Reconstruction of multi-GeV tau neutrinos in tracking detectors

30/9/2021

Workshop on Tau Neutrinos from GeV to EeV 2021 (NuTau2021)
D. Autiero, IP2I Lyon

Neutrino oscillation searches at the beginning of 90s

- The long standing (since 1968) problem of the solar neutrino deficit opened by the Homestake measurements (+ Kamiokande since 1986) → in 1992 first Gallex results confirm the deficit also for neutrinos from the pp cycle
- Atmospheric neutrino anomaly still quite weak

The controlled observation of neutrino oscillations with an accelerator neutrino beam would have been a great discovery, where to search ?

→ Prejudice towards small mixing angles and large Δm^2

✓Take the MSW solution of the solar neutrino deficit: $\Delta m^2_{\mu e} \sim 10^{-5}$ eV^2

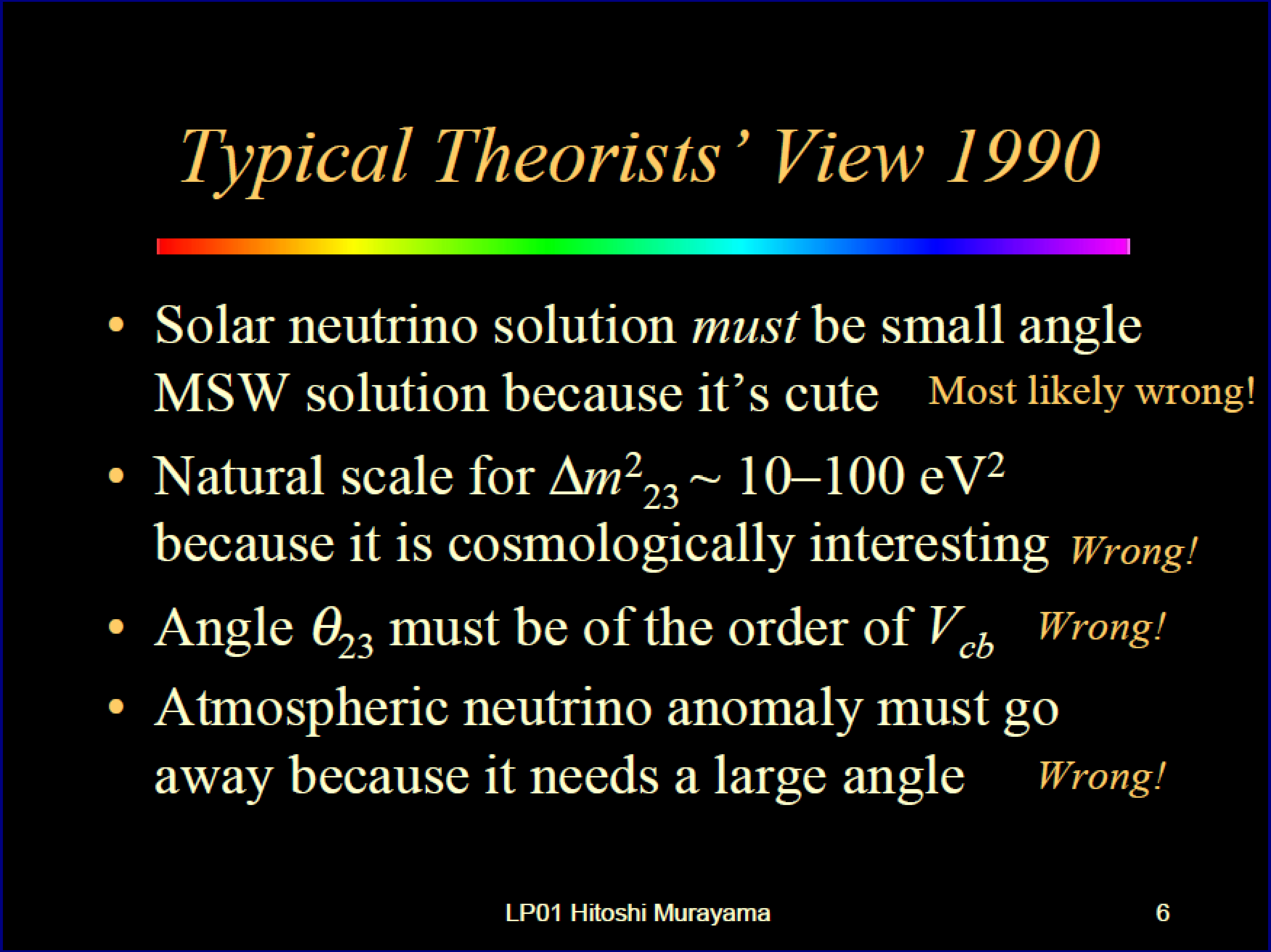
✓Assume a strong hierarchy: $m_{\nu e} \ll m_{\nu\mu} \ll m_{\nu\tau} \rightarrow m_{\nu\mu} \sim 3\times10^{-3}$ eV

✓Assume the See-Saw mechanism: $m(\nu_i)=m^2(f_i)/M$

M=very large Majorana mass $m(f_i)$= e.g. quark masses

Then: $m_{\nu\tau} \sim 30$ eV (Cosmological relevance)

« ν are an important component of the dark matter » ~ a few 10 eV
Harari PLB 1989. Harari, J. Ellis



Typical Theorists' View 1990

- Solar neutrino solution *must* be small angle MSW solution because it's cute Most likely wrong!
- Natural scale for $\Delta m^2_{23} \sim 10\text{–}100 \text{ eV}^2$ because it is cosmologically interesting *Wrong!*
- Angle θ_{23} must be of the order of V_{cb} *Wrong!*
- Atmospheric neutrino anomaly must go away because it needs a large angle *Wrong!*

With $m_{\nu\tau}$ ~ 30 eV cosmological neutrinos important component of dark matter $\Delta m^2_{\mu\tau}$ O(100 eV^2)

→ Look for $\nu_\mu \rightarrow \nu_\tau$ with short baseline experiments at accelerators, high energy beam

CERN ν_τ appearance experiments:

Search for ν_τ appearance from oscillations in the CERN wide band neutrino beam (WANF)

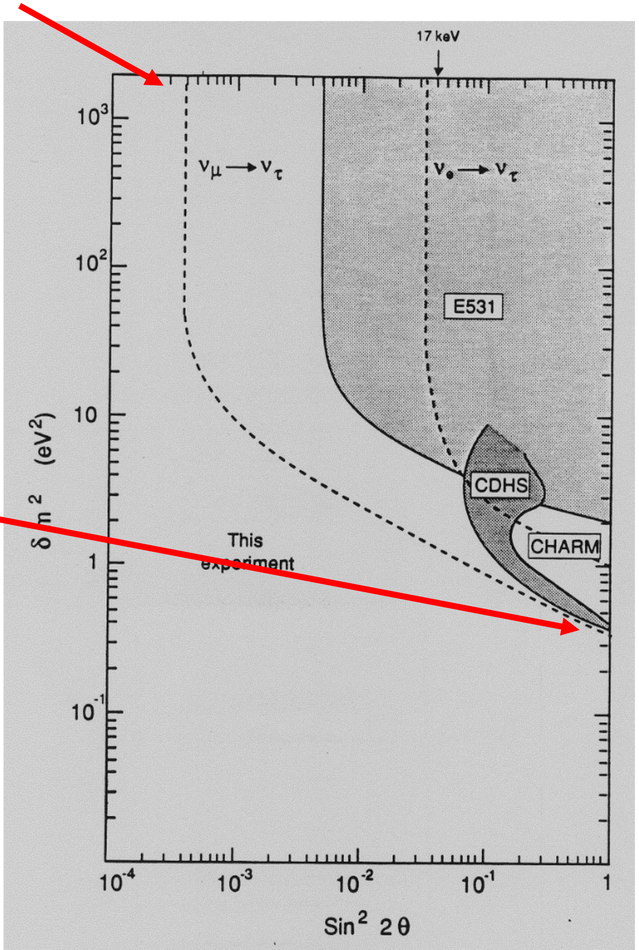
→ WANF experiments pioneers of the tau searches technique also for long baseline experiments.

→ Important samples of neutrino interactions measured in fine details (NOMAD)

sensitive down to:

$P_{\mu\tau}$~ 1.5x10^{-4} (90% CL) **(x10) improvement**

<E_ν>=24 GeV
<L>=600 m
sensitive to:
1 eV^2 < Δm^2



NOMAD (3tons target in magnetic spectrometer:

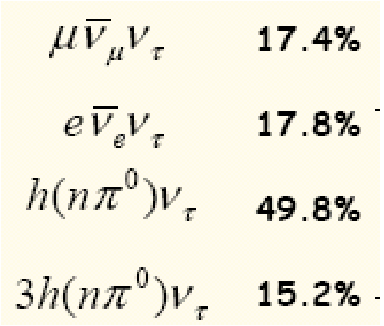
- Data-taking 95-98 (1.35 M ν_μ CC)

CHORUS (800 kg nuclear emulsions):

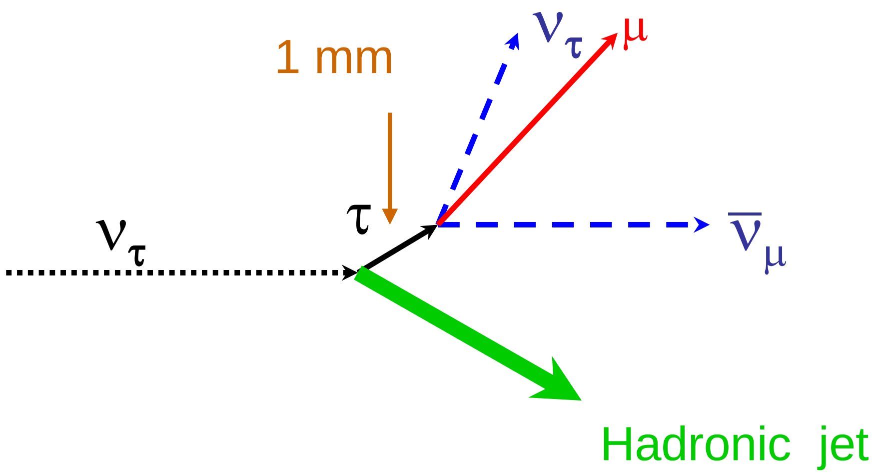
- Data-taking 1994-1997 (0.71 M ν_μ CC)

Search for τ appearance

The ν_τ are searched for through their charged current interaction followed by the τ decay.



$\mu\bar{\nu}_\mu\nu_\tau$	17.4%
$e\bar{\nu}_e\nu_\tau$	17.8%
$h(n\pi^0)\nu_\tau$	49.8%
$3h(n\pi^0)\nu_\tau$	15.2%



The τ decay can be identified using two different methods :

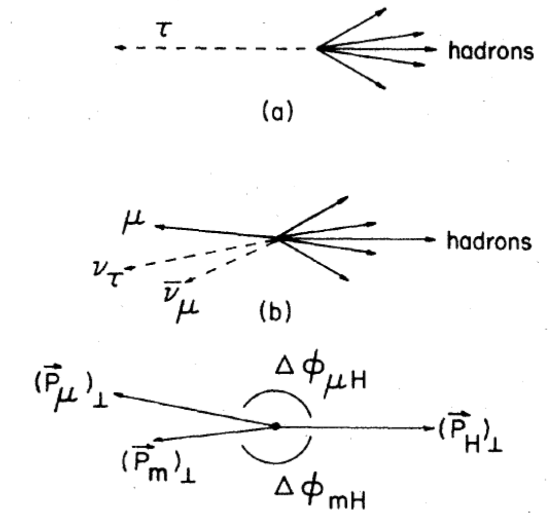
- Identification of the τ decay kink : CHORUS/DONUT/OPERA
→ high space resolution, nuclear emulsions. Main channel: muonic tau decay

- Measurement of the KINEMATIC of the τ decays : NOMAD/ICARUS/DUNE
presence of neutrino(s) in the final state, missing P_t , visible decay daughters
→ Tracking and calorimetry. Main channel: electronic tau decay (NOMAD/ICARUS)

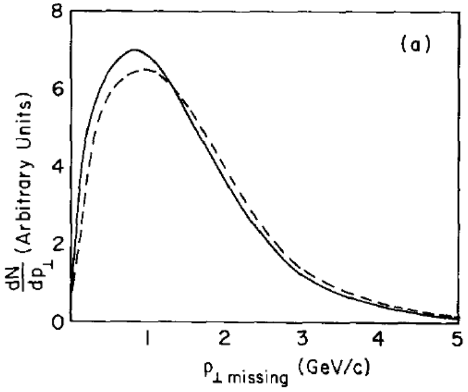
Use of kinematics to extract a ν_τ signal:

(First proposed by Albrigth and Shrock P.L.B. 1979)

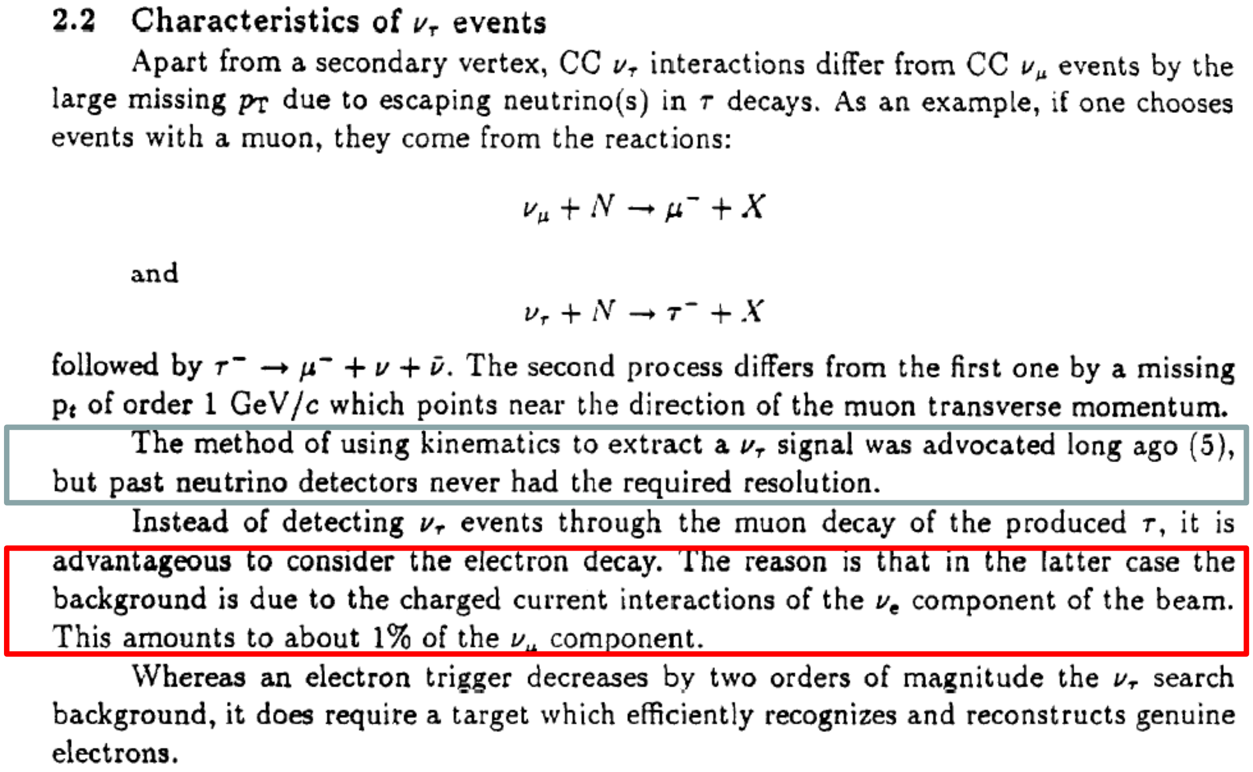
- In the plane transverse to the neutrino direction kinematic can be closed (neglecting Fermi motion of the target nucleon)
- The presence of the two neutrinos from tau decays can be detected as missing transverse momentum
- Angular correlations between the directions of the transverse momenta of the missing transverse momentum and the momentum of the hadronic system and of the charged daughter of the tau can be exploited as well



(From Albright et al.)



NOMAD proposal (1991)



2.2 Characteristics of ν_τ events

Apart from a secondary vertex, CC ν_τ interactions differ from CC ν_μ events by the large missing p_T due to escaping neutrino(s) in τ decays. As an example, if one chooses events with a muon, they come from the reactions:

$$\nu_\mu + N \to \mu^- + X$$

and

$$\nu_\tau + N \to \tau^- + X$$

followed by $\tau^- \to \mu^- + \nu + \bar{\nu}$. The second process differs from the first one by a missing p_t of order 1 GeV/c which points near the direction of the muon transverse momentum.

The method of using kinematics to extract a ν_τ signal was advocated long ago (5), but past neutrino detectors never had the required resolution.

Instead of detecting ν_τ events through the muon decay of the produced τ, it is advantageous to consider the electron decay. The reason is that in the latter case the background is due to the charged current interactions of the ν_e component of the beam. This amounts to about 1% of the ν_μ component.

Whereas an electron trigger decreases by two orders of magnitude the ν_τ search background, it does require a target which efficiently recognizes and reconstructs genuine electrons.

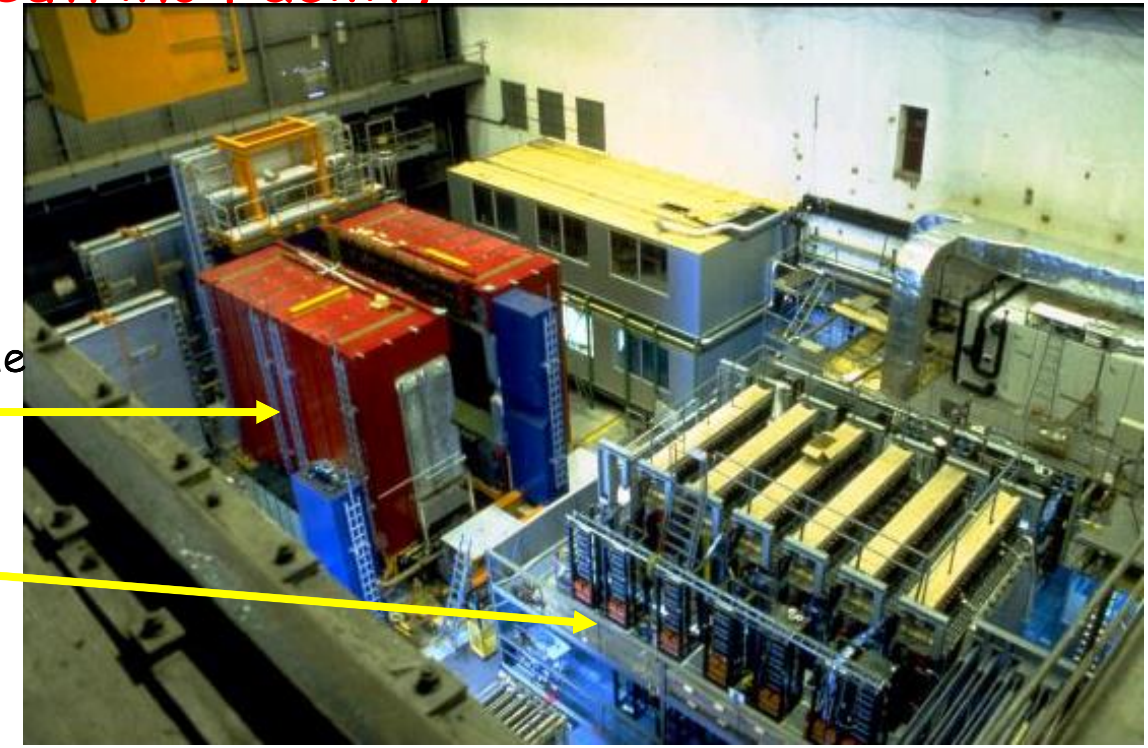
The NOMAD/CHORUS experiments at the CERN West Area Neutrino Facility

Short-baseline search for
$\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations

Running in 1994-1998

The NOMAD experiment hosted in the
UA1/NOMAD/T2K magnet
(Kinematical method)

The CHORUS experiment
(Nuclear emulsions)

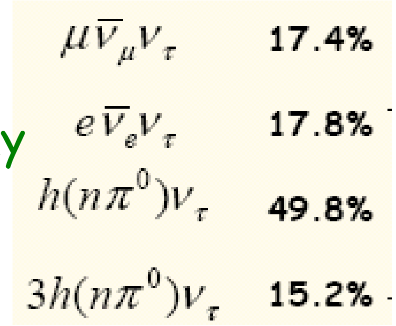


NOMAD: measurement of τ decay kinematics:

Presence of neutrino(s) in the final state, missing P_t , visible decay daughters
→ tracking + calorimetry → main channel: electronic tau decay

Collected samples:
1.35 M νμ CC
0.4 M νμ NC
13 K νe CC

τ decay modes



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Exploit the small νe background (~1%):
τ->e channel: electron id

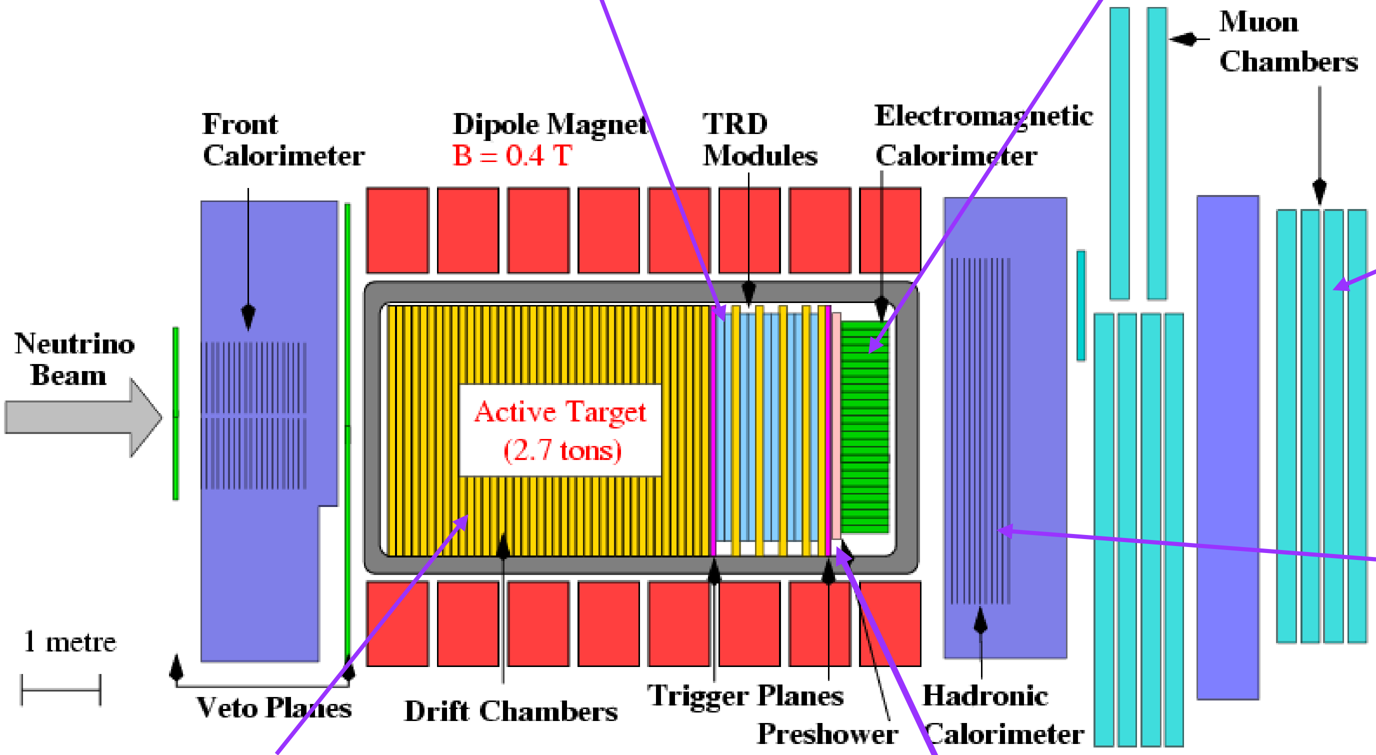
Go down to $P_{\mu\tau} \sim 10^{-4}$

The NOMAD detector

Transition Radiation Detector (TRD) (e identification) 9 modules (315 radiator foils followed by straw tubes plane) π rejection ~ 10^3 for electron efficiency > 90%

Electromagnetic Calorimeter (measurement of energy and position of e.m. shower)

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus 1\%$$



Muon Chambers (μ identification) ε~ 97% for $p_\mu > 5$ GeV/c

Hadronic calorimeter (n and k^0_L veto)

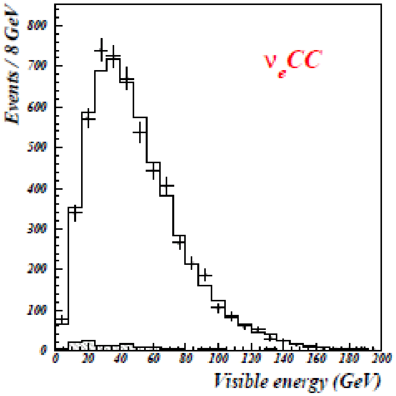
Drift chambers (target and momentum measurement) Fiducial mass 2.7 tons with average density 0.1 g/cm^3 44 chamber + 5 chambers in TRD region, momentum resolution 3.5% ~ ($p < 10$ GeV/C)

Preshower (e and γ detection) additional π rejection ~ 10^2 for electron efficiency > 90% precise γ position measurement $\sigma(x)$, $\sigma(y)$ ~ 1cm

Nomad typical events →

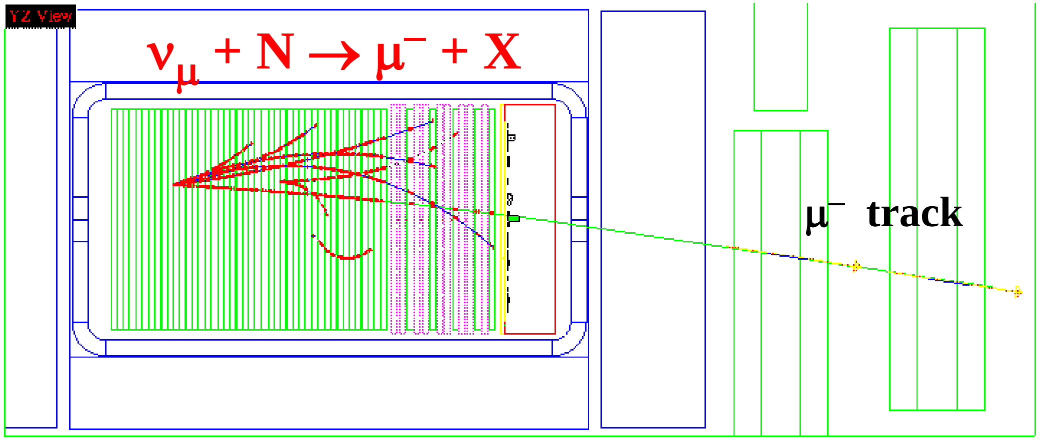
Nomad:

- Modern bubble chamber version
- Very good for electron identification and kinematical measurements
- 3 ton detector, technology not exportable to the kton scale
- Still very good as near detector in a LBL experiment

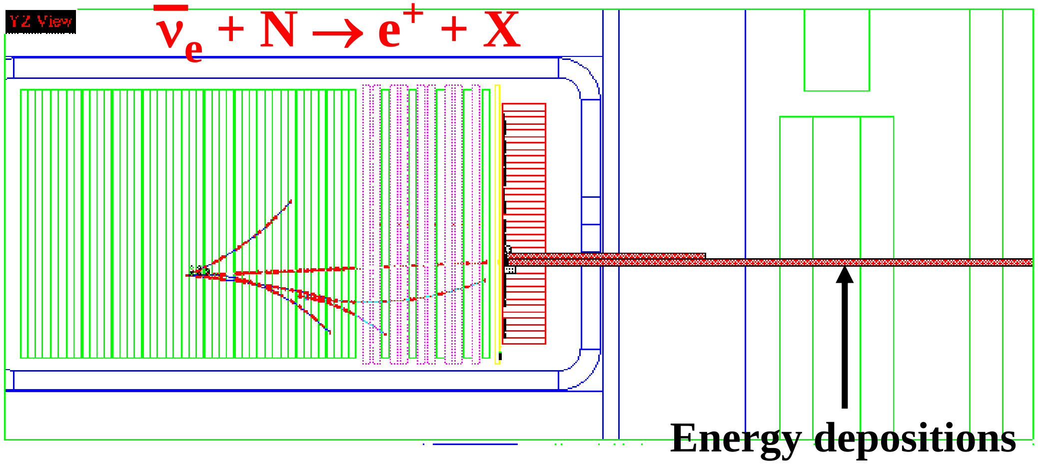


$\nu_\mu \rightarrow \nu_e$ analysis (search motivated by LSND):

5600 ν_e CC events
44% efficiency
98% purity

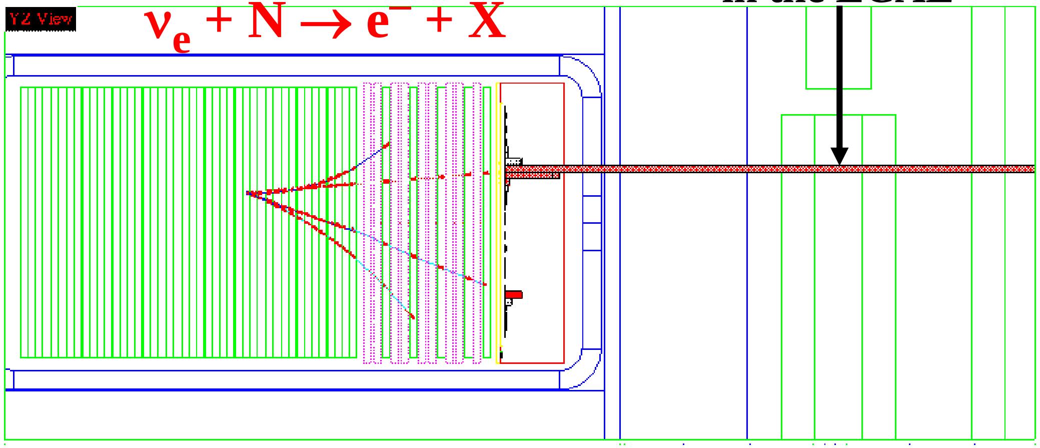


$\nu_\mu + N \rightarrow \mu^- + X$



$\bar{\nu}_e + N \rightarrow e^+ + X$

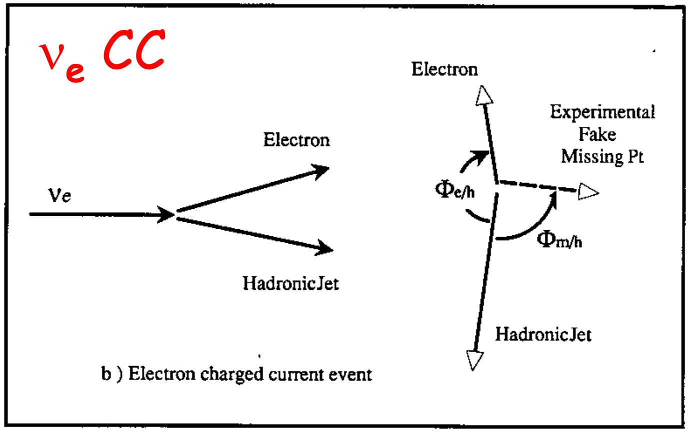
Energy depositions in the ECAL



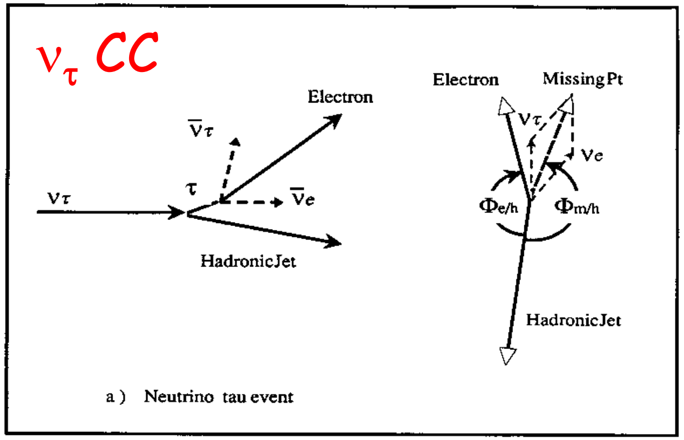
$\nu_e + N \rightarrow e^- + X$

NOMAD: fully reconstructed 1.7 M neutrino interactions, with good resolution, at single particles level:

→ could check kinematics closure on the transverse plane in ν_μ CC interactions and NC



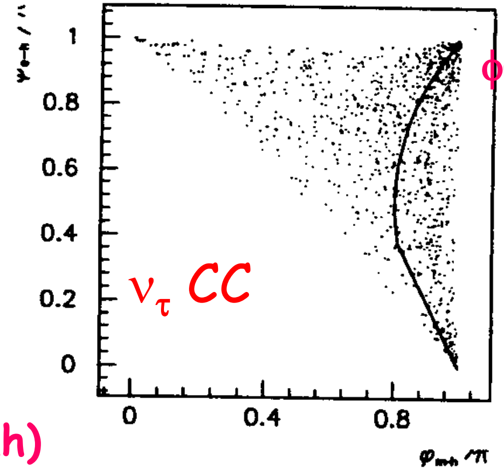
b) Electron charged current event



a) Neutrino tau event

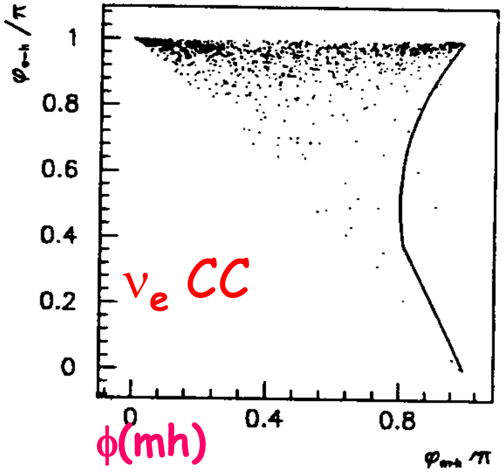
The φ- φ plot:

φ(eh)



φ(mh)

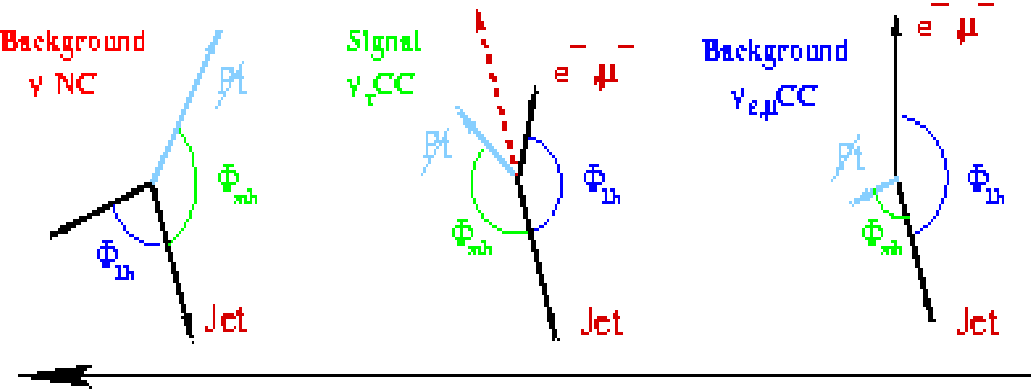
φ(eh)



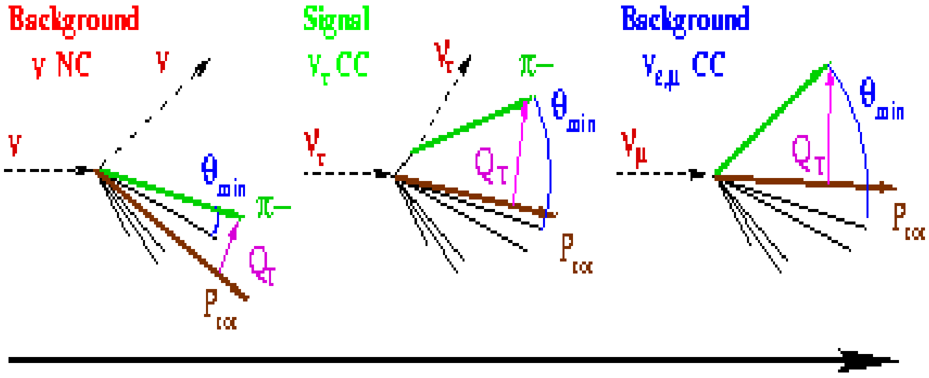
The signal contour (initially defined by eyes) on the φ–φ plot can be reproduced by a cut on a single variable:

the pt asymmetry between the hadronic system and the tau visible daughter:

$$p_T^{as} = (p_T^{\tau V} - p_T^H)/(p_T^{\tau V} + p_T^H)$$



IMBALANCE



ISOLATION

There is not a single miracle cut achieving a 10^5 rejection

The signal is half way between CC and NC background for what concerns the imbalance of the event and the isolation of the tau daughters

Combine the pdf of many variables in order to build likelihood functions for the signal and background

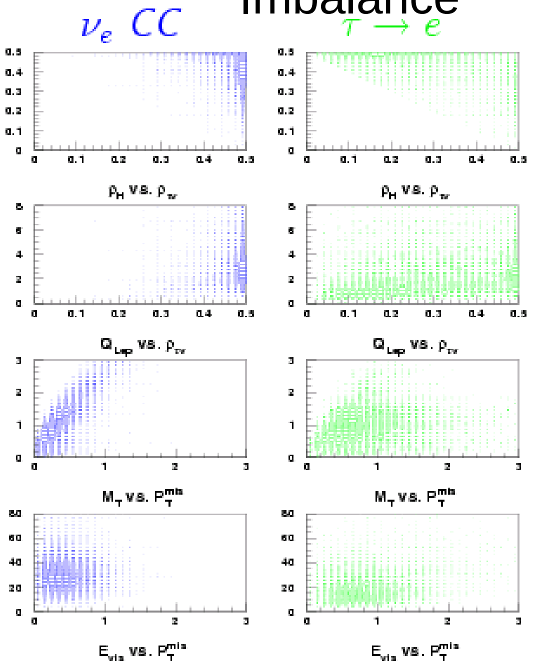
Cut on the likelihood ratio $\ln(L_S/L_B)$

Two likelihood ratios can be used in a correlated way: one to reject NC based on the isolation and one to reject CC based on the imbalance

Corrections to the Monte Carlo predictions are evaluated from the data themselves by looking at the differences between data and MC for the ν_μ CC events (Data Simulator) → the muonic decay channel is sacrificed

The analysis is performed in a blind way by not looking at the interesting region with good S/B ratio (blind box), data can be looked elsewhere, the search is performed as cross-check also for the τ^+ (purely background sample)

Imbalance



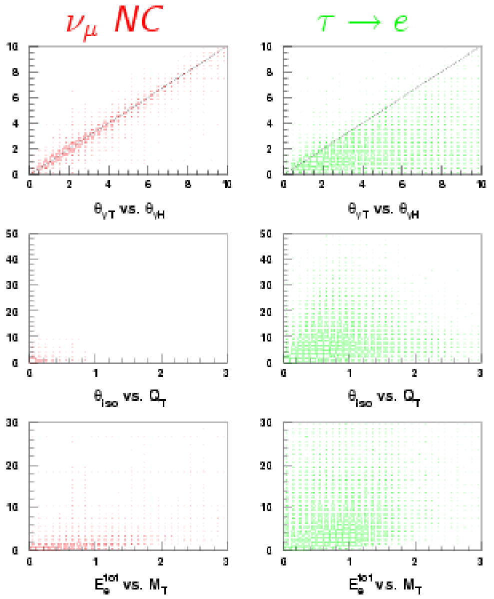
ρ_l Electron transverse momentum normalized to the sum of transverse momenta $P_T^l + P_T^H + \not{P}_T$;

ρ_h Hadronic jet transverse momentum normalized to the sum of transverse momenta;

Q_{lep} Electron momentum component $\perp$ to the hadronic jet momentum.

E_{vis} Total visible energy in the event;

Isolation

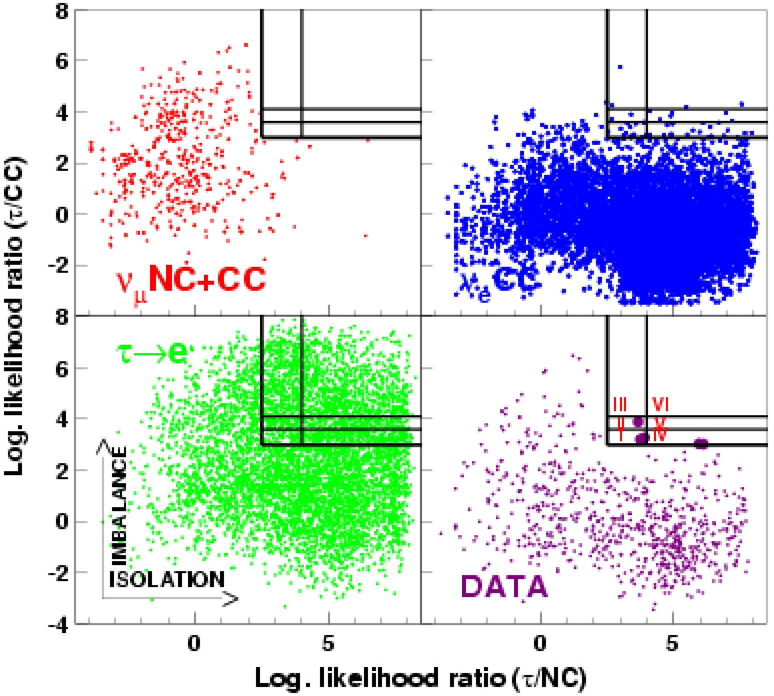


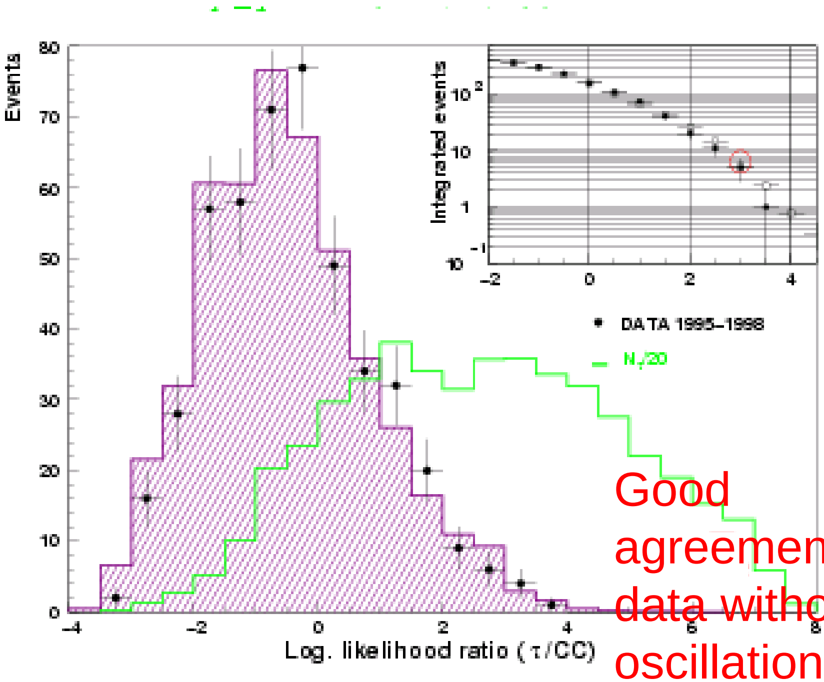
$\theta_{\nu T}$ Angle between the direction of the incident ν and the total momentum of the event;

$\theta_{\nu H}$ Angle between the direction of the incident ν and the hadronic jet momentum;

θ_{iso} Minimum opening angle between the electron and any other track in the hadronic system;

E_e^{tot} Electron energy.





Good agreement with data without oscillations

Experience on the kinematical method:

The kinematical method is a very attractive and ambitious method for tau searches. Some key aspects affect its performance:

1) Nuclear effect on the target nucleon → missing transverse momentum

2) The details of the hadronic system (which particles are produced at which angles and with which momenta)

→ **this is the most difficult part to simulate in neutrino interaction**:

- mixing of interaction processes as QE, RES, Deep Inelastic Scattering
- Fragmentation functions for Deep inelastic scattering
- Nuclear re-scattering in the intra-nuclear cascade (degrades energy and increases missing transverse momentum)

4) Energy and angular resolution of the detector, mis-reconstruction effects

5) The details of the hadronic system then are interrelated to the detector response for instance:

- ▪ Efficiency to reconstruct particles at large angles
- ▪ Thresholds to reconstruct low energy particles
- ▪ Neutrons are normally not reconstructed

→ For NOMAD (optimized for forward collimated events)

- Neutrons and K0L were lost
- Photons were escaping from the detectors sides
- Track reconstruction efficiency was low at large angles (drift chambers)
- Protons left enough hits to reconstruct a track only above 350 MeV/c

Events simulation :

The original NOMAD event generator NEG (Neutrino Event Generator) initially was not including nuclear re-scattering neither a detailed tuning of the hadronic system

In a second phase of NOMAD (around the year 2000) the generator was further developed and became NEG-N. NEG-N development benefited from the unprecedented possibility of comparing to a large data sample of charged interactions reconstructed at the level of single particles.

It then included:

- Deep inelastic scattering: A modified version of LEPTO 6.1
- Jetset 7.4 with fragmentation parameters retuned on data
- Formation Zone Intra-nuclear Cascade (FZIC) code extracted from DPMJET II.4 (J. Ranft) and interfaced with the output of Jetset

The sub-generators for non scaling processes where based on:

- QE: Lewellyn Smith formulation
- RES: Rein-Sehgal model

Events were undergoing a full GEANT simulation

NEG-N was then also used in OPERA by performing a scaling up of the intra-nuclear cascade effects from carbon to lead.

- The analysis in nuclear emulsions strongly relies on the kink topology but some kinematical criteria were also applied in OPERA
- OPERA was a hybrid detector, the performance of the electronic detector in locating the neutrino interaction also depends on the hadronic system of the events

To get confidence in the simulation in reproducing the details of the hadronic system by comparing to data takes time.

In NOMAD the simulation was initially not at these levels of sophistication so data were used to correct the simulation in the analysis with the **Data Simulator technique**

→ Take the hadronic system from numu CC events (in data and MC) and replace the muon with a simulated tau decay (Data Simulator and MC Simulators), correct efficiencies for the ratio DS/MCS**:** $\boldsymbol{\varepsilon = \varepsilon(MC) * \varepsilon(DS)/\varepsilon(MCS)}$

NOMAD was a tracker/calorimeter operating in a magnet:

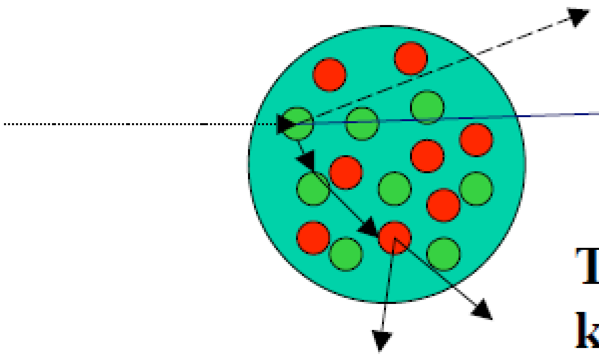
The possibility of measuring the charge of the particles offers unique handles

1) **Study separately the populations positive and negative hadrons**: pi+, pi-, protons, etc …

2) **After reconstruction check the charge of the events →** ideally the total charge should be 0 or 1 depending if the neutrino hits a neutron or a proton. $\nu\mu$ CC DIS interactions on neutrons are about twice more probably than on protons → total events multiplicity should have more pronounced peaks for even number of charged particles

3) **Perform a search for tau+ events** in a neutrino beam (cross-check channel for background)

Formation Zone Intranuclear Cascade:



The formation length was introduced in analogy to the Landau Pomeranchuk effect to explain the suppressio of the intranuclear cascade at high energies

Z. Phys C 43 (1989) 439

Z. Phys C 52 (1991) 643

The tracking of hadrons trhough the nucleus with known cross sections is performed only for hadrons formed inside the nucleus. Formation time in the rest frame of the hadron sampled from an exponential with average:

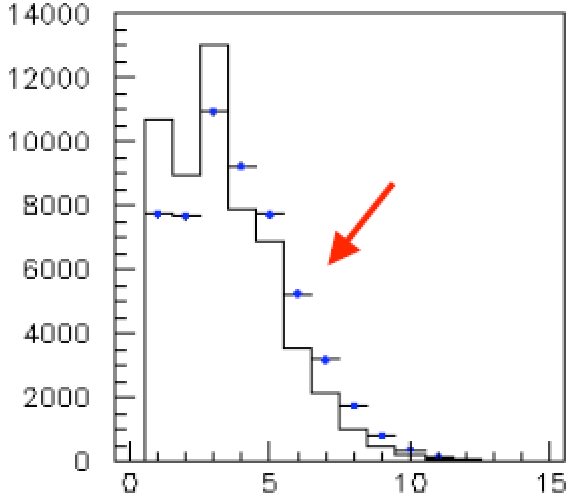
$$\tau_s = \tau_0 \frac{m_s^2}{m_s^2 + p_{s\perp}^2}.$$

τ_0 is of the order of a few fm/c. In the lab frame
$\tau=\tau_S \gamma s$ → only low energy hadrons participate

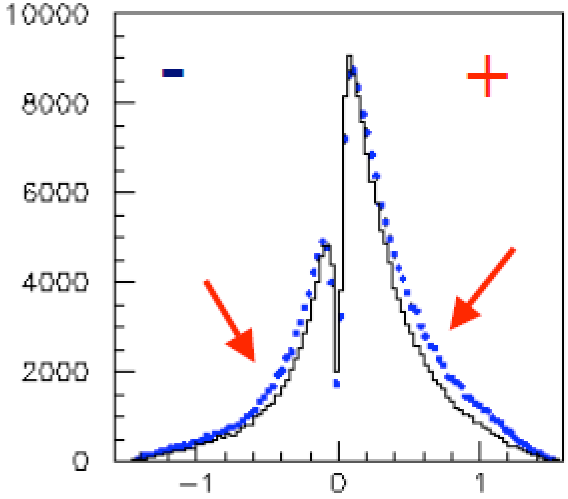
The FZIC code performs a complete sampling of the nucleus in the impulse approximation assigning momenta and positions to the nucleons and then propagates the hadrons trough the nuclear medium developing the cascade

First application to neutrino interactions by Battistoni, Lipari, Ranft, Scapparone hep-ph 9801426

(Dis)agreement Data-MC for reconstructed quantities in ν_μ CC with the Nomad MC (< year 2000) with wrong fragmentation (F) and without INC (N)

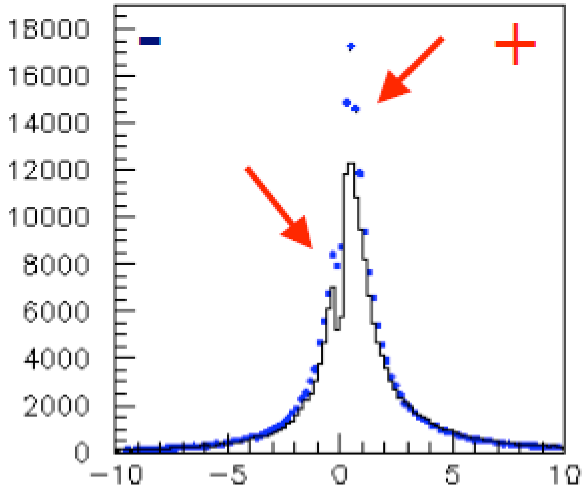


Charged hadrons multiplicity

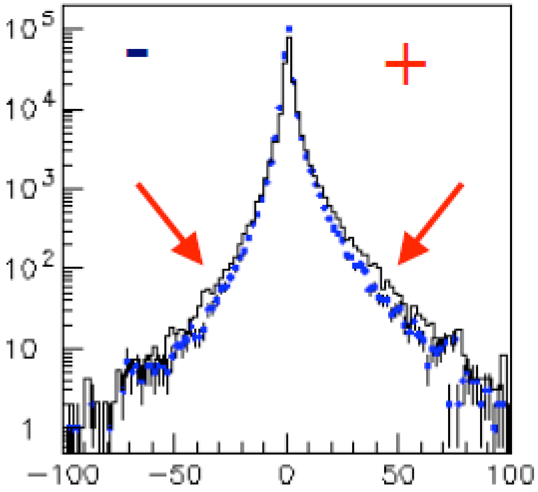


Hadrons angular dist. (rad)

Fragmentation too hard (F)
Multiplicity too small (F,N)
Too few soft particles (F,N)
Too few hadrons at large angles (F, mostly N for +)



Hadrons momenta (GeV/c)



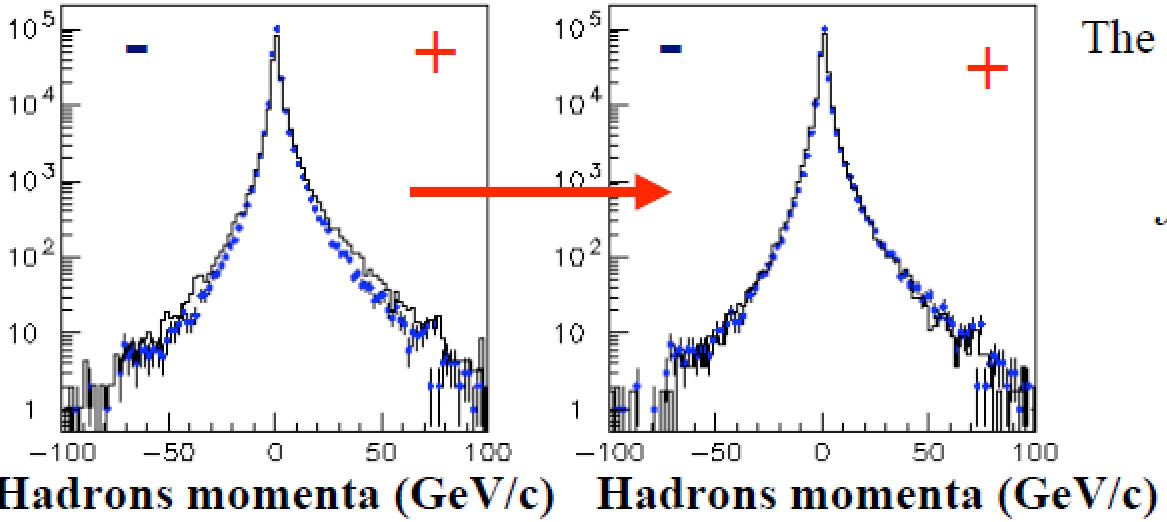
Hadrons momenta (GeV/c)

How to disentangle ?

Fix fragmentation first by looking at the tails > 5GeV where little effects from (N are expected

Some help from BEBC D dat

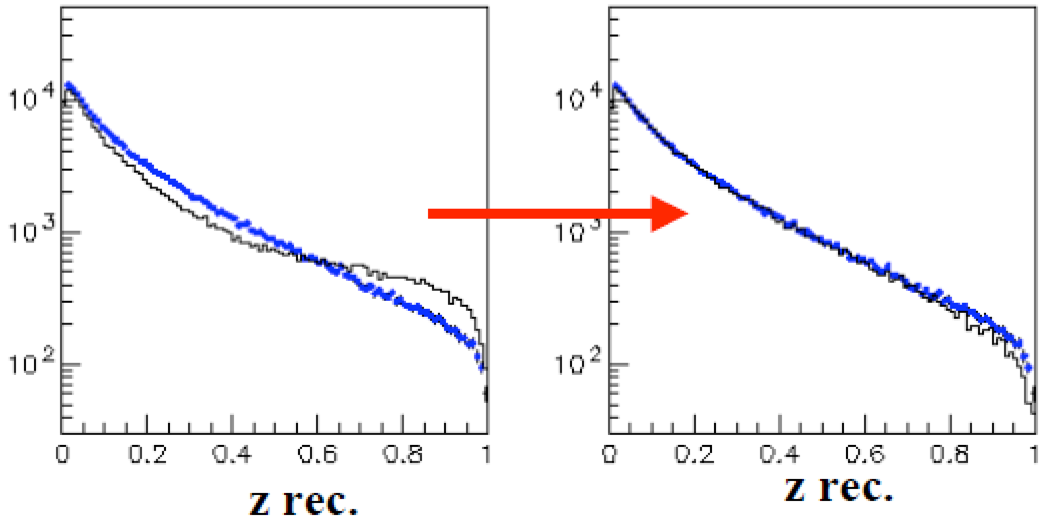
Fragmentation tuning done by generating events with a,b parameters in a grid around the BEBC values: Z. Phys C 24 (1984). By looking at the high momentum tails a minimum is found close to the BEBC values for a,b (NO INC)



The LUND fragmentation function:

$$f(z)=\frac{1}{z}(1-z)^a\exp\left(\frac{-bm_t^2}{z}\right)$$

BEBC: a=1,b=0.7
Cutoff to stop fragmentation:
0.2 GeV



The minimum was close to BEBC, kept the BEBC parameters also with the argument that on deuterium there are negligible effects of INC

- After having adjusted the fragmentation parameters the formation time was tuned on the NOMAD data aiming to a global minimization of the hadronic distributions:

- Hadronic multiplicity and total charge of the event
- Hadronic spectra for positives and negatives separately
- Angular distributions (for + and -)

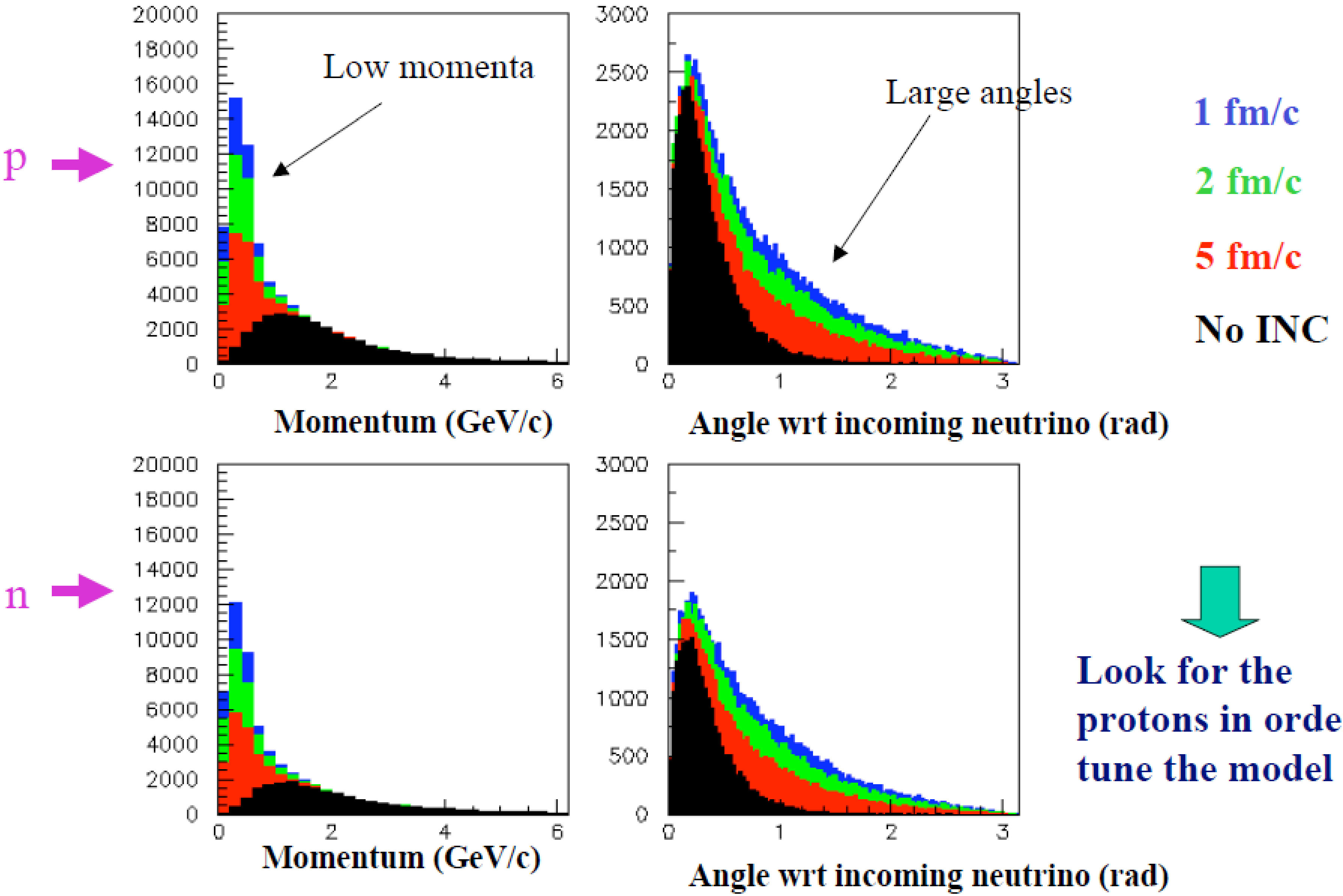
- Some distributions were in particular used to be more sensitive to the presence of the protons in the forward region:

- Hadron with the largest angle in the event (for + and -)
- Spectra of hadrons produced at large angles (for + and -)

- The formation time resulting from this minimization can be used to predict the rate of backward going protons which is measured by an independent analysis.

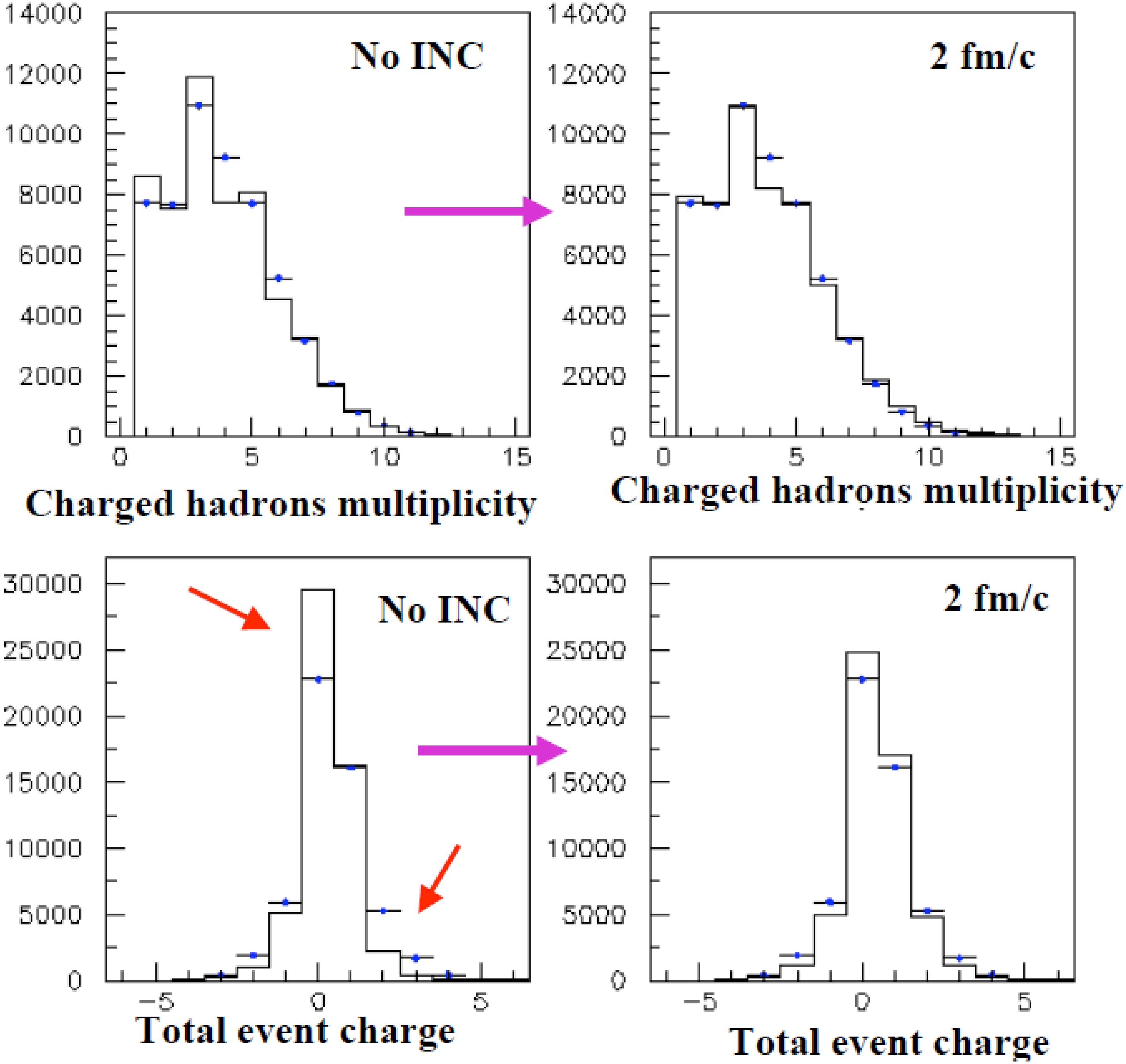
- The production of soft protons at large angles + neutrons (at any angle) degrades the energy resolution of the experiment.

Proton and neutron yields increase with the INC (DIS, Nomad beam and target, pure MC level):

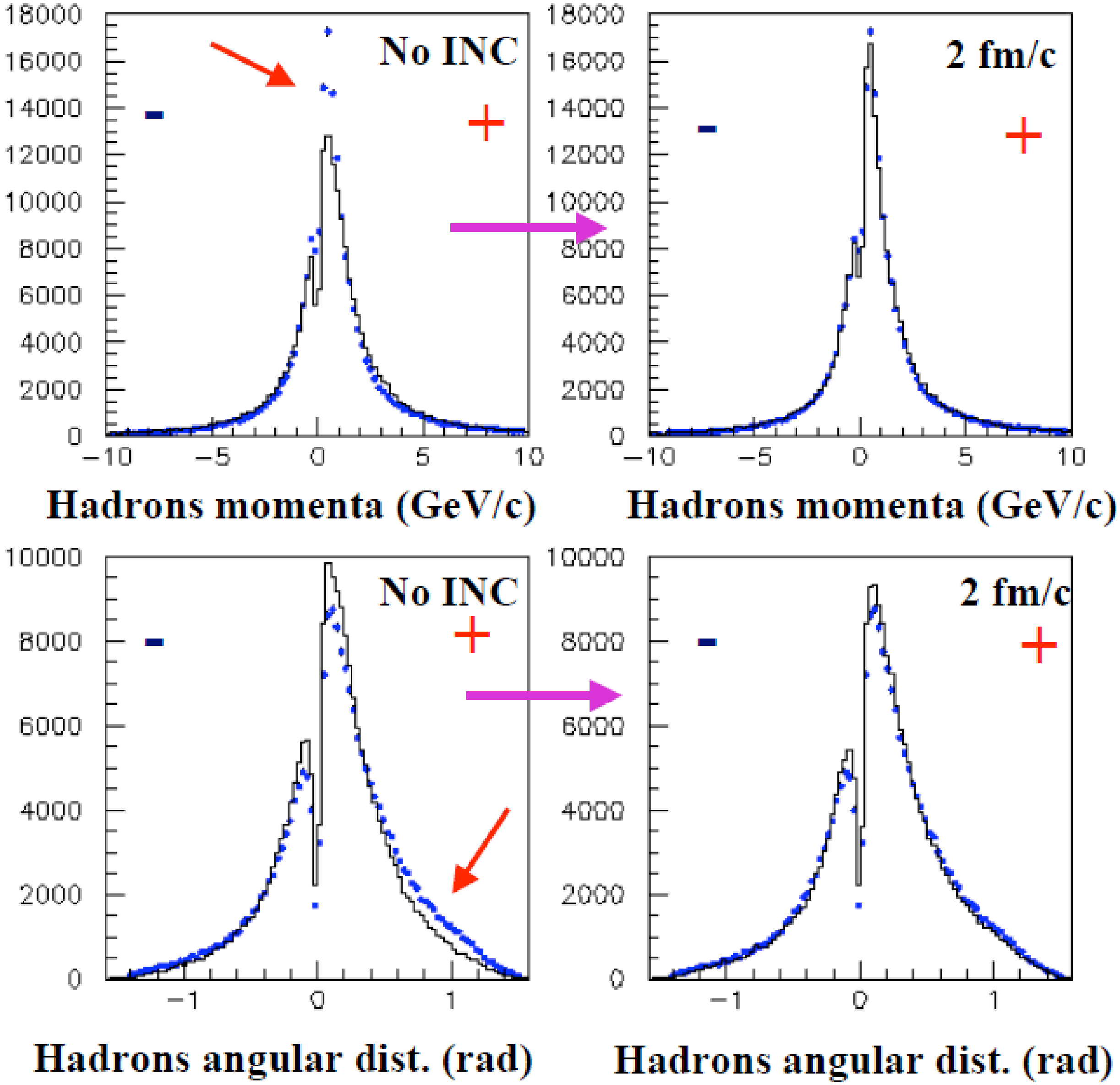


Look for the protons in order to tune the model

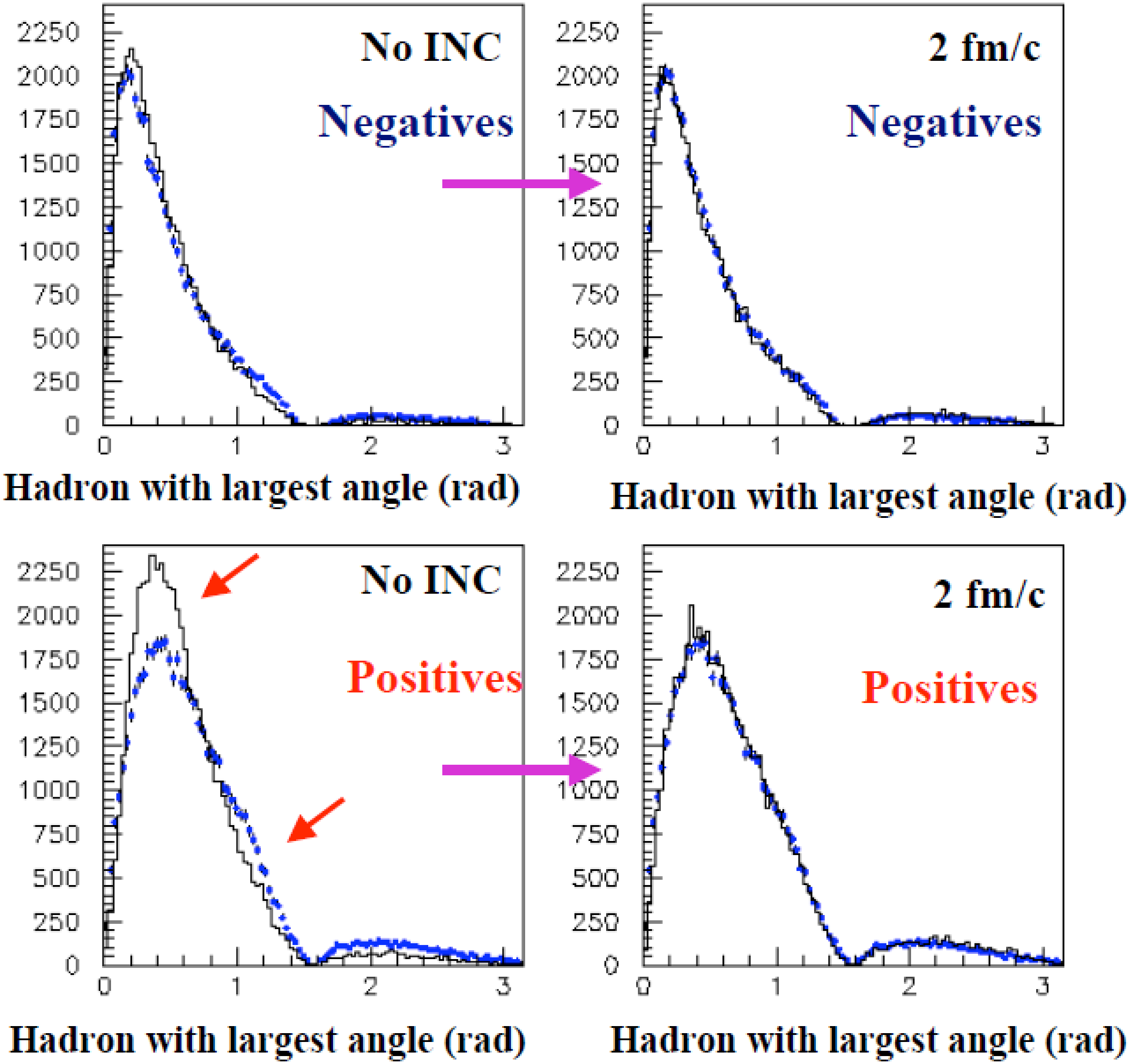
Formation time tuning, after fragmentation tuning: INC improves the agreement data-MC, (minimum found at 2 fm/c)



Hadrons spectra and angular distributions

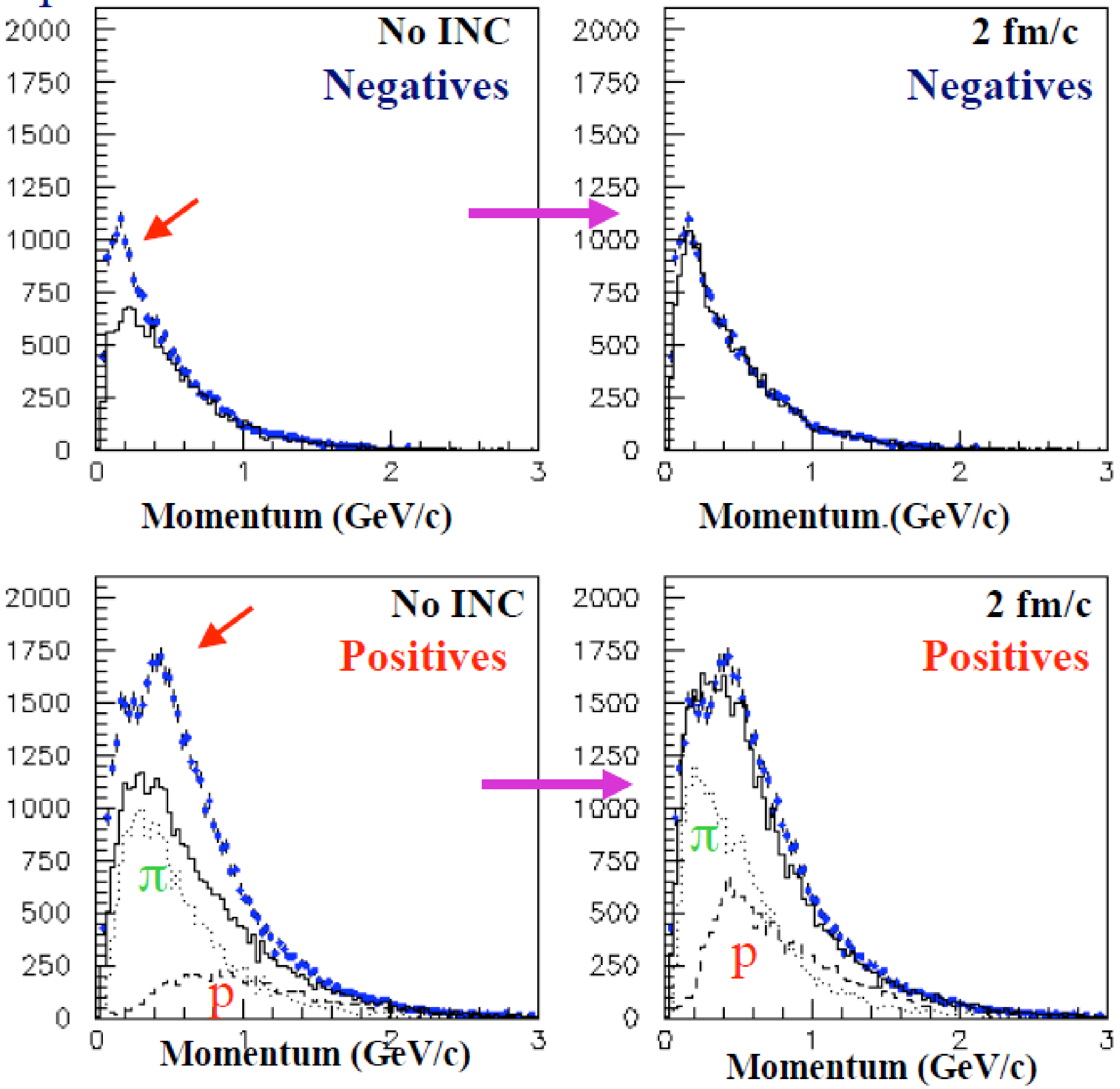


Looking for the presence of the protons from INC ….
Hadron with the largest angle (wrt incoming neutrino) in the event

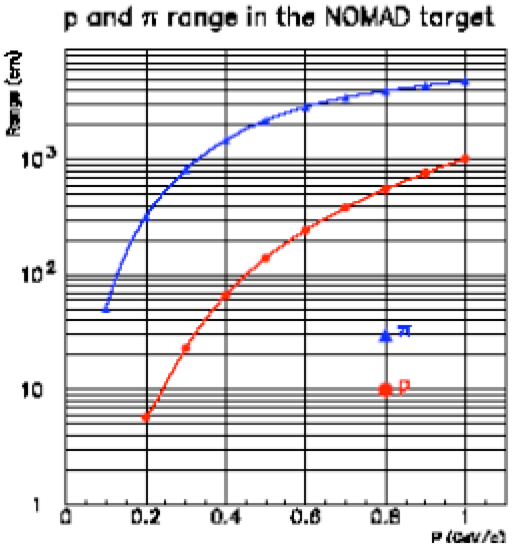


Strong improvement of the agreement data-MC for the positives due to the INC protons

Looking for the presence of the protons from INC ….
Spectra for hadrons with $0.5<\theta<1.57$

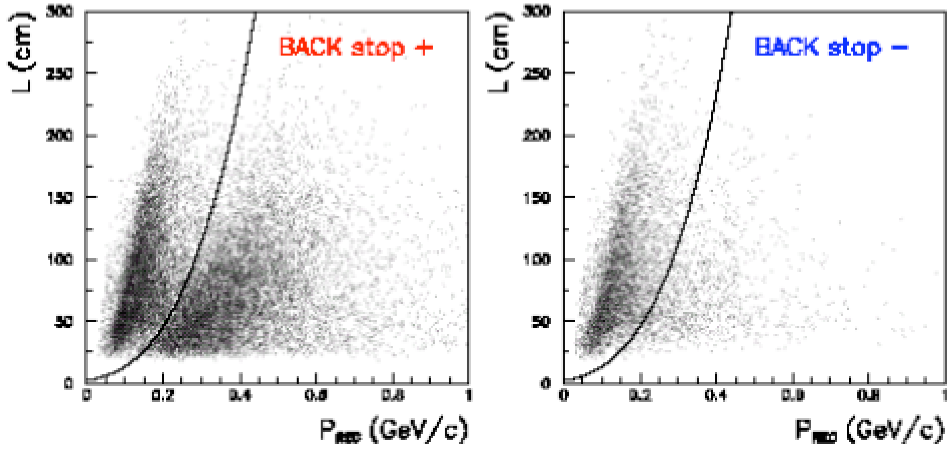


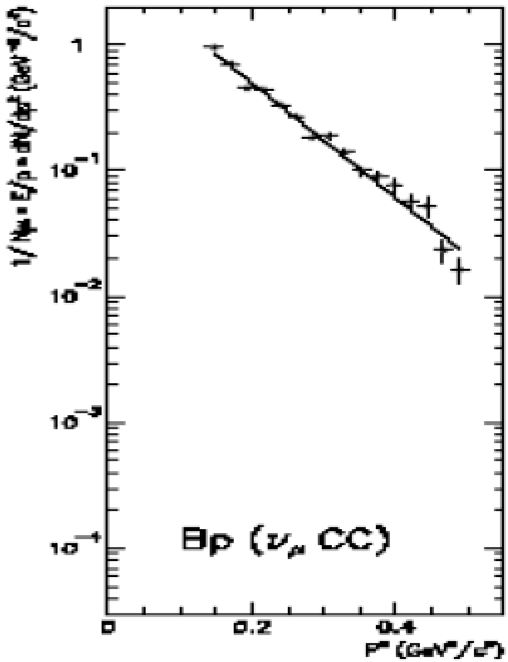
Backward protons (kinematically forbidden for neutrino interactions on stationary nucleons) are a very sensitive observable for the tuning of INC



Nomad has published a paper on the production of backward particles: P.Astier et al. Nuc. Phys. B 609 (2001), see also M. Veltri Nuint01 proc.

Protons can be identified by range looking in the sample of backward stopping particles



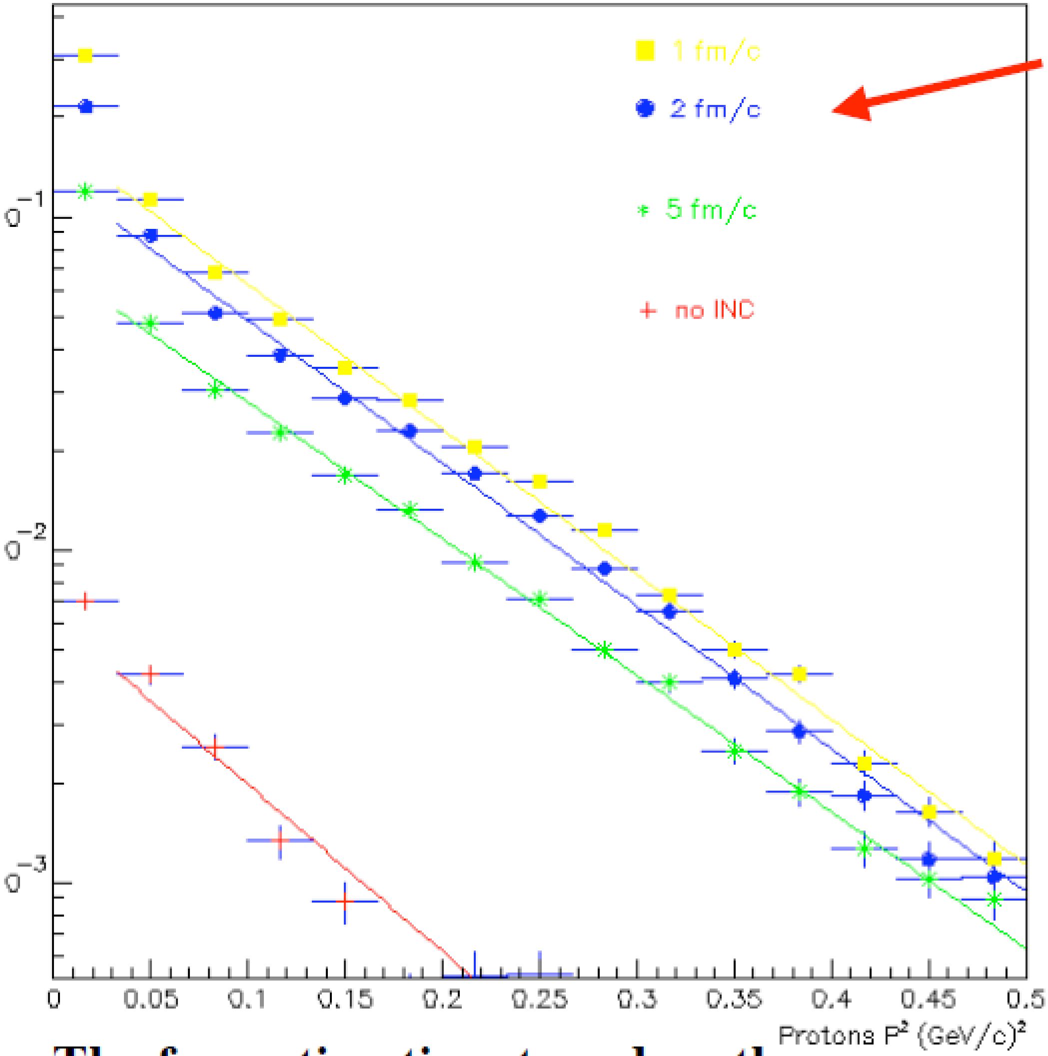


Invariant cross section:

$$\frac{1}{N_{ev}}\ \frac{E}{P}\ \frac{dN}{dP^2} = C\ e^{-BP^2}$$

# of BP per DIS ν_μ CC

$$< N_{Bp} >_{350\div800MeV/c} = \left[\ 52.8 \pm 0.6(stat.) \pm 7(syst.)\ \right] \times 10^{-3}$$



NEG-N: invariant spectrum in NOMAD for various formation times

The slope is not affected by the formation time, the rate is quite sensitive to the formation time

Formation time	NBP [350-800] MeV/c
Data	52.8 +-7 10^{-3}
NO INC	2.1 10^{-3}
5 fm/c	31.3 10^{-3}
2 fm/c	53.0 10^{-3}
1 fm/c	67.5 10^{-3}

The formation time tuned on the hadronic distributions predicts the correct rate of BP.

On the contrary one can constrain the formation time from the measurement of BP which gives: $2^{+0.9}_{-0.5}$ fm/c

NOMAD

Analysis		τ^-		τ^+		$\epsilon_\tau(\%)$	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$	$S_{\mu\tau}$
		Obs	Tot Bkgnd	Obs	Tot Bkgnd				$(\times 10^{-4})$
$\nu_\tau \bar{\nu}_e e$	DIS	5	$5.3^{+0.7}_{-0.5}$	9	8.0 ± 2.4	3.6	4318	88.0	8.0
$\nu_\tau h(n\pi^0)$	DIS	21	19.5 ± 3.5	44	44.9 ± 4.6	2.2	7522	177.4	4.0
$\nu_\tau 3h(n\pi^0)$	DIS	3	4.9 ± 1.5	10	9.9 ± 1.6	1.3	1367	33.3	22.2
$\nu_\tau \bar{\nu}_e e$	LM	6	5.4 ± 0.9	3	2.2 ± 0.5	6.3	864	8.8	55.2
$\nu_\tau h(n\pi^0)$	LM	12	11.9 ± 2.9	40	44.1 ± 9.2	1.9	857	16.7	88.9
$\nu_\tau 3h(n\pi^0)$	LM	5	3.5 ± 1.2	1	2.2 ± 1.1	2.0	298	5.2	161.0

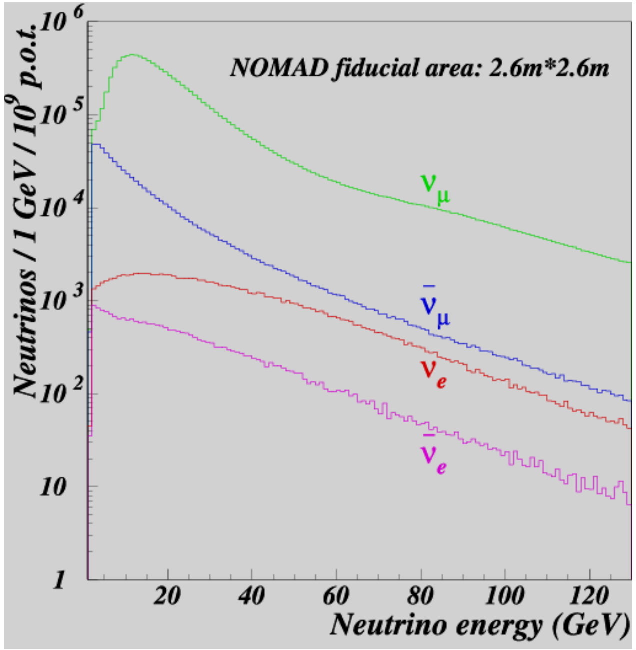
Final NOMAD results (2001)

Number of signal events expected in case of full mixing

CHORUS (Phase I)

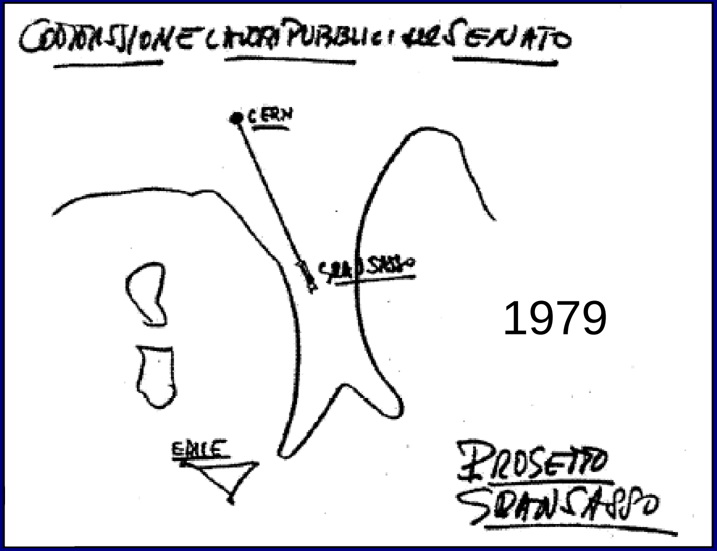
Analysis	Tot. bkg.	$N^{\tau}_{P=1}$	Data
$\nu_\tau \bar{\nu}_\mu \mu$	0.11 ± 0.03	5014	0
$\nu_\tau 0\mu$	1.10 ± 0.33	2004	0
	$\boxed{1.21^{+0.33}_{-0.33}}$	7018	0

No evidence of $\nu_\mu - \nu_\tau$ oscillations



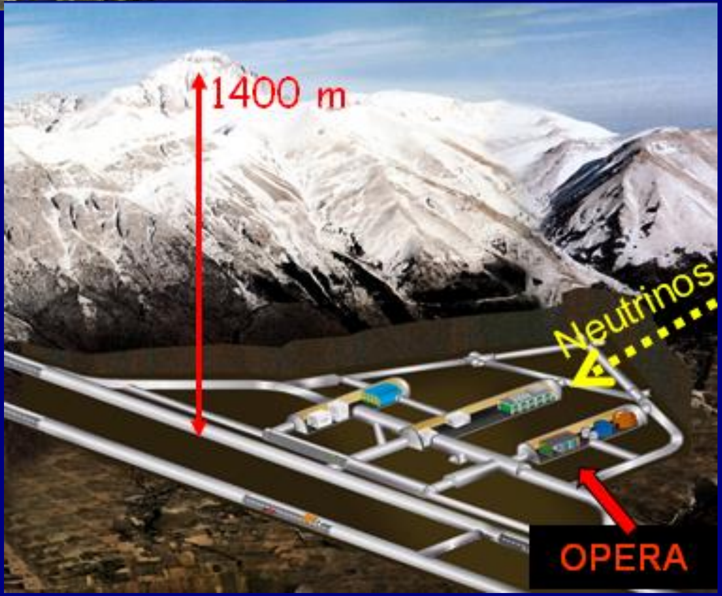
Average energy of numu in NOMAD: 24 GeV
Average energy of numu CC interactions: 48 GeV

- In order to optimize the sensitivity to oscillations at low delta *m*2, dedicated analyses at “Low Multiplicity”, *pH* < 1:5 GeV/c
- LM sample enriched in quasi-elastic and resonance events
- Overall, the QE and RES events represent 6.3% of the total *CC* interactions at the available neutrino energies.



Cern Neutrinos to Gran Sasso

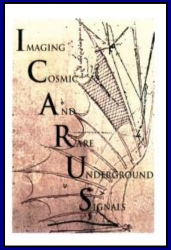
- Unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of atmospheric neutrinos by looking for ν_τ appearance in a pure ν_μ beam
- Search for subleading $\nu_\mu \rightarrow \nu_e$ oscillations



- Beam: CNGS (1999)
- ν_τ appearance experiments at LNGS
- No near detectors needed in appearance mode

CNGS1 (2000)

OPERA



CNGS2 (2002)

Number of detected τ events

ν_μ flux

Cross section for ν_τ CC pulls to high energy

$$N_\tau = C \int_{3.5GeV}^{E\max} \Phi_\mu(E) \mathrm{P}_{\mu\tau}(E) \sigma_\tau(E) dE$$

Constant representing detector mass and average detection efficiency

Pulls to low energy

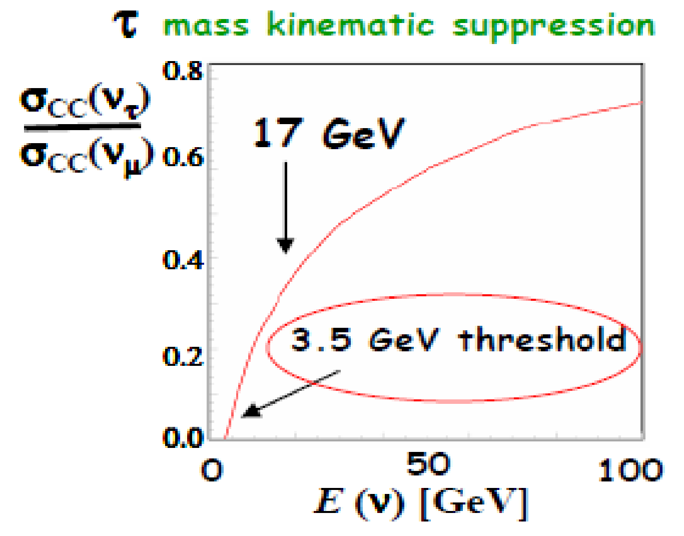
$P_{\mu\tau}$~1.7 10^{-2}
For CNGS
@ full mixing,
$\Delta m^2 = 2.4\ 10^{-3}$ eV^2

$$\mathcal{P}_{\mu\tau} = \sin^2(2\theta)\sin^2(1.27\Delta m^2 \frac{L}{E}) \approx 1.27^2 \sin^2(2\theta)(\Delta m^2)^2\left(\frac{L}{E}\right)^2$$

Small quantity for
$\Delta m^2 < 4\ 10^{-3}$ eV^2
L= 730 Km,
E>3.5 Gev
→ Long λ with respect to L
L dependence extracted from integral

CNGS:
L/E = 43 Km/GeV
«off peak »

Peak at L/E=515 Km/GeV for $\Delta m^2 = 2.4\ 10^{-3}$ eV^2



$$N_\tau \approx 1.61 \sin^2(2\theta)(\Delta m^2)^2 L^2 \int_{3.5GeV}^{E_{\max}} \Phi_\mu(E)\frac{\sigma_\tau(E)}{E^2} dE$$

$$N_\tau \approx 1.61 \sin^2(2\theta)(\Delta m^2)^2 L^2 \int_{3.5GeV}^{E_{\max}} \Phi_\mu(E) \frac{\sigma_\tau(E)}{E^2} dE$$

Quantity to be optimized playing with the beam spectrum:
ν_μ flux vs $\sigma(\tau)/E^2$

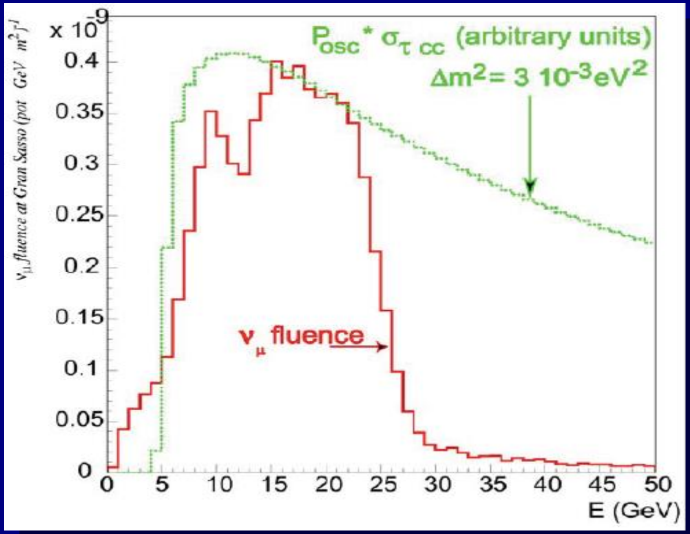
→ produce the max. number of $\nu\tau$ CC

Dependence of the events rate on $(\Delta m^2)^2$

Signal constant as a function of L for L << λ
Φ_μ contains a factor $1/L^2$

CNGS fluxes

<E (ν_μ)>	17 GeV
L	730 km
L/E	43 Km/GeV
(ν_e + ν_e)/ν_μ CC	0.87%
ν_μ / ν_μ CC	2.1%
ν_τ prompt	negligible

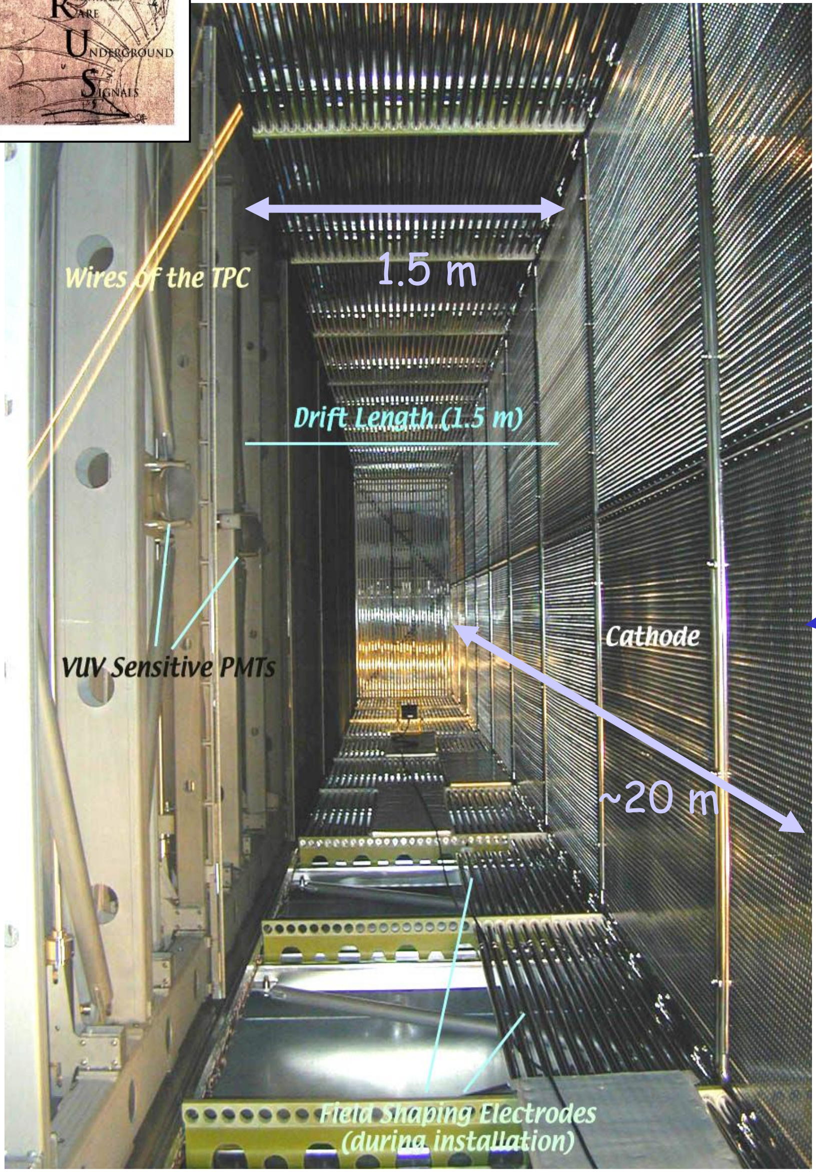


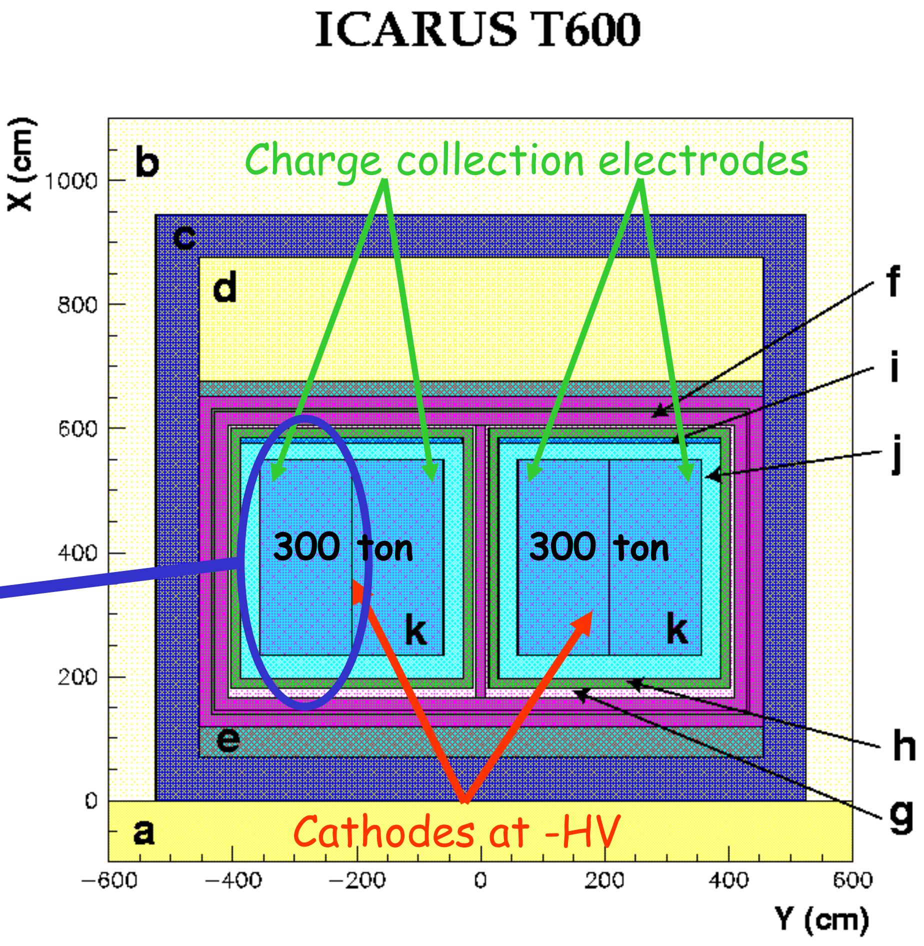
- **Nominal beam performance (4.5 10^{19} pot/y)**
- **OPERA Target mass of 1.25 kton**

→ Expected number of interactions in 5 years :
~ 23600 ν_μ CC+NC
~ 170 ν_e + ν_e CC
~ 115 ν_τ CC (Δm^2 =2.5 x 10^{-3} eV^2)

After efficiencies, 8 tau decays expected, with <1 background events

ICARUS LAr TPC T600 prototype (2001)





a) rock
b) hall B
c) neutron shield
d) cables-electronics
e) platforms
f) insulation

g) gap
h) container
i) gas phase Ar
j) inactive LAr
k) active LAr

Initially foreseen ICARUS detector configuration (T3000)

The “cloning” project

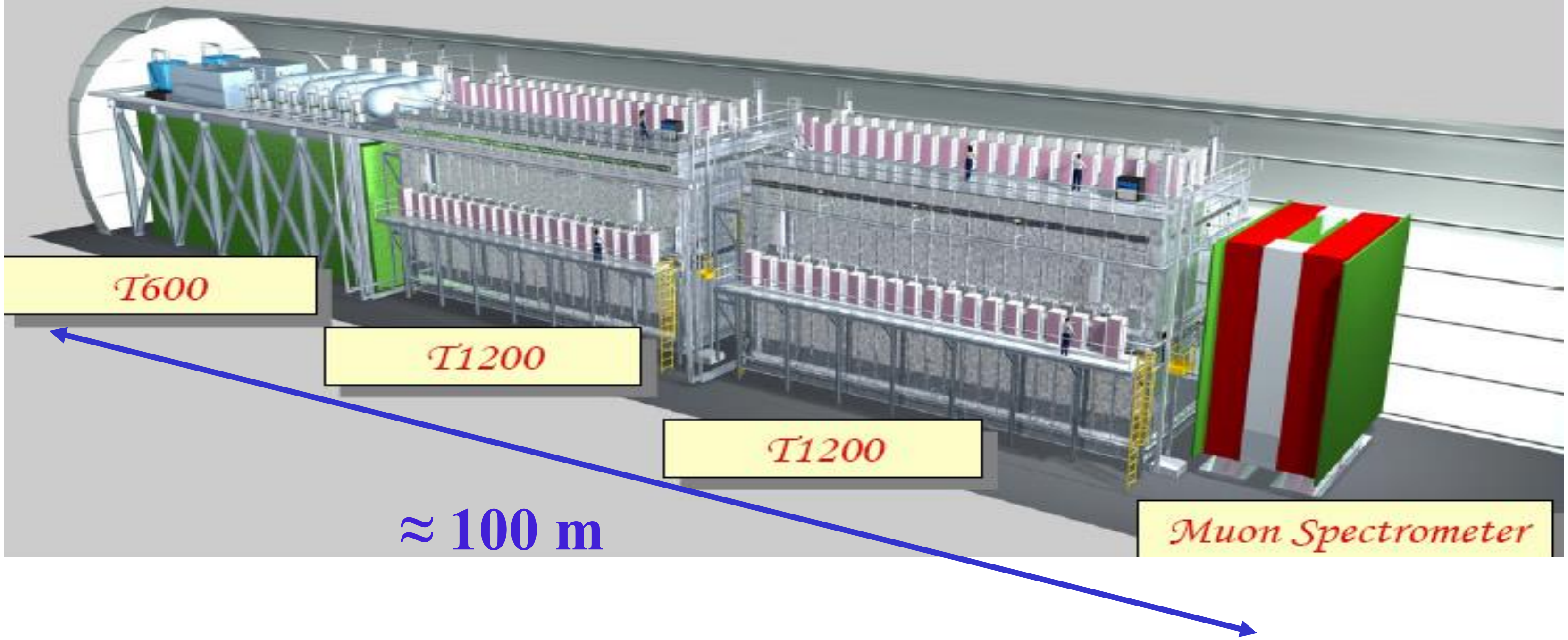
≈3 kton of liquid Argon, 2.35 Kton fiducial mass

First Unit T600 + Auxiliary Equipment

T1200 Unit (two T600 superimposed)

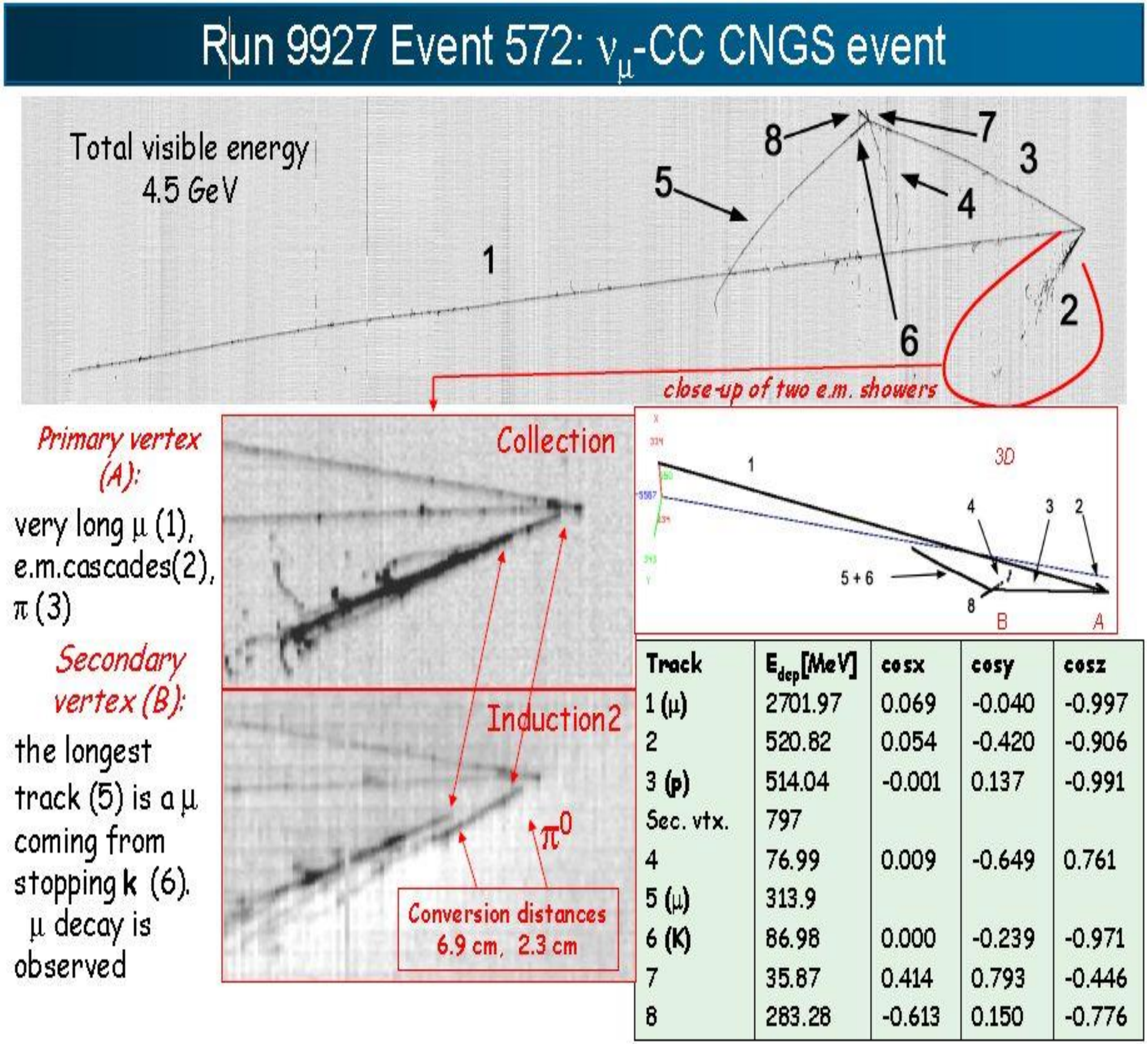
T1200 Unit (two T600 superimposed)

Magnet



The ICARUS program was then unfortunately limited to a single T600 module

The liquid argon TPC as an electronic bubble chamber



Run 9927 Event 572: ν_μ-CC CNGS event

Total visible energy 4.5 GeV

Conversion distances 6.9 cm, 2.3 cm

Primary vertex (A):

very long μ (1), e.m.cascades(2), π (3)

Secondary vertex (B):

the longest track (5) is a μ coming from stopping **k** (6). μ decay is observed

Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

$\nu_\mu \to \nu_\tau$ appearance : electron decay channel

Like for NOMAD, main background due to: $\nu_e + N \to e^- + X$
(<1% ν_e beam contamination)

Simple analysis approach: a likelihood method based on 3 variables:

- $E_{visible}$
- P_T^{miss}
- $\rho_l \equiv P_T^{lep}/(P_T^{lep} + P_T^{had} + P_T^{miss})$

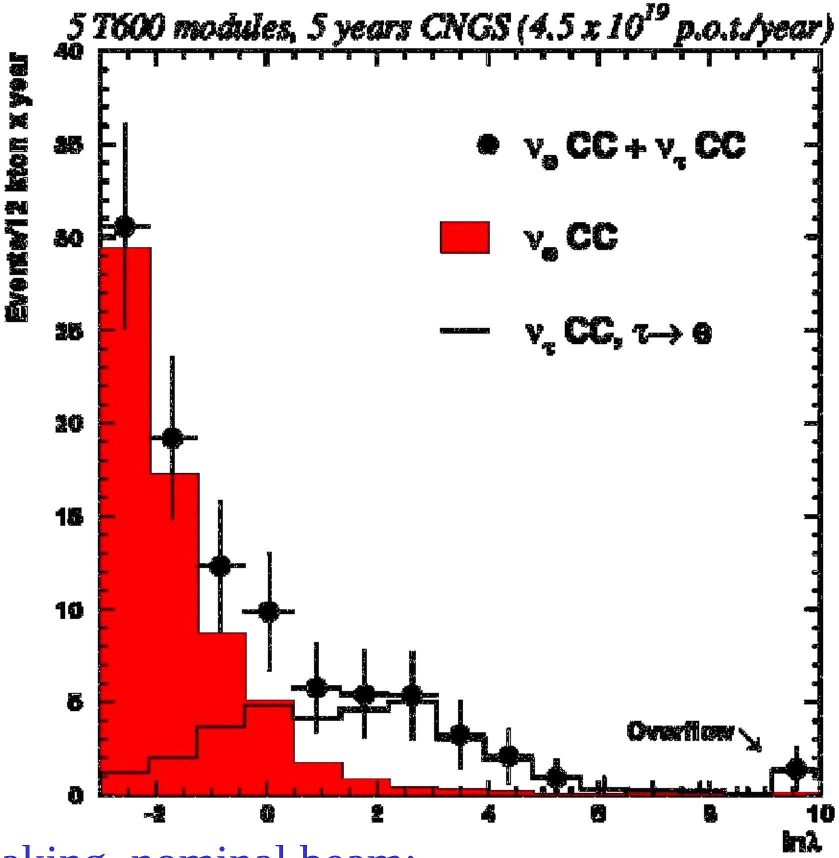
•Exploit correlation between them

- L_S ([Evisible, P_T^{miss}, ρ_l])
  (signal)
- L_B ([Evisible, P_T^{miss}, ρ_l])
  (ν_e CC background)

–Discrimination given by:

$$\boxed{\ln\lambda \equiv L([\text{Evisible}, P_T^{miss}, \rho_l]) = L_S / L_B}$$

5 T600 modules, 5 years CNGS (4.5 x 10^{19} p.o.t./year)



Signal and background events for 5 years of data taking, nominal beam:

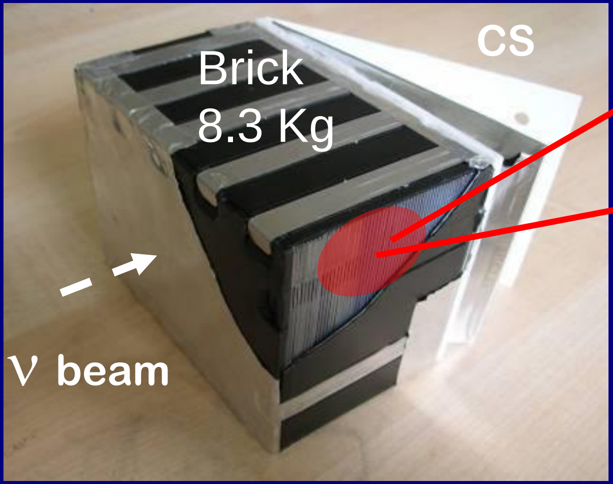
$\Delta m^2 = 1.6 \times 10^{-3}$ eV^2	$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	$\Delta m^2 = 4.0 \times 10^{-3}$ eV^2	Bck.
4.8	11.9	17.2	30.6	0.7

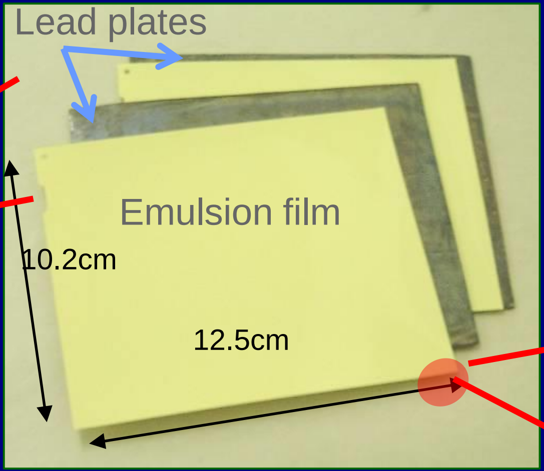
OPERA basic unit: the « Brick »

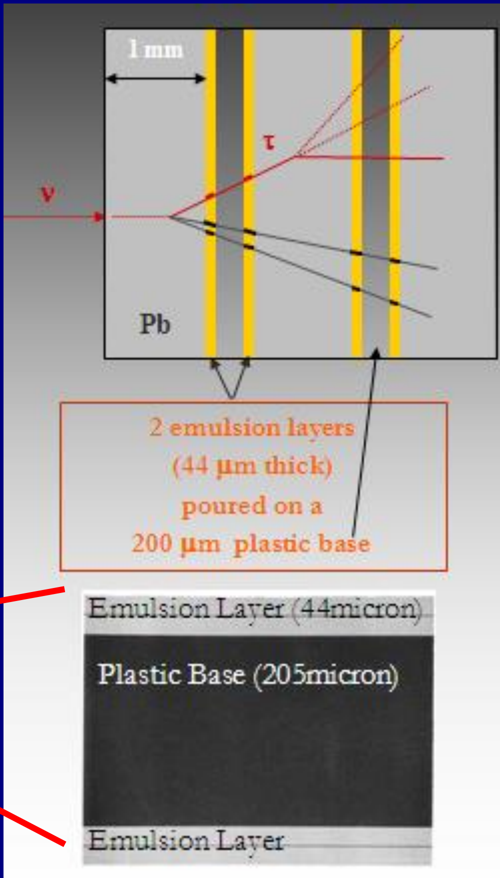
Based on the concept of the **E**mulsion **C**loud **C**hamber :

- 57 emulsion films + 56 Pb plates
- interface to electronic detectors: removable box with 2 films (Changeable Sheets)

→ High space resolution in a large mass detectors with a completely modular scheme







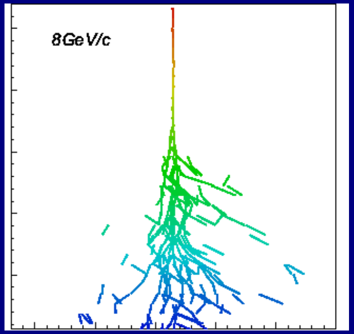
Tracks reconstruction accuracy in emulsions:

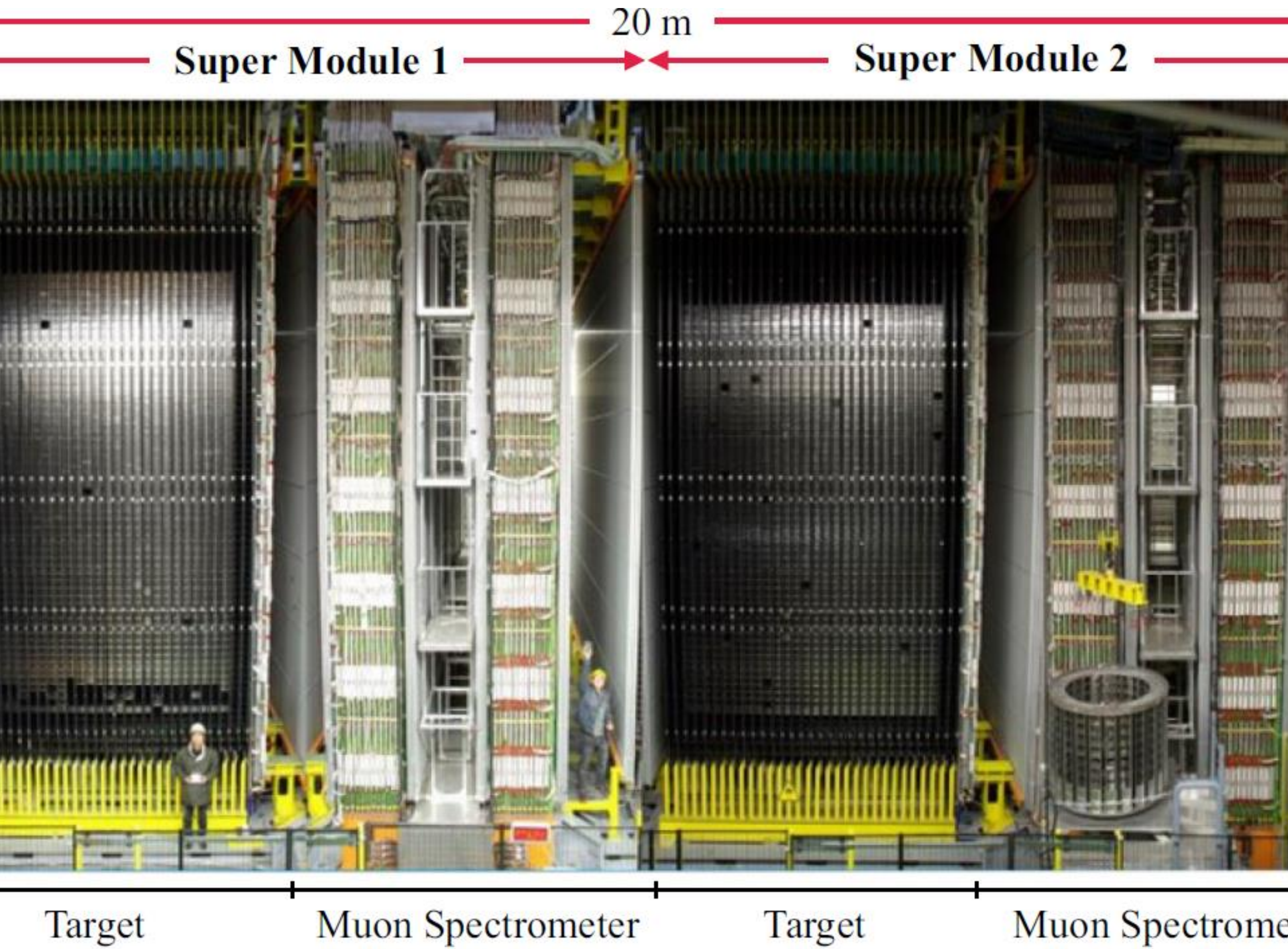
$\Delta x \approx 0.3\ \mu m \quad \Delta\theta \approx 2$ **mrad**

Bricks are complete stand-alone detectors:

- ✓ Neutrino interaction vertex and kink topology reconstruction
- ✓ Measurement of hadrons momenta by multiple Coulomb scattering
- ✓ dE/dx: pion/muon separation at low energy (at end of range)
- ✓ Electron identification and measurement of the energy of electrons and gammas (electromagnetic calorimetry)

→ Technique pioneered by DONUT for the observation of tau neutrino in 2000



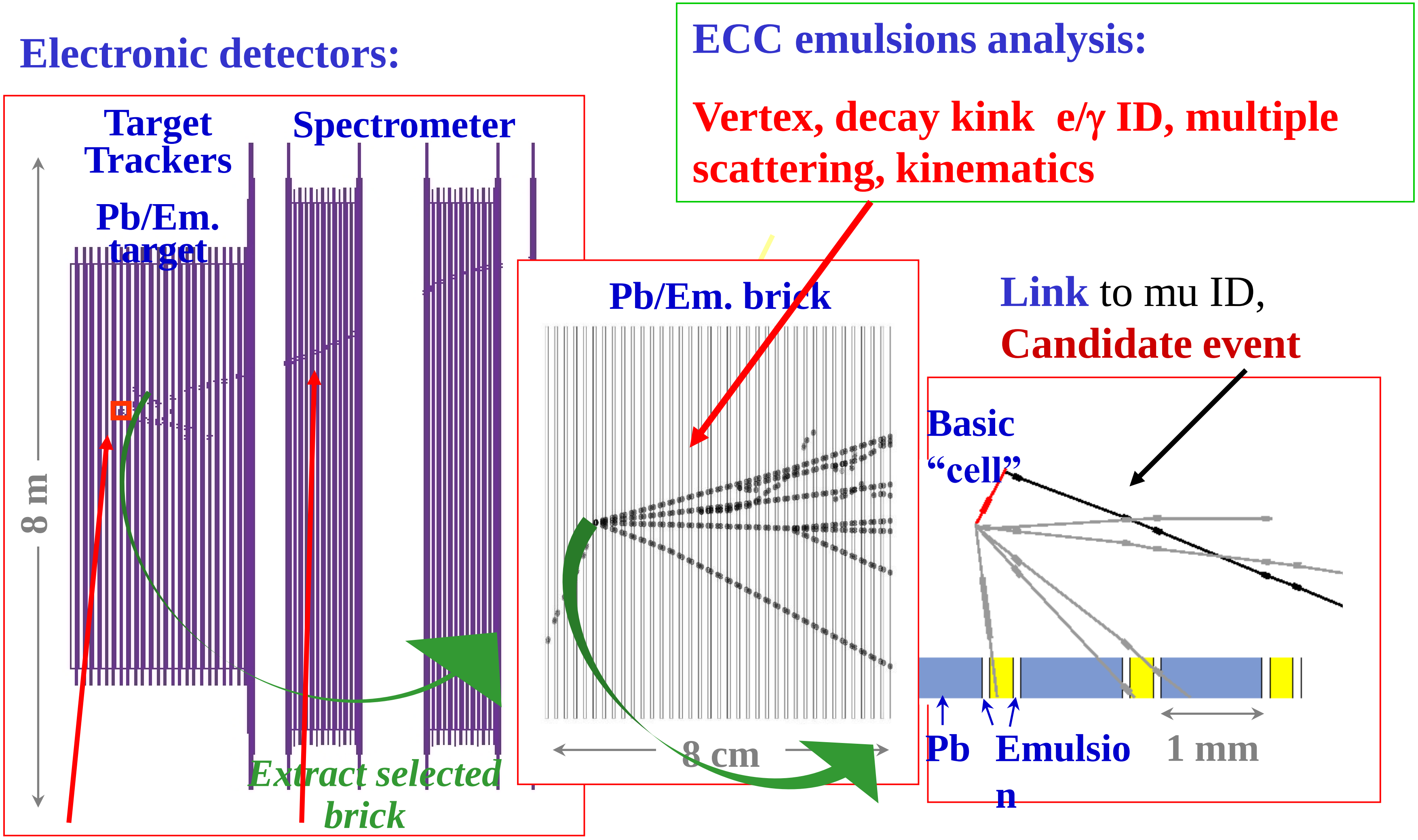

20 m
Super Module 1
Super Module 2
Target
Muon Spectrometer
Target
Muon Spectrome

Use of the electronic detectors:

- **trigger** and **localization** of neutrino interactions
- **muon** identification and momentum/charge measurement

→ need for a **hybrid** detector

Electronic detectors:



ECC emulsions analysis:

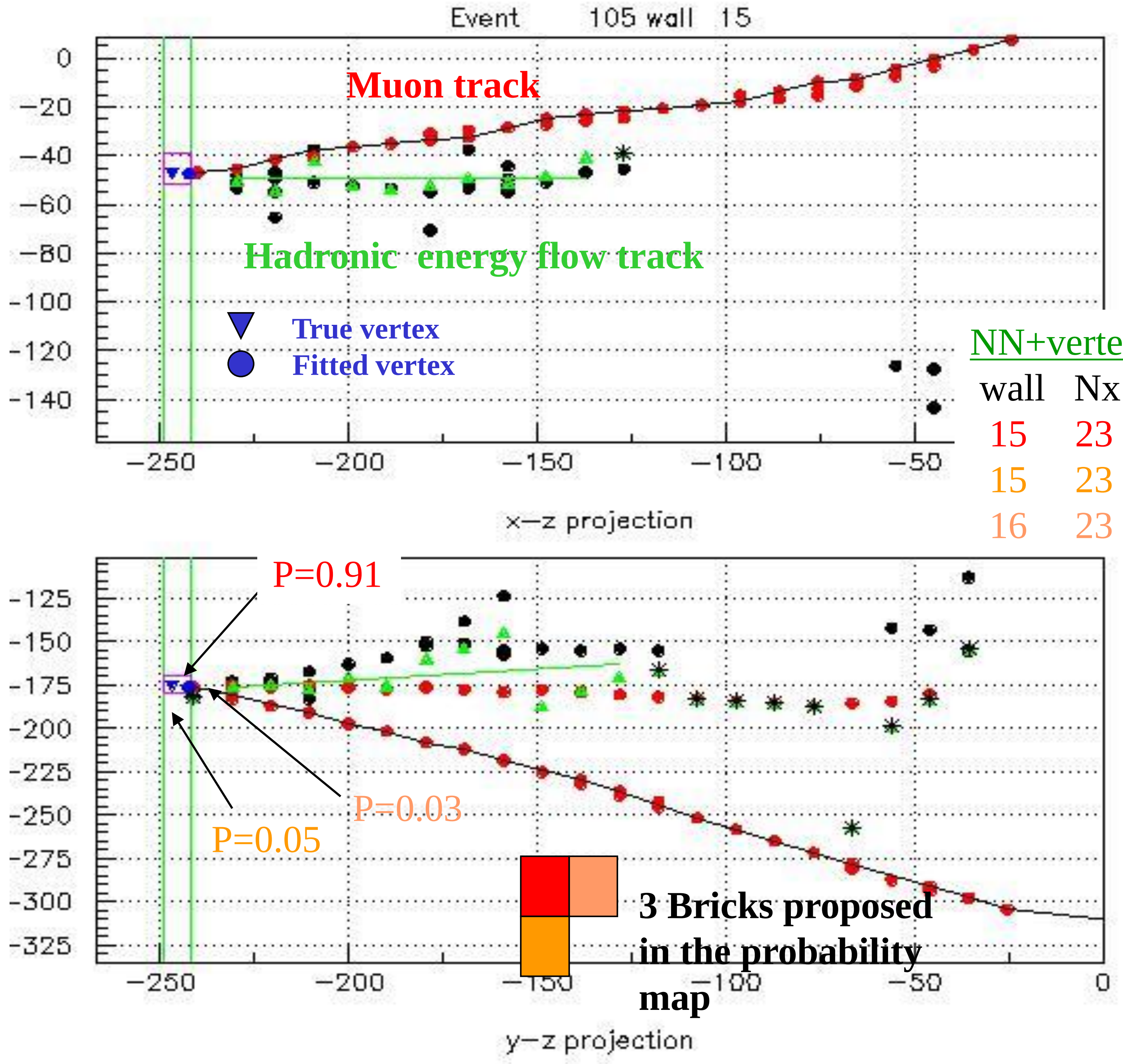
Vertex, decay kink e/γ ID, multiple scattering, kinematics

Link to mu ID,

Candidate event

Brick finding, muon ID, charge and p

Combined NN + tracking probability chart for a typical τ−>μ event



Muon track

Hadronic energy flow track

▼ **True vertex**

● **Fitted vertex**

P=0.91

P=0.03

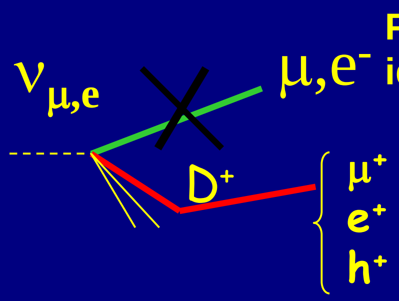
P=0.05

3 Bricks proposed in the probability map

NN+vertex Brick Prob. (P>1%)

wall	Nx	Ny	P
15	23	16	0.91
15	23	15	0.05
16	23	16	0.03

Background sources

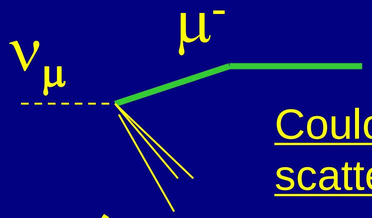


Primary lepton not identified

Charm production in CC, common to all channels

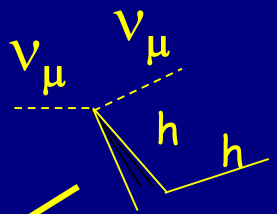
Good (~95%) muon identification is fundamental !

Same decay topology as τ



Coulombian large angle scattering of muons in Lead

Bck. to $\tau \to \mu$



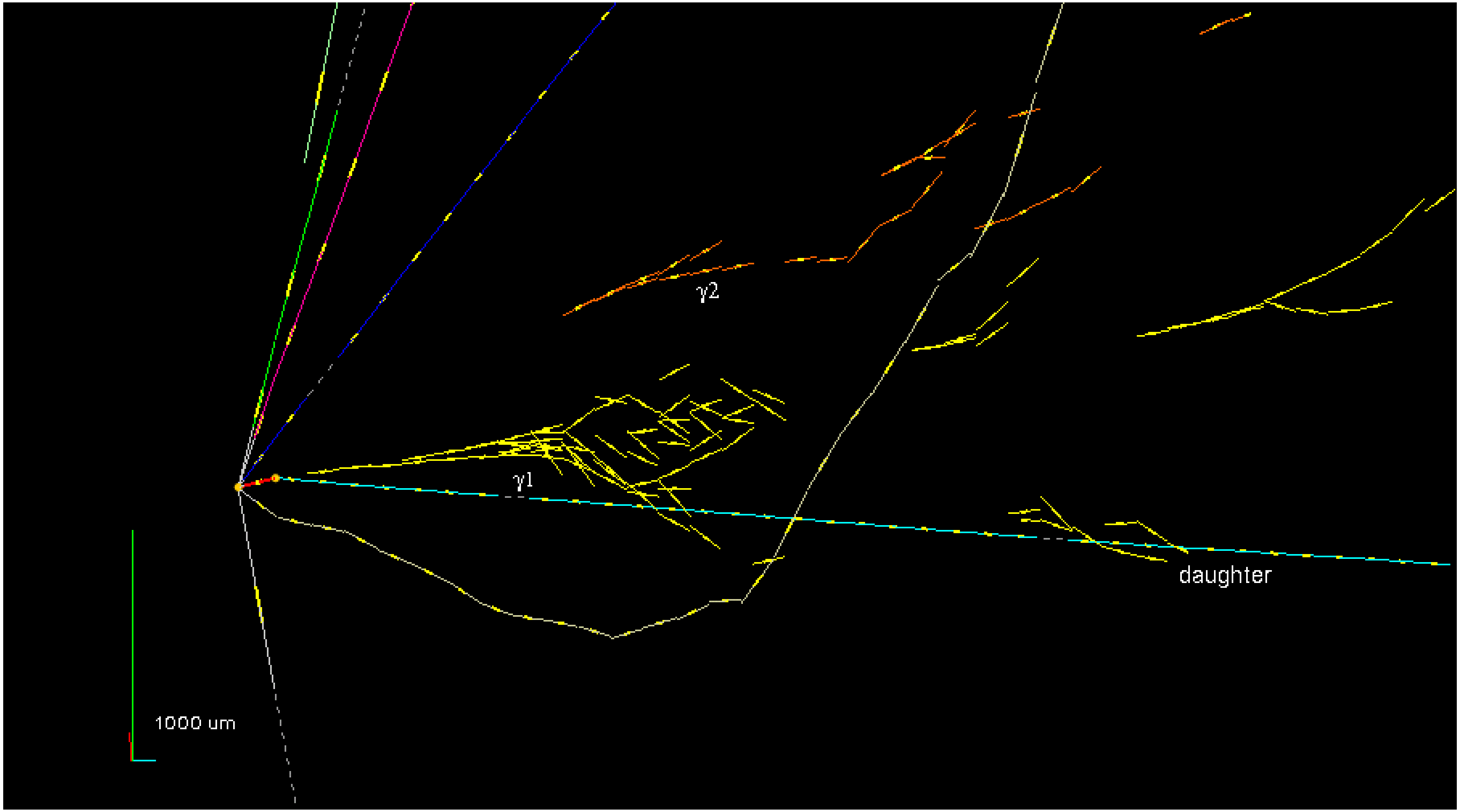
Hadronic interactions in Pb: Bck. to $\tau \to h$

Expected number of background events

	$\tau \to e$	$\tau \to \mu$	$\tau \to h$	$\tau \to 3\pi$	**Total**
Charm	0.035	0.008	0.15	0.44	0.63
Muon scattering	0	0.016	0	0	0.016
Hadronic interactions	0	0	1.28	0.09	1.37
Total	0.035	0.024	1.43	0.52	2.0

First OPERA ν_τ candidate
(single hadronic prong τ decay)

http://arxiv.org/abs/1006.1623
Physics Letters B (PLB-D-10-00744)



$$\nu_\tau + N \rightarrow \tau^- + X$$

$$\tau^- \rightarrow \rho^- + \nu_\tau$$

$$\rho^- \rightarrow \pi^- + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

Visible tau decay topology
with kink and two gammas

Final OPERA results (all channels)

Channel	Expected Background				ν_τ Exp.	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.39	2.96 ± 0.59	6
$\tau \to 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.52 ± 0.09	1.83 ± 0.37	3
$\tau \to \mu$	0.008 ± 0.002	–	0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1
$\tau \to e$	0.035 ± 0.007	–	–	0.035 ± 0.007	0.84 ± 0.17	0
Total	0.63 ± 0.10	1.37 ± 0.38	0.016 ± 0.008	2.0 ± 0.4	6.8 ± 0.75	10

Final analysis:

- **Selection of kink decay topology**

Tracks reconstruction: tan(theta)<1
tan (theta)<3 check for large angle tracks on tau candidate events

- Boosted decision tree analysis based on **kinematics**:

- Missing transverse momentum
- ϕ(lH)
- Invariant mass of daughters (only for 3 pions decay mod)

Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
z_{dec} (mm)	< 2.6	< 2.6	< 2.6	< 2.6
θ_{kink} (rad)	> 0.02	> 0.02	> 0.02	> 0.02
p_{2ry} (GeV/c)	> 1	> 1	$[1, 15]$	> 1
p^T_{2ry} (GeV/c)	> 0.15	-	> 0.1	> 0.1
charge$_{2ry}$	-	-	negative or unknown	-

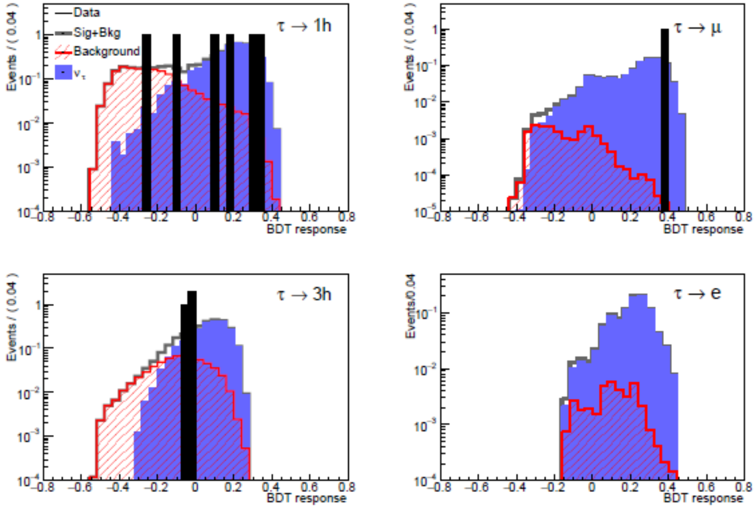
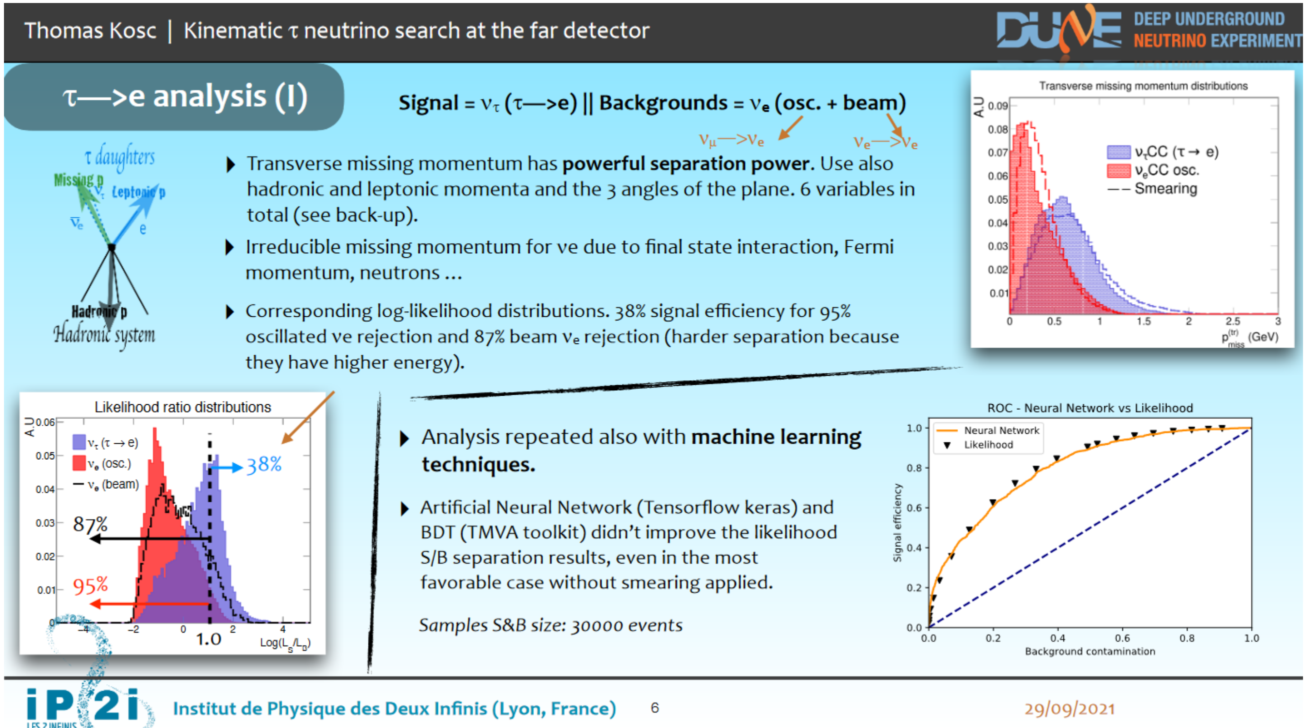


FIG. 2. BDT response for each channel.

Perspectives for DUNE:

- LAr TPC is the ideal detector (tracking/calorimeter) to extrapolate at large scale the kinematic method pioneered by NOMAD (first calculations with ICARUS)
- For the rejection in the electronic channel of photon conversions close to primary vertex exploit dE/dx measurement. Better acceptance for large angle tracks. Lower resolution
- Future searches, as in DUNE, require less strong S/B than in NOMAD/OPERA
- First application to DUNE starting from analysis experience in NOMAD for LM samples (at lower energy)
- Finer understanding in the future of detector reconstruction effects and of kinematical suppression of nutau CC cross section at low energy
- Understand also if neutrons could be measured
- → Likelihood approach computed by Thomas (e.g.for electronic channel): $\left[p_{lep}^{(tr)}; p_{miss}^{(tr)}\right] \times \left[\phi_{hm}^{(tr)}; \phi_{hl}^{(tr)}\right]$



Thomas Kosc | Kinematic τ neutrino search at the far detector

DEEP UNDERGROUND NEUTRINO EXPERIMENT

τ—>e analysis (I)

Signal = ν_τ (τ—>e) || Backgrounds = ν_e (osc. + beam)

$\nu_\mu \longrightarrow \nu_e$ $\nu_e \longrightarrow \nu_e$

- Transverse missing momentum has **powerful separation power.** Use also hadronic and leptonic momenta and the 3 angles of the plane. 6 variables in total (see back-up).
- Irreducible missing momentum for νe due to final state interaction, Fermi momentum, neutrons …
- Corresponding log-likelihood distributions. 38% signal efficiency for 95% oscillated νe rejection and 87% beam ν_e rejection (harder separation because they have higher energy).

- Analysis repeated also with **machine learning techniques.**
- Artificial Neural Network (Tensorflow keras) and BDT (TMVA toolkit) didn't improve the likelihood S/B separation results, even in the most favorable case without smearing applied.

Samples S&B size: 30000 events

Institut de Physique des Deux Infinis (Lyon, France) 6 29/09/2021

See talk by
T. Kosc at this
workshop

Conclusions:

- This talk tried to summarize past experience on $\nu\tau$ searches in tracking/calorimeters detectors (NOMAD, CHORUS, DONUT, ICARUS, OPERA)

- In particular it was tried to provide an overview on the roots of the kinematic method and what it implies from the point of view of the detector and of its response for the reconstruction of the hadronic system (which also implies a good understanding of simulations)

- LAr TPCs are the ideal detectors for massive scaling up of these techniques at the (10)kton scale

- It will be interesting to further develop and eventually apply on data this technique in DUNE