Final 1993-1998 LSND Results

Overview of the experiment

Neutrino sources and processes

New oscillation analysis

LSND Collaboration

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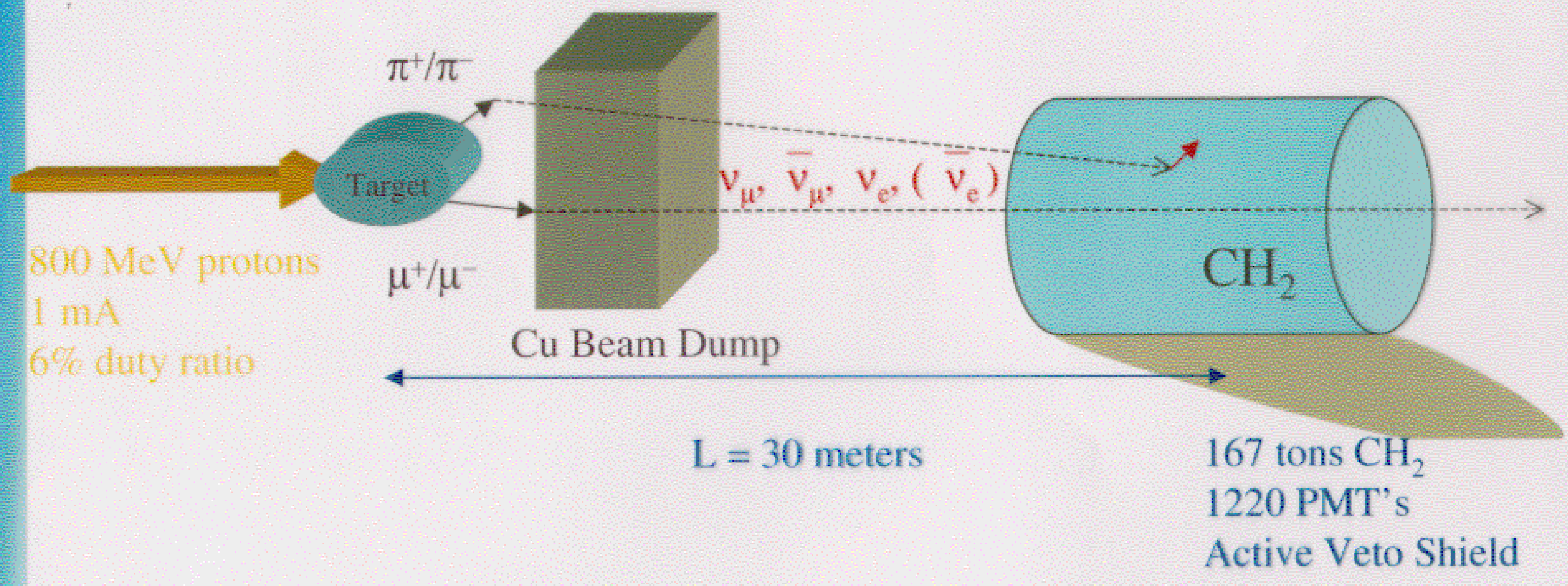
Embry Riddle Aeronautical University
Linfield College
Los Alamos National Laboratory
Louisiana State University
Southern University

The LSND Experiment



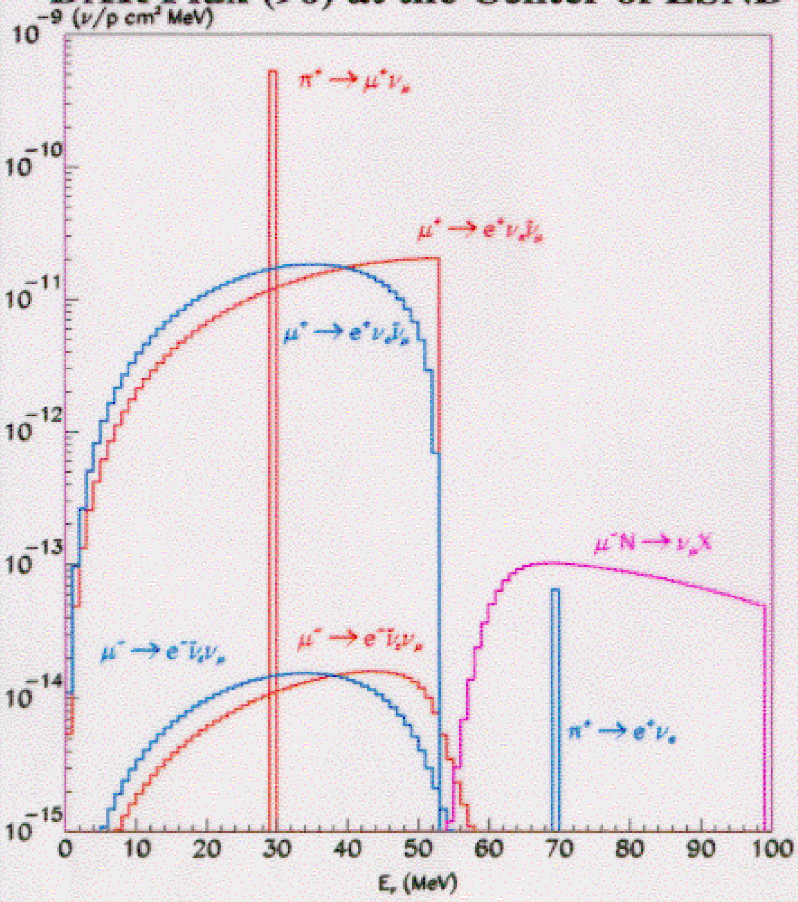
Neutrino Targets in CH_2 :

$\nu_\mu,\ \nu_e$: neutrons in ^{12}C + electrons

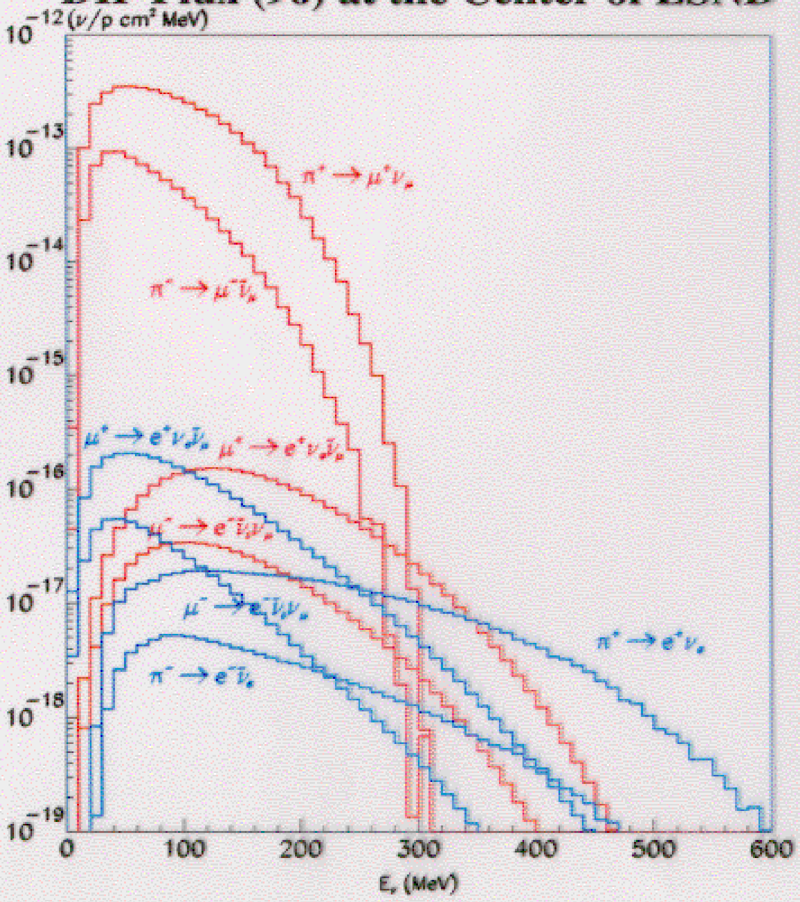
$\bar{\nu}_\mu,\ \bar{\nu}_e$: protons in ^{12}C + electrons + free protons

Neutrino Fluxes

DAR Flux (96) at the Center of LSND



DIF Flux (96) at the Center of LSND



LSND Neutrino Physics

- ν interactions on ^{12}C, e, p: 20-300 MeV

$$\nu\, C \begin{cases} \nu_e C \to e^- N\, (oscillation\ channel) \\ \nu_\mu C \to \mu^- N \end{cases} \qquad \bar{\nu}\, C \begin{cases} \bar{\nu}_e C \to e^+ B \\ \bar{\nu}_\mu C \to \mu^+ B \end{cases}$$

$$\nu(\bar{\nu})e \begin{cases} \nu_e e \to \nu_e e \\ \nu_\mu e \to \nu_\mu e \\ \bar{\nu}_\mu e \to \bar{\nu}_\mu e \end{cases} \qquad \bar{\nu}\, p \begin{cases} \bar{\nu}_e p \to e^+ n\ (oscillation\ channel) \\ \bar{\nu}_\mu p \to \mu^+ n \end{cases}$$

- Oscillation Search:

$$\bar{\nu}_\mu \to \bar{\nu}_e\ (decay\ at\ rest)$$

$$\nu_\mu \to \nu_e\ (decay\ in\ flight)$$

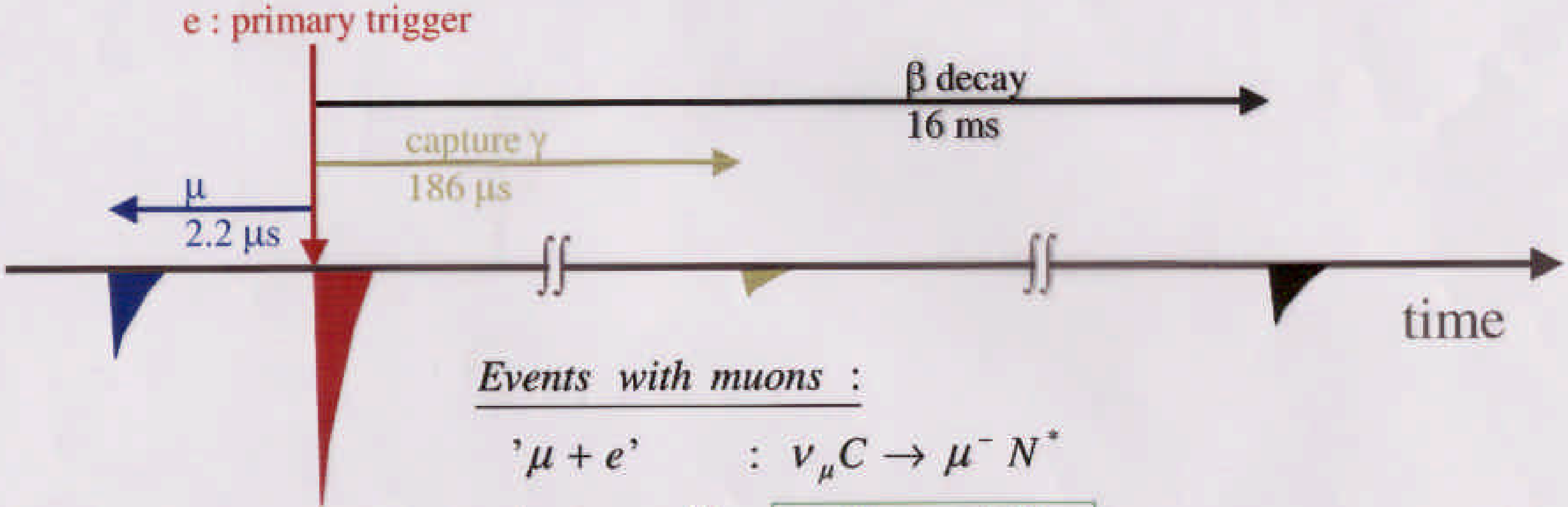
Oscillation Analysis Strategy

- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ decay at rest oscillation events in the energy range 20-60 MeV
- Search for $\nu_\mu \rightarrow \nu_e$ decay in flight oscillation events in the energy range 20-200 MeV
- Use common a 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 correlated neutron capture γ ($\bar{\nu}_e\, p \rightarrow e^+ n$) with correlated neutron capture gamma ($R_\gamma > 10$)
- Fit 20-200 MeV oscillation signal in ($E, R, L, \cos\theta_\nu$) to determine best oscillation parameter values

Analysis Improvements

- Global fit to all neutrino processes in order to constrain backgrounds
- Improved position resolution that gives better accidental gamma rejection in decay-at-rest analysis
  - Correlated gamma efficiency improves from 23% to 40%
  - Accidental background efficiency drops from 0.6% to 0.23%
- Combined decay-at-rest + decay-in-flight treatment when determining oscillation parameters

Event Time Structure



Events with muons :

'$\mu + e$' : $\nu_\mu C \rightarrow \mu^- N^*$

'$\mu + e + \beta$' : $\nu_\mu C \rightarrow \mu^- N_{GS}$

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

Events without muons :

'e' : $\nu_e e \rightarrow \nu_e e$, $\nu_e C \rightarrow e^- N^* (\nu_\mu \rightarrow \nu_e)$

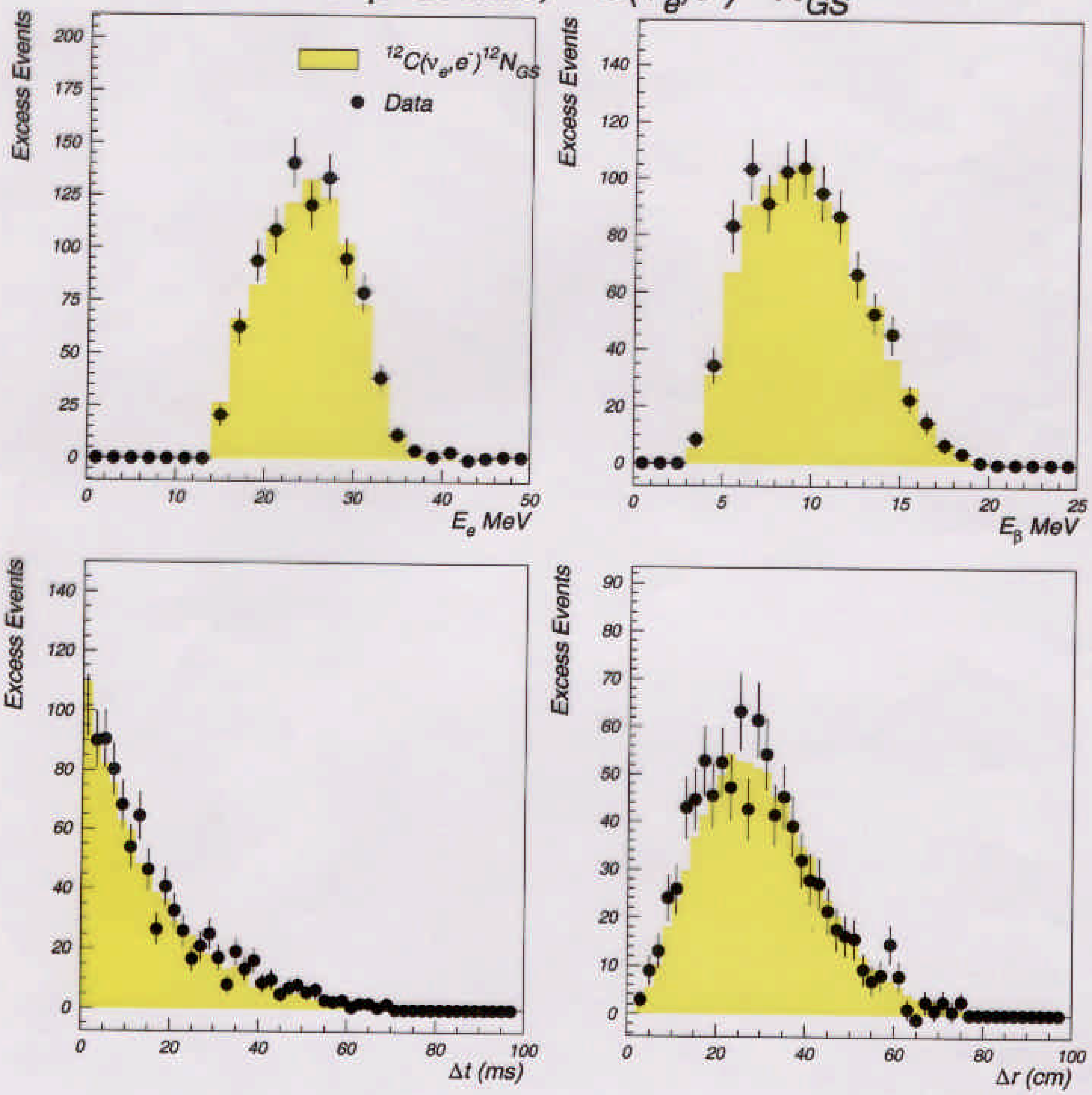
'$e + \beta$' : $\nu_e C \rightarrow e^- N_{GS}$

'$e + \gamma$' : $\bar{\nu}_e p \rightarrow e^+ n \; (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

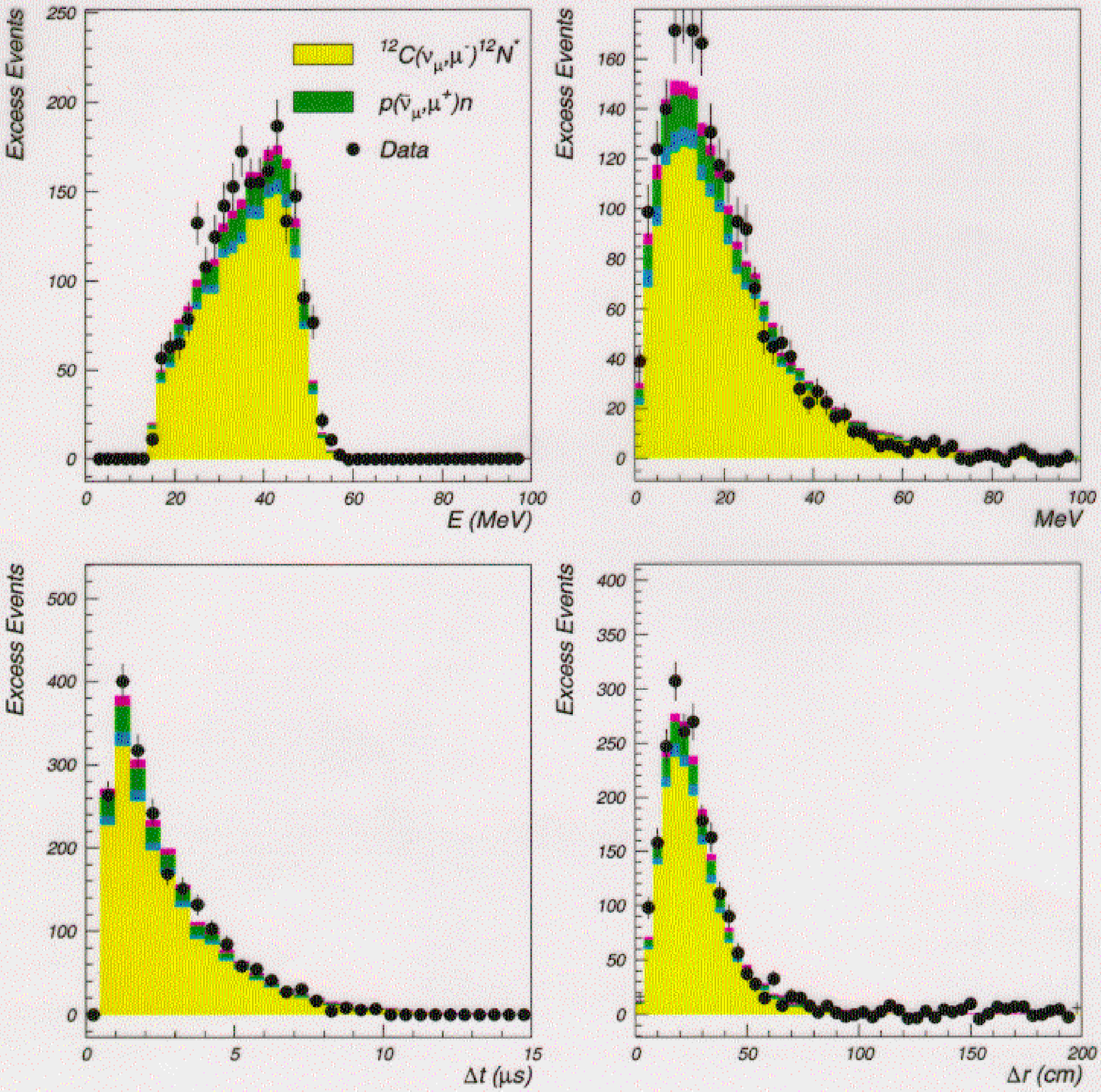
Global Fit Parameters

Exited state	:	$\nu_e\,{}^{12}C \to e^- N^*, \quad \nu_\mu\,{}^{12}C \to \mu^- N^*$
Ground state	:	$\nu_e\,{}^{12}C \to e^- N_{gs}, \quad \nu_\mu\,{}^{12}C \to \mu^- N_{gs}$
νe	:	$(\nu_e, \nu_\mu, \bar{\nu}_\mu)\,e \to (\nu_e, \nu_\mu, \bar{\nu}_\mu)\,e$
$\bar{\nu} p$	:	$(\bar{\nu}_e, \bar{\nu}_\mu)\,p \to (e^+, \mu^+)\,n$
$\nu_e\,{}^{13}C$	:	$\nu_e\,{}^{13}C \to e^-\,{}^{13}N^*$
Decay in flight flux	:	$\pi^+ \to \nu_\mu \mu^+, \nu_e e^+, \quad \pi^- \to \bar{\nu}_\mu \mu^-, \bar{\nu}_e e^-$
		$\mu^+ \to \bar{\nu}_\mu \nu_e\, e^+ \quad , \mu^- \to \nu_\mu \bar{\nu}_e\, e^-$
Decay at rest flux	:	$\pi^+ \to \nu_\mu \mu^+, \nu_e e^+$
		$\mu^+ \to \bar{\nu}_\mu \nu_e\, e^+ \quad , \mu^- \to \nu_\mu \bar{\nu}_e\, e^-$
Pion ratio	:	π^+ / π^- *production ratio*
efficiencies	:	$\mu, \mathrm{e}, \beta, \gamma$

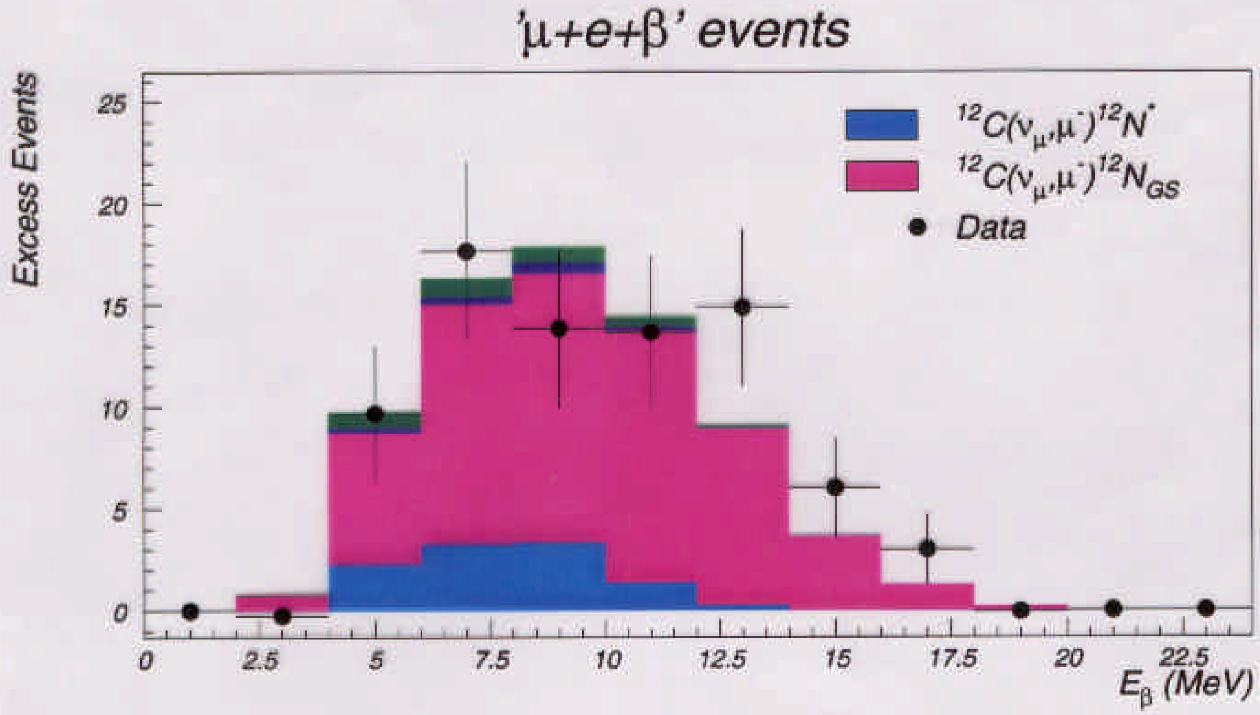
'e+β' events, $^{12}C(\nu_e,e^-)^{12}N_{GS}$

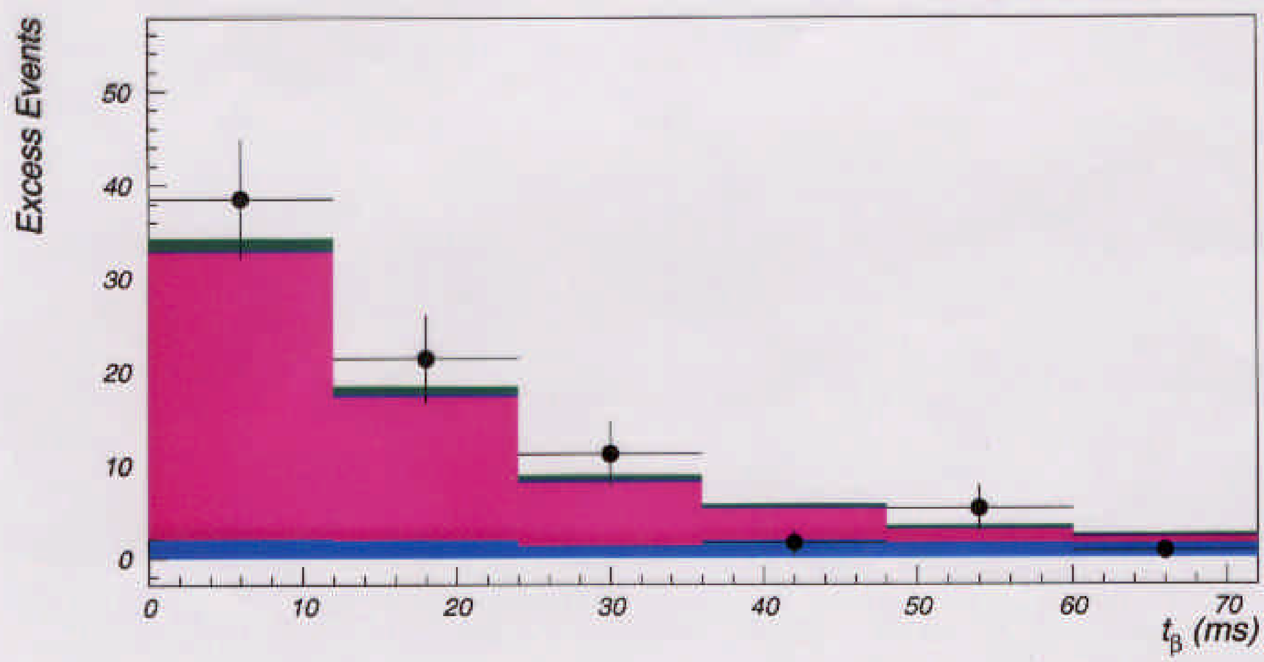


'μ+e' Events

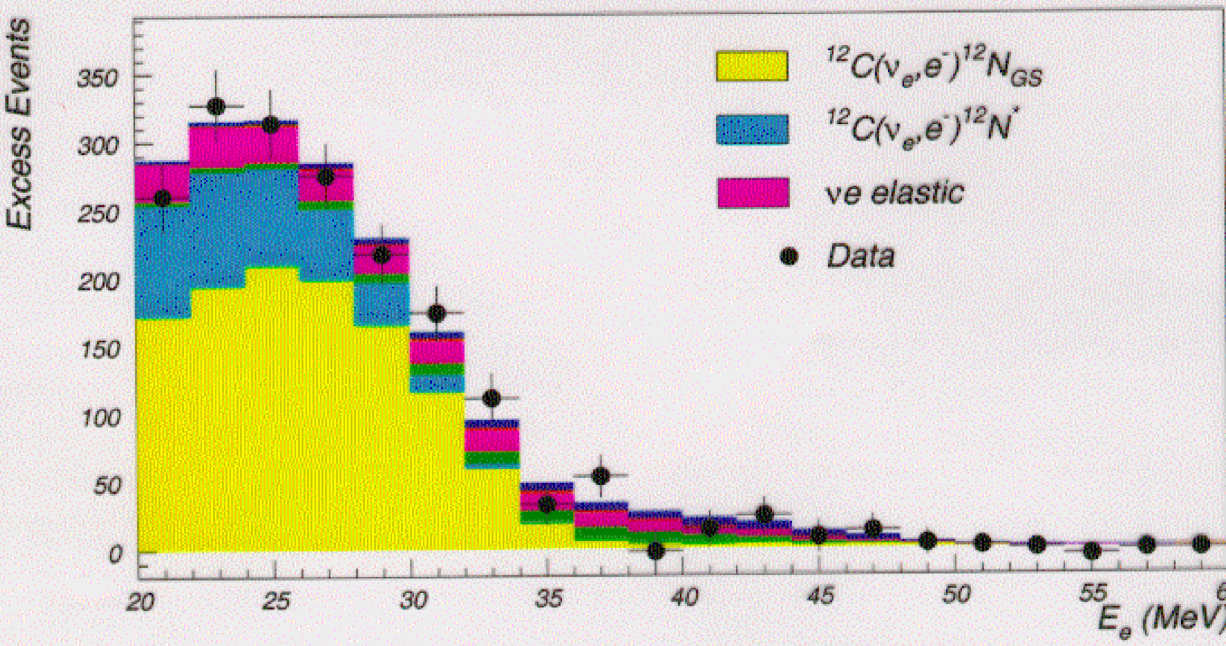


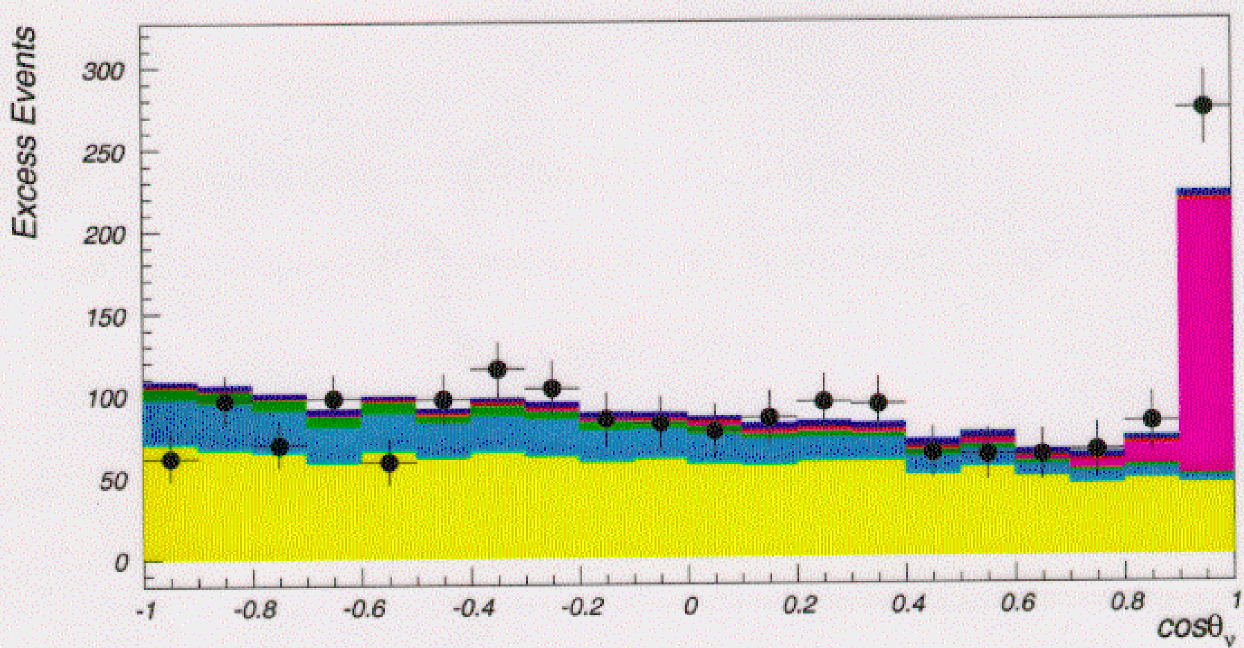
Excess Events
$^{12}C(\nu_\mu,\mu^-)^{12}N^*$
$p(\bar{\nu}_\mu,\mu^+)n$
Data
E (MeV)
Excess Events
MeV
Excess Events
Δt (μs)
Excess Events
Δr (cm)

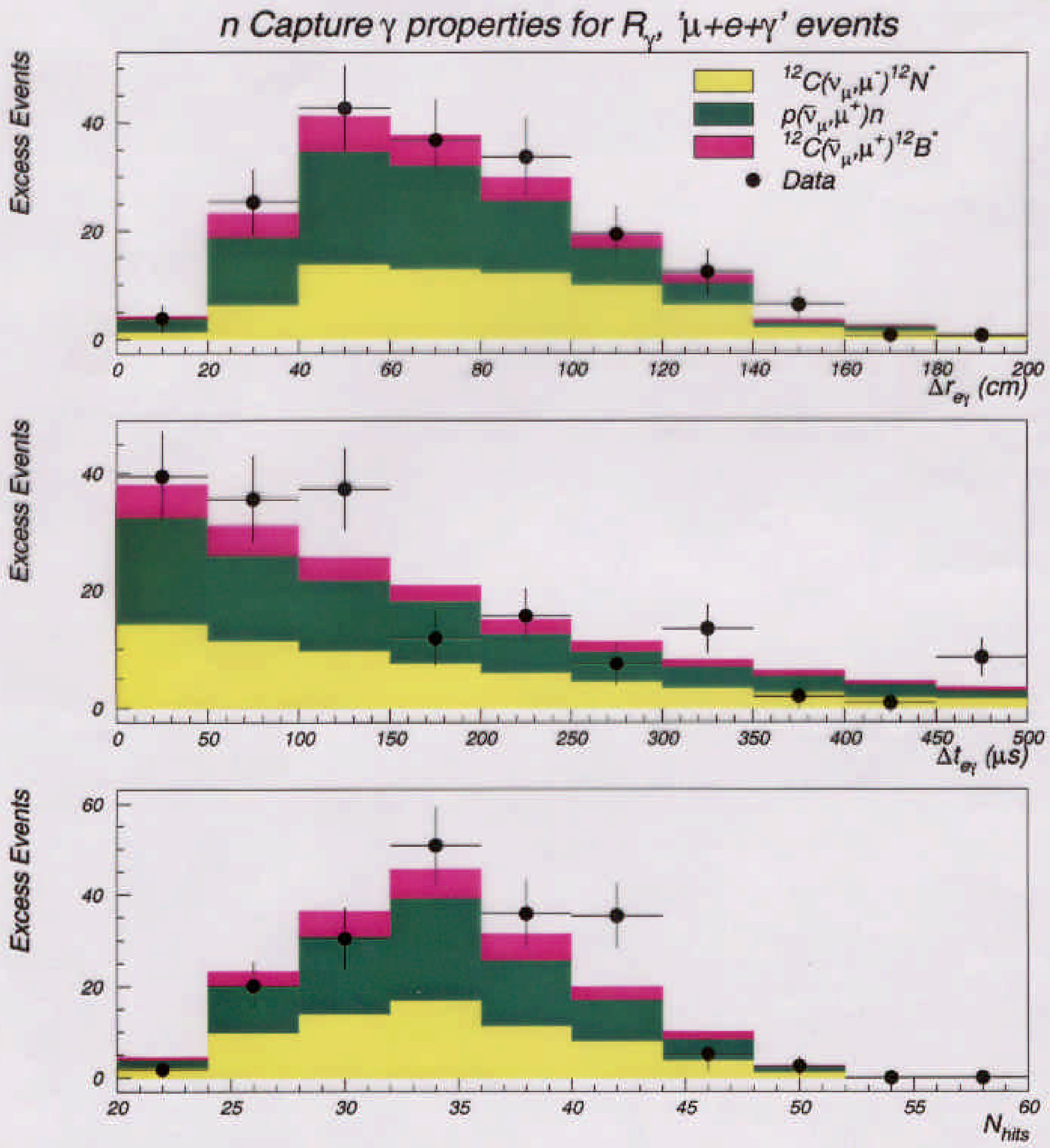

'μ+e+β' events
Excess Events
0
5
10
15
20
25
$^{12}C(\nu_\mu,\mu^-)^{12}N^*$
$^{12}C(\nu_\mu,\mu^-)^{12}N_{GS}$
Data
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
E_β (MeV)


Excess Events
0
10
20
30
40
50
0
10
20
30
40
50
60
70
t_β (ms)

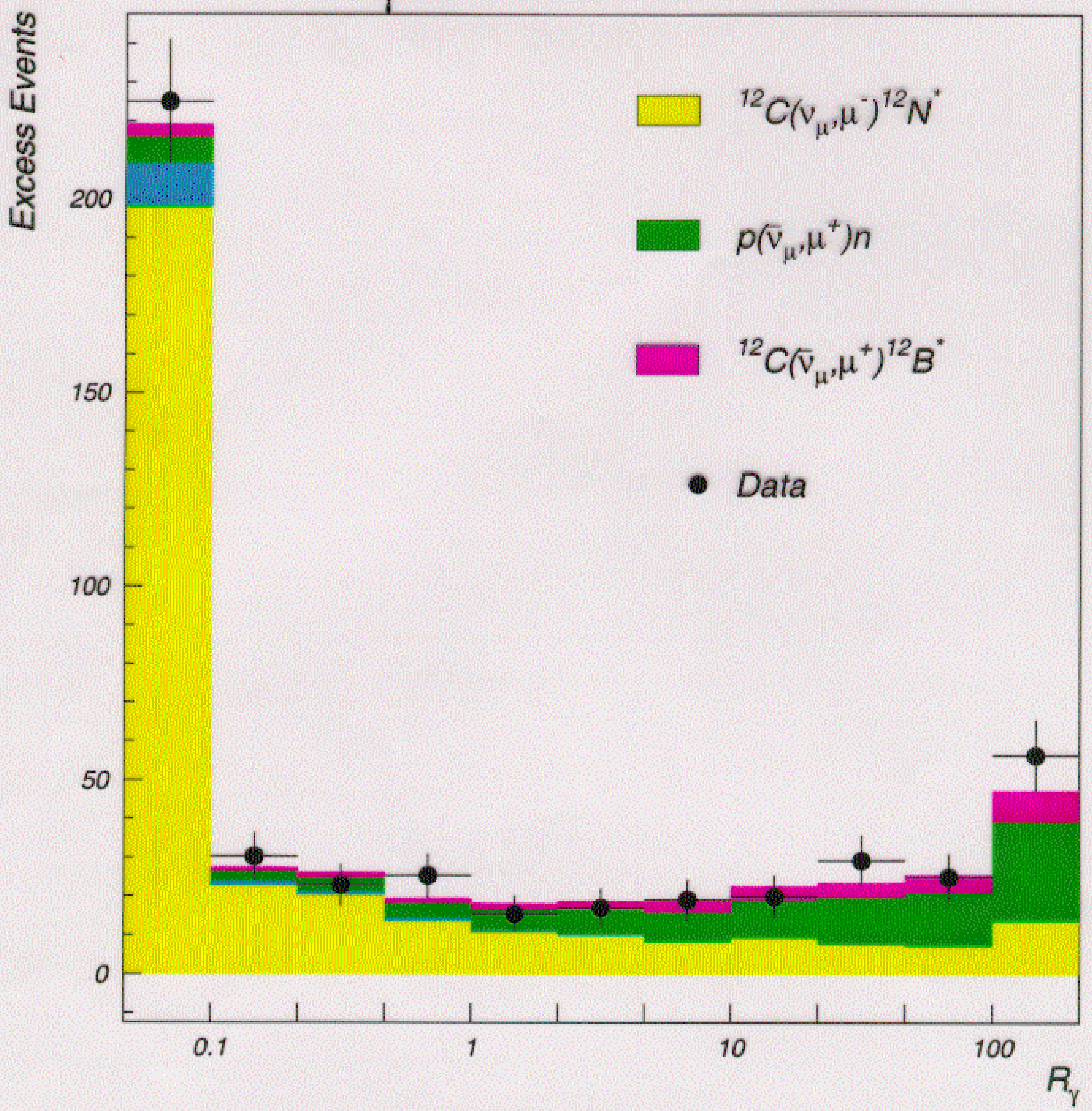
'e' events

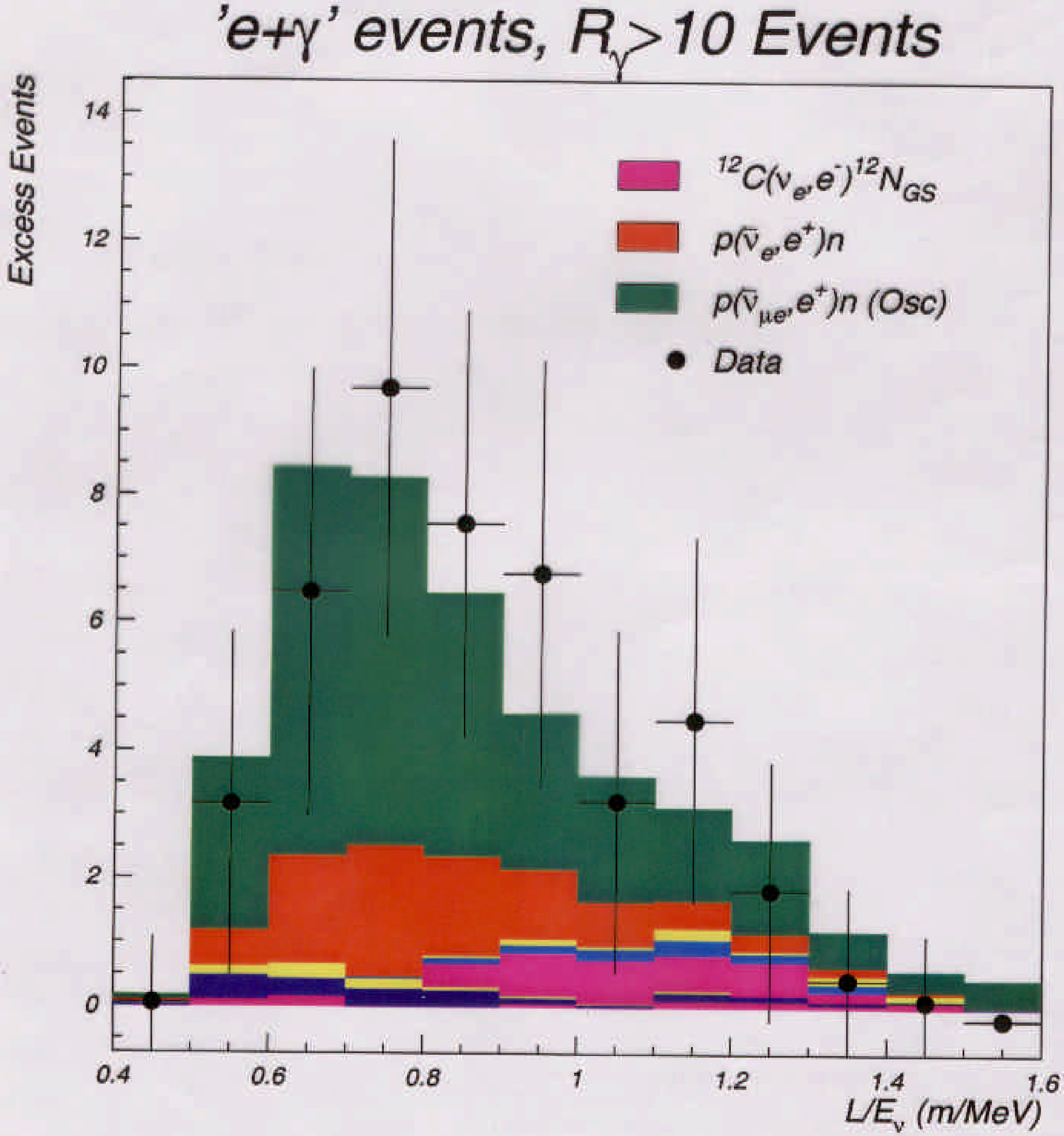

Excess Events
350
300
250
200
150
100
50
0
$^{12}C(\nu_e,e^-)^{12}N_{GS}$
$^{12}C(\nu_e,e^-)^{12}N^*$
νe elastic
Data
20
25
30
35
40
45
50
55
60
E_e (MeV)

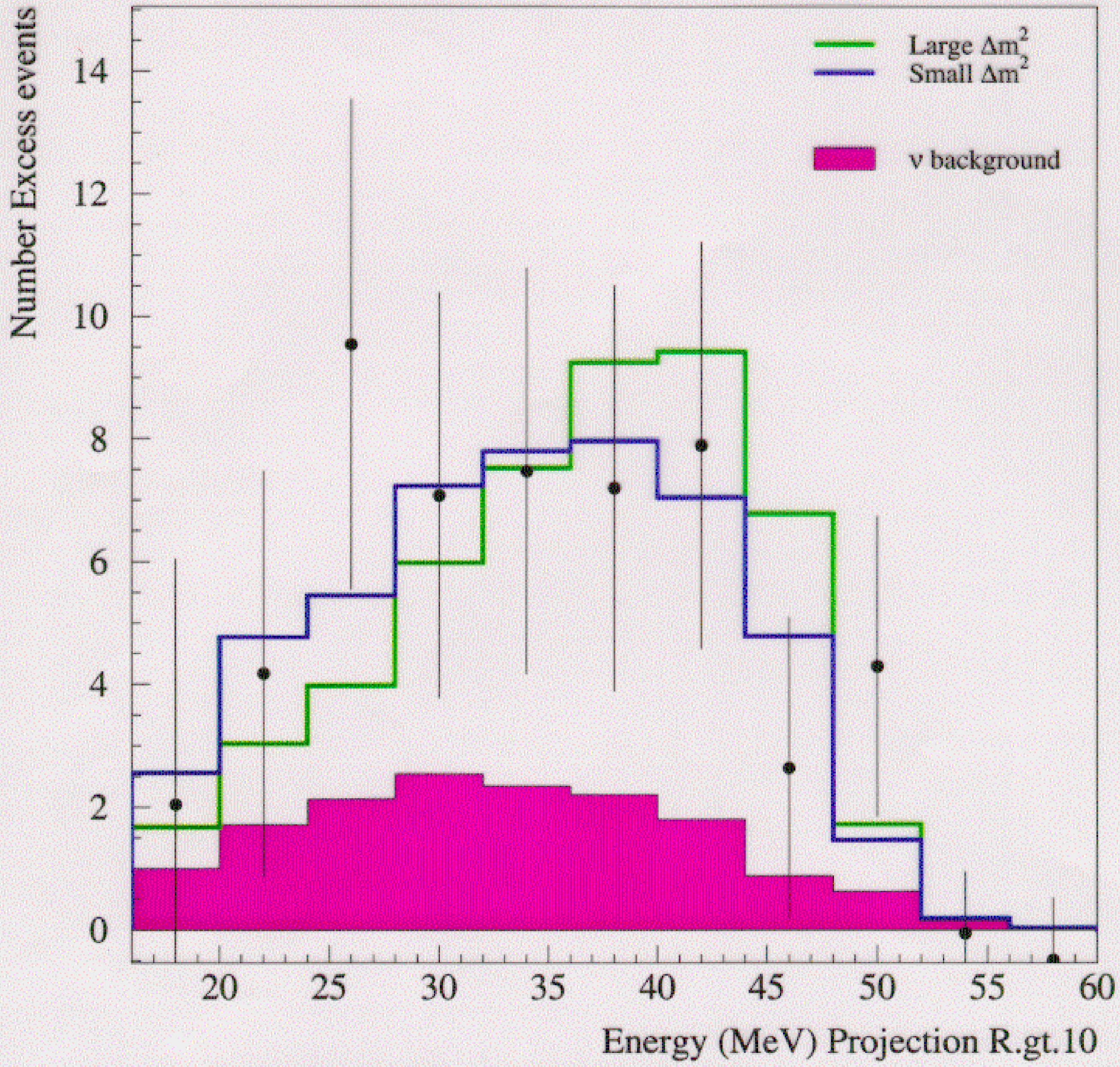

Excess Events
300
250
200
150
100
50
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
$\cos\theta_\nu$


n Capture γ properties for R_γ, 'μ+e+γ' events
$^{12}C(\nu_\mu,\mu^-)^{12}N^*$
$p(\bar{\nu}_\mu,\mu^+)n$
$^{12}C(\bar{\nu}_\mu,\mu^+)^{12}B^*$
Data
Excess Events
$\Delta r_{e\gamma}$ (cm)
Excess Events
$\Delta t_{e\gamma}$ (μs)
Excess Events
N_{hits}

R_γ, 'μ+e+γ' Events




'e+γ' events, R_γ>10 Events
Excess Events
$^{12}C(\nu_e,e^-)^{12}N_{GS}$
$p(\bar{\nu}_e,e^+)n$
$p(\bar{\nu}_{\mu e},e^+)n$ (Osc)
Data
L/E_ν (m/MeV)



Number Excess events
0
2
4
6
8
10
12
14
20
25
30
35
40
45
50
55
60
Energy (MeV) Projection R.gt.10
Large Δm^2
Small Δm^2
ν background

Neutrino Oscillations 20-60 MeV

- R>10 Selection:

on	off	ν bkgd	excess
83	(-)33.7	(-)16.6	32.7±9.2

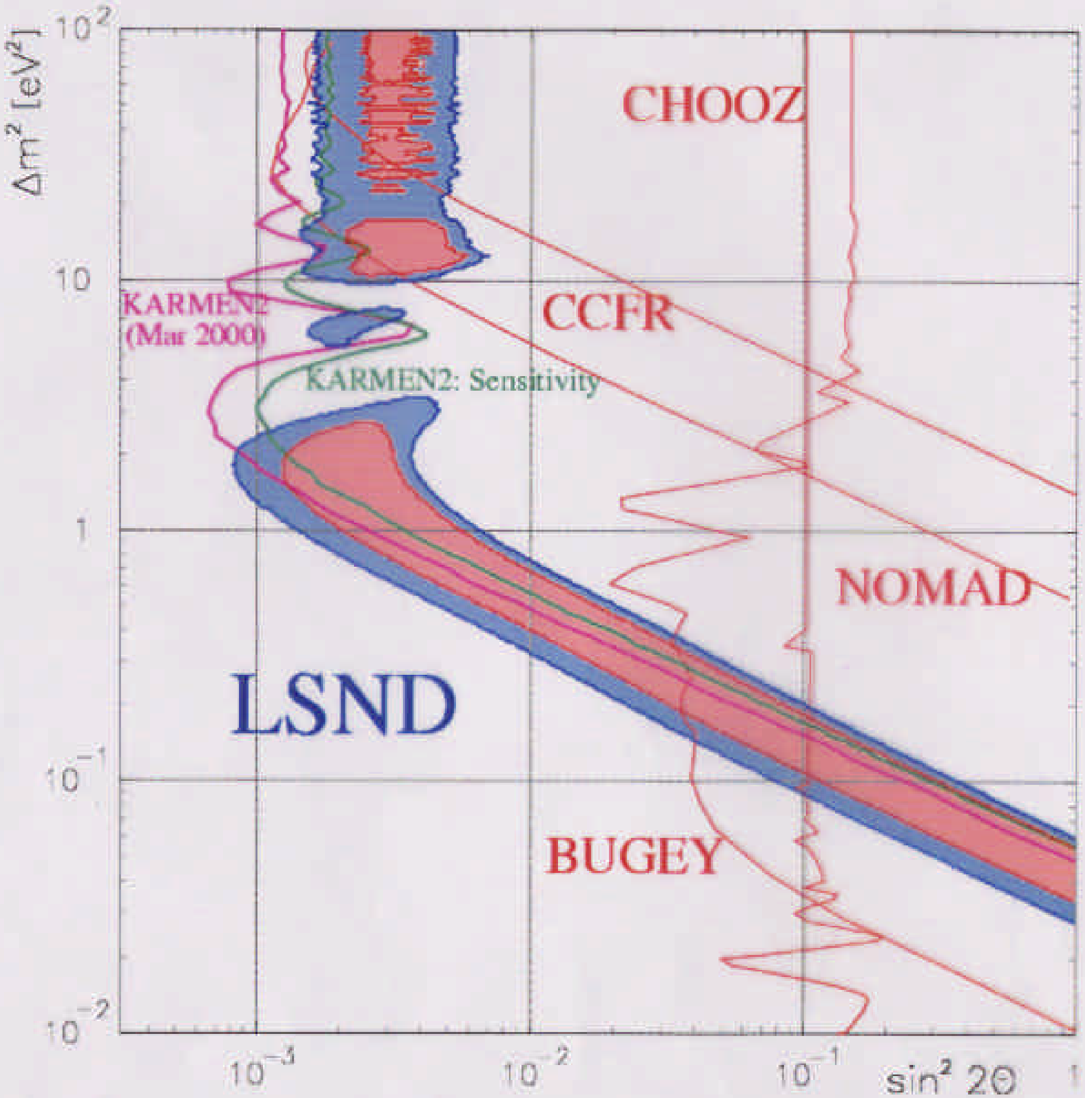
- Fit to R distribution:

Oscillation Excess	Oscillation Probability
83.3 ± 21.2	(0.25±0.06 ± 0.04)%

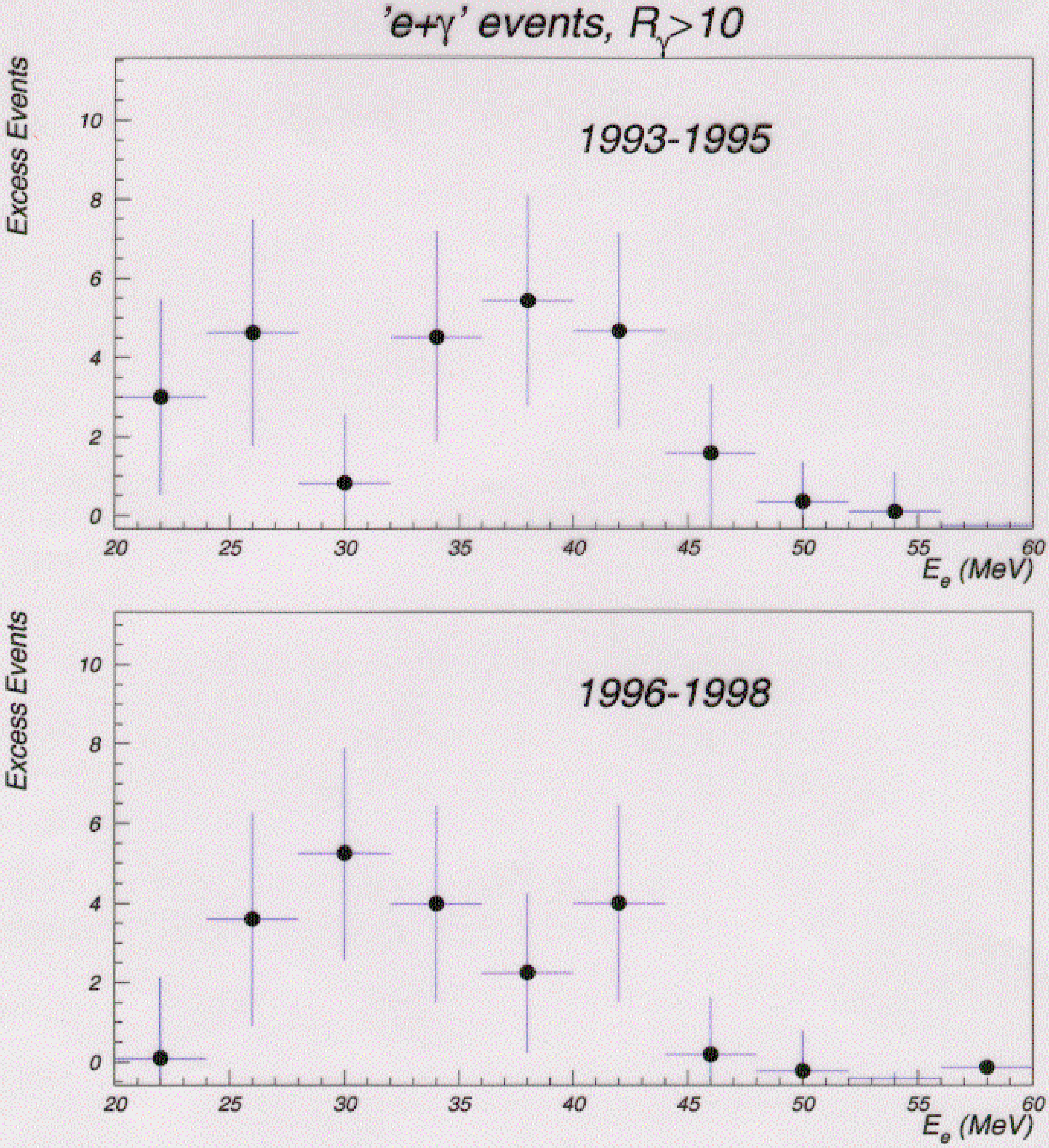
Global Oscillation Fit

- Electron selection in energy range of 20-200 MeV
- Fit all backgrounds in (E_e, R_γ, L_ν, $\cos\theta_\nu$) and calculate likelihood at each (Δm^2,$\sin^2\theta$)

$$P_{osc}\left(\Delta m^2, \sin^2 2\theta\right) = \sin^2 2\theta \times \sin^2\left(\Delta m^2 \frac{L_\nu}{E_\nu} \right)$$



Δm^2 [eV^2]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\Theta$
1
CHOOZ
CCFR
KARMEN2 (Mar 2000)
KARMEN2: Sensitivity
NOMAD
LSND
BUGEY


'e+γ' events, R_γ>10
Excess Events
1993-1995
0
2
4
6
8
10
20
25
30
35
40
45
50
55
60
E_e (MeV)
Excess Events
1996-1998
0
2
4
6
8
10
20
25
30
35
40
45
50
55
60
E_e (MeV)

Summary

- LSND observes excess $\overline{\nu}_e\, p \rightarrow e^+ n$ events which are not consistent with conventional neutrino processes
- A natural explanation is neutrino appearance due to *flavor oscillations* that have an overall probability of $(0.25 \pm 0.06 \pm 0.04)\%$ with a $\Delta m^2 > 0.2\ \text{eV}^2$
- This is the only appearance evidence of neutrino oscillations at the present time