Atmospheric Neutrino Interactions in Soudan-2: A Feldman-Cousins Case Study

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Atmospheric neutrinos:
originate in π and μ decays
in a shower of particles produced by
a cosmic-ray interaction in the atmosphere.

Detector:
960-ton Iron tracking calorimeter
700m underground in Soudan, MN.

Data selection of Fully Contained EVents:

- software filter;
- physicist scan;
- track & shower reconstruction;
- non-neutrino background correction;
- neutrino flavor determination.

Resulting sample contains

- single tracks,
- single showers,
- multiprongs.

Observation in quasielastic events (single tracks, showers):

Deficit of ν_μ-flavor events.

Two-flavor ν oscillations:

$$P(\nu_\mu \rightarrow \nu_x) = sin^2 2\theta \; sin^2(1.27\Delta m^2 \frac{L}{E})$$

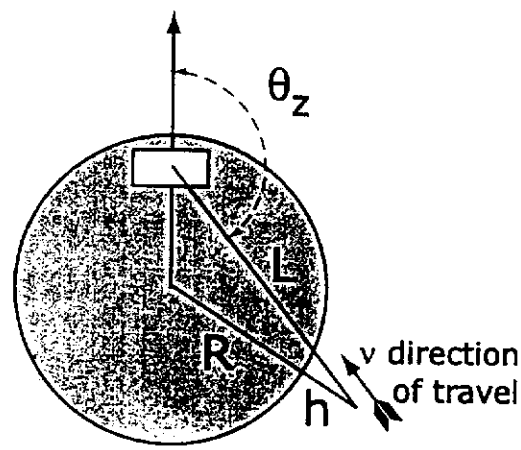
where

L = neutrino path length,

E = neutrino energy,

$\sin^2\theta$, Δm^2 - parameters to be determined.

L/E analysis mandate:
To get L right, must have the zenith angle right.



Further data selection:

- improve (angular) resolution;
- improve flavor tag,
- reduce neutral-current and non-neutrino bgr.

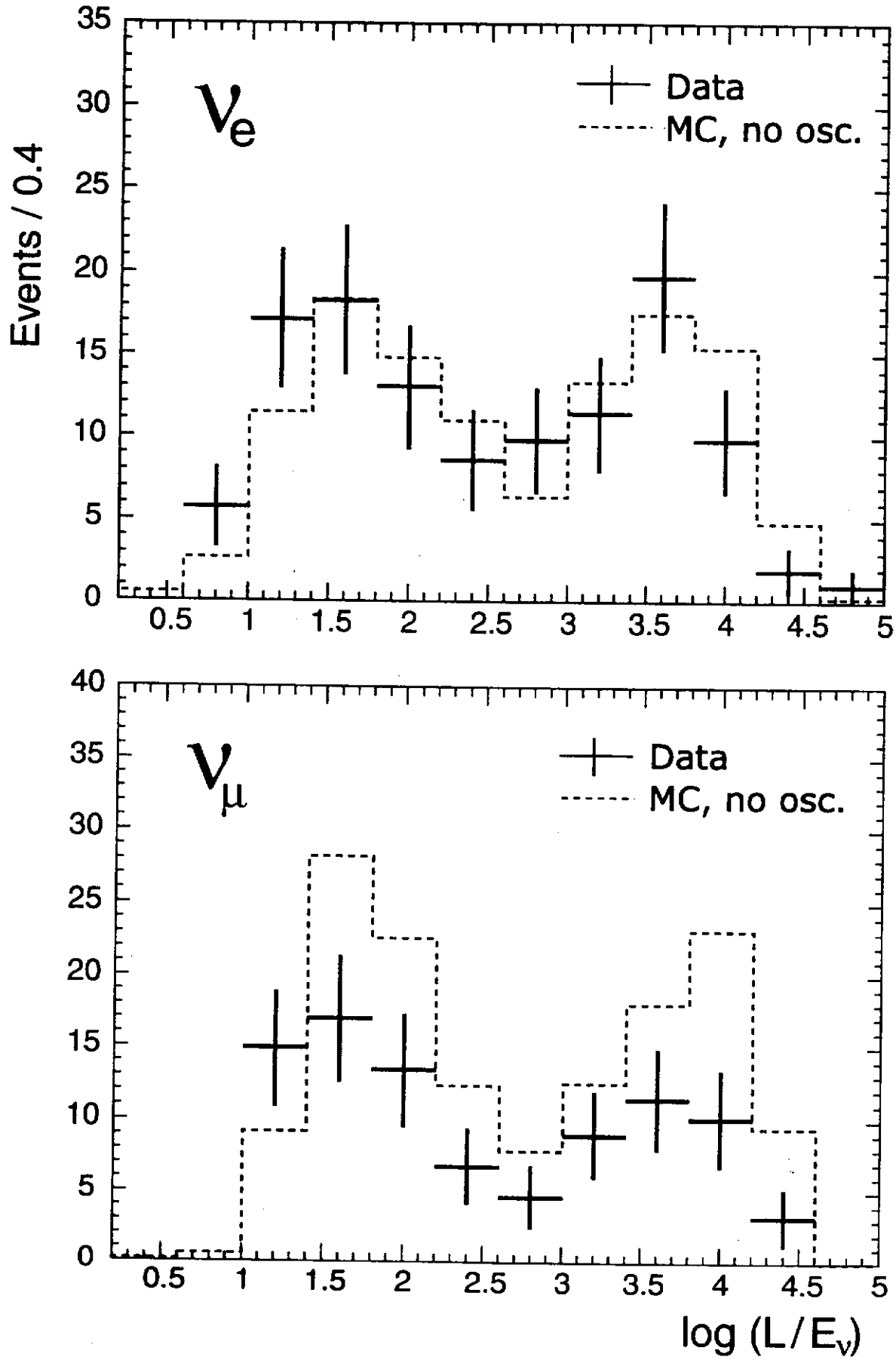
Use tracks, showers, and multiprongs.

Data sample:

	Data 4.6 kty	*MC* 25 kty
ν_μ	98	962
ν_e	123	835

L/E Distributions:

Soudan 2 at 4.6 kty



L/E distributions

To convert results of our atmospheric neutrino simulation generated under the no-oscillation hypothesis into simulated neutrino oscillation data, we apply an L/E-dependent weight to every MC event,

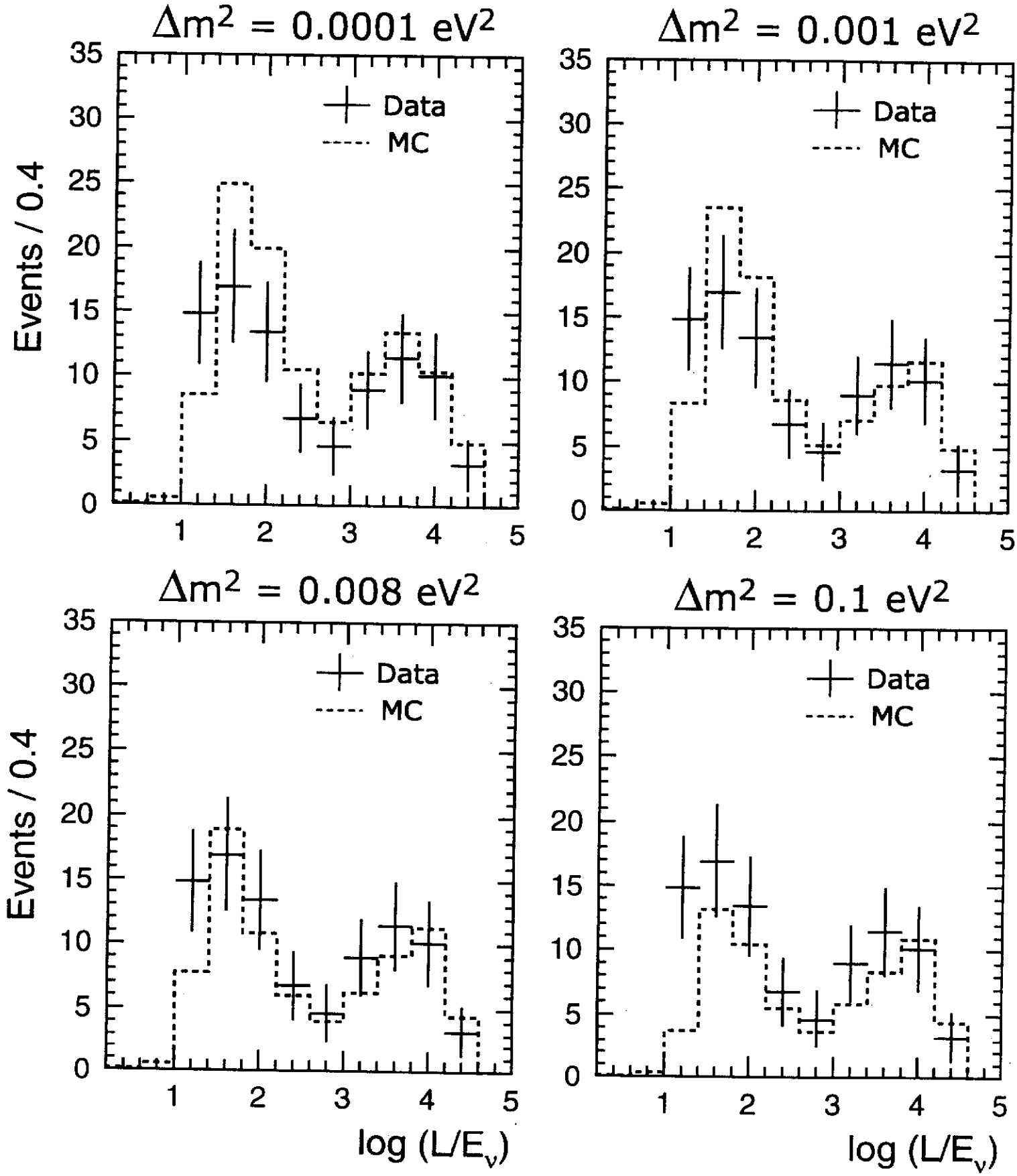
$$w_{ij}(\frac{L_{recon}}{E_{recon}}) = [1-(sin^2 2\theta)_j sin^2(1.267(\Delta m^2)_i \frac{L_{true}}{E_{true}})]$$

These weights are applied only to the ν_μ distributions.

Soudan 2 at 4.6 kty

L/E Distributions for ν_μ - Flavor Events:

$\sin^2 2\theta = 1$



To find oscillation parameters: calculate χ^2, find χ^2_{best}

$$\chi^2_{ijk} =$$

$$\sum_{\nu_\mu} \frac{[Data(L(\overline{h})/E) - f_{\nu k} \times f_{MC} \times \ w_{ij}(L(\overline{h})/E)]^2}{[Error(Data)]^2 + [Error(MC)]^2} +$$

$$\sum_{\nu_e} \frac{[Data(L(\overline{h})/E) - f_{\nu k} \times f_{MC} \times MC(L(\overline{h})/E)]^2}{[Error(Data)]^2 + [Error(MC)]^2}$$

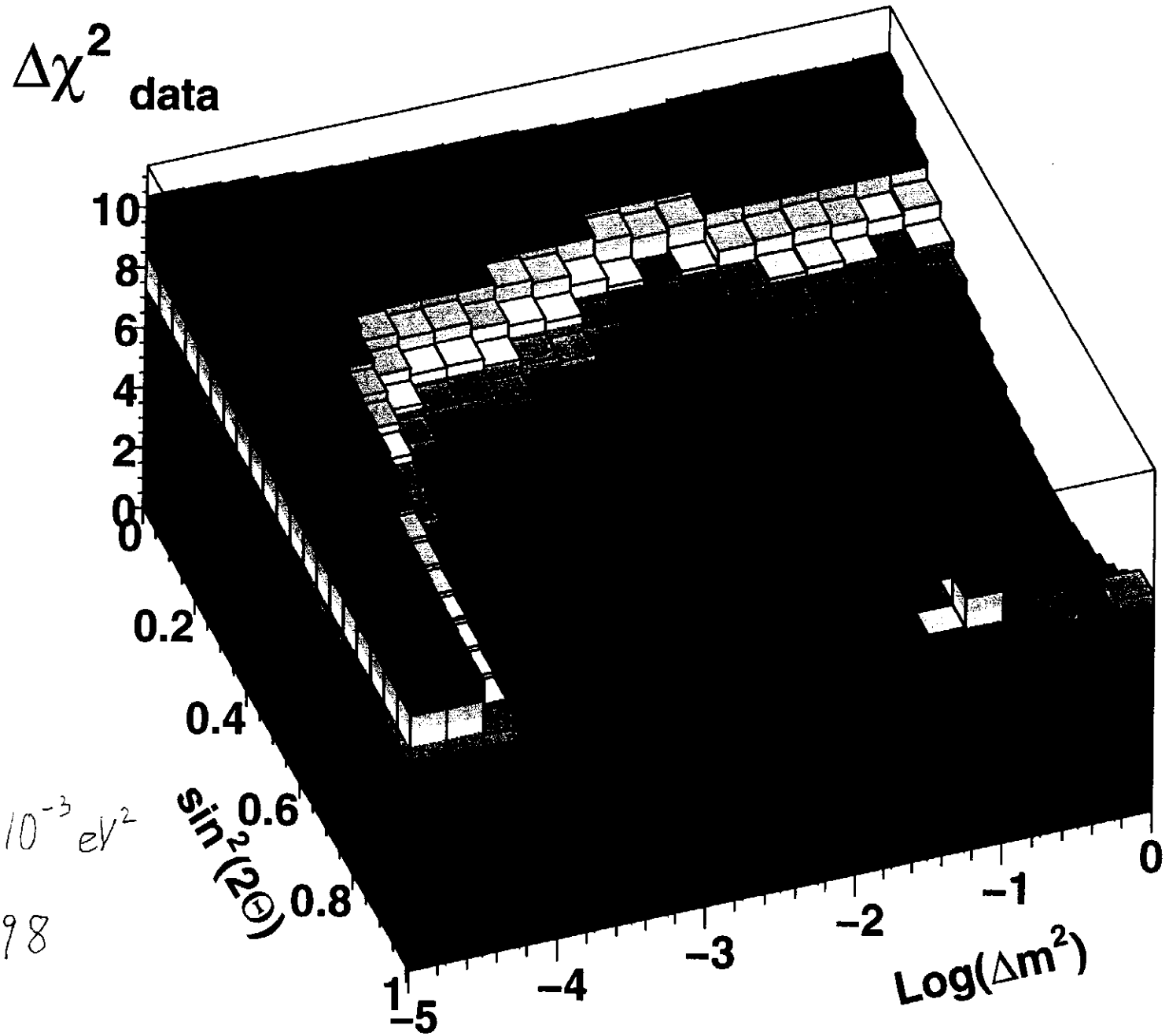
where $10^{-5} < \Delta m^2 < 1.0$, $0 < sin^2 2\theta < 1.0$,
f_ν is a fit parameter giving the relative normalization of neutrino data and MC, and
f_{MC} is the ratio of data exposure to MC exposure.

Assume that no neutrino oscillations occur in the ν_e flux, and use 7 bins for ν_μ, and 1 bin for ν_e.

3-parameter fit yields:
(χ^2_{min} = 3.6 per 5 dof)

$$\begin{aligned} \Delta m^2 &= 7.5 \times 10^{-3} \text{eV}^2 \\ sin^2 2\theta &= 0.98 \\ f_\nu &= 0.80 \end{aligned}$$

Soudan 2, 4.6 kty



$\Delta m^2 = 7.5 \times 10^{-3}\ eV^2$

$\sin^2 2\Theta = 0.98$

Need confidence limits on Δm^2, $\sin^2 2\theta$ - Feldman & Cousins to the rescue!

For each $(\Delta m^2)_i$, $(\sin^2 2\theta)_j$, i=1...40, j=1...40:

For data, calculate

$(\Delta\chi^2_{Data})_{ij} = (\chi^2_{Data})_{ij} - \chi^2_{Data\_best}$

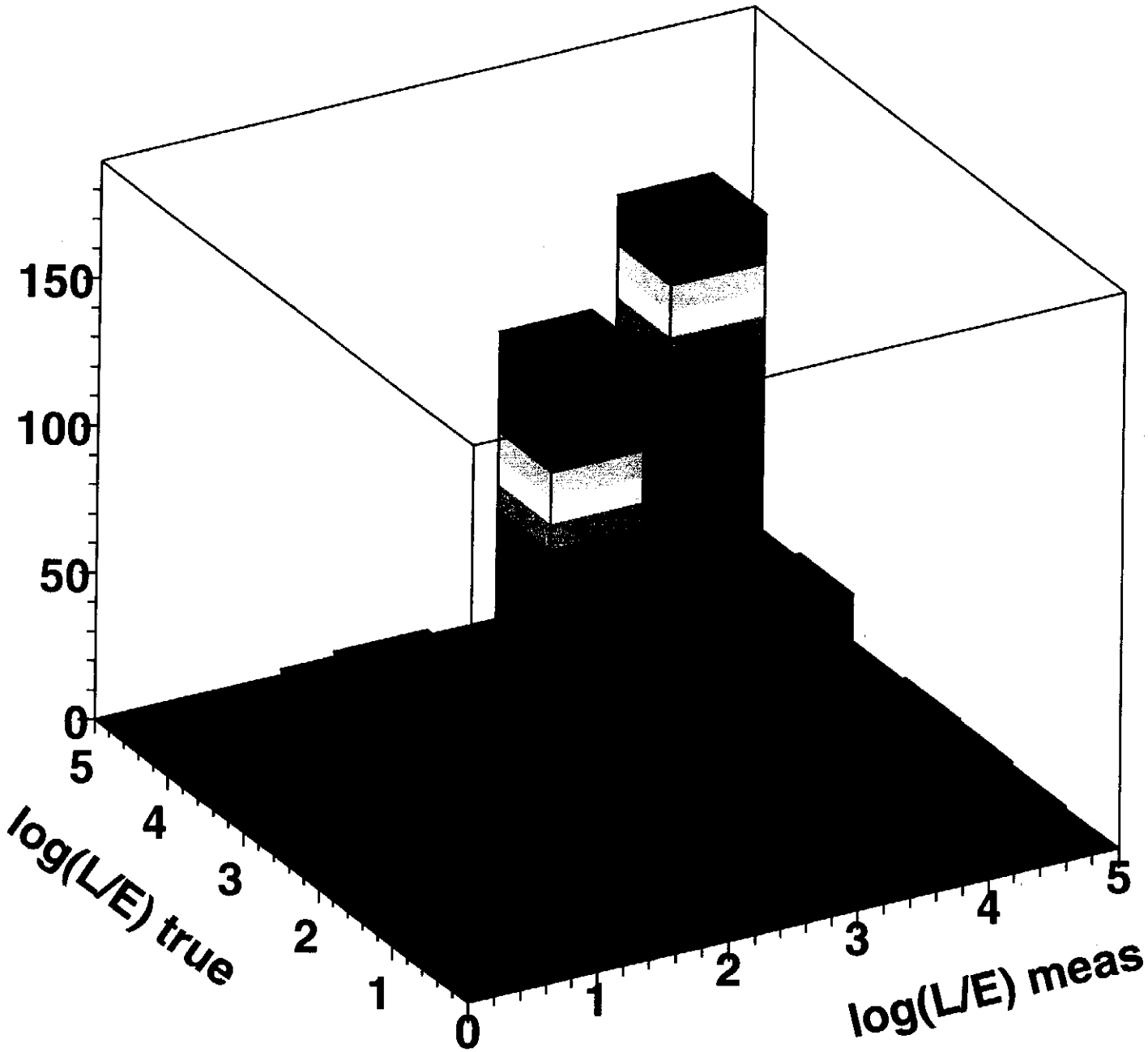
Simulate 1000 experiments, where

- n_e is Poisson with $\overline{n}_e = n_{e\_Data}$;
- n_μ is Poisson with $\overline{n}_\mu = n_{\mu\_MCosc} \times n_{e\_Data}/n_{e\_MC}$;
- choose $(L/E)_{Meas}$ according to the $(L/E)_{Meas}$ vs. $(L/E)_{True}$ MC distribution;
- calculate $\Delta\chi^2_{sim} = \chi^2_{sim} - \chi^2_{sim\_best}$ for every simulated experiment;
- find $\Delta\chi^2_{90}$ such that $\Delta\chi^2_{sim} < \Delta\chi^2_{90}$ for 90% of the simulated experiments.

Finally,

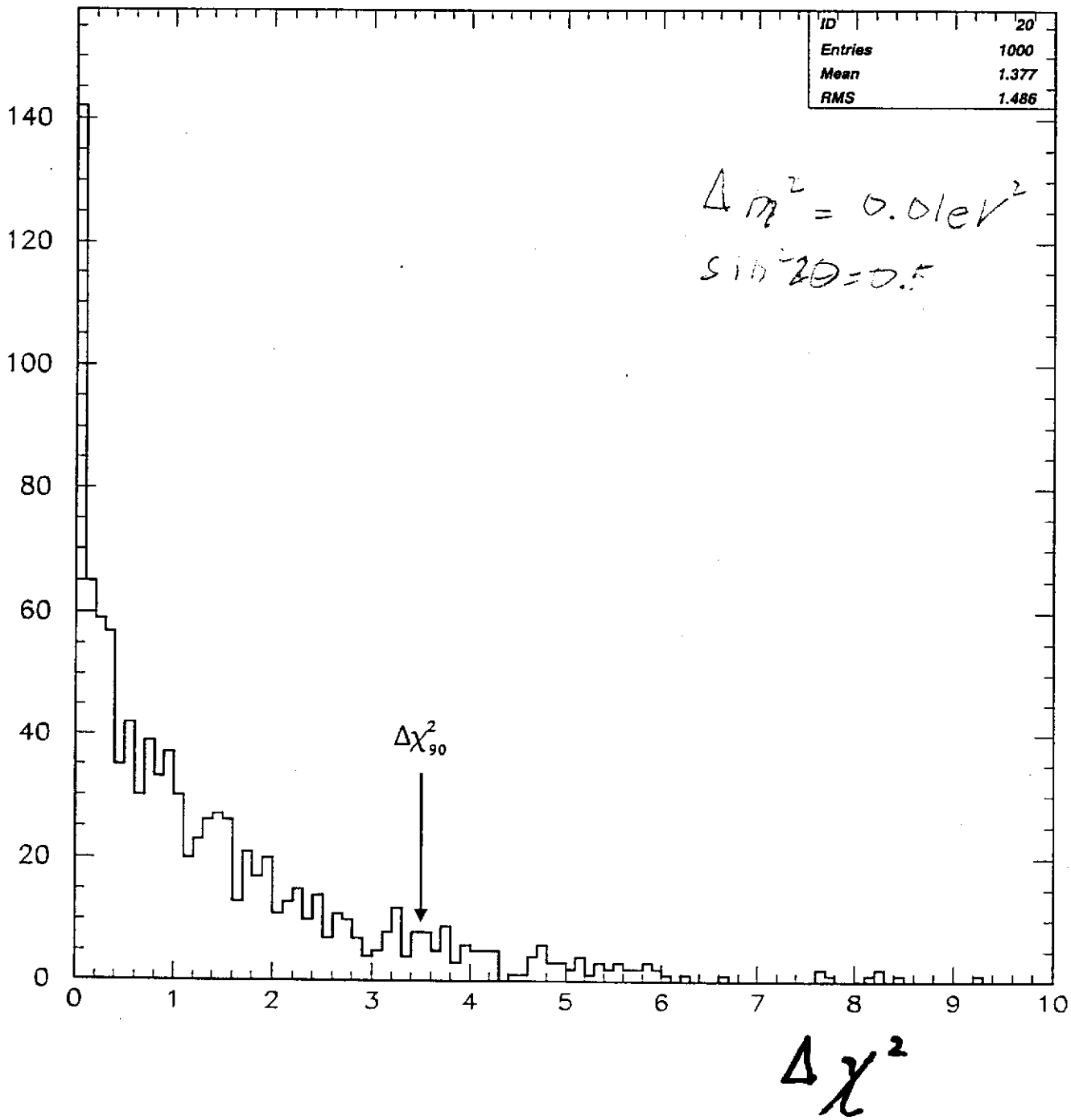
if $\Delta\chi^2_{Data} < \Delta\chi^2_{90}$, point (i, j) belongs to the allowed region of the 90% CL contour.

Soudan 2 Monte Carlo

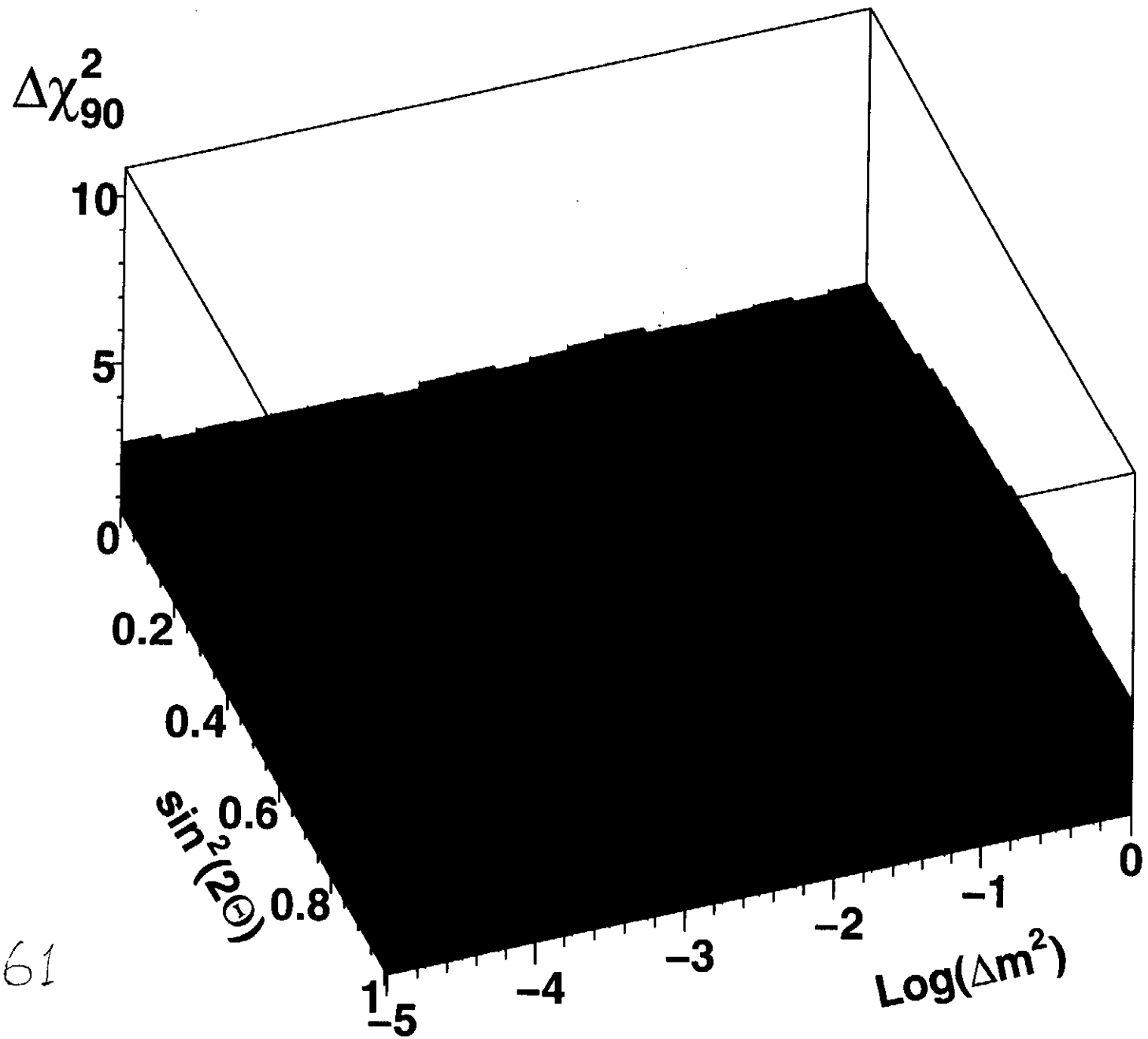


Soudan 2

1000 simulated experiments



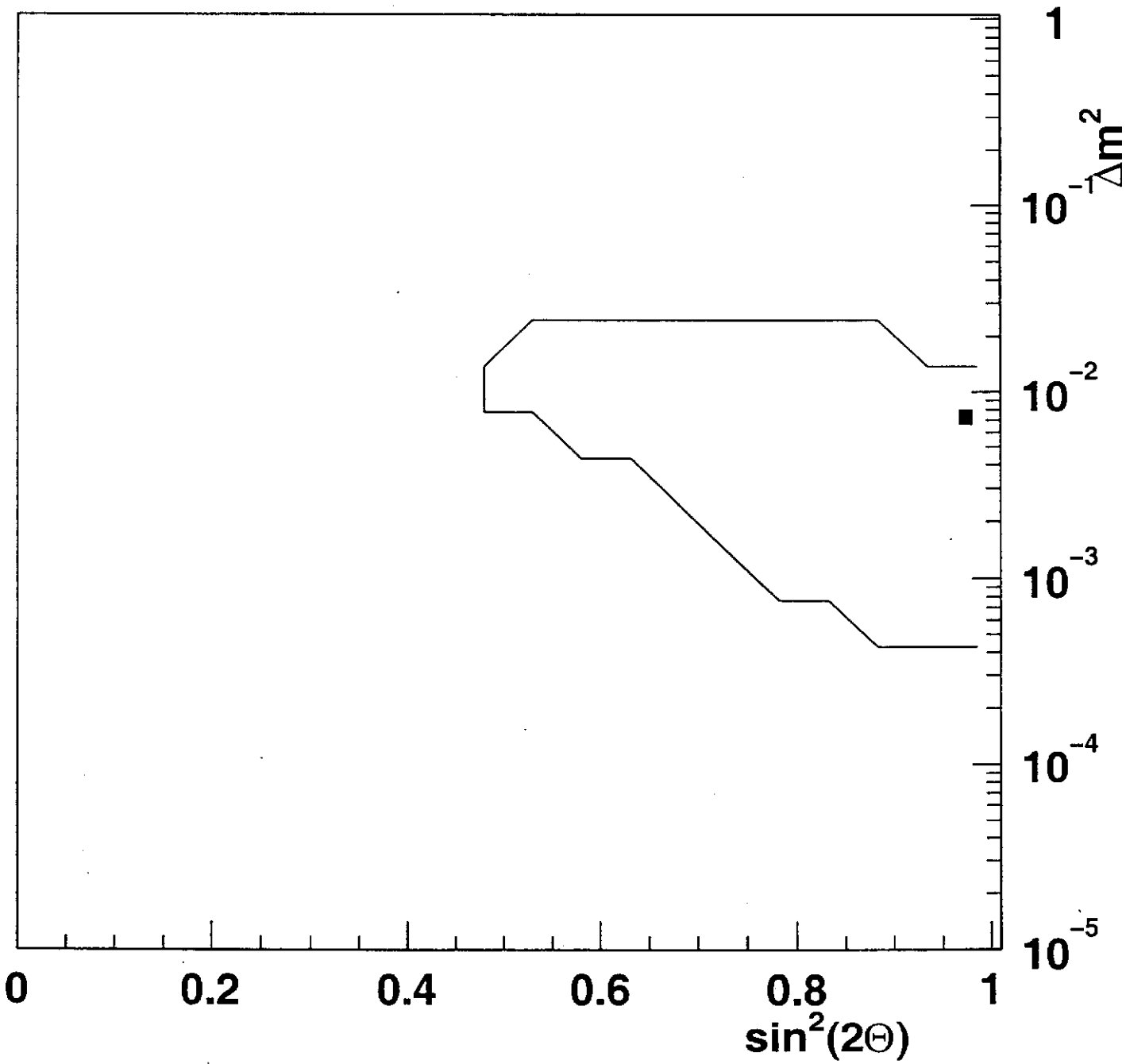
Soudan 2



$\Delta\chi^2 \neq 4.61$

Soudan 2, 4.6 kty

via Feldman & Cousins



But: 40 CPU hours!