Neutrino Oscillation Experiments at Reactors and Accelerators

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Contents

CHOOZ and PALO VERDE long baseline experiments
Search for ν_e disappearance at reactors.
Large mixing angle, small Δm^2 ($>10^{-3}$ eV^2)

KARMEN2 and LSND short baseline experiments
Search for $\nu_\mu - \nu_e$ oscillation in low energy neutrino beams.
High sensitivity, small mixing angle, large Δm^2 (few eV^2)

CHORUS and NOMAD short baseline experiments
Search for $\nu_\mu - \nu_\tau$ oscillation in high energy neutrino beams.
High sensitivity, small mixing angle, large Δm^2 (few tens eV^2)

To-morrow Byron Lundberg will give a seminar at FermiLab on

"Results from DONUT: First Direct Evidence of the Tau Neutrino”

This was expected and did no happen explicitly in Sudbury at Neutrino 2000

Neutrino Oscillation Experiments at Nuclear Reactors

Long base line experiments

at nuclear power plants of Chooz and Palo Verde

Motivation:

$\overline{\nu}_e$ disappearance
in (Δm^2 , $\sin^2 2\theta$) parameter space indicated by
ν_μ disappearance in atmospheric experiments $\nu_\mu \rightarrow \nu_e$?

Neutrino Oscillation at Reactors: pros and cons

- $E_\nu \approx$ few MeV $\Rightarrow$ Access to low Δm^2 at medium L $\quad \Delta m^2 \approx \frac{E \approx 3\ MeV}{L \approx 1000\ m} \approx 0.003\ eV^2$

  $\Rightarrow$ Below μ, τ thresholds: only disappearance $\bar{\nu}_e \rightarrow \bar{\nu}_x$

- High flux, but small σ

$$P = 1\,GW_{elec} \Rightarrow 3.3\,GW_{therm}$$

$$\text{Fission rate} \approx \frac{3.3GW}{200\,MeV} \approx 10^{20}\,s^{-1} \Rightarrow 6\ 10^{20}\ \bar{\nu}_e\ s^{-1}$$

- 4π source $\Rightarrow$ detector mass $\div L^2$

- Disappearance $\Rightarrow$ good knowledge of absolute ν flux and e^+ energy spectrum

  $\Rightarrow$ or multi-L experiment ($\geq$ 2 detectors or reactors) $\Rightarrow$

  no sensitivity at high Δm^2

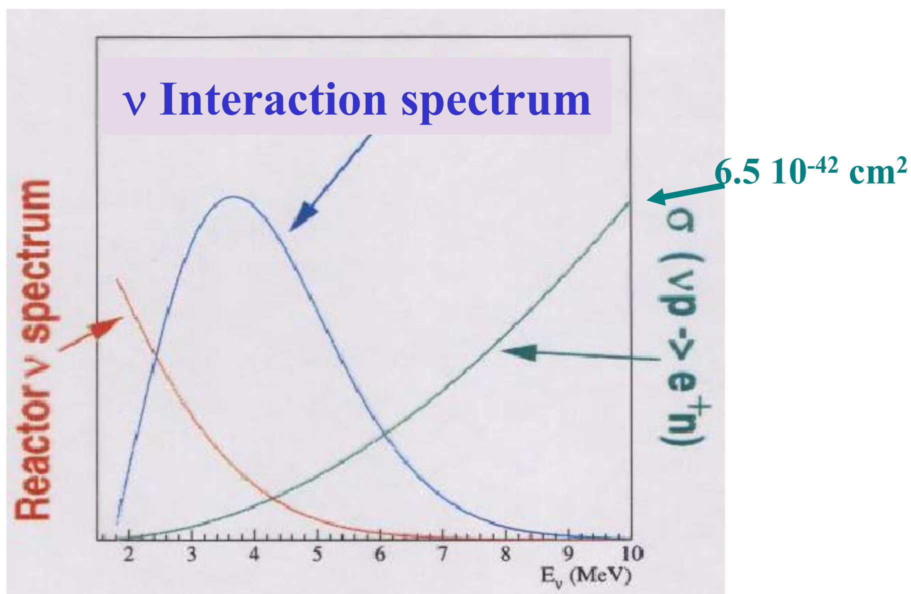
  (not serious problem with $\Delta m^2 \leq$ 0.01 eV^2

- Cheep and well known ν source

  Calculated and measured ν flux and energy spectrum at L=0 known to ~ 2% (Bugey 1995)

$$E_{\bar{\nu}_e}^{thresh} = 1.8\ MeV$$

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



Detection of neutrinos from nuclear reactors

1953 : F.Reines and C.L. Cowans discover the neutrino at Savannah River nuclear power plant

Detectors

- vessel filled with liquid scintillator doped with neutronphage
- shielding (bunker, underground) + active veto: cosmic rays, reactor n, natural radioactivity

Signal

$E_{\bar{\nu}_e}^{thresh} = 1.8\ MeV$

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

nuclear capture $\rightarrow \gamma$'s ($\sum E_\gamma$ known)

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

scintillation γ's

e^+-e^- annihilation : 2 γ of 0.511 keV

Space and delayed time correlation

Cerenkov light

The Long Base Line CHOOZ Experiment

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H. de Kerret[f], B. Dieterle[h], A. Etenko[d], J. George[h], G. Giannini[c], M. Grassi[b],
Y. Kozlov[d], W. Kropp[g], D. Kryn[f], M. Laiman[e], C.E. Lane[a], B. Lefièvre[f],
I. Machulin[d], A. Martemyanov[d], V. Martemyanov[d], L. Mikaelyan[d], D. Nicolò[b],
M. Obolensky[f], R. Pazzi[b], G. Pieri[b], L. Price[g], S. Riley[g], R. Reeder[h],
A. Sabelnikov[d], G. Santin[c], M. Skorokhvatov[d], H. Sobel[g], J. Steele[a], R. Steinberg[a],
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Phys. Let. B466 (1999) 415

CHOOZ detector

-1 detector - 2 reactors (8.5GW) : L= 998, 1114m
ΔL=116.7m

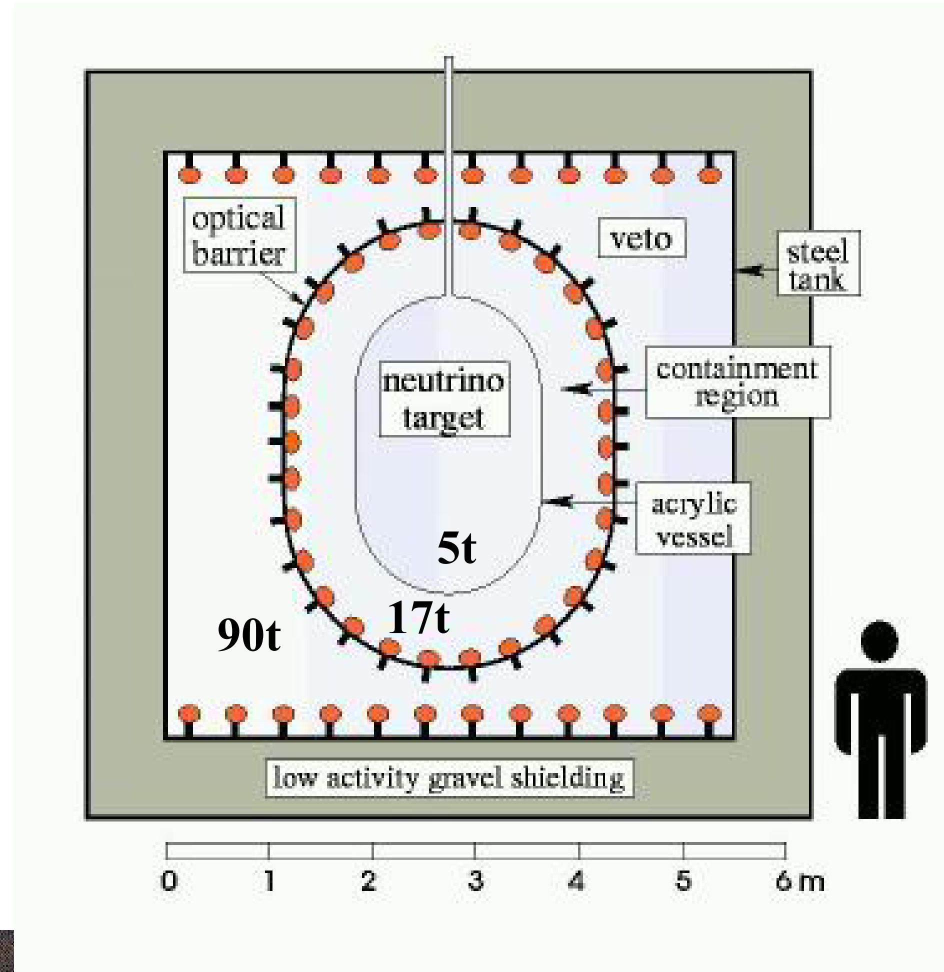
-rock overburden: 300 m water equivalent
0.4 cosmic μ m^{-2} s^{-1}

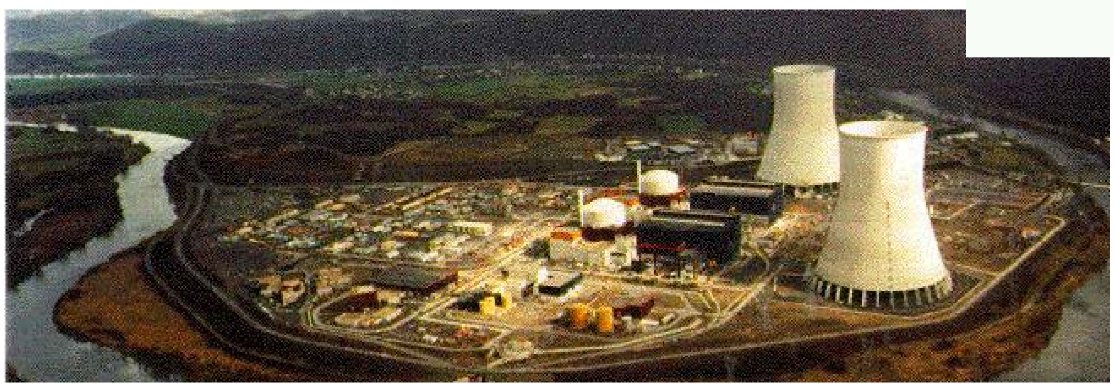
-5 tons Gd-doped liquid scintillatior (0.09%)

$$\sum E_\gamma = 8\,\mathrm{MeV}$$

-17 tons liquid scintillator : contain γ from n
PMT radioactivity shield

-90 tons active cosmic-ray muon veto





Event rates: **full power: 24.7±0.7 events/day**

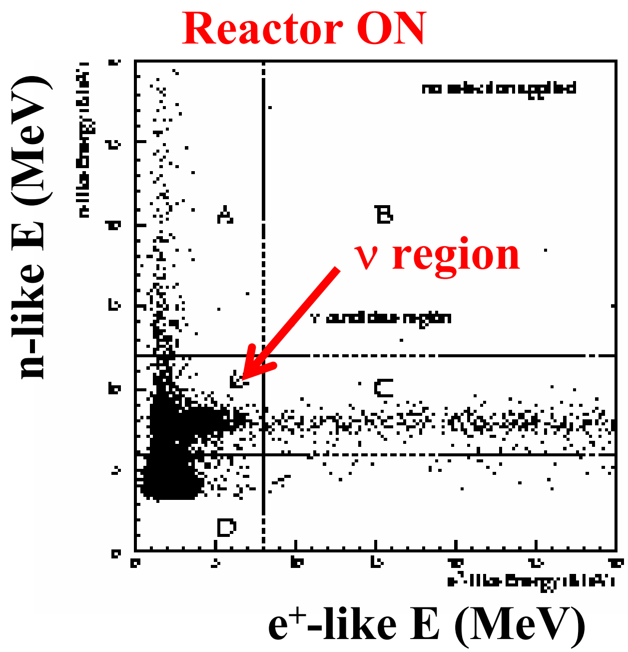
reactors off: 1.2 events/day

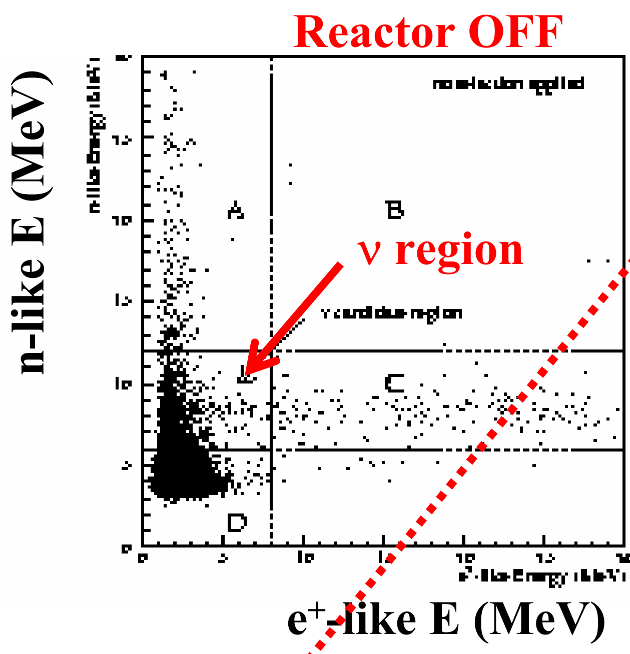
Data taking: April 1997 - July 1998		
Reactor 1 ON	2058.0 h	8295 GWh
Reactor 2 ON	1187.8	4136
Reactors 1 & 2 ON	1543.1	8841
Reactors OFF	3420.4	

Background estimates

Response calibration: γ, n and γ-n radioactive sources (^{60}Co, ^{252}Cf, Am/Be)

E_n^{abs} time dependence monitoring ($\sum E_\gamma = 8\,\mathrm{MeV}$) with n from cosmic : $\sigma_E = 0.5$ MeV

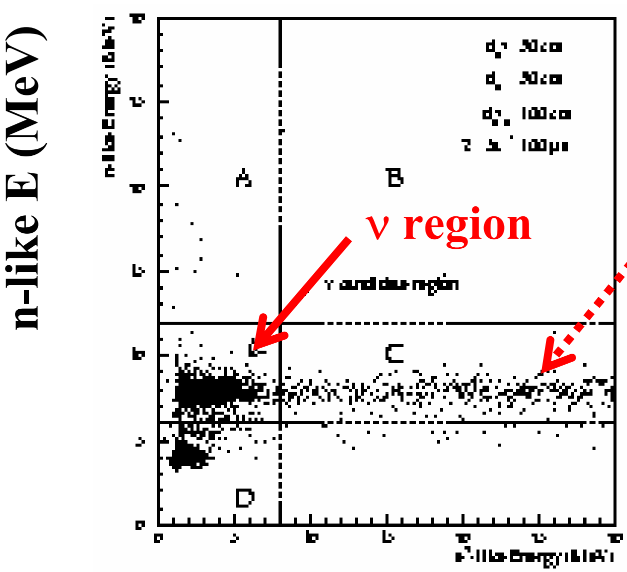


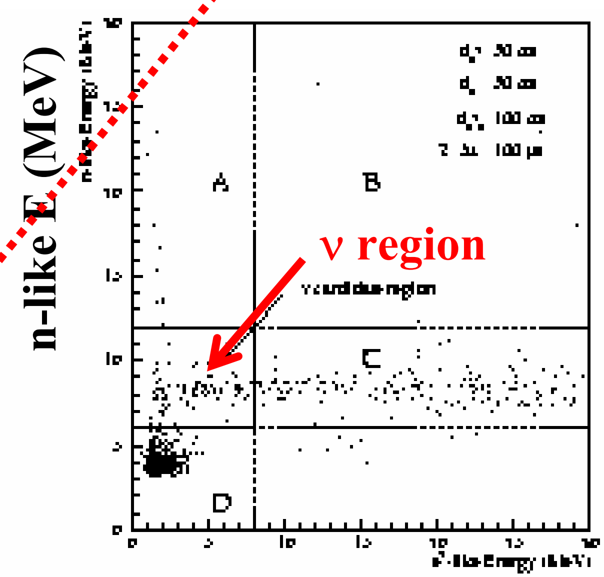


No event selection

Main background

fast spallation n in rock
+
p from n scattering (e^+ like)
+
n capture





ν selection

@ > 30 cm from wall,
n - e^+ distance < 100 cm
n - e^+ delay in (2-100) μs
E(e^+-like) in (1.3 - 8) MeV
E(n-like) in (6-12) MeV

2991 candidates
(287 reactors off)

Efficiency: 69.8%

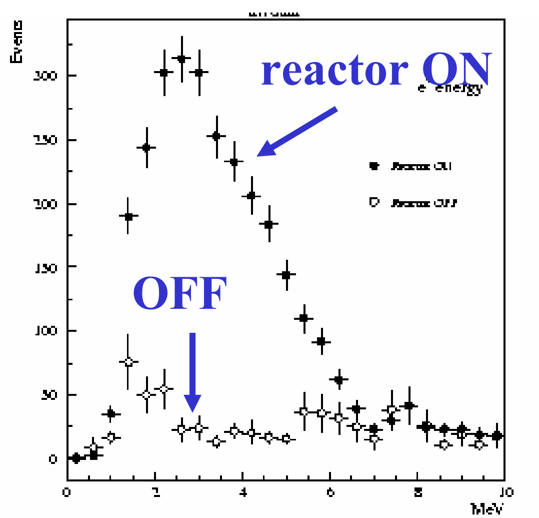
$\bar{\nu}_e$ flux known to 1.4%

- daily evolution of core isotopic evolution
- instantaneous fission rate from thermal power
- ν yield from measured β spectra of main isotopes

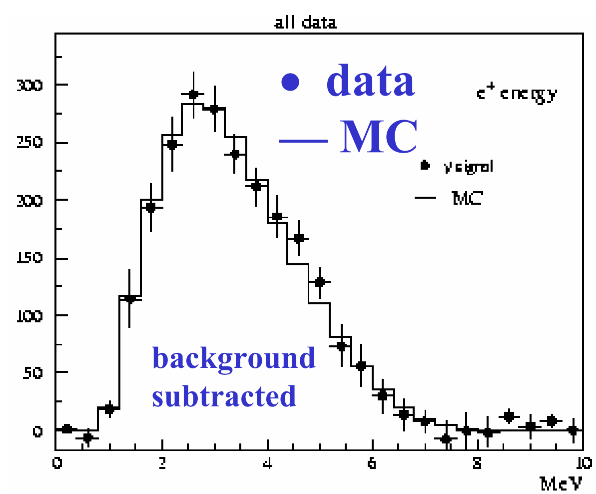
\+

E_{e+} spectrum

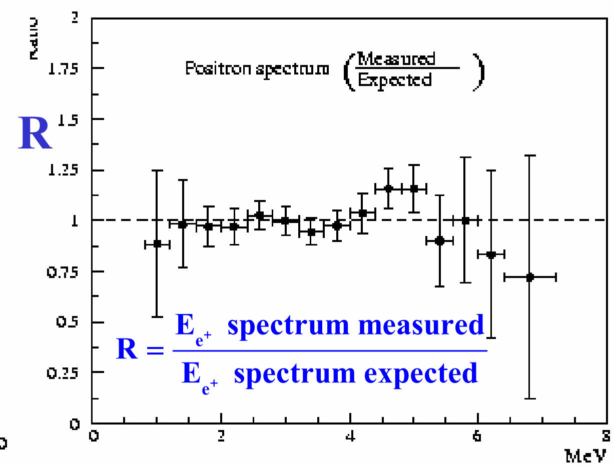
- inverse β-decay cross-section
- simulation of detector response



E_{e+} (MeV)



E_{e+} (MeV)



E_{e+} (MeV)

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

→ **No oscillation signal**

Analysis Methods

A - Compare unfolded E_{e+} absolute spectra of both reactors to expectation

Systematic uncertainty on absolute normalisation: ~2%

Two “independent” measurements

B - Ratio of spectra

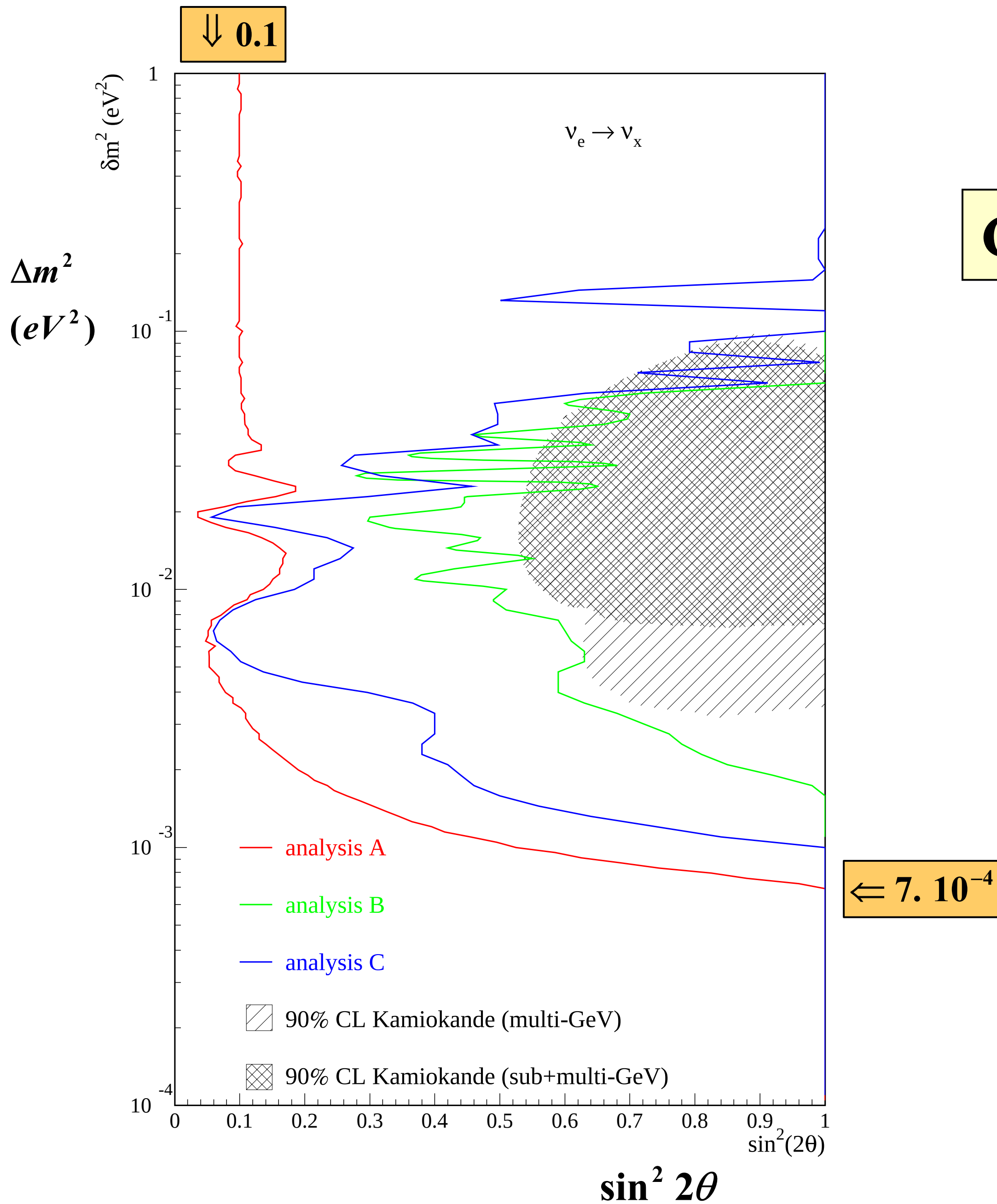
Most systematic cancel

No sensitivity at large Δm^2

C - Compare unfolded E_{e+} spectra shapes of both reactors to expectation

Intermediate sensitivity

Chooz exclusion plot



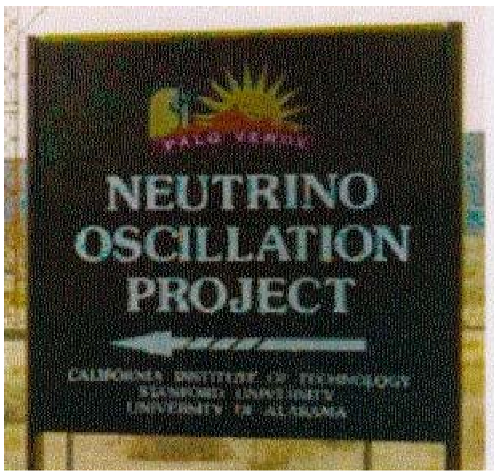
A — absolute spectra

B — spectra ratio

C — spectra shape

Kamiokande 90%

The Long Base Line Palo Verde Experiment



J. Busenitz, J. Kornis, K. McKinny, J. Wolf
University of Alabama

D. Lawrence, B. Ritchie
Arizona State University

F. Boehm, B. Cook, H. Henrikson, V. Novikov,
A. Piepke, P. Vogel, K.B. Lee
Caltech

G. Gratta, L. Miller, D. Tracy, Y-F. Wang
Stanford University

G.Gratta Neutrino 2000
F.Boehm et al. hep-ex/000322

-1 detector - 3 reactors (11.6 GW) : L= 750, 890m
ΔL= 110m

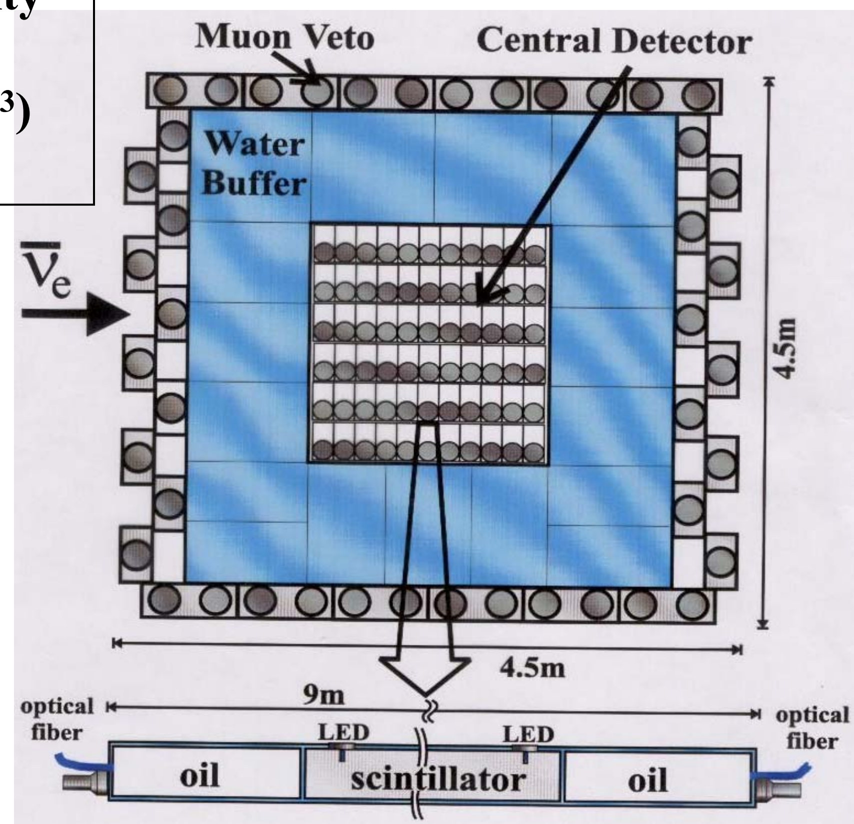
-rock overburden: 32 m water equivalent
22 cosmic μ $m^{-2} s^{-1}$

-11.3 tons Gd-doped liquid scintillation (0.1%)
$\sum E_\gamma = 8\,MeV$

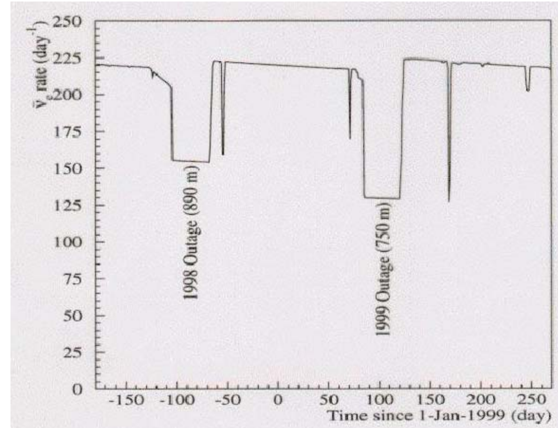
- oil and 105 tons water buffer: γ and n shield
shield PM radioactivity

-optically segmented detector (900x12.7x25.4 cm^3)
$\Rightarrow$ background suppression

Palo Verde detector



Difficulty : **No period with all reactors off** **to measure simply the reactors off background.**



Analysis based on the knowledge of the flux form
the known reactors power ⇒ True expected event number
compared to
Observed number of candidates
corrected for detector efficiencies (MC)

Unknowns :
-Background
-Overall normalisation within systematic uncertainty

Events (day^{-1})	1998 ON	1998 OFF (890 m)	1999 ON	1999 OFF (750 m)
N_{cand}	38.2±1.0	32.2±1.0	52.9±0.7	43.9±1.4
b	19.5 ± 1.7		26.3 ± 2.2	
$N_{detected}$	18.7±2.0	12.7±2.0	26.6±2.3	17.6±2.6
R_{obs}	225±24	140±22	216±19	140±21
R_{calc}	218	155	218	130

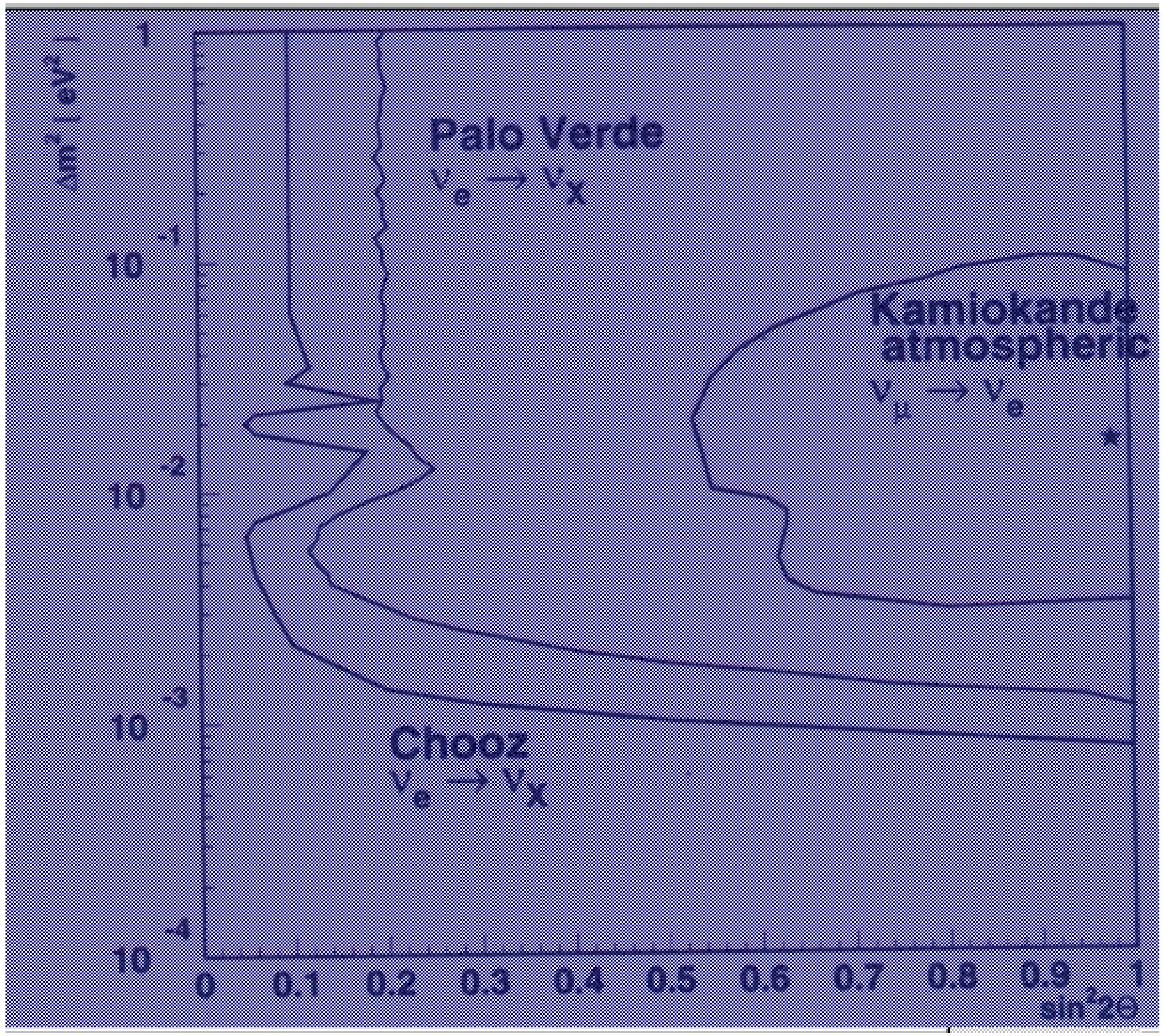
efficiency	**0.075**	**0.077**	**0.112**	**0.111**

R = 1.04 + 0.03 (stat) + 0.08 (sys) ⇒ No oscillation

Run till
end Summer 2000

2 new reduced power
periods

Not likely to do better
than Chooz



Three neutrinos families analysis

Reactor experiments

exclude two-family $\nu_\mu \rightarrow \nu_e$ oscillation

in parameters region where

ν_μ deficit in atmospheric experiments

favours two-family $\nu_\mu \rightarrow \nu_\tau$ (or ν_s)

⇓

(at least) 3-flavour analysis

3-flavour mixing parametrization

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\left.\begin{aligned} \nu_\alpha &= \sum_{k=1,}^{3} U_{\alpha k}\, \nu_k \\ \sum_{k=1,}^{3} \left|U_{\alpha k}\right|^2 &= 1 \\ \sum_{k,k' \neq k}^{=1.3} \Delta m^2_{kk'} &= 0 \end{aligned}\right\} \quad \alpha = e, \mu, \tau$$

6 (8) parameters
Dirac (Majorana)

$$\begin{cases} 2\ \Delta m^2_{kk'} \\ 3\ \left|U_{\alpha k}\right| \\ 1\ (3)\ \text{phases} \end{cases}$$

CKM-like matrix standard parametrization)

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

$$\left\{\begin{aligned} c_{ij} &= \cos\theta_{ij} \\ s_{ij} &= \sin\theta_{ij} \end{aligned}\right\} \quad i, j = 1, 3 \ \ \text{genreation nunbers}$$

3-family flavour at the strong mass hierarchy approximation

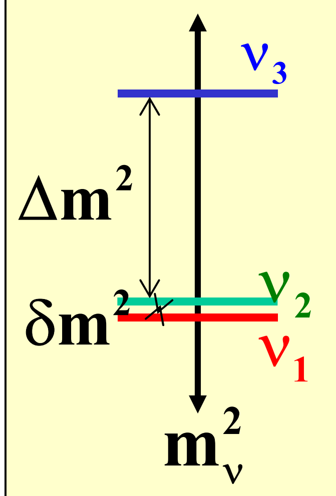
if $m_3 \gg m_1, m_2$

$\Delta m^2 = m_3^2 - m_1^2 \approx m_3^2 - m_2^2$ e.g. 10^{-3} eV^2 atmospheric neutrinos

$\delta m^2 = m_2^2 - m_1^2$ e.g. 10^{-6} eV^2 solar neutrinos

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

$\Downarrow$



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

(e.g. atmospheric neutrinos $\Delta m^2 = 10^{-3}$ eV^2, E = 1 GeV, L=1000 km)

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

$\Downarrow$

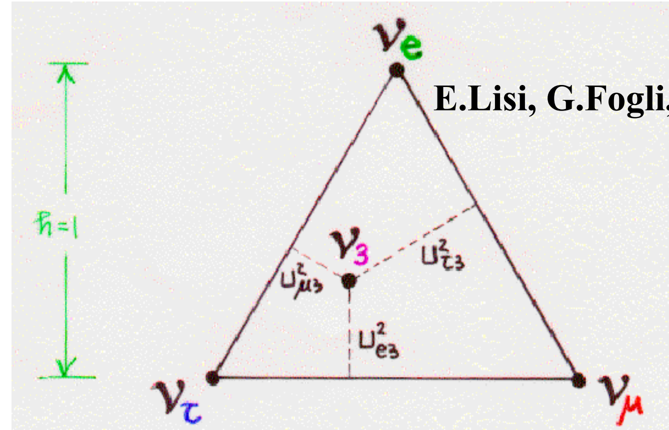
$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) \approx 4|U_{\alpha 3}U_{\beta 3}|^2 \sin^2(1.27\Delta m^2 E/L)$$

$$\sin^2 2\theta_{\alpha\beta}^{eff} = 4|U_{\alpha 3}U_{\beta 3}|^2$$

Physics governed by:

- Δm^2
- flavour contents of ν_3
- effective 2-flavour like oscillation

Effective 2-family atmospheric ν_μ disappearance in 3-family mixing

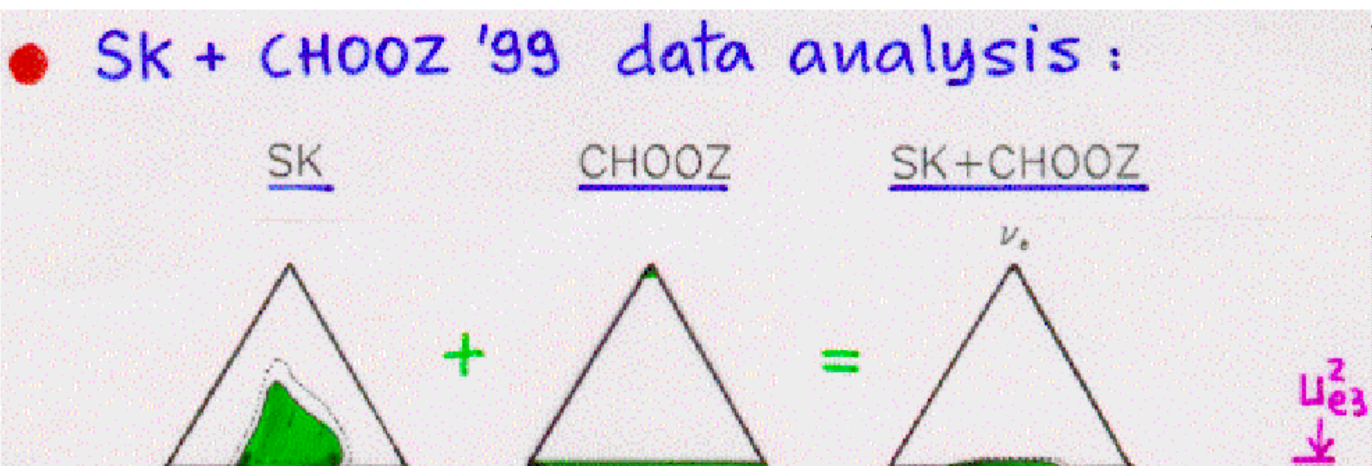


E.Lisi, G.Fogli, ...

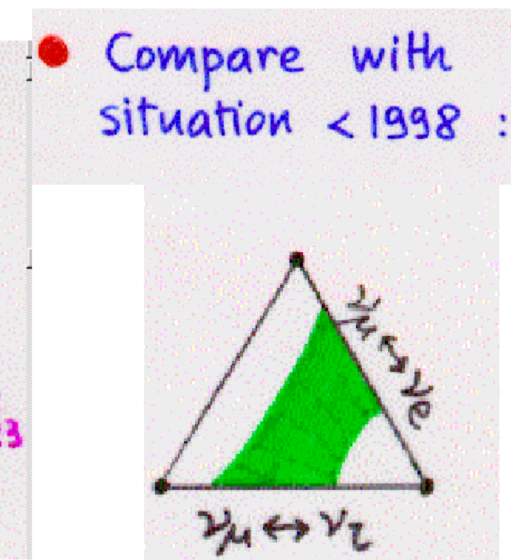
$$\sin^2 2\theta^{eff}_{\mu e} = 4\left|U^2_{\mu 3} U^2_{e3}\right| = \sin^2 2\theta_{13} \sin^2 \theta_{23}$$

$$\sin^2 2\theta^{eff}_{\mu\tau} = 4\left|U^2_{\mu 3} U^2_{\tau 3}\right| = \sin^2 2\theta_{23} \cos^4 \theta_{13}$$

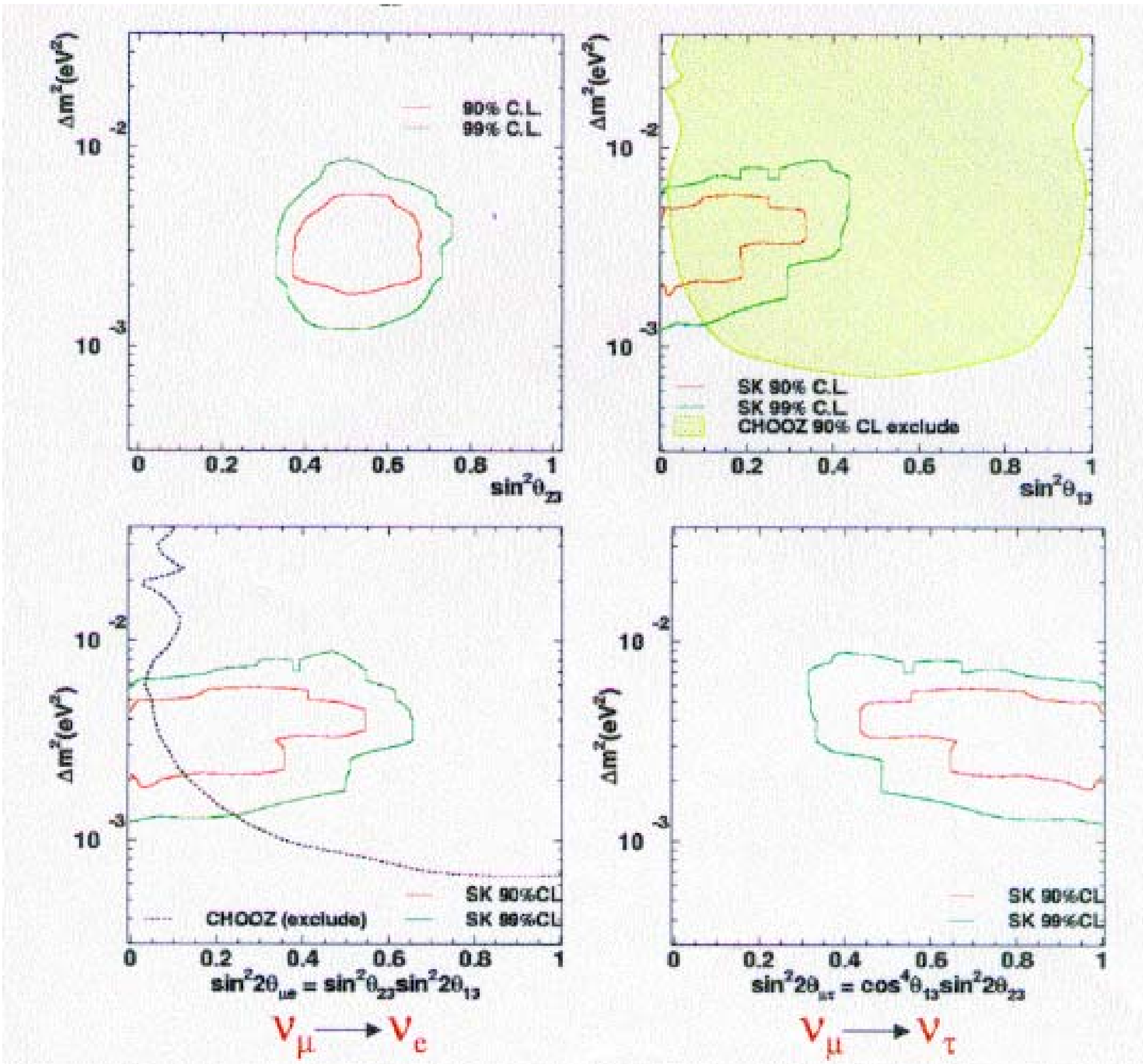
$$\left.\begin{array}{l} U^2_{e3} \ \text{small (reactors)} \\ 4\left|U^2_{\mu 3} U^2_{\tau 3}\right| \approx 1 \ \text{(full mixing atmospheric)} \\ U^2_{\mu 3} + U^2_{\tau 3} \approx 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{l} U^2_{e3} < 0.1 \ ? \\ U^2_{\mu 3} \approx U^2_{\tau 3} \approx 0.5 \ ? \end{array}\right.$$



E.Lisi, Neutrino 2000



H.Sobel Neutrino2000



Space is left for $U^2_{e3} \neq 0$

Conclusions:

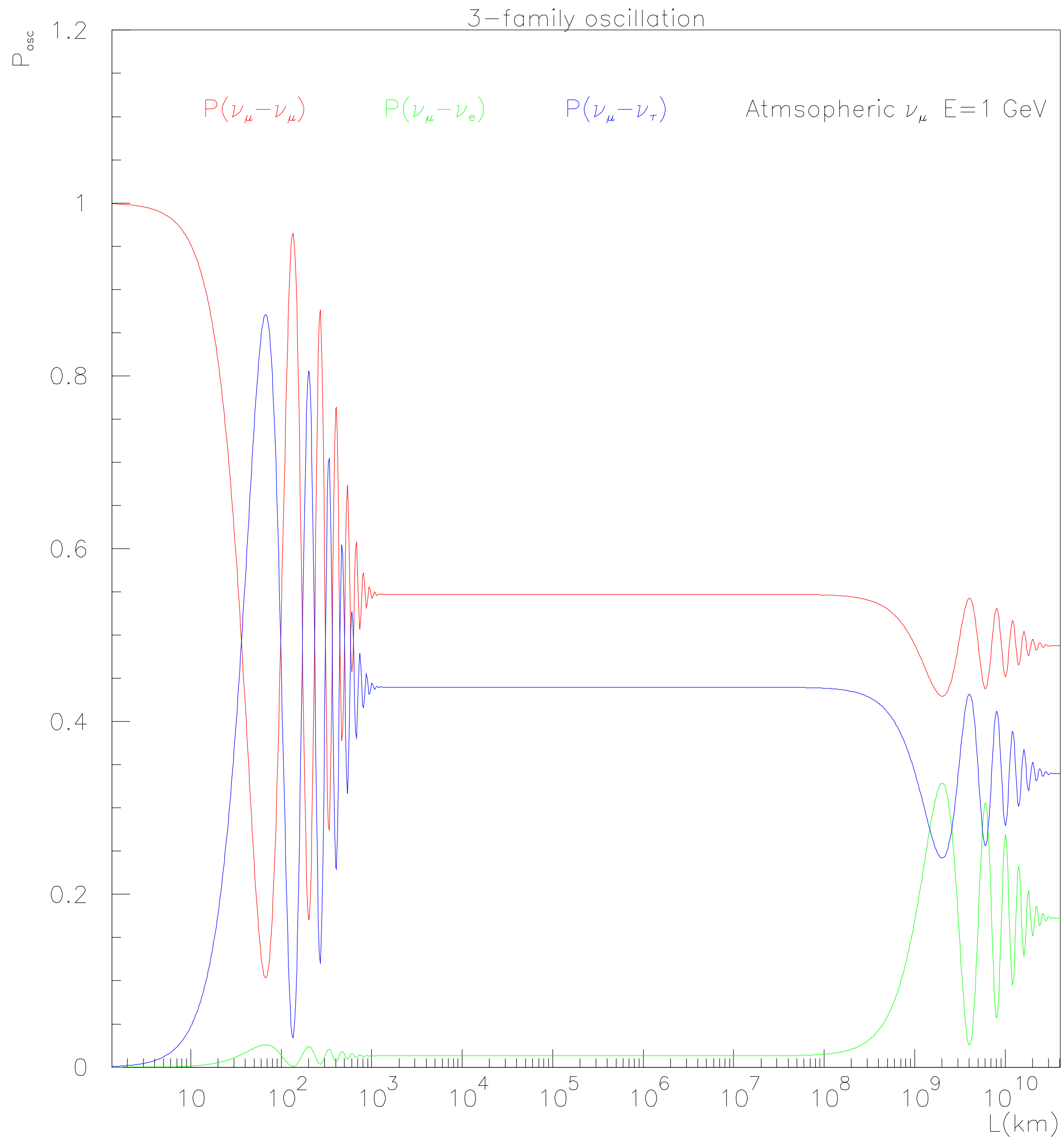
- No evidence for ν_e disappearance in LBL reactor experiments

- Reactor + Atmospheric neutrino experiments

  + in 3-flavour strong mass hierarchy model

  room left for a small ν_e contents in ν_3

- No more constraining data to be expected from reactors in near future



3−family oscillation
P_osc
1.2
1
0.8
0.6
0.4
0.2
0
P(ν_μ−ν_μ)
P(ν_μ−ν_e)
P(ν_μ−ν_τ)
Atmsopheric ν_μ E=1 GeV
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
L(km)

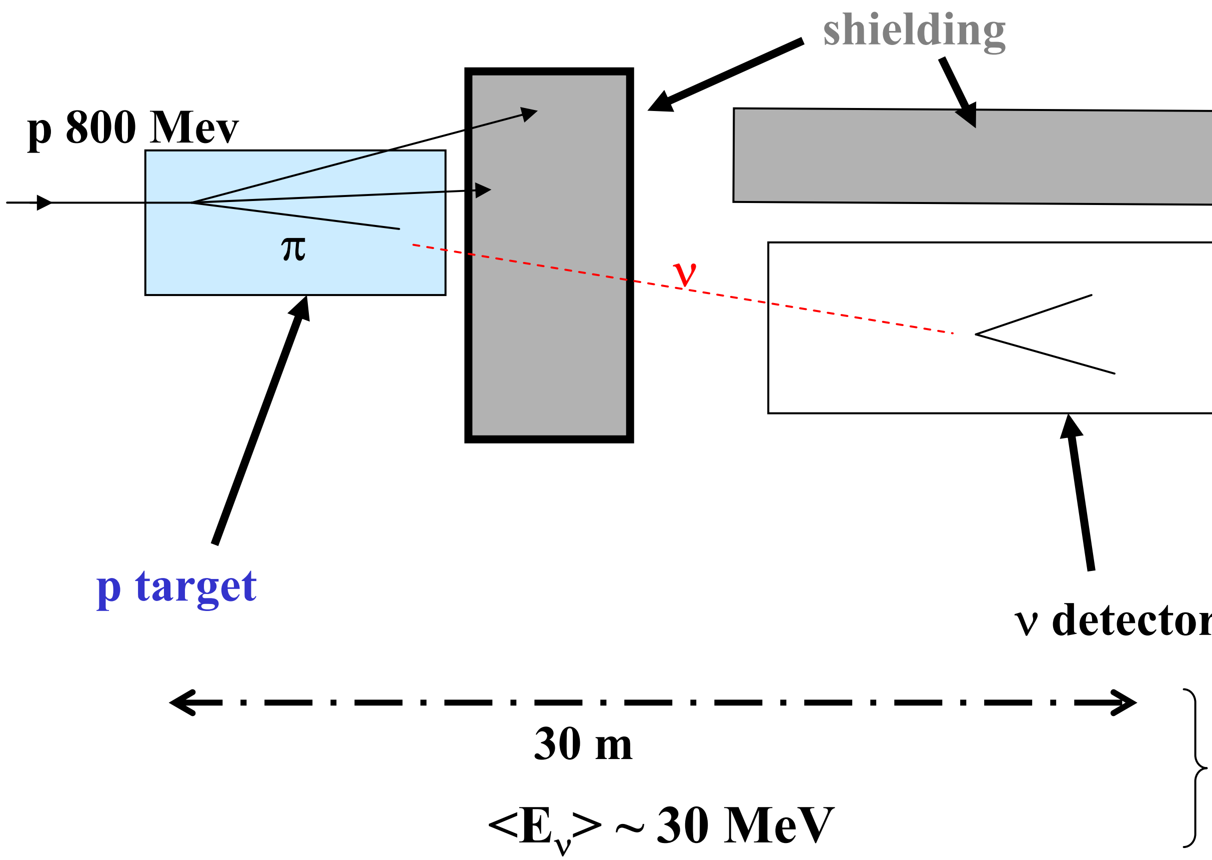
Neutrino Oscillation Experiments at Low Energy Accelerators (Beam Stoppers)

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

Compare somehow conflicting results from two similar experiments:
KARMEN2: no signal
LSND: statistically significant signal

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

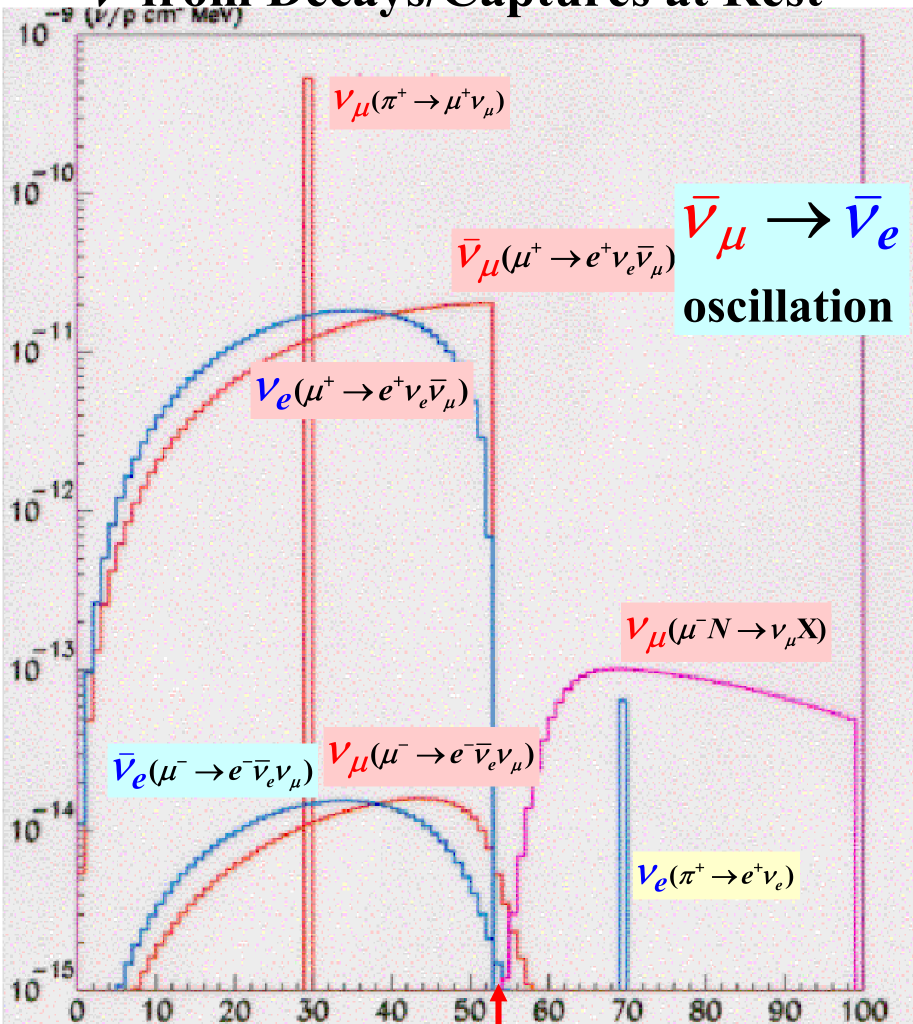
Conceptual design:



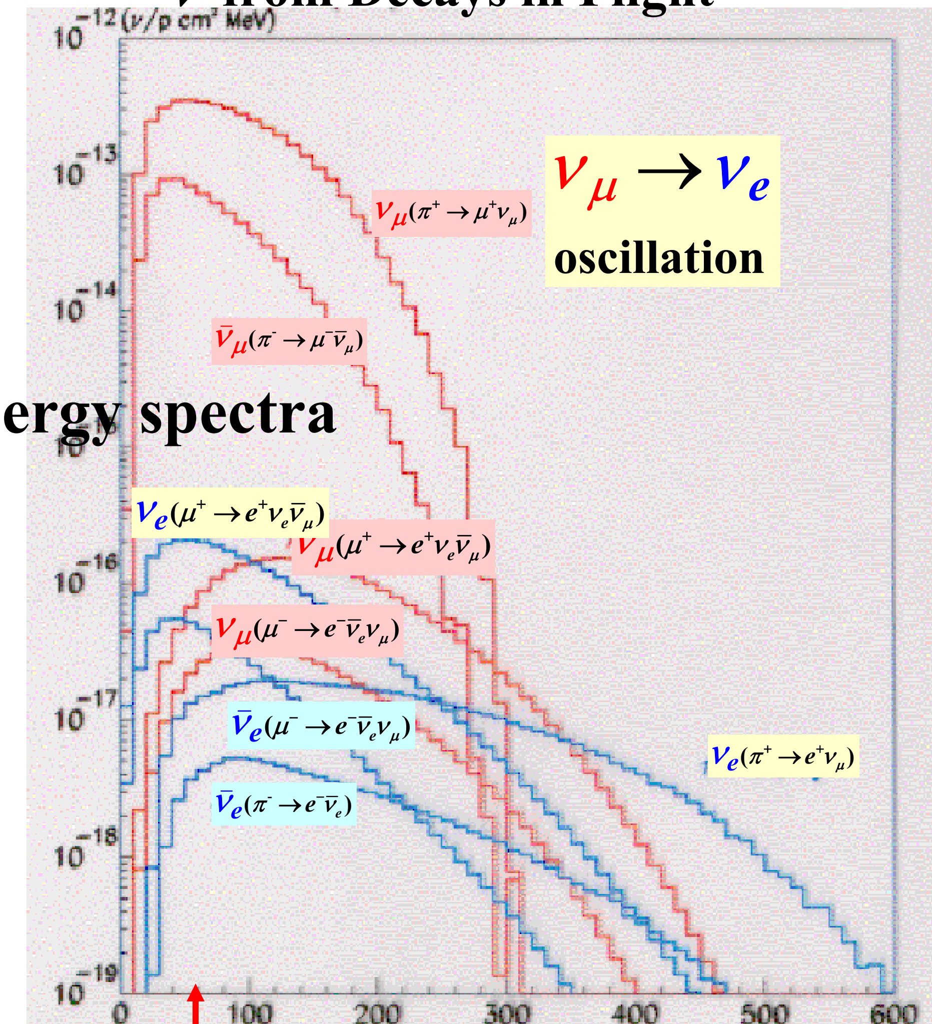
$$\Delta m^2 \approx \frac{L}{E} \approx 1\, eV^2$$

The ν Energy spectra

ν from Decays/Captures at Rest



ν from Decays in Flight



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

$E_\nu < 53 MeV$

53MeV

spectra are for LSND

53MeV

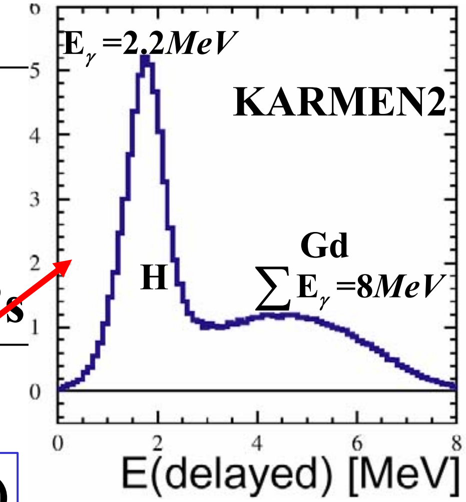
$\nu_\mu \to \nu_e$

$E_\nu > 53 MeV$

Detectors

vessel filled with oil + liquid scintillator
doped with neutronphage

several light signal by arrays of PMT's



Signal

nuclear capture $\rightarrow \gamma$'s ($\sum E_\gamma$ known)

$E^{thresh}_{\bar{\nu}_e} = 1.8\ MeV$

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

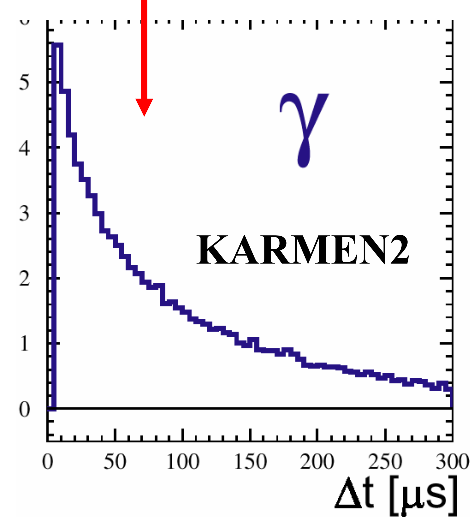
$\bar{\nu}_e + p \rightarrow e^+ n$

scintillation γ's

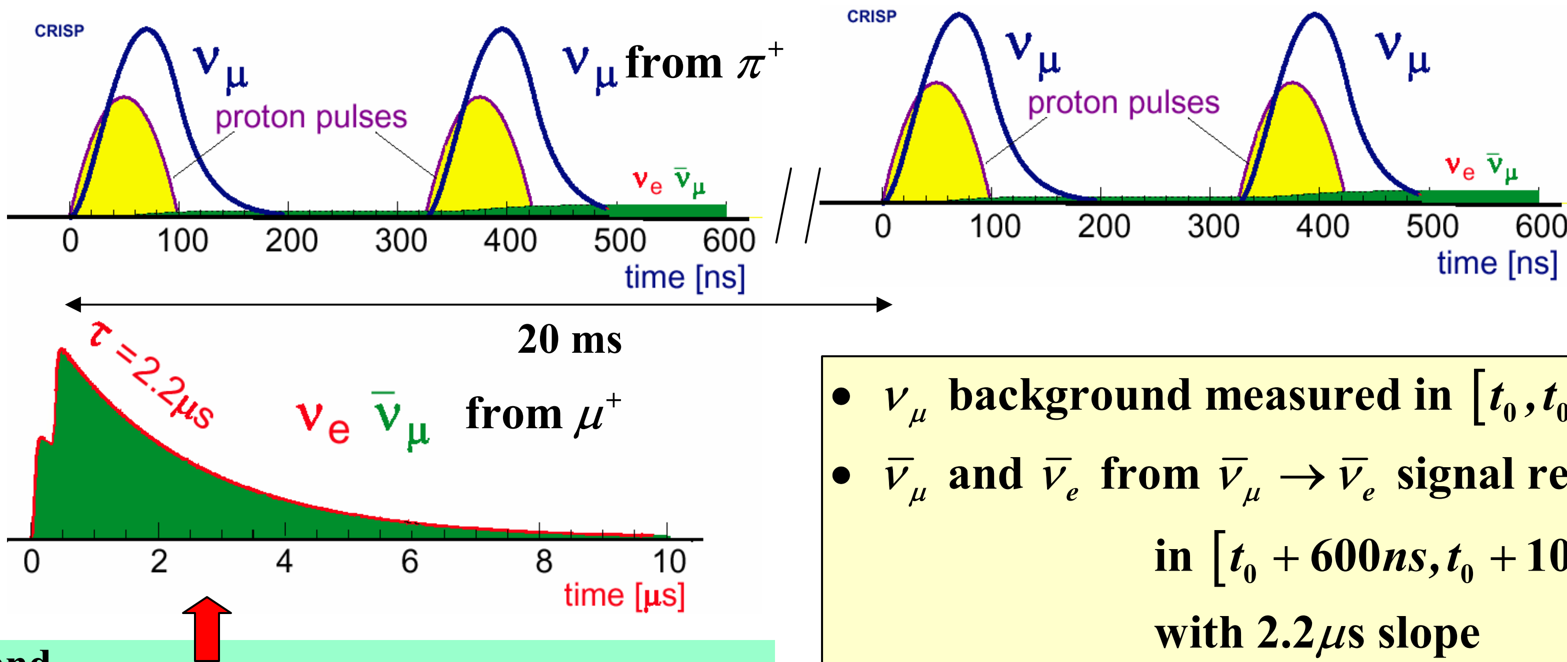
$e^+ - e^-$ annihilation : 2 γ of 0.511 keV

Cerenkov light

Space and delayed time correlation



Main Karmen2 pro: Time structure of ISIS p source



and

prompt e^+ signal from QE $\bar{\nu}_e p$

from $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation

- **ν_μ background measured in $[t_0, t_0 + 600ns]$**
- **$\bar{\nu}_\mu$ and $\bar{\nu}_e$ from $\bar{\nu}_\mu \to \bar{\nu}_e$ signal recorded**
  in $[t_0 + 600ns, t_0 + 10.6\mu s]$
  with 2.2μs slope
- **cosmic background measured**
  in $[t_0 + 10.6\mu s, t_0 + 20ms]$
- **small duty cycle $\to$ small cosmic background**

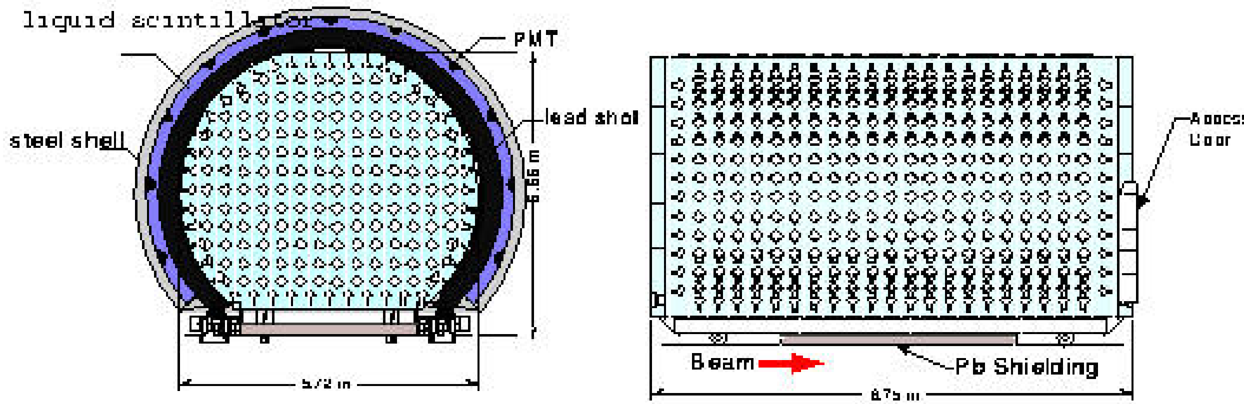
- **Segmented detector: better n-e^- space correlation**
- **High scintillator concentration: × 4 better E resolution**

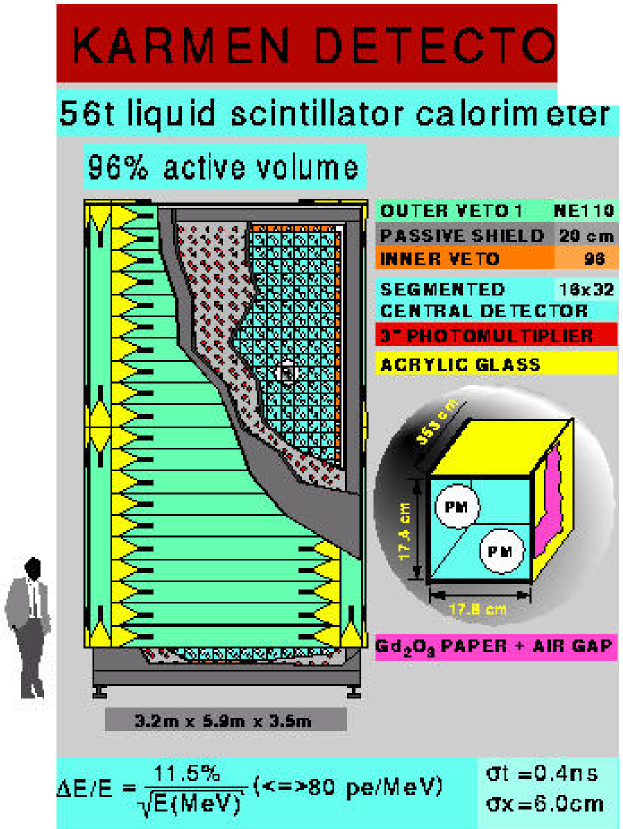
Main LSND pro: Electron ID and direction

Homogeneous detector + low scintillator concentration
$\Rightarrow$ Cerenkov ring as e^+ signature

- **$\times$3 Mass**
- **L=18m (instead of 30m) $\Rightarrow$ lower Δm^2**
- **3% of DIF $\pi^+ \to \mu^+ \nu_\mu$ (instead of 0.1%)**
  $\Rightarrow$ higher energy beam component
  $\Rightarrow$ $\nu_\mu \to \nu_e$ oscillation via $\nu_e C \to e^- N$

LSND detector
at LAMPF, Los Alamos





KARMEN-II
detector at ISIS, RAL

Statistical analysis difficulties

KARMEN-2

- **no signal and very low expected background : place an Upper Limit**
- **(for long: 0-event observed sample, 3 expected background)**
- **non physical max likelihood : $\sin^2 2\theta < 0$**

LSND

- **signal region in parameter space computed from rapidly oscillating likelihood function with many local maxima**

Profusion of recent papers and workshops
on our to fix C.L. limits from likelihood functions
(starting G.J.Feldman & R.D.Cousins, Phys Rev D57(1998)3873)

KARMEN-2 results

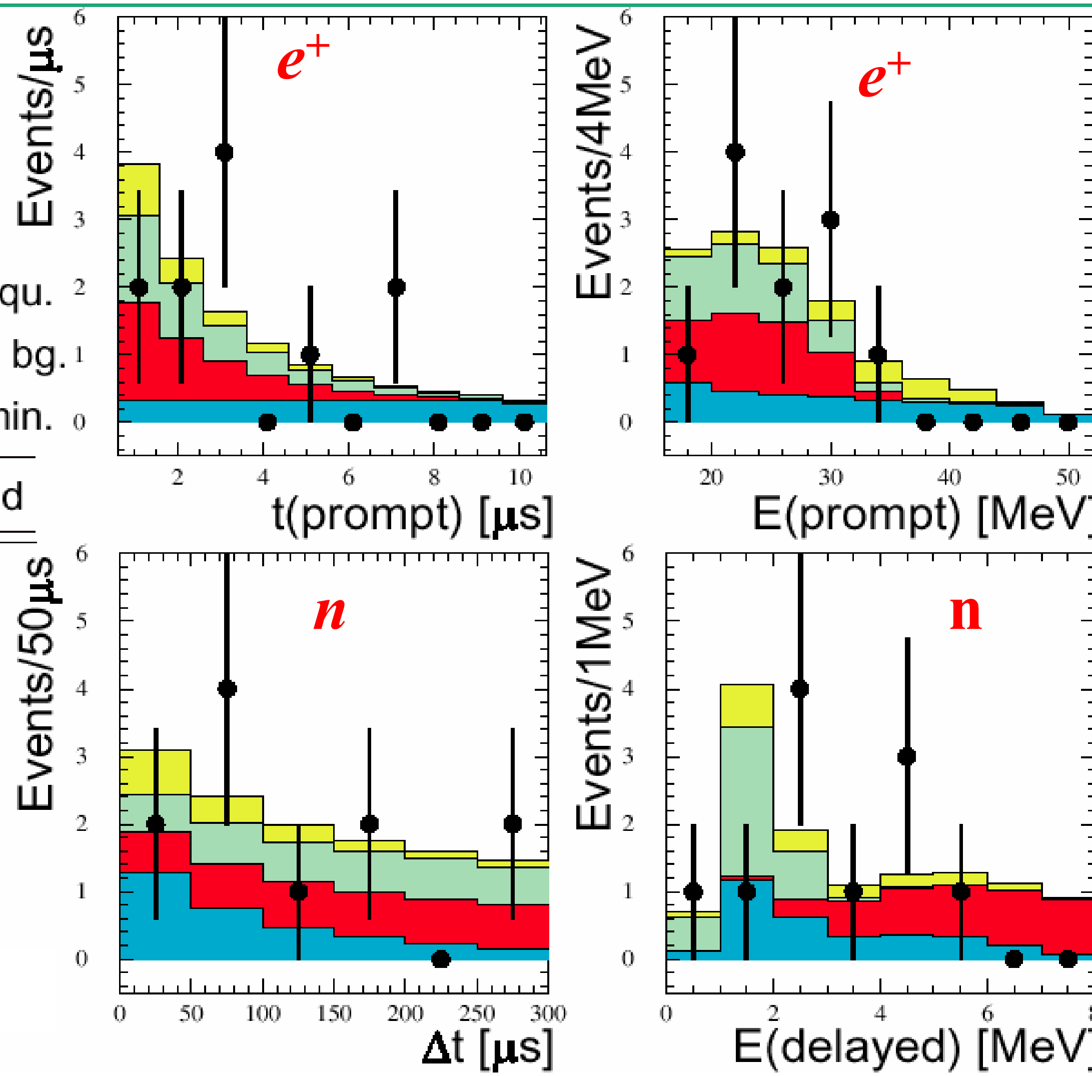
data set after final cuts

11 candidates

3.94 +- 0.51	(red)	ν_e-induced CC sequ.
3.52 +- 0.30	(light green)	ν-induced random bg.
1.67 +- 0.17	(yellow)	$\bar{\nu}_e$ intrinsic contamin.
3.17 +- 0.17	(blue)	cosmic background
12.29 +- 0.63		total background

⟹ **no osci signal**

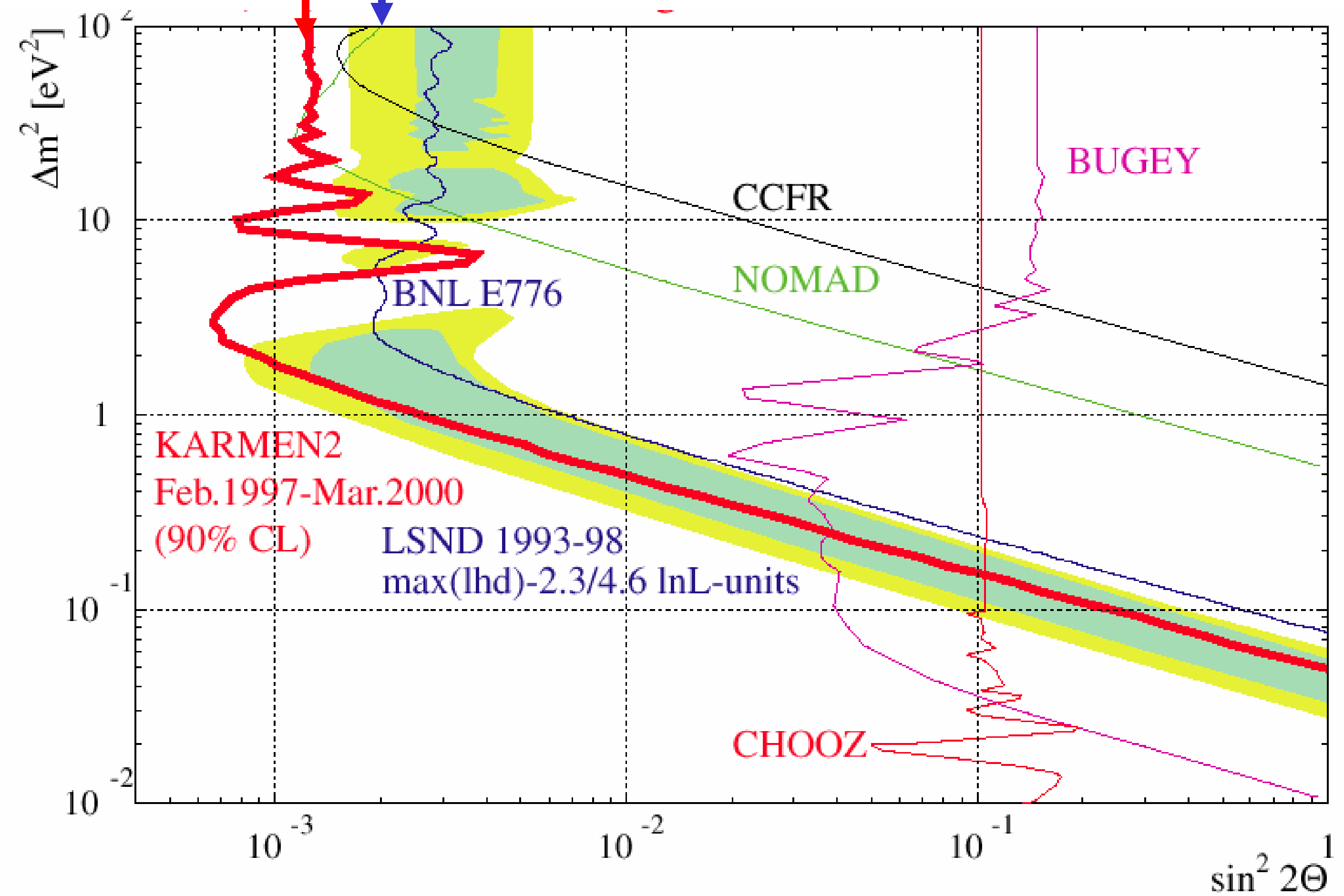
All backgrounds measured except intrinsic



KARMEN-2 exclusion plot

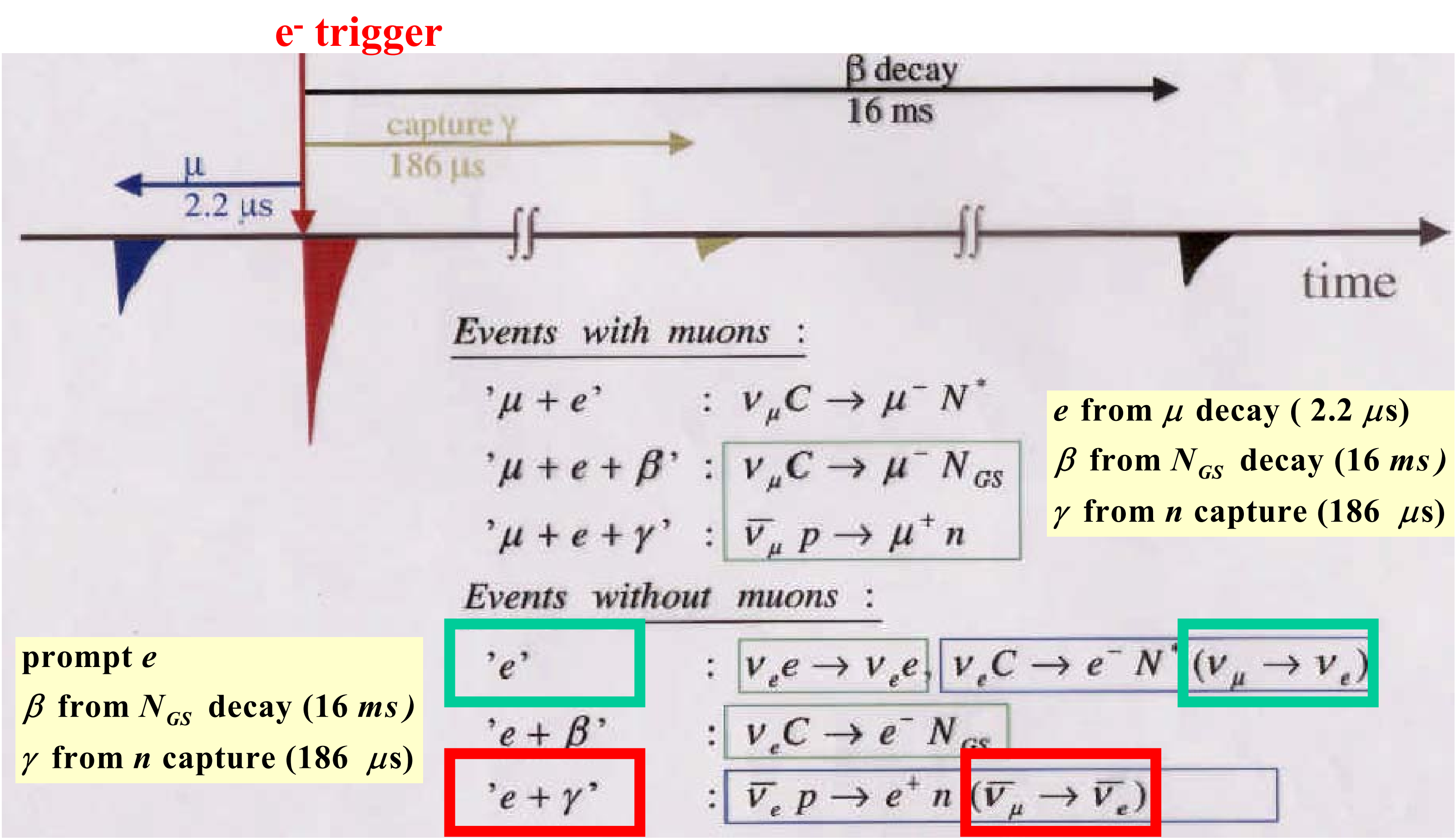
$$L(\sin^2 2\theta, \Delta m^2) = \prod_{k=1}^{11} \{ r_{osc} \cdot f_{osc}(E_{promt}, E_{delayed}, t_{prompt}, \Delta t, \Delta\vec{r})_k + (r_{back} = 1 - r_{osc}) \cdot f_{back}(E_{promt}, E_{delayed}, t_{prompt}, \Delta t, \Delta\vec{r})_k \} \times P_{oisson}(r_{back} \mid r_{back}^{exp})$$

$\sin^2 2\theta < 1.3 \cdot 10^{-3}$, sensitivity $= 1.7 \cdot 10^{-3}$ } @ large Δm^2



+ Unified frequentist approach (F.-C.)

New LSND global analysis of all event categories with a common Electron trigger and E_e in [20-200] MeV

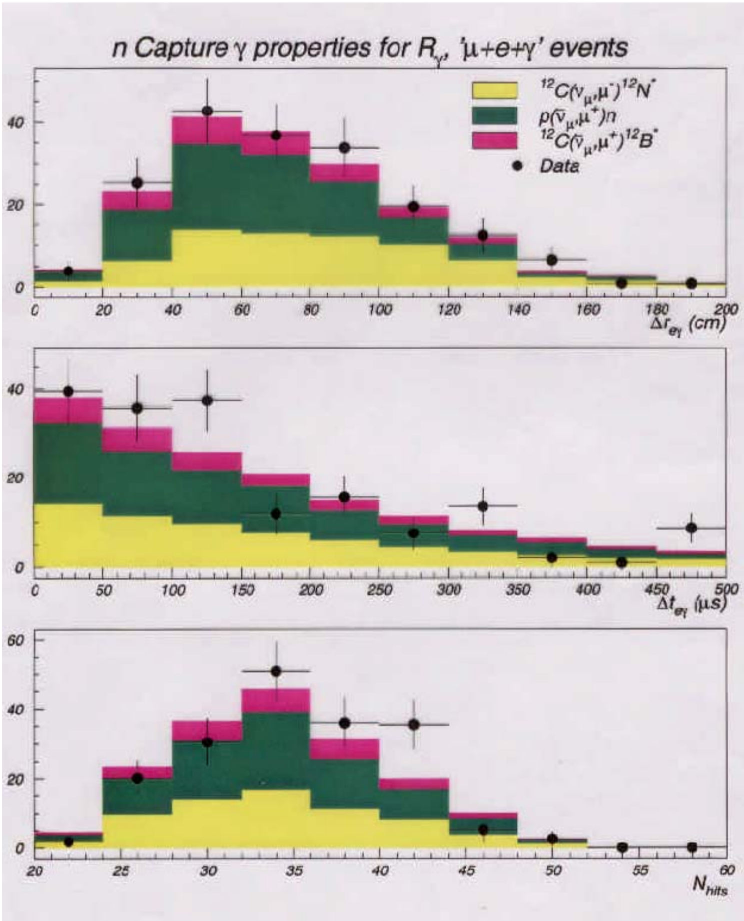


New LSND global analysis of all event categories with a common Electron trigger and E_e in [20-200] MeV

Global fit

- **to all relevant distributions**
  - ***E (e,β,γ,μ)***
  - ***Δt (e - β,γ,μ)***
  - ***Δr (e - β,γ,μ)***
  - ***θ (ν – e⁻)***
  - ***R* : ratio of likelihood of prompt (*e* ⁻) and delayed events (*γ*) to be correlated/accidental**
- **for all electron trigger events categories**
- **with parameters:**
  - **π^+/π^- production ratio**
  - **all DAR and DIF *π* and μ**
  - **efficiencies *μ, e, β, γ***

Oscillation signal : " *e γ* " events with large *R*

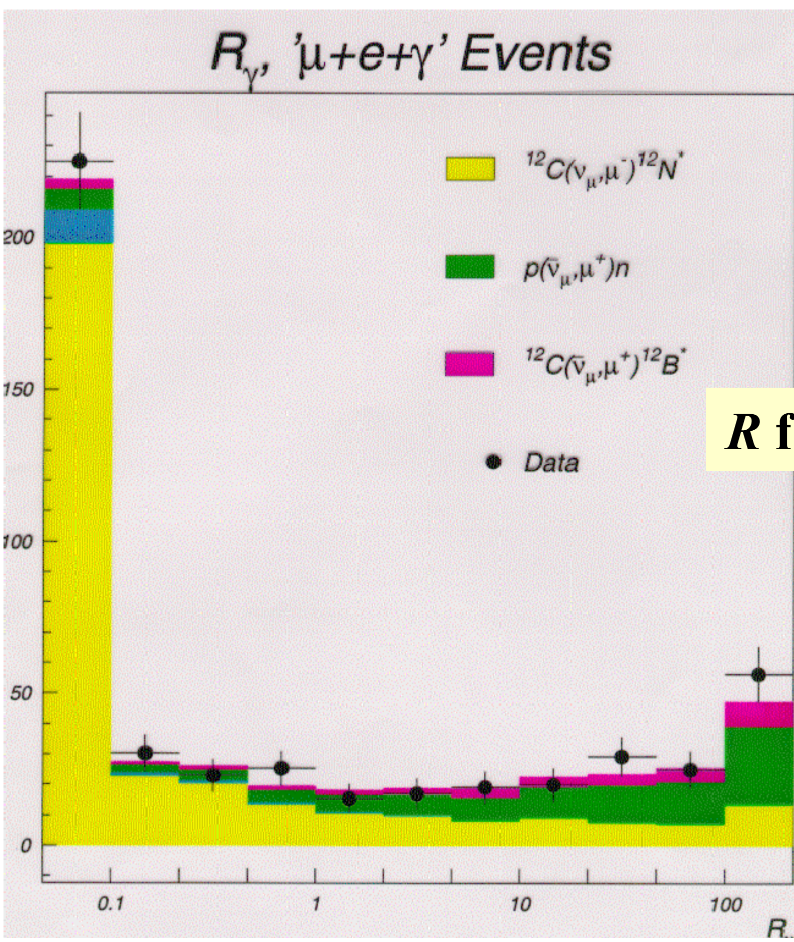


Variables entering in *R*

Δr (e - γ)

Δt (e - γ)

PMT hits ÷ E



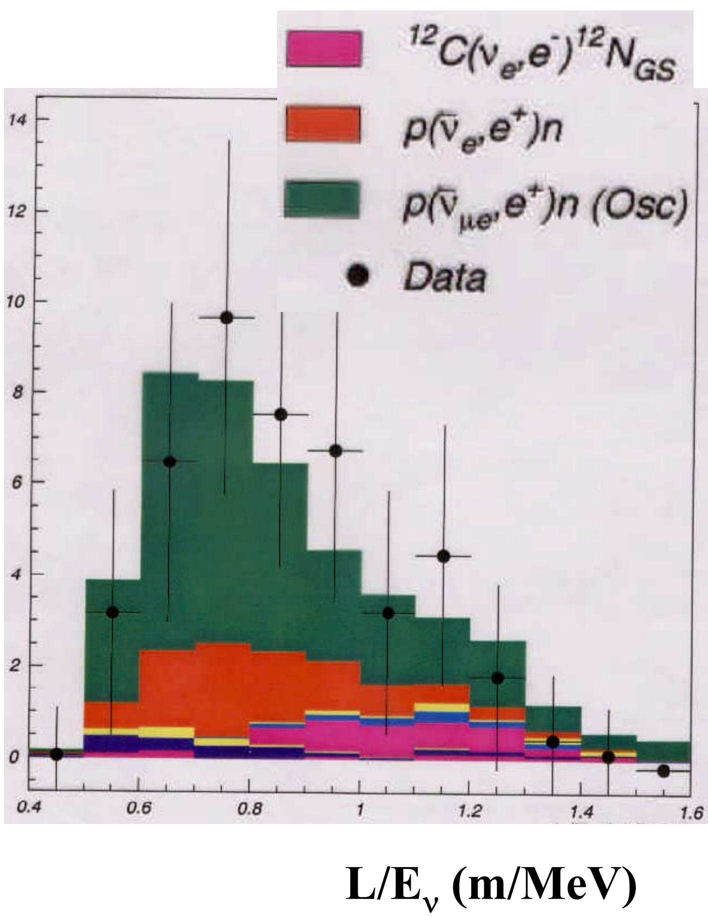
R for no-oscillation channel

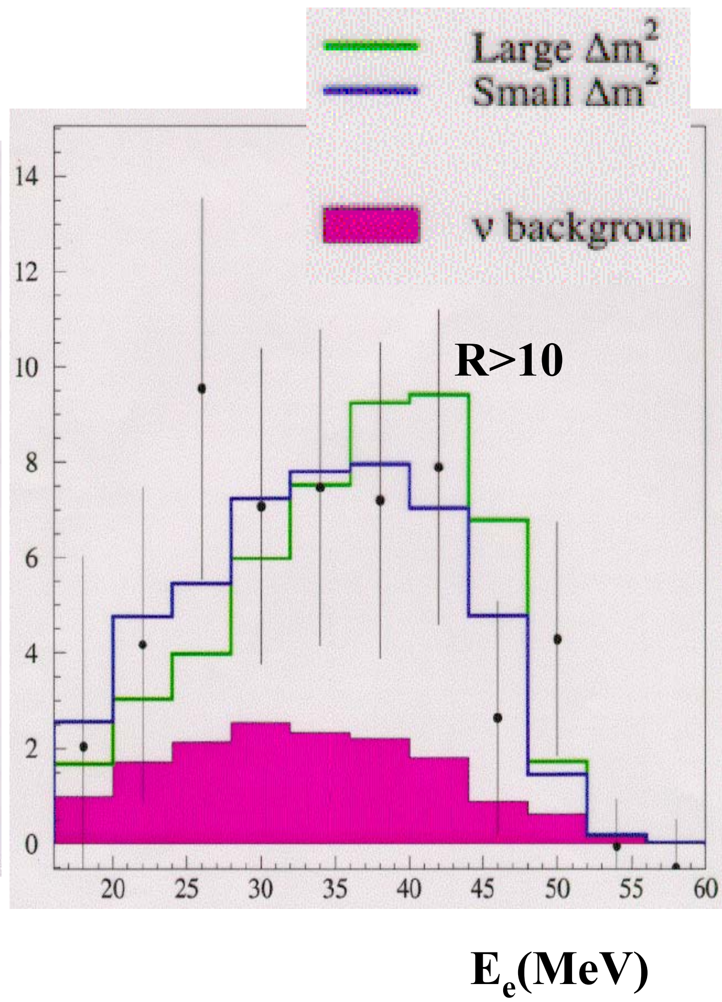
The oscillation signal in E_e in [20-60] MeV

Excess of events at R > 10 (large e-γ correlation likelihood)

beam on total	beam off background	expected ν background	excess of events
83	33.7	16.6	32.7 ±9.2

Event excess is E_e dependent





Fit to full *R* distribution P_{osc}=0.0025±0.0006 ±0.0004

LSND signal region

Relaxing cuts:
- E_e in [20-200] MeV
- R>0

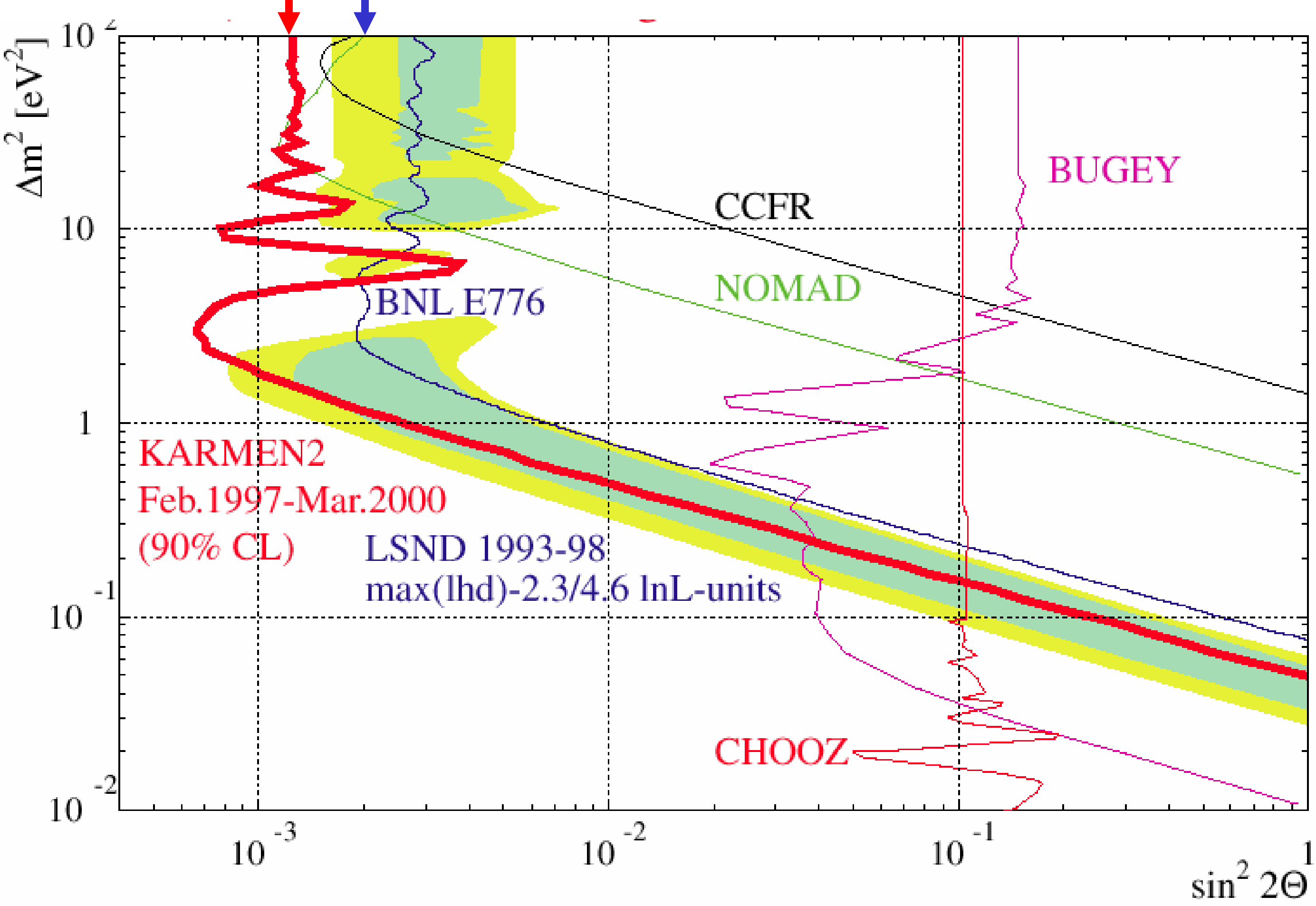
+

$$L(\sin^2 2\theta, \Delta m^2) = \prod_{k=1}^{Nevent} \{ r_{osc} \cdot f_{osc}(E_e, R, L_\nu, \cos\theta_\nu)_k + \sum_{i=1}^{back} r_i \cdot f_i(E_e, R, L_\nu, \cos\theta_\nu)_k \} \times \prod_{i=1}^{back} N_{normal}(r_i \cdot N \mid N_i^{exp})$$

+

Cut at ΔL= 2.3 (90%) 4.6 (99%)

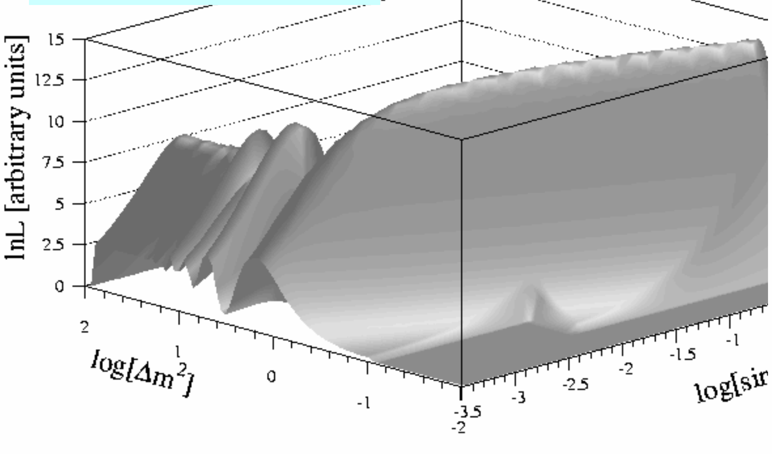
$\sin^2 2\theta < 1.3 \cdot 10^{-3}$ / sensitivity $= 1.7 \cdot 10^{-3}$ — **KARMEN2 @ large Δm^2**

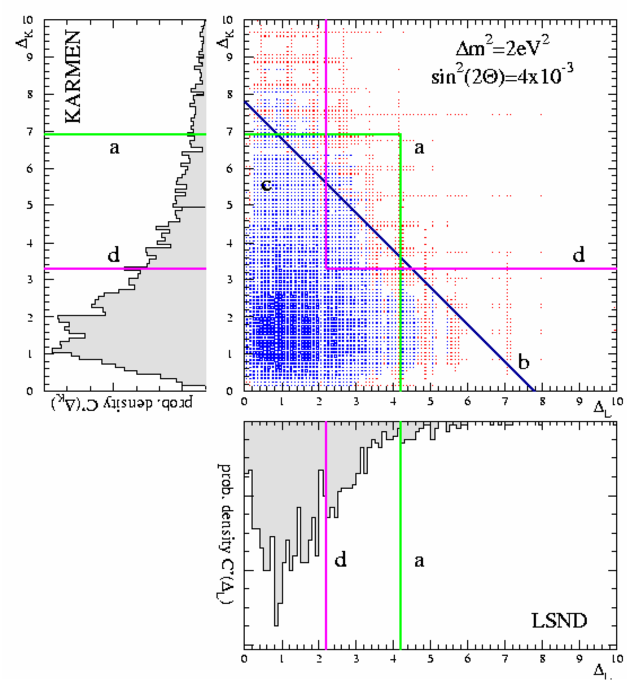


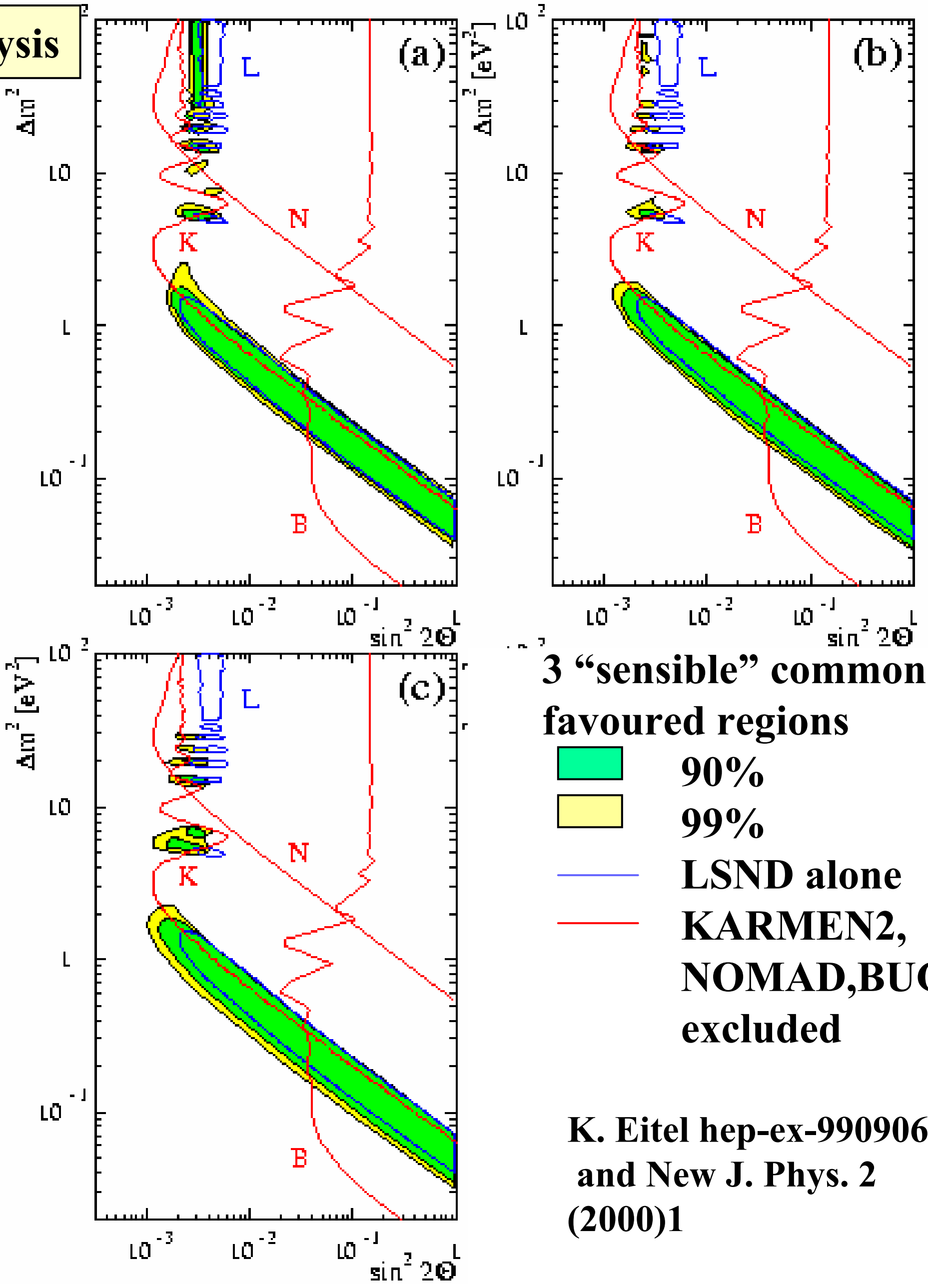
Compatible 1993-95 & 1996-98 signals

Preliminary joined KARMEN2-LSND analysis

Joined likelihood







3 "sensible" common favoured regions

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

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

Conclusions

- LSND signal in $\Delta m^2 \sim eV^2$ is one of the 3 oscillation signals
- No evidence that result is wrong
- Allowed LSND parameters space domain will not be fully covered by KARMEN2 ($\Rightarrow$ spring 2001): not enough statistics given background
- Need for a joined analysis based on a common likelihood function based on the final data,
- Need new experiment(s) with higher sensitivity: MiniBOONE approved at FERMILAB from 2001

I216 proposal at CERN PS 2001

In the mean time

either

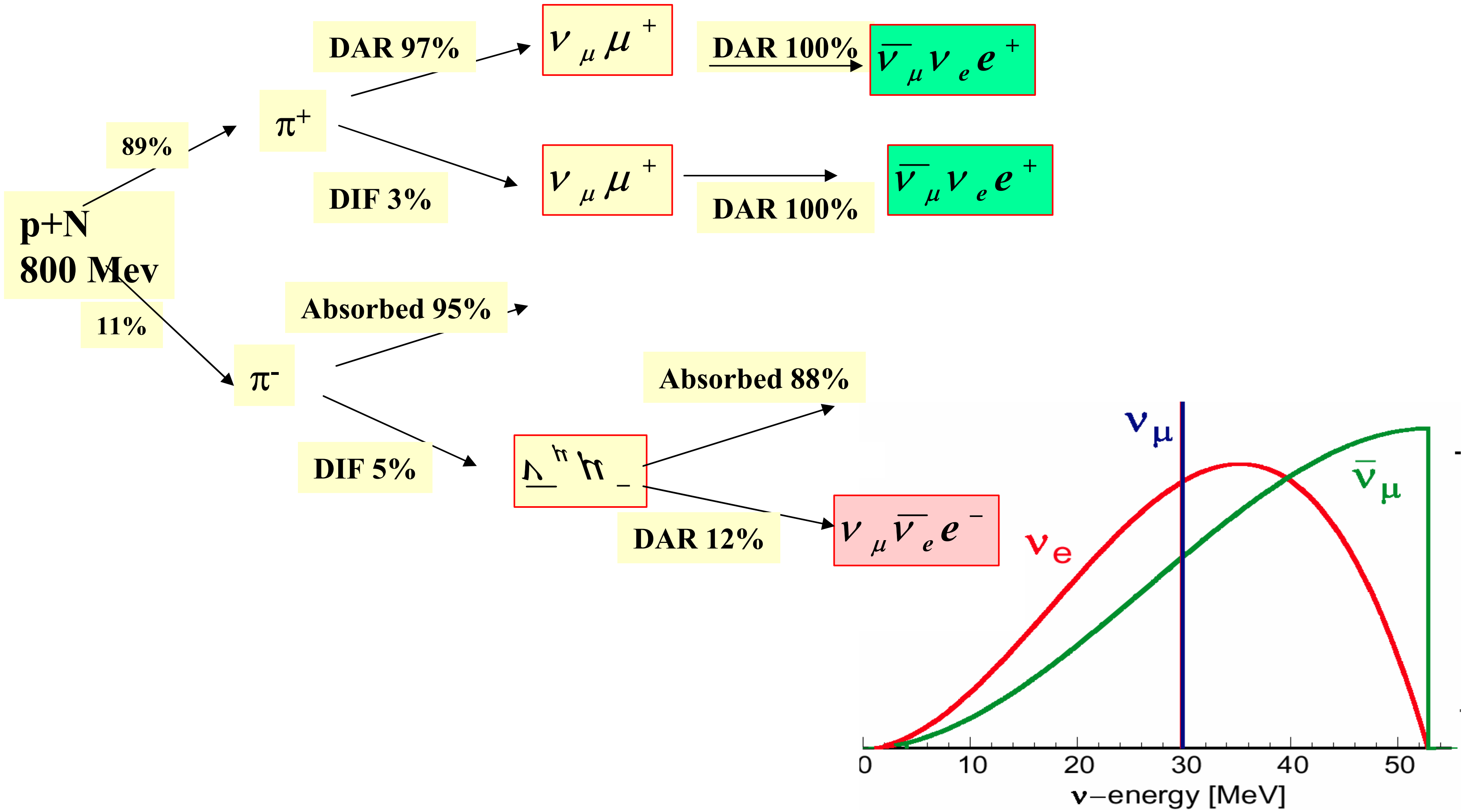
$$3 \;\; \Delta m^2$$

$$\nu_e \; \nu_\mu \; \nu_\tau \; \nu_s$$

or

©A. De Rujula
Nu2000

The neutrino production chain (numbers are for LSND)



Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from $\mu^+ \rightarrow e^+$ decays at rest

Neutrino Oscillation Experiments at High Energy Accelerators

CHORUS and NOMAD short baseline experiment

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

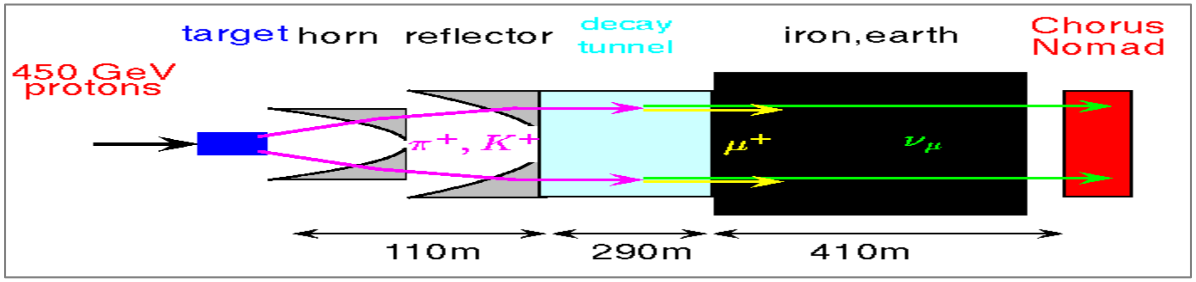
ν_τ appearance
in same high energy ν_τ free ν_μ beam
at the CERN SPS Wide Band Neutrino Beam

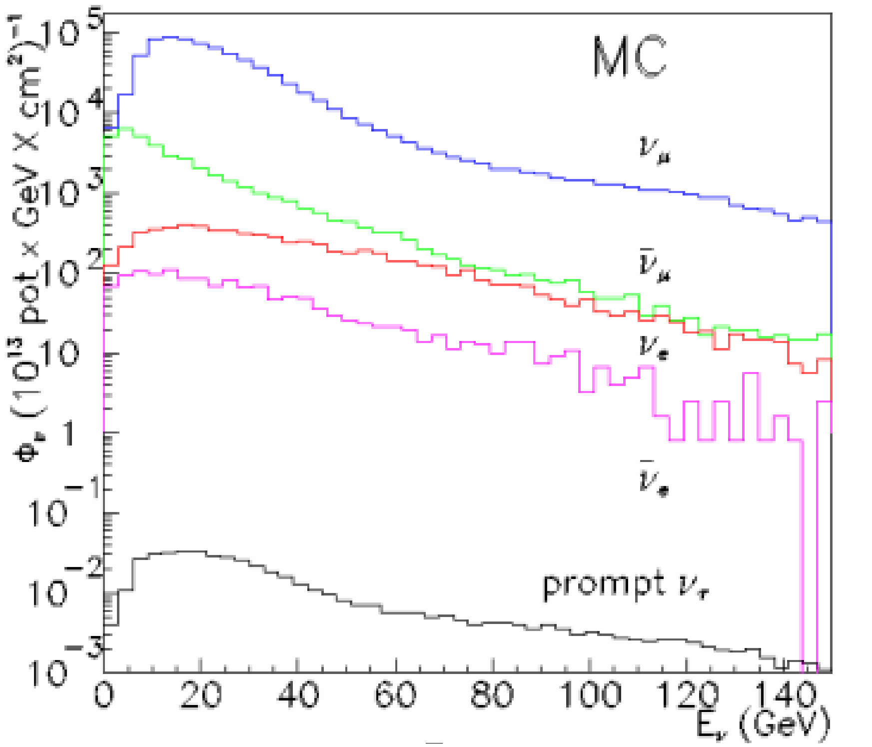
Motivation (early 1990's)

Search for "hot dark matter" candidates with $m_\nu > 1\ eV$

with ~50 times better sensitivity than E531: $P_{osc}(\nu_\mu - \nu_\tau) > 10^{-4}$

CERN Wide Energy-Band Neutrino Beam Line





	$\Phi_{relative}$	$< E_\nu >$ [GeV]
ν_μ	1	27
$\bar{\nu}_\mu$	0.056	19
ν_e	0.009	~40
$\bar{\nu}_e$	0.002	~32
ν_τ	3 10^{-6}	~43

Irreducible prompt ν_τ background
from $D_S \rightarrow \tau\ \nu_\tau$
less than 0.1 event in 4 years
well below sensitivity

Maximum sensitivity @

$$\Delta m^2 \approx \frac{27\ GeV}{0.6\ km} \approx 50\ eV^2$$

ν_μ NOMAD ν_τ

Neutrino Oscillation MAgnetic Detector

AUSTRALIA Melbourne, Sydney

CERN

CROATIA Zagreb

FRANCE LAPP Annecy, Paris LPNHE, Saclay DAPNIA

GERMANY Dortmund.

ITALY Cosenza, Firenze, Padova, Pavia, Pisa, Roma 3.

RUSSIA INR Moscow, JINR Dubna.

SPAIN Valencia.

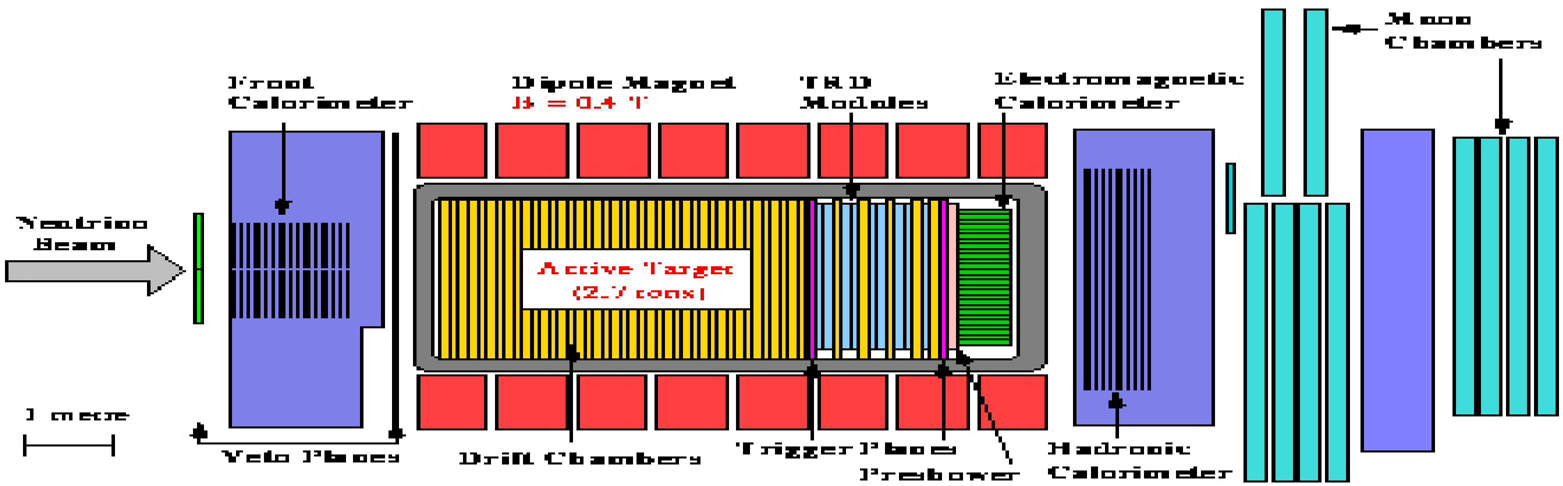
SWITZERLAND Lausanne, ETH Zurich.

USA Harvard, Johns Hopkins, South Carolina, UCLA.

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

NOMAD Detector

(NIM A404(1998)96)



- Drift Chambers (target and momentum measurement)

  Spatial resolution $< 200\ \mu m$ (small angle tracks)

  Momentum resolution $\sim 3.5\%$ ($p < 10$ GeV/c)

- Transition Radiation Detector (TRD) for $e^{\pm}$ identification

  π rejection $\simeq 10^3$ $\varepsilon(e) \geq 90\%$ for isolated tracks

- Lead Glass Electromagnetic Calorimeter

$$\frac{\sigma(E)}{E} = 1.0\% + \frac{3.2\%}{\sqrt{E(GeV)}}$$

- Muon Chambers

  $\varepsilon \approx 97\%$ for $p_\mu > 5$ GeV/c

ν_τ signal extraction technique: excess of events in kinematics box
$\Rightarrow$ precise energy/momentum & good particle ID

Decay channels

$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.8%	small CC_{ν_e} background
$\tau^- \to h^- (n\pi^0) \nu_\tau$	49.5%	kinematics very $\neq NC_\nu$
$\tau^- \to \pi^+\pi^-\pi^- (n\pi^0)\nu_\tau$	15.2%	
Total	82.5%	

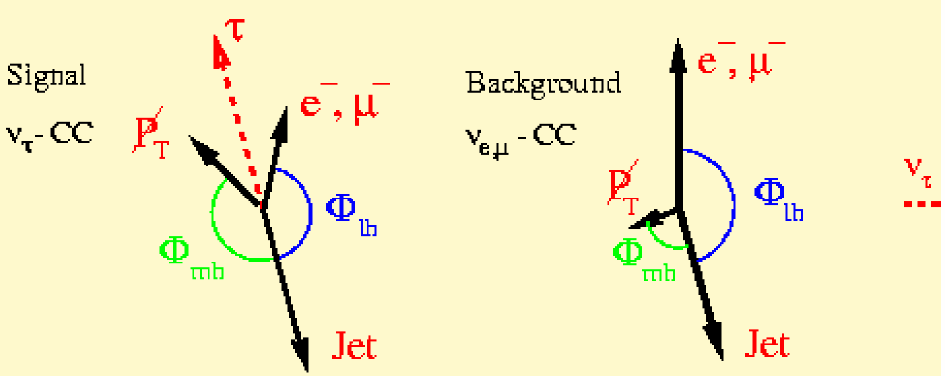
Not used

$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ 17.4%

huge CC_{ν_μ} background

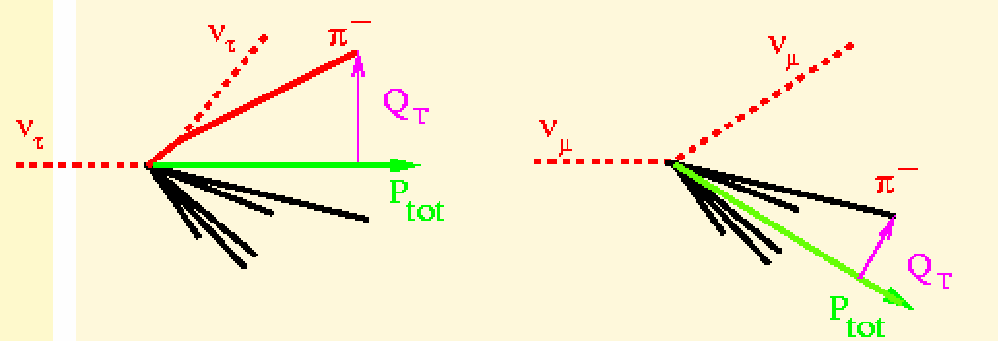
Examples of sensitive kinematics variables

Electron decay, the main source of backgrounds are ν_e CC $\Longrightarrow$ kinematics based on the missing momentum and angular relations in the transverse plane.



Hadronic decays, the main source of background are neutral current $\Longrightarrow$ isolation between the τ visible decay product(s) and the hadronic jet.

Signal Background from NC



ν_τ signal extraction technique also requires

• Precise simulation of kinematics of signal and background

In kinematics box where signal expected: background known to $\mathcal{O}$ (10^{-5})

Data Simulator

• Replace μ^- in CC_{ν_μ} Data (DS) and MonteCarlo (MCS) samples by

Monte-Carlo ν (backgound NC)

τ^- (signal CC_{ν_τ})

e^- (background CC_{ν_e})

$$\varepsilon_{Data}^{S,B} = \varepsilon_{MC}^{s,b} \frac{\varepsilon_{DS}^{S,B}}{\varepsilon_{MCS}^{S,B}}$$

Most systematic (hadron shower simulation, Fermi motion, …) cancel out

Analysis technique

- **Event classification (signal/background) based on log likelyhood ratio** $ln\ \lambda = ln\frac{\mathcal{L}_S}{\mathcal{L}_B}$
- $\mathcal{L}_S(X_i)$ $(\mathcal{L}_B(X_i))$ **is the probability for an event described by kinematics** X_i **to be signal (background)**
- X_i **choosen as most discriminating variables**
- $\mathcal{L}$ **product of (quasi)independent multivariate** $pdf(X_i, X_j, ...)$

- **Tail of** $ln\ \lambda$ **(large signal, small background probs) devided into (independent) signal bins**
- **Binning obtained from maximum sensitivity (based on MC à la Feldman-Cousins)**

- **Decay channels and signal bins combined à la Feldman-Cousins (unified frequentist approach)**

- **Blind analysis: data in potential signal region not looked at untill analysis fully defined**

$\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$

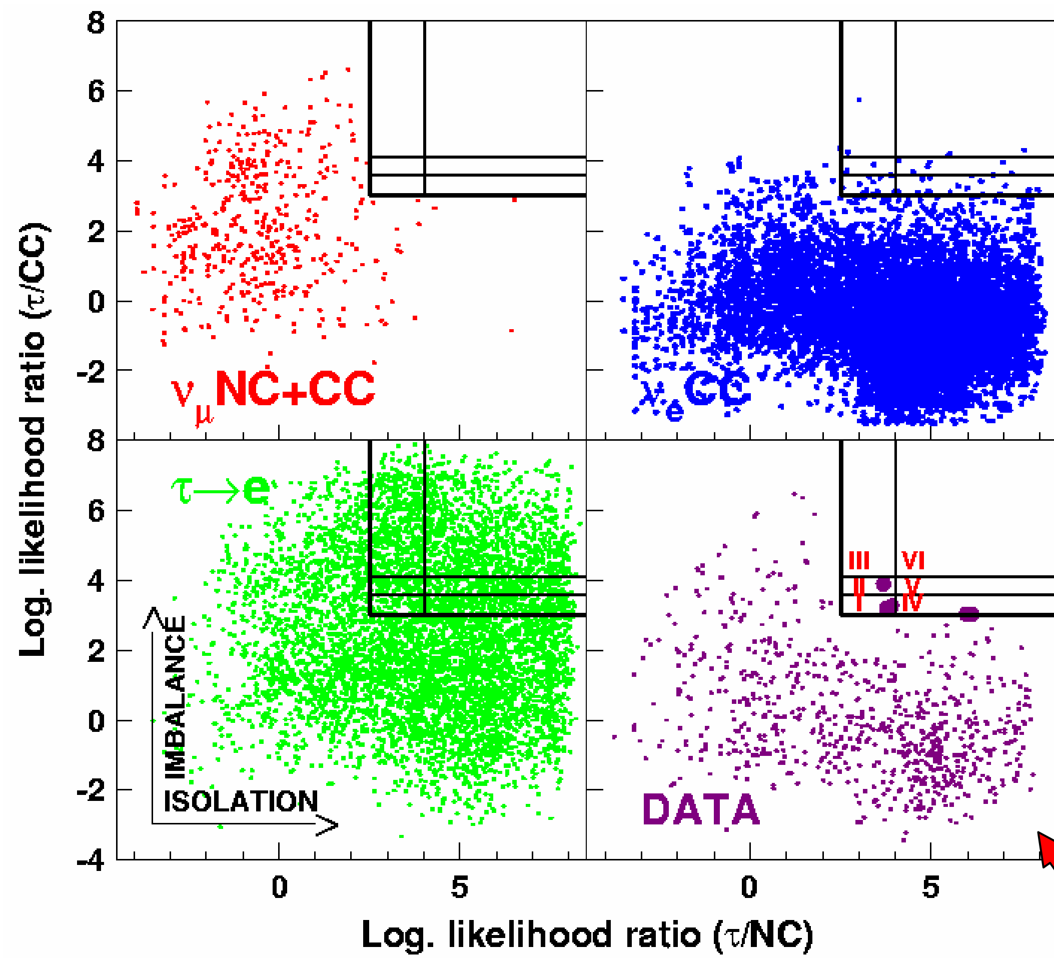
Event selection:

efficient e⁻ ID (20%)

e^-/π^- rejection ~ 10^6

e^-/π^0 rejection ~ 10^4

Signal region "blindly" selected divided in 6 bins



Background e^- and γ from NC

$$\mathcal{L}_{NC} = [[[\theta_{\nu T}, \theta_{\nu H}], \theta_{\min}, Q_T], M_T, E^{TV}]$$

***e -* isolation**

Background e^- from CC_{ν_e}

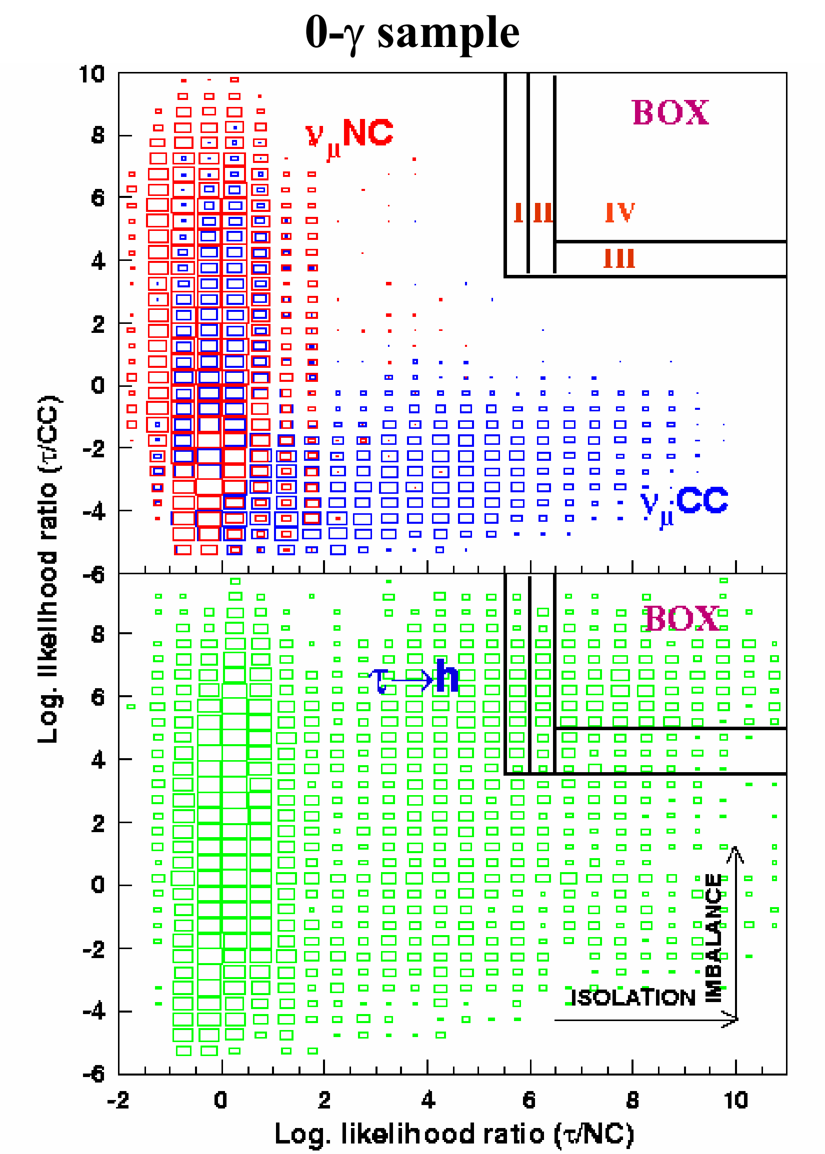
(1.5% of CC_{ν_μ})

$$\mathcal{L}_{CC} = [[Q_{Lep}, \rho_{TV}, \rho_H], p_T^m, M_T, E_{vis}]$$

Transverse momentum imbalance

6 events in bins of DATA box found after box definition

$\tau^- \to h^-(n\pi^0)\nu_\tau$ inclusive (B.R.=49.5%)



Very new event selection: *h*⁻ selection since CERN-EP 2000-049 shown at Nu2000

- **π^0 likelihood (2 γ)**
- **ρ likelihood (>1 γ)**
- **h⁻ candidate likelihood**
- **better e⁻/μ⁻ rejection**

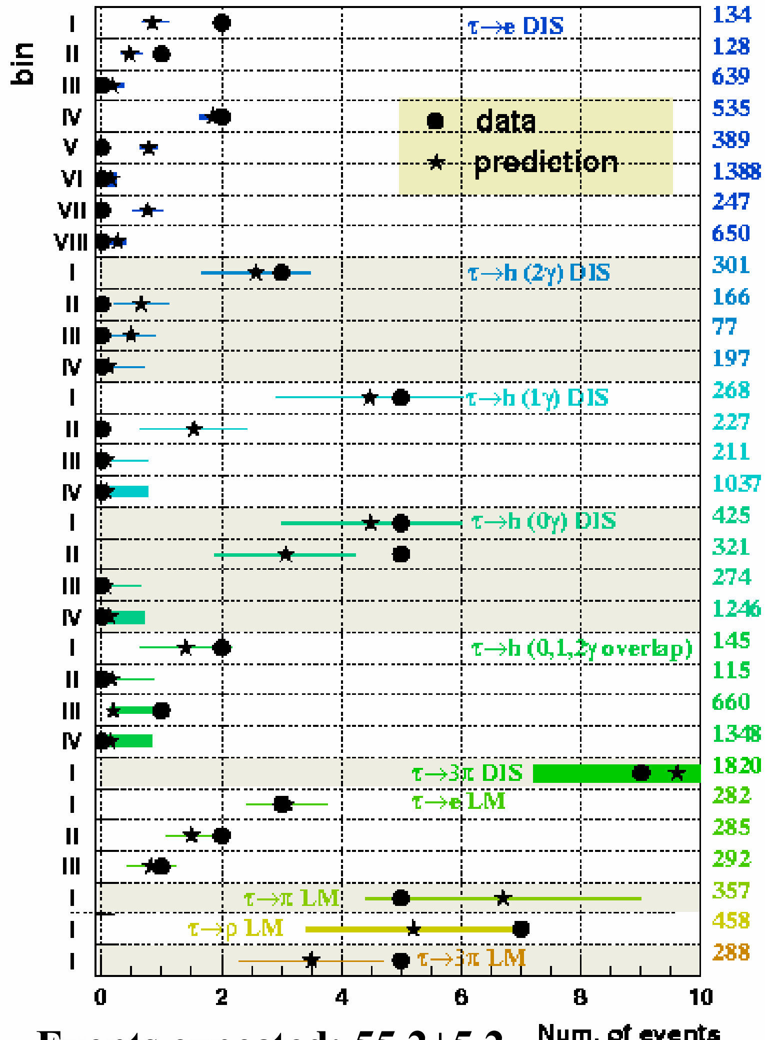
e⁻ and h⁻ channels contribute similarly to sensitivity

$$\mathcal{L}_{NC} = [[[\theta_{\nu T}, \theta_{\nu H}], \theta_{min}, Q_T], p_T^m, p_T^H]$$

$$\mathcal{L}_{CC} = [[I_G, P_T^{lep}/p_T^m, \theta_{\nu,lep}], p_T^m, M_T, E_{vis}]$$

Search Summary

N_τ = expected number of signal events if $P_{osc}(\nu_\mu - \nu_\tau) = 1$



Events expected: 55.2±5.2

Events found: 58

N_τ = 14937

Channels/Bins with very low background

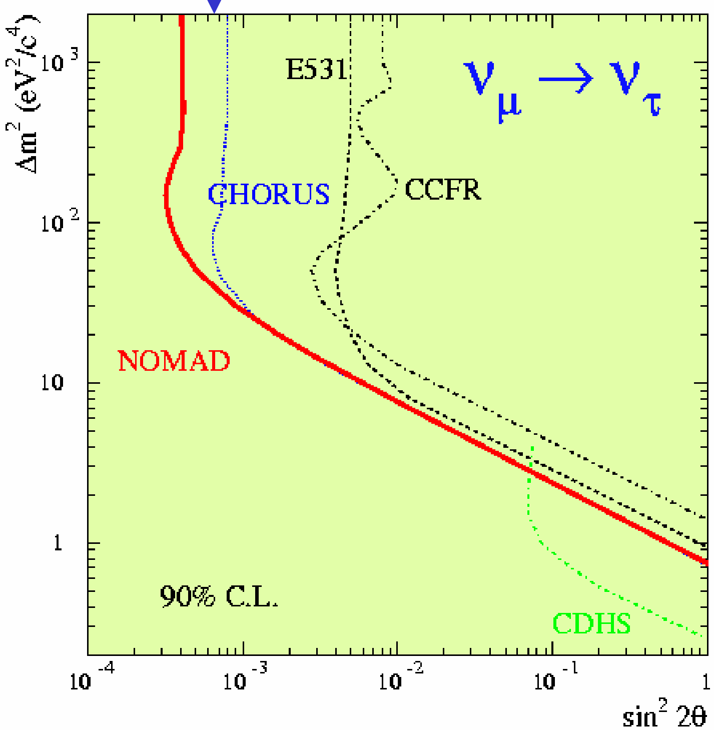
Analysis		Bin	Tot. bkg.	N_τ	Data
$\nu_\tau \bar{\nu}_e e$	DIS	III	$0.28^{+0.31}_{-0.09}$	903	0
$\nu_\tau \bar{\nu}_e e$	DIS	VI	0.25 ± 0.09	1694	0
$\nu_\tau h(0\gamma)$	DIS	III	$0.05^{+0.60}_{-0.03}$	274	0
$\nu_\tau h(0\gamma)$	DIS	IV	$0.12^{+0.60}_{-0.05}$	1246	0
$\nu_\tau h(1\gamma)$	DIS	III	$0.07^{+0.70}_{-0.04}$	211	0
$\nu_\tau h(1\gamma)$	DIS	IV	$0.07^{+0.70}_{-0.04}$	1037	0
$\nu_\tau h(2\gamma)$	DIS	IV	$0.11^{+0.60}_{-0.06}$	197	0
$\nu_\tau h(\text{overl.})$	DIS	III	$0.20^{+0.70}_{-0.06}$	660	1
$\nu_\tau h(\text{overl.})$	DIS	IV	$0.14^{+0.70}_{-0.06}$	1348	0
			$1.29^{+1.60}_{-0.18}$	7570	1

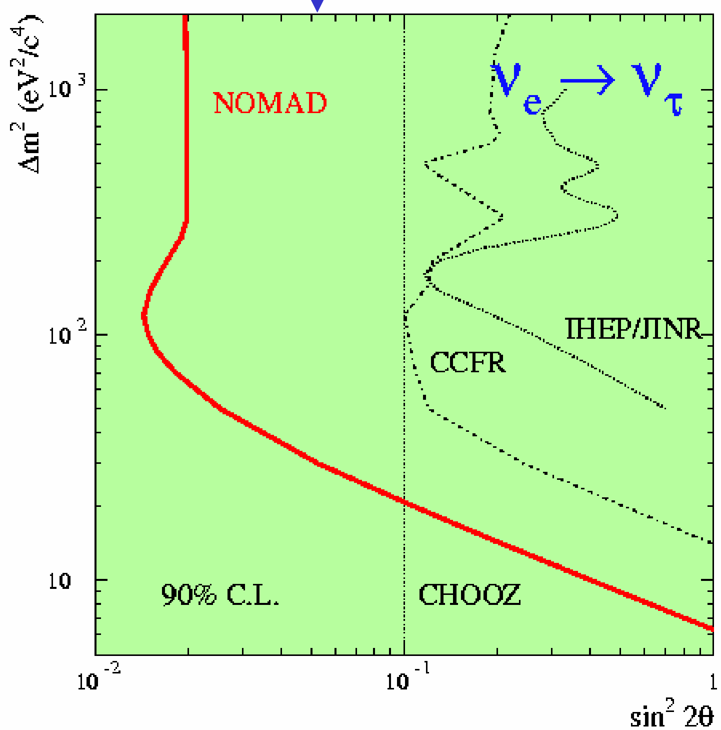
NOMAD exclusion plots (preliminary)

@90% C.L.
Unified frequentist approach

Still room for progress, i.e. $\tau \to \nu_\tau\, 3\pi$ DIS analysis.

New CHORUS (different statistical method)





$P(\nu_\mu \to \nu_\tau) \leq 2.03 \cdot 10^{-4}$, sensitivity : $2.6 \cdot 10^{-4}$

$\sin^2 2\theta_{\mu\tau} > 4.06 \cdot 10^{-4}$ **for large Δm^2**

Computed with the proper ν_e flux, 100 times smaller than the ν_μ flux.

$P(\nu_e \to \nu_\tau) \leq 1.00 \cdot 10^{-2}$, sensitivity: $1.3 \cdot 10^{-2}$

More to expect from NOMAD:

$\nu_\mu \rightarrow \nu_\tau$ **and** $\nu_e \rightarrow \nu_\tau$ **still being improved**

$\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ **channel**

$\nu_\mu \rightarrow \nu_e$ **in progress**

talk by R.Petti in PS6

Λ **polarization in** $\nu_\mu N \rightarrow \mu^- \Lambda X$

talk by Minh-Tam Tran in PS6

CHORUS experiment
Search for $\nu_\mu \rightarrow \nu_\tau$ oscillation

Collaboration

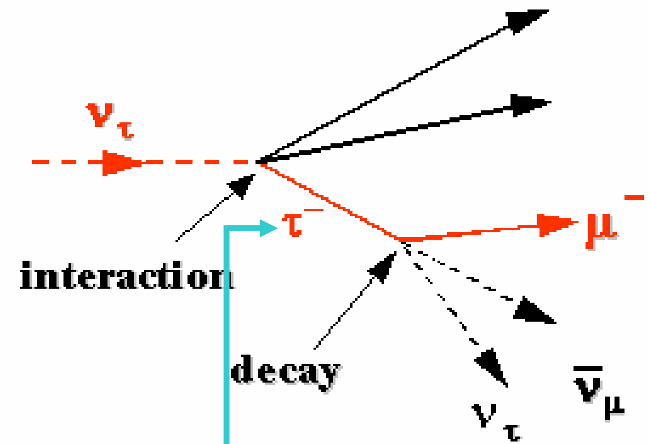
Belgium (Brussels, Louvain-la-Neuve),
CERN,
Germany (Berlin, Münster),
Israel (Haifa),
Italy (Bari, Cagliari, Ferrara, Naples, Rome, Salerno),
Japan (Toho, Kinki, Aichi, Kobe, Nagoya,Osaka, Utsunomiya) ,
Korea (Gyeongsang),
The Netherlands (Amsterdam),
Russia (Moscow),
Turkey (Adana, Ankara,Istanbul)

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

ν_τ Direct detection technique

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

$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$	**B.R.**	**18%**	
$h^- \ \nu_\tau \ (\mathrm{n}\,\pi^0)$		**50%**	
$\pi^- \pi^- \pi^+ \ \nu_\tau \ (\mathrm{n}\,\pi^0)$		**14%**	**not yet included**



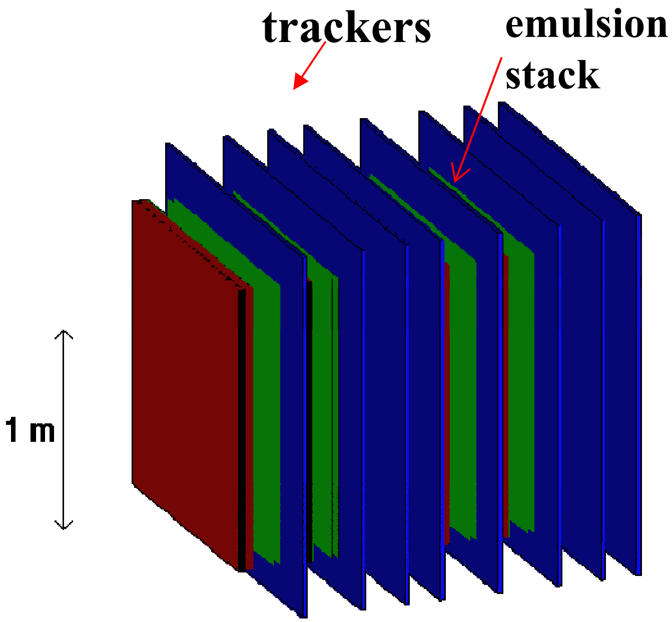
Prompt ν_τ background <~ 0.1 event in 4 years

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

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

"Kink"

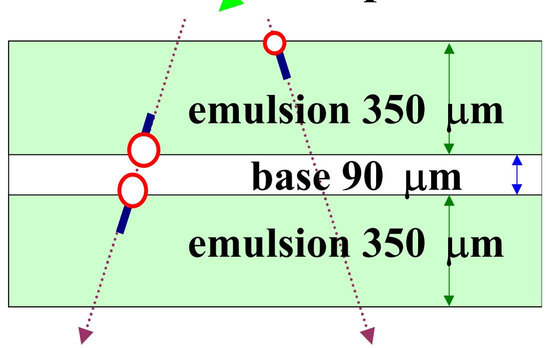
CHORUS target



4 stacks of emulsion interleaved with fibre trackers and emulsion interface trackers

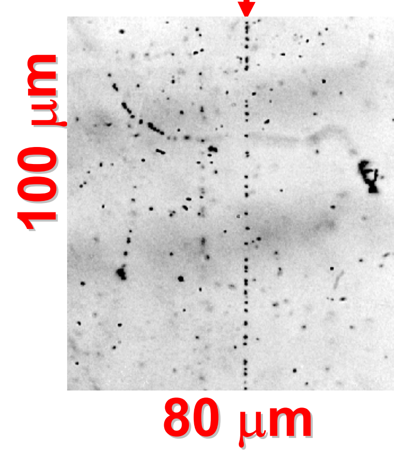
- **1 stack : 142 x 144 x 2.8 cm^3 = 36 plates of 790 μm**

1 plate

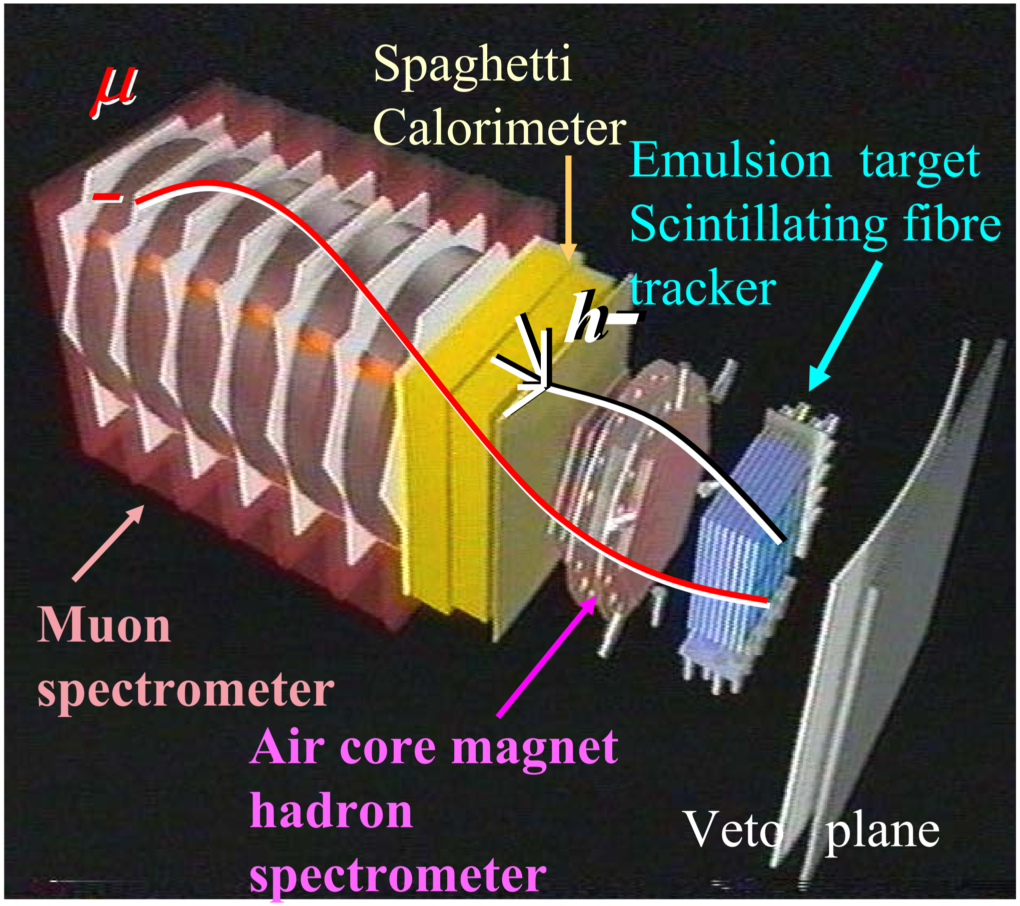


Grain size ~ 1. μm
Grain measurement ~ 0.3 μm
Angular resolution ~ 1.5 mrad

MIP
~35 grains / 100 μm



CHORUS detector : event kinematics measurement



Hadron Sign and momentum

Air-core magnet hadron spectrometer

$\Delta p/p = \sqrt{(0.035 \cdot p(GeV/c)+0.22^2)}$

Showers energy, missing P_t

Lead&fibers "spaghetti" calorimeter

$\Delta E/E=32\%/\sqrt{E}$ **(hadrons)**

$\Delta E/E=14\%/\sqrt{E}$ **(electrons)**

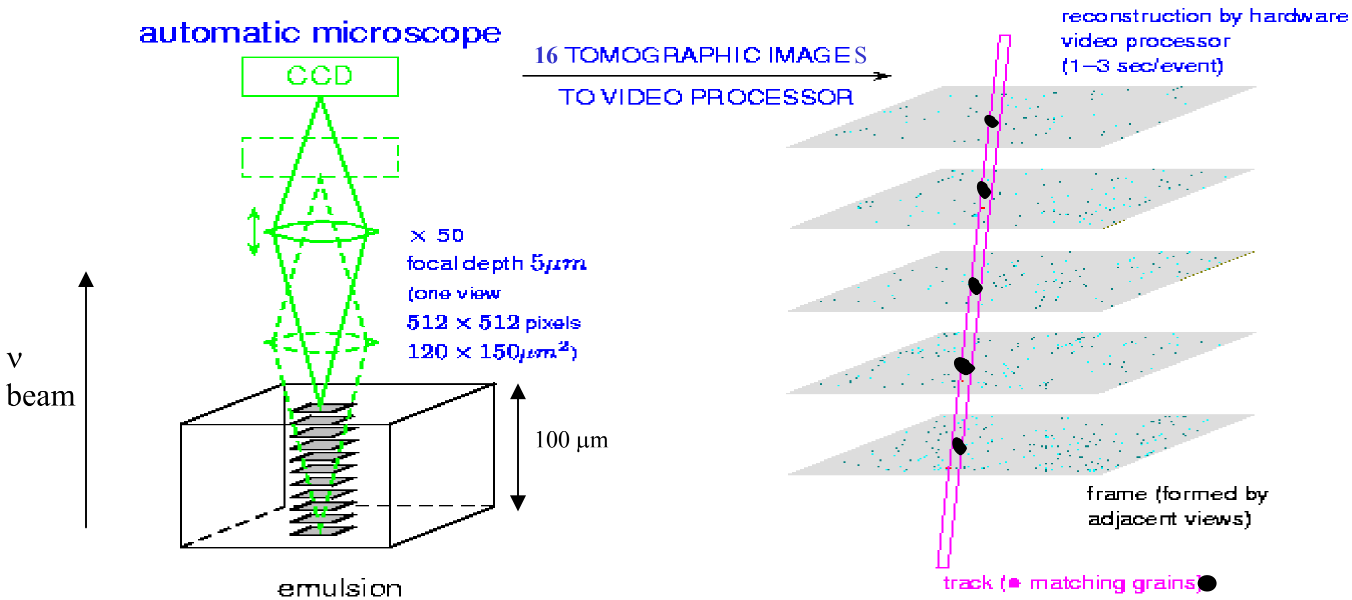
Δq_{hadr}~60 mrad @10 GeV

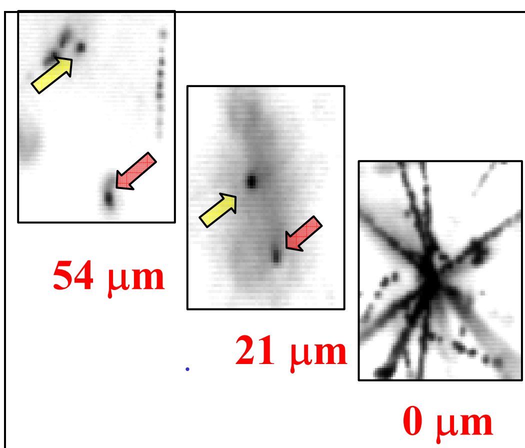
Muon ID, sign and momentum

Iron-core muon spectrometer

$\Delta p/p$~10%-15% (p<70 GeV)

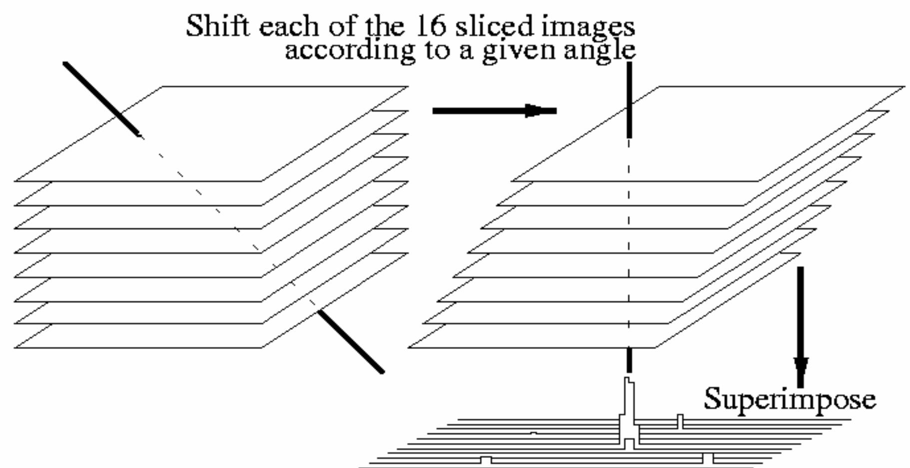
Automatic Emulsion Data Taking (K.Niwa and Nagoya University

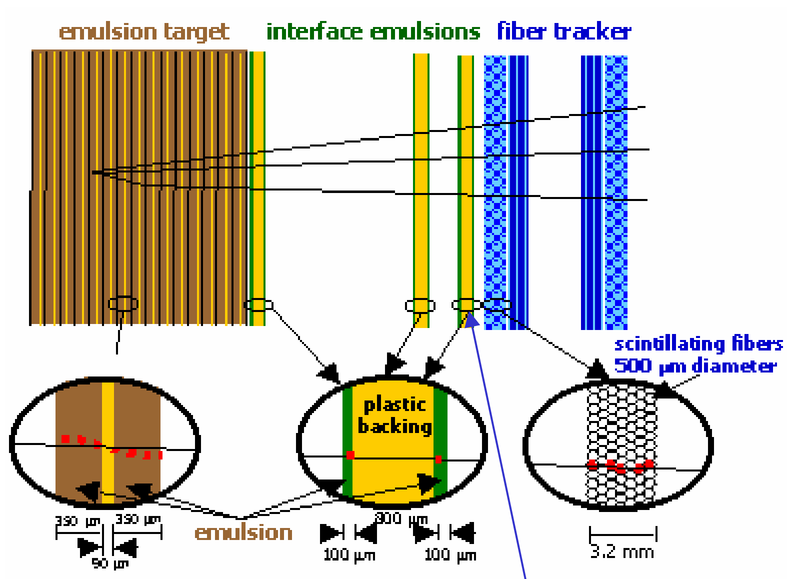




View size: 30x40 mm^2

Focal depth : ~3 mm





$$\sigma_{pos} = 150\mu m$$
$$\sigma_{\theta} = 2mrad$$

Analysis strategy

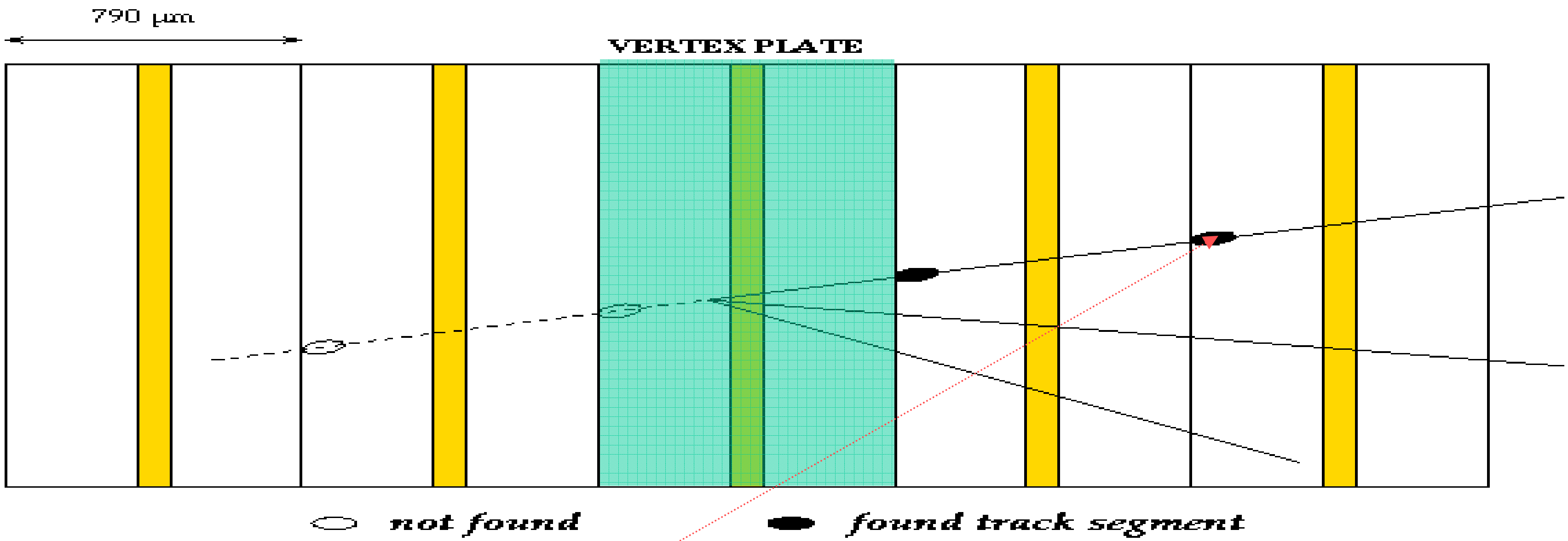
- Event reconstruction and loose kinematics selection

$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$ 1 μ^- with p_μ<30 GeV/c

$h^- \ \nu_\tau \ (n\,\pi^0)$ no μ^- and at least 1 h^- with $1<p<20$ GeV/c

- Track predictions at emulsion trackers for tracks reconstructed in scintillating fibre trackers
- Tracks found and followed by automatic microscopes in 3 successive interface emulsion trackers up to stack entry
- Followed back plate by plate in target to find vertex
- Automatic search for a "kink" decay topology: 3% of events
- Events with "kink" are analysed manually: 1% of selected events retained as candidates
- Precise kinematics analysis of candidates

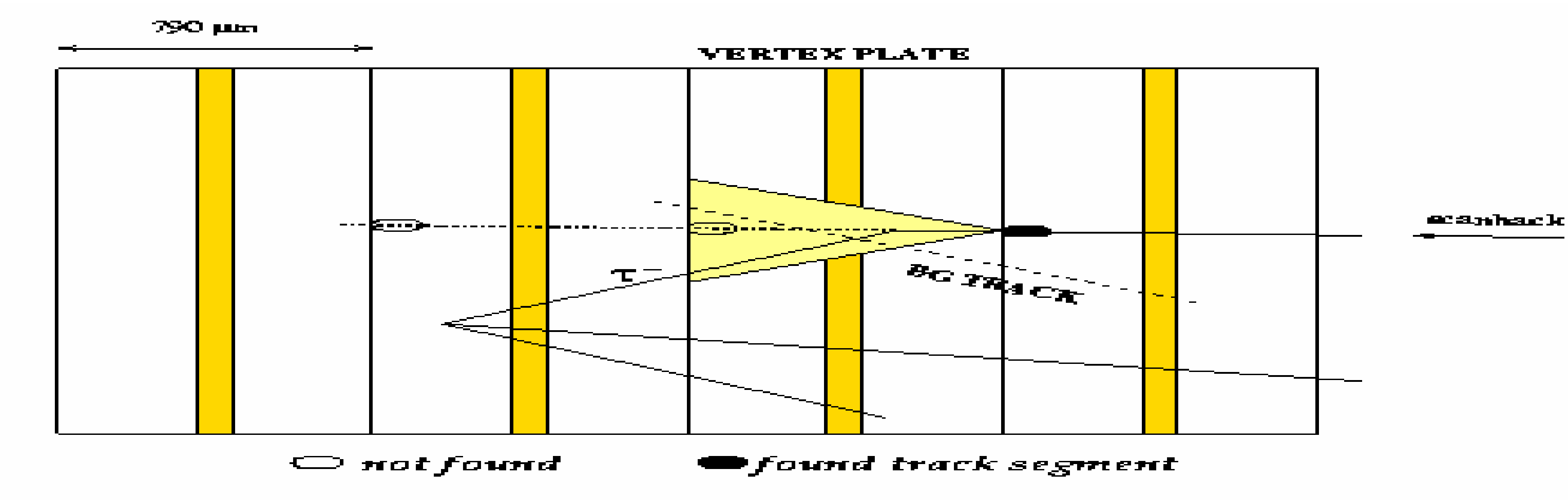
Automatic Vertex Location



- Follow-up track, plate by plate to the vertex
- 100 μm most upstream of each target plate are scanned

- Vertex defined by the first plate out of two consecutive plates where a track segment is not found

Kink Finding - Parent Search **(Large Angle-Long Path kinks)**



100 µm **most upstream of the vertex plate are searched for all track segments in a cone of width ∝ *1/P***

Segments with small impact parameters w.r.t. the follow-up track
→ Candidate track parent track
→ Manual microscope inspection (3% of scanned events)

Manual candidate event selection:
- **"clean" 1-prong kink: no sign of nuclear interaction**

1% of inspected events

Data

Year	*1994*	*1995*	*1996*	*1997*	*All*
POT / 10^{19}	0.81	1.20	1.38	1.67	5.06
Good emulsion	97%	73%	100%	100%	~93%
Expected Ncc / 10^3	120	200	230	290	840
Emulsion trigger / 10^3	422	547	617	719	2,305
1μ to be scanned	66,911	110,916	139,527	151,105	468,459
1μ scanned so far	88%	55%	81%	83%	77%
1μ vertex location and kink search	20,400	21,610	41,558	52,789	136,357
0μ to be scanned	19,846	29,350	37,143	36,073	122,412
0μ scanned so far	60%	58%	79%*	67%*	67%
0μ vertex location and kink search	3,024	4,424	8,704	7,054	23,206

Background evaluation and reduction

- *π* and *K* decays
  - P_t (daughter-parent) > 250 MeV/c : reject 100 %

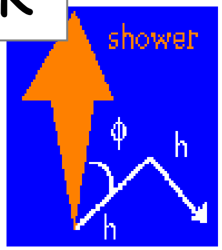
- Charm background
  - primary lepton not identified and, if D^+ , charge of secondary wrong
  - D^- produced by ν_μ/ν_e beam component

- "White kink
  - hadron elastic scattering with no sign of nuclear activity
  - badly known rate is measured at large distance from vertex
  - number within τ^- decay path computed by MC

- Charm decays and white kinks reduction in the h- channel
  - P_h dependent τ candidate decay path cut
    such that 80% of the true τ are retained $\forall\, P_h$
  - *Φ(τ-Hadron shower)* in transverse plane > 90 °

Cuts optimised for maximum sensitivity "without looking at data"

WK



τ

Background	1μ	0μ
D⁻ from $\bar{\nu}_e / \bar{\nu}_\mu$ CC with primary μ^+ / e^+ missed	0.11	0.03
$\bar{D}^+$ from $\bar{\nu}_e / \bar{\nu}_\mu$ CC with primary μ^- / e^- missed and wrong charge for decay μ^+ / h^+	0.03	0.30
CC and NC associated D^+ / D^0 missed and $D^- \rightarrow \mu^- / h^-$ + neutrals	negligible	
"White kinks" h^- elastic scattering with no nuclear activity	0	0.8
Prompt beam ν_τ from D_S decays	0.05	0.05

Results

$$P_{\mu\tau}^{osc} = N_\tau / N_\tau^{max}$$

$$N_\tau^{max}(P_{\mu\tau}^{osc} = 1) = \sum_{i=}^{\mu^-,h^-} BR_i \cdot N_i < \frac{\sigma^{CC}_{\nu_\tau}}{\sigma^{CC}_{\nu_\mu}} \frac{A_{\tau i}}{A_{\mu i}} \varepsilon_{\tau i} >= 5014 + 2004 = 7018$$

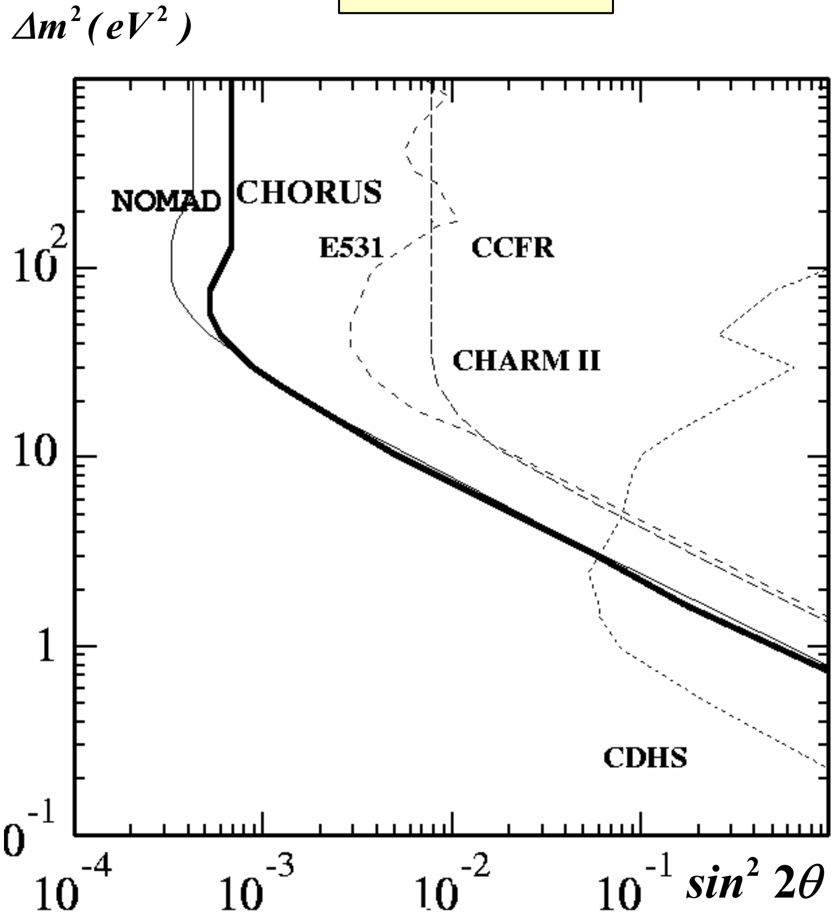
- branching ratios
- Nb events
- cross--section ratios
- location efficiency ratios
- kink finding efficiency

Channel	Observed	Expected background	N_τ^{max}
μ^-	0	0.1	5 014
h^-	0	1.1	5 004

Upper limit on N_t @ 90% $C.L.$ = 2.4
(T.Junk, NIM A434 (1999) 435)

$$P_{\mu\tau}^{osc} < 3.4 \cdot 10^{-4}$$

$\nu_\mu \rightarrow \nu_\tau$

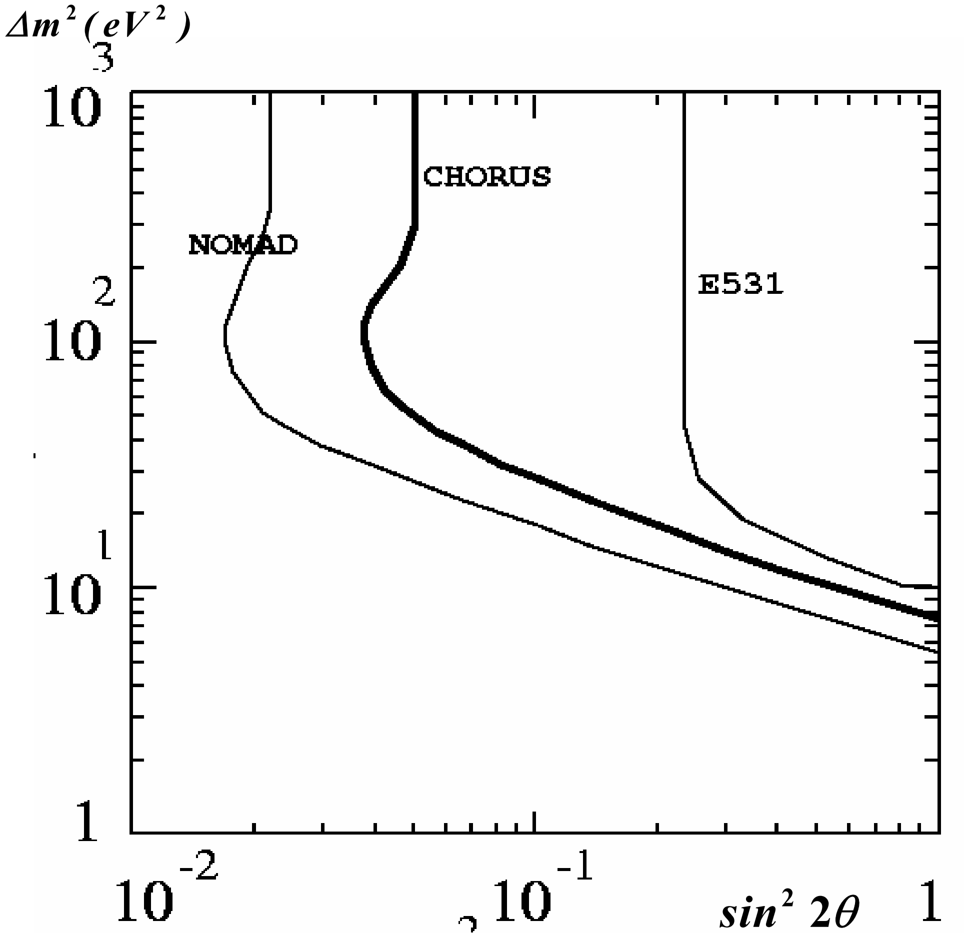


	NOMAD (Feldman-Cousins)	CHORUS (Junk)	CHORUS (F.-C.) "to compare"
sensitivity (F.C.)	$2.6 \cdot 10^{-4}$	$3.7 \cdot 10^{-4}$	$3.7 \cdot 10^{-4}$
$P^{osc}_{\nu\tau}$	$2.03 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$
$sin^2 2\theta$ @ large Δm^2	$4.06 \cdot 10^{-4}$	$6.8 \cdot 10^{-4}$	$4.0 \cdot 10^{-4}$
$\Delta m^2 (eV^2)$ @ full mixing	0.6	0.6	0.6

Junk $N_\tau < 2.4$
Feldman_Cousins $N_\tau < 1.4$
@ 90% C.L. given: 1.2 expected background, 0 observed

see talk by R.Petti in PS6

$\nu_e \rightarrow \nu_\tau$



There are 0.9% of events in the beam

$$P_{e\tau}^{osc} < 2.6 \cdot 10^{-4}$$

More to expect from CHORUS:
2 years Phase-2 analysis launched

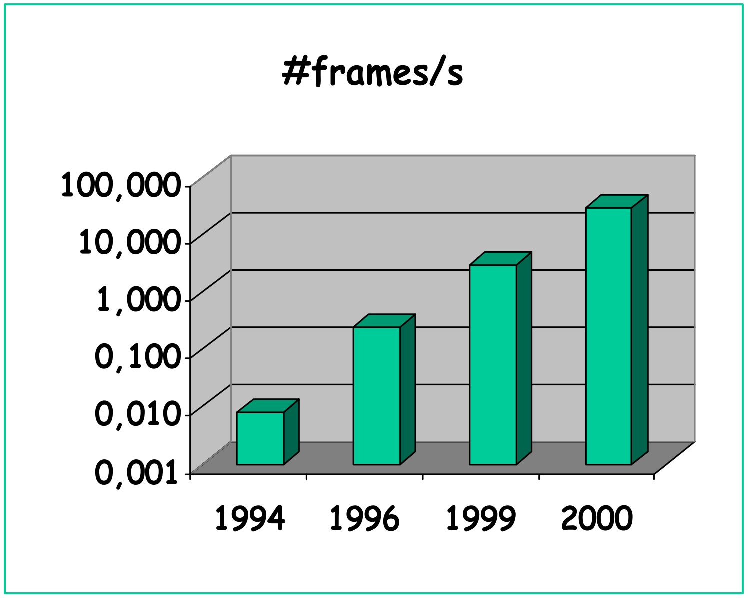
→ **Reach $P_{osc} < 10^{-4}$**

Among other things:

- improved kink (τ) finding efficiency

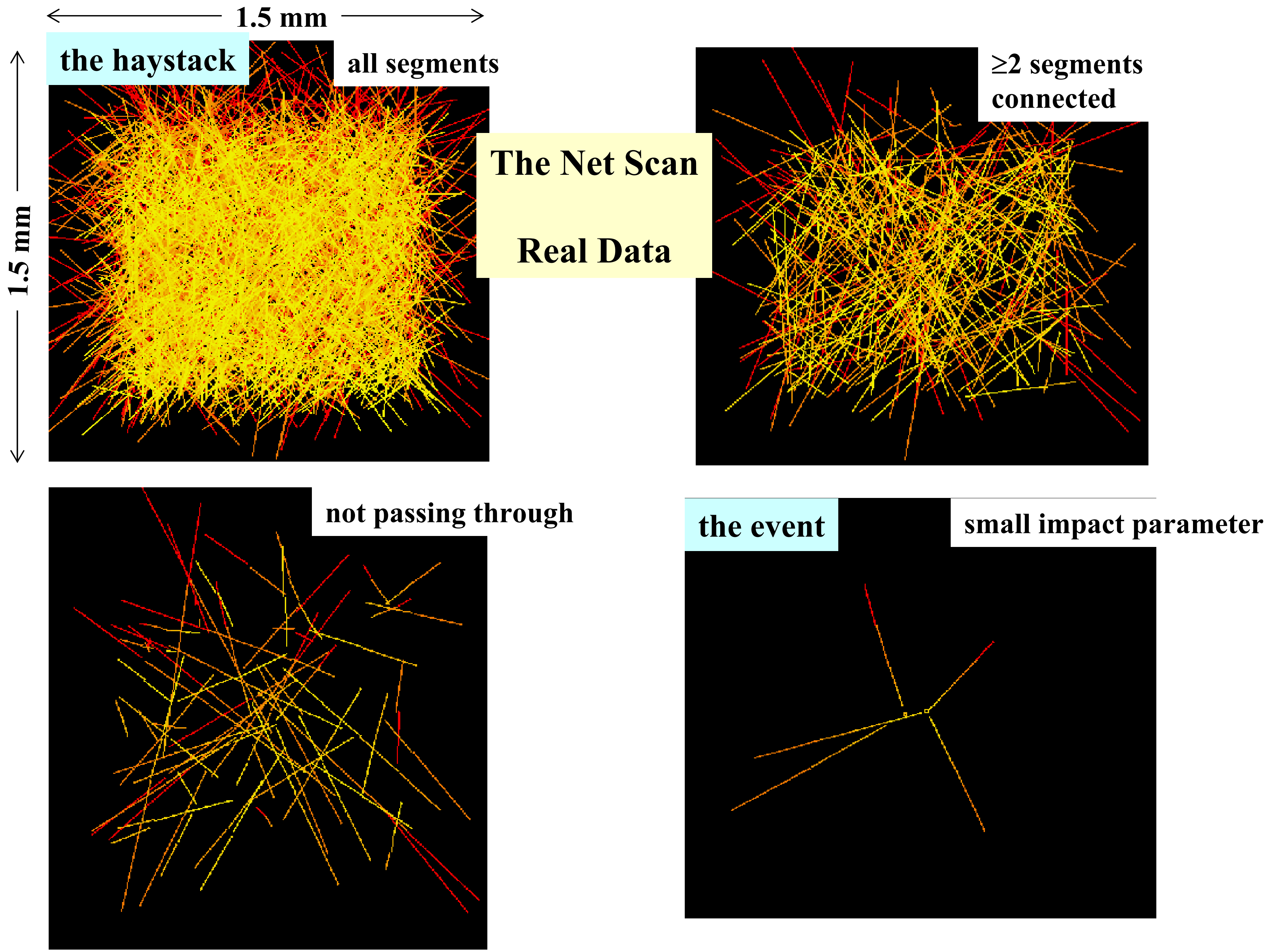
- 3-hadron and e^- decay channels

in emulsion thanks to new upgrade in automatic microscope technology



Other Physics

- **CHARM physics in emulsion (D_s^{*+} observation published) and in calorimeter as target (J/ψ production submitted)**
- **Form factors**
- **Trident ($\mu^+\mu^-\nu$) production**
- **Search for heavy neutral leptons ...**


1.5 mm
1.5 mm
the haystack
all segments
The Net Scan
Real Data
≥2 segments connected
not passing through
the event
small impact parameter