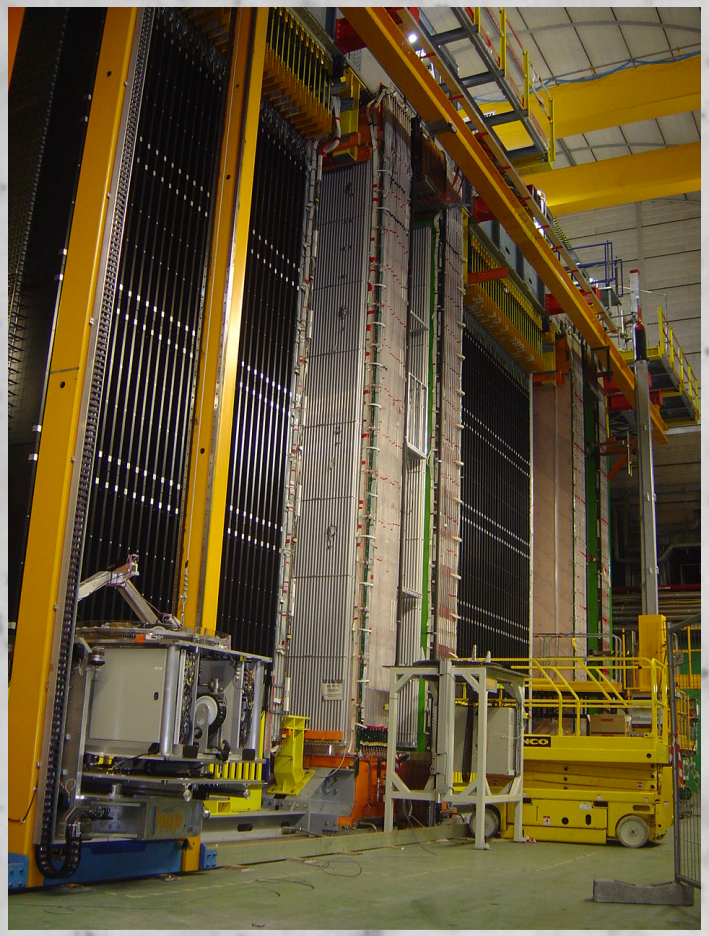
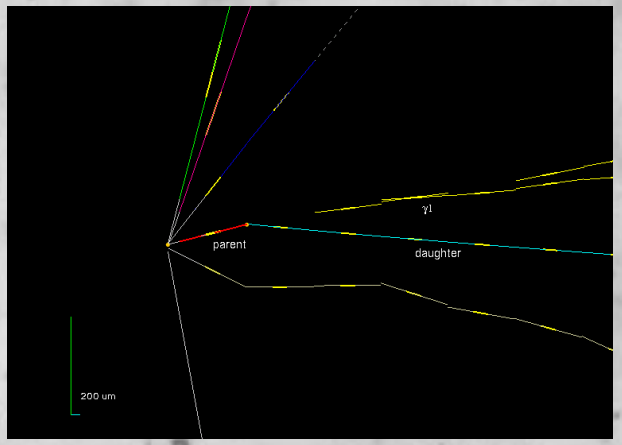
OPERA neutrino oscillation search: status and perspectives





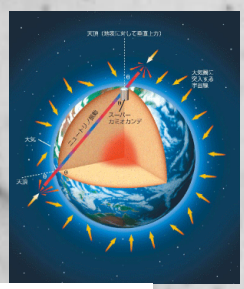
Yury Gornushkin (JINR)

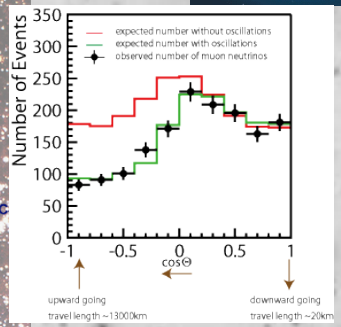
on behalf of the OPERA Collaboration

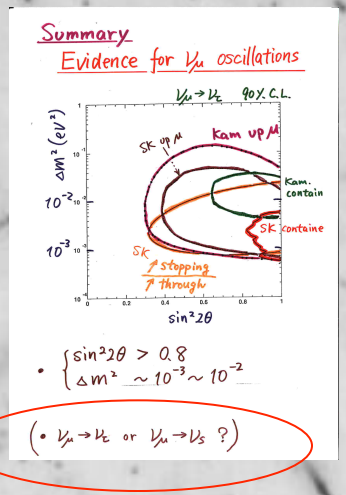
Outline

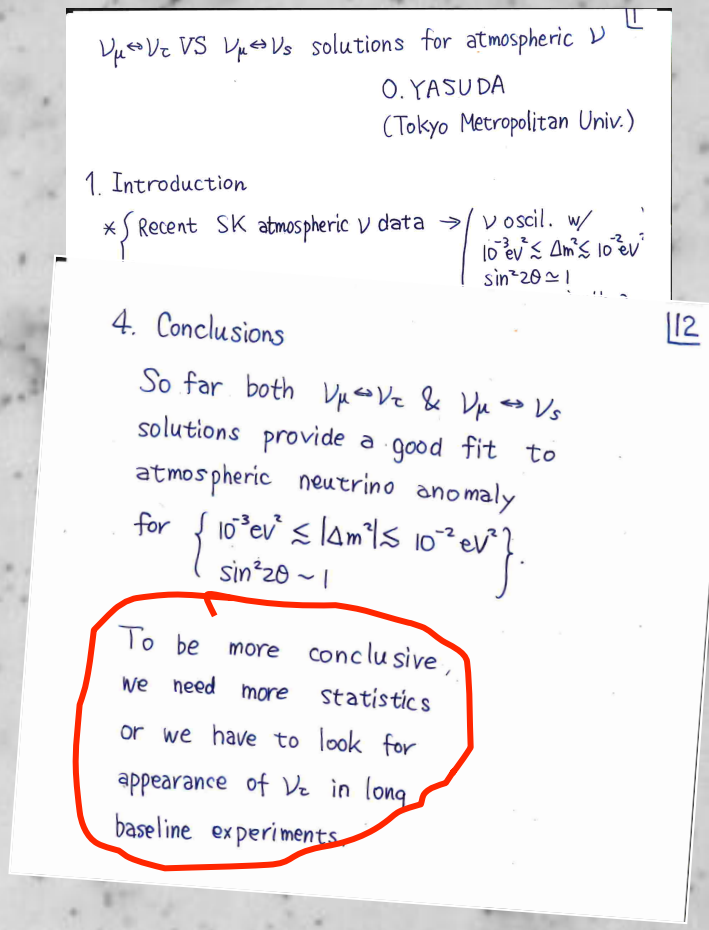
- Motivation and goals of the experiment
- Experimental technique and the detector
- Current status
- Recent results
- Conclusions

Looking back to XX century…

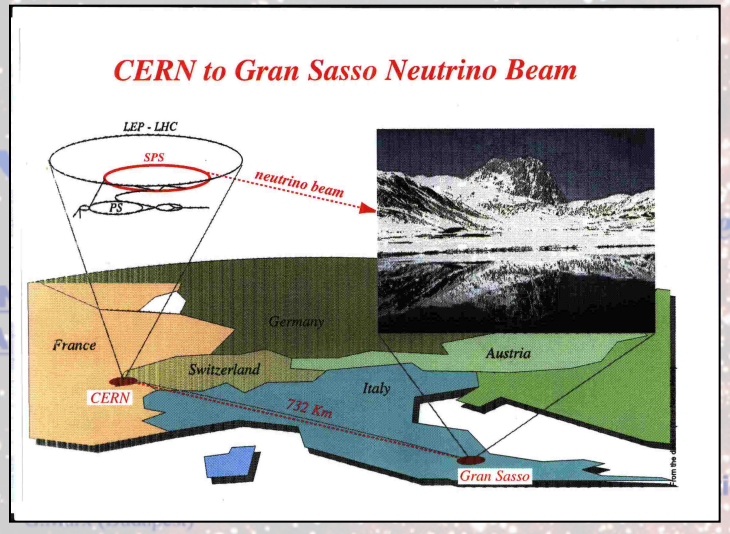








NEUTRINO'98



The OPERA emulsion detector for a long-baseline neutrino oscillation experiment

T.Kawamura, S.Ogawa, H.Shibuya
Toho Univ., Funabashi, Japan
S.Aoki, T.Hara
Kobe Univ., Kobe, Japan
A.Artamonov, P.Gorbunov, V.Khovansky
ITEP, Moscow, Russia
K.Hoshino, M.Komatsu, K.Niwa, M.Nakamura
Nagoya Univ., Japan
S.Buontempo, A.Cocco, V.Cuomo, N.D'Ambrosio, G.De Lellis, A.Ereditato, G.Fiorillo, R.Listone, M.Messina, P.Migliozzi, S.Sorrentino, P.Strolin, V.Tioukov
Naples Univ. and INFN, Italy
E.Barbuto, A.di Bartolomeo, C.Bozza, G.Grella, G.Iovane, G.Romano
Salerno Univ. and INFN, Italy
Y.Sato, I.Tetzuka
Utsunomiya Univ., Japan

LNGS-LOI 8/97 and SPSC 97-24/I218

Sensitivity and discovery potential

ν_μ CC σ_τ/σ_μ ε_τ x BR ε_{vert}

$\sin^2 2\theta_{\mu\tau}$ (large Δm^2) < 2 x 2.3 / (10000 x 0.53 x 0.38 x 0.90)

$< 2.5 \times 10^{-3}$ ← NO OBSERVED EVENTS

Δm^2 (full mixing) $< 10^{-3}$ eV^2

(90% CL)

If oscillation occurs @ :

$\Delta m^2 = 2 \times 10^{-3}$ eV^2	~ 10 detected events	total b.g. < 1 event
$\Delta m^2 = 5 \times 10^{-3}$ eV^2	~ 50 " "	
$\Delta m^2 = 7 \times 10^{-3}$ eV^2	~ 100 " "	

Further information:
URL: http://ww
E-mail: nu98@su

Supported by
- International Union of Pure and Applied P
- Japan National Committee for Physics, Science Council of Japan

P.Monacelli (Gran Sasso)
L.Okun (Moscow)
M.Roos (Helsinki)
B.Sadoulet (Berkeley)
J.Steinberger (CERN)
S.Weinberg (Austin)
S.Wojcicki (Stanford)
B.Barish (Caltech)
J.Cronin (Chicago)
J.Ellis (CERN)
S.Glashow (Harvard)
T.Kirsten (Heidelberg)
L.Lederman (Fermilab)
A.McDonald (Queens)
A.Morales (Zaragoza)
F.Reines (Irvine)
C.Rubbia (CERN)
J.Schneps (Tufts)
F.Vannucci (Paris)
K.Winter (CERN)
G.Zatsepin (Moscow)

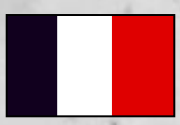
LOCAL ORGANIZING COMMITTEE

OPERA collaboration

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

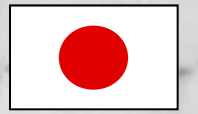


Germany
Hamburg

Israel
Technion Haifa

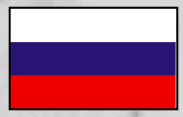
Italy
Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi edu.
Kobe
Nagoya
Toho
Utsunomiya



Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna



Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

（11 countries、30 Institutes、~160 researchers）

CNGS

In the end of 1999 CERN Council approved the CNGS project.

In September of 2000 civil construction started.

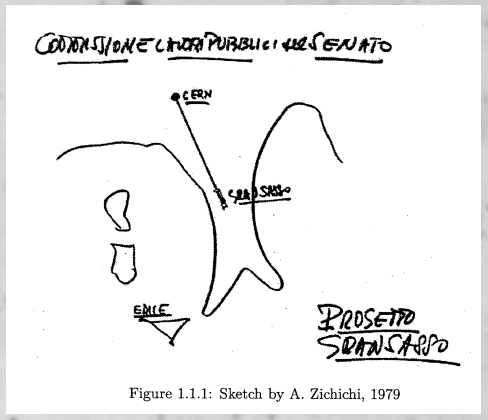


Figure 1.1.1: Sketch by A. Zichichi, 1979

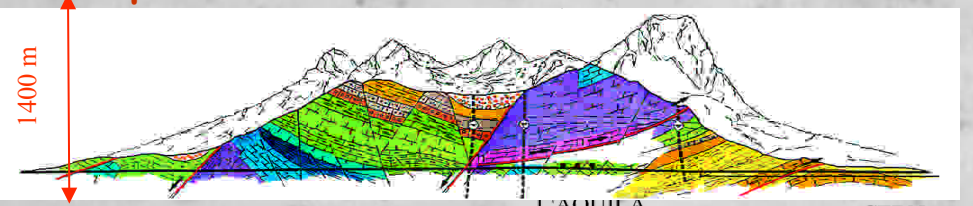
CNGS innagurated in September 2006

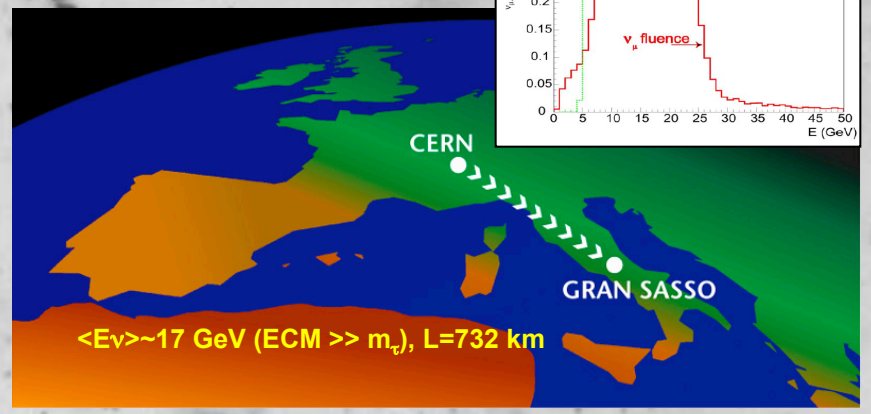
OPERA physics goals

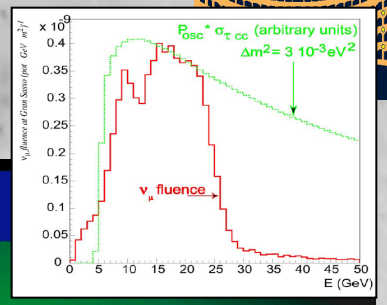
First direct detection of $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations in appearance mode

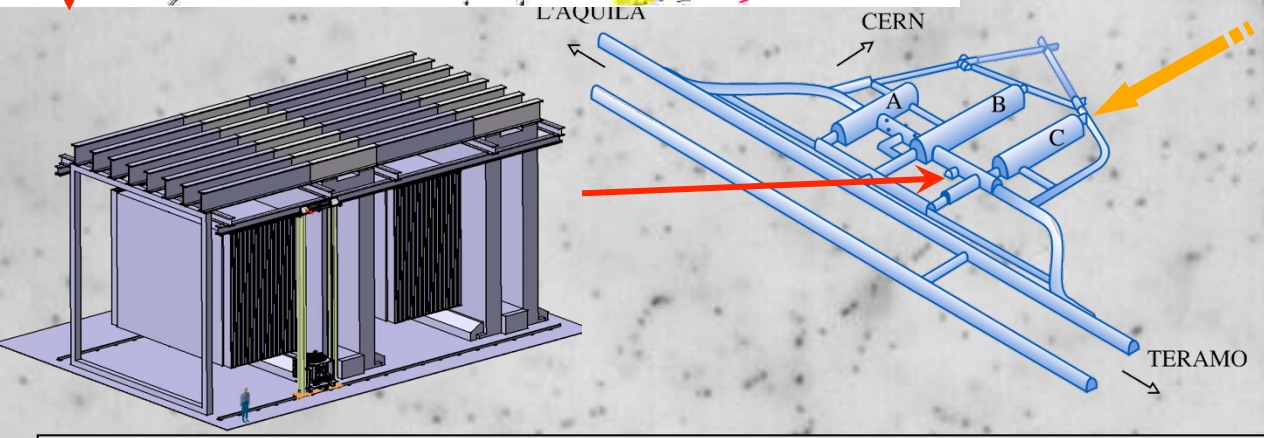
following the Super- Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams.

Important, missing tile in the oscillation picture.









4.5x10^{19} pot/year

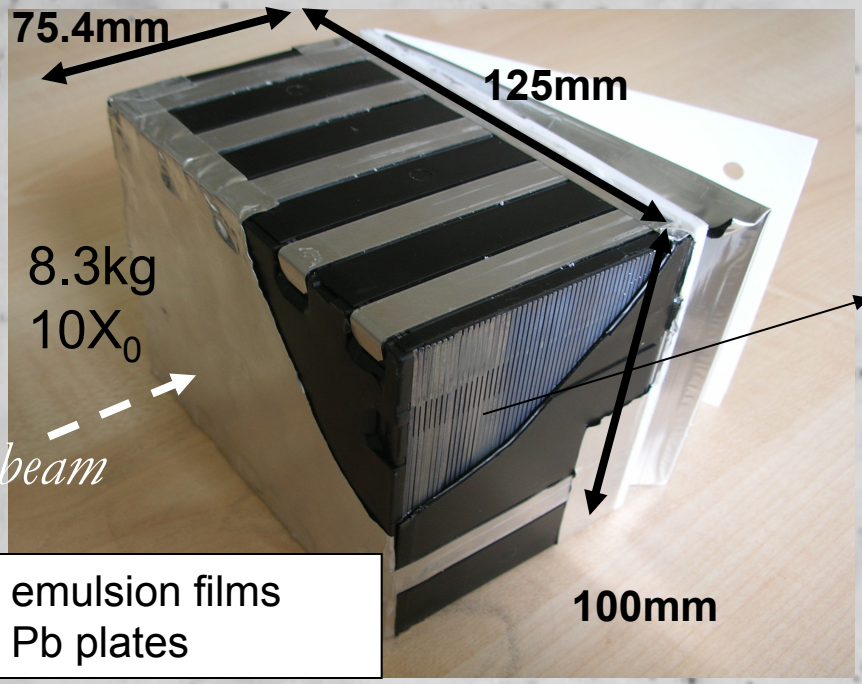
ν_μ CC / kton	2900
ν_μ NC / kton	875
$< E >_\nu$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.85 %
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	negligible

Challenge of OPERA:

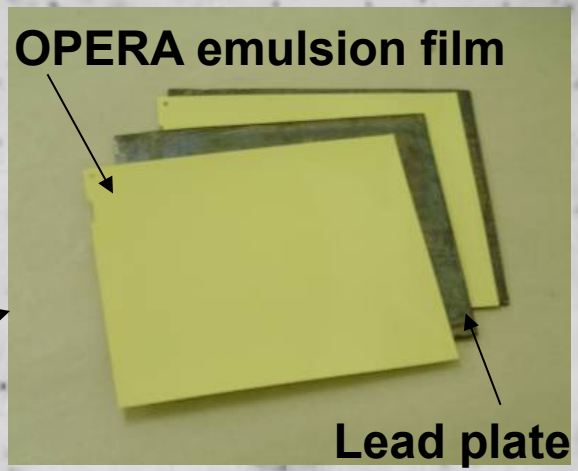
Detector should be ν target and τ decay detector at the same time – **ECC**

(massive) (excellent resolution)

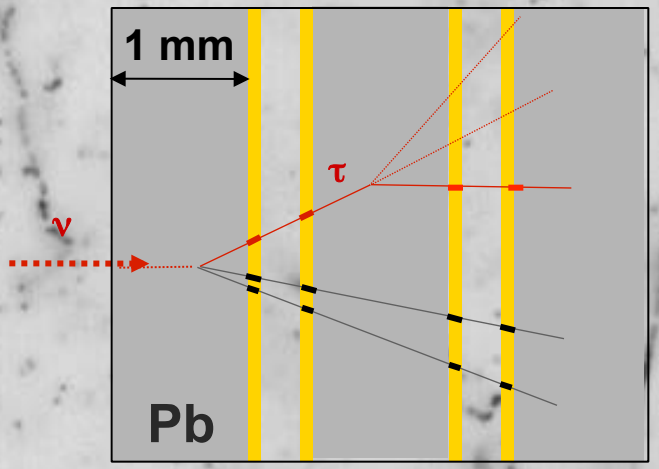
OPERA ECC brick



57 emulsion films
56 Pb plates



2 emulsion layers
(44 μm thick) poured on
a 200 μm plastic base



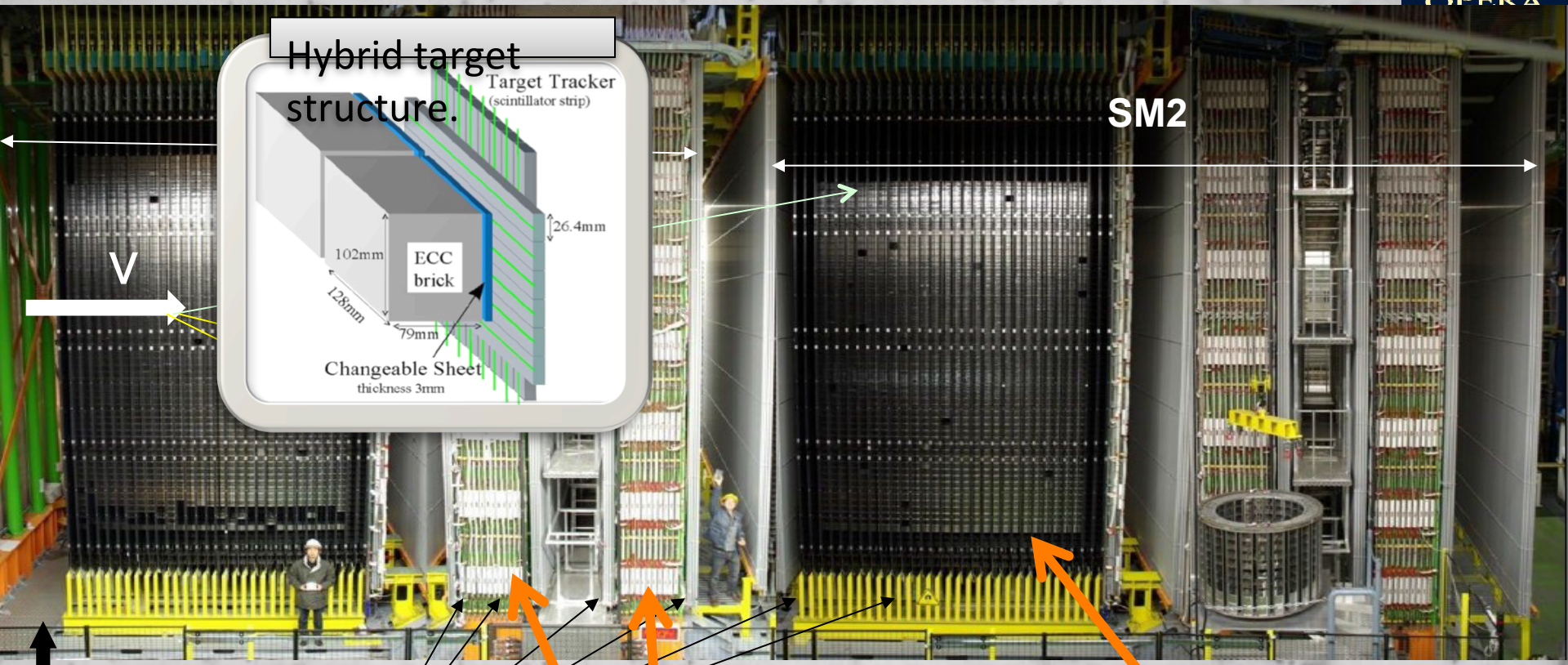
"Emulsion Cloud Chamber"

ECC is the detector allowed first observation of ν_τ **events in** DONUT **experiment at FERMILAB:** 9 τ events, 1.5BG.

K. Kodama et al. (DONuT Collaboration), Phys. Lett. B 504, 218 (2001).

The OPERA target consists of 150'000 ECC bricks.
Total 105' 000 m^2 of lead surface
and 111' 000 m^2 of film surface
(~ 8.9 million films)
Total target mass: 1.25 kton

OPERA hybrid detector: 150000 bricks, 1.25 kT, 3100 m.w.e., 1 μ/m2/h



Veto plane (RPC)

High precision tracker
- 6 4-fold layers of drift tubes

Instrumented dipole magnet
- 1.53 *T*
- 22 XY planes of RPC in both arms

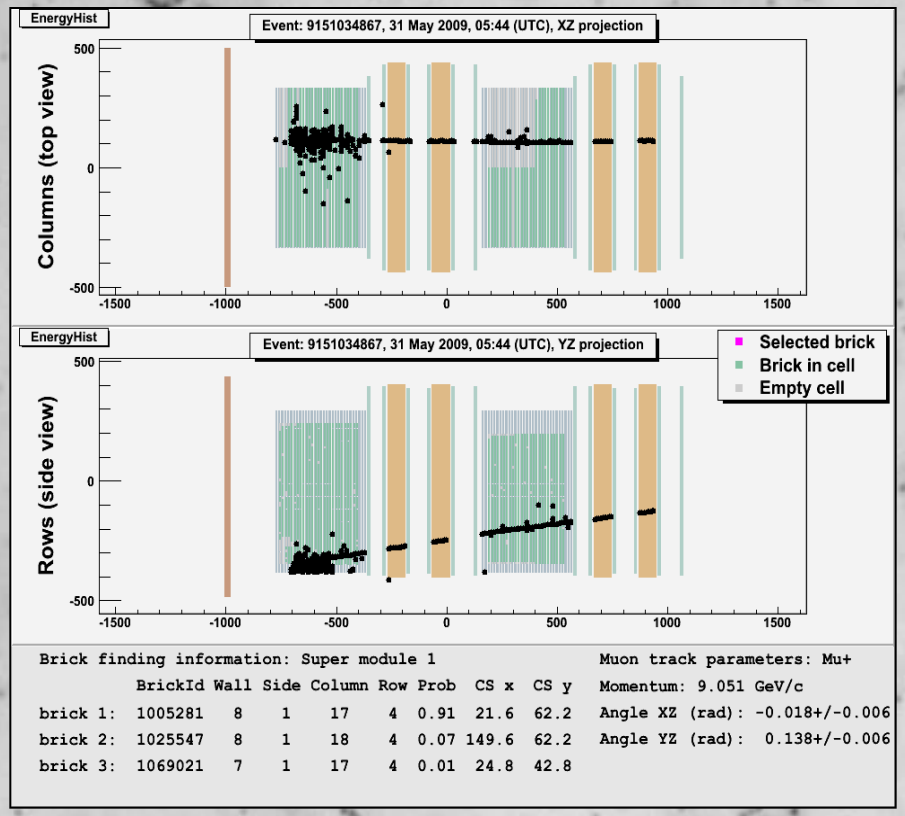
Muon spectrometer (8×10 m^2)

Target and Target Tracker (6.7m)^2

- Target : 77500 bricks, 29 walls
- Target tracker : 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT for
  - Brick selection
  - Calorimetry

Vertex brick finding – first step of the analysis

Event trigger and reconstruction

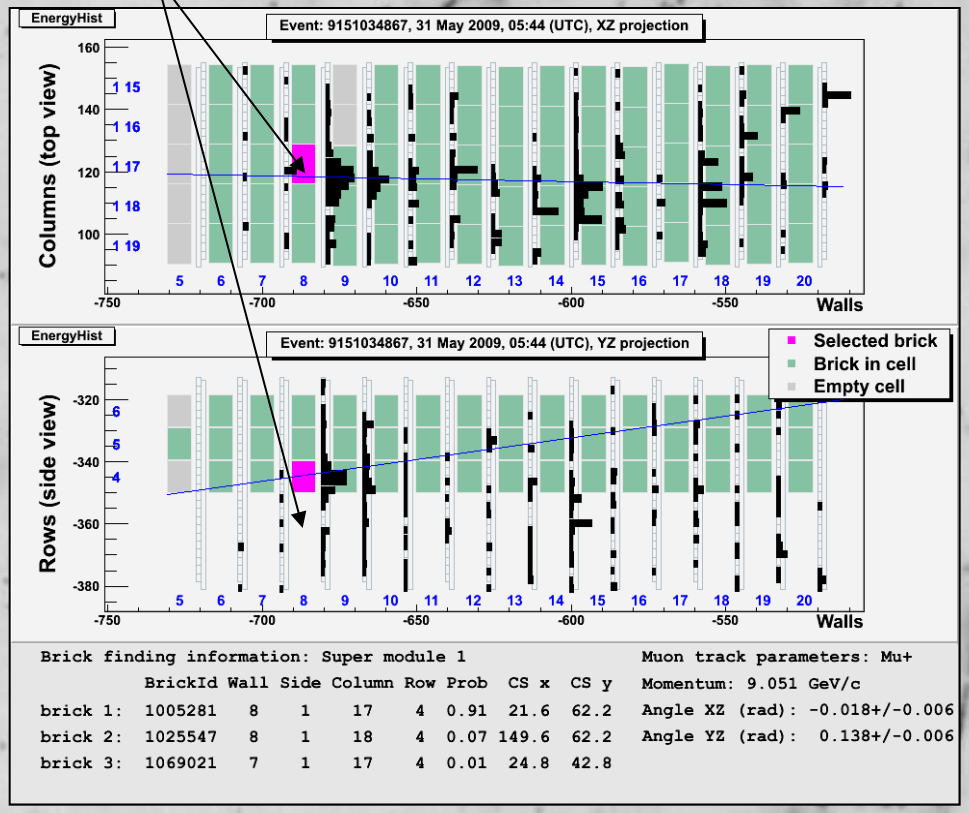


Brick finding information: Super module 1

	BrickId	Wall	Side	Column	Row	Prob	CS x	CS y
brick 1:	1005281	8	1	17	4	0.91	21.6	62.2
brick 2:	1025547	8	1	18	4	0.07	149.6	62.2
brick 3:	1069021	7	1	17	4	0.01	24.8	42.8

Muon track parameters: Mu+
Momentum: 9.051 GeV/c
Angle XZ (rad): -0.018+/-0.006
Angle YZ (rad): 0.138+/-0.006

Vertex brick identification



Brick finding information: Super module 1

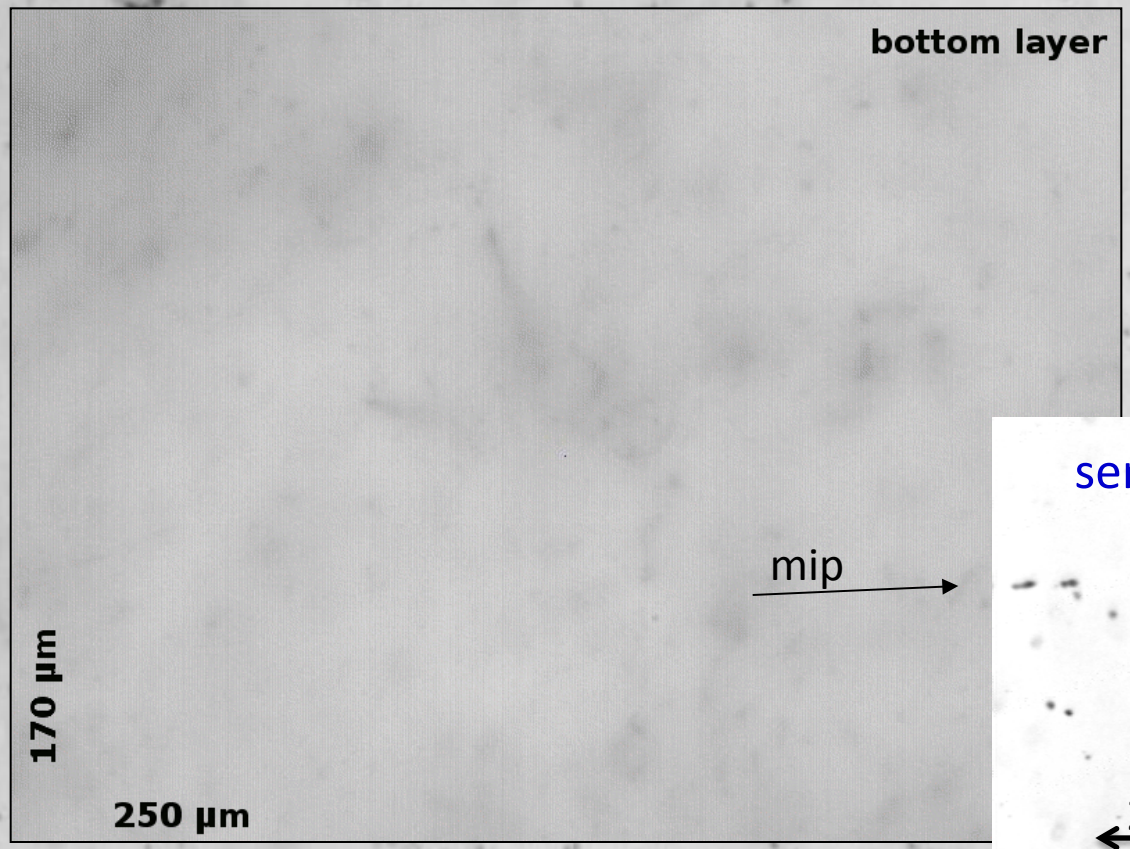
	BrickId	Wall	Side	Column	Row	Prob	CS x	CS y
brick 1:	1005281	8	1	17	4	0.91	21.6	62.2
brick 2:	1025547	8	1	18	4	0.07	149.6	62.2
brick 3:	1069021	7	1	17	4	0.01	24.8	42.8

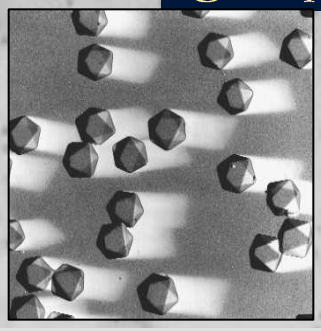
Muon track parameters: Mu+
Momentum: 9.051 GeV/c
Angle XZ (rad): -0.018+/-0.006
Angle YZ (rad): 0.138+/-0.006

Selection of a brick most probably containing the neutrino interaction

- Reduce scanning load
- Minimize the target mass loss

OPERA emulsion films as a detector and data storage media



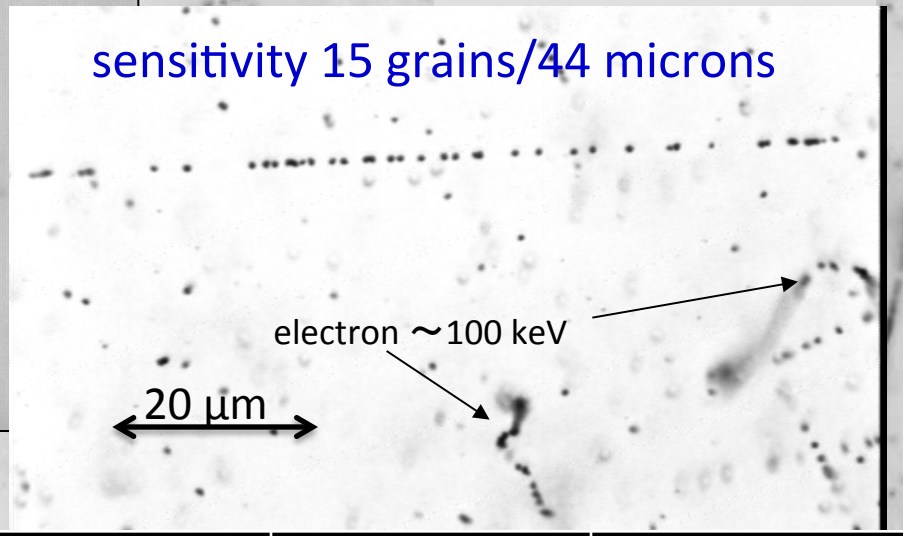


basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

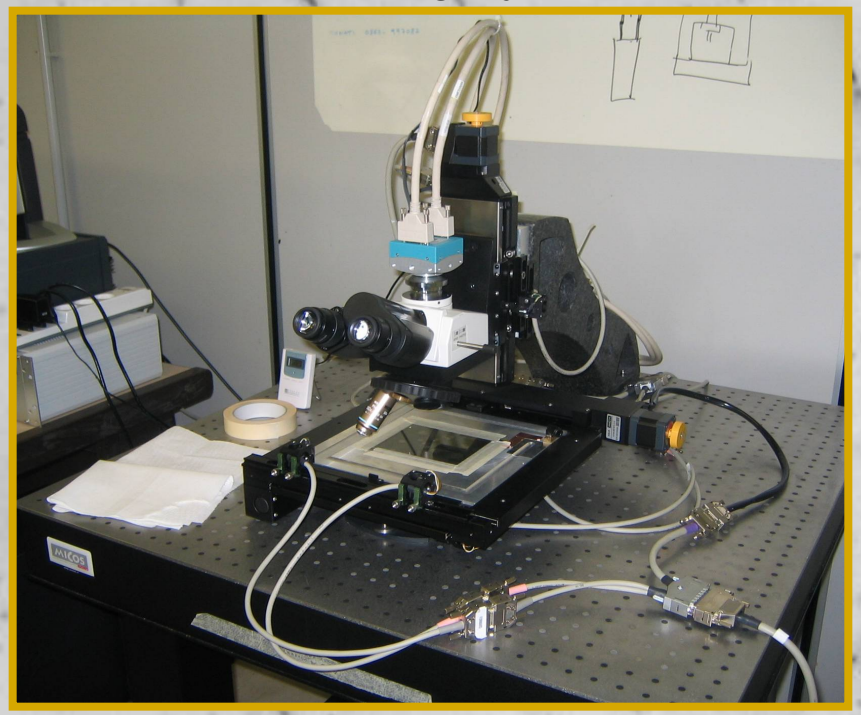
10^{13} "detectors" per film



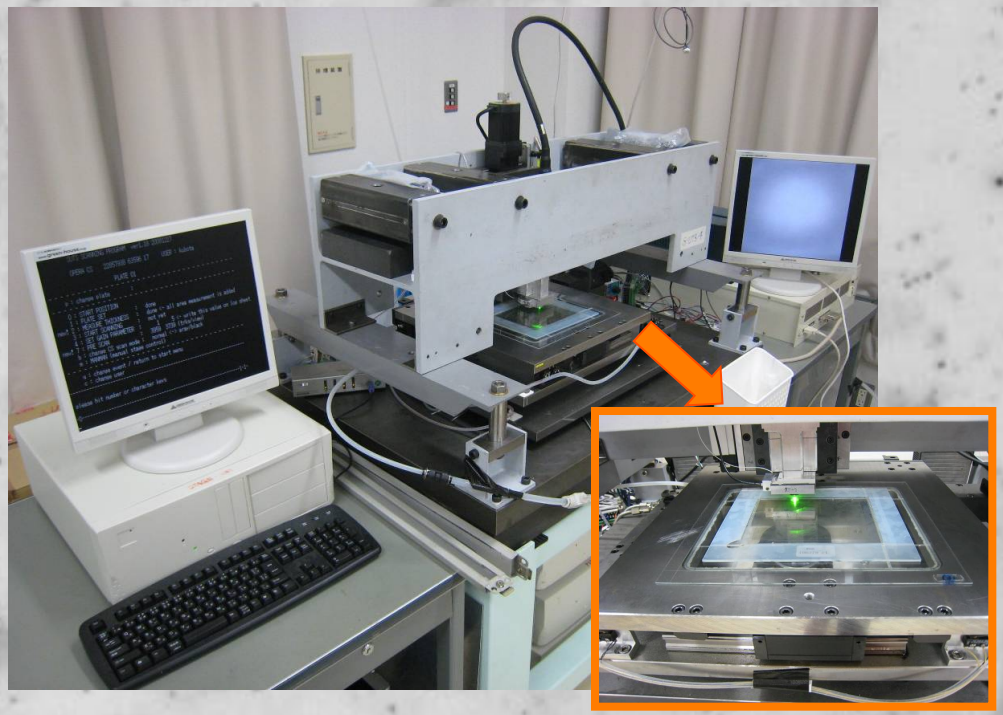
DVD	12 cm	8.5 GB	177Mbps
Blue-ray	12 cm	50 GB	216 Mbps
OPERA film	12.5x10 cv	556 GB	839 Mbps

Automatic Emulsion Scanning Stations - data readers

EU: ESS
(European Scanning System)



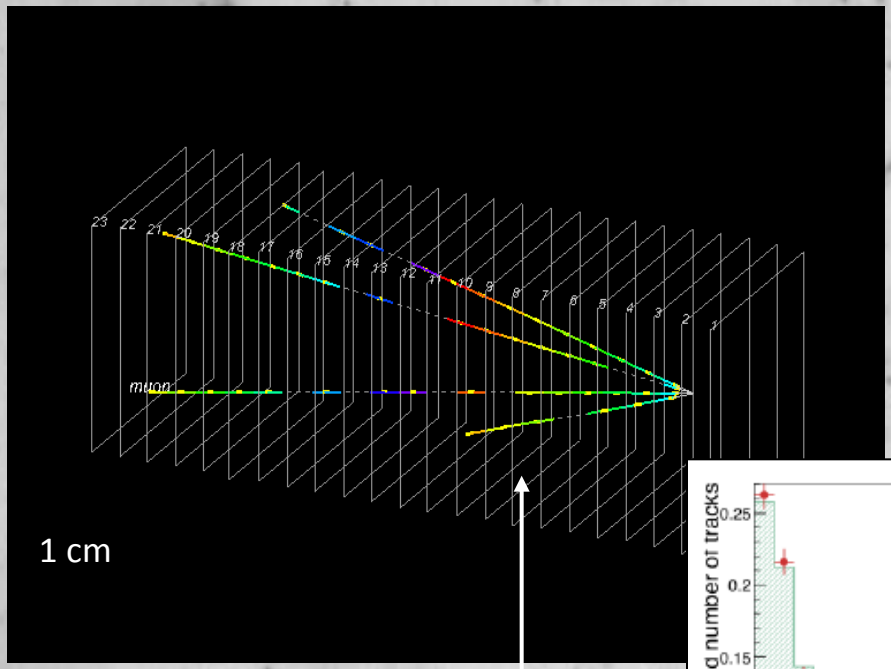
Japan: SUTS
(Super Ultra Track Selector)

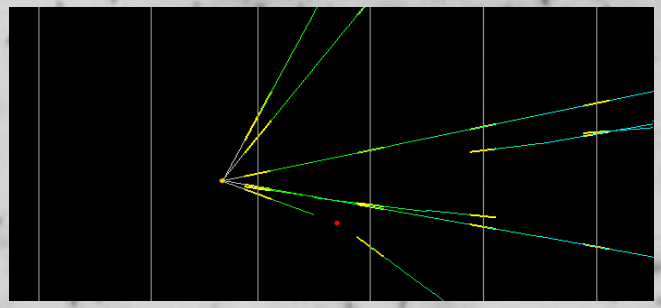


- Scanning speed/system: 20cm^2/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

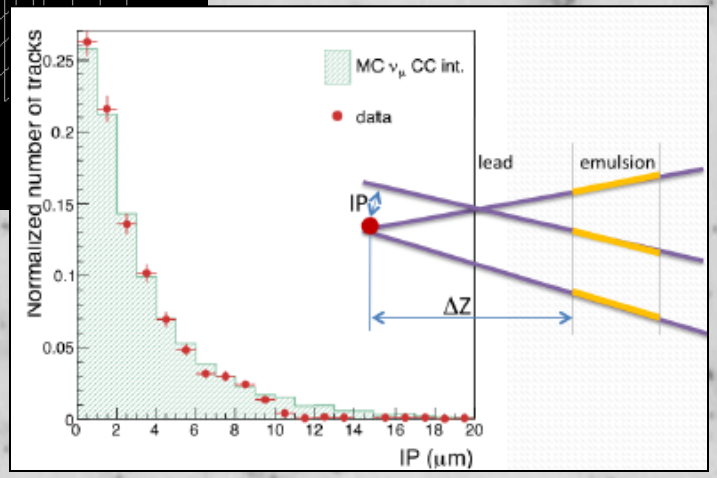
- Scanning speed/system: 75cm^2/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

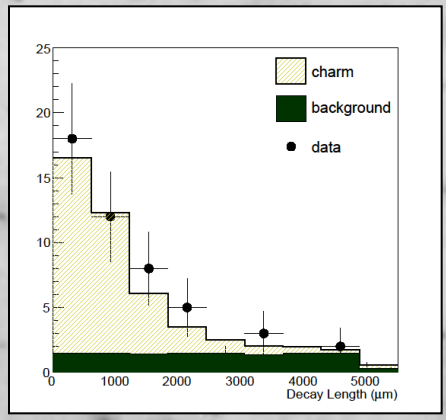
Location of Neutrino Interaction





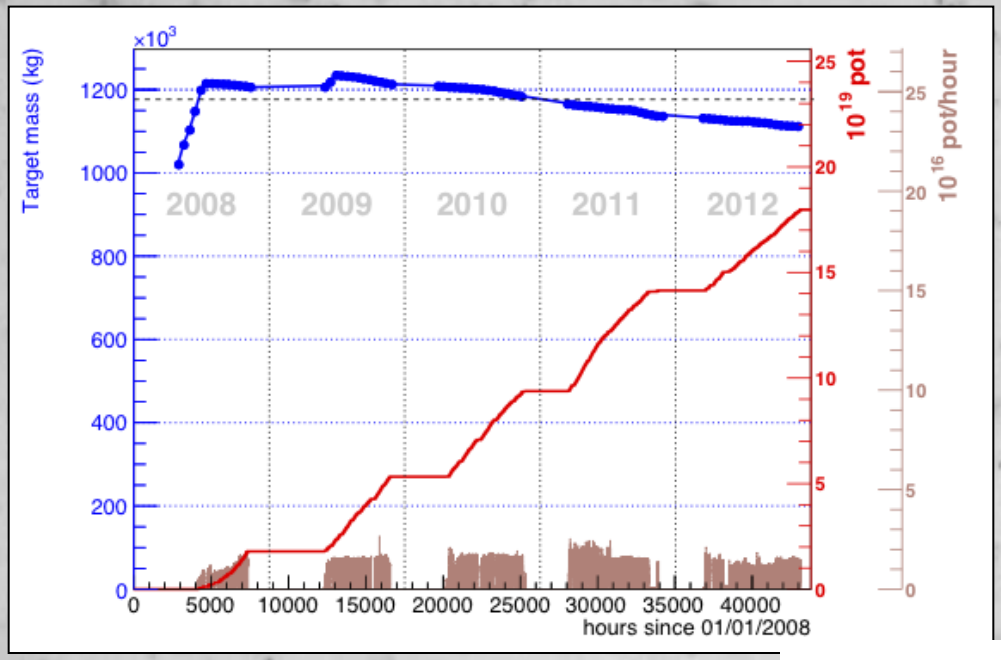
Charm events as a control sample





Emulsion gives 3D vector data, giving a micrometric precision of the vertexing accuracy.
(The frames correspond to scanning area. Yellow short lines → measured tracks. The other colored lines → interpolation or extrapolation. The colors indicate the Z-depth in the module.)

Data taking with CNGS in 2008-2012



17.97 x 10^{19} POT (~80 % of expected)

19600 event registered
~80% of the data processed
~7000 events were located
~6300decay searched

Analysis is on going

1st ν_τ (2009): $\tau \rightarrow$ h

NEUTRINO2010 Phys. Lett. B691 (2010) 138

2nd ν_τ (2011): $\tau \rightarrow$ 3h

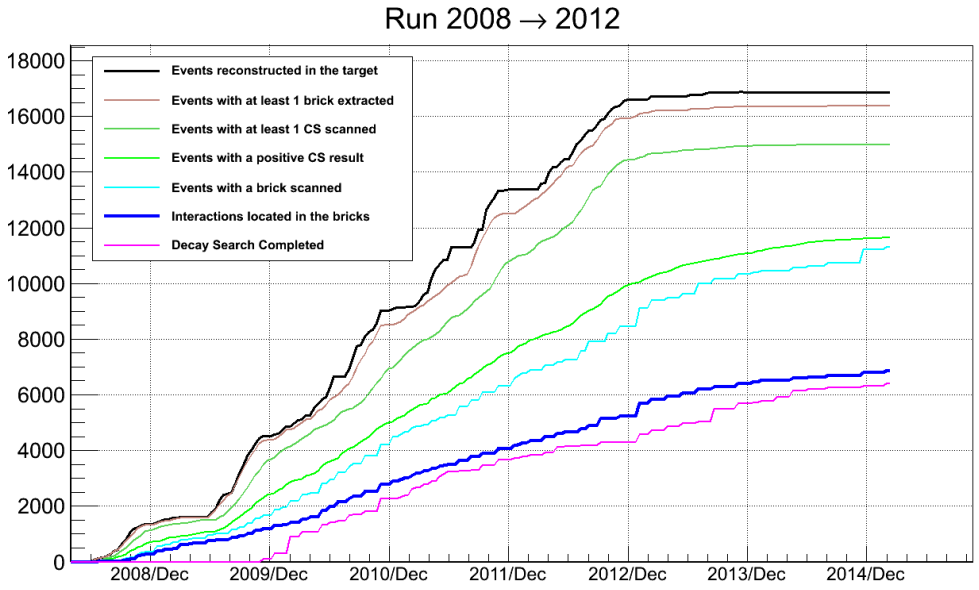
2012 NEUTRINO2012 JHEP 11 (2013) 036

3rd ν_τ (2011): $\tau \rightarrow \mu$

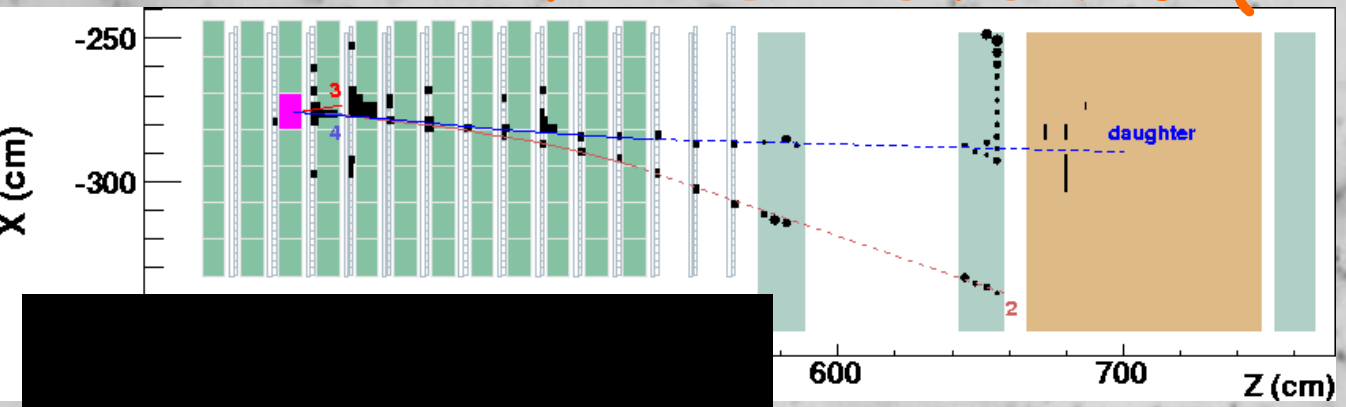
JPS 2013 Spring Phys. Rev. D 89 (2014) 051102(R)

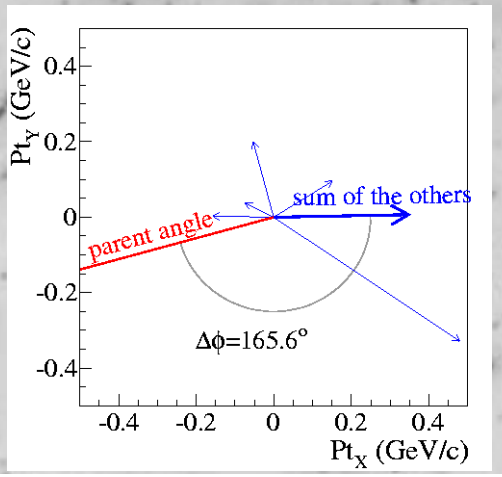
4th ν_τ (2012): $\tau \rightarrow$ h

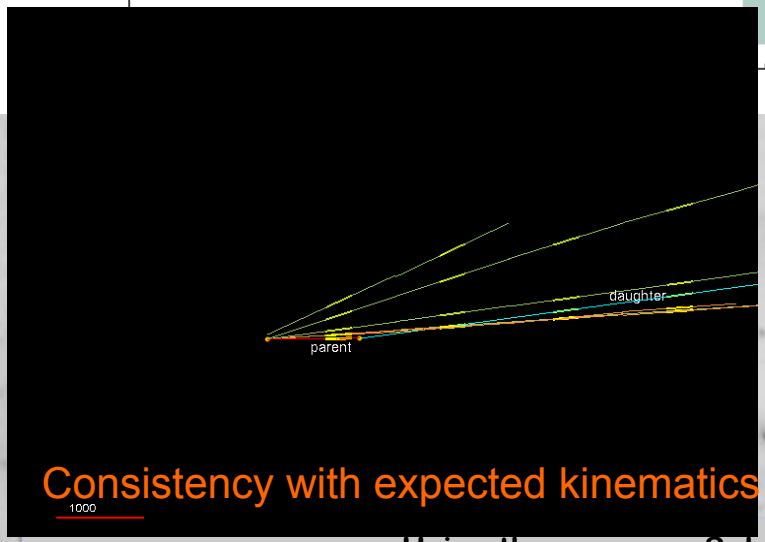
NEUTRINO2014 PTEP 2014 (2014) 1 , 101C01



4th tau events (τ→h)

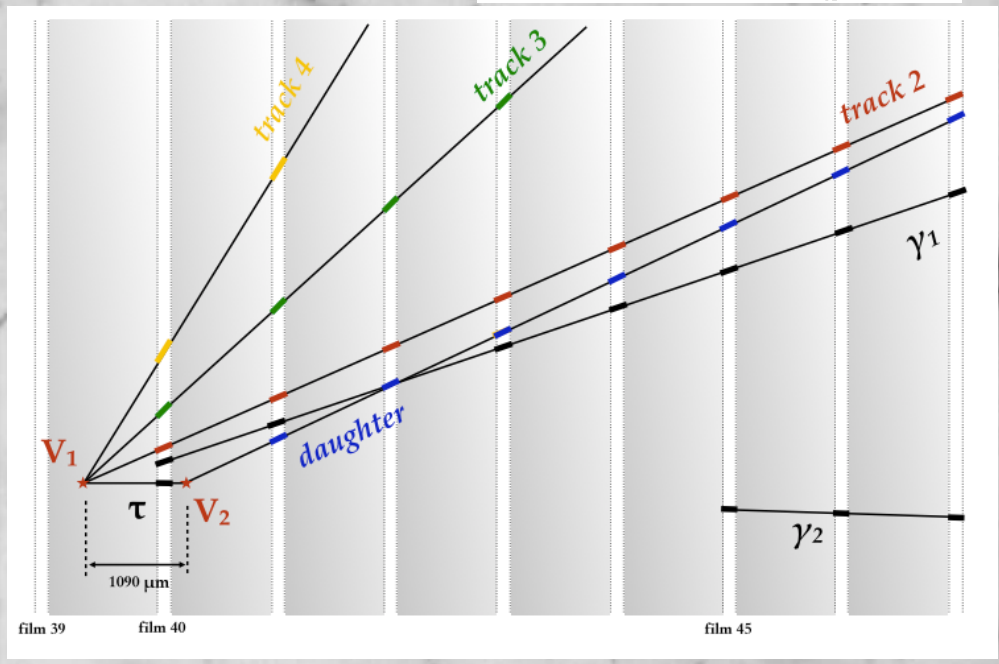






Consistency with expected kinematics

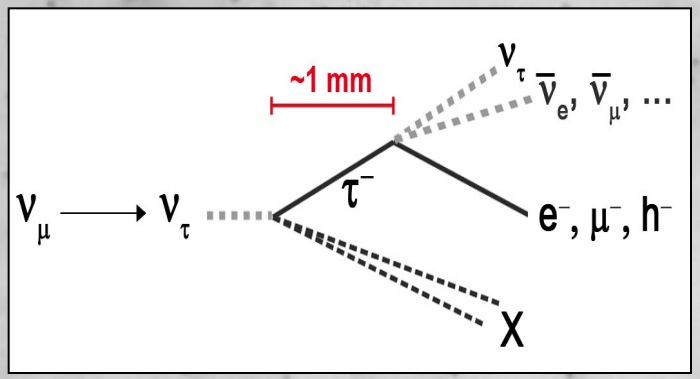
	Using the mean values	Selection criteria
P daughter (GeV/c)	$6.0^{+2.2}_{-1.2}$	>2
P_t at kink (GeV/c)	$0.82^{+0.30}_{-0.16}$	>0.6
P_t miss at 1ry (GeV/c)	$0.55^{+0.30}_{-0.20}$	<1
Phi (deg)	166^{+2}_{-31}	>90
Kink angle (deg)	137 ± 4	>20
Flight length (um)	1090 ± 30	<2600

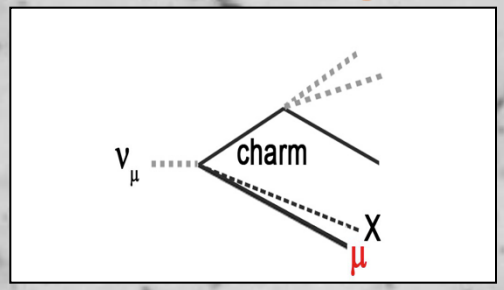


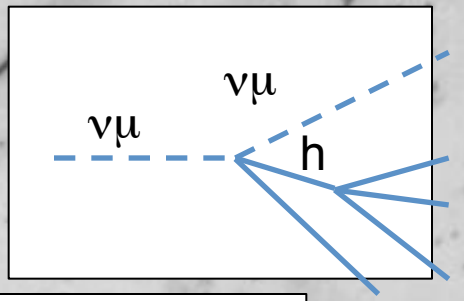
huile - 2015

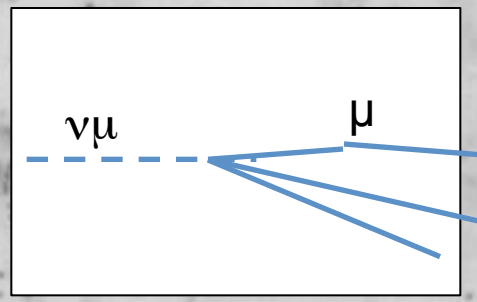
NEUTRINO2014
PTEP 2014 (2014) 10, 101C01

Background









Signal:

- τ - creation in ν_τ CC interaction
- Decay of the τ-- lepton after ~ 600 μm
- Topology: 'kink' characteristic of the tau decay (missing energy)

- ν_μ CC interactions with charm production & undetected muon(s)
- Hadronic re-interactions of secondary hadrons in lead
- Large-angle μ scattering

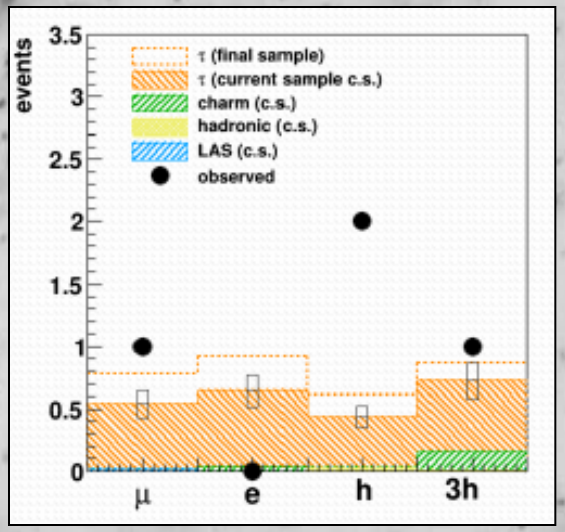
Estimation by MonteCarlo
Validation by OPERA data or test beam studies.
Work on the background clarification continues.

Oscillation analysis

Data samples
4686 events (979 0μ + 3707 1μ)

2008 – 2009: 1st brick + 2nd brick
2010 – 2012: 1st brick

Decay channel	Signal expectation	Total background	Observed events
$\tau \rightarrow h$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau \rightarrow 3h$	0.57 ± 0.11	0.155 ± 0.03	1
$\tau \rightarrow \mu$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau \rightarrow e$	0.61 ± 0.12	0.027 ± 0.005	0
Total	**2.1 ± 0.42**	**0.23 ± 0.04**	**4**



Combination of four single channel p-value was calculated in order to take account the difference of background with decay channels

P-value = $p^\star = \prod_{i=1}^{4} p(n_i, b_i) = \prod_{i=1}^{4} e^{-b_i} \sum_{j=n_i}^{\infty} \frac{b_i^j}{j!}$ = 1.03 x 10^{-5}

➔ No oscillation case excluded with 4.2σ significance

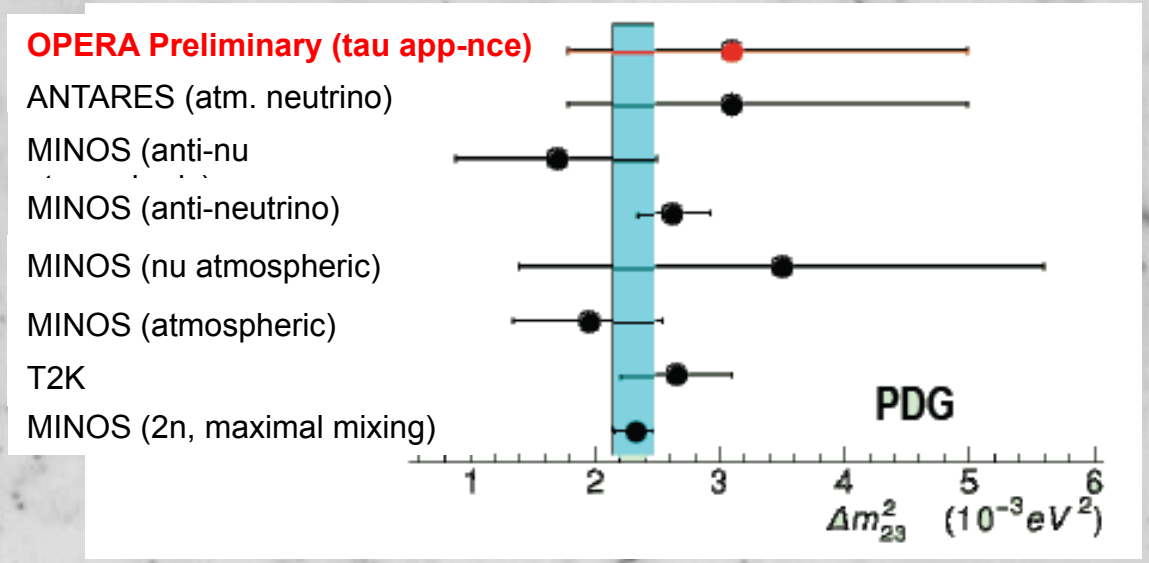
Observation of ν_τ appearance

Oscillation parameter from ν_τ appearance

$$n_{exp}(\Delta m^2) = \int \Phi(E) \cdot \sigma(E) \cdot oscprob(\Delta m^2, E) \cdot \varepsilon(E)\, dE$$

flux — cross section — detection efficiency

90 % C.L. intervals on Δm^2_{23} by Feldman & Cousin method: [1.8 - 5.0] x 10^{-3} eV^2 (assuming full-mixing)

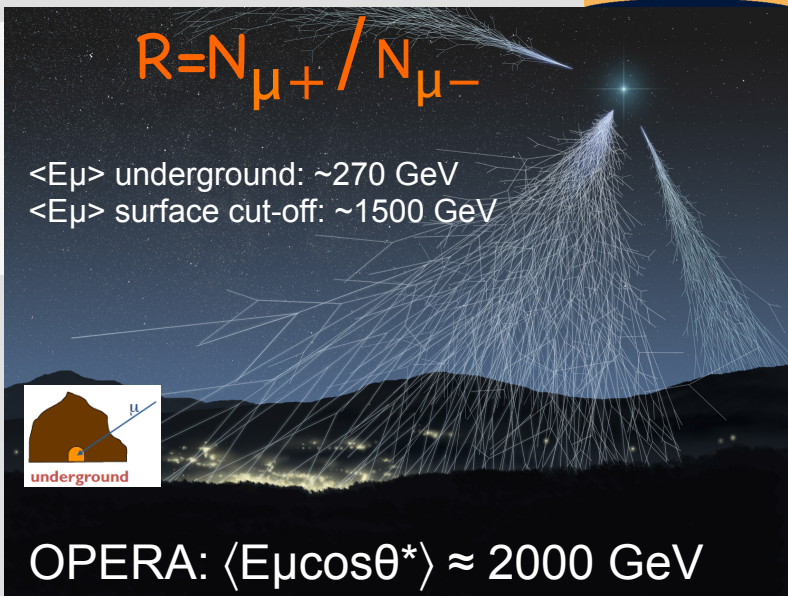


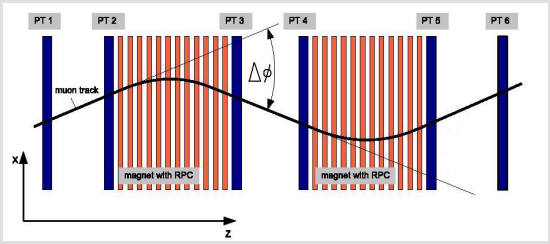
Consistent with other experiments

Measurement of the TeV atmospheric muon charge ratio

The atmospheric muon charge ratio Rμ ≡ Nμ+/Nμ- is being studied and measured since many decades
– Depends on the chemical composition and energy spectrum of the primary cosmic rays
– Depends on the hadronic interaction features
– At high energy, depends on the prompt component

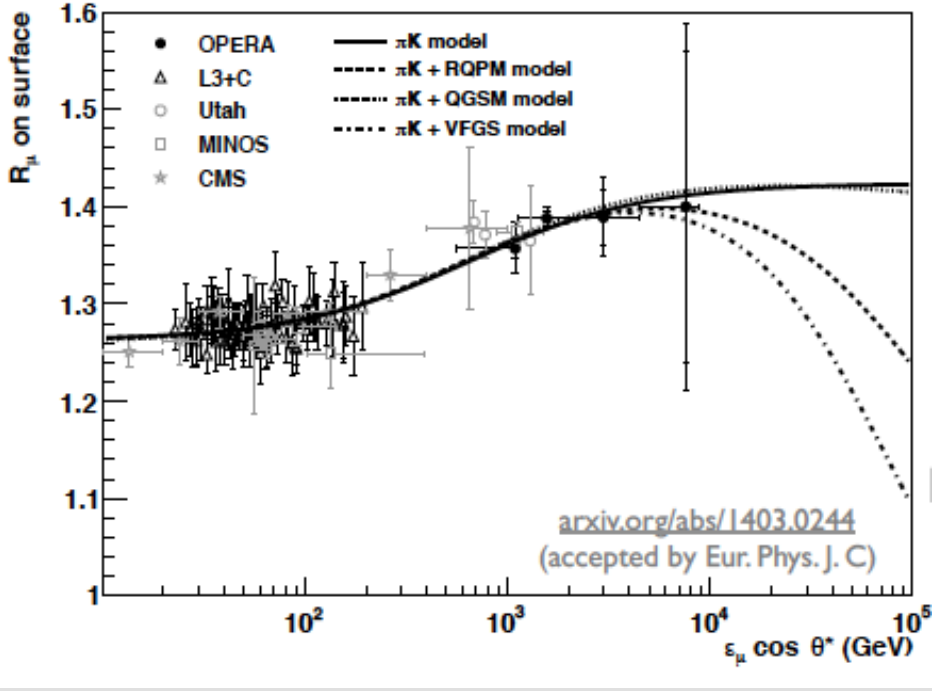
- Possibility to check HE hadronic interaction models (E>1TeV) in the fragmentation region (phase space complementary to collider's one)
• Atmospheric muons are kinematically related to atmospheric neutrinos (same sources) ◊ Rμ provides a benchmark for atmospheric ν flux computations (e.g. background for neutrino telescopes)





Results:

¬ a strong reduction of the charge ratio for multiple muon events
¬ The integral value and the energy dependence of the charge ratio for single muons are compatible with the expectation from a simple π-K model
¬ No significant contribution of the prompt component up to Eμ cos θ* ~ 10 TeV
¬ The Rμ behaviour as a function of Eμ supports the validity of Feynman scaling in the fragmentation region up to Eμ ~ 20 TeV, corresponding to primary energy/ nucleon EN ~ 200 TeV



CONCLUSIONS AND OUTLOOK

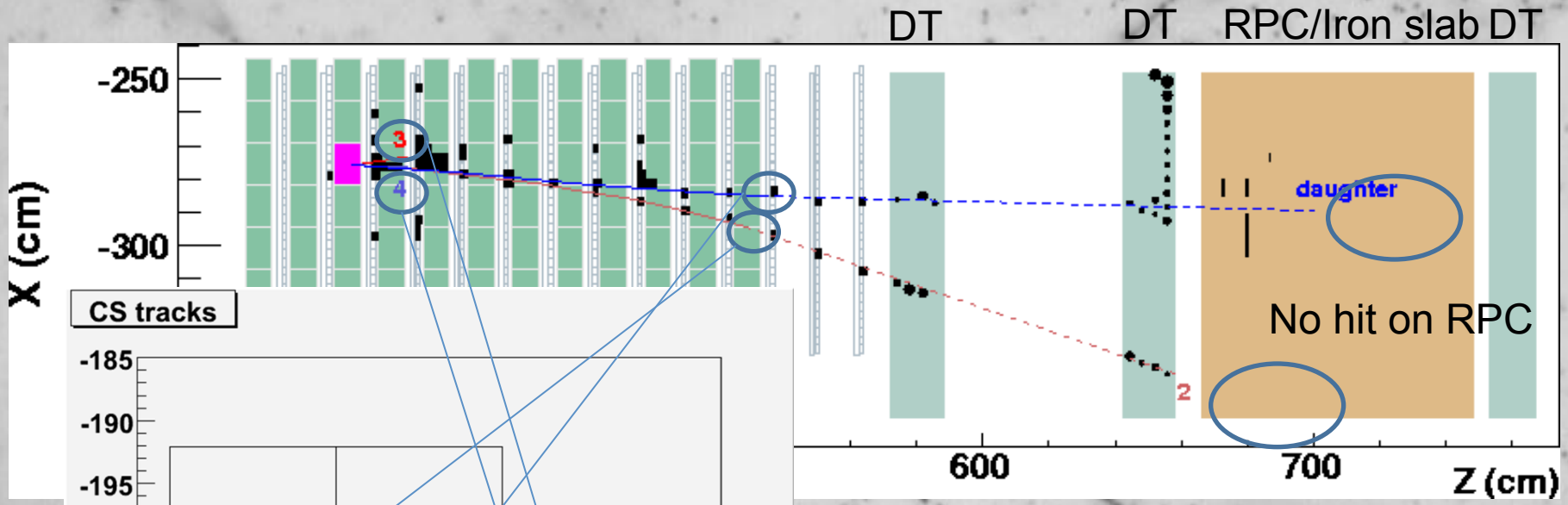
- The OPERA experiment at LNGS aimed at the first detection of neutrino oscillations in appearance mode through the study of the $\nu_\mu \rightarrow \nu_\tau$ channel.

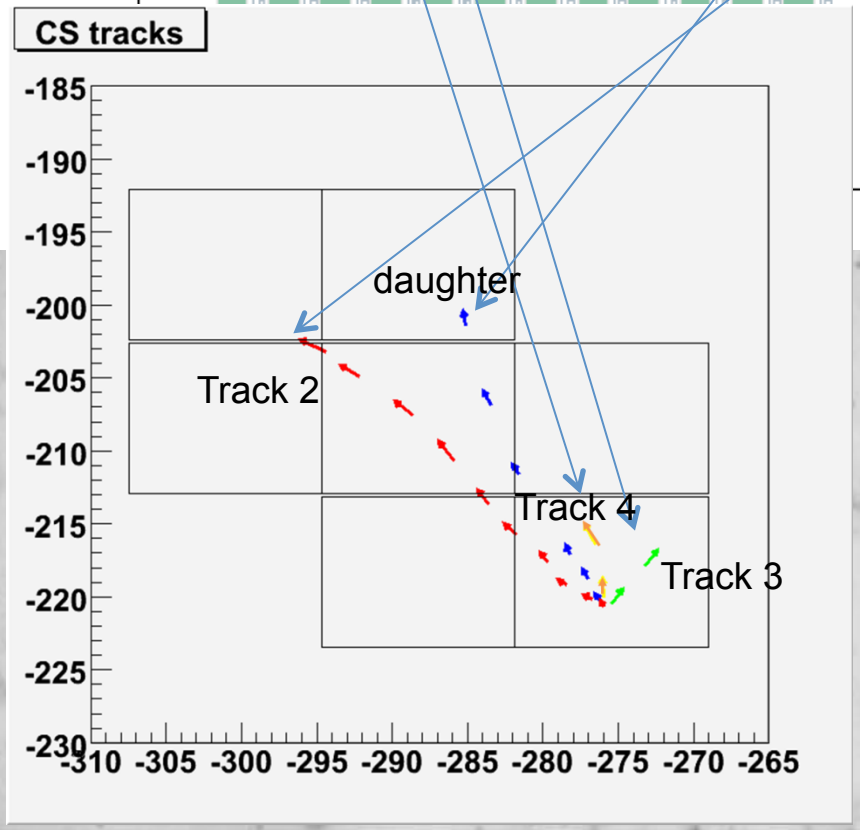
- The data taking was completed in 2012. 19600 events were registered in the target. 80% of the events are processed with ~7000 vertex fully located.

- So far, 4 candidate events were found with expected background of 0.23 events providing **significance of of 4.2 σ of the observation of the oscillations.** The collaboration continues processing aiming to finish it this year.
- Results for the measurement of the atmospheric muon charge ration are obtained for the highest
- The decommissioning of the detector started at LNGS to be completed next year.
- Excellent operation of the detector and demonstration of the full capability of the technique for the τ-neutrino physics studies makes prospective for its further application in the future experiment.

Follow down studies of the 4th event

Track follow down was performed on relevant ECC for all tracks



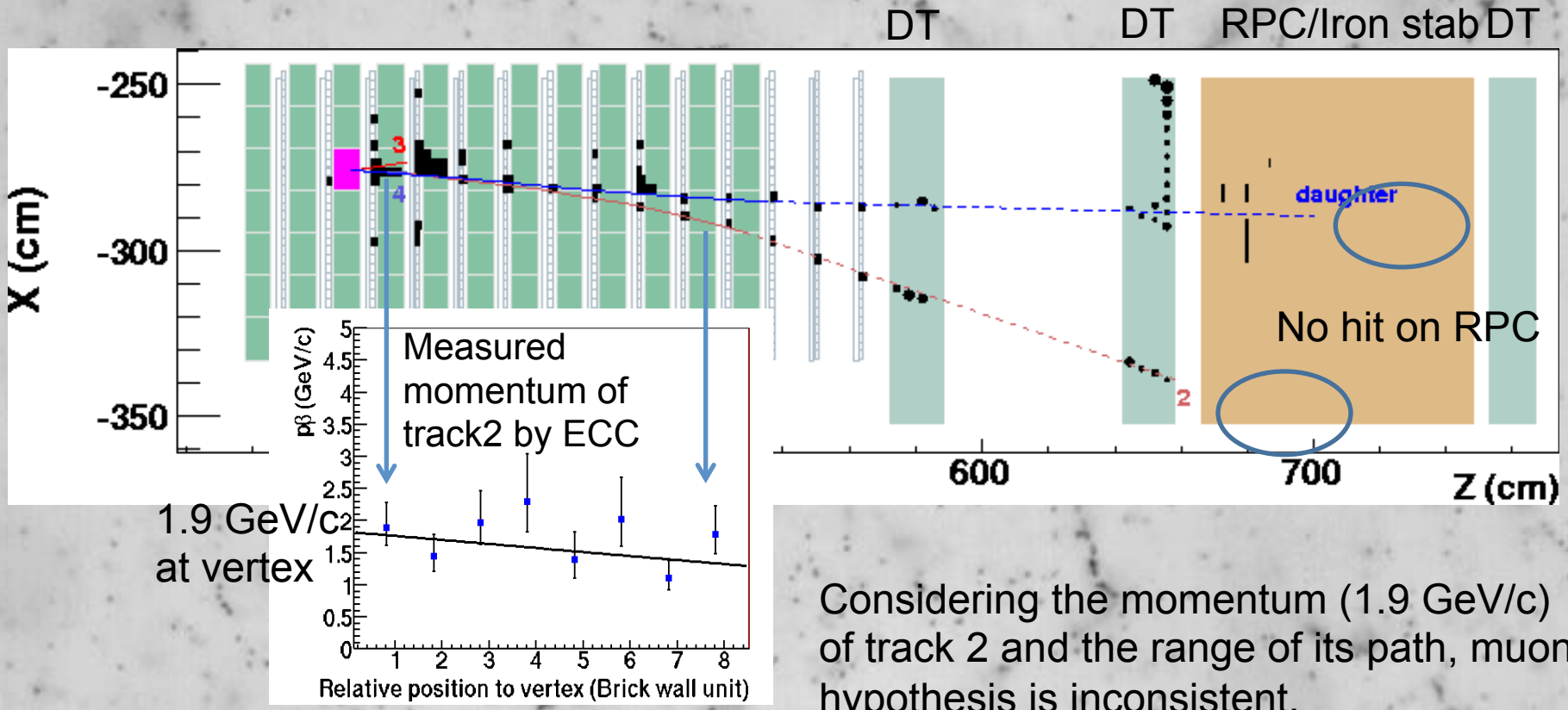


Track 3: interacted at 2 downstream ECC

Track 4: missed at 2 downstream ECC

Daughter & Track 2: passed all 9 downstream ECC without interaction and stopped at spectrometer

Particle ID



1.9 GeV/c at vertex

Considering the momentum (1.9 GeV/c) of track 2 and the range of its path, muon hypothesis is inconsistent.

Track 2 is hadron.
Daughter also was judged as hadron by same analysis

→ No muon at 1ry vertex