Medium baseline neutrino oscillation searches

LSND: $\bar{\nu}_{\mu}$ ♦ $\bar{\nu}_{e}$ $20 < E_{\nu} < 60$ MeV μ^{+} decay at rest

ν_{μ} ♦ ν_{e} $20 < E_{\nu} < 200$ MeV π^{+} decay in flight

Final results, 1993-98 data
event excess, evidence for oscillations

KARMEN: $\bar{\nu}_{\mu}$ ♦ $\bar{\nu}_{e}$ $20 < E_{\nu} < 60$ MeV μ^{+} decay at rest

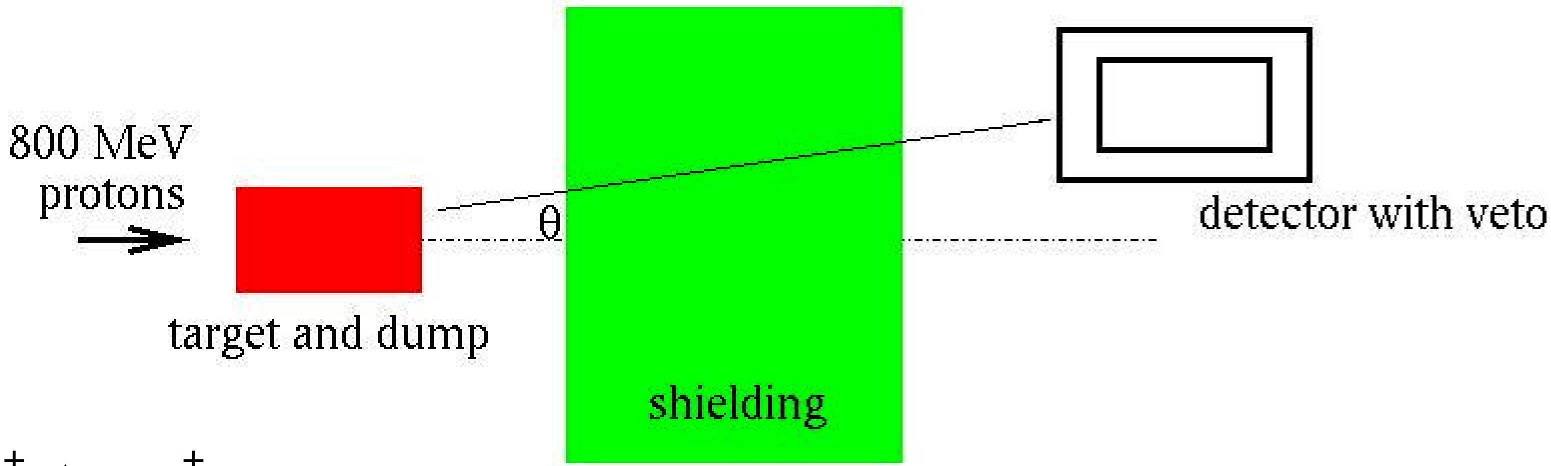
Results based on 75% of expected data, Feb 97 - Mar (Nov) 00
experiment ended March 2001
no excess, does not confirm LSND, but does not rule it out either

MiniBooNE: ν_{μ} ♦ ν_{e} $500 < E_{\nu} < 1500$ MeV

Under construction
first data summer 2002

8 GeV protons, 3 GeV π^{+}

LSND and KARMEN experimental scheme



$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$ muon decay at rest

$\quad\quad \hookrightarrow \bar{\nu}_e$ appearance experiment

$\bar{\nu}_e p \rightarrow e^+ n$ detect prompt e track, $20 < E_e < 60$ MeV

neutron capture: $np \rightarrow d\gamma$ 2.2 MeV, $Gd(n,\gamma)$ 8 MeV

γ correlated in position and in time with e

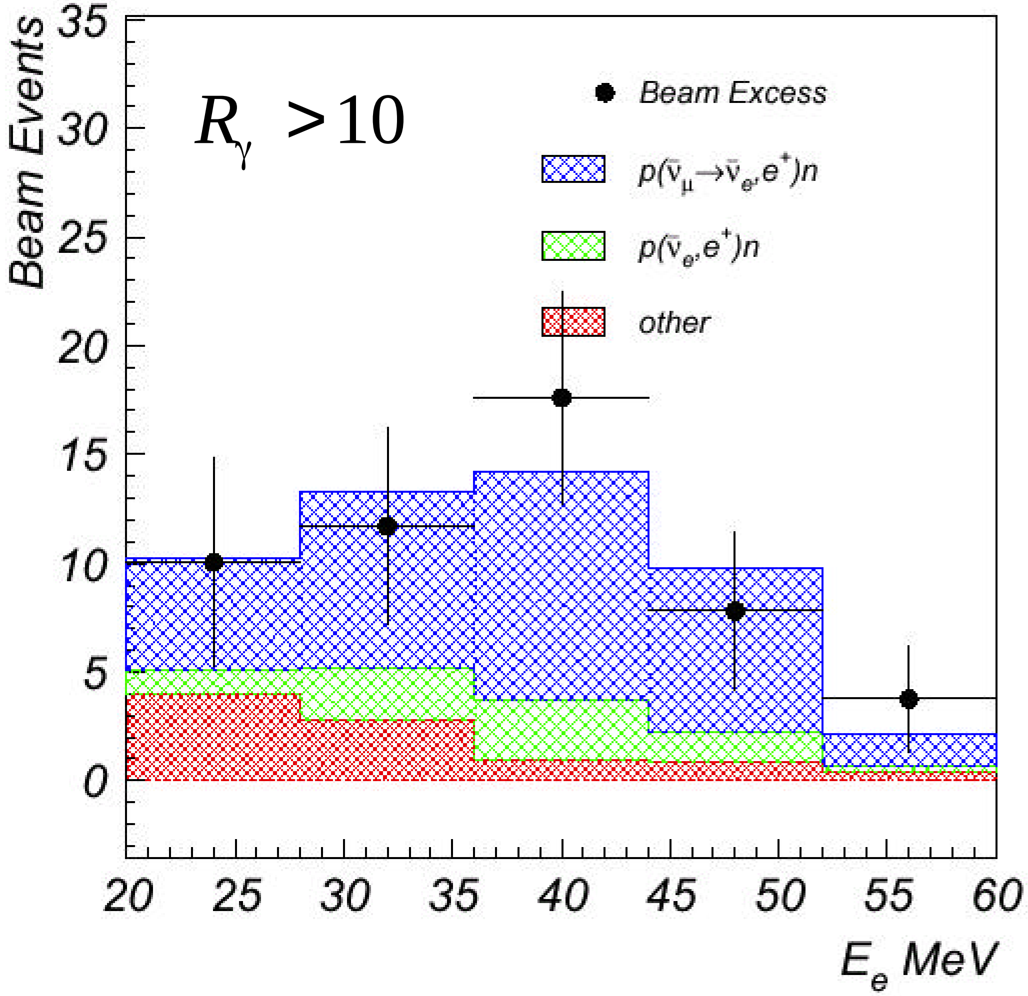
no B-field, e and γ sequence distinguishes e^+ from e^-

LNSD Results

$R_\gamma > 10$ and $20 < E_e < 60$ MeV

$$\begin{aligned} &\text{beam on}: \ 86 \text{ events} \\ &\text{beam off}: \ 36.9 \pm 1.5 \\ &\nu \text{ bkgd}: \ 16.9 \pm 2.3 \\ \hline &\text{total excess } 32.2 \pm 9.4 \pm 2.3 \end{aligned}$$

Evidence for oscillations



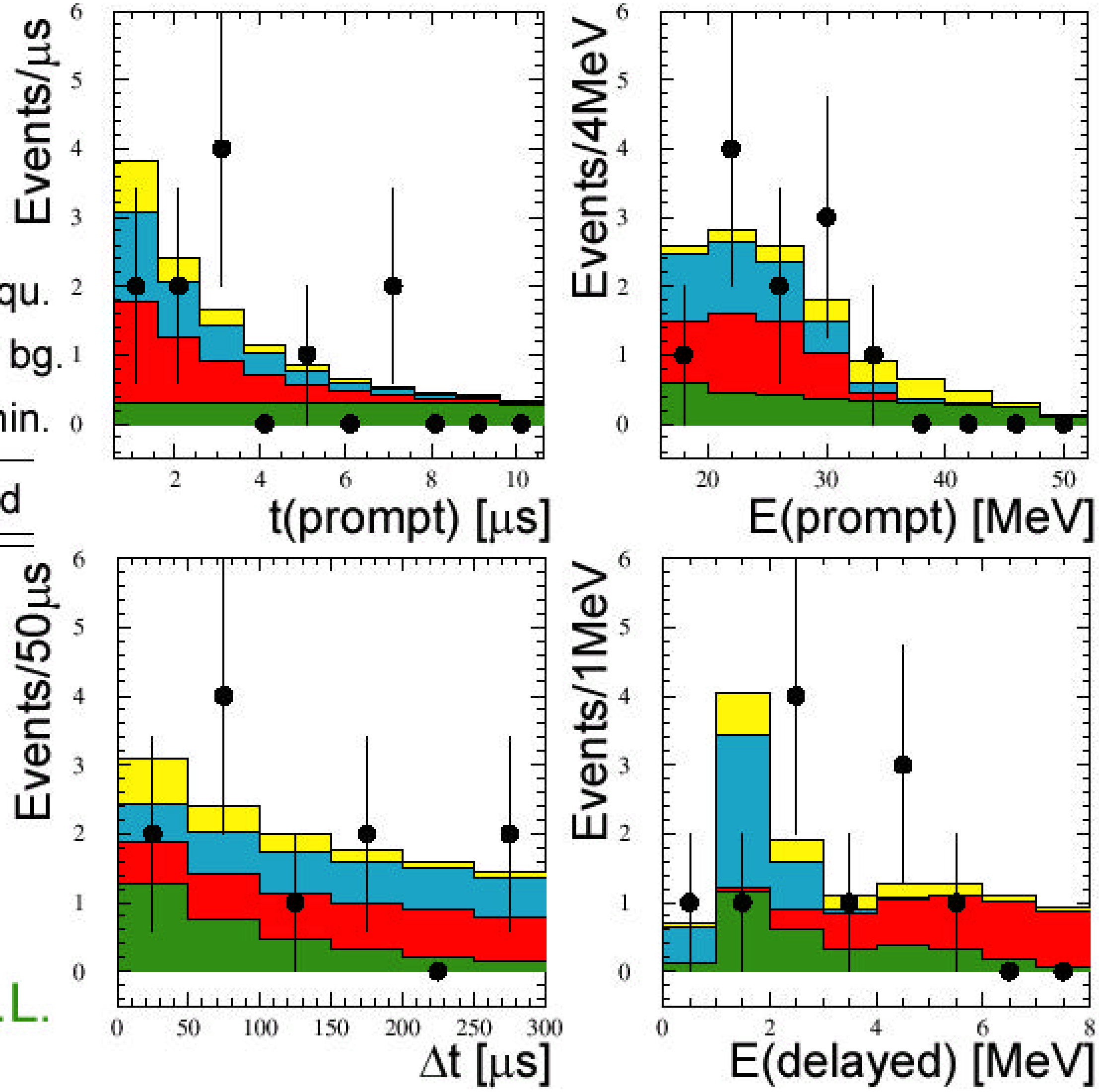
KARMEN Results

11 candidates

3.9 +- 0.5	(red)	ν_e-induced CC sequ.
3.5 +- 0.3	(blue)	ν-induced random bg.
1.7 +- 0.2	(yellow)	$\bar{\nu}_e$ intrinsic contamin.
3.2 +- 0.2	(green)	cosmic background
12.3 +- 0.6		total background

⟹ **no osci signal**

Bayes:
signal > 6.3 evts
excluded @ 90% C.L.



MiniBooNE

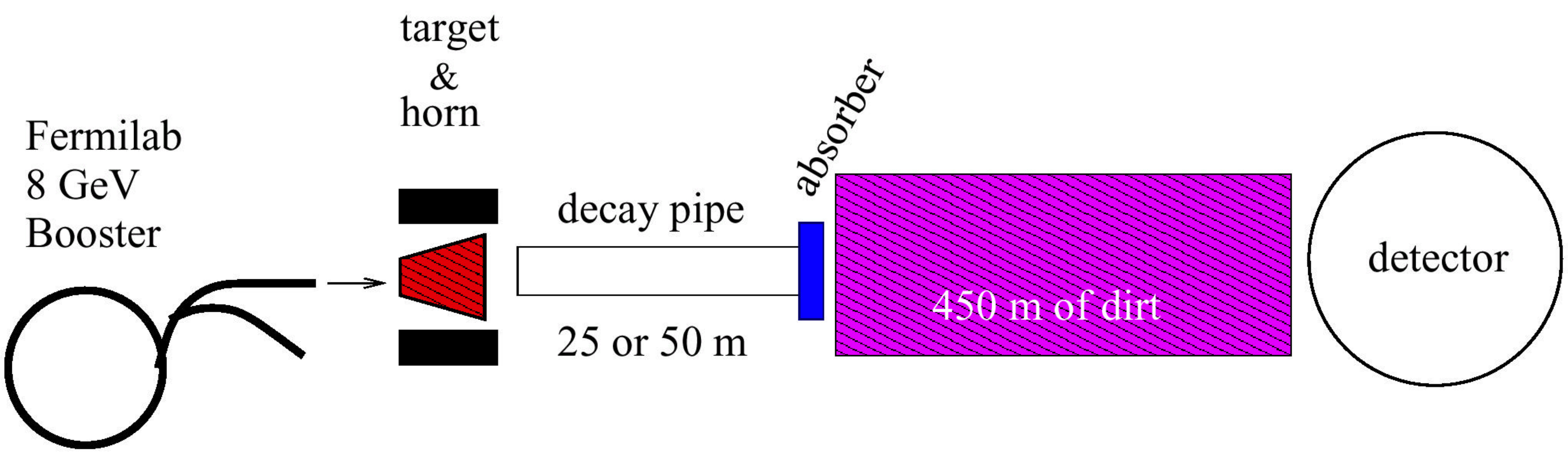
At Fermilab starting soon…..

Search for ν_μ ♦ ν_e appearance

ν_μ disappearance

With *L/E*~1 (same as LSND)

but at order-of-magnitude higher energies

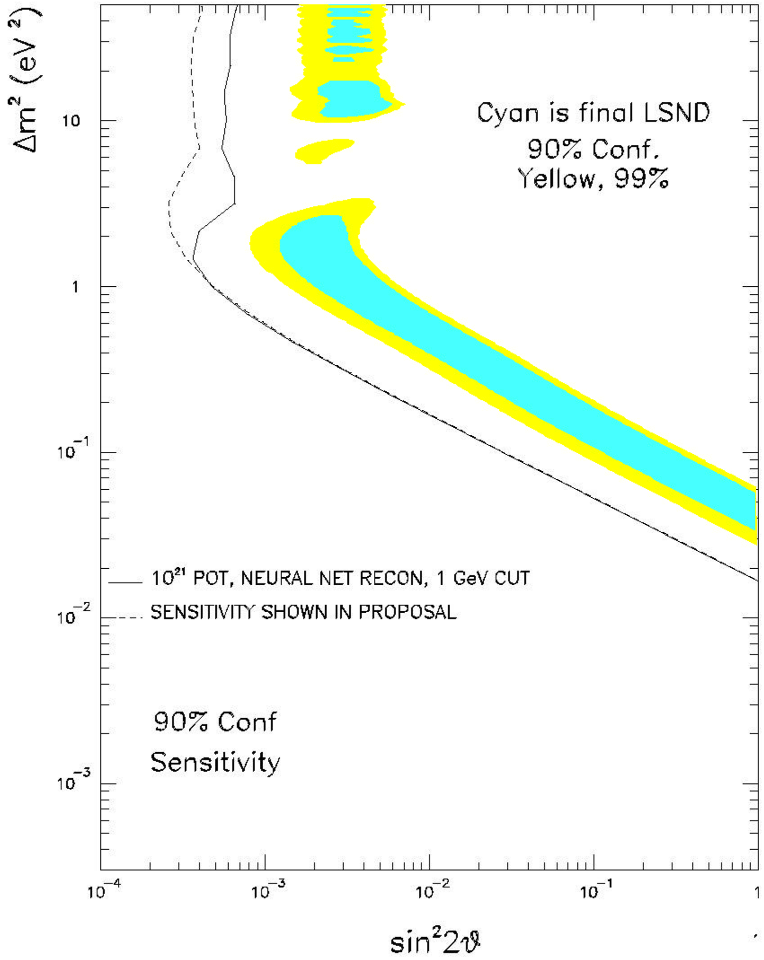


Medium Baseline Summary

LSND observes appearance of ν_μ ♦ ν_e oscillations at relatively high Δm^2 and low mixing angle

KARMEN does not confirm LSND, but does not rule it out.

MiniBooNE will start collecting data in summer 2002, and will make a definitive statement about LSND after two years.

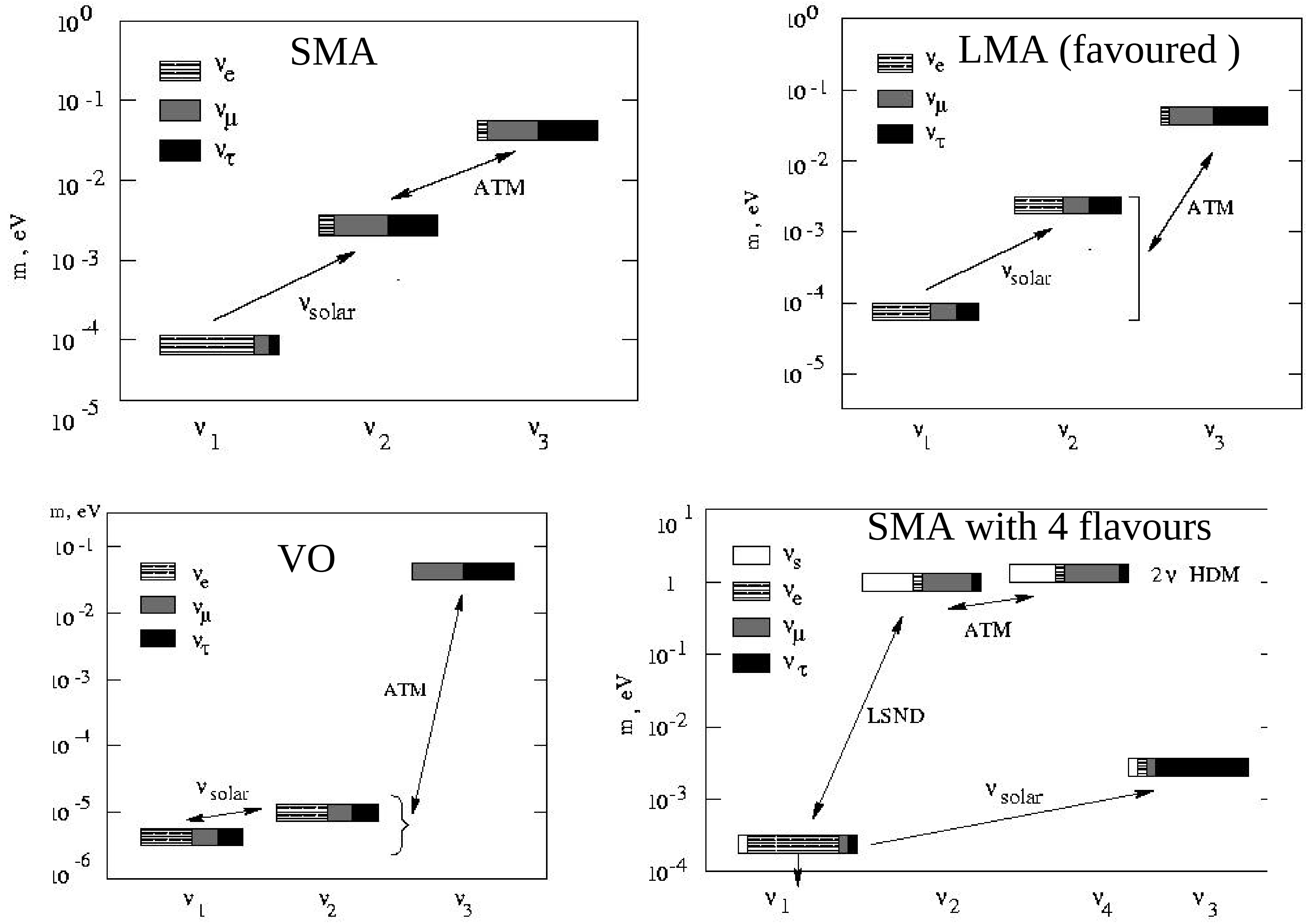


Summary

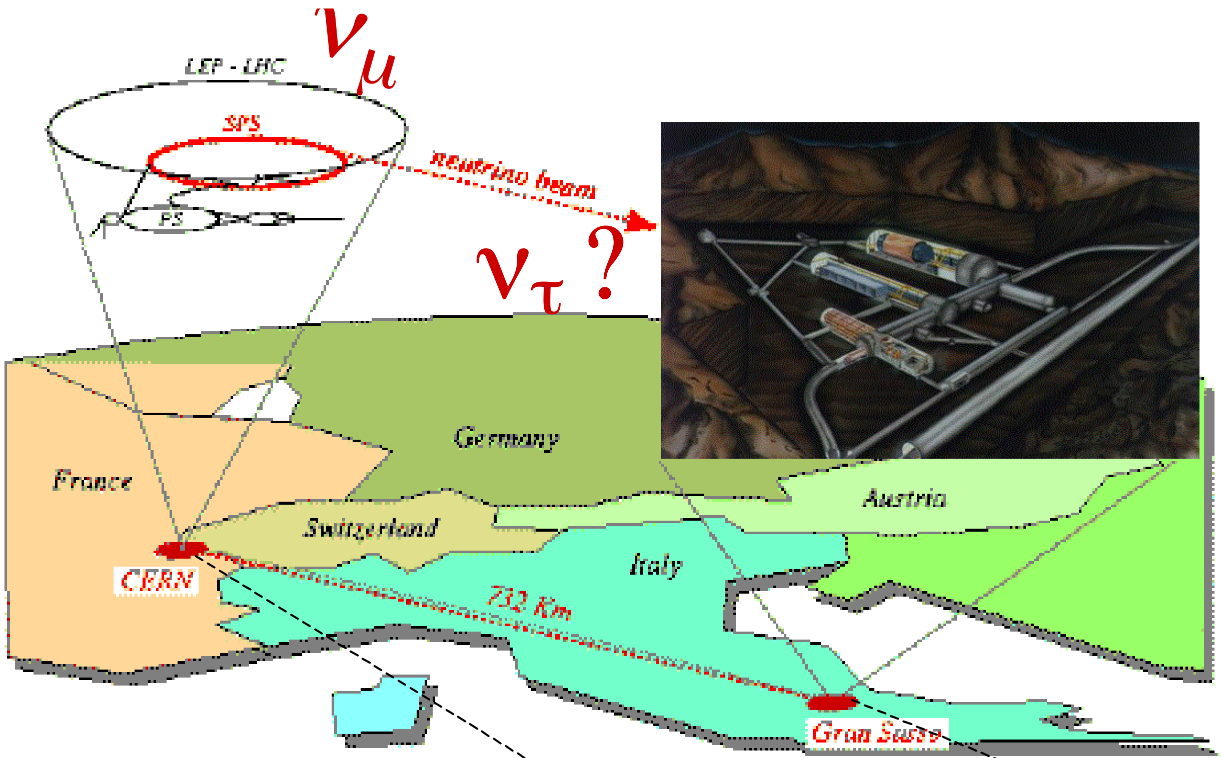
Most people ignore LSND result
From Solar and Atmospheric results situation is clarifying:

$$\begin{array}{lll} \mathrm{SMA:} & \Delta m^2_\odot \simeq (4-10)\cdot 10^{-6}\ \mathrm{eV}^2\,, & \sin^2 2\theta_\odot \simeq (0.1-1.0)\cdot \\ \mathrm{LMA:} & \Delta m^2_\odot \simeq (2-20)\cdot 10^{-5}\ \mathrm{eV}^2\,, & \sin^2 2\theta_\odot \simeq 0.65-0.97 \\ \mathrm{VO:} & \Delta m^2_\odot \simeq (0.5-5)\cdot 10^{-10}\ \mathrm{eV}^2\,, & \sin^2 2\theta_\odot \simeq 0.6-1.0 \\ \mathrm{Atm:} & \Delta m^2_{atm} \simeq (2-6)\cdot 10^{-3}\ \mathrm{eV}^2\,, & \sin^2 2\theta_{atm} \simeq 0.82-1.0 \end{array}$$

Possible Neutrino Masses and Mixings



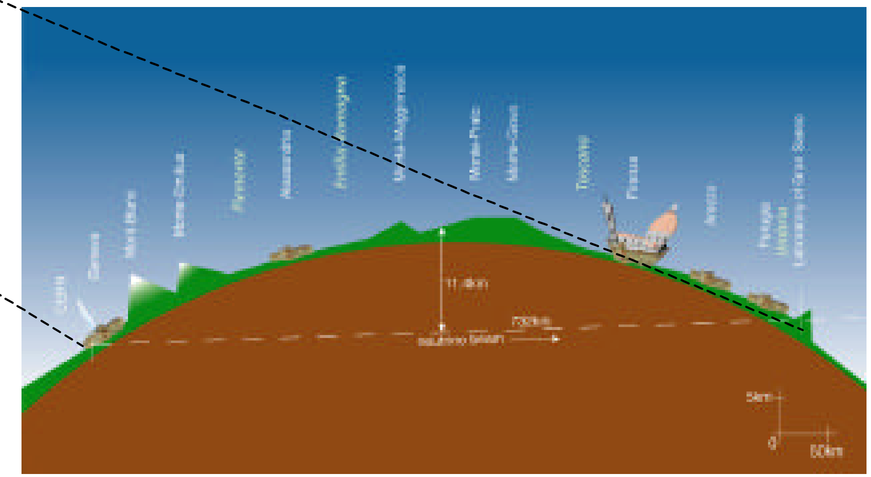
The European Long Baseline Program



CERN
to
Gran Sasso

$< E >_\nu$ = 17 GeV

L = 732 km



Detection of the $\nu_\mu \to \nu_\tau \to \tau^-$ signal and background rejection

ν_μ .... ν_τ $\to$ τ^- + X

oscillation

CC interaction

Decay mode	BR
$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$	18 %
$h^- \ \nu_\tau \ n\pi^o$	50 %
$e^- \ \nu_\tau \ \bar{\nu}_e$	18 %
$\pi^+ \pi^- \pi^- \ \nu_\tau \ n\pi^o$	14 %

ICARUS: Detailed general picture in Liq. Argon

Kinematics *(à la NOMAD)*

Momentum unbalance from unseen ν_τ in τ decay

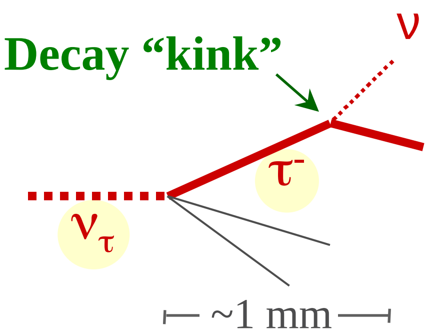
Energy measurement

OPERA: Observation of the decay "signature" at microscopic scale *(à la CHORUS)*

⬇

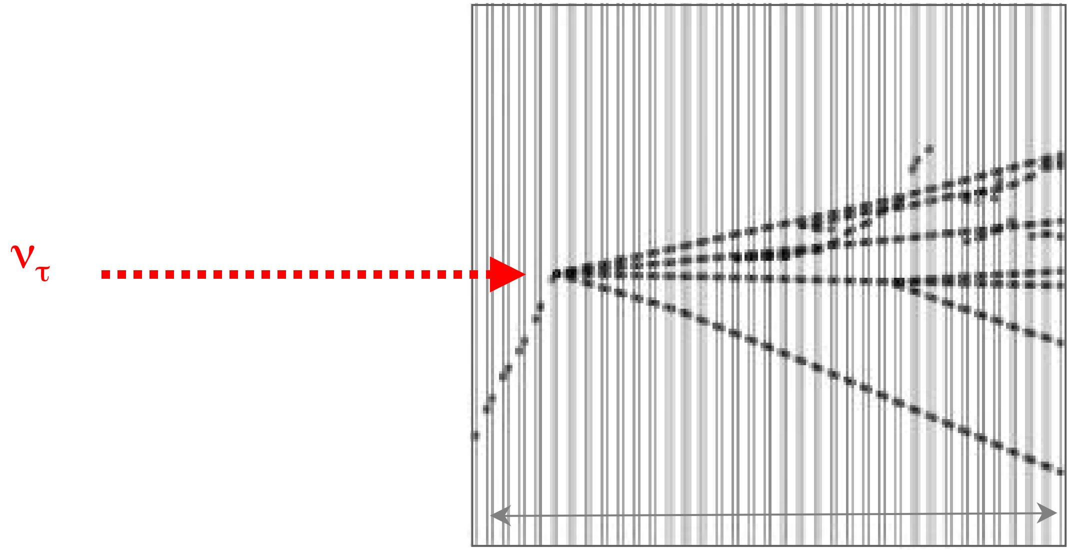
"nuclear" photographic emulsion

(~ **1μm** granularity)



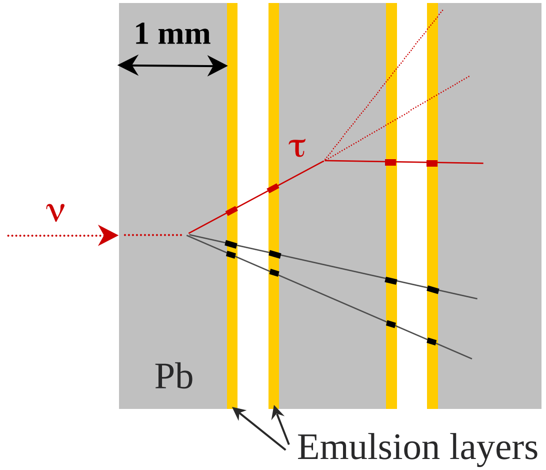
The OPERA experiment

Brick
(56 Pb/Emulsions. “cells”)

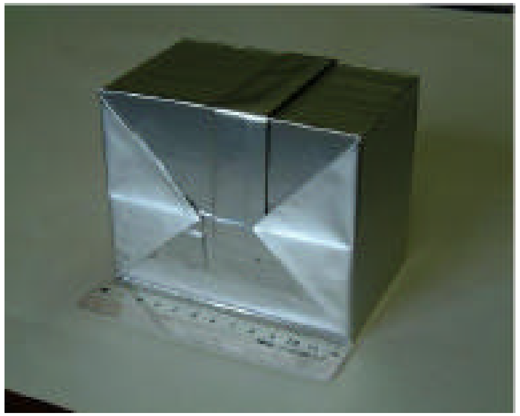


8 cm ($10X_0$)

The experimental technique



- **Emulsion Cloud Chamber (ECC)**
  (emulsions for tracking, passive material as target)
  - Basic technique works
    - charmed “X-particle” first observed in cosmic rays (1971)
    - DONUT/FNAL beam-dump experiment: ν_τ events observed
- **$\Delta m^2 = (1.6 - 4) \times 10^{-3}\ eV^2$** (SuperK) $\rightarrow$ **$M_{target} \sim$ 2 kton** of “compact” ECC (baseline)
  - large detector $\rightarrow$ sensitivity, complexity
  - modular structure (“bricks”): basic performance is preserved



- **Ongoing developments,** required by the large vertex detector mass:
  - industrially produced emulsion films
  - automatic scanning microscopes with ultra high-speed

Experience with emulsions and/or ν_τ searches : E531, CHORUS, NOMAD and DONUT

Sensitivity to $\nu_\mu \rightarrow \nu_\tau$ oscillations

Summary of τ detection efficiencies

(in % and including BR)

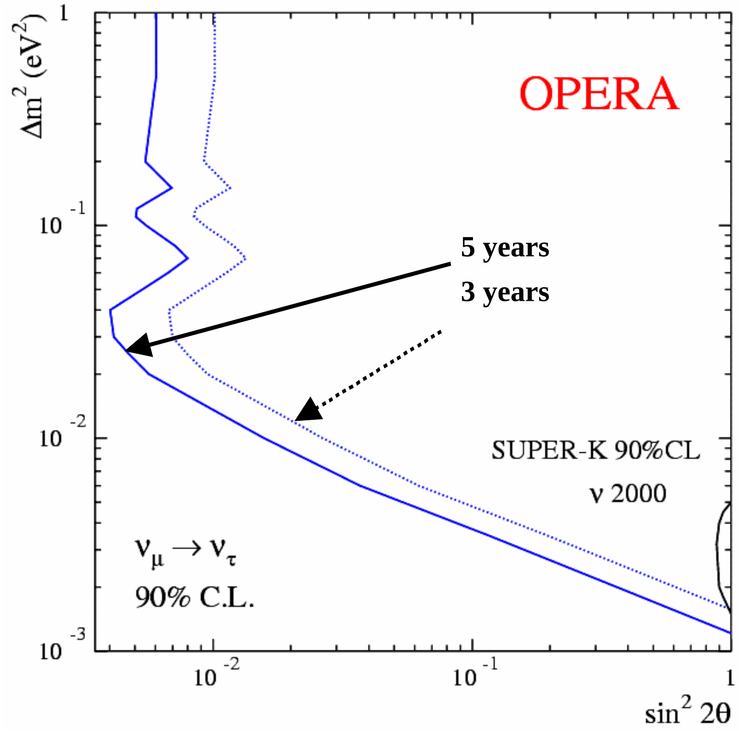
Decay mode	*DIS long*	*QE long*	*DIS short*	*Overall*
τ ♦ *e*	3.0	2.6	1.3	3.7
τ ♦ μ	2.7	2.8	-	2.7
τ ♦ *h*	2.2	2.8	-	2.3
Total	8.0	8.3	1.3	8.7

Expected ν_τ events (**2.25×10^{20} pot, 1.8KTon, accounting for removed bricks**)

$\Delta m^2 (10^{-3}\ eV^2)$

τ *decay*	*1.6*	*2.5*	*4.0*	*b.g.*
e	1.9	4.7	11.8	0.19
μ	1.5	3.5	8.8	0.13
h	1.3	3.0	7.6	0.25
Total	4.7	11.2	28.2	0.57

Events $(\Delta m^2)^2$



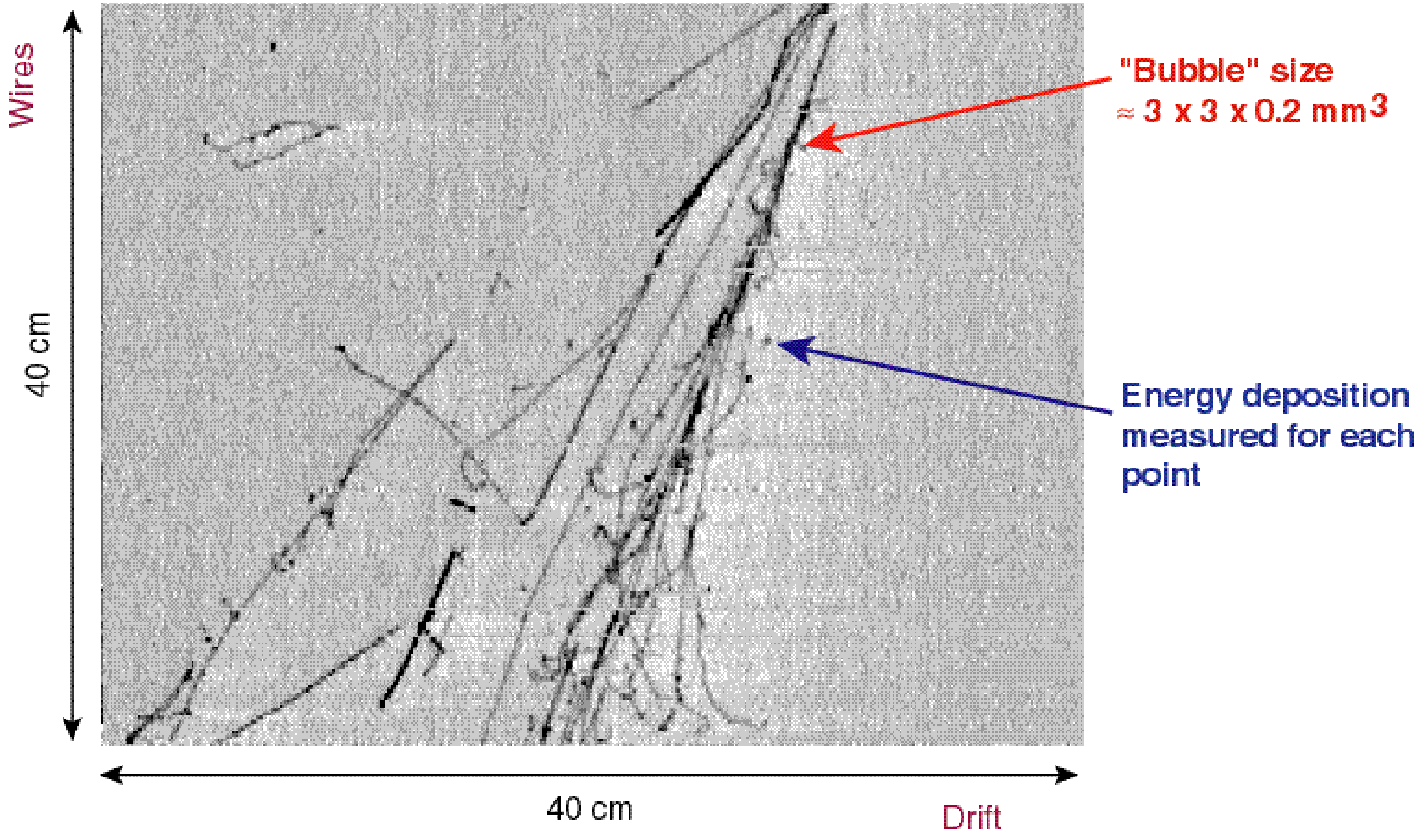
After 5 years data taking

$\Delta m^2 = 1.2 \times 10^{-3}$ eV^2 at full mixing

$\sin^2(2\theta) = 6.0 \times 10^{-3}$ at large Δm^2

The ICARUS experiment

C.R. shower from 3 ton prototype



The ICARUS Liquid Ar Time Projection Chamber

- **Event reconstruction in 3D with measurement of the primary ionization**
  1. drift time
  2. induction wires
  3. collection wires

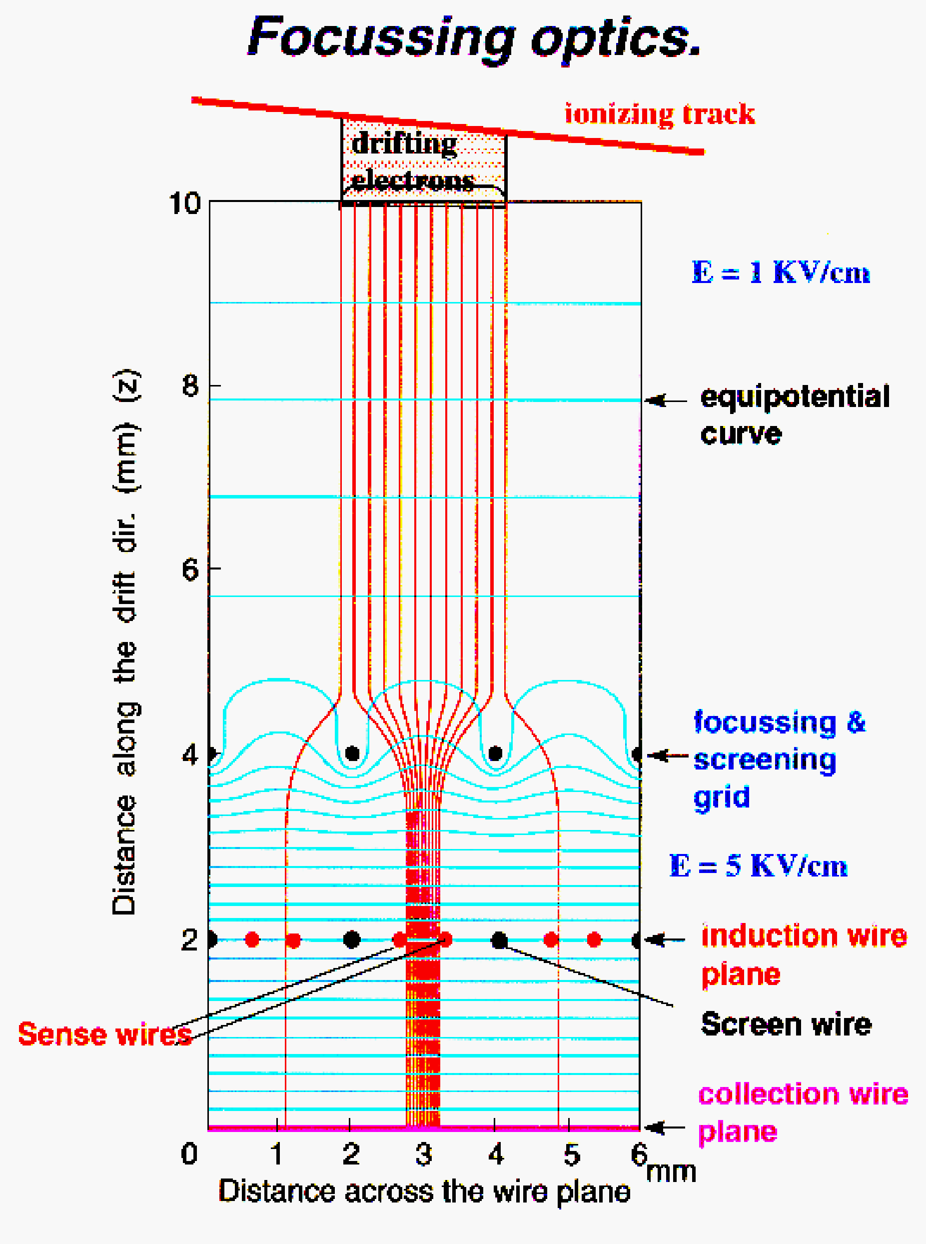
- **Space resolution around 1 mm**

- **Maximum drift length** in the Liq. Ar
  1.5 m in the 600 ton module
  (requiring < 0.1 ppb O_2 equiv. impurities)

- **Calorimetric energy resolution:**

$$\frac{\sigma(E)}{E} \quad \frac{0.03}{\sqrt{E}}(Em.)$$

$$\frac{\sigma(E)}{E} \quad \frac{0.12}{\sqrt{E}}(Hadr.)$$



$\nu_\mu \rightarrow \nu_\tau$ oscillations (Icarus)

- Analysis of the electron sample
  - Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)
  - Exploit the unique e/π^0 separation

$\nu_\mu \longrightarrow \nu_\tau$

$$\nu_\tau + \mathbf{N} \longrightarrow \tau + \mathbf{jet}; \ \tau \longrightarrow e\nu\nu$$

Charged current (CC) Br ~18%

$\Delta m^2 = 3.5 \times 10^{-3} eV^2$

$110 \ \ events$

Background:

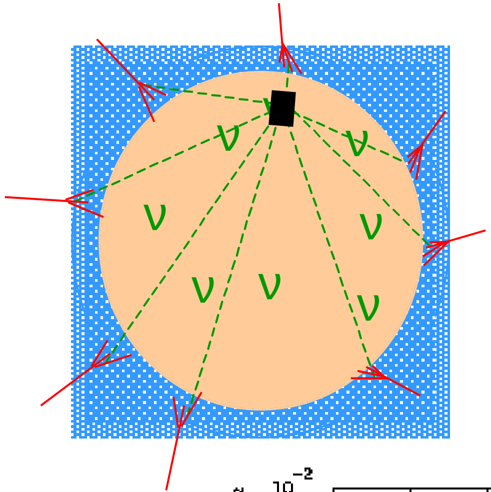
$$\nu_e + \mathbf{N} \longrightarrow \mathbf{e} + \mathbf{jet}$$

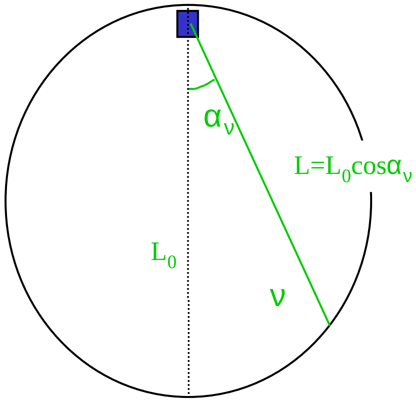
Charged current (CC)

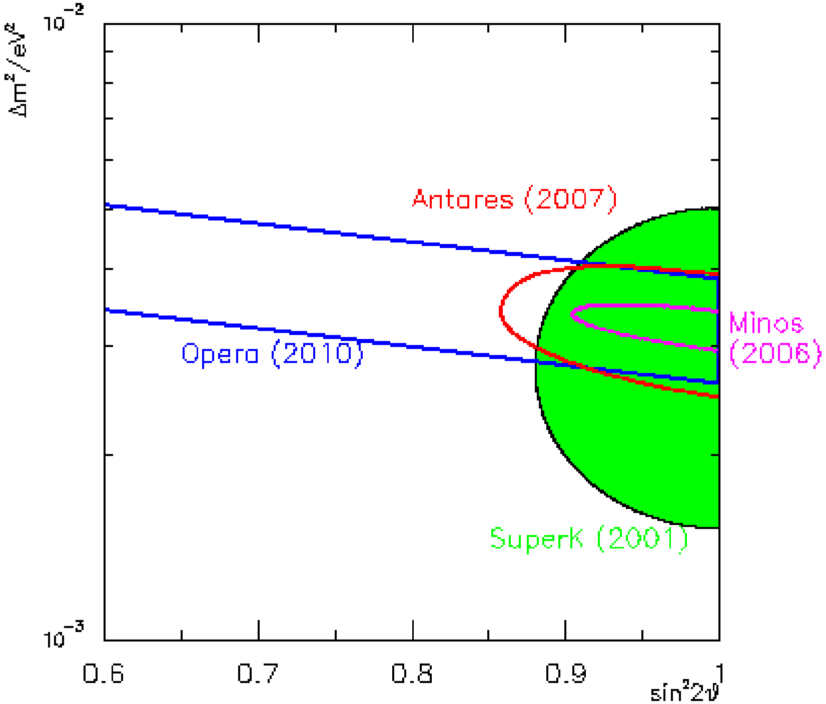
$470 \ \ \nu_e CC$

Statistical excess visible before cuts ⇒ this is the main reason for performing this experiment at long baseline !

Atmospheric Neutrinos Oscillations in ANTARES

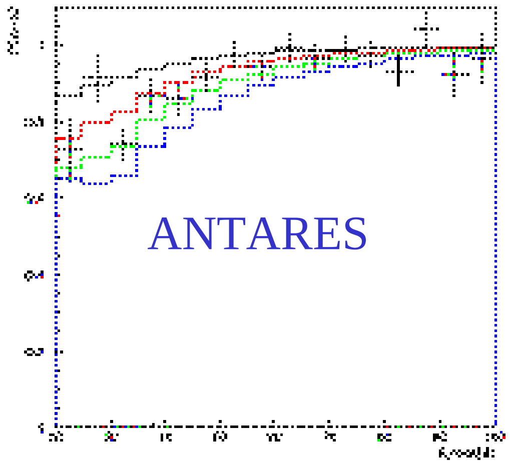


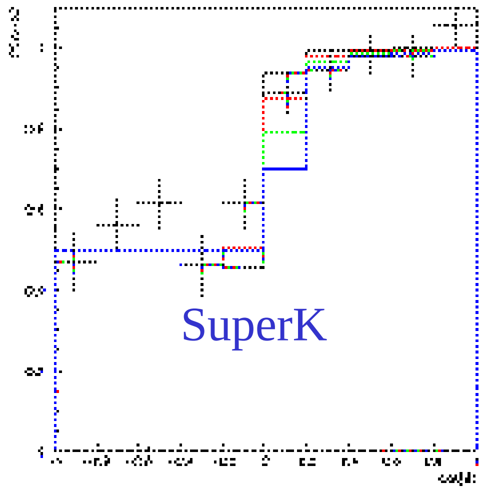




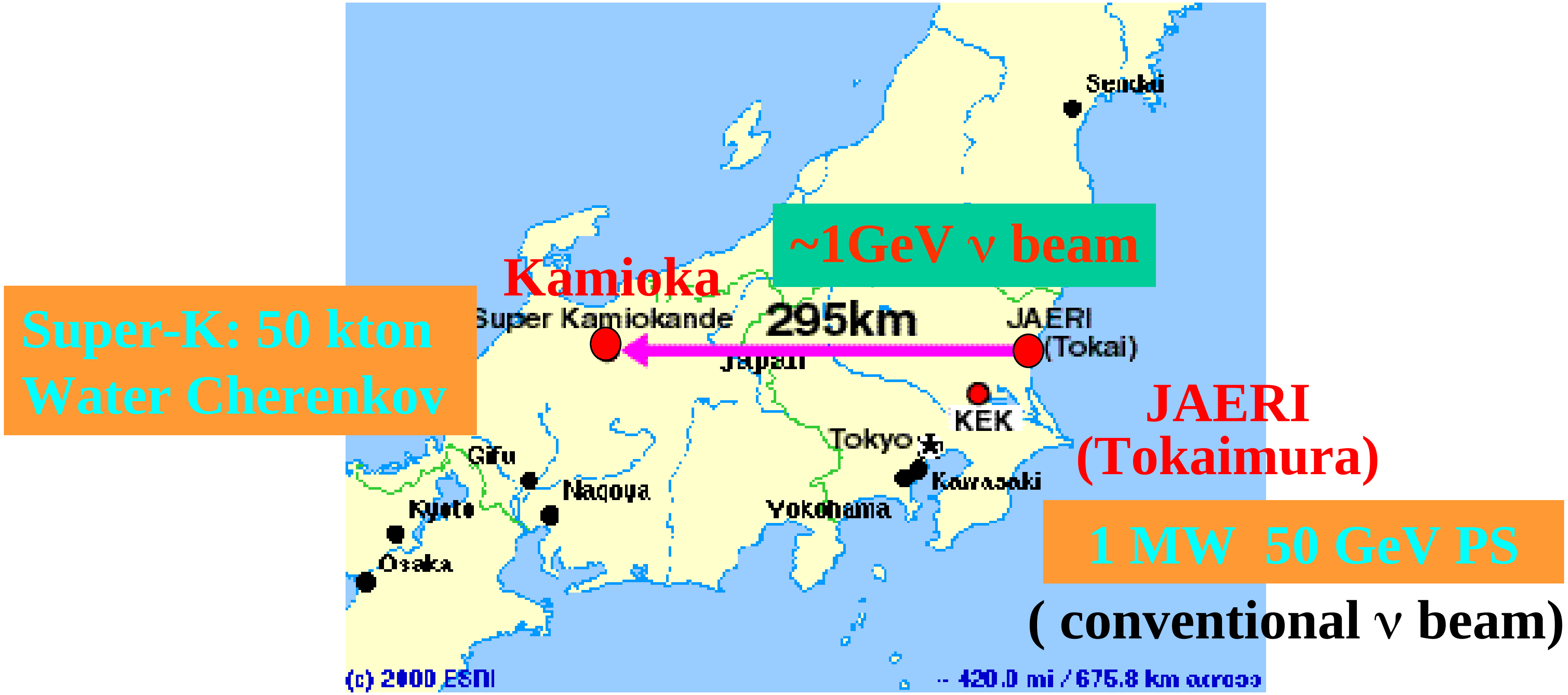
Precision in Δm^2 ANTARES vs. SuperK

Δm^2 = 0.002, 0.003, 0.004, 0.005 eV^2





JHF-to-SK Neutrino Project



- **νμ_ νx** disappearance__δ_Δm_{23}^2__10^{-4} eV^2, δ_$\sin^2 2\theta_{23}$__0.01
- **νμ_ νe** appearance $\sin^2 2\theta_{13}$__0.01
- NC measurement ν_μ _ ν_τ / ν_μ _ ν_s

MNS Matrix and Parameters

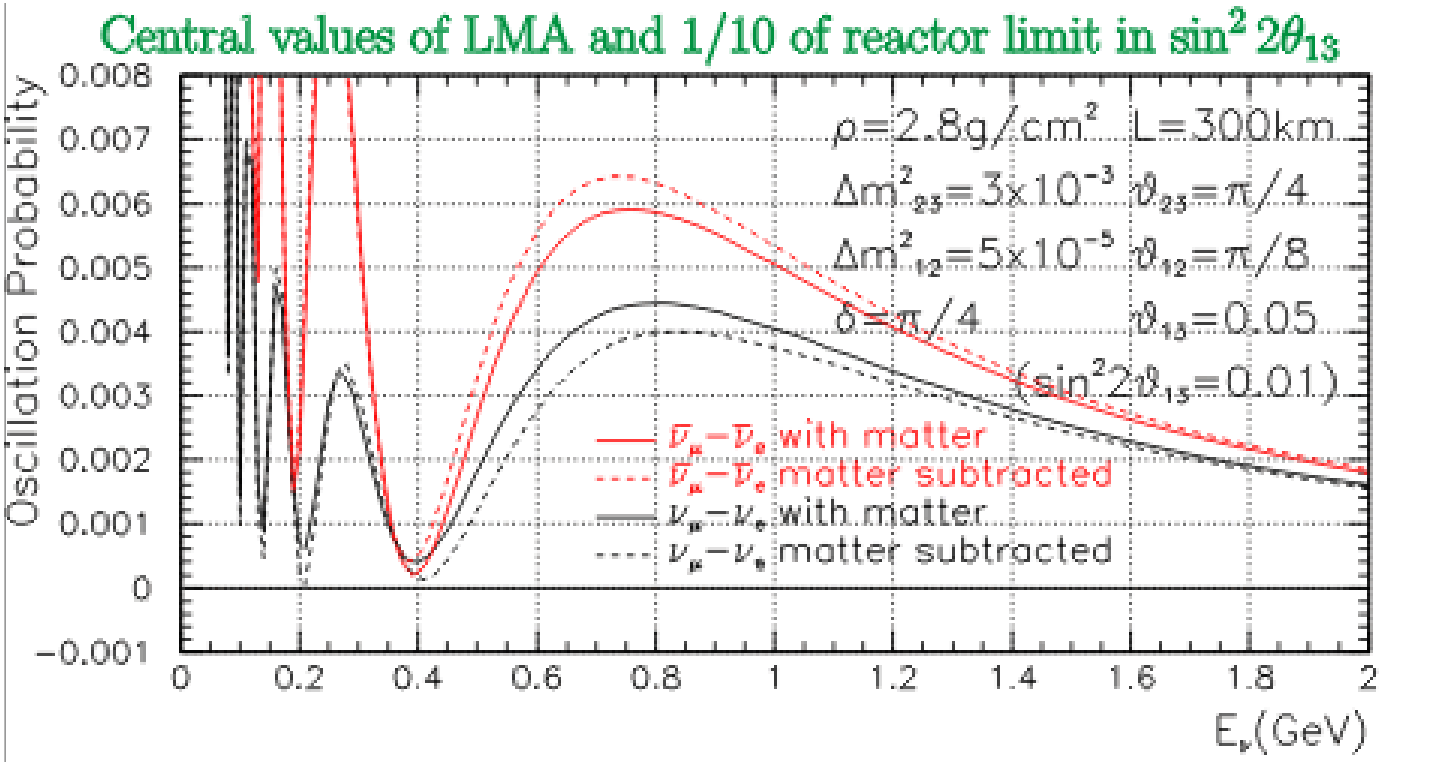
- MNS mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- **three mixing parameters** $\theta_{12}, \theta_{13}, \theta_{23}$
- **violating phase** δ
- **mass-squared differences** $\Delta m^2_{21}, \Delta m^2_{32}$

CP Violation

$$A_{CP} = \frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}$$
$$= \frac{1.27\Delta m_{12}^2 L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot sin\delta$$



Neutrino Oscillations

Situation rapidly developing

LSND result a mystery - to be resolved by MiniBoone

Longbase experiments in progress

Neutrino Factories being proposed