

# Observations on Atmospheric Neutrinos with Soudan-2

Anthony Mann, Tufts University

*for the Soudan-2 Collaboration:*

Argonne - Minnesota - Oxford - Rutherford - Tufts

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# I. Soudan Detector; Event Imaging

Topologies:

Contained track, shower, and multiprongs events;

Partially Contained two-prongs and multiprongs

# II. Neutrino Flavor Ratio (4.2 kty)

"Sub-GeV" measurement of track and shower events;

Treatment of cosmic-ray induced background events

# III. $\nu_\mu, \nu_e$ CC "High Resolution" Samples (4.4 kty)

( $\nu$ -direction  $\Rightarrow L, E_{vis} \Rightarrow E_\nu$ )  $\Rightarrow L/E_\nu$

1) Zenith angle,  $E_\nu, L/E_\nu$  distributions

2)  $\chi^2$ -fitting to oscillation parameters

*Preliminary*

# IV. Partially Contained $\nu_\mu$ CC Events (4.2 kty)

Zenith angle,  $E_{vis}, L/E_{vis}$  distributions

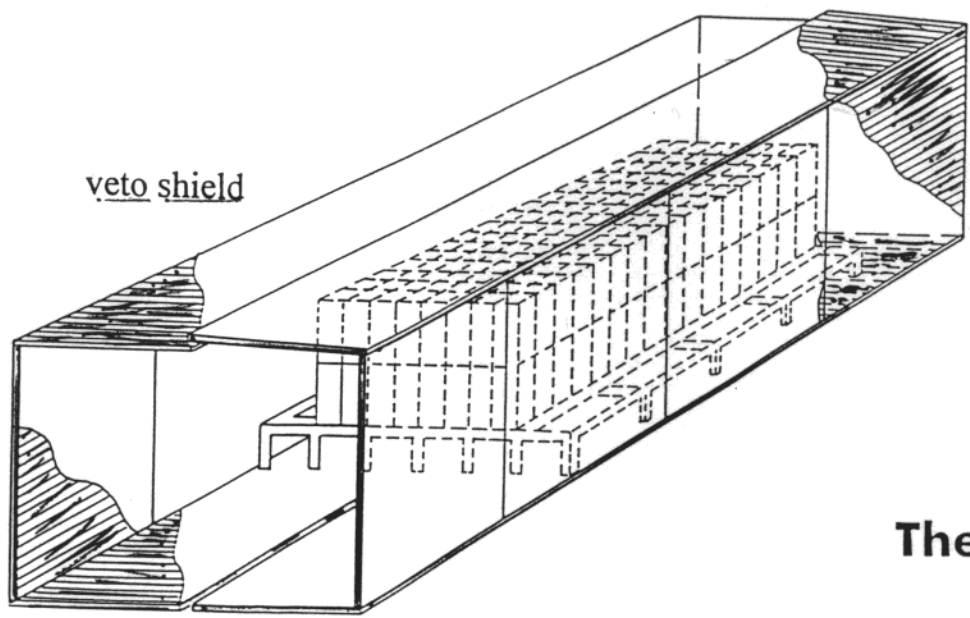
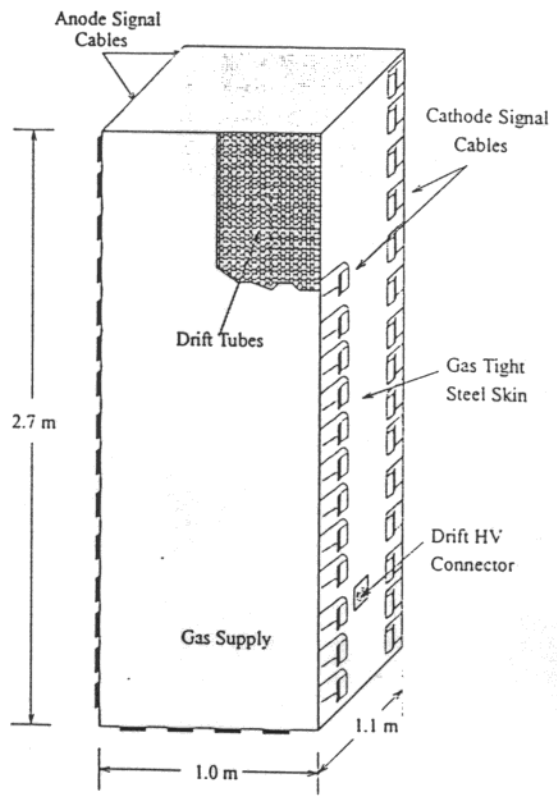
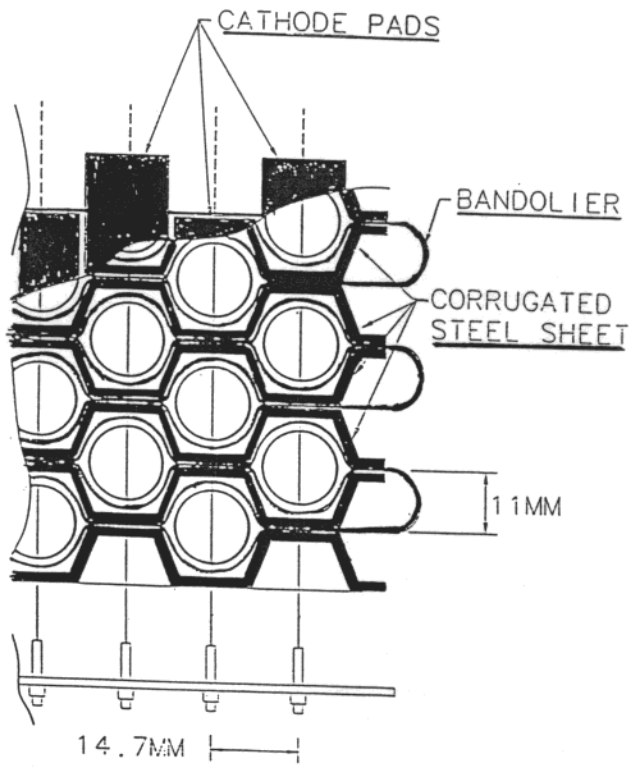
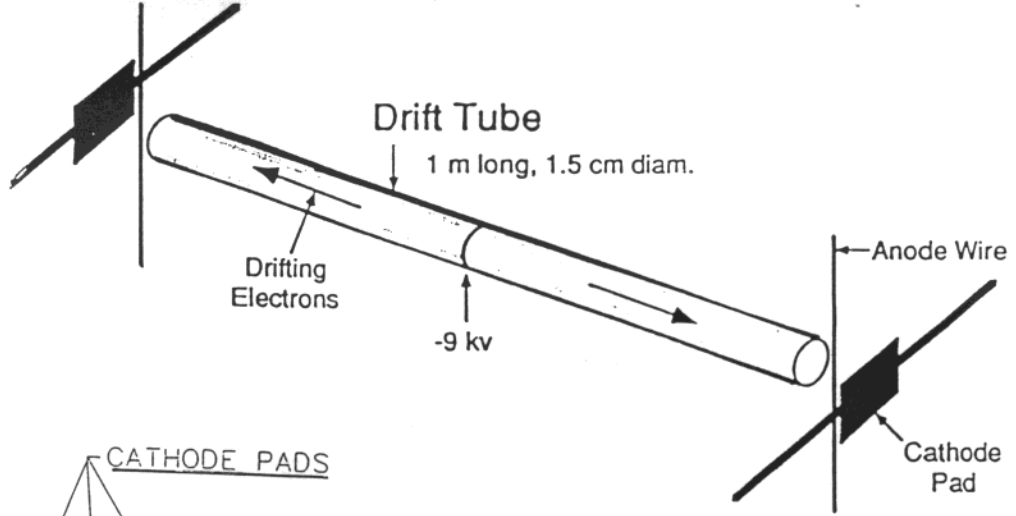
*Preliminary*

# V. $(\sin^2 2\theta, \Delta m^2)_{\nu_\mu \leftrightarrow \nu_x}$ from Soudan data

$\chi^2$ -fitting to HiRes CEV( $L/E_\nu$ ) + PCE( $L/E_{vis}$ )

*Preliminary*

# VI. Summary and Outlook



**The Sudan 2 Detector**

# Data: Contained Event

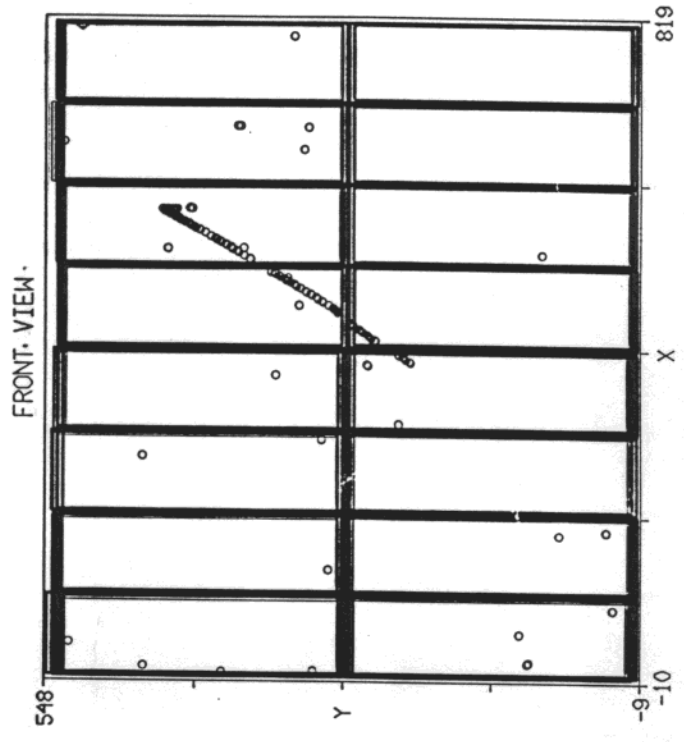
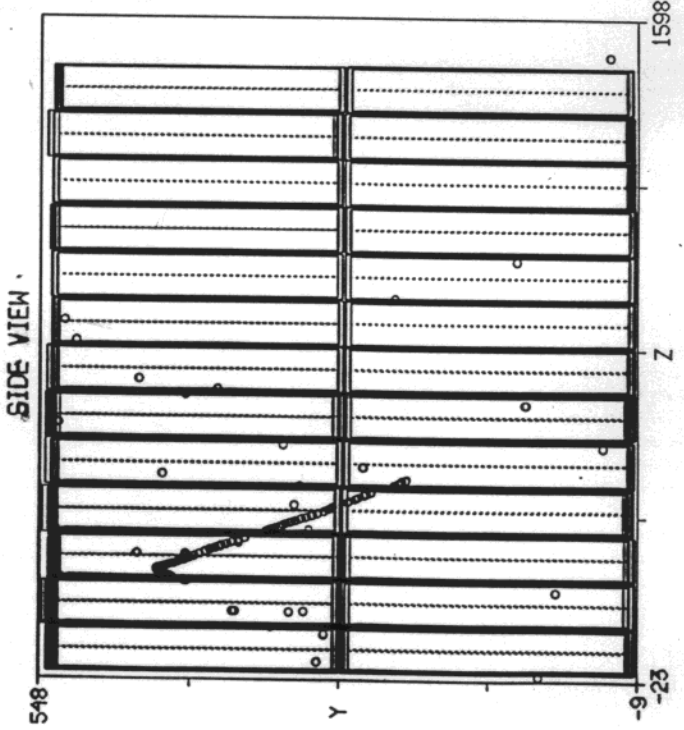
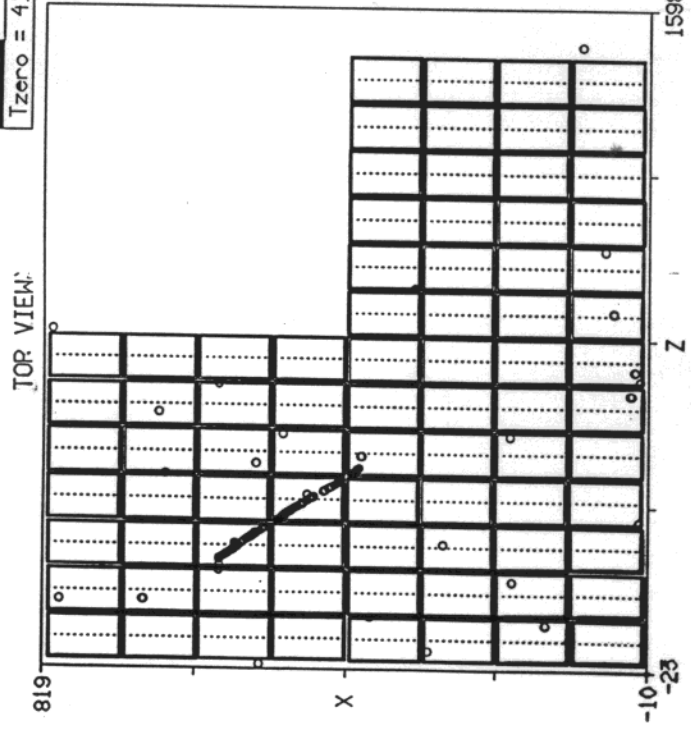
Soudan2 Data  
Run 62052 Event 247  
29-Jun-1995 06:38:57.93

Tzero = 416 Set by 2D SEARCH loom crossers and TODET

Shield ADJC's  
No SHLA bank. HEAD says SPLASH ran OK.  
Shield Ovlaps  
No SHLA bank. HEAD says SPLASH ran OK.

↳ Veto Shield is "quiet".

$E_{vis} = 1215 \text{ MeV}$   
 $|\vec{p}_{net}| = 1156 \text{ MeV}/c$

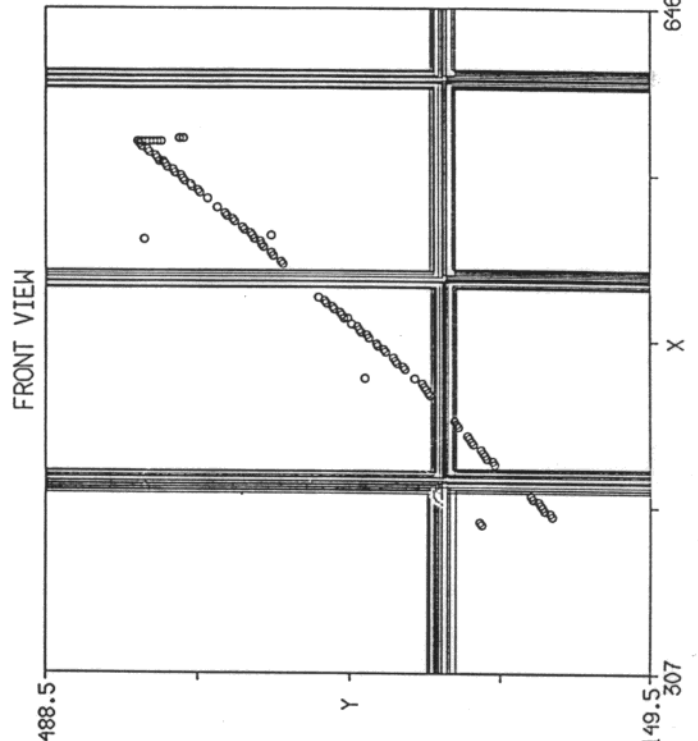
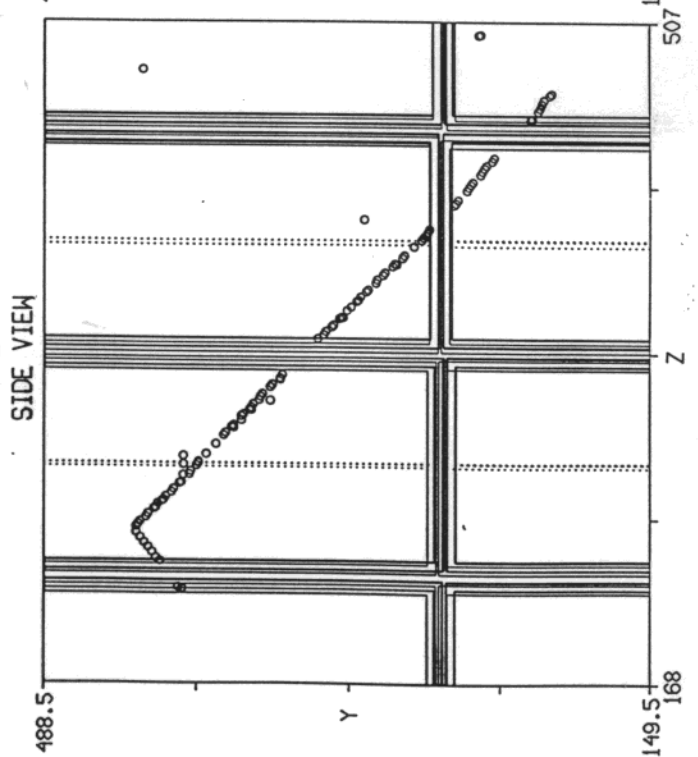
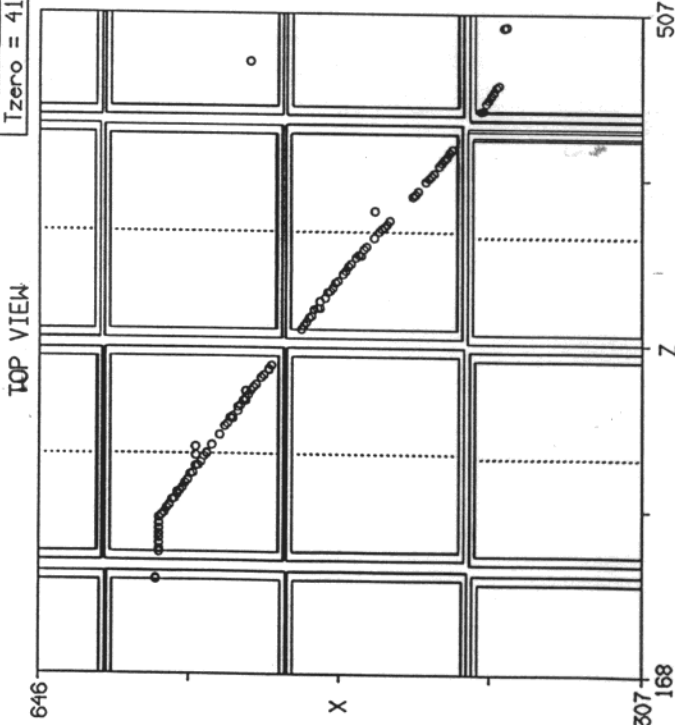


# $\nu_n$ quasi-elastic Reaction:

Soudan2 Data  
Run 62052 Event 247  
29-Jun-1995 06:38:57.93

Zero = 416 Set by 2D SEARCH loop crossers and TODET

Shield ADJC's  
No SHLA bank. HEAD says SPLASH ran OK.  
Shield Ovlaps  
No SHLA bank. HEAD says SPLASH ran OK.



No endpt shwr



ionization  
multiple scattering

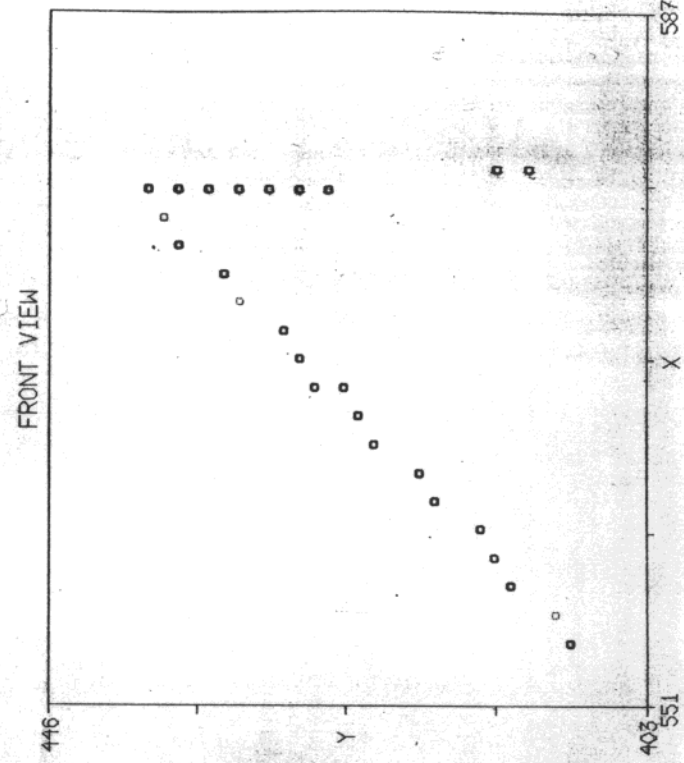
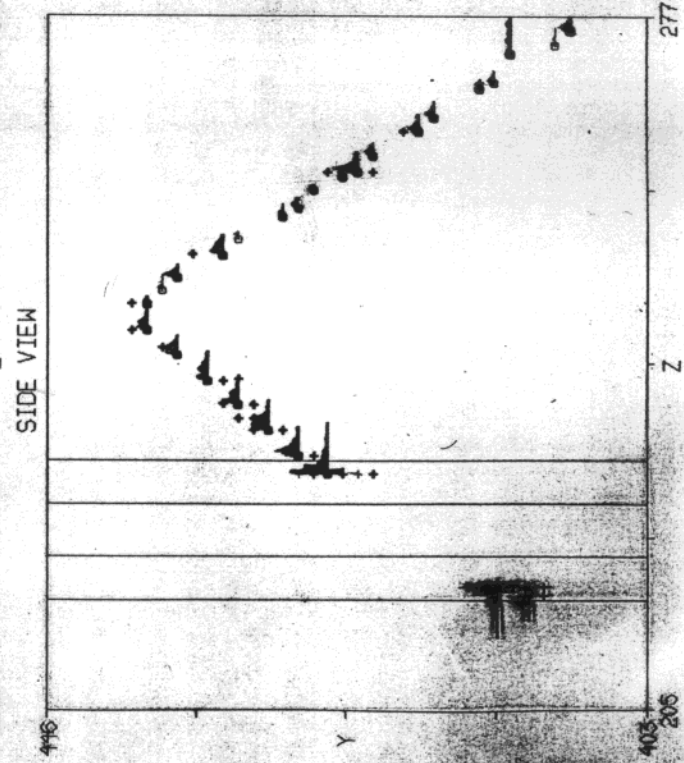
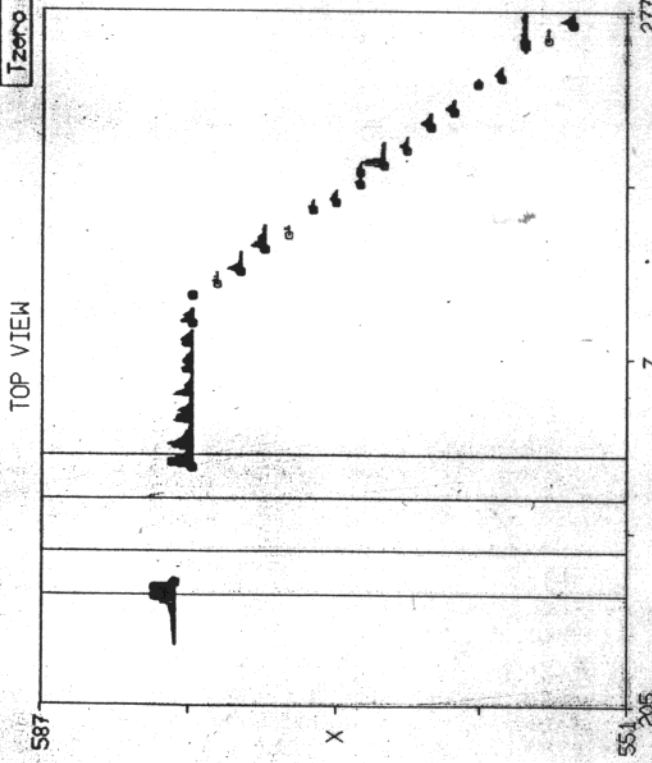
track is straight,  
heavily ionizing

# Ionization, Mult. Scattering Signatures :

Zero = 416 Set by 2D SEARCH loom crossers and TODET

No SHLA bank, HEAD says SPLASH ran OK.

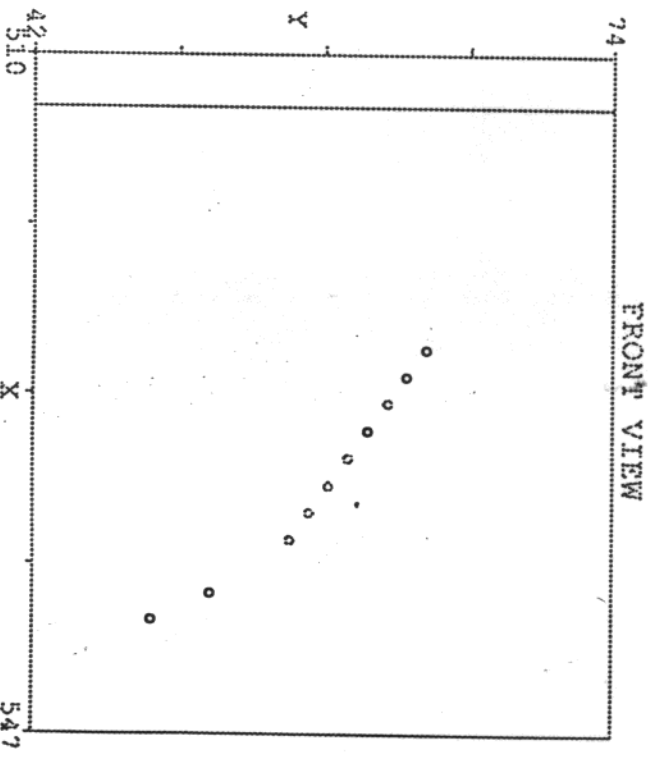
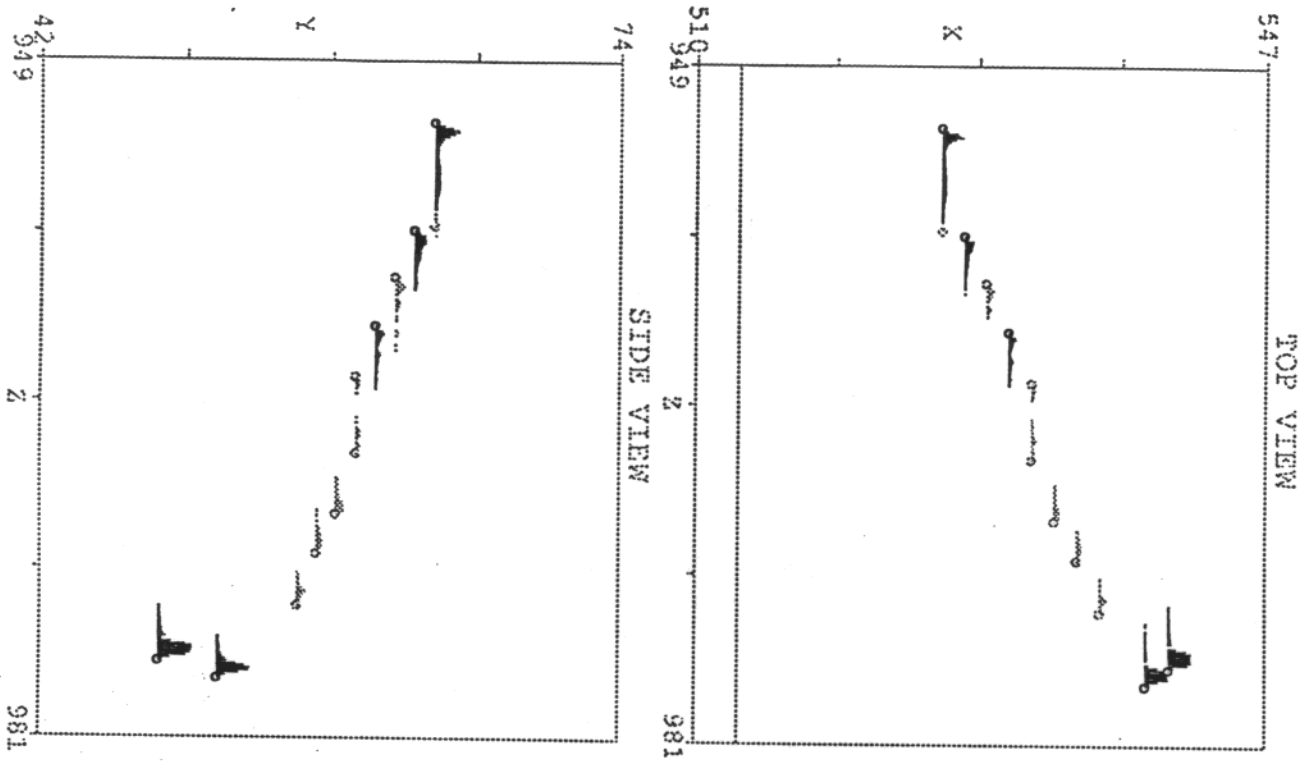
No SHLA bank, HEAD says SPLASH ran OK.



Neutrino direction from visible final state:  
 $\langle \Delta \theta_{v.fs} \rangle \approx 10^\circ !$

'single track'

Mine Data  
 Run 36543 Event 1277  
 14-Jun-1992 10:59:46.08



$$\nu_{\mu} + n \rightarrow \bar{\mu} + p$$

# "Single Shower" Event



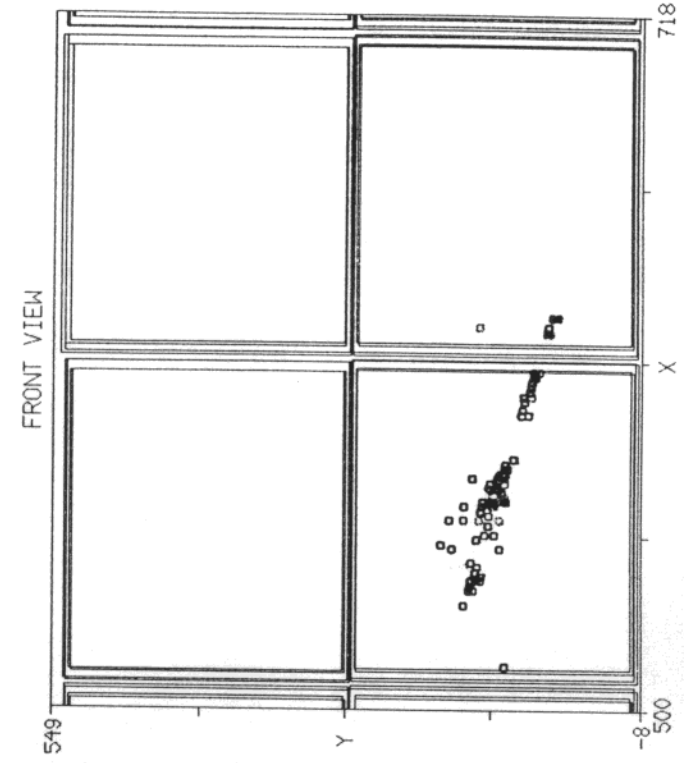
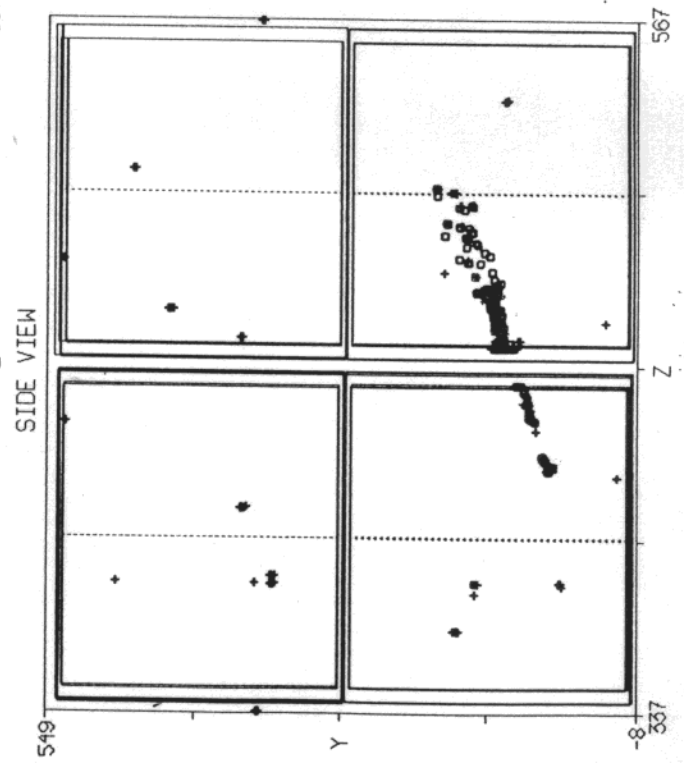
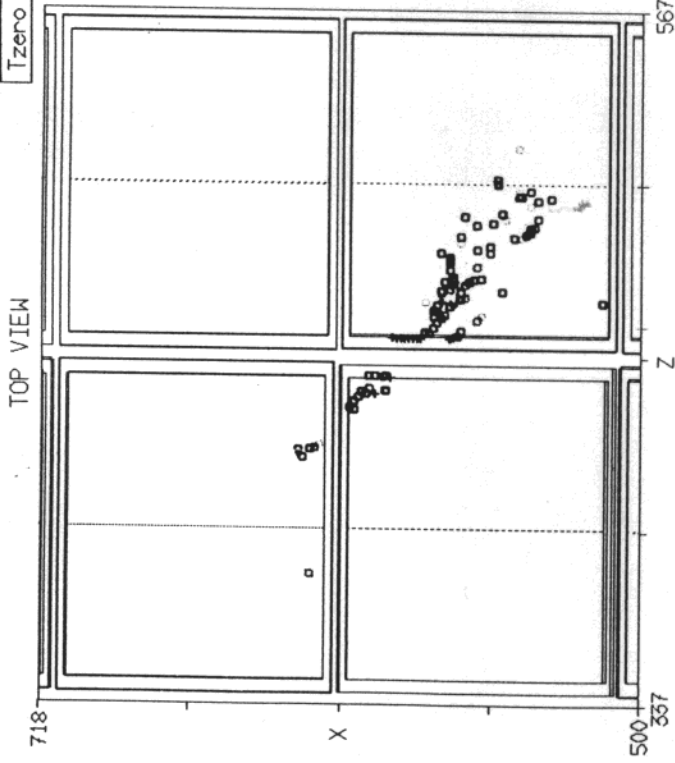
Tzero = 453 Set by Hand with STING

SHLA ADJUSTS

No SHLA bank. HEAD says SPLASH ran OK.

SHLA ADJUSTS

No SHLA bank. HEAD says SPLASH ran OK.





Soudan2 Data  
 Run 75247 Event 122  
 01-Jan-1997 17:17:24.53

Izero

Izero = 440.041 Set by 2D SEARCH loop crossers and TODET

Shield ADJC's  
 (2 at 364->369 E)

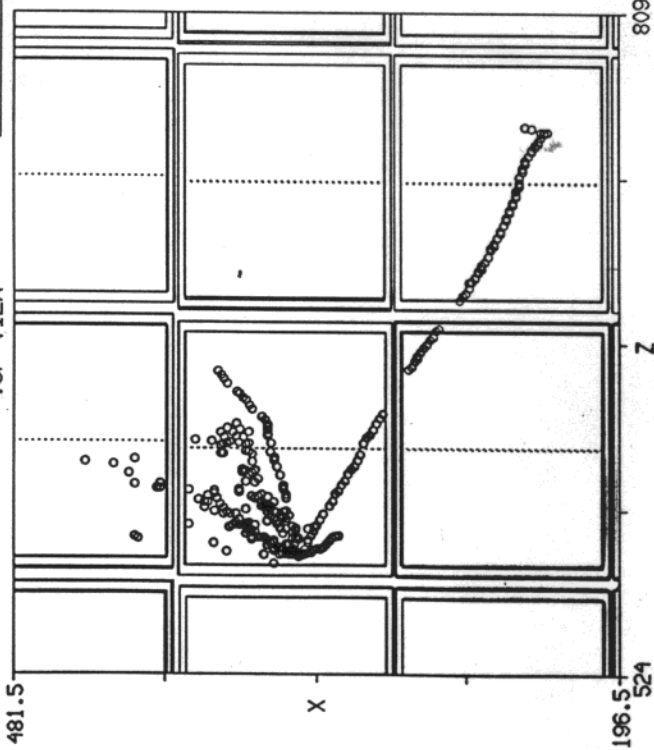
Shield Ovlaps  
 No SHLA bank. HEAD says SPLASH ran OK.

Contained Multiprong Event

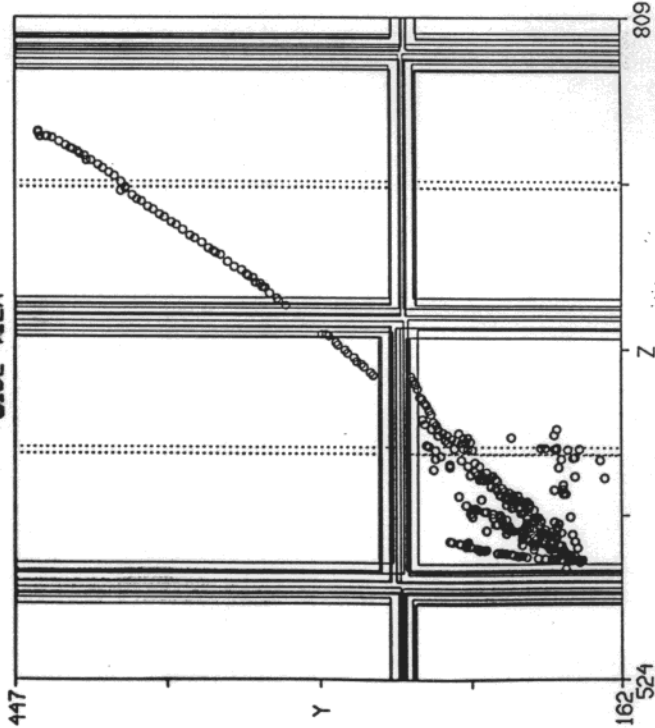
$\bar{\nu}_\mu$  Flavor

$E_{vis} > 4.0$  GeV

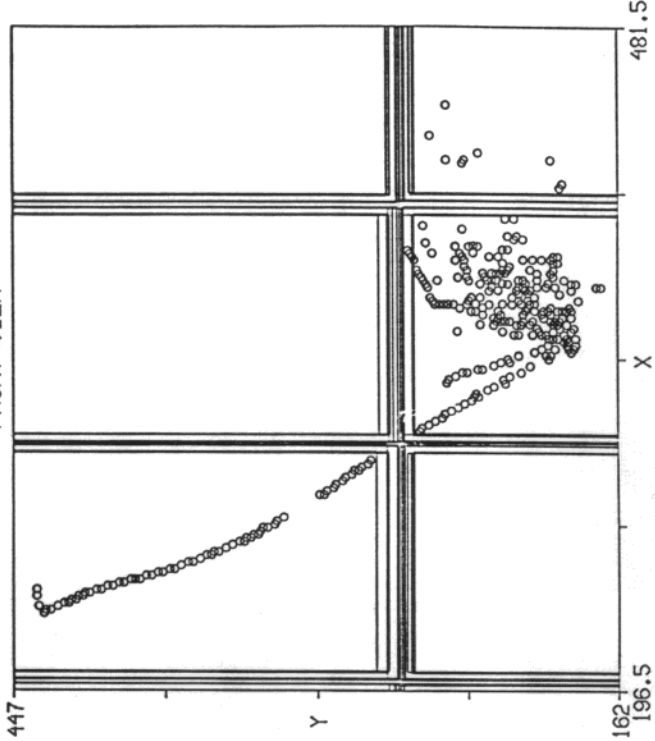
TOP VIEW



SIDE VIEW



FRONT VIEW

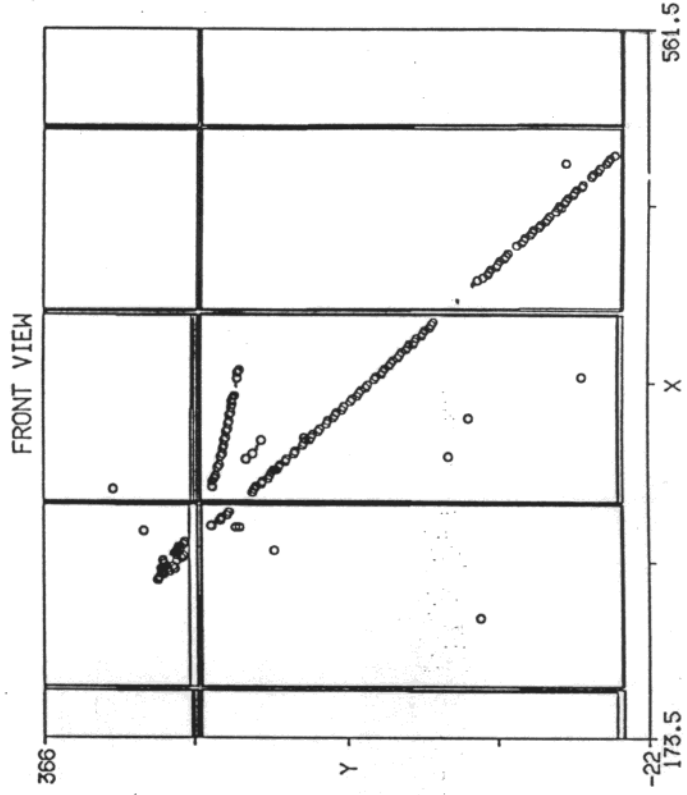
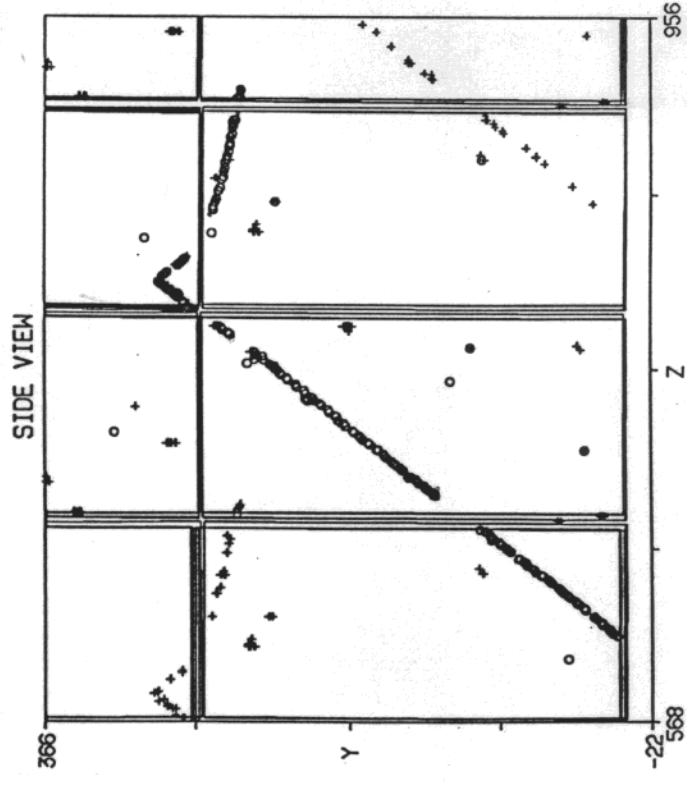
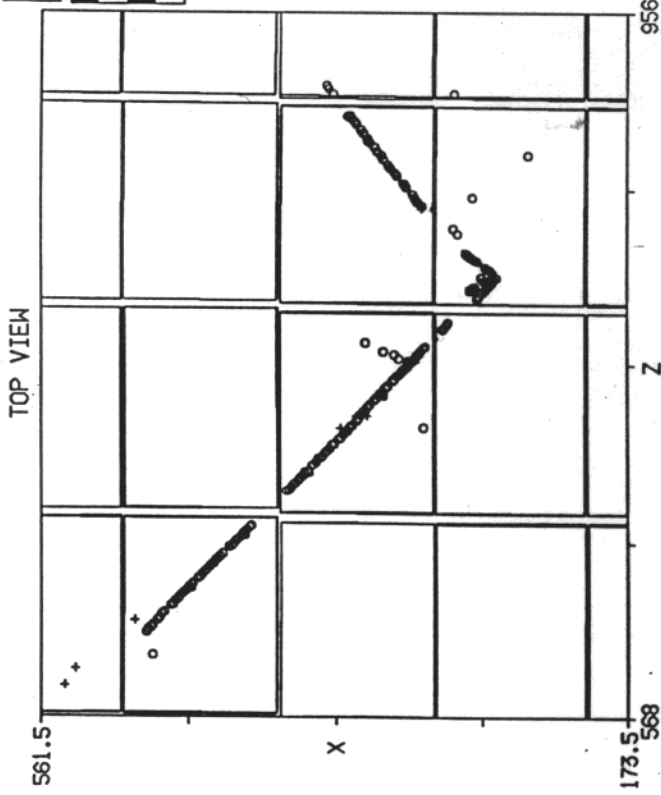


Soudan2 Data  
 Run 89196 Event 1553  
 09-Jul-1998 12:32:49.26

Izero = 156 Set by VS & Blobs v Tracks in SEARCH/TODET  
 Shield ADJC's  
 (2 at 269->274 N) (1 at 454 F) (1 at 454 F)  
 Shield Ovlaps  
 (1/1 at 34->44 C) (1/1 at 169 C)

Partially Contained Event (PCE):

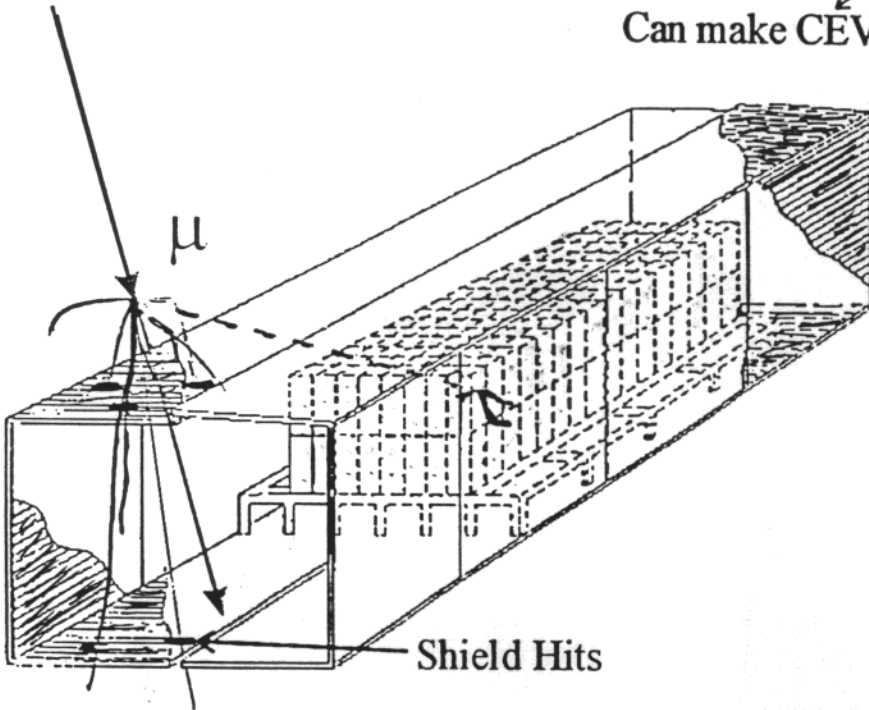
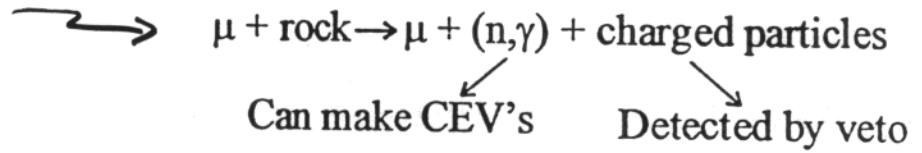
$\bar{\nu}_\mu + N \rightarrow \mu + \text{hadrons}$   
 $\hookrightarrow$  exits detector



# Contained Events

1:  $\nu$  Interactions

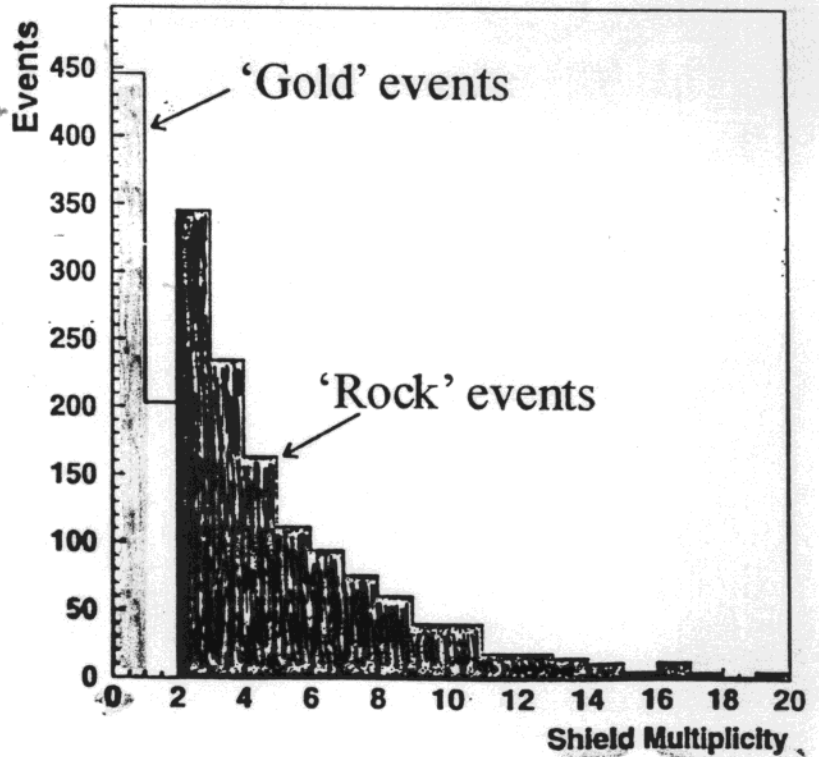
2: Background



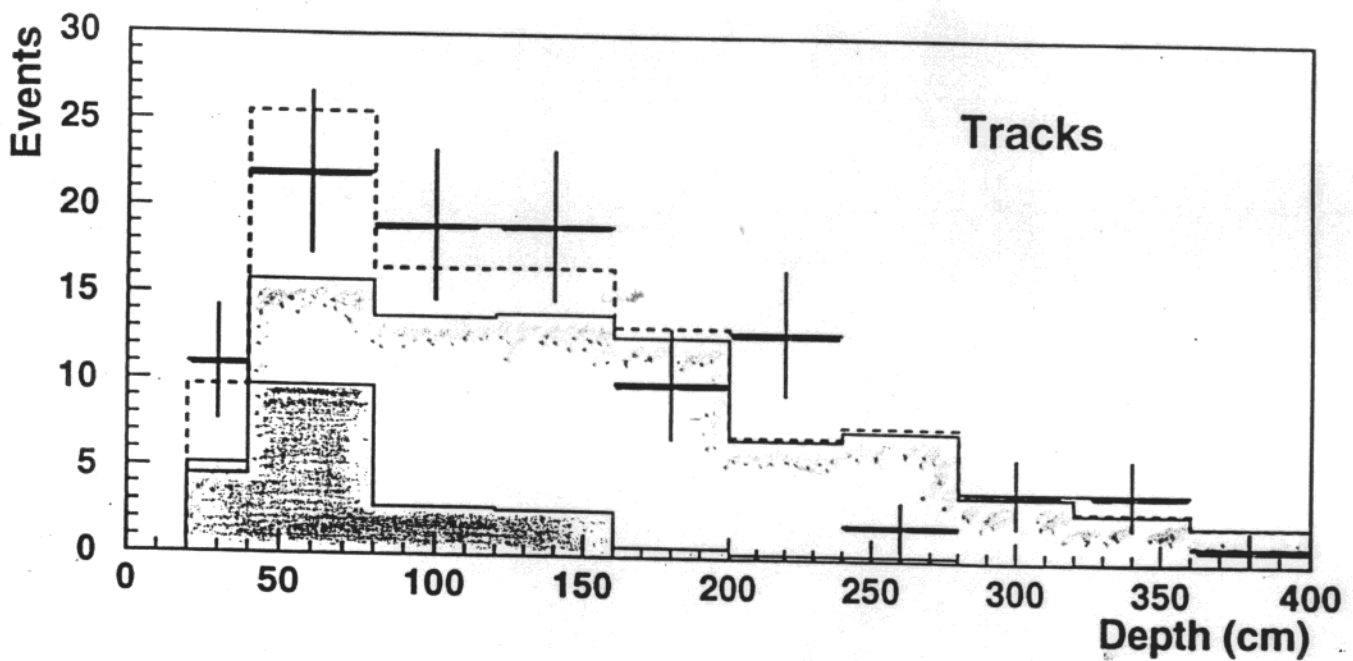
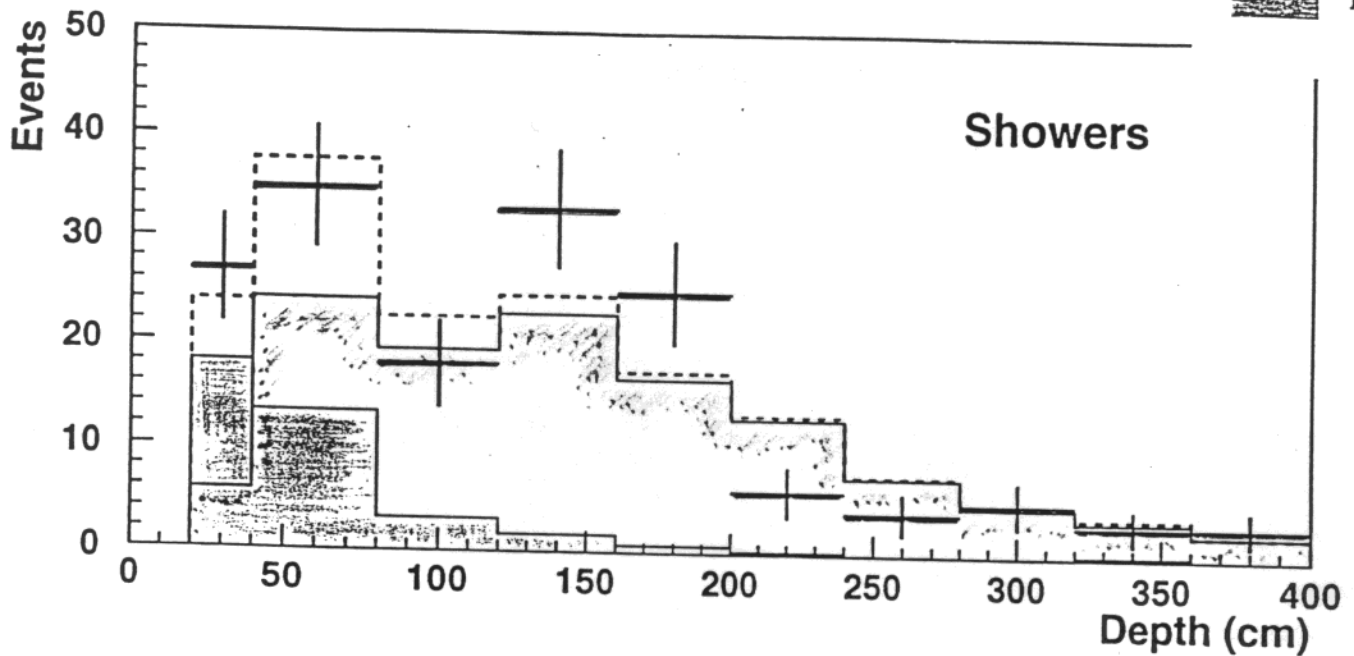
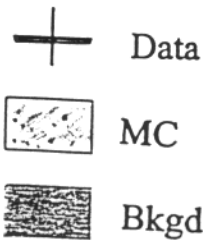
Muon-induced CEV's are identified by the presence of shield hits.

Rock Events: Shield-tagged background sample >1 shield hit

Contained Event Shield Hits



# Background determination:



- Fit gold data depth distributions to sum of expected neutrino (MC) and background (Rock data) depth distributions.

Atmospheric Neutrino Flavor Ratio  
from  
4.2 kiloton years (fiducial)

Measure:

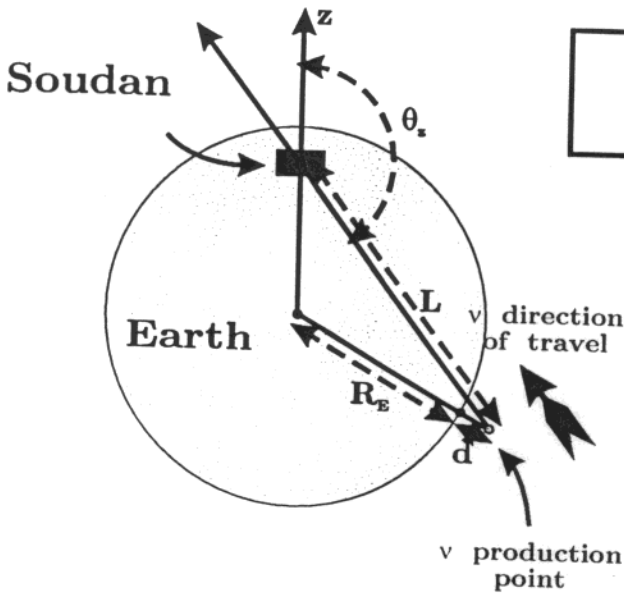
$$R = \frac{(\text{Tracks/showers})_{\text{DATA}}}{(\text{Tracks/showers})_{\text{MC}}} \approx \frac{(\nu_{\mu}/\nu_e)_{\text{DATA}}}{(\nu_{\mu}/\nu_e)_{\text{MC}}}$$

Single Track and Shower events

Number of Gold Tracks	105
Number of Gold Showers	159
Number of MC Tracks	847 (155.4)
Number of MC Showers	805 (147.7)
Corrected Number of $\nu$ Tracks	$83.6 \pm 11.2$
Corrected Number of $\nu$ Showers	$119.7 \pm 12.9$
Corrected Value of R	$0.66 \pm 0.11$

$$\underline{R} = \underline{0.66 \pm 0.11}(\text{stat}) \pm \underline{0.06}(\text{syst})$$

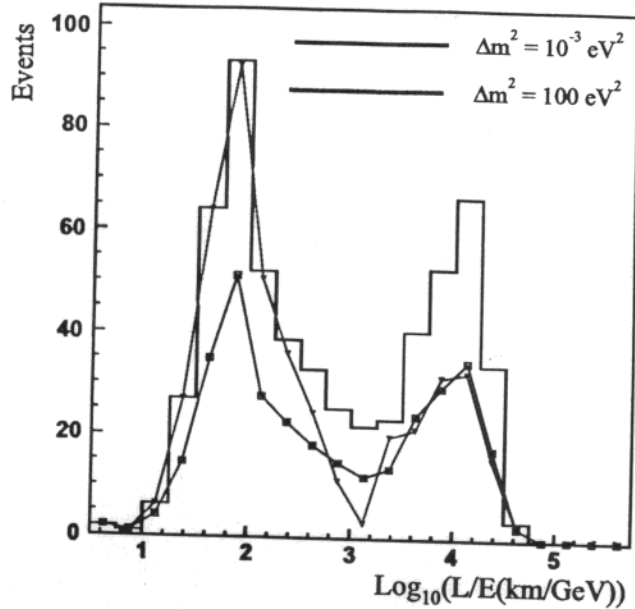
# Oscillation Analysis



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right)$$

$$L(\vartheta_z) = \sqrt{R^2 \cos^2 \vartheta_z + 2Rd + d^2} - R \cos \vartheta_z$$

Track L/E Distribution

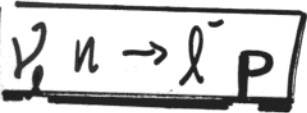


Good angular resolution for the neutrino direction is crucial.

Degraded by:

Physics: Fermi motion  
Neutrals in the final state (neutrons)

Detector: Charged particle reconstruction  
Failure to image all final state charged particles



QEL events:

$E_{lep}(\text{MeV})$

	0-200	200-400	400-600	>600
$\overline{\Delta\theta}$ ( $\nu$ - lepton)	$\sim 90^\circ$	$75^\circ$	$49^\circ$	$28^\circ$
$\overline{\Delta\theta}$ ( $\nu$ - lep+rec)	$30^\circ$	$23^\circ$	$15^\circ$	$8^\circ$

Energy Cuts

# The High Resolution Sample

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## 1) Quasi-elastics (Tracks, Showers)

$$P_{\text{lept}} > 150 \text{ MeV/c if a recoil is measured}$$

Or

$$P_{\text{lept}} > 600 \text{ MeV/c if a recoil is absent}$$

## 2) Multiprongs

$$E_{\text{vis}} > 700 \text{ MeV}$$

$$|\Sigma \vec{p}_{\text{vis}}| > 450 \text{ MeV/c (improved directionality)}$$

$$P_{\text{lept}} > 250 \text{ MeV/c (improve flavor tag)}$$

## Resolutions

$\nu_{\mu}$  CC

$\nu_e$  CC

Energy:  
( $\Delta E/E$ )

20%

23%

Angle:

$\angle \vec{p}_\nu(\text{true}) \cdot \vec{p}_\nu(\text{recon})$

$33.2^\circ$

$21.3^\circ$

L/E:

$|\text{Log}(\text{true L/E}) - \text{Log}(\text{recon L/E})|$

0.49

0.43

	$\nu_{\mu}$ CC	$\nu_e$ CC
Energy: ( $\Delta E/E$ )	20%	23%
Angle: $\angle \vec{p}_\nu(\text{true}) \cdot \vec{p}_\nu(\text{recon})$	$33.2^\circ$	$21.3^\circ$
L/E: $ \text{Log}(\text{true L/E}) - \text{Log}(\text{recon L/E}) $	0.49	0.43

# Contained Events:

## Soudan-2 high-resolution event samples, 4.4 kty

Category	Data		MC (BARTOL * 0.86)
	Before bgr. subtraction	After	
Tracks	54.0 ± 7.3	<u>47.7</u> ± 7.4	102.5 ± 4.1
Showers	77.0 ± 8.8	<u>73.8</u> ± 8.8	71.9 ± 3.4
MP, $\nu_\mu$	39.0 ± 6.2	<u>37.6</u> ± 6.7	41.9 ± 2.6
<u>MP, <math>\nu_e</math></u>	44.0 ± 6.6	<u>41.7</u> ± 6.7	43.6 ± 2.6
<hr/>			
$\nu_\mu$		<u>85.4</u> ± 9.7	144.4 ± 4.8
<u><math>\nu_e</math></u>		<u>115.6</u> ± 11.1	115.6 ± 4.3 (norm-ed)

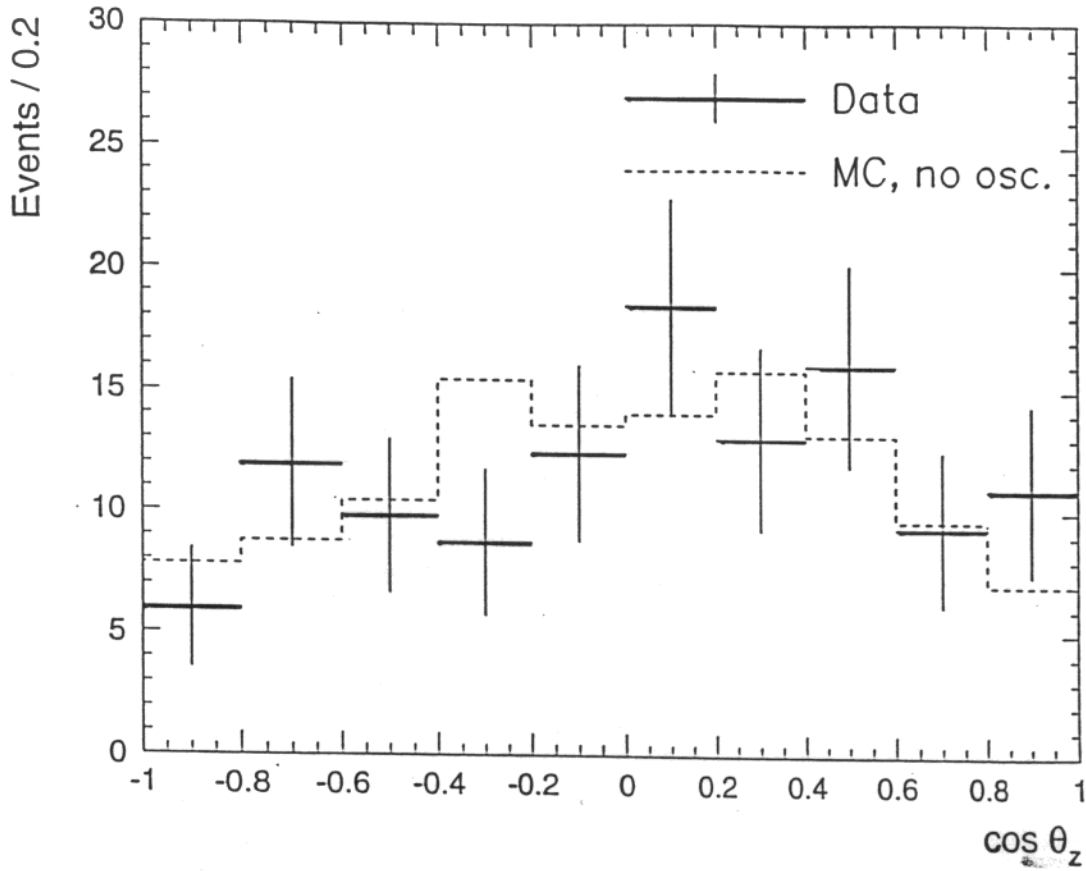
### Notes:

- Rock-muon associated background correction is small after cuts, 5.8% for the quasielastics and 4.6% for the multiprongs. Nevertheless, the correction is important because of directional preference of rock events to point downward.
- The Monte Carlo sample represents 24 kty of exposure; numbers given here were normalized to 4.4 kty.
- In this sample of mostly higher energy events, the ratio of ratios is  $R = 0.59 \pm 0.09$ , also significantly below 1.

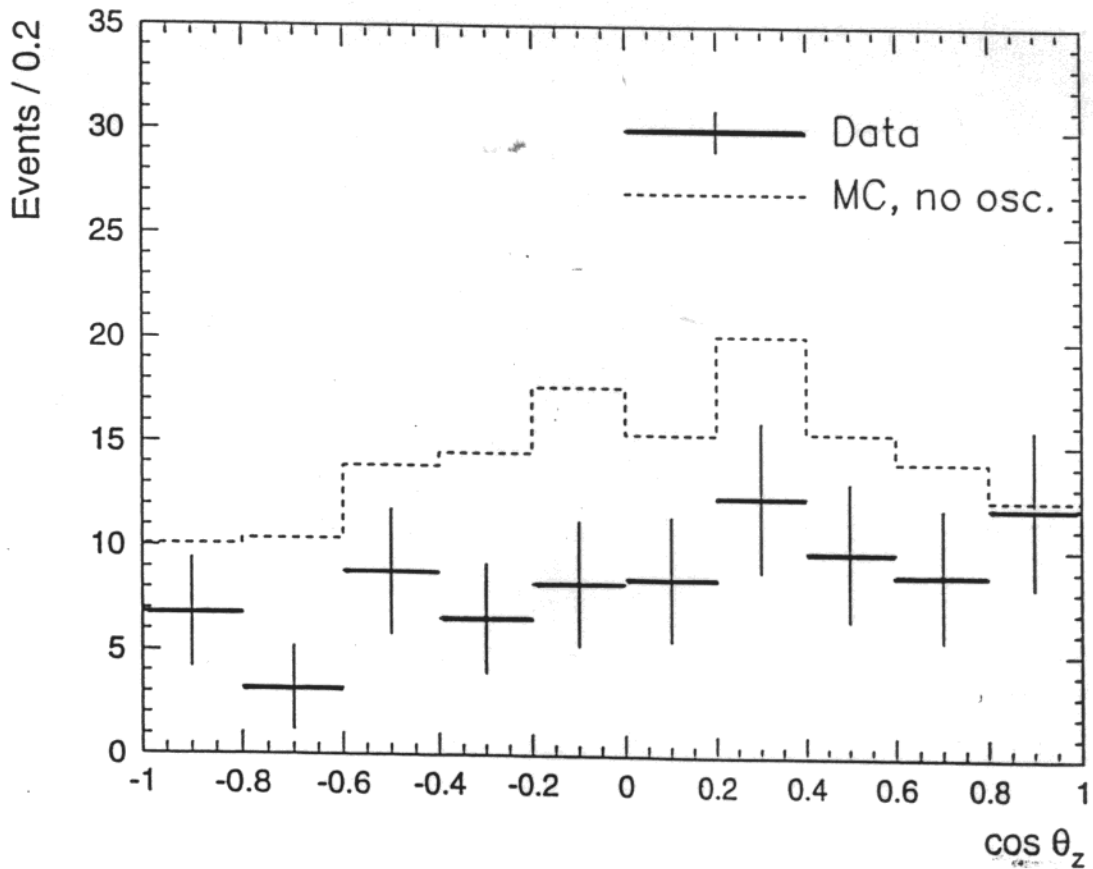


Zenith  
Angles:

### $\nu_e$ CC, High Res., 4.4 kty

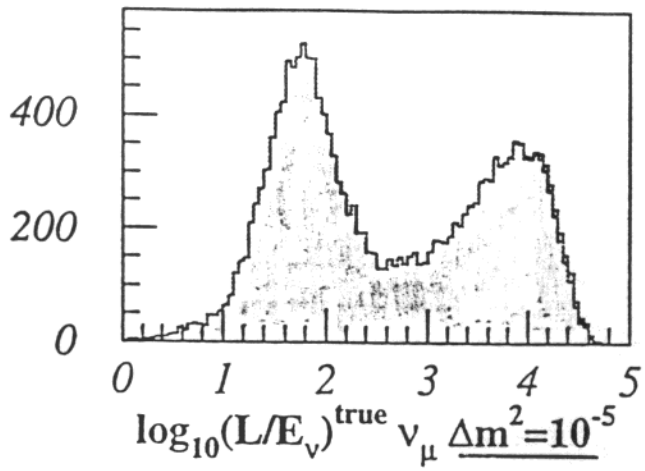


### $\nu_\mu$ CC, High Res., 4.4 kty

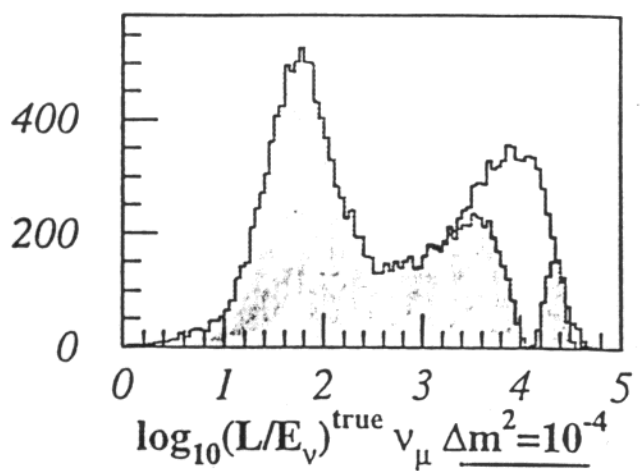


# $L/E_\nu$ Distributions:

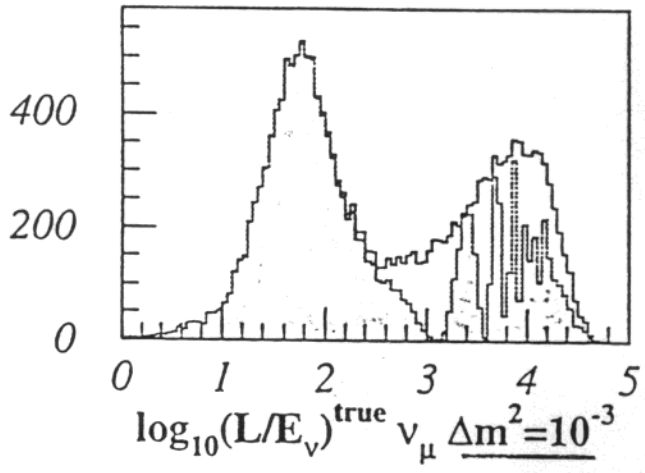
#Events



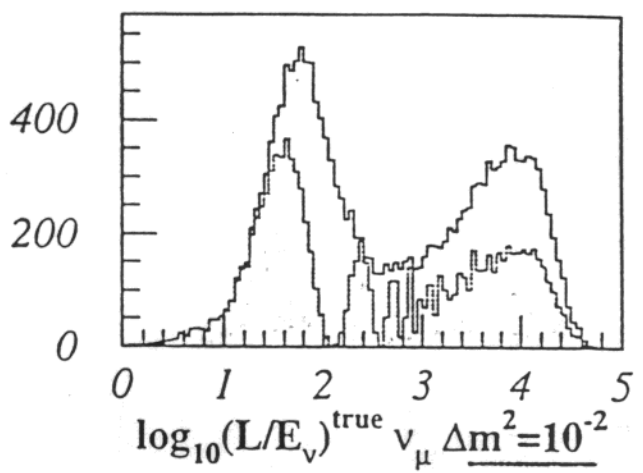
#Events



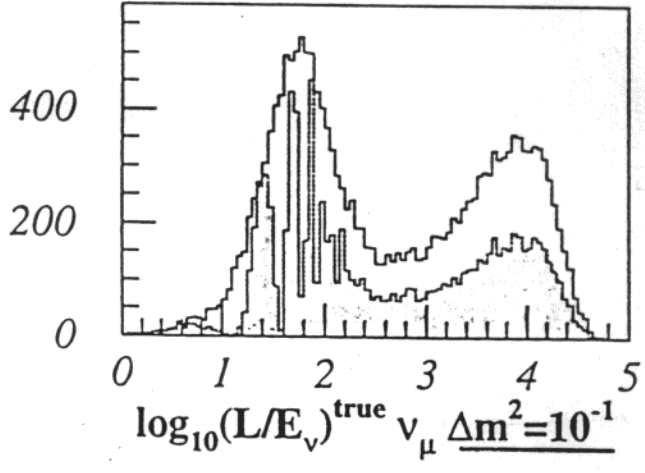
#Events



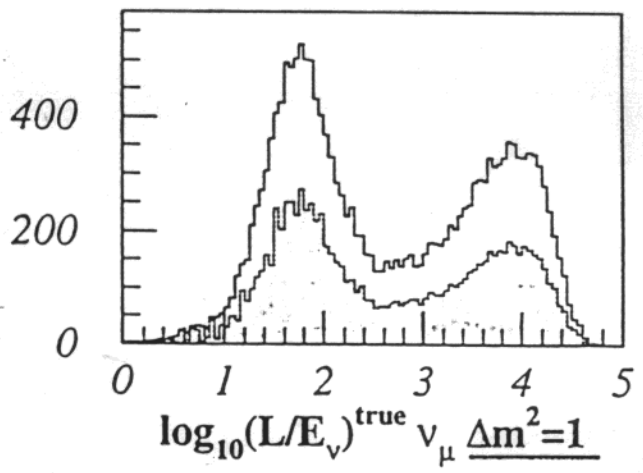
#Events



#Events

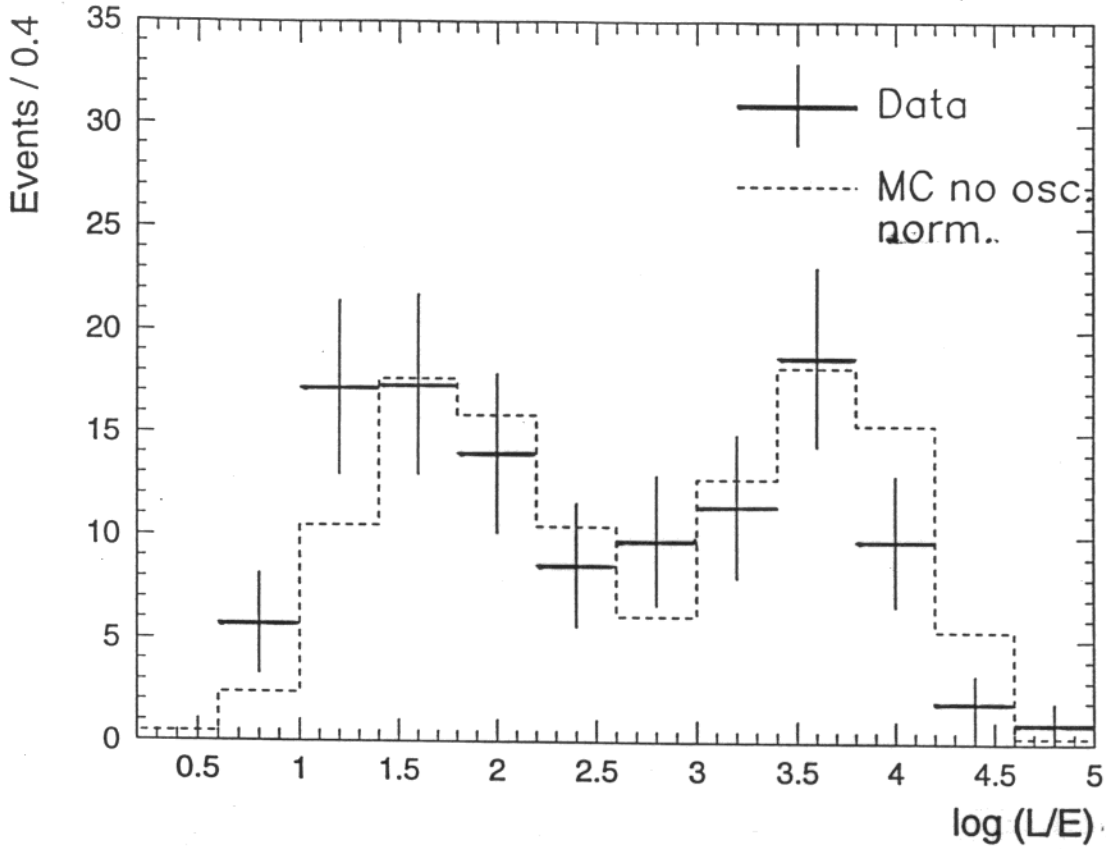


#Events

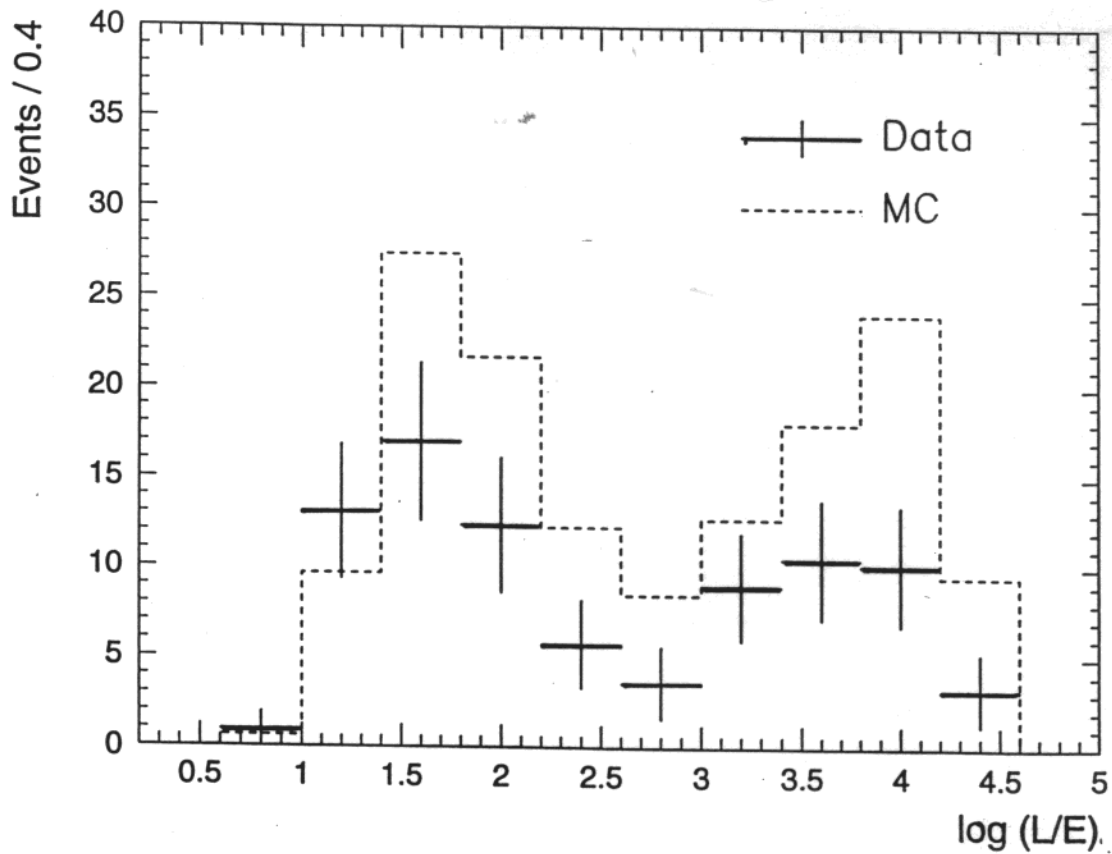


Distributions of true  $L/E_\nu$  for muon neutrinos generated in the upper atmosphere under  $\nu_\mu \leftrightarrow \nu_\tau$  mixing.

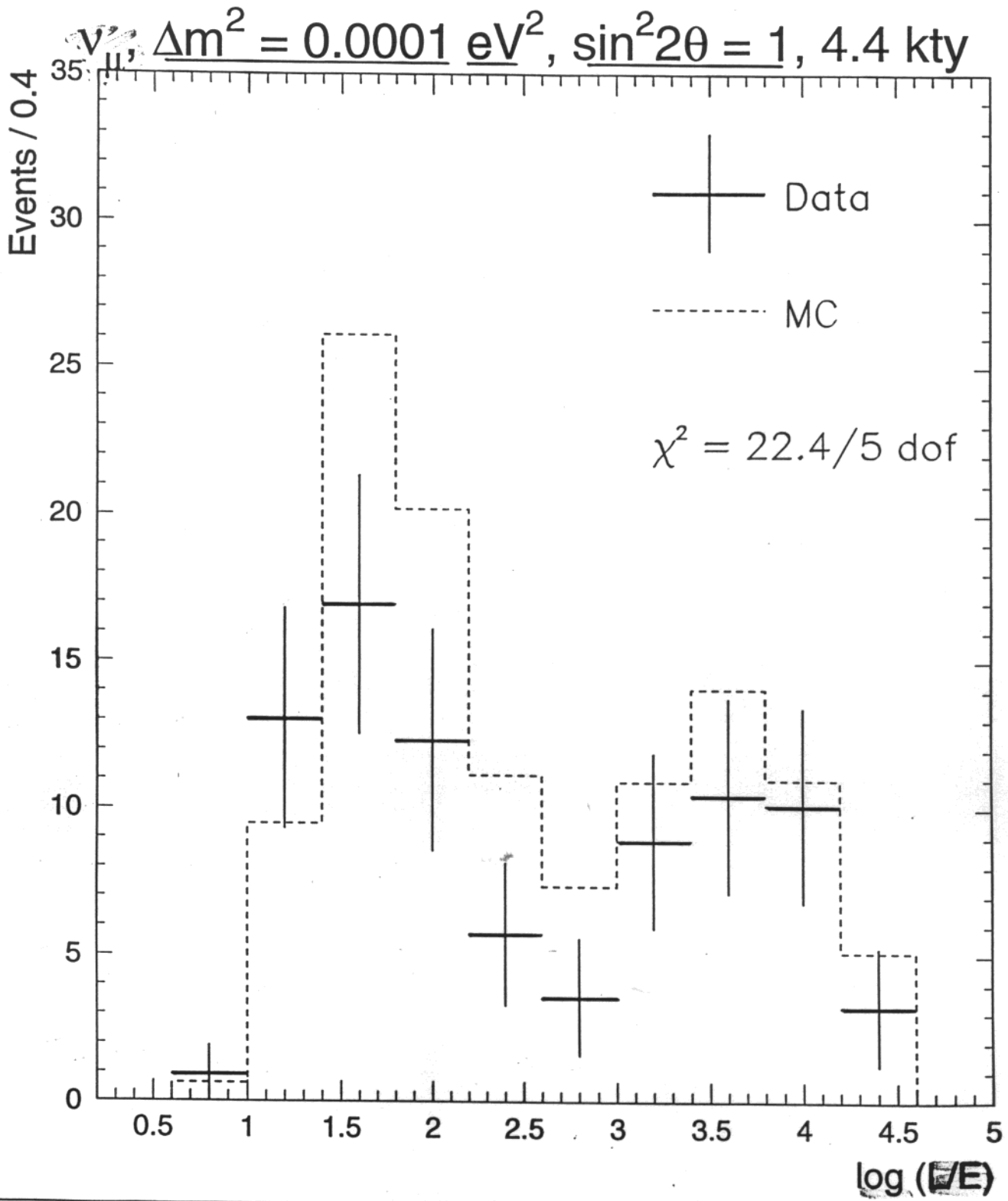
### $\nu_e$ , No oscillations, 4.4 kty



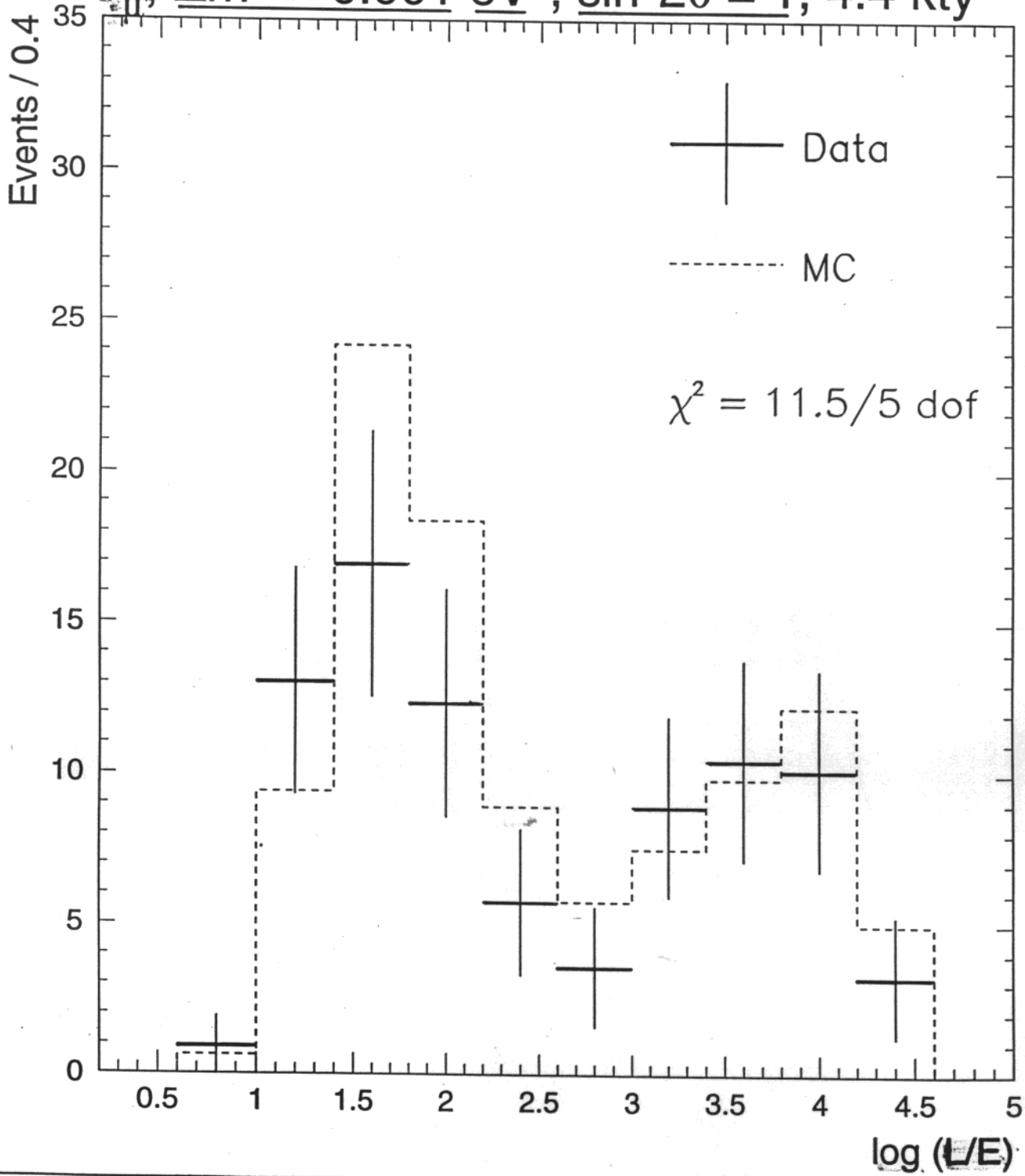
### $\nu_\mu$ , No oscillations, 4.4 kty



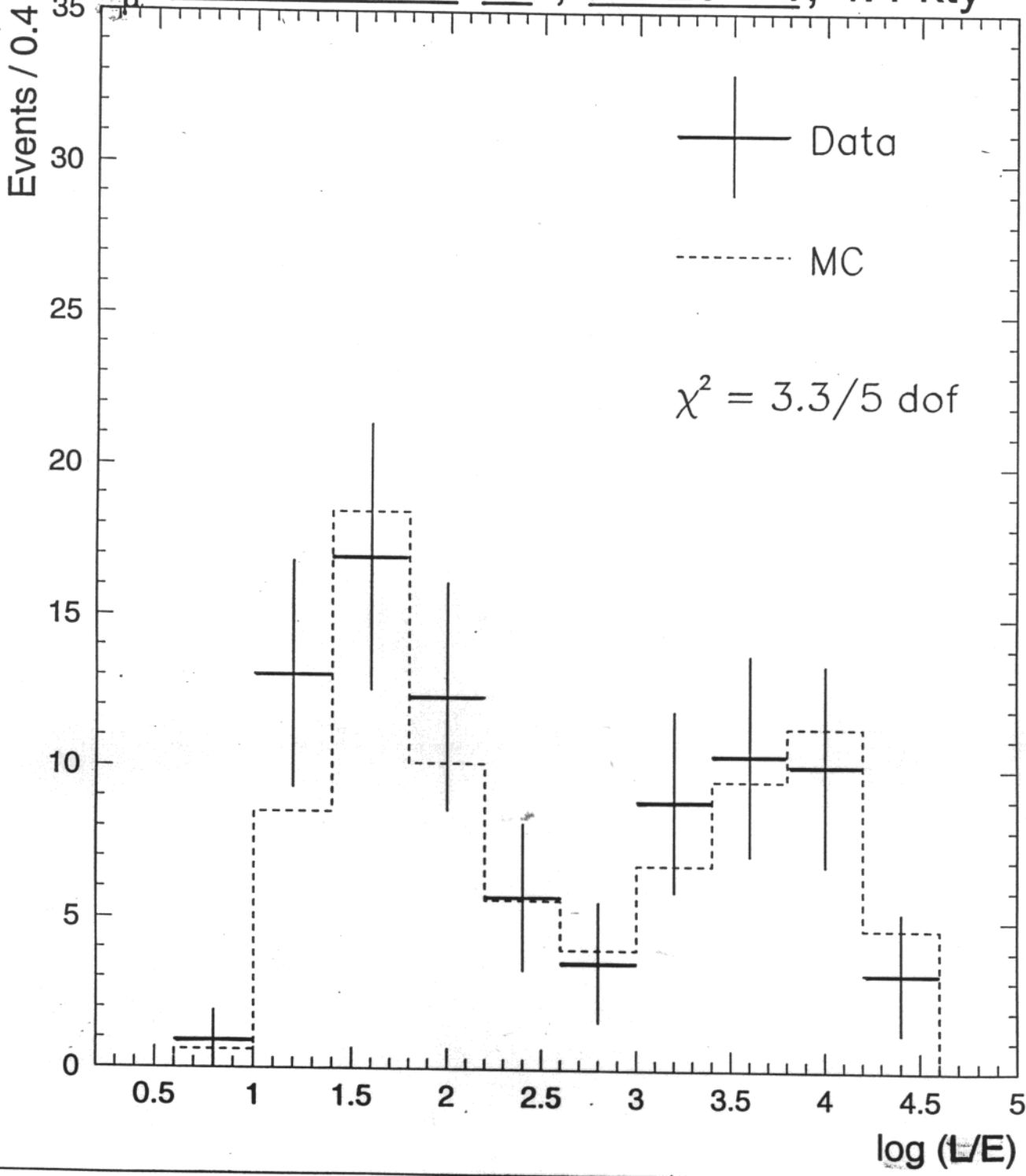
MC normalization set via  $\nu_e$  sample (BARTOL \* 0.86) :



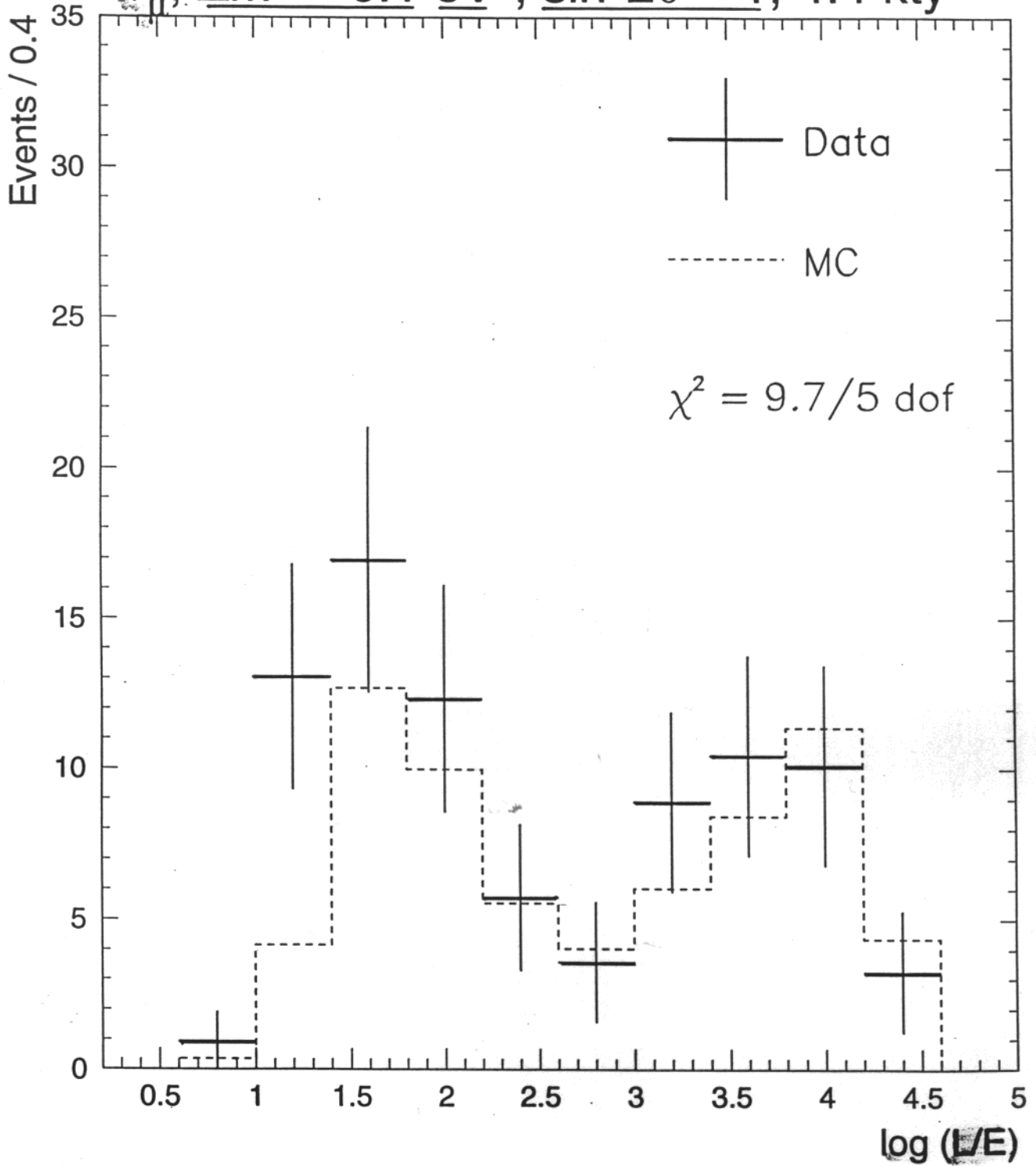
$\nu_{\mu}$ ,  $\Delta m^2 = 0.001 \text{ eV}^2$ ,  $\sin^2 2\theta = 1$ , 4.4 kty



$\nu_{\mu}$ ,  $\Delta m^2 = 0.009 \text{ eV}^2$ ,  $\sin^2 2\theta = 1$ , 4.4 kty



$\nu_{\mu}$ ,  $\Delta m^2 = 0.1 \text{ eV}^2$ ,  $\sin^2 2\theta = 1$ , 4.4 kty



## $\chi^2$ fitting for oscillation parameters

To determine the neutrino oscillation parameters  $\sin^2 2\theta$  and  $\Delta m^2$  from our  $\nu_\mu$  data, we fit the atmospheric Monte Carlo distribution including the effects of neutrino oscillations to the  $L/E$  distribution for our data corrected for the rock background, by minimizing  $\chi^2$ . At the same time, we assume that no neutrino oscillations occur in the  $\nu_e$  flux.

$$\chi_{ijk}^2 = \sum_{\nu_\mu} \frac{[Data(\frac{L(\bar{h})}{E}) - f_{\nu k} \times f_{MC} \times \int dh w_{ij}(\frac{L(h)}{E})]^2}{[Error(Data)]^2} + \frac{[\sum \nu_e Data - f_{\nu k} \times f_{MC} \times \sum \nu_e MC]^2}{[Error(\sum \nu_e Data)]^2}$$

where the fit parameters span the ranges of  $0.0001 < \Delta m^2 < 0.5 \text{ eV}^2$ ,  $0 < \sin^2 2\theta < 1.3$ , and  $0.65 < f_\nu < 1.0$ .  $f_{MC}$  is the ratio of data exposure to MC exposure and  $f_\nu$  determines the relative normalization of data and MC.

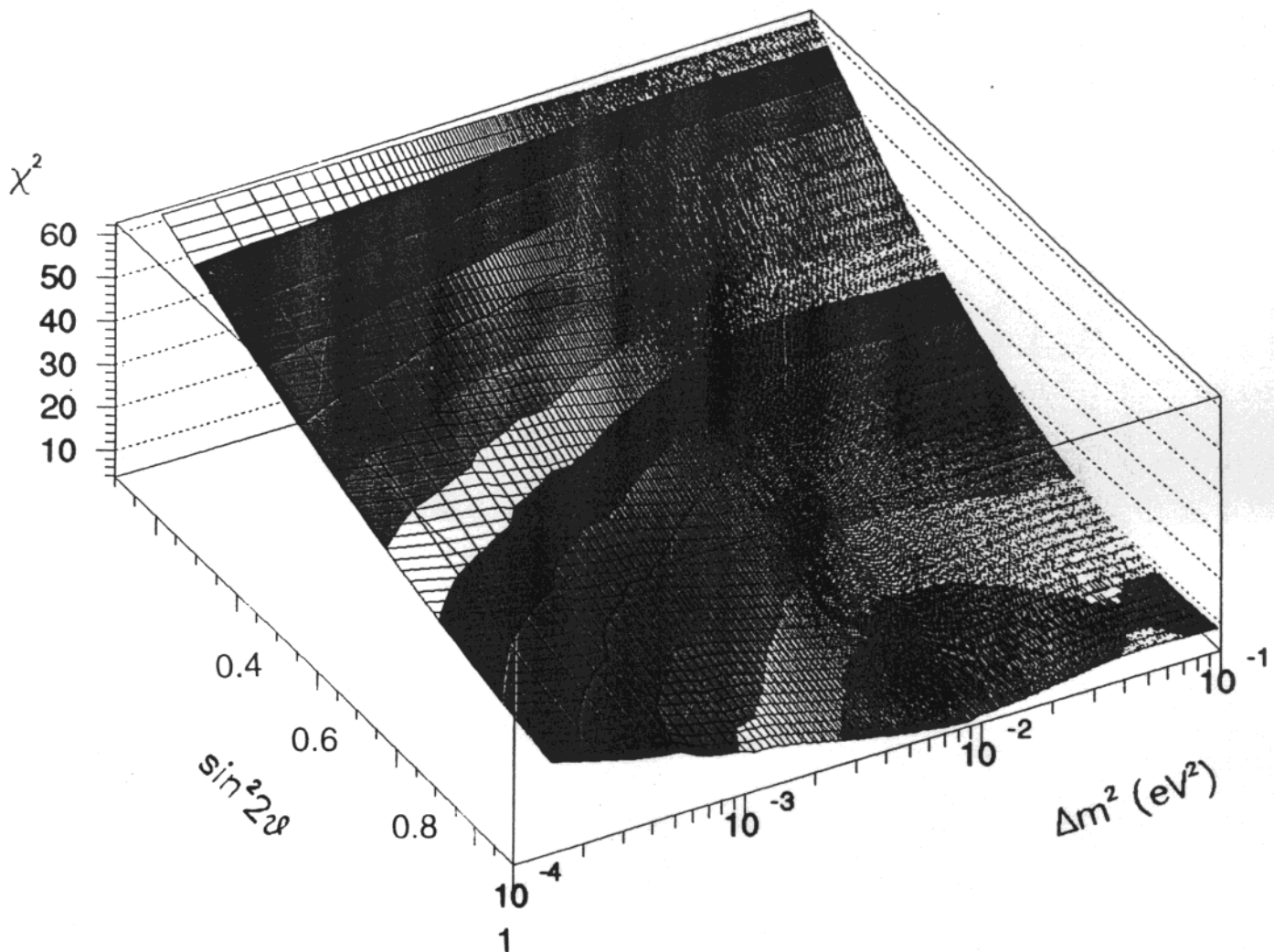


Contour boundaries are

$$\chi^2_{\min} + N * 4.61, \quad N = 1, 2, 3 \dots$$

$$\chi^2_{\min} \text{ at } \underline{\Delta m^2 = 0.0090}, \quad \underline{\sin^2 2\theta = 1.06},$$
$$\underline{f_\nu = 0.87}.$$

$\chi^2$  vs.  $\Delta m^2$  and  $\sin^2 2\theta$



## A Sample of Partially Contained Events (PCE)

(two-prong and multiprong events)

- \* Triggered data reprocessed through a new software filter that allows events to have prongs which cross fiducial volume boundary.
- \* Events that passed the filter were single-scanned by physicists - 16,000 data and Monte-Carlo events.
- \* For two-prong PCEs, require shorter prong to have > 10 hits, to eliminate incoming stopping and decaying muon tracks.
- \* Impose High Resolution multiprong cuts on all PCE events.
- \* "Gold" neutrino events have shield hits associated only with exiting prongs.

We obtain

$\nu_\mu$ -flavor PCEs:

40 gold data events

264 gold Monte Carlo events

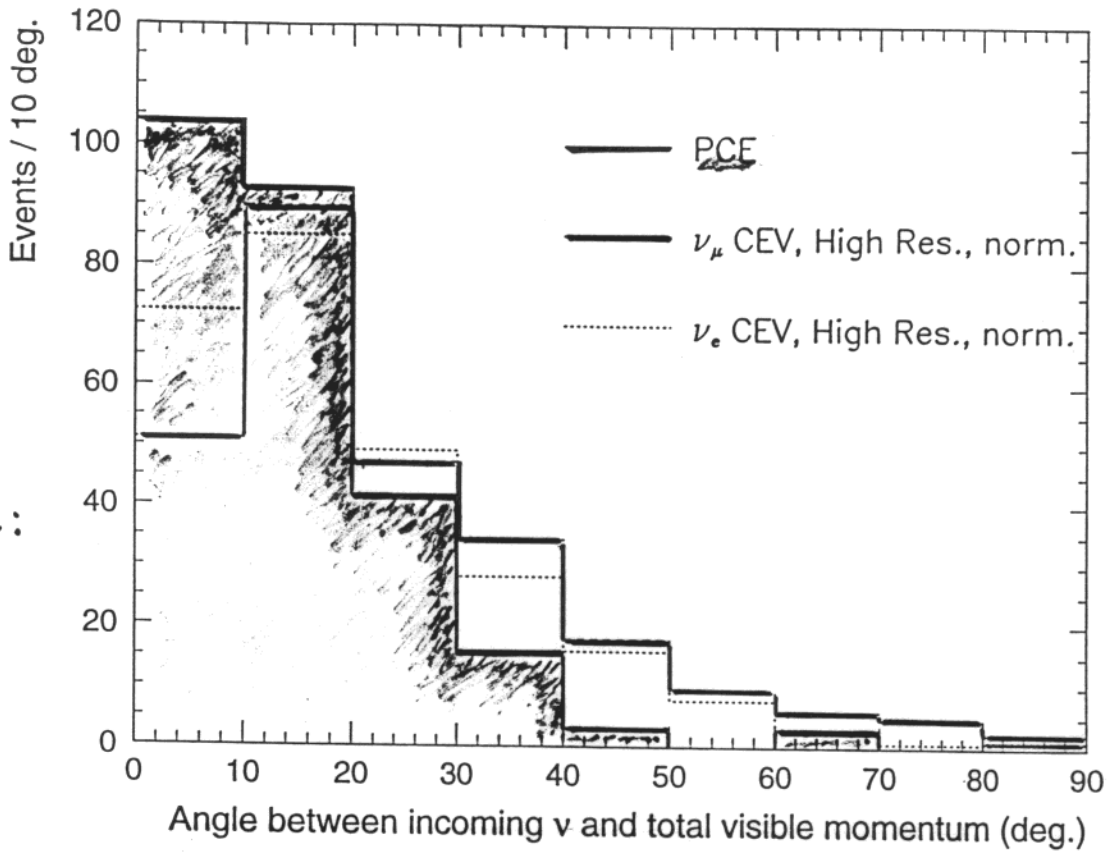
Topologies of gold  $\nu_\mu$  PCEs:

- 4 muon + proton
- 12 muon + charged pion (+ proton)
- 4 muon + showers
- 3 muon +  $\geq 2$  charged pions
- 17 muon + charged pion(s) + shower(s)

Rock event background in  $\nu_\mu$ -flavor PCE sample is  $\leq 1$  event.

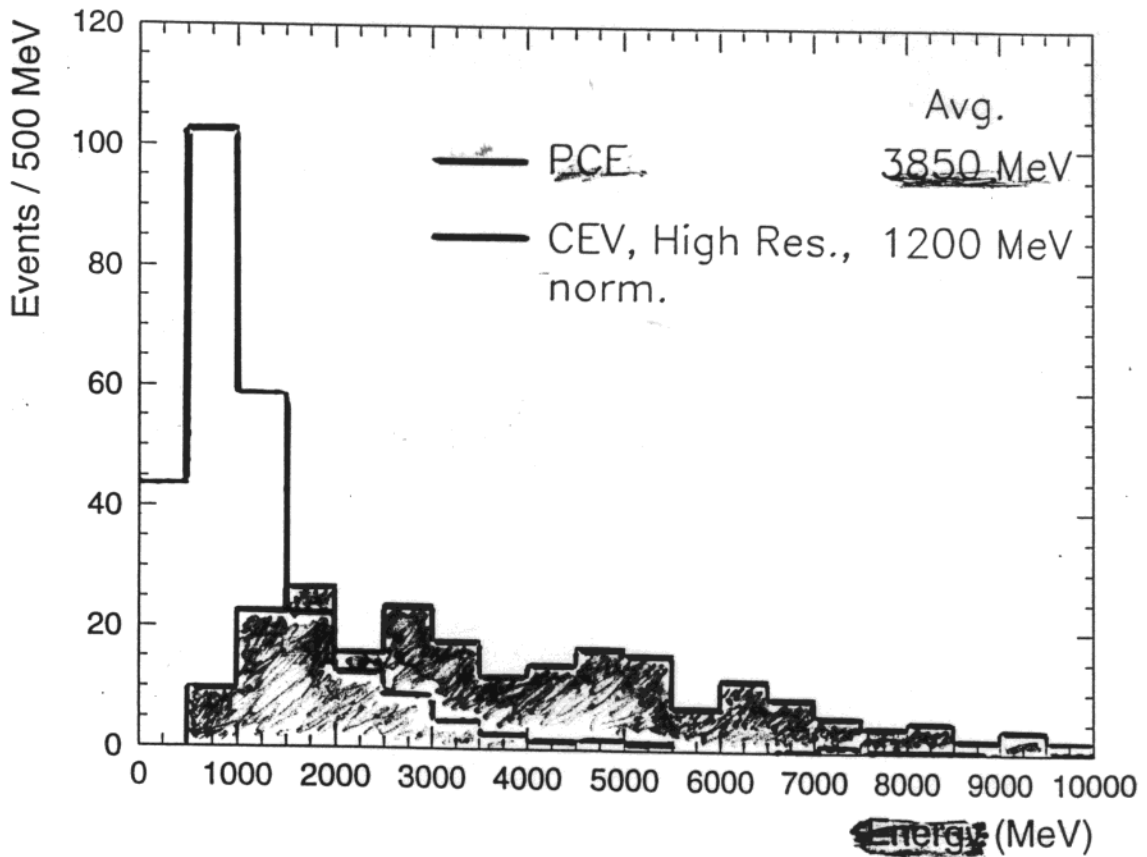
$\nu_\mu$  CC, PCE, 4.2 kty

Neutrino  
Direction:



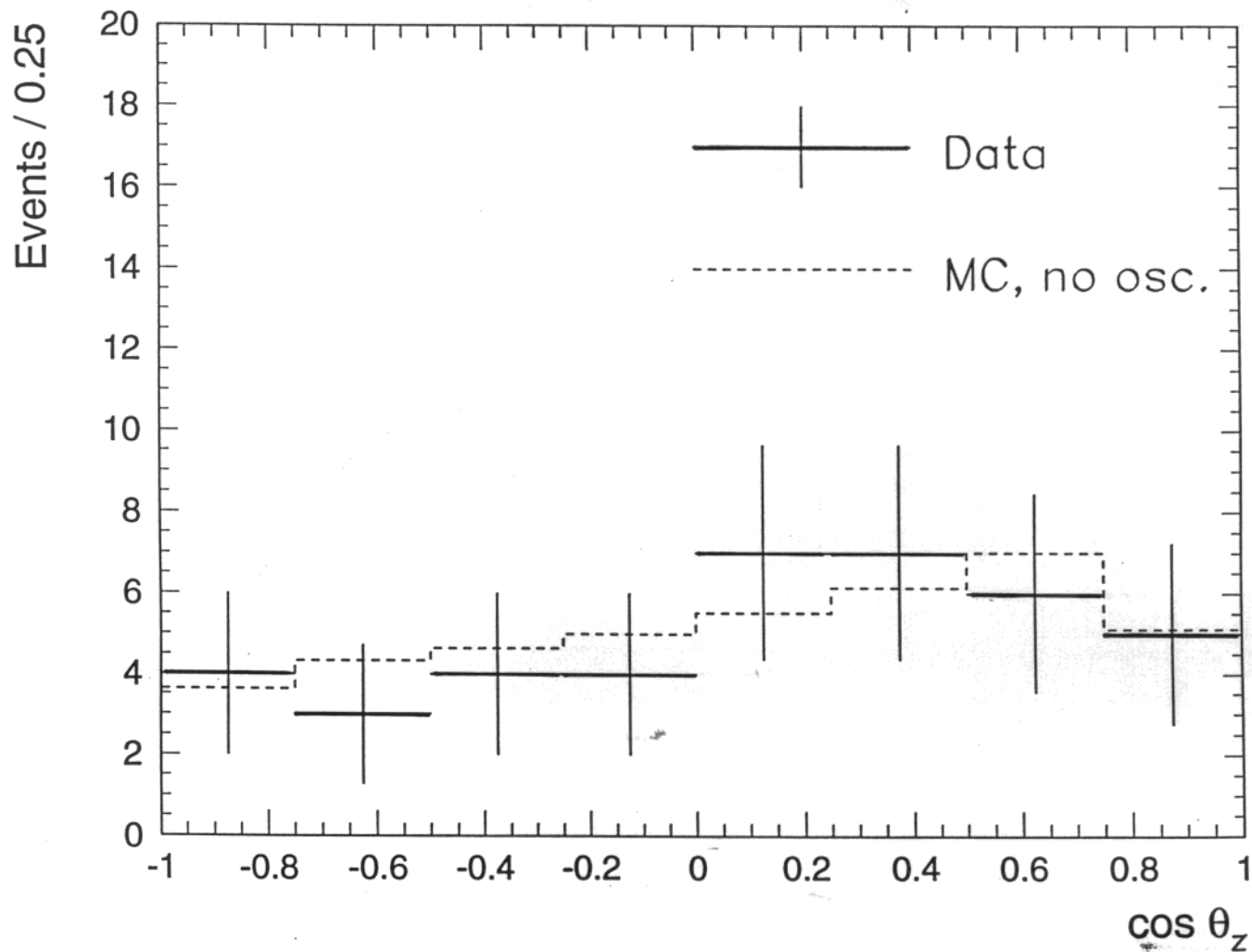
$\nu_\mu$  CC, MC truth

Neutrino  
Energy:

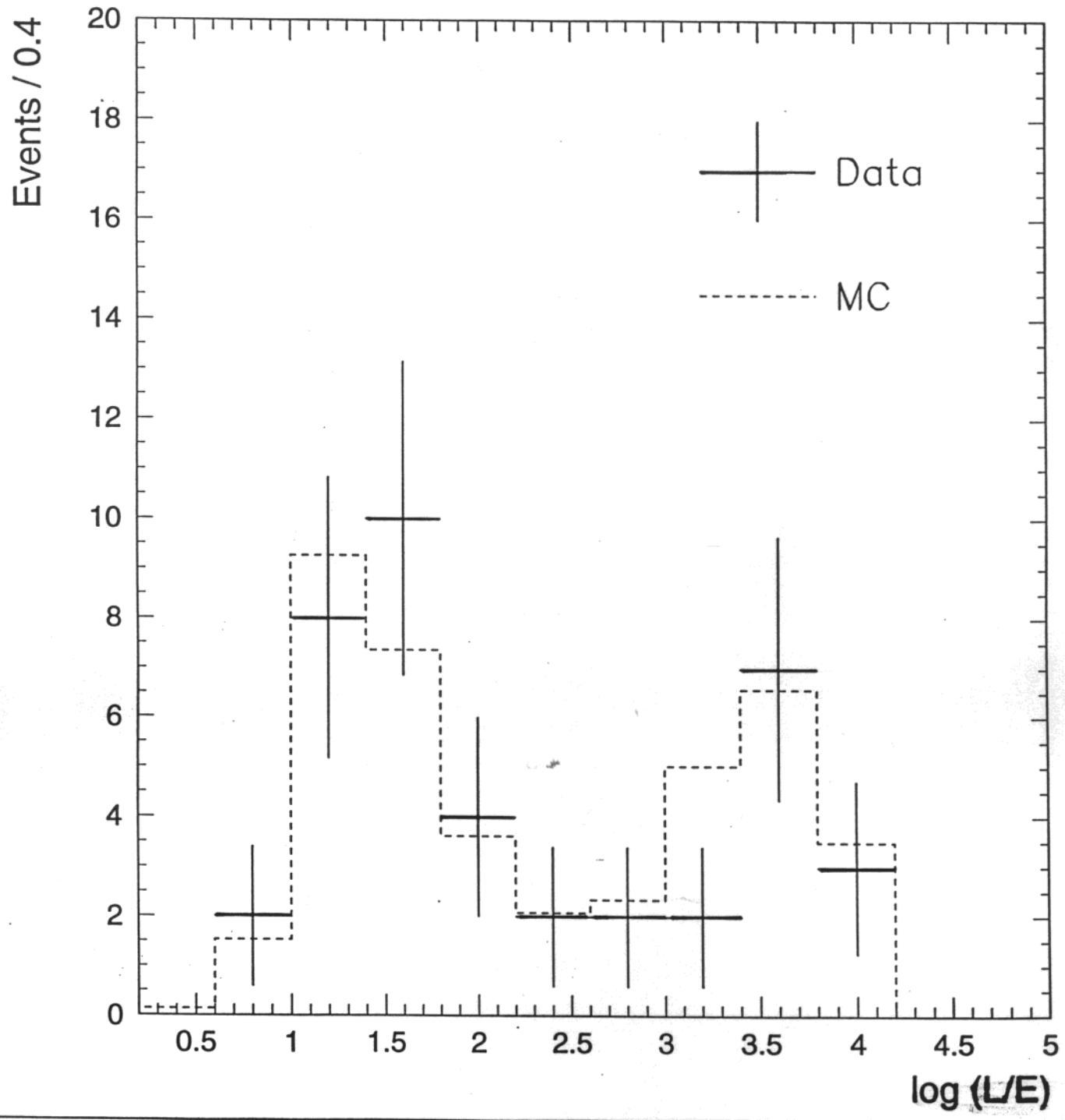


Zenith angles:

$\nu_\mu$  CC, High Res., PCE, 4.2 kty



~~$\nu_\mu$~~  PCE, No oscillations, 4.2 kty

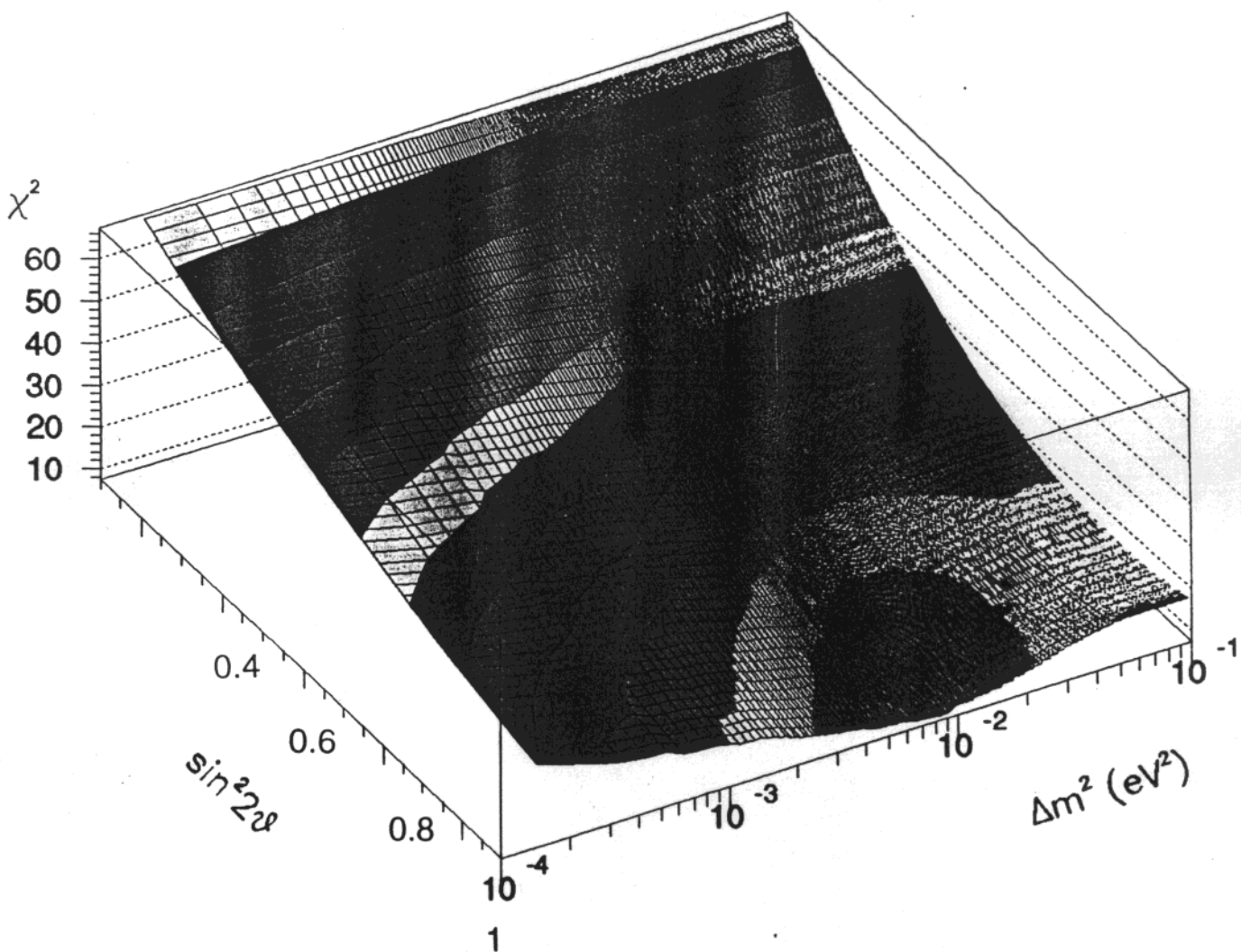


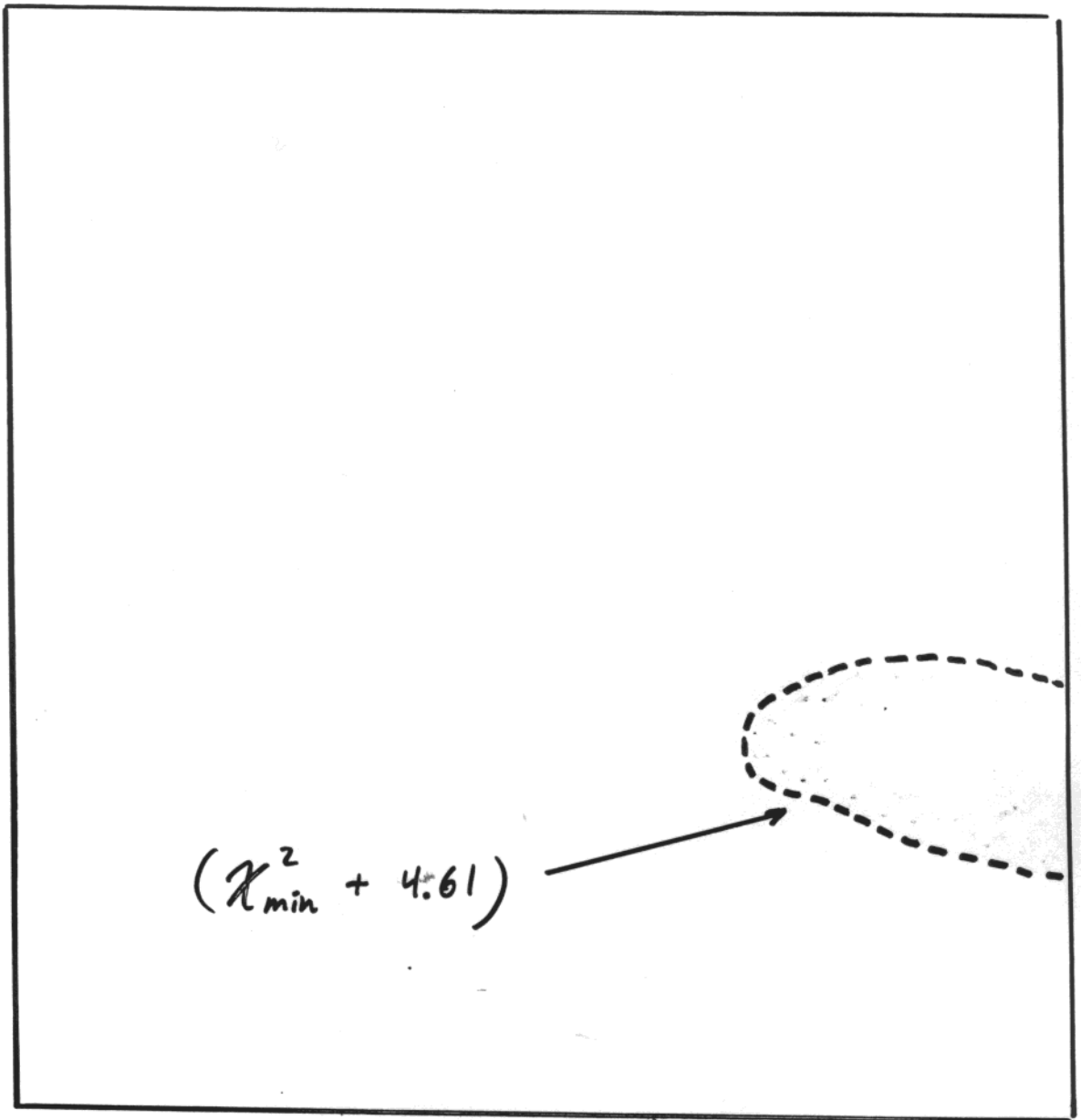
$L/E_{vis}$

$\chi^2$  now includes  $\nu_m$ -PCE  $L/E_{\nu}$  bins :

$$\chi^2_{\min} \text{ at } \underline{\Delta m^2 = 0.0088},$$
$$\underline{\sin^2 2\theta = 1.0},$$
$$F_\nu = 0.88.$$

$\chi^2$  vs.  $\Delta m^2$  and  $\sin^2 2\theta$



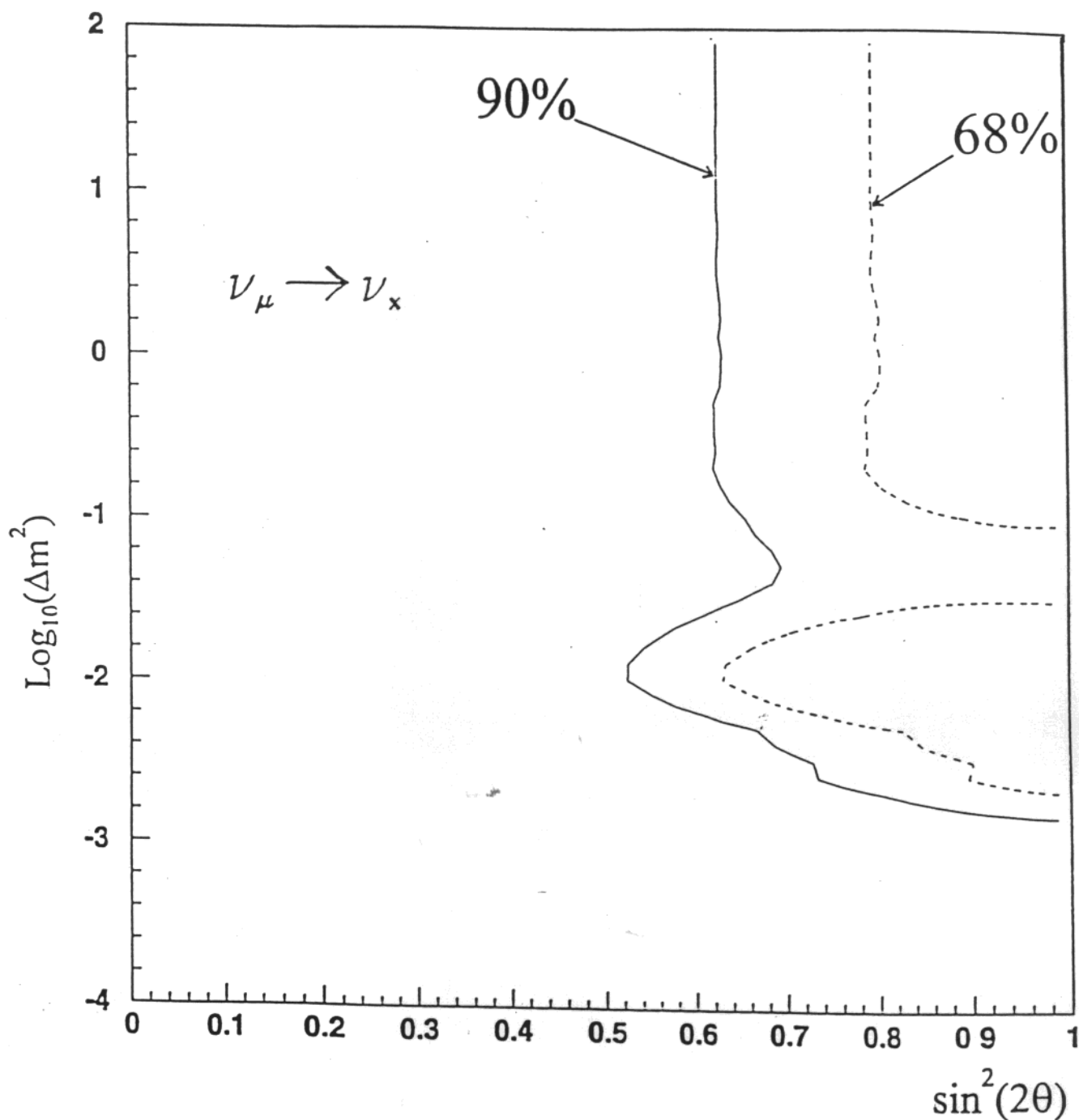


Soudan 2 at Neutrino Telescopes  
( 4.4 KTY CEVs + 4.2 KTY PCEs )



# Soudan 2 Atmospheric Allowed Regions

(US DPF: Jan. '99 ; WINN '99)



## In summary:

- \* Atmospheric Neutrino Flavor Ratio (4.2 kty)

$$\underline{R = 0.66 \pm 0.11 \pm 0.06}$$

- \* High-resolution Contained Events (4.4 kty)

$\nu_e$ : zenith angle and  $L/E_\nu$  consistent with no oscillations.

$\nu_\mu$ : Dearth of events (relative to no-oscillation MC) pervades downward as well as upward fluxes.

No dramatic up-down asymmetry, but ...

- \* Partially Contained  $\nu_\mu$  Events (4.2 kty):

$$\langle \delta\theta_\nu \rangle = 14^\circ, \quad \langle E_\nu \rangle = 3.85 \text{ GeV}$$

40 events vs. 41 expected

No dramatic up-down asymmetry, but ...

- \*  $\chi^2$ -fitting to  $\text{CEV}(L/E_\nu) + \text{PCE}(L/E_{vis})$ :

At 90% CL,

$$\underline{\sin^2 2\theta > 0.68}$$

$$\underline{2 \times 10^{-3} < \Delta m^2 < 3 \times 10^{-2} \text{ eV}^2}$$

( $f_\nu = 0.88 \times \text{Bartol}$ ).

# Outlook

## Refinements:

Event reconstruction

*L/E* analysis

## More data from:

Current exposure + continued running  
(0.7 fid. kty per calendar year)

Upgoing stopping muon events

Horizontal muons