MiniBooNE: testing short-baseline ν_e appearance

P.Meyers – Princeton University

July 17, 2003

8” PMT’s at BooNE south pole

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*

L.Bugel, J.M. Conrad, J. Link, J. Monroe, M.H. Shaevitz, M. Sorel, G.P. Zeller *Columbia*

D. Smith *Embry Riddle*

L.Bartoszek, C. Bhat, S J. Brice, B.C. Brown, 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. Russell, P. Spentzouris, R. Stefanski *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*

If weak (flavor) ≠ mass (energy) eigenstates…
(2-neutrino case for simplicity)

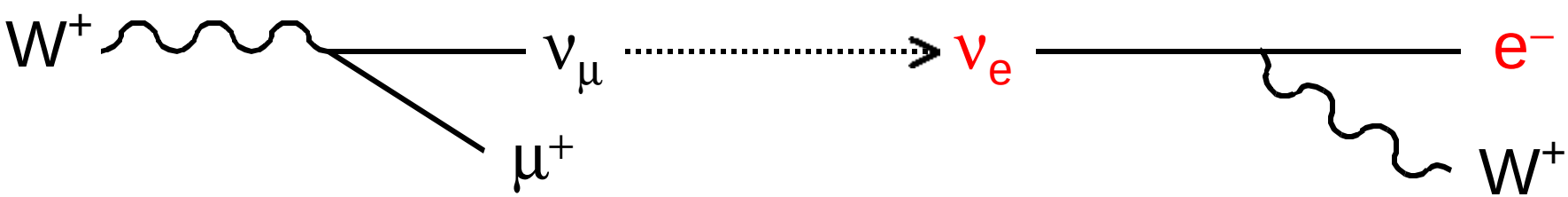
$$\left|n(t=0)\right\rangle = \left|n_m\right\rangle = \cos q \left|n_1\right\rangle + \sin q \left|n_2\right\rangle$$

$$\left|n(t)\right\rangle = \cos q \left|n_1\right\rangle e^{-iE_1 t} + \sin q \left|n_2\right\rangle e^{-iE_2 t} \neq \left|n_m\right\rangle \text{ if } m_1 \neq m_2$$

$$P(n_m \to n_e) = \left|\left\langle n_e \middle| n(t)\right\rangle\right|^2$$

$$= \sin^2 2q \sin^2\left[1.27\underline{\Delta m^2}(\mathrm{eV}^2)\underline{L}(\mathrm{m})/\underline{E}(\mathrm{MeV})\right]$$

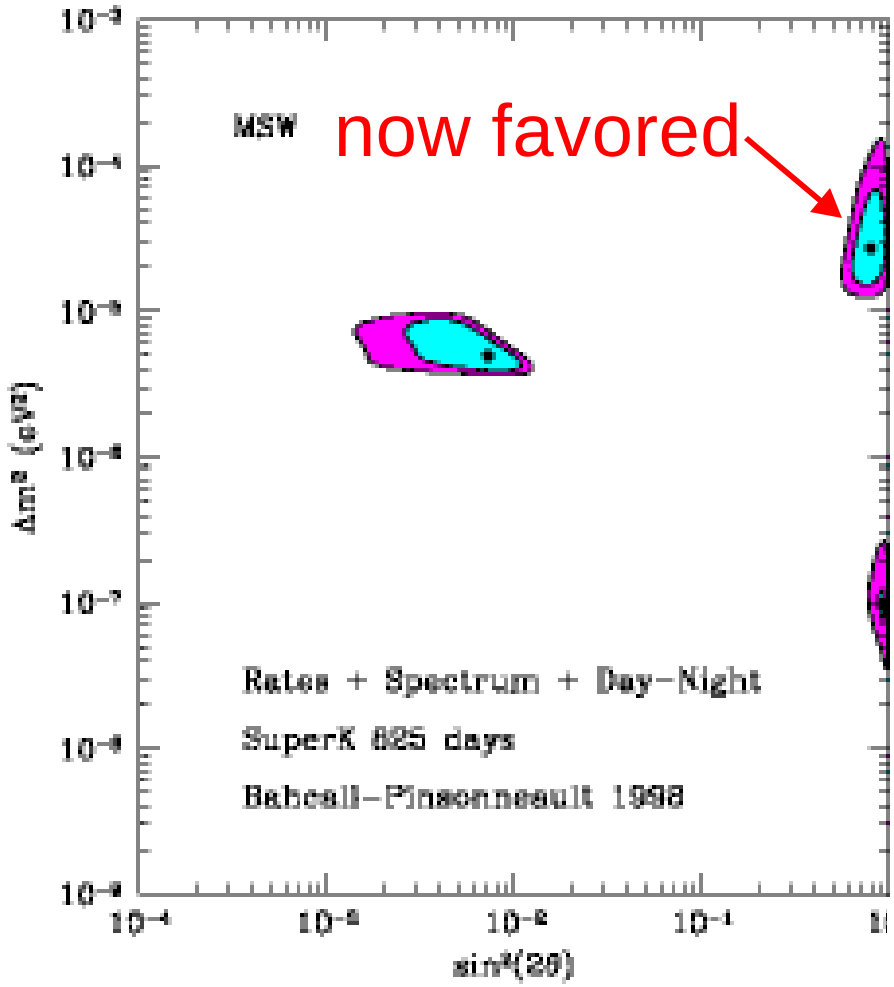
$$\text{with } \Delta m^2 \equiv m_2^2 - m_1^2$$

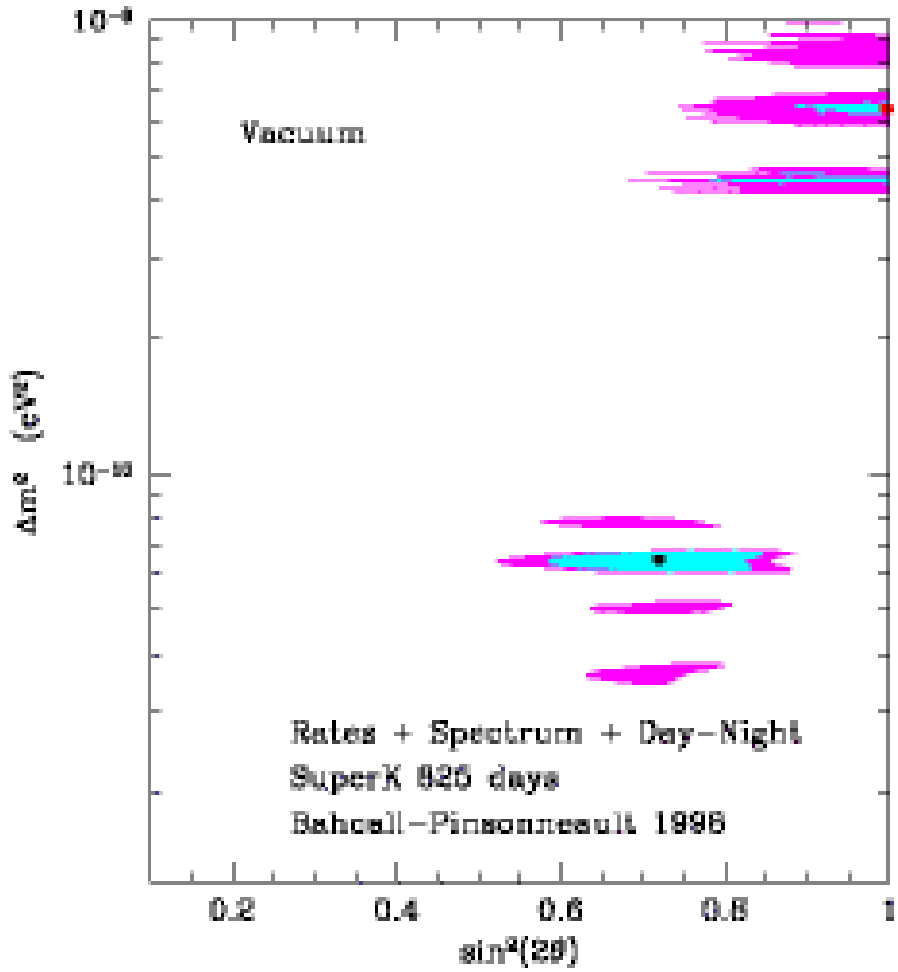


First Oscillation Evidence

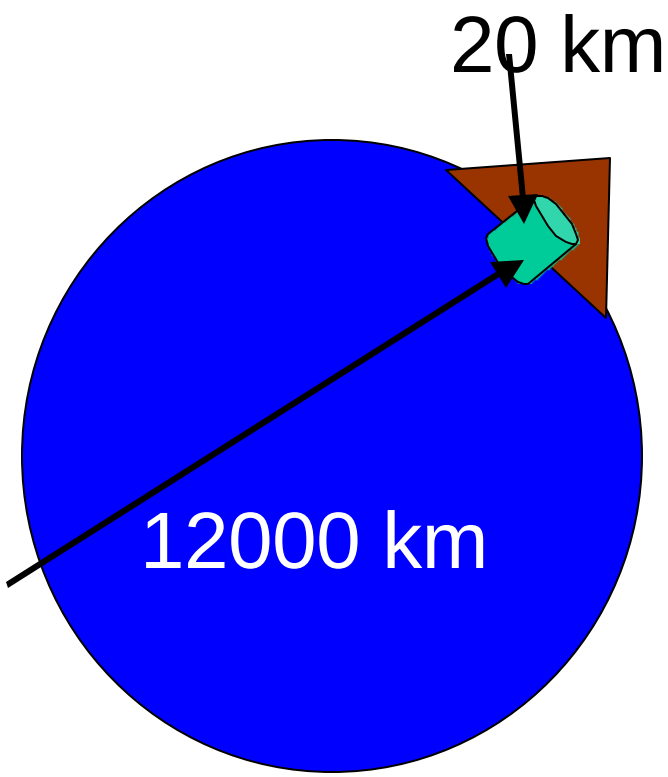
Setup	E	L	Δm^2 (eV^2)
Solar	3 MeV	1.5×10^{11} m	2×10^{-11} Best: ~5×10^{-5}
Atmospheric	500 MeV-1 GeV	20-12000 km	5×10^{-2} – 4×10^{-5} Best: ~3×10^{-3}
LSND	30 MeV	30 m	1

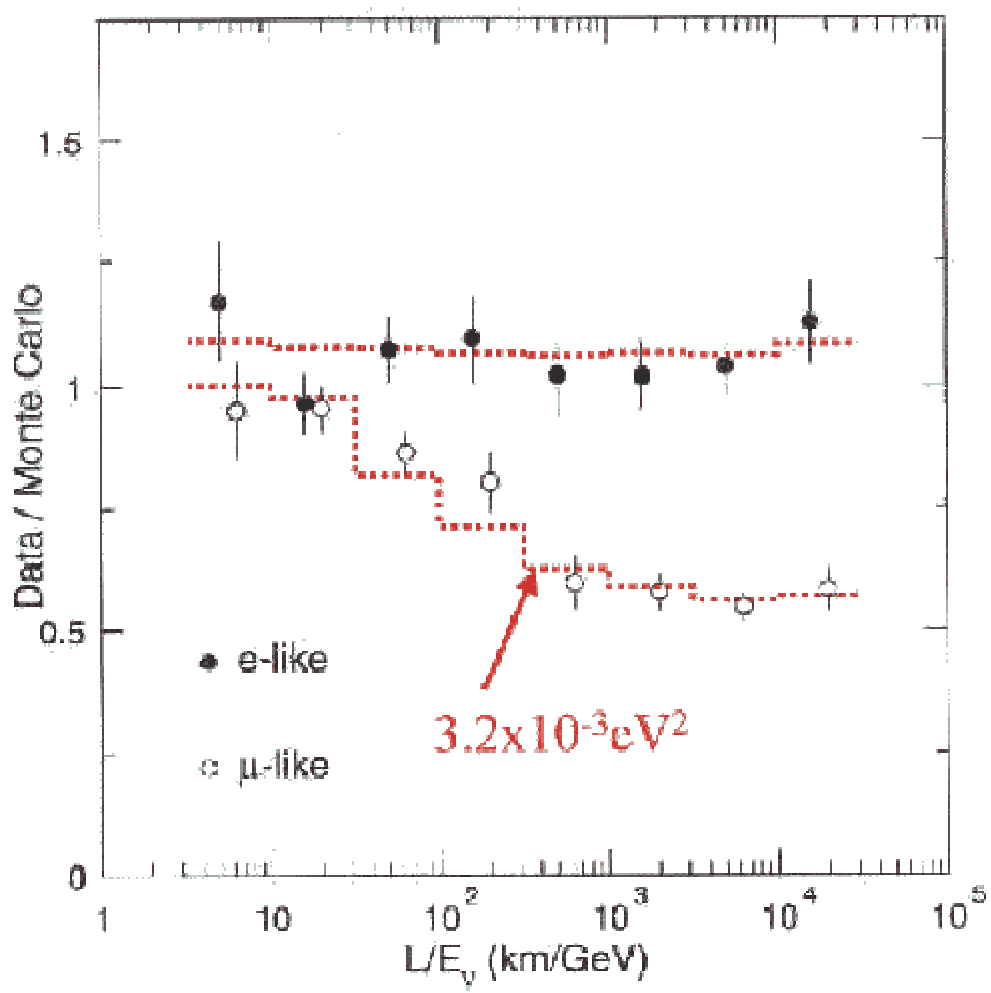
Solar neutrino oscillations



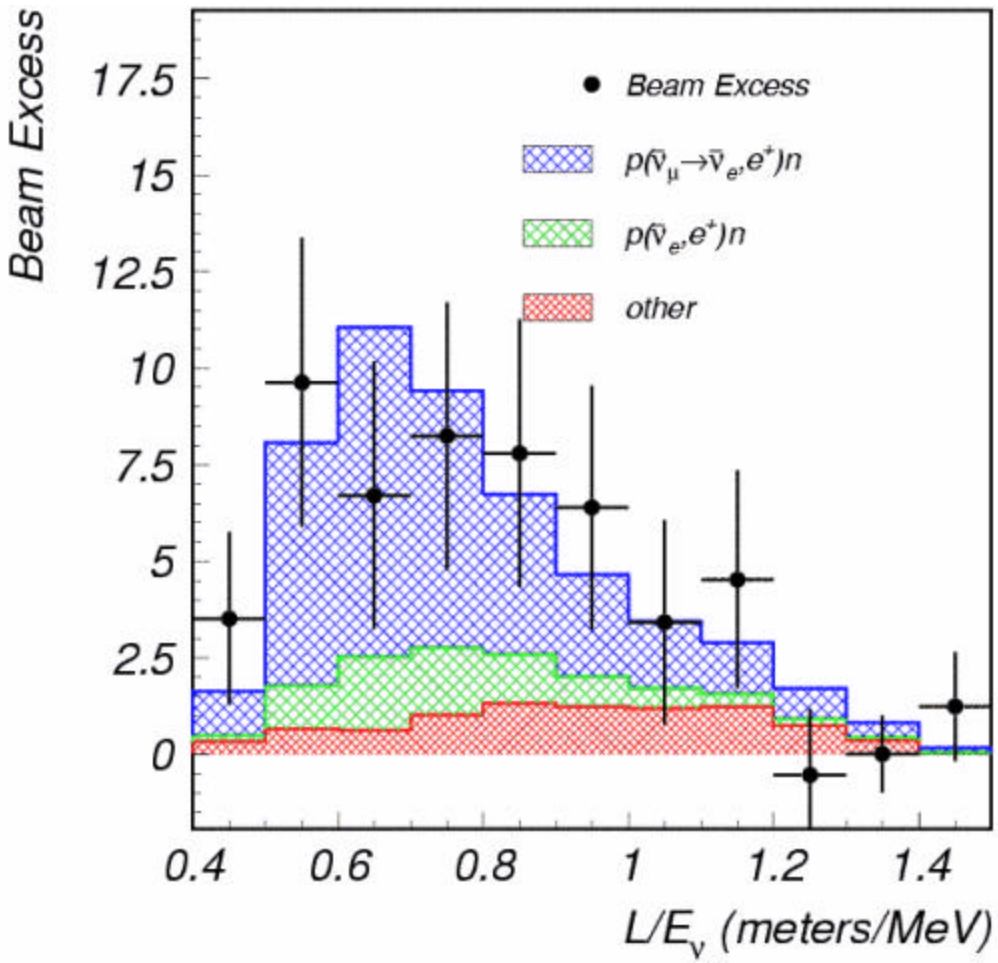


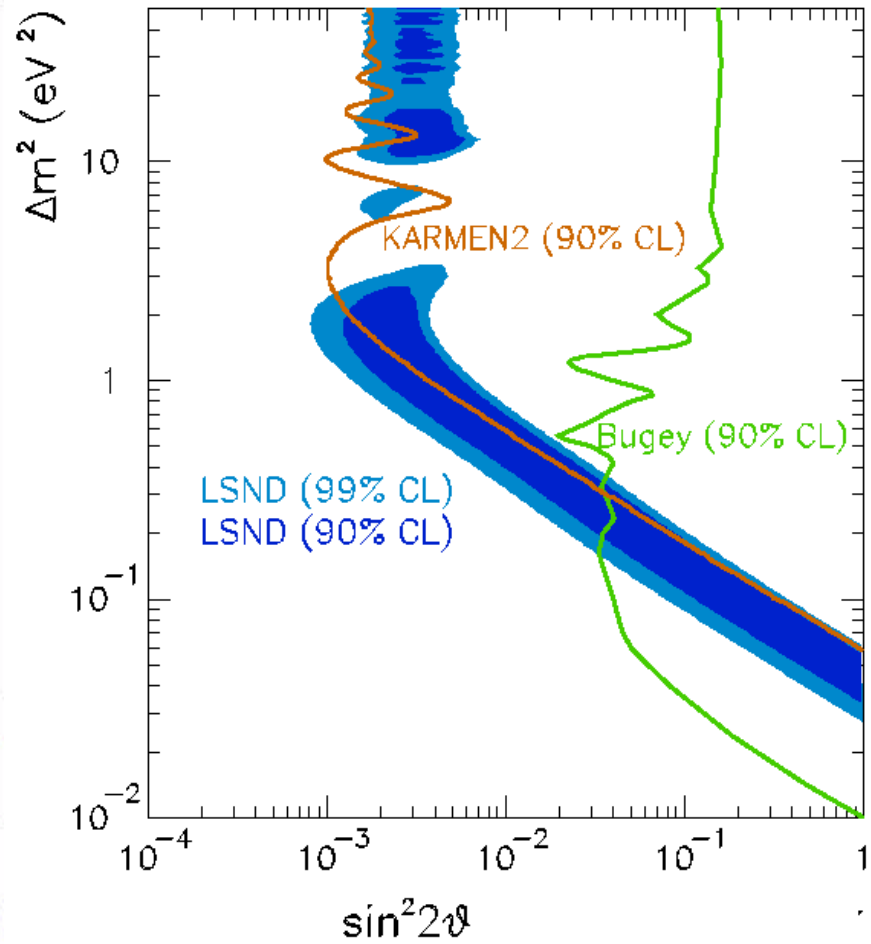
Atmospheric Neutrinos





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





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?

LEP Z^0 lineshape:

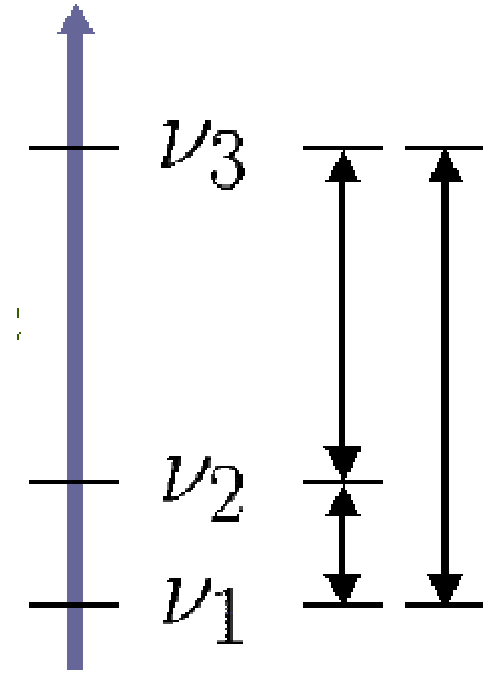
- $N_n = 2.994 + 0.012$

Solar neutrinos:

- $\Delta m^2 \approx 5\times10^{-5} eV^2$

Atmospheric neutrinos:

- $\Delta m^2 \approx 3\times10^{-3} eV^2$



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

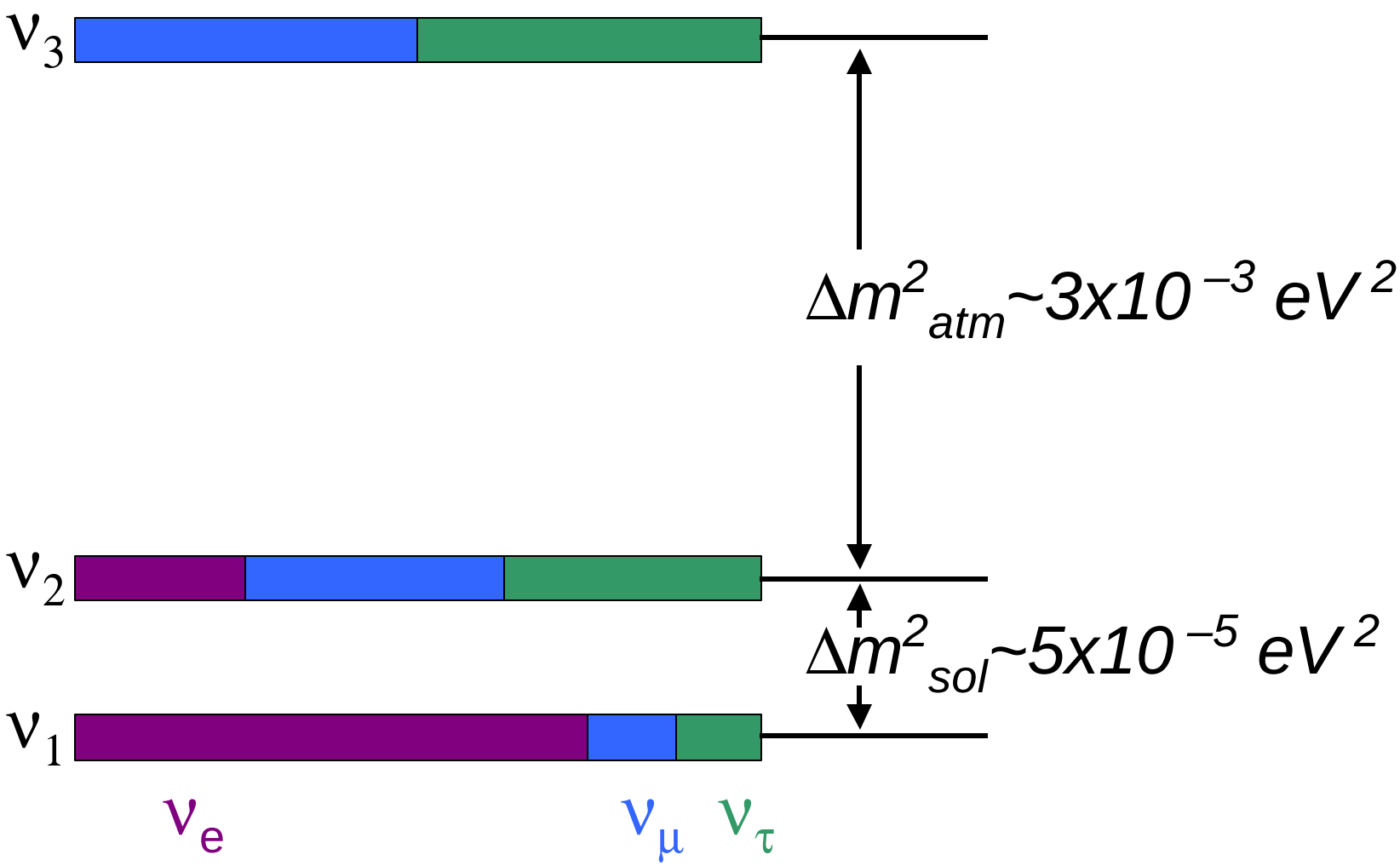
Where does LSND's Δm^2~0.2-10 eV^2 fit in this picture??

Oscillation Evidence

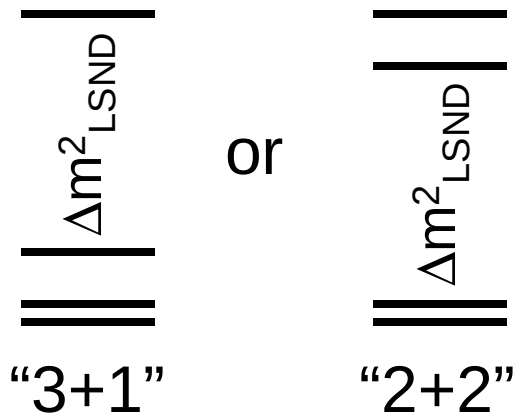
Evidence	Effect real?	Is it osc?	Δm^2 (eV^2)	Flavor
Solar: Homestake missing ν_e	Gallex,SAGE, K, Super-K SNO, (KamLAND)	SNO	5×10^{-5} (MSW)	$\nu_e \rightarrow \nu_\mu, \nu_\tau$ <13% ν_s ($\bar{\nu}_e \rightarrow ?$)
Atmospheric: Kamiokande missing ν_μ	Super-K, (K2K)	(Super-K)	3×10^{-3}	$\nu_\mu \rightarrow \nu_\tau$ <20% ν_e <25% ν_s
LSND: accelerator $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$		appear- ance	0.3-1	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Direct (kinematic) limits: $m(\nu_{e,\mu,\tau}) < 3$ eV, 0.2 MeV, 18 MeV
- WMAP: $\Sigma m_\nu < 0.7$ eV

Solar + atmospheric ⇨ a consistent picture

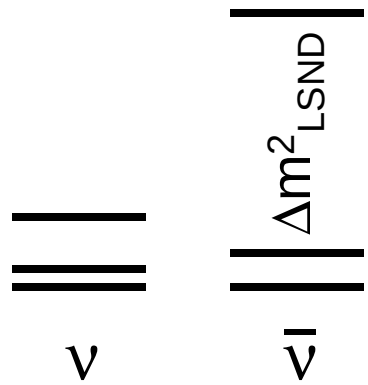


3 active + 1 sterile



- hard to make work
- limits on ν_s in solar and atmospheric: ~~2+2~~
- short-baseline exclusion on disappearance: ~~~3+1~~
- on to "3+2"?

CPT violation



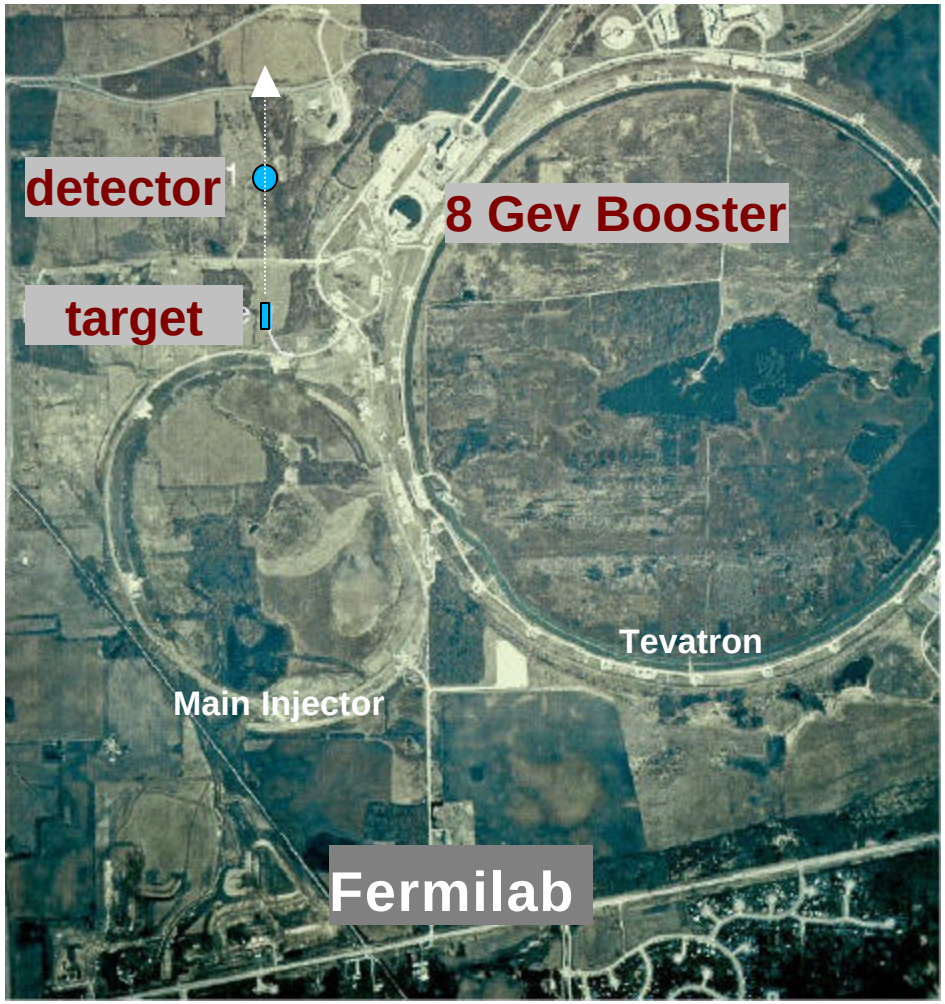
- level of ~~CPT~~ required is < K^0-$\bar{K}^0$ mass limit
- on the other hand, it *is* a theorem…
- incompatible with atmospheric?

Need to definitively check the LSND result.

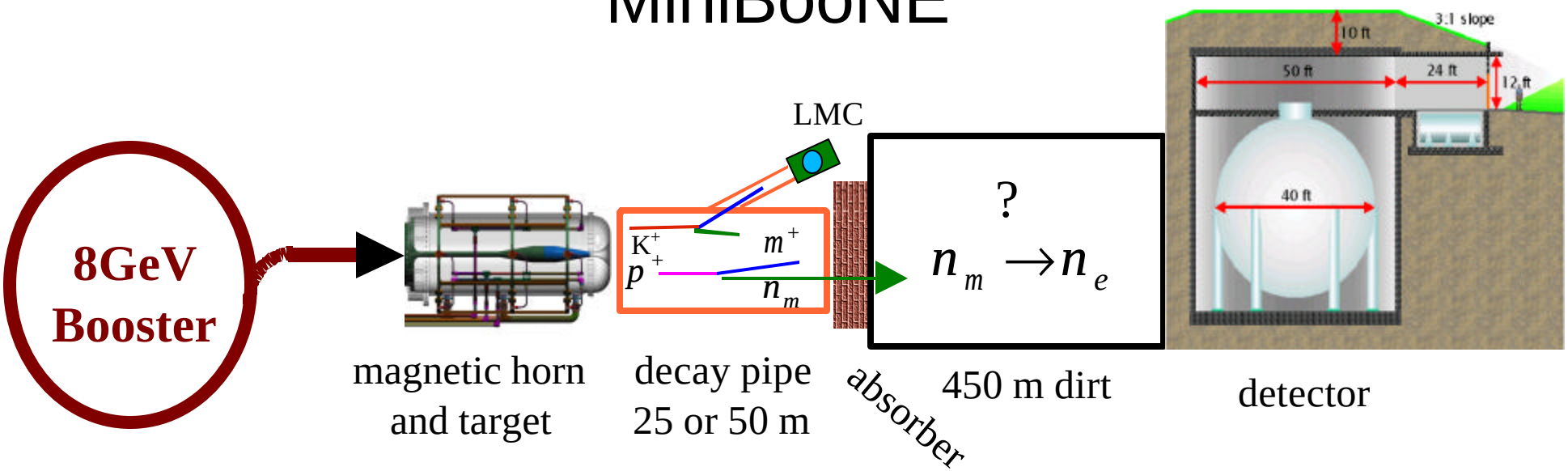
Goal: test LSND with 5-σ sensitivity over whole allowed range

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

MiniBooNE!



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

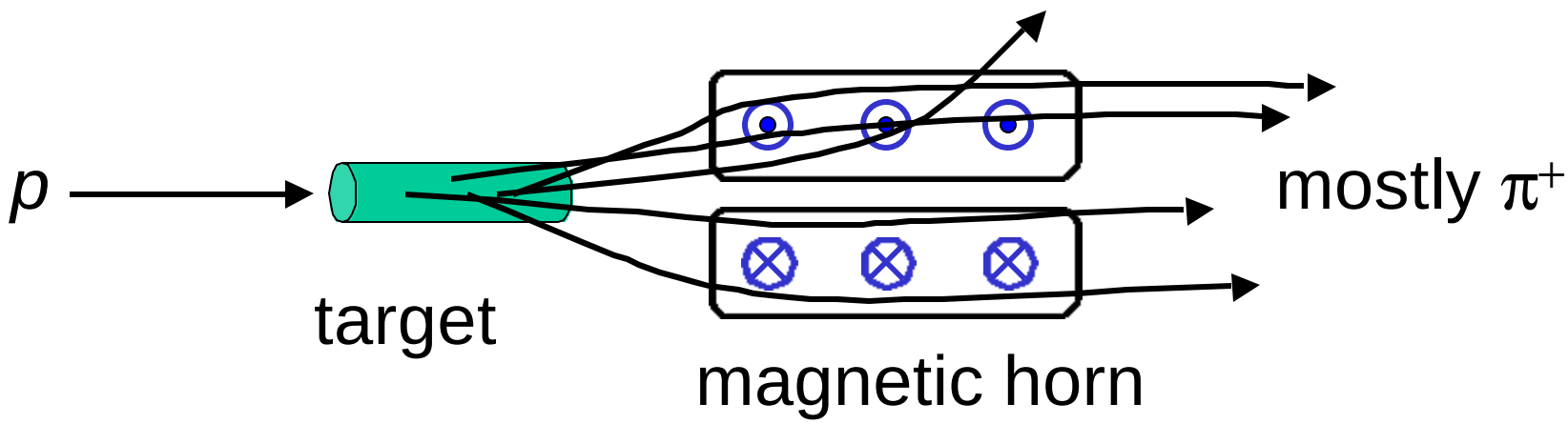
charged particles produce light

detected by phototube array

Look for electrons produced by mostly-ν_μ beam

Nature's gift: a flavor-selected ν beam

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



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

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

…the miracle of Helicity Suppression.

(discussion of loopholes coming…)

BooNE Flux in Round Numbers: Demand

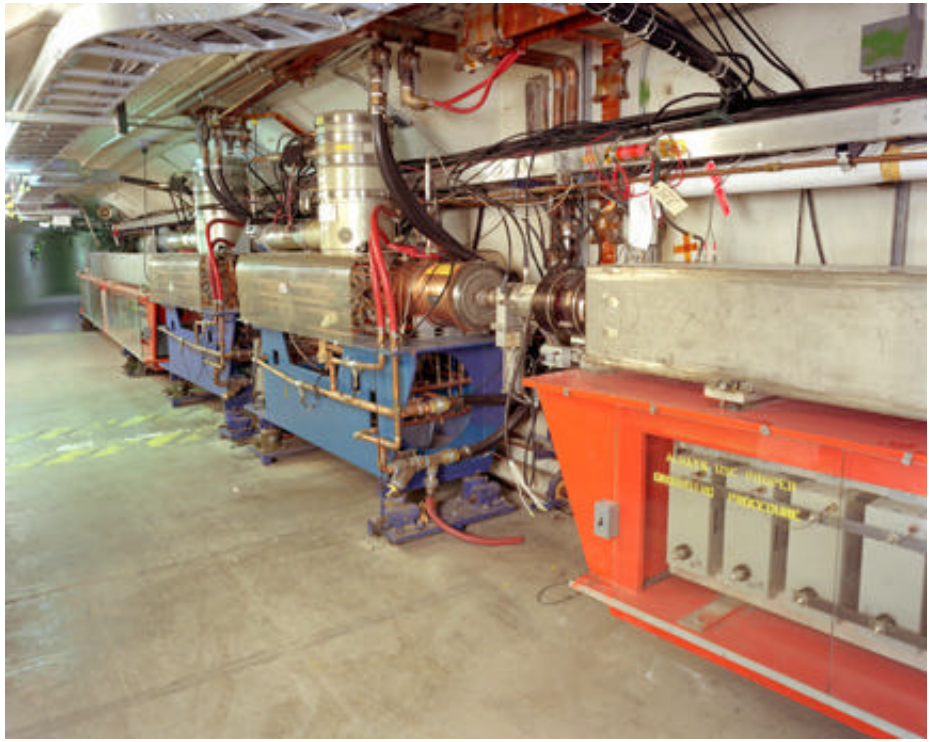
- Fiducial mass ~ 445 tons of CH_2
- $\sigma(\nu_\mu C \rightarrow \mu N) \sim \sigma(\nu_e C \rightarrow eN) \sim 4 \times 10^{-38}$ cm^2
- ν_μ flux ~ 10^{-9} ν_μ/ cm^2/p.o.t.
- LSND oscillation probability ~ 0.002

$(5\text{-}10) \times 10^{20}$ p.o.t. ⇒ 500,000 $\nu_\mu C \rightarrow \mu N$

1,000 $\nu_e C \rightarrow eN$

(osc signal if LSND)

BooNE Flux in Round Numbers: Supply



Fermilab Booster

- 8-GeV protons
- ~7 Hz (5 Hz to BooNE)
- 5×10^{12} p/pulse

$$\frac{(5\text{-}10)\times 10^{20}\ \text{p.o.t.}}{5\ \text{pulse/s} \times 5\times 10^{12}\ \text{p/pulse}} = (2\text{-}4)\times 10^{7}\ \text{s} \sim 1\ \text{year}$$

but…

Booster Limitations

- Actually a 15-Hz machine, but some components limited to lower rates.

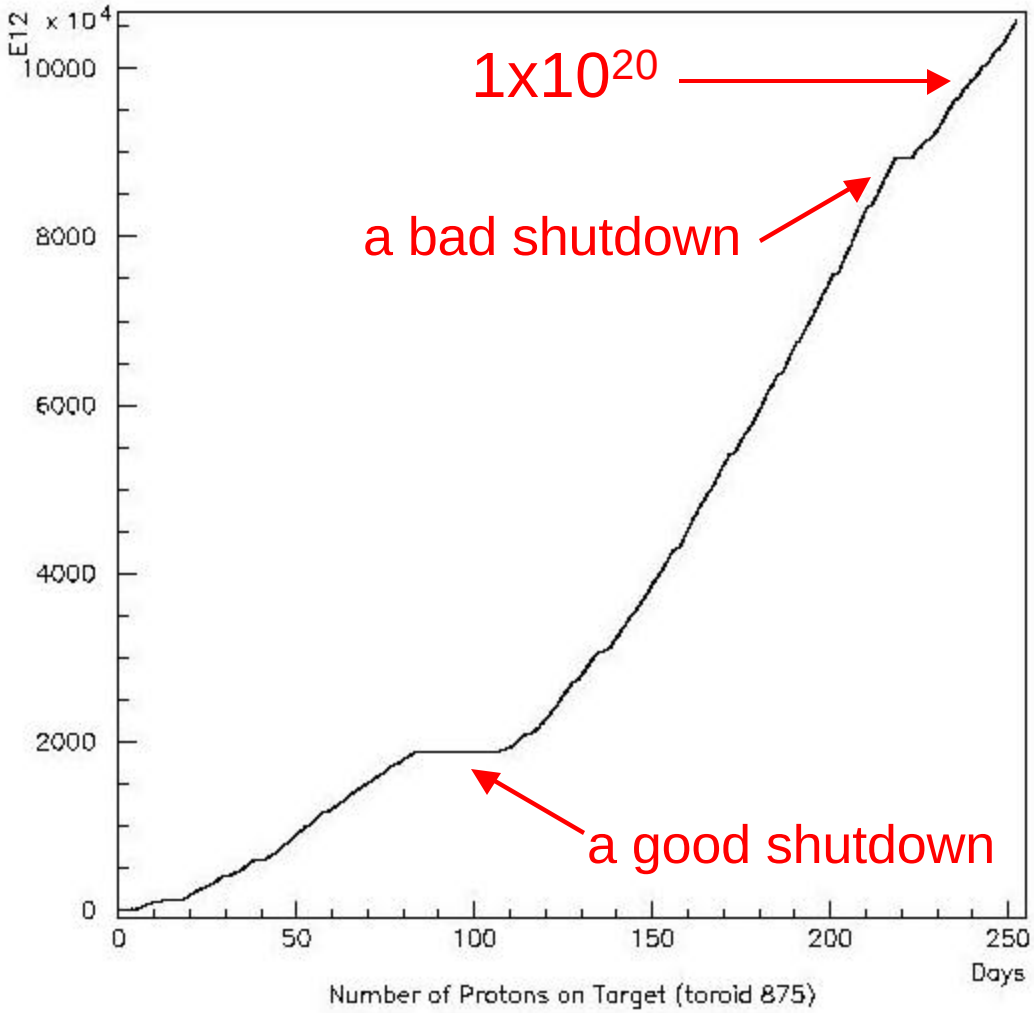
  All upgraded to at least 7 Hz.
- Radiation limits *integrated* flux (protons/hour).
  - Booster is lossy, and we are pushing it *hard*
  - External (offices and people)

    Shielding upgrade before run
  - Internal (Booster itself)
    - Current optimum: 4×10^{12} ppp, 2-3 Hz

      A factor of ~2-3 short – it <u>was</u> ~20

      To full intensity after August shutdown?
- A long, hard road – necessary for whole program.

As of July 4


E12 x 10^4
10000
8000
6000
4000
2000
0
0
50
100
150
200
250
Days
Number of Protons on Target (toroid 875)
1x10^20
a bad shutdown
a good shutdown

LSND:

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

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

$e^+ n \longrightarrow$ capture on $p \longrightarrow$ 2.2 MeV γ

$e^+ n \longrightarrow E_e$~40 MeV

Most backgrounds have accidental neutron or low-E γ

BooNE:

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

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

$e^- p \longrightarrow E_e$~300 MeV

Backgrounds: beam ν_e

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

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

Intrinsic beam background

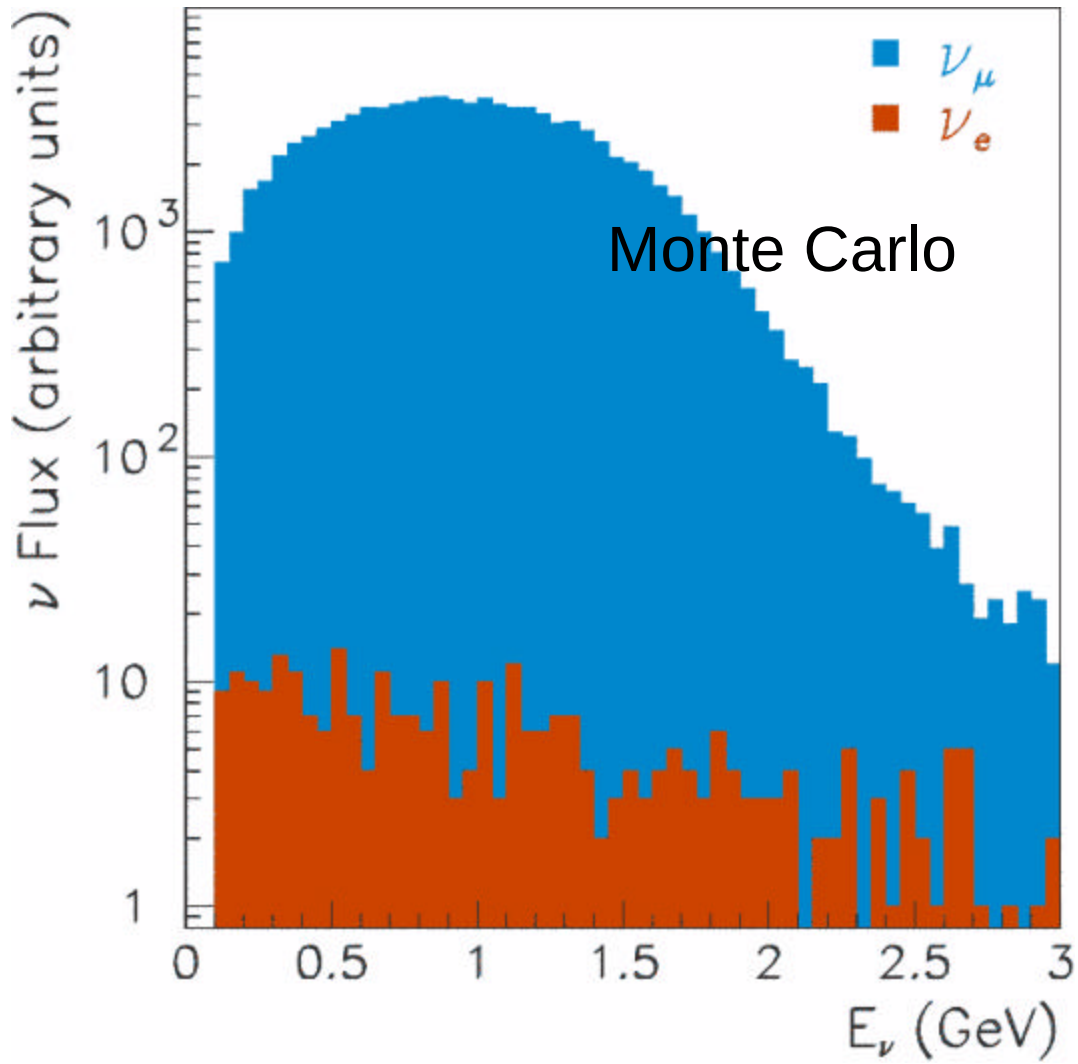
$\pi^+ \rightarrow \mu^+ \nu_\mu$

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

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

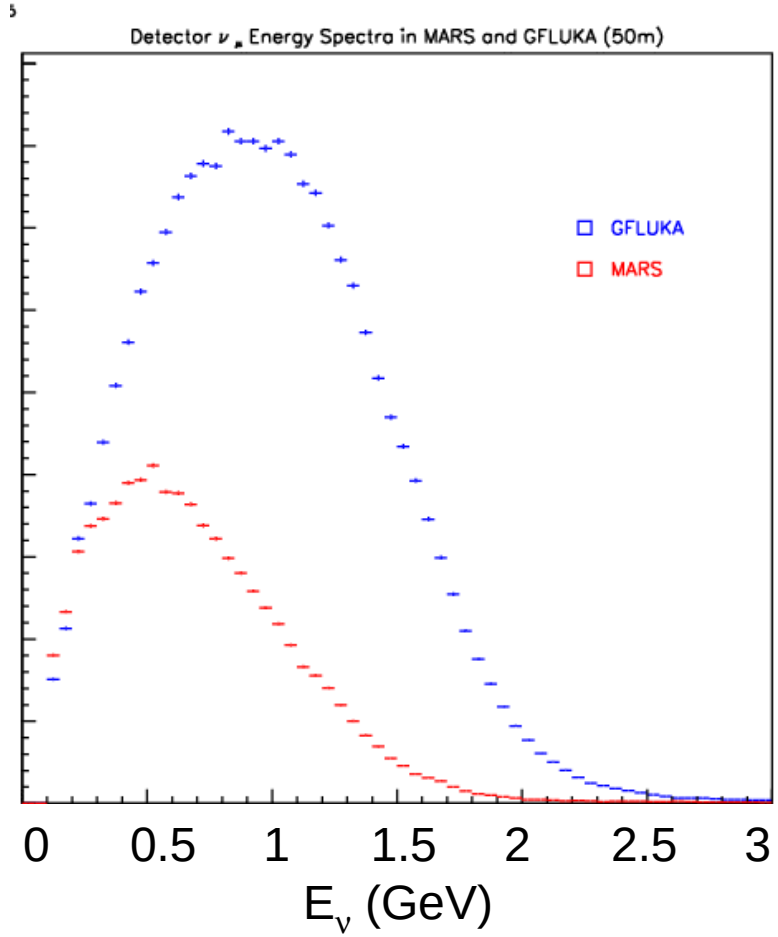
$K_L \rightarrow \pi^- e^+ \nu_e$

Not bad, but comparable to level of LSND signal



Beam background tactics

- Events identical to signal
- Can't just Monte Carlo



We must *measure* them:

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

- ν_μ spectrum
- change absorber

$K^+, K_L \rightarrow \nu_e$

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

All

- HARP (CERN experiment)

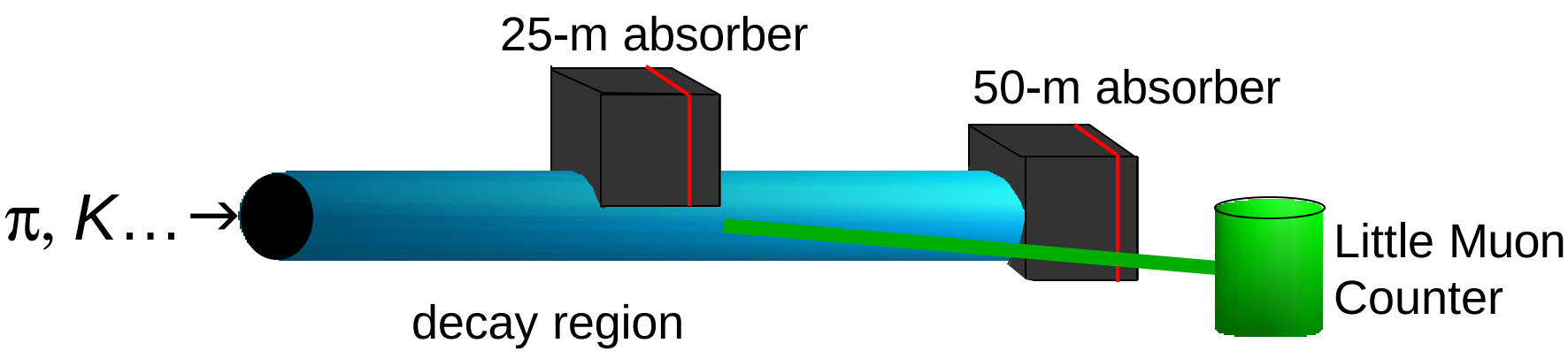
Beam background tactics

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

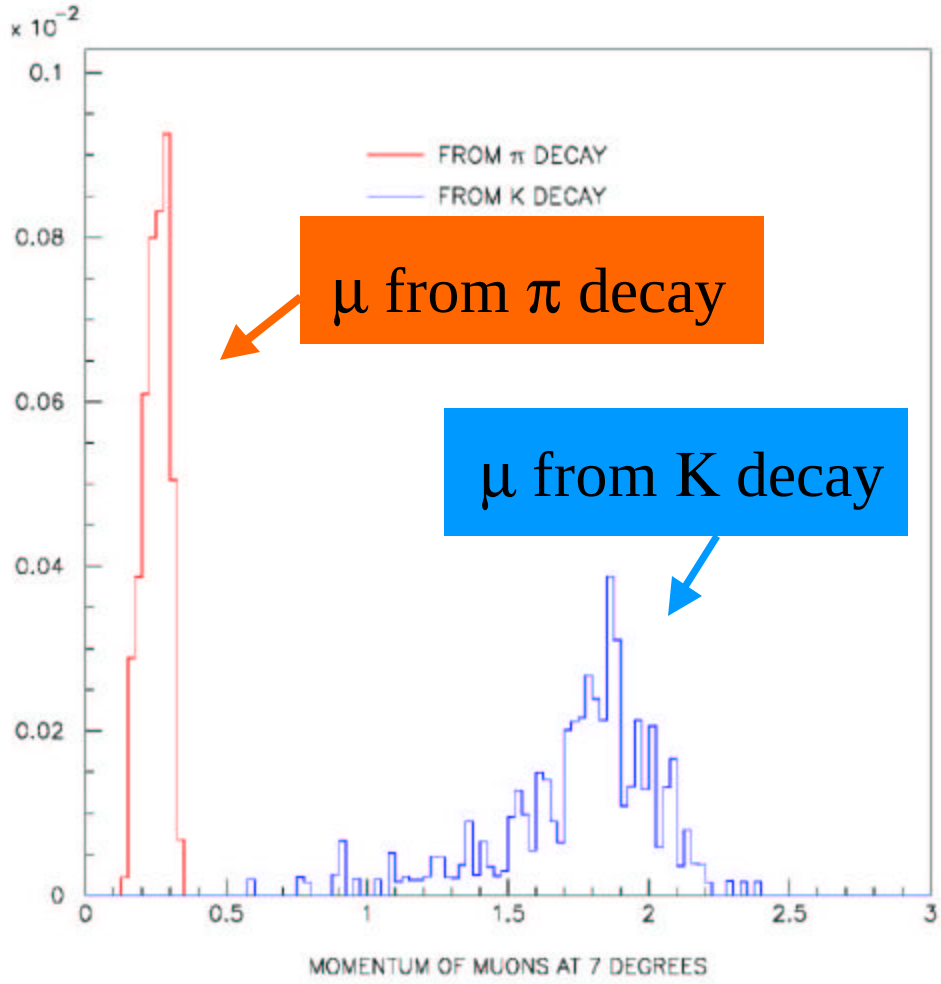
- ν_μ quasi-elastic: E_μ, $\theta_\mu \rightarrow E_\nu$
  forward π decay: $E_\nu \rightarrow E_\pi$ } π spectrum from data; the rest easy
- change to 25-m absorber:
  signal x ½; background x ¼

K^+, $K_L \rightarrow \nu_e$

- "Little muon counter"

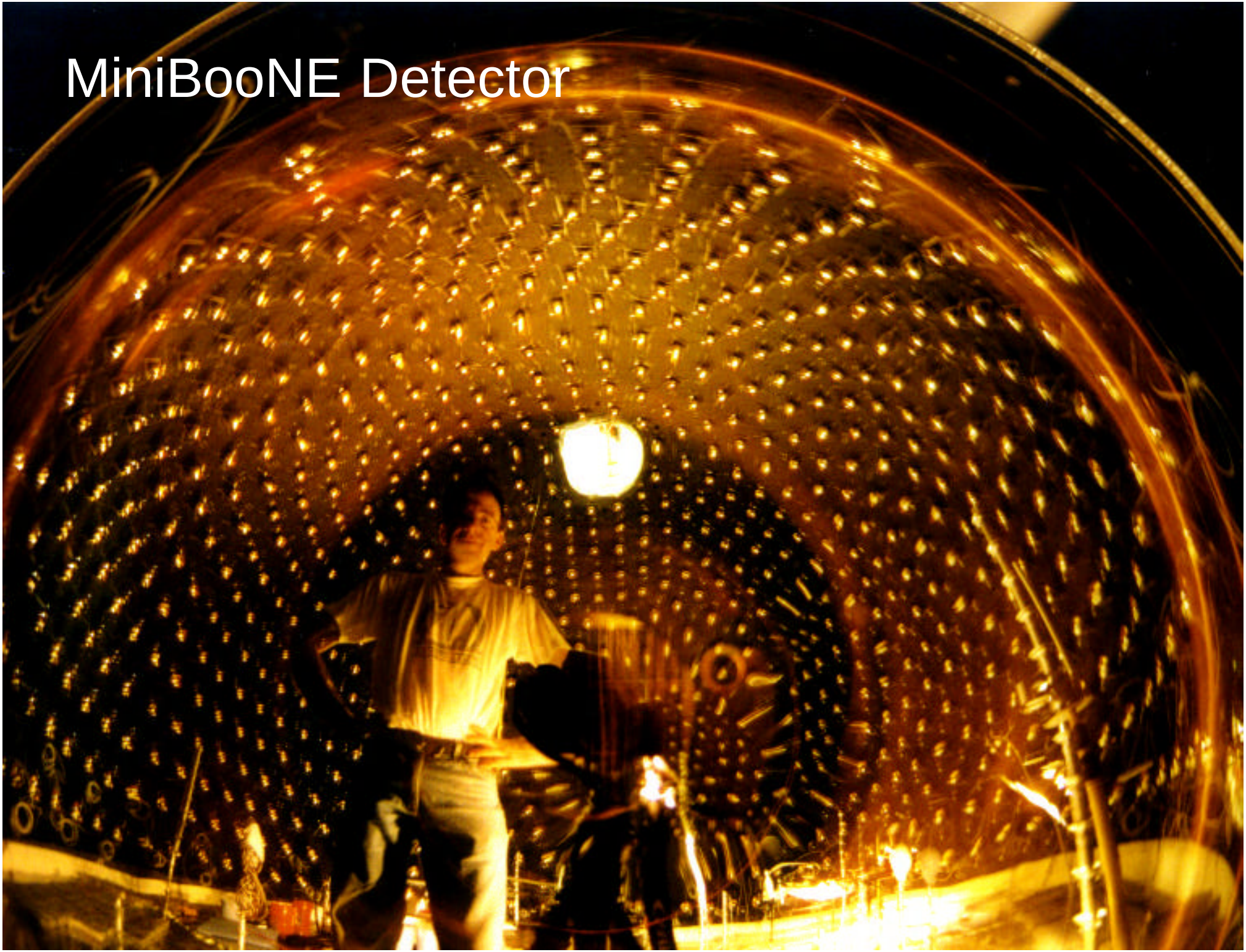


Beam background tactics: LMC



muon momentum at 7 degrees

MiniBooNE Detector



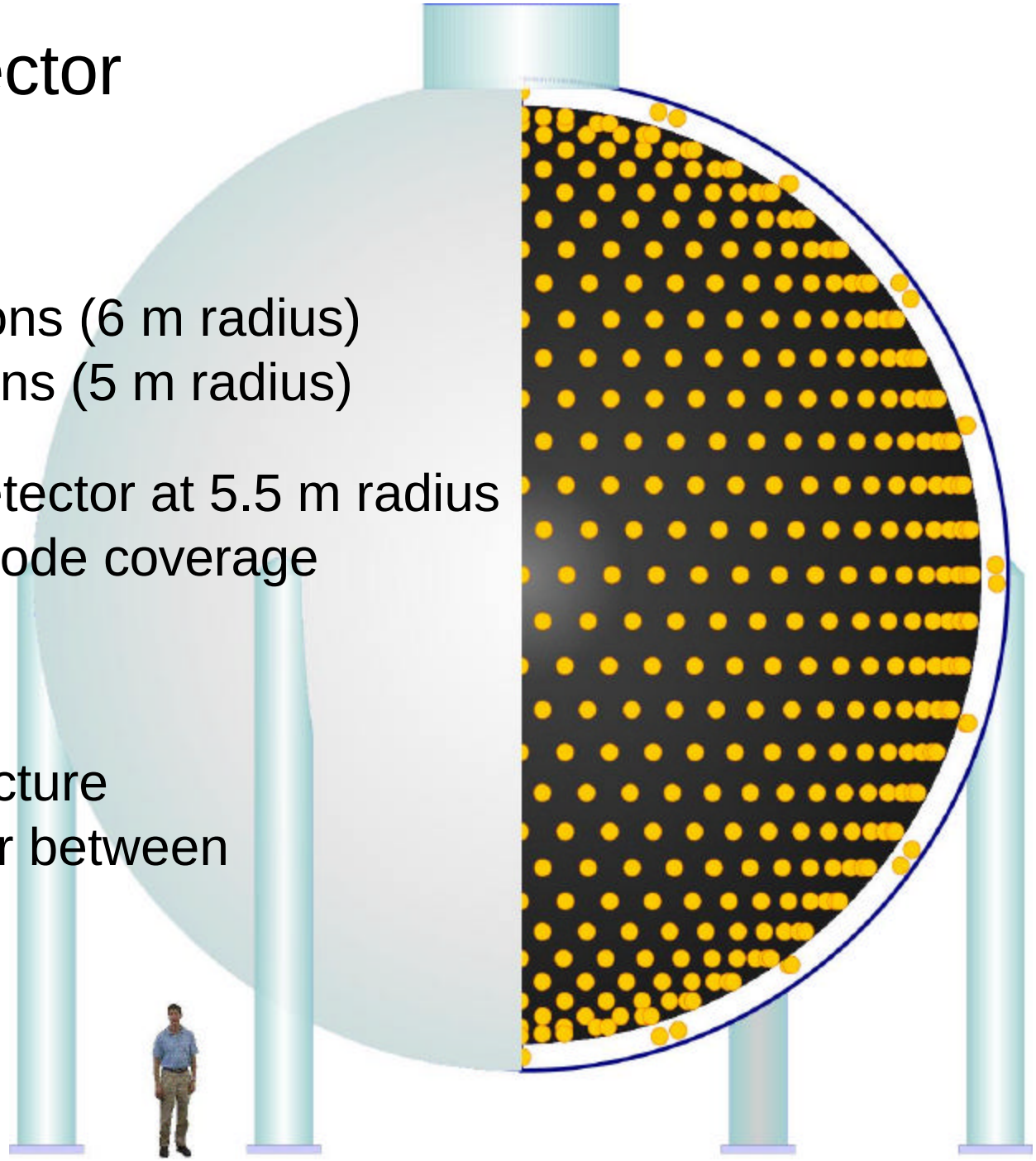
MiniBooNE detector

pure mineral oil

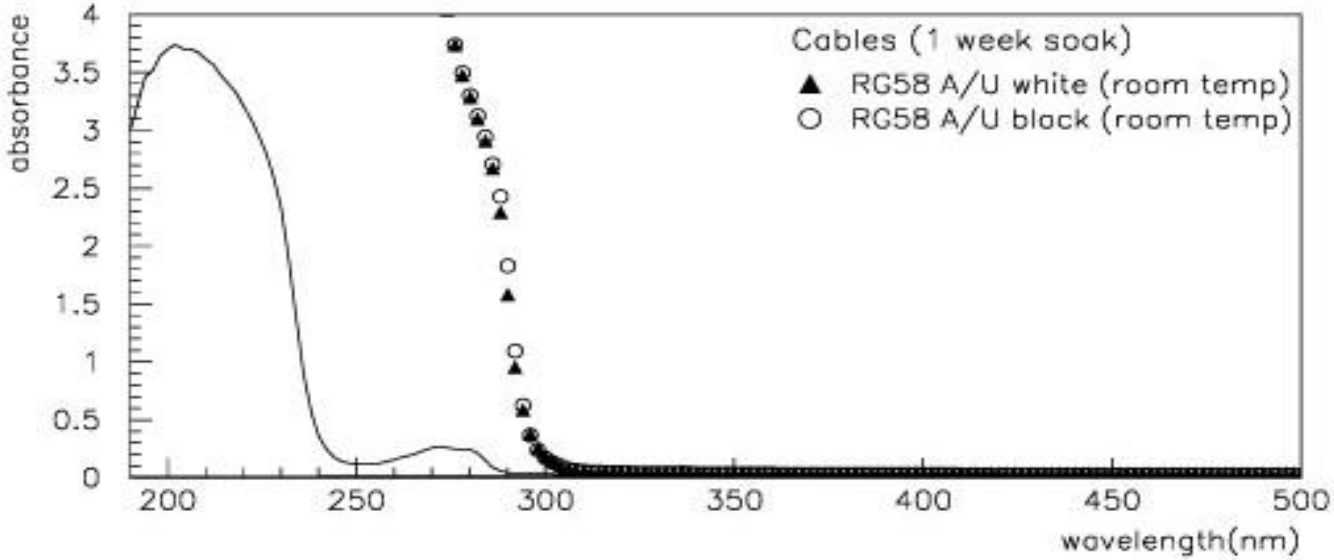
total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5 m radius)

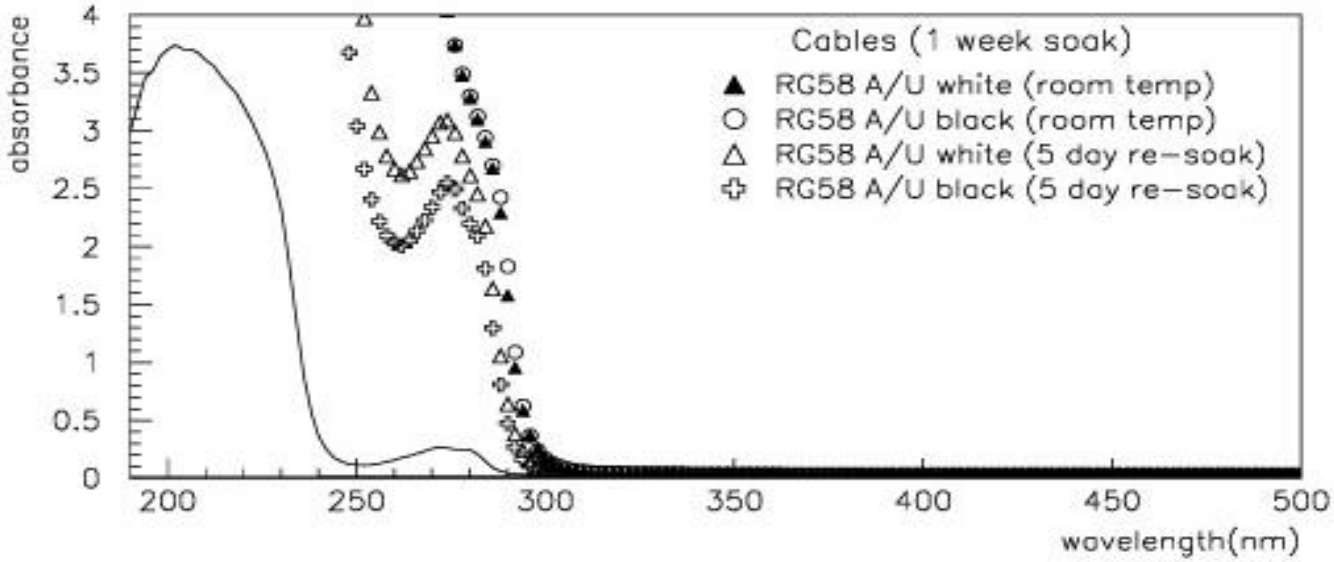
1280 20-cm PMTs in detector at 5.5 m radius
10% photocathode coverage
240 PMTs in veto

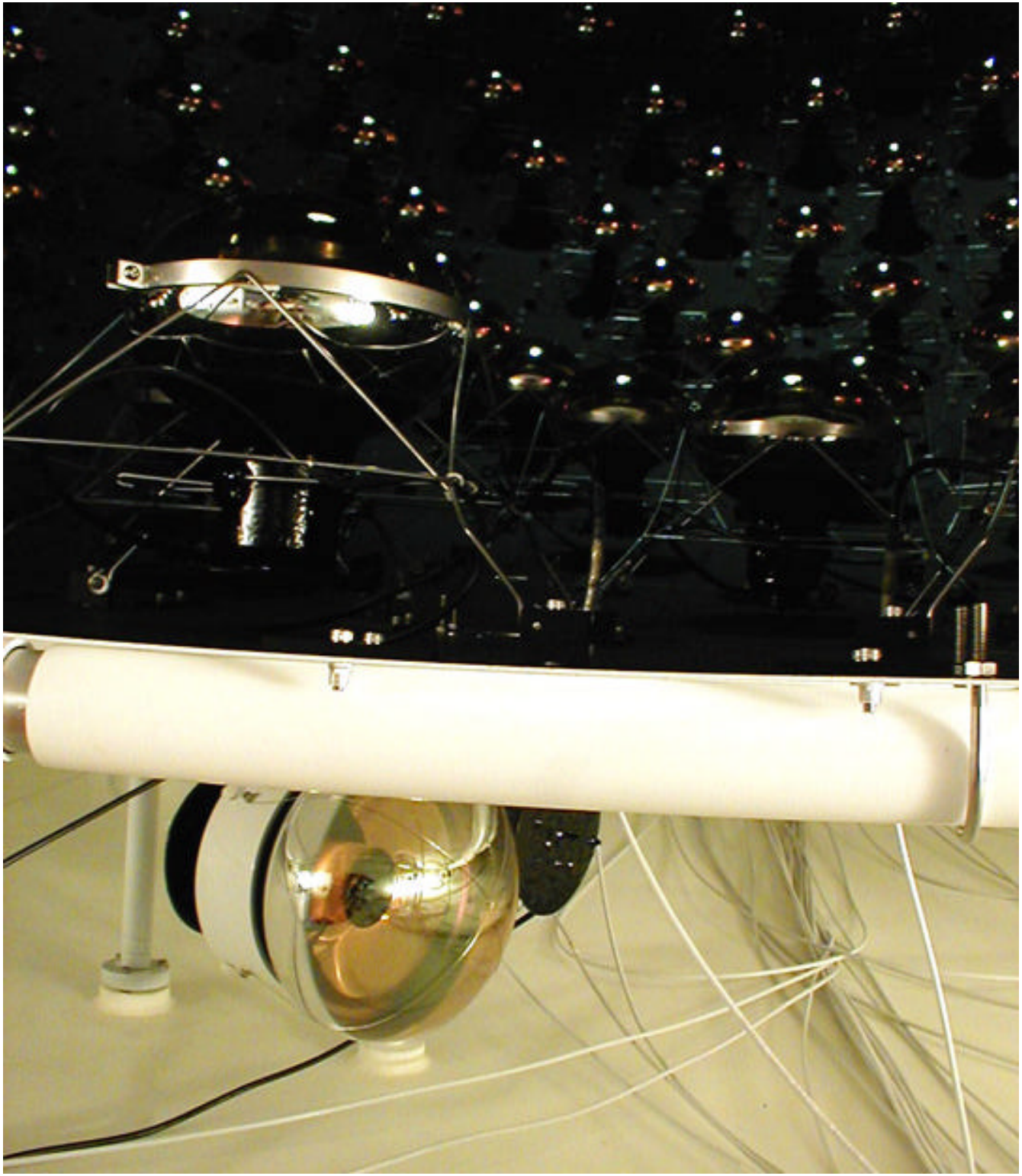
Phototube support structure
provides opaque barrier between
veto and main volumes

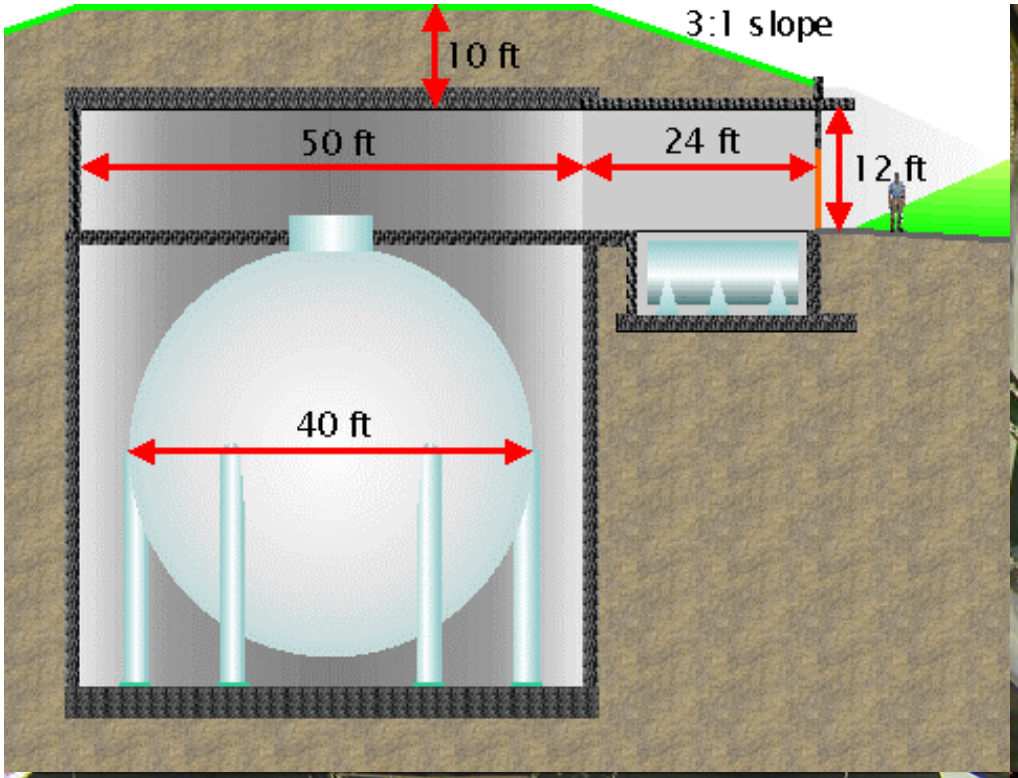


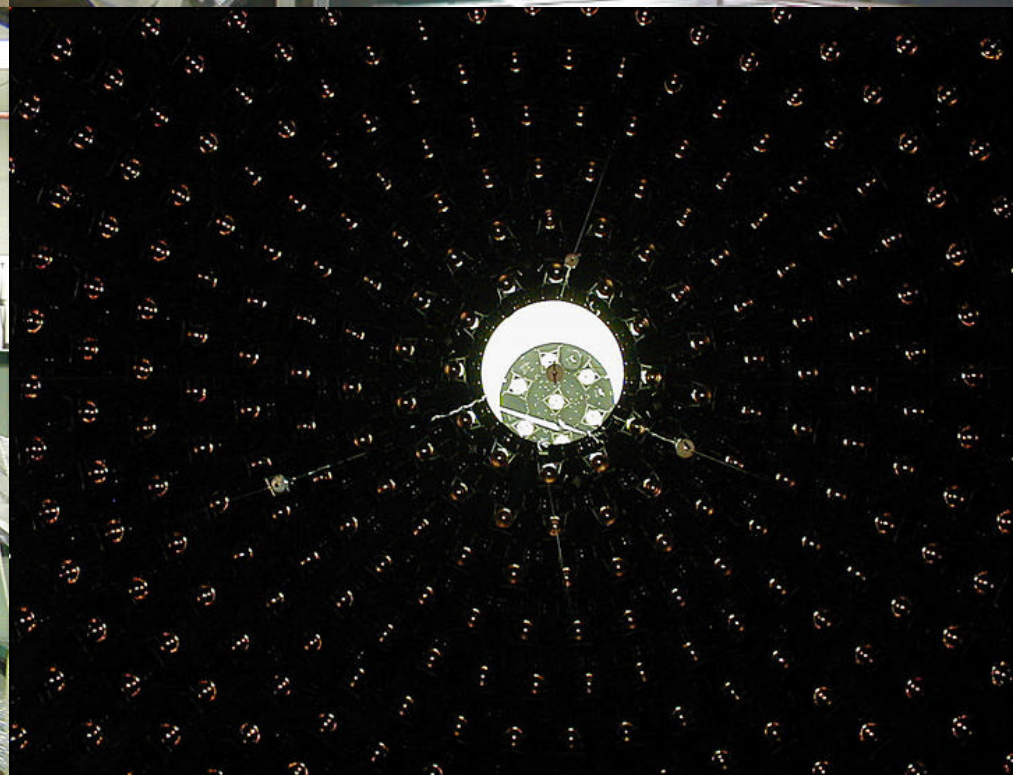
Oil-compatibility studies

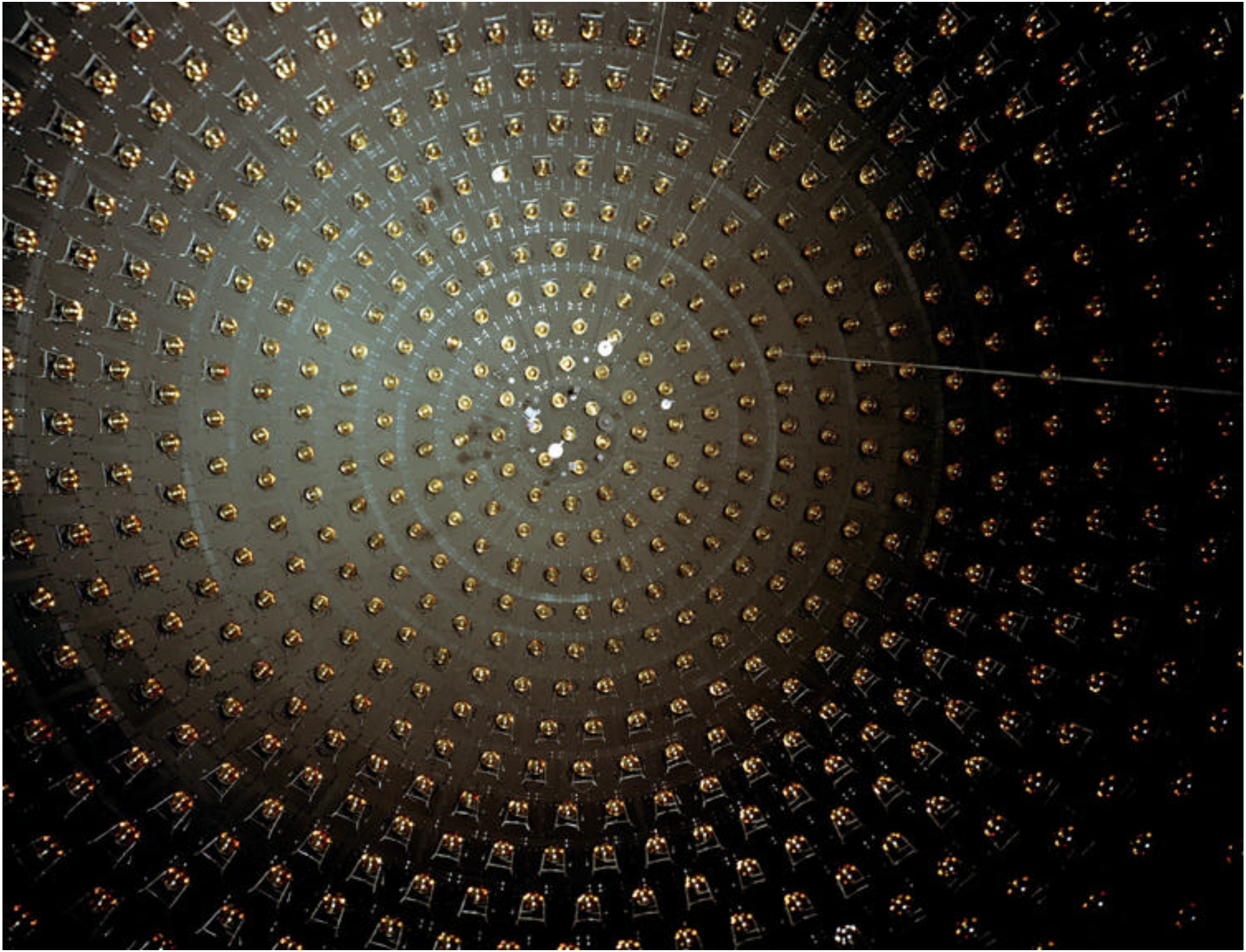







3:1 slope
10 ft
50 ft
24 ft
12 ft
40 ft





Detection and Reconstruction of Events

Charged particles in the mineral oil emit

Cherenkov radiation

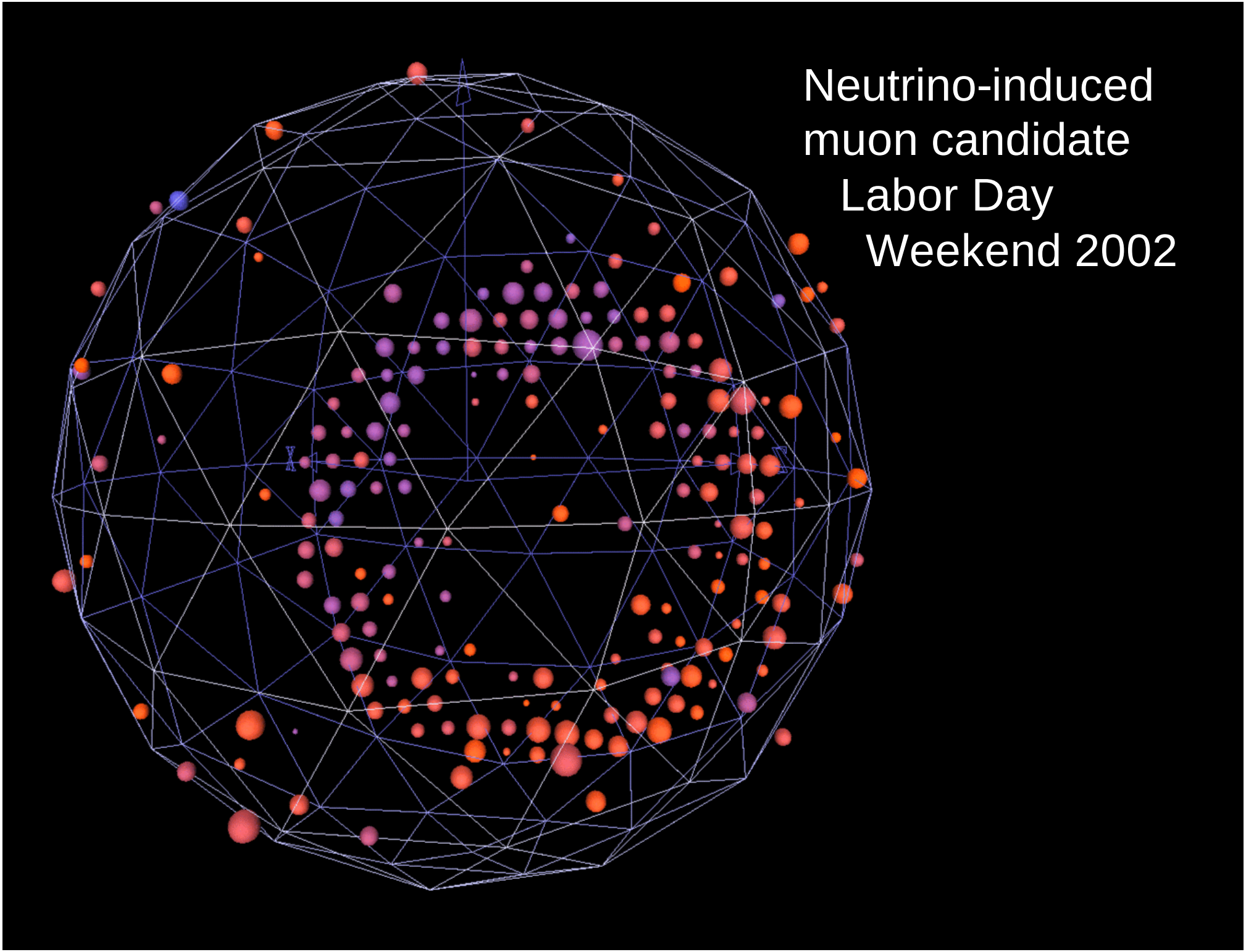
- prompt
- in cone (θ_c=47.4^o for β~1)
- ~ path above threshold

Scintillation light

- emission time constant ~ 18 ns
- isotropic
- ~ kinetic energy

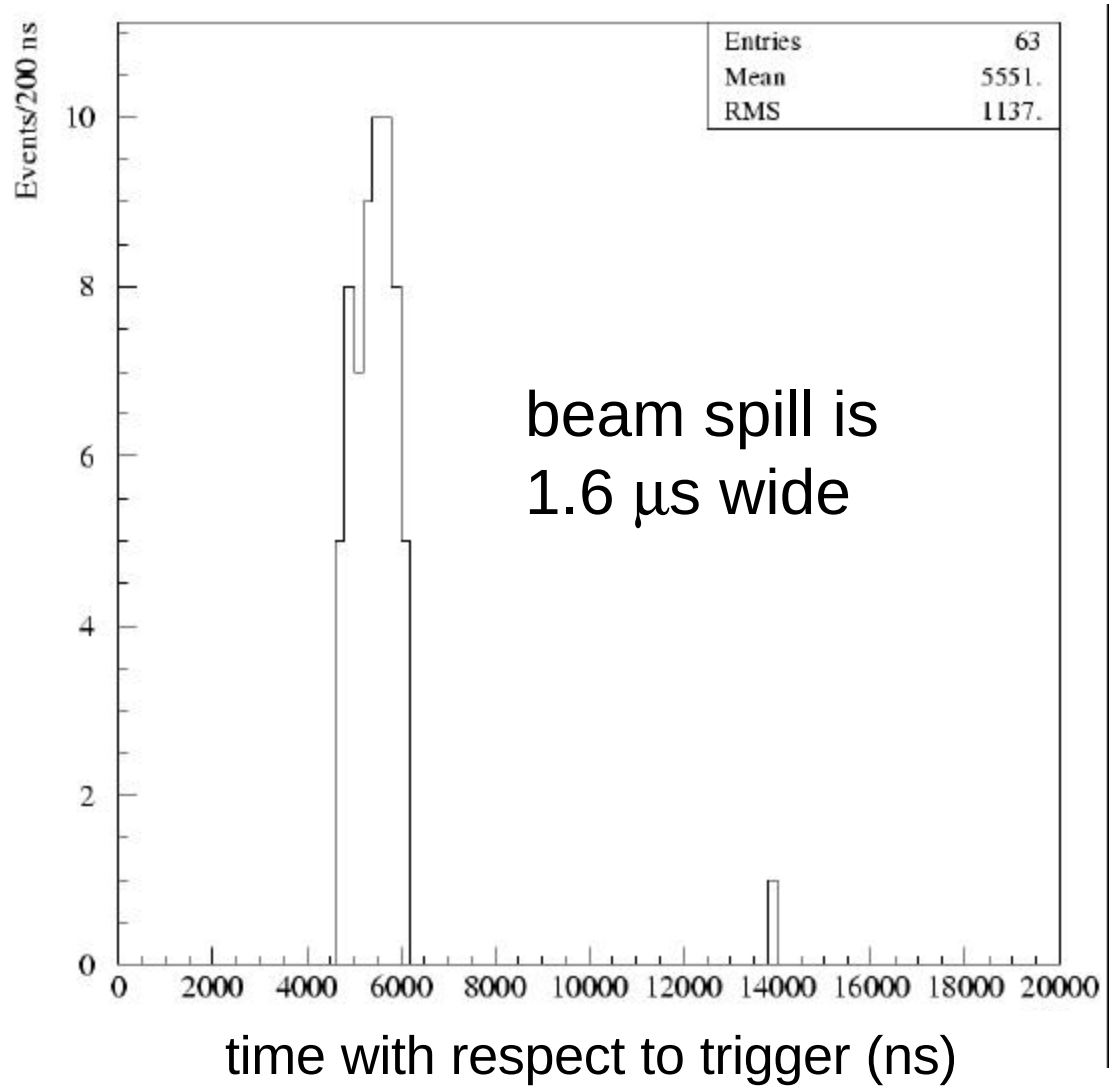
particle ID

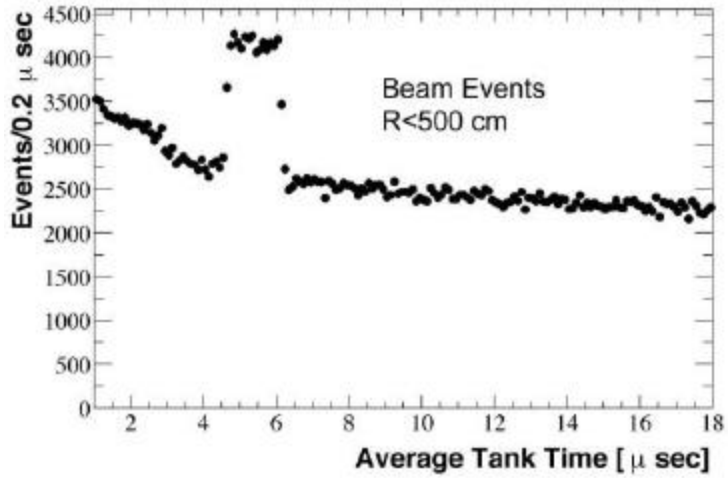
In pure mineral oil, Cherenk:scint ~ 4:1

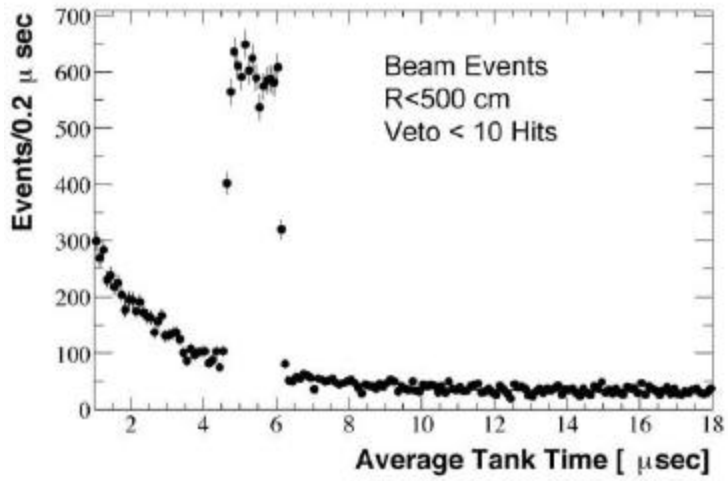

Neutrino-induced
muon candidate
Labor Day
Weekend 2002

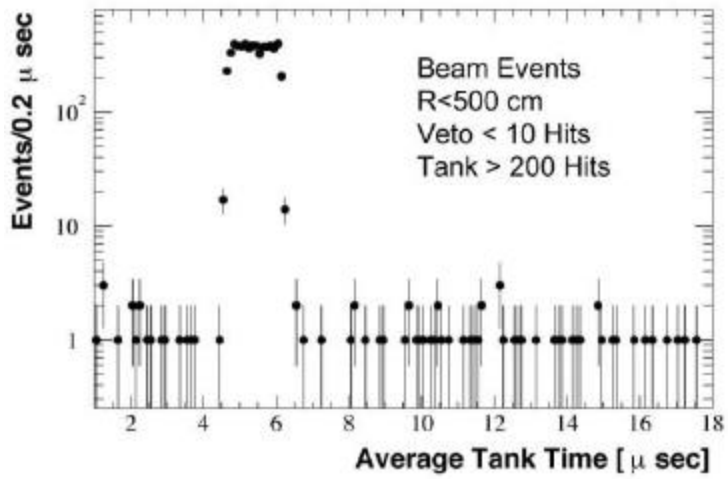
How do we know?

63 events over
Labor Day Weekend
with:
< 6 veto tubes hit
> 200 tank tubes hit

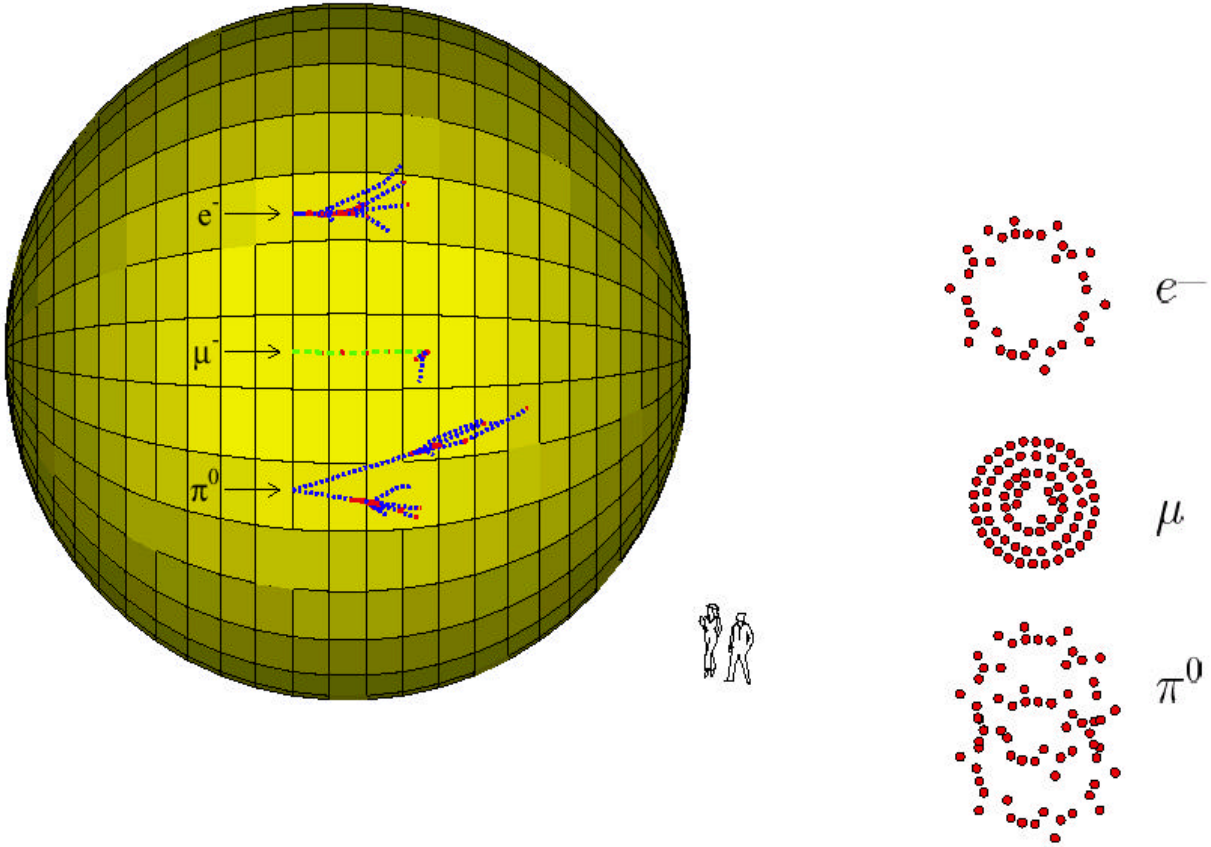


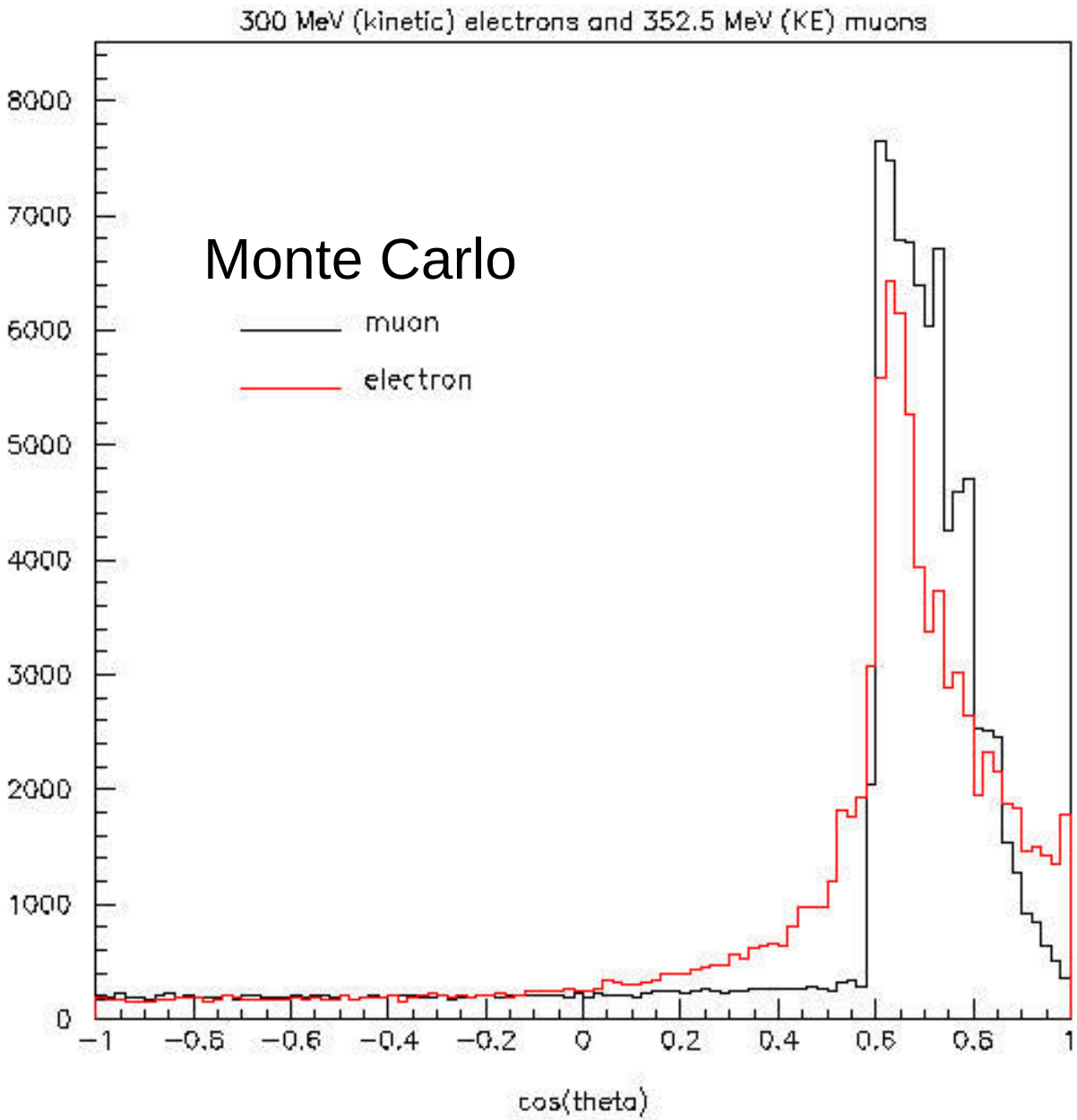

Beam Events
R<500 cm
Events/0.2 μ sec
Average Tank Time [μ sec]


Beam Events
R<500 cm
Veto < 10 Hits
Events/0.2 μ sec
Average Tank Time [μsec]


Beam Events
R<500 cm
Veto < 10 Hits
Tank > 200 Hits
Events/0.2 μ sec
Average Tank Time [μ sec]

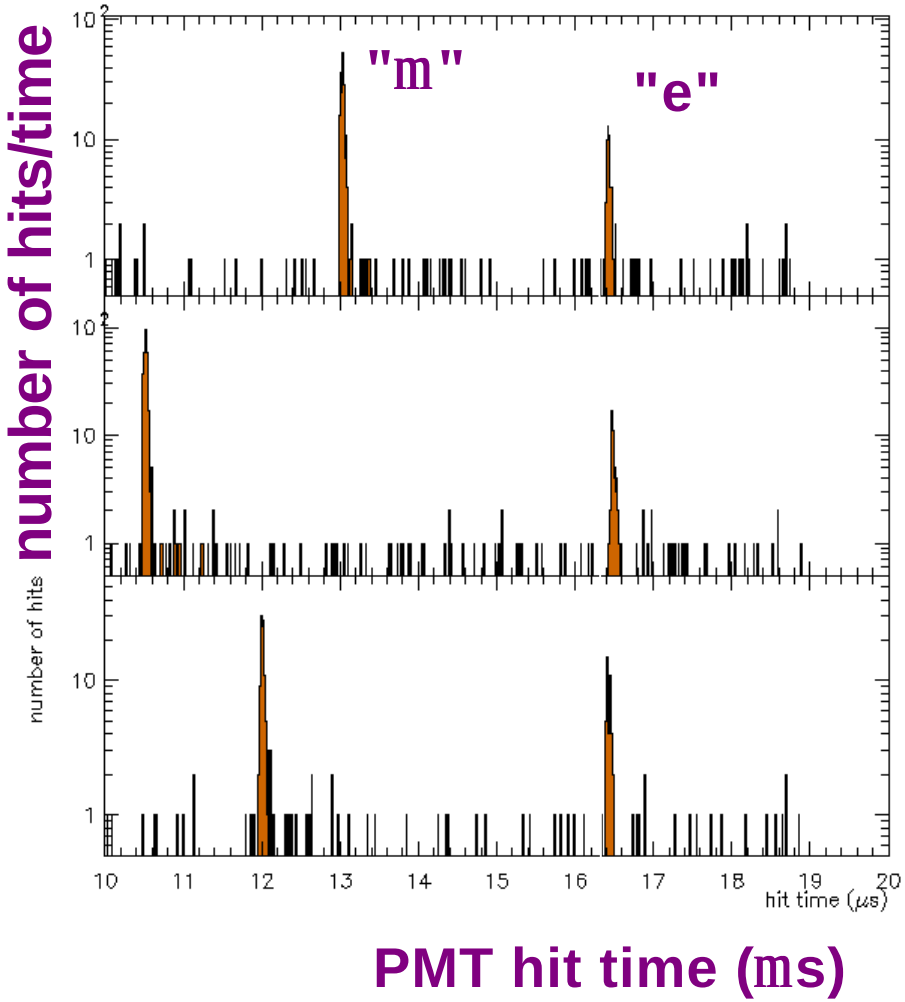
Pattern of hit tubes (with charge and time information) allows reconstruction of track location and direction and the separation of different event types.

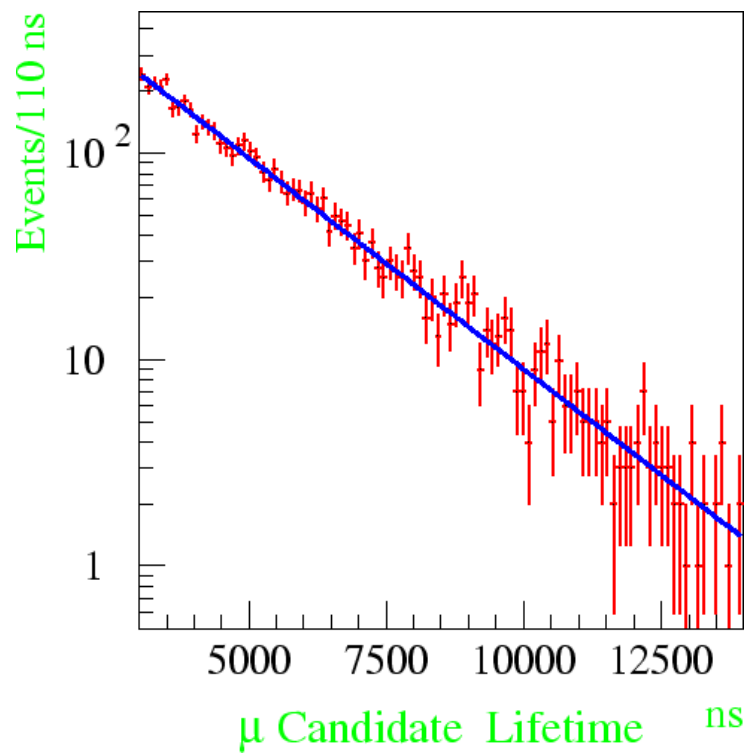



300 MeV (kinetic) electrons and 352.5 MeV (KE) muons
Monte Carlo
muon
electron
8000
7000
6000
5000
4000
3000
2000
1000
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
cos(theta)

Muon Decays

hit times for 3 "Michel" decays
in cosmic-ray events



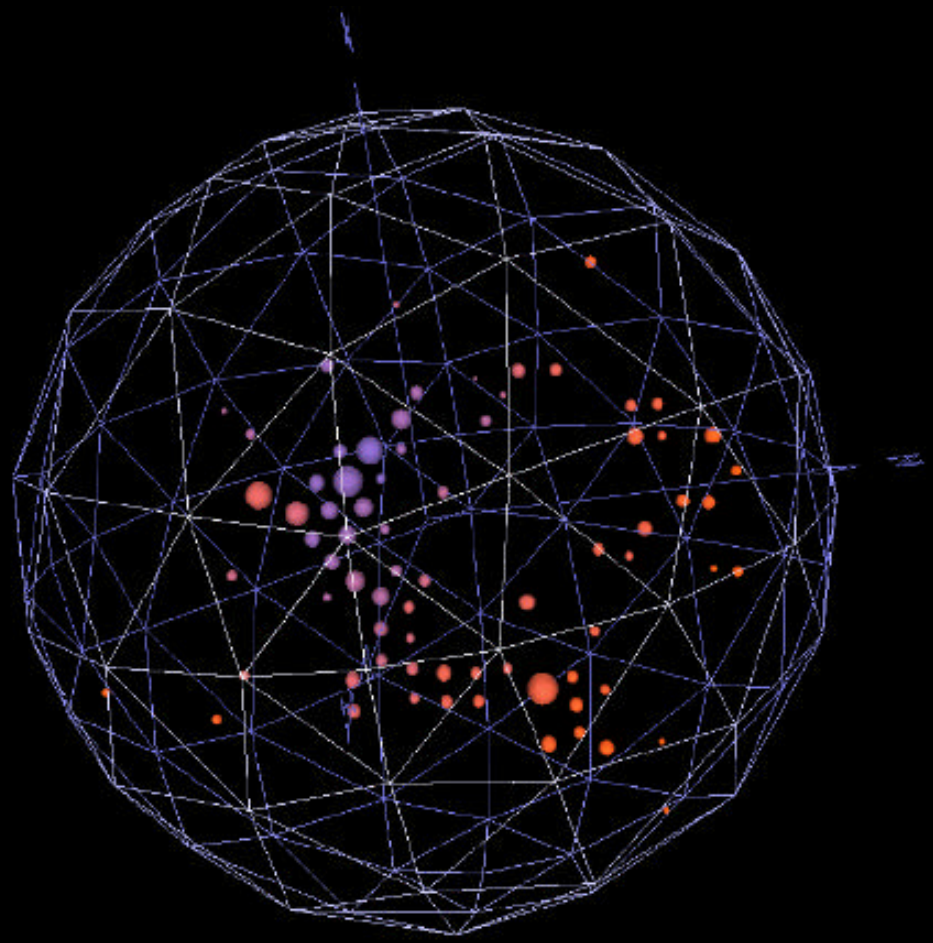


Fit Lifetime: 2.12 ± 0.05 μs

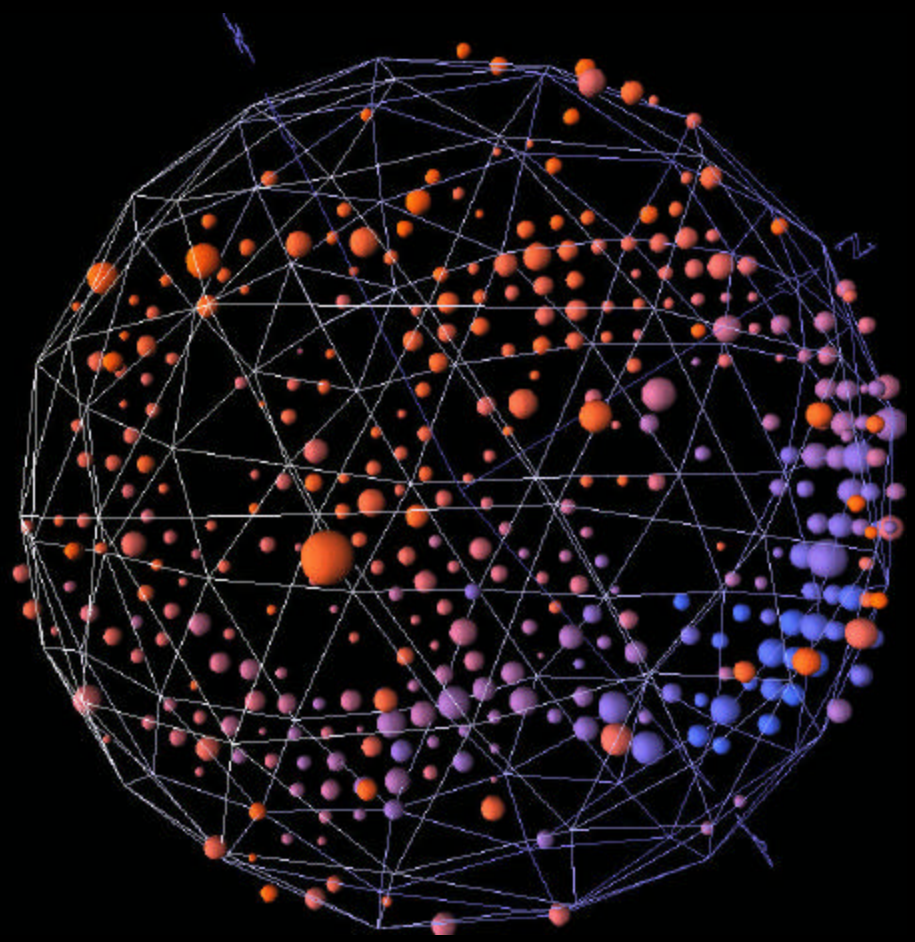
Expected μ lifetime in oil: 2.13 μs

with 8% μ^- capture on carbon.

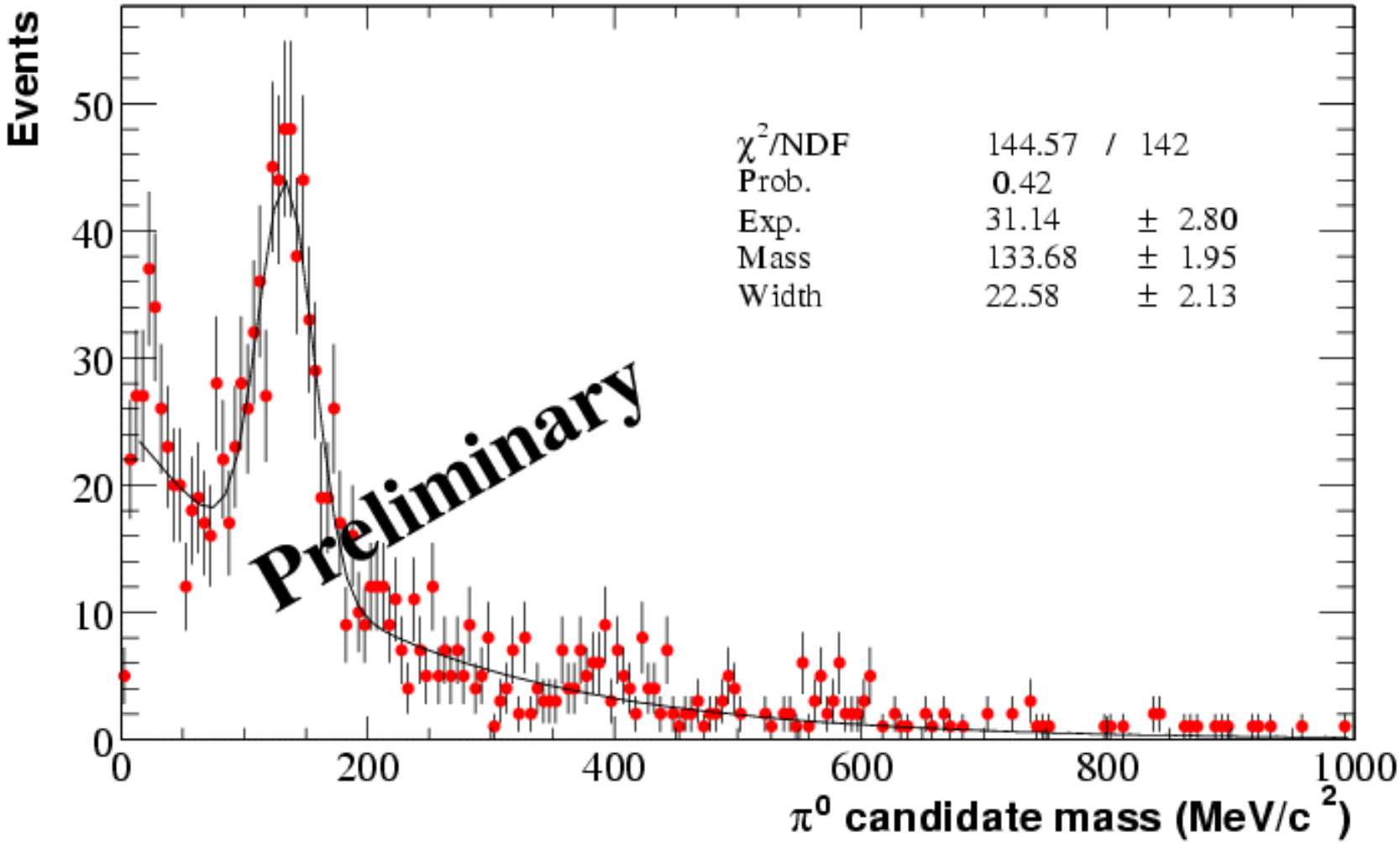
- *Known* muons
(can reject ~92%)
- *Known* electrons
(with a *known* spectrum.)



Electron from decay
of neutrino-induced muon

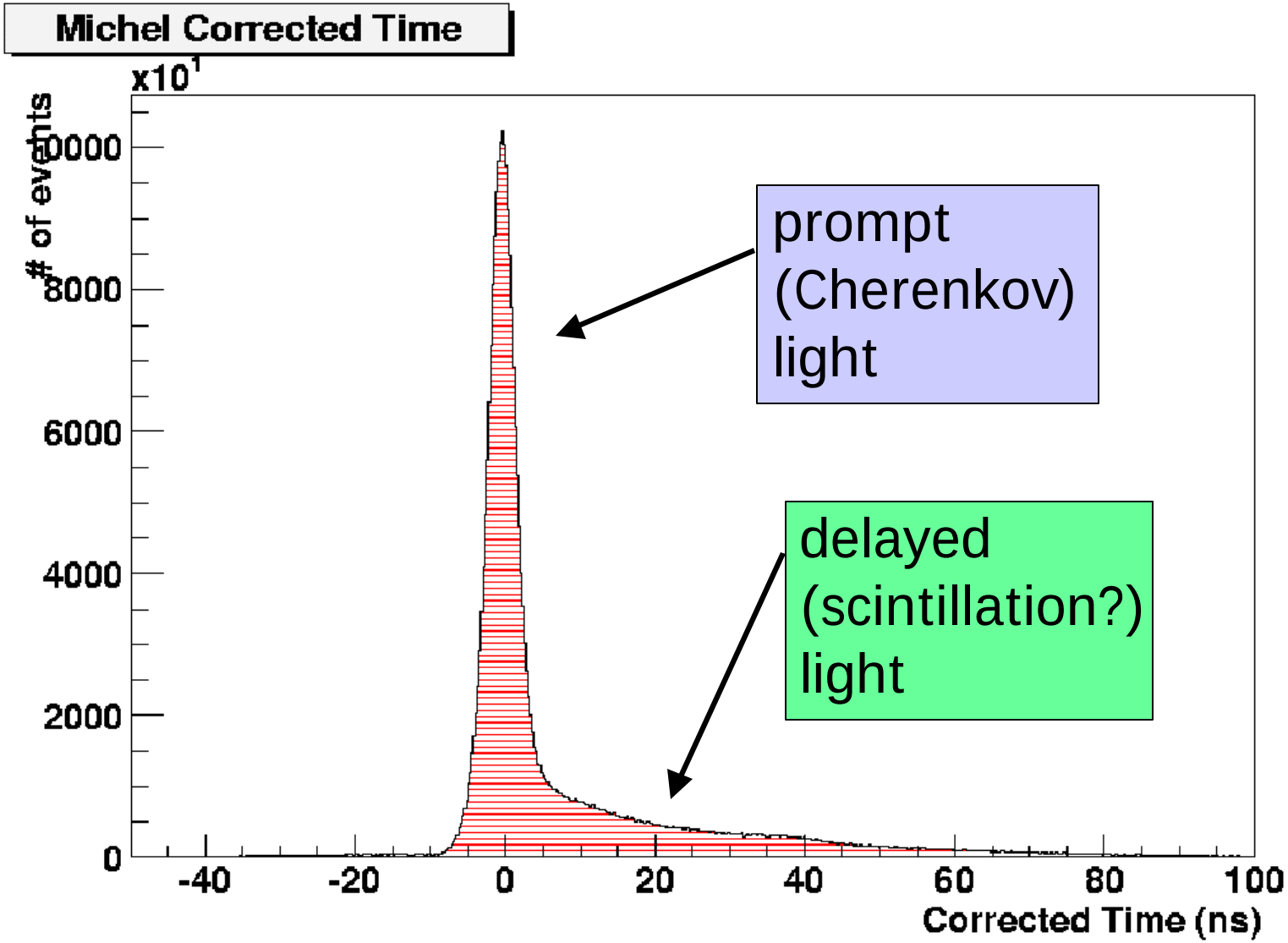


π^0 candidate


Events
50
40
30
20
10
0
0
200
400
600
800
1000
π^0 candidate mass (MeV/c ^{2})
χ^2/NDF 144.57 / 142
Prob. 0.42
Exp. 31.14 ± 2.80
Mass 133.68 ± 1.95
Width 22.58 ± 2.13
Preliminary

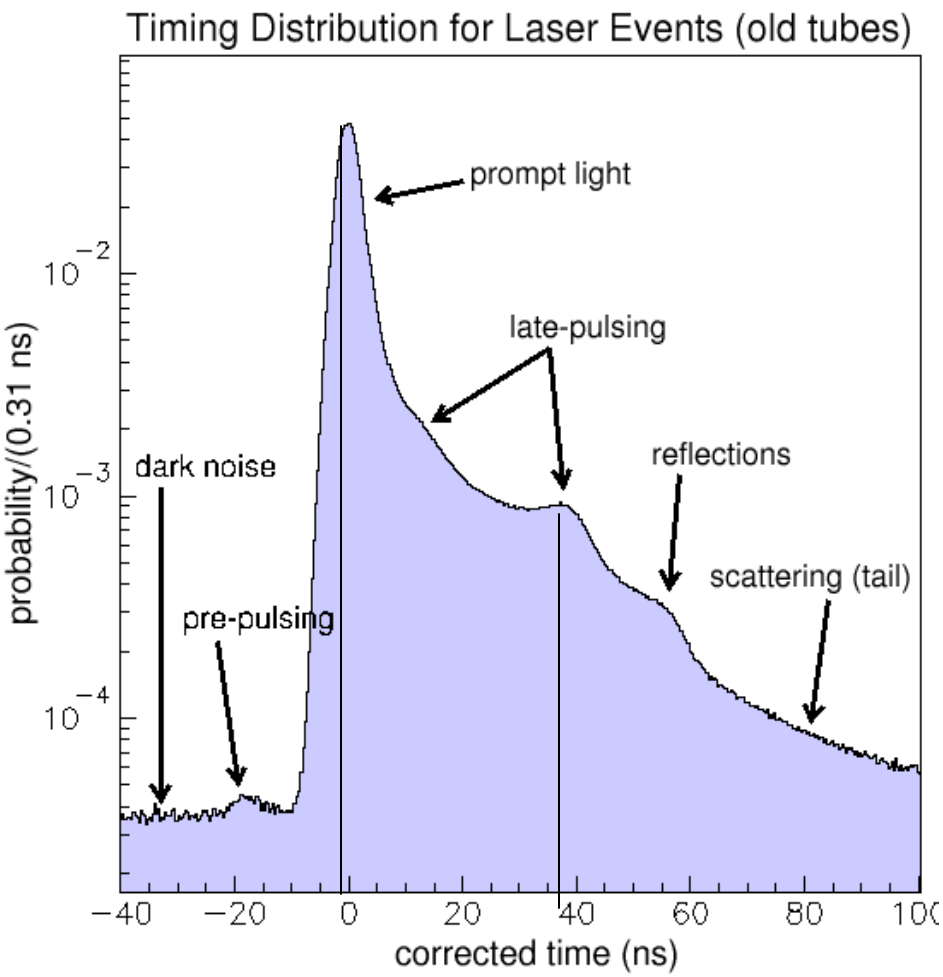
Time spectrum of light from Michel electrons

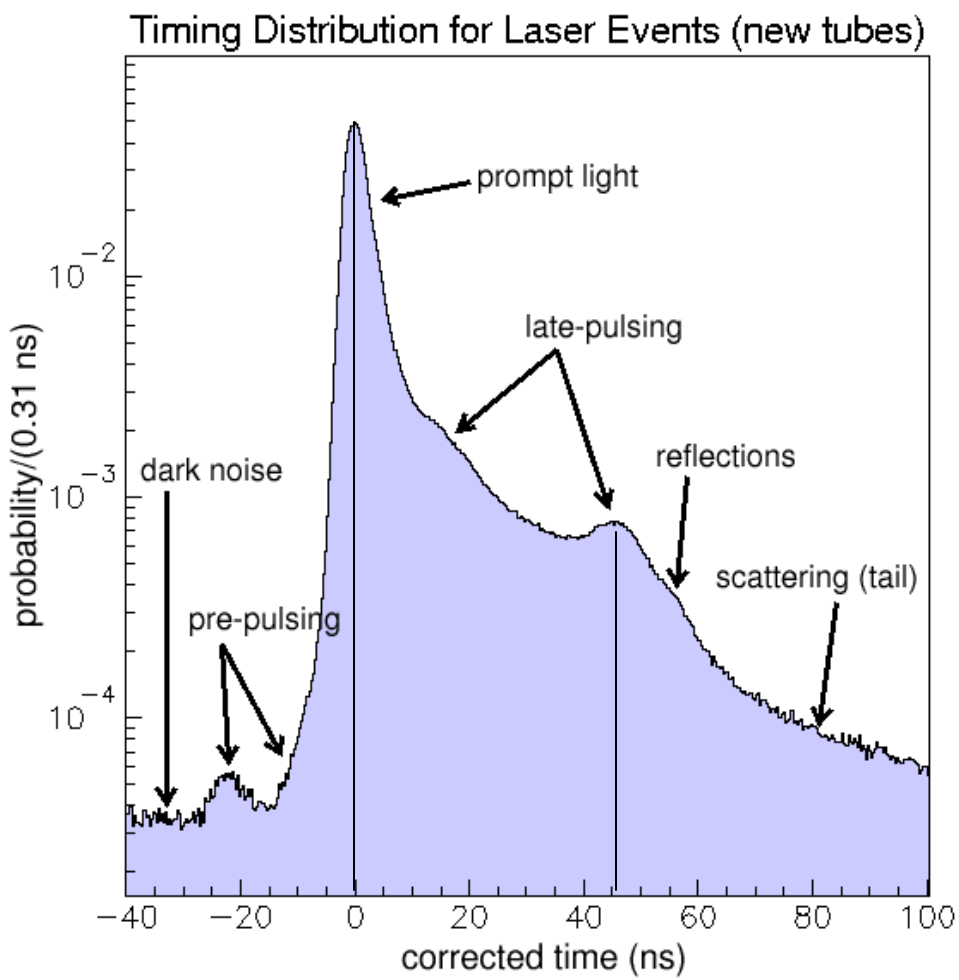
Measure, e.g., time resolution
scintillation time constant



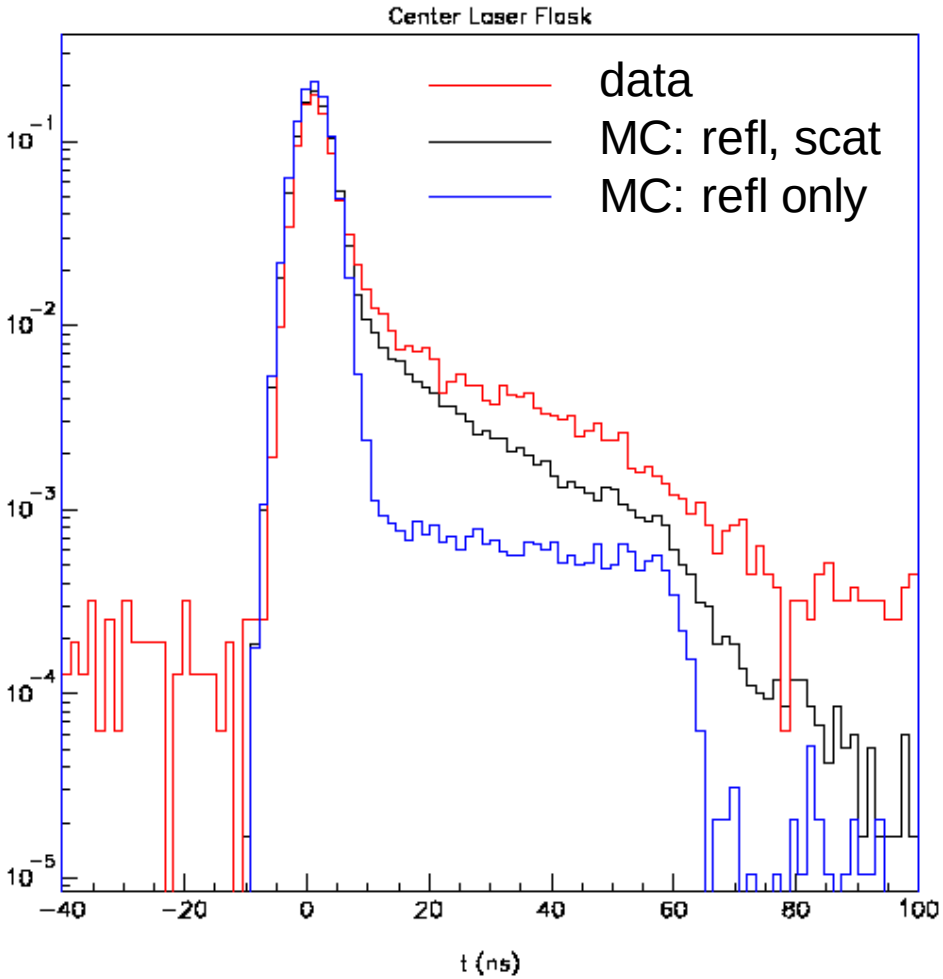
Or is it?

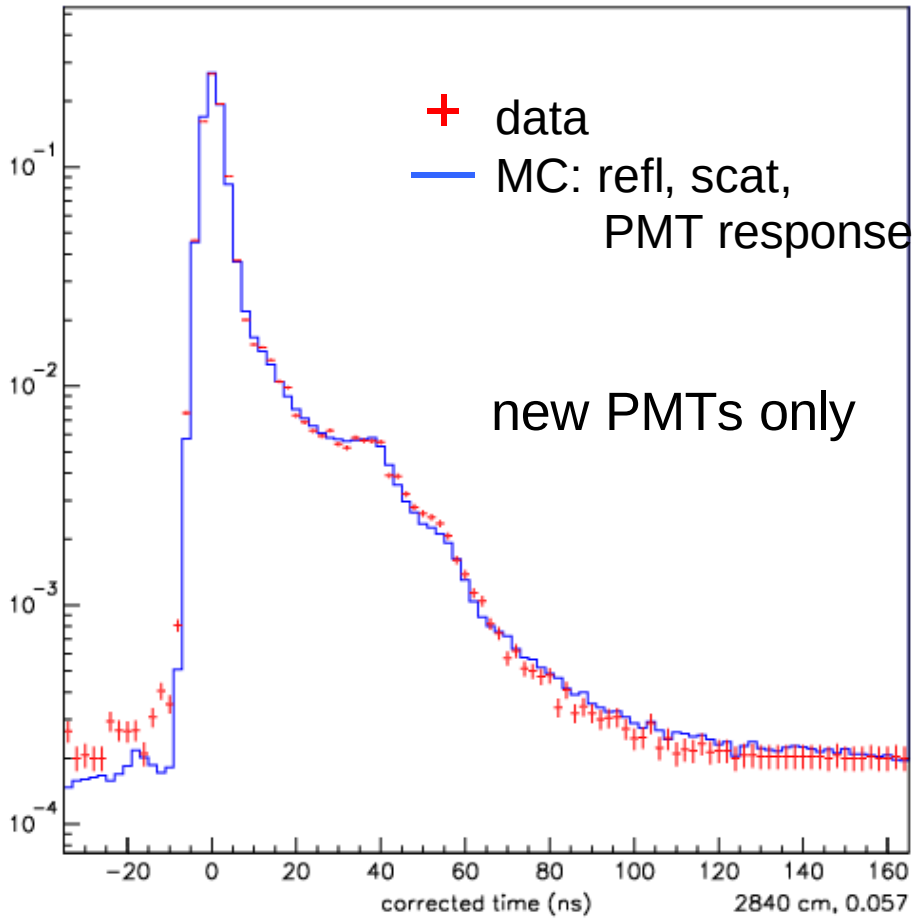
laser data
(*no* scintillation!)





Modeling “late light”



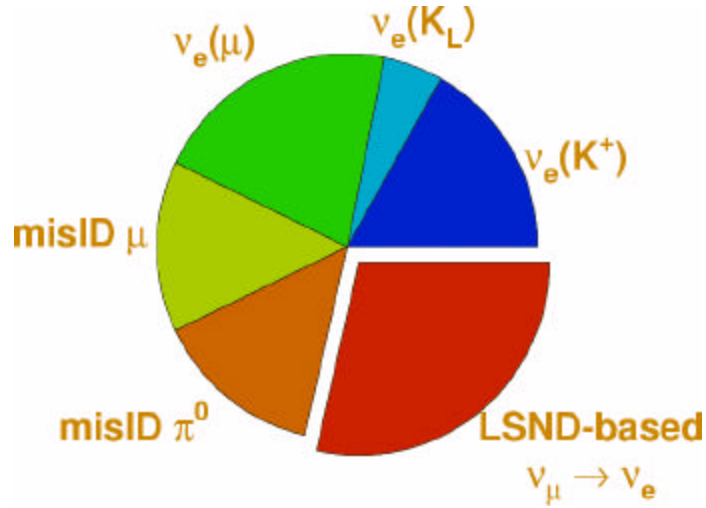


…and scintillation will sit on top of this

MiniBooNE expected signal

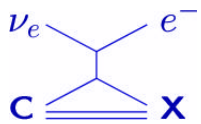
with (5-10)x10^{20} protons on target

~500k ν_μC charged current QE events

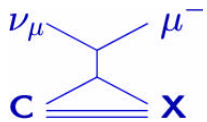


Approximate number of electron neutrino-like events

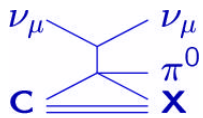
Intrinsic ν_e background: 1,500 events



μ mis-ID background: 500 events



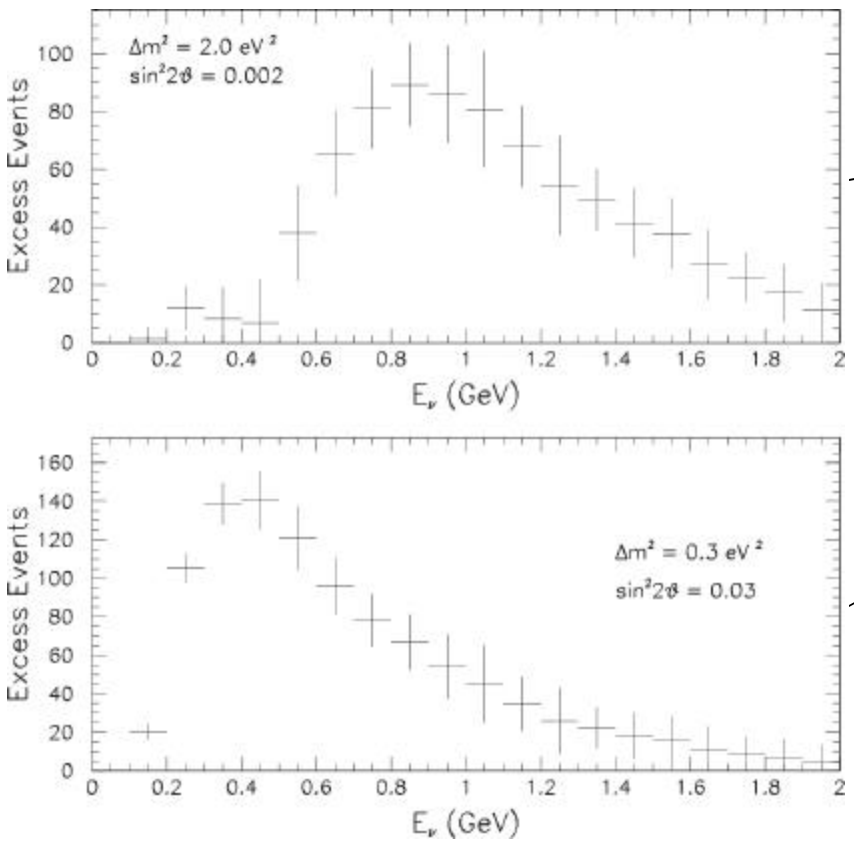
π^0 mis-ID background: 500 events

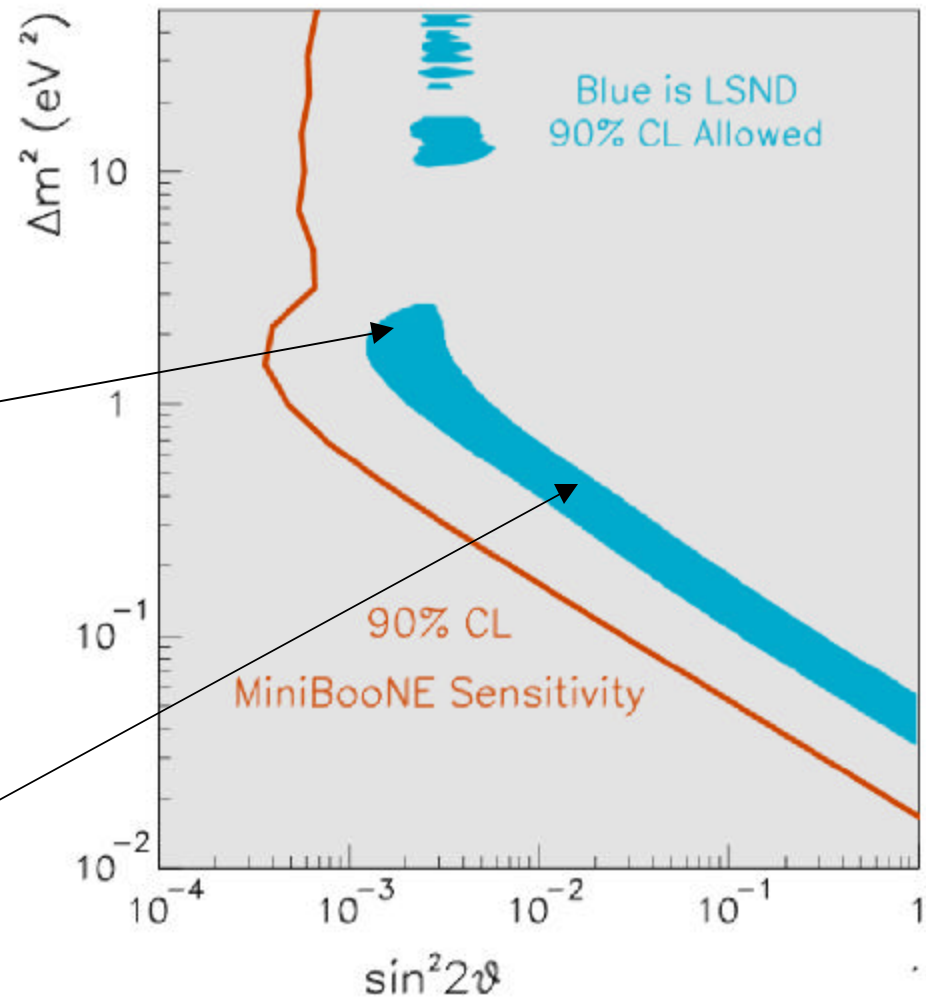


LSND-based $\nu_\mu \rightarrow \nu_e$: 1,000 events

MiniBooNE expected sensitivity

With ~two years of running MiniBooNE should be able to confirm or rule out the entire LSND signal region.

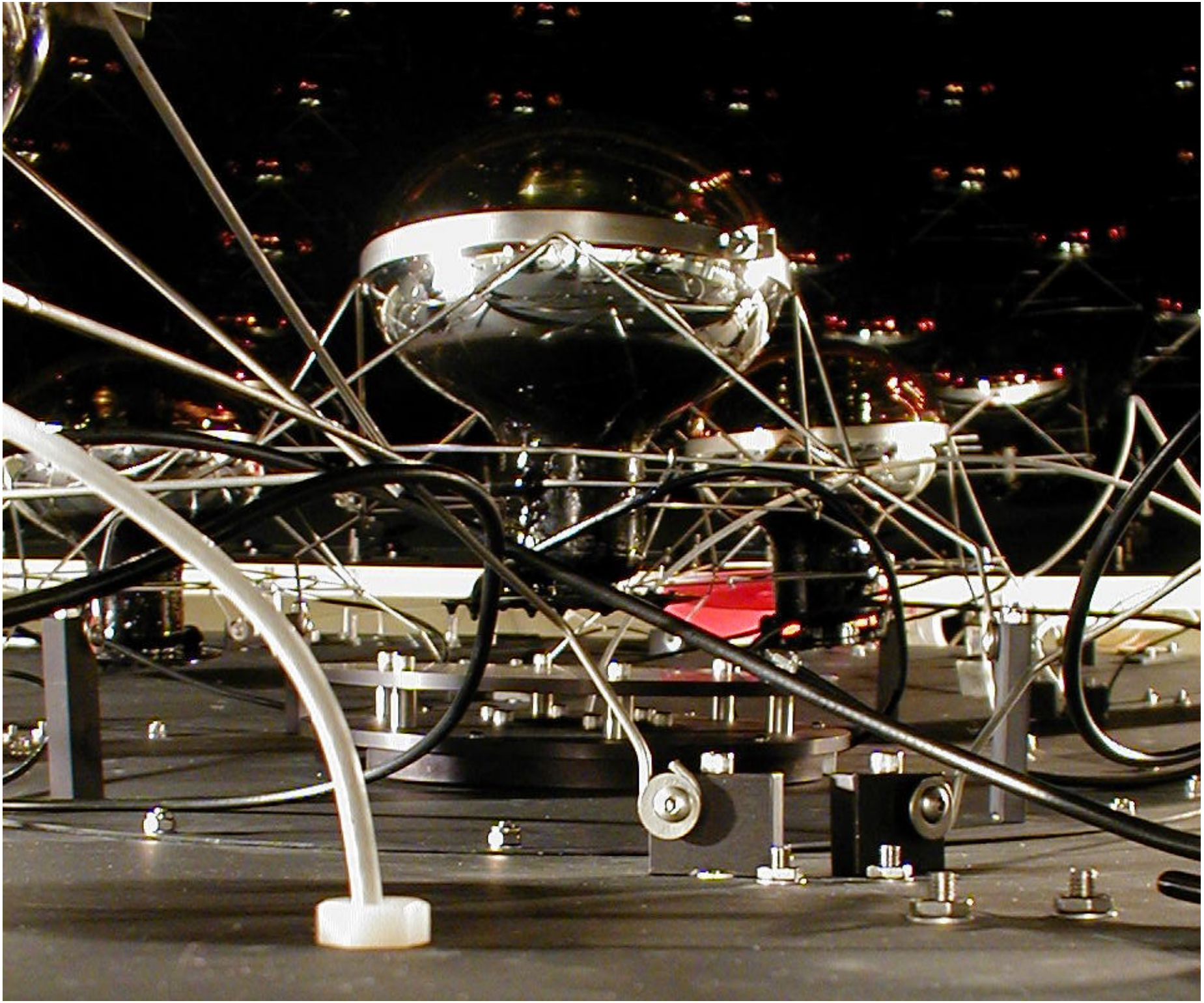




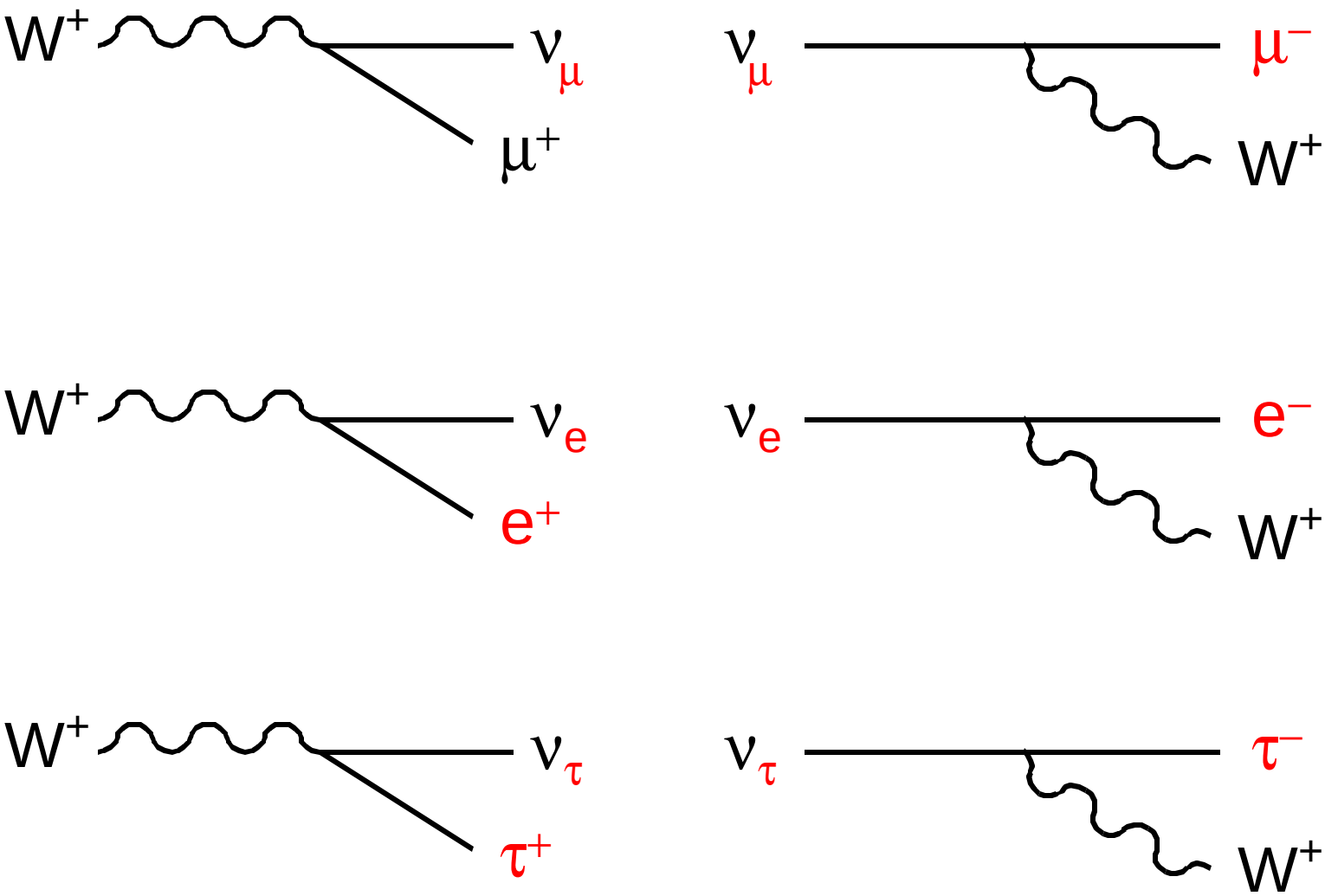
MiniBooNE status and plan

- Current run: goal ~10^{21} p.o.t. for ν
  - accumulated ~ 10% so far
  - ~2 years (with modest Booster optimism)

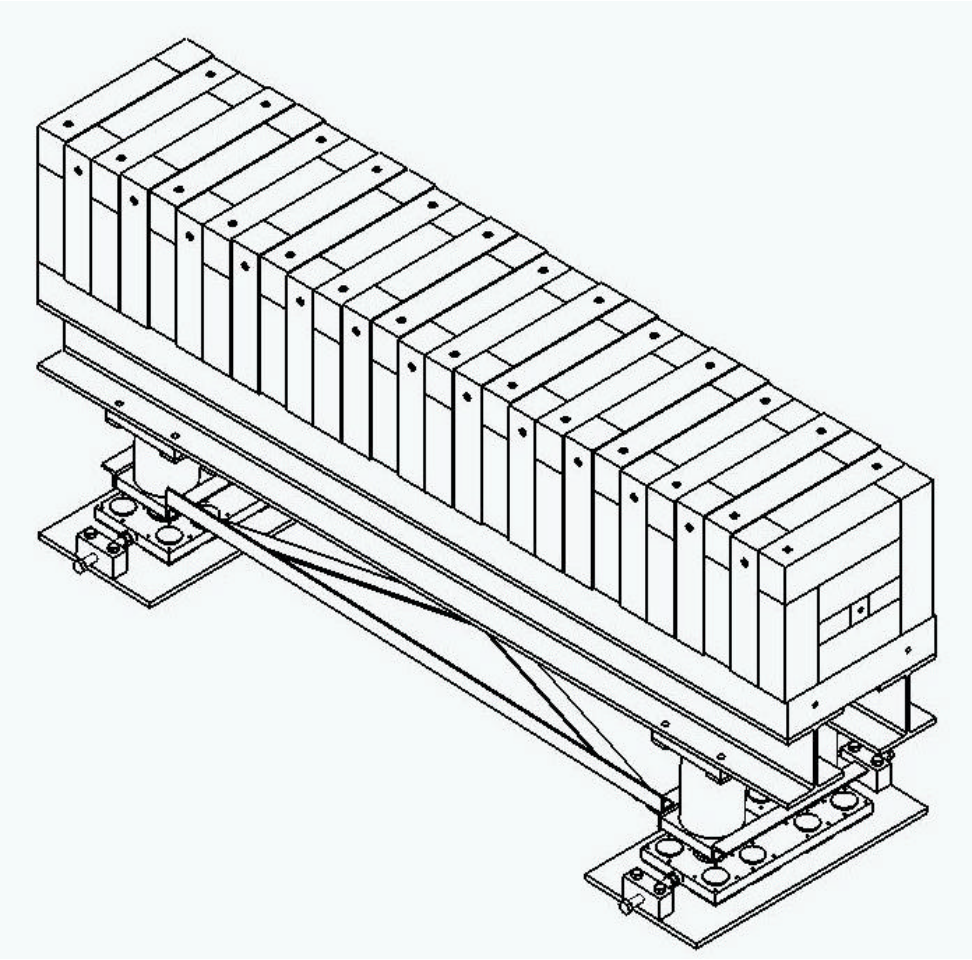
- Switch to $\bar{\nu}$!
  - LSND was $\bar{\nu}$…
  - different backgrounds
  - only 1/3 the interaction rate of ν running
  - NuMI running competes for protons
  - Short test run in the Fall

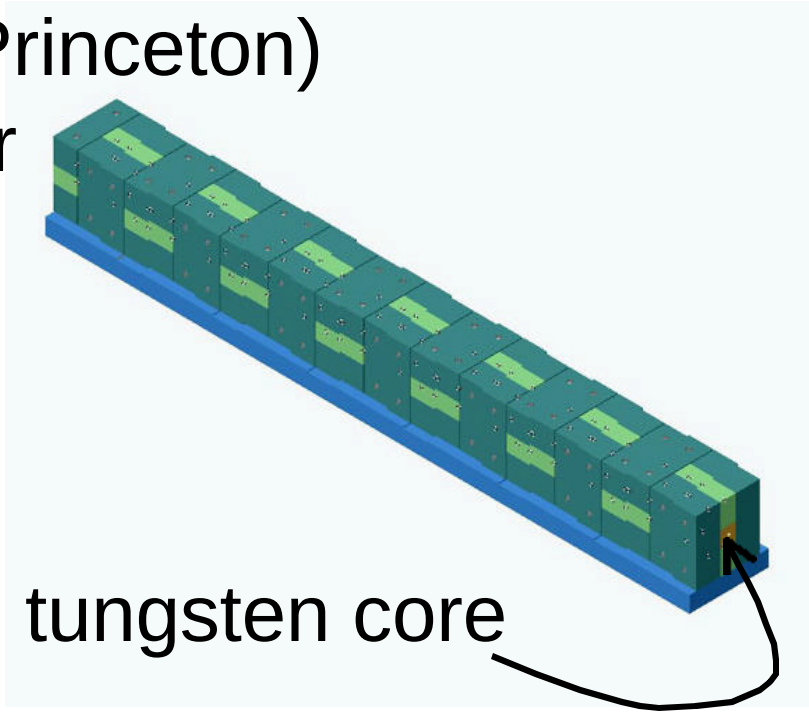


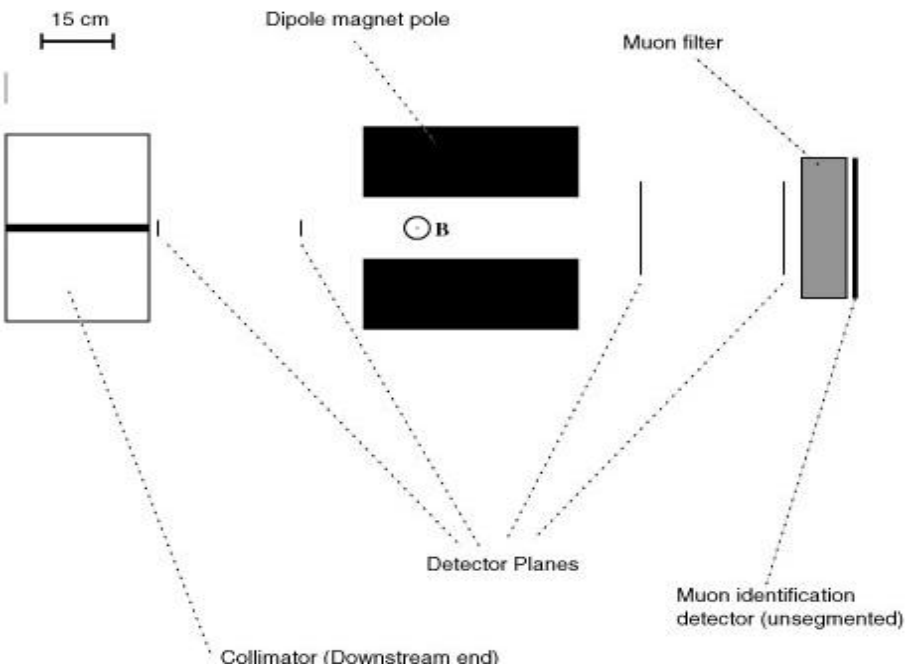
Weak Interactions: conserve lepton “flavor”



LMC tungsten collimator (Princeton) and magnetic spectrometer (Colorado and Princeton)





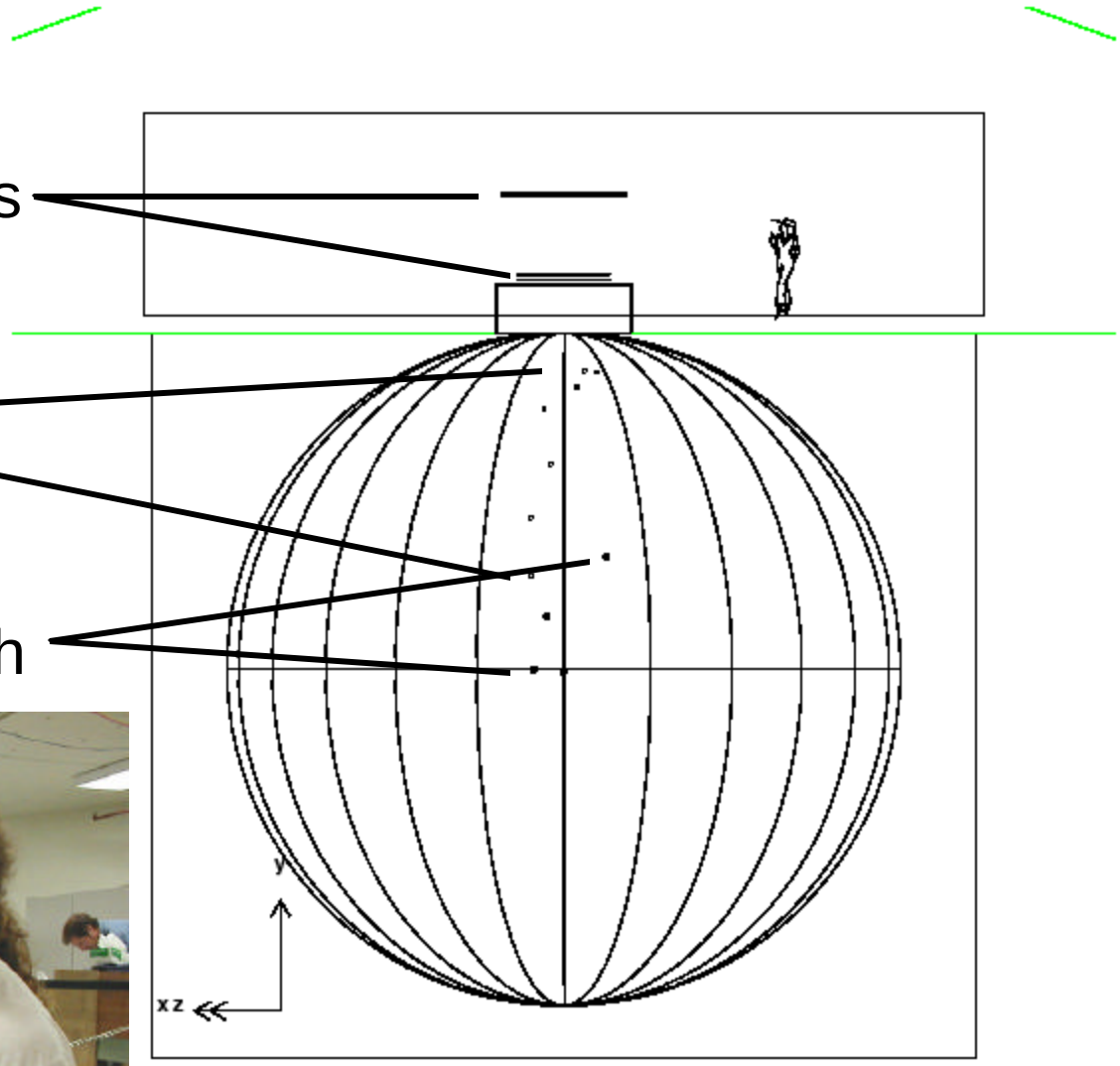


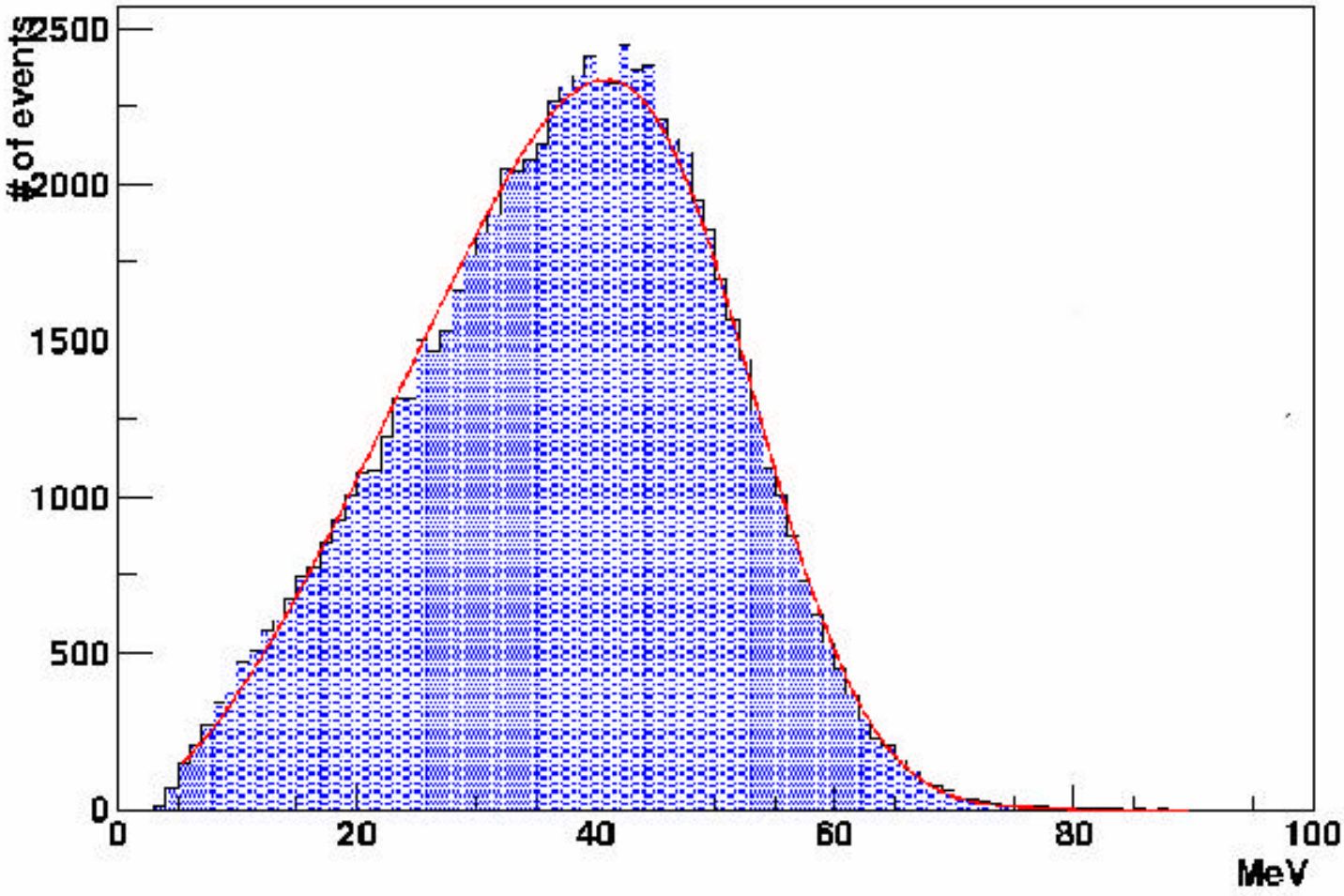
BooNE calibration systems

Muon tracker:
4 planes of scint strips

Scintillator cubes:
at 7 depths

Laser flasks:
~isotropic, <1 ns width





PRELIMINARY

A Michel electron energy spectrum. The solid line is the expected spectrum, 52.8*(3-2*x)*x^2 MeV, where x=E/52.8, convolved with a gaussian resolution factor whose width is proportional to sqrt(E). The endpoint indicates 14.8% energy resolution.