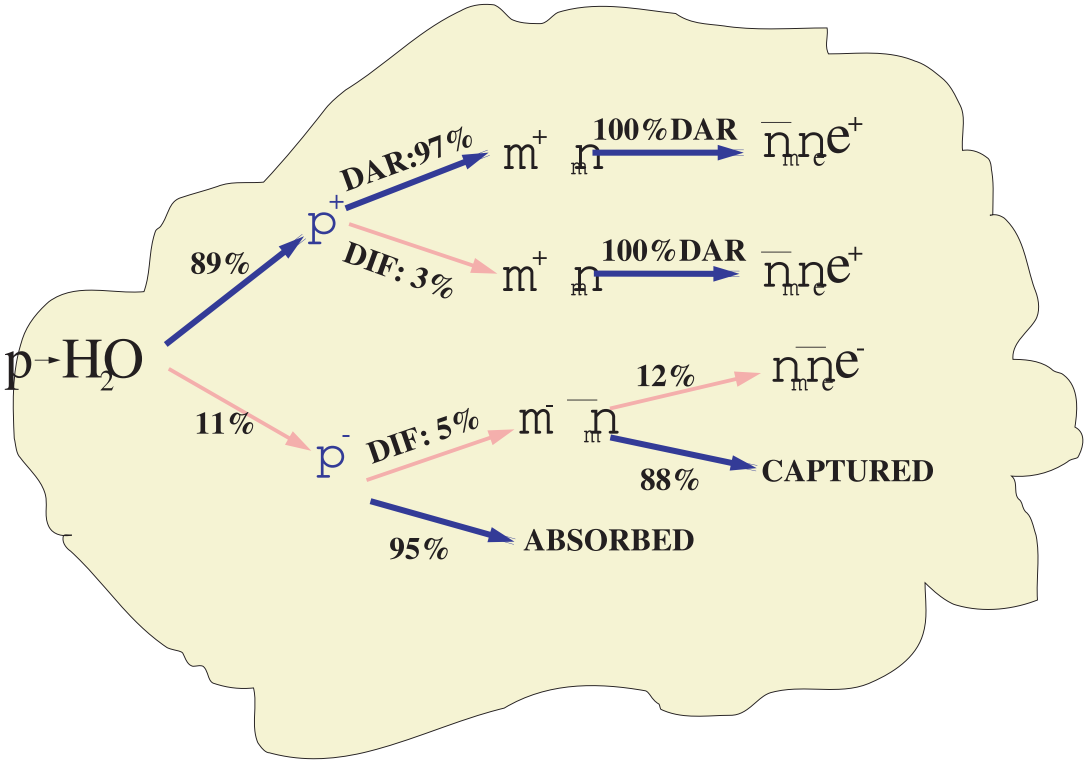
LSND experiment at the Los Alamos Meson Physics Facility (LAMPF)

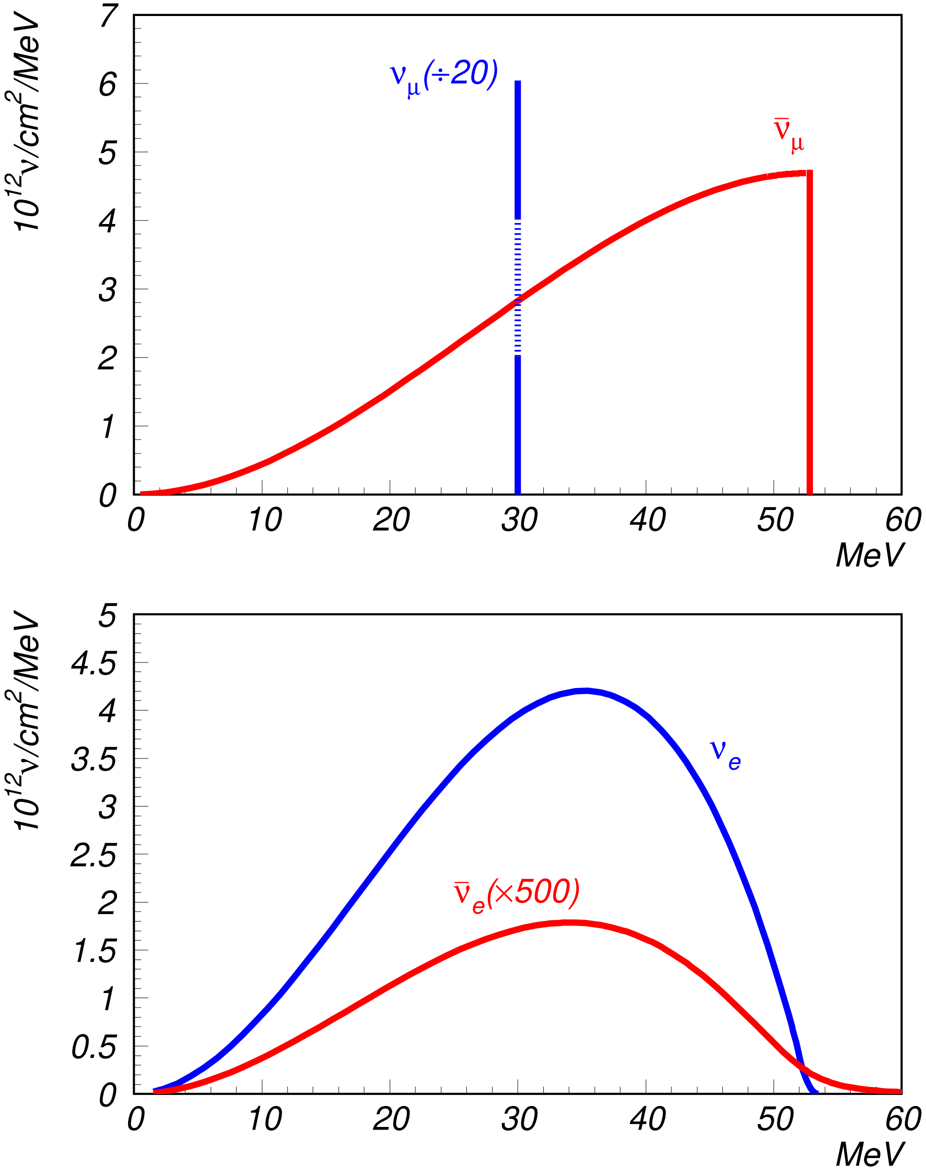
Neutrino Source High intensity (1mA) low energy (800 MeV) p beam into stop target

Look for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation from decay at rest (DAR) neutrino flux and for $\nu_\mu \rightarrow \nu_e$ oscillation from decay in flight (DIF) neutrino flux.

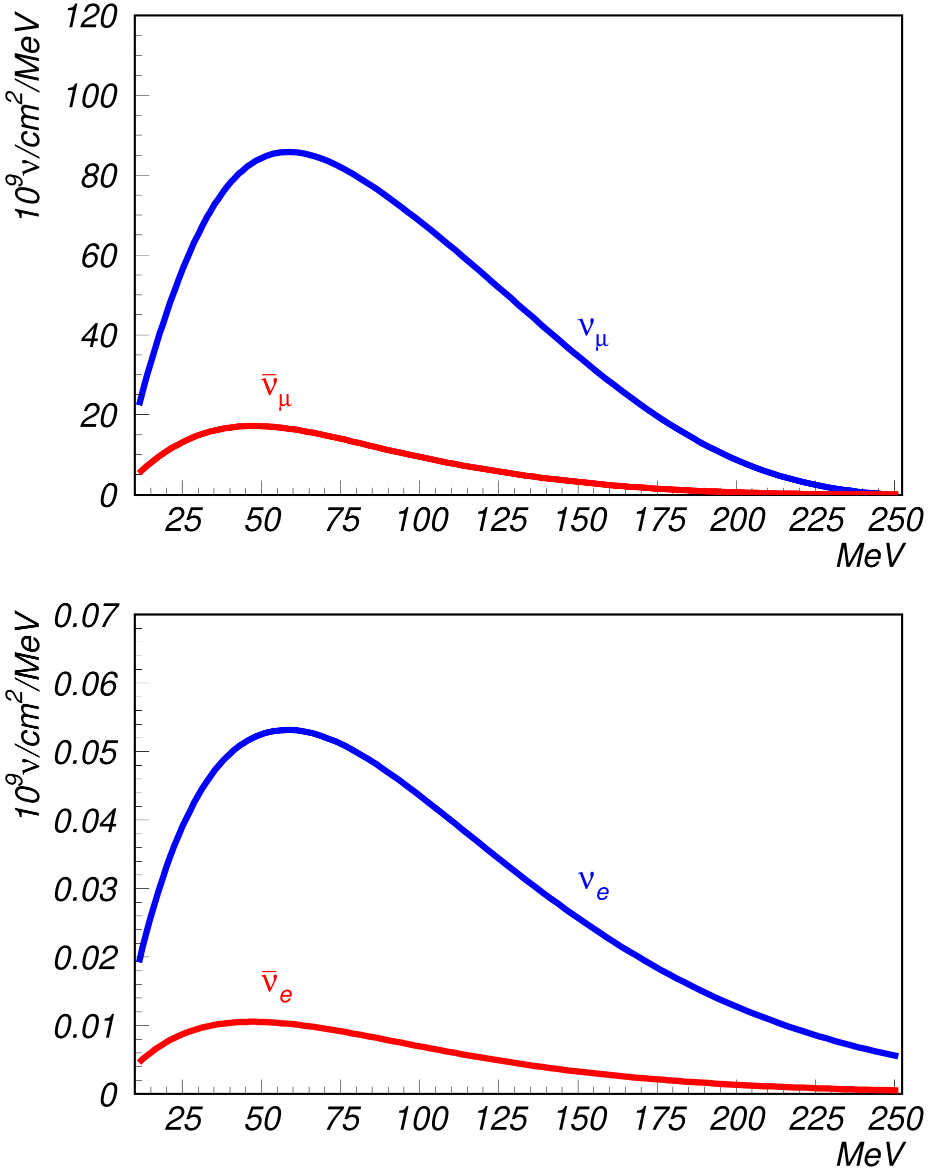


- $\overline{\nu}_e$ flux is $\overline{\nu}_e / \overline{\nu}_\mu$ (DAR) = $7.8 \cdot 10^{-4}$
- Oscillated $\overline{\nu}_e$ events have a maximum energy of 52.8 MeV.
- No electron from ν_e above 36 MeV ($\nu_e^{12}C \rightarrow e^{-}\,{}^{12}N$)
- No electron with a correlated γ above 20 MeV ($\nu_e^{12}C \rightarrow e^{-} n^{11}N$)

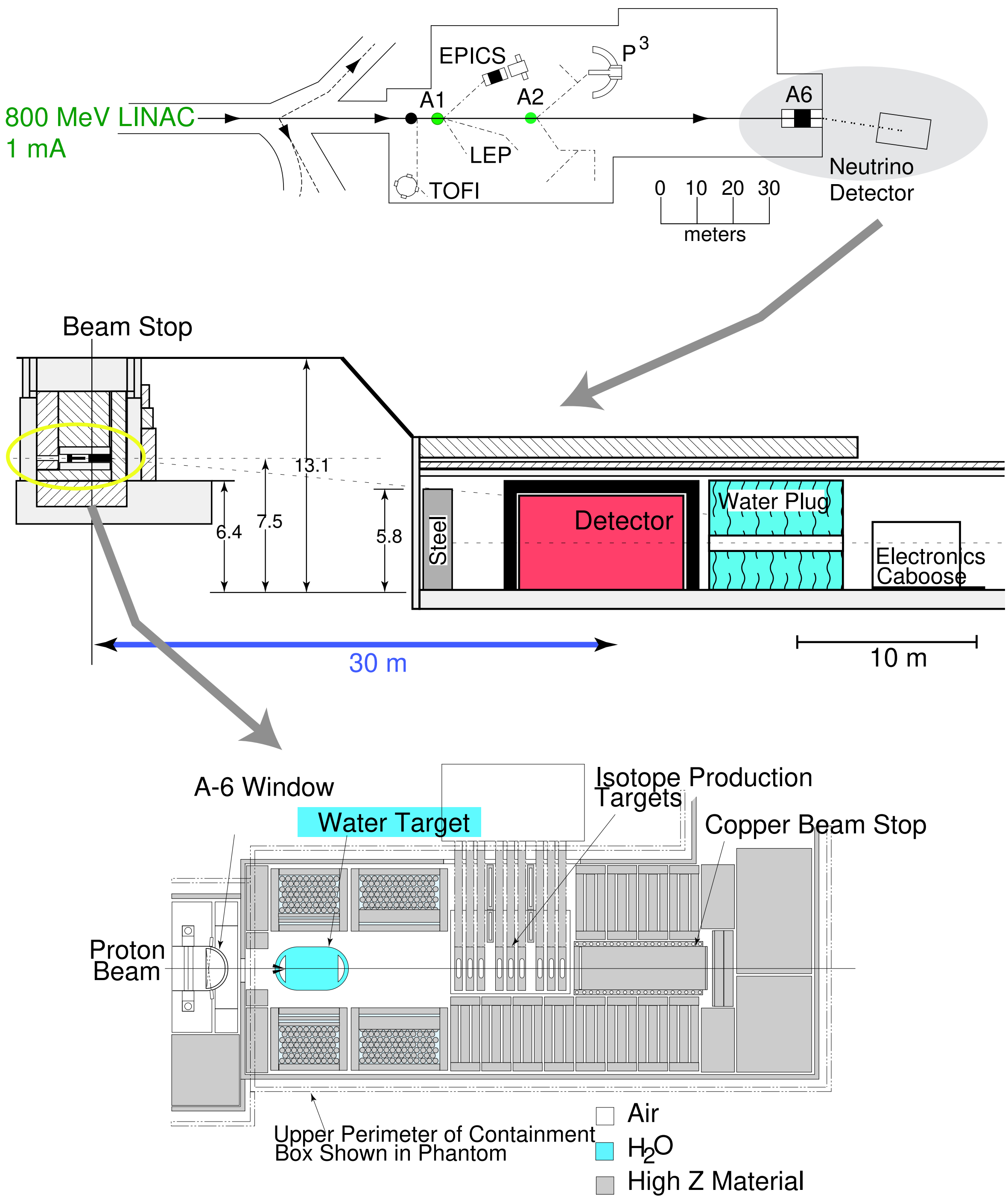
DAR FLUXES



DIF FLUXES



LSND Experimental Layout



M. Mezzetto, INFN Padova, Lezioni di Dottorato di Ricerca, Padova, Aprile 2003

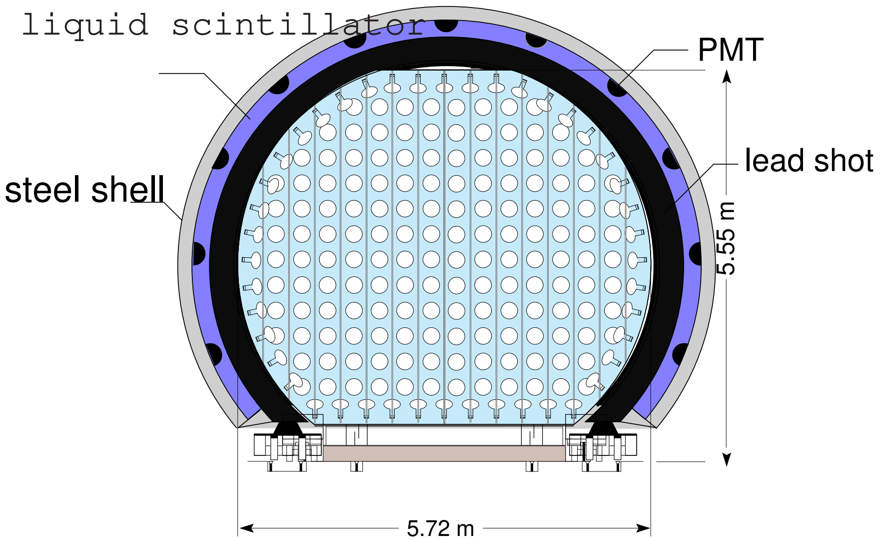
Liquid Scintillator Neutrino Detector

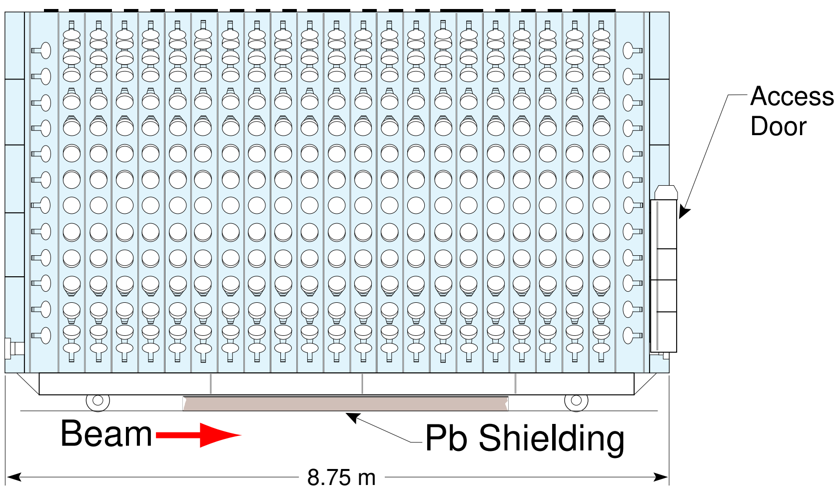
167t of Dilute Mineral Oil

Cerenkov light (n=1.47): threshold+direction
Scintillation : energy
Cerenkov/scintillation: particle identification

central detector: 1220x8" PMT (25% surface coverage)
mineral oil (CH2) doped with 0.031 g/l of b-PBD .

veto detector: 292x8" PMT,
passive shield: ~2 Kg/cm2

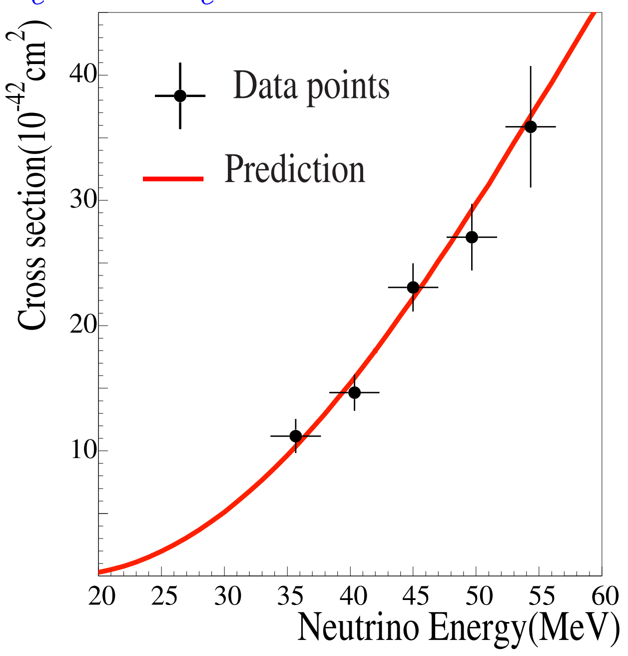




DATA TAKING

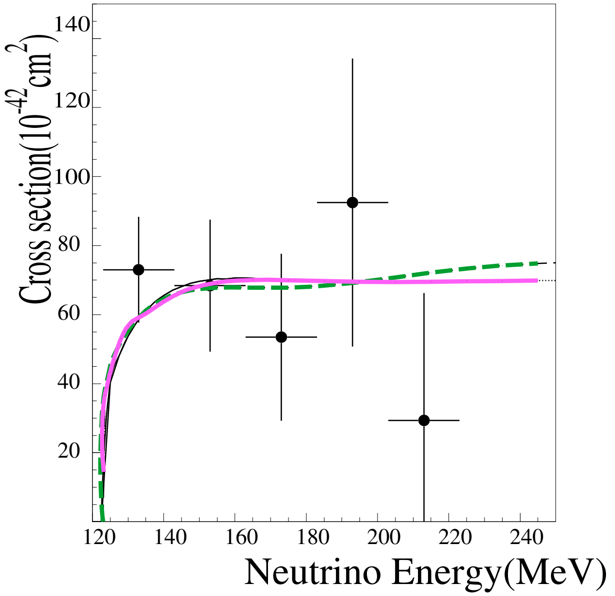
YEAR	COULOMBS	
1993	1787	
1994	5904	First DAR paper: ”Candidate events ..” (PRL 75(1995)2650)
1995	7081	Second DAR paper: “Evidence for ...”, (Ph.Rev.C 54(1996)2685 and PRL 77(1996)3082 ”
		DIF paper: ” Results on ...”, (PRL 81(1998)1774 and Ph.Rev.C 58(1998)2489)
1996	3790	Water tank substituded with high Z target.
1997	7181	Preliminary results at Neutrino 1998
1998	3154	End of data taking 21 dec 1998

ν_e detected and flux measured by $\nu_e\ {}^{12}C \rightarrow {}^{12}\ N_{gs} e^-$ and $\nu_e\ e^- \rightarrow \nu_e\ e^-$



$\overline{\nu}_\mu$ flux known at 7% through the results of a subsidiary experiment.

ν_μ detected and flux measured by $\nu_\mu^{12}C \rightarrow^{12}\ N_{gs}\mu^-$



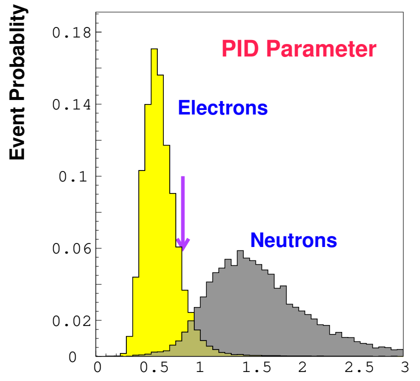
DAR OSCILLATION SEARCH

prompt positron signal, energy range.

$$\overline{\nu_e}\, p \to e^+ n$$

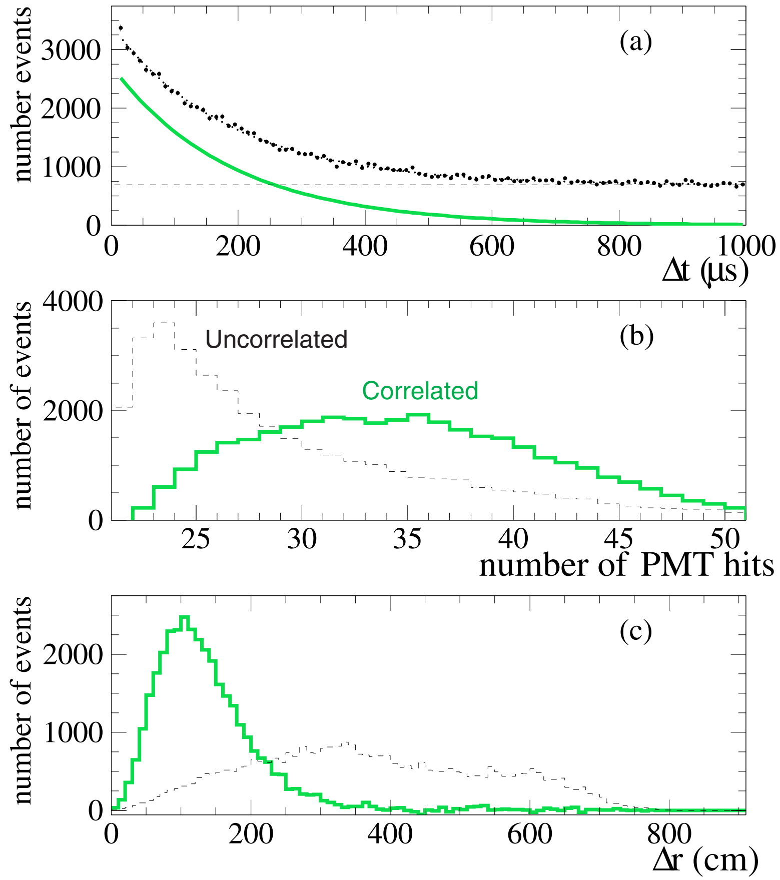
$$n + p \underset{\tau \simeq 186\ \mu s}{\longrightarrow} d + \gamma (2.2\ MeV)$$

delayed correlated photon.

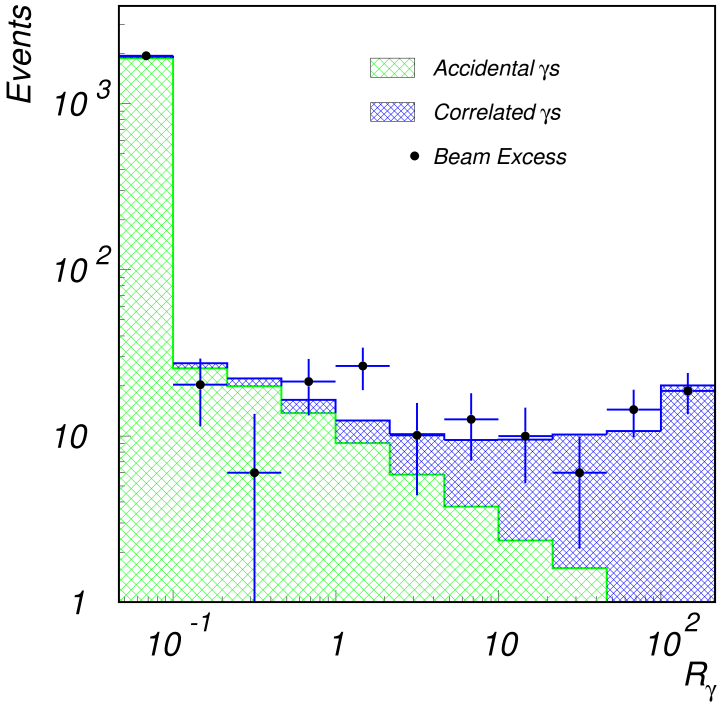


1. Particle identification through position, direction, #PMT (e^- calibration through Michel e^- from CR μ decays)
2. CR veto through veto on detector activity before and after the trigger.
3. Correlated γ through likelihood function $\mathcal{R}$ (built with CR muons and/or MC)
4. Energy range: $20 \leq E_e \leq 60$ or $36 \leq E_e \leq 60\ MeV$ (golden sample).

Overall $\overline{\nu}_e$ detection efficiency: 22%



EXCESS OF $\overline{\nu_e}$ EVENTS



BACKGROUNDS

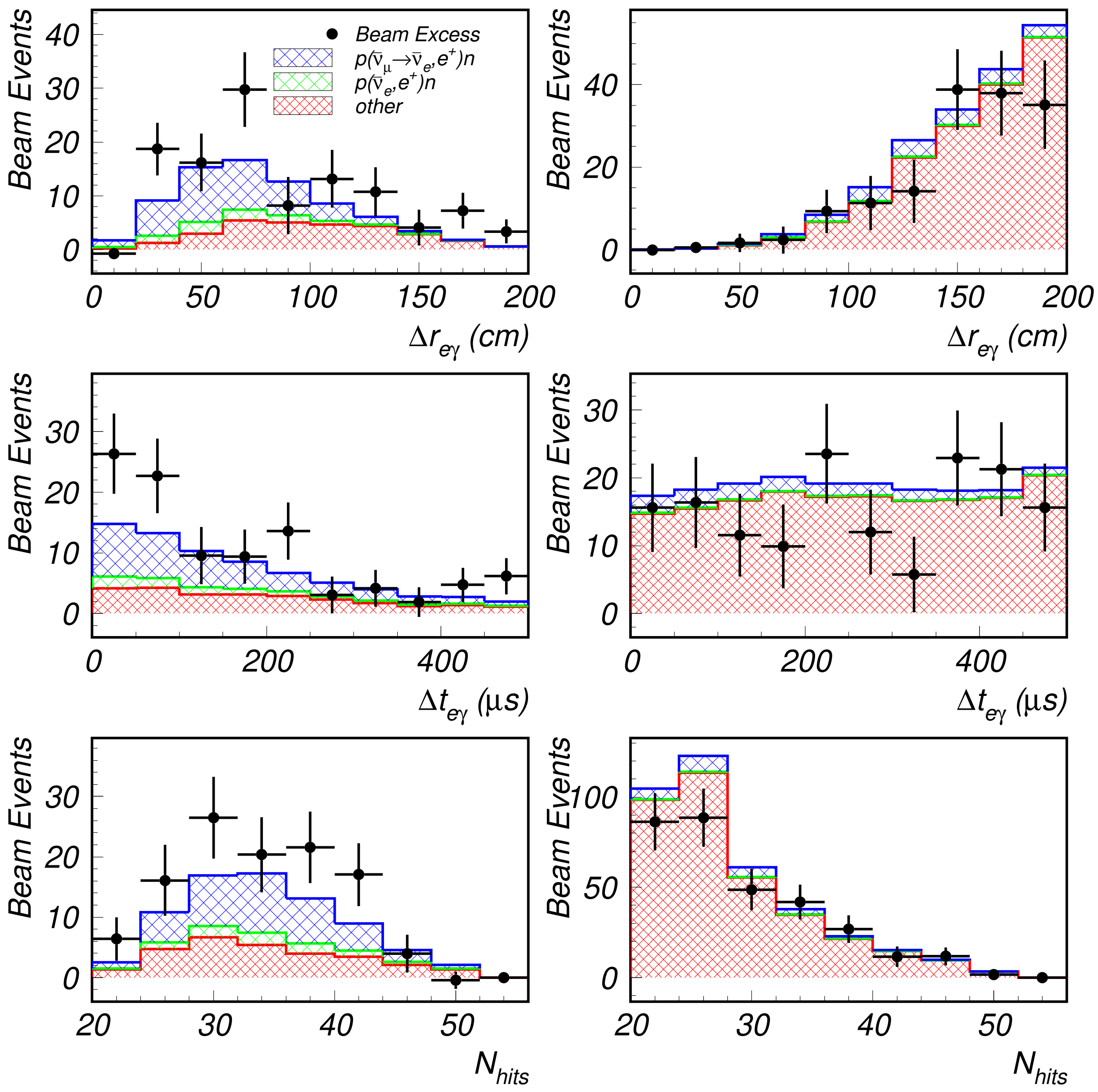
1. Cosmic Rays. Measured in beam off data (beam-off/beam-on$\simeq$ 13, $\rightarrow$ good statistical accuracy for background subtraction).
2. Beam interactions with a random γ (measured)
3. Genuine $\overline{\nu}_e$ and $\overline{\nu}_\mu$ with a correlated γ. Studied via MC simulations.

Selection	Beam-On Events	Beam-Off Background	ν Background	Event Excess	Probability
$R_\gamma > 1$	205	106.8 ± 2.5	39.2 ± 3.1	$59.0 \pm 14.5 \pm 3.1$	7.8×10^{-6}
$R_\gamma > 10$	86	36.9 ± 1.5	16.9 ± 2.3	$32.2 \pm 9.4 \pm 2.3$	1.1×10^{-4}
$R_\gamma > 100$	27	8.3 ± 0.7	5.4 ± 1.0	$13.3 \pm 5.2 \pm 1.0$	1.8×10^{-3}

Events with $20 \leq E_e \leq 60\ MeV$, $R_\gamma > 10$:

Analysis	Excess Events	Oscillation Probability
Present Analysis (1993-1998)	$87.9 \pm 22.4 \pm 6.0$	$(0.264 \pm 0.067 \pm 0.045)\%$
Previous Analysis (1993-1995)	$51.0^{+20.2}_{-19.5} \pm 8.0$	$(0.31 \pm 0.12 \pm 0.05)\%$

Excess events fit oscillated event characteristics:

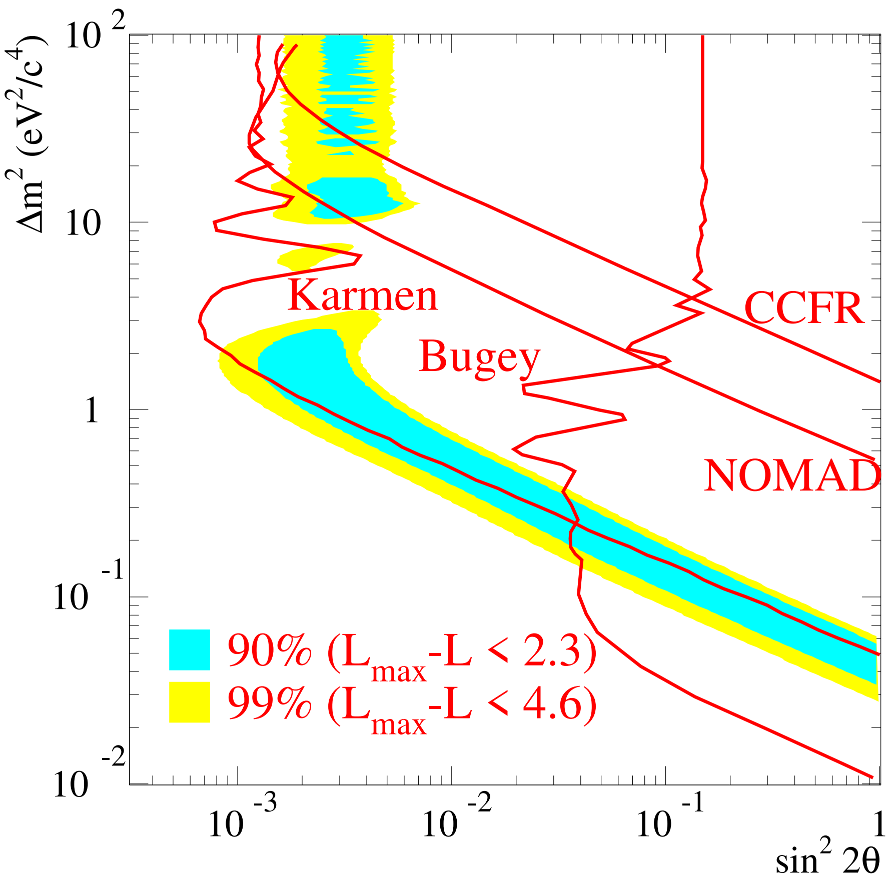


While don't fit backgrounds:

- Fit the excess with the μ^- background: it must be multiplied by 8.6 and χ^2 is 2.2 units worse than oscillation fit
- π^- DIF backgrounds studied with a special trigger during 1995, in order to increase sensitivity to muons associated to small activity: it resulted compatible with the MC predictions.

SIGNAL PLOT

- Global $\overline{\nu}_\mu - \overline{\nu}_e$ and $\nu_\mu - \nu_e$ analysis (DAR + DIF).
  5697 candidate events with $20 < E_\nu < 200$ MeV.
- 3600 bins in 4 variables: the energy, the likelihood R_γ, the angle respect the beam direction ($\cos\theta_b$) and the path length L
- Systematics included: neutrino flux $\times$ detection efficiency $= 10\%$.
- Bidimensional $(sin^2(2\theta), \Delta m^2)$ grid, selecting $\Delta\chi^2 = 2.6(90\%)$ and $4.5(99\%)$ above the minimum.
- The other exclusion curves in the plot are built with several different statistical methods!.



KARMEN EXPERIMENT

Performed at ISIS neutron spallation facility at RAL.

The detector (56 t), is at 17 m, 90^0, from the beam stop. Beam current is 0.2 mA.

The time structure of the beam permits a separation between neutrinos from μ^+ DAR and those from π decay (both DAR and DIF).

KARMEN 1: 1990-1995, 9120 Coulombs. Seen 171 events, expected 140 from cosmic rays and beam backgrounds.
Beam excess $= 31 \pm 17$ (2.4σ), delayed event seen but prompt positron do not exhibit time and energy distribution from oscillations. A lower limit on oscillation probability: $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) < 4.25 \cdot 10^{-3}$ $(90\% CL)$ was set.
Also performed a search for $\nu_\mu \rightarrow \nu_e$ oscillation, with a 90% CL limit of $2 \cdot 10^{-2}$ on the probability.

UPGRADE (KARMEN 2): new 300 m^2 active veto layer surrounding the iron blockhouse (4λ)

- throughgoing or stopping muons can be off-line vetoed
- Cosmic background suppression reduced by a factor 43.

KARMEN2 Neutrino Oscillation Search

measuring period : 2/97 - 2/02 (9.425 C p.o.t.) ν- flux : $2.71 \times 10^{21}\ \bar{\nu}_\mu$

main feature:

μ-ind. HE neutrons suppressed by veto, enhanced n-detection efficiency

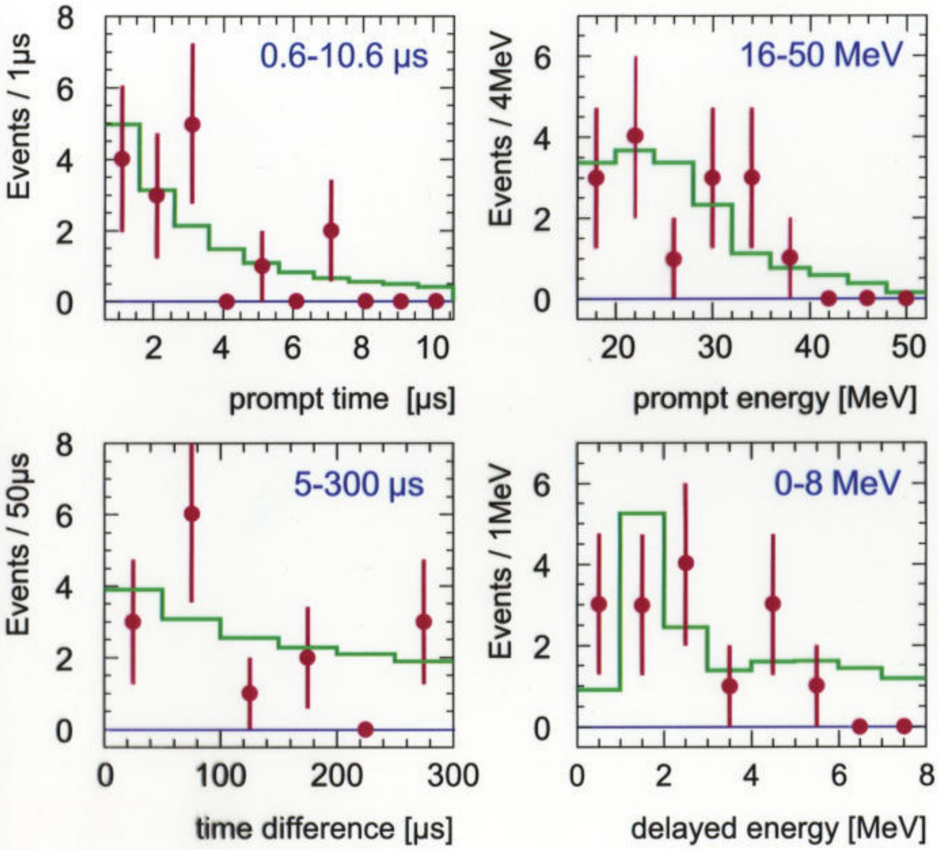
data analysis - I : single events 3.7×10^9 evts

- no prompt activity in 2 inner vetos
  skip events with module hit spread > 40 ns
- no previous activity :
  up to 24 μs : central detector, 2 inner vetos
  up to 17 μs : new outer veto counter system
- no prompt activity in outer veto counter

data analysis - II : coincidences 3464 evts

- require spatially correlated (1.5m³) coincidence
- MC optimised cuts for prompt and delayed event → final event ensemble

final KARMEN2 candidate event ensemble



15 candidate events

(15.8 ± 0.5) background events are expected

cosmic background : 3.9 ± 0.2 evts

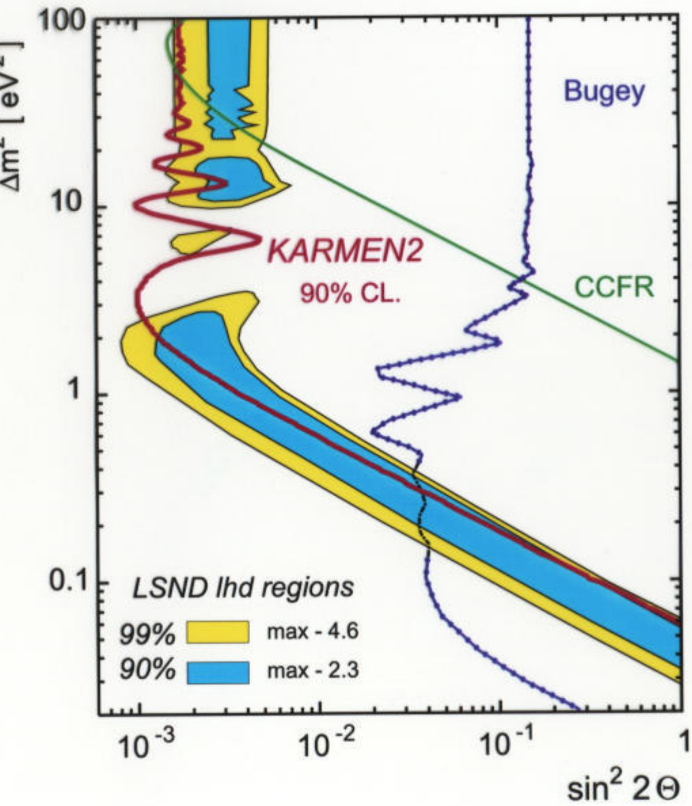
ν_e-induc. excl. CC : 5.1 ± 0.2 evts

ν_e-ind. CC & rand. γ : 4.8 ± 0.3 evts

intrin. contamination : 2.0 ± 0.2 evts

no oscillation excess

Final KARMEN2 limit and final LSND regions



4y KARMEN2 data taking 2/97 - 2/02

unified (frequentist) approach
Feldman-Cousins

oscillation limit :

$\sin^2 2\theta < 1.7 \times 10^{-3}$ (90% CL.)

large Δm^2

oscillation sensitivity :

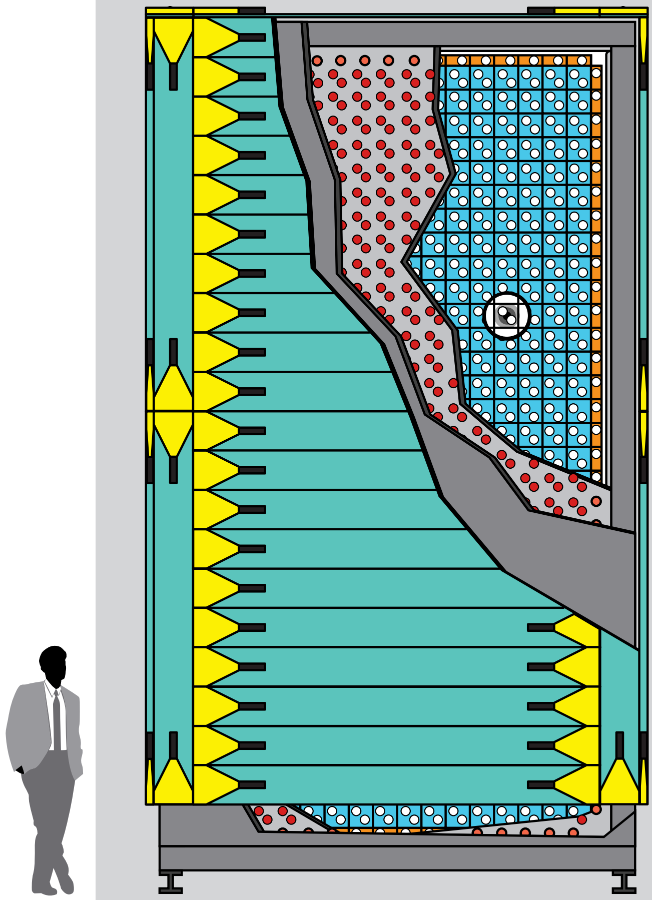
$\sin^2 2\theta < 1.6 \times 10^{-3}$ (90% CL.)

KARMEN2 excludes a significant part of the LSND parameter space

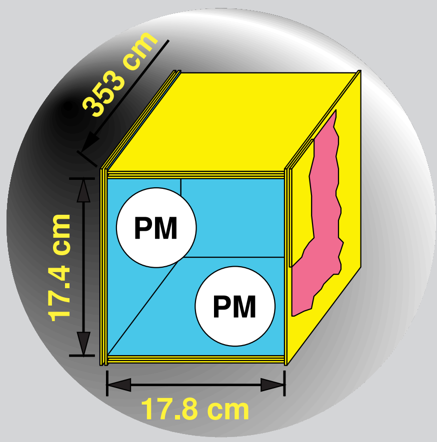
KARMEN DETECTOR

56t liquid scintillator calorimeter

96% active volume



OUTER VETO 1	NE110
PASSIVE SHIELD	20 cm
INNER VETO	96
SEGMENTED CENTRAL DETECTOR	16x32
3" PHOTOMULTIPLIER	
ACRYLIC GLASS	



Gd_2O_3 PAPER + AIR GAP

3.2m x 5.9m x 3.5m

$$\Delta E/E = \frac{11.5\%}{\sqrt{E(MeV)}} \quad (<=>80 \text{ pe/MeV})$$

$\sigma t = 0.4$ns
$\sigma x = 6.0$cm

17.05.98

Compatibility Analysis LSND - KARMEN2

- Q: level of statistical compatibility, if both results are correct
- frequently used A: region of statistical compatibility is LSND region left of 90%CL. KARMEN2 exclusion

  straightforward, but misleading!
- can do much better :

  use full experimental information (likelihood function)
- need full access to primary experimental data (open resources)
- LSND-KARMEN2 analysis showcase for other areas such as $0\nu\beta\beta$, dark matter, Higgs searches, ...

for details see :

E.D. Church, K. Eitel, G.B. Mills, M. Steidl, hep-ex/0203023, acc. for publ. in PRD

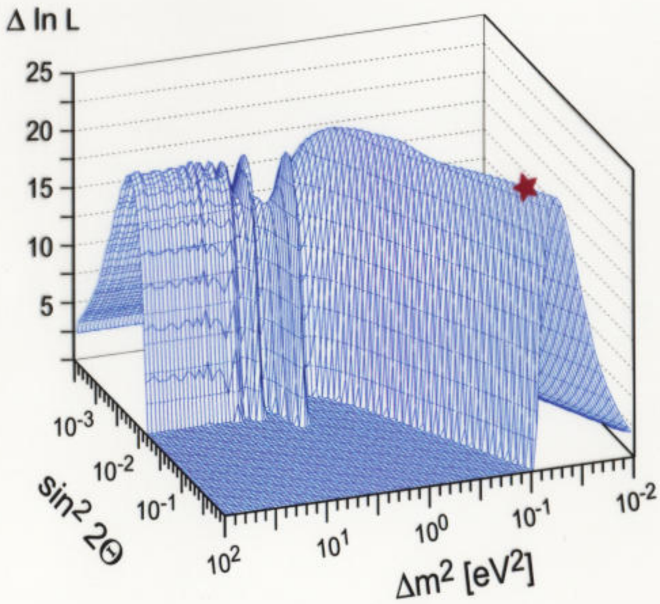
K. Eitel, New Jour. Phys. 2 (2000) 1.1

Poster by K. Eitel and M. Steidl on tuesday

Comparison of Likelihood Contours

LSND evidence

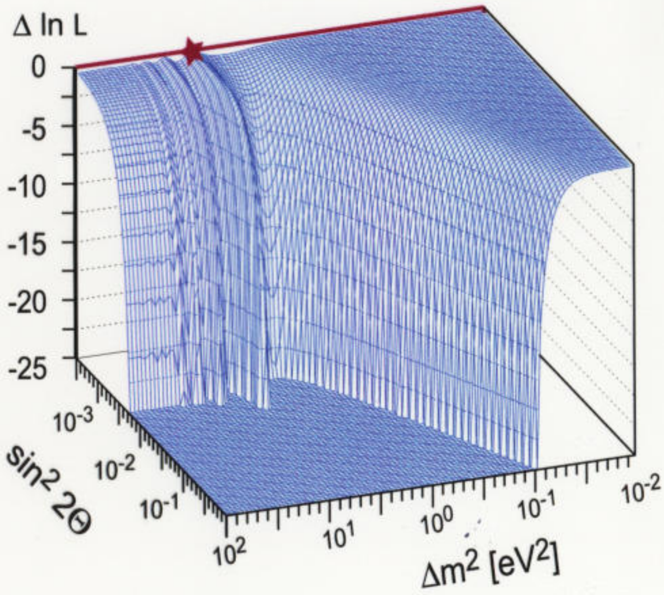
$\Delta \ln L_{max} = 23.5$ (66.7 events)



$\Delta m^2 = 0.055\ eV^2$ $\sin^2 2\Theta = 0.85$

KARMEN2 exclusion

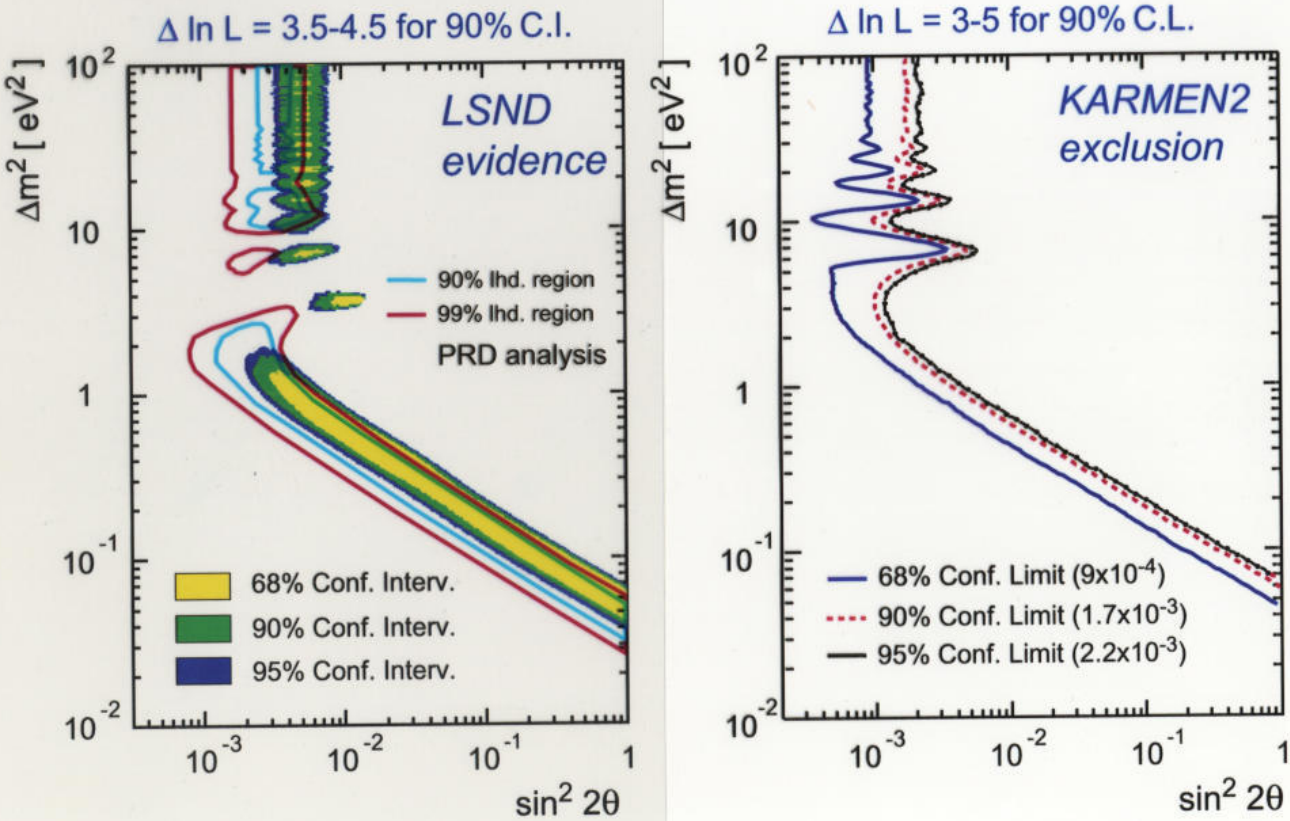
$\Delta \ln L_{max}$ at boundary: no oscil. signal



$\sin^2 2\Theta = 0.0$ (no oscillations)

LSND and KARMEN2 Confidence Intervals/Limits

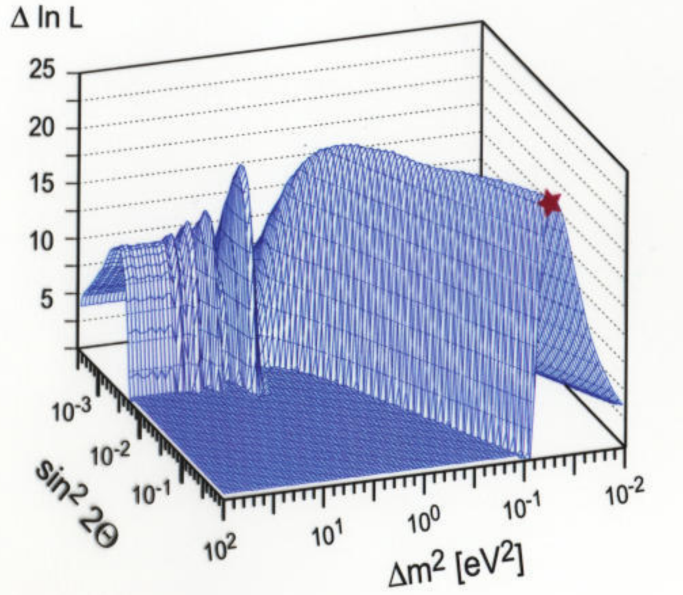
regions based on unified frequentist approach of Feldman/Cousins



Compatibility Analysis of LSND and KARMEN2

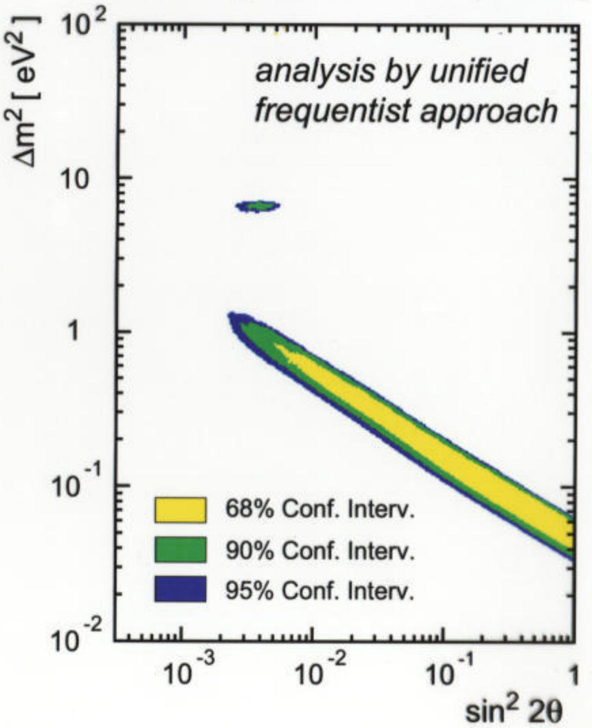
based on full experimental information from likelihood functions

Combined Likelihood Function
LSND-KARMEN2 : add ln L



shape for high Δm^2-values significantly modified

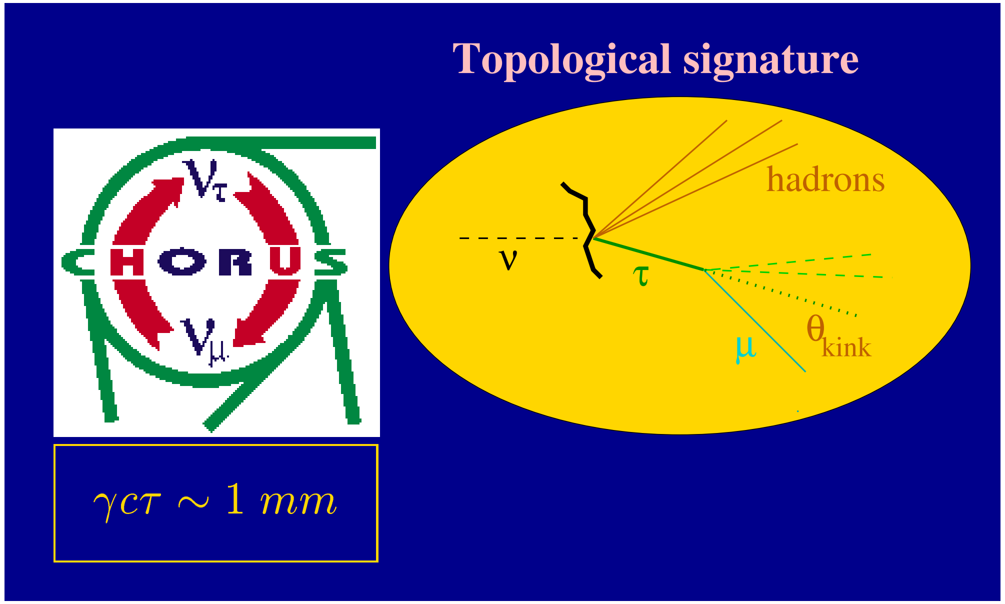
combined confidence regions
assuming statistical compatibility

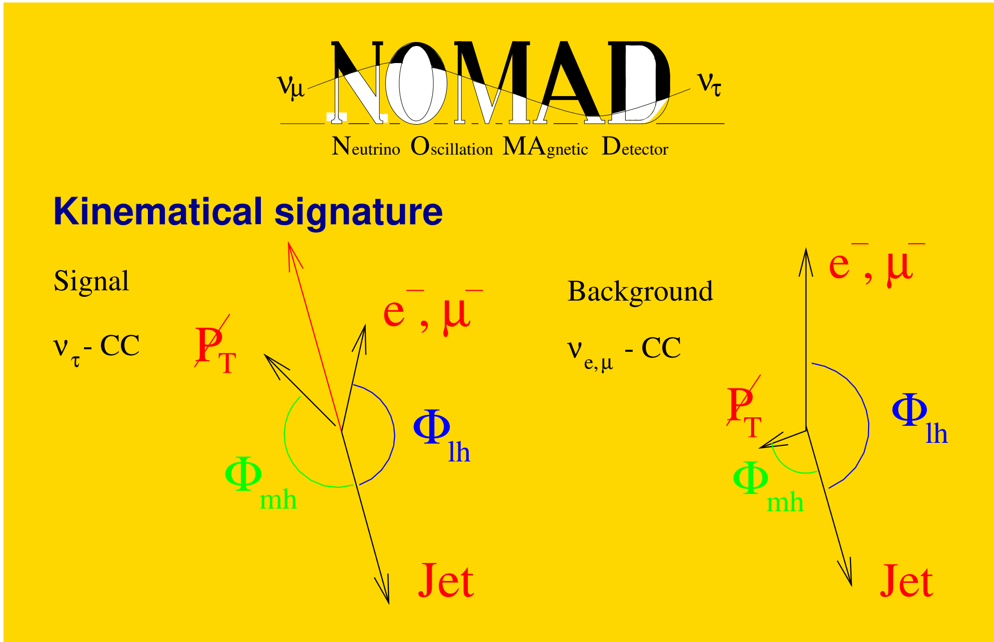


$\nu_\mu \rightarrow \nu_\tau$ search at the CERN Wide Band Beam

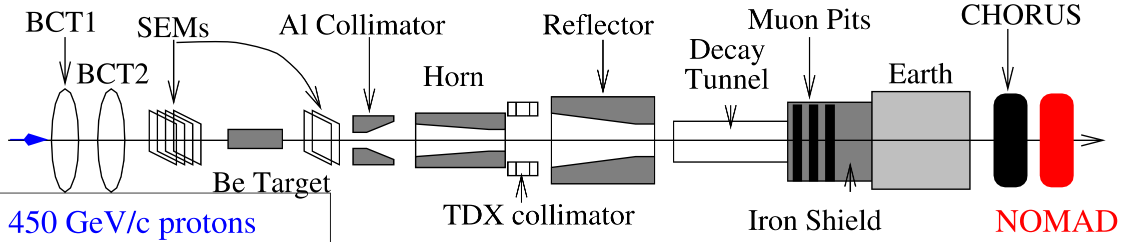
In the mass scale above $1\ eV$, inspired by Dark Matter scale

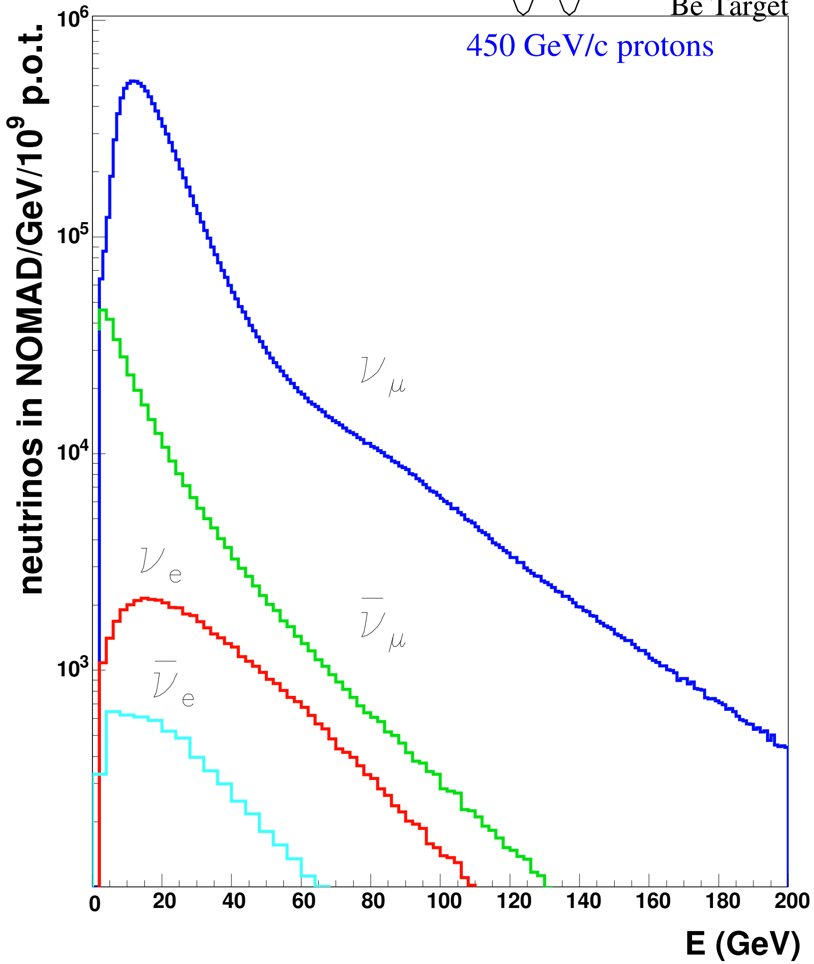
The first dedicated exploration of the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation parameter space





CERN Wide Band Beam (WANF)





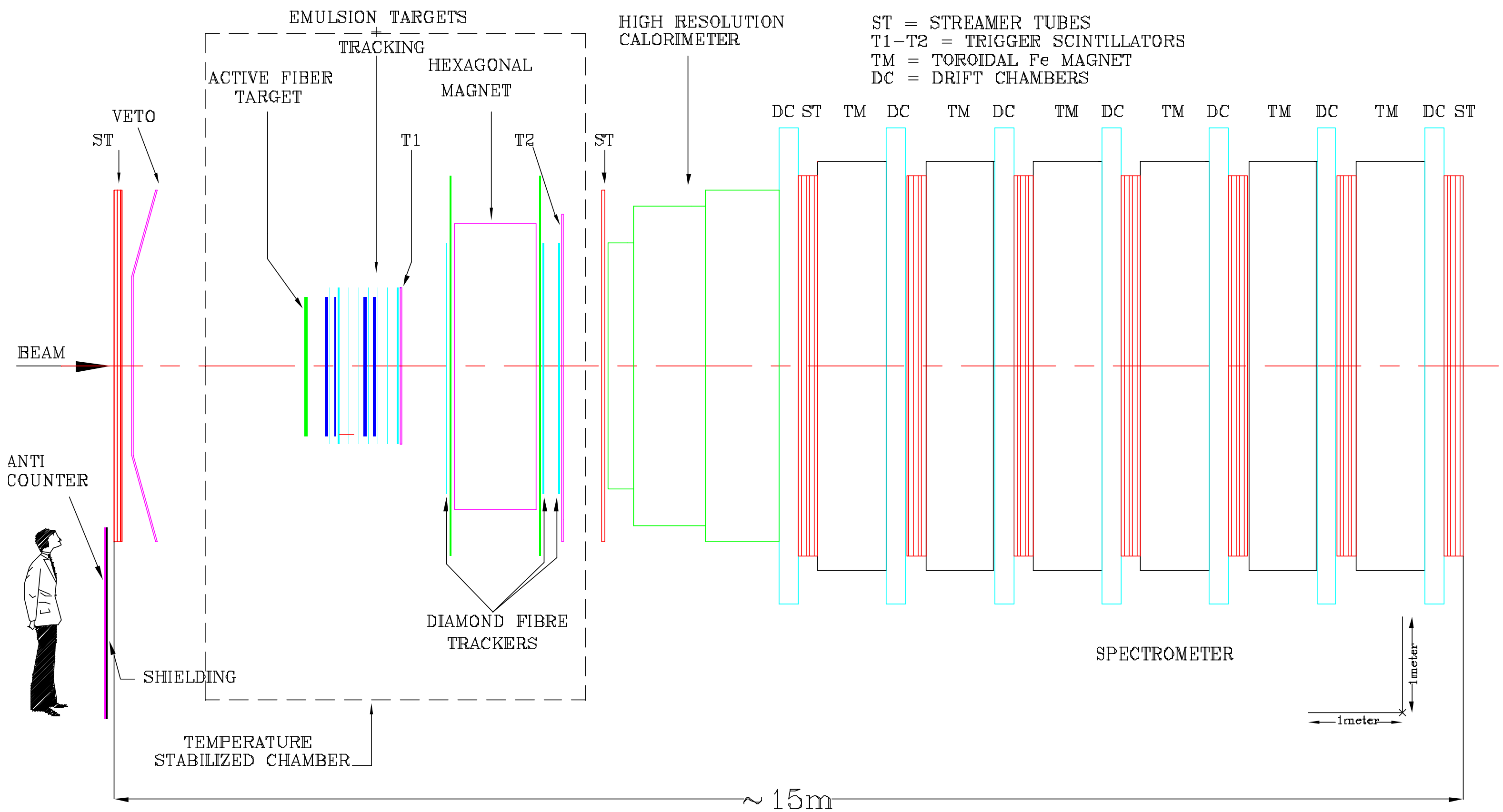
Distance of detector from target $\sim 800m$.

Effective neutrino flight path $\sim 600m$.

Flavour	Rel. Flux	$\langle E_\nu \rangle$ (GeV)
ν_μ	1	23.5
$\overline{\nu}_\mu$	0.061	19.2
ν_e	0.0094	37.1
$\overline{\nu}_e$	0.0024	31.3

ν_τ flux is negligible (less than 0.1 expected interactions in 4 years).

Chorus detector



Chorus target and target tracker

Fibre tracker: $\sim 10^6$ scintillating fibers of $500\ \mu m$ in diameter.

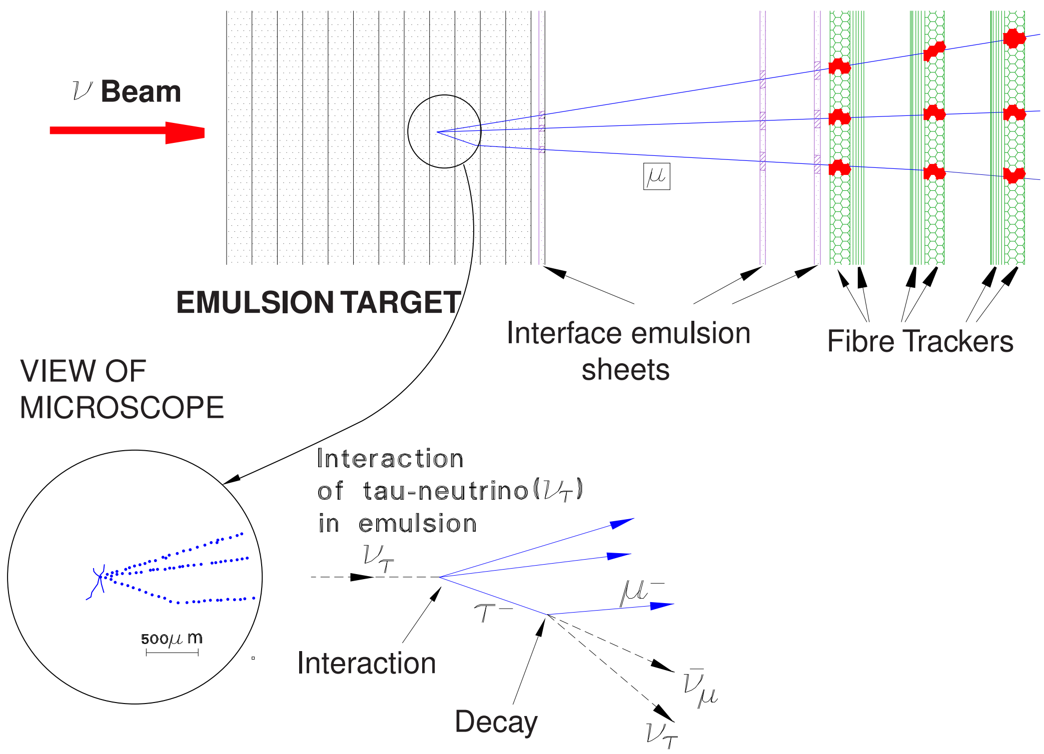
Resolutions: 2 $mrad$ and 150 μm.

Emulsion Target: $(4 \times 200\ Kg)$

Spatial resolution $\sim 1\mu m$,

grain density $\sim 300/mm$.

Ideal to detect the τ decay kink.

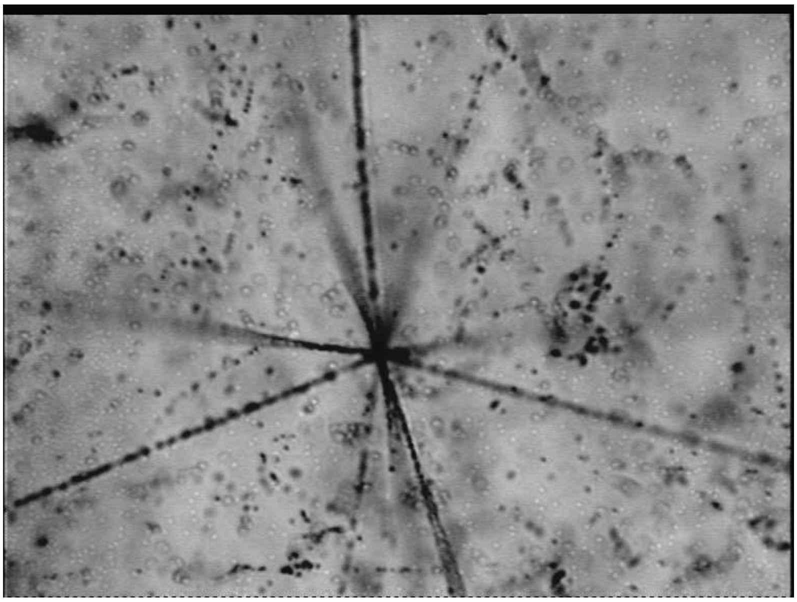


Chorus scanning

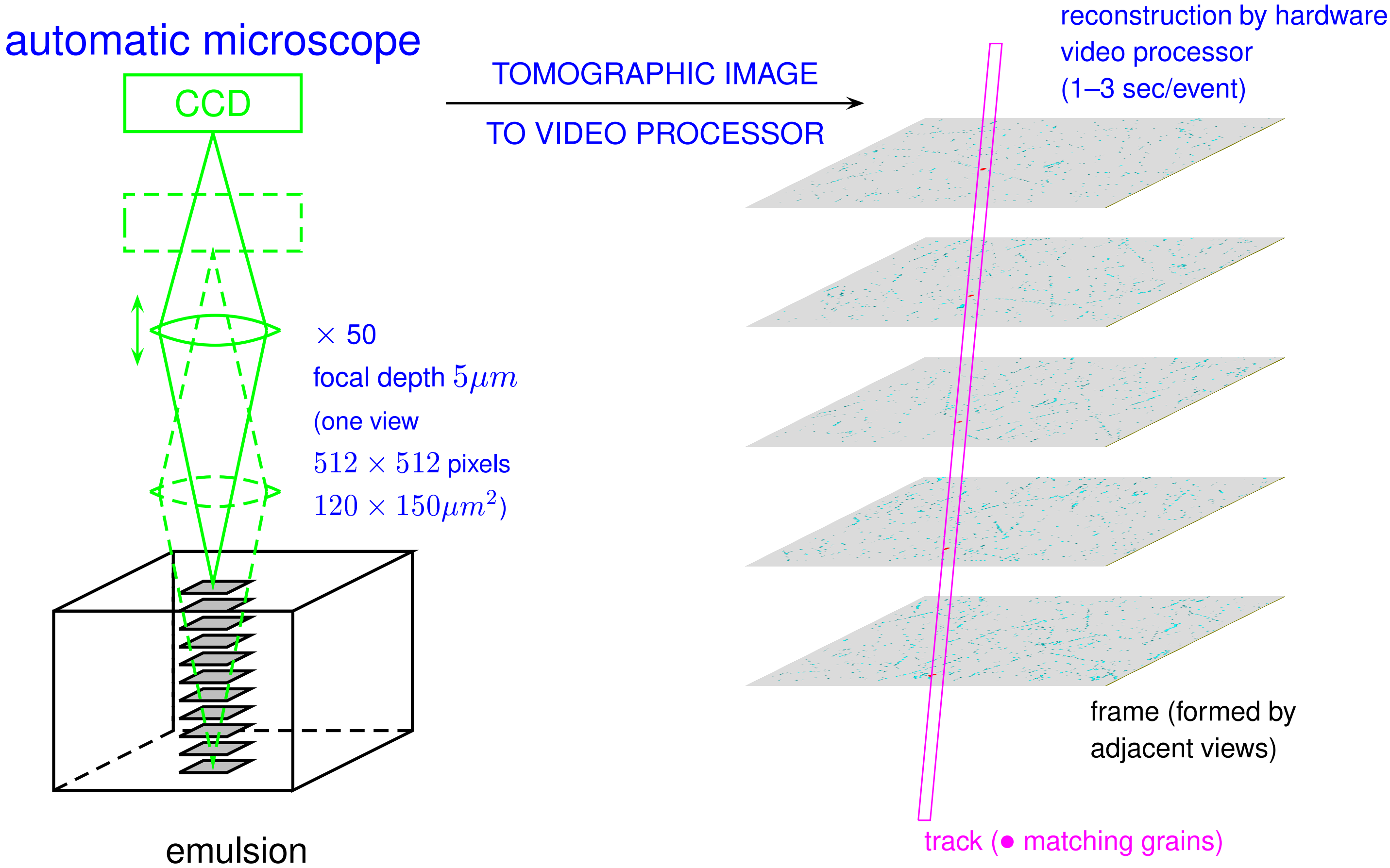
Scanning speed is dramatically increased:

year	views/s
1994	0.5
1995	6
1998	180
2000	1800

Emulsion perpendicular to the beam



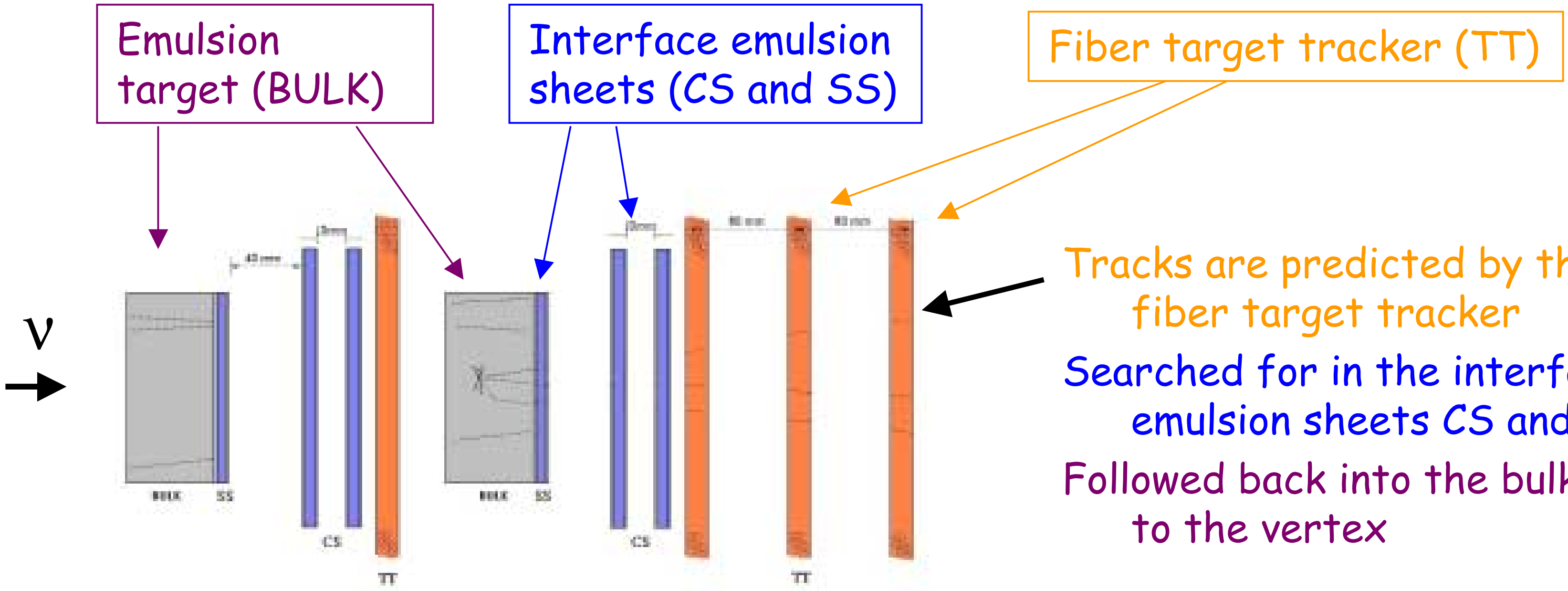
Automatic scanning: Track Selector (Nagoya)



The event location in emulsion

1μ sample: 1 negative muon from the primary interaction vertex with P < 30 GeV/c

0μ sample: at least one negative track with P $\in$ [-1,-20] GeV/c



Tracks are predicted by the fiber target tracker

Searched for in the interface emulsion sheets CS and SS

Followed back into the bulk up to the vertex

Location efficiency higher for 1μ (40%) than for 0μ (27%) independently from track angle

Chorus signal definition

One Muon Channel (the golden one)

Negative μ track, $p < 30\ GeV$

No other primary lepton

Kink on muon track $p_T > 250\ MeV$

Short flight length < 5 plates (4mm)

Background

Charm production by antineutrinos (very small)

To check scanning efficiency: Use events with 2 muons in the final state ($\sim\ 2\%$ of the total) scan the emulsion searching for a kink $\rightarrow$ charm dimuon candidates (D^+ decay).

	1995	1996
Expected events	7.4 ± 0.7	15.4 ± 2.2
Events found	8	17

Zero μ channel (Sensitive to $\tau \rightarrow \nu_\tau\, h^-(nh^0)$, $\tau \rightarrow \nu_\tau\, \overline{\nu}_e\, e^-$, $\tau \rightarrow \nu_\tau\, \overline{\nu}_\mu\, \mu^-$ where the μ^- is not identified)

Negative non-muon track

$1 < p < 20\ GeV$

No primary lepton

Kink on negative track

Strict flight length cut < 3 planes

Background

Charm production by antineutrinos (very small)

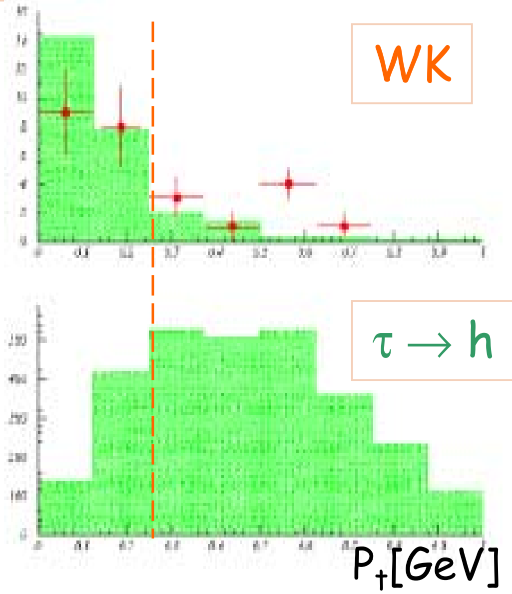
NC events with a kink-like pion (0.5 events with the present statistic)

Data flow in Chorus Phase I

Emulsion triggers: 2,305K

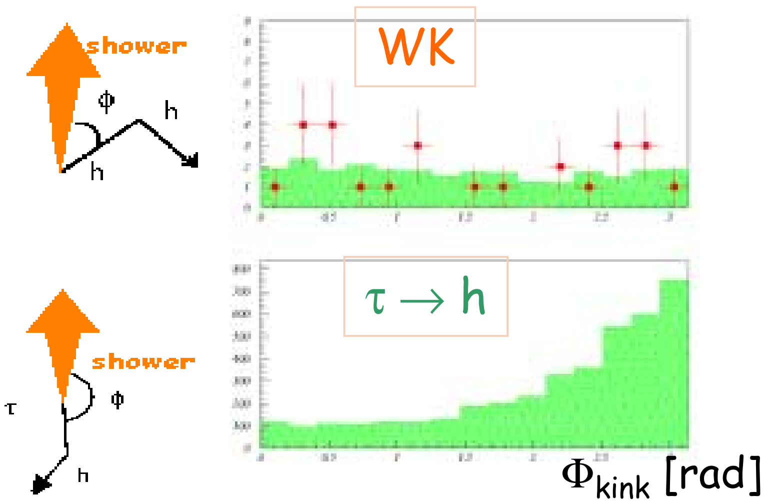
1μ		0μ	
Initial sample	713,000	Initial sample (CC contamination)	335,000 (140,000)
Momentum cut + angle cut	477,600	≥1 negative tracks + Momentum cut + angle cut	122,400
Events scanned	355,395	Events scanned	85,211
Vertex located	143,742	Vertex located	20,081
Selected for eye-scan	11,398	Selected for eye-scan	2,282

White kink background



- 1-prong nuclear interaction with no ionizing activity at interaction point
- CHORUS <u>measured</u> $\lambda_{WK}(P_t > 250 MeV/c) = 24.0 \pm 8.5$ m

$\Rightarrow 2.6 \pm 0.8$ WK expected in the signal region



Post scanning WK rejection

- Φ_{kink} cut: τ opposite to the shower in the transverse plane
- L_{decay} cut: τ flight length shorter and correlated with p_{had}

Cuts optimisation by the a-priori criterium of maximising the exclusion power, independently from data.

Results of the $\nu_\mu \rightarrow \nu_\tau$ oscillation search

CHORUS:

Total bkgd	N_τ^{max}	Data
1.2	7018	0
(±30% syst)	(±15% syst)	

NOMAD:

Total bkgd	N_τ^{max}	Data
50.5	15226	52
(±20% syst)	(±10% syst)	

Calculation of Limit @ 90% CL

$L_{osc}(\nu_\mu \rightarrow \nu_\tau) = 3.4 \times 10^{-4}$
$S_{osc}(\nu_\mu \rightarrow \nu_\tau) = 3.7 \times 10^{-4}$
$P(\leq L_{osc}) = 28\%$

$L_{osc}(\nu_\mu \rightarrow \nu_\tau) = 1.63 \times 10^{-4}$
$S_{osc}(\nu_\mu \rightarrow \nu_\tau) = 2.5 \times 10^{-4}$
$P(\leq L_{osc}) = 37\%$

$L_{osc}(\nu_\mu \rightarrow \nu_\tau) = 2.1 \times 10^{-4}$
$S_{osc}(\nu_\mu \rightarrow \nu_\tau) = 3.4 \times 10^{-4}$
$P(\leq L_{osc}) = 29\%$

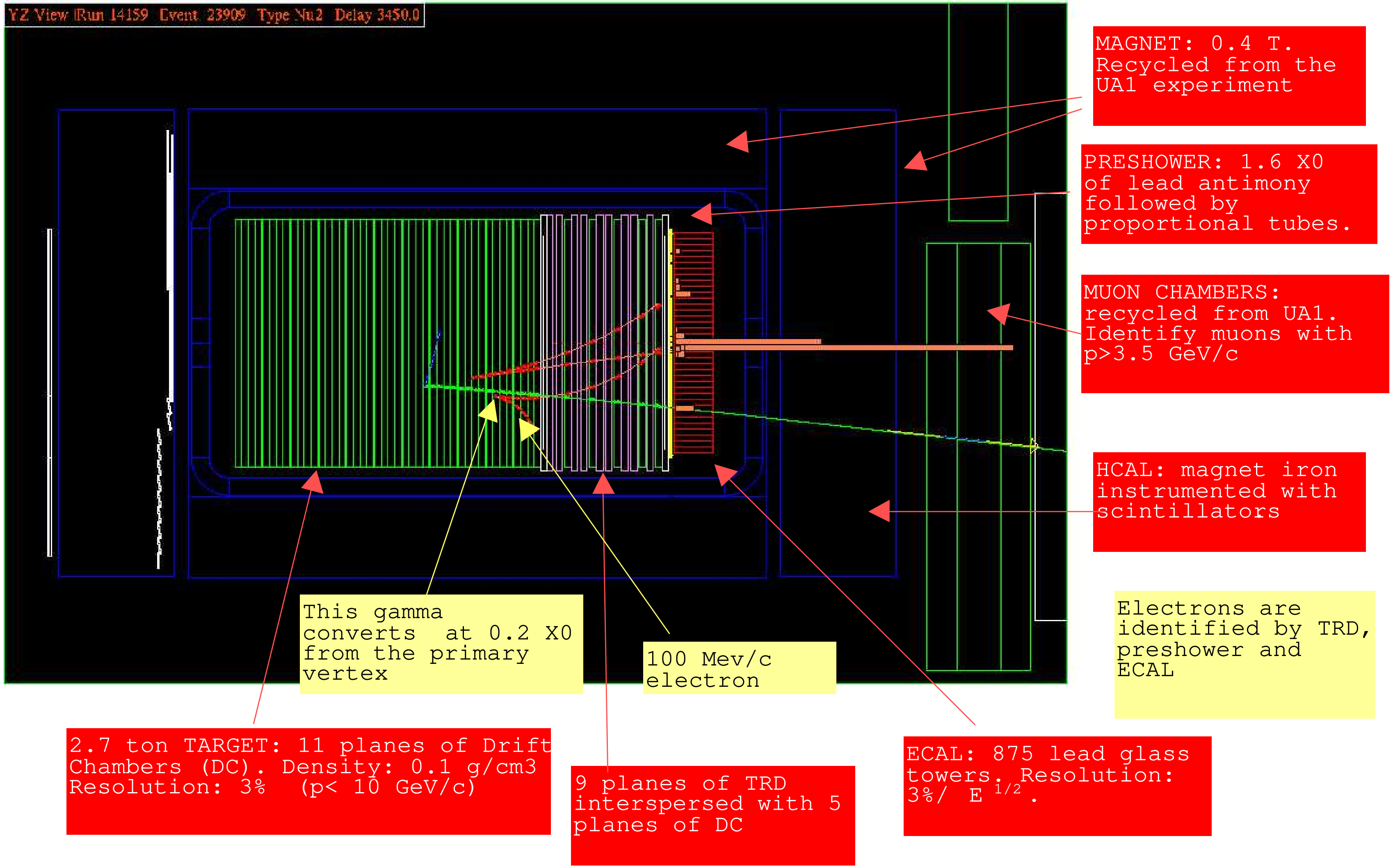
T.Junk, NIM A434 (1999) 435

G.J.Feldman & R.D.Cousins,
Phys.Rev. D57 (1998) 3873

NOMAD DETECTOR

Neutrino Oscillation MAgnetic Detector

Full data sample (1995-98) 1.35 10^6 ν_μ CC



The ν_τ search: general principles

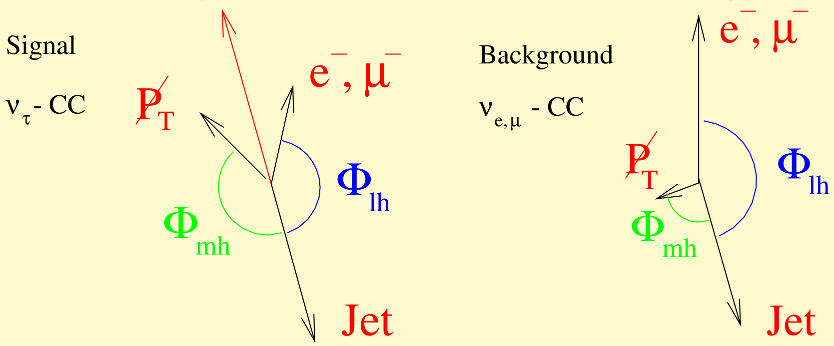
Appearance experiment. ν_τ is detected by CC interactions $\nu_\tau + N \rightarrow \tau^- + X$

Indirect τ identification through its secondary visible decay products. Analyses are specialized in Low and High Multiplicity events, separated by a cut on the hadronic momentum $p_H > 1.5\ GeV/c$.

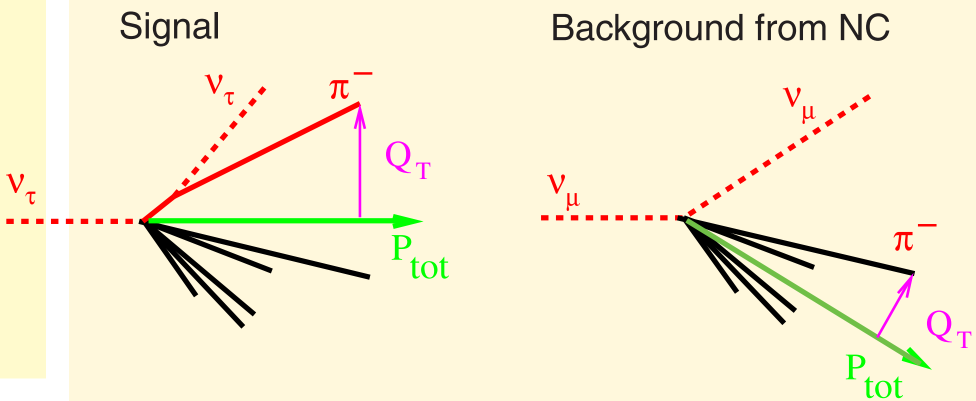
$$\tau^- \rightarrow \left\{ \begin{array}{ll} e^- \overline{\nu}_e\, \nu_\tau & 17.8\% \\ h^-\,(n\pi^\circ)\nu_\tau & 49.5\% \\ \pi^-\pi^-\pi^+\,(n\pi^\circ)\nu_\tau & 15.2\% \\ \hline \mathrm{TOTAL} & 82.5\% \end{array} \right.$$

Kinematic criteria to extract the signal from background.

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.



Nomad analysis in its maturity

The optimal rejection power is achieved using the full topology of the events, in principle 5 degrees of freedom + internal structures.

A probability density function, $pdf\ \mathcal{L}$ can be defined, describing the probability for an event with a given set of variables X_i to be signal ($\mathcal{L}_S$) or background ($\mathcal{L}_B$).

The global $pdf\ \mathcal{L}$ is subdivided into n-dimensional partial pdf's with n up to 4 (higher values are not practical given the statistic of the MonteCarlo samples) chosen among the most discriminating internal correlations of X_i.

Event classification is based on likelihood ratio between the signal and background hypotheses: $ln\lambda = ln\frac{\mathcal{L_S}}{\mathcal{L_B}}$

The optimal treatment would be to fit the shape of the tail of $ln\lambda$. In practice $ln\lambda$ is subdivided into bins. The position of the bins is decided exclusively taking into account the sensitivity of the analysis (sensitivity is defined in Cousins & Feldman, Phys. Rev. D57(1998)3873.).

The independent measurements from different decay modes and signal bins are combined within the frequentist Unified Approach.

Three important steps for a solid analysis

DATA SIMULATOR: The large kinematical suppression and the use of likelihood functions exploiting multidimensional correlations require precise knowledge of the backgrounds down to $\mathcal{O}(10^{-5})$. Not possible to rely only on the MonteCarlo predictions.

- Use identified ν_μ^{CC} in both Data (DS) and MonteCarlo (MCS) samples and replace the leading μ^- by the appropriate MC particle: ν for neutral currents, τ for the signal, e^- for ν_e^{CC} .
- Compute efficiency for signal and background as $\epsilon = \epsilon_{MC} \frac{\epsilon_{DS}}{\epsilon_{MCS}}$
- In this ratio the systematics of the method itself, of the MC hadronic simulation and of the nucleon Fermi motion cancels.

Search for τ^+ candidates: Given the beam composition and the published limits no τ^+ signal is expected $\rightarrow$ Search for τ^+ in the data and demonstrate that background predictions agree with data.

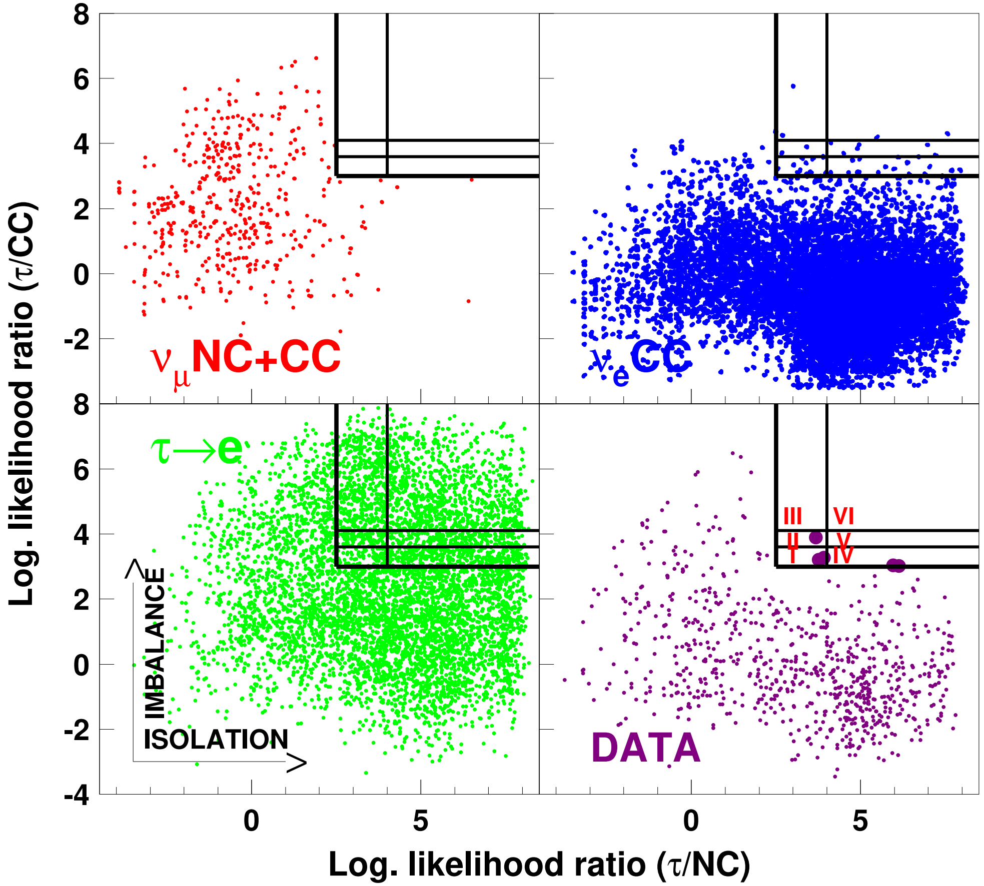
Blind Analysis To avoid ANY bias in selecting the events, define a “signal” region (box) and never look at the data there. Robust prediction of backgrounds must be demonstrated before opening the box. The choice between different analyses in each decay channel is made according to their sensitivity, before opening the box

$\tau \rightarrow e\nu_\tau\overline{\nu_e}$ (ν_e CC are 1.5% of ν_μ CC).

Electrons from ν_e CC

Discriminated by a 4D likelihood function mainly based on the topology in the transverse plane:

$$\mathcal{L}_{\rm CC} = [[q_{lep}, \rho_{x_{vis}}, \rho_H], p_T^m, M_T, E_{vis}]$$



Electrons and γ from Neutral Currents

- Select well measured electrons with tight identification criteria.
- Exploit the excellent performance of the detector (at signal efficiency $\sim 20\%$):
  - e^-/π^- rejection: $\mathcal{O}(10^6)$
  - e^-/π° rejection: $\mathcal{O}(10^4)$

The remaining neutral current background is rejected by a 3D likelihood function mainly based on the isolation of the candidate electron from the hadronic jet:

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

Events are classified in the plane defined by the 2 likelihood functions

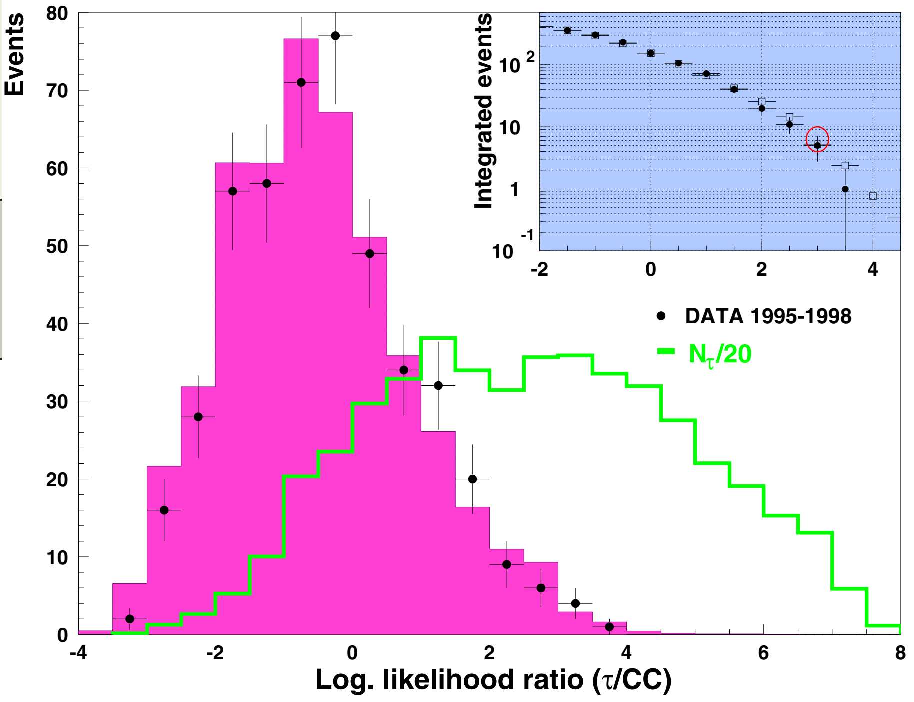
The selected (blind) region is further subdivided in 6 bins.

$\tau \to e\nu_\tau\overline{\nu_e}$, final results

Analysis	Bin #	Tot bkgnd	Data	N_τ
$\tau^- \to e\nu\nu$	I	$0.85^{+0.26}_{-0.16}$	2	134
($E_{vis} > 12$ GeV)	II	$0.46^{+0.23}_{-0.12}$	1	128
	III	$0.18^{+0.18}_{-0.08}$	0	639
	IV	1.85 ± 0.22	2	535
	V	0.78 ± 0.15	0	389
	VI	0.16 ± 0.08	0	1388
($E_{vis} < 12$ GeV)	I+IV+V	0.77 ± 0.26	0	247
	II+III+VI	0.27 ± 0.13	0	650

$N_\tau = N_\mu/\varepsilon_\mu \times \sigma_\tau/\sigma_\mu \times \sum_i (\epsilon_i \times BR_i)$ =number of oscillated events in case of $P(\nu_\mu \to \nu_\tau) = 1$.

Very good agreement between Data and Background Monte Carlo.



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

A new analysis scheme that unifies the selection of the 1 prong hadronic decays.

1) τ **daughter candidate tag** maximizing

$$\lambda_{\rm cand} = \mathcal{L}^{\tau}_{\rm cand}/\mathcal{L}^{\rm random}_{\rm cand}$$

2 γ events

π° candidate $\quad \mathcal{L}_{\pi^\circ} = [M_{\pi^\circ}, \theta_{\gamma\gamma}, E^{max}_{\gamma}/E_{vis}]$

ρ candidate $\quad \mathcal{L}_{\rho} = [\mathcal{L}_{\pi^\circ}, M_{\rho}, \theta_{\pi^-\pi^\circ}, E_{\pi^\circ}/E_{vis}]$

τ daughter candidate $\quad \mathcal{L}_{cand} = [\mathcal{L}_{\rho}, I_G, Y_{BJ}, \theta_{\rho H}]$

1 γ events:

ρ candidate $\quad \mathcal{L}_{\rho} = [M_{\rho}, \theta_{\pi^-\pi^\circ}, E_{\pi^\circ}/E_{vis}]$

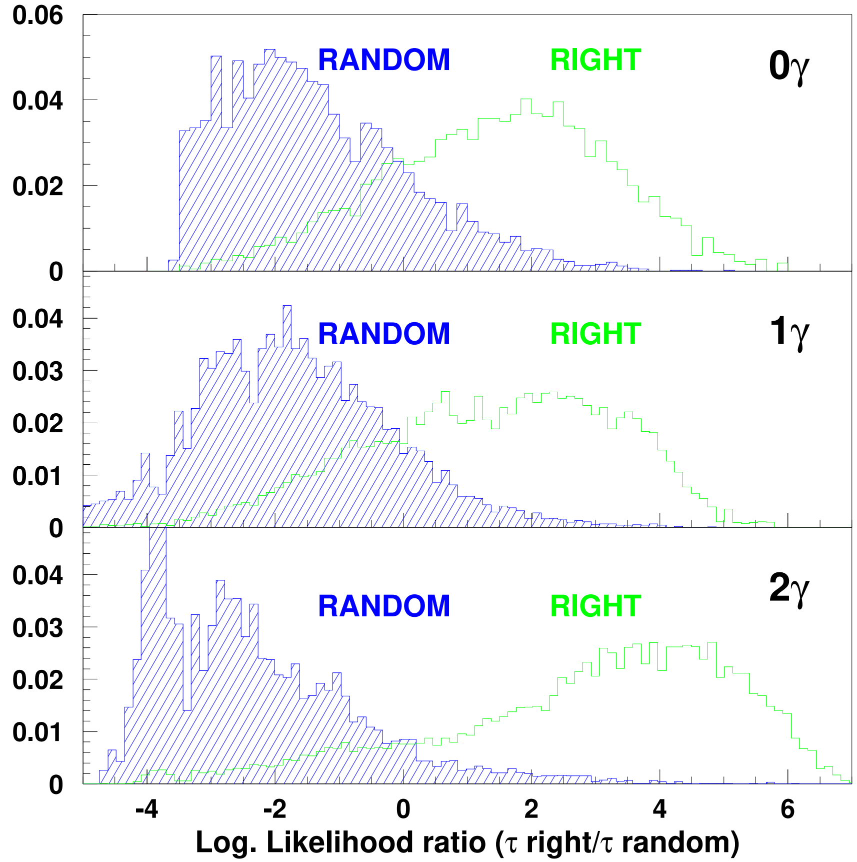
τ daughter candidate $\quad \mathcal{L}_{cand} = [\mathcal{L}_{\rho}, I_G, Y_{BJ}, \theta_{\rho H}]$

A cut on $\lambda_\rho = \mathcal{L}^{\tau}_{\rho}/\mathcal{L}^{\rm BKGND}_{\rho}$ is subsequently made for the 1γ and 2γ topologies.

0 γ events:

τ daughter candidate $\quad \mathcal{L}_{cand} = [I_G, Y_{BJ}, \theta_{\pi H}]$

$\mathcal{L}_{cand}$ distributions for the right and the random choices of the τ daughter in the τ MC sample.



$\tau \to h^-(+n\pi^0)\nu_\tau$ inclusive (continue)

2) Jet consistency: In the background events the choice of the candidate is mostly made inside the hadronic jet. It is essential to check the quality and structure of the remaining jet after the candidate selection.

3) Lepton Veto A three step procedure:

- No identified lepton at the primary vertex
- A most likely lepton candidate tag based on kinematical criteria.
- Tighter lepton veto criteria, based on ECAL, HCAL and μ chambers information, against the tagged lepton candidate.

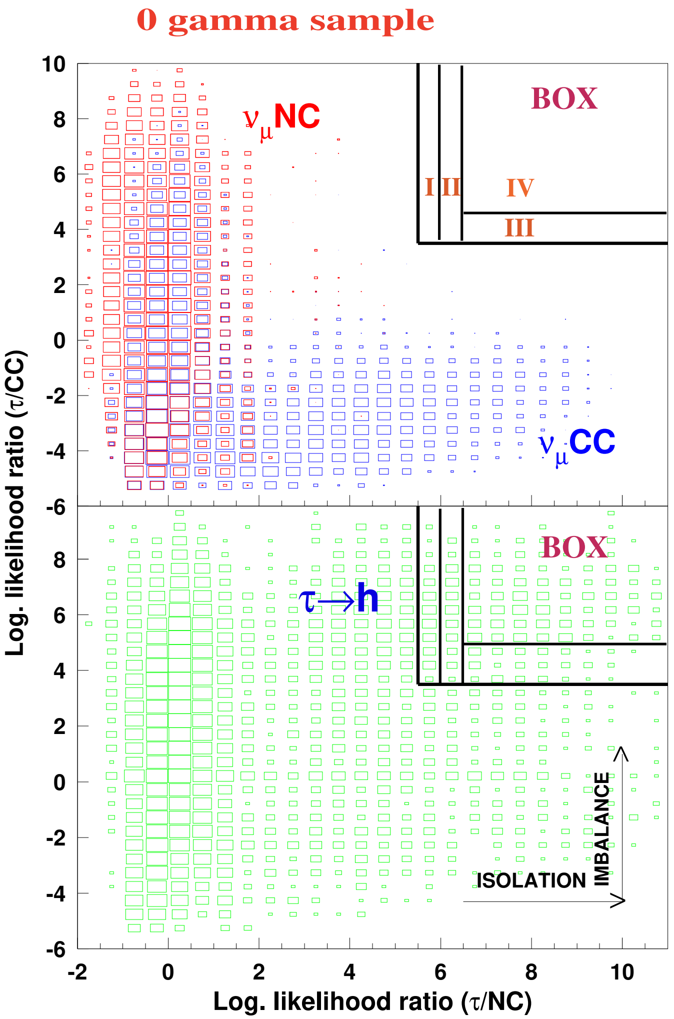
4) Final kinematical selection Two likelihood functions are built to separate signal from NC and CC events:

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

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

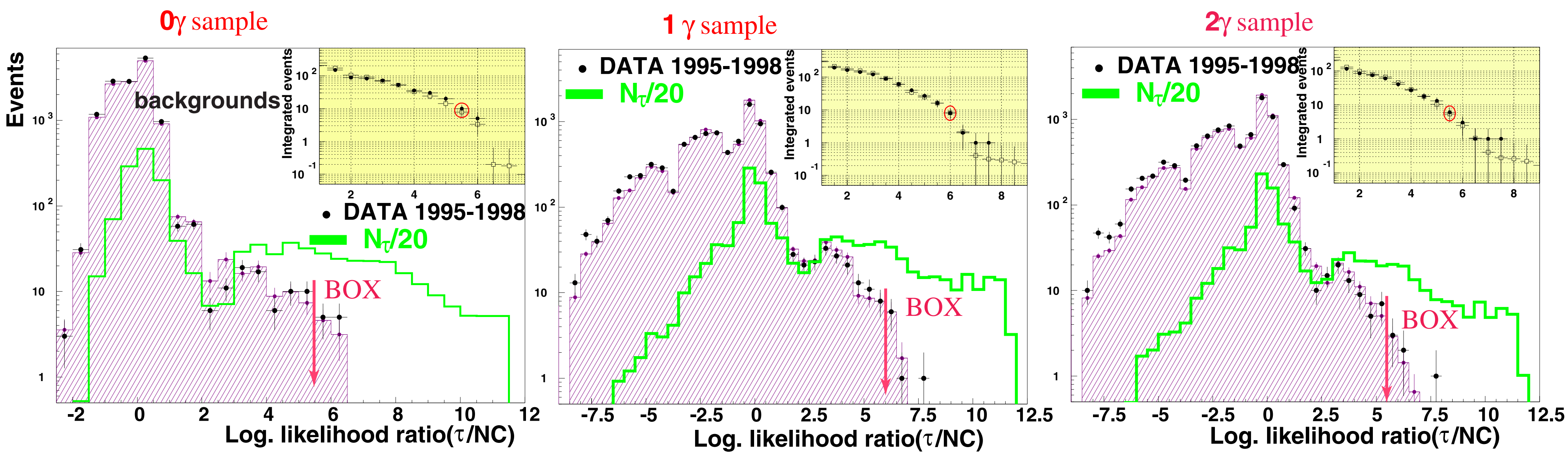
Again the event candidate selection is made in the plane defined by the 2 likelihood functions

$\tau \to h^-(+n\pi^0)\nu_\tau$ inclusive, final results

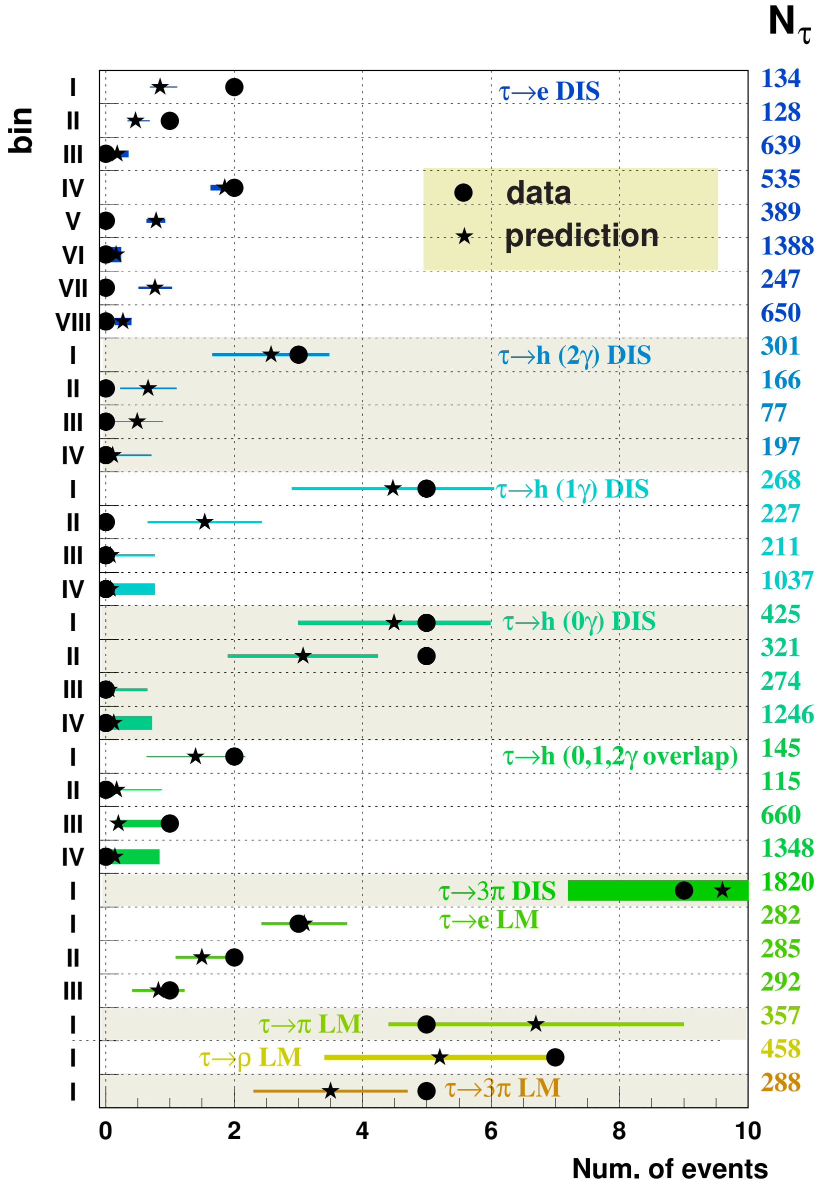


Analysis	Bin	Tot. bkg.	Data	N_τ
$\nu_\tau h(0\gamma)$	I	4.49 ± 1.50	5	425
$\nu_\tau h(0\gamma)$	II	3.07 ± 1.17	5	321
$\nu_\tau h(0\gamma)$	III	$0.05^{+0.60}_{-0.03}$	0	274
$\nu_\tau h(0\gamma)$	IV	$0.12^{+0.60}_{-0.05}$	0	1246
$\nu_\tau h(1\gamma)$	I	4.47 ± 1.58	5	268
$\nu_\tau h(1\gamma)$	II	1.54 ± 0.89	0	227
$\nu_\tau h(1\gamma)$	III	$0.07^{+0.70}_{-0.04}$	0	211
$\nu_\tau h(1\gamma)$	IV	$0.07^{+0.70}_{-0.04}$	0	1037
$\nu_\tau h(2\gamma)$	I	2.57 ± 0.91	3	301
$\nu_\tau h(2\gamma)$	II	0.66 ± 0.44	0	166
$\nu_\tau h(2\gamma)$	III	0.49 ± 0.40	0	77
$\nu_\tau h(2\gamma)$	IV	$0.11^{+0.06}_{-0.63}$	0	197
$\nu_\tau h(\mathrm{overlap})$	I	1.40 ± 0.77	2	145
$\nu_\tau h(\mathrm{overlap})$	II	$0.17^{+.70}_{-0.08}$	0	115
$\nu_\tau h(\mathrm{overlap})$	III	$0.20^{+0.70}_{-0.06}$	1	660
$\nu_\tau h(\mathrm{overlap})$	IV	$0.14^{+0.70}_{-0.06}$	0	1348

Data and MonteCarlo agreement: $\mathcal{L}_{NC}$ distributions



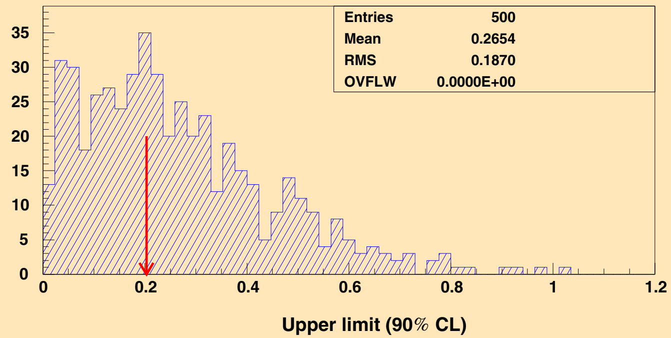
NOMAD Final results, no evidence for oscillation



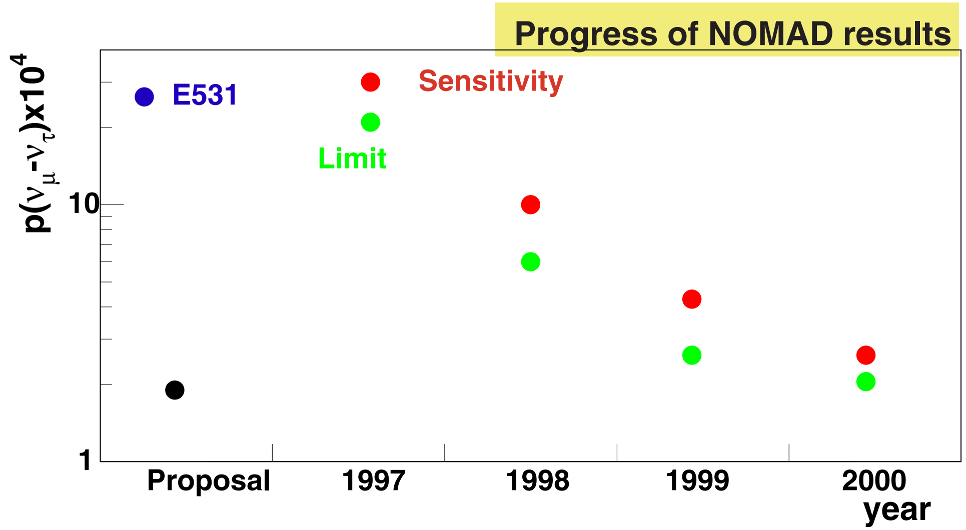
FINAL LIMIT ON P($\nu_\mu \to \nu_\tau$): $2.03 \cdot 10^{-4}$

FINAL SENSITIVITY ON P($\nu_\mu \to \nu_\tau$): $2.6 \cdot 10^{-4}$

Probability to obtain this limit (or smaller): 46%



55.2 ± 5.4 expected events, 58 found. Total N_τ = 14937



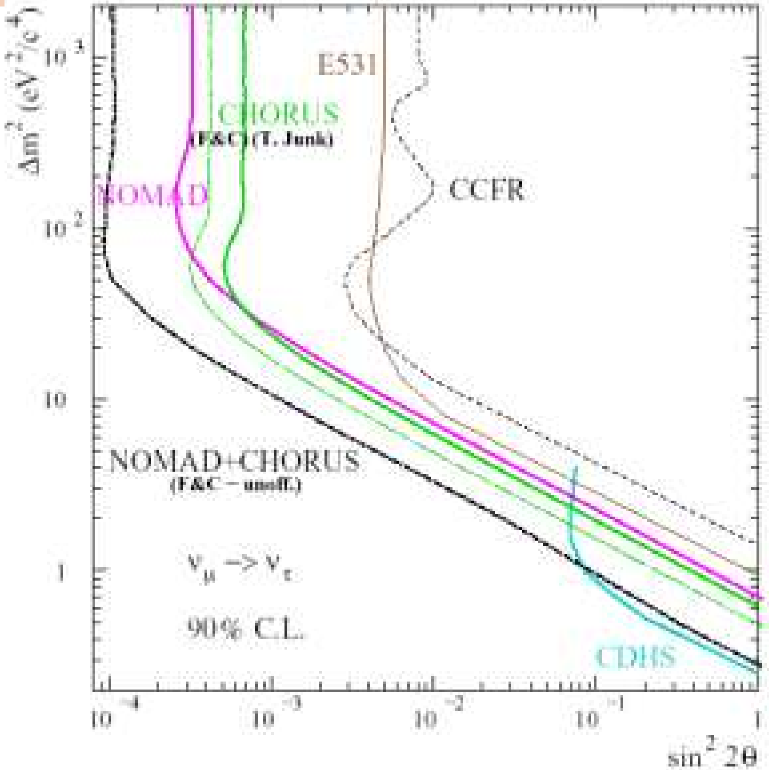
NOMAD as a ZERO background experiment

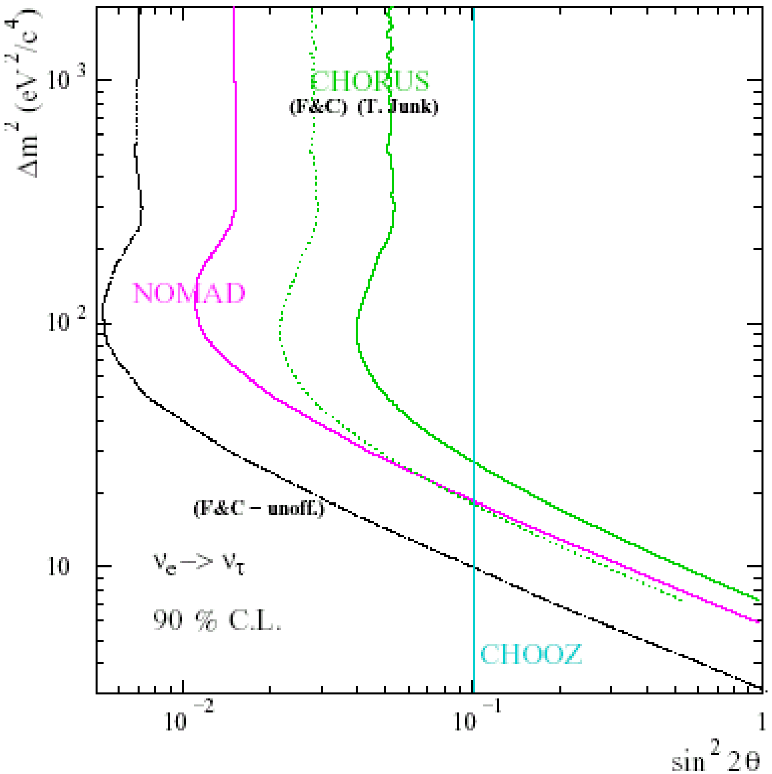
Most of the NOMAD sensitivity is in the bins with a background prediction close to zero:

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
$\nu_\tau h(\mathrm{overl.})$	DIS	III	$0.20^{+0.70}_{-0.06}$	660	1
$\nu_\tau h(\mathrm{overl.})$	DIS	IV	$0.14^{+0.70}_{-0.06}$	1348	0
			$\mathbf{1.29^{+1.60}_{-0.18}}$	**7570**	1

75% of the final sensitivity comes from the low background bins

Exclusion plots





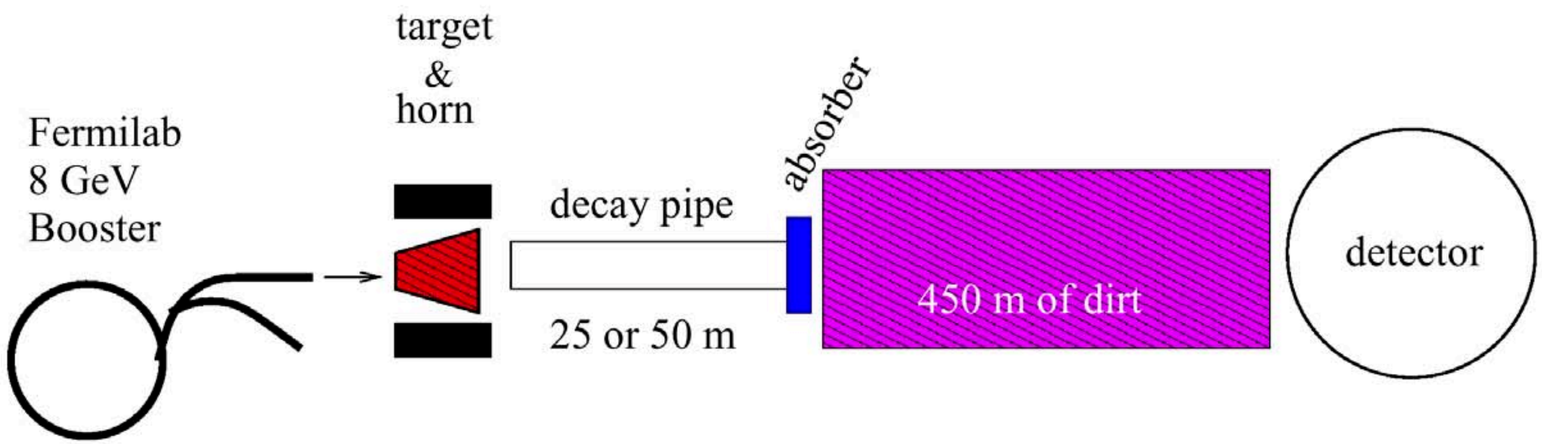
Combined result with F&C (*)

$L_{osc}(\nu_\mu \to \nu_\tau) = 0.5 \times 10^{-4}$
$S_{osc}(\nu_\mu \to \nu_\tau) = 1.7 \times 10^{-4}$
$P(\leq L_{osc}) = 15\%$

$L_{osc}(\nu_e \to \nu_\tau) = 0.4 \times 10^{-2}$
$S_{osc}(\nu_e \to \nu_\tau) = 0.9 \times 10^{-2}$
$P(\leq L_{osc}) = 25\%$

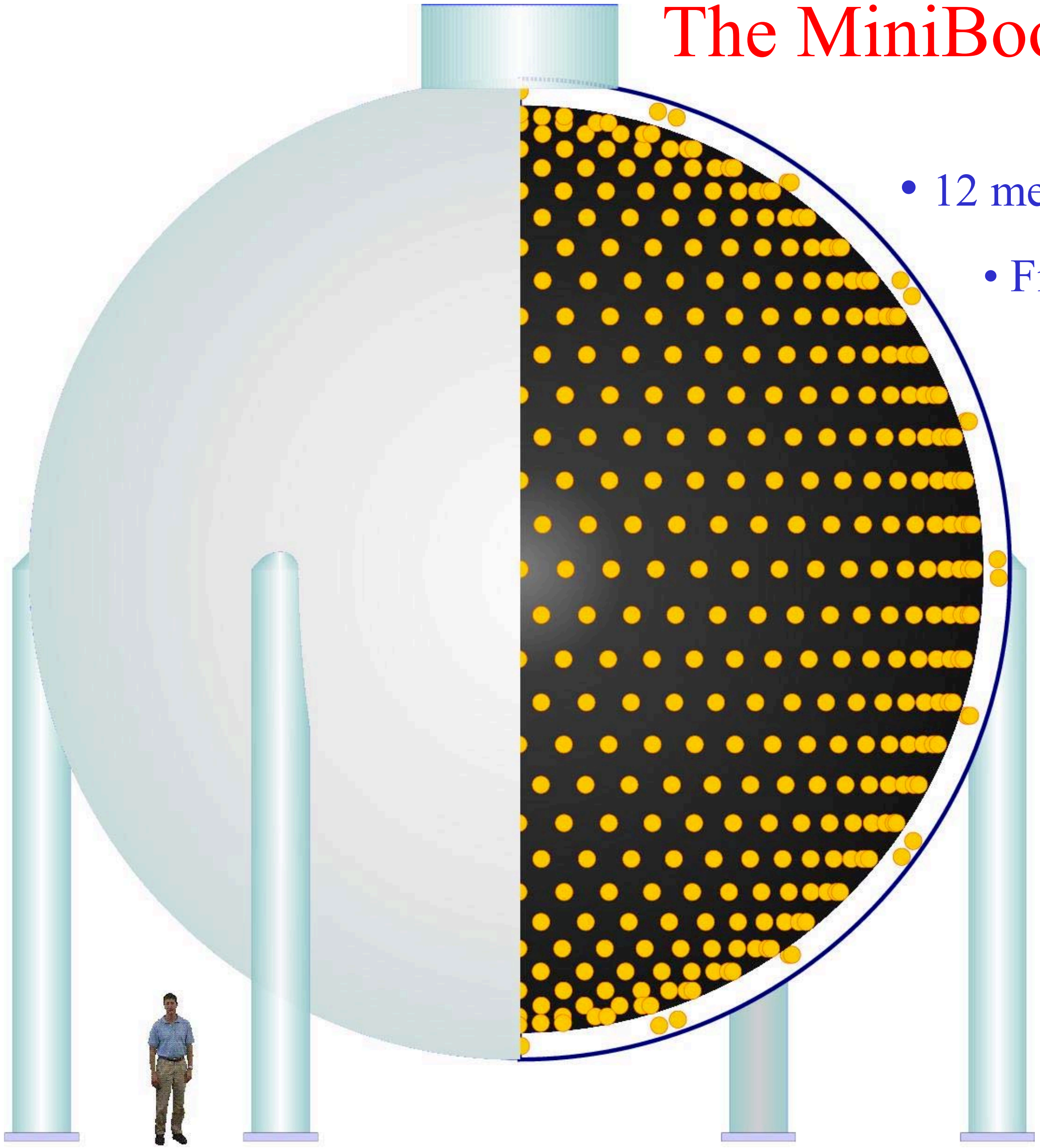
(*) by courtesy of R. Petti

MiniBooNE



The FNAL Booster
injects beam to the target
resulting mesons decay and
neutrinos traverse 450 m of dirt
to the oil-based Cerenkov detector

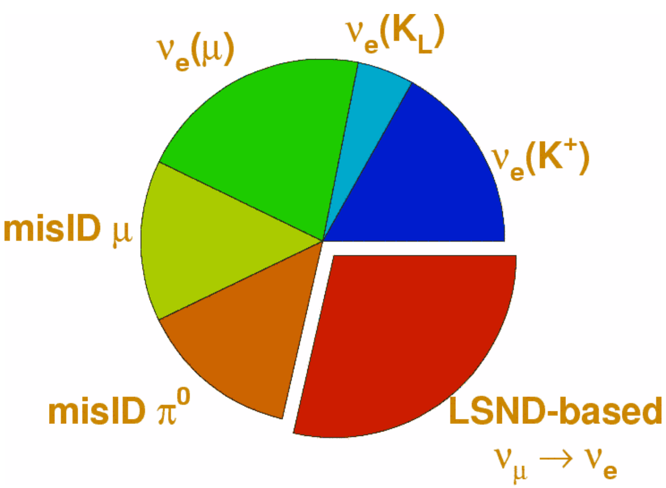
The MiniBooNE Detector



- 12 meter diameter sphere
  - Filled with 950,000 liters of undoped mineral oil
    - Light tight inner region with 1280 photomultiplier tubes
    - Outer veto region with 241 PMTs.

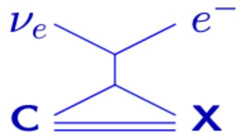
Neutrino interactions in oil produce:

- Prompt Čerenkov light
- Delayed scintillation light



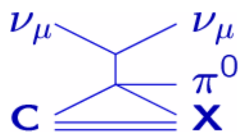
Approximate number of electron neutrino-like events expected in MiniBooNE with two years of running before cuts

Intrinsic ν_e background: 1,000 events

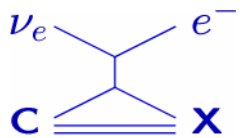


μ mis-ID background: 500 events

π^0 mis-ID background: 500 events



LSND-based $\nu_\mu \rightarrow \nu_e$: 1,000 events



MiniBooNE Sensitivity to LSND

With two years of running MiniBooNE should be able to completely include or exclude the entire LSND signal region.