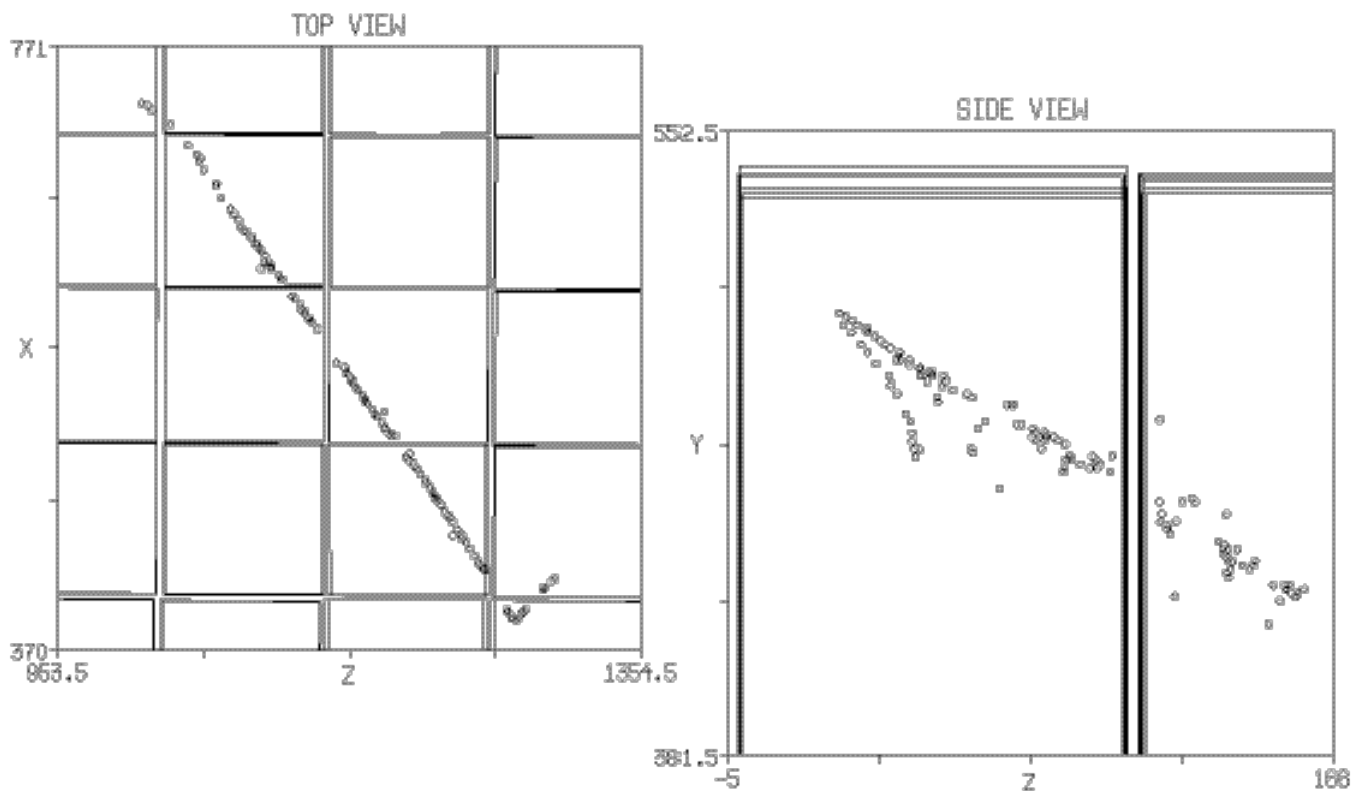


Oscillation Investigations in Soudan 2:

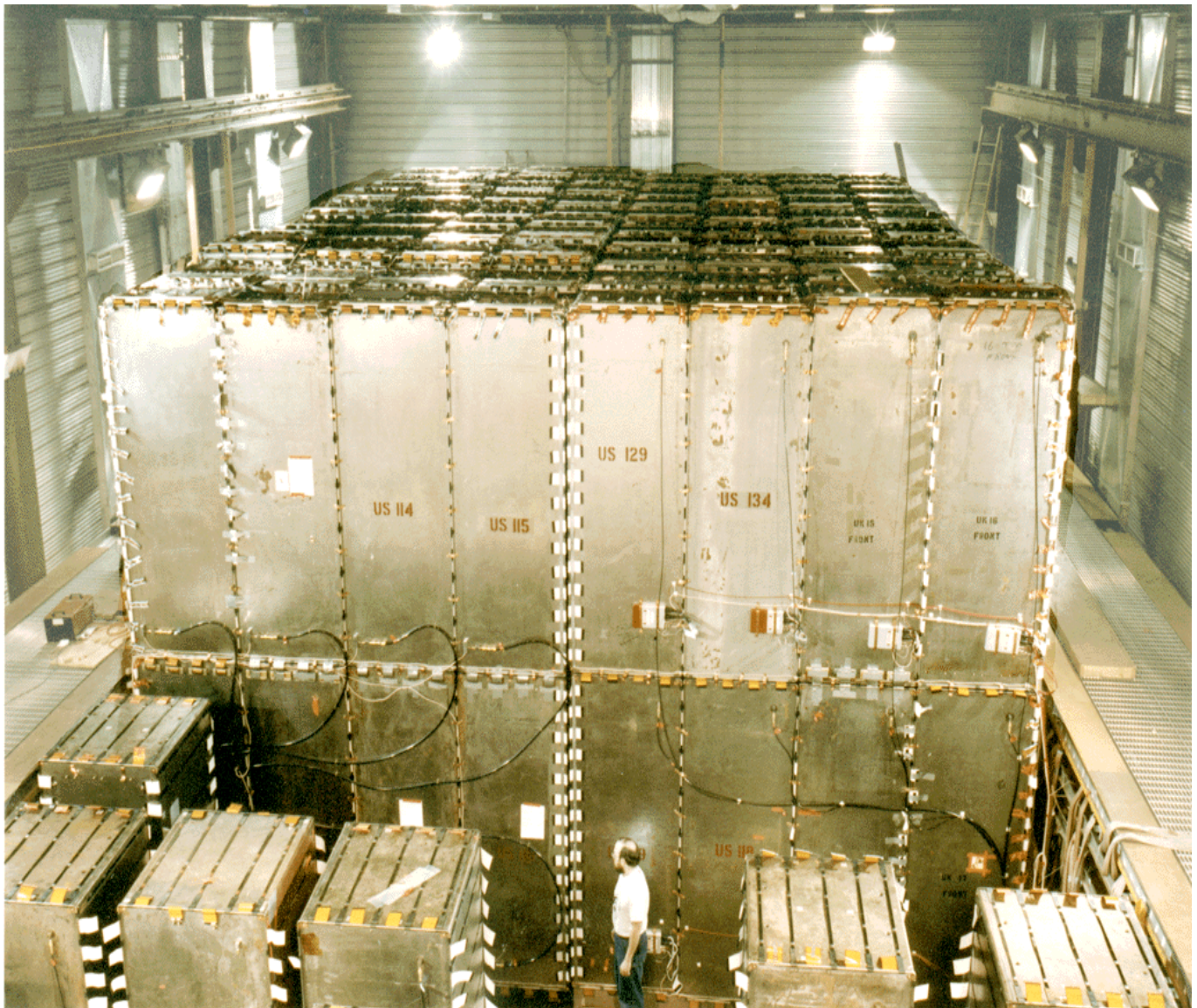
Atmospheric $\nu_{\mu} \leftrightarrow \nu_{\tau}$
and
 $n \leftrightarrow \bar{n}$ in Iron

Argonne, Minnesota, Oxford, Rutherford,
Tufts, W. Washington

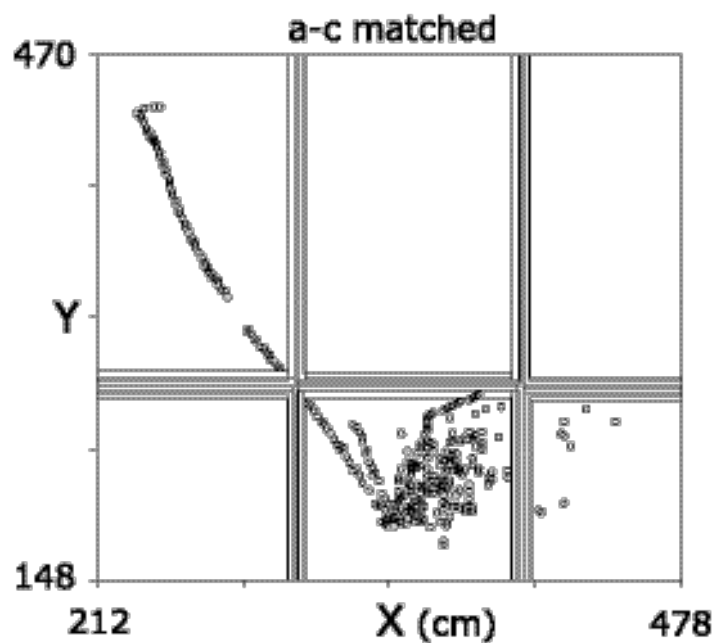
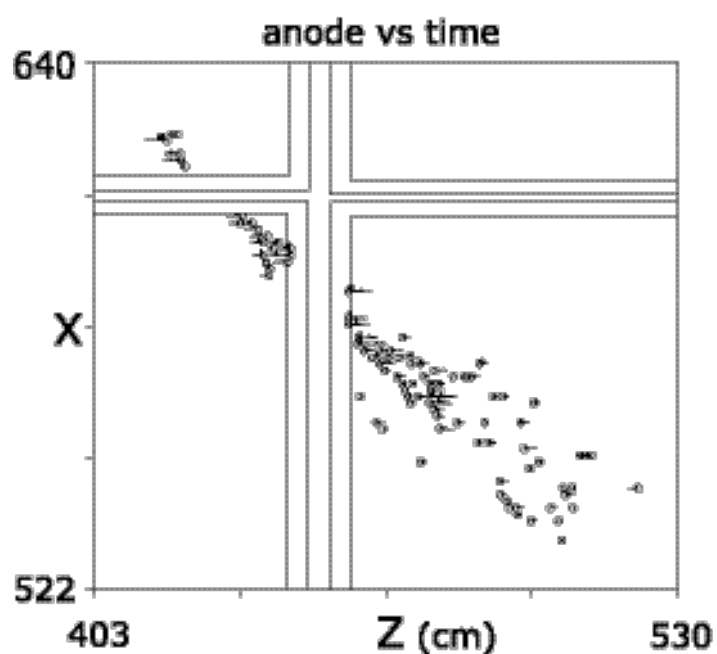
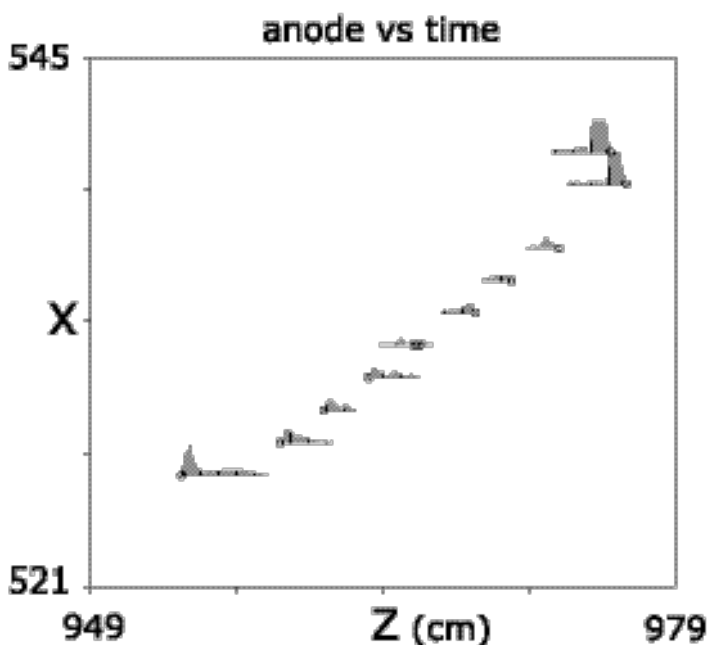
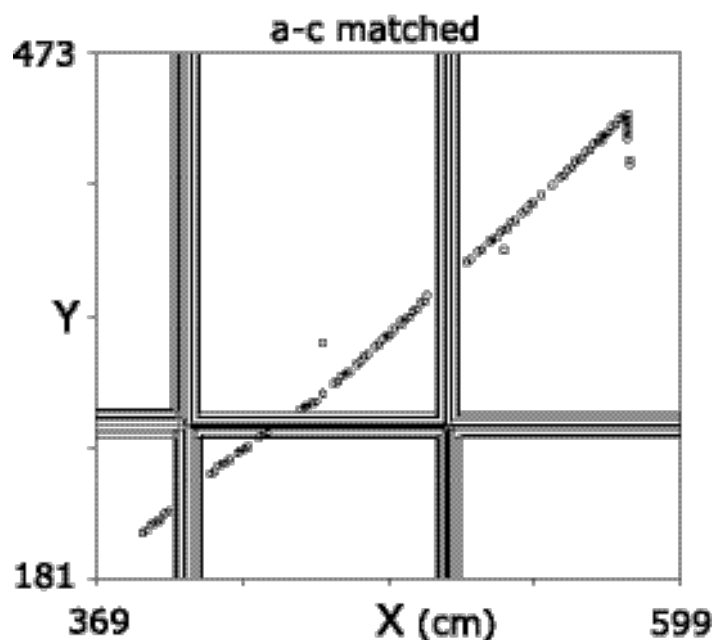


The Soudan 2 Detector:

- Soudan 2 is located in the Soudan mine in Northern Minnesota under 2100 mwe overburden.
- Data-taking: April 1989 to June 2001.
- Data exposure is 5.90 fiducial kiloton-years

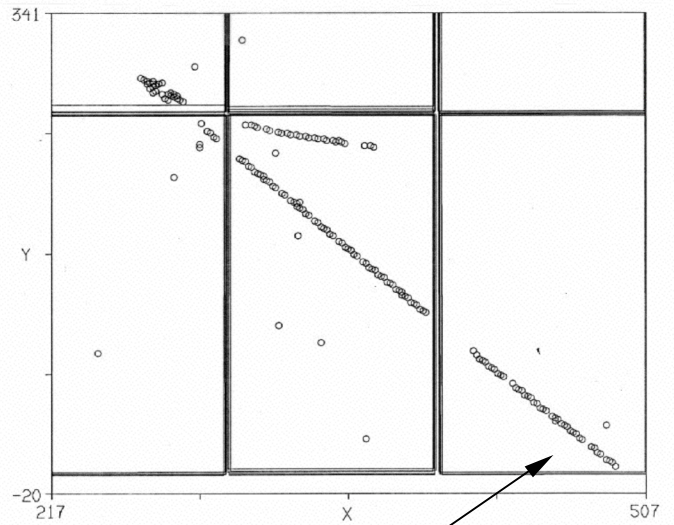
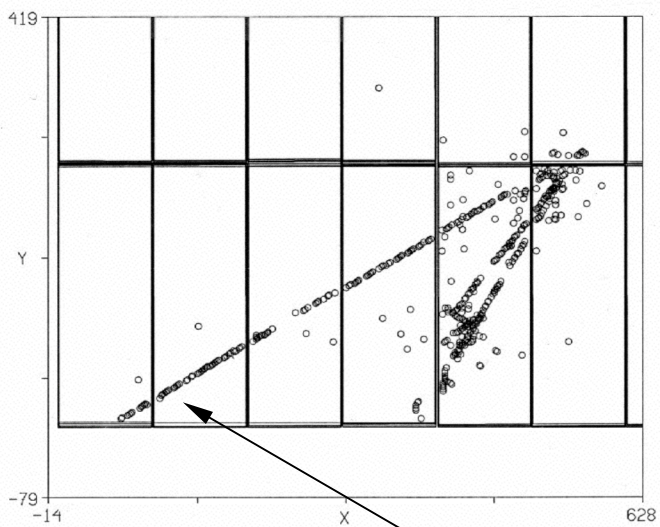
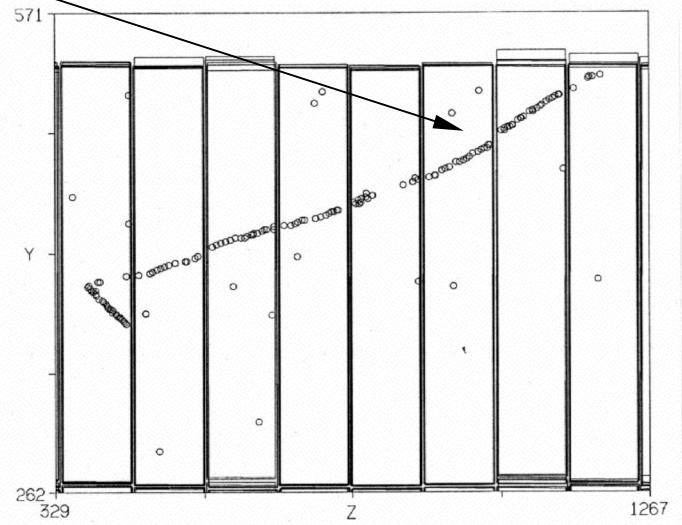
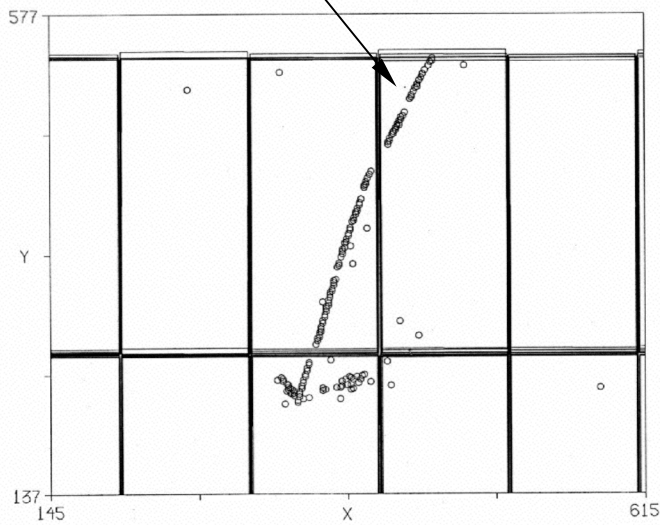


Track, Shower, Multiprongs Events in Soudan 2:



Partially contained \square events:

exiting muon



exiting muon

Neutrino data samples:

Event Category	Neutrino flavor	No. Events (bkgrd-subt'ed)
Contained, L/E $_{\mu}$ HiRes	$\bar{\nu}_{\mu}$	102.1
	ν_e	144.0
Contained, L/E $_{\mu}$ LoRes	$\bar{\nu}_{\mu}$	58.3
	ν_e	65.7
Partially Contained (ν^{\pm} exits)	$\bar{\nu}_{\mu}$	49.0
Neutral Current + ambig. flavor	-	33.3
Total Neutrino Events Analyzed		452.4

Oscillations of atmospheric neutrinos

- Neutrinos $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ originate with cosmic ray interactions in upper atmosphere.
- Neutrino flux at underground sites:
 - ν_e -flavor component at expected strength
 - BUT ν_μ flavor component diminished.
- ν_μ depletion varies with neutrino zenith angle i.e with neutrino path length L .
- ν_μ disappearance is described by

$$P(\nu_\mu \rightarrow \nu_\mu) = \sin^2(2\theta) \sin^2\left[\frac{1.27 \text{ eV}^2 L}{E_\mu}\right]$$

θ Measure $\sin^2(2\theta)$ and eV^2 .

We measure via the flavor **ratio of ratios**:

$$R = \frac{(\mu\mu \text{ like} / e\mu \text{ like})_{DATA}}{(\mu\mu \text{ like} / e\mu \text{ like})_{MC}} \quad \begin{array}{l} \text{MC} = \text{null osc.} \\ R = 1.0 \text{ if no osc.} \end{array}$$

- Use all contained events having identified flavor (multiprongs events now included).

$$R_{\text{raw}} = 0.73 \pm 0.10$$

- De-convolve using **Flavor Identification**

Matrix:

	μ	e	“NC”
μ_{μ}	1466	46	76
μ_e	67	1337	72
NC	123	111	77

$$R_{\mu_{\mu}/\mu_e} = 0.68 \pm 0.12$$

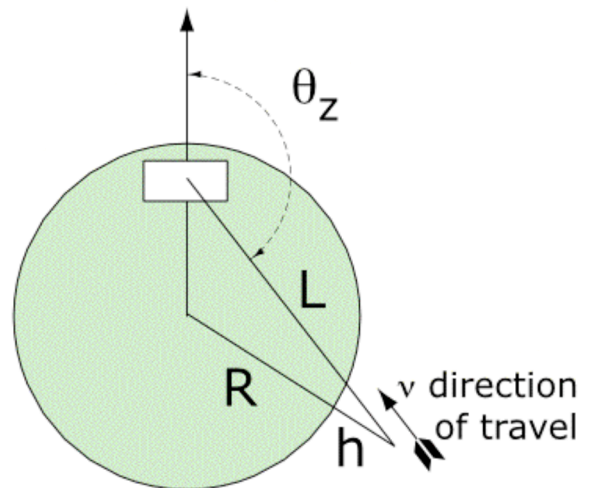
Dependence on L/E_ν :

- Neutrino energy E_ν : For charged current interactions, we reconstruct E_ν from final state track and shower prongs.

	ν_μ CC	ν_e CC
$\sigma(E/E)$	20%	23%

- Neutrino path length L :

We reconstruct the neutrino zenith angle θ_z and calculate:



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

Good θ_z , L determination when:

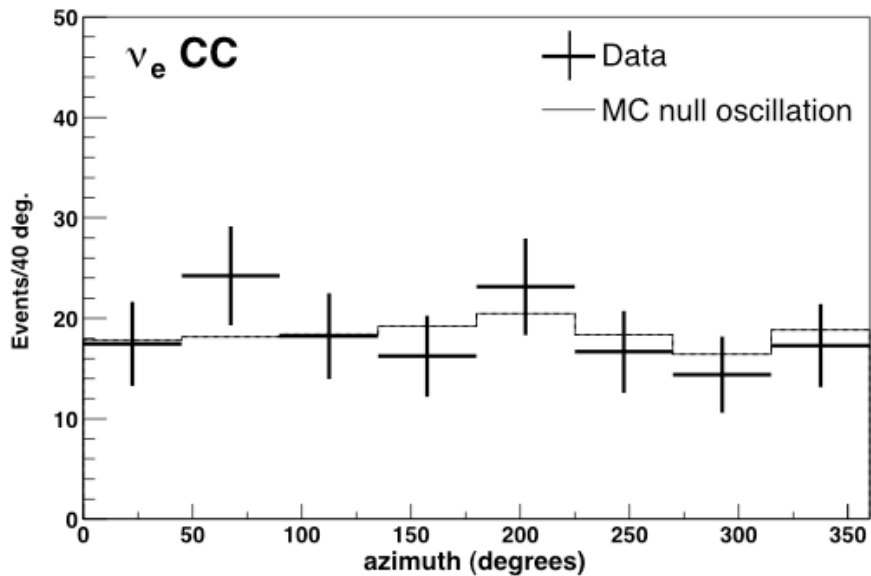
- 1) Lepton energy is high,
and/or
- 2) recoil hadronic system is imaged.

Lepton Energy (MeV)	0-200	200-400	400-600	>600
θ_z -lepton (degrees)	$\sim 90^\circ$	75°	49°	28°
θ_z (lepton+proton) (degrees)	30°	23°	15°	8°

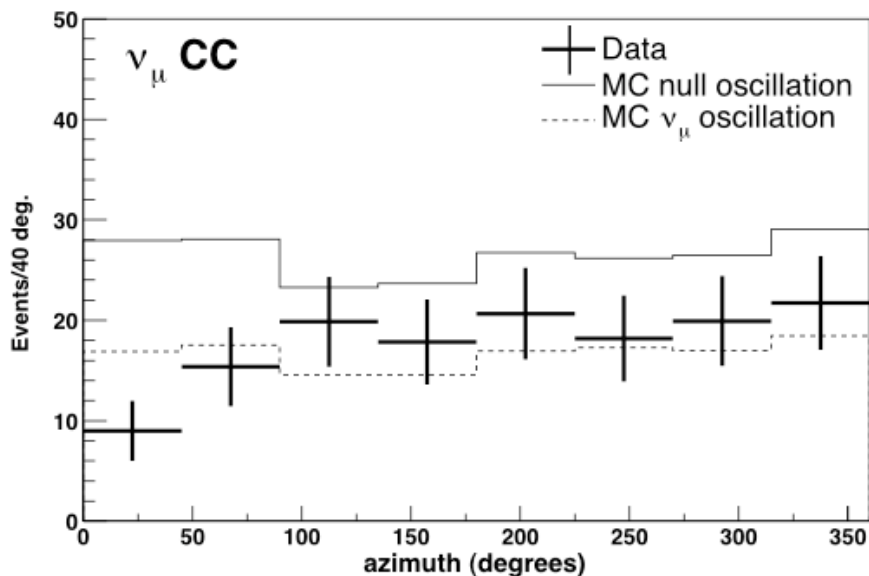
- We define a “High Resolution” sample:
 - High energy quasi-elastics
 - Low energy quasi-elastics with proton
 - High energy multiprongs

Neutrino azimuthal angle:

- Observe azimuthal symmetry for both ν_e and ν_μ fluxes - as expected.

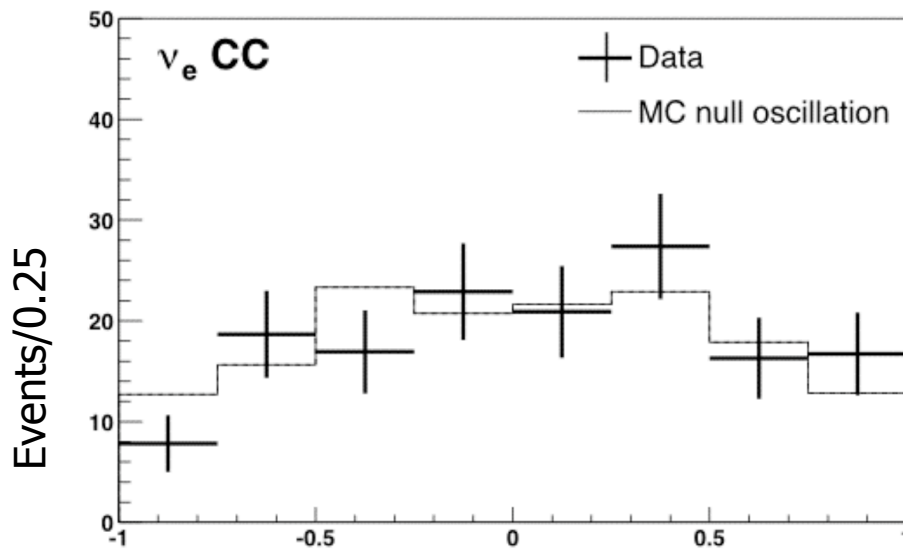


- The ν_μ is uniformly depleted relative to null oscillation expectation.

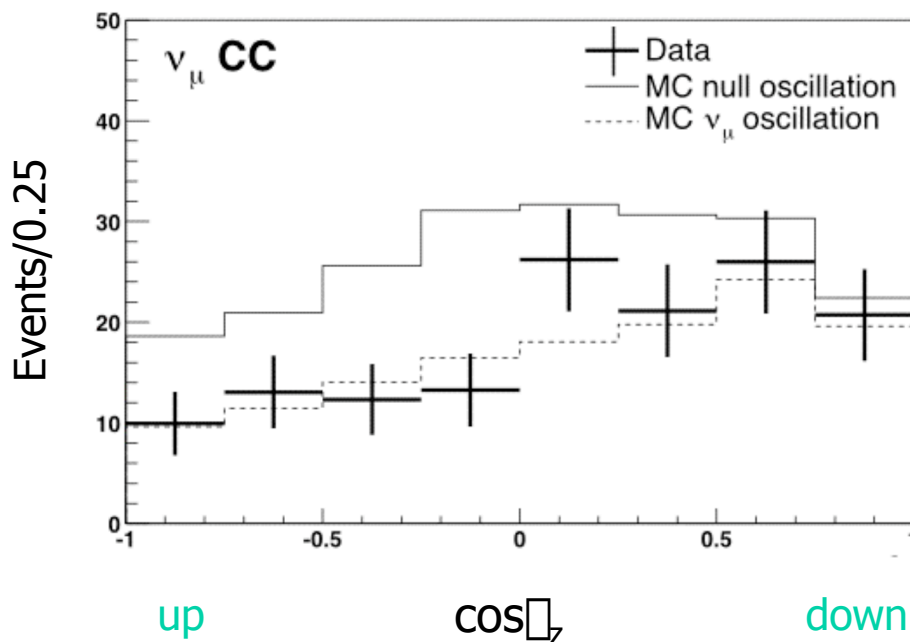


Neutrino zenith angle:

- ν_e flux follows null oscillation expectation.

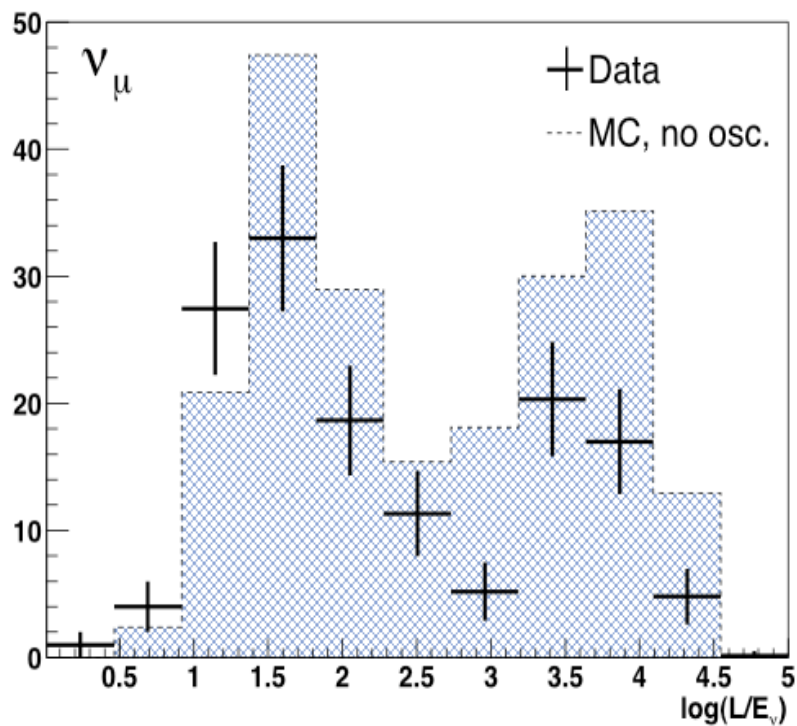
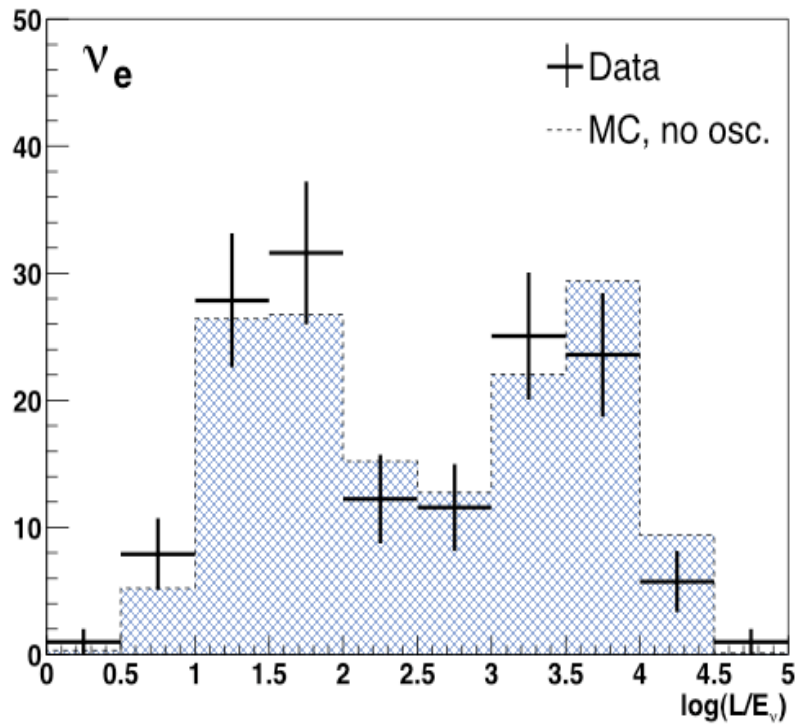


- ν_μ disappearance:



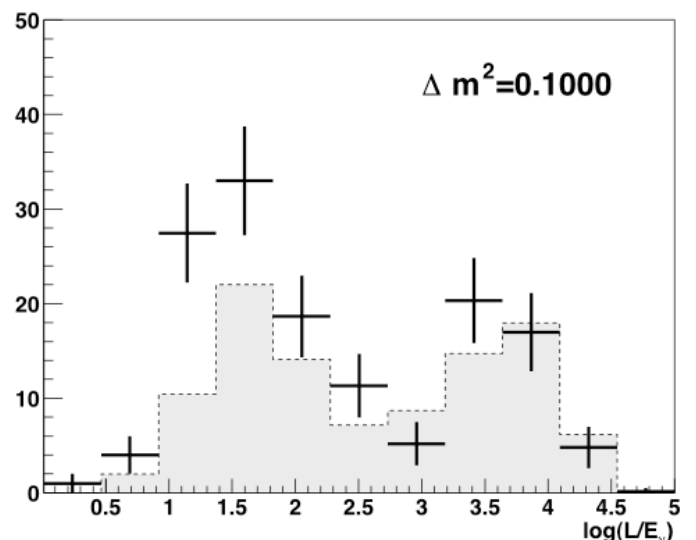
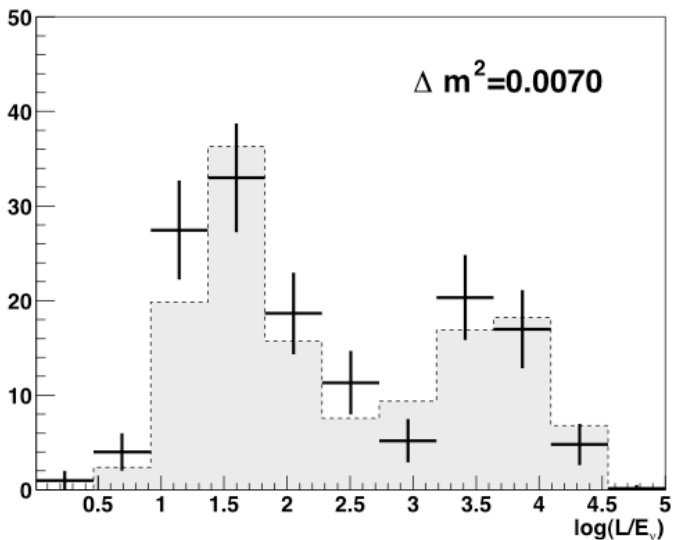
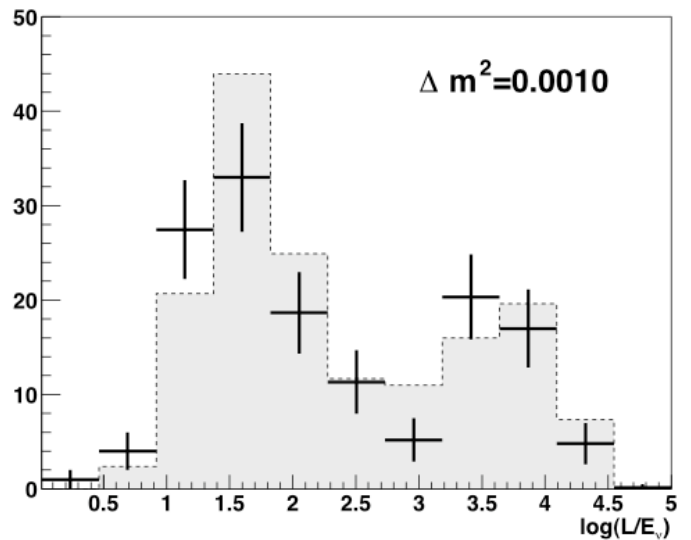
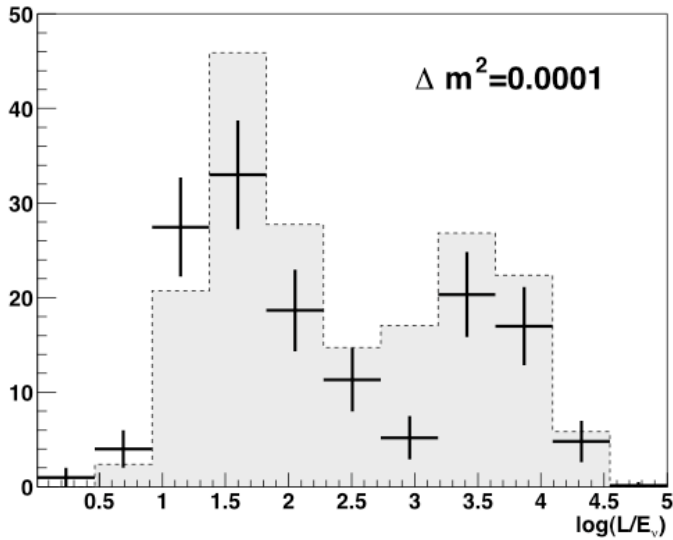
L/E_{ν}

Data versus null oscillations



L/E_{ν} :

ν_{μ} -data vs. oscillation hypotheses



Feldman-Cousins analysis:

We assume $\theta_{\mu} \ll \theta_{\nu}$; θ_e is unaffected.

For points (i, j) over the physical region of the $(\sin^2(2\theta)_{\mu}, \log_{10} \theta_{\nu}^2)$ plane, we fit the oscillation expectation to our data at each point using Maximum-Likelihood:

$$(\mathcal{L}_{\text{data}})_{ij} = \mathcal{L}(\sin^2(2\theta)_{\mu}, \log_{10} \theta_{\nu}^2; f_{\mu})$$

where $f_{\mu} = \theta_{\mu}$ flux normalization (Bartol '96 atm. flux).

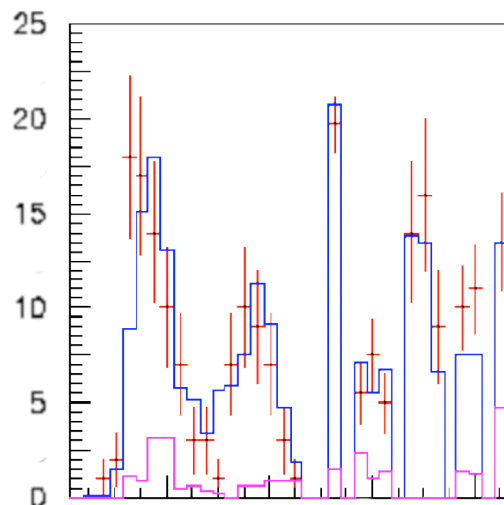
We find $(\mathcal{L}_{\text{data}})_{\text{min}}$, and plot:

$$(\Delta \mathcal{L}_{\text{data}})_{ij} = (\mathcal{L}_{\text{data}})_{ij} - (\mathcal{L}_{\text{data}})_{\text{min}}$$

The likelihood function includes:

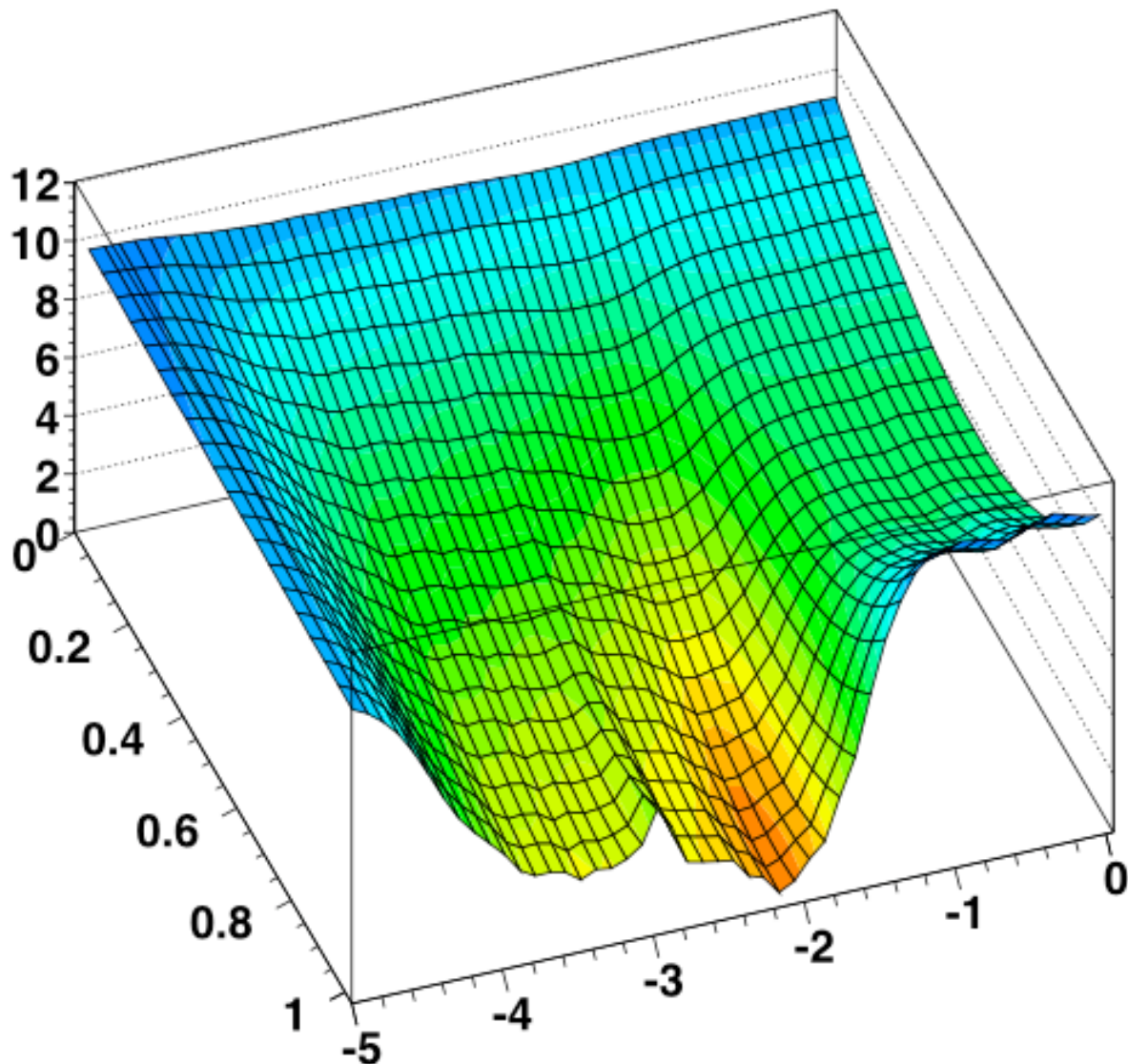
L/E_{μ} for contained HiRes μ_{μ}	20 bins
L/E_{μ} for partially contained μ_{μ}	5 bins
Rate for contained μ_e	1 bin
L/E_{μ} for LoRes track events	3 bins
Rate for LoRes multiprong events	1 bin
Rate for NC/flavor ambig. events	1 bin

Schematically μ



\mathcal{L} surface over the
 $(\sin^2(2\phi), \phi^2)$ plane:

Flux normalization f_ϕ is allowed to
adjust at each point.

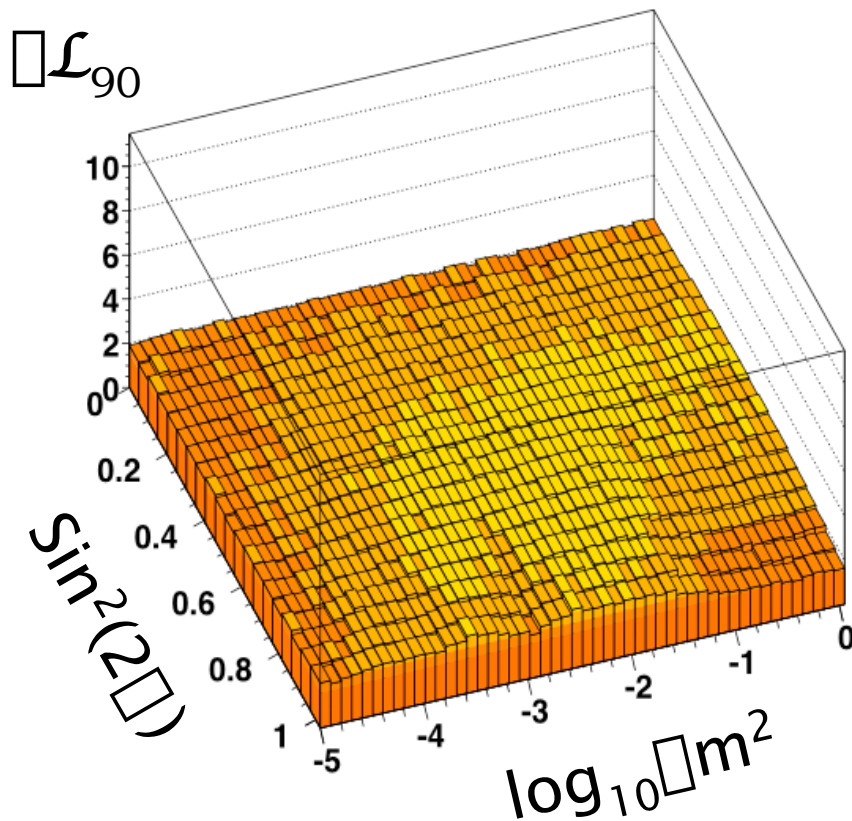


Feldman-Cousins procedure to find 90% confidence level region:

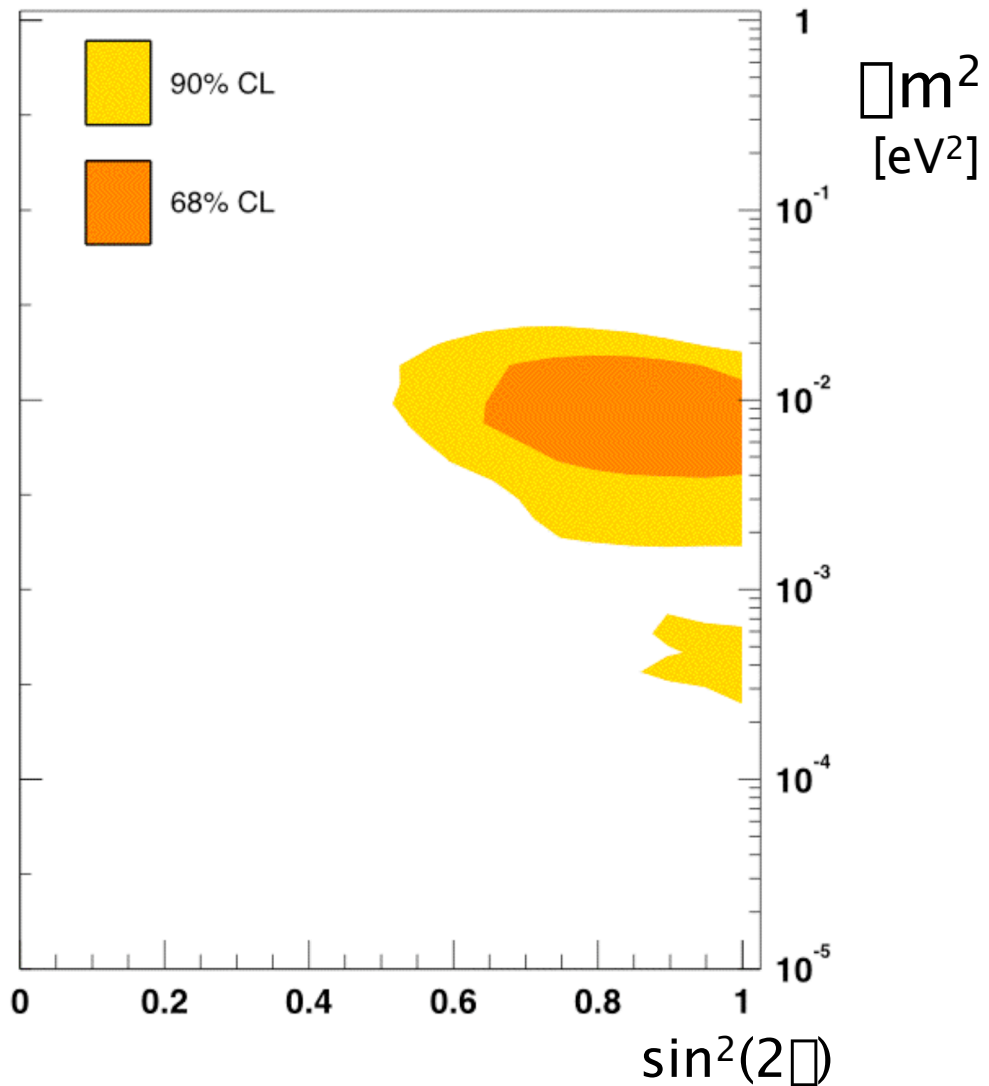
At each of 2000 points $(i, j) = (\sin^2(2\theta)_i, \log_{10}\sigma m^2_j)$ in the physical region, we run 1000 simulated experiments.

We find $(\Delta\mathcal{L}_{90})_{ij}$ such that $(\Delta\mathcal{L}_{\text{sim}})_{ij} < (\Delta\mathcal{L}_{90})_{ij}$ for 90% of the experiments at (i, j) .

The surface defined by local $\Delta\mathcal{L}_{90}$ over the oscillation parameters plane:



Oscillation parameters allowed region: (Feldman-Cousins)



Best Fit:

$$\Delta m^2 = 0.007$$

$$\sin^2 2\theta = 0.98$$

$$f_{\chi^2}(\text{data/MC}) = 0.90$$

MC χ^2 Bartol '96 flux

$$\chi^2/\text{dof} = 33.2/28$$

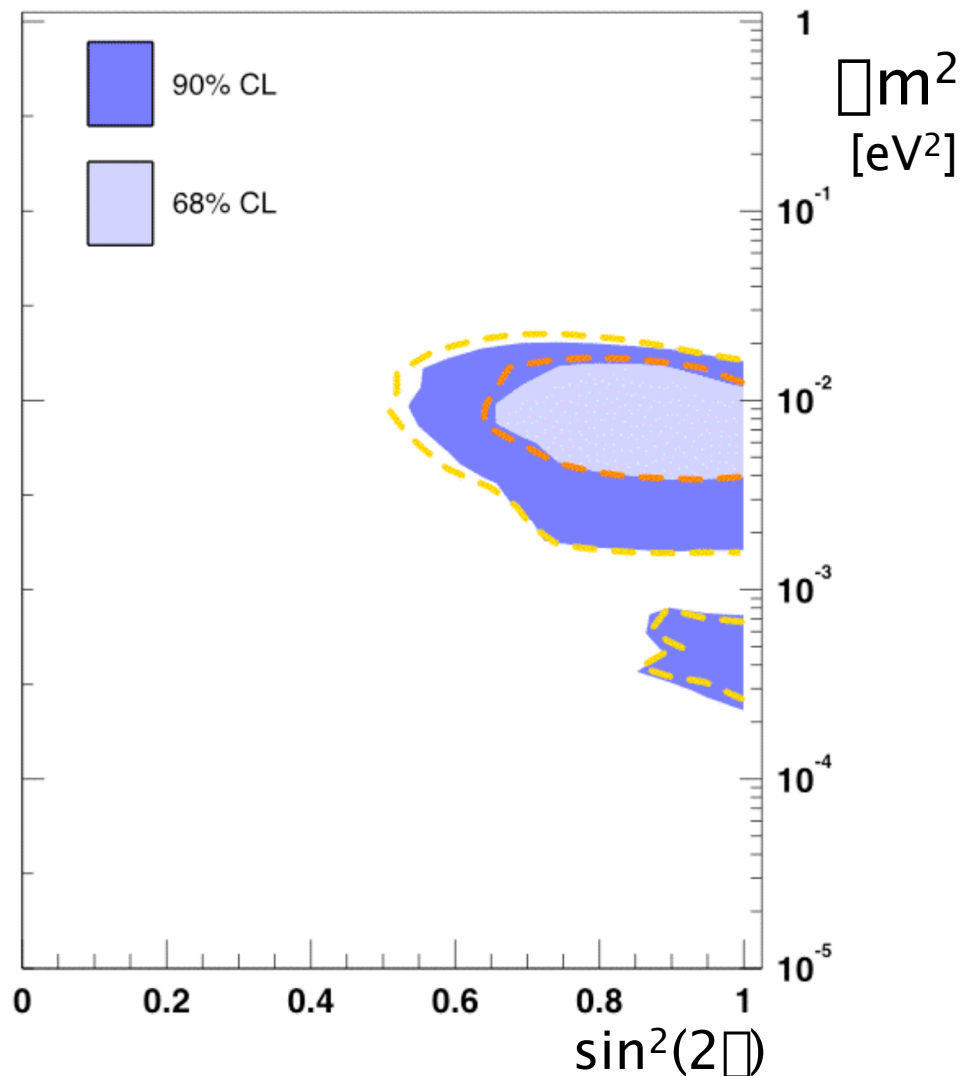
Bartol '96 flux \square Battistoni 3D flux

Results based on \square flux calculation using 1-dimensional model atmosphere.

We have also fitted using Battistoni et al. neutrino flux based on 3-dimensional model atmosphere.

- Main differences are:
 - Overall flux normalization for 3D model is lower.
 - Use of FLUKA (Battistoni) vs. TARGET (Bartol) for hadronic processes.
 - Flux shape: The 3D atmospheric flux peaks near the horizon; the effect is dramatic at few-hundreds MeV neutrino energies.

Allowed region using 3D atmospheric flux calculation:



Best Fit:

$$\Delta m^2 = 0.007$$

$$\sin^2 2\theta = 0.98$$

$$f_{\chi^2}(\text{data}/\text{mc}) = 1.05$$

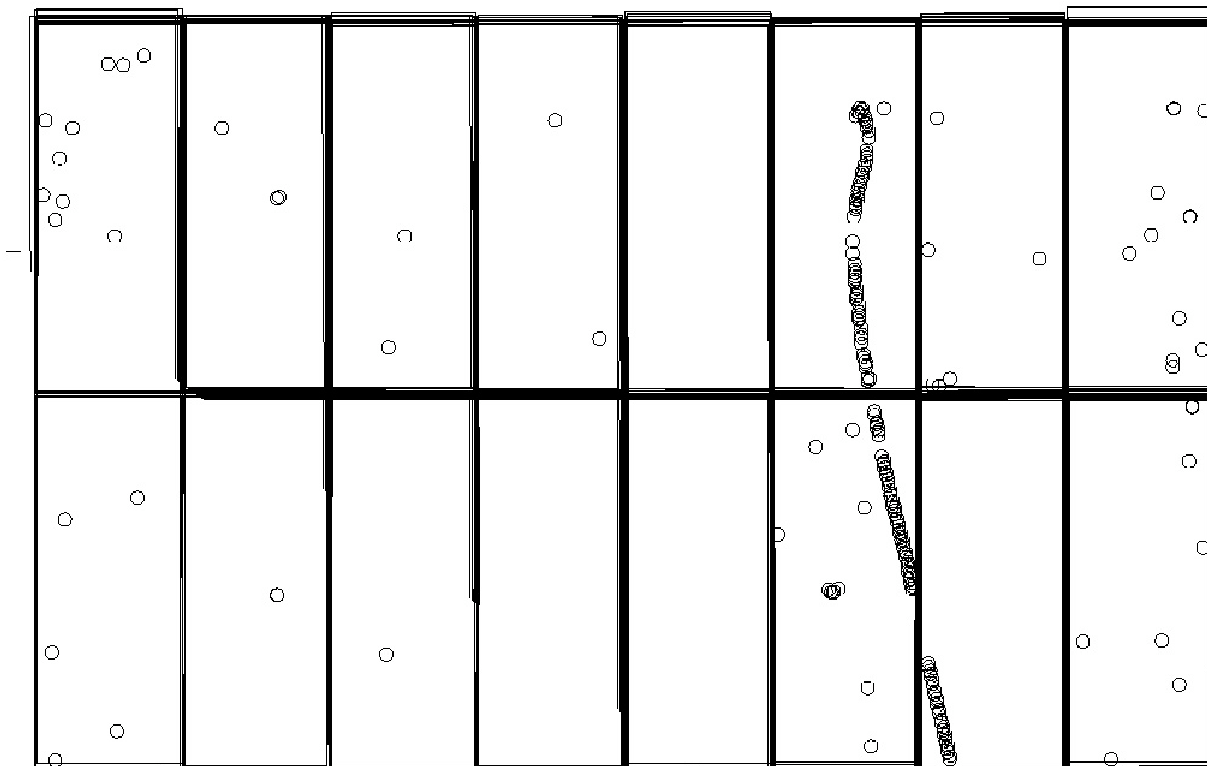
MC χ^2 Battistoni '02

$$\chi^2/\text{dof} = 34.7/28$$

Upward stopping muons

- We have isolated a data sample of upward range-to-stopping muons containing 40 events.
- A realistic Monte Carlo for neutrino production of this is in preparation.
- We hope to include these events in a future analysis.

FRONT VIEW



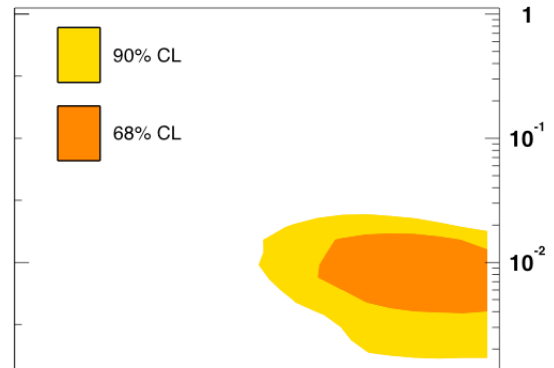
- Allowed region and best fit values are robust with respect to exchange of Bartol 1D and Battistoni 3D atmospheric neutrino flux calculations:

□artol '96

$$\square m^2 = 0.007 \text{ eV}^2$$

$$\sin^2 2\square = 0.98$$

$$f_{\square} = 0.90$$

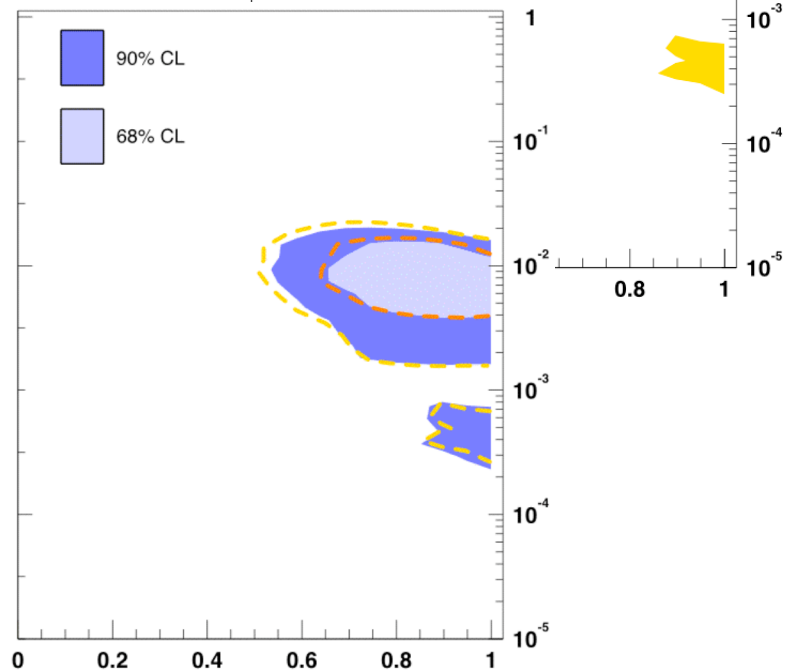


□attistoni '02

$$\square m^2 = 0.007 \text{ eV}^2$$

$$\sin^2 2\square = 0.98$$

$$f_{\square} = 1.05$$

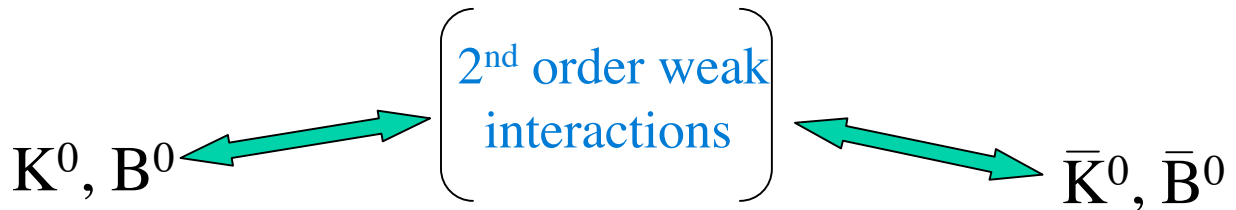


We've mostly done what we can do...

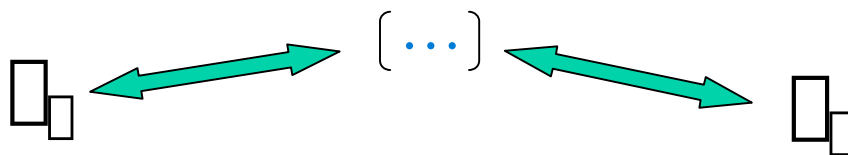
Onward with MINOS !

$n \leftrightarrow \bar{n}$ transitions — “too crazy”?

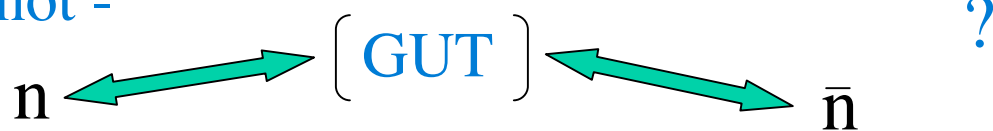
But neutral meson $lq\bar{q}$ states oscillate -



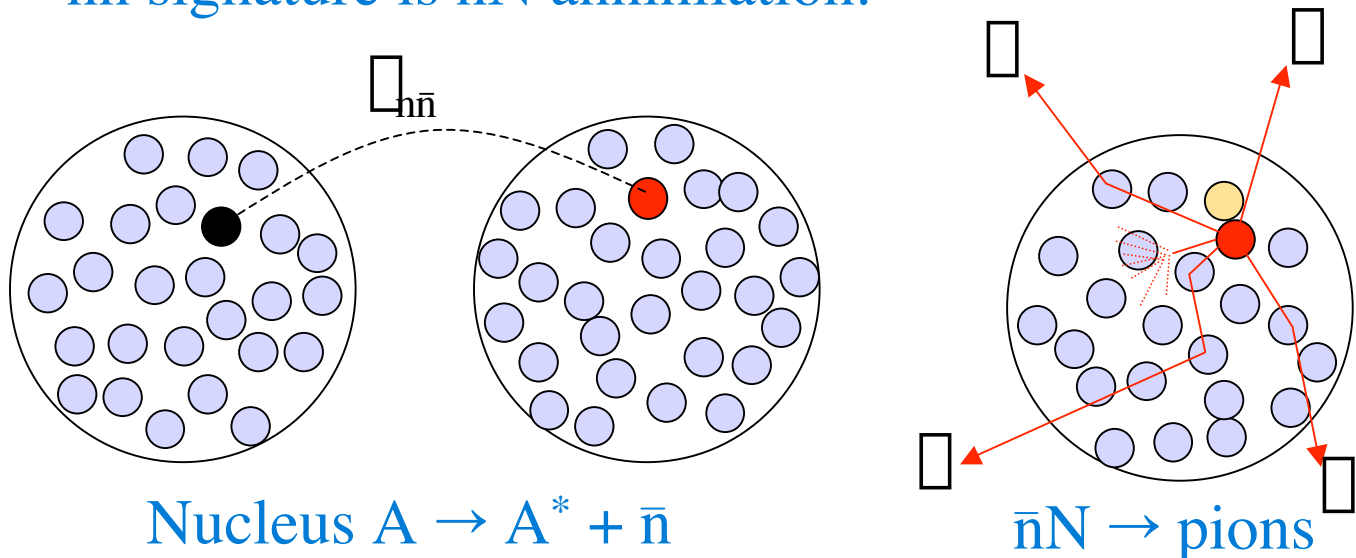
And neutral fermions can oscillate too -



So why not -



$n\bar{n}$ signature is $\bar{n}N$ annihilation:



Neutron oscillation time:

$$\tau_{n\bar{n}} = \sqrt{\frac{T_A}{T_R}}$$

Lower limits for T_A and $\tau_{n\bar{n}}$ previously obtained by many underground expt's - Homestake, NUSEX, KOLAR, IMB, Kamiokande, Frèjus.

New Soudan 2 measurement

J. Chung et al., Phys. Rev. **D** 66, 032004 (2002)
offers

- i) Modest refinements to expt'l approach,
 - ii) Modest improvement in oscillation time limits for T_A and $\tau_{n\bar{n}}$,
 - * iii) Evidence for an irreducible neutrino background $\sim (0.7 \mu\text{-multiprongs})/(\text{kiloton-year})$.
- Implications for future searches - underground vs reactor neutron beam.

Simulation of $\bar{n}N$ annihilation in iron nuclei

Considerations for coding an $\bar{n}N$ generator:

- Assign initial state \bar{n} and $N = n$ or p momenta in accord with Fermi motion.
- $\bar{n}N$ reactions weighted according to cross section data for $\bar{p}p$, $\bar{p}d$ annihilation at rest.
- Generate secondary decays for π^0 , π^0 , π^0 , π^0 ... according to known branching ratios.
- Include pion IntraNuclear reScattering processes (INS). For pions born in Fe, probable fates are-

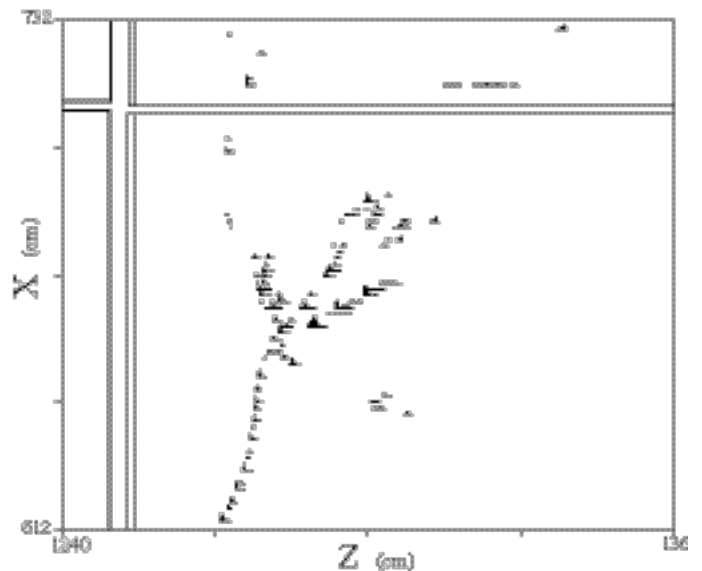
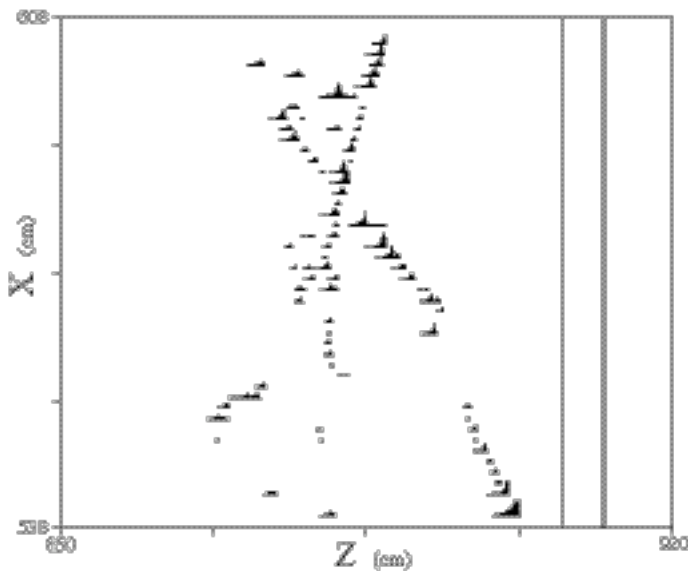
No scatter or elastic scatter:	45%
Inelastic scatter:	16%
Charge exchange:	9%
→ Absorption:	30%

$\bar{n}N$ events are fed to the detector Monte Carlo for simulation of particle tracking, detector noise, and electronic response. Events then subjected to the same processing chain as for data events.

For the primary simulation -

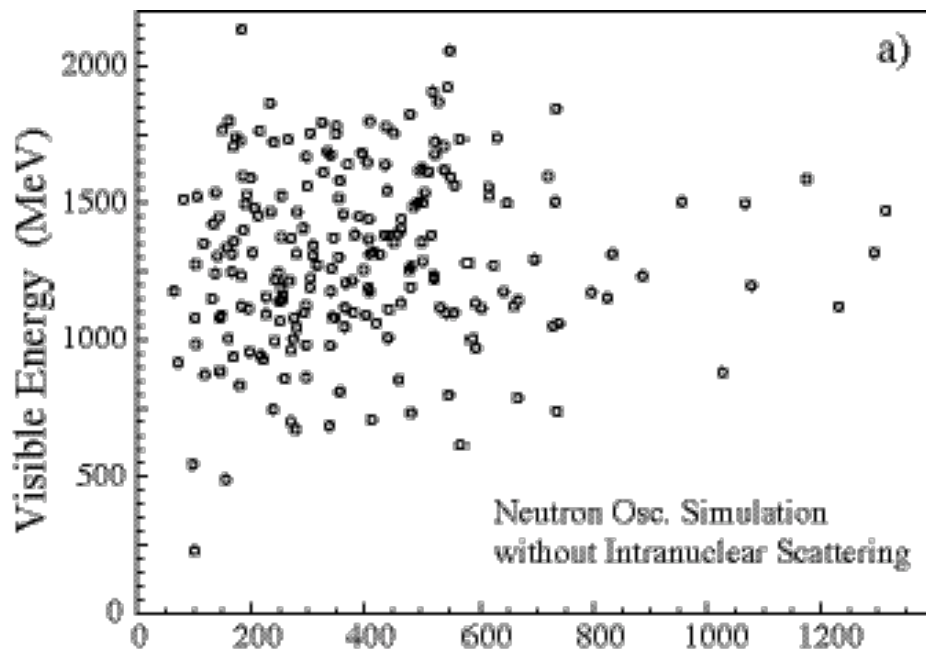
	emerge from nucleus	after all processing
□meson multiplicity□	3.8	—
□prong multiplicity□	5.0	4.8

Scan views (magnified) of two $\bar{n}N$ events:

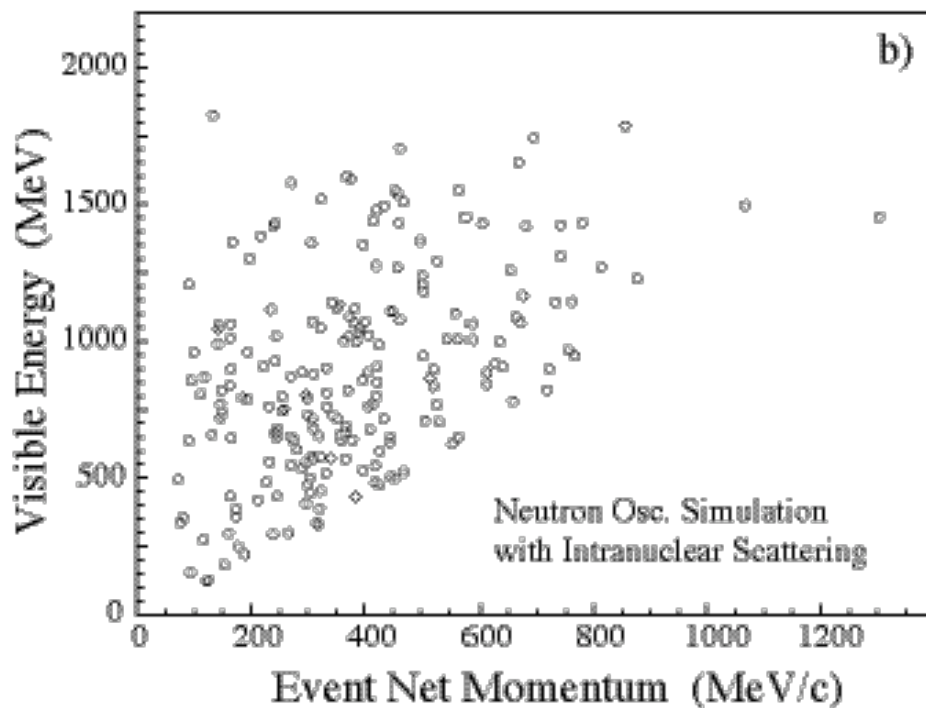


$\bar{n}N$ in the Soudan 2 calorimeter - Effect of pion intranuclear rescattering:

Without
INS \leftrightarrow



With
INS \leftrightarrow



How to distinguish $n \rightarrow \bar{n} \rightarrow \bar{n}N$ from atmospheric neutrino events?

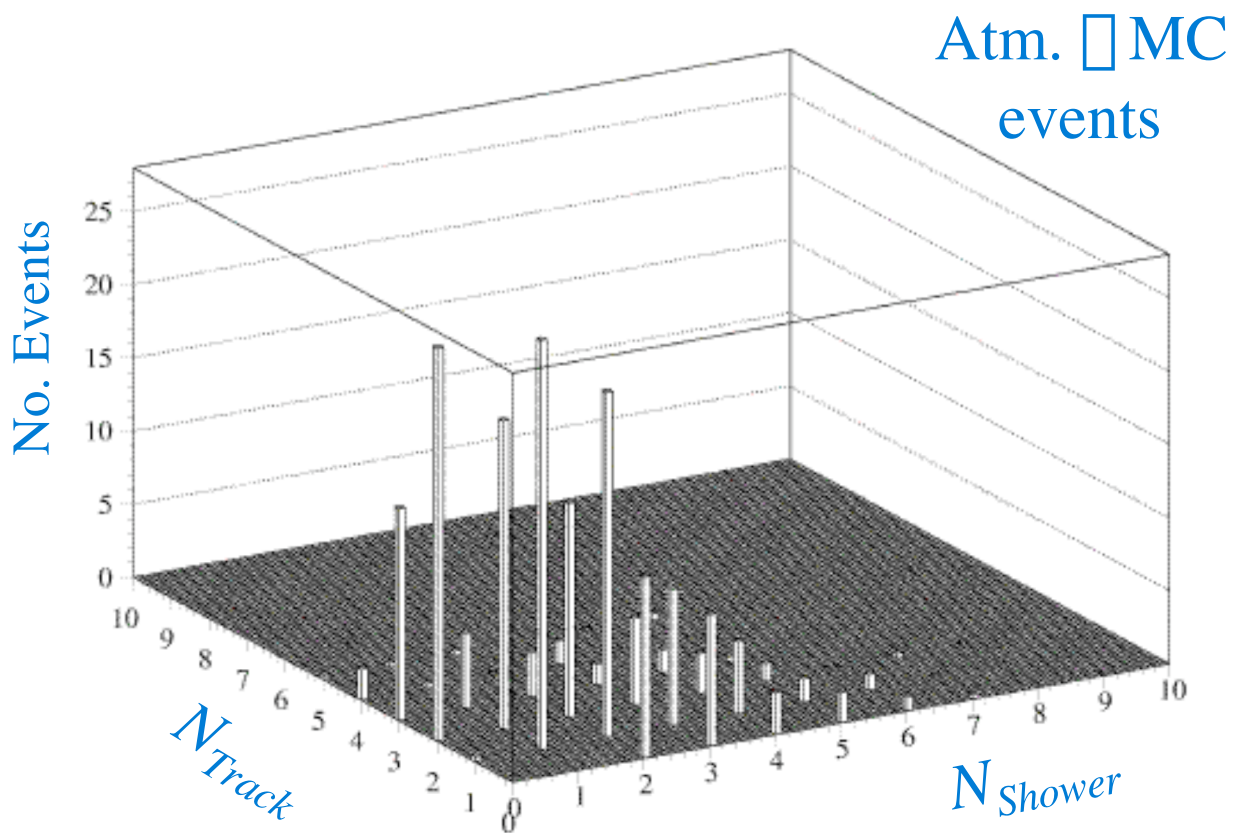
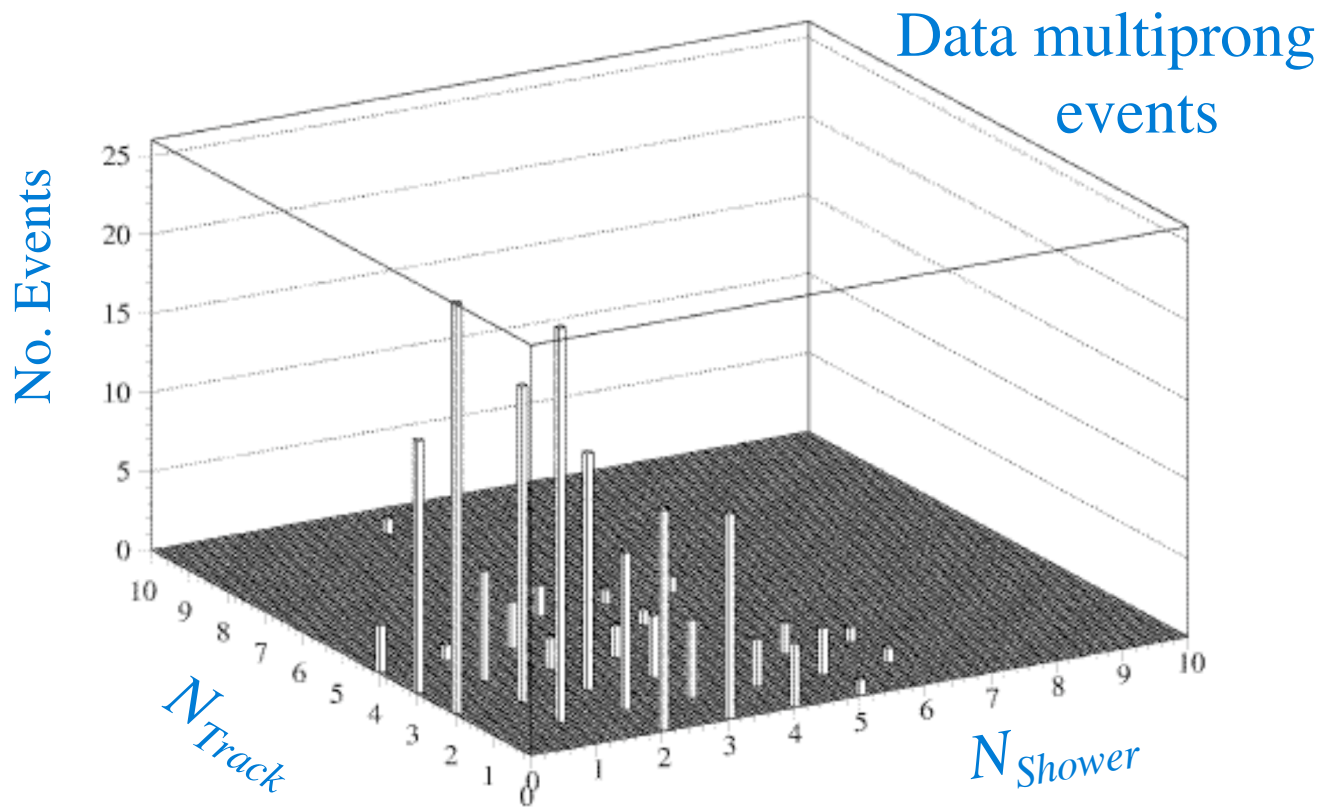
From $\bar{n}N$ simulations and knowledge about neutrino interactions, we note -

- i) $\bar{n}N$ yields energetic, isotropic events.
- ii) $\bar{n}N$ yields relatively high prong multiplicities.
- iii) $\bar{n}N$ does not produce primary protons of momenta above tracking threshold.
- iv) $\bar{n}N$ does not produce prompt leptons i.e. no leading muon tracks.

To formulate kinematic separation of $\bar{n}N$ from $\bar{\nu}N$, we rely upon our atmospheric neutrino Monte Carlo:

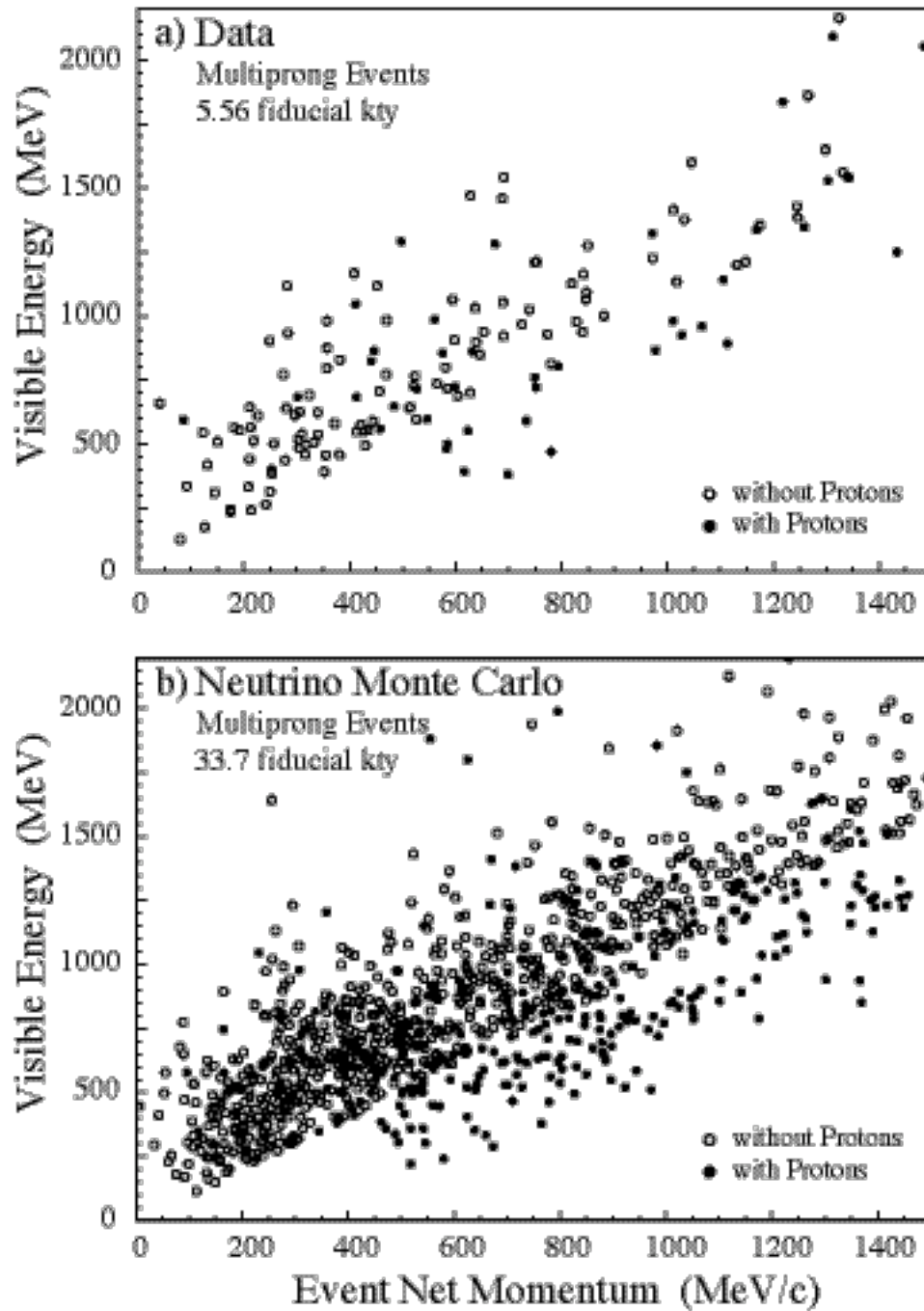
NEUGEN with Bartol '96 atm. $\bar{\nu}N$ flux.

Event topology distributions:



E_{vis} versus P_{net} distributions:

Data compared to atm. neutrino Monte Carlo



$n \leftrightarrow \bar{n}$ candidate criteria

- 1) Require prong multiplicity (tracks+showers)

$$N_{prong} \geq 4.$$

- 2) Exclude events with primary proton tracks (~24% of atm. neutrino events have visible recoil protons).

- 3) Exclude events having a non-scattering “muon” track > 150 cm (hadronic interaction length = 80 cm; mitigates against \square_{\square} CC events).

- 4) Event kinematics - require

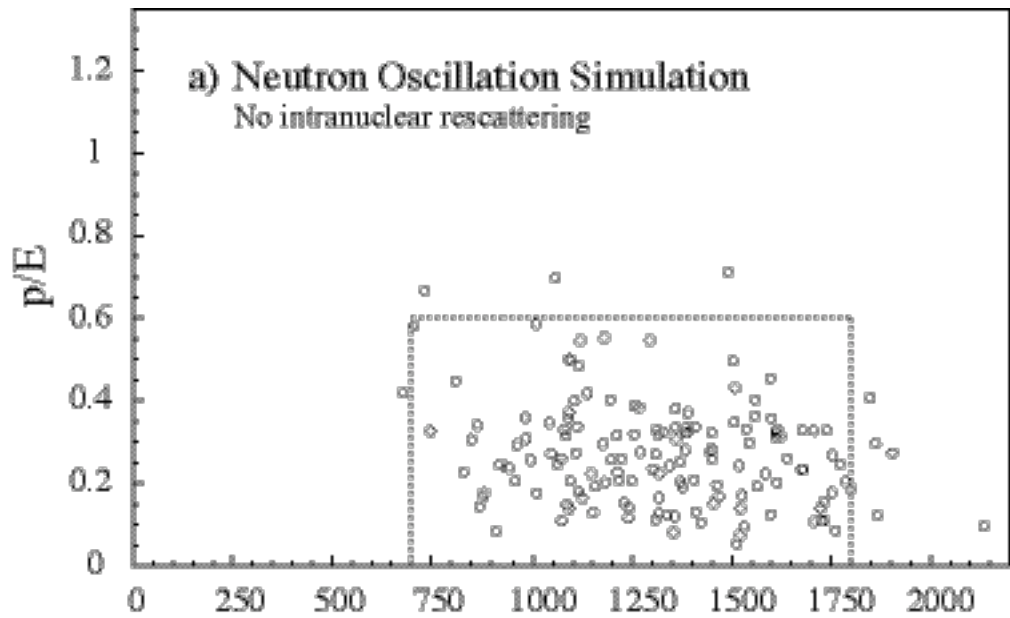
$$700 < E_{vis} < 1800 \text{ MeV}$$

and

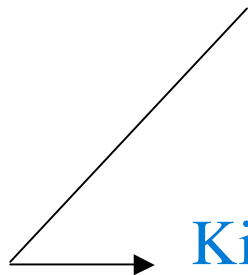
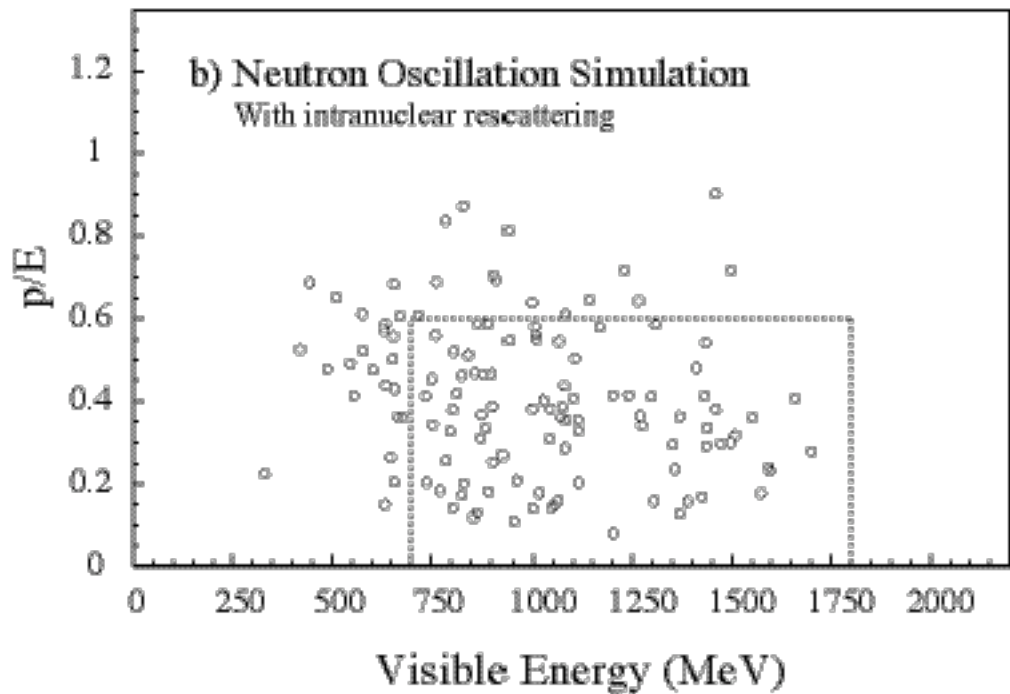
$$P_{net} / E_{vis} < 0.6.$$

Momentum fraction P/E vs E_{vis} for $n\bar{n}$ simulations after topology cuts:

Without INS:



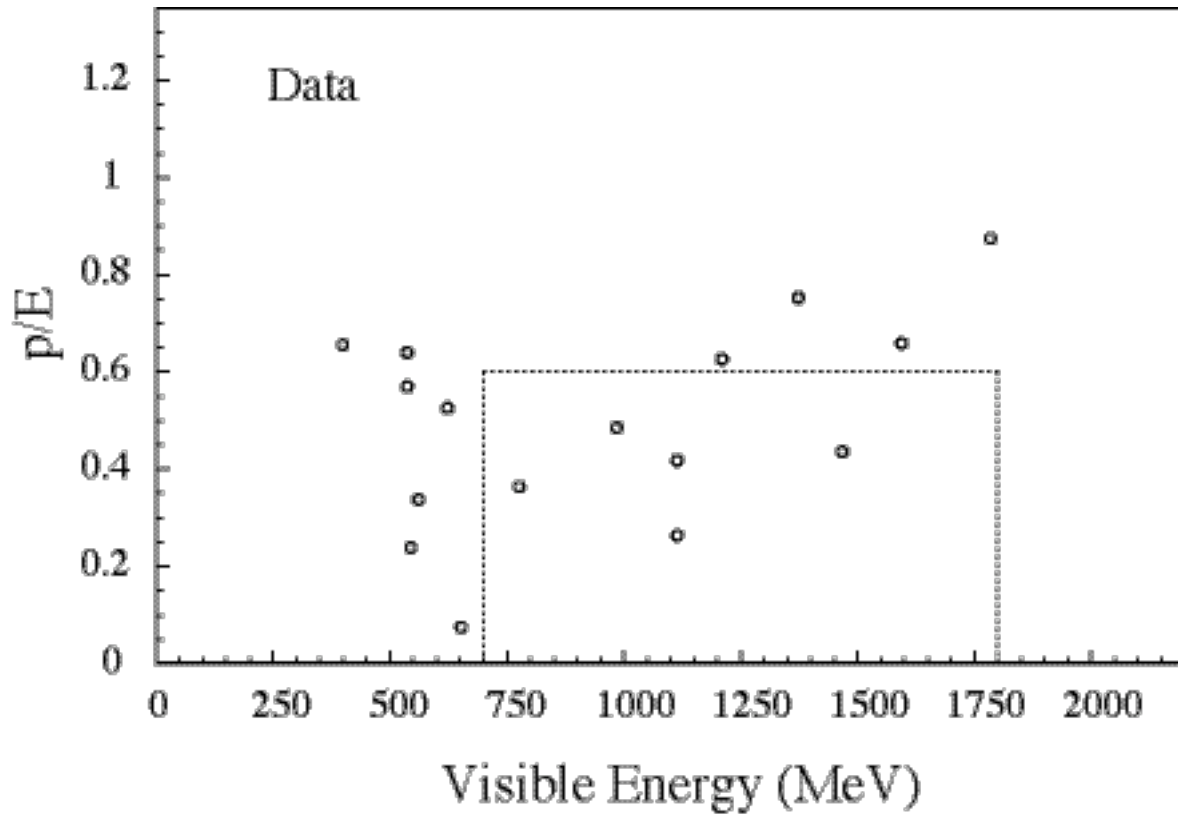
With INS:



Kinematic selection leaves 70% of $n\bar{n}$ in search region.

Neutron oscillation candidates:

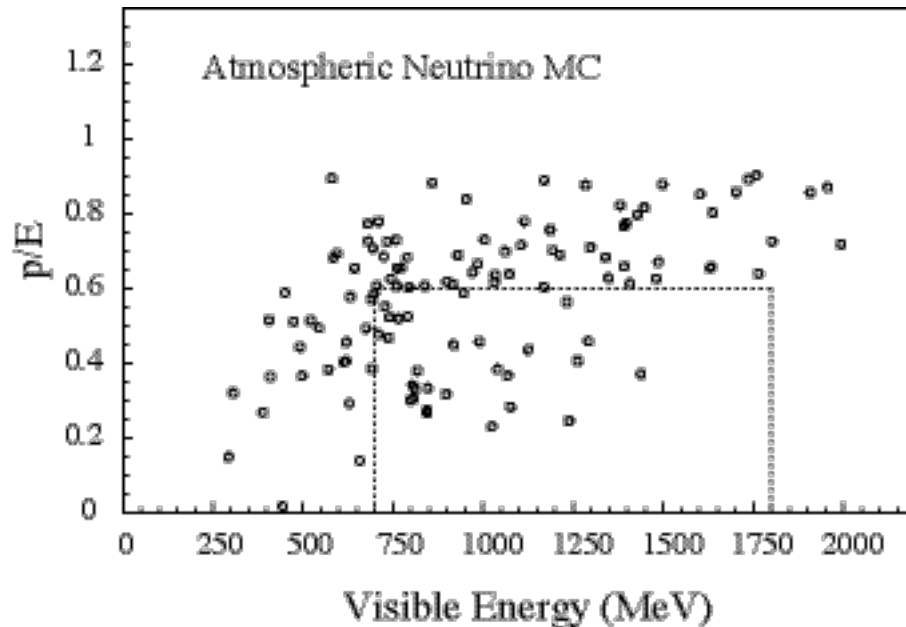
- Upon applying selections (1) - (4) to data, five candidate events are found:



Run_event	No. of Tracks	No. of Showers	E_{vis} (MeV)	P_{net} (MeV/c)
31606_633	1	4	1462.	623.
58856_477	3	2	982.	469.
6882_746	4	0	1118.	289.
68882_746	2	2	772.	277.
88430_57	3	1	1119.	455.

Background rates:

Atmospheric neutrino MC events after topology selections -



- i) Atmospheric neutrino background:
 - Selected (null μ osc. MC): 28 events
 - Correction for $\mu \rightarrow \tau$: 24.5 events
 - Norm to data exposure: 4.0 ± 1.0 μ bkgrd

- ii) “Rock” events:
 - (188 events) $\square 0.06 \square 0.04 = 0.5 \pm 0.5$ rock bkgrd

 - $\square 4.5 \pm 1.2$ background events (neutrinos + rock)

Limit on $n\bar{n}$ oscillation time:

Data candidate events: 5.0 events

Backgrounds (\square 's + CR n 's): 4.5 events

At 90% CL, $n_{90} = 5.5$ events and we use

$$T_A > \frac{N_n \cdot T_f \cdot \square}{n_{90}}$$

where,

$N_n = 3.15 \square 10^{32}$ neutrons per kton-yr
in Soudan 2

$T_f = 6.96$ kton-years
(detector total exposure)

$\square = 0.18 \pm 0.02$
(detection efficiency for full detector).

We obtain, at 90% confidence level,

$$T_A > 7.2 \square 10^{31} \text{ years} \quad (\text{A} = \text{Fe})$$

using

$$\square_{n\bar{n}} = \sqrt{\frac{T_A}{T_R}}$$

With $T_R = 1.4 \square 10^{23} \text{ s}^{-1}$ for iron, we obtain

$$\square_{n\bar{n}} > 1.3 \square 10^8 \text{ seconds.}$$

n \bar{n} Simulation	T_A lower limit	$\square_{n\bar{n}}$ lower limit
n \bar{n} without INS	11.0 $\square 10^{31}$ yr	1.6 $\square 10^8$ s
n \bar{n} in nuclear periphery, with INS	8.4 $\square 10^{31}$ yr	1.4 $\square 10^8$ s
n \bar{n} throughout nucleus, with INS	7.2 $\square 10^{31}$ yr	1.3 $\square 10^8$ s

Experimental limits:

Expt's	Grenoble (1990)	Kamioka (1986)	Fréjus (1990)	Soudan 2 (2002)
Source of neutrons	Reactor beam	^{16}O	^{56}Fe	^{56}Fe
T_R (10^{23} s^{-1})	—	1.0	1.4	1.4
Kton yrs fiducial (total)	—	1.11	1.56 (2.56)	5.56 (6.96)
Est. bkgrd	0	1.2	2.5, 2.1	4.5
Candidate events	0	0	0	5
T_A (10^{31} yr)	—	4.3	6.5	7.2
$\square_{\bar{n}}$ (10^8 s)	0.86	1.2	1.2	1.3

Recap and conclusion:

A 5.56 fiducial kty exposure of Soudan 2 has been used to set a new lower limit for $n\bar{n}$ oscillations in iron:

$$T_A(\text{Fe}) > 7.2 \times 10^{31} \text{ years} \quad - \text{ at } 90\% \text{ CL.}$$

The corresponding limit for free neutrons, assuming $T_R = 1.4 \times 10^{23} \text{ s}$, is

$$\tau_{n\bar{n}} > 1.3 \times 10^8 \text{ seconds.}$$

Background arising from multiprong interactions of atmospheric neutrinos is observed:
 $\sim 0.7 \times \text{evts/kty.}$

Limit-setting to $\tau_{n\bar{n}} > (4 - 5) \times 10^8 \text{ secs}$ is achievable “soon” by SNO and SuperK.

Extending search limit sensitivity to/beyond $\tau_{n\bar{n}} = 10^9 \text{ secs}$ requires a different approach. For $n\bar{n}$ exploration, the future lies with new reactor neutron beam experiments.