Latest Results on Neutrino Oscillation from NOMAD

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for

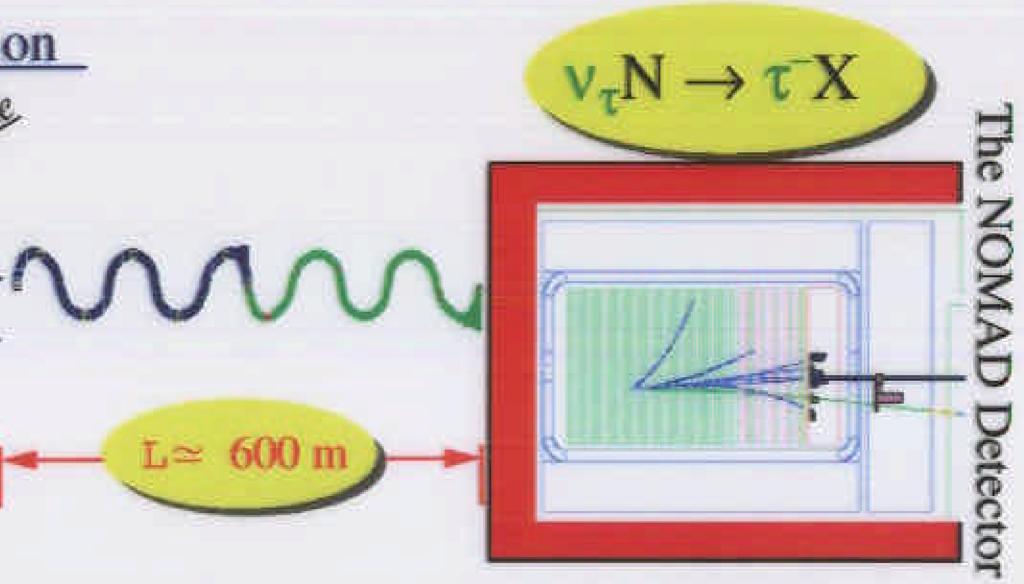
ν_μ NOMAD ν_τ

Neutrino Oscillation MAgnetic Detector

A ν_τ Appearance Experiment

The CERN Wide Band Beam

	Flux		CC interaction	
Flavour	<E>(GeV)	Abundance	<E>(GeV)	Abundance
ν_μ	23.5	1	43.8	1
$\bar{\nu}_\mu$	19.2	0.061	42.8	0.025
ν_e	37.1	0.0094	58.3	0.015
$\bar{\nu}_e$	31.3	0.0025	54.5	0.016
ν_τ	< 1 interactions in 4 years			



$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$

Range of Δm^2 sensitivity defined by :

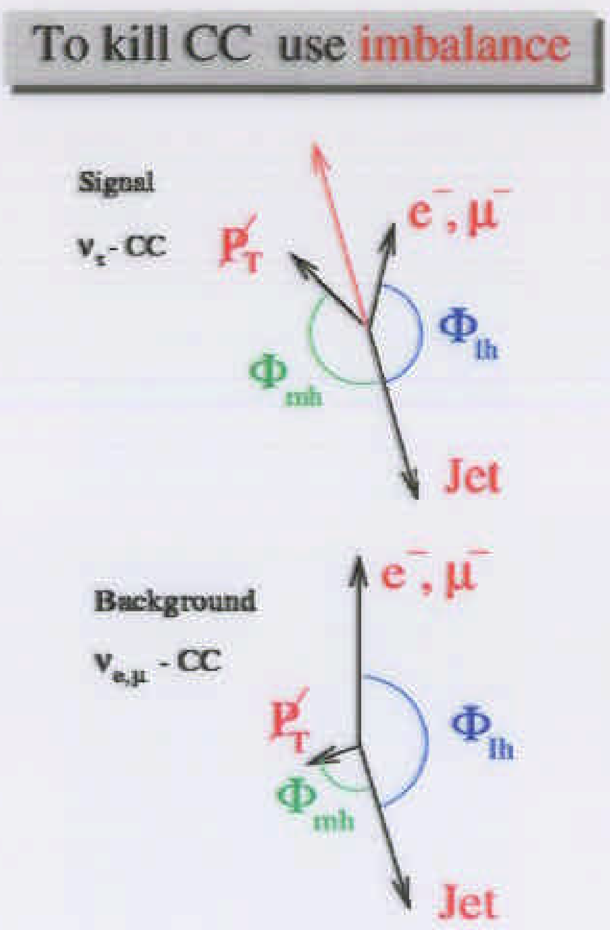
$\langle L\rangle/\langle E\rangle \simeq 2 \times 10^{-2}$ Km/Gev

$\Rightarrow 1\ eV^2 \leq \Delta m^2$

Which τ *Decay Products*

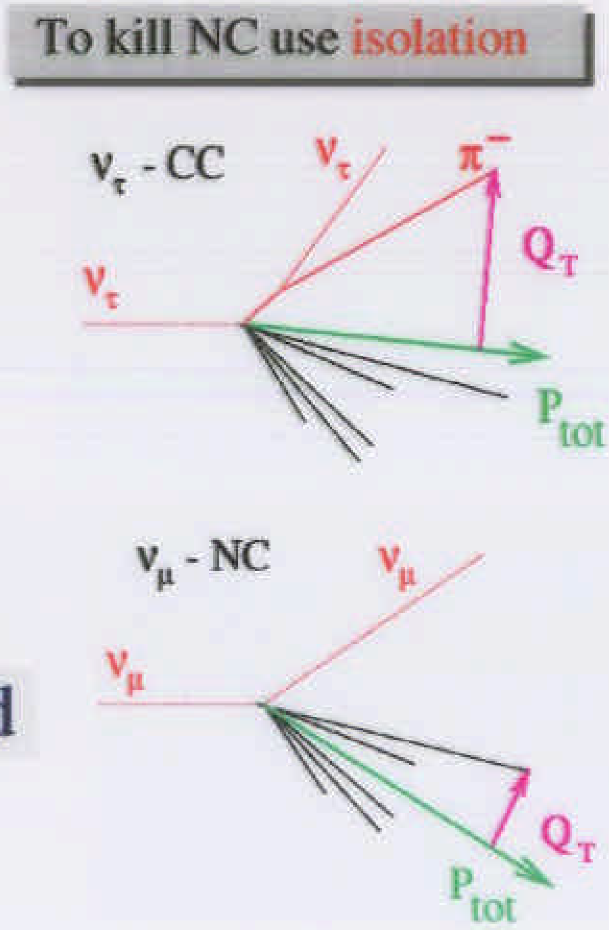
$$\tau^- \rightarrow \begin{cases} e^-\bar{\nu}_e\nu_\tau & 17.8\% \\ h^-(n\pi^o)\nu_\tau & 49.5\% \\ \pi^-\pi^-\pi^+(n\pi^o)\nu_\tau & \underline{15.2\%} \\ & 82.5\% \end{cases}$$

The Basics of Kinematical Criteria



Signal

Background



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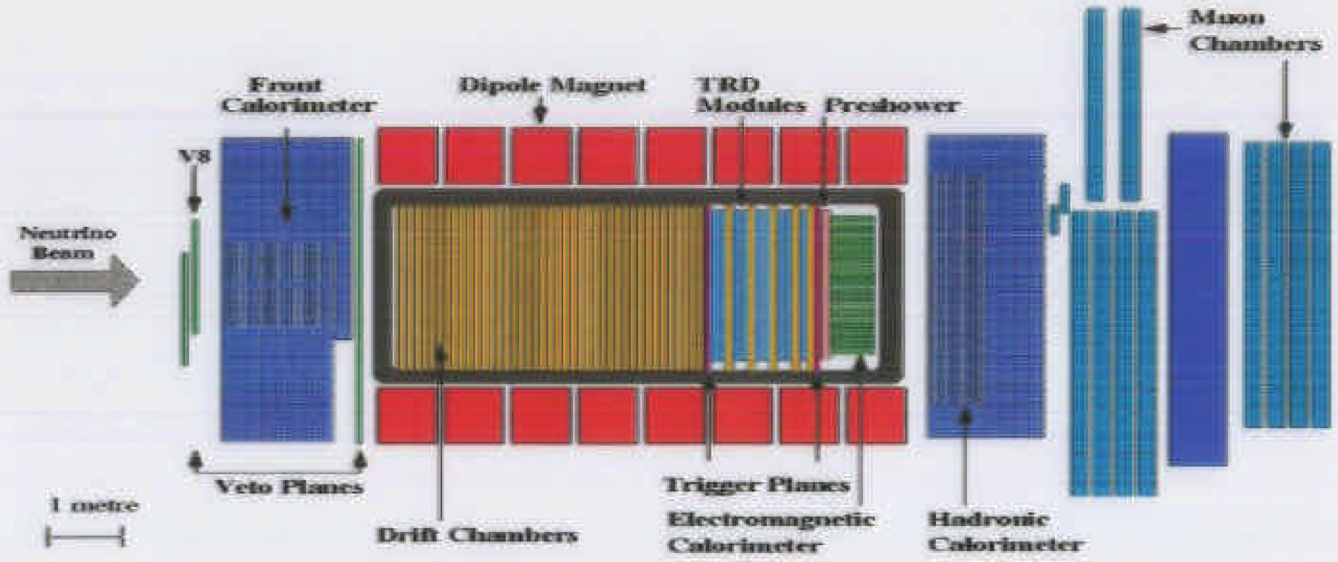
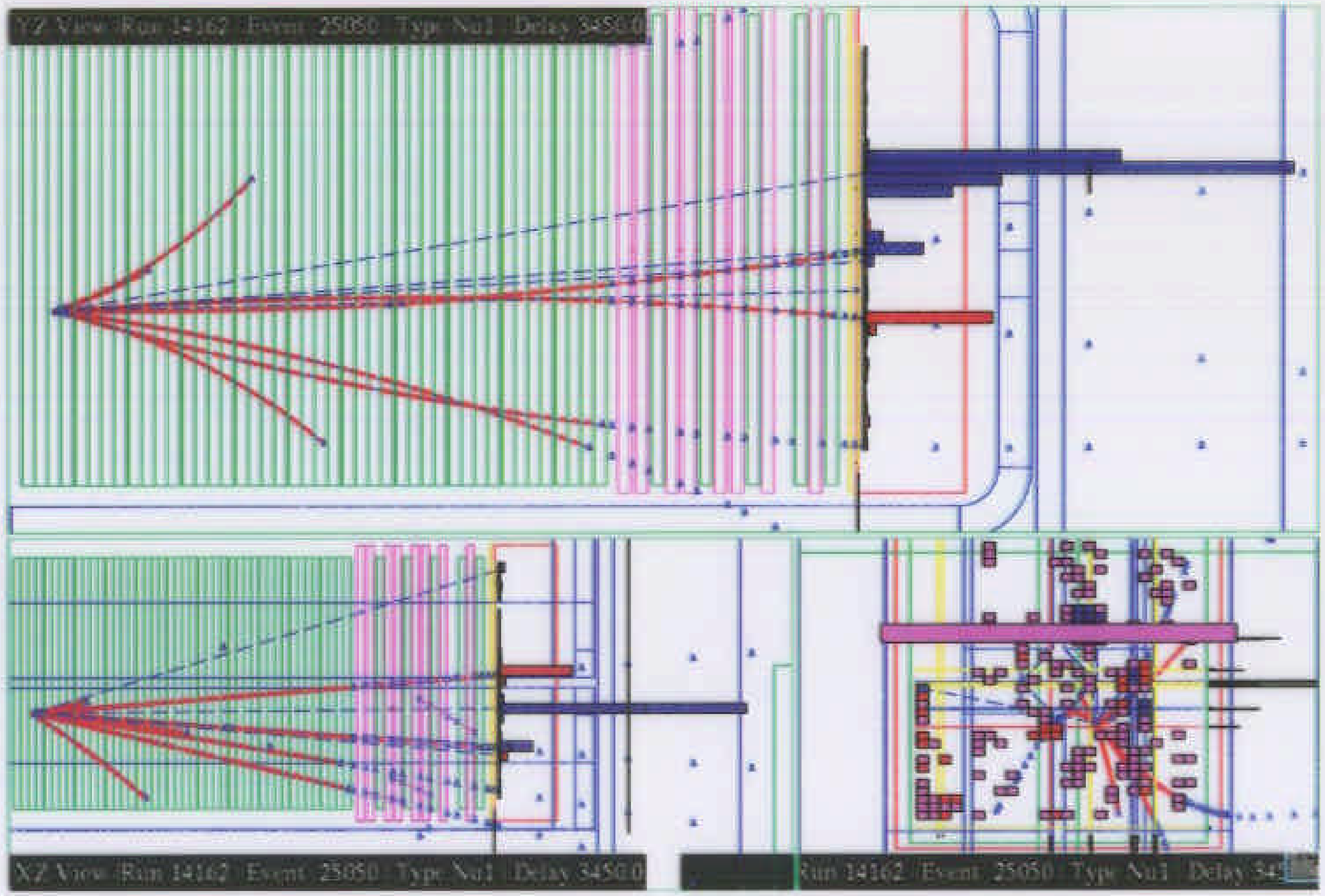
NOMAD Detector

1.35 M ν_μ CC interactions



- Target mass : 2.7 tons
- Momentum measurement : Drift Chambers $\sigma(p) \sim 3.5\ \%$ $p < 10$ GeV
- Energy measurement : Ecal ($\sigma(E)/E = 3.2\%/\sqrt{E(GeV)} \oplus 1\%$) Hcal
- $\mu^{\pm}$ id : μ chambers ($\varepsilon \sim 97\%$ @ $p > 5$ GeV) + calorimetric measurements
- $e^{\pm}$ id : TRD ($e/\pi = \mathcal{O}(10^{-3})$ @ ele. Eff. $\geq 97\%$) + momentum/energy consistency

DATA EVENT - $\tau^- \to h^- + \gamma_s$



Analysis Strategy

$SIGNAL_{Nomad} \equiv$ statistical excess on predicted background

Use Blind Analysis *to obtain an*

Unbiased background prediction

Blind Analysis : the kinematic region most sensitive to the signal in each decay channel is not analysed until all analysis has been defined and background prediction is validated on data control samples.

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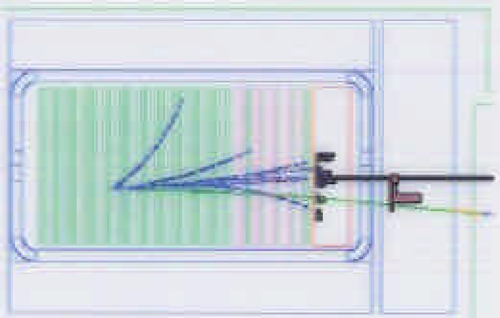
Control Samples

Validation of Background prediction is done by checking :

- **τ^+ analysis** given the beam composition no signal is expected
- **τ^- analysis** outside the "box"

If background prediction are proved to be correct the most sensitive analysis in the channel is chosen and the data inside the BOX are analysed.

$\mathscr{L}$ikelihood Method

1. 

Global Kinematic Internal τ decay structure (for hadronic channels)

$$= \overbrace{(X_1, \ldots, X_n)}^{\text{Global Kinematic}} + \overbrace{(Y_1, \ldots, Y_n)}^{\text{Internal }\tau\text{ decay structure}}$$

2. As a function of (X_i, Y_j) define **Probability Density Functions** and build **probability to be signal ($\mathscr{L}_{sig}$) or background ($\mathscr{L}_{bkg}$)** ➡ $\ln(\lambda) = \ln \dfrac{\mathscr{L}_{sign}}{\mathscr{L}_{bkg}}$

3. Best treatment woud be → fit tail $\ln(\lambda)$ but too few events expected.
   • Tail of $\ln(\lambda)$ → **binned** and each bin is treated as an **independent measurement**.

4. Results from various bins (and variuos decay channels) are combined using the **Unified Approach** (Ref.: Feldman & Cousins Phys. Rev. D57 (1998) 3873).

Background Prediction Evaluation

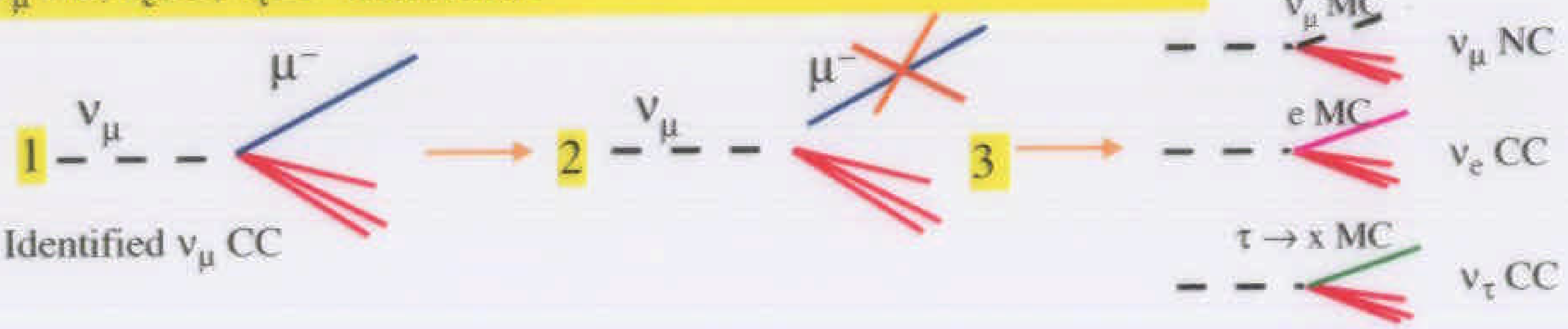
Large kinematical suppression and use of correlation between kinematical variable require the knowledge of background down to a level of $\mathcal{O}(10^{-5})$

it is NOT possible to rely entirely on MC
background predictions are obtained using :

→ **MC + Data Simulator**

Data Simulator

Use identified ν_μ CC in Data and MC to create MCS and DS for ν_μ NC, ν_eCC, ν_τCC interaction :



DATA ⟶ DS

MC ⟶ MCS

Analysis is carried out on 3 samples : MC, DS, MCS ⇒

$$\varepsilon \stackrel{def}{\equiv} \varepsilon(MC) \times \frac{\varepsilon(DS)}{\varepsilon(MCS)}$$

- ✔ Method allows to correct for jet structure, instrumental effect, tail due to fermi motion, nuclear reinteractions..
- ✔ Not applicable to ν_μ CC ⇒ $\tau^- \to \mu^- \nu_\mu \nu_\tau$ is not usable

The two most powerful decay channels

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

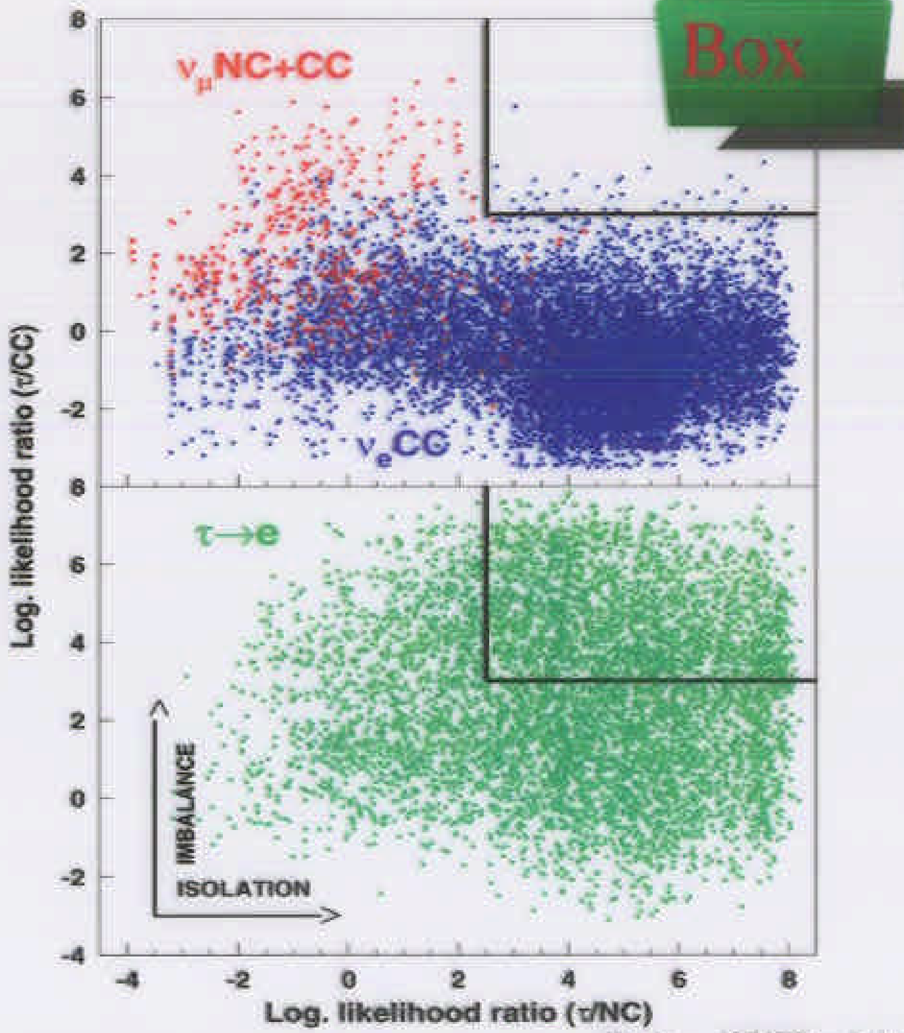
$$\tau \rightarrow h^- (+n\, \pi^o) \nu_\tau$$

$\tau^- \to e^- \overline{\nu}_e \nu_\tau$ Analysis

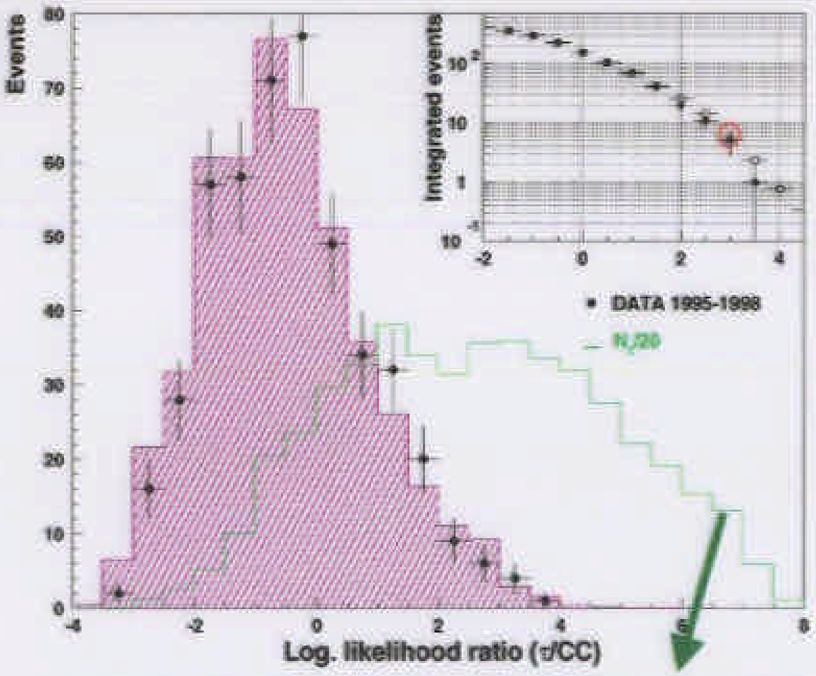
ν_e Charged Currents $\mathcal{O}(10^{+4})$ ⟵ Background ⟶ Neutral Currents $\mathcal{O}(10^{+5})$

ν_e Charged Currents	Neutral Currents
Candidate = Real primary electron	Candidate = e^- { γ conversions; π^o decays }
	Tight electron identification criteria +
Likelihood function against **CC**	Likelihood function against **NC**
$\mathcal{L}^{cc} \stackrel{def}{\equiv} [[\rho_h,\rho_l,Q_{lep}],p_T^m,M_T,E_{vis}]$	$\mathcal{L}^{nc} \stackrel{def}{\equiv} [[[\theta_{\nu T},\Theta_{\nu H}]\theta_{min},Q_T,]M_T,E_e]$
Most of the rejection power comes from imbalance (transverse plane kinematics)	Most of the rejection power comes from isolation (longitudial plane kinematics)

$\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$ *Final results*



Data are consistent with predicted background ⇒ No oscillation seen



N_τ : number of τ if P osc. = 1

$\tau \rightarrow h^- (+n\, \pi^o) \nu_\tau$ *Analysis*

A new analysis for 1 prong

Candidate Choice

Must choose the **correct** combination among many **random** combinations ⇒ **maximise** :

$$\lambda_{can} = \frac{\mathcal{L}_{can}^{\tau}}{\mathcal{L}_{can}^{random}}$$

Which $\mathcal{L}_{can}$?

3 different topologies :

- $\tau \rightarrow$ single π — 0γ
- $\tau \rightarrow \pi + 1$ e.m cluster — 1γ
- $\tau \rightarrow \pi + 2$ e.m. cluster — 2γ

(1γ, 2γ) } $\rho \rightarrow \pi^- \pi^o$

Same global event kinematic
Different internal decay structure

0γ $\mathcal{L}_{can} \overset{def}{\equiv} [\, I_G, Y_{Bj}, \Theta_{\pi h}]$

1γ $\mathcal{L}_{can} \overset{def}{\equiv} [M_\rho, \theta_{\pi-\pi^o}, E_{\pi^o}/E_{vis}], I_G, Y_{Bj}, \Theta_{\pi h}]$

2γ $\mathcal{L}_{can} \overset{def}{\equiv} [[[M_{\pi^o}, \theta_{\gamma\gamma}, E_{\gamma max}/E_{vis}], M_\rho, \theta_{\pi-\pi^o}, E_{\pi^o}/E_{vis}], I_G, Y_{Bj}, \Theta_{\pi h}]$

$\tau \rightarrow h^{-} (+n\,\pi^{o})\,\nu_{\tau}$ *Analysis*

ν_{μ}, ν_{e} Charged Currents $\mathcal{O}(10^{+6})$ ⟵ Background ⟶ Neutral Currents $\mathcal{O}(10^{+5})$

Primary lepton unidentified

Kinematical criteria are used to tag the most likey lepton + particle id

+

Likelihood function against **CC**

$$\mathcal{L}^{cc} \stackrel{def}{\equiv} [[I_g, p_T^{lep}/p_T^{m}, \theta_{\nu l}], p_T^{m}, M_T, E_{vis}]$$

Most of the rejection power comes from imbalance (transverse plane kinematics)

Candidate inside the jet

Check jet structure after candidate selection

+

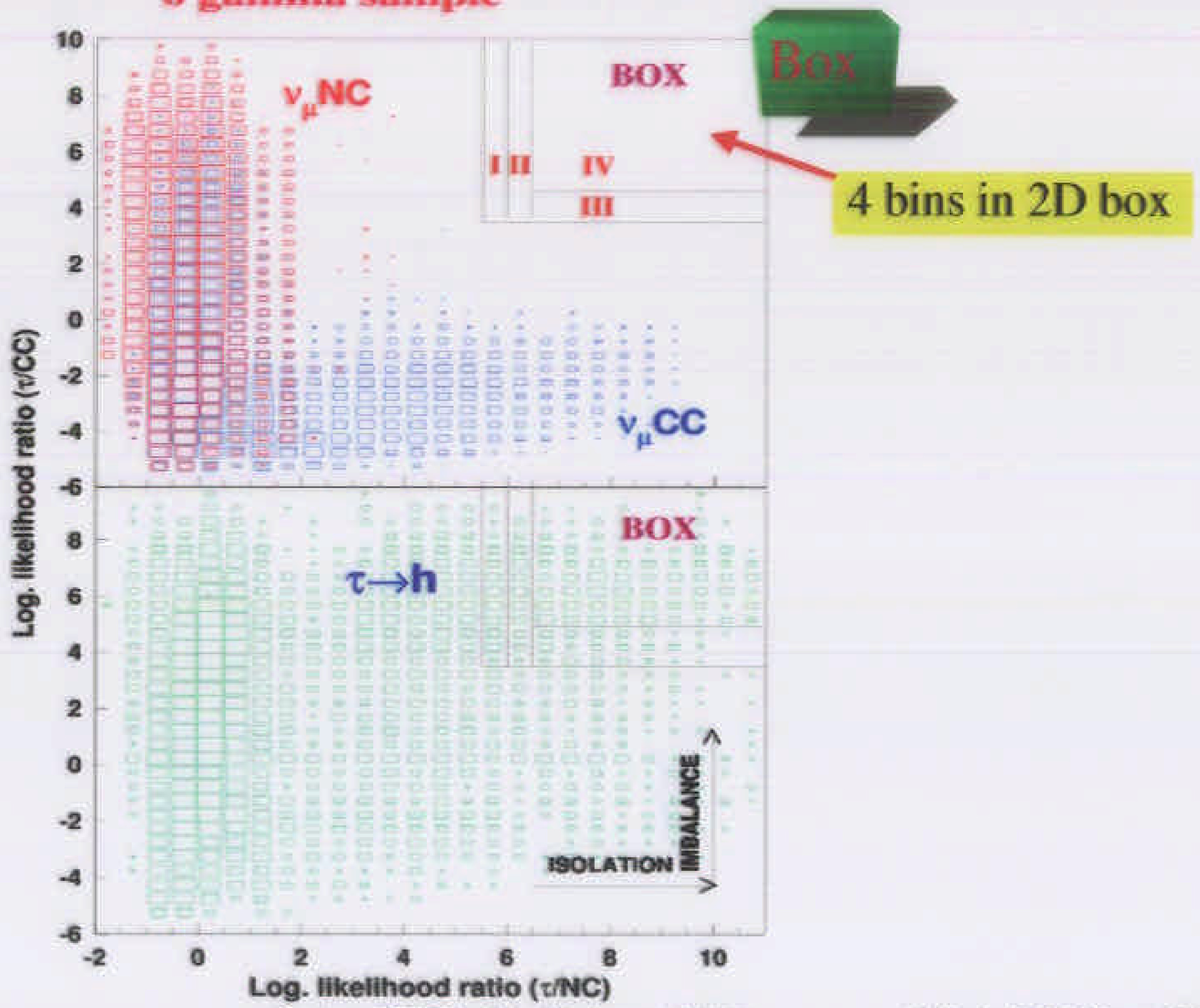
Likelihood function against **NC**

$$\mathcal{L}^{nc} \stackrel{def}{\equiv} [[[\theta_{\nu T}, \Theta_{\nu H}]\theta_{min}, Q_T,]p_T^{m}, p_T^{H}]$$

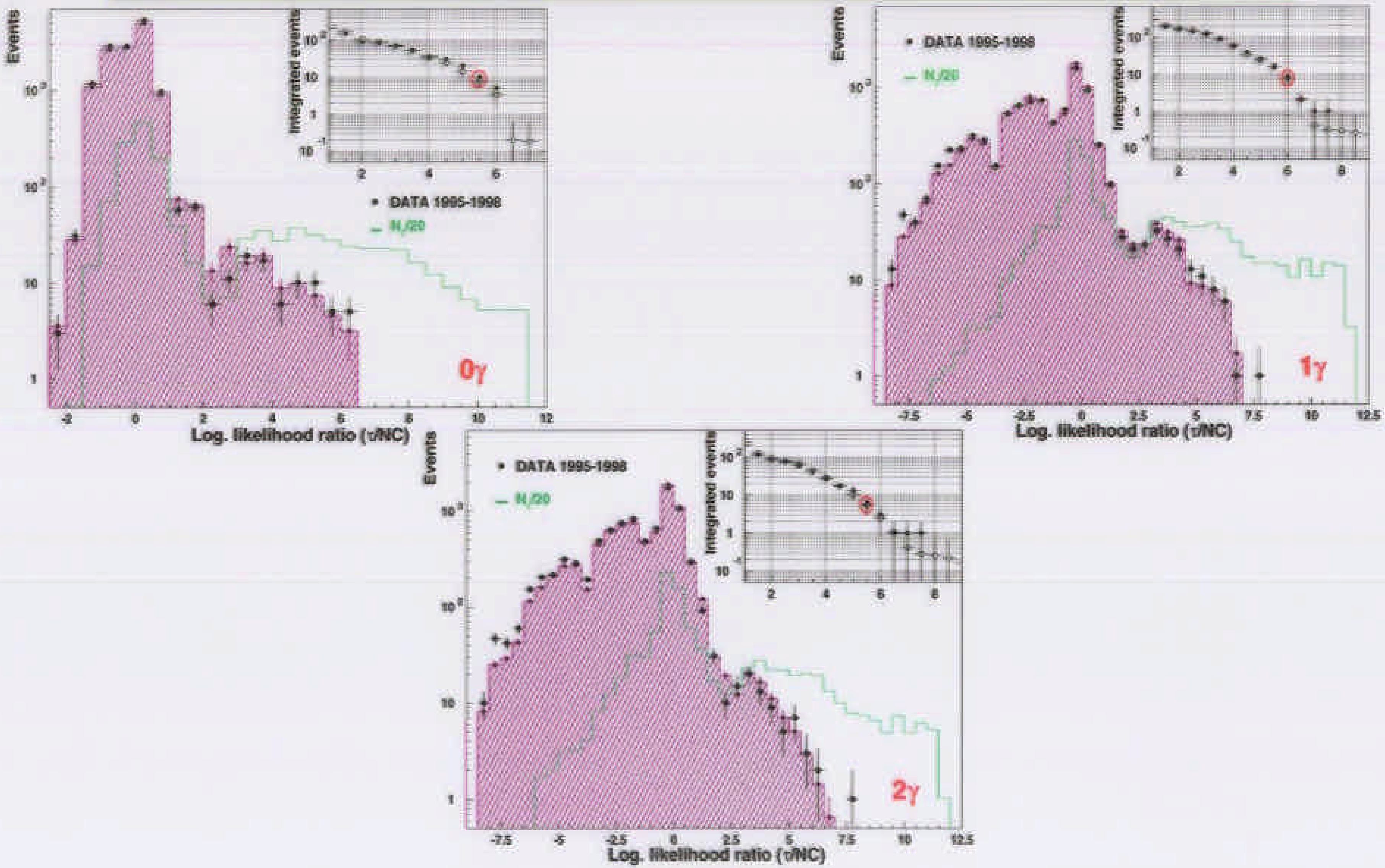
Most of the rejection power comes from isolation (longitudial plane kinematics)

$\tau \rightarrow h^- (+n\,\pi^o)\,\nu_\tau$ *Results*

0 gamma sample



Data is consistent with predicted background ⇒ No oscillation seen



NOMAD Final Results

Data in all bins are consistent with expected background.

Limit on $P(\nu_\mu \rightarrow \nu_\tau) = 2.0 \times 10^{-4}$
Sensitivity on $P(\nu_\mu \rightarrow \nu_\tau) = 2.6 \times 10^{-4}$
P(to have this limit or smaller) = 46%

Proposal Sensitivity = **1.9** $\times 10^{-4}$

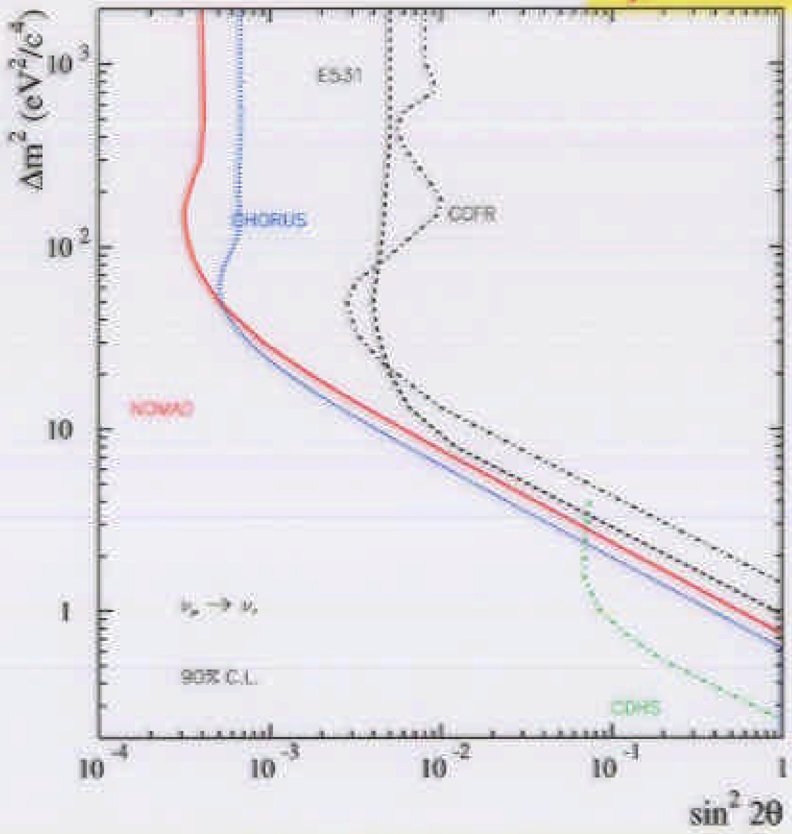
Tot. exp. Background 55.2 ± 5.4
Tot. events found 58
N_τ(τ for Posc = 1) 14937

75% of the sensitivity comes from SMALL background bins

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
$\nu_\tau h(1-2\gamma)$	DIS	III	$0.20^{+0.70}_{-0.06}$	680	1
$\nu_\tau h(0-1\gamma)$	DIS	IV	$0.14^{+0.70}_{-0.05}$	1348	0
			$1.29^{+1.60}_{-0.18}$	7570	1

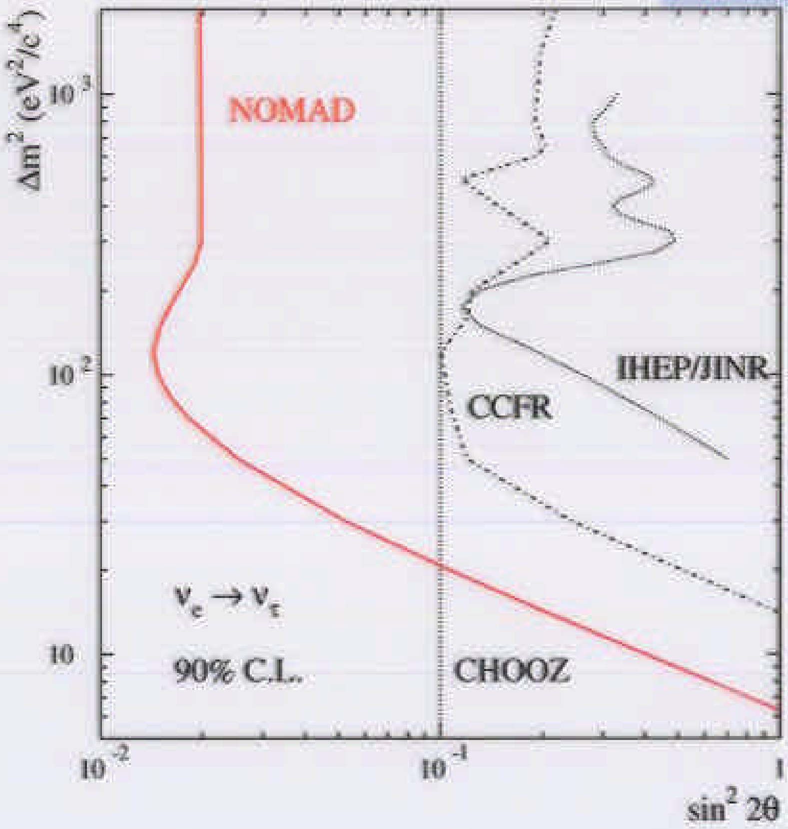
NOMAD Exclusion Plots

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



Limit on $P(\nu_\mu \rightarrow \nu_\tau) = 2.03 \times 10^{-4}$
Sensitivity on $P(\nu_\mu \rightarrow \nu_\tau) = 2.6 \times 10^{-4}$
P(to have this limit or smaller) = 46%

$\nu_e \rightarrow \nu_\tau$



Limit on $P(\nu_e \rightarrow \nu_\tau) = 1.0 \times 10^{-2}$
Sensitivity on $P(\nu_e \rightarrow \nu_\tau) = 1.3 \times 10^{-2}$
P(to have this limit or smaller) = 48%