united nations educational, scientific and cultural organization

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SMR.1508 - 7

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

NEUTRINO PHYSICS

Lecture III

S. PARKE
Fermilab
Batavia, IL
U.S.A.

strada costiera, 11 - 34014 trieste italy - tel. +39 0402240111 fax +39 040224163 - sci_info@ictp.trieste.it - www.ictp.trieste.it

3+ Neutrino Oscillations

- $3\,\nu$ picture { · what's known · what we would like to know
- beyond 3
  LSND , mini BOONE

Atmospheric / K2K: $\nu_\mu \leftrightarrow \nu_\tau$

$$|\delta m^2_{atm.}|^2 = 1.6 - 3.9 \times 10^{-3} eV^2$$

$$0.35 < \sin^2\theta_{atm} < 0.65$$

$$(\sin^2 2\theta_{atm} > 0.91)$$

Solar / KamLAND: $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

$$\delta m^2_{\odot} = +7 \text{ or } 15 \times 10^{-5} eV^2$$
$$(5-20)$$

$$0.25 < \sin^2\theta_{12} < 0.40$$

$$\left(\begin{array}{c}\sin^2 2\theta_{12} \simeq 0.85 \\ \text{and} < 1\end{array}\right)$$

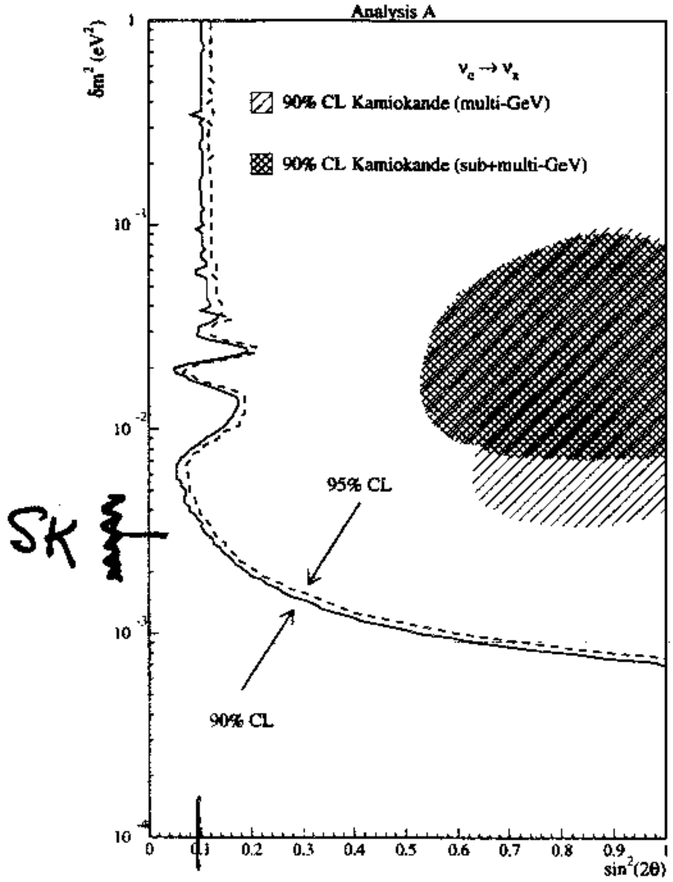
What about ν_e for

$$\delta m^2_{atm} \sim 3 \times 10^{-3} eV^2$$

? ? ? ?

SK and Chooz

Chooz: ν_e Disappearance

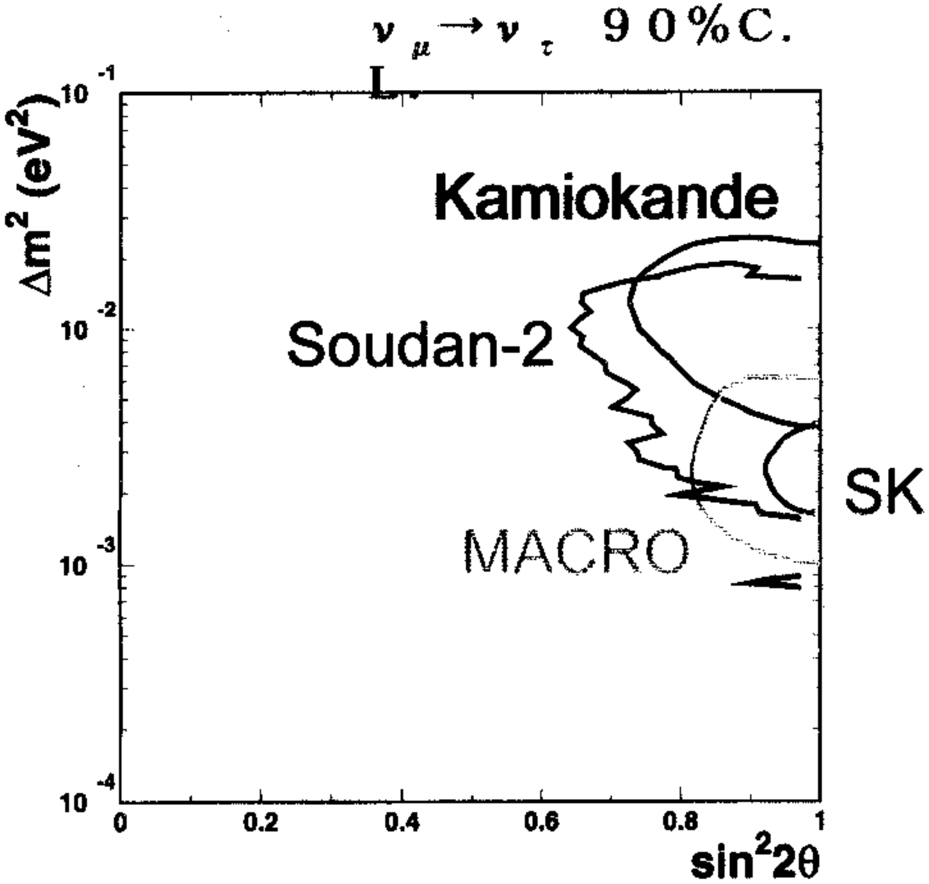


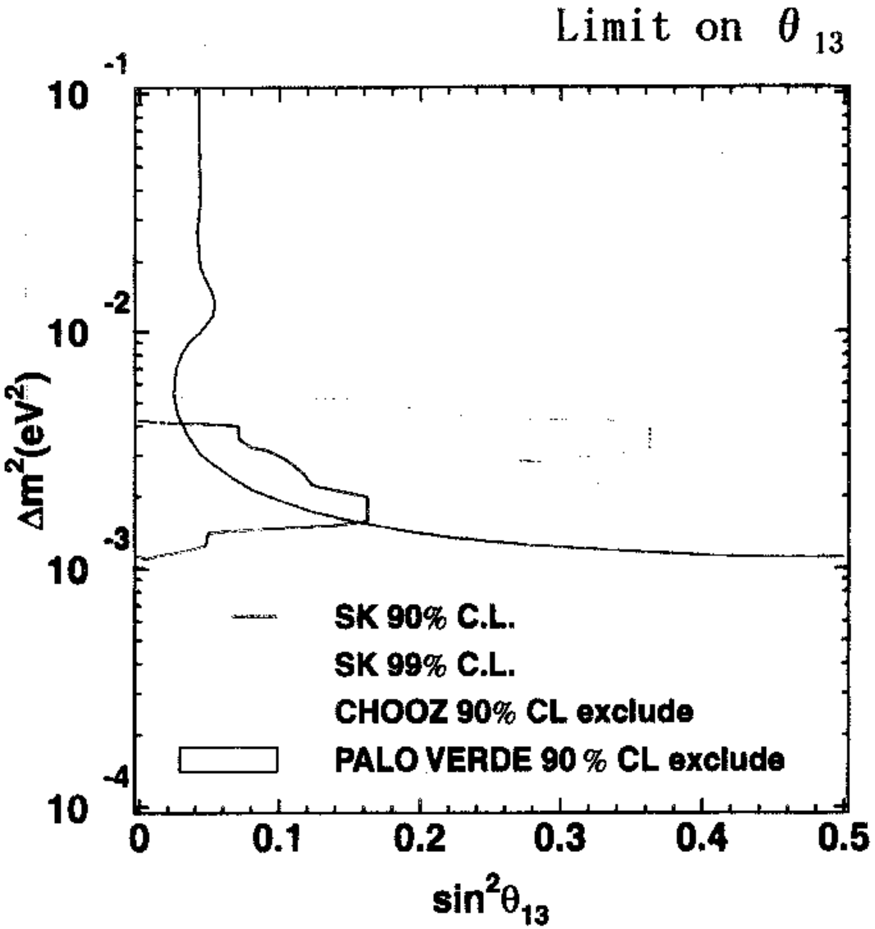
- at $|\delta m^2_{atm}| = 3 \times 10^{-3} eV^2$

$$\sin^2 2\theta_{13} < 0.1$$

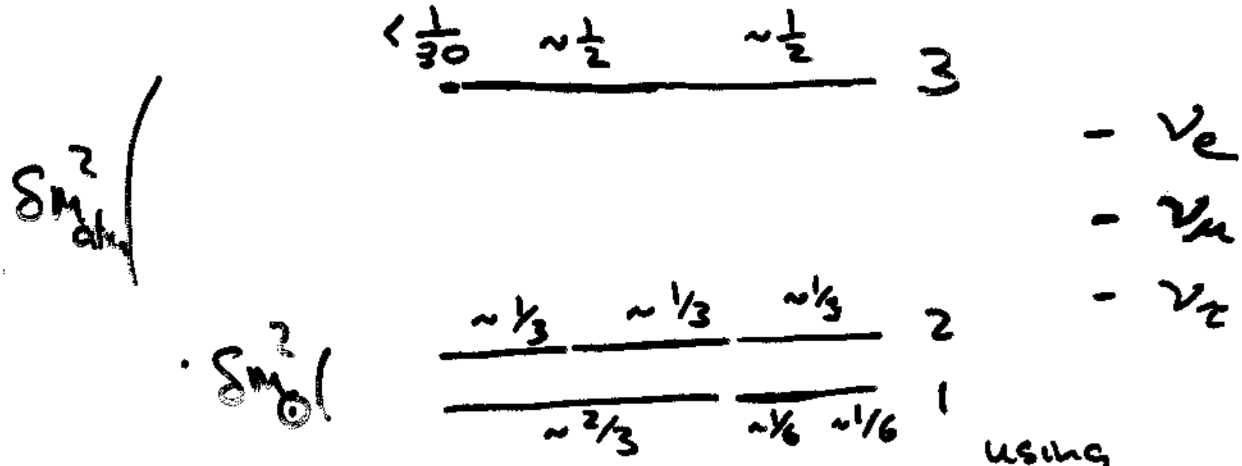
- for all $|\delta m^2_{atm}|$ $\sin^2 2\theta_{13} < 0.05$

Oscillation parameters





The three Neutrino Picture



using

$\sin^2\theta_{atm} = \frac{1}{2}$

& $\sin^2\theta_\odot = 1/3$

$\sin^2\theta_{chooz} < \frac{1}{30}$

3 active flavors

(but can be easily modified to accommodate 3+1)

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

The parameterization used for the unitary MNS matrix, U, is $\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$e^{i\alpha_1}$ $e^{i\alpha_2}$

where $c_{jk} \equiv \cos\theta_{jk}$ and $s_{jk} \equiv \sin\theta_{jk}$.

check unitarity

The primary element of interest here is

$$|U_{e3}|^2 \quad \text{or} \quad \sin^2 2\theta_{13}$$

and δ.

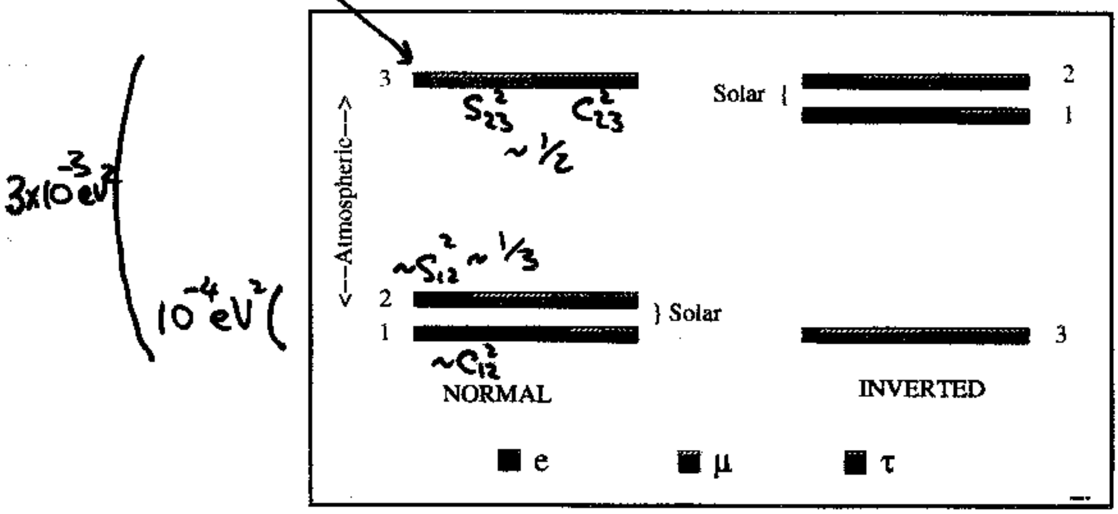
$$\nu_3 = S_{13} e^{i\delta} \nu_e + C_{13} S_{23} \nu_\mu + C_{13} C_{23} \nu_\tau$$

$$\nu_2 = C_{13} S_{12} \nu_e + (\cdots) \nu_\mu + (\cdots) \nu_\tau$$

$$\nu_1 = C_{13} C_{12} \nu_e + (\cdots) \nu_\mu + (\cdots) \nu_\tau$$

Mass Order:

$|S_{13}|^2 \lesssim 0.03$



Order on 1 an 2 known:
from matter effect for solar nu's.

Oscillation Summary:

Atmospheric / K2K $\quad \nu_\mu \leftrightarrow \nu_\tau$

$$|\delta m_{atm}|^2 = 1.6 - 3.9 \times 10^{-3}\, eV^2$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

$$(\sin^2 2\theta_{23} > 0.91)$$

Solar / KamLAND $\quad \nu_e \leftrightarrow \nu_\mu, \nu_\tau$

$$\delta m_\odot^2 = +7 \times 10^{-5}\, eV^2$$

$$(5 - 20)$$

$$0.25 < \sin^2\theta_{12} < 0.40$$

$$(\sin^2 2\theta_{12} \approx 0.85)$$

Reactor – Chooz

$$\sin^2\theta_{13} \leq 0.03 \qquad \theta_{13} < \frac{\pi}{20} = 9^\circ$$

WHAT WE DON'T KNOW:

- Majorana OR Dirac
- Absolute mass of lighest neutrino.

  (except $< \sim 1\,\text{eV}$)

- Size of θ_{13}: (ν_e in the "3" state.)

  $\sin^2\theta_{13} < 0.03$

- Is $\theta_{23} = \text{ or } \lessgtr \pi/4$ the $\mu \leftrightarrow \tau$ symmetric point.

  (maximal mixing)

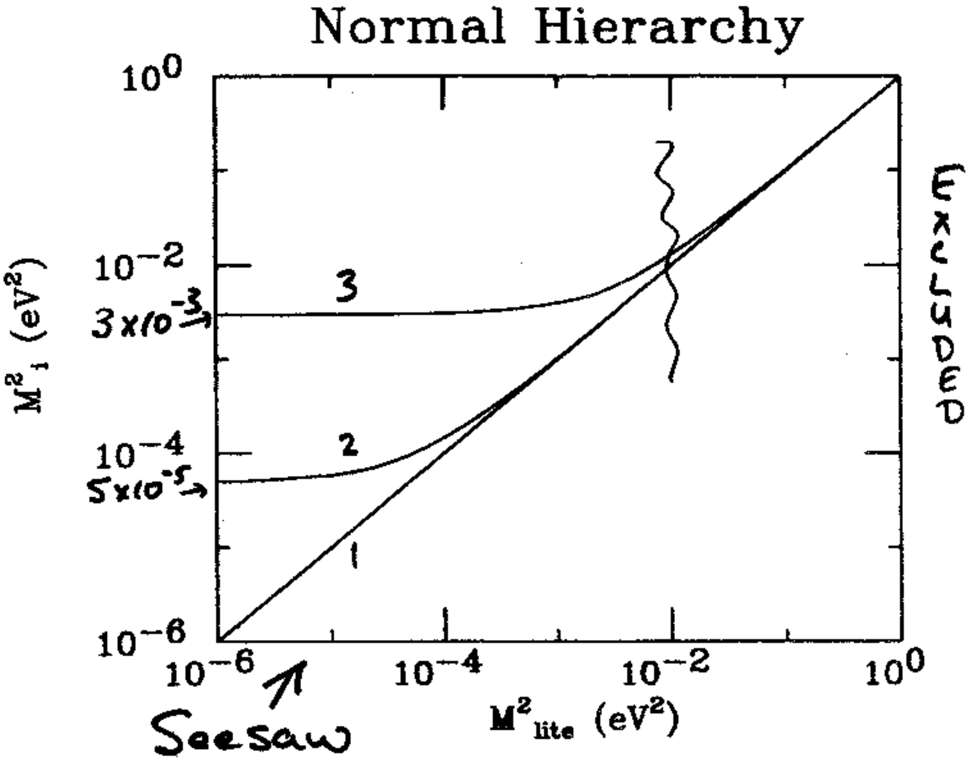
  $0.35 < \sin^2\theta_{23} < 0.65$

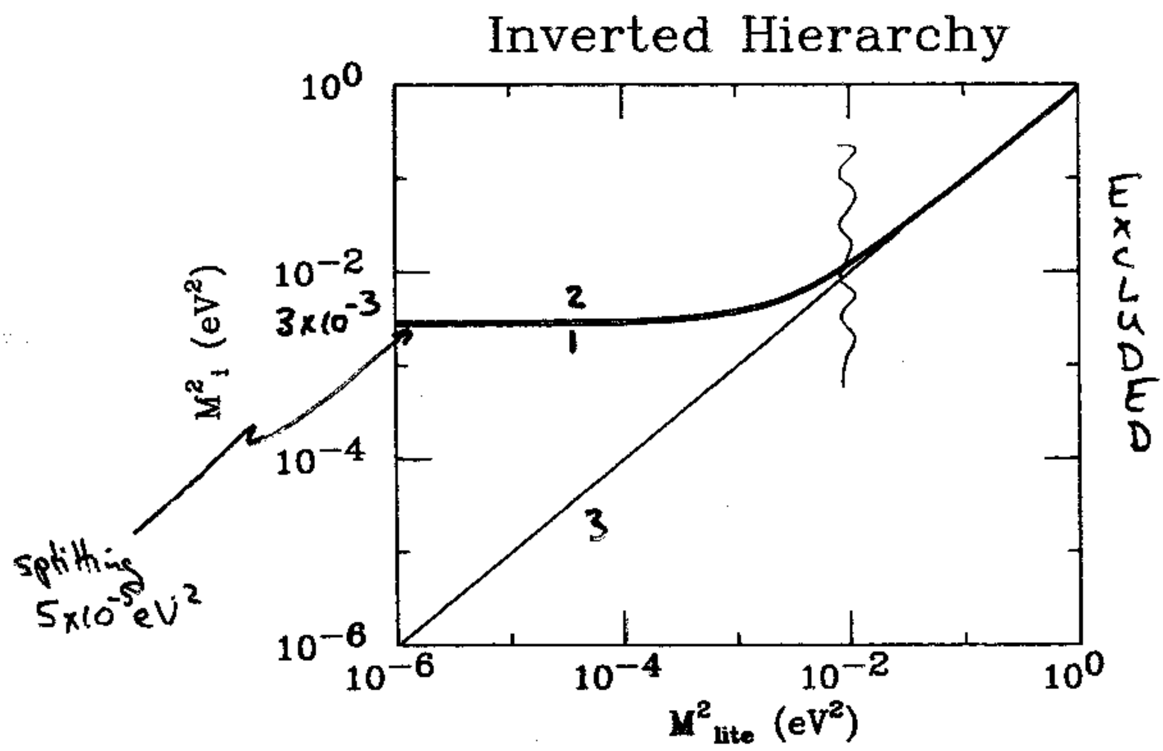
- Sign of δm^2_{atm} ()

  type of spectrum

- phase $\delta \Leftarrow$ if $\neq 0$ leads to CP violation

- Number of light Neutrinos: 3 or are there more than 3


Normal Hierarchy
10^0
10^{-2}
3×10^{-3}
10^{-4}
5×10^{-5}
10^{-6}
M^2_1 (eV^2)
3
2
1
EXCLUDED
10^{-6}
10^{-4}
10^{-2}
10^0
M^2_{lite} (eV^2)
Seesaw


Inverted Hierarchy
10^0
10^{-2}
3×10^{-3}
10^{-4}
10^{-6}
M^2_1 (eV^2)
2
1
3
EXCLUDED
splitting
5×10^{-5} eV^2
10^{-6}
10^{-4}
10^{-2}
10^0
M^2_{lite} (eV^2)

Beacom + Bell

LSND "Diamond in the rough" ???

Decay at Rest:

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$
$$\hookrightarrow \bar{\nu}_e$$

$$(\bar{\nu}_e p \to e^+ n)$$

$87.9 \pm 22.4 \pm 6.0$ events

note: anti-neutrinos

$$P_{\mu \to e} = 0.264 \pm 0.067 \pm 0.045\,\%$$

Decay in Flight:

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow \nu_e$$

different kinematics than ν_e from DAR

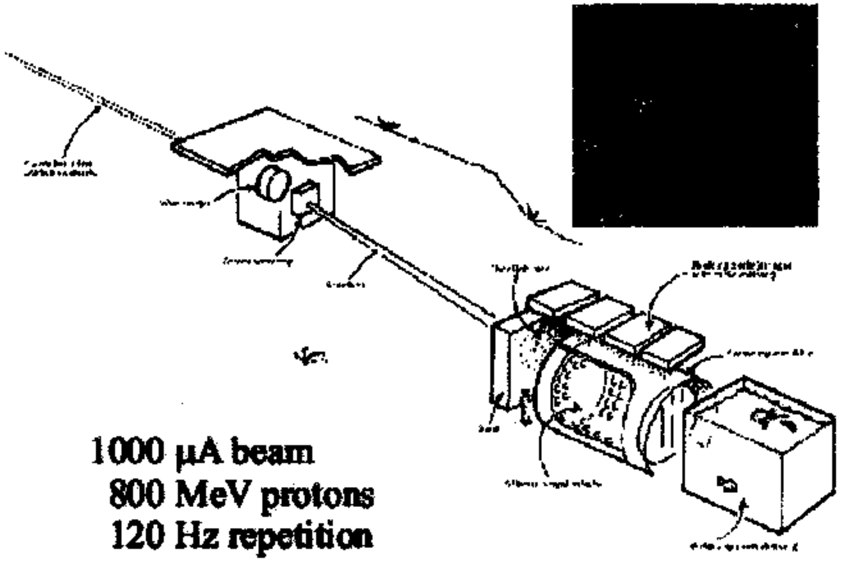
$8.1 \pm 12.2 \pm 1.7$

~~$0.10 \pm 0.16 \pm 0.04$ %~~ events

$$P_{\mu \to e} = 0.10 \pm 0.16 \pm 0.04\,\%$$

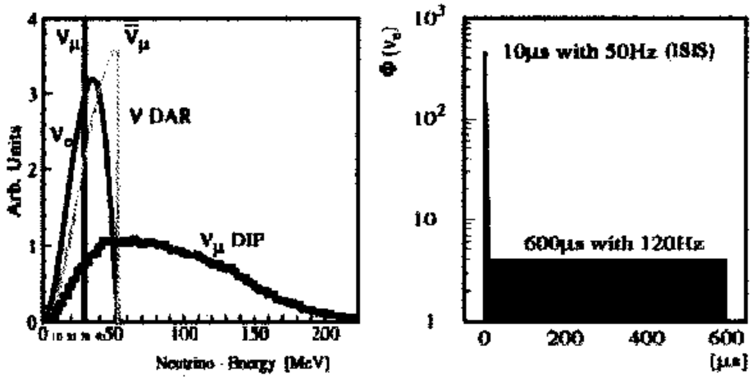
BUT $\nu_\mu \rightarrow \nu_e$ $P_{\nu_\mu \to \nu_e} = (0.264 \pm 0.067 \pm 0.045)\%$

LSND at LANSCE



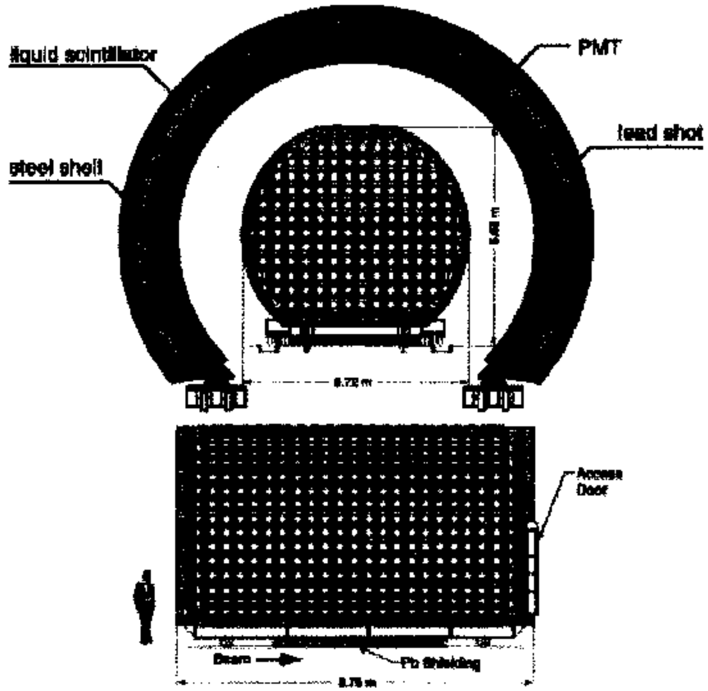
1000 μA beam
800 MeV protons
120 Hz repetition
600 μs pulse length

π and μ decay at rest and in flight



LSND Detector

- 167 t hybrid oil Cherenkov detector
- sees Cherenkov and scintillation light
- Central detector:1220 8"-PMTs
- Veto detector: 292 5"-PMTs
- Shielding: 8m iron equivalent



MiniBooNE

FERMILAB http://www.fnal.gov.

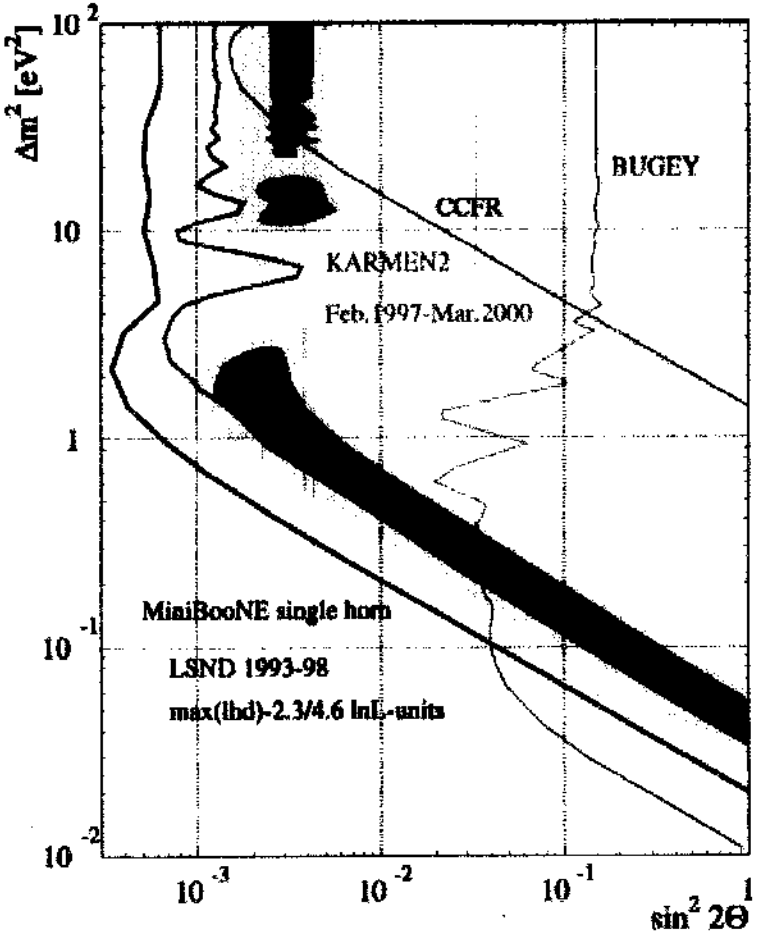
- Proton from
  8 GeV Booster
  5 x 10^{20} POT/yr

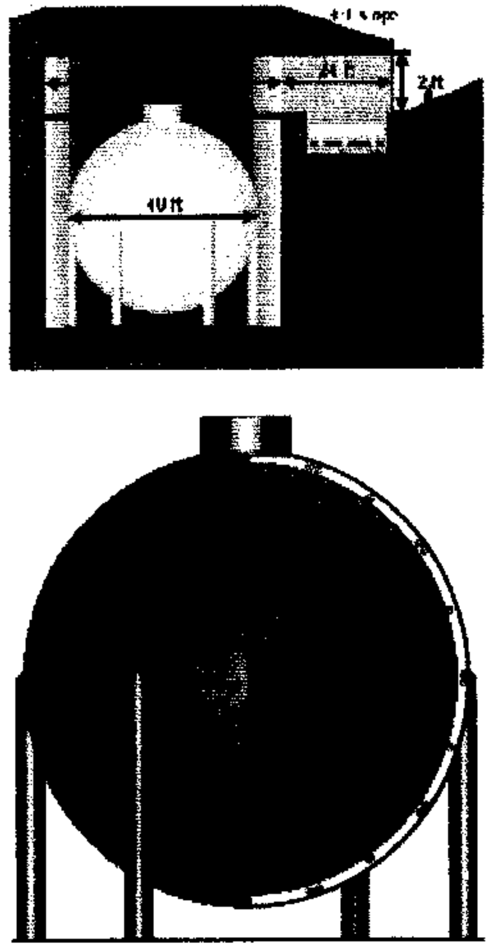
- Detector at
  500m from
  Target & Horn

Current mode:

$\pi^+ \to \mu^+ \nu_\mu$
$\hookrightarrow \nu_e$

- definitive test of the LSND signal as oscillations.
- ~1000 events/year if LSND is true
- Start: 2002 (detector ready by the end of 2001)



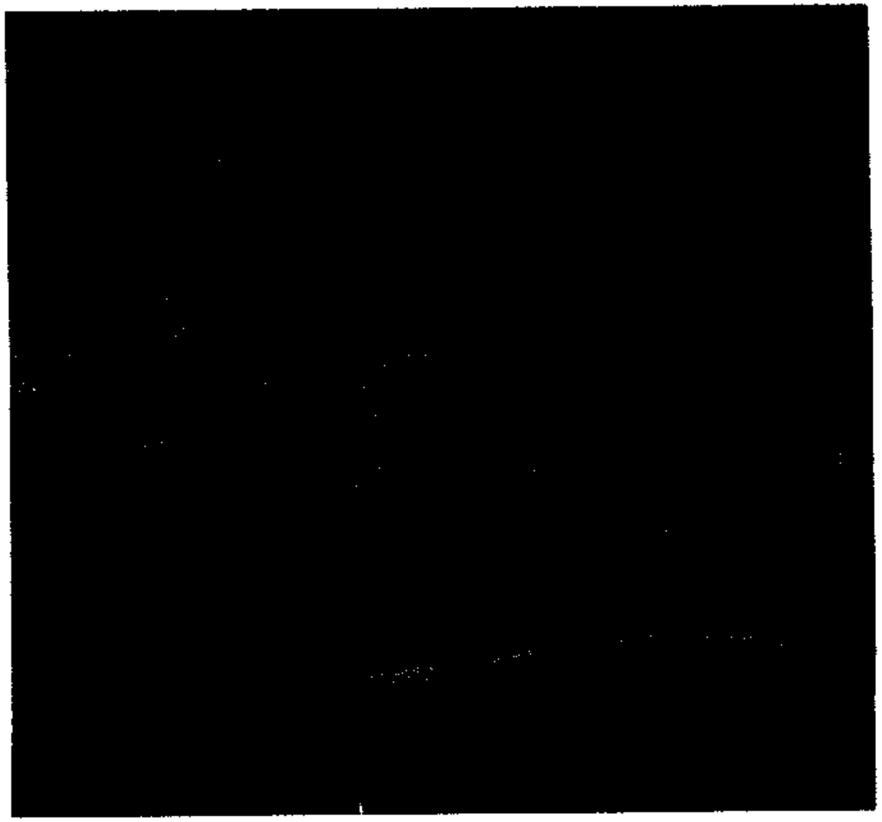


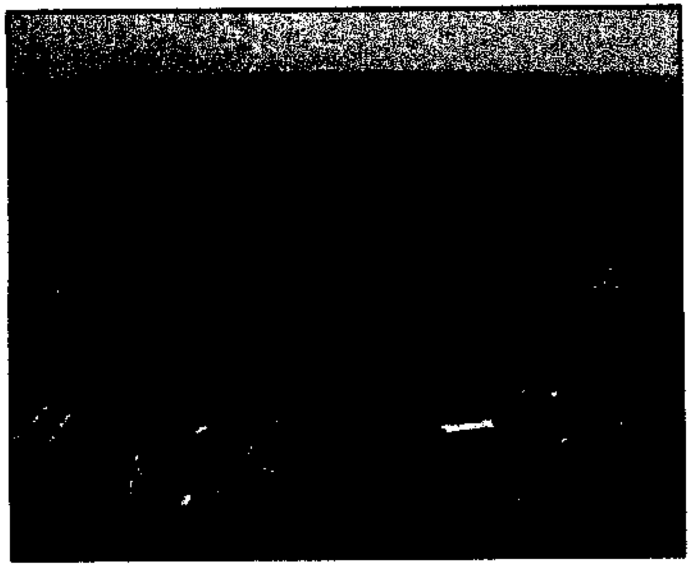
Joachim Wolf

The FNAL Booster

8 GeV proton accelerator built to supply beam to the Main Ring, it now supplies the Main Injector

Booster must now run at record intensity





MiniBooNE will run simultaneously with the other programs:
e.g. Run II + BooNE; 5×10^{12} protons per pulse at a rate of 7.5 Hz; (5 Hz for BooNE)

5×10^{20} p.o.t in one year

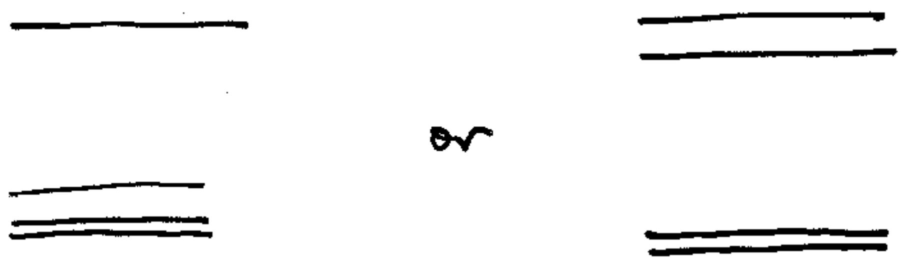
Challenges are radiation issues, losses

$$\Delta m^2_{LSND} \sim 1\ eV^2$$

$$\Delta m^2_{ATM} \sim \text{few} \times 10^{-3}\ eV^2$$

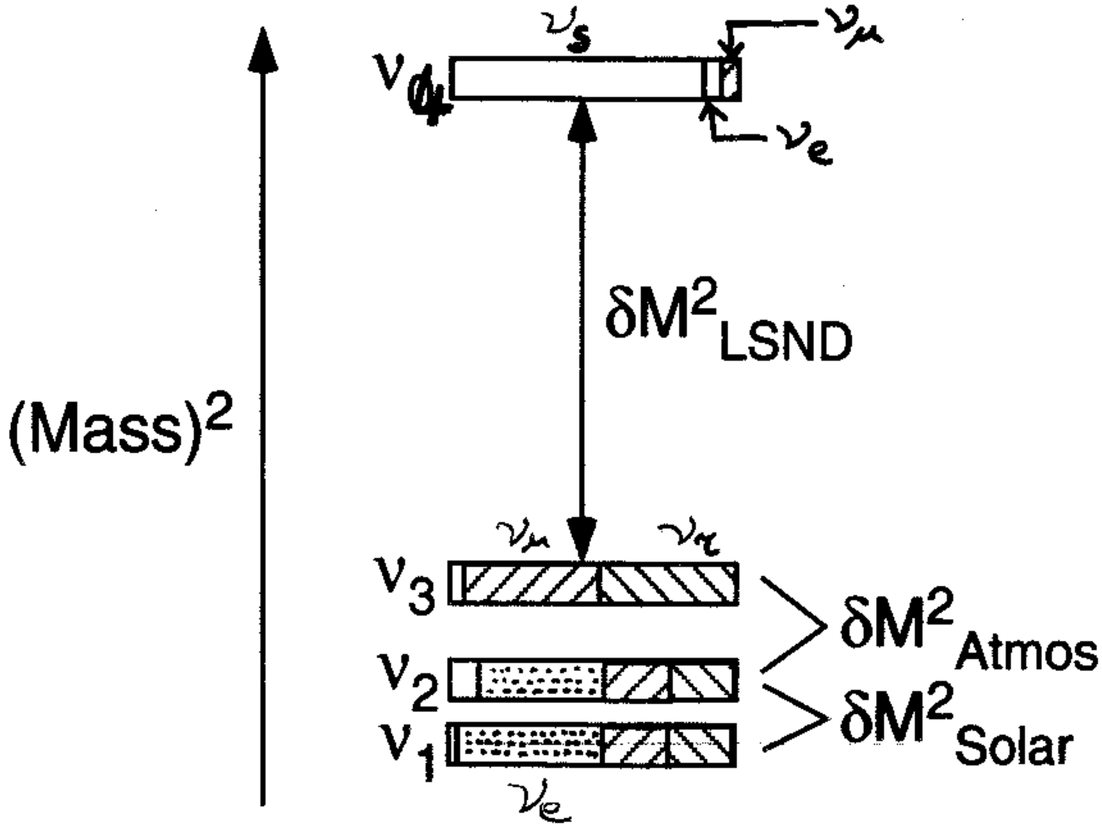
$$\Delta m^2_{SOLAR} \lesssim 10^{-5}\ eV^2$$

If LSND is to be explained by neutrino oscillations we need more neutrinos (sterile)



3+1 2+2

3 + 1



- LSND is small effect ($\mathcal{O}$(few $\times 10^{-3}$)) at large $\delta M^2 \sim 1eV^2$

- suggesting a small ν_s component in ν_1, ν_2 and ν_3

- For LSND Energies and Distances:

we have an effective 2 neutrino scenario

$$P(\nu_\mu \to \nu_e) = \underbrace{4|U_{\mu 4}|^2|U_{e4}|^2}_{\sin^2 2\theta_{LSND}} \sin^2(\frac{\delta M^2 L}{4E})$$

BUT

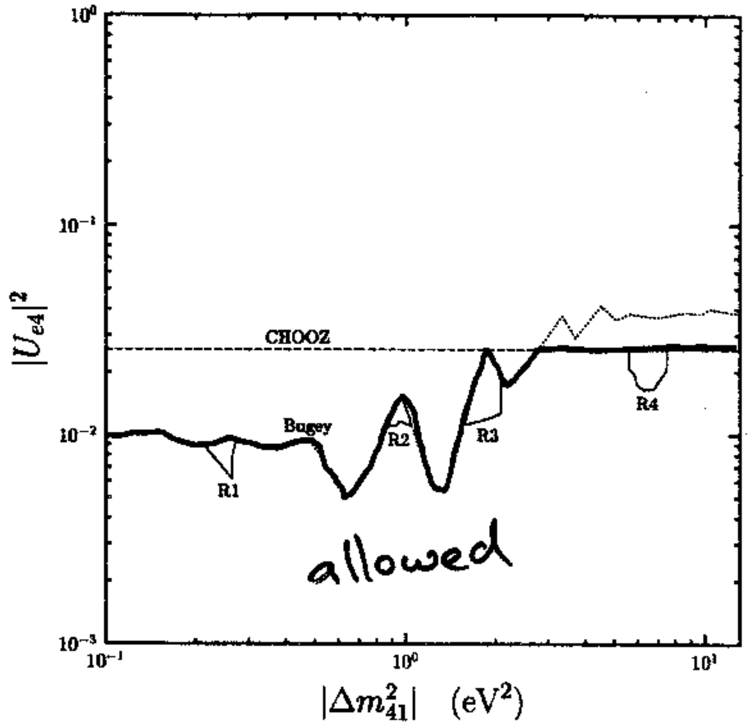
- ν_e disappearance: Bugey and Chooz

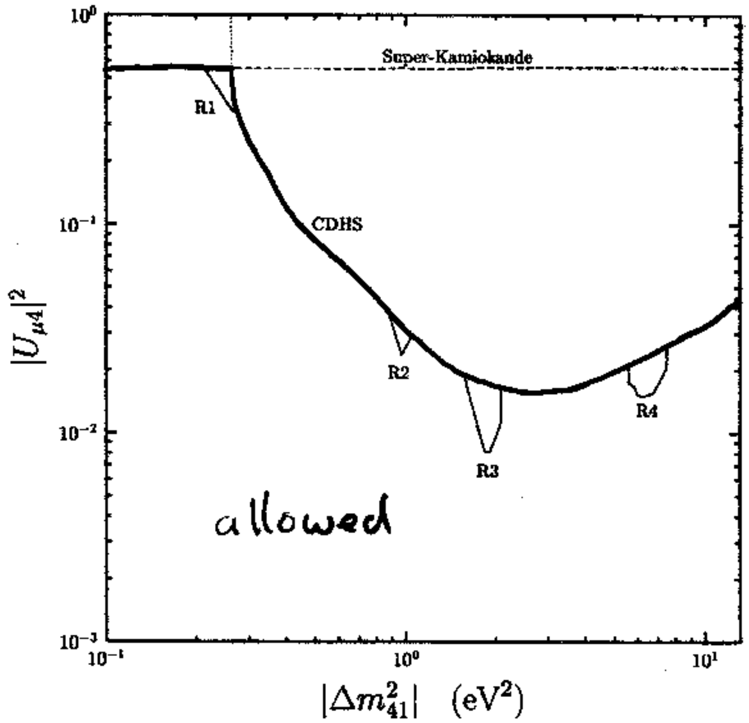
$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2(\frac{\delta M^2 L}{4E})$$

- ν_μ disappearance: CDHS and SuperK

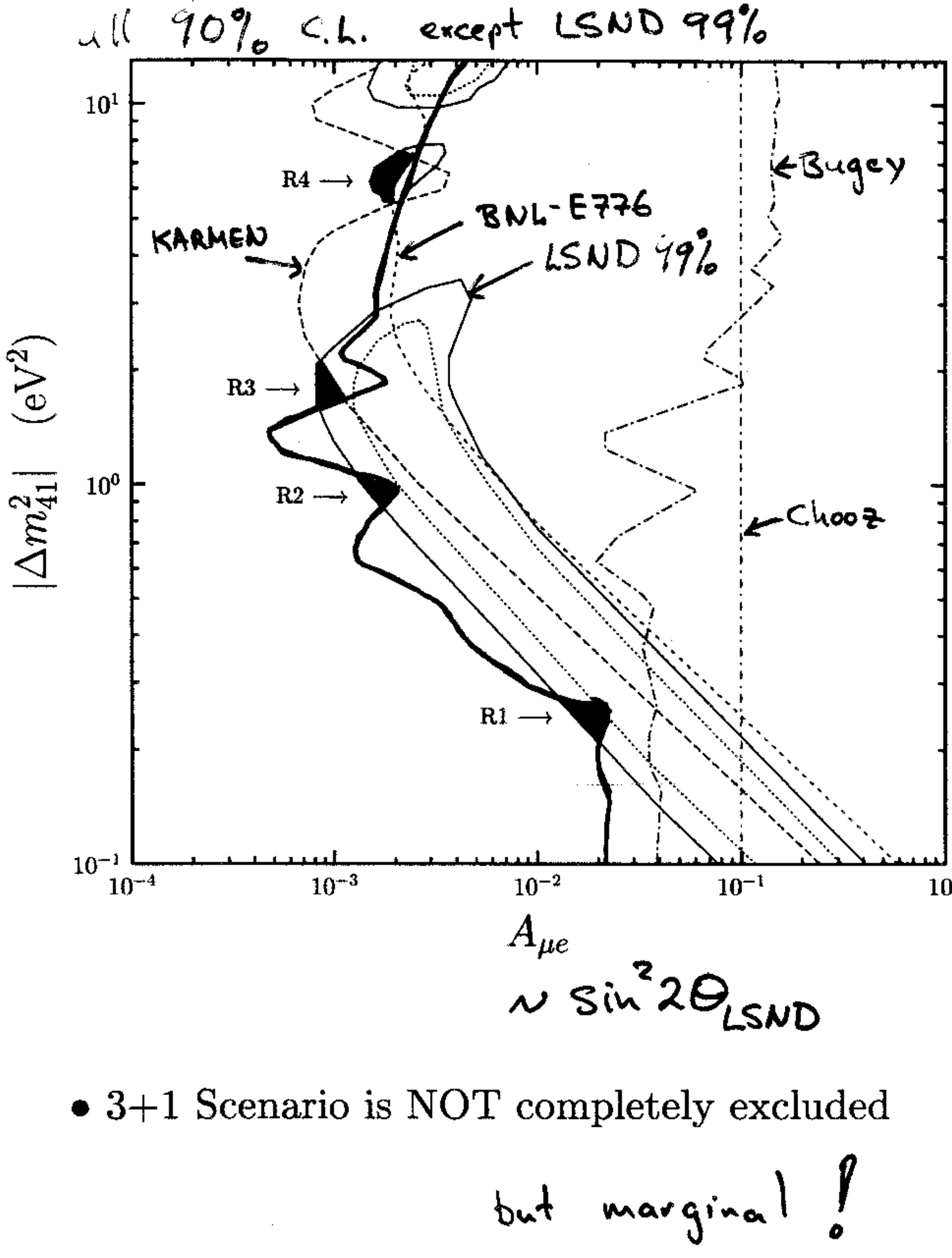
$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \sin^2(\frac{\delta M^2 L}{4E})$$

Giunti
hep-ph/0012236
+ ...





Giunti



- 3+1 Scenario is NOT completely excluded

but marginal!

If LSND is correct then in this 3+1 scenario,

- ν_e disappearance

AND

- ν_μ disappearance

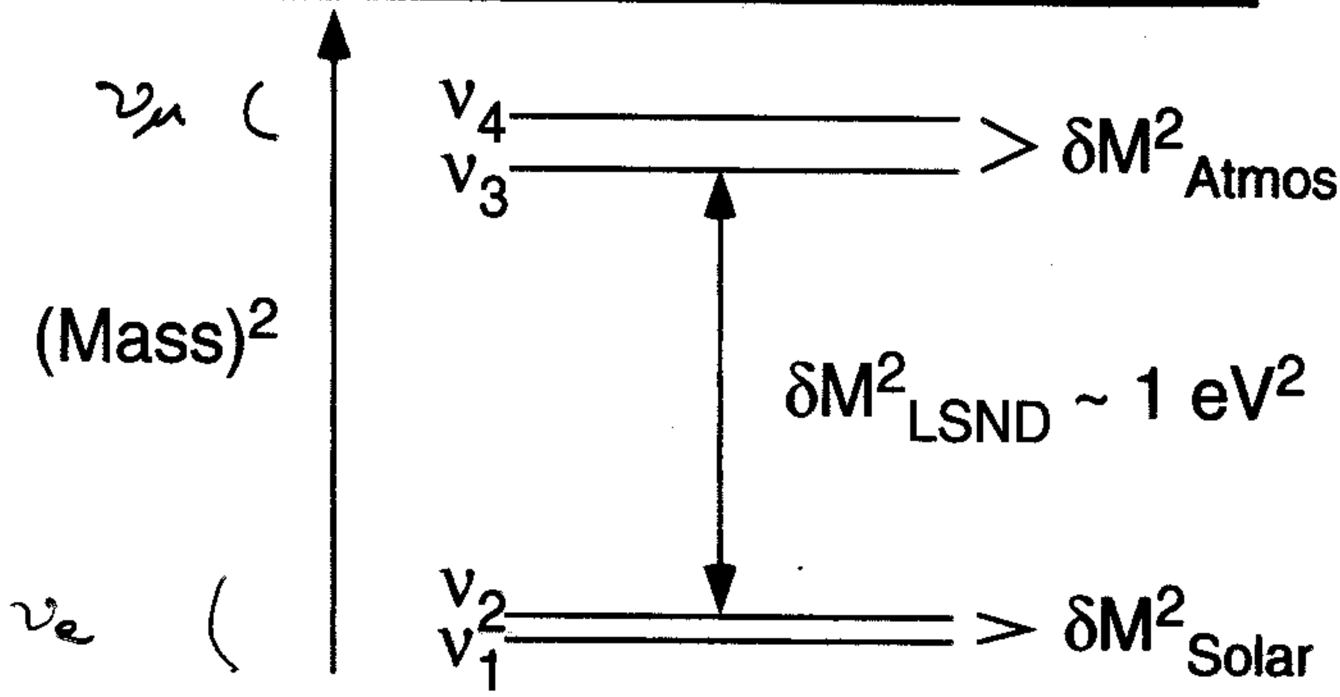
effects are just beyond current limits for $\delta M^2 \sim 1\text{eV}^2$.

- In this scenario, mini-BOONE, as well as confirming the LSND signal, should be able to see ν_μ disappearance. SOON - fall 2003 !

- maybe also K2K near detector

BUT What about 3+2 ? $\Delta m^2_{new} \sim 20\text{eV}^2$
Sorel, Conrad, Shaevitz hep-ph 0305255

2 + 2



- the Solar Pair (ν_1, ν_2) involves ν_e
- the Atmospheric Pair (ν_3, ν_4) involves ν_μ

BUT

- the LSND + ... results implies there is only small mixing between the Atmospheric Pair and the Solar Pair

ν_s must be involved in the Atmospheric and/or Solar Oscillation.

** Almost ruled out **

- thus the Solar Pair is a mixture of

$$\nu_e \text{ and } (\cos\alpha\ \nu_s\ +\ \sin\alpha\ \nu_\tau)$$

- and the Atmospheric Pair is a mixture of

$$\nu_\mu \text{ and } (-\sin\alpha\ \nu_s\ +\ \cos\alpha\ \nu_\tau)$$

THUS, EITHER

- the Solar Pair has a significant sterile neutrino, ν_s, component

OR

- the Atmospheric Pair has a significant sterile neutrino, ν_s, component

OR BOTH

Peres + Smirnov
Kayser

Define:

$$\eta_s^{\odot} = \frac{P(\nu_e \to \nu_s)}{P(\nu_e \to \nu_s) + P(\nu_e \to \nu_\tau)} = \cos^2\alpha$$

$$\eta_s^{\otimes} = \frac{P(\nu_\mu \to \nu_s)}{P(\nu_\mu \to \nu_s) + P(\nu_\mu \to \nu_\tau)} = \sin^2\alpha$$

Then $\eta_s^{\odot} + \eta_s^{\otimes} = \cos^2\alpha + \sin^2\alpha = 1$

i.e. Sterile neutrino cannot hide.

Atmospheric (SK)

$$\eta_s^{\otimes} < 20\%$$

Solar (SNO + models)

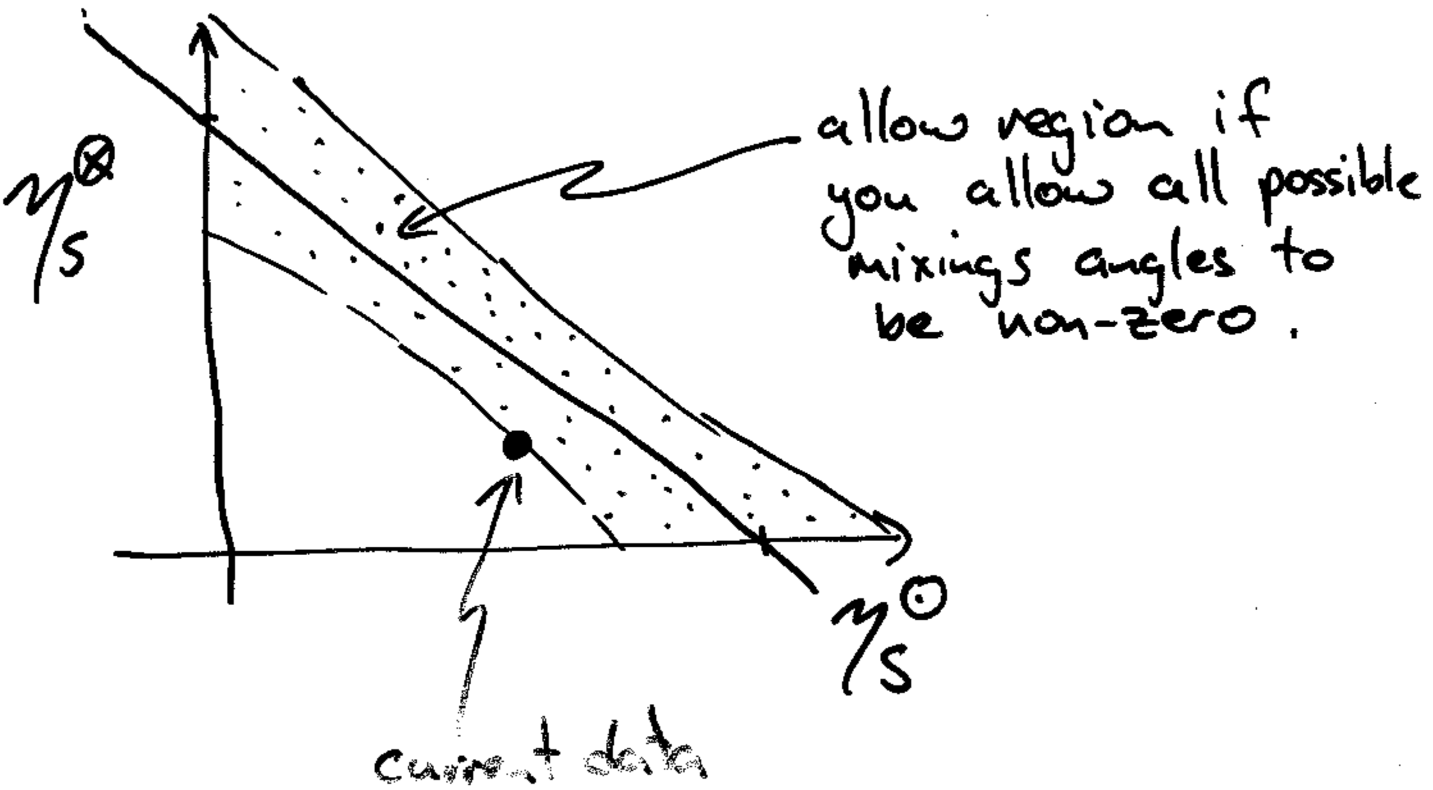
$$\eta_s^{\odot} < 50\%$$

(could be improved if D/N asym. observed.)

2+2 is being squeezed!

BUT ???

Pas, Song + Weiler



- the size of the allowed region is surprisingly BIG !!

— still under discussion —

2+2 marginally allowed

* If mini-BOONE confirms LSND and 3+1 and 2+2 are firmly ruled out then

GREAT !!!

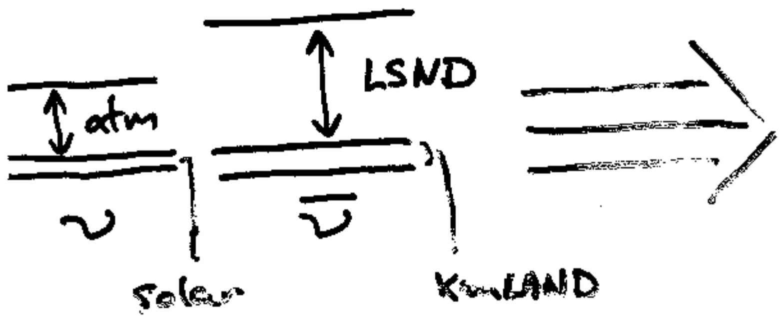
theorists have something new to explain.

* If mini-BOONE rules out LSND with neutrinos. Should Fermilab run with anti-neutrinos?

(takes 3x as many protons. flux↓ σ↓)

pit: mini BOONE against MINOS

— this checks CPT violation explaination.



⟹ atmospheric ν̄ are different than atmospheric ν

MINOS IS CHECKING THIS — B field

7/4