Recent Results from the short baseline neutrino oscillation experiments at CERN

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Motivation

ν contribution to Hot Dark Matter?

$\Rightarrow$ mass range of interest

$1 < m_\nu < 10$ eV

Solar ν MSW interpretation

& mass hierarchy hypothesis

$\Rightarrow 1 < m_{\nu_\mu} < 10$ meV

$1 < m_{\nu_\tau} < 10$ eV

$\Downarrow$

$1 < \Delta m^2_{\nu_\mu \nu_\tau} < 100$ eV^2

Neutrino oscillations

Necessary conditions:

- massive neutrinos
- mixing (mass eigenstates $\neq$ flavour eigenstates)

For 2 flavours mixing: $P_{\nu_\alpha \to \nu_\beta}(L) = \sin^2(2\theta)\sin^2(\pi\frac{L}{\lambda})$

where $\lambda(\mathrm{km}) = 2.48\frac{E(\mathrm{GeV})}{\Delta m^2(\mathrm{eV}^2)}$

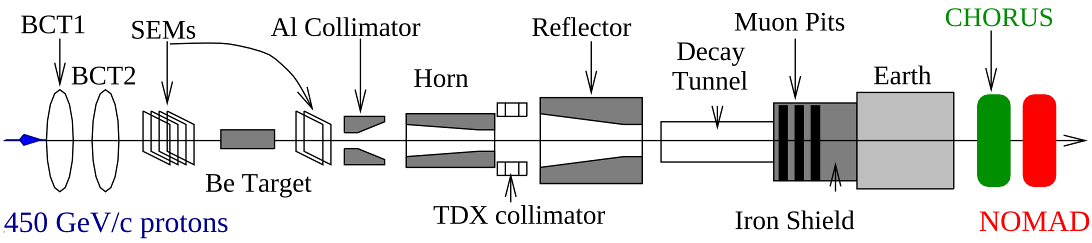
$\Downarrow$

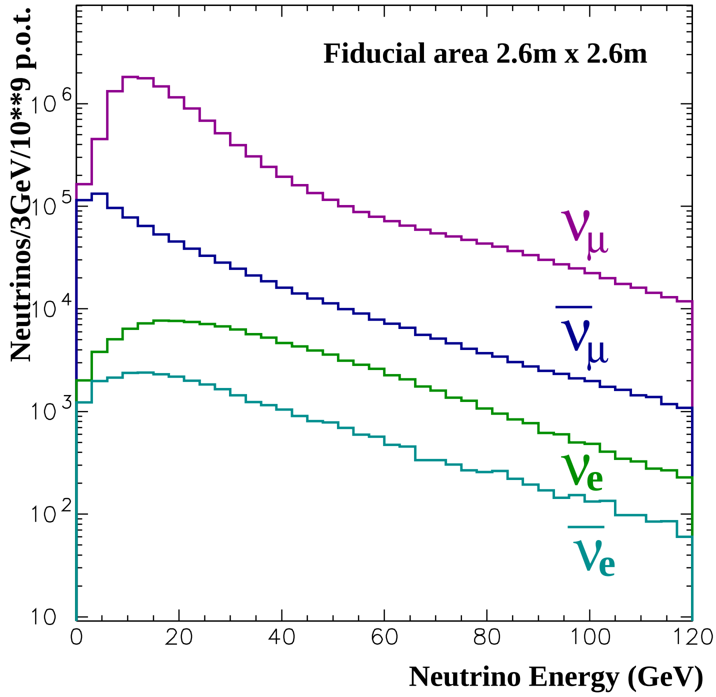
Short baseline ($\langle L \rangle$ $\approx$1 km) accelerator experiments ($\langle E_{\nu_\mu} \rangle \approx 25$ GeV) are sensitive to $\nu_\mu \to \nu_\tau$ oscillations in the range $1 < \Delta m^2_{\nu_\mu \nu_\tau} < 100$ eV^2

$\Downarrow$

CHORUS   NOMAD (Neutrino Oscillation MAgnetic Detector)

The CERN Neutrino Beam





	Flux		CC interactions	
Neutrino	$\langle E_\nu \rangle [GeV]$	rel. abund.	$\langle E_\nu \rangle [GeV]$	rel. abund.
ν_μ	23.5	1.0	41.5	1.0
$\overline{\nu}_\mu$	22.7	0.054	51.5	0.027
ν_e	36.9	0.0086	55.6	0.0134
$\overline{\nu}_e$	31.3	0.0026	52.1	0.0018
ν_τ	~ 35	$\simeq 5 \times 10^{-6}$		

The signal

- $\nu_\mu \to \nu_\tau$ oscillation $\Leftrightarrow$ appearance of ν_τ in a ν_μ beam
- ν_τ identified via its charged current (CC) interaction

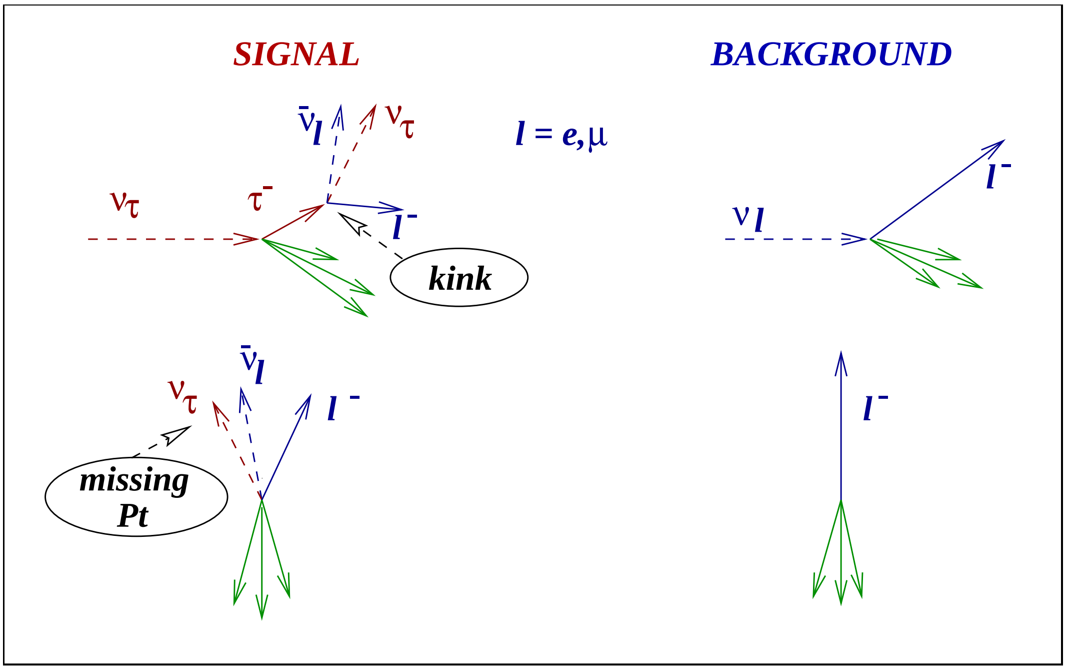
$$\nu_\tau \mathcal{N} \to \tau^- X$$

$\Rightarrow$ τ appearance

- τ identified through its decay properties:
  - lifetime $\approx$ 0.3 ps $\Rightarrow$ secondary vertex
  - mass $\approx$ 1.8 GeV/c^2 $\Rightarrow$ high $P_\perp$ decay products
  - neutrino(s) in the final state $\Rightarrow$ missing $P_\perp$

τ decay modes	BR
$\tau^- \to \mu^- \nu_\tau \overline{\nu_\mu}$	17%
$\tau^- \to e^- \nu_\tau \overline{\nu_e}$	18%
$\tau^- \to h^- (n\pi^0) \nu_\tau$	50%
$\tau^- \to h^- h^+ h^- (n\pi^0) \nu_\tau$	15%

τ identification



CHORUS	NOMAD
τ lifetime	τ mass & final neutrino(s)
$\Downarrow$	$\Downarrow$
kink, secondary vertex	high $P_\perp$ and missing $P_\perp$
$\Downarrow$	$\Downarrow$
nuclear emulsions	tracking & calorimetry
$\Downarrow$	$\Downarrow$
unambiguous signal	statistical excess
0 background	background subtraction

CHORUS

detector

emulsion scanning

efficiency

1μ analysis

0μ analysis

results

NOMAD

Neutrino Oscillation MAgnetic Detector

detector

kinematics

data simulator

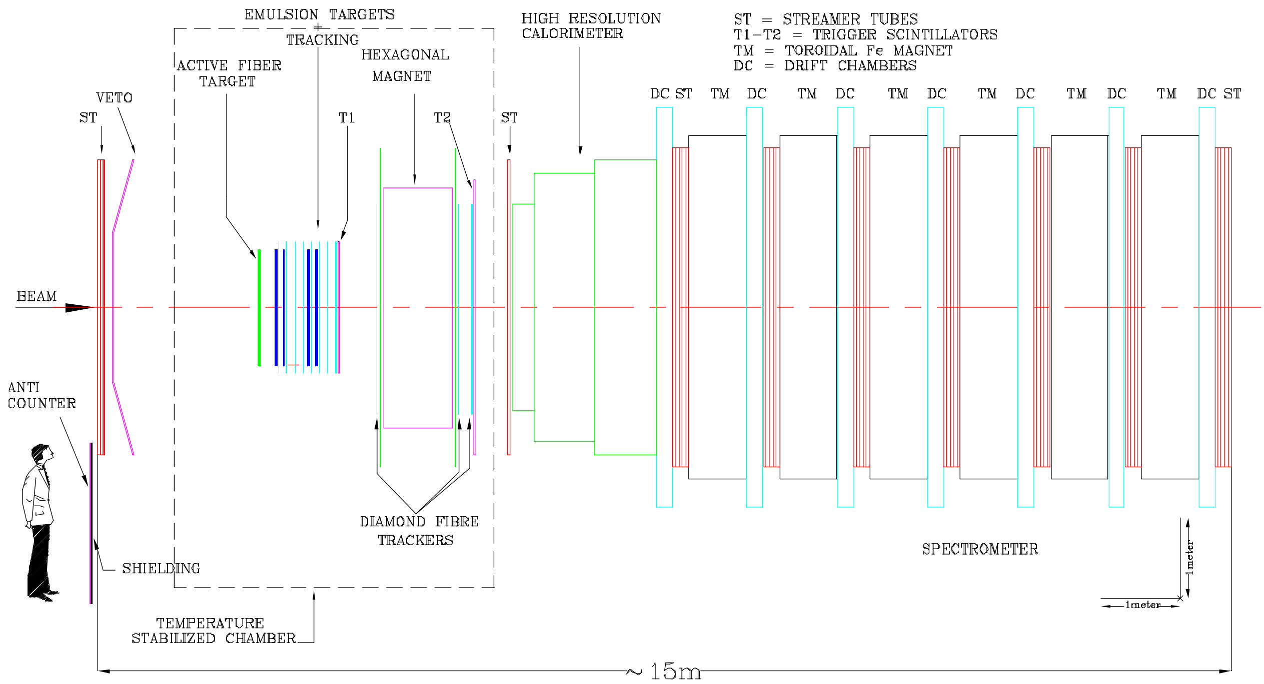
electron channel

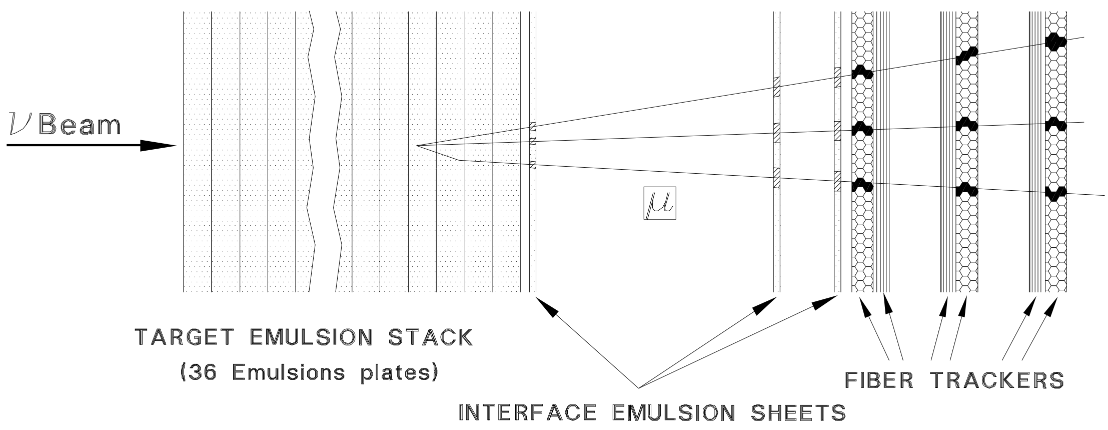
π^- channel

3π channel

results

detector


EMULSION TARGETS
TRACKING
ACTIVE FIBER TARGET
HEXAGONAL MAGNET
HIGH RESOLUTION CALORIMETER
ST = STREAMER TUBES
T1−T2 = TRIGGER SCINTILLATORS
TM = TOROIDAL Fe MAGNET
DC = DRIFT CHAMBERS
VETO
ST
T1
T2
ST
DC ST TM DC TM DC TM DC TM DC TM DC TM DC ST
BEAM
ANTI COUNTER
DIAMOND FIBRE TRACKERS
SHIELDING
SPECTROMETER
TEMPERATURE STABILIZED CHAMBER
1meter
1meter
~ 15m

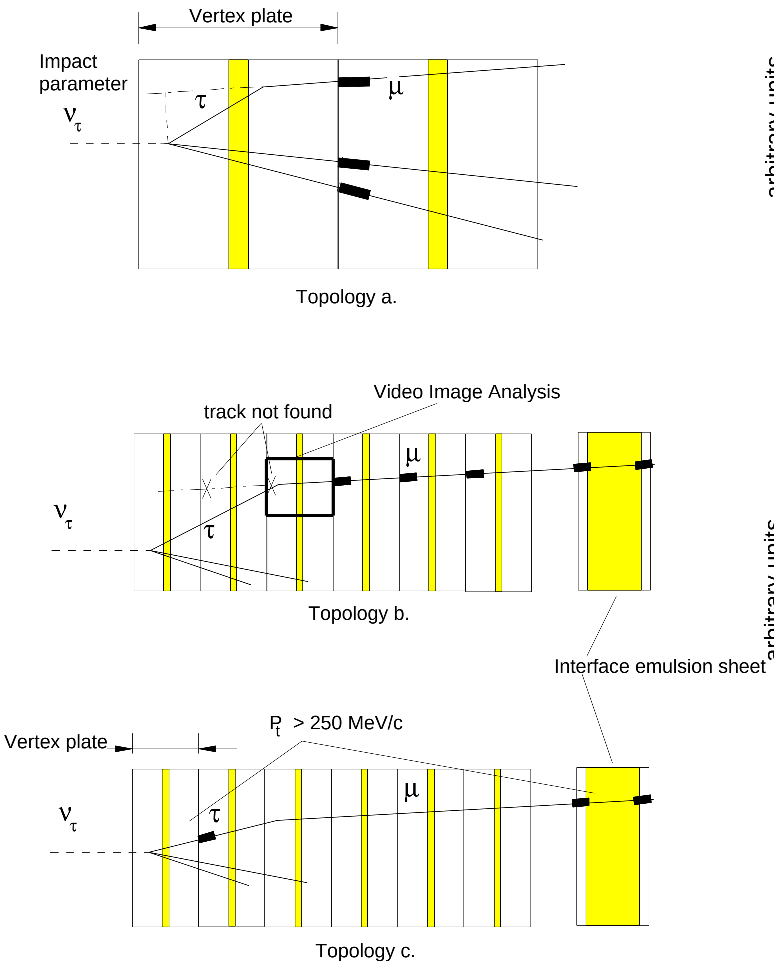

ν Beam
μ
TARGET EMULSION STACK
(36 Emulsions plates)
INTERFACE EMULSION SHEETS
FIBER TRACKERS

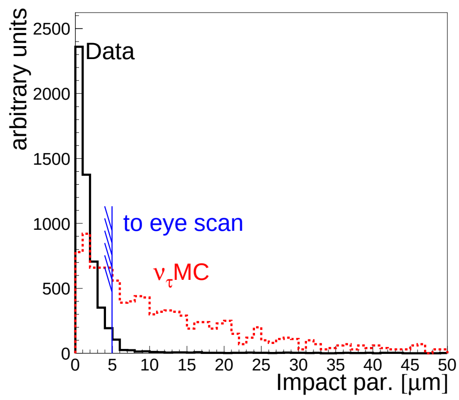
emulsion scanning

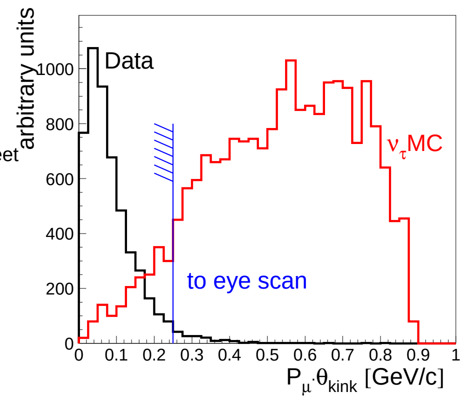
1. other subdetectors

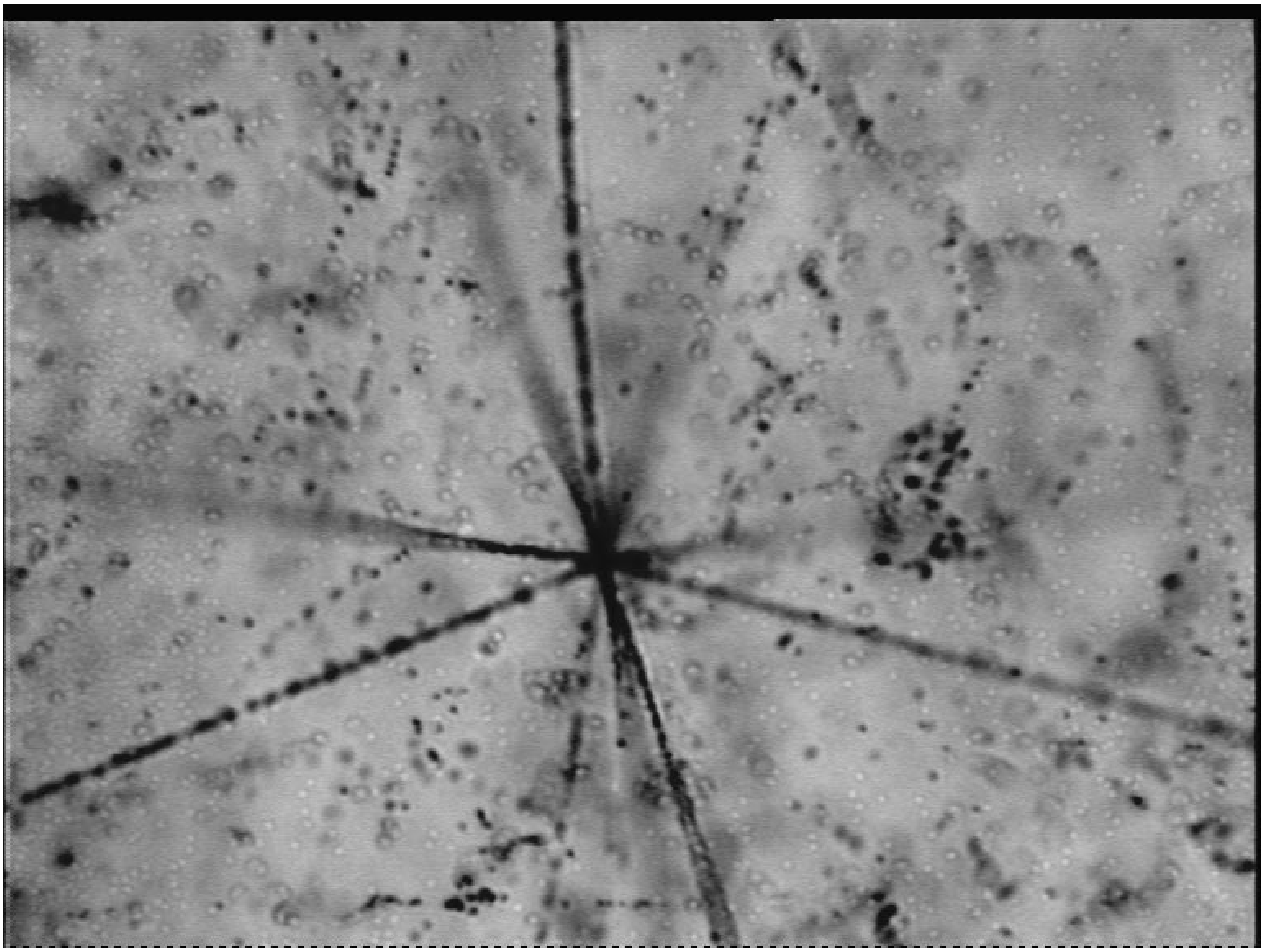
   ⇒ prediction of track location and slope

2. automatic scan-back of the track







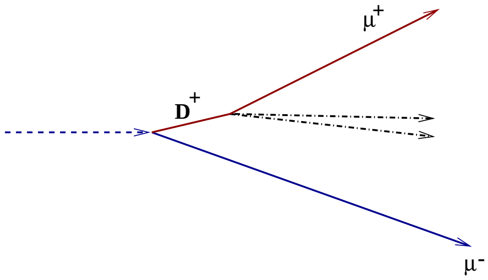


kink efficiency

- select events with 2 muons in the final state (2$\%$ of ν_μCC)
- locate the 2 muon tracks in emulsions
- scan the emulsions looking for a kink

$\Downarrow$

Charm dimuon candidates (1 prong D^+ decays)



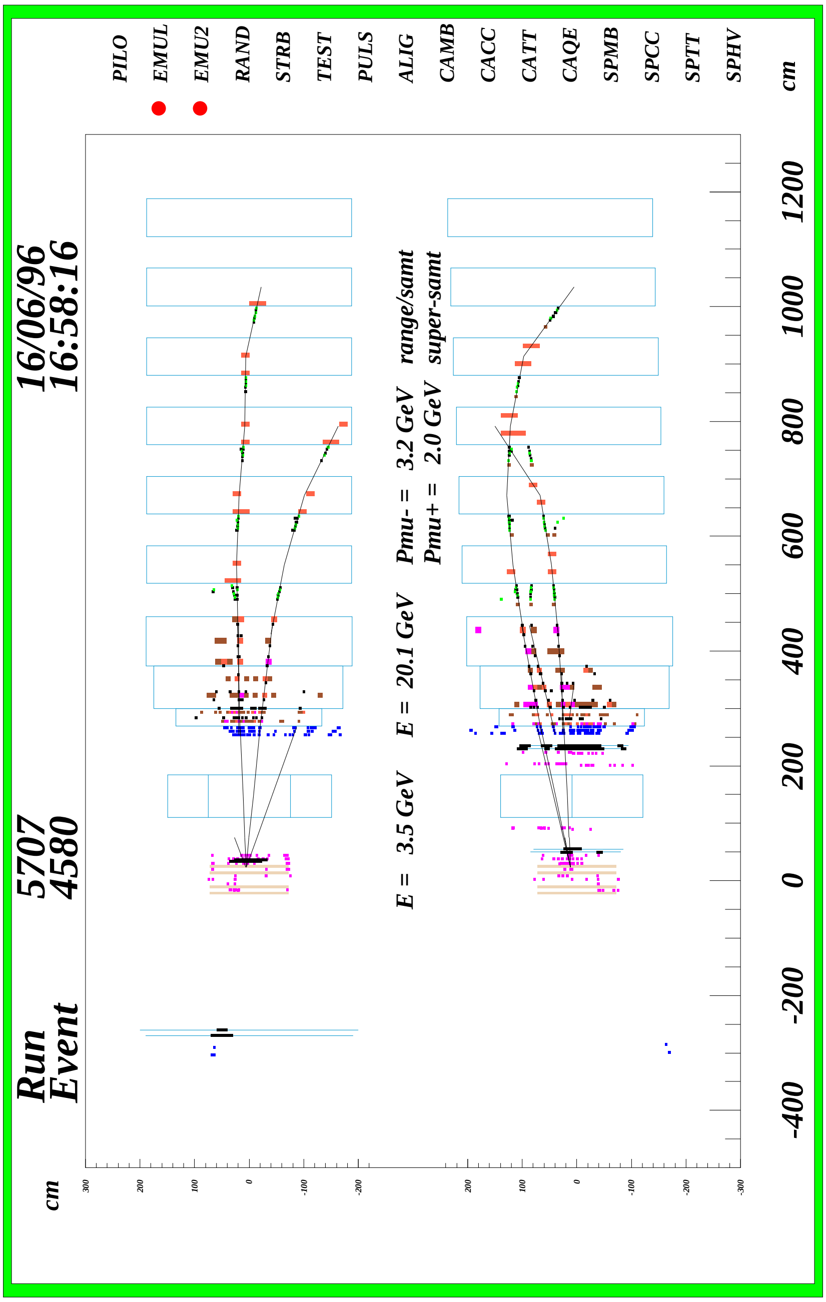
Yield in agreement with Monte Carlo expectations assuming

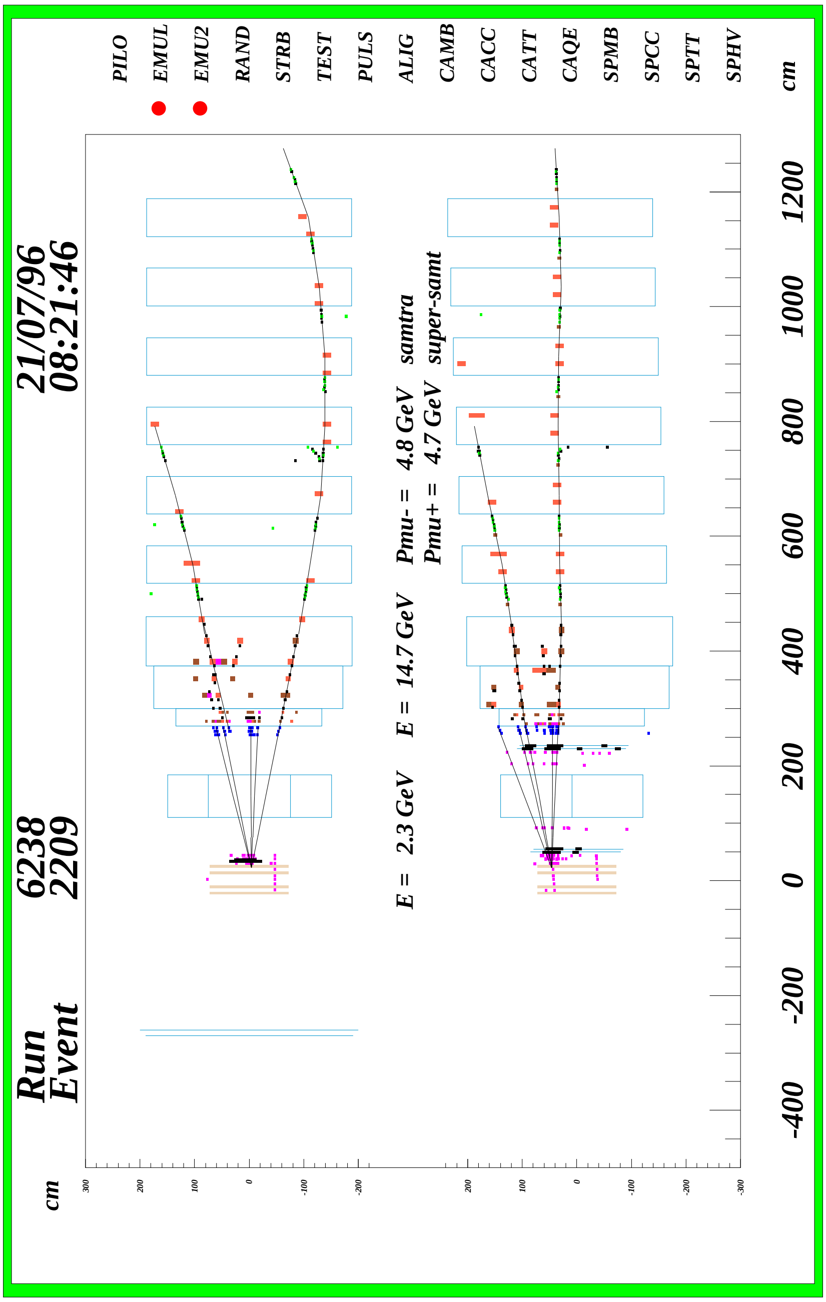
$$\sigma_{charm}/\sigma_{CC} = 5\%$$

Run (Year)	1995	1996
Expected events	7.4 ± 0.7	15.4 ± 2.2
Found events	8	17

$\Downarrow$

$$\eta(kink)$$


Run 5707
Event 4580
16/06/96
16:58:16
PILO
EMUL
EMU2
RAND
STRB
TEST
PULS
ALIG
CAMB
CACC
CATT
CAQE
SPMB
SPCC
SPTT
SPHV
cm
E = 3.5 GeV
E = 20.1 GeV
Pmu- = 3.2 GeV range/samt
Pmu+ = 2.0 GeV super-samt
-400
-200
0
200
400
600
800
1000
1200
cm


Run 6238
Event 2209
21/07/96
08:21:46
PILO
EMUL
EMU2
RAND
STRB
TEST
PULS
ALIG
CAMB
CACC
CATT
CAQE
SPMB
SPCC
SPTT
SPHV
cm
E = 2.3 GeV E = 14.7 GeV
Pmu- = 4.8 GeV samtra
Pmu+ = 4.7 GeV super-samt
-400
-200
0
200
400
600
800
1000
1200
cm

1μ channel

$$\tau^- \rightarrow \mu^- \nu_\tau \overline{\nu}_\mu \quad BR = 17\%$$

- identify the muon track and require

  $P_\mu < 30$ GeV

- veto other leptons at the primary vertex

- require a kink along the muon track with

  $P_\perp = \Delta\theta P_\mu \geq 250$ MeV/c

- Background

  $\overline{\nu}_{\mu,e} CC \rightarrow D^- \rightarrow \mu^-$

  with μ^+ or e^+ not identified

  1.6×10^{-6}

0μ channel

$$\tau^- \to h^- (n\pi^0)\nu_\tau \quad BR = 50\%$$

- identify the hadron candidate track and require

  $1 < P_h < 20$ GeV

- veto leptons at the primary vertex

- require a kink along the hadron track with

  $P_\perp = \Delta\theta P_h \geq 250$ MeV/c

- Background

  2×10^{-5} from white kinks

  2×10^{-6} from charm production

CHORUS Results

Run (Year)	1994*	1995*	1996	1997	ALL
p.o.t. ($\times 10^{19}$)	0.8	1.2	1.4	1.7	5.1
ν_μCC	120k	200k	230k	290k	840k
1μ prediction	67k	111k	130k	151k	459k
1μ scanned $\%$	63	34	56	0	33
1μ located	18k	18k	30k	0	66k
0μ prediction	18k	28k	32k	38k	116k
0μ scanned $\%$	50	29	0	0	15
0μ located	3.4k	3.7k	0	0	7.1k

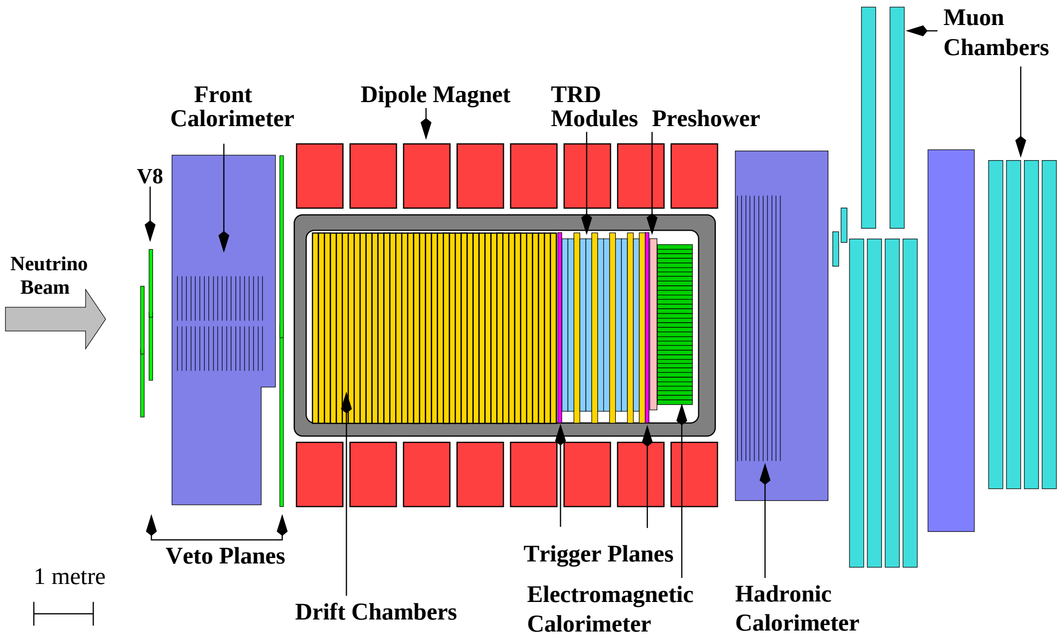
No τ decay observed, $N_\tau(P = 1) = 3804$

$$\Downarrow$$

$$P(\nu_\mu \rightarrow \nu_\tau) < 6.3 \times 10^{-4} \text{ (90\% C.L.)}$$

* CERN-EP/98-73

NOMAD detector



- Drift Chambers (target and momentum measurement)

  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

$$\frac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \frac{(3.22 \pm 0.07)\%}{\sqrt{E(GeV)}}$$

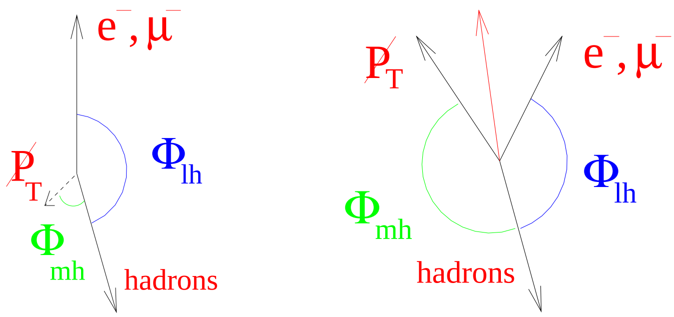
- Muon Chambers

  ε $\approx$ 97% for p_μ $>$ 5 GeV/c

kinematical method to search for $\nu_\mu \rightarrow \nu_\tau$

1. Transverse plane triangle $\rightarrow \vec{p}_\perp^{\,l} + \vec{p}_\perp^{\,H} + \vec{p}_\perp^{\,m} = 0$

Background: $\nu_{\mu,e}$ CC   Signal: ν_τ CC

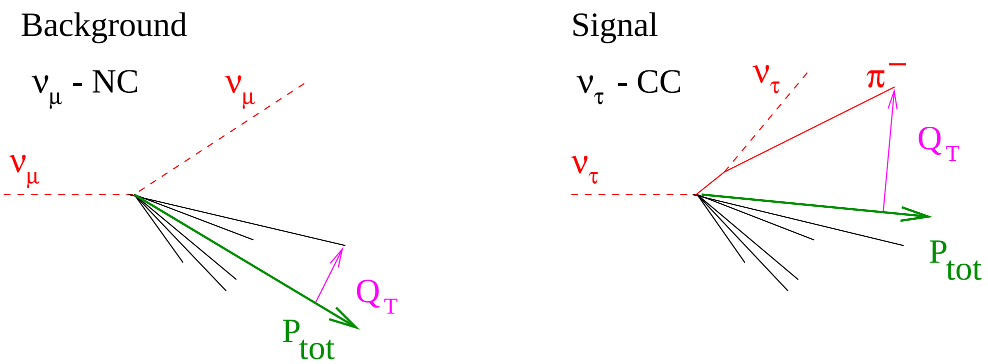


2 independent variables for the triangle shape

for example Φ_{mh} and Φ_{lh} , or $\rho_i = p_\perp^i / (p_\perp^m + p_\perp^l + p_\perp^H)$

1 variable for the scale $m_\perp = \sqrt{(\vec{p}_\perp^{\,m} + \vec{p}_\perp^{\,l})^2 - (\vec{p}_\perp^{\,H})^2}$

2. Isolation of Candidate wrt hadronic jet



NOMAD Data Simulator

1. Difficulties with Monte Carlo

   - Modelling of detector (nuclear secondary interactions)
   - Modelling of “physics” (fragmentation for ν interactions)

   $\Rightarrow$ efficiency calculations and background predictions cannot be based on MC only

   $\Rightarrow$ use Data to correct MC evaluations

2. Data Simulator: compare

   a MC sample (MCS) and
   a Data sample (DS) of ν_μCC

   - First replace the identified μ in MCS and DS samples by a MC l

     (a) Replace $\mu \to \nu$ yields a “Fake NC”

     (b) Replace $\mu \to e$ yields a “Fake ν_eCC”

     (c) Replace $\mu \to \tau$ yields a “Fake ν_τCC”

   - Perform full analysis in three samples: MC, MCS & DS
   - Compute efficiency for signal and background as:

$$\epsilon = \epsilon_{MC}(\epsilon_{DS}/\epsilon_{MCS})$$

electron channel

$$\tau^- \to e^- \nu_\tau \overline{\nu}_e \quad BR = 17\%$$

1. candidate selection

- one (and only one) electron from the primary vertex

  ID provided by the combined information of TRD, PRS and ECAL
- isolated from any positive track in the event ($m_\pm \geq 0.12$ GeV)

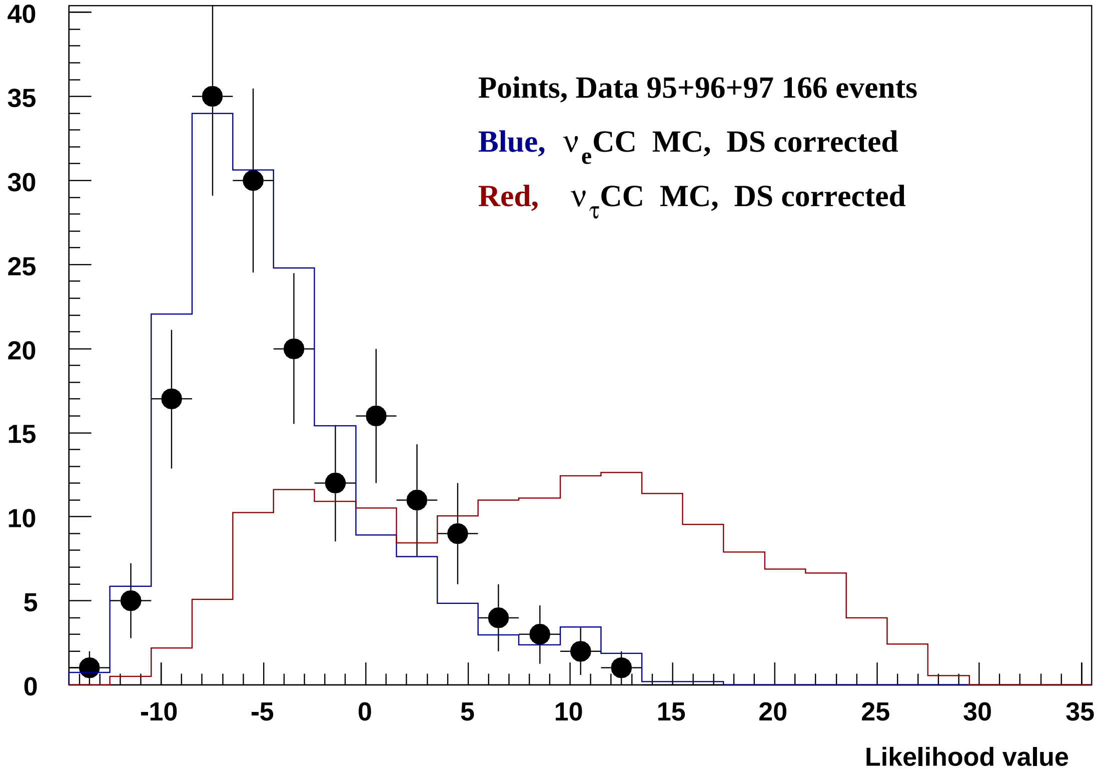
$\Rightarrow 2\%$ of NC and 37% of ν_eCC

2. NC background rejected by

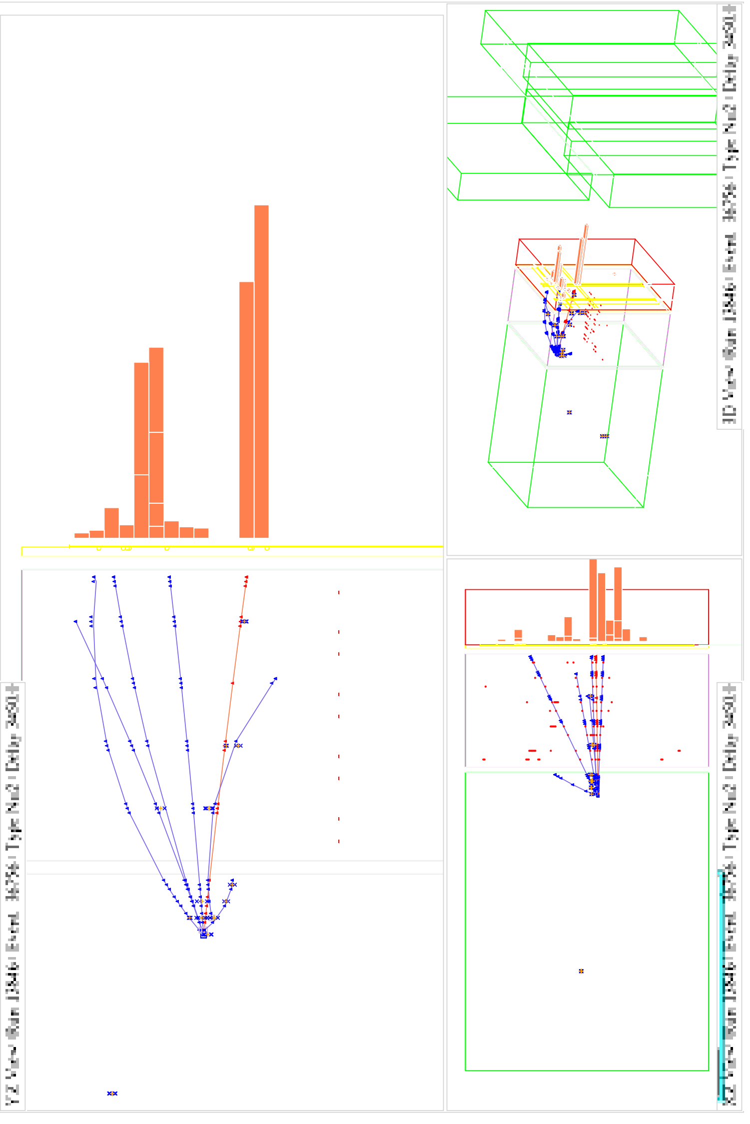
- requiring the electron isolation wrt the hadronic jet

3. ν_eCC background rejected by

- an upper cut on the electron Q_T wrt the jet
- requiring $0.2 < m_\perp < 1.8$ GeV
- a likelihood function built using the other transverse plane variables, the electron momentum and the total visible energy



Likelihood	N_τ(P=1)	Expected Bkgnd	Data
6.5-10	693	3.4 ± 0.7	4
10-13	623	4.1 ± 0.9	2
> 13	1594	0.6 ± 0.4	1



NOMAD π^- channel

$$\tau^- \to \pi^-(K^-, \rho^-)\nu_\tau \qquad BR = 38\%$$

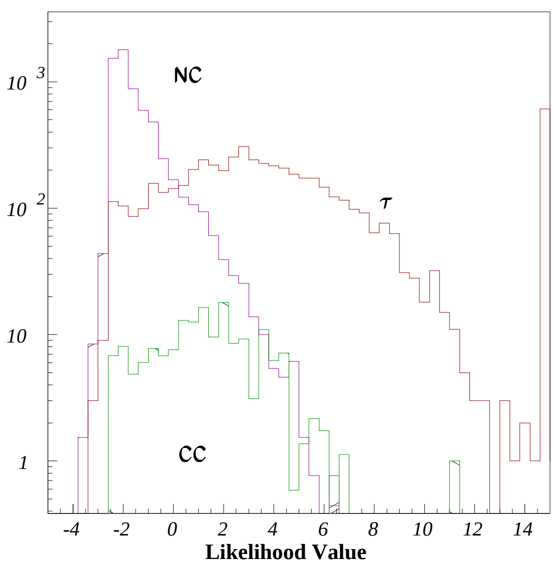
1. candidate selection

   - no primary leptons, or high $P_\perp$ tracks escaping detector acceptance
   - choose π^- as the most isolated negative track in the event

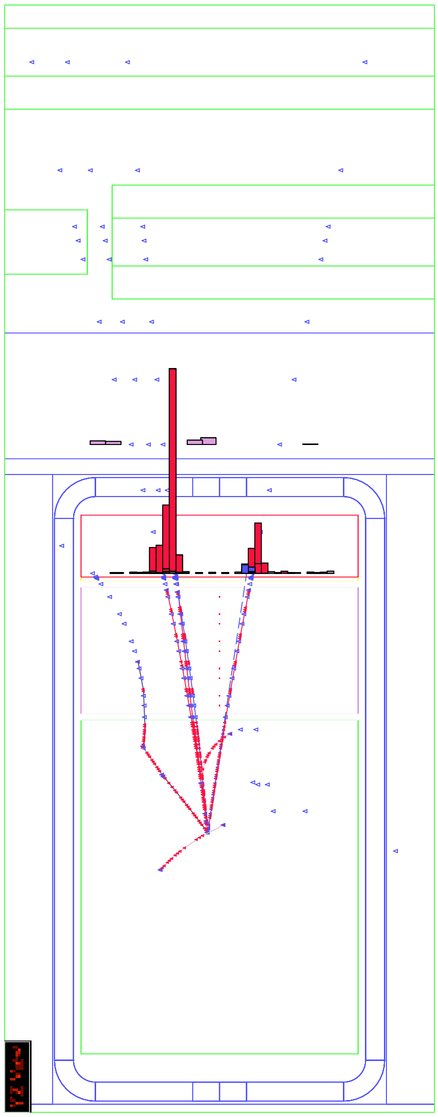
   $\Rightarrow 8.5\%$ of NC, 0.34% of ν_μCC , 0.6% of ν_eCC

2. NC and CC residual backgrounds rejected by

   - a likelihood function built using Q_T, m$_\perp$, ρ_m, Y_bj and $P_\perp^H$



$\mathcal{L}$	N_τ	Exp. Bkgd.	Data
7-9	664	2.3 ± 0.8	3
9-11	234	$1.1^{+0.8}_{-0.6}$	2
> 11	1133	$1.1^{+0.7}_{-0.5}$	0

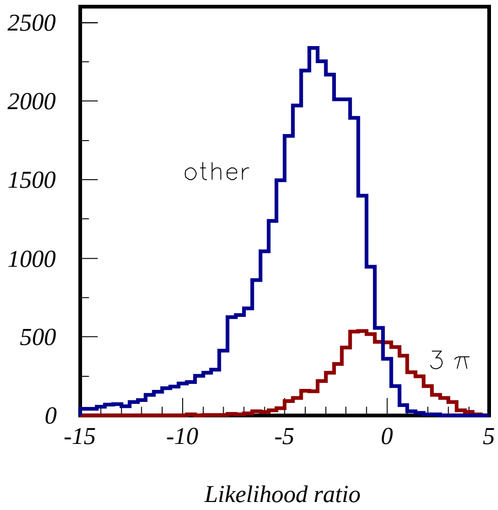


NOMAD 3π channel

$$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$$

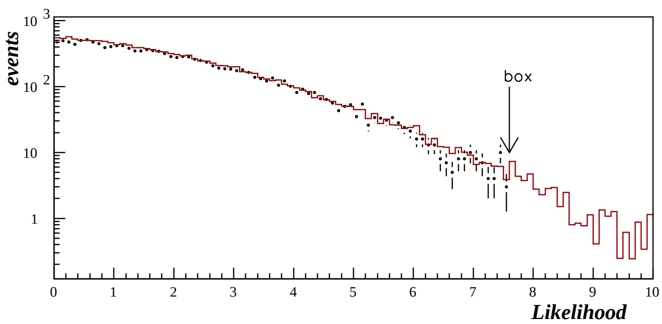
1. candidate selection

- apply lepton veto (see π^- channel)
- a likelihood ratio is defined to favour the correct choice of the 3 candidate tracks in τ decays (in the hypothesis $\tau \to A_1\nu \to \rho\pi\nu \to \pi\pi\pi\nu$)

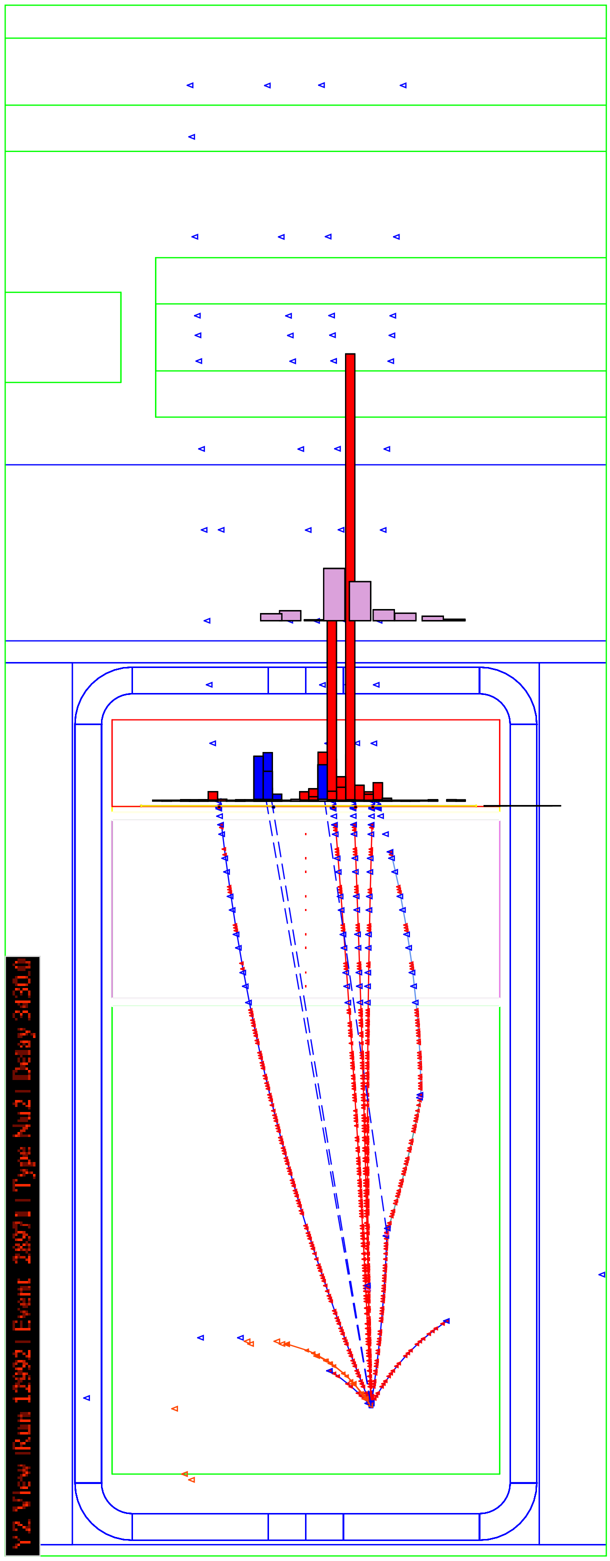


2. NC and CC rejection

- apply cuts on the transverse plane variables and on Q_T
- use the same likelihood ratio



$\Rightarrow$ 5 events in data, expect 7.0 ± 2.7, for $N_\tau = 1011$


YZ View |Run 13992 | Event 28971 | Type Nu2 | Delay 3430.0

NOMAD Results

1. '95 Analysis (180k ν_μCC)

- CERN-EP/98-57 (to be published in Physics Letters B)

$$P(\nu_\mu \to \nu_\tau) < 2.1 \times 10^{-3} (90\% C.L.)$$

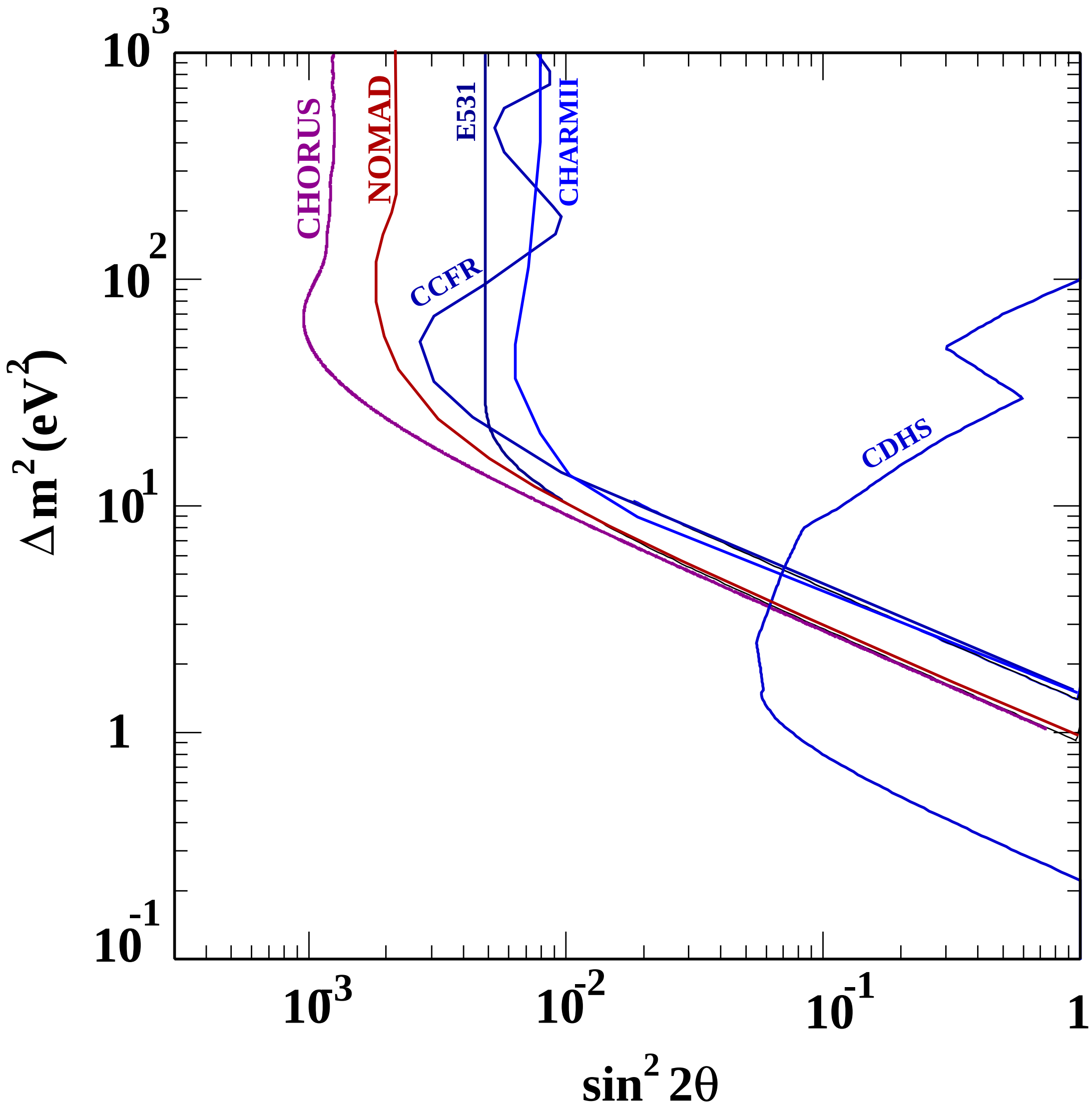
2. Updated Analysis('96: 380k ν_μCC, '97 382k ν_μCC)

channel	N_τ	est. backg	obs.	analysis
$\tau \to e$ DIS	2910	8.1 ± 1.4	7	95-97
$\tau \to e$ LM	218	0.5 $^{+0.6}_{-0.2}$	0	95
$\tau \to h^-(\pi^0)$ DIS	2032	4.5 ± 1.4	5	95-97
$\tau \to h^-(\pi^0)$ LM	198	0.1 $^{+0.3}_{-0.1}$	1	95
$\tau \to \rho$ DIS	128	0.5 $^{+2.1}_{-0.3}$	0	95
$\tau \to 3\pi$ DIS	1011	7 ± 2.7	5	95-96
$\tau \to 3\pi(n\pi^0)$ LM	108	0.4 $^{+0.6}_{-0.4}$	0	95

$\Downarrow$

$$P(\nu_\mu \to \nu_\tau) < 1.1 \times 10^{-3} \text{ (90\% C.L.)}$$

Results



10^3
10^2
10^1
1
10^{-1}
$\Delta m^2 (eV^2)$
CHORUS
NOMAD
E531
CHARMII
CCFR
CDHS
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$

Conclusions

- Chorus data taking is finished in 1997, Nomad is still taking data
- The analysis is in progress for both experiments
- Chorus has shown that automatic scanning procedures are reliable and fast

  $\Rightarrow$ the emulsion technique can be used also in the search for rare events
- Nomad has shown that kinematical criteria can be used in the τ identification at least for large mixing angles

  $\Rightarrow$ a valid technique for the future long baseline experiments