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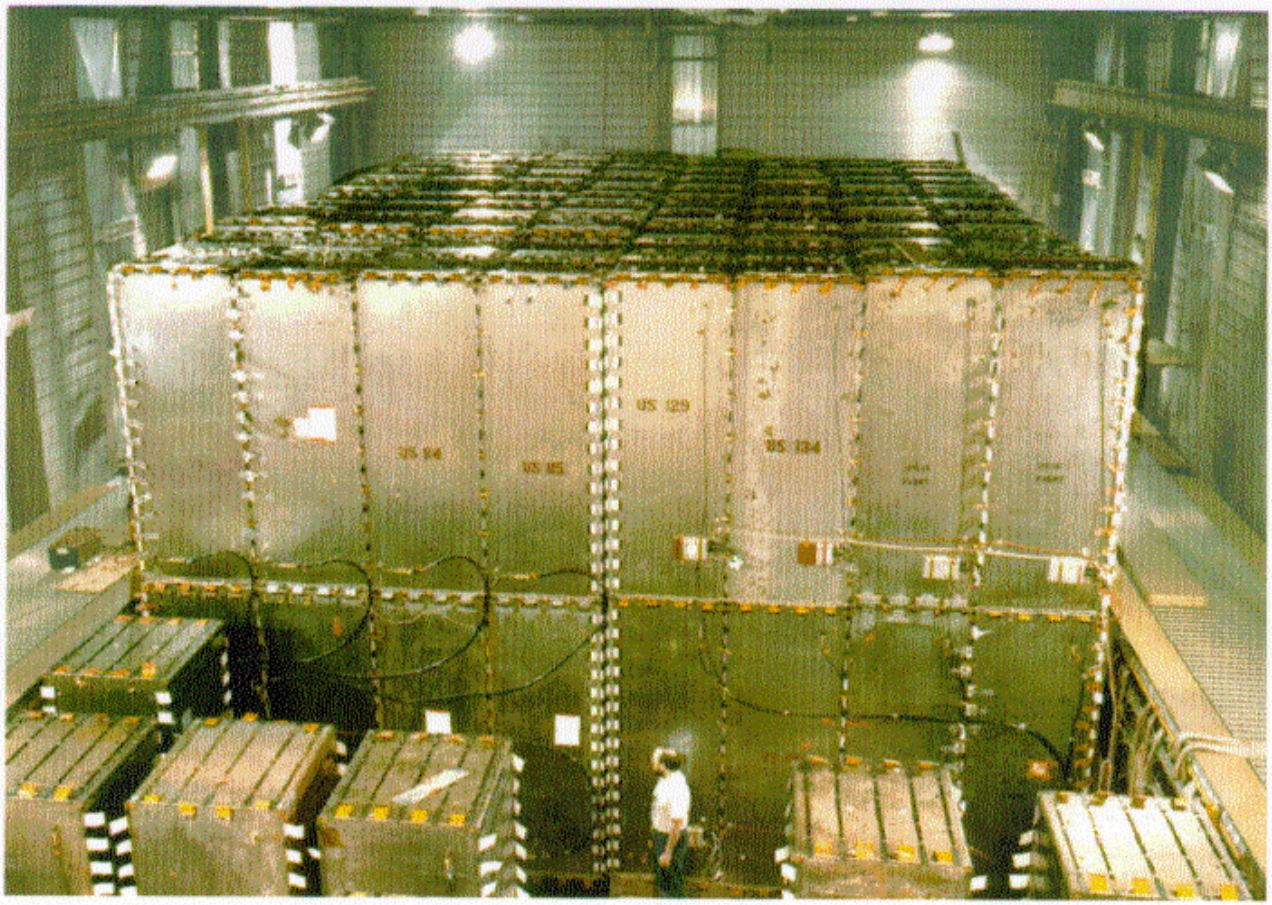
New Results on Atmospheric Neutrinos from Soudan 2

ANL, Minnesota, Oxford, RAL,
Tufts, Western Washington

Soudan 2 is located in the Soudan Mine in northern Minnesota under 2100 mwe overburden.
Exposure to date is 5.40 fiducial kty.



$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\,\sin^2\left(\frac{1.27\,\Delta m^2\,L}{E_\nu}\right)$$

In this Talk:

I. Neutrino flavor ratio at 5.1 kty.

II. ν_μ, ν_e CC samples for L/E_ν analysis.

III. Determination of $\sin^2 2\theta$, Δm^2 allowed region for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

IV. Zenith angles and L/E_{vis} for ν_μ partially contained events.

Upgrades this millenium:

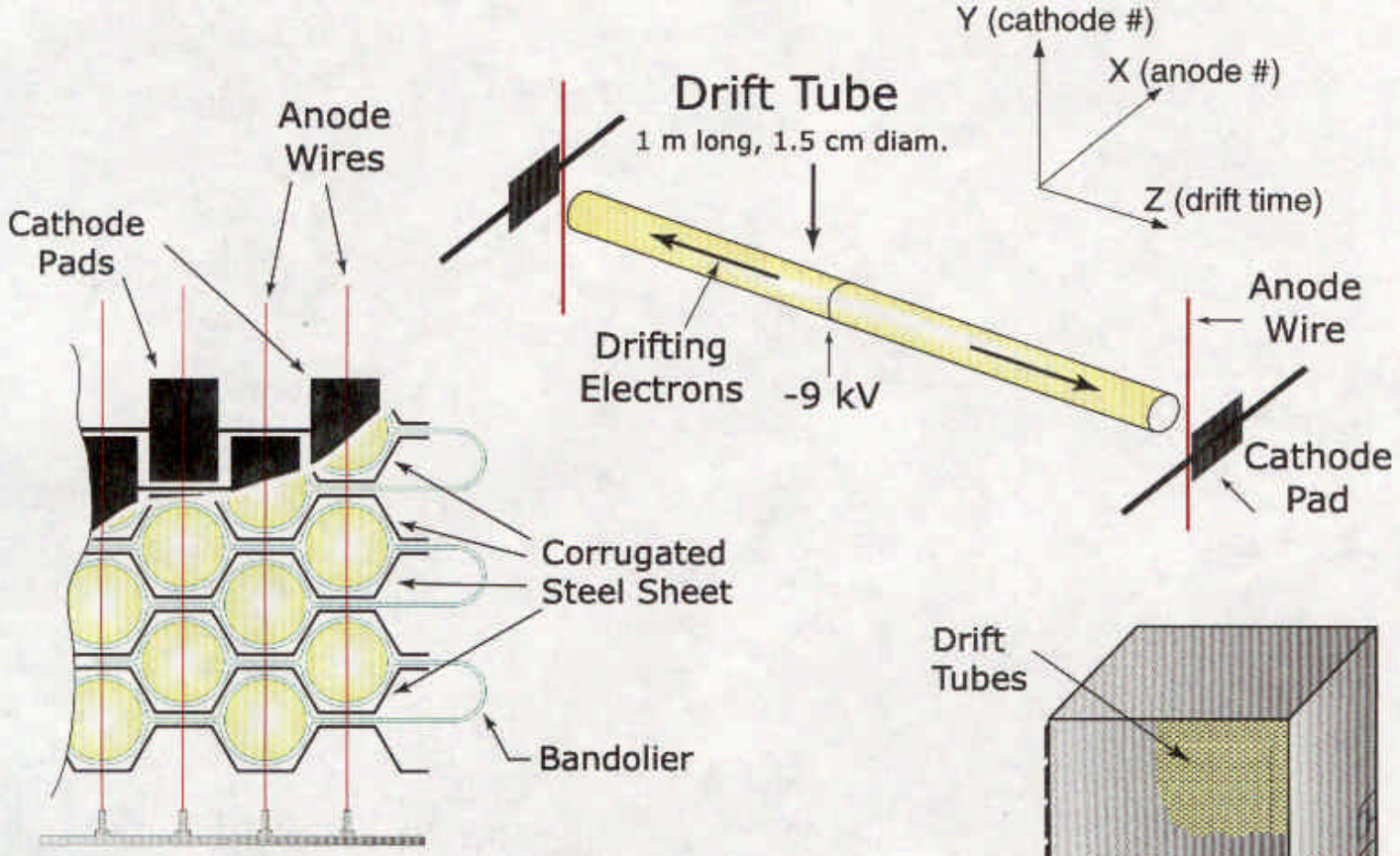
More data: 4.6 → 5.1 fiducial kty.

Monte Carlo: Bartol '89 → '96 ν fluxes.

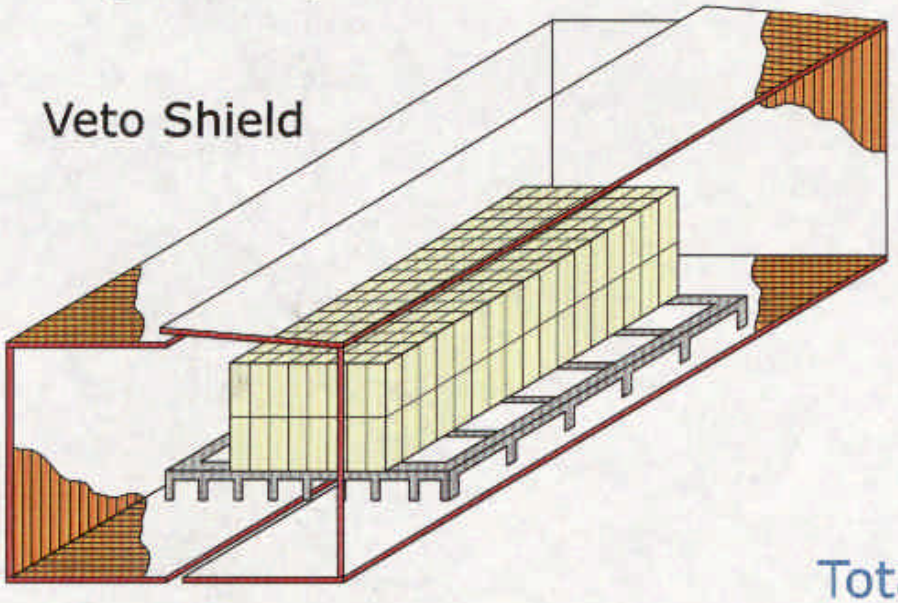
CL contour from Feldman-Cousins procedure.

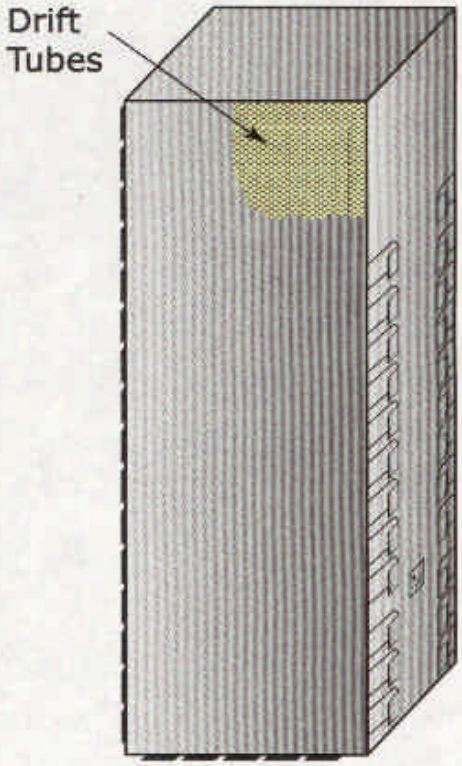
The Soudan 2 Detector:

Slow-drift time projection chamber



Honeycomb lattice geometry



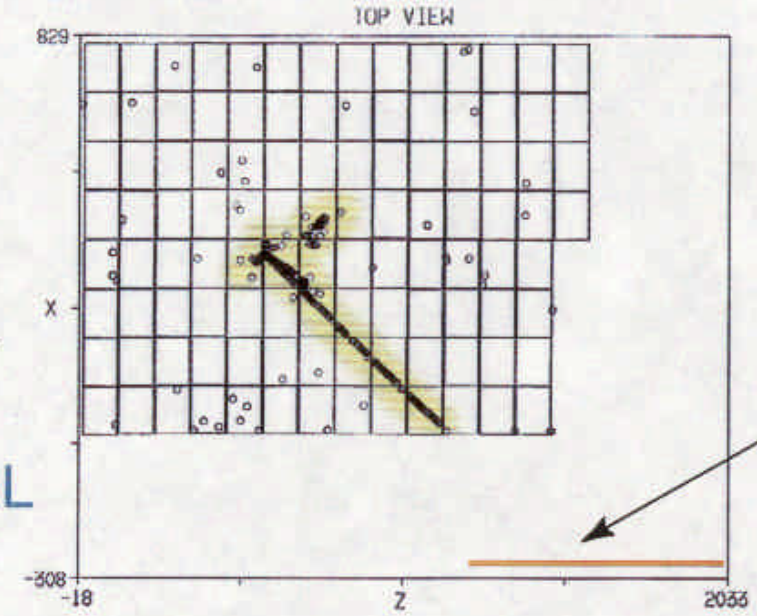


4.3 ton Module

Total mass: 963 tons

$\overset{(-)}{\nu}_\mu + N \rightarrow \mu^{\pm} +$ hadrons

↳ exits detector



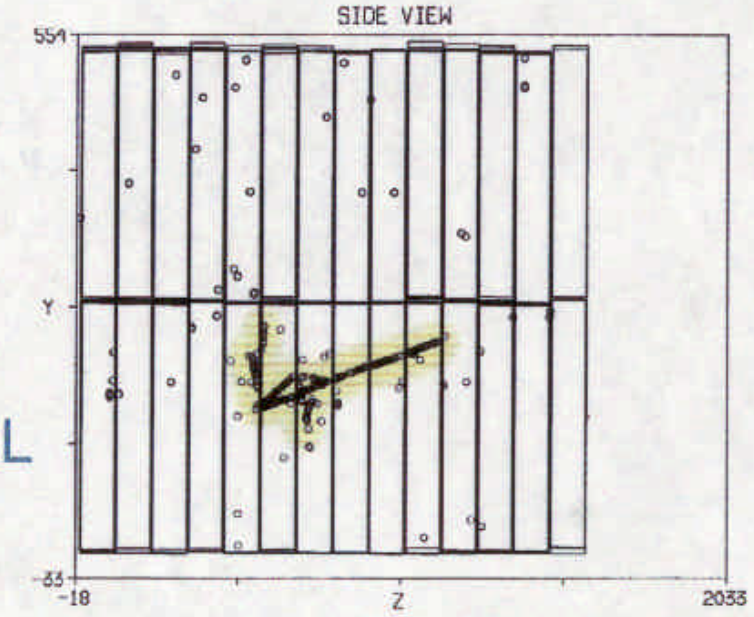
Soudan2 Data
Run 60837 Event 676
05-May-1995 06:01:29.73

Tzero
Tzero = 405 Set by VS & Blobs v Tracks in SEARCH/TODET

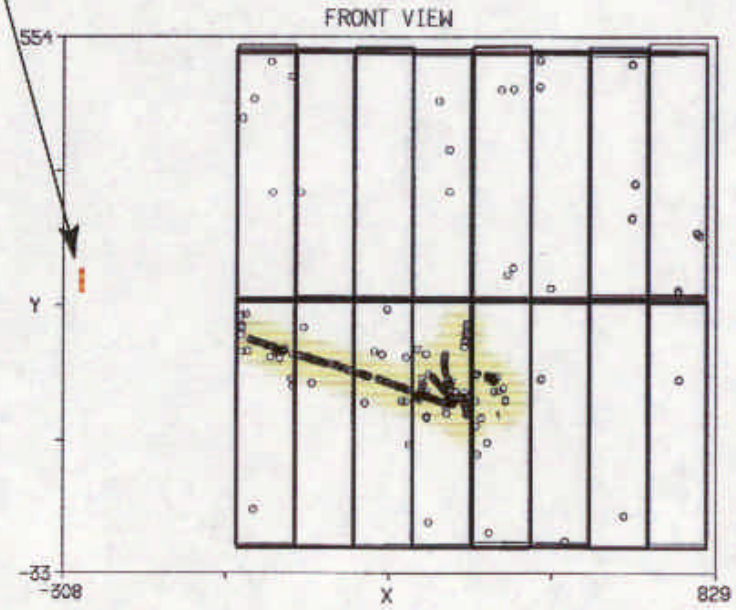
Shield ADC's
(2 at 404 E)
Shield Bytes
No SHLA bank. HEAD says SPLASH ran OK.

to FNAL

veto shield double layer "hit"



to FNAL



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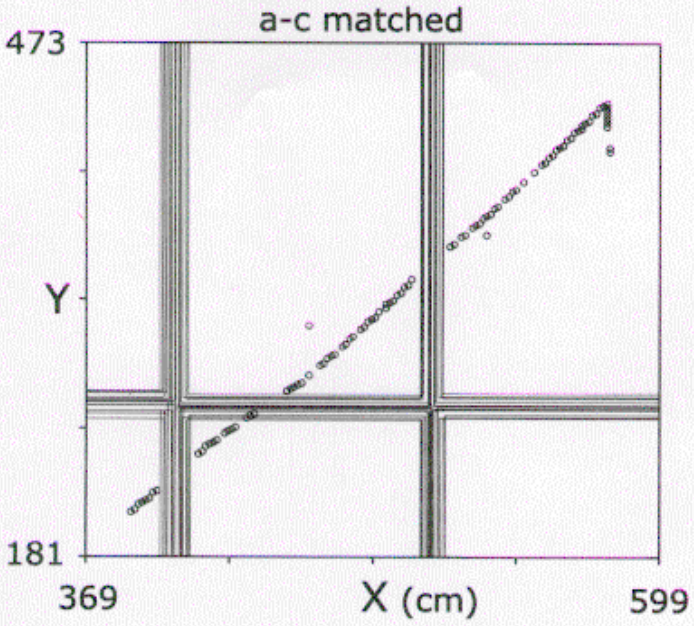
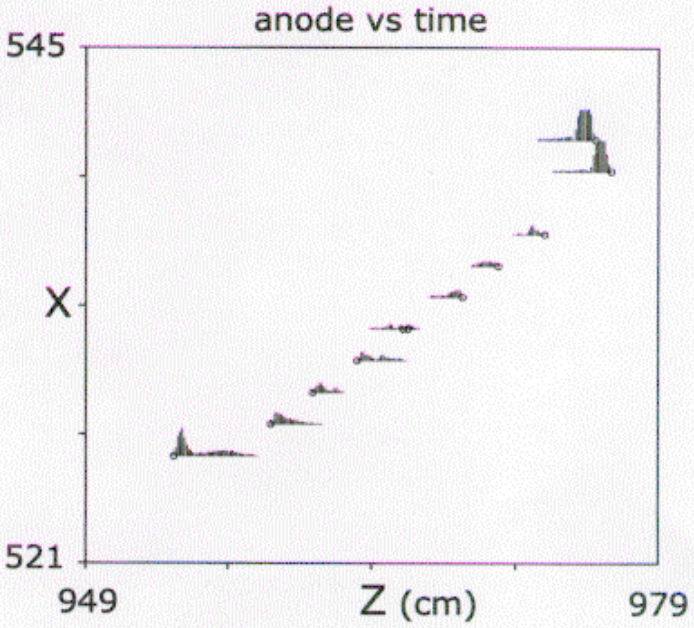
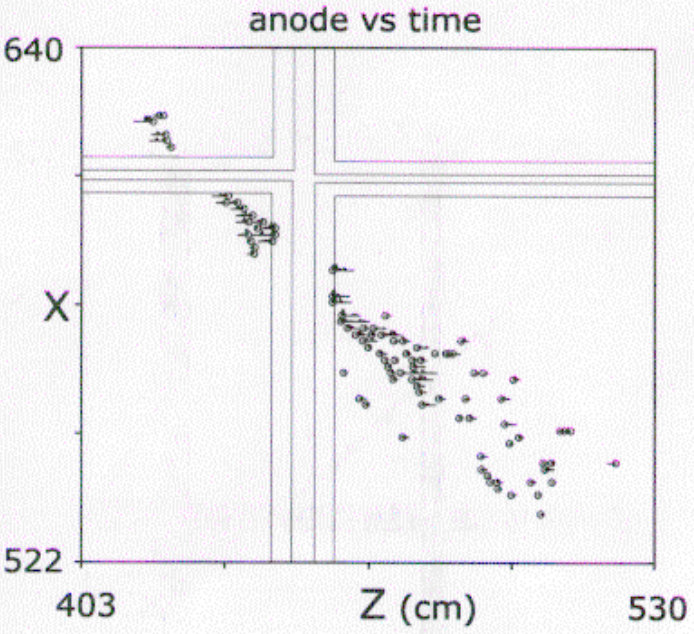
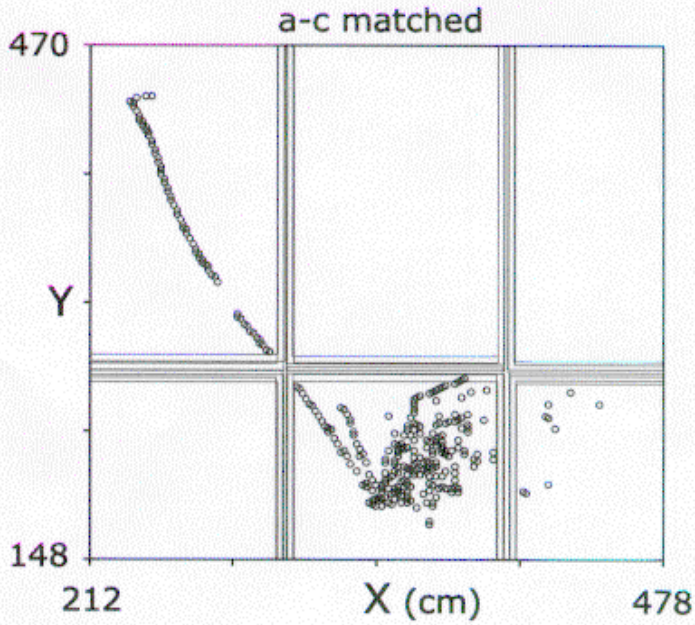
Track, Shower, Multiprong Events in Soudan 2:



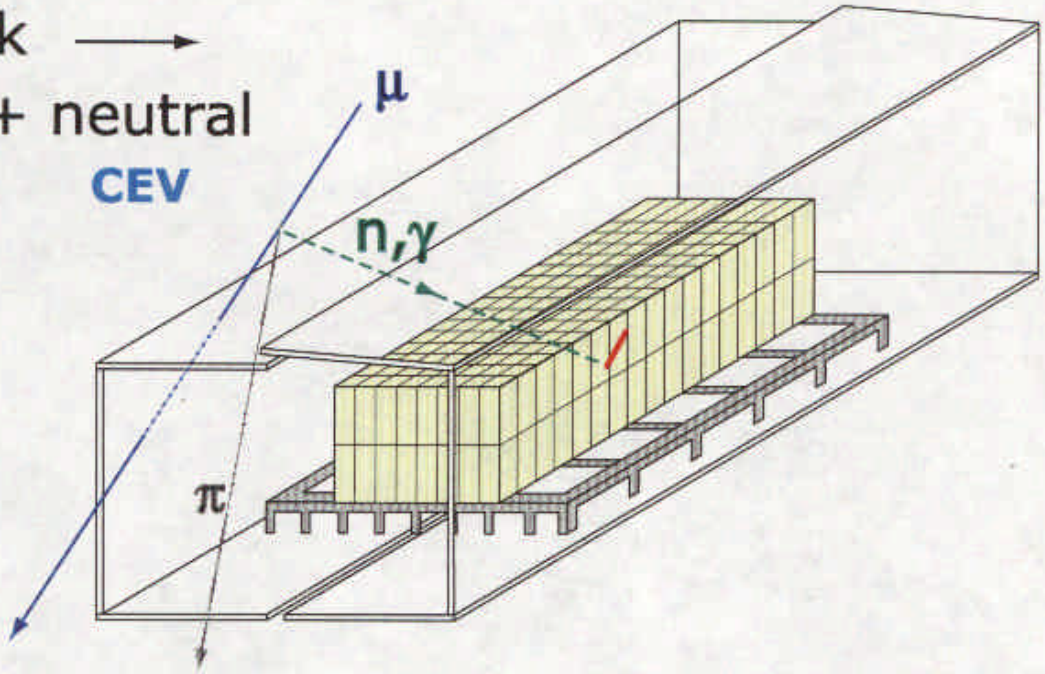






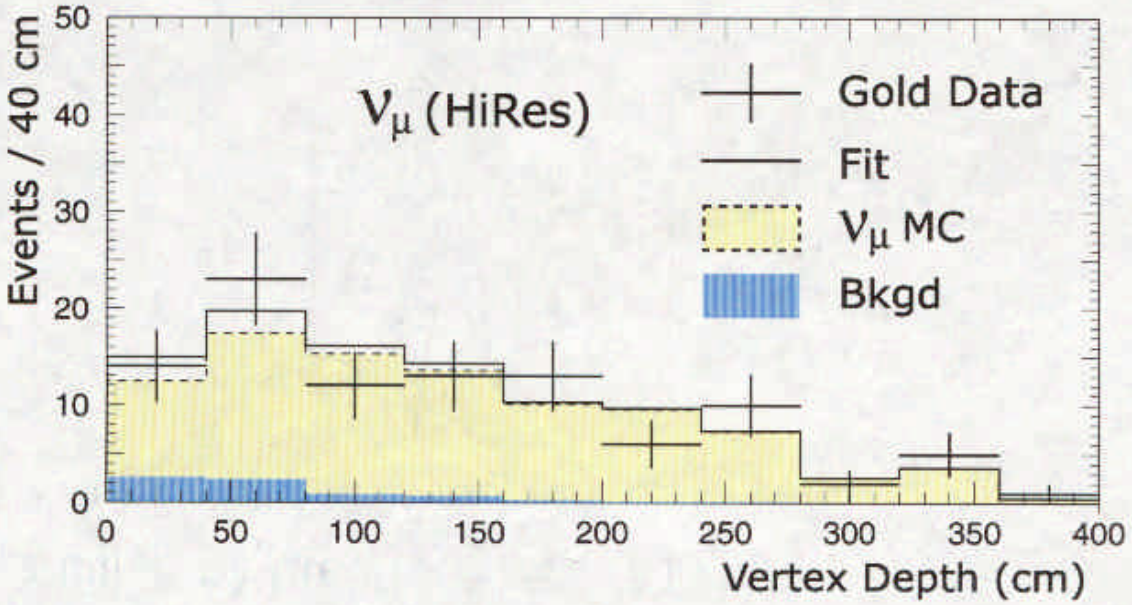
Non-neutrino cosmic-ray background:

μ + Rock ⟶
μ + charged + neutral
shield hits **CEV**



"Rock event" sample-
identified by presence of shield hits.

The residual zero-shield-hit background is calculated by fitting contained event vertex-depth distributions to a combination of Rock and ν Monte Carlo distributions:



Soudan 2 at 5.1 kty

Atm. ν flavor ratio:

Fully contained events (> 20 cm from det. edge)

Single Track and Single Shower Events

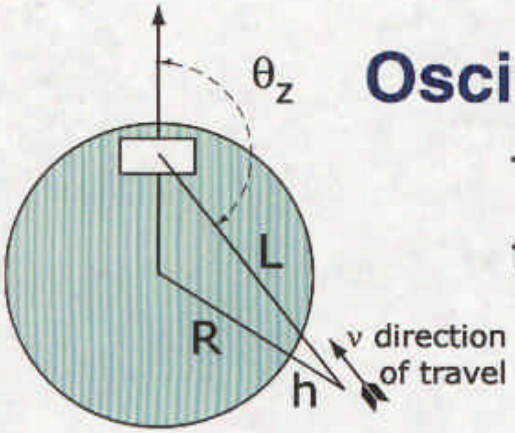
Cosmic-ray induced background:

Veto Shield tags most CR-induced bkgrd (n, γ)

Residual bkgrd estimated via vertex depth distr.

Number of Gold Tracks	133
Number of Gold Showers	193
Number of MC Tracks	1097 (193.1)
Number of MC Showers	1017 (179.0)
Corrected Number of ν Tracks	105.1 ± 12.7
Corrected Number of ν Showers	142.3 ± 13.9

$$R' = 0.68 \pm 0.11 \text{ (stat)} \pm 0.06 \text{ (sys)}$$



Oscillation analysis using L/E_ν:

To determine L, we reconstruct the neutrino zenith angle θ_z.

$$L(\theta_z) = \sqrt{R^2 \cos^2\theta_z + 2Rh + h^2} - R\cos\theta_z$$

The high-resolution data selection:

1) Quasi-elastics (Tracks, Showers)

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

Or

E_{vis} > 600 MeV if a recoil is absent

2) Multiprongs

E_{vis} > 700 MeV

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

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

Resolutions:

	ν_μ CC	ν_e CC
Energy: ($\Delta E/E$)	20%	23%
Angle: $\angle\vec{p}_\nu(\text{true})\bullet\vec{p}_\nu(\text{recon})$	33.2°	21.3°
L/E: |Log(true L/E) - Log(recon L/E)|	0.49	0.43

Soudan-2 high-resolution event samples:

Exposure = 5.1 kty

Category	Data		MC
	Before bgr. subtraction	After	(Bartol x 0.79)
ν_μ	114.0 ± 10.7	106.3 ± 14.7	158.5 ± 4.8
ν_e	140.0 ± 11.8	132.8 ± 13.4	132.8 ± 4.4 (norm'ed)

Notes:

- Event identification matrix:

Data category	*Monte Carlo truth* ν_μ *CC*	ν_e *CC*	*NC*
ν_μ flavor	92.5%	3.1%	4.4%
ν_e flavor	2.6%	92.0%	5.4%

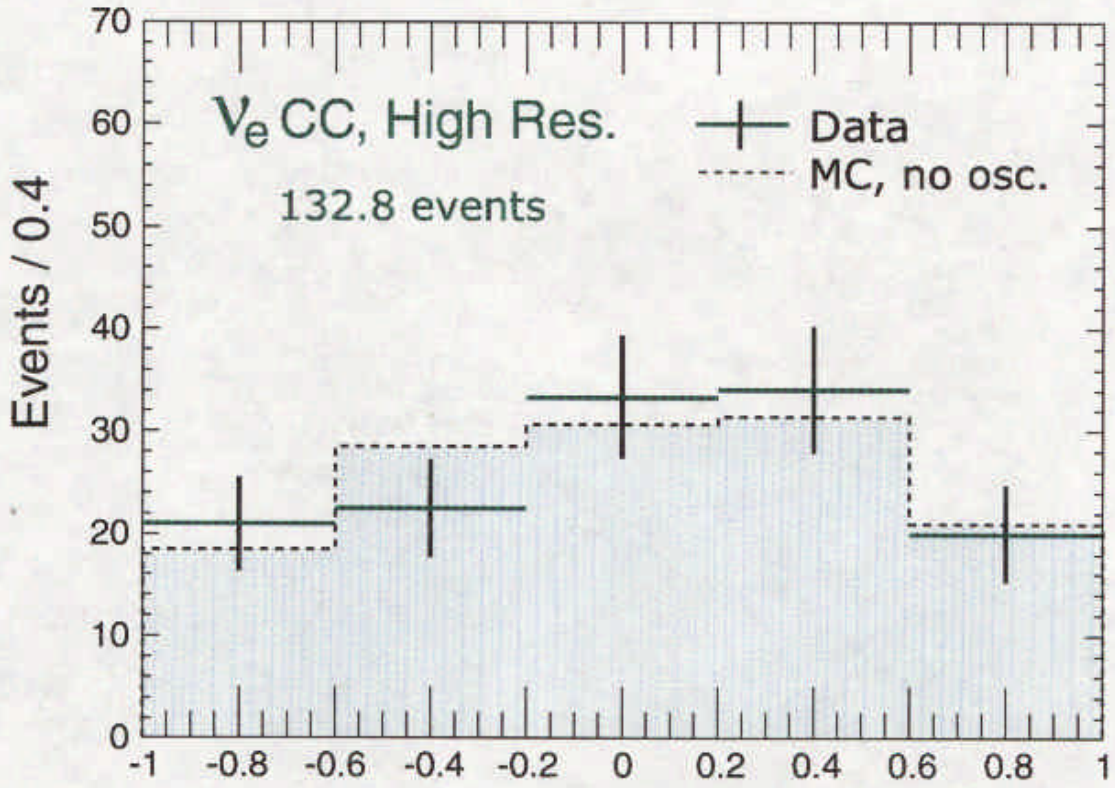
- Rock-muon associated background correction is 6.8% for ν_μ flavor and 5.1% for ν_e flavor.

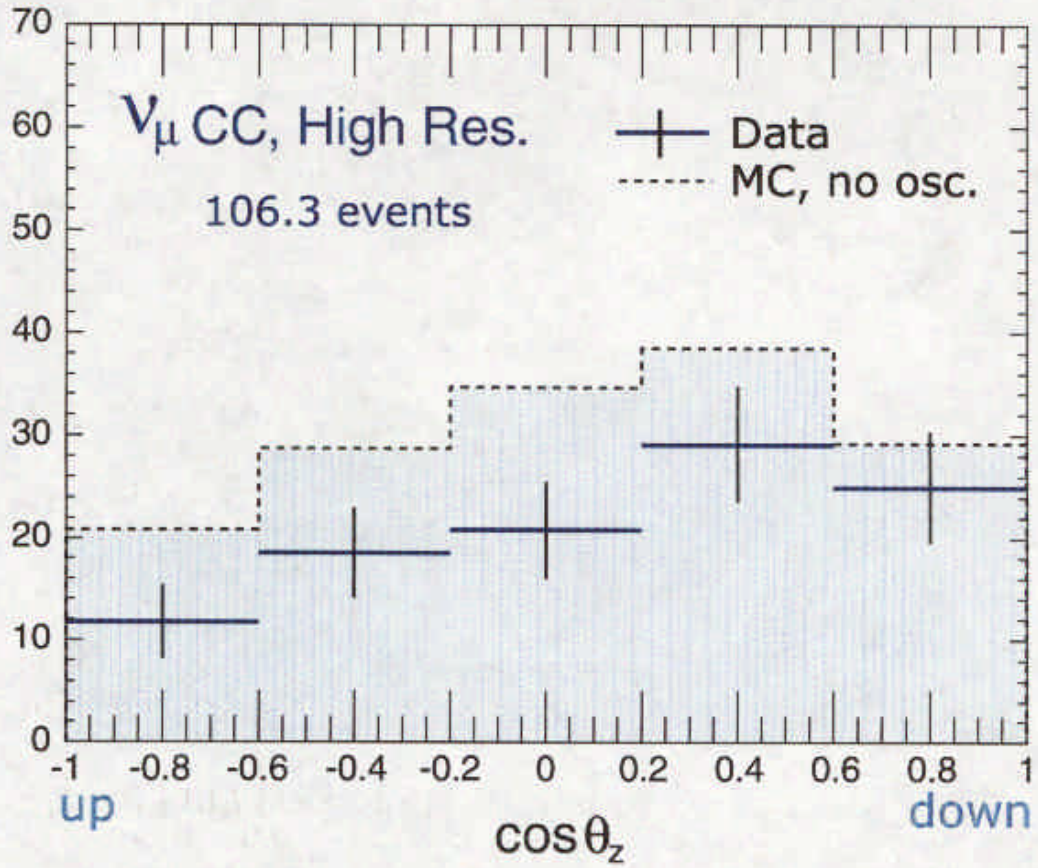
- The Monte Carlo sample represents 28.2 kty of exposure; numbers given here are normalized to 5.1 kty.

- In this sample of mostly higher energy events, the ratio of ratios is R = 0.67 ± 0.12, also significantly below 1.

Zenith Angles:

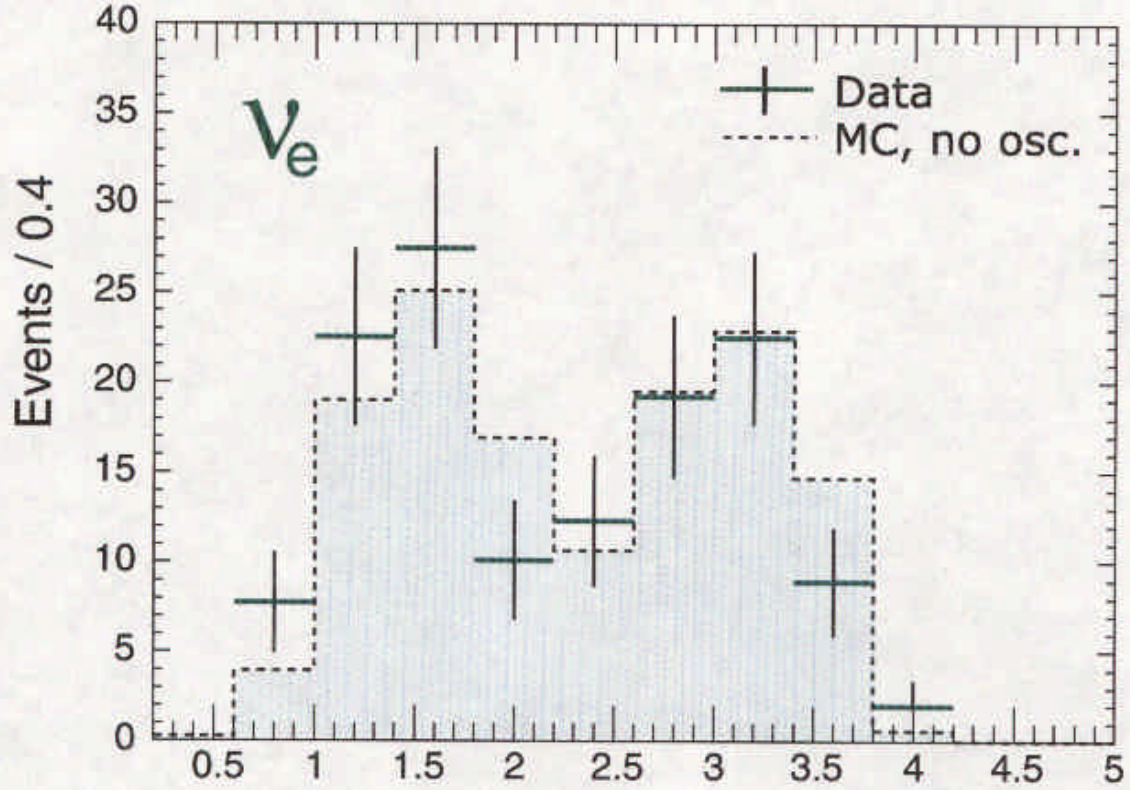
Soudan 2 at 5.1 kty

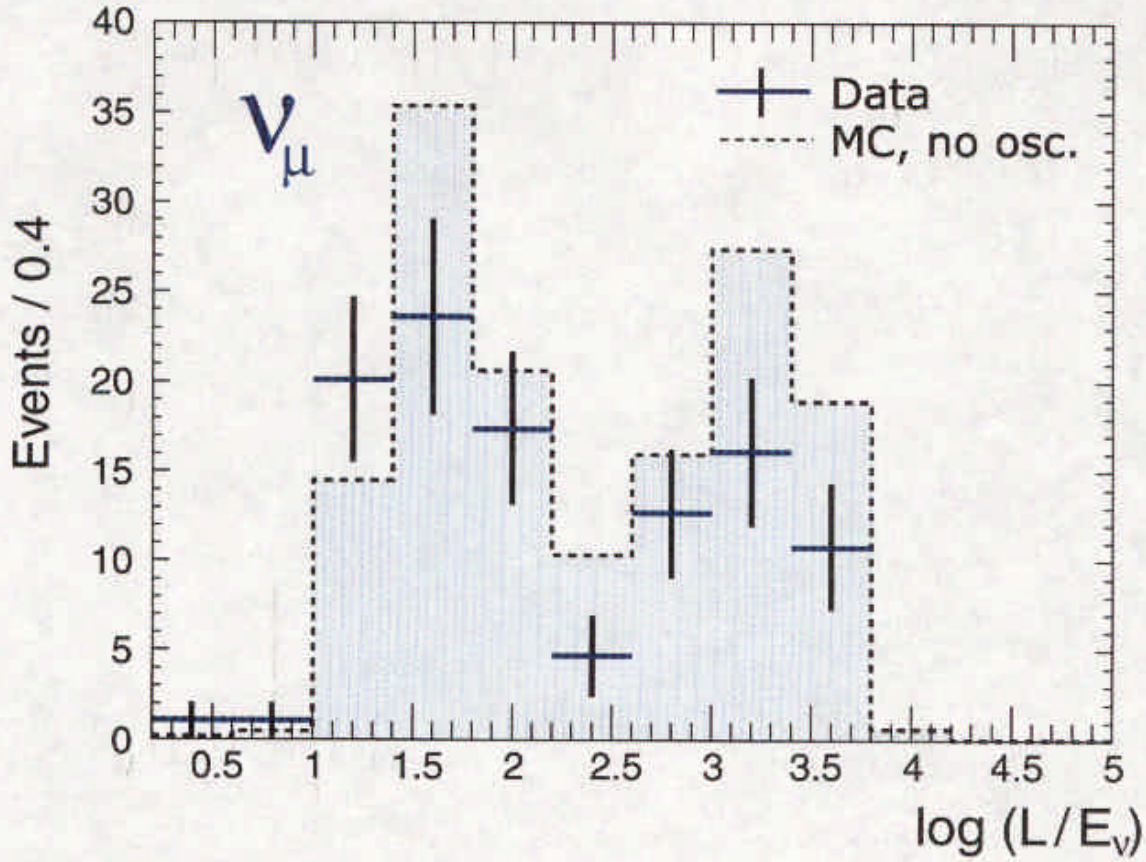




L/E Distributions:

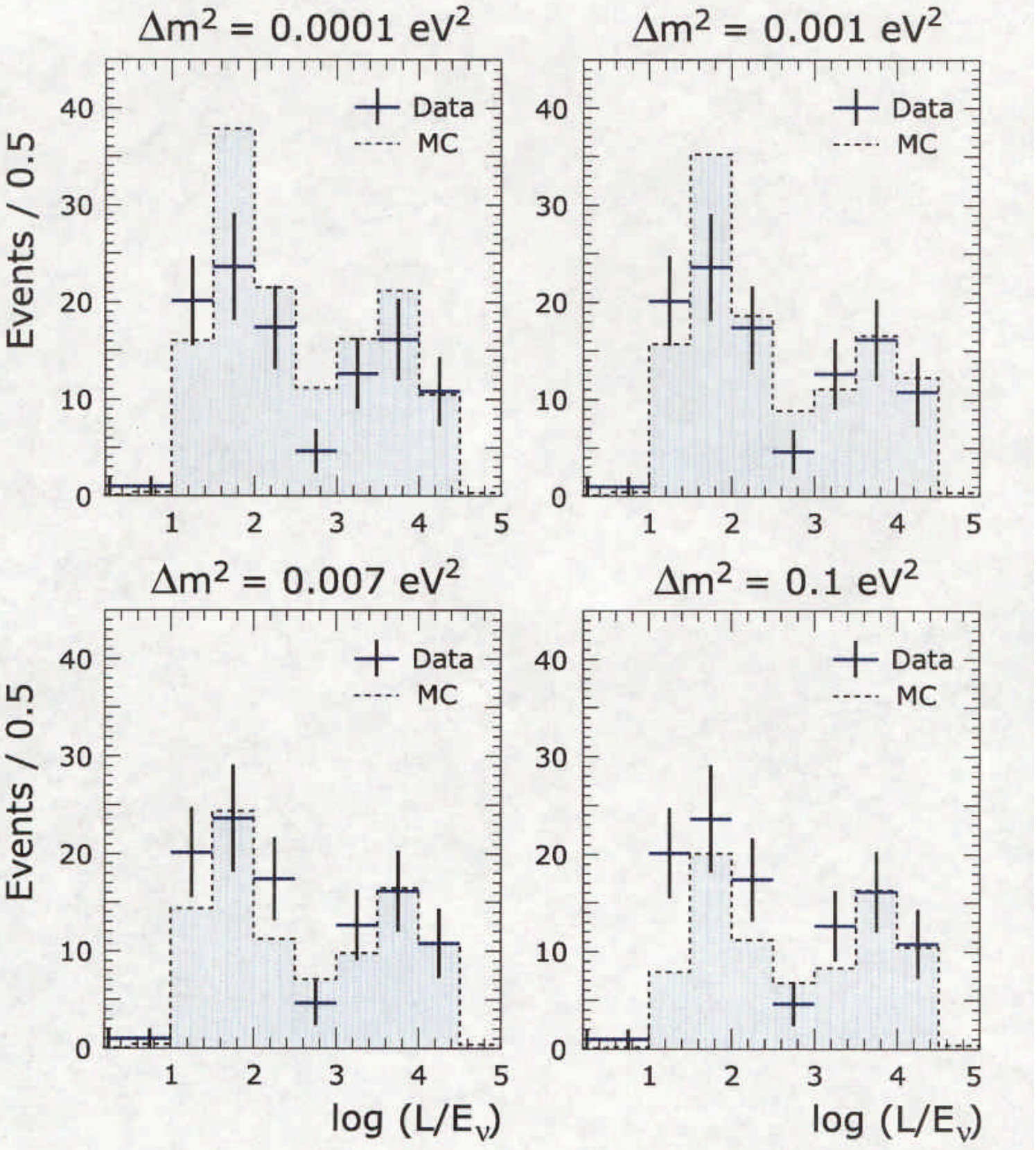
Soudan 2 at 5.1 kty





L/E Distributions for ν_μ - Flavor Events:

$\sin^2 2\theta = 1$



In our analysis -

We assume $\nu_\mu \rightarrow \nu_\tau$; ν_e is unaffected.

From our HiRes ν_μ and ν_e samples we use

1) the L/E_ν distribution of ν_μ events;

2) the total number of ν_e events.

For points (i, j) over the physical region of the $(\sin^2 2\theta_i,\ \log_{10} \Delta m^2_j)$ plane, we do a fit of the MC expectation to our data at each point:

$$(\chi^2_{data})_{ij} = \chi^2\,(\sin^2 2\theta_i,\ \Delta m^2_j;\ f_\nu)$$

where f_ν = MC flux normalization.

(Bartol '96 atm. flux)

χ^2 for Oscillation Parameters Determination:

$$\chi^2_{\text{data}} = \sum_{k=1}^{8} \frac{(\,N_k(\text{data - bkgd}) - f_\nu \cdot N_k(\text{MC}))^2}{\sigma_k^2}$$

where k = 1,7 for ν_μ $\log_{10} L/E_\nu$ bins,
and k = 8 for ν_e events.

Here, σ_k^2 accounts for finite statistics in the neutrino Monte Carlo and the "Rock" background samples, and uncertainty in the fraction of Rock in the data.

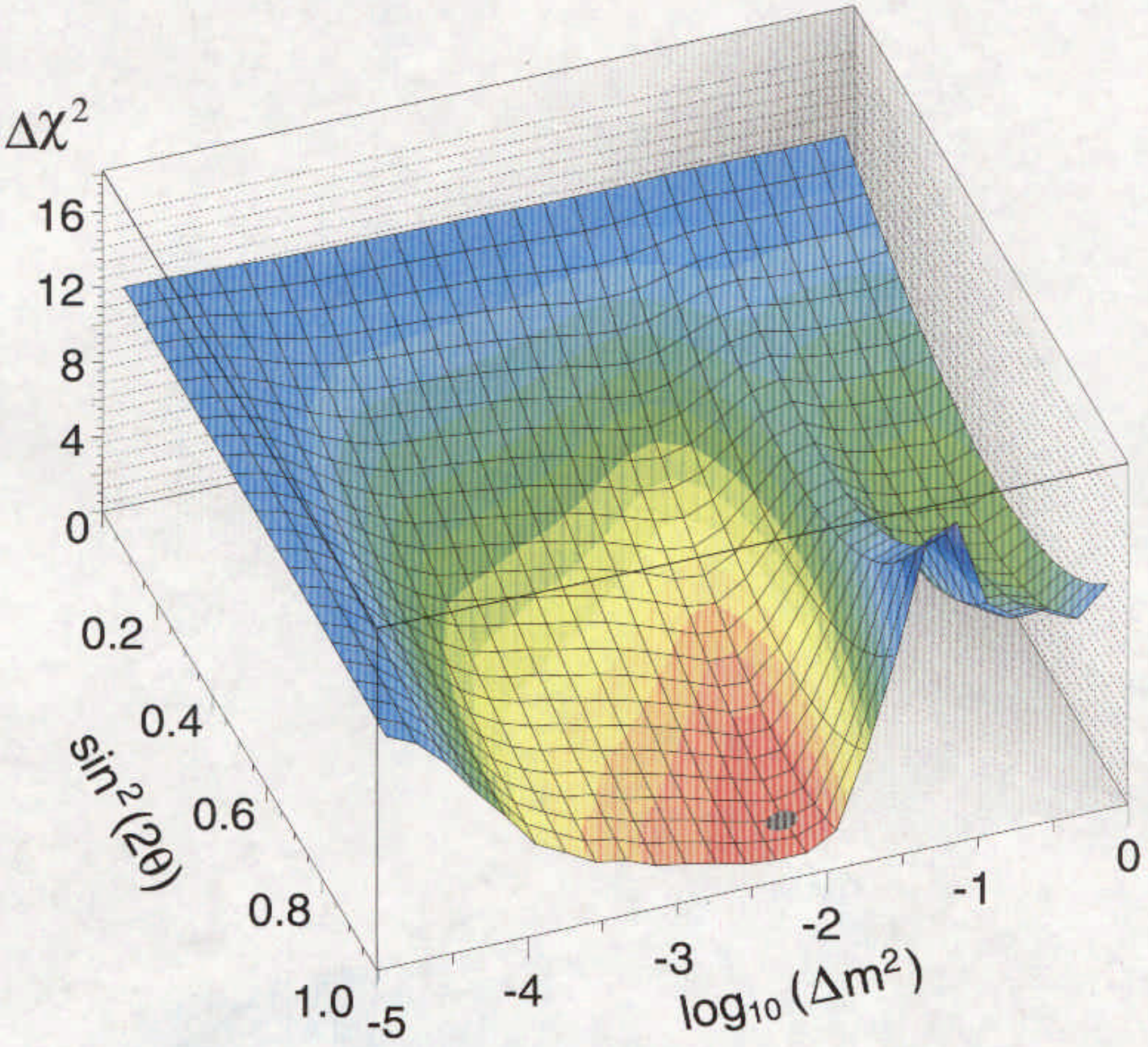
$N_k(\text{MC})$ is constructed using oscillation weight factors. For the l^{th} ν_μ MC event in bin k,

$$\omega_{kl} = [\,1 - \sin^2 2\theta \cdot \sin^2\!\left(1.27 \cdot \Delta m^2 \cdot \left(\frac{L_{true}}{E_{true}}\right)_l\right)\,]$$

We find $(\chi^2_{data})_{min}$, and plot

$$(\Delta\chi^2_{data})_{ij} = (\chi^2_{data})_{ij} - (\chi^2_{data})_{min.}$$

$\Delta\chi^2$ surface using L/E_ν distributions:



χ^2_{min} at

$\sin^2 2\theta = 0.90$

$\Delta m^2 = 7.9 \times 10^{-3}\ eV^2$

($f_\nu = 0.78$)

Feldman and Cousins procedure to find the 90% confidence region:

At each of 2500 points $(i, j) = (\sin^2 2\theta_i, \Delta m^2_j)$ in the physical region, run 1000 simulated experiments.

Find $(\Delta\chi^2_{90})_{ij}$ such that $(\Delta\chi^2_{sim})_{ij} < (\Delta\chi^2_{90})_{ij}$

for 90% of the simulated experiments at (i, j).

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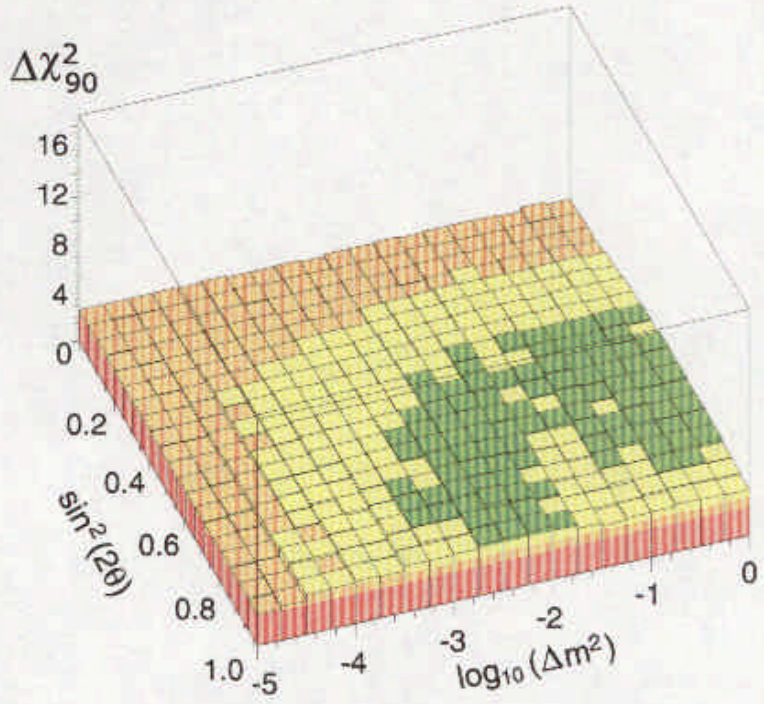
The surface defined by local $\Delta\chi^2_{90}$ over the oscillation parameters plane: $\Longrightarrow$

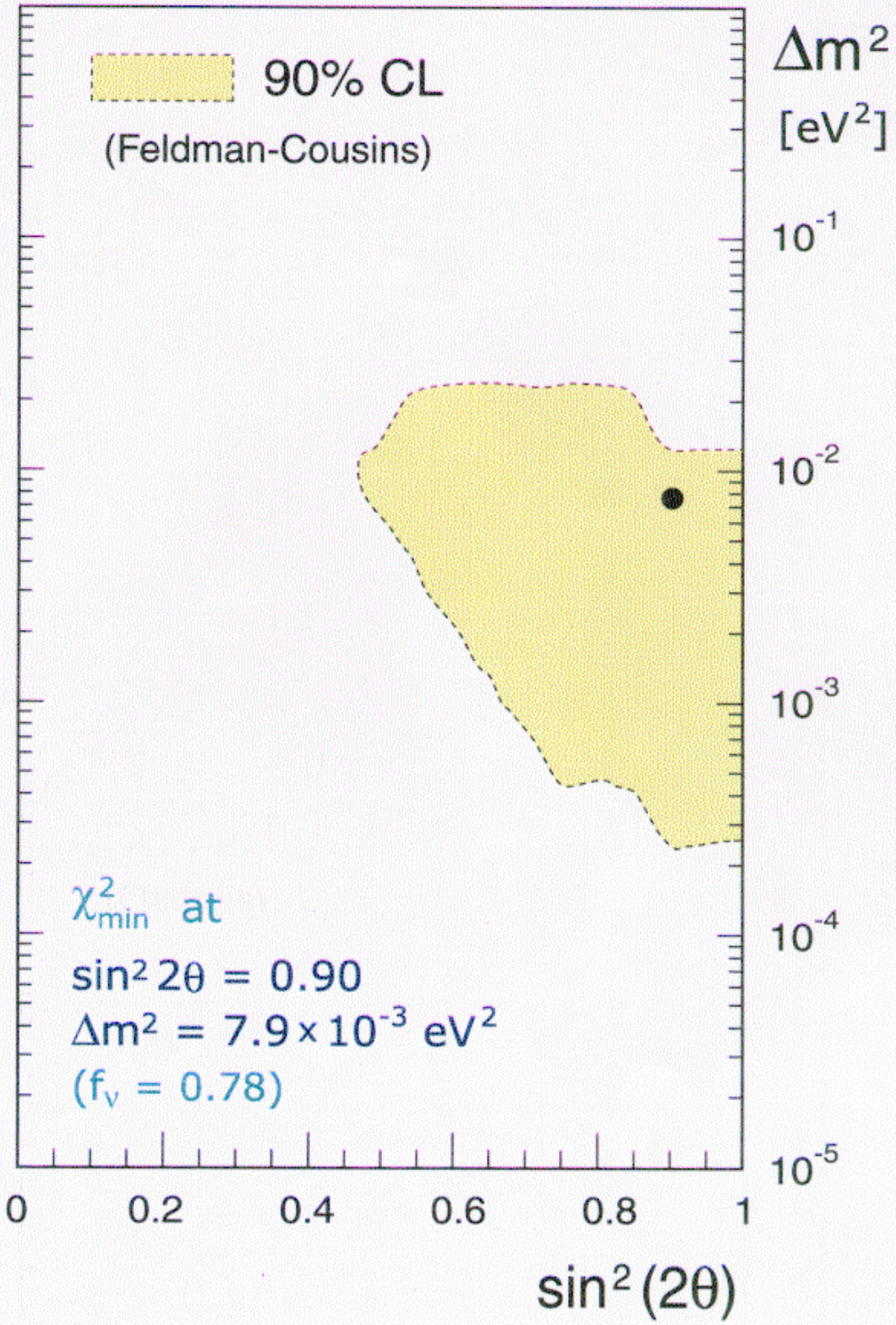


$\Delta\chi^2_{90} \neq 4.61$!

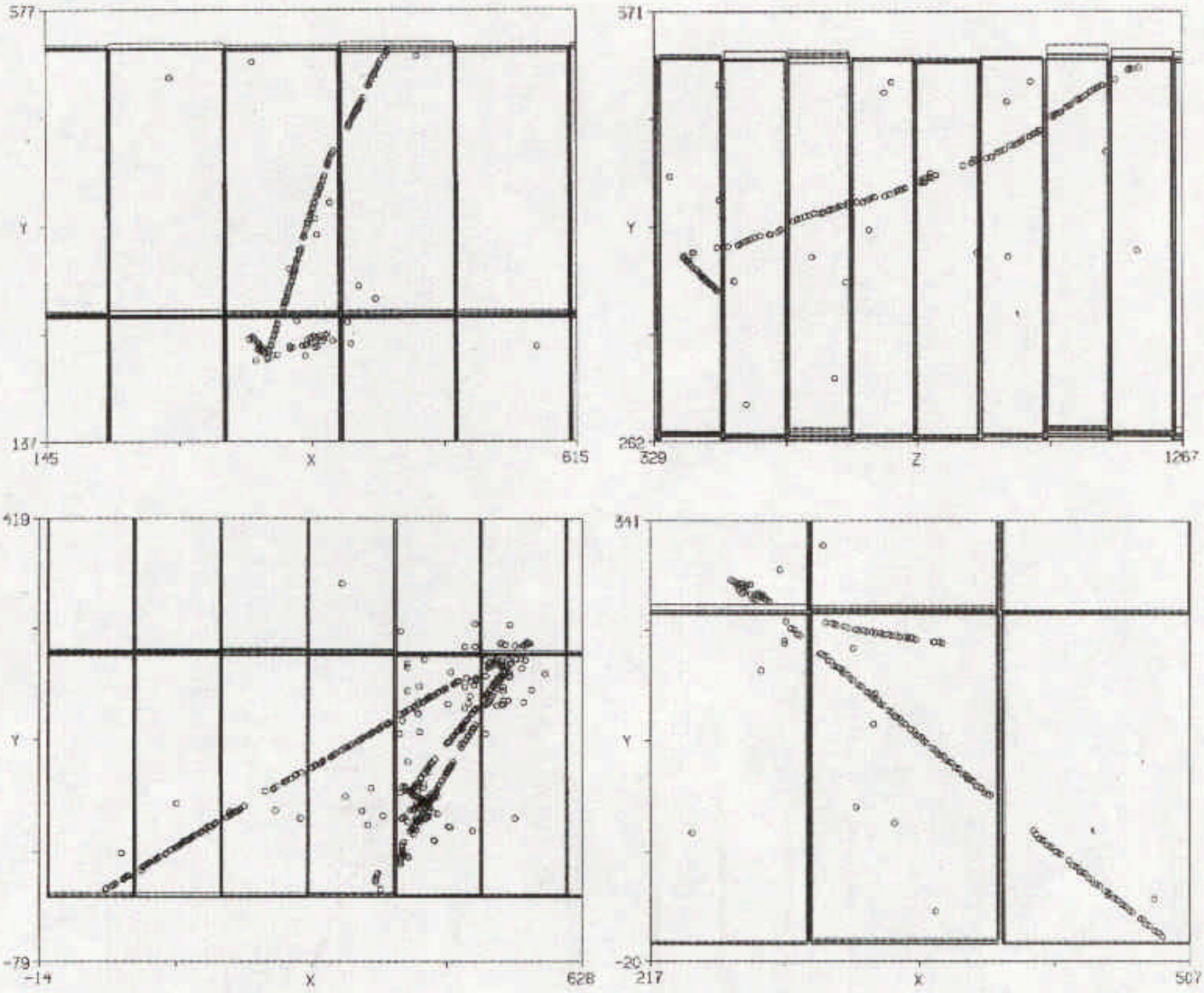
Finally,

if $(\Delta\chi^2_{data})_{ij} < (\Delta\chi^2_{90})_{ij}$, then (i, j) belongs to the allowed region of the 90% CL contour.

preliminary



Partially contained ν_μ events (PCEs):



Select events with non-scattering, exiting track;

ν_μ - flavor assignment is reliable (> 98%).

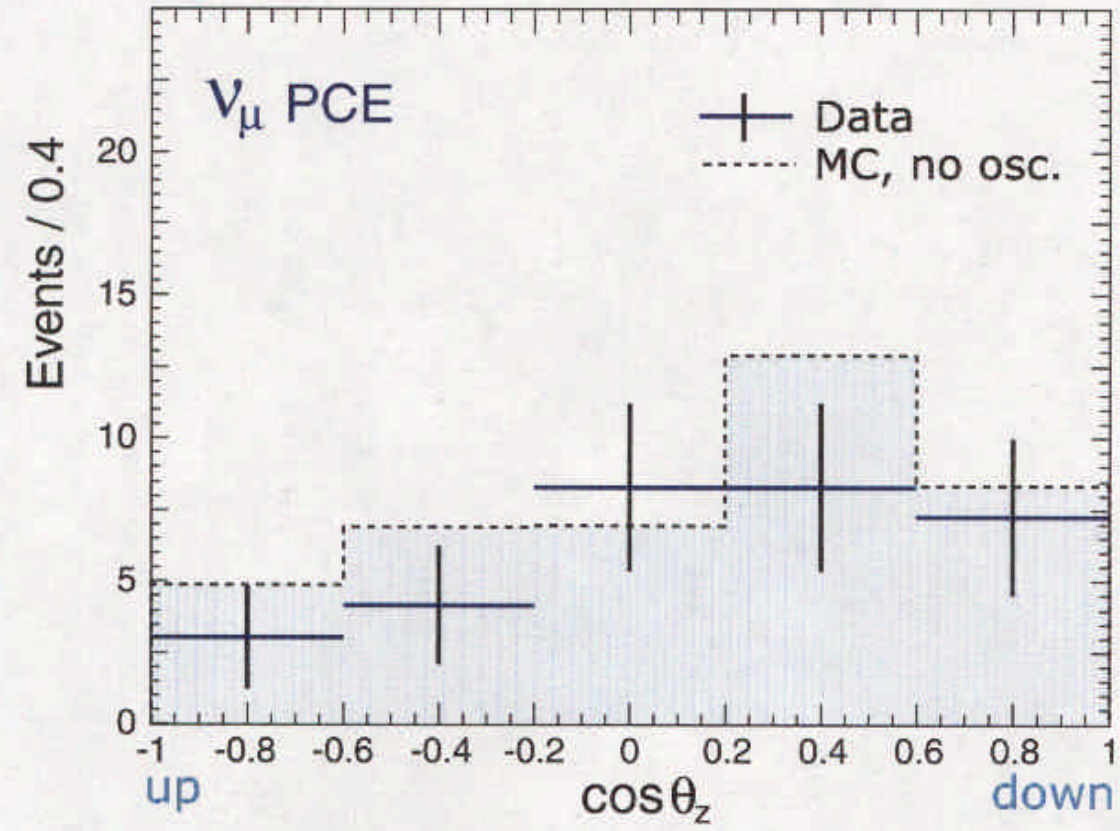
ν_μ PCEs are energetic and "point" well:

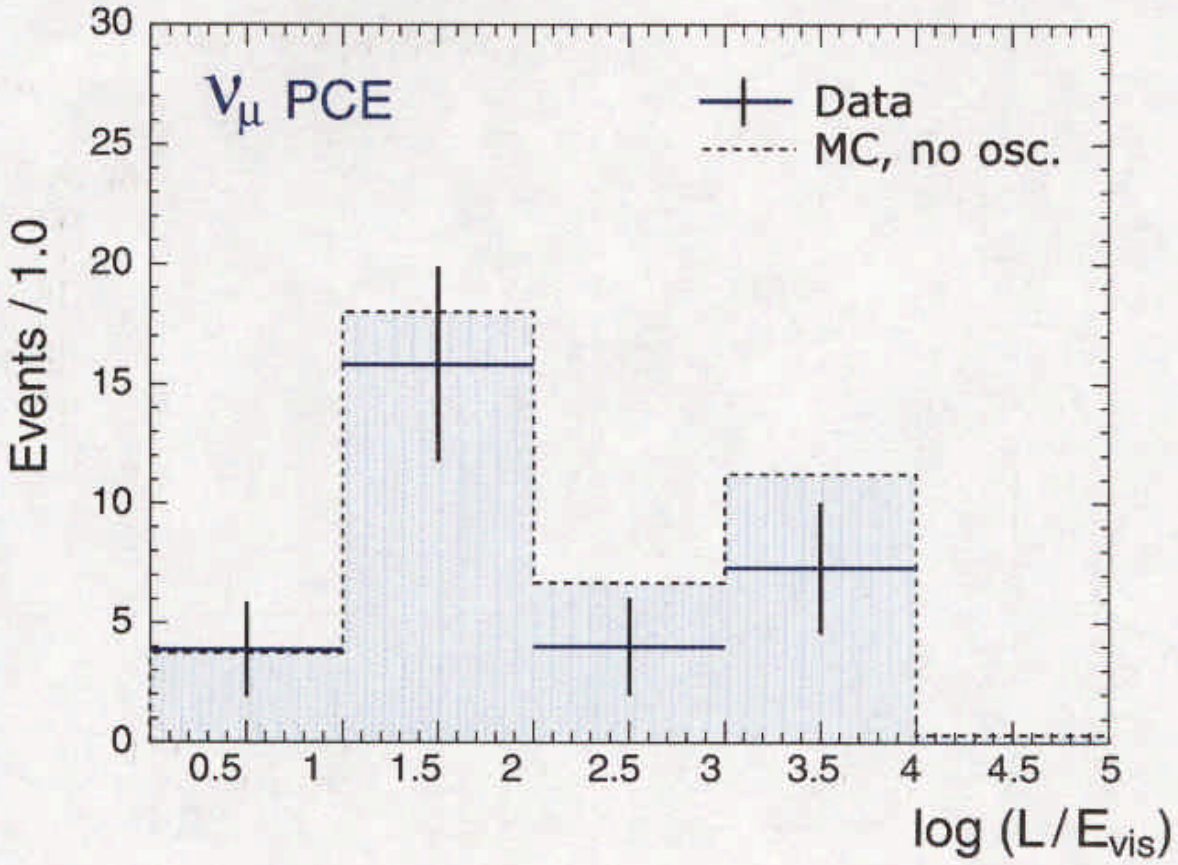
$\langle E_{vis} \rangle_{PCE}$ = 4.7 GeV (vs 1.3 GeV for ν_μ HiRes)

$\langle$Angle ν_μ vs recon.$\rangle_{PCE}$ = 14°.

Partially Contained ν_μ Events:

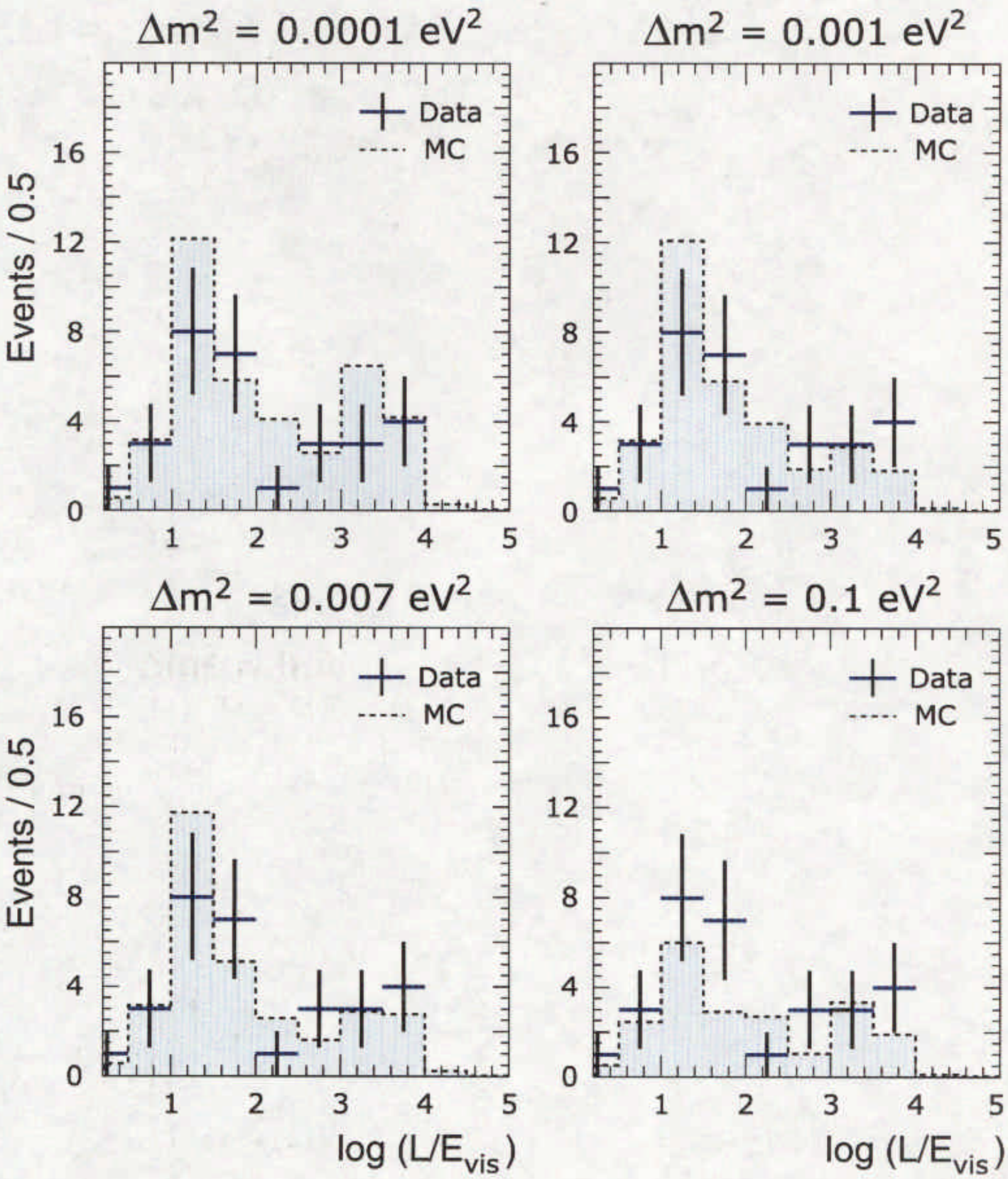
Soudan 2 at 5.1 kty





L/E_{vis} for ν_μ partially contained events:

$\sin^2 2\theta = 1$



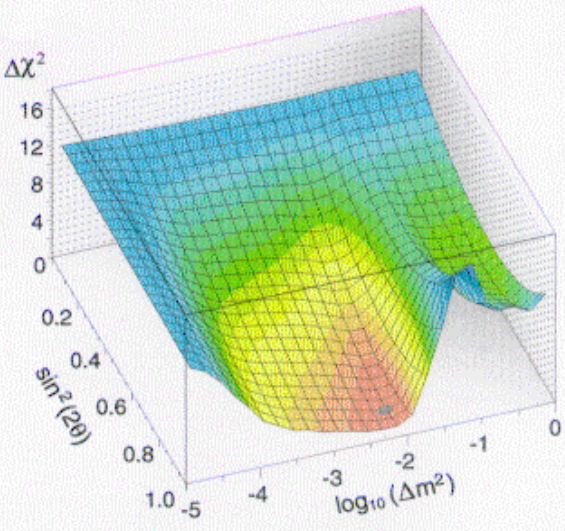
In Summary:

Soudan 2 at 5.1 kty

1) Atm. ν flavor ratio:

$R' = 0.68 \pm 0.11\ (stat) \pm 0.06\ (sys)$

2) $\nu_\mu \rightarrow \nu_\tau$ allowed region:



χ^2_{min} at

$\sin^2 2\theta = 0.90$

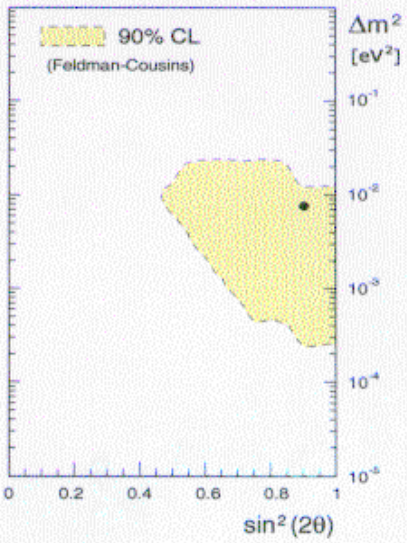
$\Delta m^2 = 7.9 \times 10^{-3}\ eV^2$

($f_\nu = 0.78$)

90% CL contour

using Feldman-Cousins

procedure:



3) Partially contained

ν_μ events:

31 events vs. 40 expected,

- hint of an up-down asymmetry in zenith angle and $\log_{10}(L/E_{vis})$.

For the near future:

- Finalize the PCE sample and include these events in the L/E fit.
- Analyze the upward-stopping muon event sample.
- Continue taking data.
- Keep the detector running and tuned for the switch of beams:

Atmospheric to Fermilab in 2003 *!* (MINOS)