τ detection and ν oscillation

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Prof. Jean SACTON

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Contents

- The neutrino identity (brief)
- Limits on neutrino masses
- Neutrino oscillation phenomenology (brief)
- Status of search for neutrino oscillation
- OPERA : search for $\nu_\mu \Leftrightarrow \nu_\tau$ oscillation in LBL accelerator experiment (refer to K.Niwa's talk)
- The neutrino mass and the mass budget of the Universe (if time allows)

The Standard Model neutrino

- **The electron-neutrino ν_e is the**
  massless,
  chargeless,
  colourless,
  spin 1/2,
  partner of the electron in the left handed SU(2) × U(1) lepton doublet

- **Neutrinos also exist in 3 families like the other fermions**
  (measured at LEP from the width of the Z^0; why? why 3?)

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

- **The lepton numbers L_e, L_μ, L_τ are conserved independently**

$$B.R.(\mu^- \to e^- \gamma) < 5 \times 10^{-11}$$

- **Only ν_L and $\bar{\nu}_R$ have CC and NC weak interactions (P conservation is fully violated)**

- **If they exist, ν_R and $\bar{\nu}_L$ are sterile**

Massless ν and $\bar{\nu}$ are distinct by their observable helicity
$\equiv$ invariant chirality

Massless neutrinos may not be overtaken and their spin cannot be flipped

What if neutrinos have (even tiny) mass
Dirac or Majorana neutrinos?

- $\bar{\nu}_{+}$ **emitted in** β^{-} **decay has v**$_{\nu}$**<c**

  may be overtaken and undergo spin flip $\rightarrow$ $\bar{\nu}_{-}$
- **Is it different from the** ν_{-} **emitted in** β^{+} **decay? They only differ by** L

If yes: Dirac neutrinos, like other fermions, distinguished by $L = \pm 1$ **eigenvalues**

If no : Majorana neutrinos, $\nu \equiv \bar{\nu}$

apparent distinction is artefact of - their V-A interactions

- the difficulty to "flip spin"

Limits on the neutrino masses:
1/ Direct measurements from decay kinematics

- $m_{\nu_e} < 2.2 - 2.3\ eV$ @ 95% C.L.

  from end of E_{e^-} spectrum in $^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

  (Troitsk and Mainz experiments, 2000)

- $m_{\nu_\mu} < 170\ keV$ @ 90% C.L

  from E_{μ^+} in $\pi^+ \rightarrow \mu^+ \nu_\mu$

  (Assagam et al, PSI, 1996)

- $m_{\nu_\tau} < 18.2\ MeV$ @ 90% C.L

  from phase space in $\tau^\pm \rightarrow 3(5)\pi^\pm \nu_\tau (\bar{\nu}_\tau)$

  (LEP -ALEPH 2000)

Limits on the neutrino masses:
2/ Big Bang cosmology

- At $T \approx 2\times 10^{10}\,K \approx 2\;MeV \gg m_\nu \qquad (t = (1/kT)^2 \approx 0.25\;s)$

  γ and $\nu/\bar{\nu}$ decouple : $\nu + \bar{\nu} \not\leftrightarrow \gamma + \gamma$

  $n_\nu \approx n_\gamma$

  $T_\nu \approx T_\gamma$

- Taking account of
  - the thermodynamics of fermions/bosons
  - the adiabatic expension of the univers
  - γ and e^+/e^- decouple: $e^+ + e^- \not\leftrightarrow \gamma + \gamma$ at $T \approx m_e \approx 0.5\;eV$

$$n_\nu^0 = \frac{3}{11} n_\gamma^0 (= 412\;cm^{-3}\;) = 113\;cm^{-3} \text{ at present epoch}$$

$$T_\nu^o = (\frac{4}{11})^{1/3} T_\gamma^0 (= 2.73\;K) = 1.9\;K \approx 2\times 10^{-4}\,eV$$

- **Yet undetected primeval neutrinos are non-relativistic if $m_\nu > 10^{-4}$ eV**

$$m_\nu \times n_\nu^0 = \rho_\nu^0 < \rho_c = \frac{3H_0^2}{8\pi G_N} \approx 4.5\ keV\ cm^{-3}$$

with $H_0 = 65 \pm 7\ km\ s^{-1}\ kpc^{-1}$

⇓

$$\sum_i m_{\nu_i} \leq 60\ eV$$

Limits on the neutrino masses:
3/ Supernovae SN1987A

- **February 23, 1987, 7h33 UT, 23 neutrino interactions in 3 underground experiments (Kamiokande, Japan; IMB, Ohio; Baksan, Caucase) in 12.3 s time gate**

- **SN1987A: death of Sanduleak in LMC at *150 000 ly***
  SN-II models: 99% of $\sim 2.\ 10^{46}$ *J* released $\rightarrow \sim 10^{58}\ \nu$ with $\langle E_\nu \rangle = 10$ *MeV*

  after *150 000 y* : *10s* flash of $\sim 4.\ 10^{43}\ \nu$ cross the Earth

- **From measured and model energy spectrum**
  model emission time dispersion
  measured arrival time dispersion

  ⇓

Confirmation of the SN-II models

$$m_{\bar{\nu}_e} \leq\sim 25\ eV$$

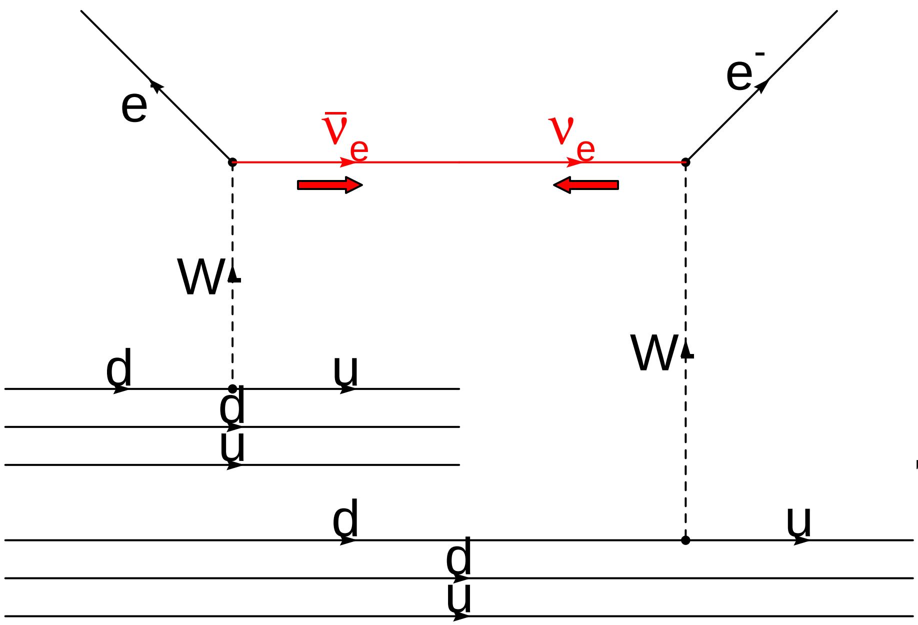
- **Identical fluxes of all ν and $\bar{\nu}$ species expected**

  Events expected to be $\bar{\nu}_e$ (much larger $\bar{\nu}_e + n \rightarrow e^- + p$ cross-section)

Limit on the neutrino masses:
4/ 0νββ decay experiments

- **The nuclear $0\nu\beta\beta$ decay experiment is THE ν spin-flip experiment**

$$(A,Z) \rightarrow (A,Z+2) + 2\,e^- \qquad\qquad \Delta L = 2$$



Process possible if the

emitted right-handed $\bar{\nu}_e$ together with e^-

absorbed as left-handed ν_e to produce e^-

Massive Majorana neutrino :

$\nu_e \equiv \bar{\nu}_e$ and spin flipped

$$T_{1/2}(\,^{76}_{32}Ge \rightarrow \,^{76}_{34}Se + 2e^-\,) > 10^{25}\,y \quad @90\%\ C.L.$$

$$m_{\nu_e} \leq 0.46\ eV$$

Massive neutrinos: Mixing & Neutrino oscillations

B.Pontecorvo
1957
B.Pontecorvo, V.N. Grimov
1967

$\nu_l \qquad l = e, \mu, \tau$ family eigenstates

$\nu_k \qquad k = 1,3$ mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \left.\begin{array}{l} \nu_l = \sum_{k=1,}^{3} U_{lk}\, \nu_k \\ \sum_{k=1,}^{3} |U_{\alpha k}|^2 = 1 \end{array}\right\} \; l = e, \mu, \tau$$

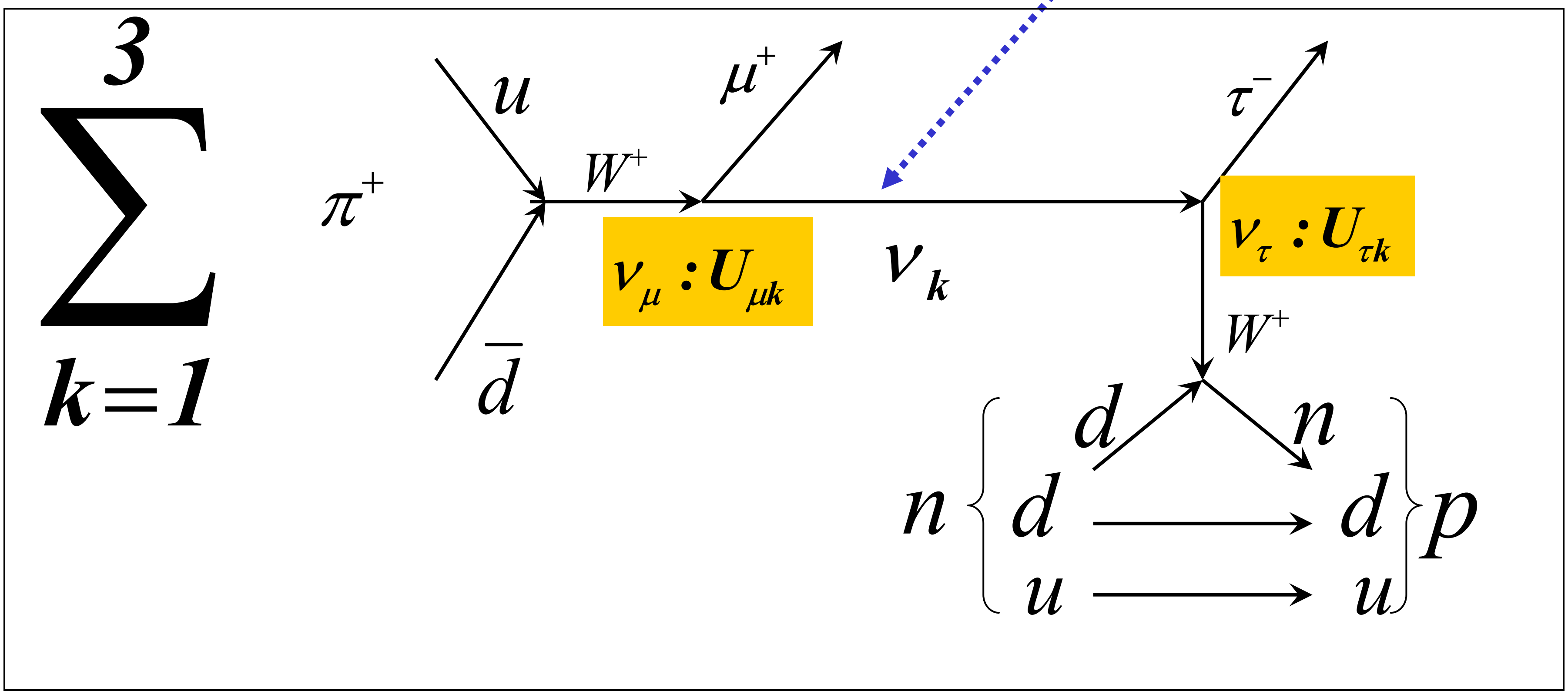
4 (6) parameters $\left\{ \begin{array}{l} 3\ |U_{lk}| \\ 1\ (3)\ \text{phases} \end{array} \right.$
Dirac (Majorana)

Straightforward extension to more than 3 neutrinos families, e.g. sterile neutrinos

Oscillation cannot distinguish Dirac from Majorana neutrinos

Propagation phase

$$E \approx p >> m \;\Rightarrow\; e^{-i(E_k t - p_k L)} \approx e^{-i(m_k^2/(2E))L}$$



Coherent propagation of different mass eigenstates over long *L*

Oscillation probability (in practical units)

$$P(\nu_l(L=0) \rightarrow \nu_{l'}(L)) = \delta_{ll'} -$$

$$4\,\mathrm{Re}\Big(\underbrace{\sum_{k,k'>k}^{1,3} \underbrace{U^*_{l'k}U_{l'k'}U_{lk}U^*_{lk'}}_{\text{Mixings define Maximum probability}} \quad \underbrace{\sin^2 1.27\,\frac{\Delta m^2_{kk'}[eV^2]\; L[km]}{E[GeV]}}_{L/E\ \text{Oscillation term}}}_{\text{Sum on pairs of mass eigenstates}}$$

$$\Delta m^2_{kk'} = m^2_k - m^2_{k'} \qquad \Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$$

Neutrinos oscillate if massive and masses are non degenerate

and

if mixing between mass and weak eigenstates

One mixing negligible : effective 2-family approximation

e.g. $\nu_\tau \approx \nu_3$ $\quad U \approx \begin{pmatrix} \cos\theta_{e\mu} & \sin\theta_{e\mu} \\ -\sin\theta_{e\mu} & \cos\theta_{e\mu} \end{pmatrix}$ 1 mixing angle, no phase

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{e\mu} \quad \sin^2(1.27 \quad \frac{\Delta m^2_{12}\ L}{E})$$

All mixings small : effective 2-family approximation

all $\nu_l \approx \nu_k$ $\quad U \approx \begin{pmatrix} 1 & \theta_{e\mu} & \theta_{e\tau} \\ -\theta_{e\mu} & 1 & \theta_{\mu\tau} \\ -\theta_{e\tau} & -\theta_{\mu\tau} & 1 \end{pmatrix}$

$$P(\nu_l \to \nu_{l'\neq l}) = (2\theta_{ll'}) \quad \sin^2(1.27 \quad \frac{\Delta m^2_{kk'}\ L}{E})$$

Strong mass hierarchy : effective 2-family approximation

if $m_3 \gg m_1, m_2$ like quarks and charged leptons

$\Delta m^2 = m_3^2 - m_1^2 \approx m_3^2 - m_2^2$

$\delta m^2 = m_2^2 - m_1^2$

$\Delta m^2 \gg \delta m^2$

$\Downarrow$

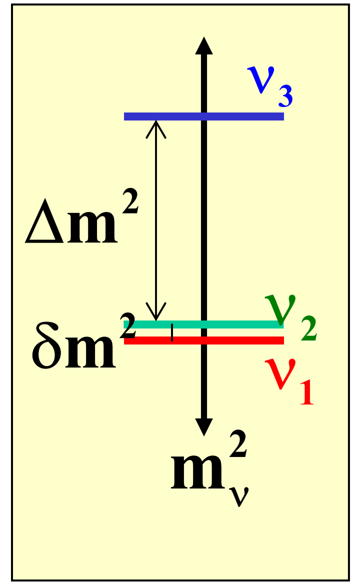
L/E region where $\Delta m^2 L/E$ causes oscillation

and $\delta m^2 L/E \approx 0$

$\Downarrow$

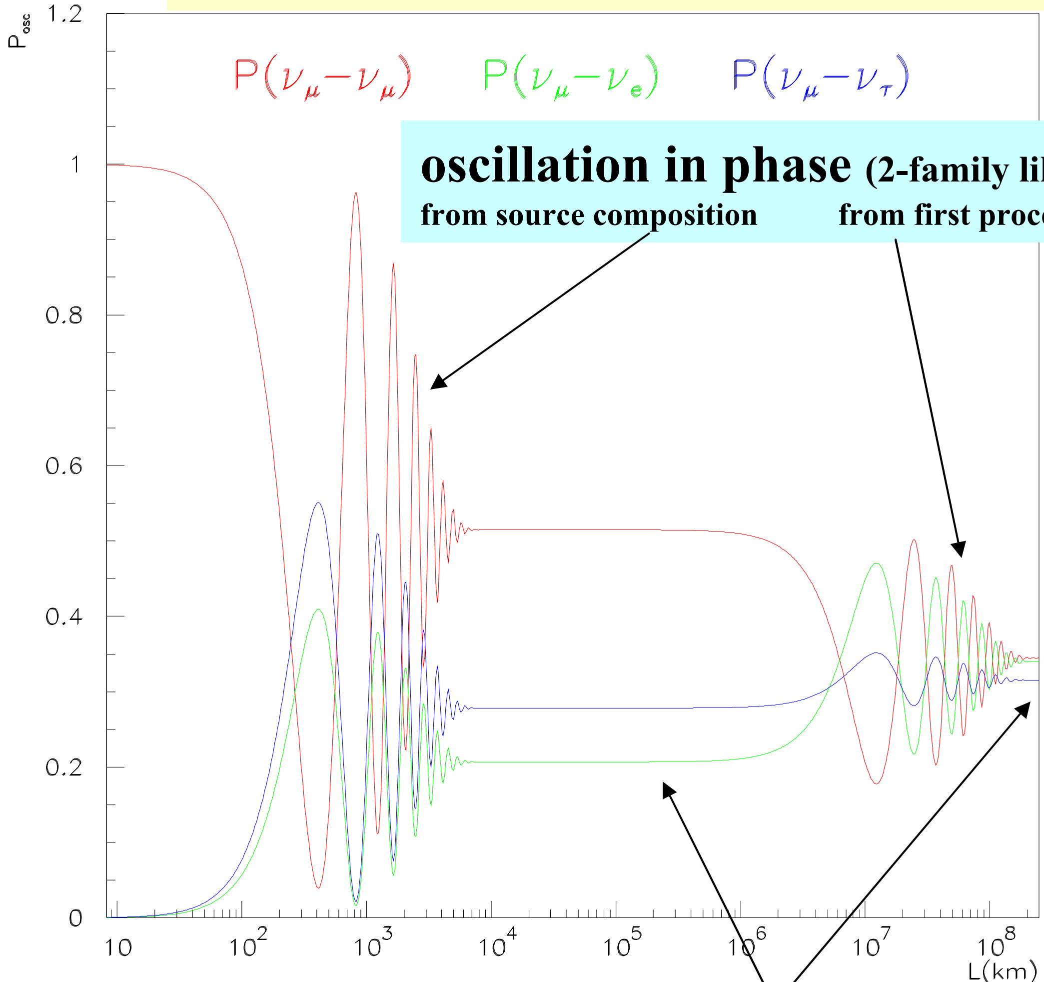
$$P(\nu_l \to \nu_{l'\neq l}) \approx \sin^2 2\theta_{ll'}^{eff} \sin^2(1.27\Delta m^2 E/L)$$

$$\sin^2 2\theta_{ll'}^{eff} = 4|U_{l3}U_{l'3}|^2$$



Physics governed by: • Δm^2
• family composition of ν_3 only

Example of 2-family approximation: large mixing and strong mass hierarchy



oscillation in phase **(2-family like)**

from source composition **from first process**

$E = 1GeV$

strong mass hierarchy

$\Delta m^2 = 3 \times 10^{-3} eV^2 \rightarrow \lambda = 825km$

$\delta m^2 = 1 \times 10^{-7} eV^2 \rightarrow \Lambda = 2.5 \times 10^7 km$

large mixing

$$U = \begin{pmatrix} -0.567 & 0.820 & -0.0782 \\ 0.515 & 0.279 & -0.811 \\ 0.643 & 0.500 & 0.580 \end{pmatrix}$$

oscillation damping for large Δm^2
dispersion and resolution in L/E

$$\left\langle \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)\right\rangle \Rightarrow \frac{1}{2}$$

Matter effect on neutrino oscillations

- **Propagation phase in matter for weakly interacting particles**

$$e^{ipx}e^{-iEt} \Rightarrow e^{i\mathbf{n}px}e^{-iEt} \qquad n = 1 + 2\pi\rho f(0)/E$$

$$E_\nu = 1MeV: \qquad 0 < |n-1| = 6.10^{-19}\frac{Z}{A}\rho\,[g\ cm^{-3}] \ll 1$$

- $\nu_e, \nu_\mu, \nu_\tau, \nu_s$ **have different interactions thus** $n_{e,\mu,\tau,s}$ **:**

$$\nu_{e,\mu,\tau} + e^-, q \rightarrow \nu_{e,\mu,\tau} + e^-, q \qquad \text{(NC)}$$

$$\nu_e + e^- \rightarrow e^-\nu_e \qquad \text{(CC)}$$

$$\nu_s \qquad \text{no interaction}$$

- **Mass eigenstates have different family eigenstates composition**

$\Rightarrow$ **Coherence of mass eigenstates propagation is affected by matter**

Matter effect on neutrino oscillations

Oscillation enhancement

Oscillation can be enhanced by matter and is maximum for given electron density $\rho_R(E \mid \Delta m^2, \theta)$ where mixing is full even if mixing in vacuum is extremely small

MSW effect

If neutrinos travel through medium where ρ_e varies and crosses slowly ρ_R (e.g. through the Sun): ν_e created in the Sun core may disappear totally into ν_μ by reaching the Sun surface.

Energy spectrum distortion

$\rho_R = \rho_R(E)$

Solar neutrino oscillation experiments

Firsts experimental hints of neutrinos oscillation dates back from 1968

The solar neutrino deficit problem

Radiochemical

$\nu_e + (Z,A) \rightarrow e^- + (Z+1,A)$

$\tau(Z,A+1) \approx 10$ days

Counting experiment

Low E threshold

Experiments

Water Cerenkov

$\nu + e^- \rightarrow \nu + e^-$

$\nu_e + e^- \rightarrow e^- + \nu_e$

High E threshold

Measure E, θ, t

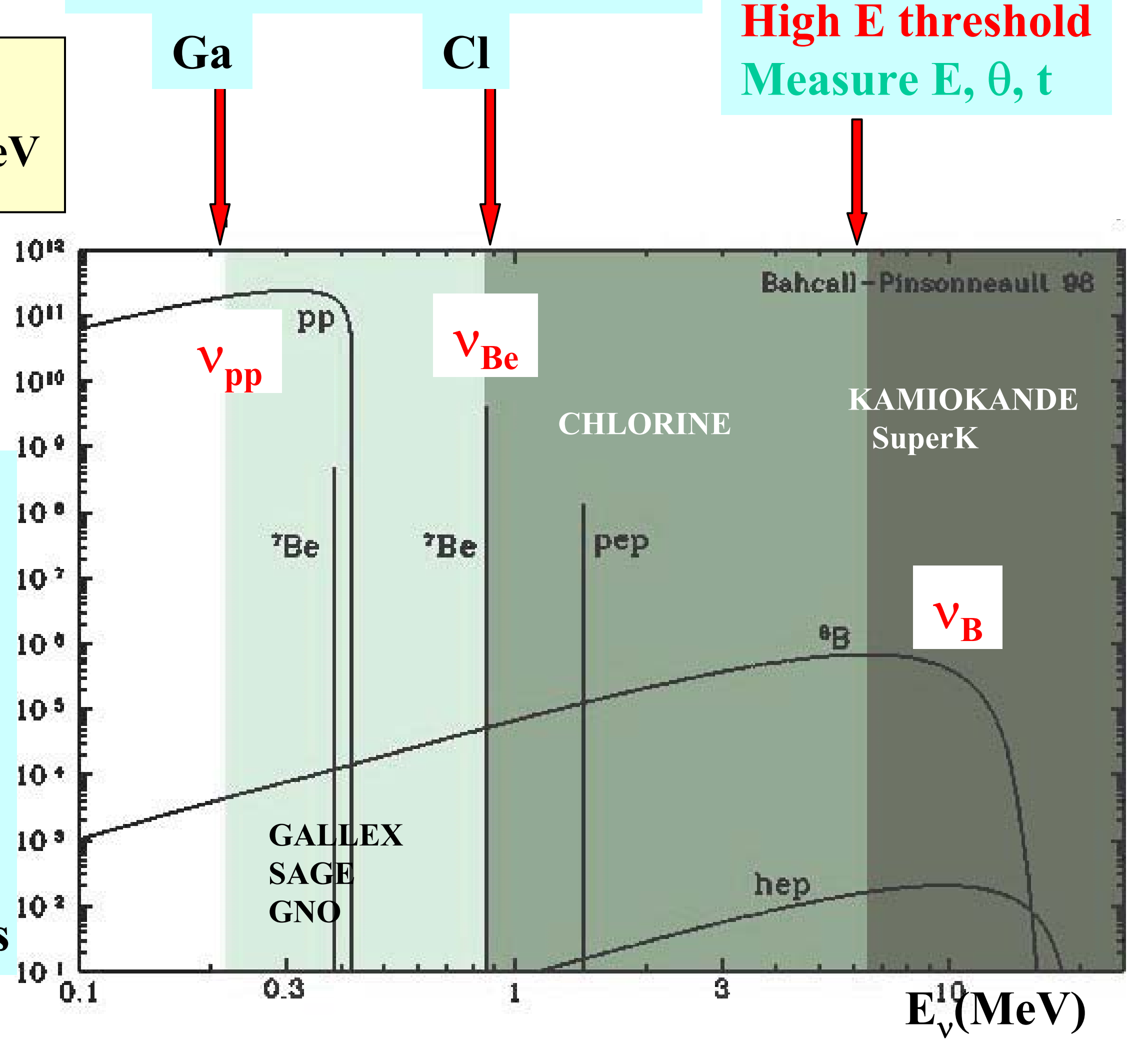
nuclear fusion pp cycle

$4\ {}^1H \rightarrow {}^4He + 2\ e^+ + 2\ \nu_e + 25\ MeV$

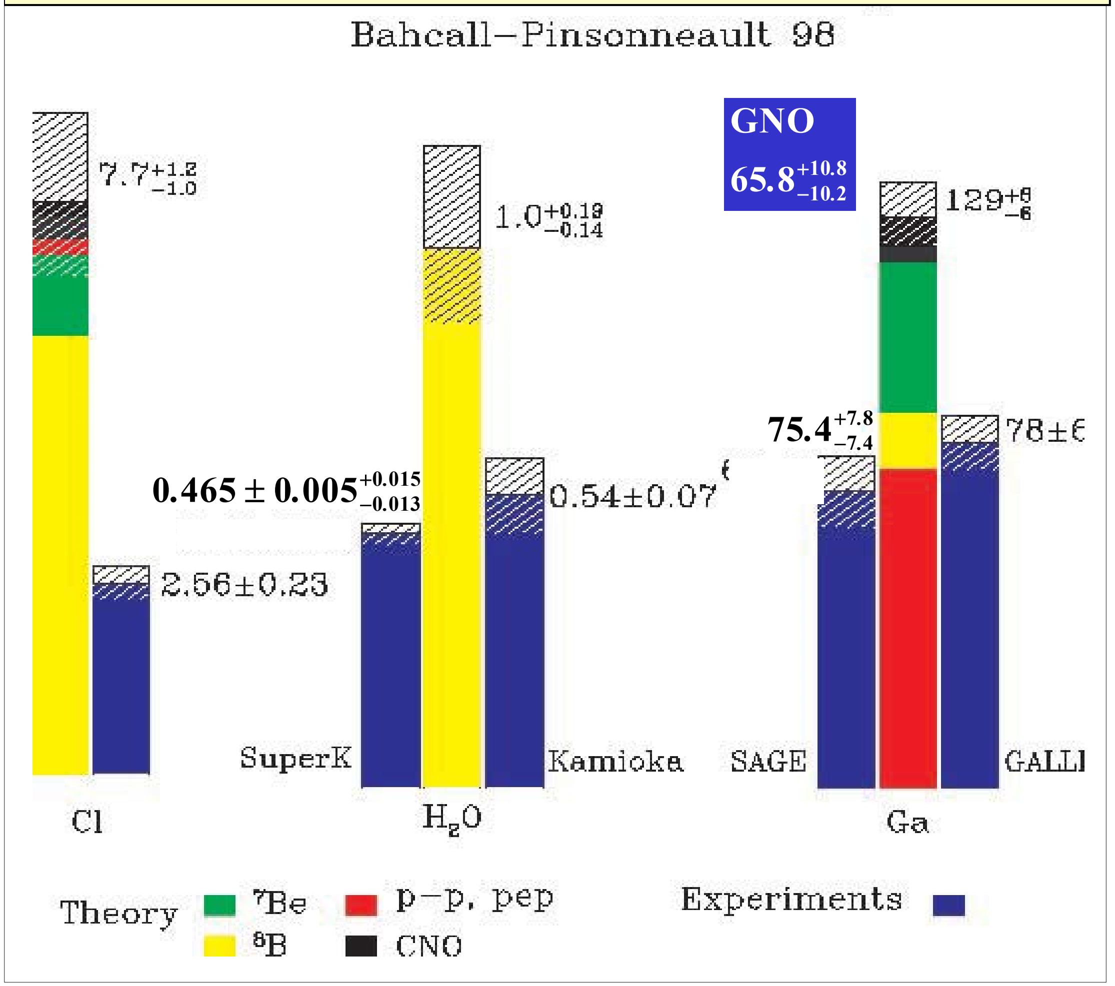
$\Phi(Sun) = 1.8 \times 10^{38} \nu_e\ s^{-1}$

$\Phi(Earth) = 6.5\ 10^{10}\ \nu_e\ cm^{-2}\ s^{-1}$

- ν_{pp} 99.75% of flux:
  - bound by Sun luminosity
  - very low energy
  - very difficult to detect
  - extremely low rate
- Strong correlation $\nu_{Be} - \nu_B$ fluxes



Measured event rates v.z. SSM predictions



Overall flux deficit

$0.3 \le \Phi^{meas} / \Phi^{pred} \le 0.6$

A Crude solution

$\Phi^{meas}_{\nu pp} \approx \Phi^{pred}_{\nu pp}$ **bound by Luminosity**

$\Phi^{meas}_{\nu B} \approx 0.5 \quad \Phi^{pred}_{\nu B}$ **not well known**

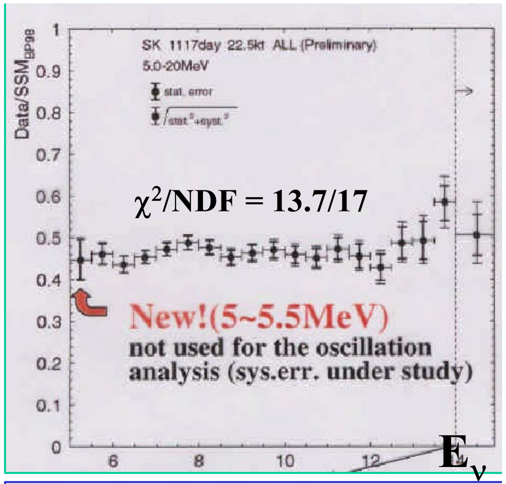
$\Phi^{meas}_{\nu Be} \approx 0$ **not well known**

Contradiction with strong $\Phi^{pred}_{\nu Be} - \Phi^{pred}_{\nu B}$ correlation

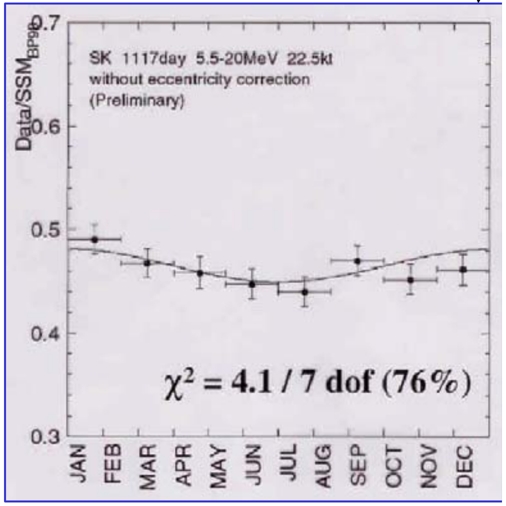
No astrophysical explanation

$\nu_e \rightarrow \nu_x$ (ν_μ, ν_τ, ν_s) Oscillation Signals? Inside the Sun? Between Sun-Earth?

- Total flux too low by factor 0.3-0.5 in all 6 experiments



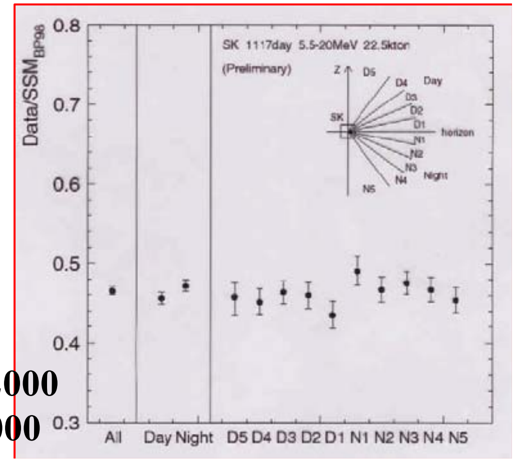
- E spectrum distortion:
  SuperK and SSM spectra agree (E_n >6.5 MeV):



- Seasonal effects:
  Effect of Sun-Earth distance variation (besides $1/L^2$):
  SuperK flux time dependence agrees with $1/L^2(t)$

- Day/Night effect: matter effect inside Earth ?
  SuperK flux time dependence compatible with no effect

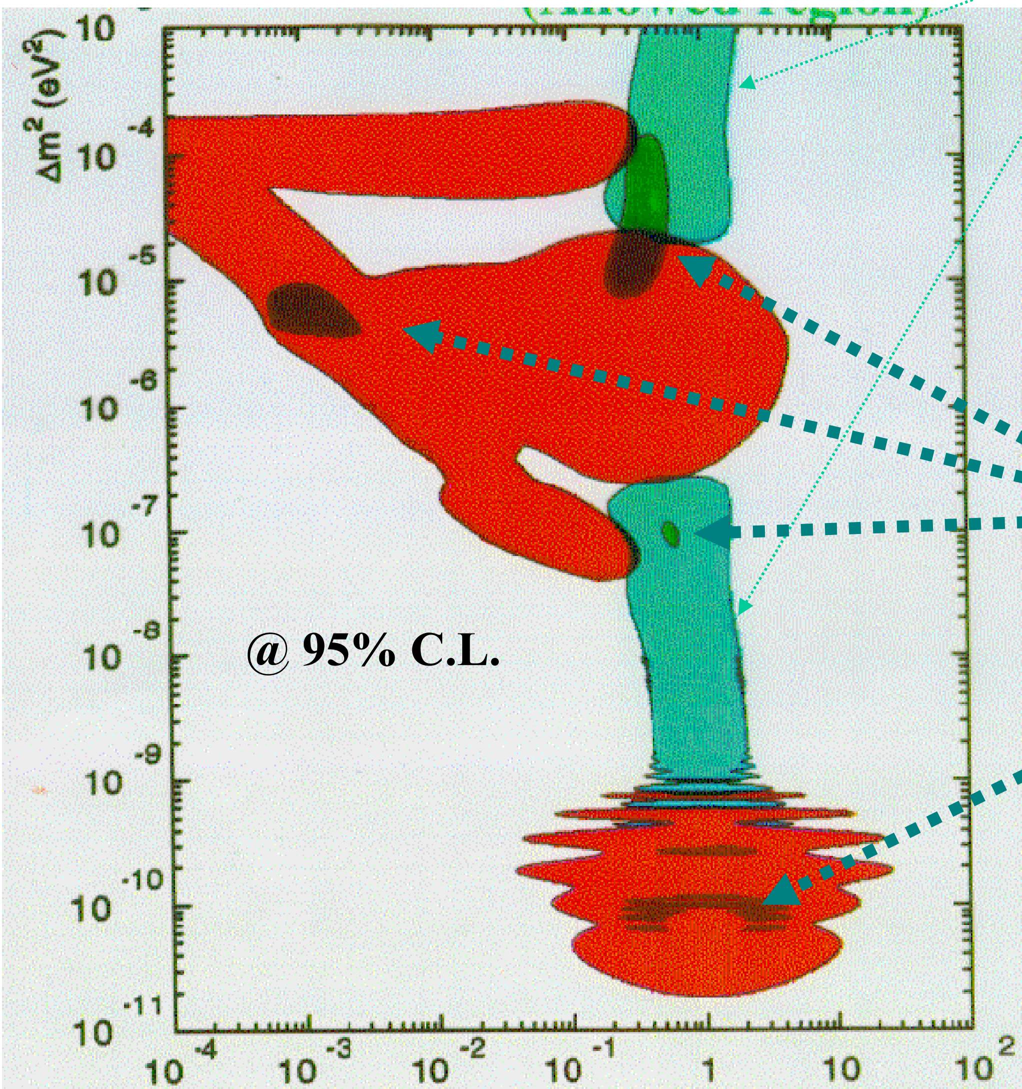
$$\frac{D-N}{(D+N)/2} = -0.034 \pm 0.022^{+0.013}_{-0.012}$$



Flux deficit is the only smoking gun

Y.Suzuki Neutrino 2000
Y.Susuki Vietnam 2000

Global fit for $\nu_e \rightarrow \nu_{active}$ $(\nu_\mu$ or $\nu_\tau)$



$\tan^2\theta$ ← Note

Allowed by SK
All measurements

Excluded by SK
Day/Night spectrum only

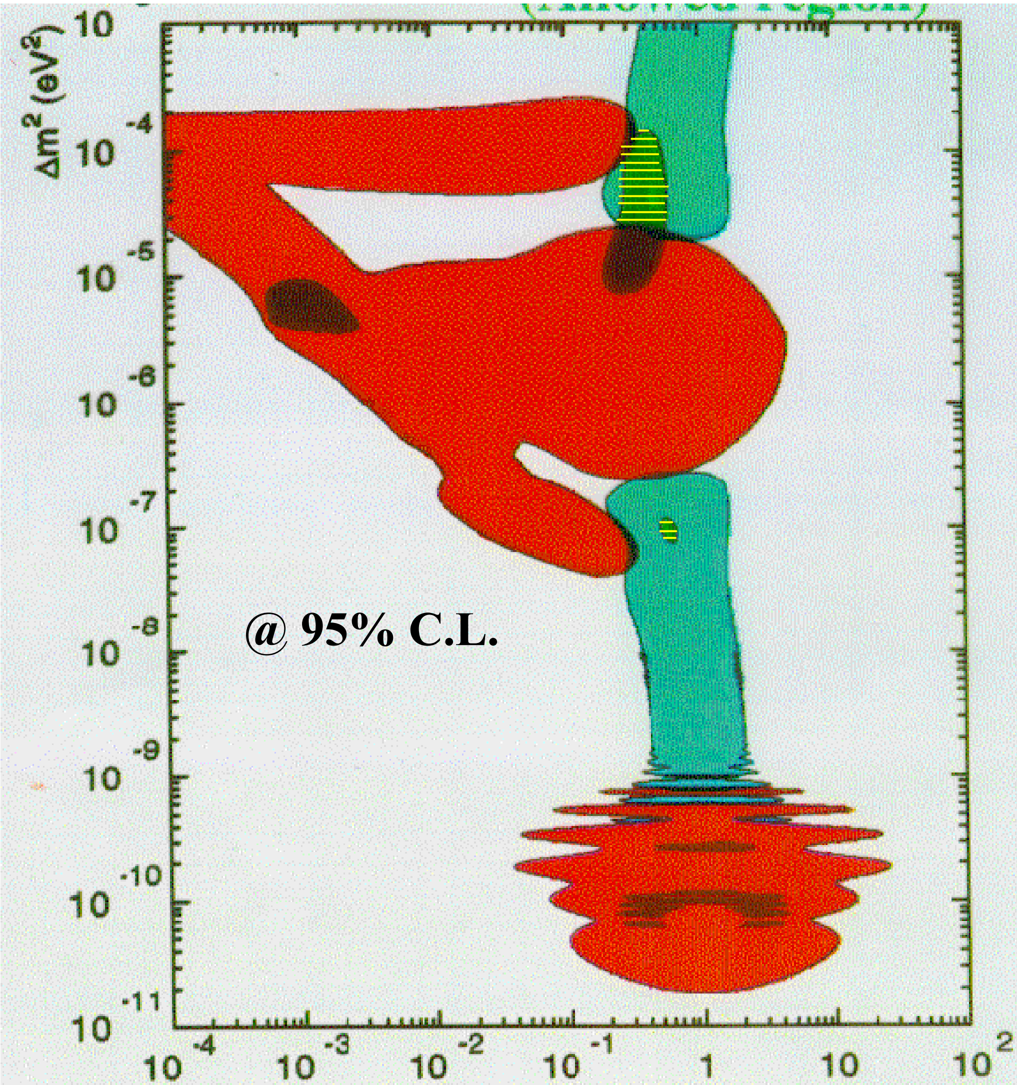
Allowed by Ga+Cl+SK
Flux measurements only

Oscillation in Sun matter

Oscillation in vacuum

Y.Suzuki Neutrino 2000
Y.Susuki Vietnam 2000

Global fit for $\nu_e \rightarrow \nu_{active}$ $(\nu_\mu$ or $\nu_\tau)$



$\tan^2\theta$ ← Note

Y.Suzuki Neutrino 2000
Y.Susuki Vietnam 2000

2 solutions at $\sin^2 2\theta \approx 1$

$\Delta m^2 \approx 10^{-4} - 10^{-5}\, eV^2$

$\Delta m^2 \approx 10^{-7}\, eV^2$

$\nu_e \rightarrow \nu_s$
disfavoured at 95% C.L.

Solar neutrino oscillation: Summary and Future

The solar neutrino deficit can be explained by ν_e oscillation to active neutrinos

@ 95% C.L. 2 sets of parameters are favoured by combining all data

$$\sin^2 2\theta \approx 1 \quad \text{(maximum mixing)} \quad \begin{cases} \Delta m^2 \approx 10^{-5}\, eV^2 \\ \Delta m^2 \approx 10^{-7}\, eV^2 \end{cases}$$

@ 95% C.L. oscillation to sterile neutrinos is disfavoured

SNO: measures independently the CC and NC solar event rates (NC rate unaffected by oscillation between active neutrinos)

KAMLAND, BOREXINO: Very LBL reactors experiments (L>100 km) (from 2001) reach $\Delta m^2 \geq 10^{-5}\, eV^2$

Neutrino Oscillation Experiments at Accelerators

Motivation

Search for neutrinos with masses of cosmological relevance:
"Hot dark matter" candidates with $m_\nu > 1$ eV
with sensitivity to $P_{osc} > 10^{-3}$ -10^{-4} (given previous results)

$m_\nu > \sqrt{\Delta m^2} > 1$ eV

High sensitivity = low intrinsic background = well know source
Large Δm^2 = high energy
High sensitivity + Large Δm^2 = accelerator experiment

Neutrino Oscillation Experiments at High Energy Accelerators

CHORUS and NOMAD short baseline experiments

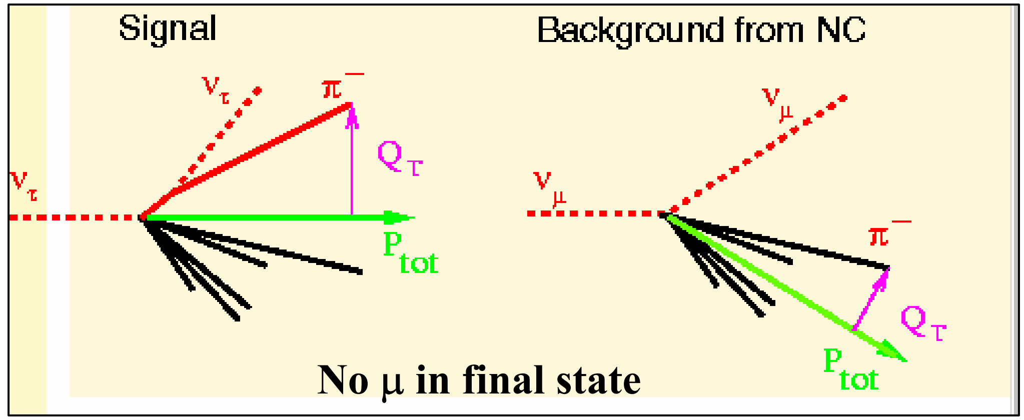
Search for $\nu_\mu - \nu_\tau$ oscillation

ν_τ appearance in ν_τ free ($\sim 10^{-6}$) ν_μ beam
at the CERN SPS Wide Band Neutrino Beam

Sensitivity $P_{osc}(\nu_\mu - \nu_\tau) > 10^{-4}$

Same beam, Complementary concepts

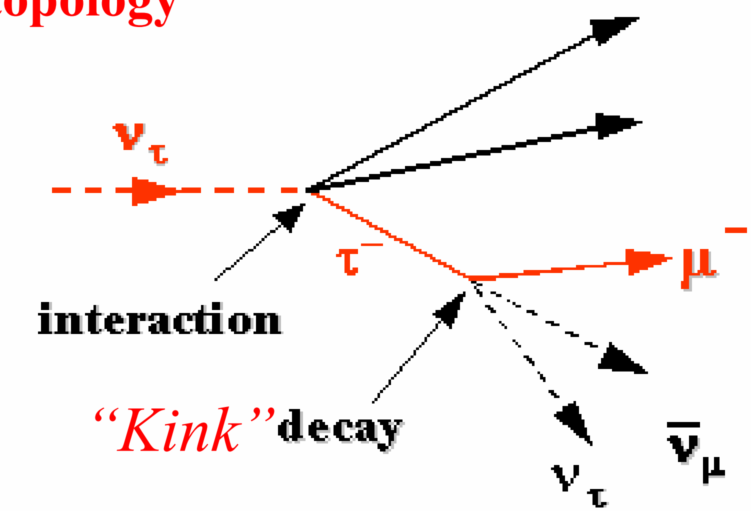
NOMAD: ν_τ **signal extraction technique: excess of events in kinematics box**



CHORUS: Observation of the τ-lepton track produced in CC ν_τ interactions in 770 kg nuclear emulsion target : "kink" topology

$\tau_\tau = 2.9\ \ 10^{-13}\sigma$

$< \beta\gamma c\tau_\tau > \approx 1.5$ mm



See talk by K.Niwa

Results

NOMAD:

- expects 55.2 ± 5.2 background events
- observes 58
- would have seen 14937 ν_τ,
  would all ν_μ have oscillated

$$P_{osc}(\nu_\mu \rightarrow \nu_\tau) < 2.03 \times 10^{-4}$$

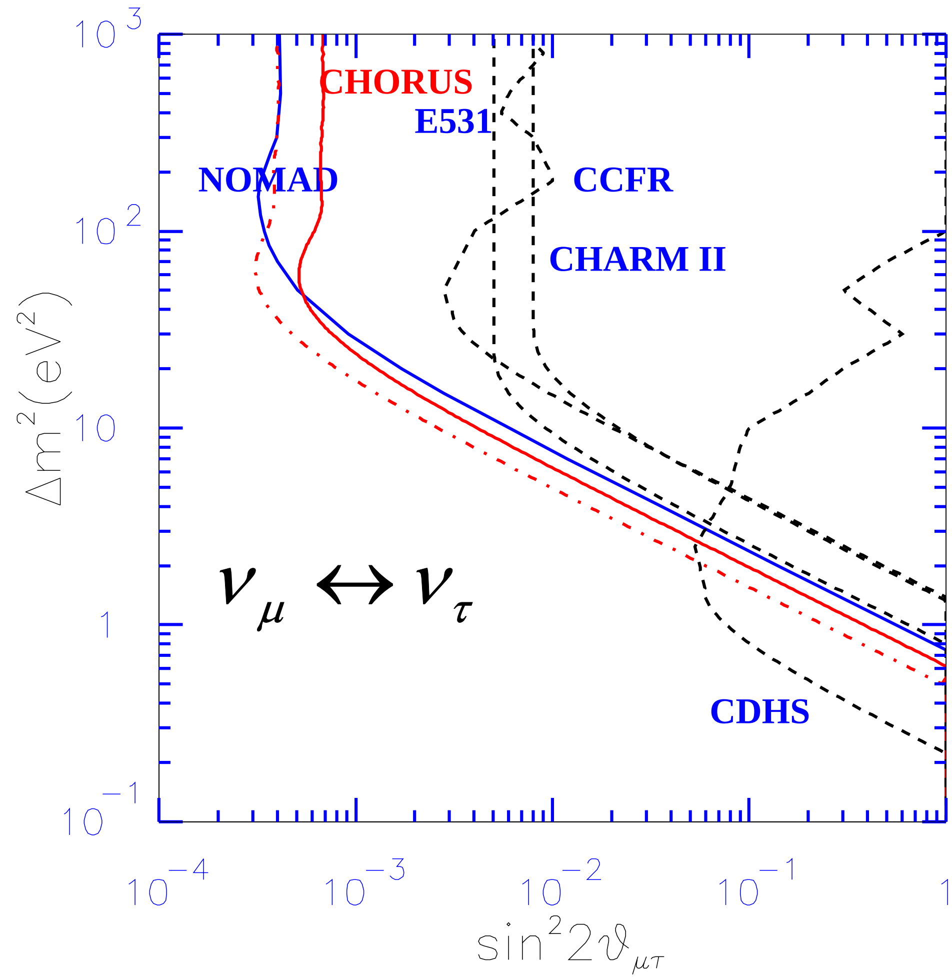
M. Mezzetto Neutrino 2000
P.Astier at al. CERN-EP-2000-049)

CHORUS:

- expects 1.2 background events
- observes 0
- would have seen 10018 ν_τ,
  would all ν_μ have oscillated

$$P_{osc}(\nu_\mu \rightarrow \nu_\tau) < 3.4 \times 10^{-4}$$

- CHORUS is able to detect events:
  relaxed selection cuts:
  3.3 background expected
  4 events observed



E.Eskut at al. CERN-EP-2000-0??)

Neutrino Oscillation Experiments at Low Energy Accelerators

Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at rather large $\Delta m^2 >\sim 0.1 eV^2$

Sensitivity $P_{osc}(\bar{\nu}_\mu - \bar{\nu}_e) > 10^{-3}$

Concept:

- **800 MeV p beam dump**
- **π^+, μ^+ stopped and decays at rest**
- **only $\nu_\mu, \bar{\nu}_\mu, \nu_e$ produced (below 53 MeV)**
- **Almost no $\bar{\nu}_e$ ($<10^{-3}$)**

- 800 MeV p beam dump
- 2ndry π,μ stopped in dump
- mostly $\nu_\mu, \bar{\nu}_\mu, \nu_e$ produced in π^+, μ^+ decays at rest below 53 MeV
- **Almost no $\bar{\nu}_e$ ($<10^{-3}$)**

↓

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

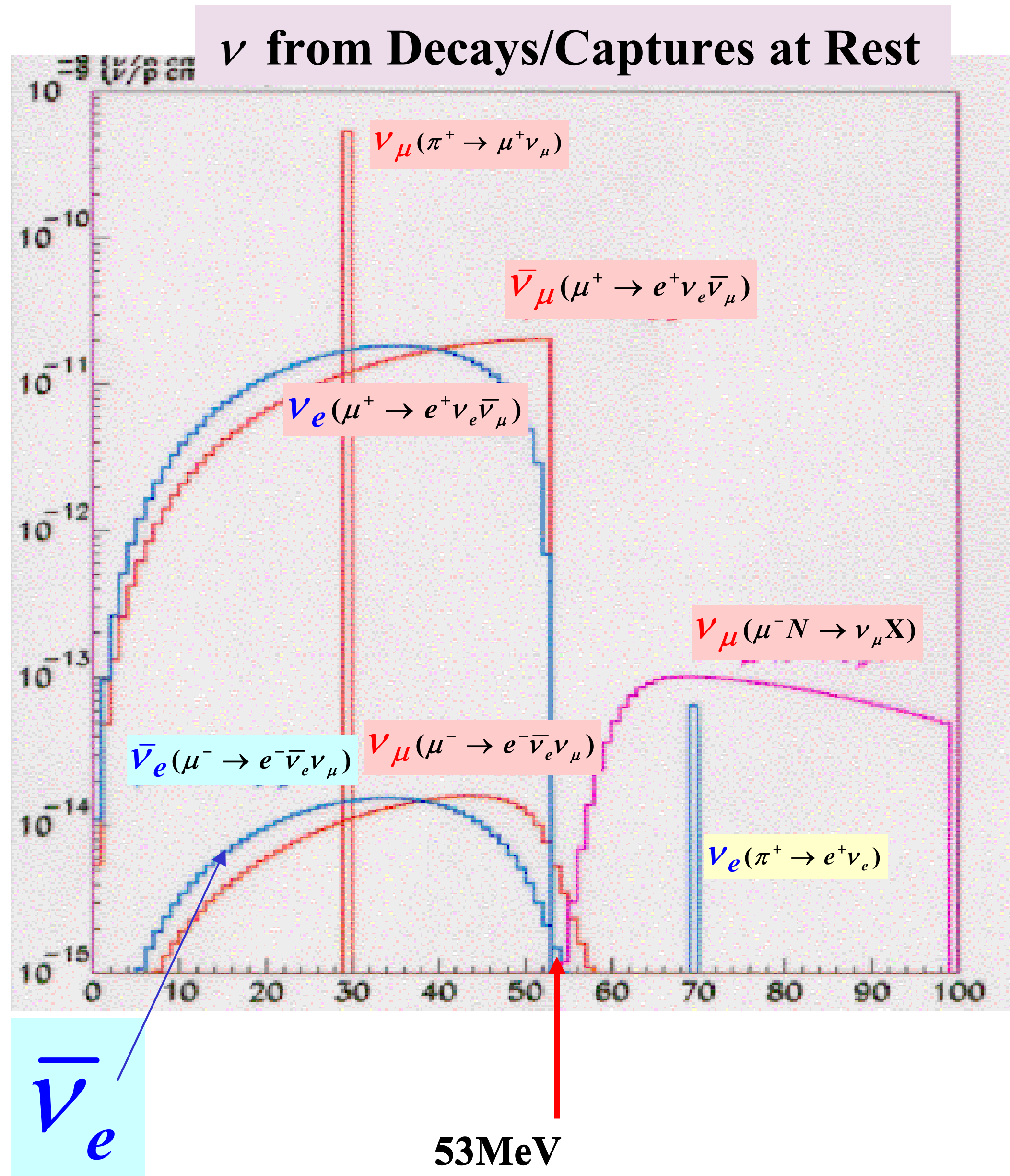
oscillation search

$E_\nu < 53\,MeV$

Signal: Inverse β decay

$\bar{\nu}_e + p \rightarrow e^+ n$

Concept



Results

KARMEN-II

expects 12.29 ± 0.69 $\bar{\nu}_e$ background events

observes 11

LSND

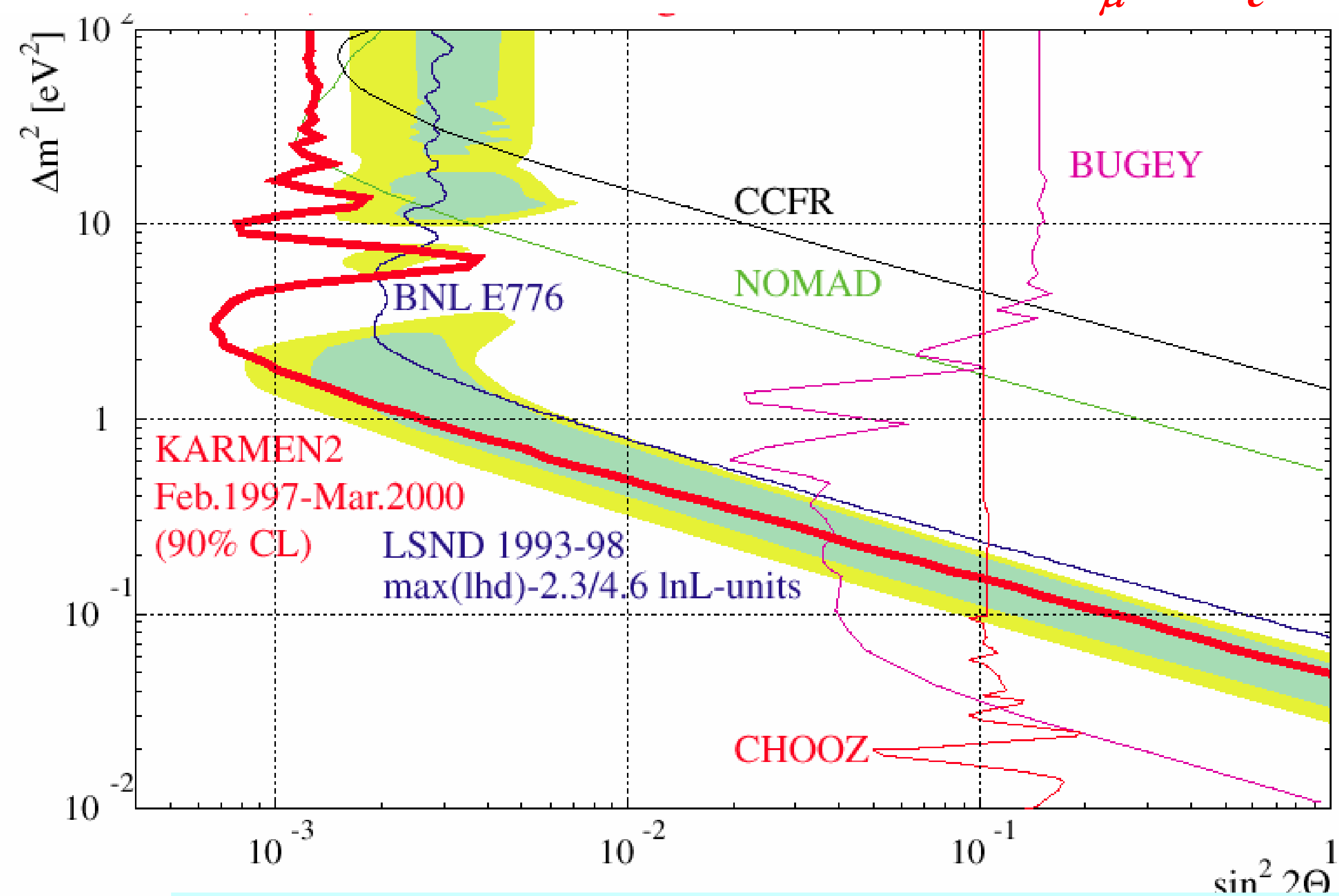
expects 50.3 $\bar{\nu}_e$ background events

observes 83

excess 32.7 ± 9.2

all measurememts well fitted by

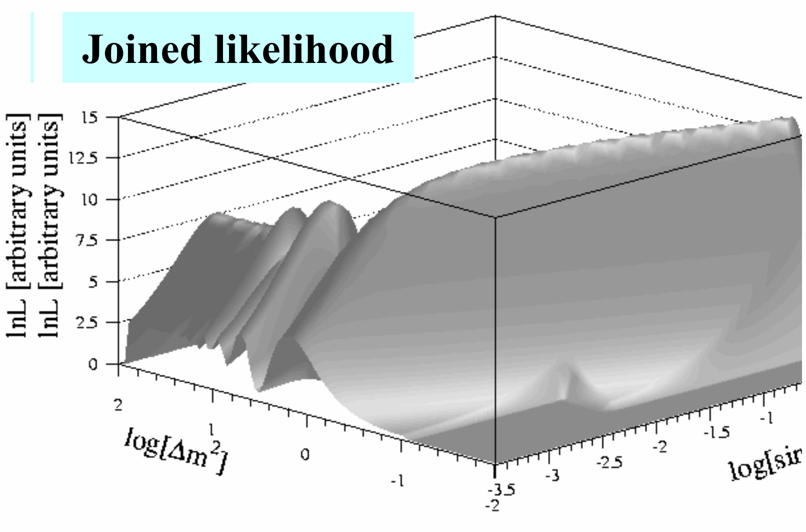
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation

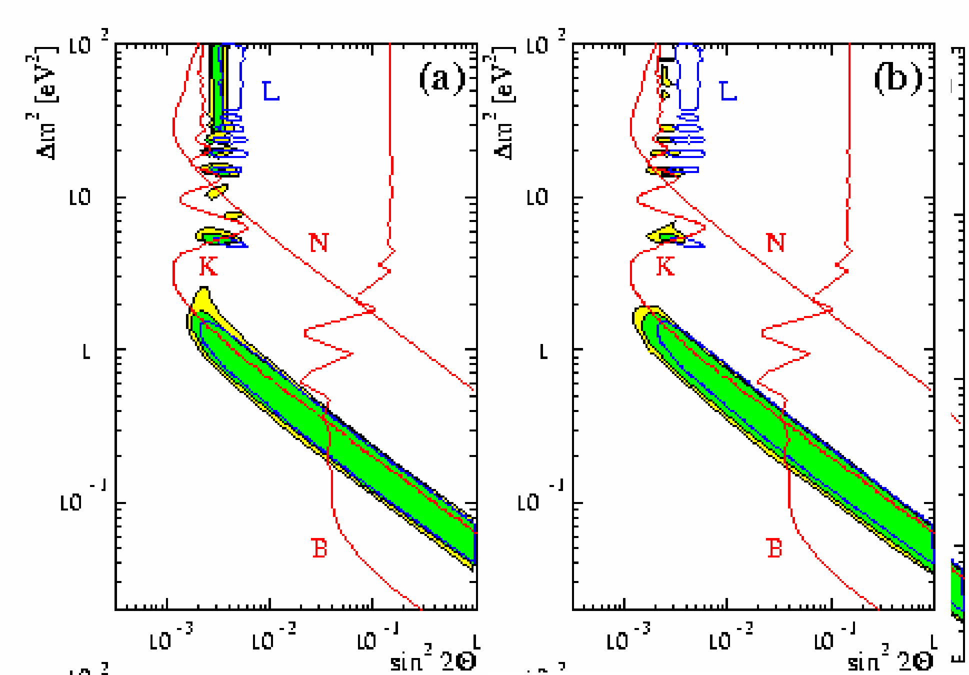


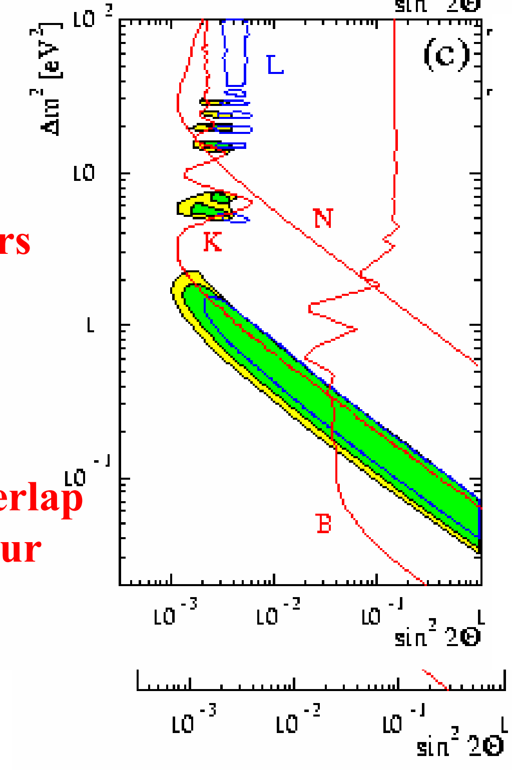
LSND: G.Mills Neutrino 2000
KARMEN2: K.Eitel

Final word by MiniBOONE at Fermilab in 2002(3)

Preliminary joined KARMEN2-LSND analysis







Statistical analysis of small event numbers is very touchy: Bayesian v.z. frequentist variations

CERN 2000-005 Yellow report

The result of two analysis is NOT the overlap of an exclusion contour on a signal contour

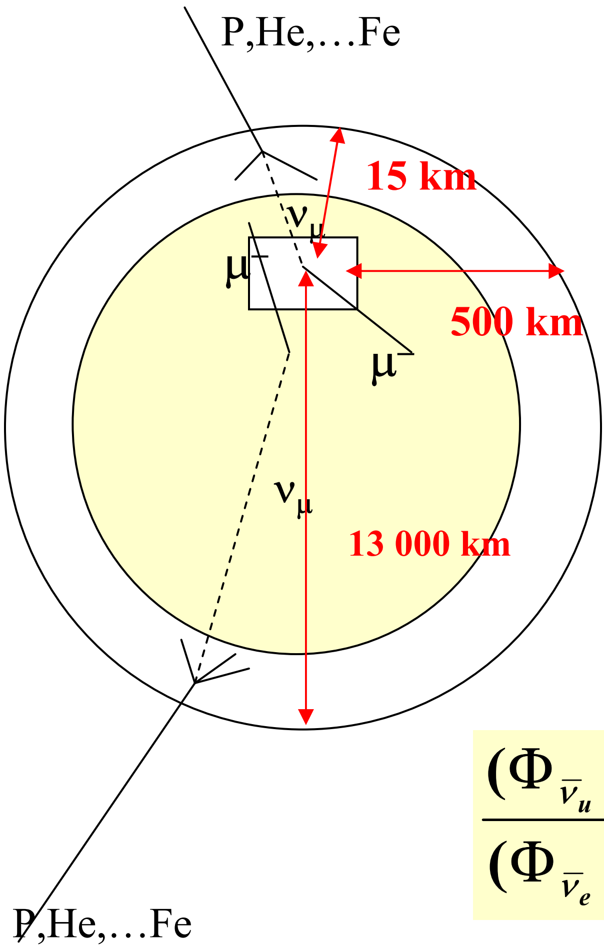
K. Eitel hep-ex-990906 and
New J. Phys. 2(2000)1

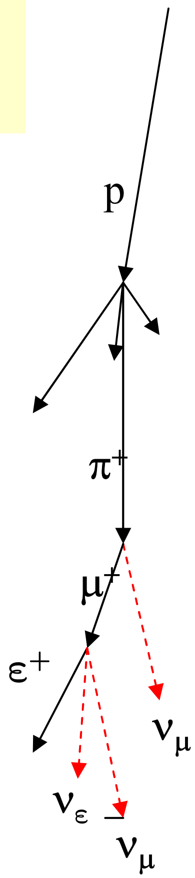
3 "sensible" common favoured regions

- **90%**
- **99%**
- **LSND alone**
- **KARMEN2, NOMAD,BUGEY excluded**

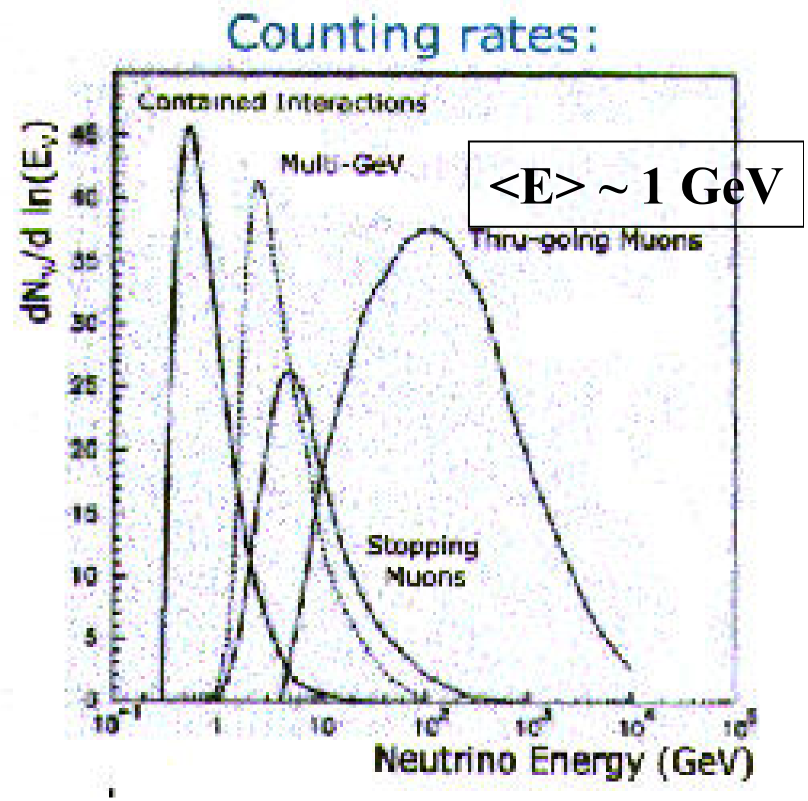
Atmospheric Neutrinos Oscillation Experiments

Beautiful atmospheric neutrinos beam line





$$\frac{(\Phi_{\bar{\nu}_u} + \Phi_{\nu_u})}{(\Phi_{\bar{\nu}_e} + \Phi_{\nu_e})} \approx 2$$



Wide L/E range
E measured
L measured from θ
How precise are the flux MC predictions?

Rates

$$R = \frac{(\nu_\mu/\nu_e)_{Data}}{(\nu_\mu/\nu_e)_{MC}}$$

most model and experiment systematic cancels

SuperK (Water Cerenkov tank)

H.Sobel Neutrino 2000
Y.Susuki Vietnam 2000

Sub-GeV events	Multi-GeV events
$R = 0.652 \pm 0.019 \pm 0.051$	$0.668 \pm 0.034 \pm 0.079$

Soudan-2 (tracking calorimeter)

$R = 0.68 \pm 0.11 \pm 0.06$

T.Mann Neutrino 2000

Macro (tracking calorimeter)

$R = 0.731 \pm 0.028 \pm 0.044$

B.Barrish Neutrino 2000

Is the ν_μ deficit due to $\nu_\mu \rightarrow \nu_X$ oscillation?

What is ν_X ? ν_e ? ν_τ ? ν_s ?

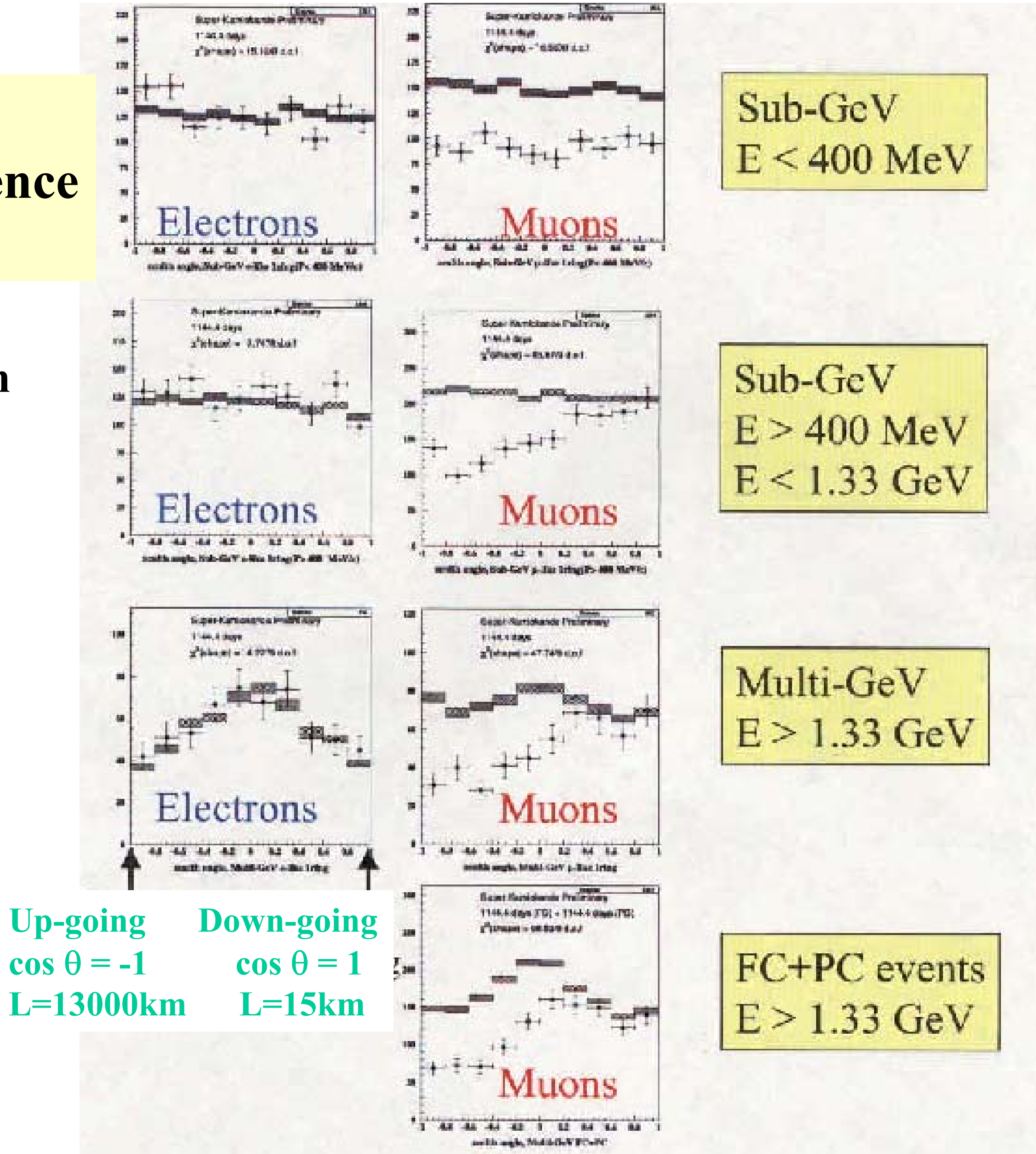
Not just rates, but L and E dependence of rates needed to confirm oscillation

SuperK
L(θ) and E dependence of rates

— MC no oscillation

+ data

Deficit depends on L and E



SuperK

Signal region

Best fit

$\sin^2 2\theta = 1$ (full mixing)

$\Delta m^2 = 3.2 \times 10^{-3}\, eV^2$

Macro

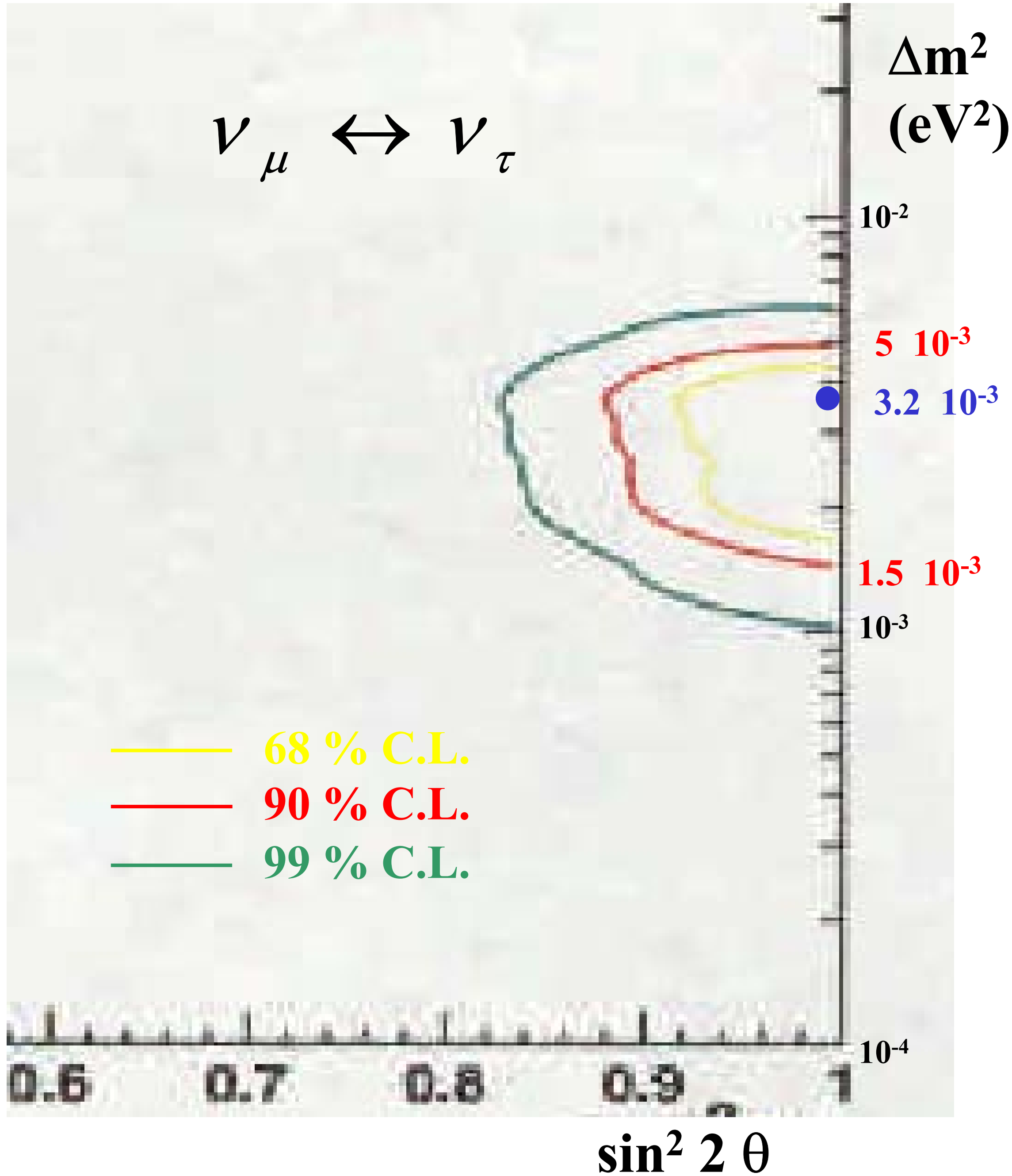
$\sin^2 2\theta = 1$

$\Delta m^2 \approx 2.5 \times 10^{-3}\, eV^2$

Soudan 2

$\sin^2 2\theta = 0.9$

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

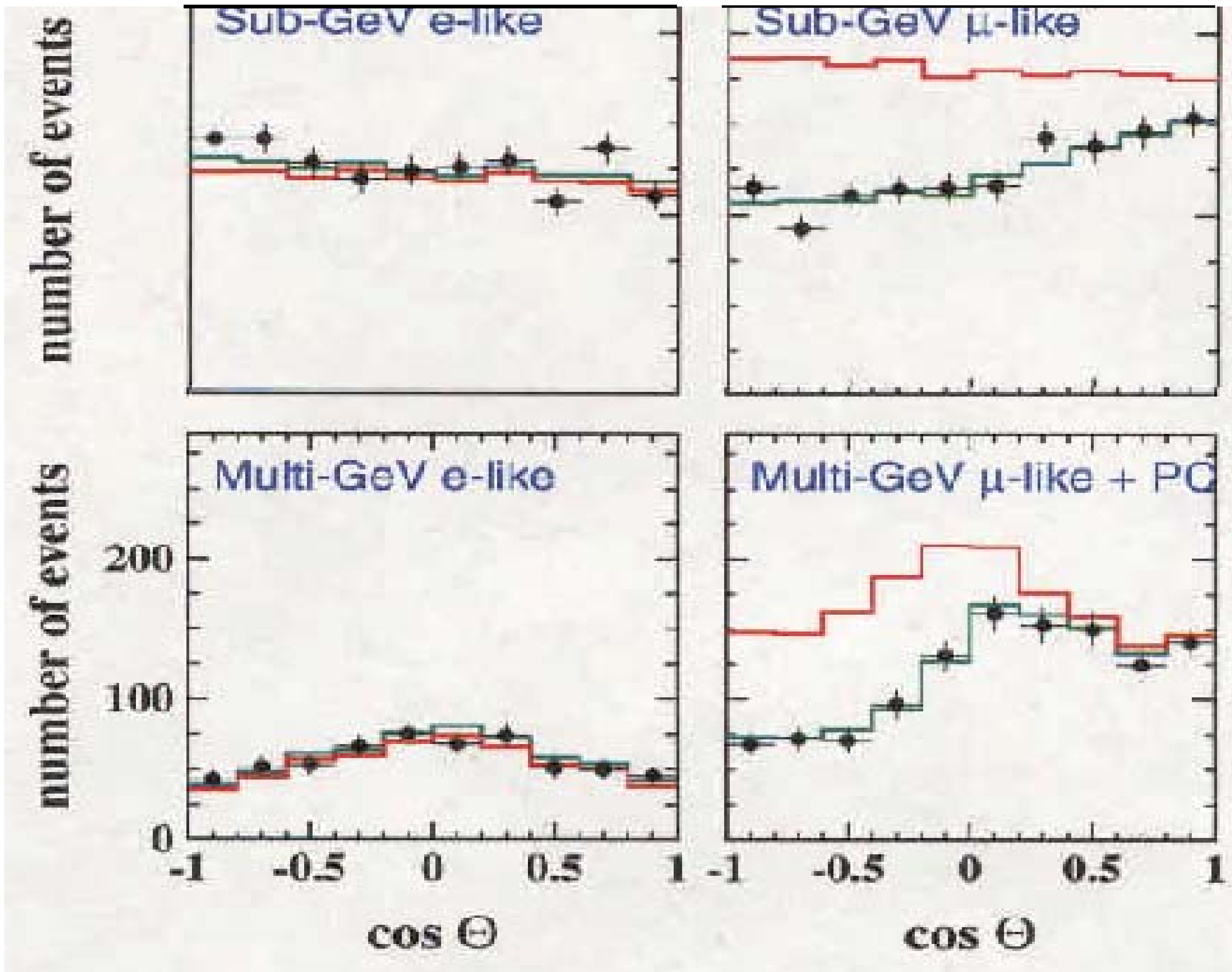


SuperK checks of the oscillation hypothesis $\nu_\mu \leftrightarrow \nu_\tau$

Angular distribution

Sub GeV

Multi GeV



— MC best fit
— MC no oscillation
+ data

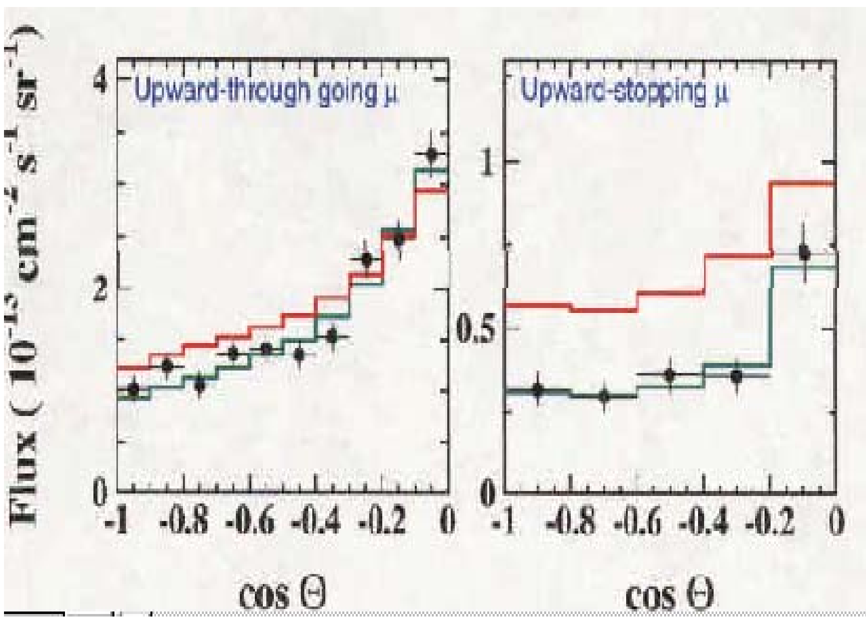
e-like

μ-like

SuperK checks of the oscillation hypothesis $\nu_\mu \leftrightarrow \nu_\tau$

Angular distribution upward going ν_μ events

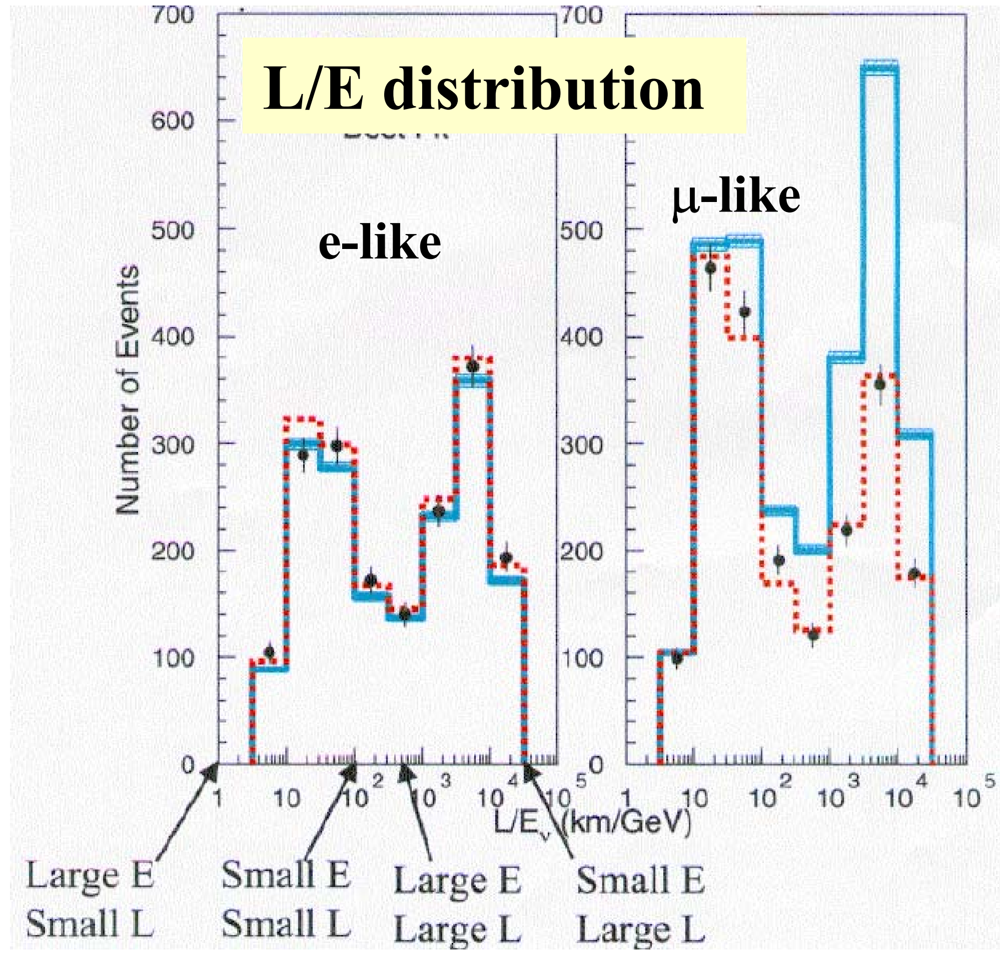
MC best fit
MC no oscillation
+ data



higher energy

lower energy

MC best fit
MC no oscillation
+ data



$\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\mu \leftrightarrow \nu_s$ oscillation?

Discrimination based on L dependence of the matter effect in Earth

$\nu_\mu \leftrightarrow \nu_s$ excluded at 99% C.L.

$\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\mu \leftrightarrow \nu_e$ oscillation?

- **Data is compatible with a some $\nu_\mu - \nu_e$ mixing**
- **$\nu_\mu - \nu_e$ mixing must be small:**
  - **- all ν_e data agree with model predictions without oscillation**
  - **- large $\nu_\mu \rightarrow \nu_e$ affect ν_e data significantly**
- **Strong restriction from reactor experiments**

$\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\mu \leftrightarrow \nu_s$ oscillation?

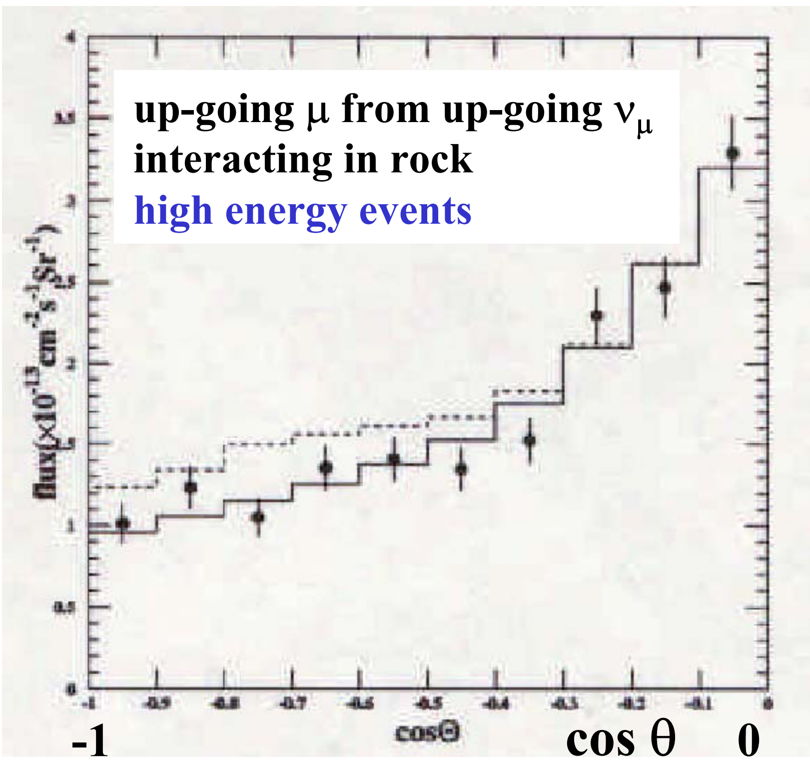
Discrimination based on L (or θ) dependence of the matter effect in Earth

Matter has no effect on $\nu_\mu \leftrightarrow \nu_\tau$ oscillation: same σ_{NC}

Matter effects suppress $\nu_s \leftrightarrow \nu_\mu$ oscillation and

suppression increases with E (not trivial!)

Suppression increases with amount L of matter traversed (θ)



L=13000km **L=500km**

···· $\nu_\mu \leftrightarrow \nu_s$

— $\nu_\mu \leftrightarrow \nu_\tau$

\+ data

$\nu_\mu \leftrightarrow \nu_s$ excluded at 99% C.L.

CHOOZ Nuclear Reactor Long Base Line (1 km) experiment

Calculated and measured $\bar{\nu}_e$ flux and energy spectra **at L=0** agree to ~ 2% (Bugey 1995)

Signal: Inverse n β decay

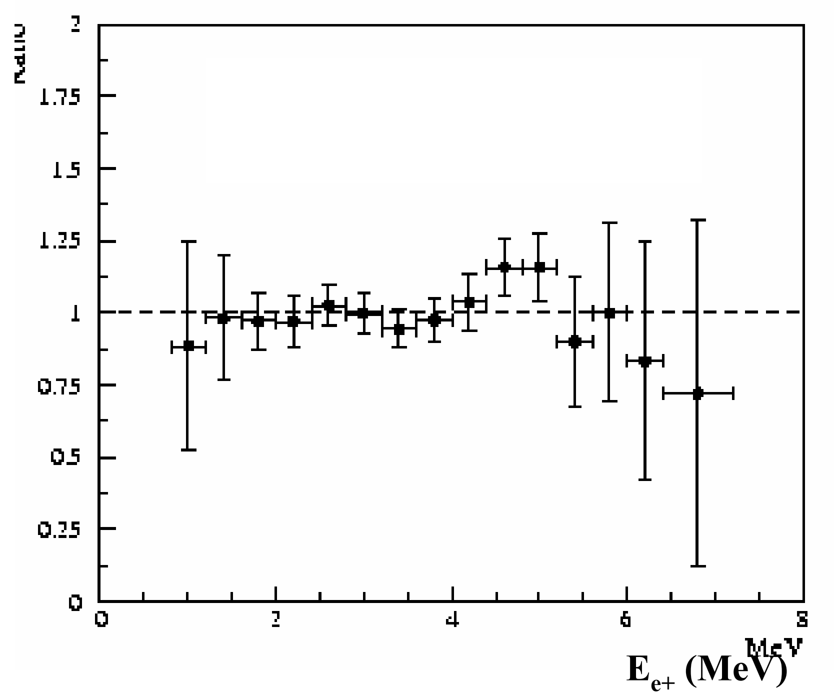
$$\bar{\nu}_e + p \rightarrow e^+ n$$

$$< E_{e^+} > \approx 3 \quad MeV$$

$$L / E \approx 10^{-3}$$

Absolute E_{e+} spectrum at L=1km

$$R = \frac{E_{e^+} \text{ spectrum measured}}{E_{e^+} \text{ spectrum expected if no oscillation}}$$



$$R = 1.010 \pm 0.028 \quad (stat) \pm 0.027 \quad (syst)$$

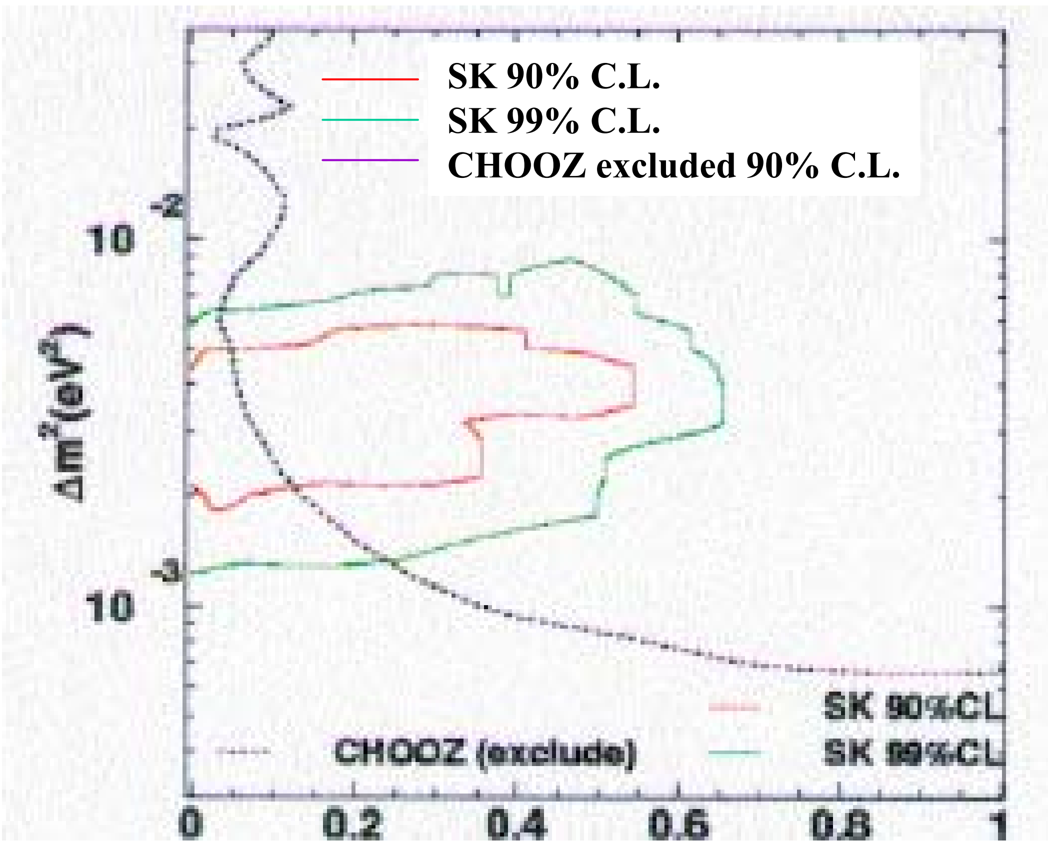
No $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ oscillation signal

Is $\nu_\mu \leftrightarrow \nu_e$ oscillation in atmospheric neutrinos fully excluded by CHOOZ/PaloVerde negative result?

3-family mass hierarchy model (Sun + Atmospheric signals)

$\Delta m^2 \approx 3.5 \times 10^{-3}\, eV^2$ **: atmospheric**

$\delta m^2 < 10^{-5}\, eV^2$ **: solar**



0 $\sin^2 2\theta_{e\mu}^{eff}$ 1

Space for small $\nu_\mu \leftrightarrow \nu_e$ mixing

Summary of oscillation signals

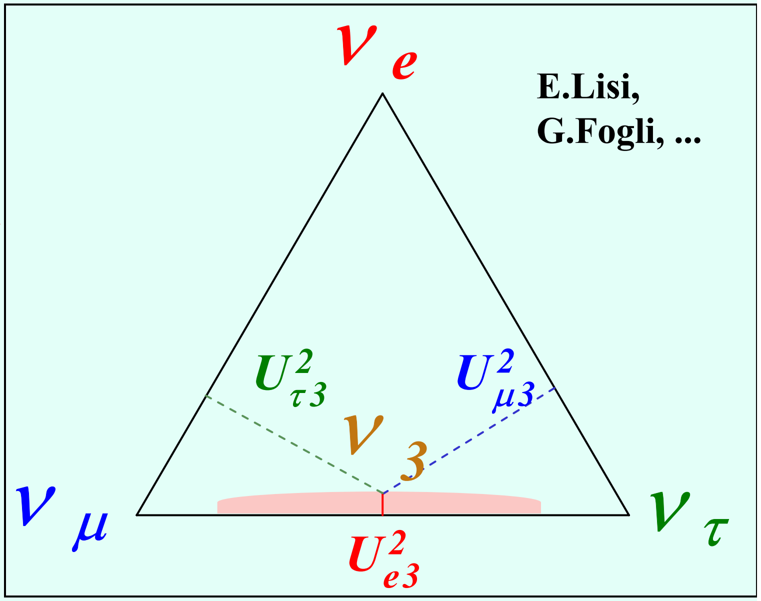
3-family mass hierarchy model

$\Delta m^2 \approx 1.5 - 5.0 \times 10^{-3} eV^2$:atmospheric

+ negative $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$: reactor

$\delta m^2 < 10^{-5} eV^2$ $\nu_e \leftrightarrow \nu_{active}$:solar

full mixing



LSND $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ at small mixing $\sin^2 2\theta \approx\sim 10^{-2} - 10^{-3}$

large $\Delta m^2 \approx 0.1 - 1 eV^2$

requires 4 eigenstates and a ν_s neutrino

e.g. $$\underbrace{\overbrace{m_1 < m_2}^{\Delta m^2_{sun}} \ll \overbrace{m_3 < m_4}^{\Delta m^2_{atm}}}_{\Delta m^2_{LSND}}$$

How to probe/improve the atmospheric neutrino signal?

Atmospheric neutrinos - project

MONOLITH in Gran Sasso underground laboratory:
More precision on E and θ, thus L
being submitted, to start in2005

Long Base Line accelerator neutrinos - running

K2K: KEK to Kamioka mine: L = 250 km
<E> = 1.4 GeV
$\Delta m^2 = 5.6\ 10^{-3}\ eV^2$
ν_μ disappearance experiment
ν_μ flux Near/Far (Super Kamiokande) detectors
1 year data taking : expects 29.3 ± 3.4 events
sees 17
Compatible with atmospheric neutrino signal
2-sigma incompatibility with no oscillation
Statistics still small

Long Base Line accelerator neutrinos - approved, in preparation

MINOS: Fermilab to Soudan mine: L = 730 km

$\langle E \rangle = 2$ GeV tuneable for aimed Δm^2

ν_μ disappearance experiment
ν_μ flux Near/Far detectors
ν_μ Energy spectrum distortion Near/Far detectors
CC ν_μ / NC

Data taking to start in fall 2003

Long Base Line accelerator neutrinos - submitted

OPERA: CERN to Gran Sasso underground laboratory

ICANOE: CERN to Gran Sasso underground laboratory ???

The OPERA Long Base Line Neutrino Oscillation Project

OPERA

COLLABORATION

Belgium
IIHE(ULB-VUB) Brussels

China
IHEP Beijing, Shandong

CERN

France
IPLN Lyon, LAL Orsay, LAPP Annecy, Strasbourg

Germany
Berlin, Hagen, Hamburg, Münster, Rostock

Israel
Technion Haifa

Italy
Bari, LNF Frascati, Naples, Padova, Rome, Salerno

Japan
Aichi, Toho, Kobe, Nagoya, Utsunomiya

Russia
ITEP Moscow

Switzerland
Bern

Turkey
METU Ankara

~ 120 physicists

Physics Motivation

Confirm unambiguously $\nu_\mu \rightarrow \nu_\tau$ oscillation explanation to atmospheric ν_μ deficit

How?

Direct observation of CC ν_τ +N $\rightarrow \tau^-$ + X interactions
Identified τ^- track through 1-prong decay topologies

$\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$ **B.R. 17.8%**

$\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$ **B.R. 17.4%**

$\tau^- \rightarrow h^- \nu_\tau (\mathrm{n}\ \pi^0)$ **B.R. 49.5%**

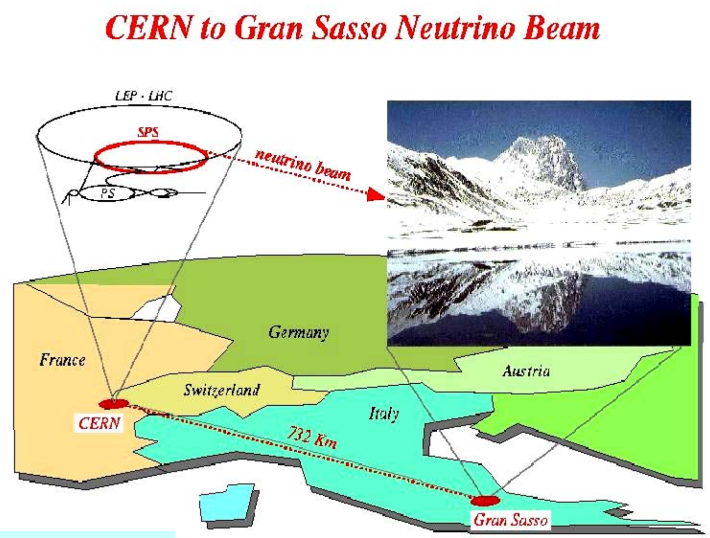
Requirements

High sensitivity in 90% C.L. parameter space of SuperK

$1.5 \times 10^{-3} \leq \Delta m^2 \leq 5.0 \times 10^{-3}\ eV^2$ **at full mixing**

How?

Long Base Line experiment



CERN CNGS new ν_μ beam points to
OPERA detector in LNGS underground laboratory
@ 730 km from CERN
under Gran Sasso 3800 w.e.m. (1400m)

$$\frac{\langle E_\nu \rangle = 17 GeV}{L = 730 km} \rightarrow \text{access to small } \Delta m^2$$

Prompt ν_τ free beam

cosmic muons fluence ~ 1 m^{-2} h^{-1}

How?

High resolution Emulsion chambers (ECC) massive target (2kt)

Why High resolution? $\langle \tau^- \text{ decay length} \rangle \approx 0.5mm$

Why massive? expected ν_μ event rate : 30 / day / 2kt

CHORUS @ CERN: 700 kg plain emulsion target sees charm decays

2 kt plain emulsion : ∞ cost prohibitive

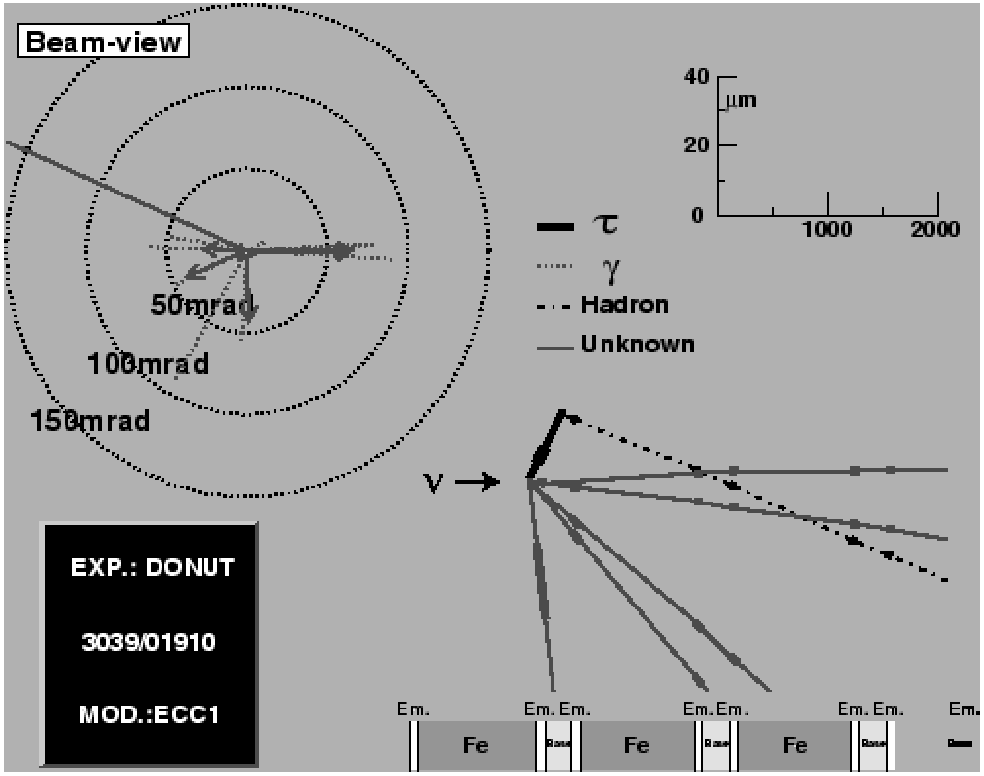
DONUT @ Fermilab: ECC (Fe-emulsion tracker sandwiches)

ν_τ discovery

"On-line" event analysis

- **Segmented ECC target ("bricks) + Electronics detector**
- **Remove, process and analyse daily ~40 bricks identified to contain~30 events**

DONUT ν_τ event



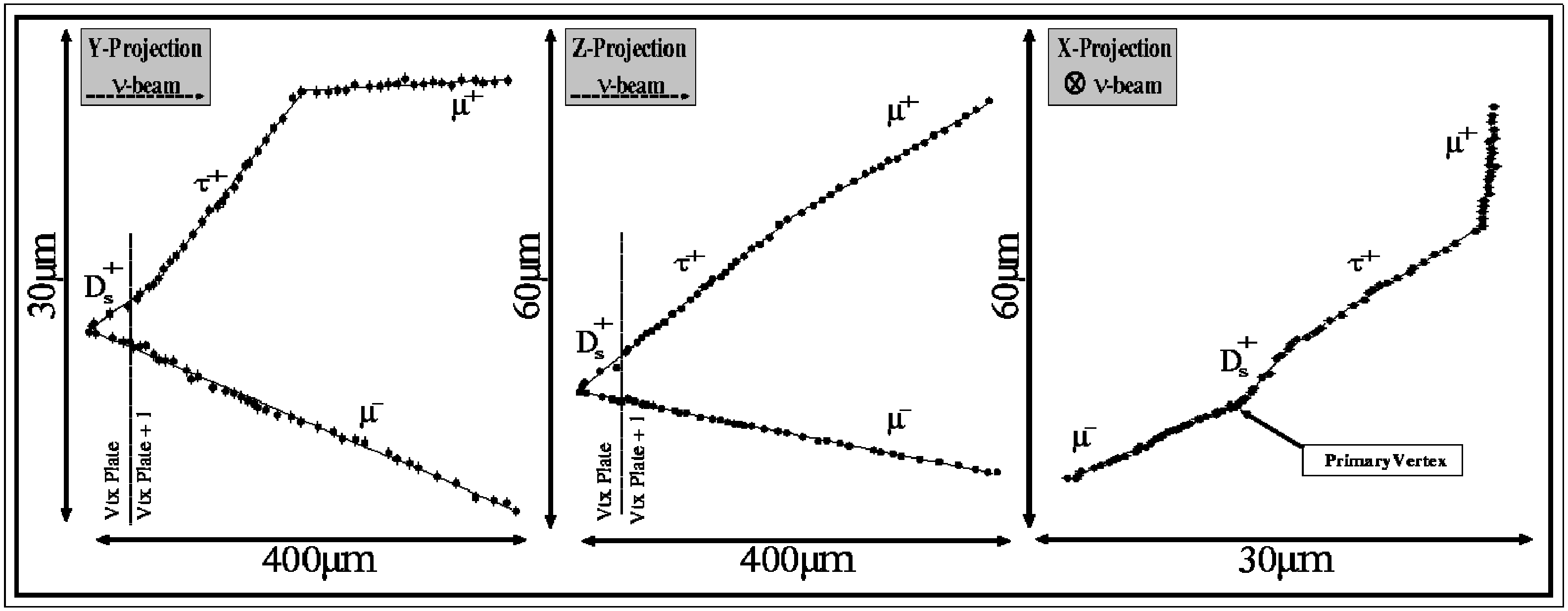
$\nu_\mu N \to \mu^- \quad D_s^{*+} N$

$\to D_s^+ \gamma$

$\to \tau^+ \nu_\tau$

$\to \mu^+ \nu_\mu \bar{\nu}_\tau$

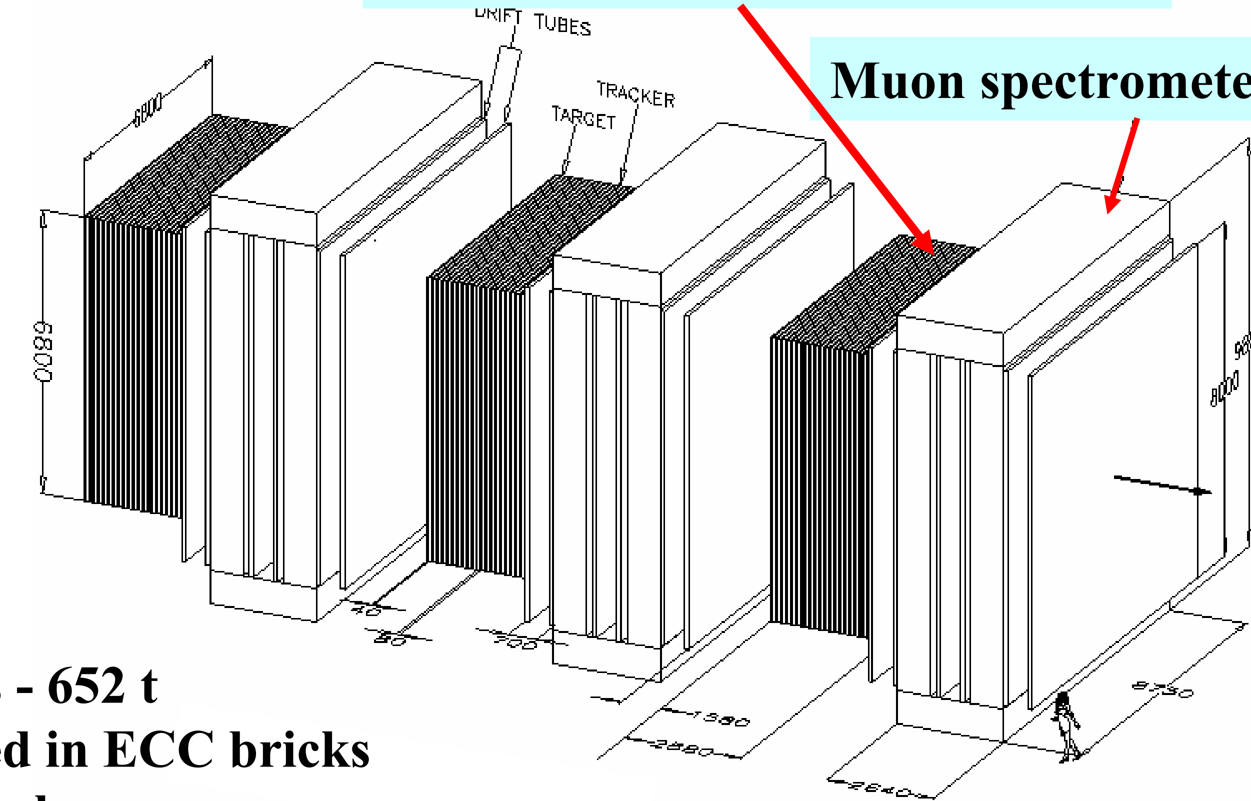
CHORUS



OPERA detector
3 Super-Modules

Instrumented & segmented target

Muon spectrometer



Target: 24 planar modules - 652 t

Module: Wall segmented in ECC bricks
H-V Target tracker

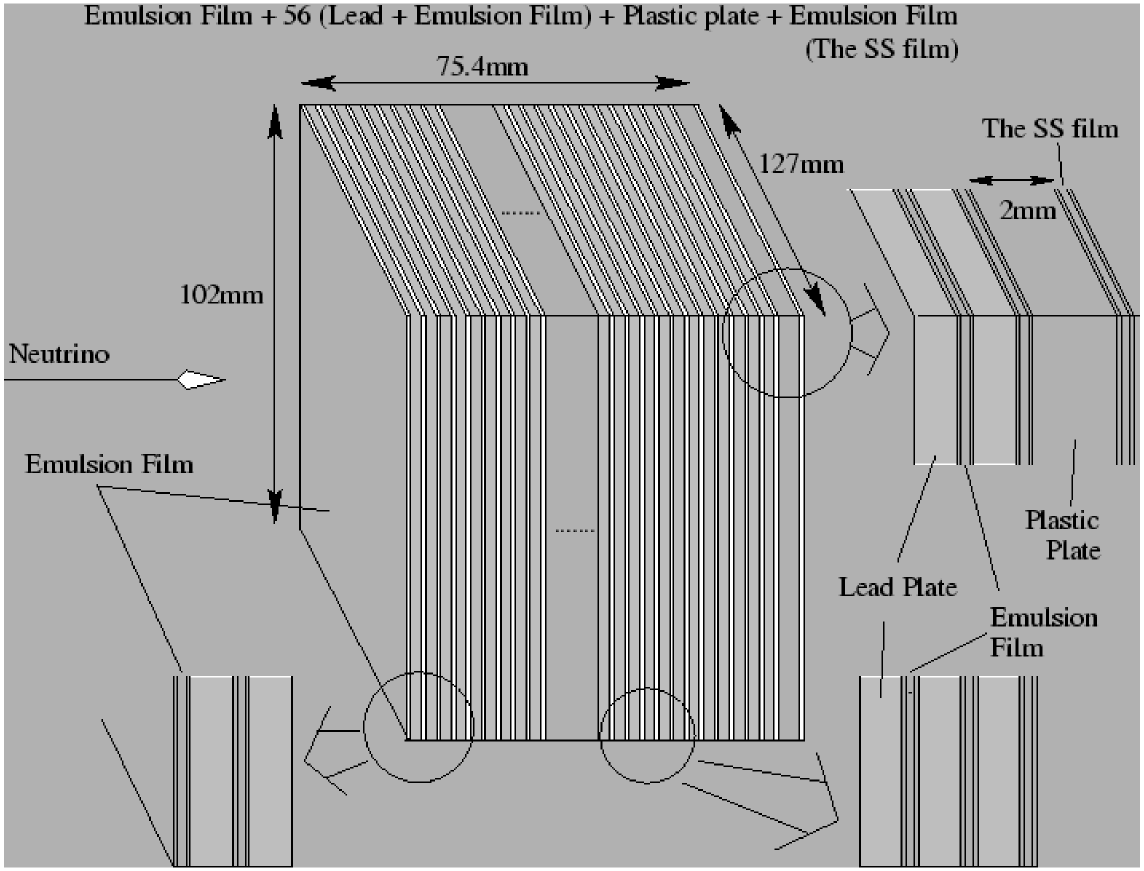
Wall: 6.75 × 6.75 m² × 7.5 cm
3264 bricks

Brick: 5" × 4" × 7.5 cm
56 cells
10 X_0 - 8.3 kg

Cell: 5" × 4" × 1.3 mm
1 mm Pb layer
0.3 mm emulsion tracker

Tracker: 2 planes: H & V
256 7 m scintillator strips

Strip: 2.6 × 1 cm² × 7 m
light collected by WLS fibres
read-out at both ends
by 64-channel PMT
8 tubes / plane

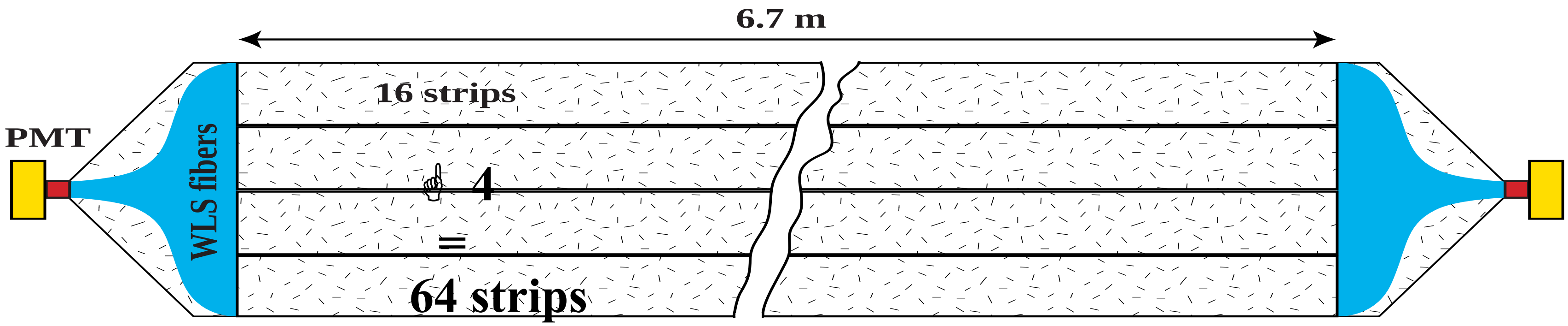


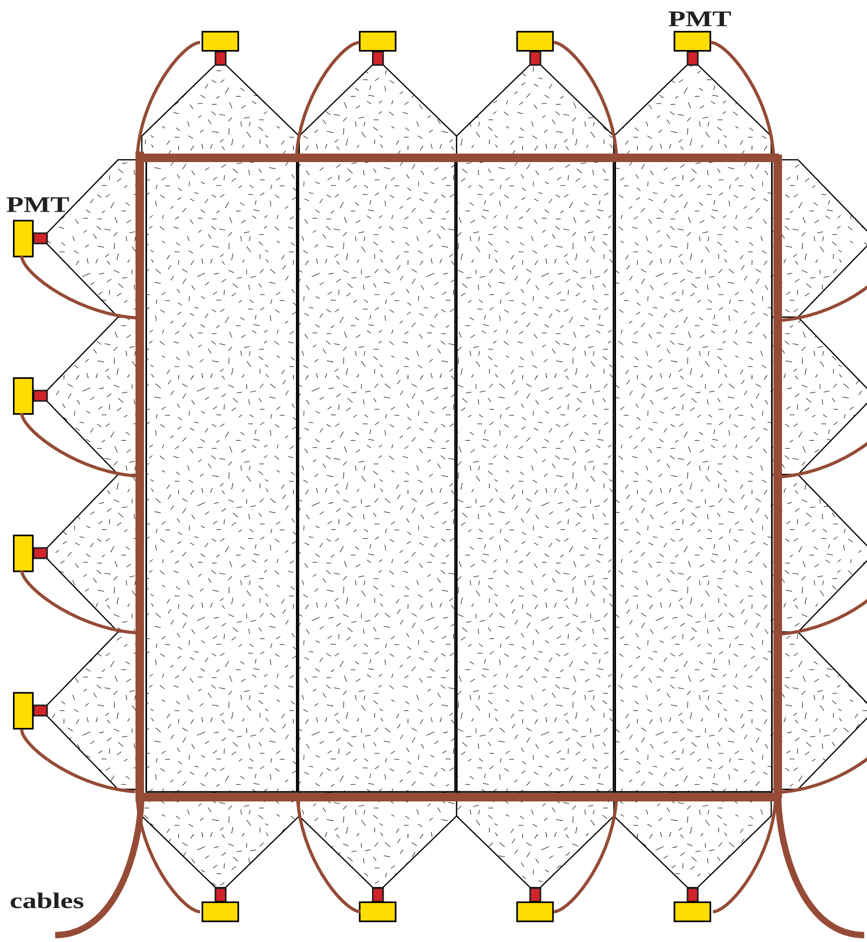
OPERA ECC brick

235 000 bricks - 1.96 kt

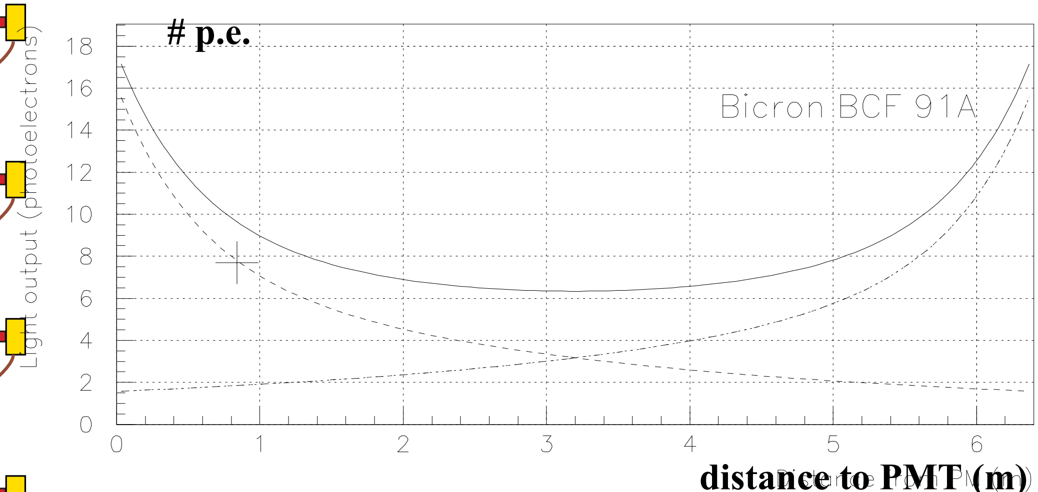
⬇

Full automatization of
Brick assembly, packing
Wall construction
Removal of bricks fired by events



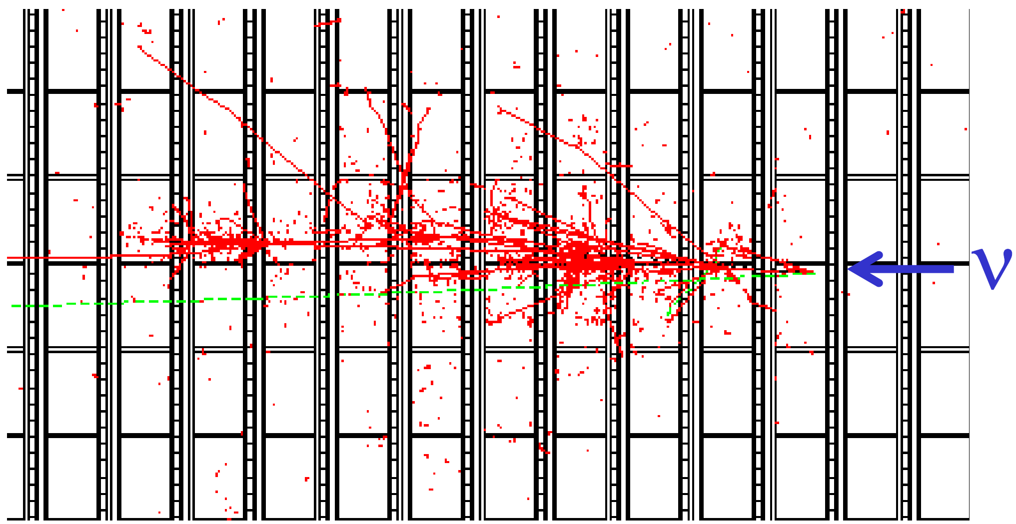


OPERA Scintillator strip target trackers



Light read at both WLS fibre ends
Prob (0 p.e.) = 0.05%

Role 1 of target trackers: identify event brick



Target structure design:

Brick size
large: easier to identify
small: less dead target
⊗
High scanning power +
Low cosmic/beam background
allows coarse tracking
⊗
Tracker resolution
identify bricks efficiently
⊗
Largest target transverse dimensions
⊗
Brick removing strategy

Role 2 of target trackers + ECC : Hadron shower calorimetry

Kinematics analysis of ν_τ candidates

$$\frac{\Delta E}{E} = \frac{0.65}{\sqrt{E[GeV]}} + 0.16$$

OPERA muon spectrometers

- -identify, measure p and charge of muons
- -tag ν_μ CC event
- -kinematics analysis of ν_τ candidates
- -reduce the $C \rightarrow \mu^+$ background
- - + target calo: measure E_ν spectrum

1.55 T Dipole magnet

2 Fe walls : 12 Fe plates + 11 RPC
instrumented with RPC chambers
H-V 3.5 cm strips

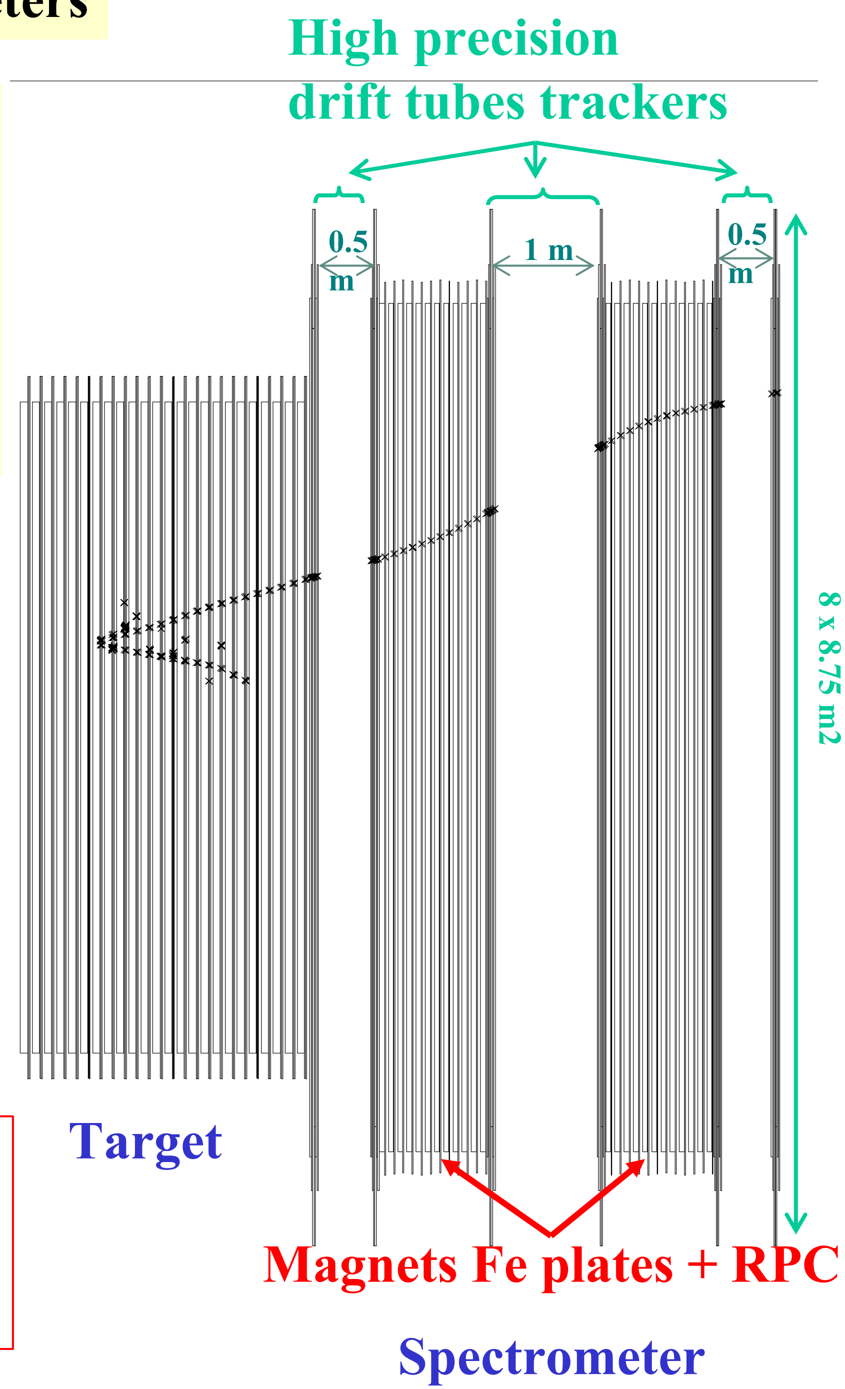
3 external high resolution trackers

2-plane 3-layer 35 mm drift tubes
overall σ_x = 0.5mm

Alignment is not a small issue
no beam!
no cosmic!

$$\frac{\sigma_p}{p} < 25\% \quad \text{for } p < 25GeV/c$$

Wrong charge < 0.5 %



More on the emulsion, ECC and automatic scanning

see K.Niwa's talk

in addition to be a high resolution target, 10 X_0 bricks of ECC allow to:

- **identify electron by multiple scattering and shower analysis**
- **measure electron energy by counting track segments in shower**
- **detect photons**
- **measure hadron and muon momentum by multiple scattering**
- **identify muon by comparing p from multiple scattering and E from range**

CNGS Beam

$$E(GeV) = \frac{2L\,[=730km]}{2.47\ \Delta m^2\ [=3.2\times 10^{-3}\,eV^2]} \approx 2\ GeV < E_{thresh}(\nu_\tau \rightarrow \tau\ \ \text{production})$$

Spectrum optimized for ν_τ production and detection

$$\Phi_{\nu_\mu}(E_\nu)\ \otimes\ P_{osc}^{\nu_\mu\rightarrow\nu_\tau}(E_\nu\,|\,L=730km,\ \sin^2 2\theta_{\mu\tau}=1,\ \Delta m^2=3.2\times 10^{-3}\,eV^2)\ \otimes\ \sigma_{\nu_\tau}(E_\nu)\ \otimes\ \varepsilon_{\nu_\tau}(E_\nu)$$

$\langle E_\nu \rangle = 17 GeV$

$4.5\times 10^{19}\ p.o.t./\,yr$

$\Rightarrow$ $30\ \nu_\mu$ **interactions /** ***day*** **in a** ***2 kt*** **detector (OPERA)**

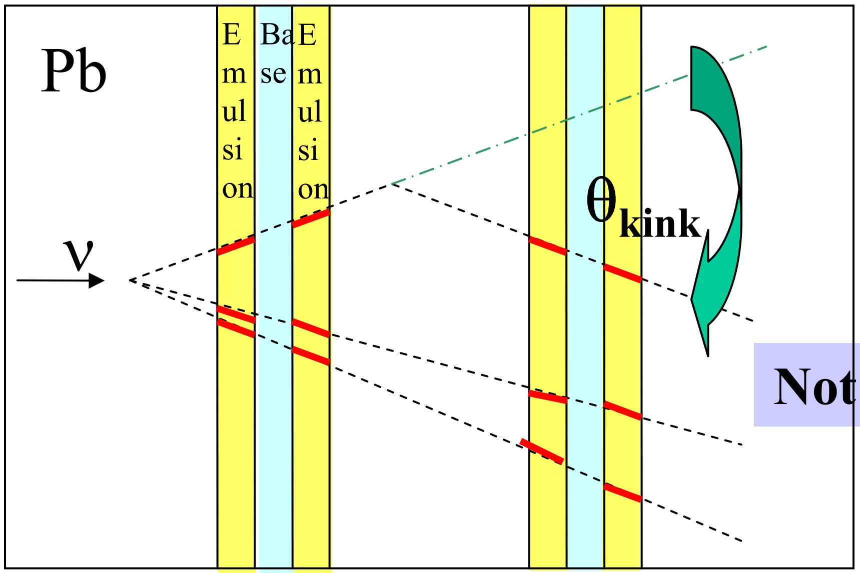
$\Rightarrow$ $50\ \nu_\tau$ **interactions /** ***yr*** **for** $\Delta m^2 = 3.2\times 10^{-3}\,eV^2$

$\Rightarrow$ $250\ \nu_\tau$ **interactions in 5 years of run**

number ν_τ interactions $\div \left(\Delta m^2\right)^2$

Search for ν_τ candidates : $\tau \rightarrow e^-, \mu^-, h^-(\pi^-, \rho^-)$

"Long" decays (~ 40 % of τ)

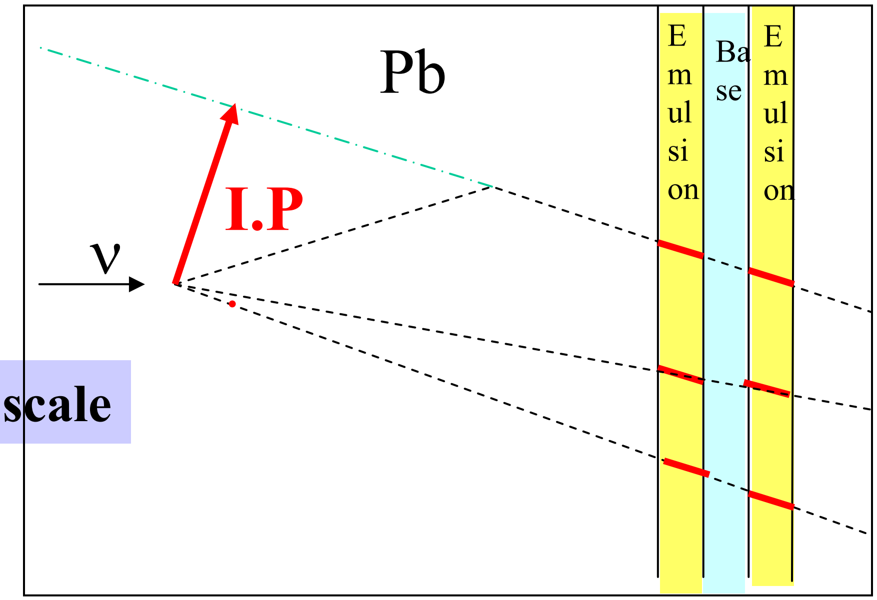


Search for a "kink"

$\theta_{kink} > 20$ mrad

$\varepsilon_{kink} \approx 90\%$

"Short" decays (~ 60 % of τ)



Not to scale

Search for a large impact parameter

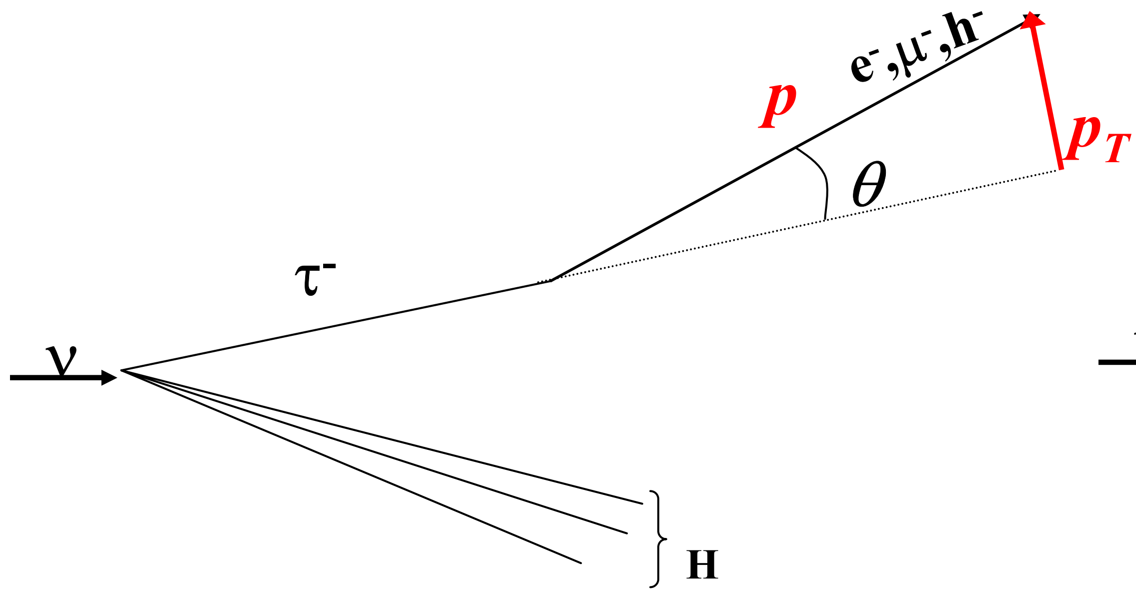
At least 2nd high p track

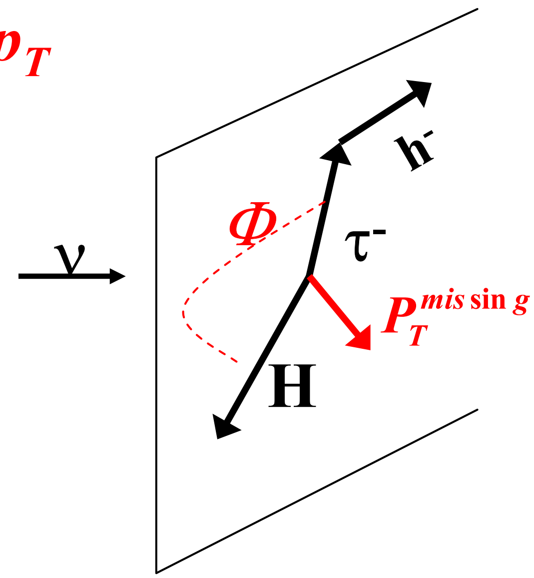
IP > 5-20 μm (depends of event depth)

$\varepsilon_{2t} \times \varepsilon_{IP} \approx 66\% \times 45\% = 30\%$

Total $\varepsilon \approx 54\%$ very conservative

Kinematics selection of ν_τ candidates in view of background reduction





$$\tau^- \to e^-, \mu^-, h^-(\pi^-, \rho^-)$$

$$\tau^- \to h^-$$

High p, high $_{pT}$ reject
low E scatters
π^-,K^- decays
h^- scatters

Select isolated h^- outside H shower

Monte-Carlo estimate of background

	$\tau^- \to e^-$	$\tau^- \to \mu^-$	$\tau^- \to h^-$	Total
charm production	0.162	0.028	0.140	0.330
ν_eCC and π^0	0.006			0.006
large μ^- scatter		0.100		0.100
h^- interaction			0.100	0.100
Total	0.168	0.128	0.240	**0.530**

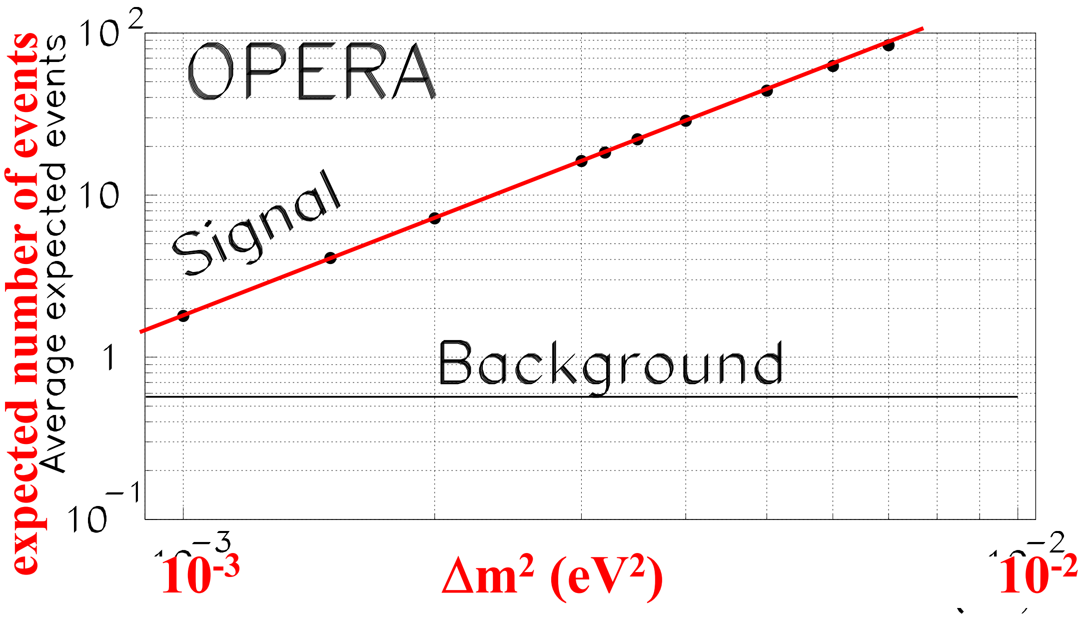
The background is given in events for $2.\ 10^4$ ν_μ DIS CC expected **in 5 years data taking**

$2.25\ \ 10^{20}$ p.o.t.

known to 50%
test measurements
in progress

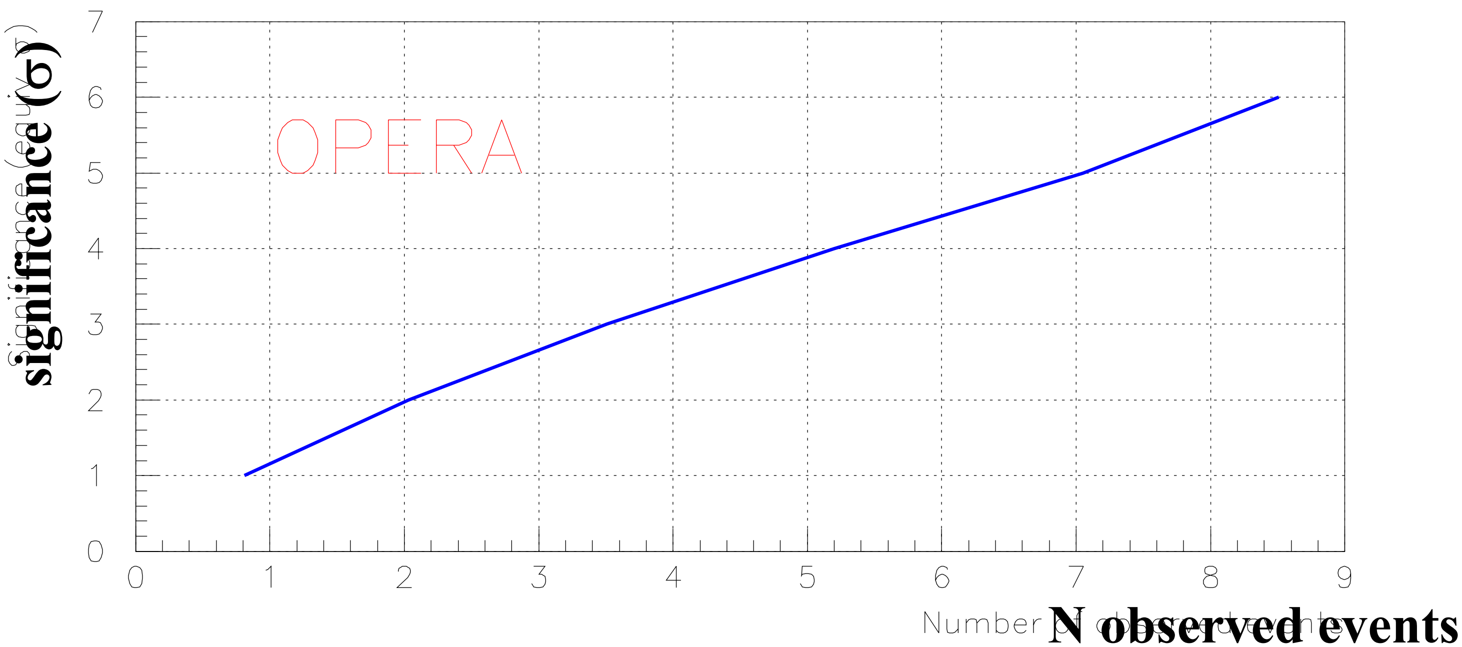
Signal
5-year run

Events for maximal mixing and 5 years running				
τ decay	Δm^2 (in 10^{-3} eV^2)			Bckgd
	1.5	3.2	5.0	
e	1.7	7.7	18.5	0.19
μ	1.3	5.7	13.8	0.13
h	1.1	4.9	11.8	0.25
Total	4.1	18.3	44.1	0.57



number ν_τ interactions $\div \left(\Delta m^2\right)^2$

Discovery potential 5-year run



Probability - in equivalent # of σ - that background fakes signal

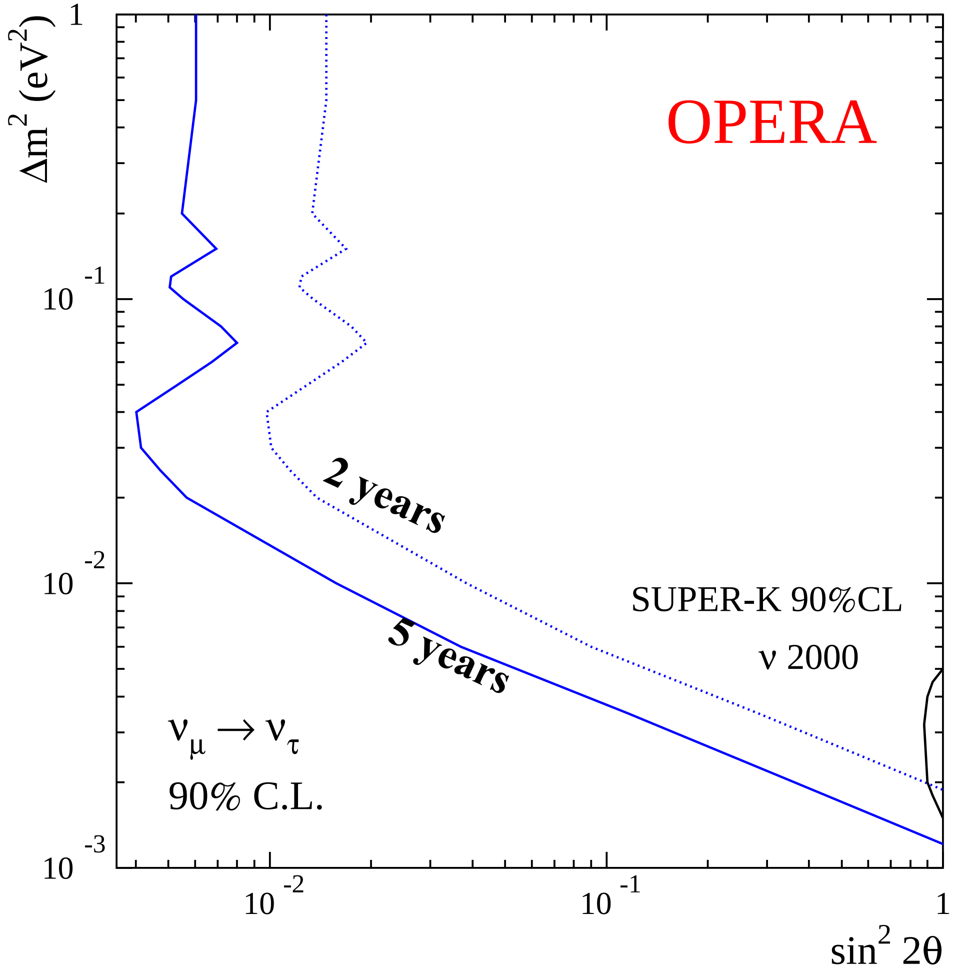
> 5 events is a "DISCOVERY" at $\geq 4\ \sigma$

$\Delta m^2 = 1.8 \times 10^{-3}\, eV^2$ **and 5 years of run**

SuperK @ 90% C.L.: $1.5 \times 10^{-3} \leq \Delta m^2 \leq 5.0 \times 10^{-3}\, eV^2$

Sensitivity 5-year run

average 90 % CL upper limit for a large # exp.^{ts}
in the absence of a true signal

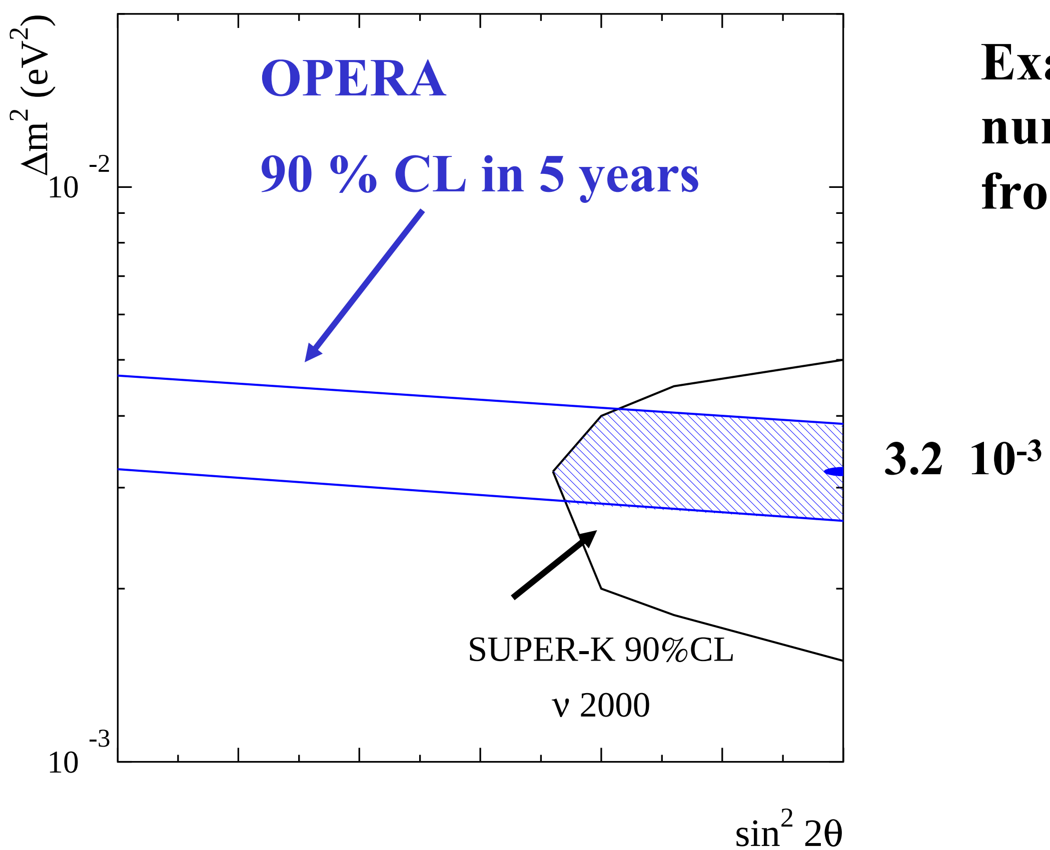


@ $\sin^2(2\theta) = 1$

Δm^2 (eV^2) < 1.2 10^{-3} eV^2

Constraint on oscillation parameters

Number of events $\div \sin^2 2\theta \times (\Delta m^2)^2$ for small Δm^2



Example in case observed number of events = expected from SK best fit $\Delta m^2 = 3.2\ 10^{-3}\ eV^2$

Status - schedule

CNGS beam

- **Construction approved December 1999**
- **Beam for physics May 2005**

OPERA detector

- **Proposal July 2000**
- **Presentation to SPSC on September 5, 2000**
  Officious green light
- **Presentation to LNGSSC on September 11, 200**
- **Hope for approval end 2000**
- **Ready to take data in May 2005**
  Because of modular structure, need not be fully completed when beam arrives.