CM} = \pi/2$  $\cos\theta_{CM} = 0$	⇨ small $\gamma\,\gamma$ opening angle
$\theta_{CM} = 0$  $\cos\theta_{CM} = 1$	⇨ photon energies asymmetric



cos θ_{CM}



π^0 momentum

$\nu_\mu \rightarrow \nu_e$ search

signal: ν_e CC quasi-elastic

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

backgrounds:

muon mis-id: $\nu_\mu + n \longrightarrow \mu^- + p$

π^0 mis-id:

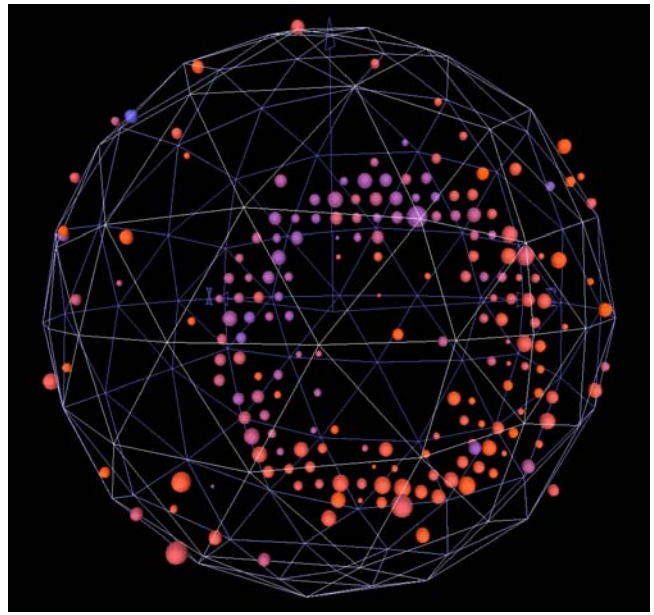
$$\nu_\mu + (n/p) \longrightarrow \nu_\mu + \pi^0 + (n/p)$$

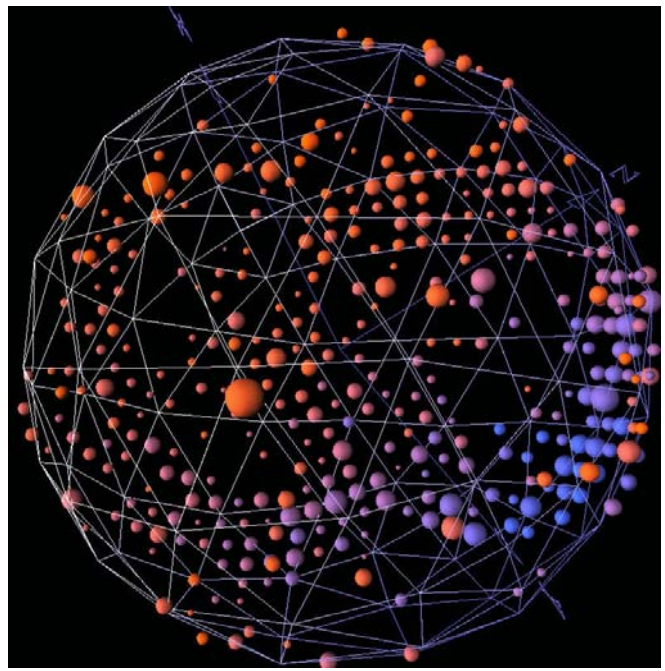
radiative Δ decay:

$$\nu_\mu + (n/p) \longrightarrow \nu_\mu + \Delta$$

$$\Delta \longrightarrow (n/p)\gamma$$

intrinsic ν_e in the beam





MiniBooNE's goal is to acquire 10^{21} protons on target, likely to get ~ 5×10^{20} by April 2005

Sensitivity at MiniBooNE: background and signal (if LSND)

summary of expected event statistics for 10^{21} protons on target

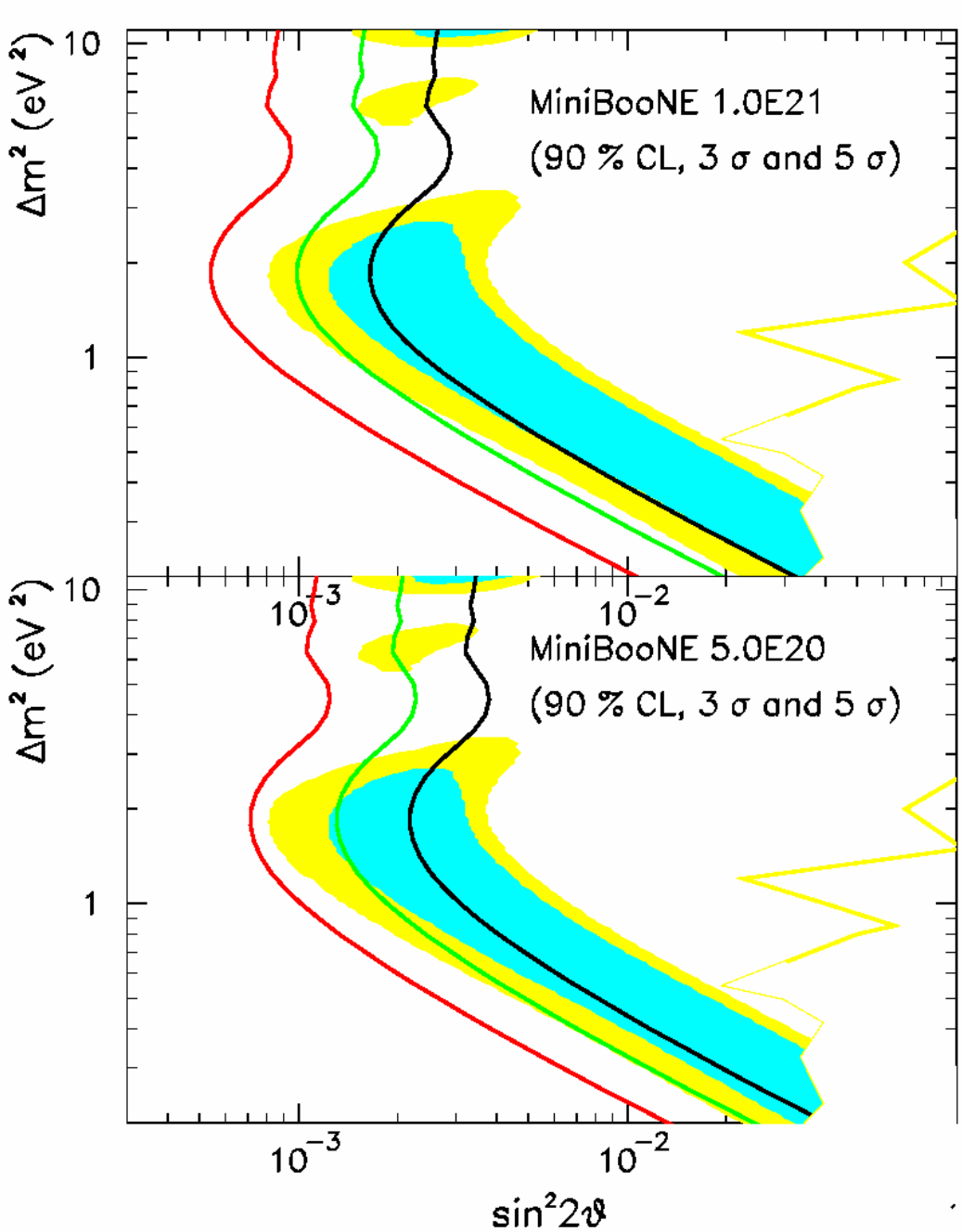
ν_μ CC QE	10
π^0 mis-id	290
$\Delta \rightarrow N\gamma$	80
ν_e from K^+ decay	120
ν_e from K^0 decay	40
ν_e from μ decay	190
total background	730

signal (Δm^2=1.0 eV^2, $\sin^2 2\theta$ =0.004)	260
signal (Δm^2=0.4 eV^2, $\sin^2 2\theta$ =0.017)	320

Sensitivity

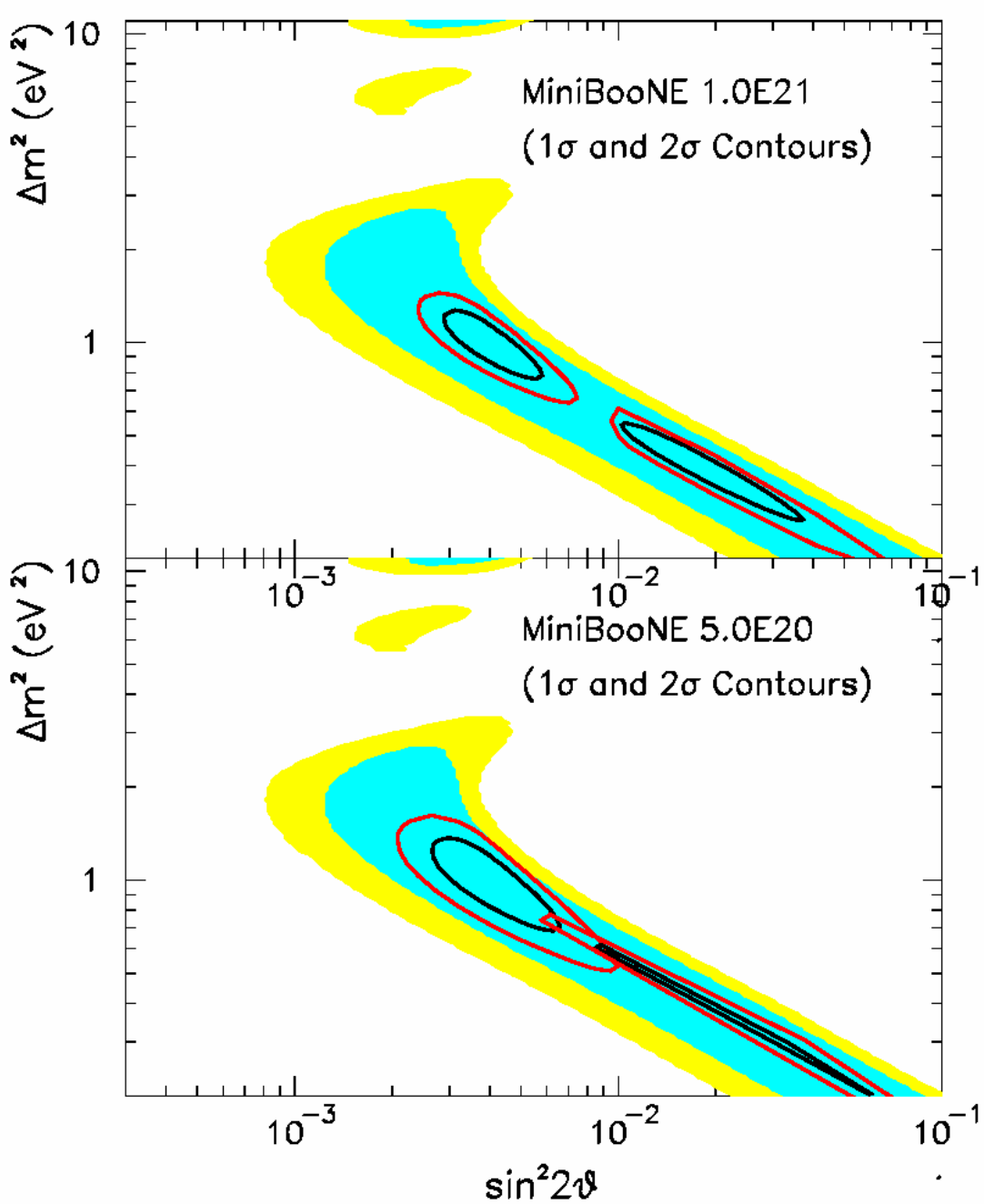
Expected for 1 x 10^{21} p.o.t

and for 5 x 10^{20} p.o.t.



Parameter measurement capability

expected contours for signals at $\Delta m^2 = 1.0$ and $0.4\ eV^2$ at the center of LSND's allowed region



Run plan

steadily collecting data (NuMI will start to get proton priority)

plan is to open the box when the analysis is ready
and when sufficient data has been collected
(definition: presumably > 5 x 10^{20} p.o.t.; end of FY 2005)
→ current estimate late 2005

MiniBooNE approved for FY 2006 run
could be in antineutrino mode
(2006 configuration depends on MB result)

Summary/Outlook

Goal is to make a definitive statement about LSND
confirmation has dramatic implications for neutrino physics

We are busy with systematic studies
bring offline measurements and in situ into agreement
for both beam and detector

