Current Status of LSND & BooNE

- **LSND**

  Preliminary $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results from 1993–1998

  Published $\nu_\mu \rightarrow \nu_e$ results from 1993–1995

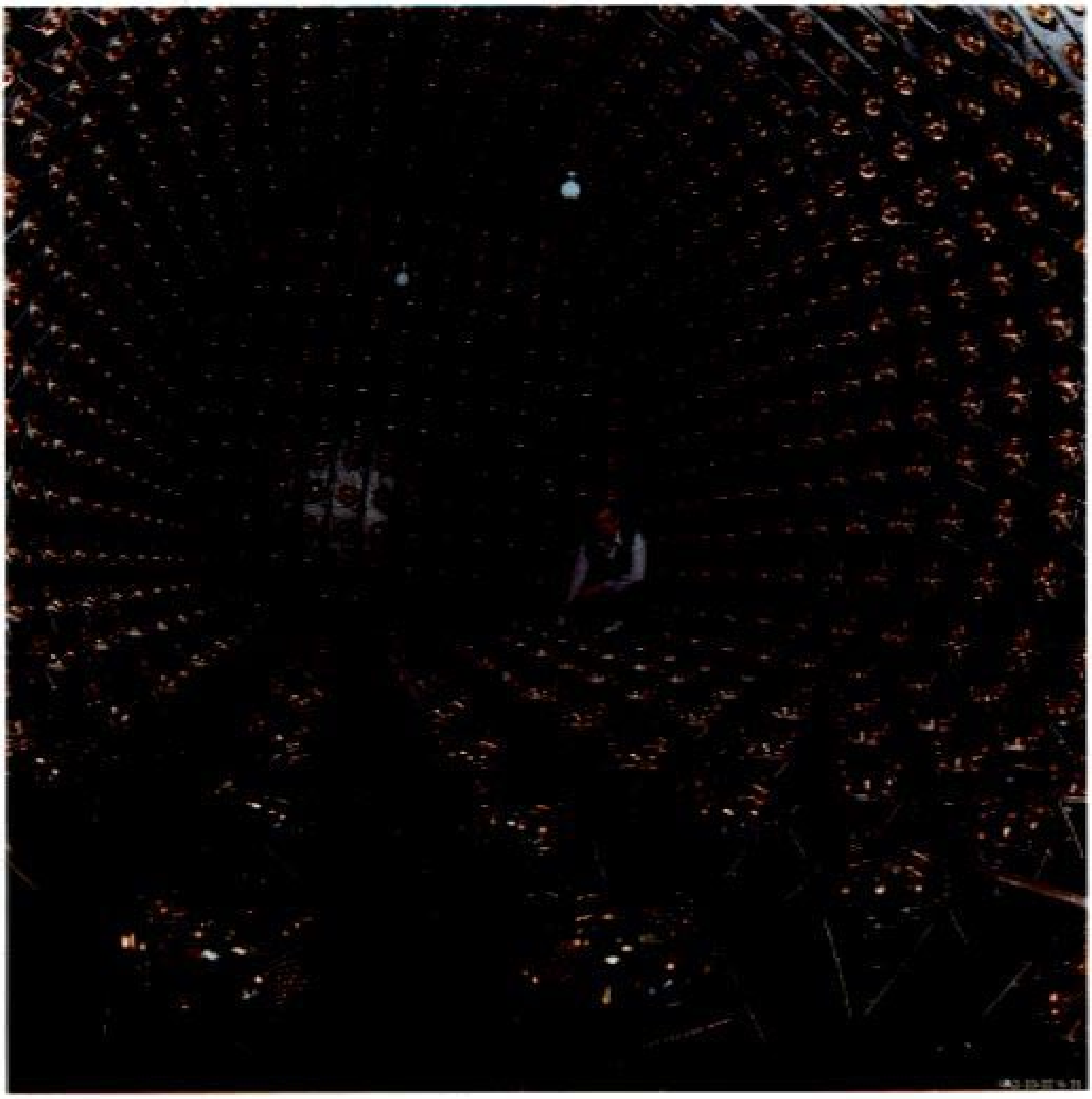
  Final global analysis results (ν oscillations, ν C, ν e, ν p) by the end of 1999

- **BooNE**

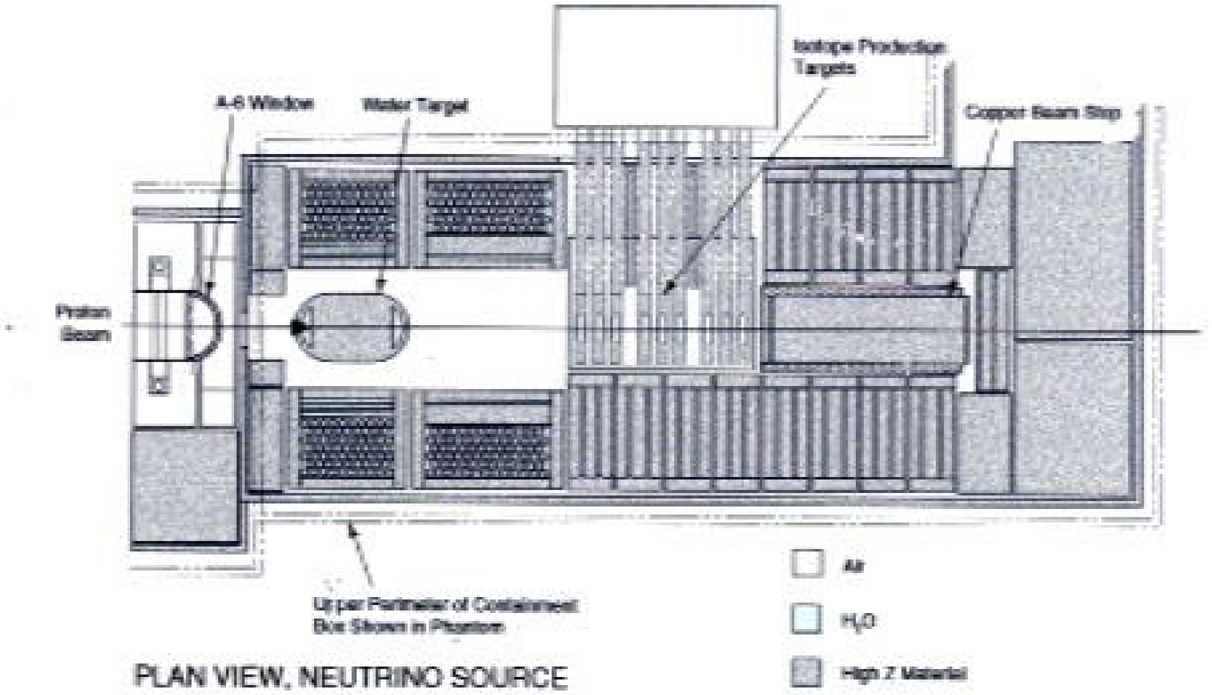
  Definitive test of the LSND signal

  Construction begins in October, 1999

  Data taking begins in December, 2001



Target and Beam Dump

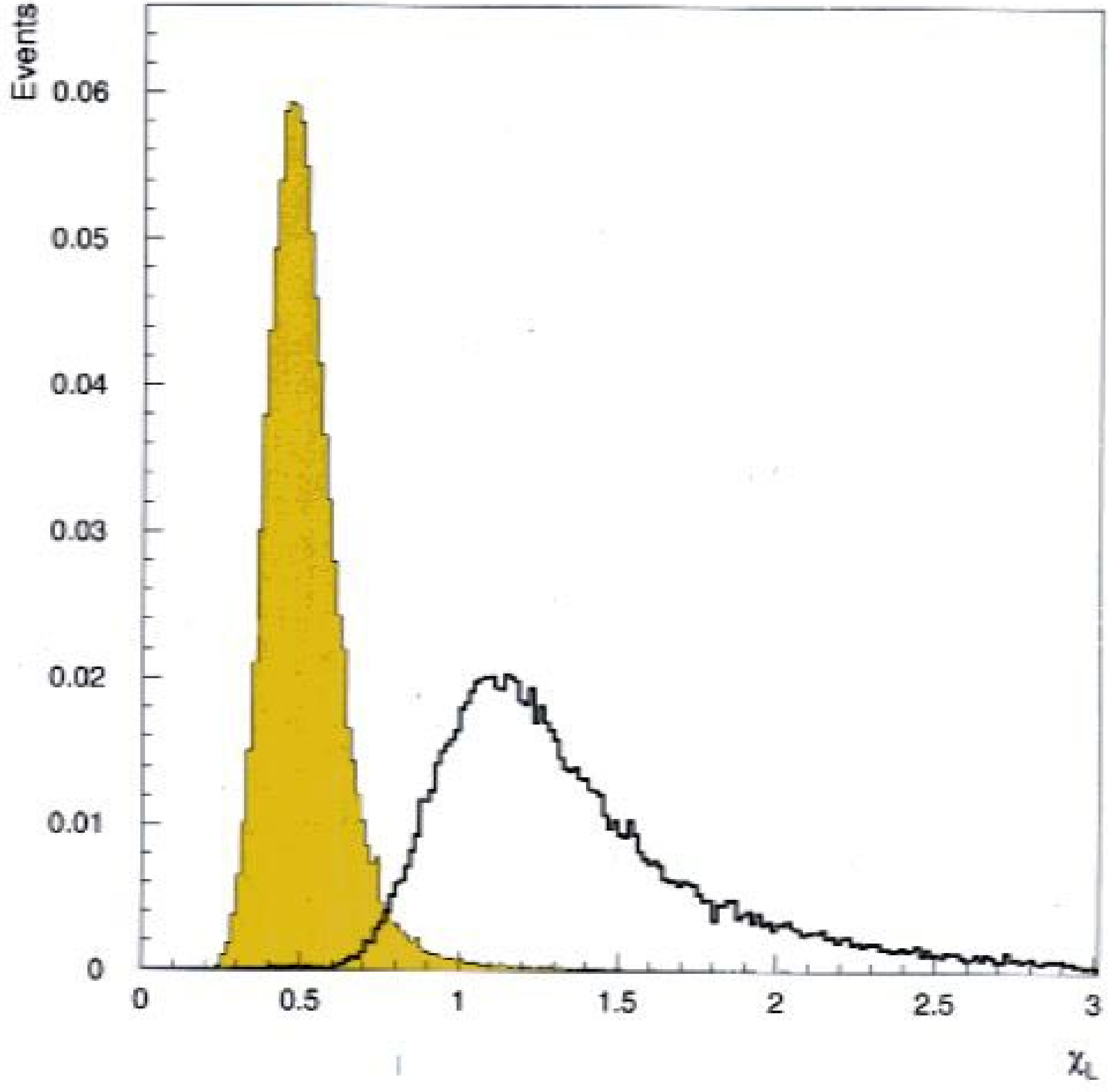


PLAN VIEW, NEUTRINO SOURCE

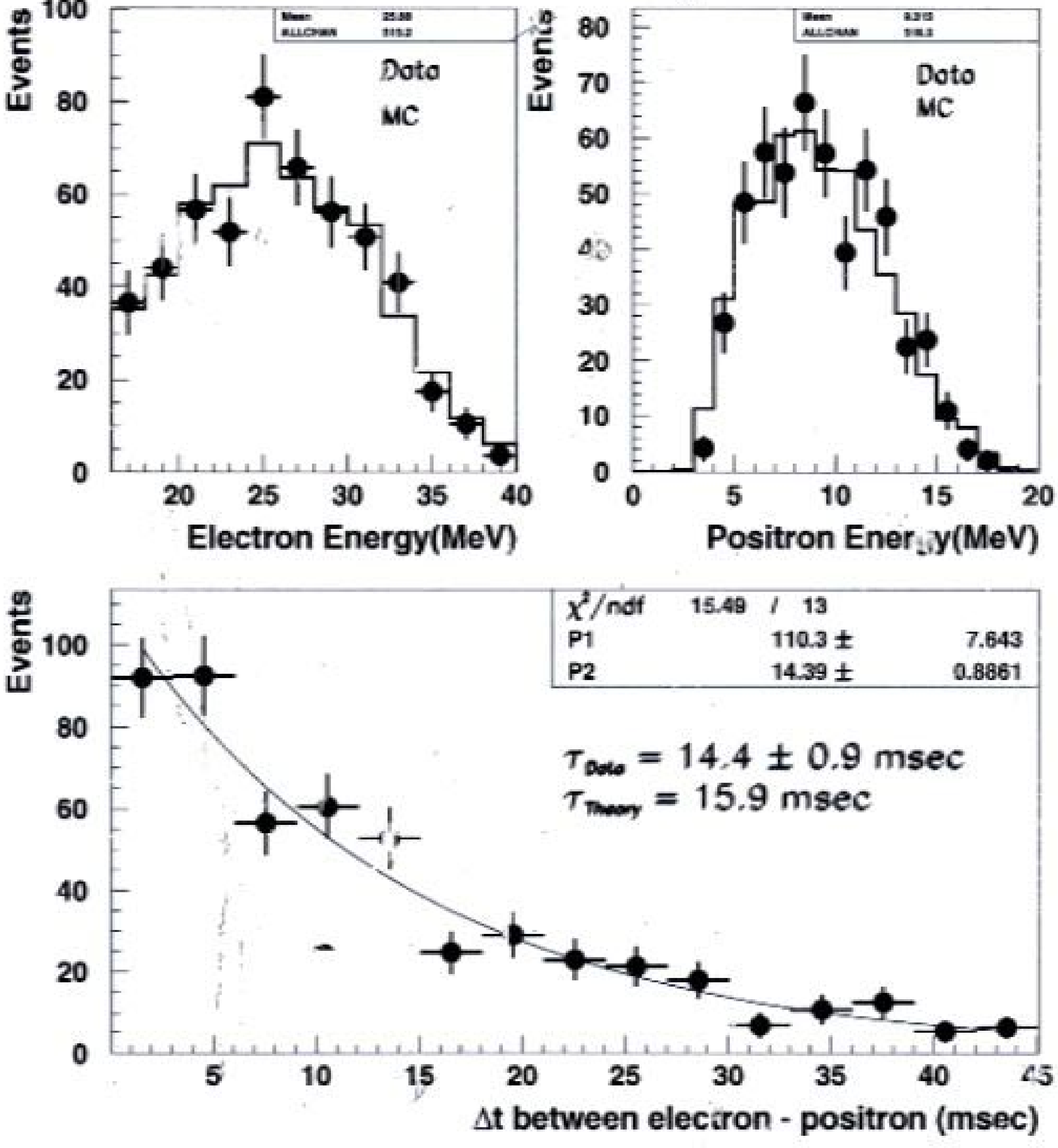
$$\pi^+ \to \mu^+ \nu_\mu$$

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

Particle Identification



$\nu_e C \dashrightarrow e^- N_{g.s.}$

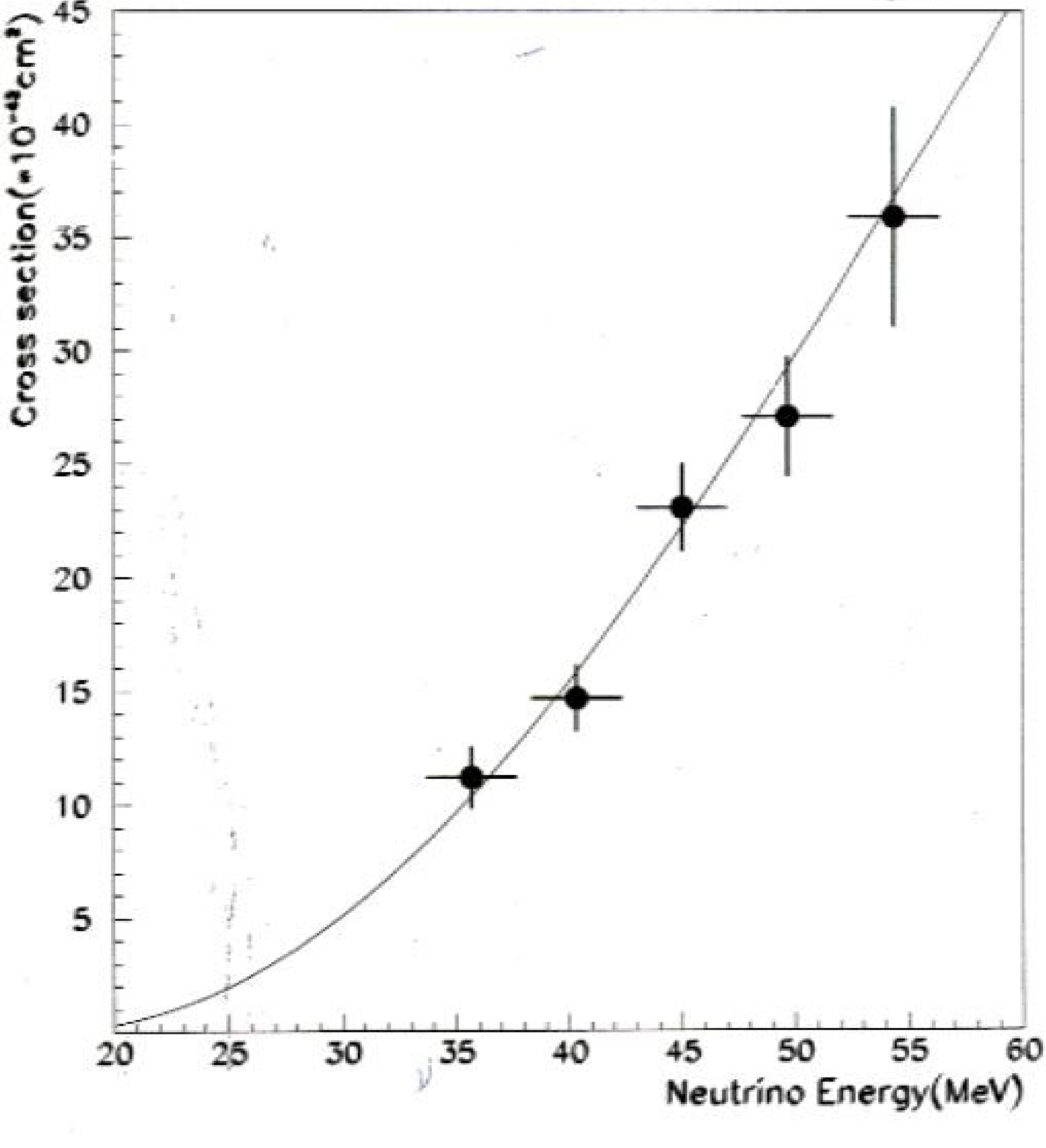


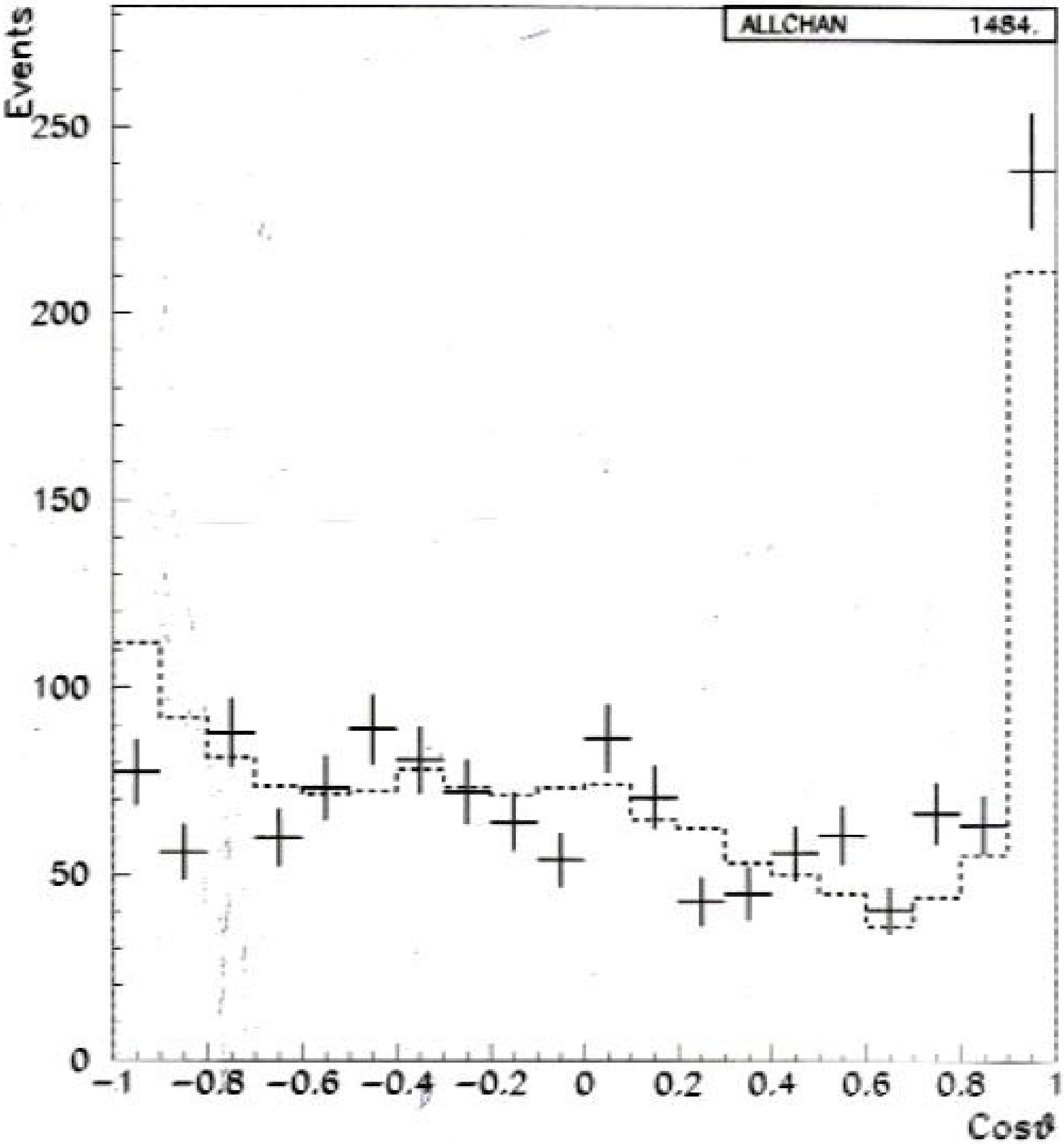
$\sigma = (9.1 \pm 0.4 \pm 0.9) \times 10^{-42}$ cm^2 (LSND)

$(9.4 \pm 0.5 \pm 0.8) \times 10^{-42}$ cm^2 (KARMEN)

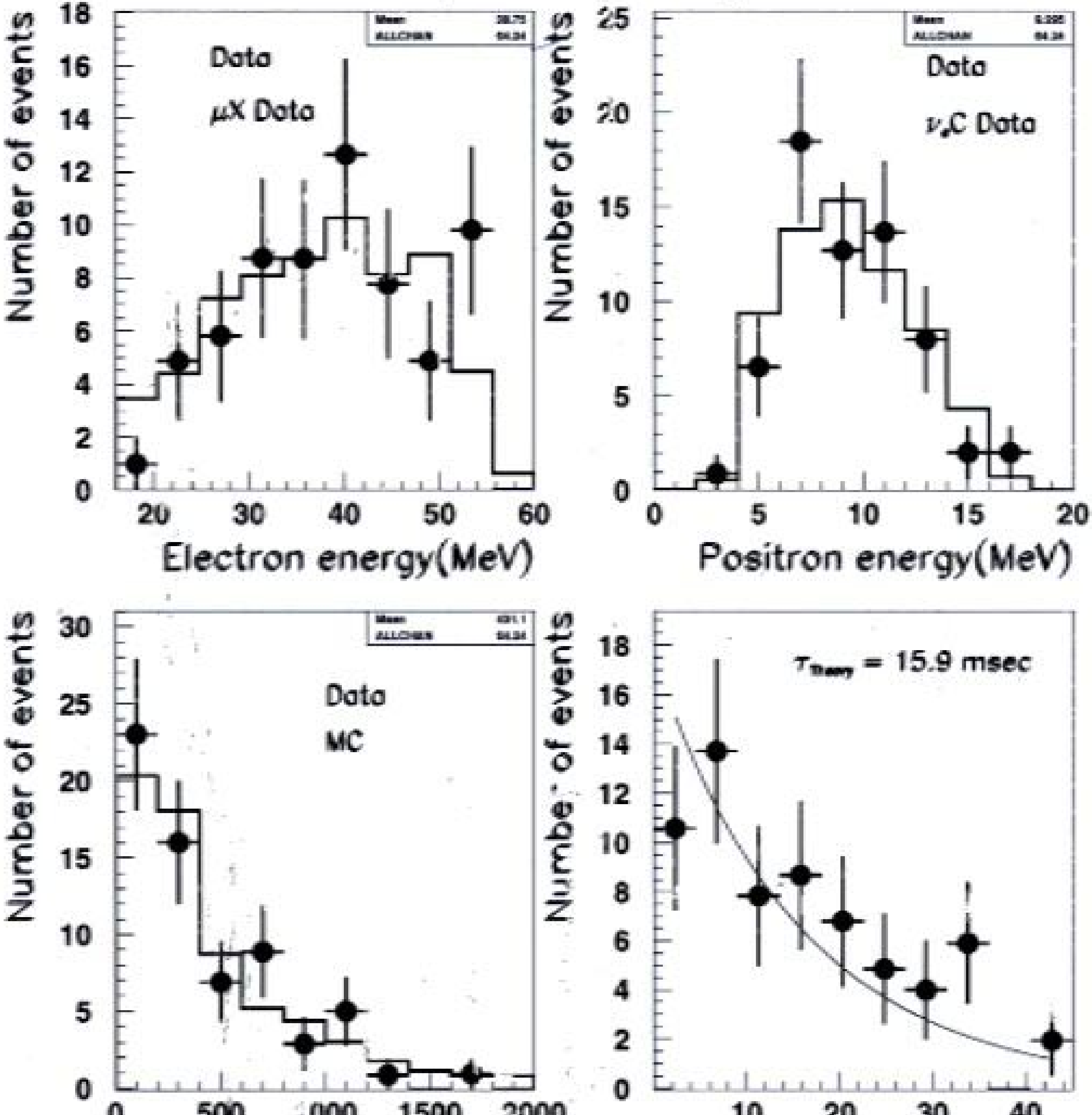
$(9.3 - 9.4) \times 10^{-42}$ cm^2 (theory)

Cross section of $\nu_e C \dashrightarrow e^- N_{g.s.}$



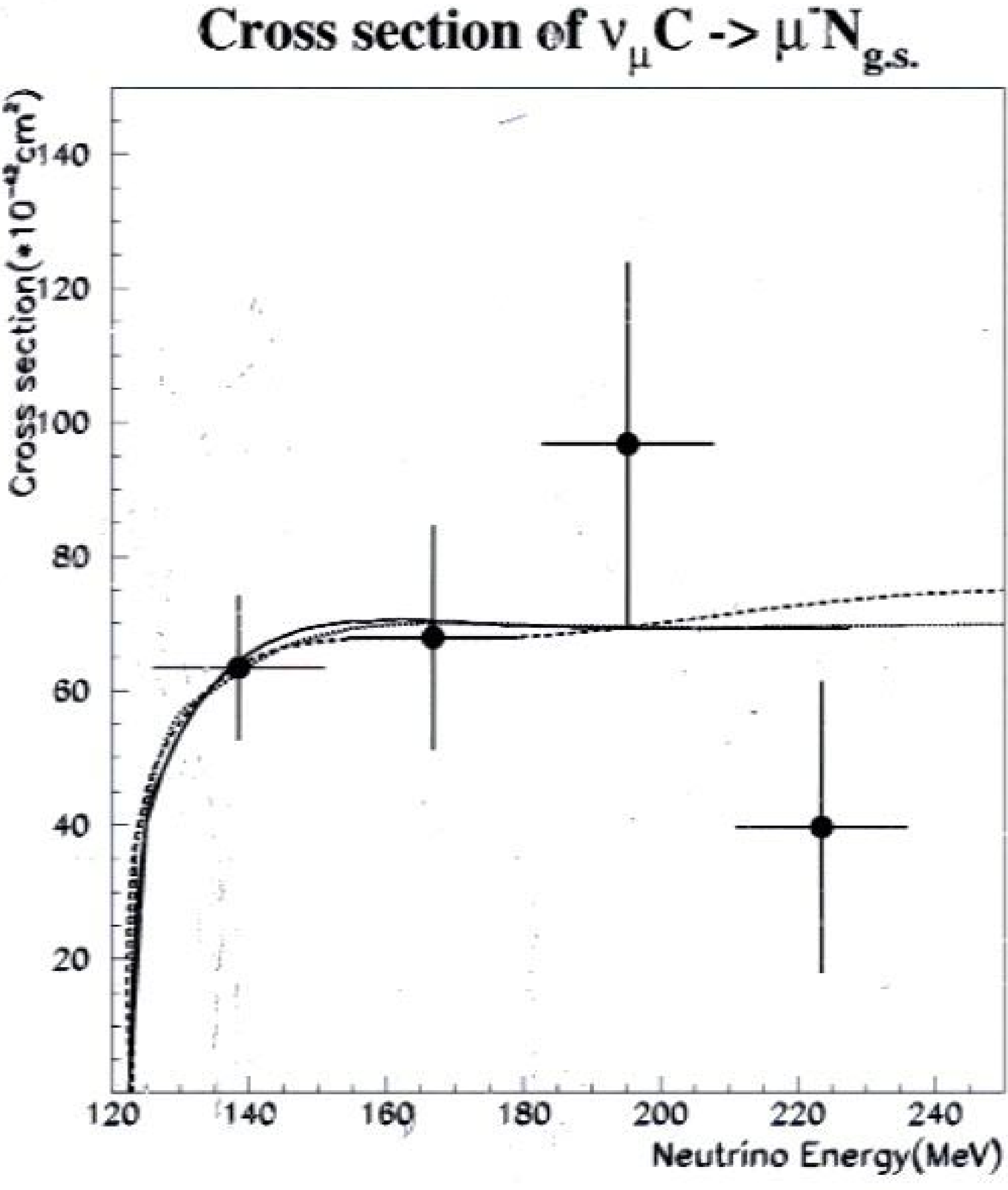

ALLCHAN 1484.
Events
250
200
150
100
50
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Cosθ

$\nu_\mu C \dashrightarrow \mu^- N_{g.s.}$



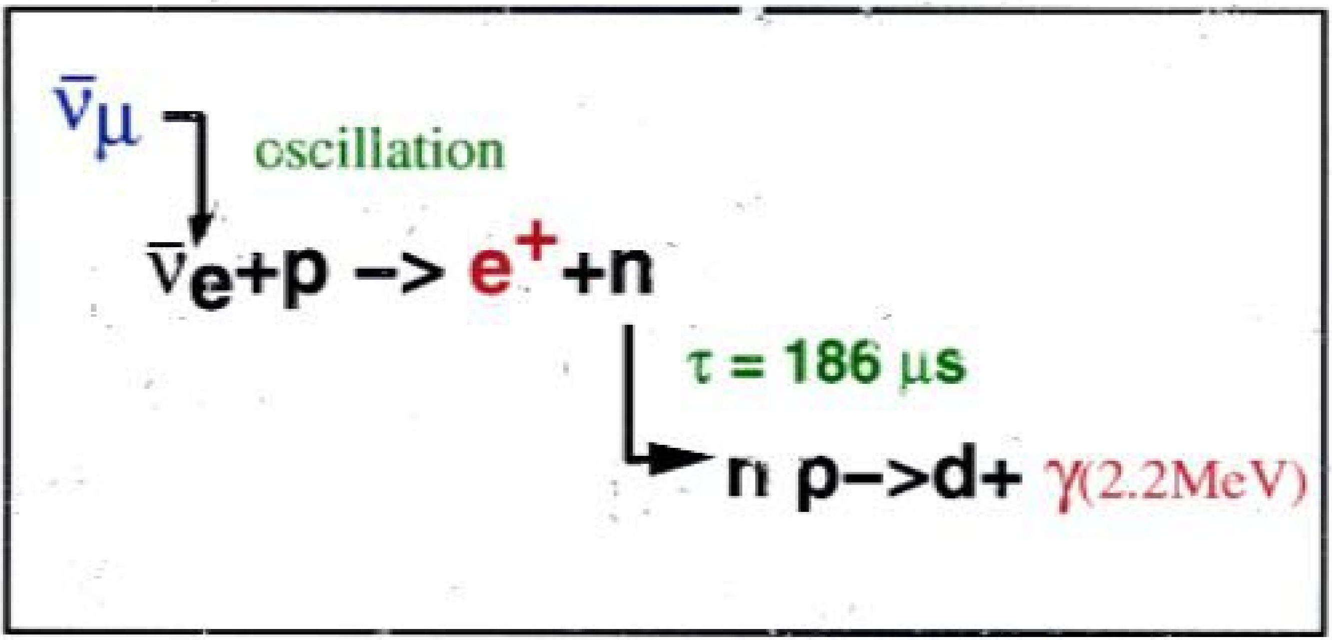
$\sigma = (6.5 \pm 1.0 \pm 1.0) \times 10^{-41}\ cm^2$ (LSND)

$(6.3 - 6.6) \times 10^{-41}\ cm^2$ (theory)



Cross section of $\nu_\mu C \rightarrow \mu^- N_{g.s.}$

ν Oscillation Events Signature



$\bar{\nu}_\mu$ oscillation

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

$\tau = 186\ \mu s$

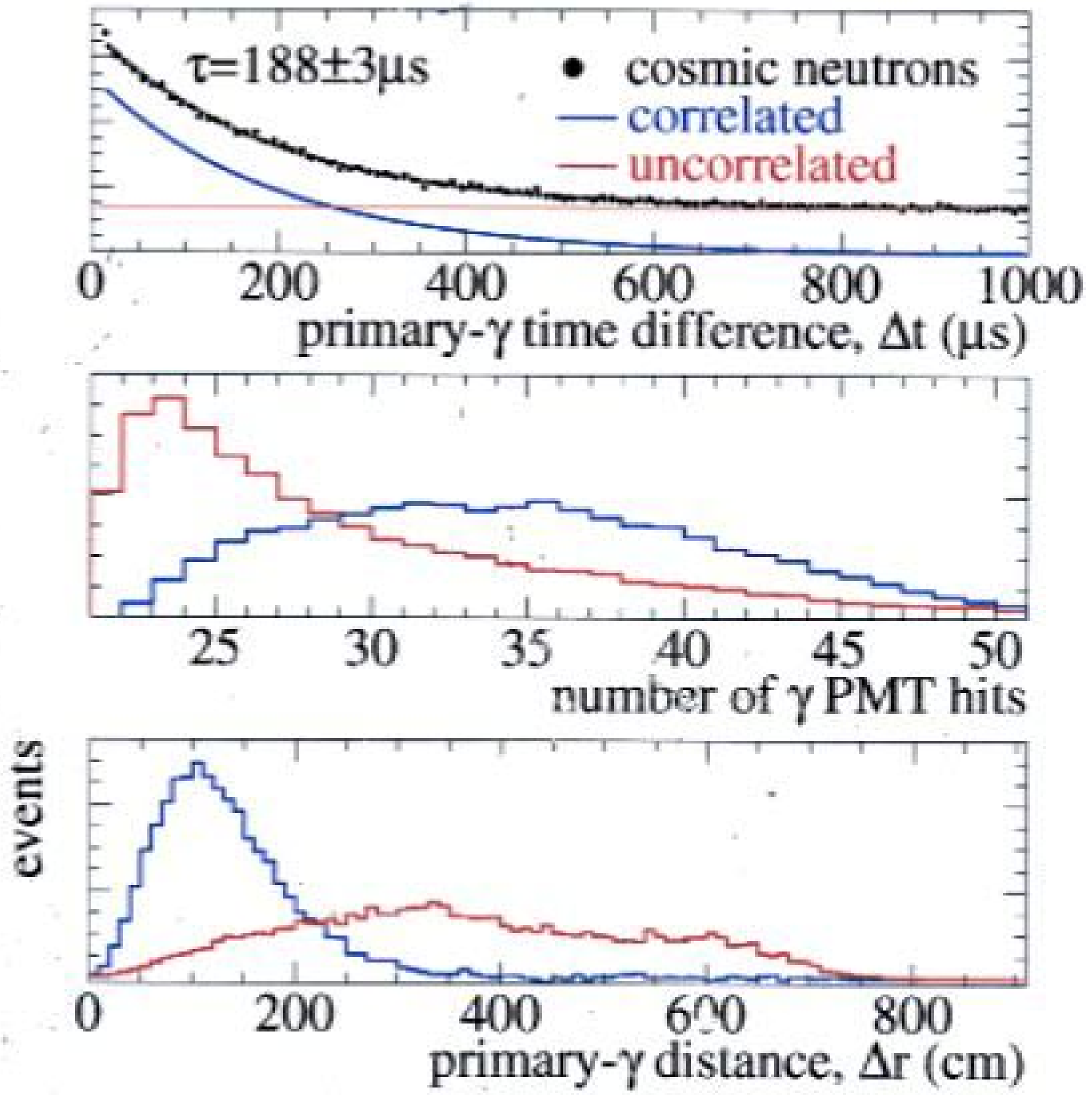
$n\ p \rightarrow d + \gamma$(2.2MeV)

- e^+ selection

Particle ID : cut cosmic neutrons
$d_{PMT} > 35cm$: fiducial volume
$\Delta t_{previous} > 20\mu s$: cut cosmics
$\Delta t_{next} > 8\mu s$: cut muons
$n_\gamma < 2$: cut cosmic neutrons
< 4 veto hits: cut cosmics
$S > 0.5$: cut cosmics
Efficiency : 0.37

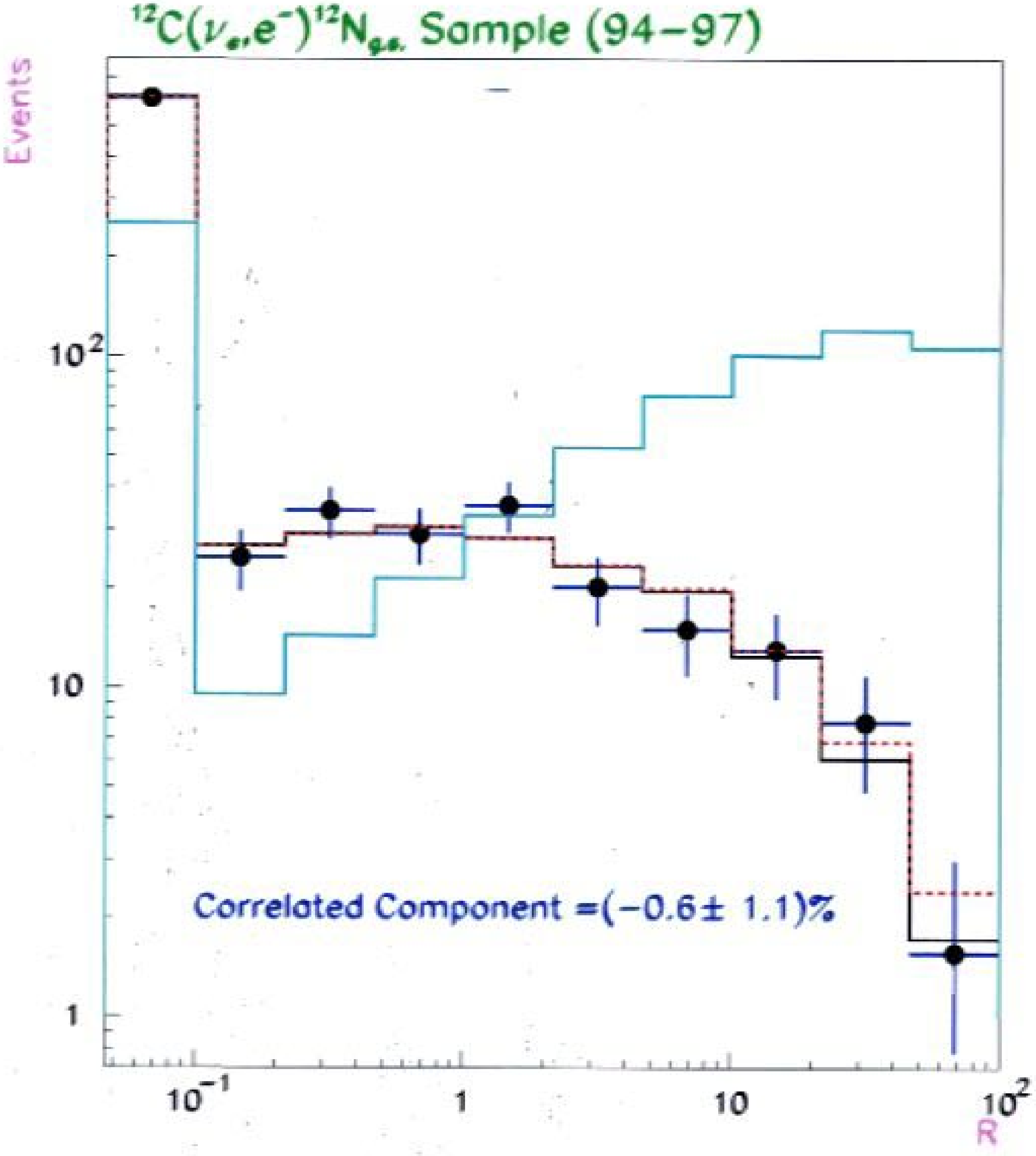
- γ selection : Likelihod ratio, R method

Correlated γ ID



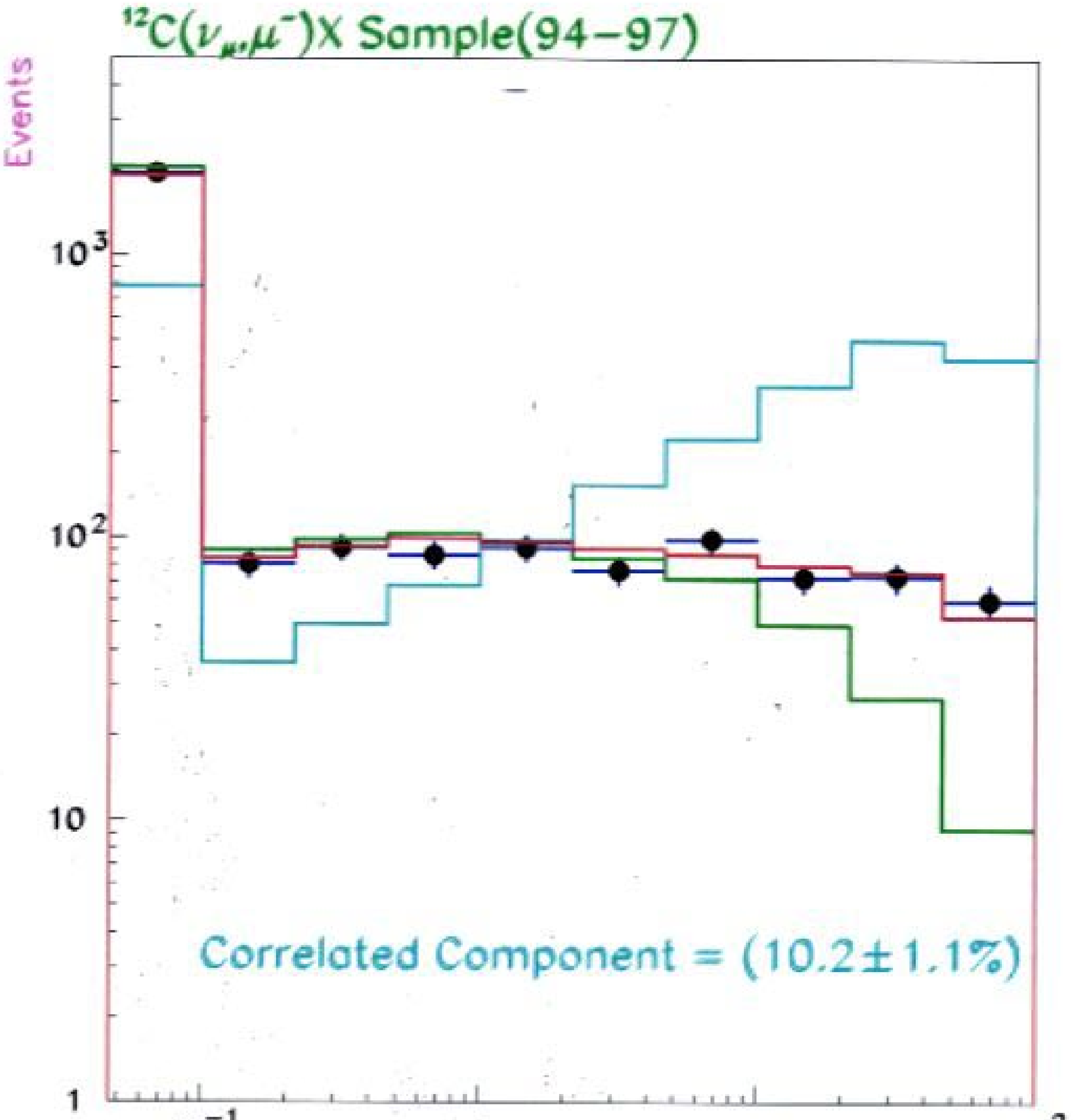
- **define** $L = P(\Delta t)\ \ P(\#\ \text{hits})\ \ P(\Delta r)$

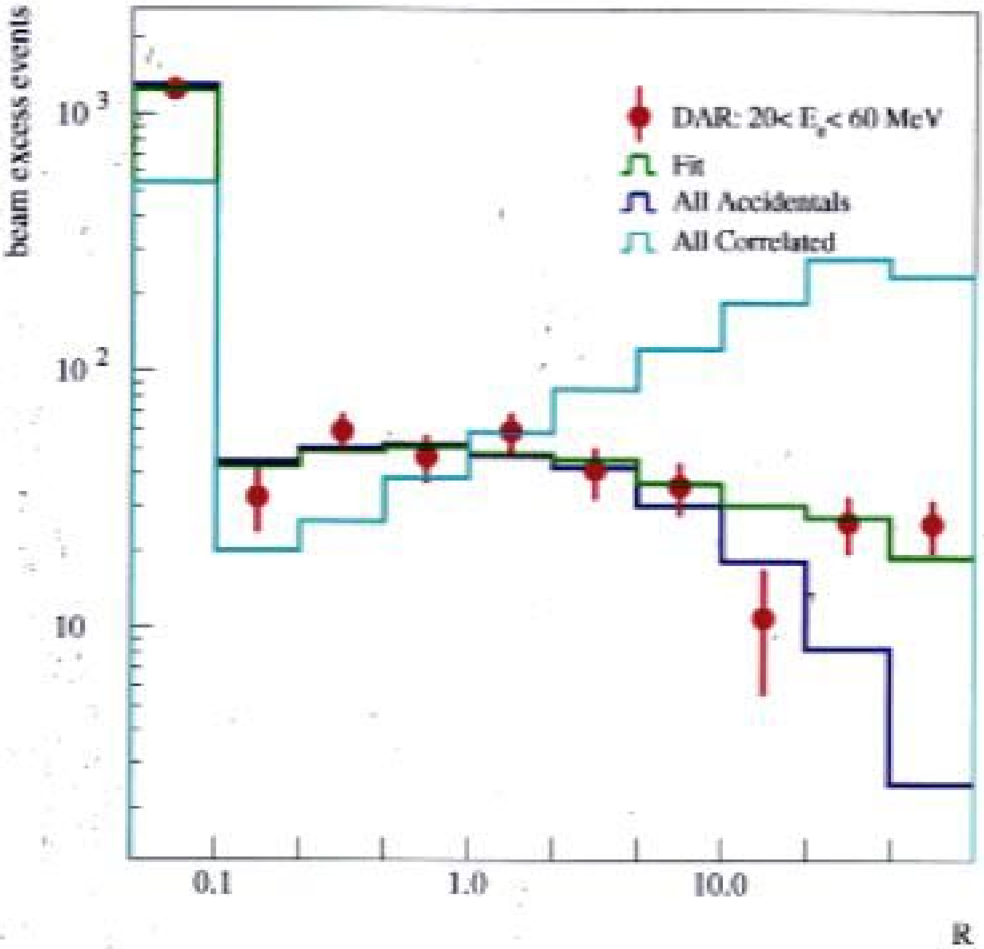
- **form** $R = L(\text{correlated})/L(\text{accidental})$



$^{12}C(\nu_e,e^-)^{12}N_{g.s.}$ Sample (94–97)

Correlated Component =(−0.6± 1.1)%


$^{12}C(\nu_\mu,\mu^-)X$ Sample(94–97)
Events
10^3
10^2
10
1
10^{-1}
1
10
10^2
R
Correlated Component = (10.2±1.1%)


beam excess events
10^3
10^2
10
0.1
1.0
10.0
R
DAR: 20< E_e< 60 MeV
Fit
All Accidentals
All Correlated

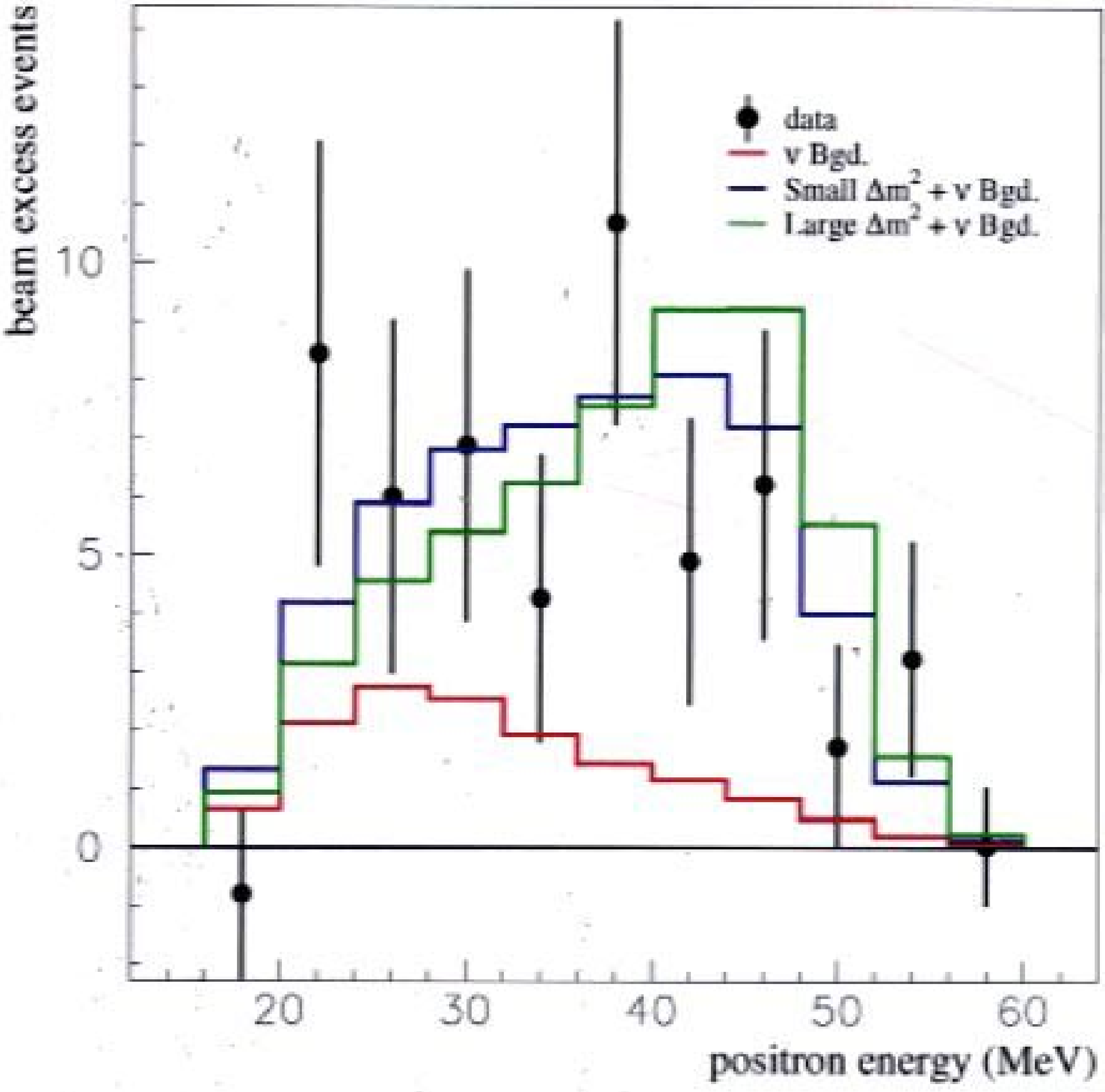
Preliminary LSND $\overline{\nu}_{\mu}$ -> $\overline{\nu}_{e}$ Results for 1993–1998

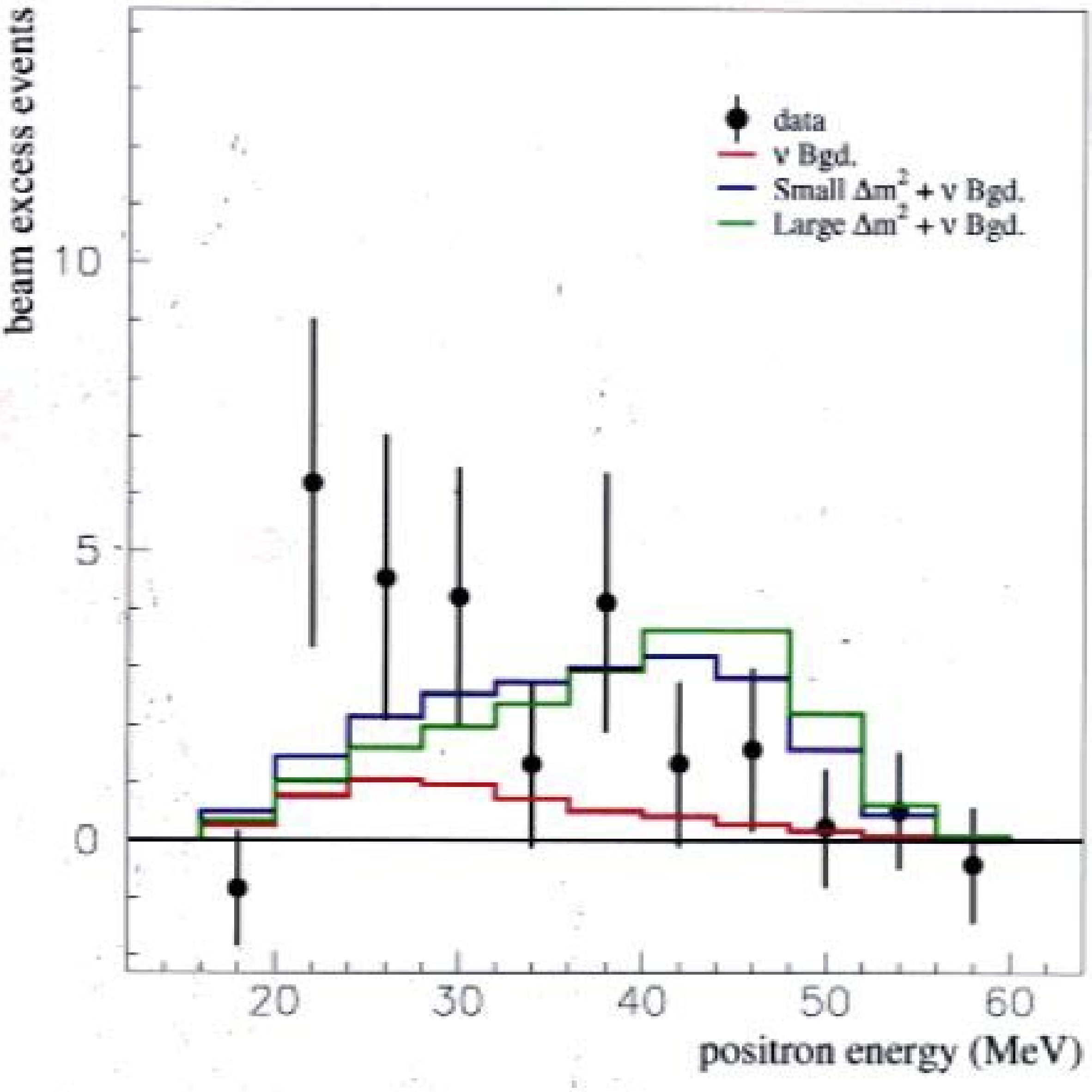
Selection	Beam On	Beam Off	ν Background	Total Excess
R>30 20<E<60	70	17.7+–1.0	12.8+–1.7	39.5+–8.8
R>30 36<E<60	33	6.2+–0.6	3.3+–0.7	23.5+–5.8

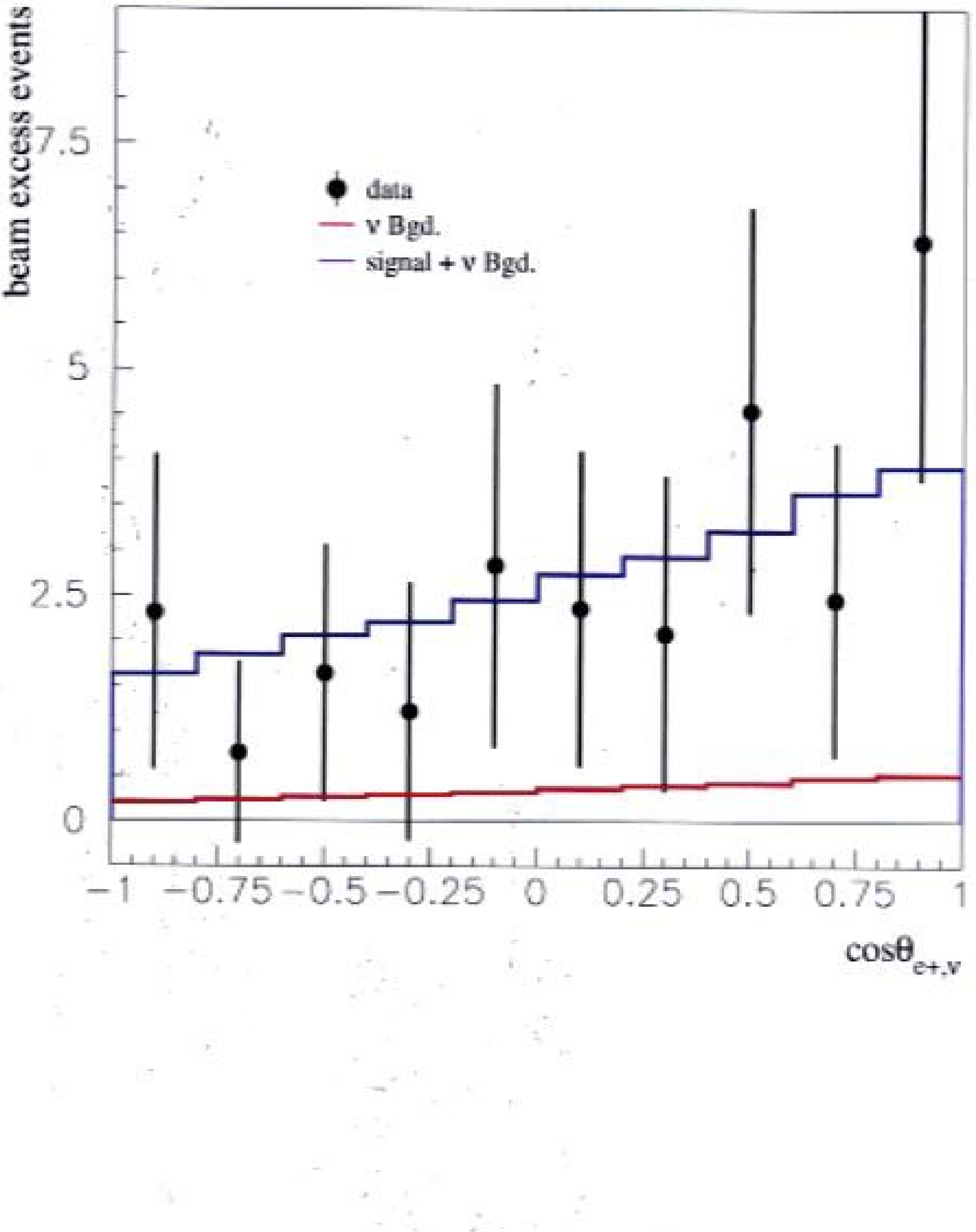
	20–36 MeV	36–60 MeV	20–60 MeV
1993–1995 (low,high Δm2)	3.7+–4.2 (11.0,7.1)	17.4+–4.7 (14.1,16.6)	21.1+–6.3
1996–1998 (low,high Δm2)	12.3+–5.1 (6.7,4.7)	6.1+–3.4 (7.7,11.0)	18.4+–6.1
1993–1998 (low,high Δm2)	16.0+–6.6 (17.7,11.9)	23.5+–5.8 (21.8,27.6)	39.5+–8.8

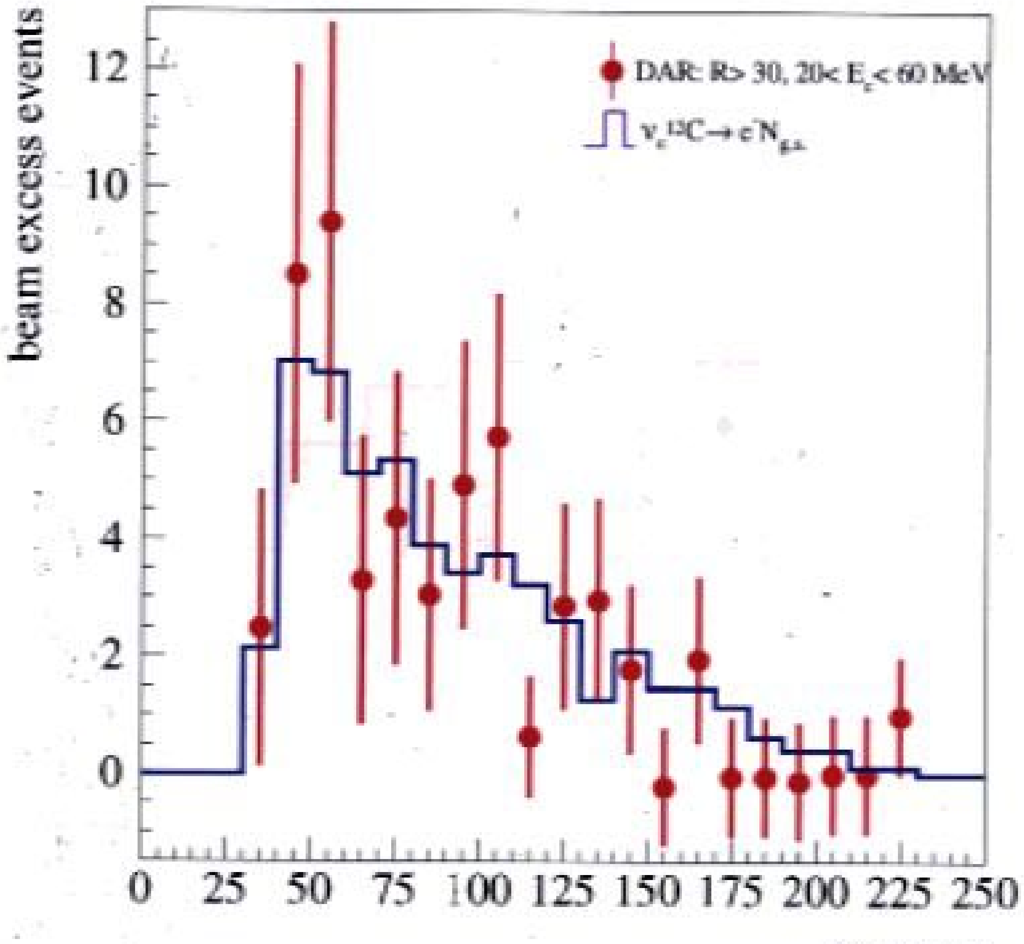
Data Sample	Fitted Excess	Total Excess	Oscillation Prob.
1993–1995	63.5+–20.0	51.0+–20.2	(0.31+–0.12+–0.05)%
1993–1998	111.8+–25.6	90.9+–26.1	(0.33+–0.09+–0.05)%

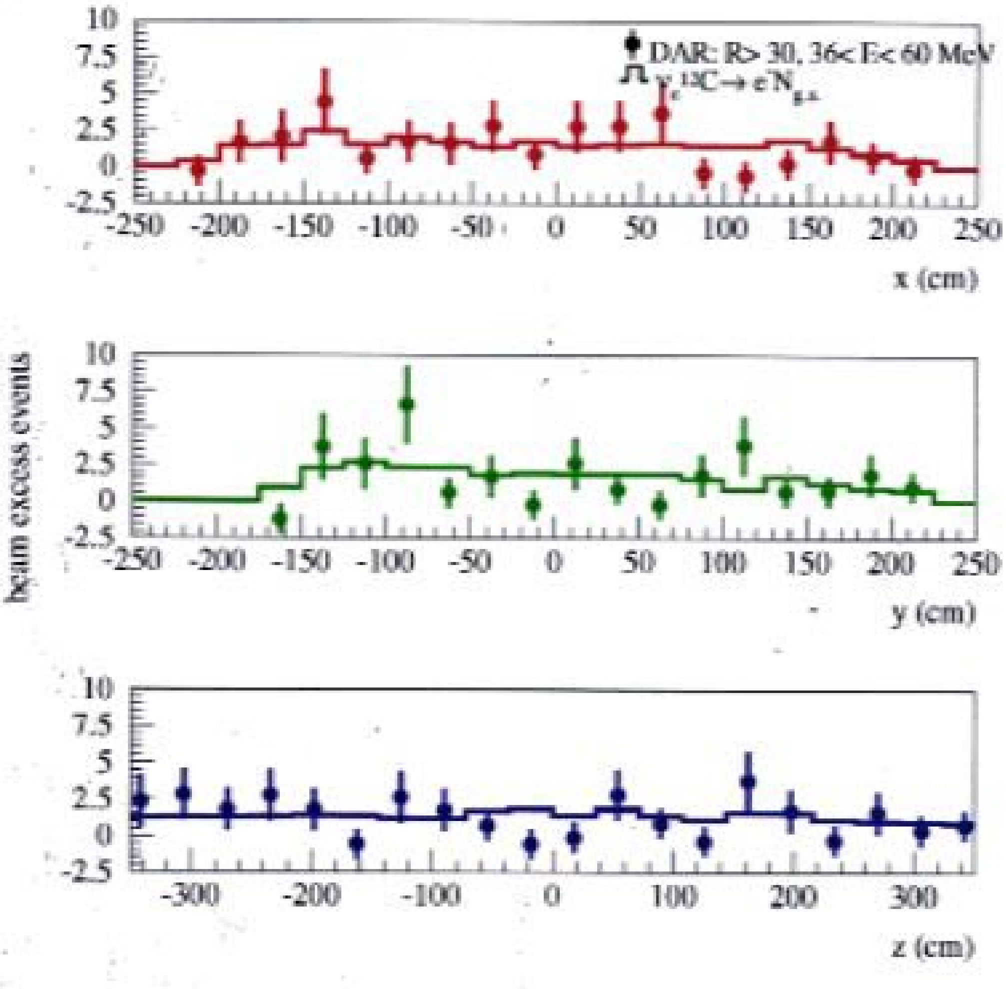
N.B.: The absolute electron efficiency, energy calibration, duty factor, and neutrino flux have been estimated for the 1996 through 1998 data and are subject to change. A global analysis of all of the data (DAR and DIF) is underway.

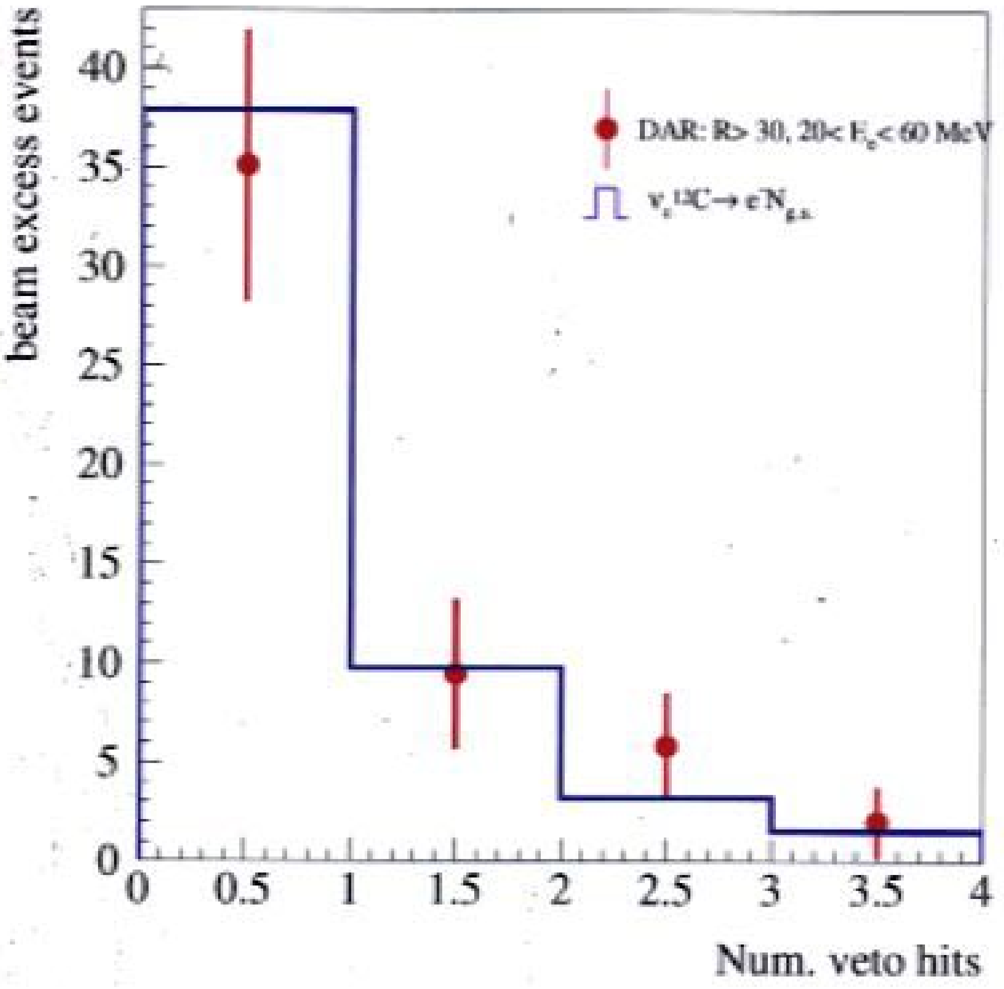

beam excess events
10
5
0
20
30
40
50
60
positron energy (MeV)
data
ν Bgd.
Small Δm^2 + ν Bgd.
Large Δm^2 + ν Bgd.

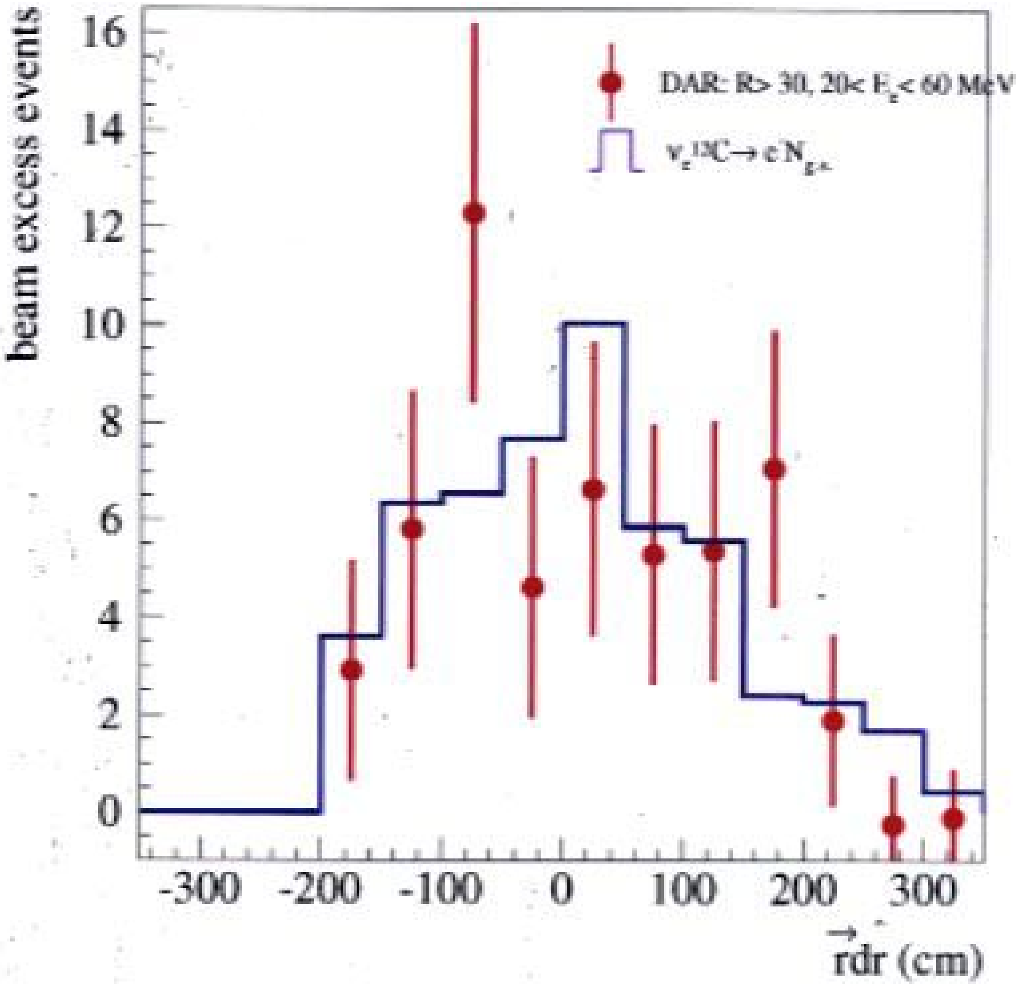

beam excess events
10
5
0
20
30
40
50
60
positron energy (MeV)
data
ν Bgd.
Small Δm² + ν Bgd.
Large Δm² + ν Bgd.


beam excess events
7.5
5
2.5
0
data
ν Bgd.
signal + ν Bgd.
−1
−0.75
−0.5
−0.25
0
0.25
0.5
0.75
1
cosθ$_{e+,\nu}$


beam excess events
12
10
8
6
4
2
0
DAR: R> 30, 20< E_e < 60 MeV
$\nu_e\,{}^{12}C \rightarrow e^- N_{g.s.}$
0
25
50
75
100
125
150
175
200
225
250
dist (cm)


DAR: R> 30, 36< E< 60 MeV
$\nu_e\,^{12}C \rightarrow e^- N_{g.s.}$
beam excess events
10
7.5
5
2.5
0
-2.5
-250
-200
-150
-100
-50
0
50
100
150
200
250
x (cm)
y (cm)
-300
-200
-100
0
100
200
300
z (cm)


beam excess events
0
5
10
15
20
25
30
35
40
0
0.5
1
1.5
2
2.5
3
3.5
4
Num. veto hits
DAR: R> 30, 20< E_e< 60 MeV
$\nu_e{}^{12}C \rightarrow e N_{g.s.}$


beam excess events
16
14
12
10
8
6
4
2
0
-300
-200
-100
0
100
200
300
$\vec{r}dr$ (cm)
DAR: R> 30, 20< E_e < 60 MeV
$\nu_e\,^{13}C \rightarrow e\,N_{g.s.}$

Events with Multiple Gammas

I. (20<E<60) & (R>30)

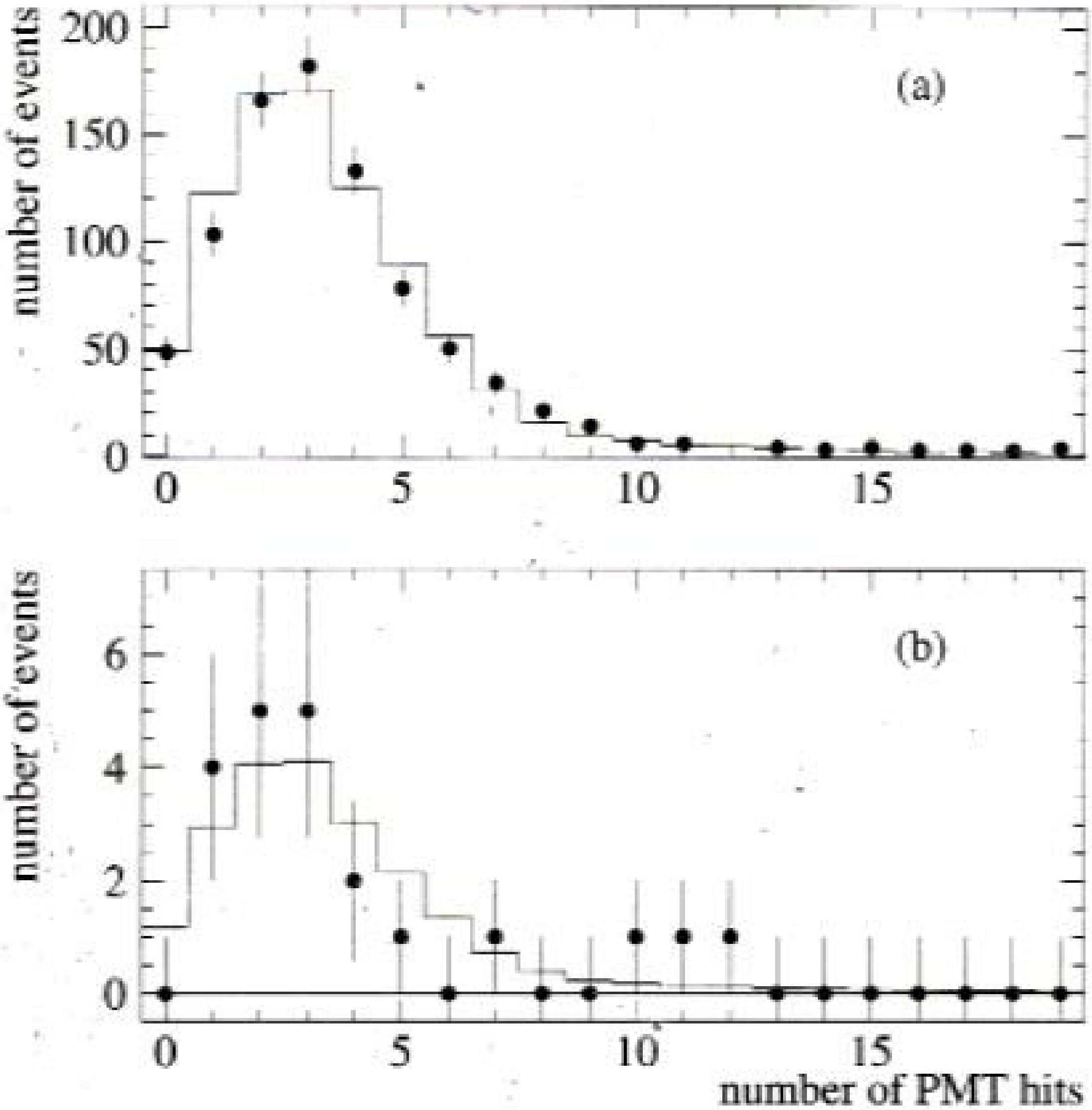
#γ = 1 =>	70 on,	308 off,	52.3+–8.4 excess
#γ > 1 =>	6 on,	99 off,	0.3+–2.5 excess
Ratio =>	0.09	0.32	0.01+–0.05

II. (36<E<60) & (R>30)

#γ = 1 =>	33 on,	113 off,	26.8+–5.8 excess
#γ > 1 =>	1 on,	41 off,	–1.4+–1.1 excess
Ratio =>	0.03	0.36	–0.05+–0.04

We expect that for primary neutrons, the events would have multiple gammas with Ratio = 0.60. Therefore, our signal is NOT due to primary neutrons!

~~π^- DIF BKGD~~



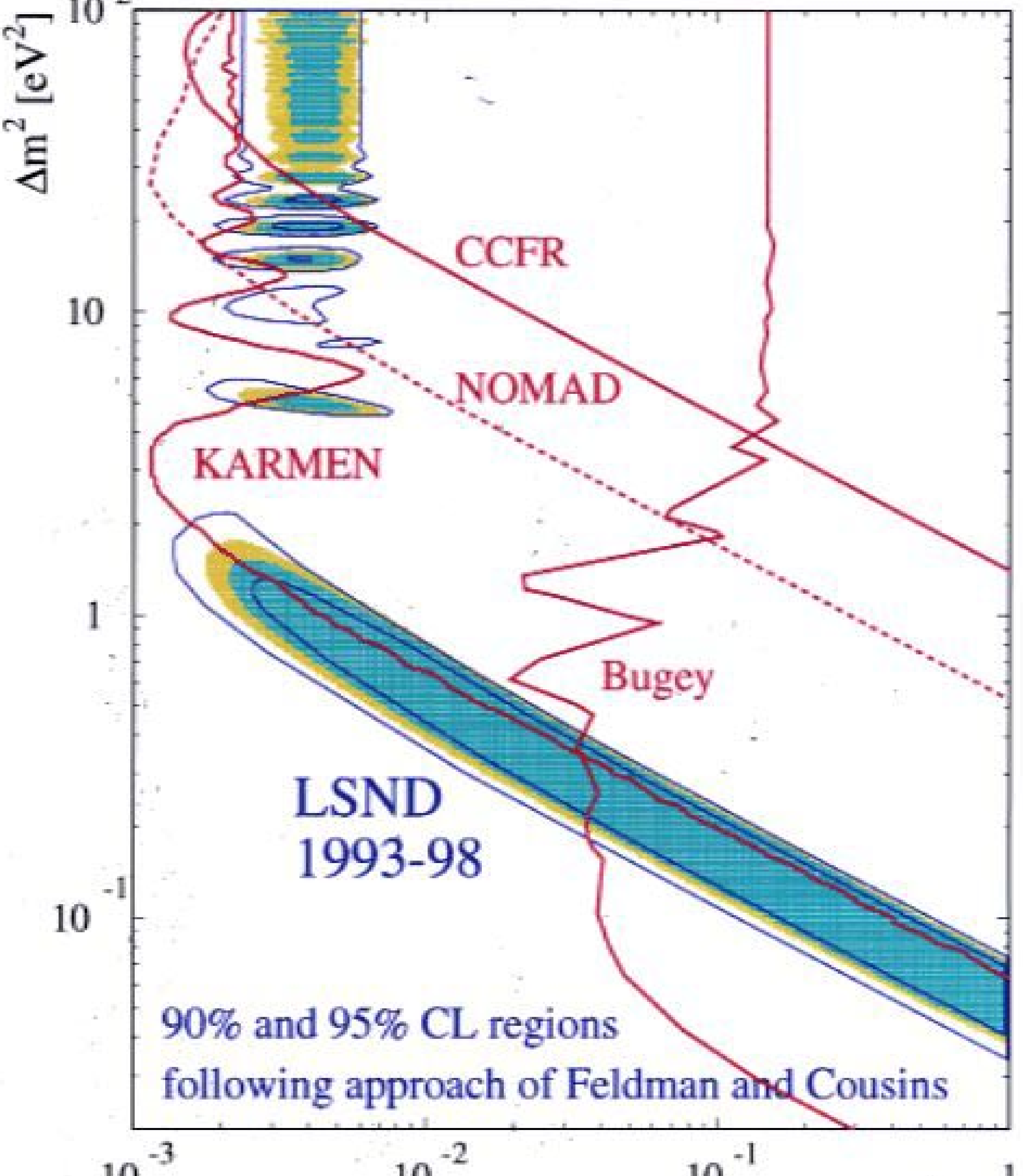
R≥0

R>30

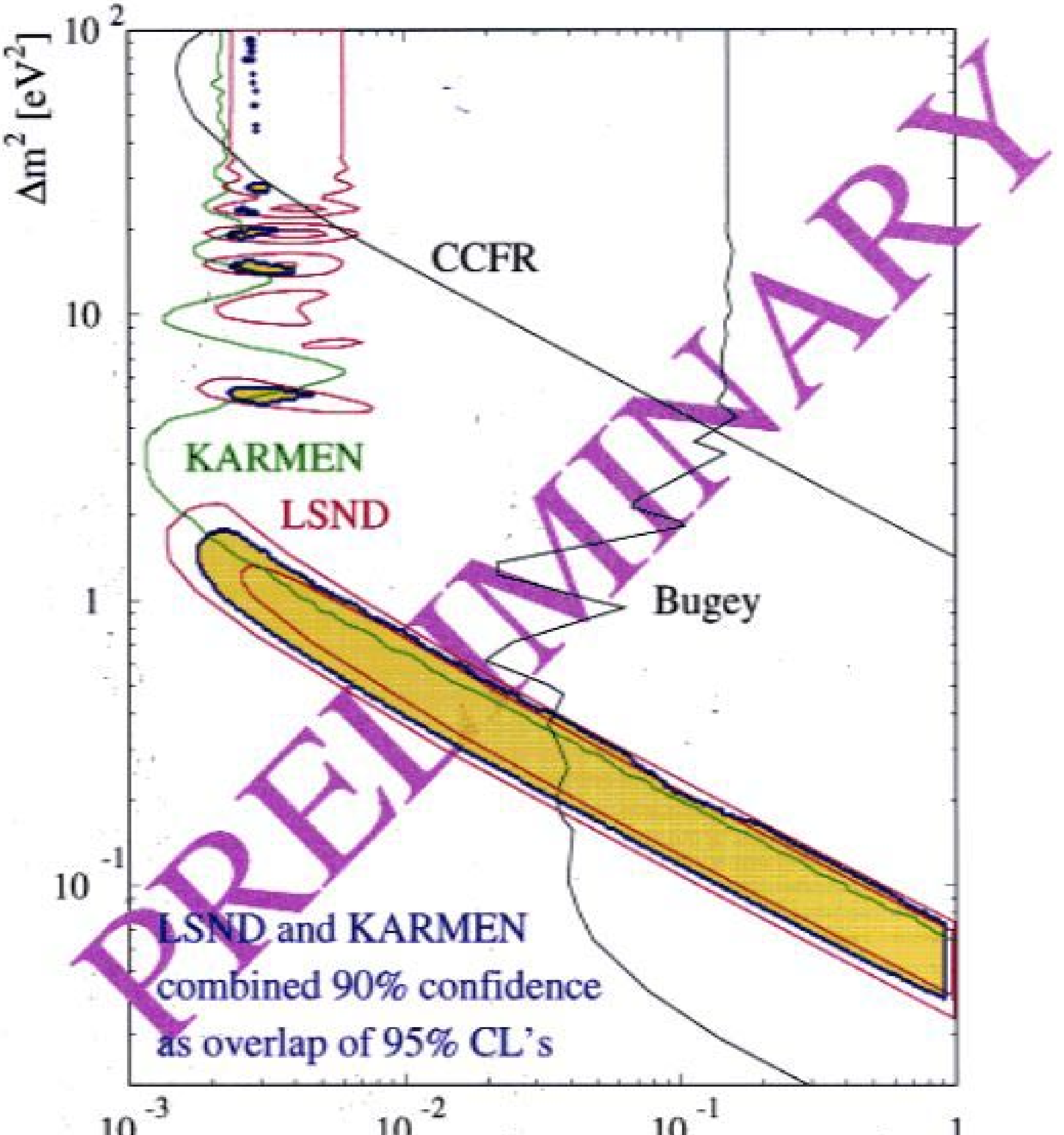
FIG. 32. The total number of hit PMTs in the detector tank for the extra events that occur $0-3\mu s$ and $3-6\mu s$ prior to oscillation candidate events. The candidates are in the $25 < E_e < 60$ MeV energy range with (a) $R \geq 0$ and (b) $R > 30$. The data points are the beam-on events, while the solid curve is what is expected from random PMT hits as determined from the sample of laser calibration events.

$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ Checklist

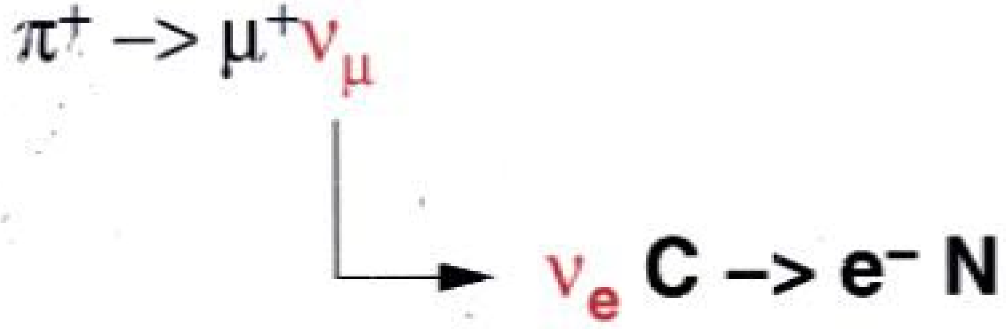
OK	1. Spatial Distribution
OK	2. Energy Distribution
OK	3. Correlated γ Distribution
OK	4. Angular Distribution
OK	5. Veto Distribution
OK	6. Events with Multiple γs
OK	7. Hit PMTs in Lookback
OK	8. H_2O Target vs High z Target



Δm^2 [eV^2]
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\Theta$
CCFR
NOMAD
KARMEN
Bugey
LSND
1993-98
90% and 95% CL regions
following approach of Feldman and Cousins


Δm^2 [eV^2]
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\Theta$
CCFR
KARMEN
LSND
Bugey
LSND and KARMEN
combined 90% confidence
as overlap of 95% CL's
PRELIMINARY

$\nu_\mu \rightarrow \nu_e$ DIF Oscillation Search



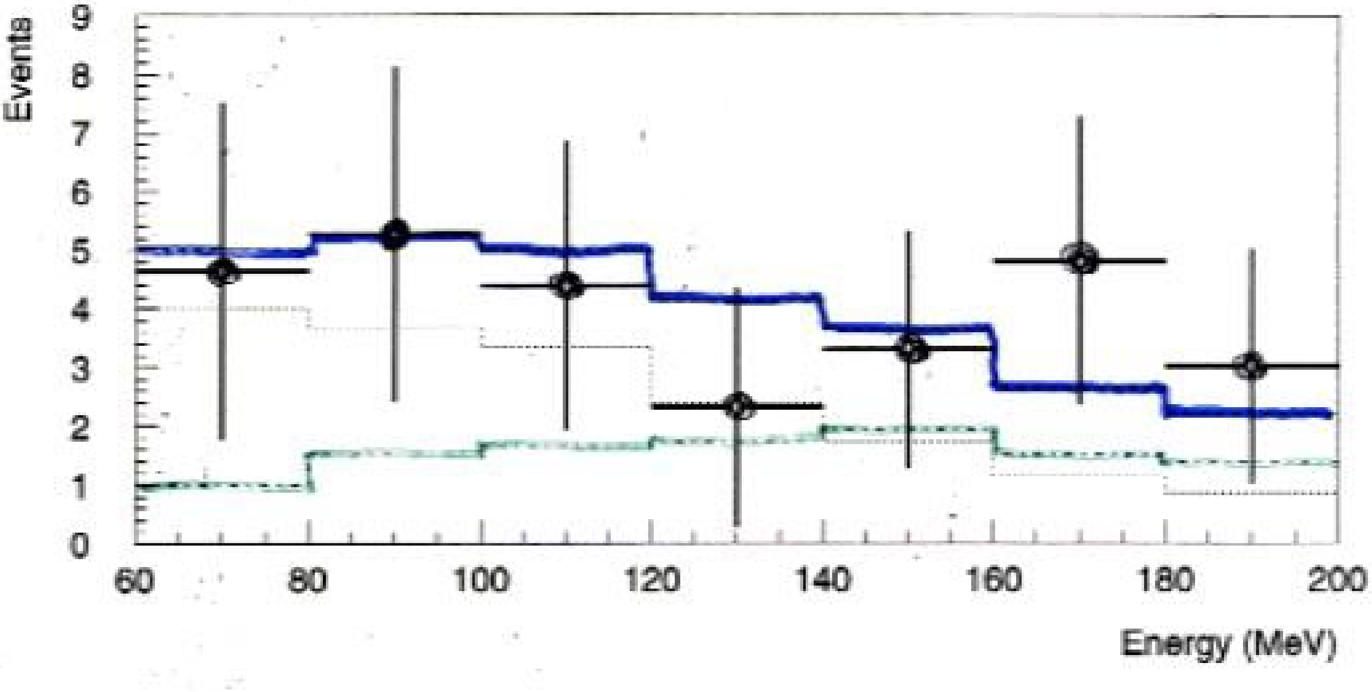
$\pi^+ \rightarrow \mu^+ \nu_\mu$

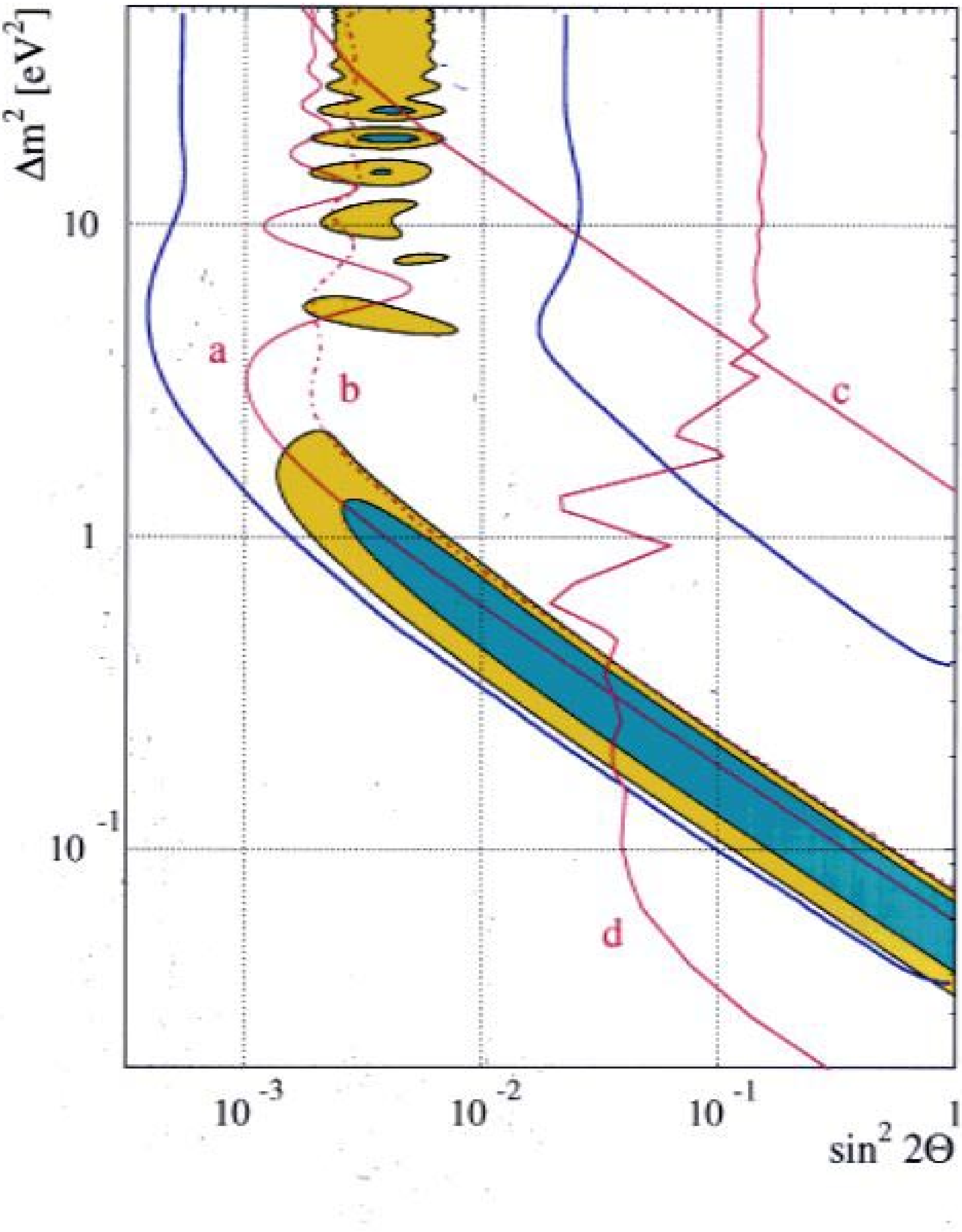
$\nu_e \, C \rightarrow e^- N$

- Different systematics than DAR
- Different backgrounds than DAR

  $\mu \rightarrow e \, \nu_\mu \, \nu_e$ and $\pi \rightarrow e \, \nu_e$
- Different coverage of Δm^2 and $\sin^2 2\theta$
- However, only a single signature

18.1 ± 6.6 excess events





Δm^2 [eV^2]
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\Theta$
a
b
c
d

The BooNE Collaboration

July 13, 1999

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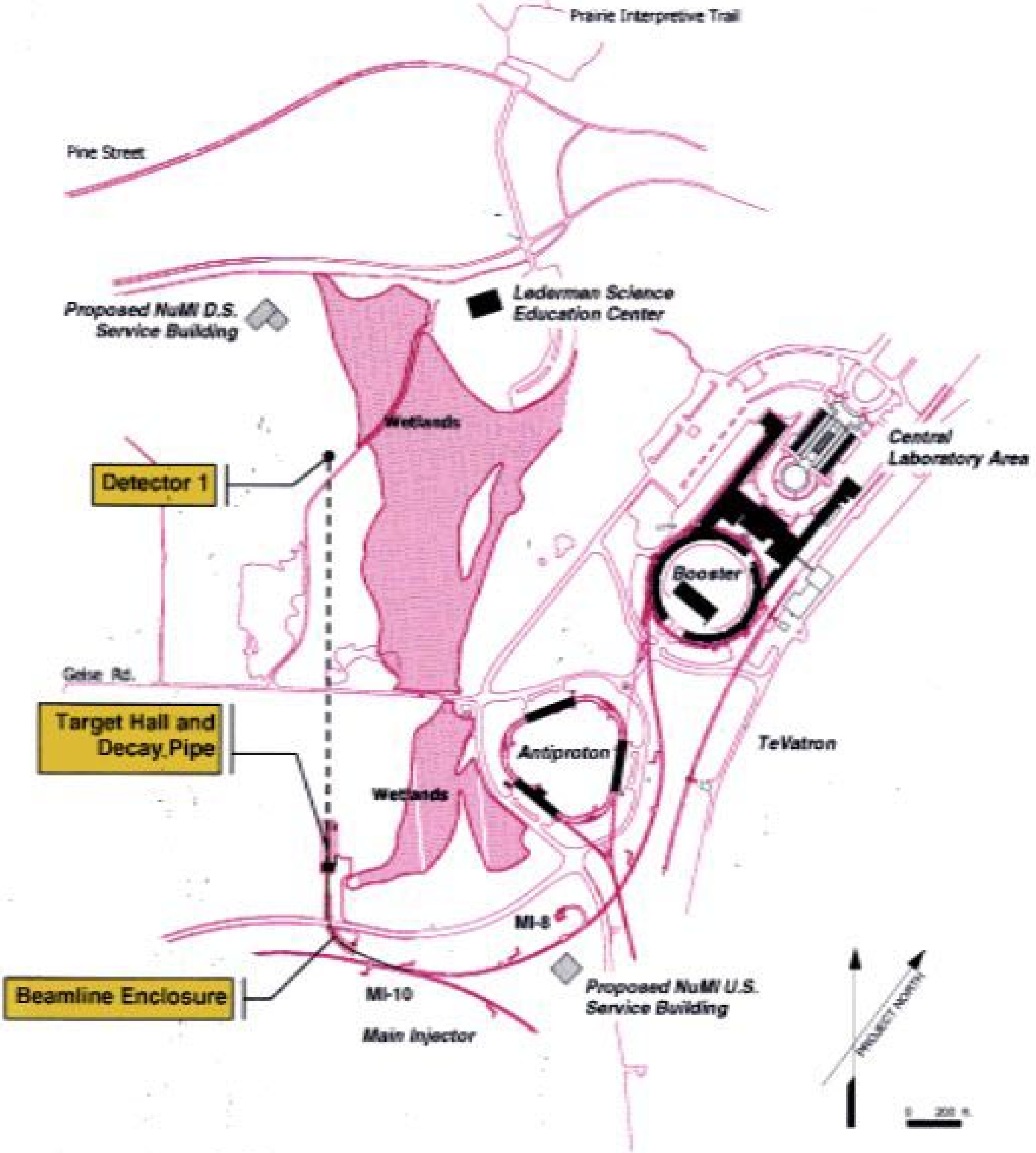
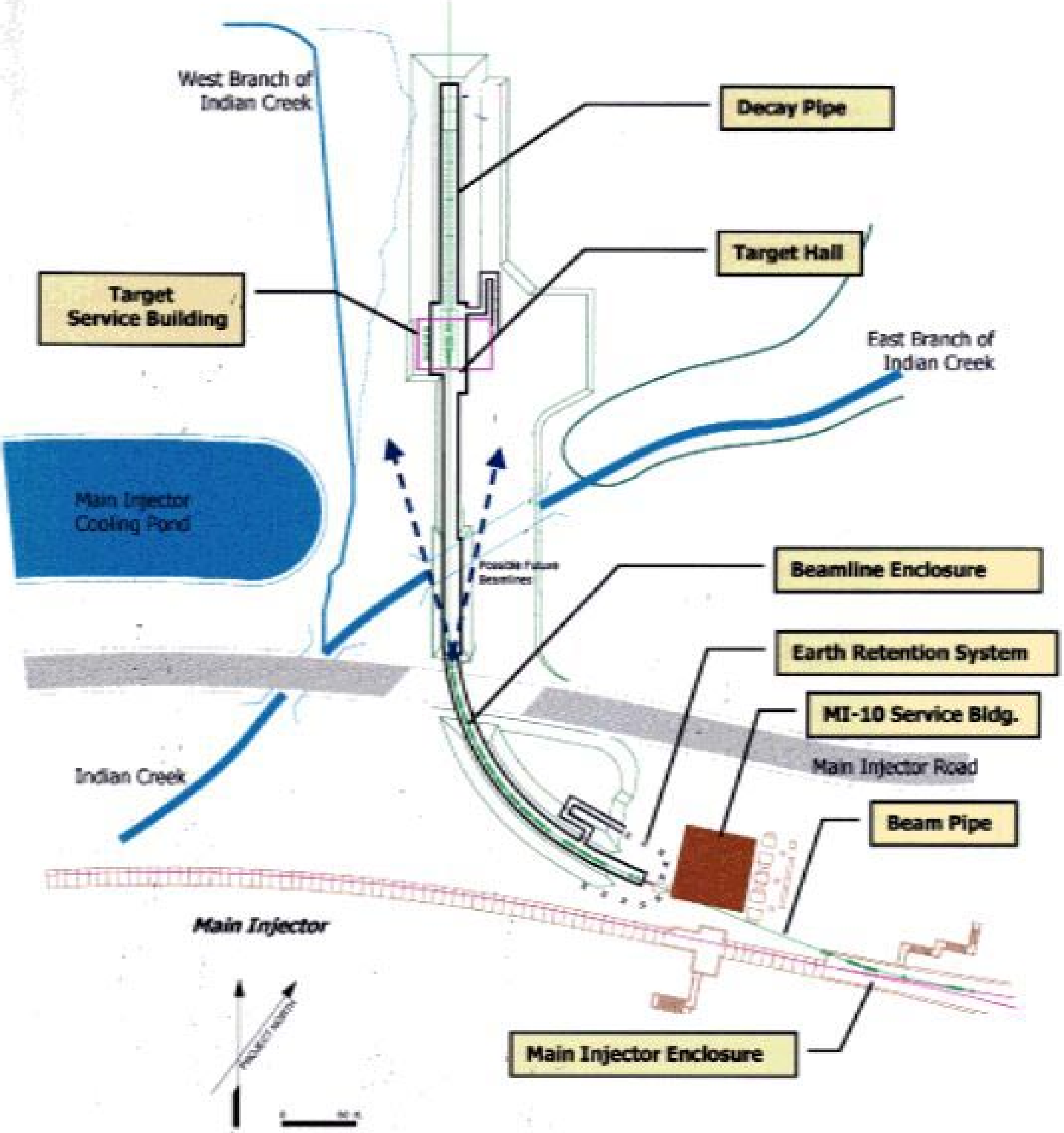
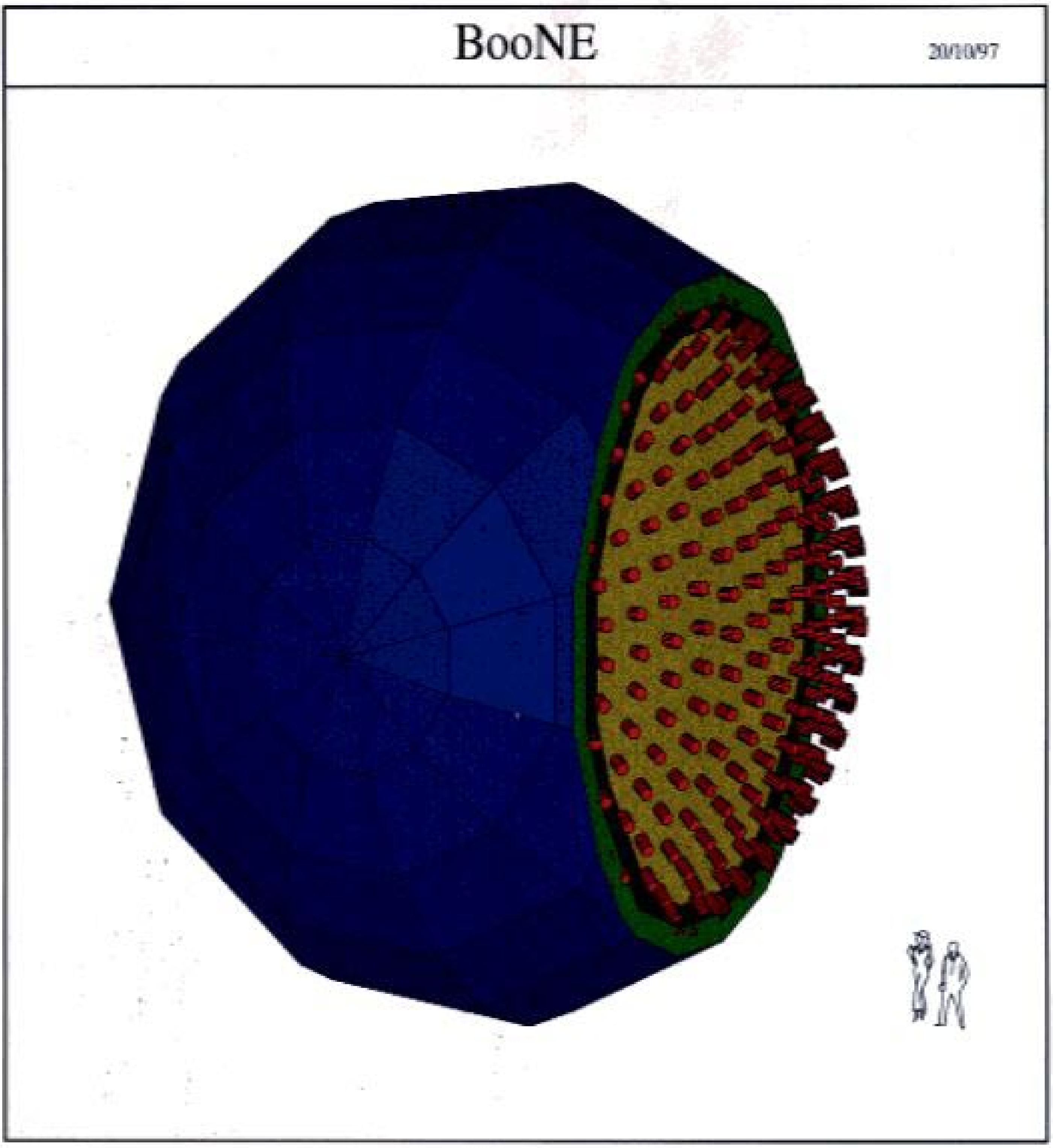
BooNE Detectors and Site Layout


Prairie Interpretive Trail
Pine Street
Proposed NuMI D.S. Service Building
Lederman Science Education Center
Wetlands
Central Laboratory Area
Detector 1
Booster
Gelse Rd.
Target Hall and Decay Pipe
Antiproton
TeVatron
Wetlands
MI-8
Beamline Enclosure
MI-10
Proposed NuMI U.S. Service Building
Main Injector
PROJECT NORTH
0 200 ft.

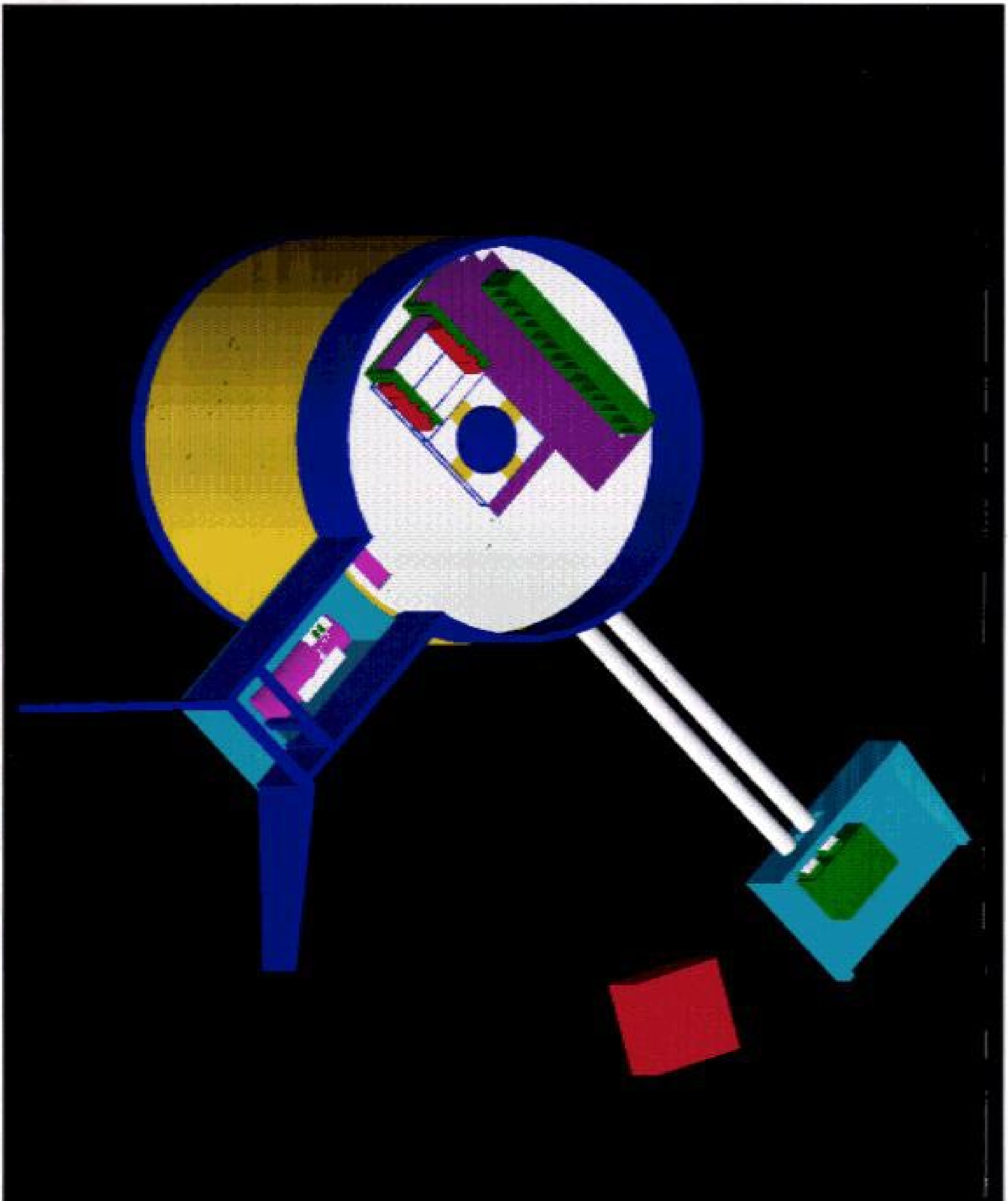

West Branch of Indian Creek
Decay Pipe
Target Hall
Target Service Building
East Branch of Indian Creek
Main Injector Cooling Pond
Possible Future Beamlines
Beamline Enclosure
Earth Retention System
MI-10 Service Bldg.
Main Injector Road
Indian Creek
Beam Pipe
Main Injector
PROJECT NORTH
0
Main Injector Enclosure

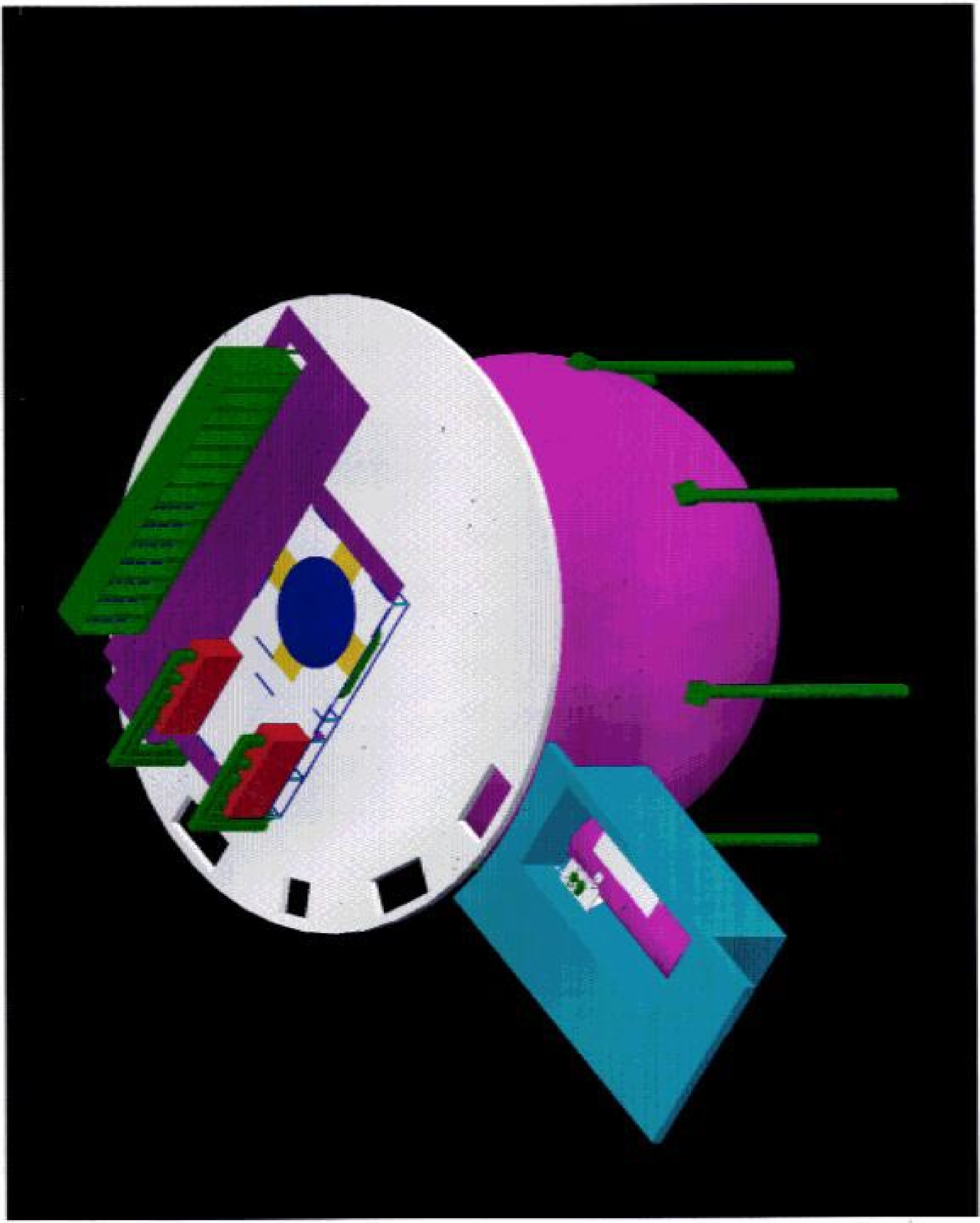


BooNE

20/10/97

40–feet diameter sphere
1520 8–inch PMTs (1280 detector + 240 veto PMTs)
807 tons of mineral oil
445 ton fiducial volume





Oil vs Water

- More Cerenkov light (x1.45)

oil –>	$n=1.47$, $\rho=0.85$
water –>	$n=1.33$, $\rho=1.00$

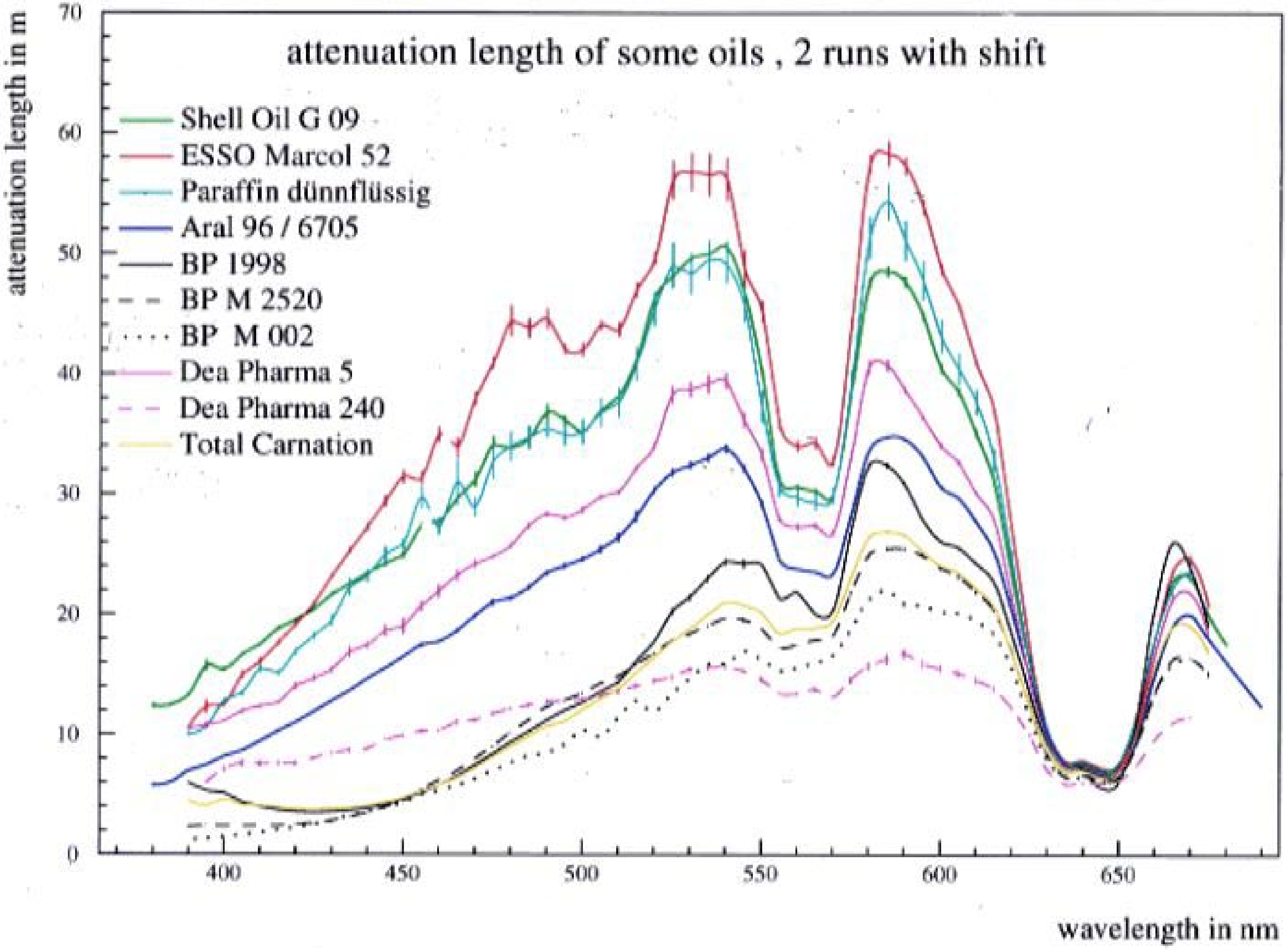
- No need for a purification system
- No worry about liquid seeping into bases
- Oil has less multiple scattering

oil –>	$X_0 = 44.8$ g/cm^2
water –>	$X_0 = 36.1$ g/cm^2

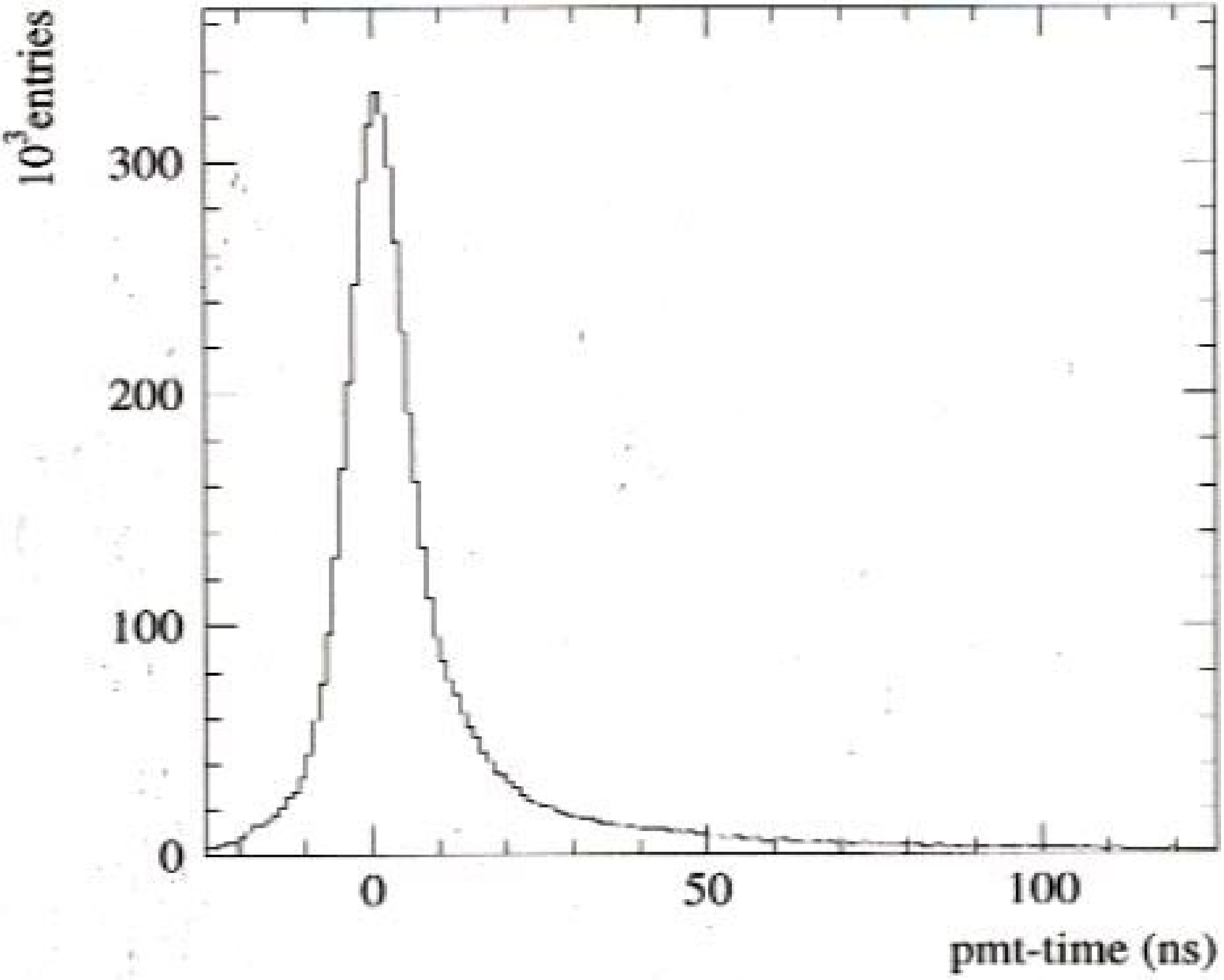
- Oil has lower μ^- capture rate

oil –>	8%
water –>	18%

- Pure mineral oil produces a little scintillation light


attenuation length of some oils , 2 runs with shift
Shell Oil G 09
ESSO Marcol 52
Paraffin dünnflüssig
Aral 96 / 6705
BP 1998
BP M 2520
BP M 002
Dea Pharma 5
Dea Pharma 240
Total Carnation
attenuation length in m
0
10
20
30
40
50
60
70
400
450
500
550
600
650
wavelength in nm

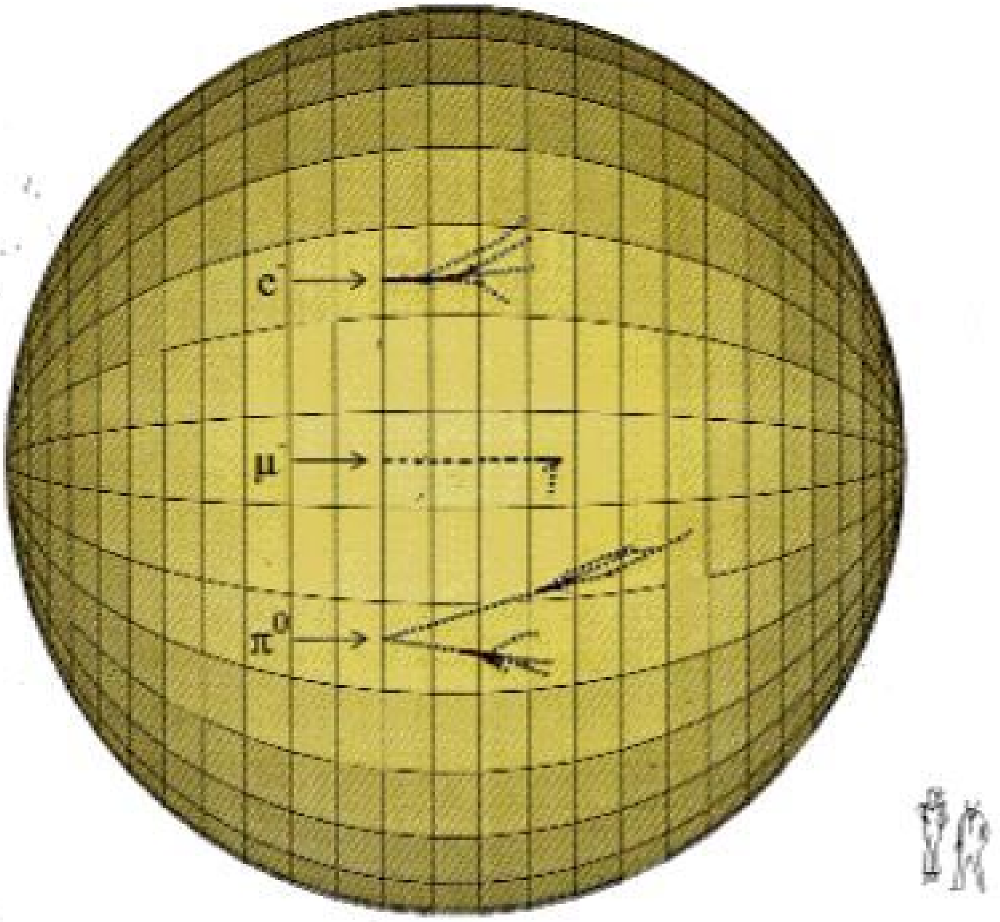
The electron time distribution in pure oil



Run 664 LSND data and Texas A&M cyclotron tests indicate that for pure oil:

(i) 75% Cerenkov light & 25% scintillation light
(ii) Scintillation time constant of ~ 35 ns

Full GEANT Monte Carlo Simulation



$\nu_e C \rightarrow e^- N$	Signal
$\nu_\mu C \rightarrow \mu^- N$	Background
$\nu_\mu C \rightarrow \nu_\mu \pi^0 X$	Background

Event Reconstruction & PID

1. electron event reconstruction

   $\delta r \sim 21$ cm

   $\delta t < 1$ ns

   $\delta\theta \sim 3.6^0$

   $\delta E/E \sim 10\%$

2. muon event reconstruction

   mis–id background < 0.1%

   $\delta E/E \sim 29\%$

3. π^0 event reconstruction

   mis–id background ~ 1%

   $\delta E/E \sim 10\%$

The χ^2 Particle ID Method

Signature:	Cerenkov Ring	Track Extent	Hit Timing
	$\chi_\alpha = \Sigma q_i (\alpha_i - 47°)^2/Q$ (consistent w/ β=1)	$\chi_r = \Sigma q_i (t_i - r_i/v - t_0)^2/Q$ (consistent w/ "point source")	$\chi_t = \dfrac{\Sigma N_i (t_i > 10ns)}{\Sigma N_i (t_i < 500ns)}$ (consistent w/ "late light")
Particle:			
e	β=1 →Cerenkov angle: α=47° Ring is "Fuzzy" due to mult. scat. & brems	Short Track (point source)	More Cerenkov light (prompt) than Scintillation light (late)
μ	Sharp outer edge of ring (less mult. scat. than for e's) Diffuse inner edge of ring (β<1 → smaller Cerenkov angle)	Long Track (extended source)	Higher fraction of late light (less time above threshold)
π^0	Two rings	Extended source because of 2 γs	Recoil Proton produces Scint Light

Systematic Errors from Particle Mis-id

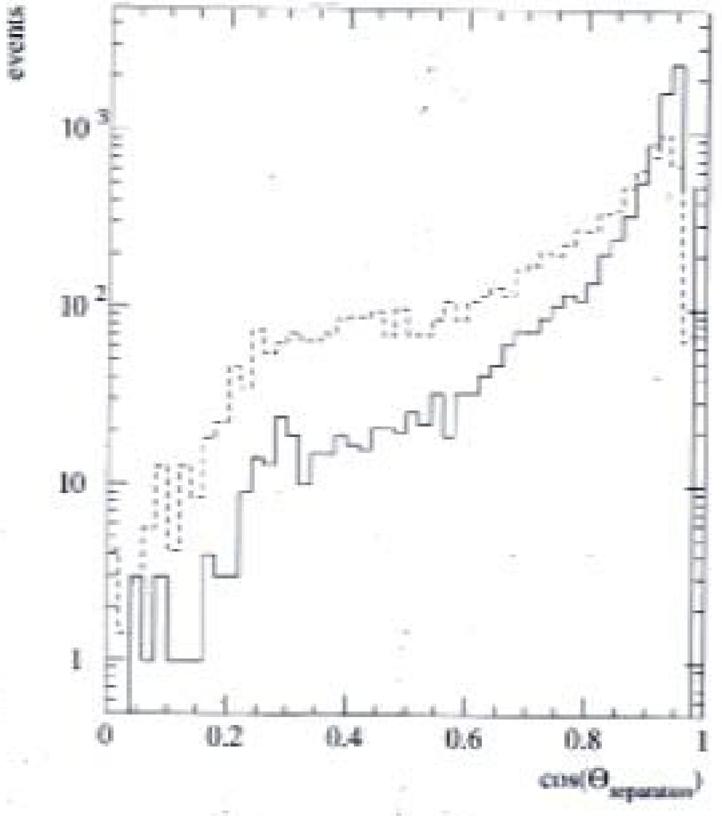
μ^-: <5% systematic error

Use decay μ^- events to determine the mis-id rate:

- 92% are tagged by the decay e^-
- 8±0.1% are captured

π^0: ~5%

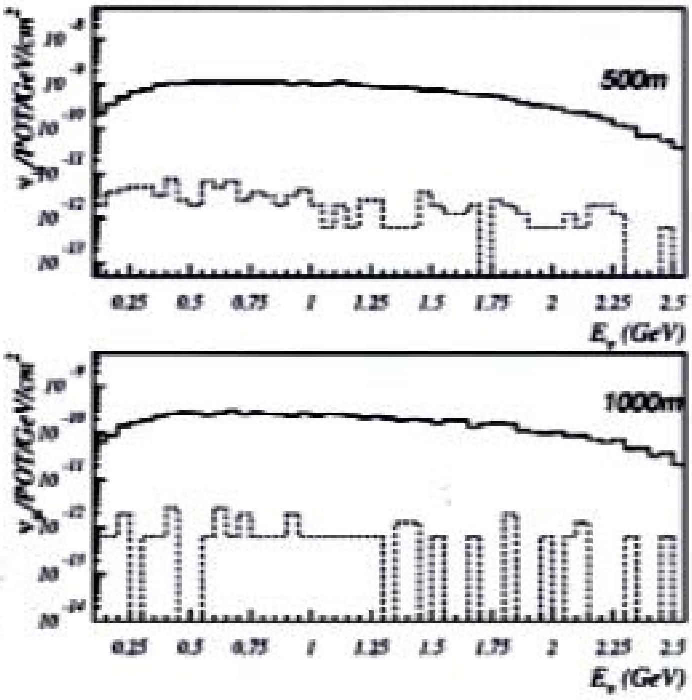
Use symmetric π^0 decays to determine the mis-id rate:



Angular distribution between 2 fitted rings

The BooNE ν beam *(Full Geant Simulation)*

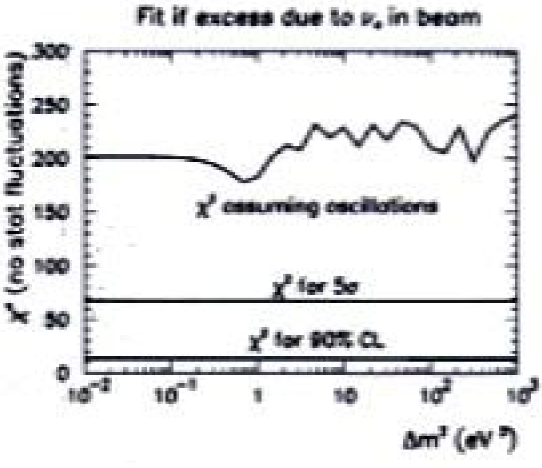
- Al target within 2-horn secondary focusing system



Solid – ν_μ flux,
Dashed – ν_e background

Sources of ν_e background (0.3% of beam):

- μ decays (75% of total ν_e, 5% systematic error)
- K decays (25% of total ν_e, 10% systematic error)
- The ν_e beam background does not fit the energy shape for the oscillation hypothesis.

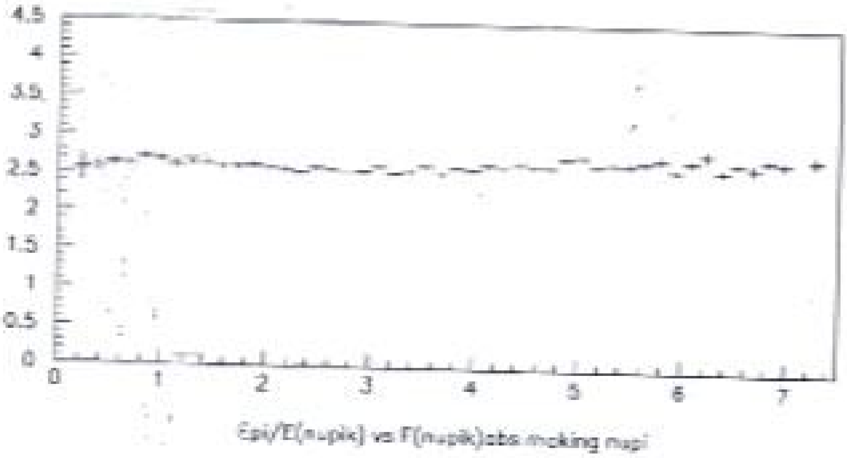


To know ν_e's from μ decays, we need the π spectrum...

$$\pi^+ \to \nu_\mu \, \mu^+$$
$$\hookrightarrow e^+ \, \overline{\nu}_\mu \, \nu_e$$

The ν_μ energy spectrum is *highly correlated* to the π spectrum!

(Because the detector subtends a very small solid angle)



$E_\pi / E_\nu \approx 2.5$
for all E_π !

This means we can...

Measure the ν_μ flux

↓

Apply a simple relation to convert ν_μ flux to π spectrum

↓

Decay π to μ to ν_e to get predicted ν_e flux

Investigating method using Monte Carlo:
We can constrain the ν_e from μ decay to 5%

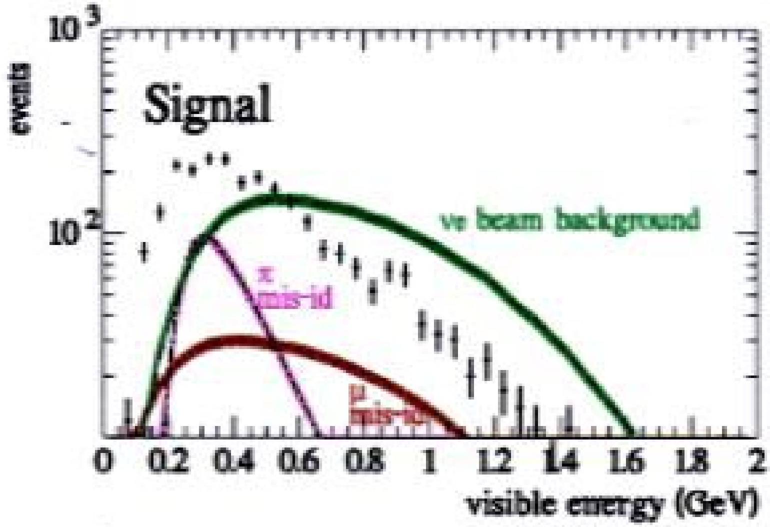
Estimated Number of Events after 1 year (2×10^7 s)

Reaction	Number of Events
ν_μ C -> μ^- N	590,000
ν_μ e -> ν_μ e	130
ν_μ C -> μ^- π^0 X	65,000
ν_μ p,n -> ν_μ p,n	72,000
ν_e C -> e^- N	
(100% transmutation)	617,000
$\Delta m^2=0.4$ eV^2, $\sin^2 2\theta=0.02$	1200
Intrinsic ν_e	1800
μ^- Misidentification	600
π^0 Misidentification	600

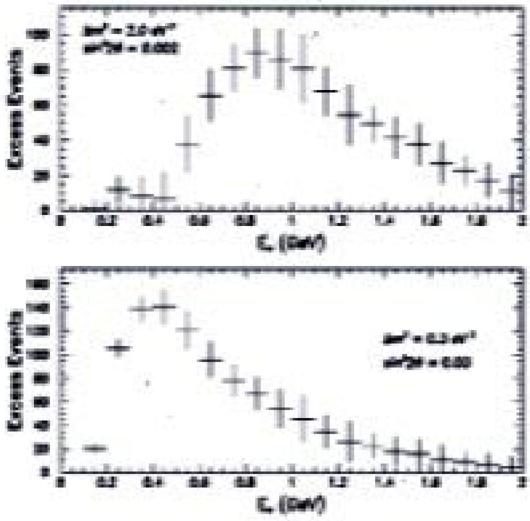
The background is low at low energies...

Points: $\Delta m^2 = 0.4$ eV^2,
$\sin^2 2\theta = 0.04$
colored bands show
systematic errors

note log scale →

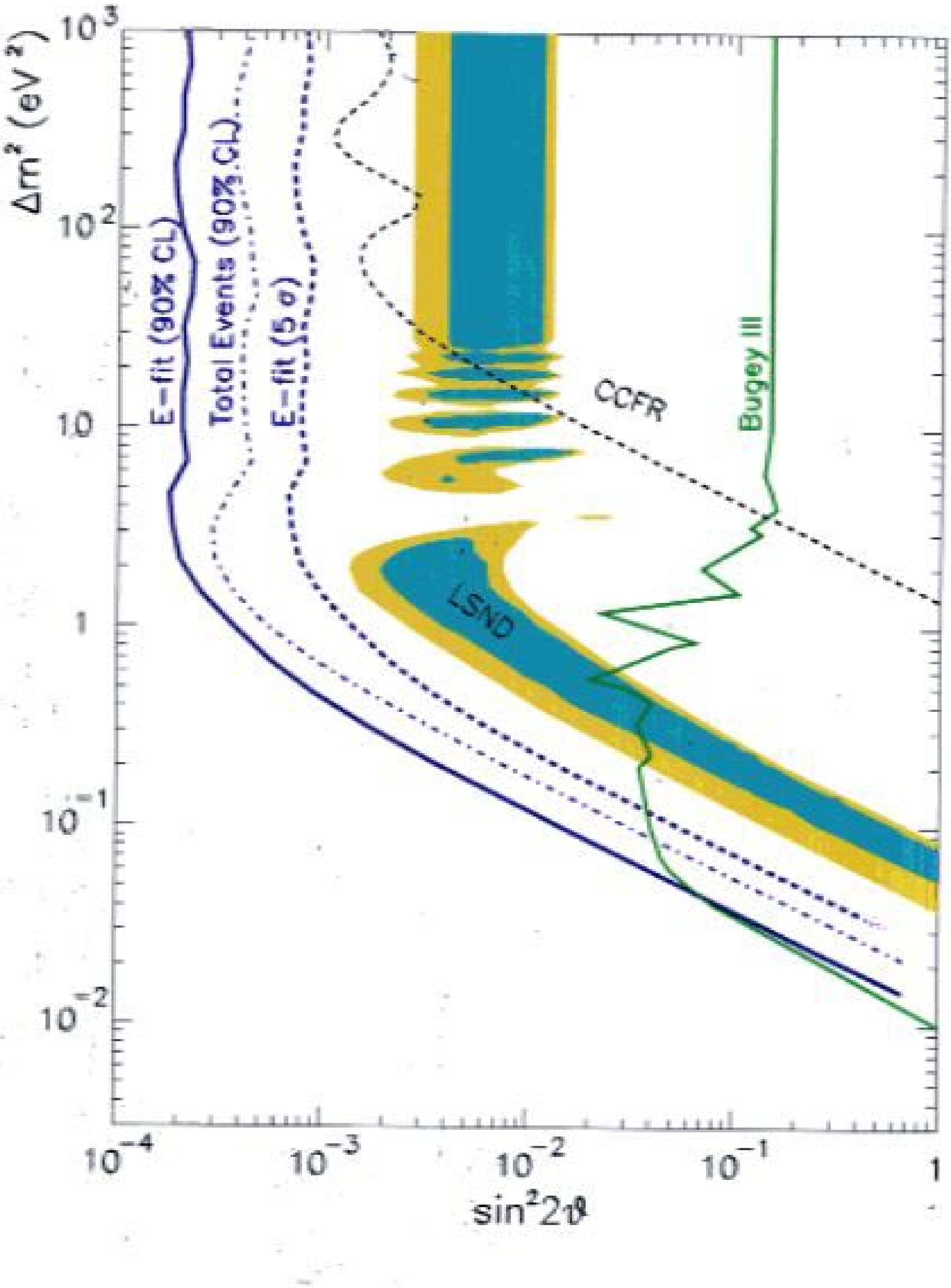


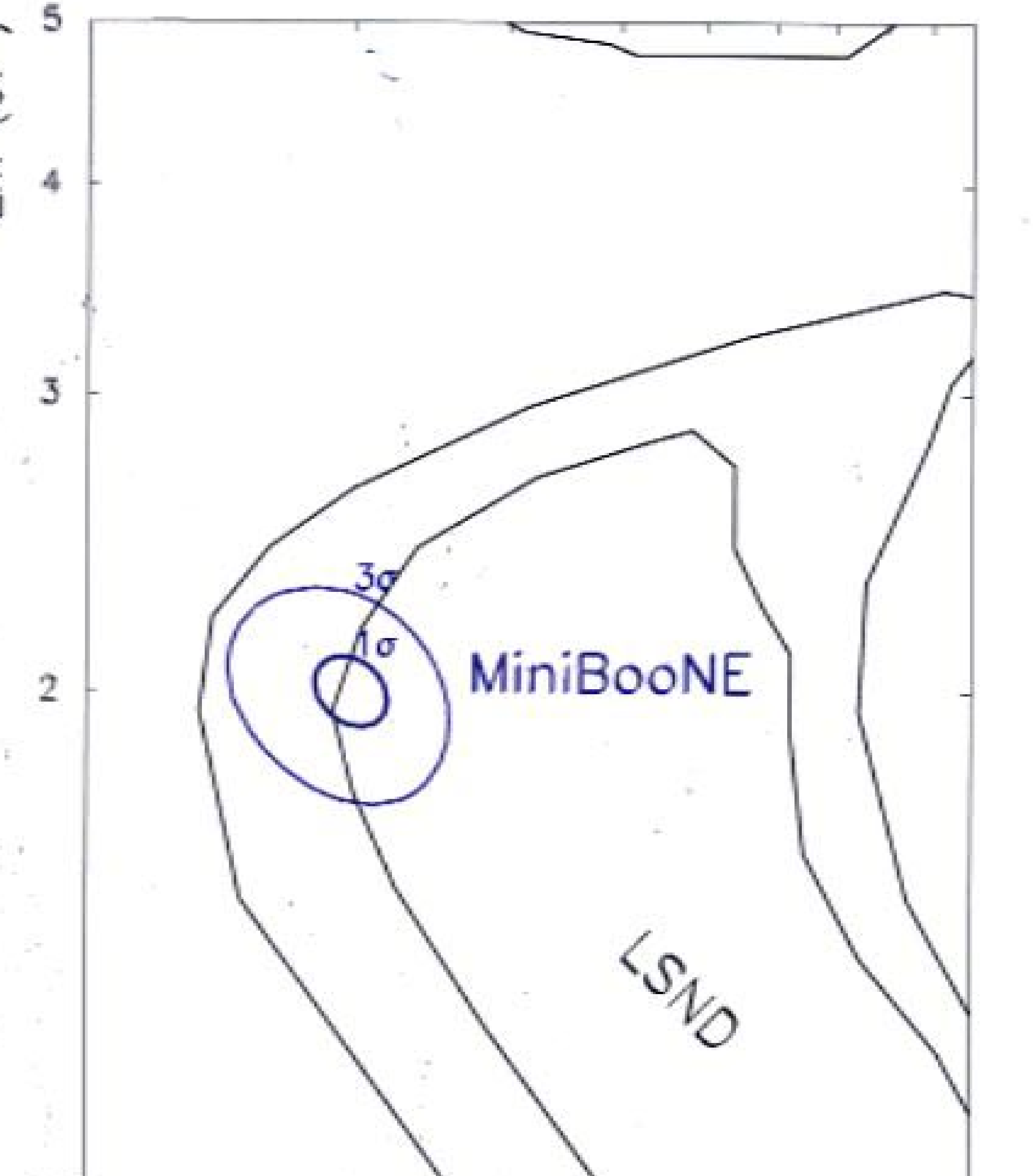
Signal after Bkgd Subtraction for Two Possible Osc. Parameters:



- Statistical uncertainty for signal is included in errors.
- Sys. and stat. uncertainty from background is included in errors.
- (Statistical fluctuations of data points not shown).

MiniBooNE can clearly establish a signal!
The signal indicates where to place the 2nd detector


Δm² (eV²)
10³
10²
10
1
10⁻¹
10⁻²
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
sin²2ϑ
E-fit (90% CL)
Total Events (90% CL)
E-fit (5 σ)
CCFR
Bugey III
LSND

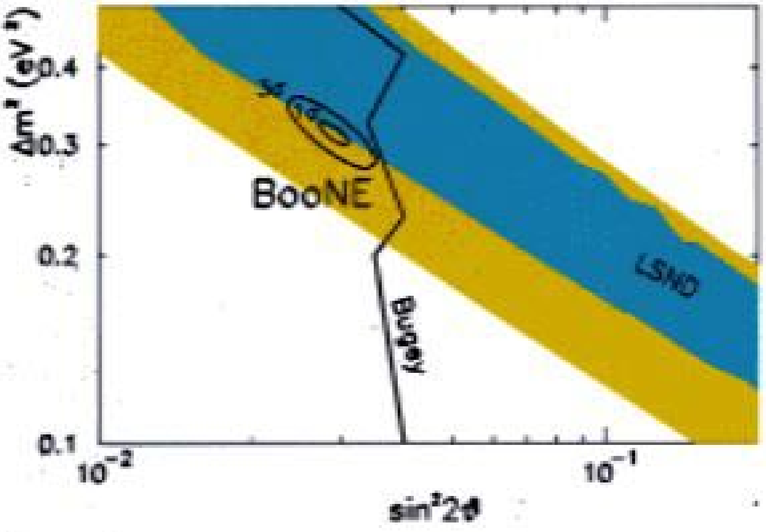

5
4
3
2
1
Δm² (eV²)
10⁻³
10⁻²
sin²2ϑ
3σ
1σ
MiniBooNE
LSND

A "Measurement" Experiment!

Two examples for MiniBooNE (1 detector) measurements:

Δm_0^2	$\sin^2 2\theta_0$	$\delta\left(\Delta m^2\right)$	$\delta\left(\sin^2 2\theta\right)$	Signal Signif.
$0.3\ \left(\mathrm{eV}^2\right)$	0.03	$0.10\ \left(\mathrm{eV}^2\right)$	0.02	$44\ \sigma$
$2.0\ \left(\mathrm{eV}^2\right)$	0.002	$0.10\ \left(\mathrm{eV}^2\right)$	0.0002	$15\ \sigma$

Example BooNE (2 detector) measurement



And tests of CP violation with ν and $\bar{\nu}$ running

Conclusions

- Evidence for ν oscillations from LSND !

  $\bar{\nu}_\mu \to \bar{\nu}_e$ search yields 39.5+–8.8 events

  PRC 54, (1996) 2685 & PRL 77, (1996) 3082

  $\nu_\mu \to \nu_e$ search yields 18.1+–6.6 events

  PRC 58, (1998) 2489 & PRL 81, (1998) 1774

  $m_\nu > 0.4$ eV

- The BooNE experiment will make a definitive test of the LSND signal and will make precision measurements of Δm^2 and $\sin^2 2\theta$ if ν oscillations occur.

- BooNE construction begins 10/99
  Gain beneficial occupancy on 1/01
  Detector operational on 10/01
  Beam complete & taking data on 12/01