Medium baseline neutrino oscillation searches

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Les Houches, 20 June 2001

LSD: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad 20 < E_\nu < 60$ MeV $\quad \mu^+$ decay at rest

$\nu_\mu \rightarrow \nu_e \quad 20 < E_\nu < 200$ MeV $\quad \pi^+$ decay in flight

Final results, 1993-98 data

event excess, evidence for oscillations

KARMEN: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad 20 < E_\nu < 60$ MeV $\quad \mu^+$ decay at rest

Results based on 75% of expected data, Feb 97 - Mar (Nov) 00

experiment ended March 2001

no excess, does not confirm LSND, but does not rule it out either

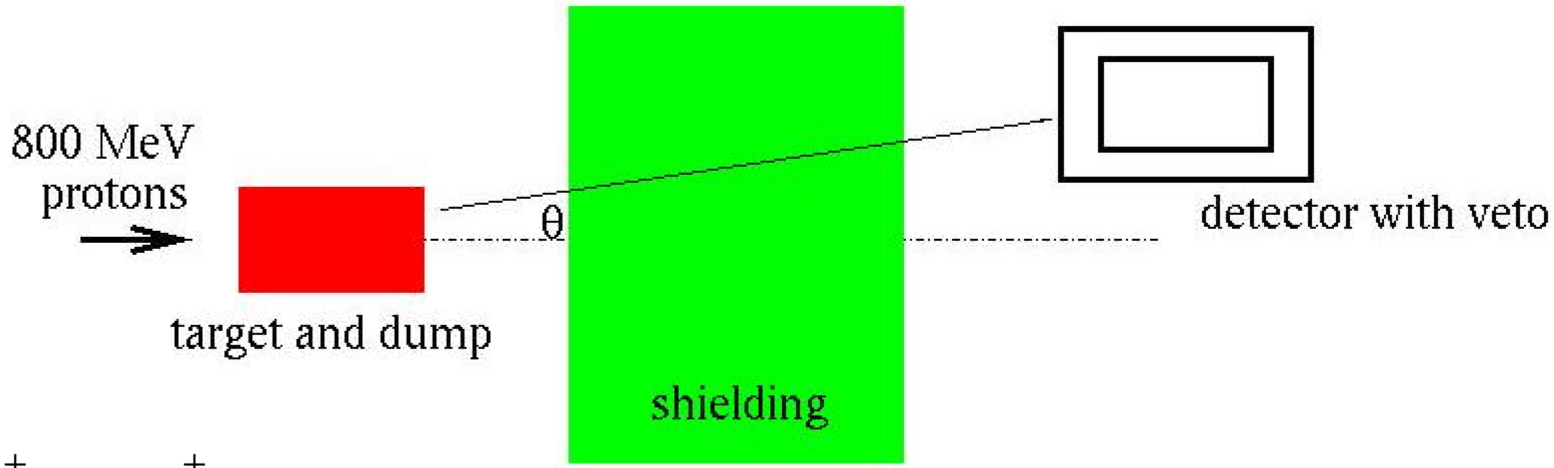
MiniBooNE: $\nu_\mu \rightarrow \nu_e \quad 500 < E_\nu < 1500$ MeV

Under construction

first data summer 2002

8 GeV protons, 3 GeV π^+

LSND and KARMEN experimental scheme



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

muon decay at rest

$\bar{\nu}_e p \to e^+ n$ detect prompt *e* track, $20 < E_e < 60$ MeV

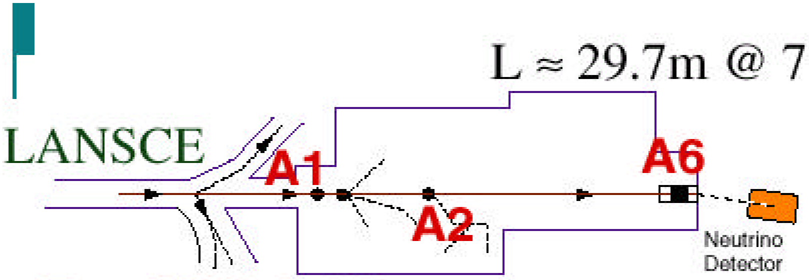
neutron capture: $np \to d\gamma$ 2.2 MeV, $Gd(n,\gamma)$ 8 MeV

γ correlated in position and in time with *e*

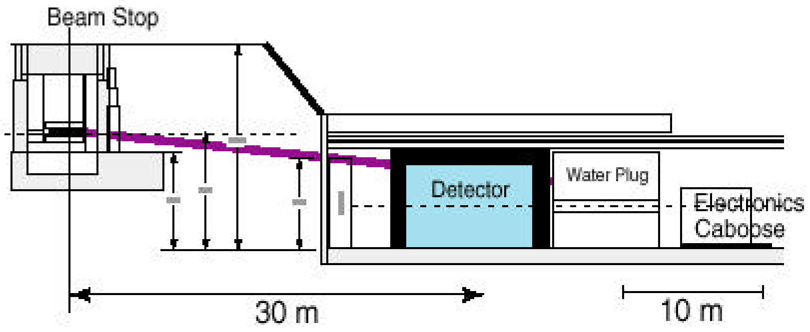
no B-field, *e* and γ sequence distinguishes e^+ from e^-

LSND experimental layout

L ≈ 29.7m @ 7°

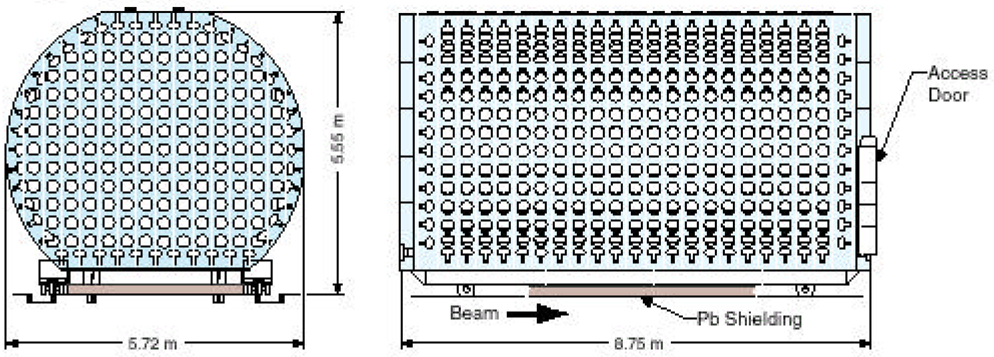


E_p=800MeV



C_nH_{2n+2}

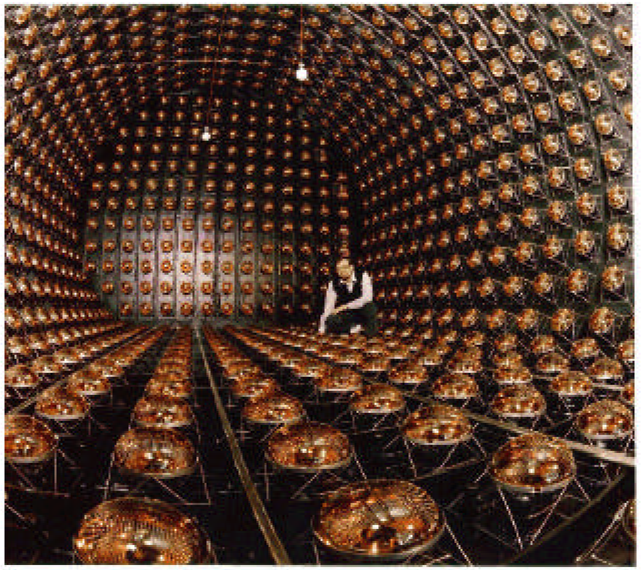
8.75m



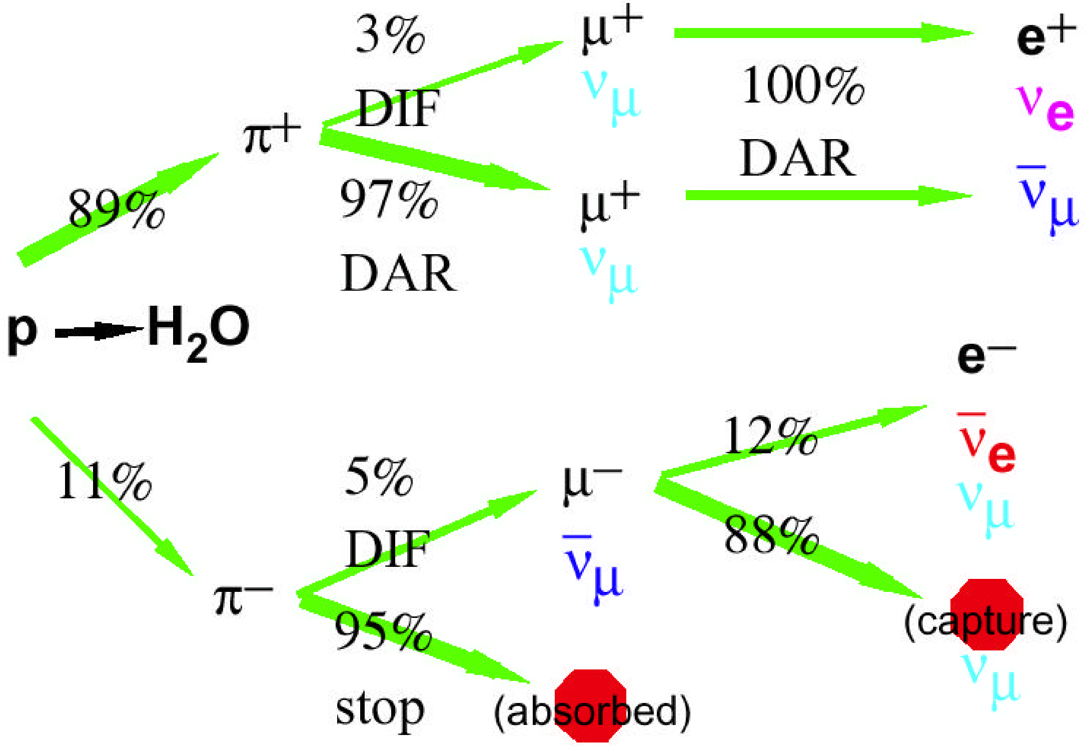
167t

1220 8" PMT's

5.7m



LSND
neutrino fluxes



$p \rightarrow H_2O$

89% π^+

3% DIF μ^+ ν_μ

97% DAR μ^+ ν_μ

100% DAR e^+ ν_e $\bar{\nu}_\mu$

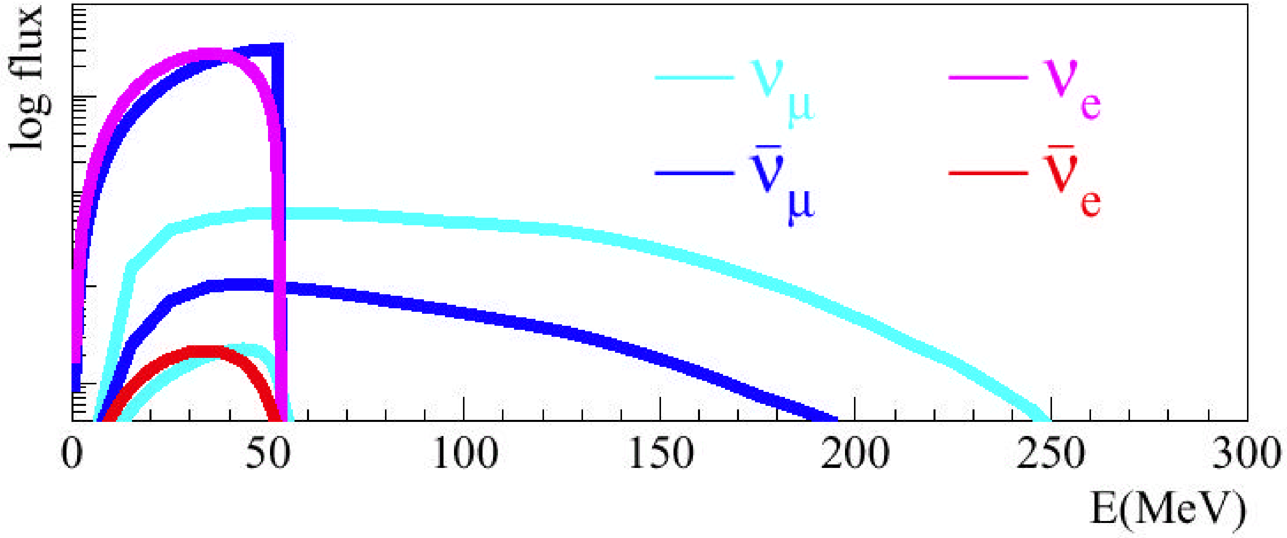
11% π^-

5% DIF μ^- $\bar{\nu}_\mu$

95% stop (absorbed)

12% e^- $\bar{\nu}_e$ ν_μ

88% (capture) ν_μ



LSND analysis strategy

Particle detection and identification via Cherenkov and scintillation light

Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ DAR osc. events in energy range 20-60 MeV

Search for $\nu_\mu \rightarrow \nu_e$ DIF osc. events in energy range 20-200 MeV

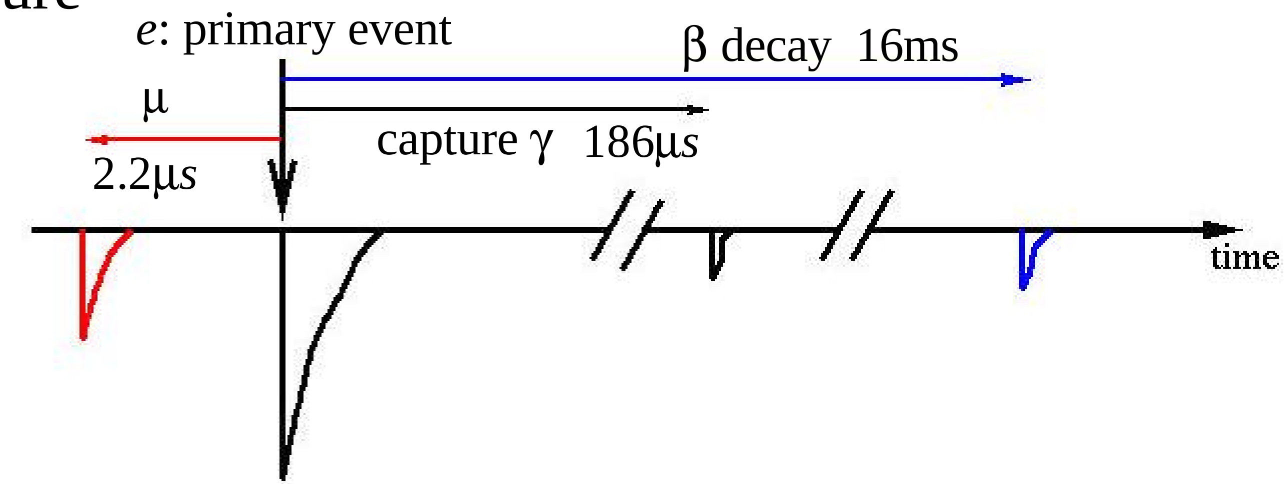
Use common primary event electron selection across all neutrino processes.

Simultaneously fit all neutrino processes to constrain fluxes and backgrounds.

Identify 20-60 MeV electron events with a correlated neutron capture γ

Fit 20-200 MeV oscillation candidate events in $(E, R, z, \cos\theta)$ to determine best oscillation parameter values.

Event time structure



Data acquisition: PMT time and pulse height

primary trigger: >150 hit PMTs (~4 MeV electron equiv.)
with <4 veto PMTs hit and no event with >5 veto hits
within previous 15.2 μs

“past” event: any activity with >17 PMT hits or >5 veto hits
during the preceding 51.2 μs

“future” event: any activity with >21 PMT hits during the following 1 ms.

e.g. μ+*e* events: the μ is the past event, its decay *e* is the primary event

μ+β events: $\nu_e C \rightarrow e^- N_{g.s.}$ β decay electron is future event

Conventional neutrino processes

Measurements used to constrain fluxes, efficiencies, cross sections and backgrounds

Events with muons

μ+e: $\nu_\mu C \to \mu^- N^*$

$\mu+e+\beta$: $\nu_\mu C \to \mu^- N_{g.s.}$

$\mu+e+\gamma$: $\bar{\nu}_\mu p \to \mu^+ n$

Events without muons

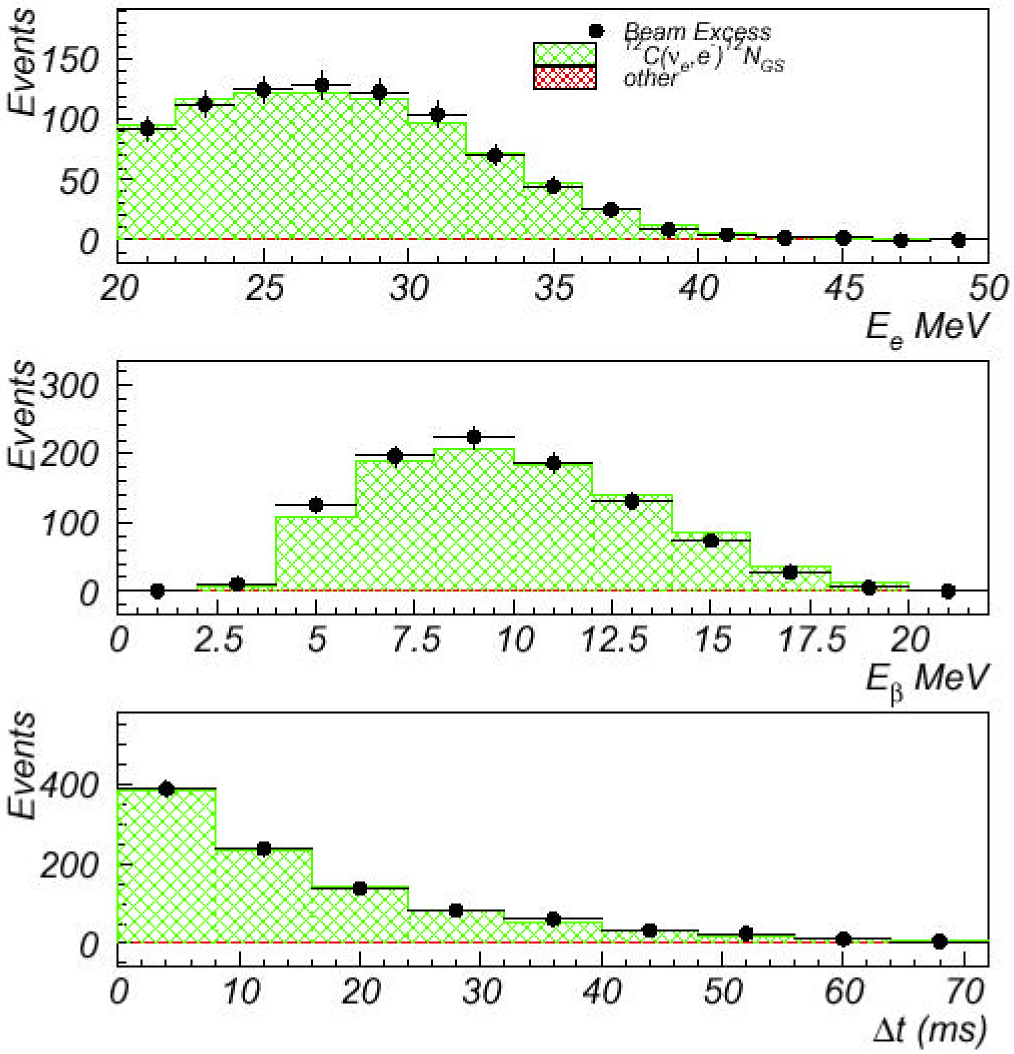
e: $\nu e \to \nu e,\ \nu_e C \to e^- N^*\ (\nu_\mu \to \nu_e)$

$e+\beta$: $\nu_e C \to e^- N_{g.s.}$

$e+\gamma$: $\bar{\nu}_e p \to e^+ n\quad (\bar{\nu}_\mu \to \bar{\nu}_e)$

e+β events

$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$



e energy

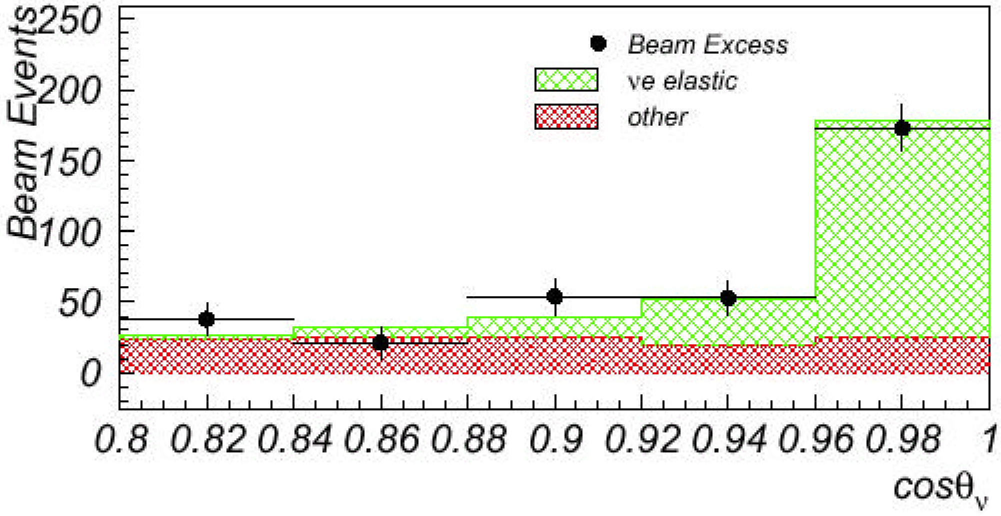
β energy

time between the *e* and β

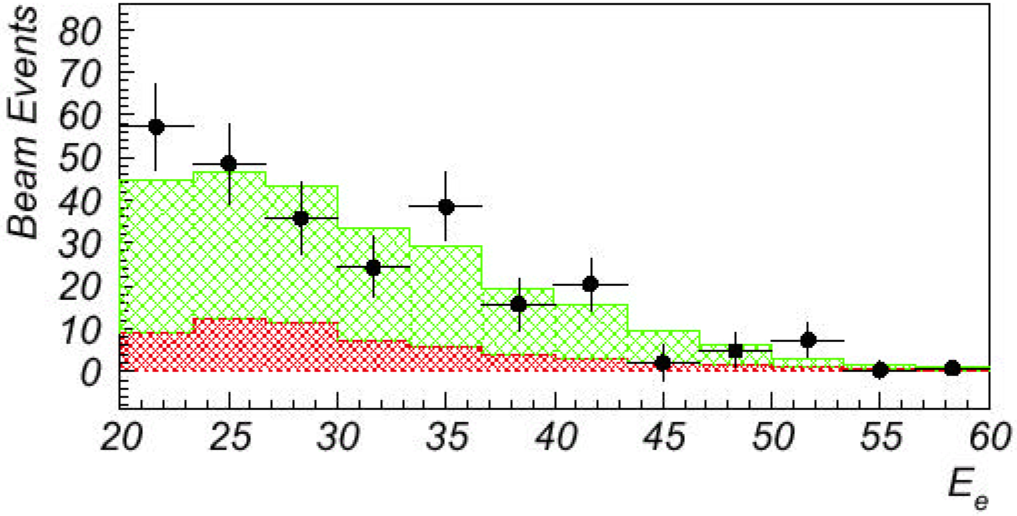
e events

$\nu e \rightarrow \nu e$

cos θ : angle between e and ν



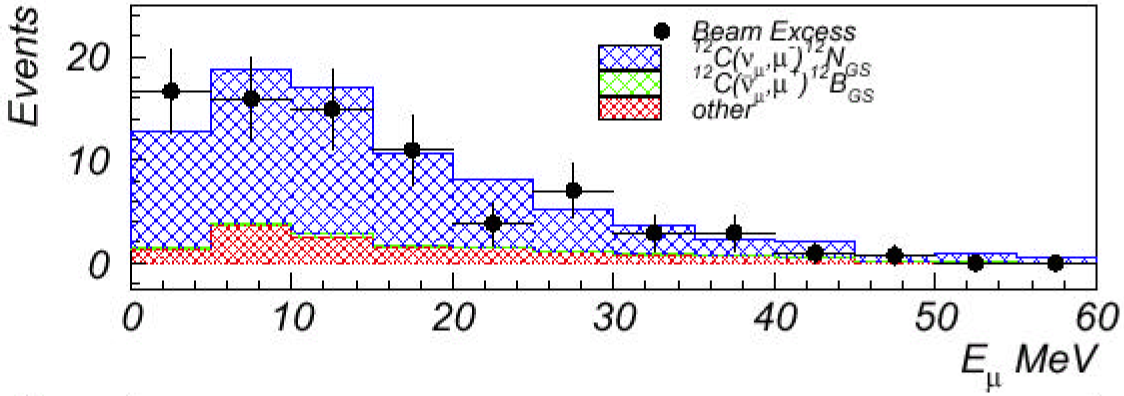
e energy



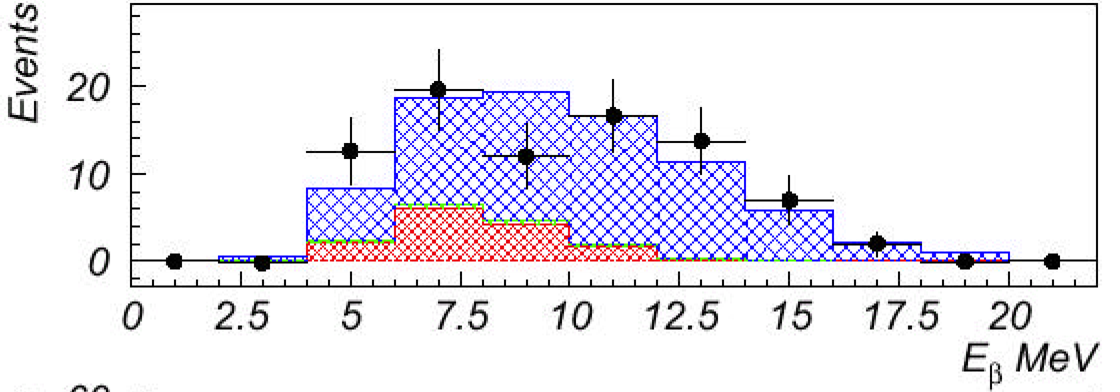
μ+*e*+β events

$^{12}C(\nu_\mu,\mu^-)^{12}N_{g.s.}$

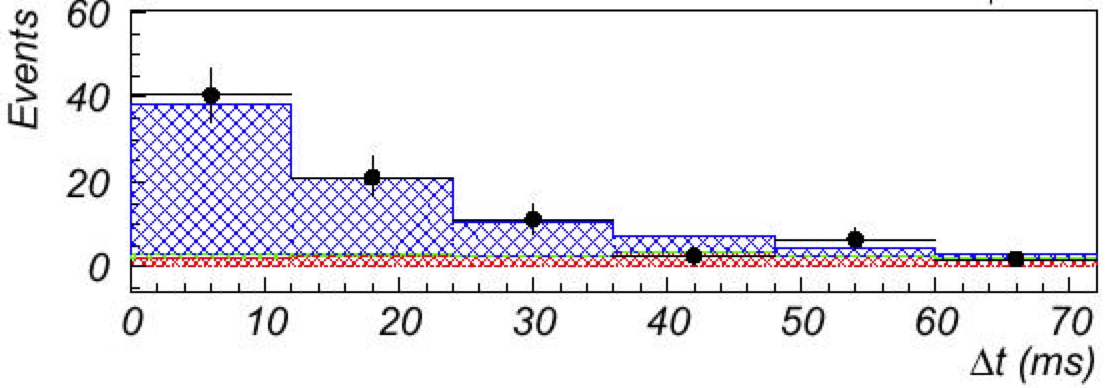
μ energy



β energy



time between the μ and β

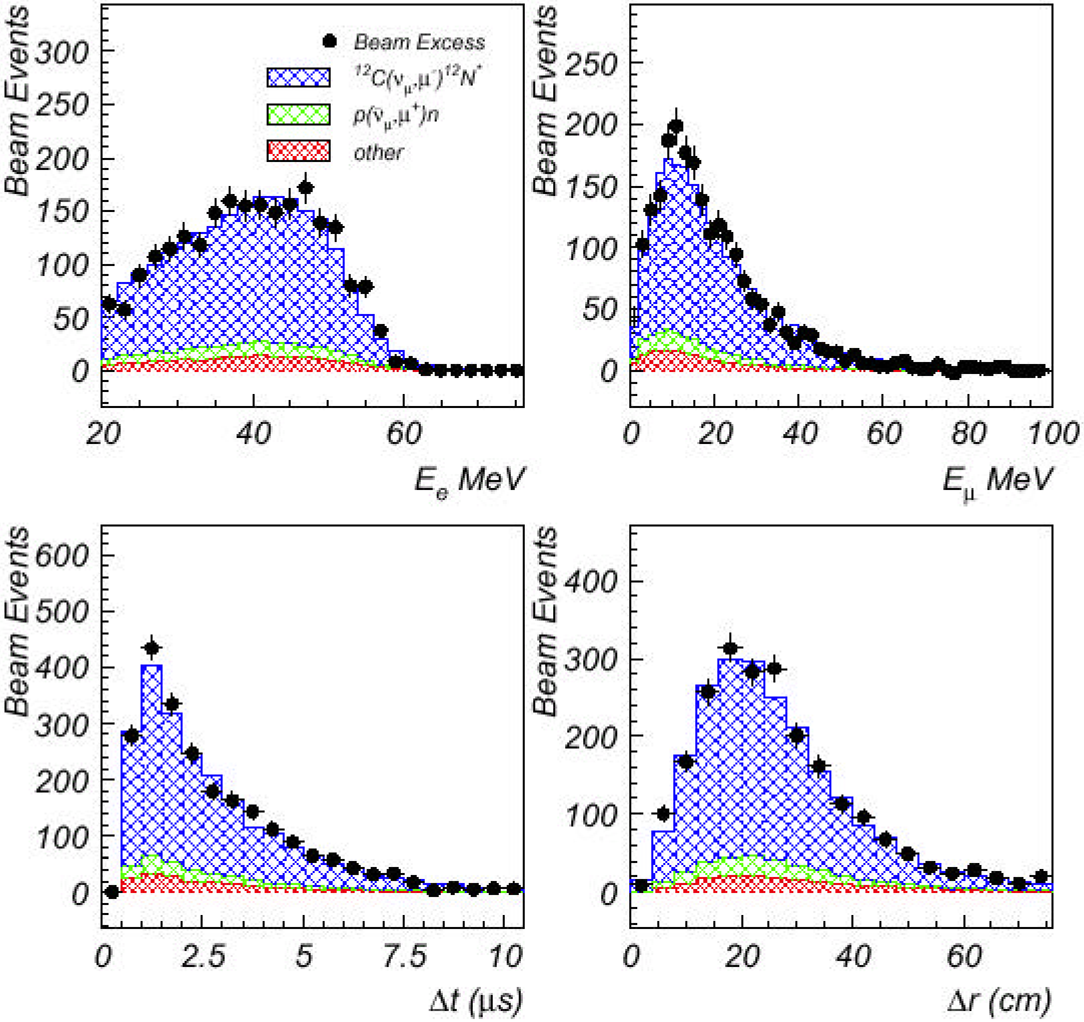


μ+*e* events

$$\nu_\mu C \to \mu^- N,\ \ \bar{\nu}_\mu C \to \mu^+ B,\ \ \bar{\nu}_\mu p \to \mu^+ n$$

Michel *e* energy
and μ energy

time and distance
between μ and *e*



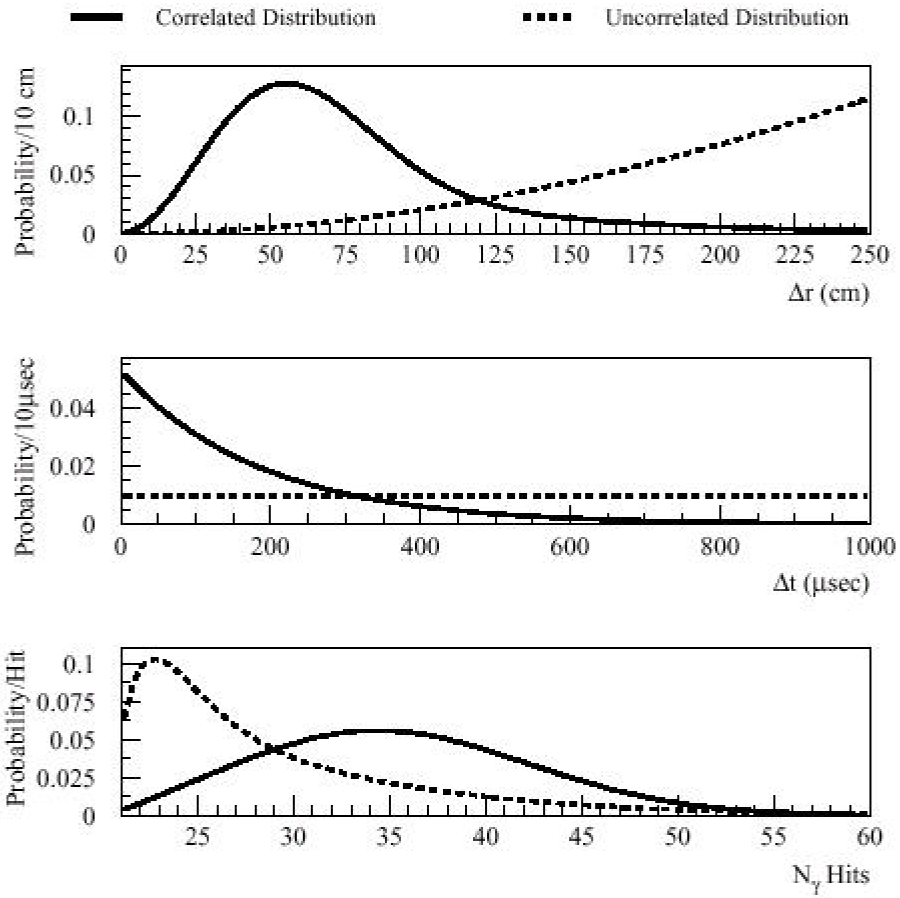
The correlated 2.2 MeV γ: R_γ

$$R_\gamma = \frac{\text{likelihood that } \gamma \text{ is correlated}}{\text{likelihood that } \gamma \text{ is uncorrelated}}$$

depends on: distance between e and γ

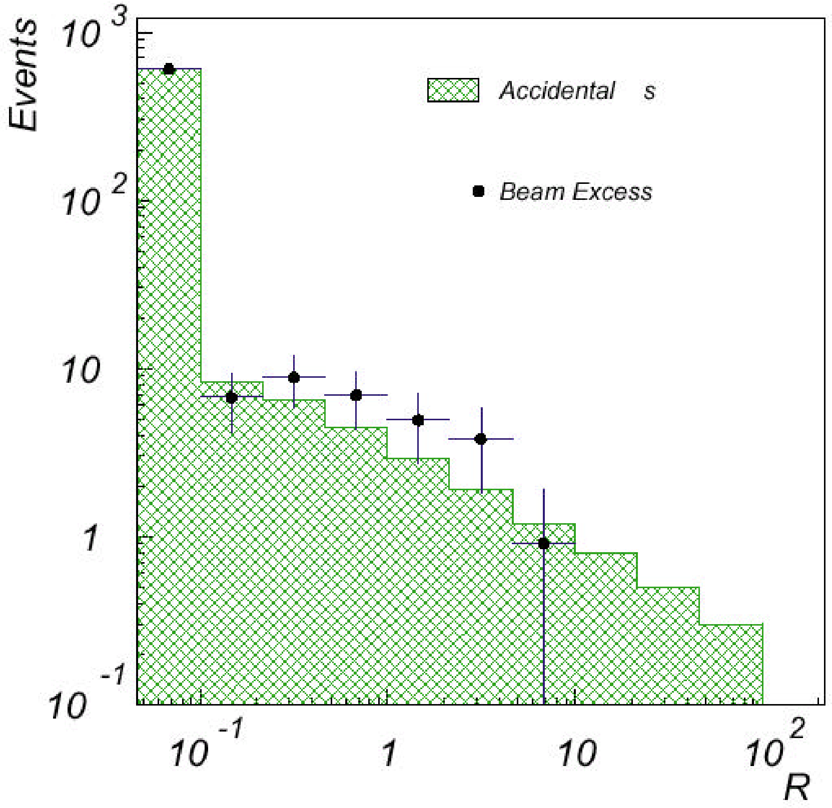
time interval between e and γ

number of PMT hits for the γ



Checks of the R_γ likelihood distributions:

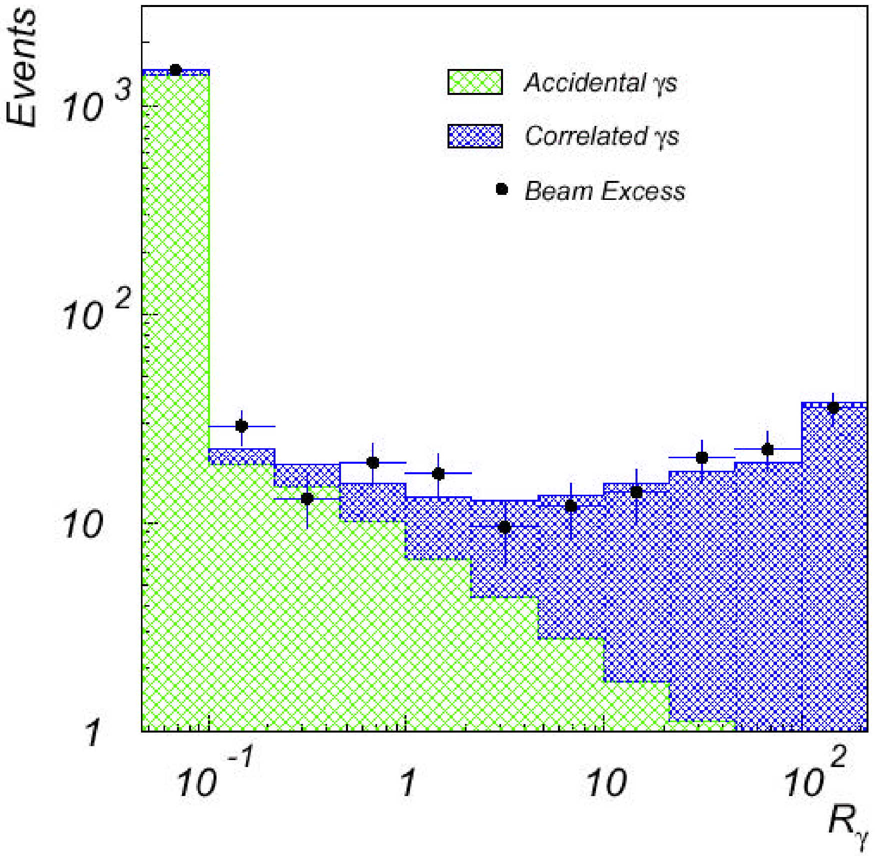
measure fraction of events with correlated γ



$$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$$

expected: $f_c = 0.0$

measured: $f_c = -0.004 \pm 0.007$



$$\nu_\mu C \to \mu^- N,\ \bar{\nu}_\mu C \to \mu^+ B,\ \bar{\nu}_\mu p \to \mu^+ n$$

expected: $f_c \approx 0.14$

measured: $f_c = 0.129 \pm 0.013$

Oscillation results

$20 < E_e < 60\ \text{MeV}$

R_γ distribution for events that satisfy primary search

$$f_c = 0.057 \pm 0.011$$

Beam on–off excess

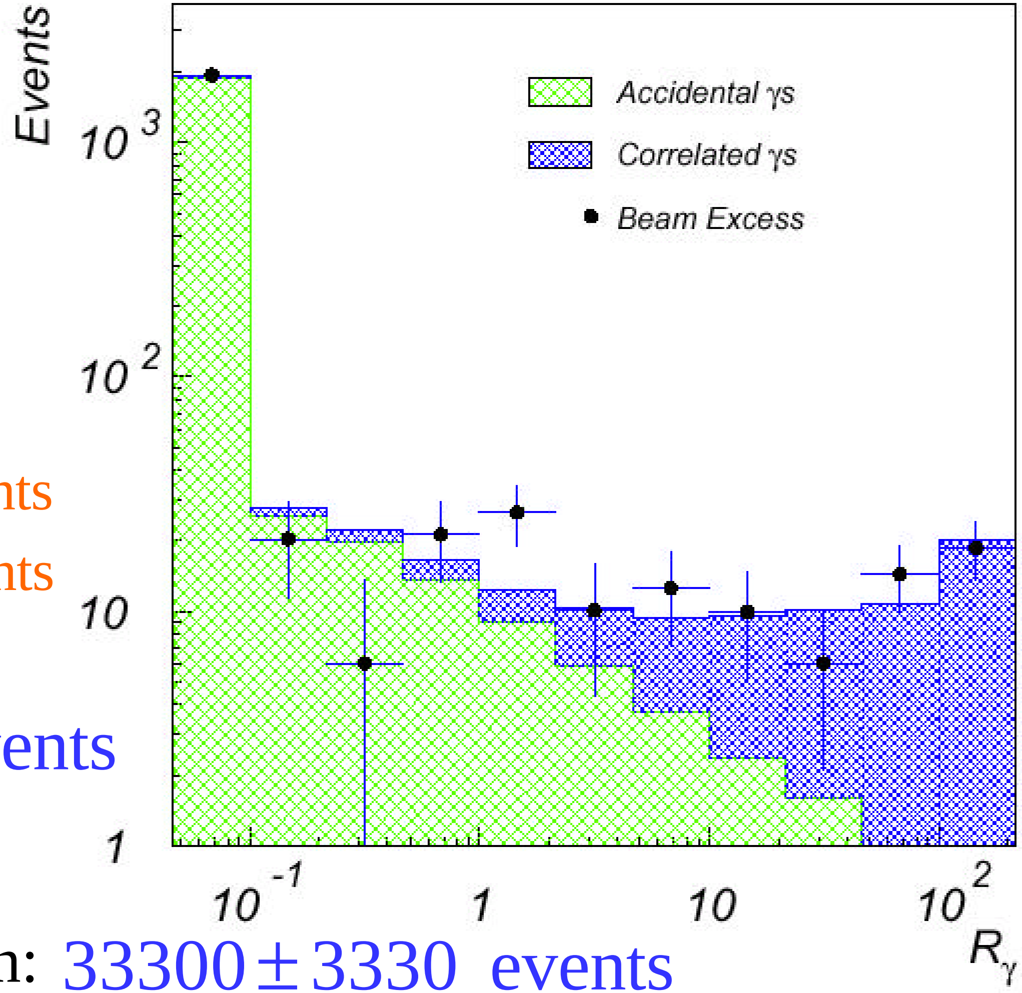
117.9 ± 22.4 events

bkgd : μ^- DAR 19.5 ± 3.9 events

π^- DIF 10.5 ± 4.6 events

Total excess:

$87.9 \pm 22.4 \pm 6.0$ events



Excess for 100% transmutation: 33300 ± 3330 events

Oscillation probability $(0.264 \pm 0.067 \pm 0.045)\%$

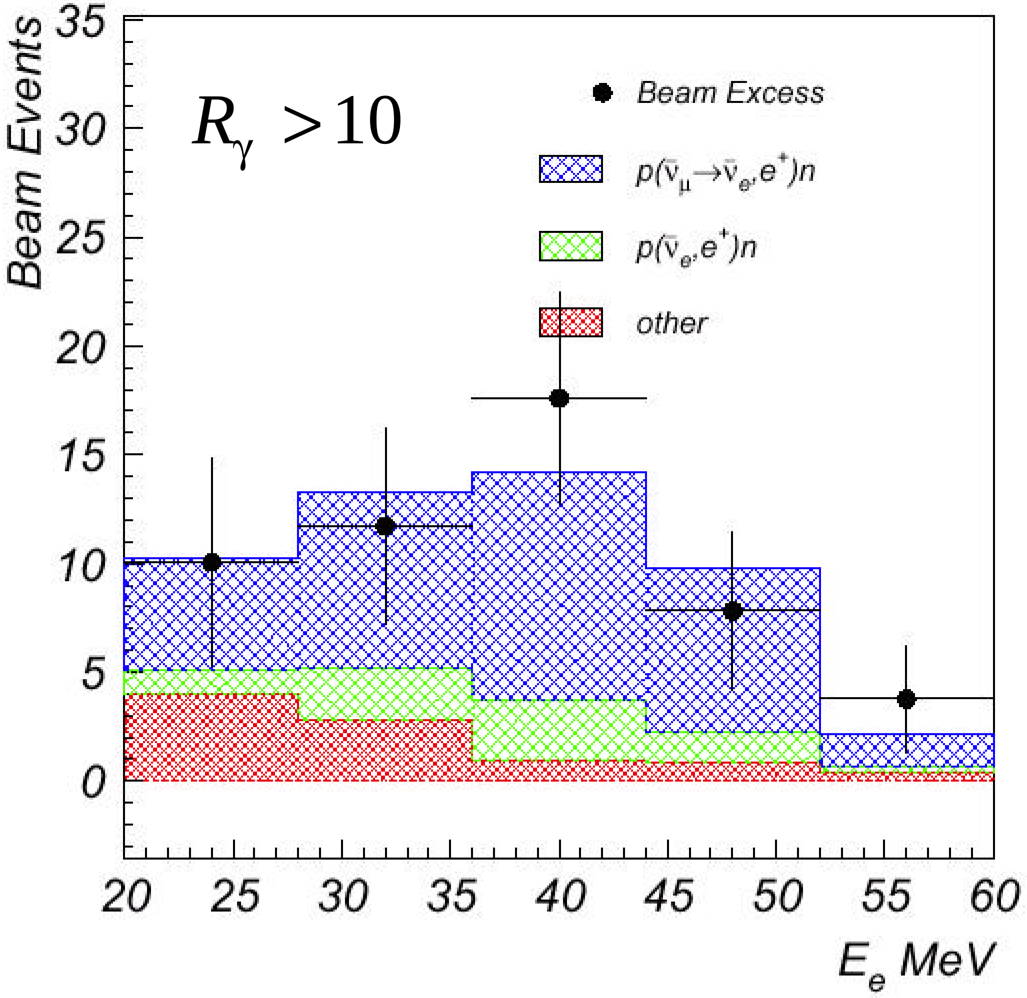
$R_\gamma > 10$ and $20 < E_e < 60$ MeV

$\text{beam on}: \; 86 \text{ events}$

$\text{beam off}: \; 36.9 \pm 1.5$

$\nu \text{ bkgd}: \; 16.9 \pm 2.3$

$\text{total excess } 32.2 \pm 9.4 \pm 2.3$

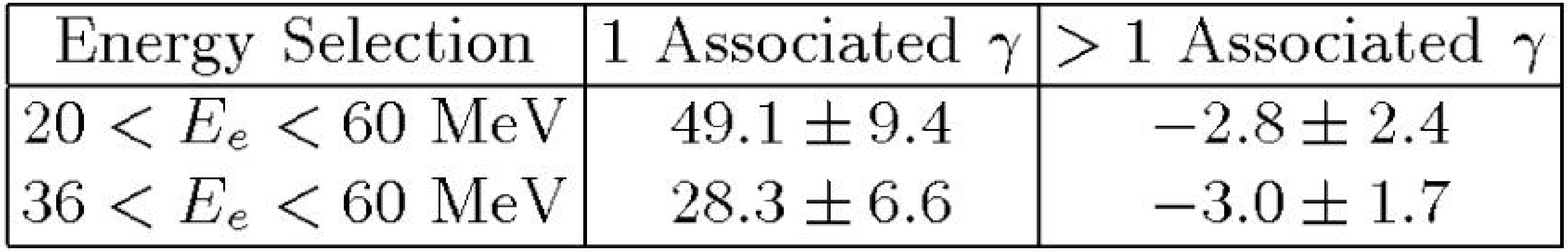


Tests of the DAR oscillation hypothesis

Is there an excess of events with >1 correlated γ?

recoil n from $\bar{\nu}_e p \rightarrow e^+ n$ is < 5 MeV, too low in energy to knock out additional neutrons

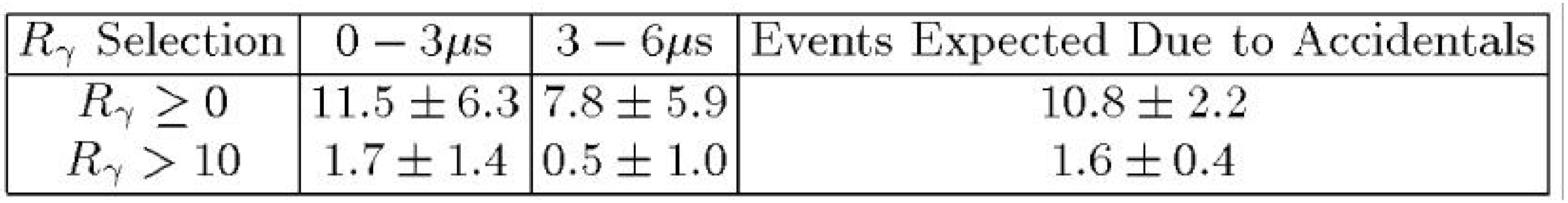
if excess involves higher energy neutrons from cosmic rays or the beam (>20 MeV)
then would expect large excess with >1 correlated γ, as observed in the beam-off data



Energy Selection	1 Associated γ	> 1 Associated γ
$20 < E_e < 60$ MeV	49.1 ± 9.4	-2.8 ± 2.4
$36 < E_e < 60$ MeV	28.3 ± 6.6	-3.0 ± 1.7

“event lookback” check: Is there an excess of events with early activity just below the 18 PMT hit muon threshold?

Extra trigger added in 1995 to read out all PMTs in the 6 μs interval before the primary event provided >11 PMTs hit.



R_γ Selection	$0-3\mu s$	$3-6\mu s$	Events Expected Due to Accidentals
$R_\gamma \geq 0$	11.5 ± 6.3	7.8 ± 5.9	10.8 ± 2.2
$R_\gamma > 10$	1.7 ± 1.4	0.5 ± 1.0	1.6 ± 0.4

Is the $\bar{\nu}_\mu$ flux estimate correct, and thus is the correlated neutron background from this source estimated correctly?

R_γ distribution for $\nu_\mu C \rightarrow \mu^- N,\ \bar{\nu}_\mu C \rightarrow \mu^+ B,\ \bar{\nu}_\mu p \rightarrow \mu^+ n$

had correlated γ expectation of ~14% and 0.129 ± 0.013 was found

DIF analysis

Analysis extended up to 200 MeV. However,

event selection was optimized for the DAR analysis

therefore, beam-off backgrounds above 60 MeV are large

Applying the above analysis to the $60 < E_e < 200$ MeV data (except no correlated γ):

Beam on–off excess: 14.7 ± 12.2 events

bkgd: 6.6 ± 1.7 events

Total excess: $8.1 \pm 12.2 \pm 1.7$ events

Osc. prob: $(0.10 \pm 0.16 \pm 0.04)\%$

Less precise than previous analysis of 1993-95 data, where the total excess was $18.1 \pm 6.6 \pm 4.0$ events

Osc. prob: $(0.26 \pm 0.10 \pm 0.05)\%$

Neutrino oscillation fit

Likelihood in the $\sin^2 2\theta - \Delta m^2$ plane is formed over each of the 5697 beam-on events that pass the oscillation cuts.

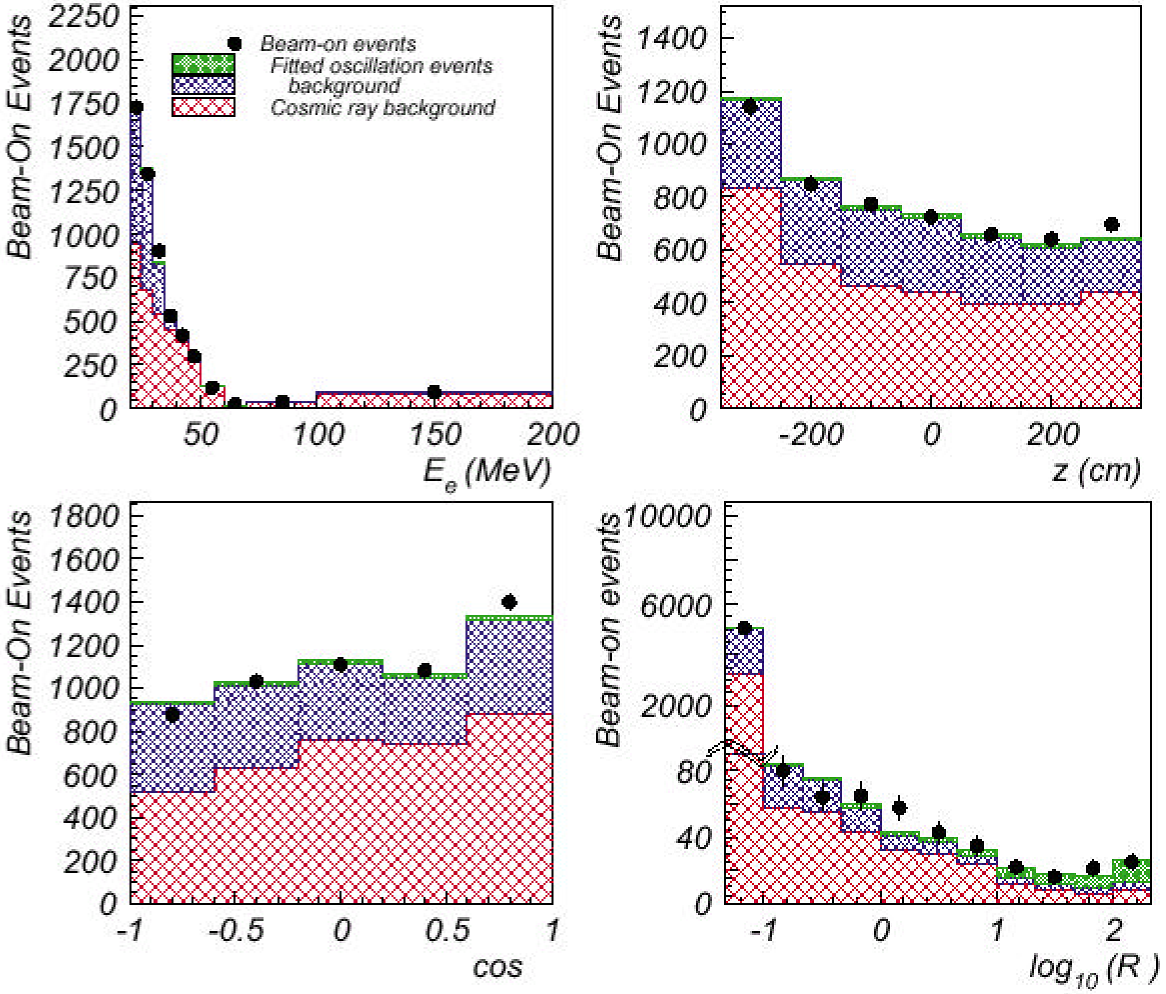
Beam related backgrounds are determined from MC.

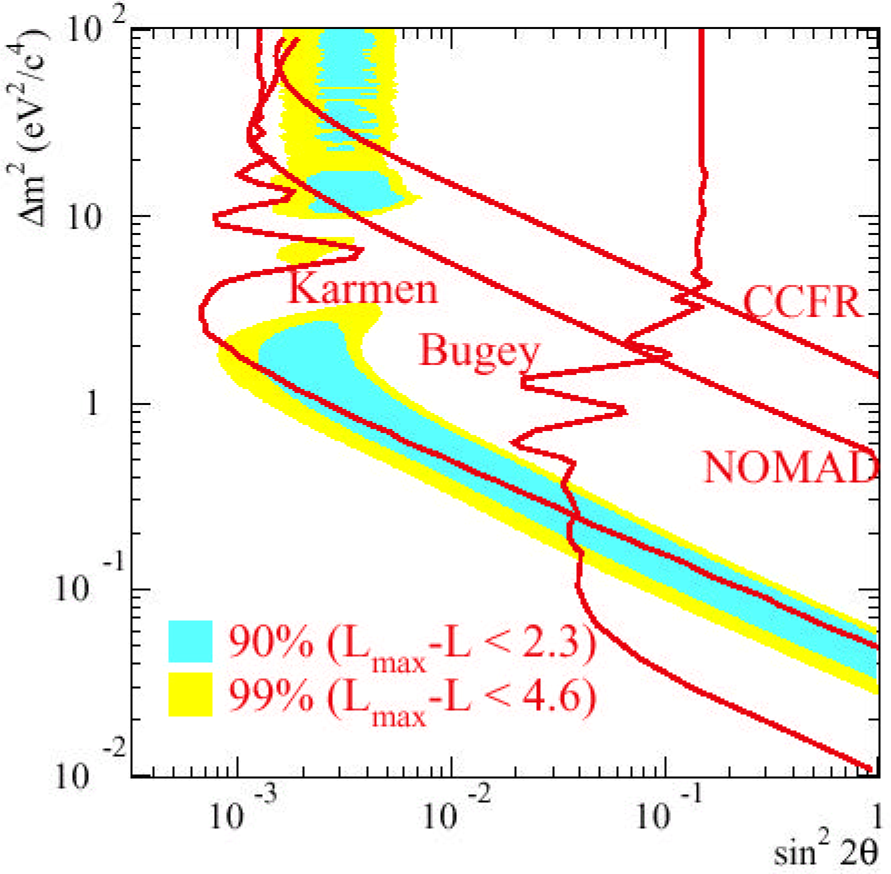
Fit over $20 < E_e < 200$ MeV — both DAR and DIF

Each beam-on event characterized by four variables:

- electron energy E_e
- electron reconstructed distance along the tank z
- direction the electron makes with the ν $\cos\theta_\nu$
- correlated γ likelihood ratio R_γ

Neutrino oscillation fit

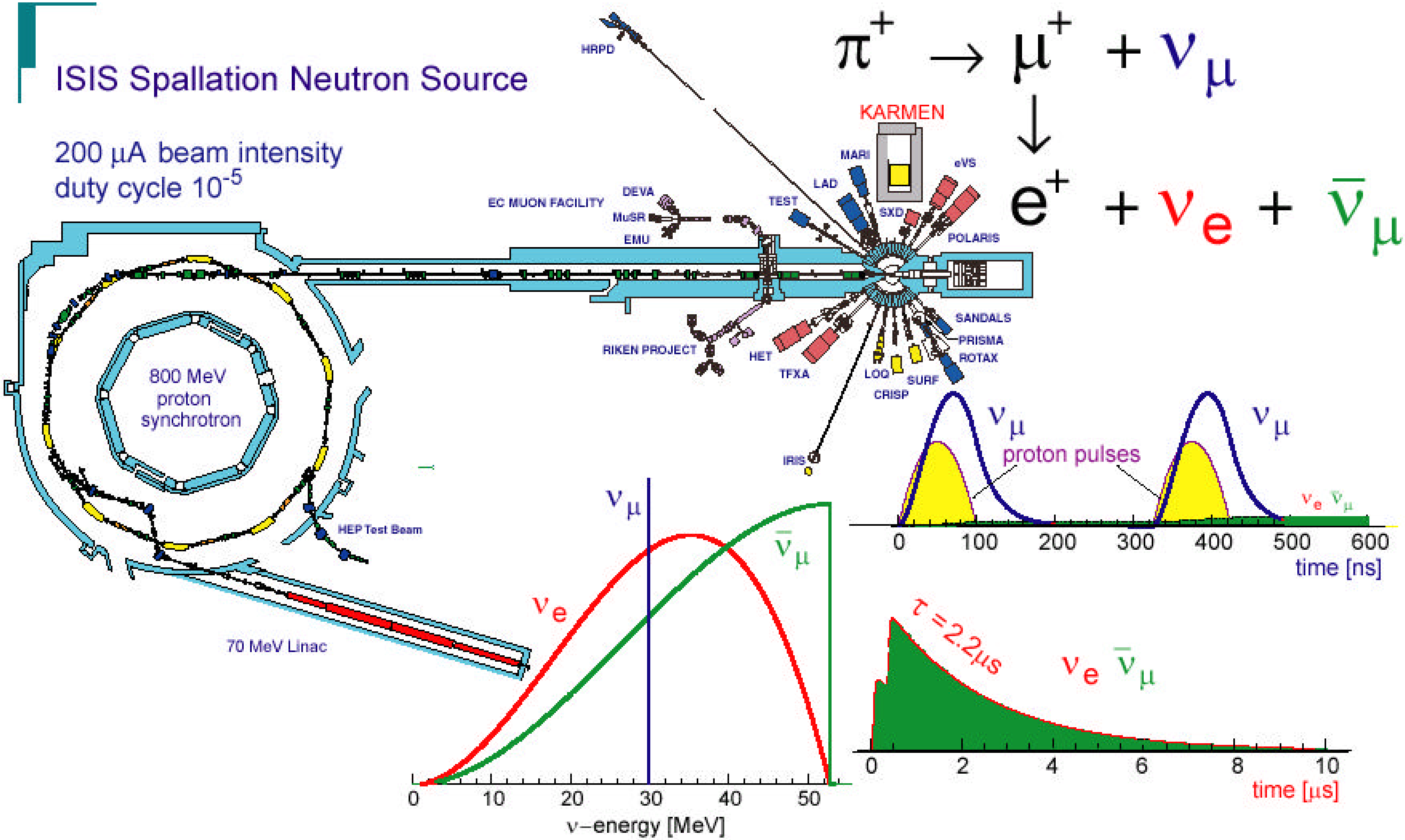




LSND oscillation parameter fit results

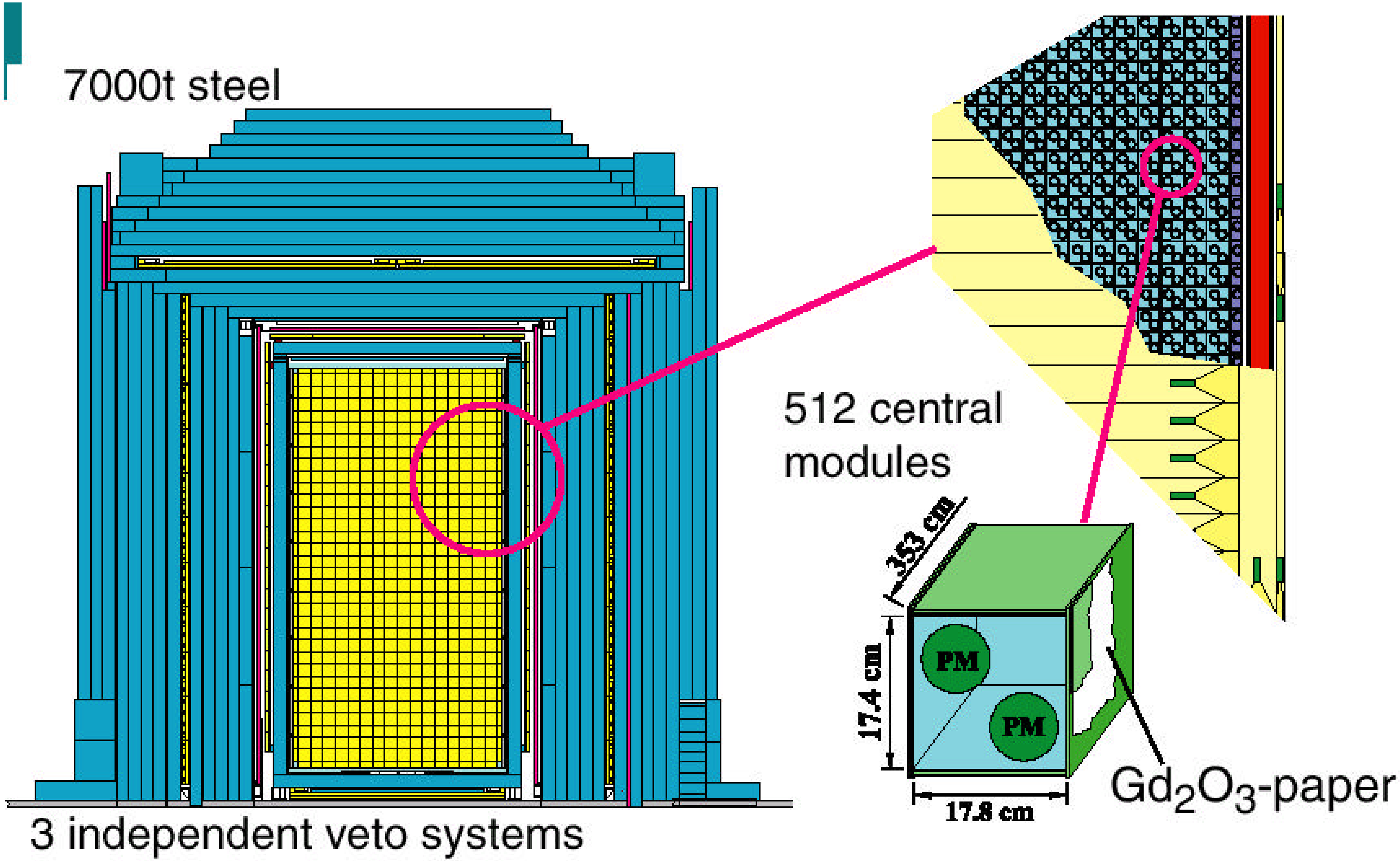
90% CL limits from other experiments

KARMEN


ISIS Spallation Neutron Source
200 µA beam intensity
duty cycle 10⁻⁵
800 MeV proton synchrotron
70 MeV Linac
HEP Test Beam
HRPD
EC MUON FACILITY
DEVA
MuSR
EMU
TEST
LAD
MARI
KARMEN
SXD
eVS
POLARIS
SANDALS
PRISMA
ROTAX
RIKEN PROJECT
HET
TFXA
LOQ
SURF
CRISP
IRIS
π⁺ → µ⁺ + νµ
↓
e⁺ + νe + ν̄µ
νµ
proton pulses
νe ν̄µ
0
100
200
300
400
500
600
time [ns]
νµ
νe
ν̄µ
0
10
20
30
40
50
ν−energy [MeV]
τ =2.2µs
νe ν̄µ
0
2
4
6
8
10
time [µs]

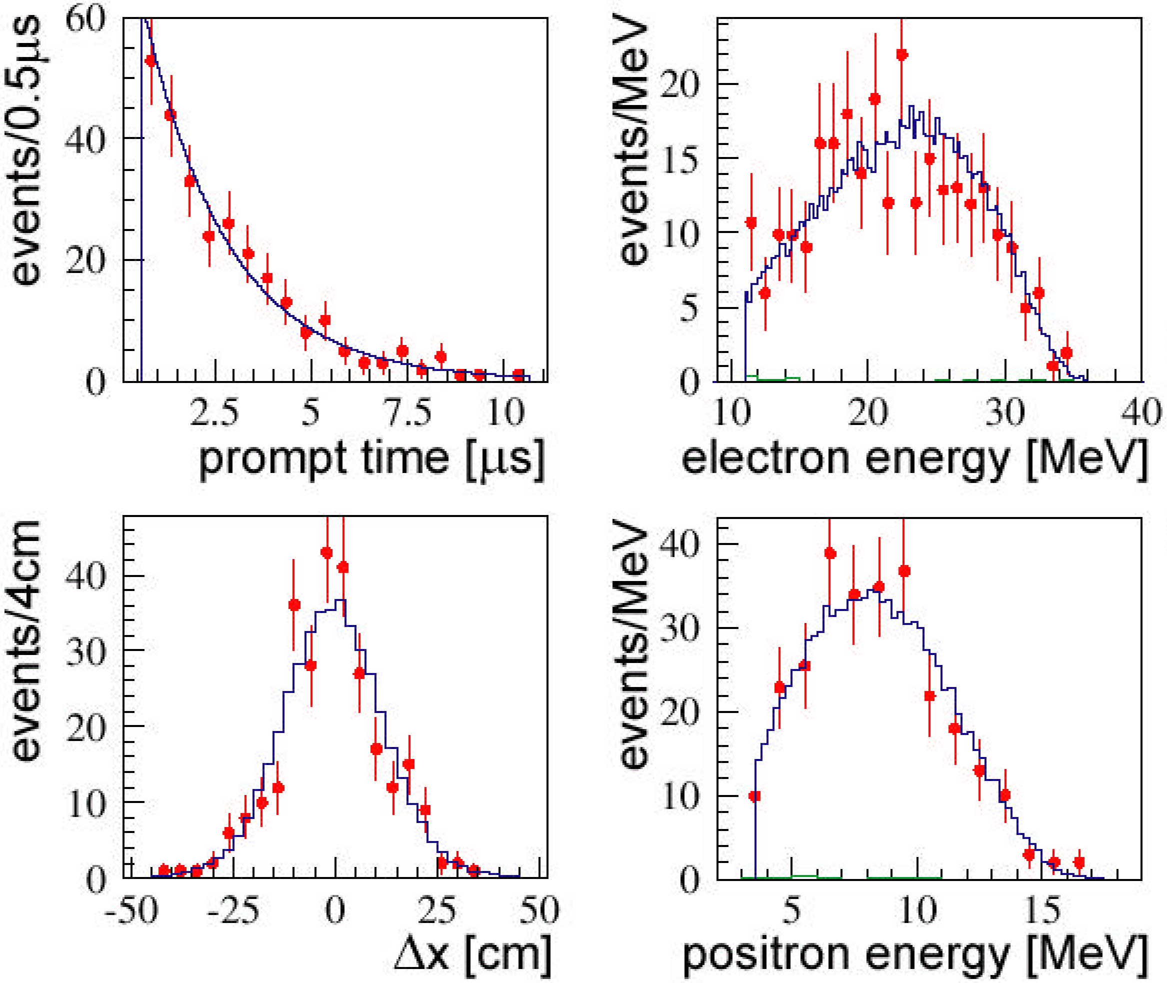
KARMEN detector

Position from struck module and PMT signals from each end.



e+β events

$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$



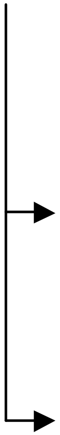
274 sequences,

1.3 cosmic bg

281 sequences
expected
from KARMEN1

Oscillation signature at KARMEN

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

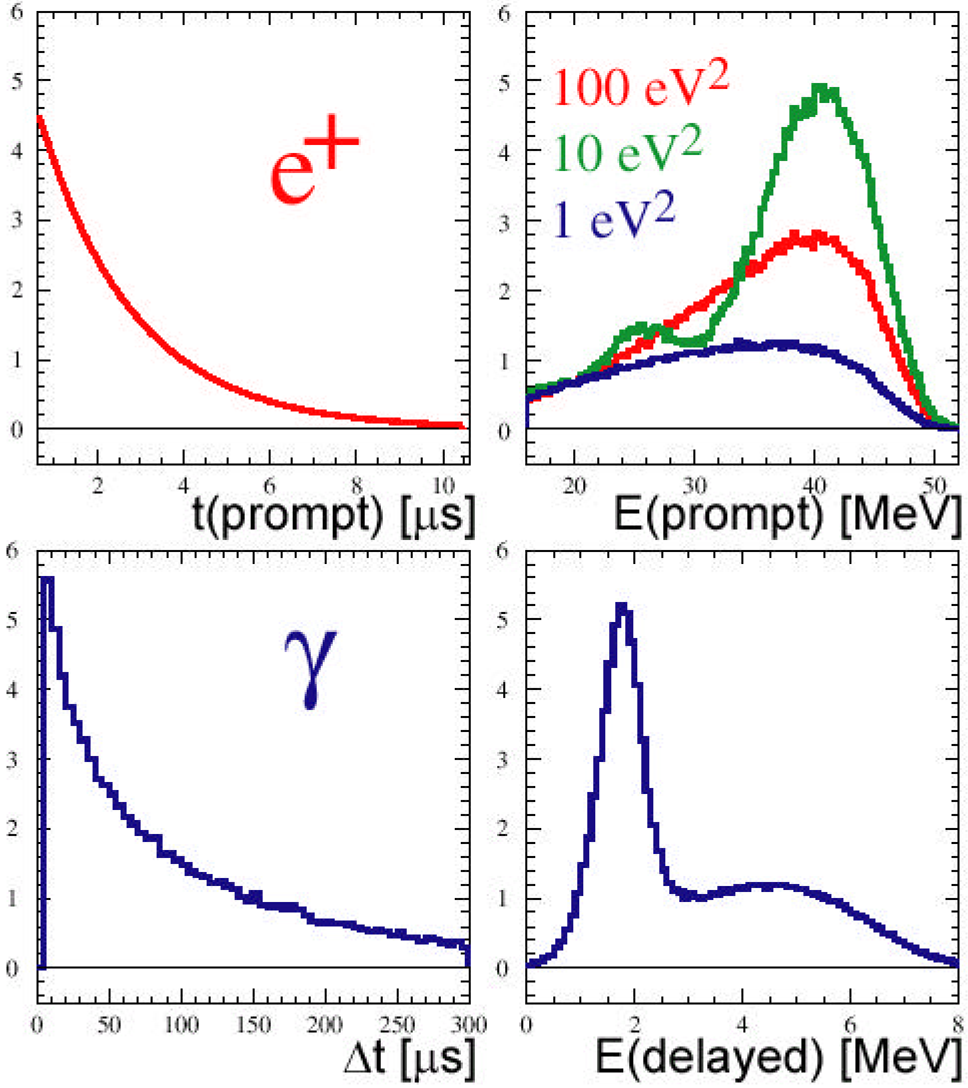


$Gd(n,\gamma)$

$\Sigma E_\gamma = 8\,\mathrm{MeV}$

$p(n,\gamma)$

$\Sigma E_\gamma = 2.2\,\mathrm{MeV}$



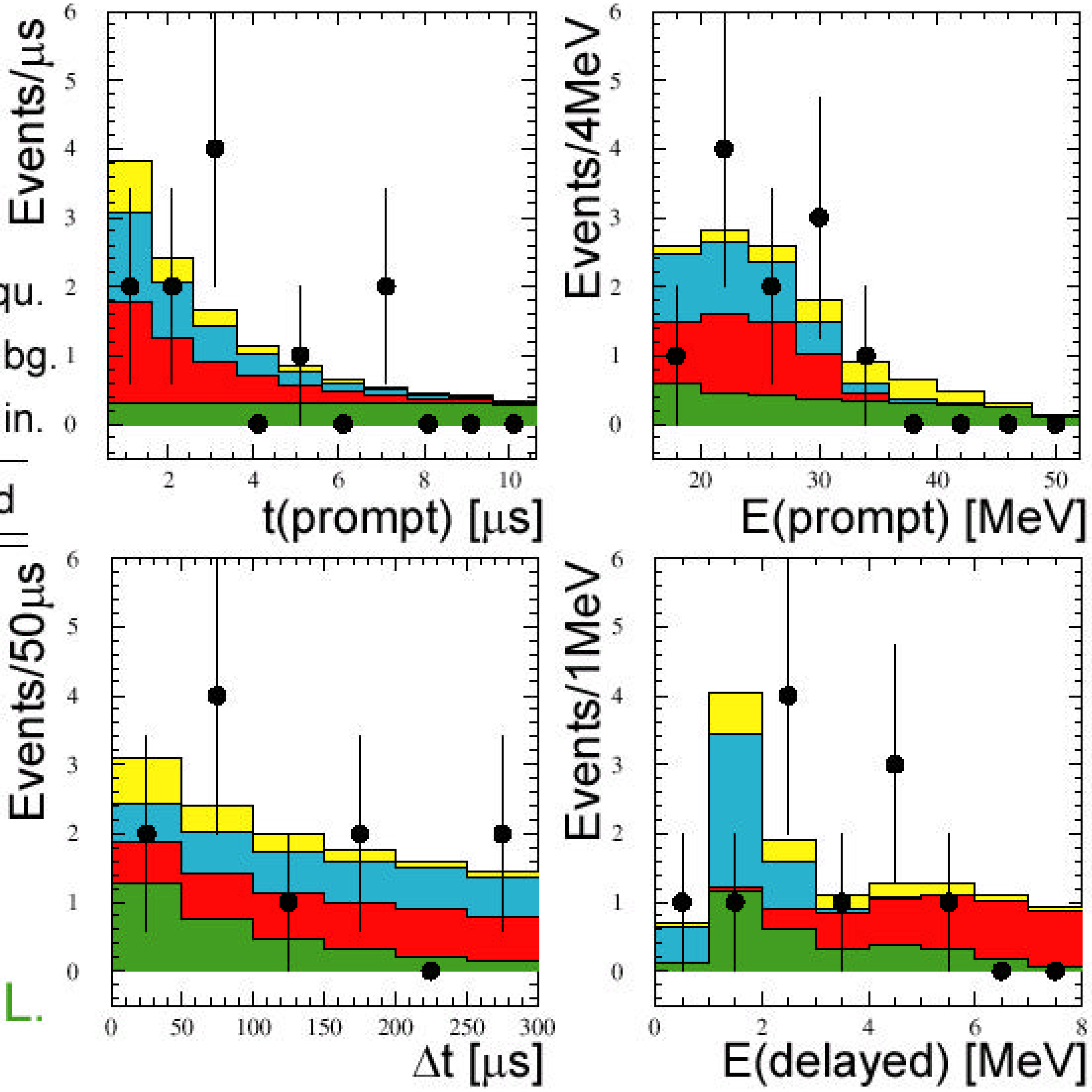
KARMEN oscillation results

11 candidates

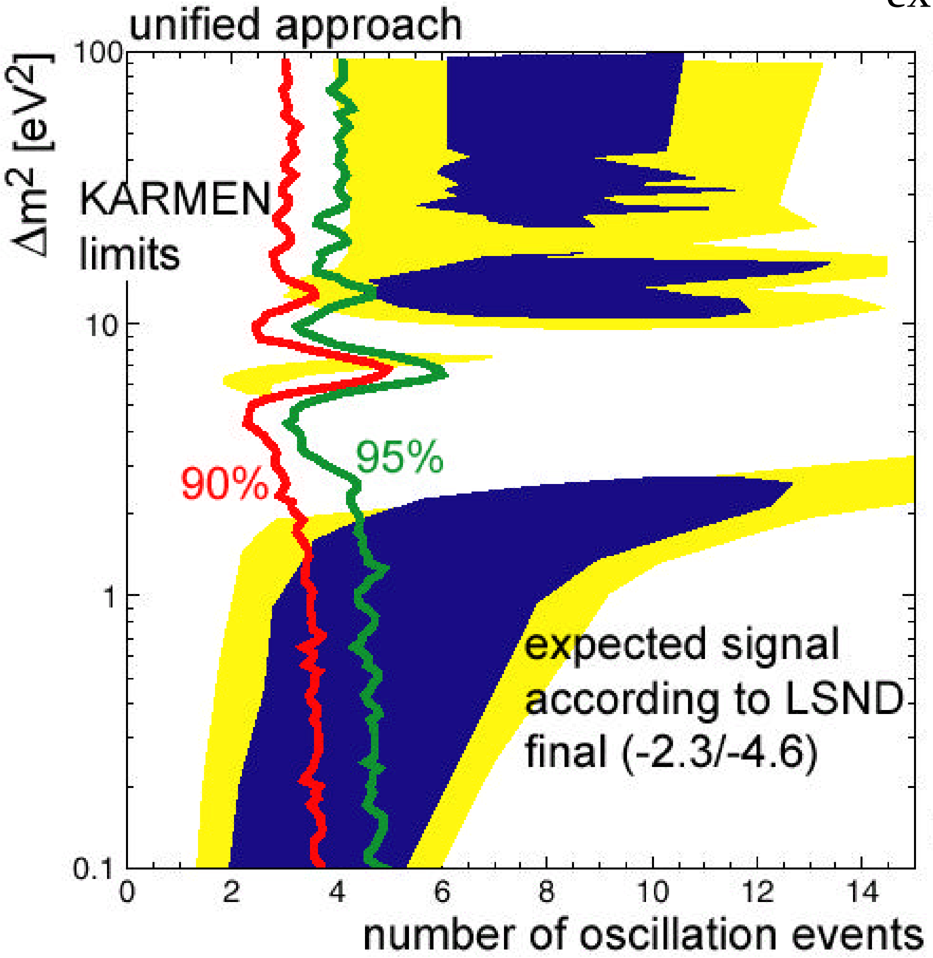
3.9 +- 0.5	🟥	ν_e-induced CC sequ.
3.5 +- 0.3	🟦	ν-induced random bg.
1.7 +- 0.2	🟨	$\bar{\nu}_e$ intrinsic contamin.
3.2 +- 0.2	🟩	cosmic background
12.3 +- 0.6		total background

⟹ **no osci signal**

Bayes:
signal > 6.3 evts
excluded @ 90% C.L.



KARMEN: expected excess for LSND hypothesis



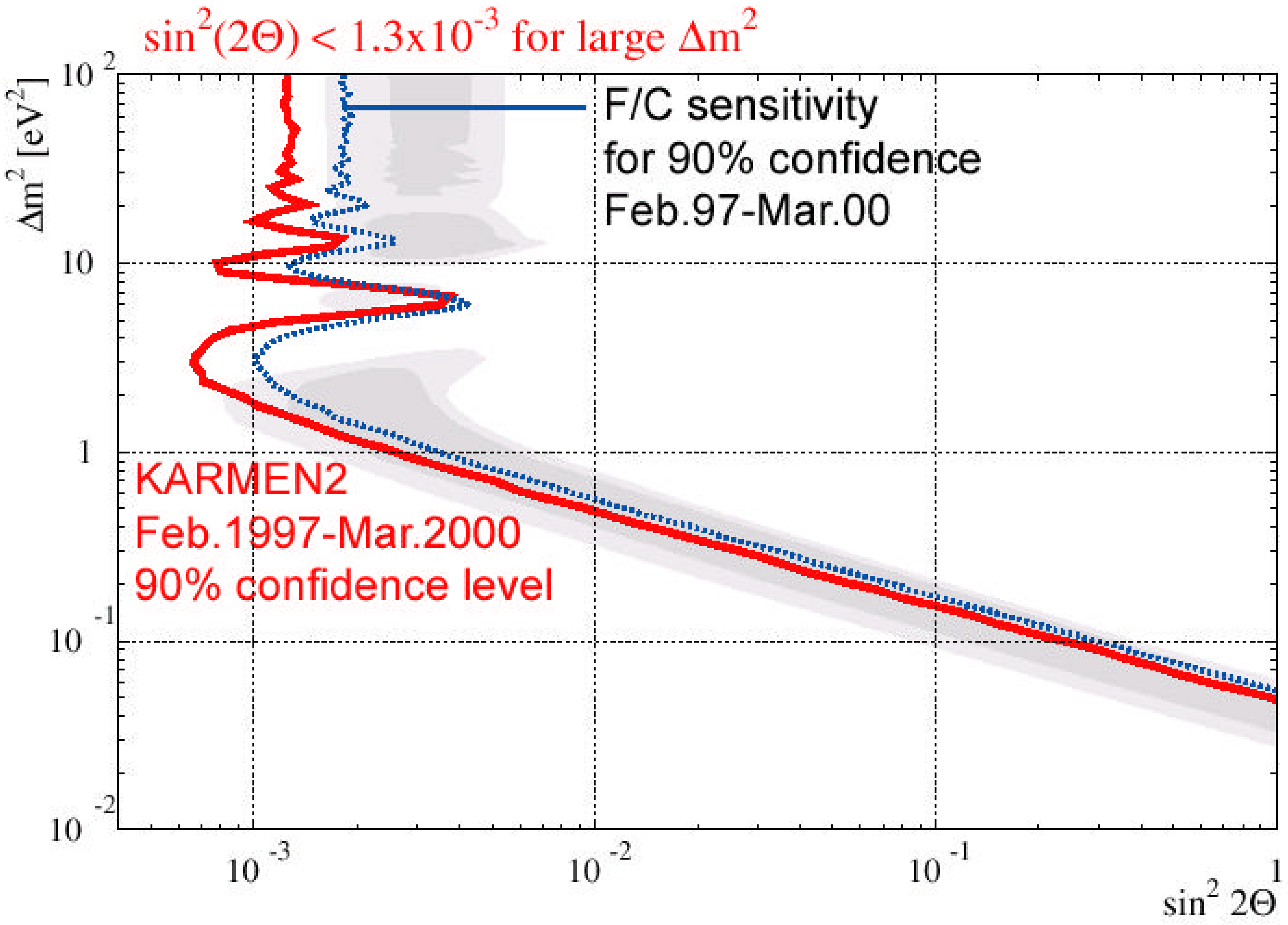
excess for 100% transmutation

N(expected)=2442 for $\sin^2(2\Theta)=1$

N(osc)<**3.1** (90% CL)
$\Delta m^2=100\,\mathrm{eV}^2$

N(osc)<**3.8** (90% CL)
$\Delta m^2=0.1\,\mathrm{eV}^2$

KARMEN sensitivity plot



KARMEN November 2000 status report

data Feb.´97-March 2000
(7160C prot.-on-target):

11 candidates

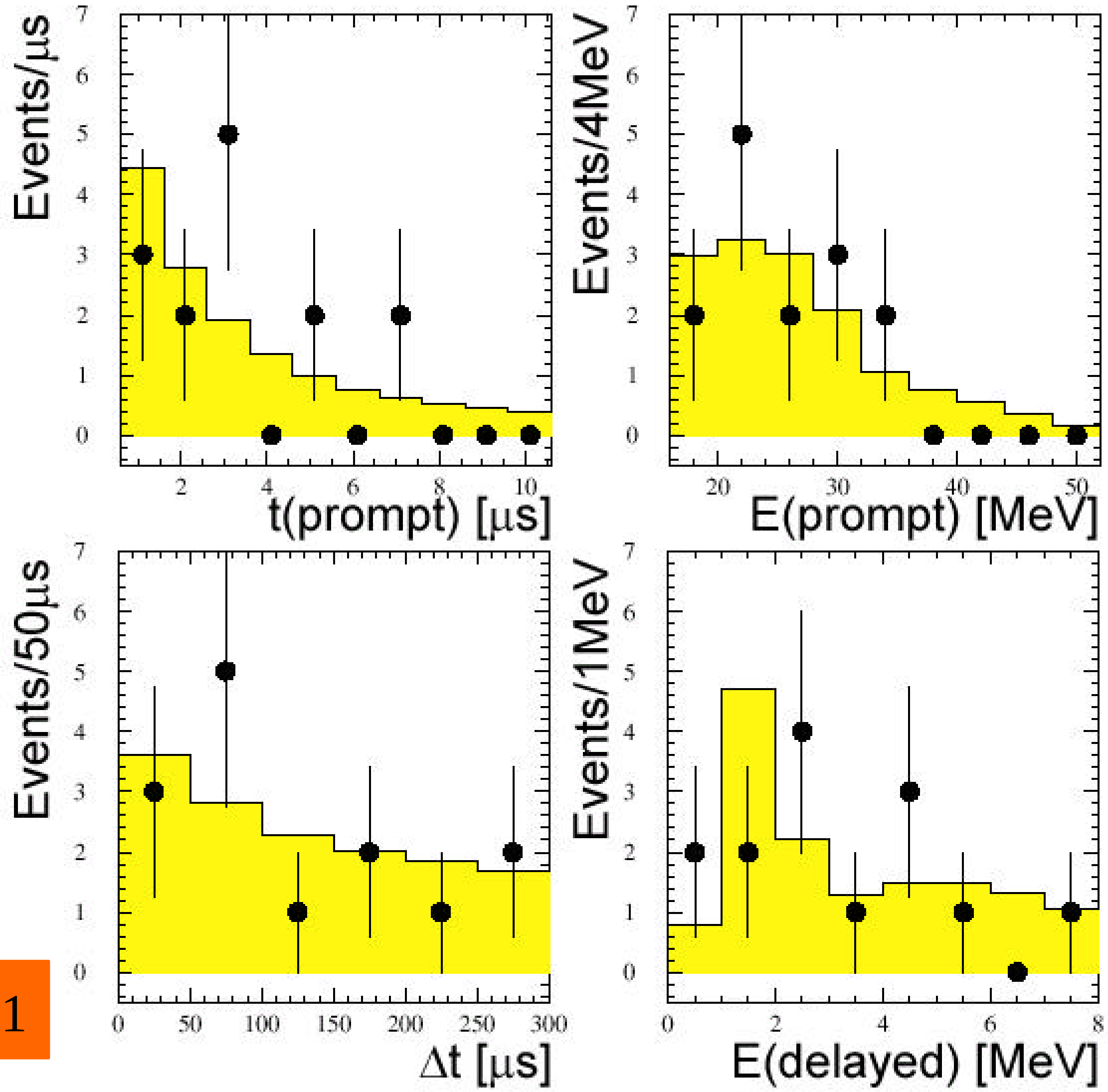
12.3 bg events
sensitivity: $\sin^2 2\Theta < 1.7\times10^{-3}$

data Feb.´97-Nov. 2000
(8300C prot.-on-target):

14 candidates

14.3 bg events

KARMEN ended March 2001



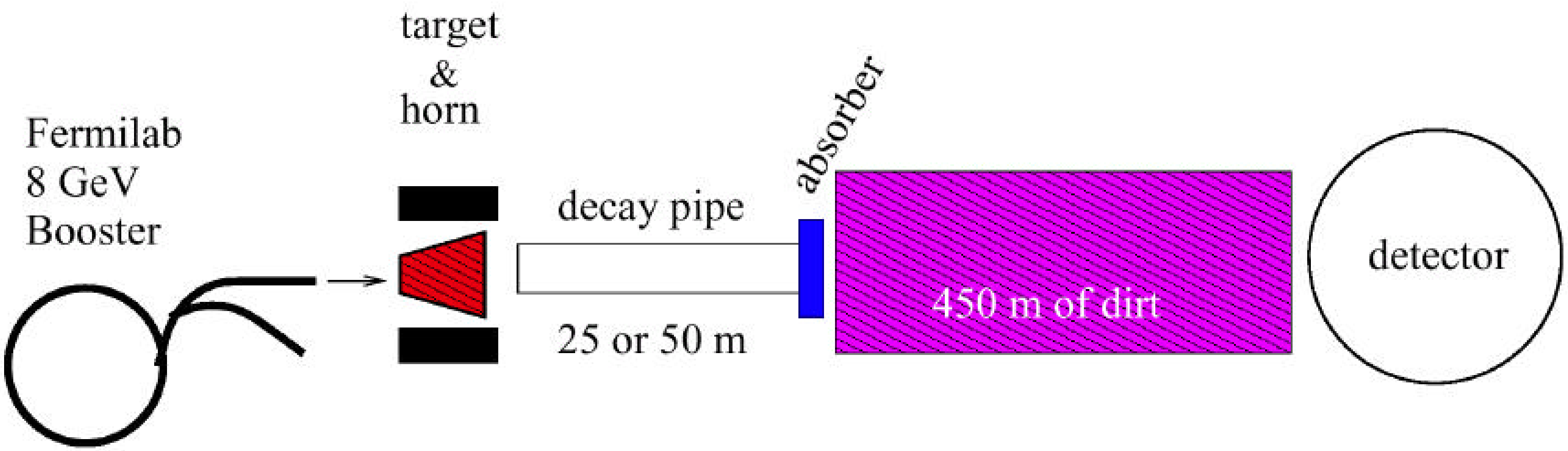
MiniBooNE

Search for $\nu_\mu \rightarrow \nu_e$ appearance

ν_μ disappearance

With *L/E*~1 (same as LSND)

but at order-of-magnitude higher energies



The Booster

8 GeV proton accelerator built
to supply beam to the Main Ring,
it now supplies the Main Injector

Booster must now run at
record intensity

MiniBooNE will run simultaneously with the other programs:
e.g. Run II + BooNE
5×10^{12} protons per pulse at a rate of 7.5 Hz
(5 Hz for BooNE)

BooNE: 5×10^{20} p.o.t in one year

Challenges are radiation issues, losses

MiniBooNE detector

mineral oil

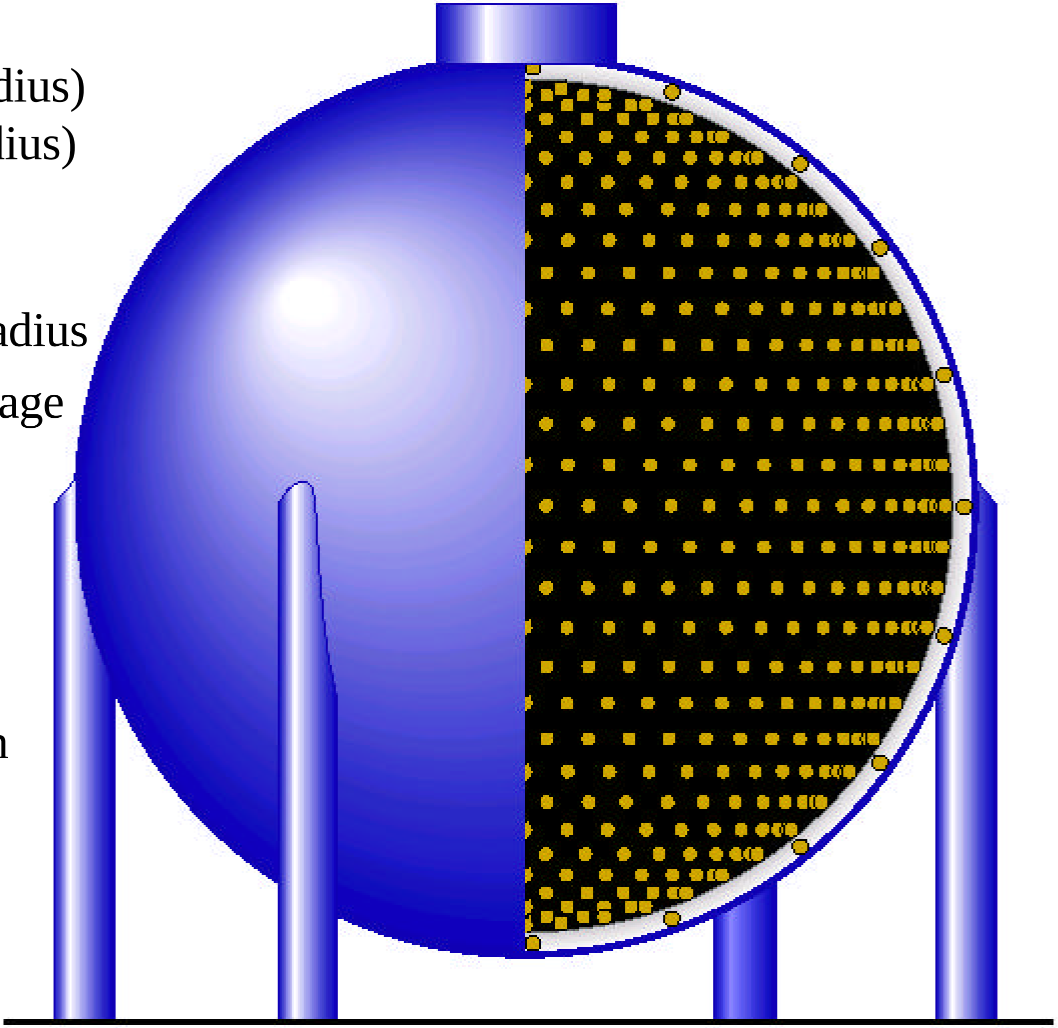
total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5m radius)

1280 PMTs in detector at 5.5 m radius

→ 10% photocathode coverage

240 PMTs in veto

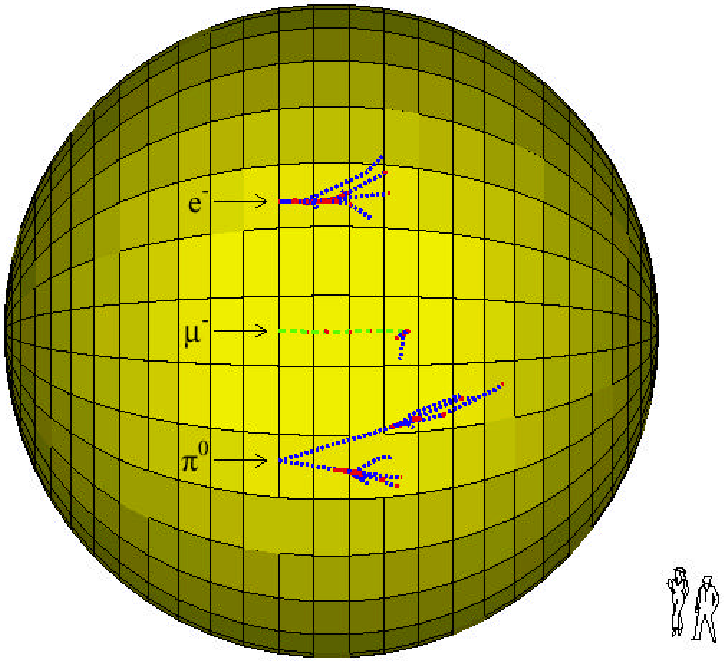
Phototube support structure provides opaque barrier between veto and main volumes

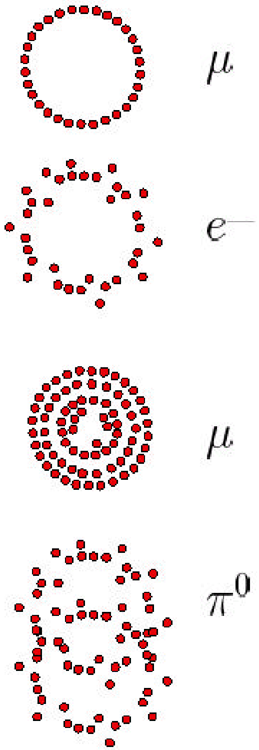


Analysis : e, μ, π^0 discrimination

PID based on ring id, track extent, ratio of prompt/late light
signatures substantially different from LSND
x10 higher energy
neutron capture does not play a role

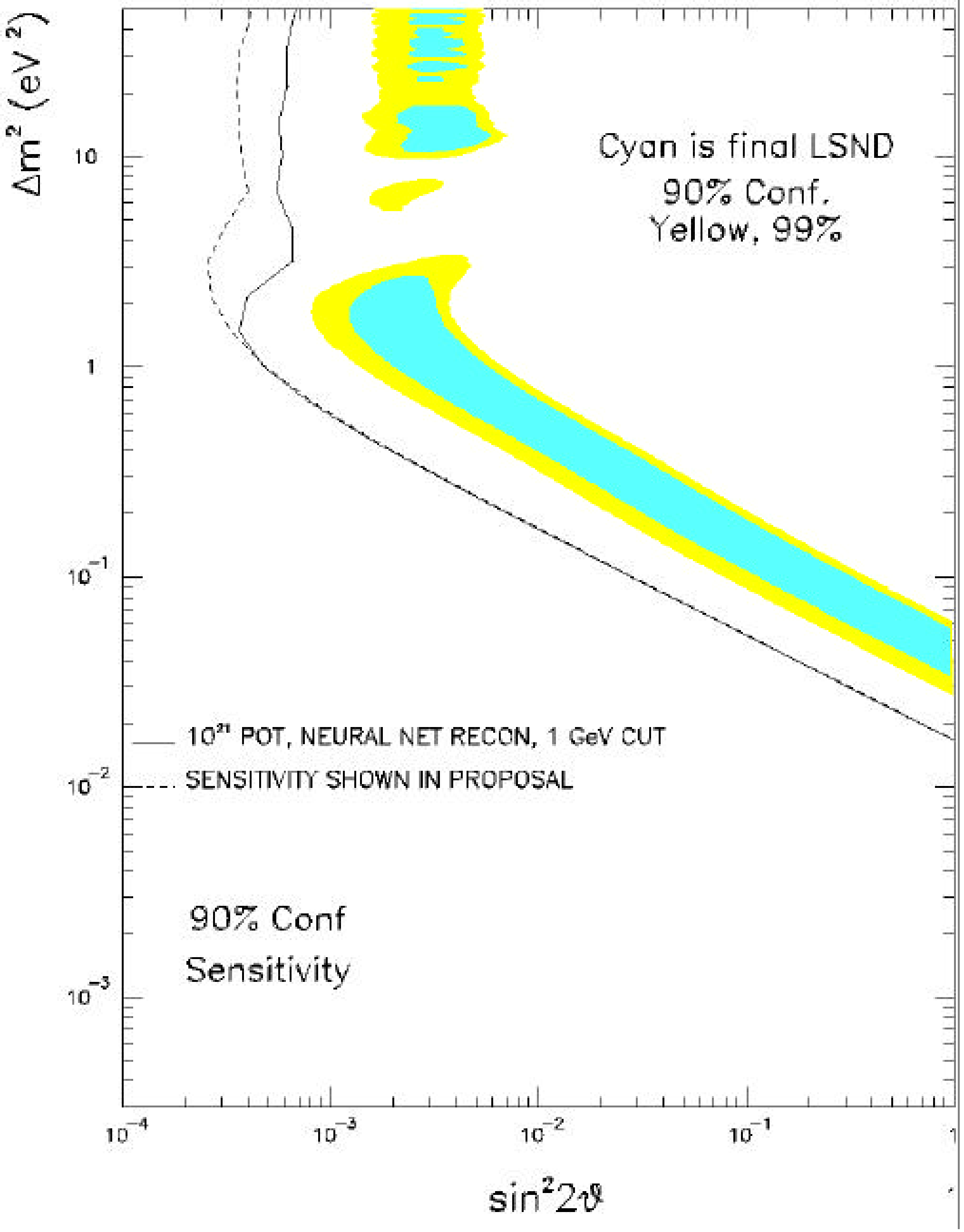
If LSND correct:
~500 events (2 years)





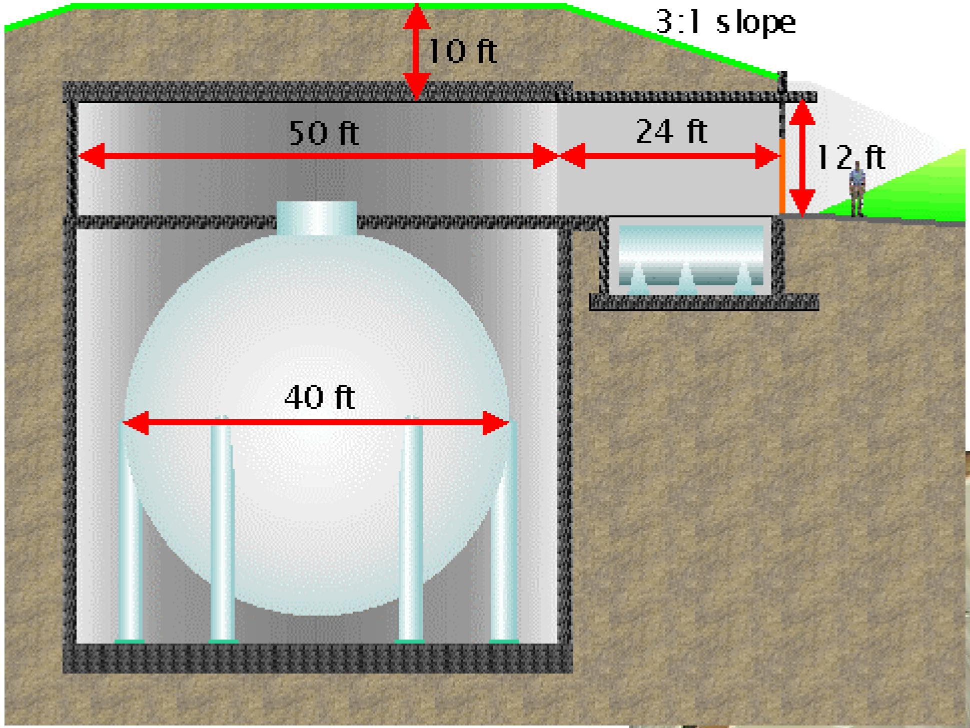
Backgrounds are mis-id of
μ's and π's,
and intrinsic ν_e in the beam

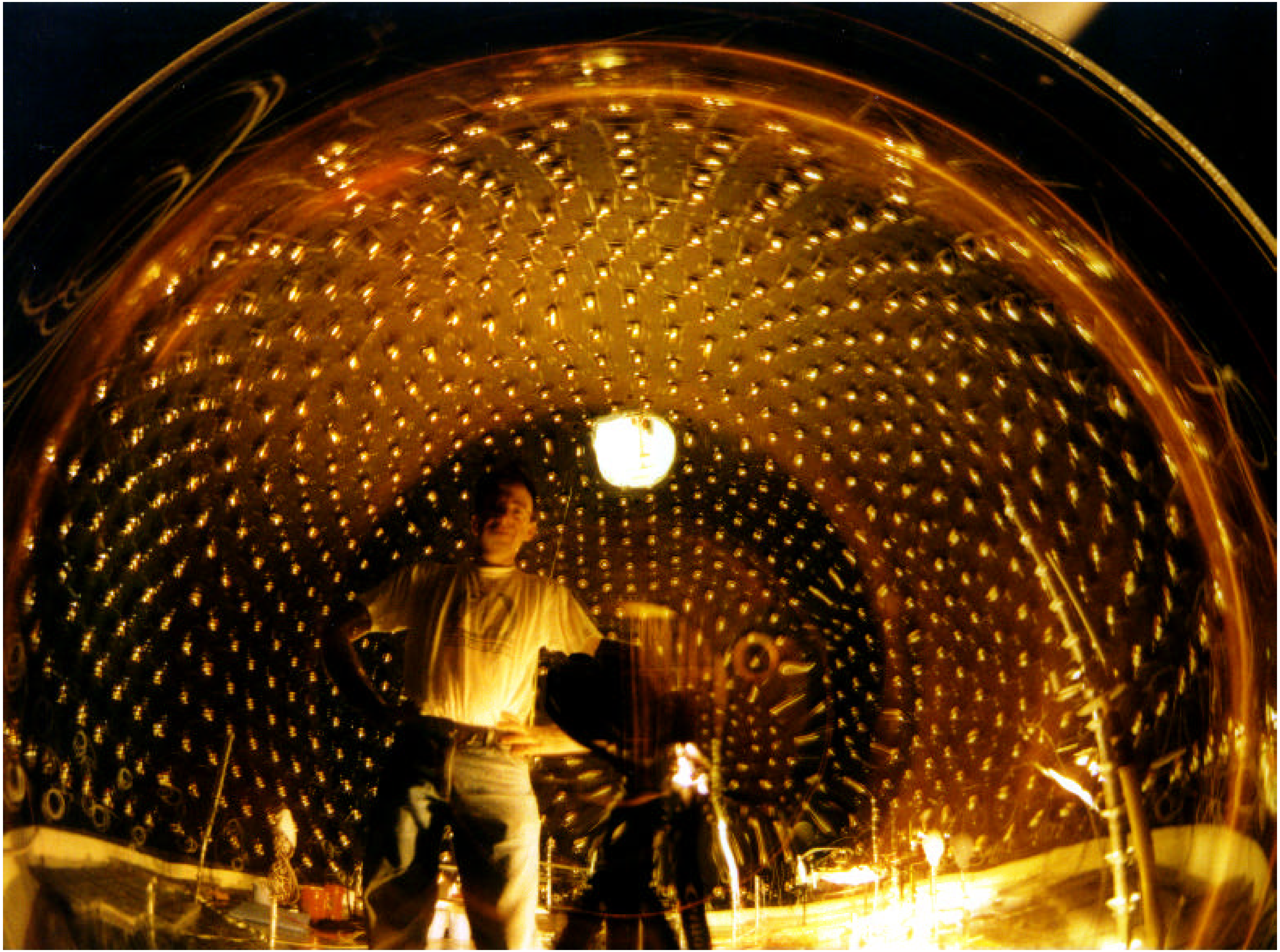
MiniBooNE
expected
sensitivity



MiniBooNE status

1000 PMTs installed





Summary

LSND observes appearance of $\nu_{\mu} \rightarrow \nu_{e}$ oscillations at relatively high Δm^2 and low mixing angle

This observation needs confirmation.

KARMEN does not confirm LSND, but does not rule it out.

MiniBooNE will start collecting data in summer 2002, and will make a definitive statement about LSND after two years.