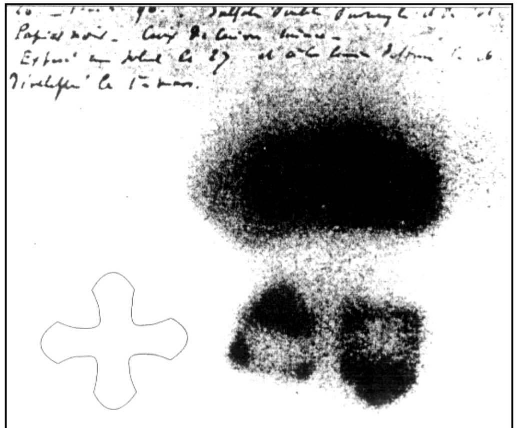
Le oscillazioni di neutrino e l'esperimento OPERA

Pasquale Migliozzi

INFN - Napoli

The discovery of the radioactivity

- ✓ In 1896 H. Becquerel discovered "by chance" that uranium salts emit a new type of radiation (le rayon uraniques)
- ✓ In a series of experiments, from 1897-1902, Rutherford, Chadwick, Curie and Villard show that the radiations are of three
radiation (helium nuclei),
(electrons) and
(very energetic photons)

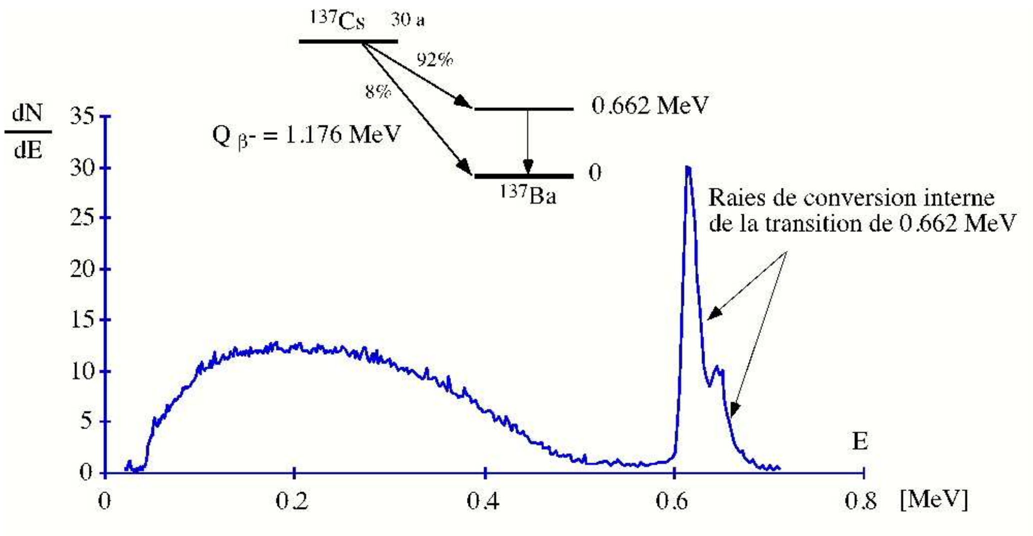


Une des plaques photographiques de Becquerel impressionnée, malgré le papier opaque à la lumière, par les rayons issus d'une des substances étudiées. On remarque en bas du cliché un « blanc » en forme de croix de Malte. C'est l'empreinte d'une croix de cuivre insérée entre la substance radioactive et le papier enveloppant la plaque. Le cuivre est donc opaque aux rayonnements.

The continous β spectrum

At that time the common believe was that the electron is emitted alone in a β decay ⇒ mono-energetic electron

BUT several experiments confirmed the continous spectrum of electrons emitted in a β decay



Spectre d'énergie des bêta mesuré à l'IPHE

Two possible explanations for the continuous β spectrum

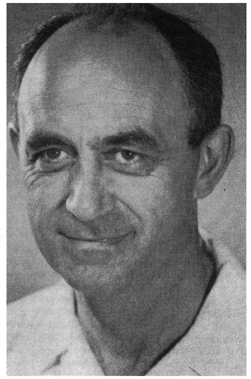
- ✓ Niels Bohr Non conservation of the energy

"… at the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β decay, are even led to complications in trying to do so. Of course, a radical departure from this principle would imply strange consequences…"

- ✓ Wolfgang Pauli "A desperate way out"

"… there could exist in the nucleus electrically neutral particles, which I shall call *neutronen*, which have spin ½ and satisfy the exsclusion principle and which are further distinct from light-quanta in that they move with light velocity. The mass of the *neutronen* should be of the same order of magnitude as the eelctron mass and in any case not larger than 0.01 proton mass. The continous β spectrum would then become understandable from the assumption that in β decay a *neutronen* is emitted along with the electron, in such a way that the sum of the energies of the *neutronen* and the electron is constant."

The Fermi theory of β decay



The basic assumptions of the Fermi theory (1933) are

- A neutral particle (called *neutrino* by Fermi) is emitted along with the e^- in β decay.
- The nucleus consists of protons and neutrons
- The total number of e^- and ν is not necessarily constant. Moreover he stated "… to every transition from neutron to proton is correlated the *creation* of an e^- and ν … Note that by this the conservation of the charge is assured…"
- Protons and neutrons might by simply different quantum states of the same basic particle **(Isospin hypothesis W. Heisenberg)**
- The *weak interaction* (the new force responsible for the β decay) is a contact interaction

After about 60 years....

1930	ν existence postulated	Pauli
1934	ν interaction theory and name	Fermi
1938	Solar ν flux calculation	Bethe
1946	Idea of ν chlorine detector	Pontecorvo
1956	ν interactions observed	Reines & Cowan

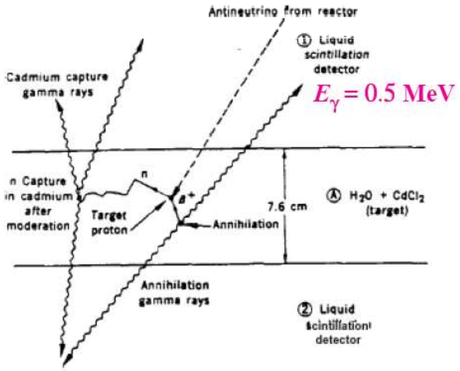
I have done a terrible thing:
I have postulated a particle that cannot be detected
Wolfgang Pauli

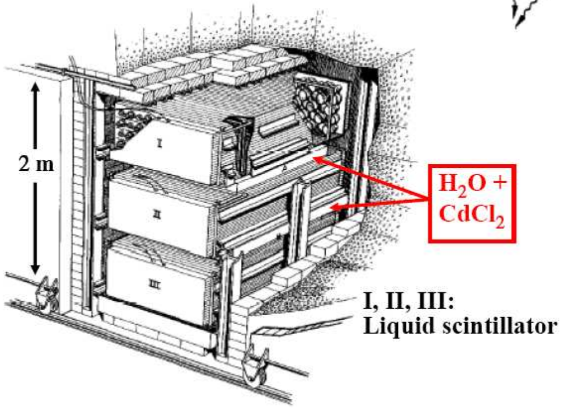
First neutrino detection

(Reines, Cowan 1953)

$\overline{\nu} + p \rightarrow e^{+} + n$

- detect 0.5 MeV γ-rays from $e^{+}e^{-} \rightarrow \gamma\gamma$ ($t = 0$)
- neutron "thermalization" followed by capture in Cd nuclei ⇒ emission of delayed γ-rays (average delay ~30 μs)





Event rate at the Savannah River nuclear power plant:

3.0 ± 0.2 events / hour

(after subracting event rate measured with reactor OFF)

in agreement with expectations

The troublesome neutrino history is not over....

- In 1957 a wrong rumor reached B. Pontecorvo: R. Davies had observed the reaction

$$\bar{\nu}_e + {}^{37}\mathrm{Cl} \rightarrow \mathrm{e}^- + {}^{37}\mathrm{Ar}$$

- This is an example of Leptonic Number Violation: B. Pontecorvo postulated the existence of a new interaction that allows (in analogy with the K^0-K^0bar)

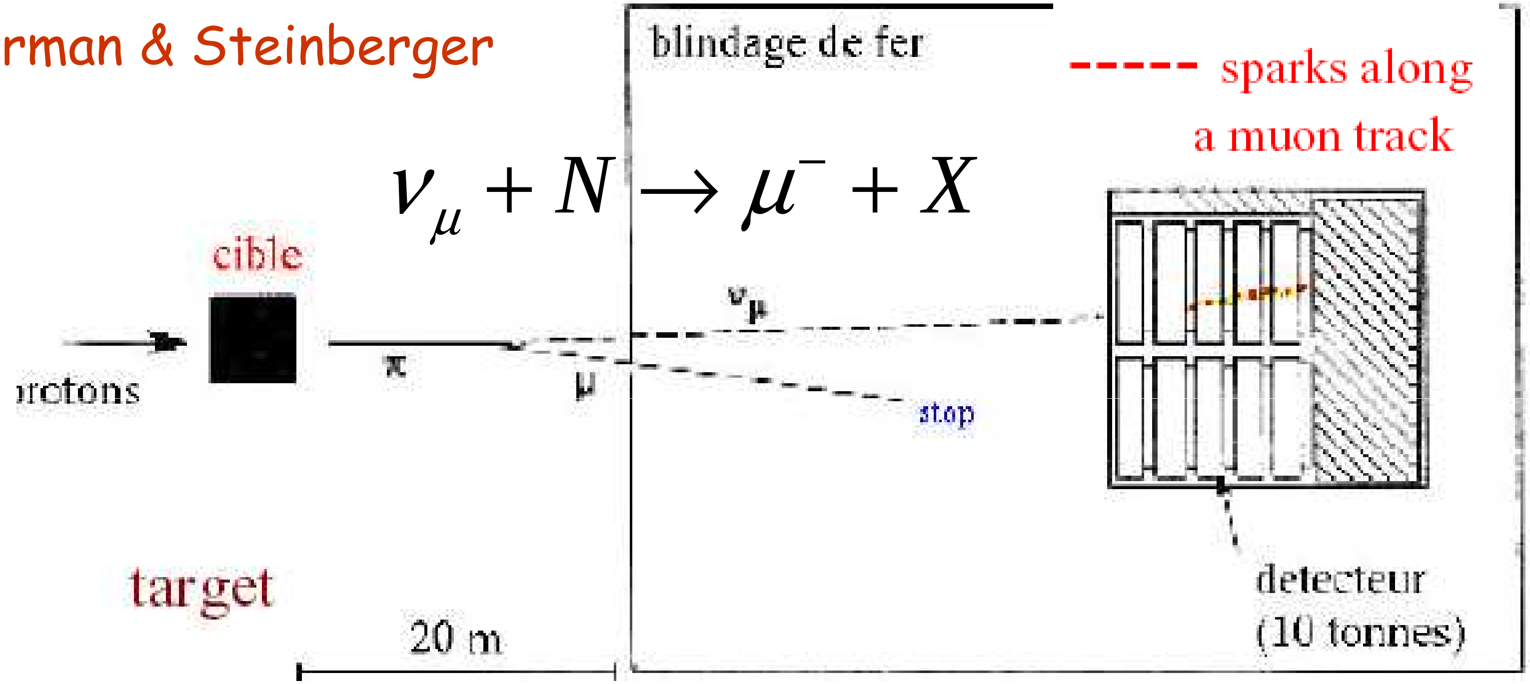
$$\bar{\nu}_e \longrightarrow \nu_e$$

- Note that at the time of this hypothesis only one type of neutrinos was know

The discovery of ν_μ (1962)

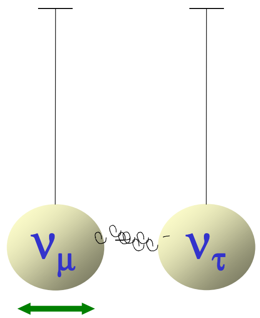
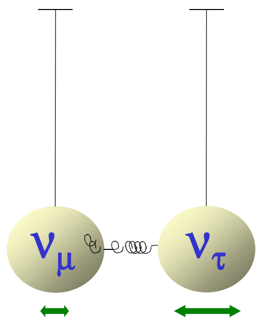
Swartz, Lederman & Steinberger

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



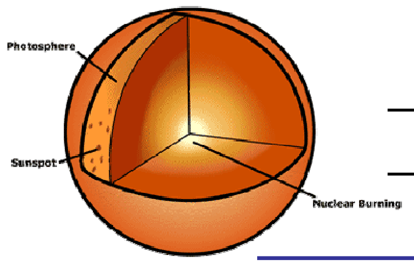
Immediately after this result B. Pontecorvo formulated his neutrino oscillation theory in terms of transition between flavour!

Coupled pendulums’ analogy

	Classical physics		Quantum mechanics
Production	Movement of pendulum ν_μ (“visible” eigenstate) Coupling		ν_μ production (Weak Int. eigenstate) Mixing
Propagation based on	Principal modes of oscillation ν_1 ν_2 (with different time evolution)		Mass eigenstates ν_1 ν_2 (with different space-time evolution)
Observation	energy “**oscillates**” from ν_μ to ν_τ and back		ν_μ and ν_τ disappear and appear with space-time

Neutrino oscillation formalism (I)

source

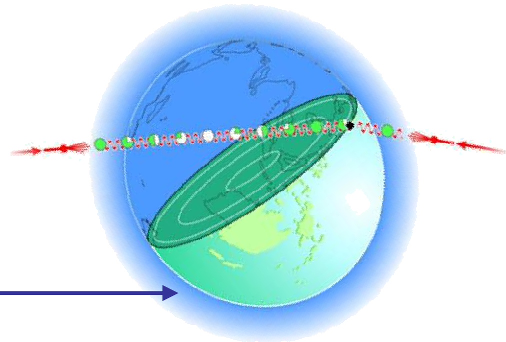


ν_e

propagation

L

detection



The weak interaction

produces neutrinos

of a given flavor

$$\left|\nu(x_0)\right\rangle = \left|\nu_e\right\rangle$$
$$= c\left|\nu_1\right\rangle + s\left|\nu_2\right\rangle$$

The mass eigenstates

Propagate at different velocities

$$\left|\nu(x)\right\rangle = c\left|\nu_1\right\rangle e^{i(Et-\vec{k}_1 \vec{x})}$$
$$+ \quad s\left|\nu_2\right\rangle e^{i(Et-\vec{k}_2 \vec{x})}$$

Detection again via

weak interaction

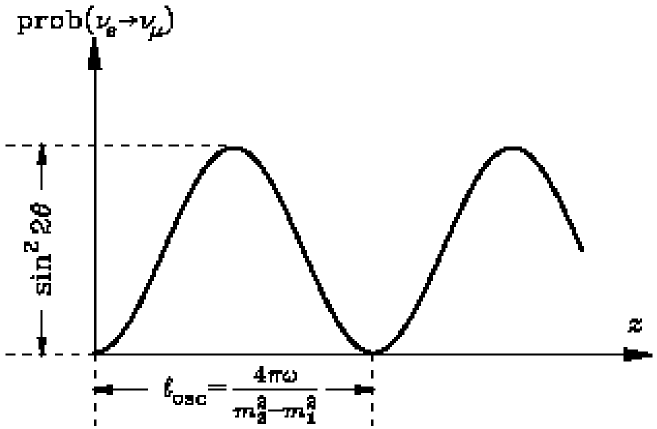
$$\nu_\mu N \to \mu^- X$$
$$\nu_e N \to e^- X$$

$$P(\nu_e \to \nu_\mu) = |< \nu_\mu \mid \nu(t) >|^2$$

Neutrino oscillation formalism (II)

$$P_{\nu_e \to \nu_\mu}(L) = \sin^2(2\theta)\sin^2(1.27\frac{\Delta m^2(eV^2)}{E(GeV)}L(km))$$

$$P_{\nu_e \to \nu_e}(L) = 1 - P_{\nu_e \to \nu_\mu}(t)$$



$$L_{osc}(Km) \approx \frac{E(GeV)}{1.27\Delta m^2(eV^2)}$$

Neutrino oscillation formalism (III)

3x3 Unitary Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

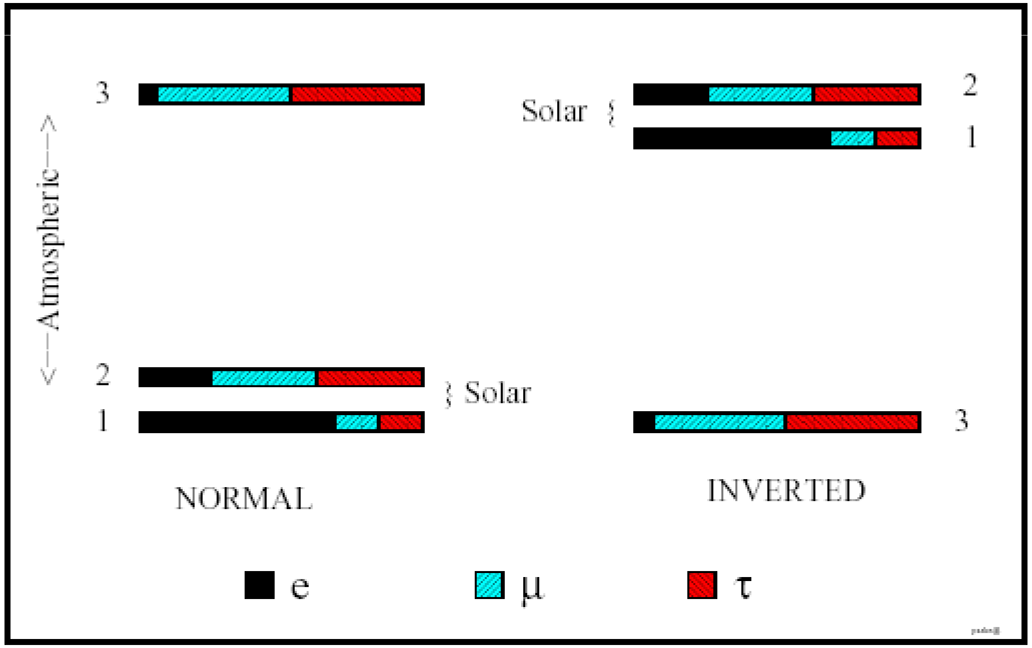
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric terms **Unknown terms** **Solar terms**

$c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij}$

Neutrino oscillation formalism (IV)

- Mixing parameters: $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix
- Mass-gap parameters: $M^2 = \Delta m^2_{12}\ , \pm \Delta m^2_{23}$



The absolute neutrino mass scale should be set by direct mass measurements:

- β-decay
- 0ν2β-decay
- "W-MAP"

Disappearance experiment

Use a beam of ν_α and measure ν_α flux at distance L from source

Measure

$$\mathcal{P}_{\alpha\alpha} = 1 - \sum_{\beta \neq \alpha} \mathcal{P}_{\alpha\beta}$$

Examples:

- **Oscillation experiments using $\bar{\nu}_e$ from nuclear reactors**

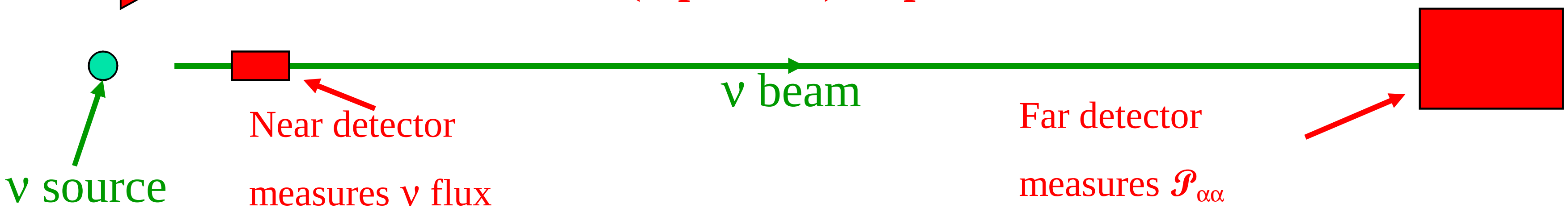
  ($E_\nu \approx$ few MeV: under threshold for μ or τ production)

- **ν_μ detection at accelerators or from cosmic rays**

  (to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations if E_ν is under threshold for τ production)

Main uncertainty: knowledge of the neutrino flux for no oscillation

the use of two detectors (if possible) helps



Appearance experiment

Use a beam of ν_α and detect ν_β ($\beta \neq \alpha$) at distance L from source

Examples:

- **Detect ν_e + Nucleon $\rightarrow$ e^- + hadrons in a ν_μ beam**

- **Detect ν_τ + Nucleon $\rightarrow$ τ^- + hadrons in a ν_μ beam**

  (Energy threshold $\approx$ 3.5 GeV)

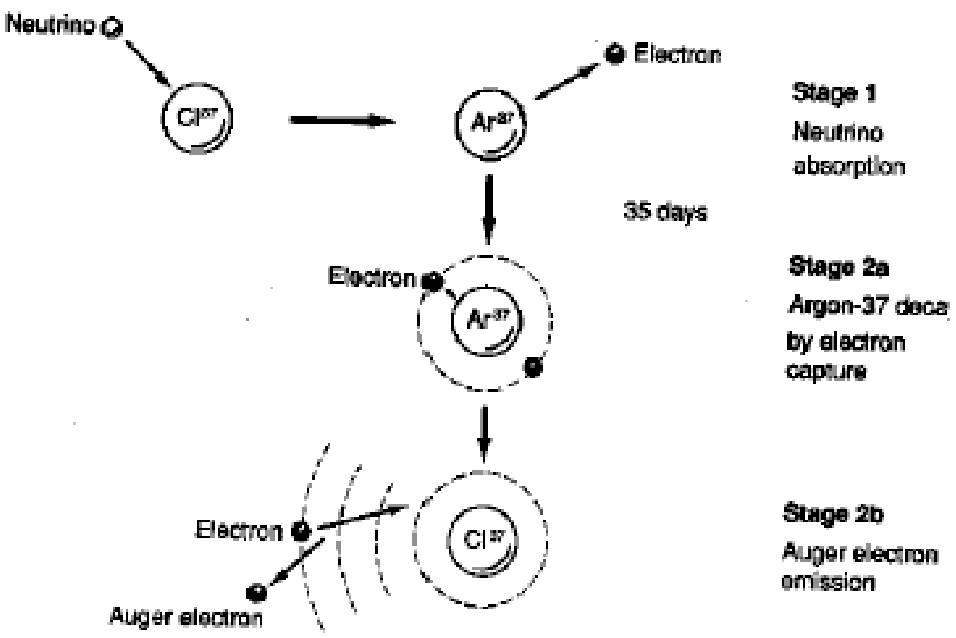
NOTES

- **ν_β contamination in beam must be precisely known**

  ($\nu_e/\nu_\mu \approx 1\%$ in ν_μ beams from high-energy accelerators)

- **Most neutrino sources are not mono-energetic but have wide energy spectra. Oscillation probabilities must be averaged over neutrino energy spectrum.**

The chlorine experiment (1968)



The chlorine experiment

Ar is chemically very different from Chlorine. An inert gas that can be eventually removed from chlorine. It is radioactive and reverts to Cl^{37} emitting an Auger electron (Pontecorvo ideas)

Cl^{37} $\rightarrow$25% of all natural chlorine

Inverse beta decay (0.86 MeV threshold)

$Cl^{37} + \nu \rightarrow Ar^{37} + e^{-}$

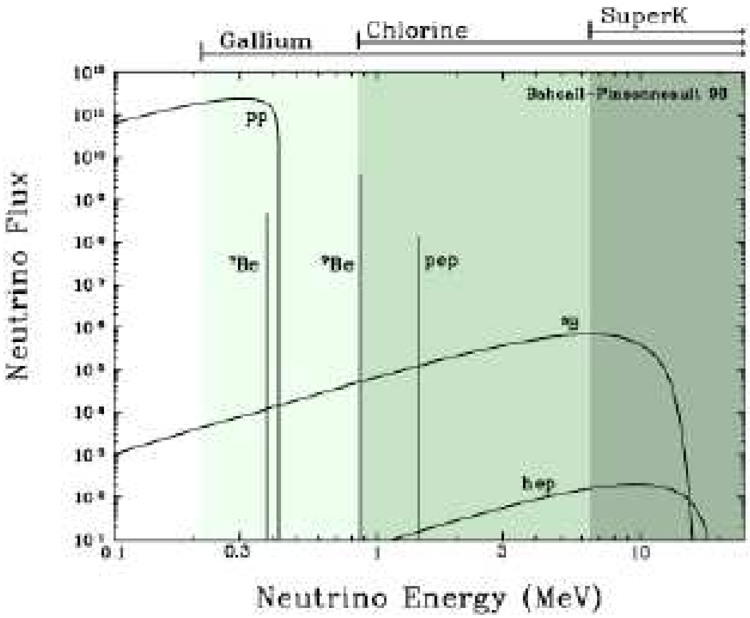
R. Davis

Chlorine by numbers

$^{37}Cl(\nu_e, e)^{37}Ar$ (E_{thr} = 813 keV)

K_{shell} **EC** τ = **50.5** d

^{37}Cl + 2.82 keV (*Auger* e^-, *X*)



Expects

8.2 SNU ± 1.8

Observs

2.56 SNU ± 0.23

The solar neutrino problem

- Also called “paradox”, “dilemma”, “puzzle” and other nice words that showed that every body (secretly) believed that:
- Davis (Chlorine experiment) was wrong
- Bahcall (The solar model) was wrong

Or, more likely: Both were wrong!

“*It appears that the explanation in terms of neutrino mixing …*

Is much more actractive and much more natural than other explanations”

Lepton mixing and the solar neutrino puzzle

Bilenky,Pontecorvo

Dubna Report E 10545 1977

In 1988 a new hypothesis

Light neutrinos as cosmological dark matter. A crucial experimental test

Haim Harari a, b

a Weizmann Institute of Science, 76100, Rehovot, Israel

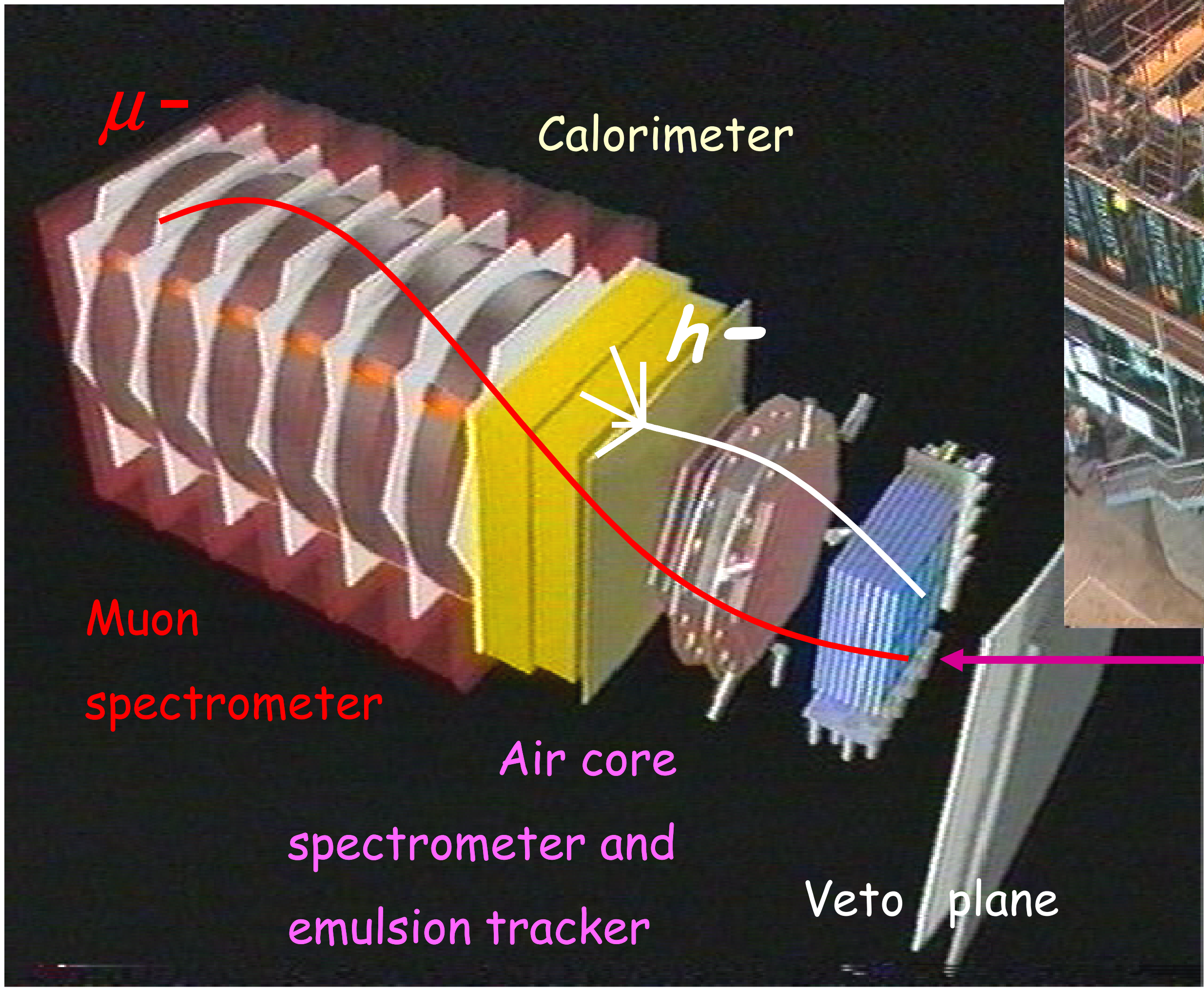
b Fermi National Laboratory, Batavia, IL 60510, USA

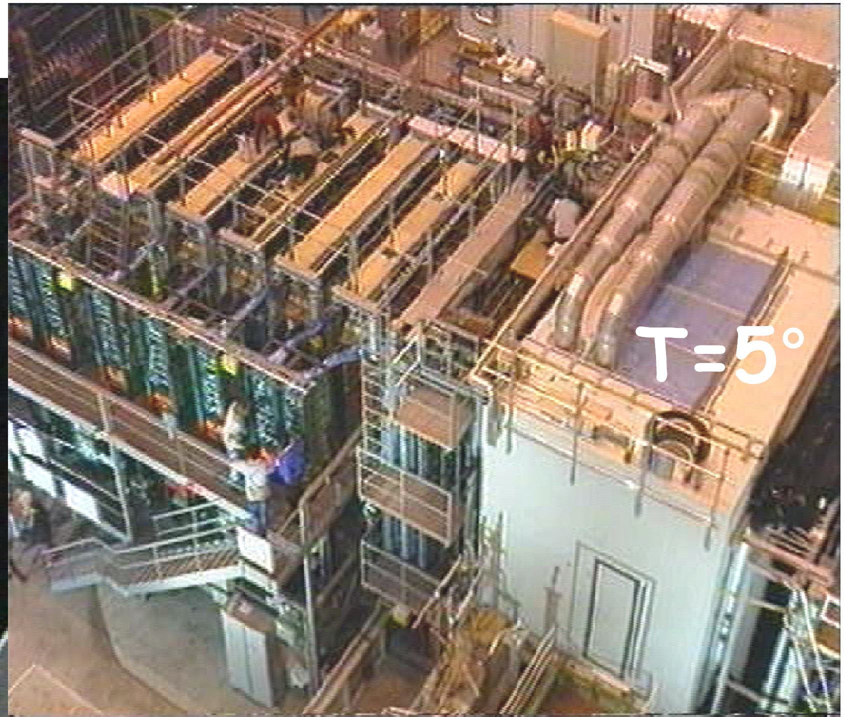
Received 15 September 1988.

Abstract

Cosmological dark matter allegedly dominates the energy of the universe. Among all dark matter candidates, the light neutrino is the only particle actually known to exist in nature. The most likely light neutrino candidate is ν_τ with mass $m(\nu_\tau)$ similar, equals 15–65 eV. The only practical way to show that $m(\nu_\tau)$ is in that range, is to search for ν_μ–ν_τ oscillations reaching values of $\sin^2 2\theta_{\mu\tau}$ as low as 4×10^{-4}. This calls for an improvement of the best existing experiment by one order of magnitude. A dedicated accelerator experiment with an emulsion followed by a spectrometer, detecting at least 40000 neutrino interactions, can settle the issue. Such an experiment does not seem impossible. A positive result would prove that most of the universe consists of ν_τ particles.

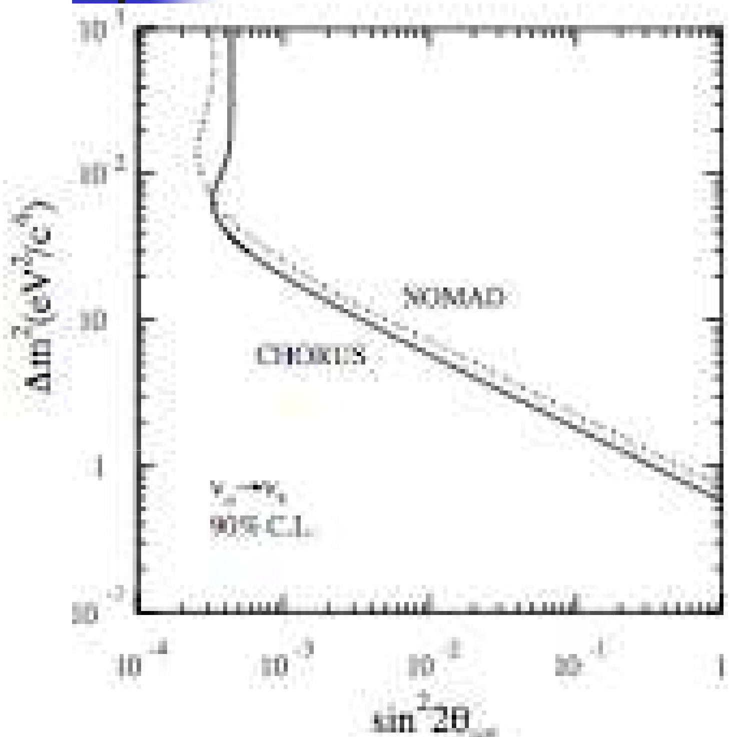
The CHORUS experiment: a high sensitivity experiment to observe oscillations with mass $m(\nu_\tau)$ similar, equals 15–65 eV^2





770 kg emulsion target and scintillating fibre tracker

CHORUS results: oscillations and charm physics



Final results on nu(mu) ---> nu(tau) oscillation from the CHORUS experiment.

Published in Nucl.Phys. B793 (2008) 326-343

New results from a search for nu/mu --> nu/tau and nu/e --> nu/tau oscillation.
Published in Phys.Lett. B497 (2001) 8-22

Search for muon-neutrino ---> tau-neutrino oscillation using the tau decay modes into a single charged particle.
Published in Phys.Lett. B434 (1998) 205-213

A Search for muon-neutrino ---> tau-neutrino oscillation.
Published in Phys.Lett. B424 (1998) 202-212

Leading order analysis of neutrino induced dimuon events in the CHORUS experiment.
Published in **Nucl.Phys. B798 (2008) 1-16**

Associated Charm Production in Neutrino-Nucleus Interactions.
Published in **Eur.Phys.J. C52 (2007) 543-552**

Charged Particle Multiplicities in Charged-Current Neutrino and Anti-Neutrino Nucleus Interactions.
Published in **Eur.Phys.J. C51 (2007) 775-785**

Measurement of nucleon structure functions in neutrino scattering.
Published in **Phys.Lett. B632 (2006) 65-75**

Measurement of topological muonic branching ratios of charmed hadrons produced in neutrino-induced charged-current interactions.
Published in **Phys.Lett. B626 (2005) 24-34**

Search for superfragments and measurement of the production of hyperfragments in neutrino nucleus interactions.
Published in **Nucl.Phys. B718 (2005) 35-54**

Measurement of D*+ production in charged-current neutrino interactions.
Published in **Phys.Lett. B614 (2005) 155-164**

Measurements of D0 production and of decay branching fractions in neutrino nucleon scattering.
Published in **Phys.Lett. B613 (2005) 105-117**

Measurement of charm production in antineutrino charged-current interactions.
Published in **Phys.Lett. B604 (2004) 11-21**

Measurement of fragmentation properties of charmed particle production in charged-current neutrino interactions.
Published in **Phys.Lett. B604 (2004) 145-156**

Experimental study of trimuon events in neutrino charged-current interactions.
Published in **Phys.Lett. B596 (2004) 44-53**

Cross-section measurement for quasi-elastic production of charmed baryons in nu N interactions.
Published in **Phys.Lett. B575 (2003) 198-207**

Measurement of the Z/A dependence of neutrino charged-current total cross-sections.
Published in **Eur.Phys.J. C30 (2003) 159-167**

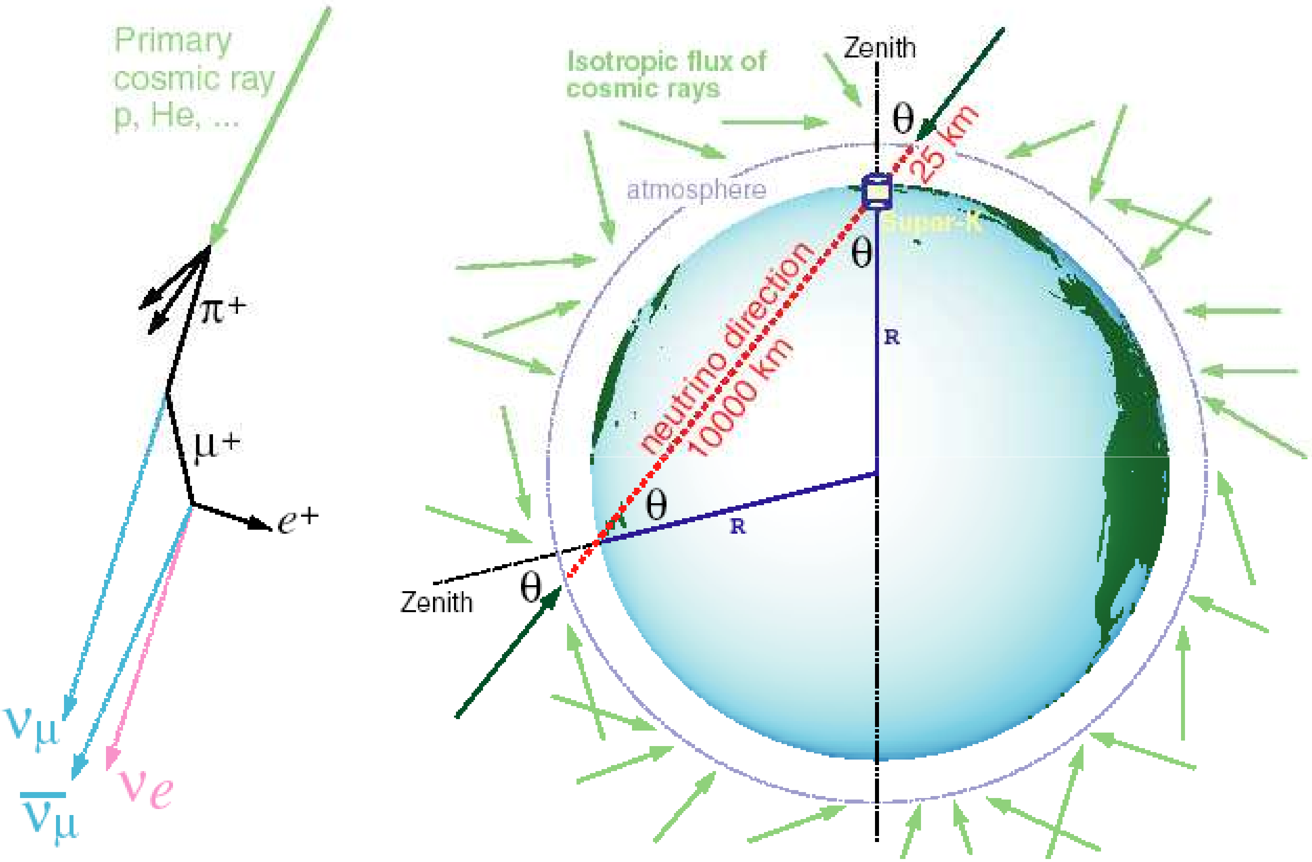
Measurement of Lambda/c+ production in neutrino charged-current interactions.
Published in **Phys.Lett. B555 (2003) 156-166**

Determination of the semi-leptonic branching fraction of charm hadrons produced in neutrino charged-current interactions.
Published in **Phys.Lett. B549 (2002) 48-57**

Observation of one event with the characteristics of associated charm production in neutrino charged-current interactions.
Published in **Phys.Lett. B539 (2002) 188-196**

Measurement of D0 production in neutrino charged-current interactions.
Published in **Phys.Lett. B527 (2002) 173-181**

THE 1998 REVOLUTION!

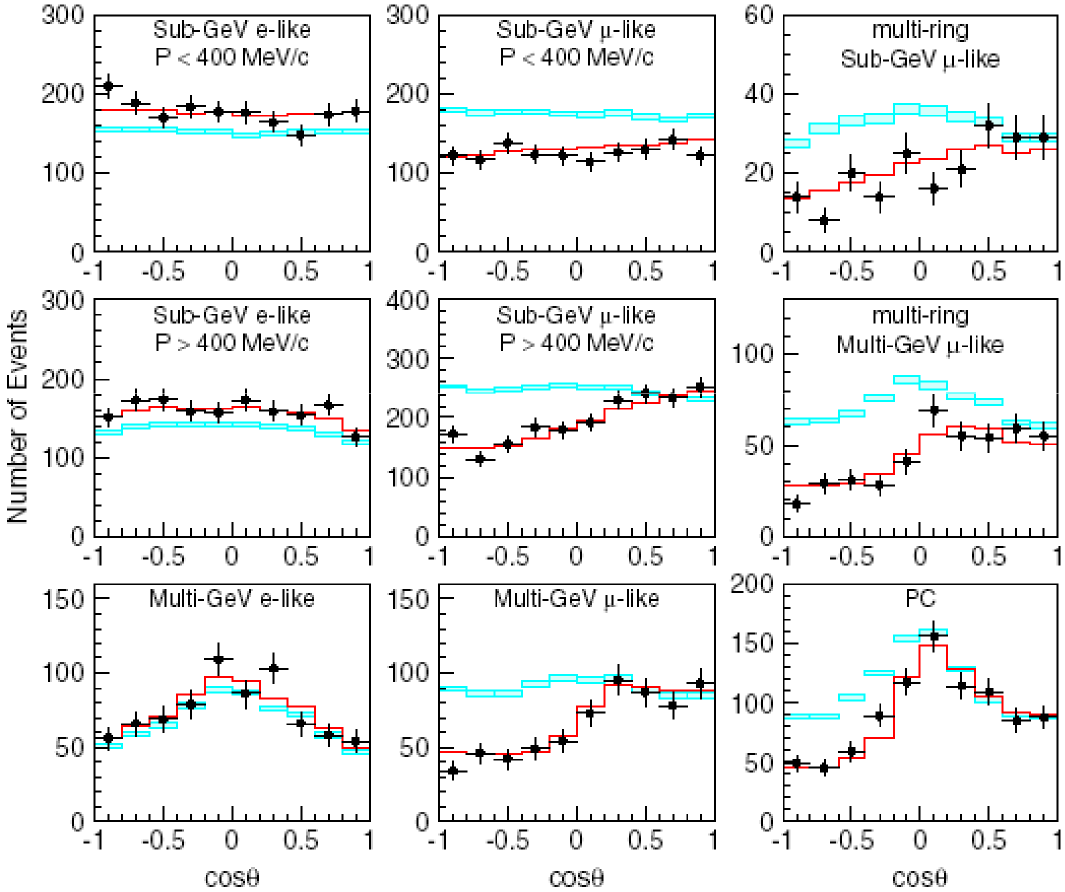


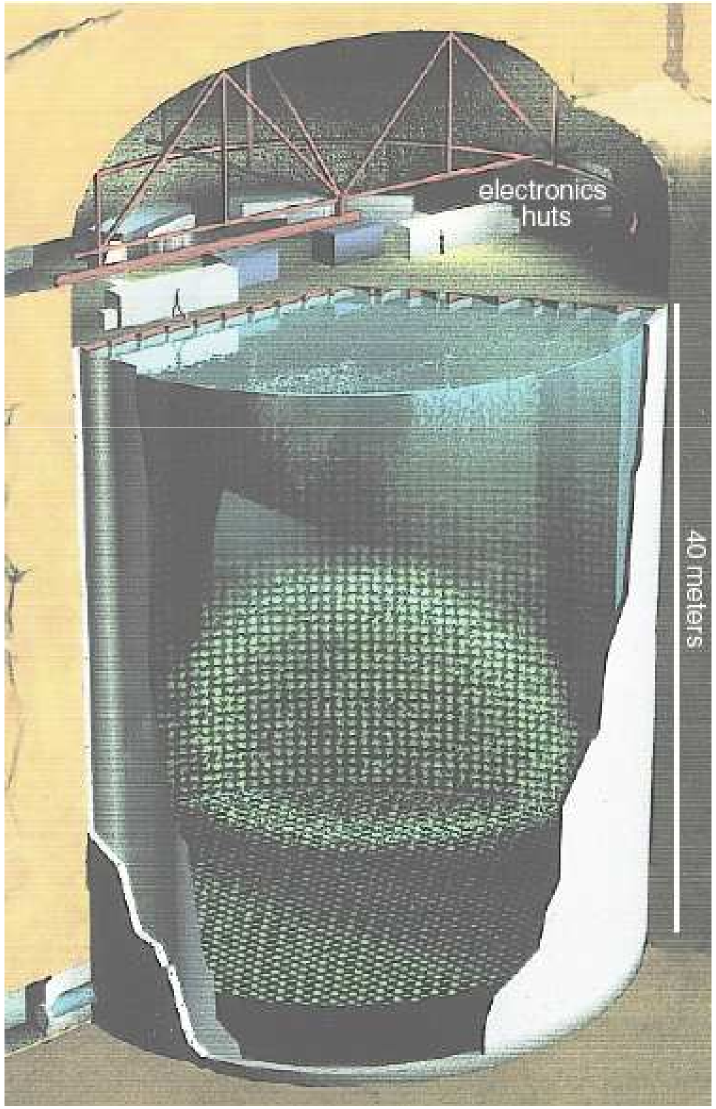
Ratio of $\nu_\mu/\nu_e \sim 2$
(for E_ν < few GeV)

Up/Down Symmetric Flux
(for E_ν > few GeV)

Note that atmospheric neutrinos were studied as background for proton decay!

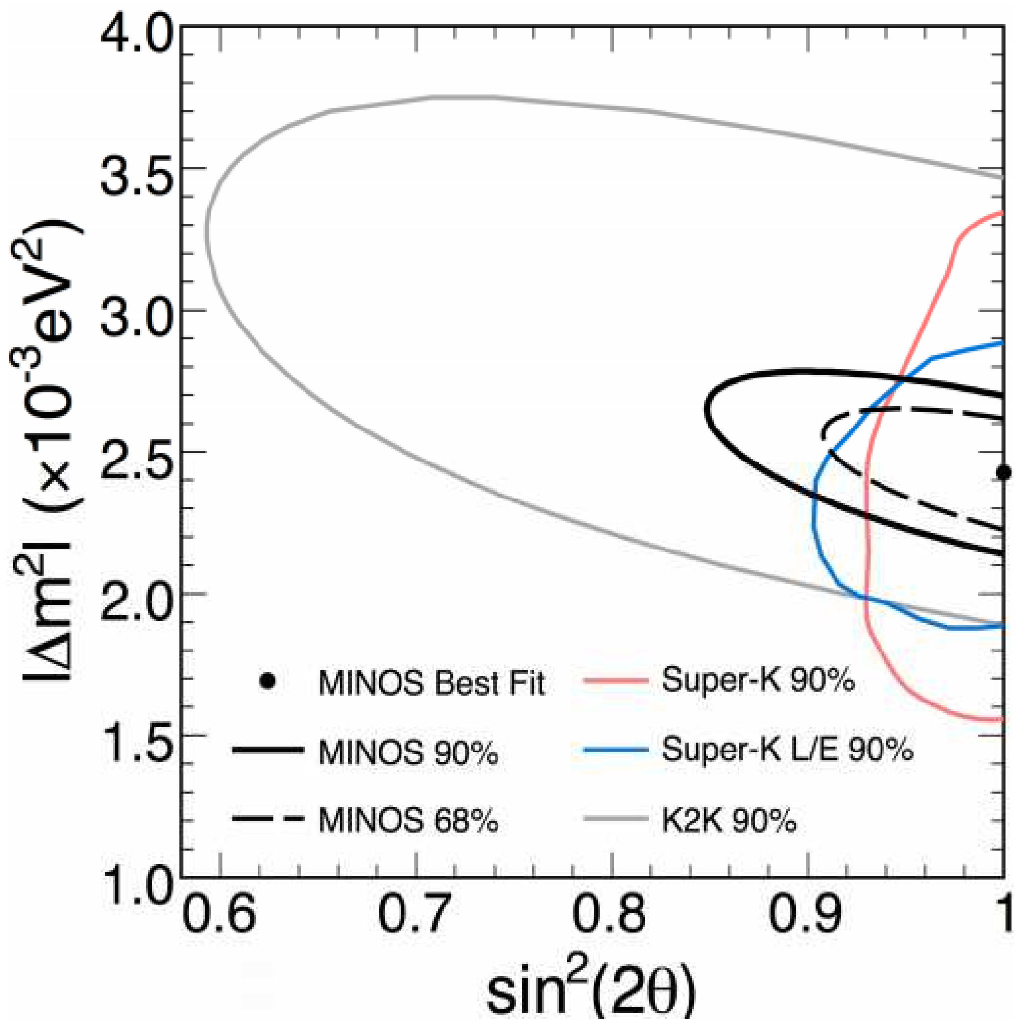
Super-Kamiokande observes a deficit of atmospheric neutrinos





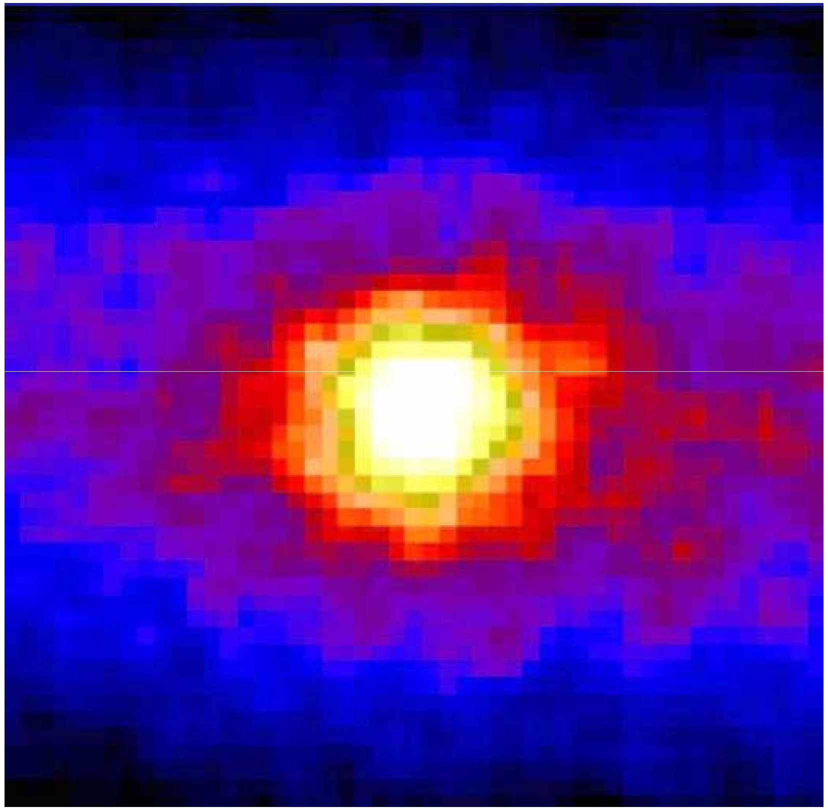
The deficit depends on the energy and the path length!

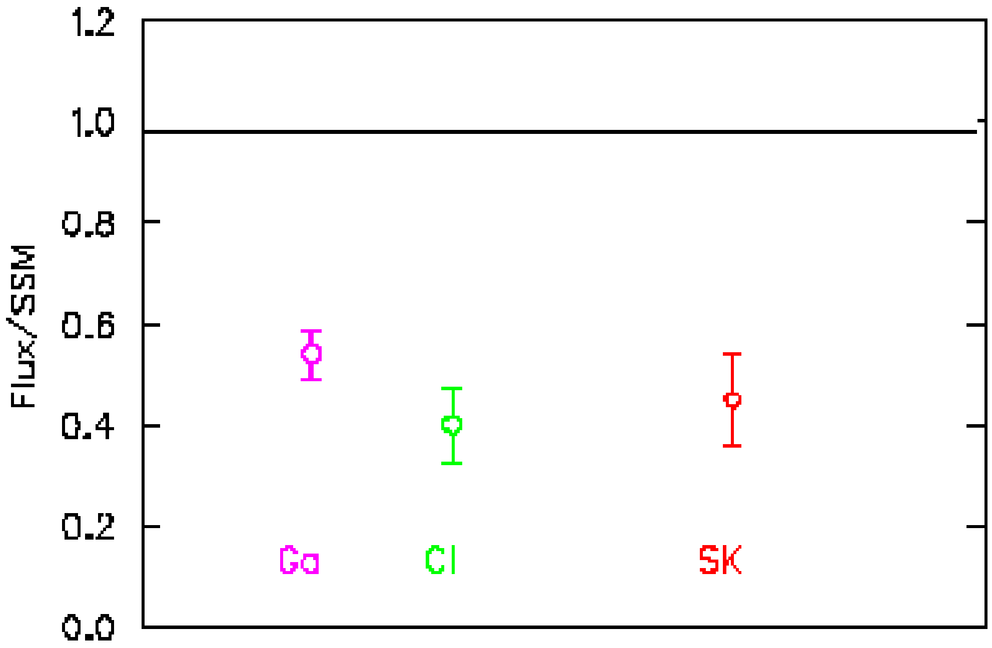
Since 1998 many exps contributed to the understanding of the PMNS matrix



But, what about the solar neutrino problem/paradox/... ?

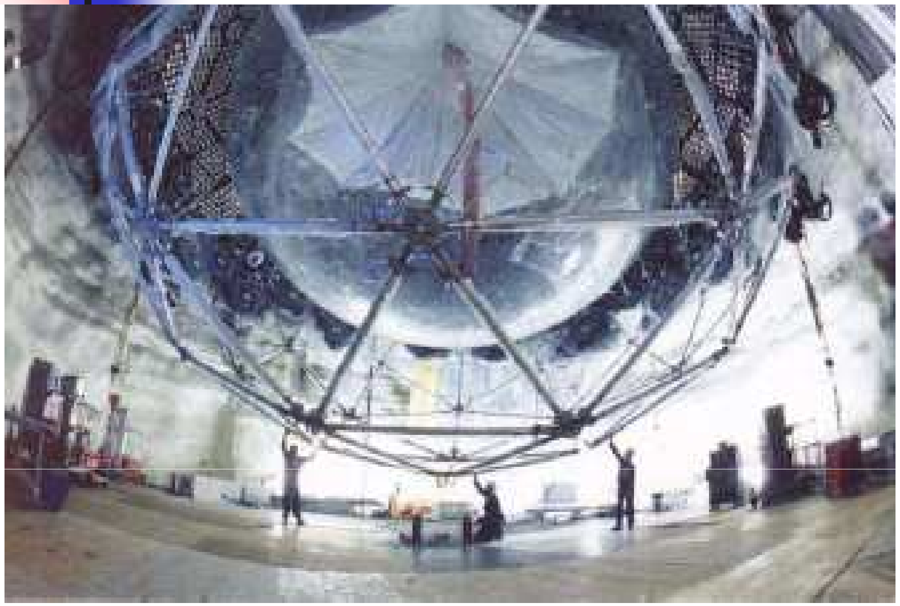
Many years after R. Davis...

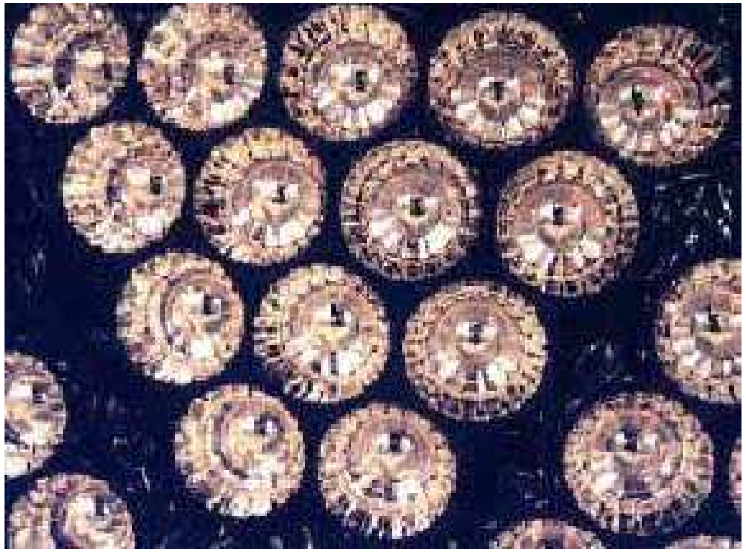


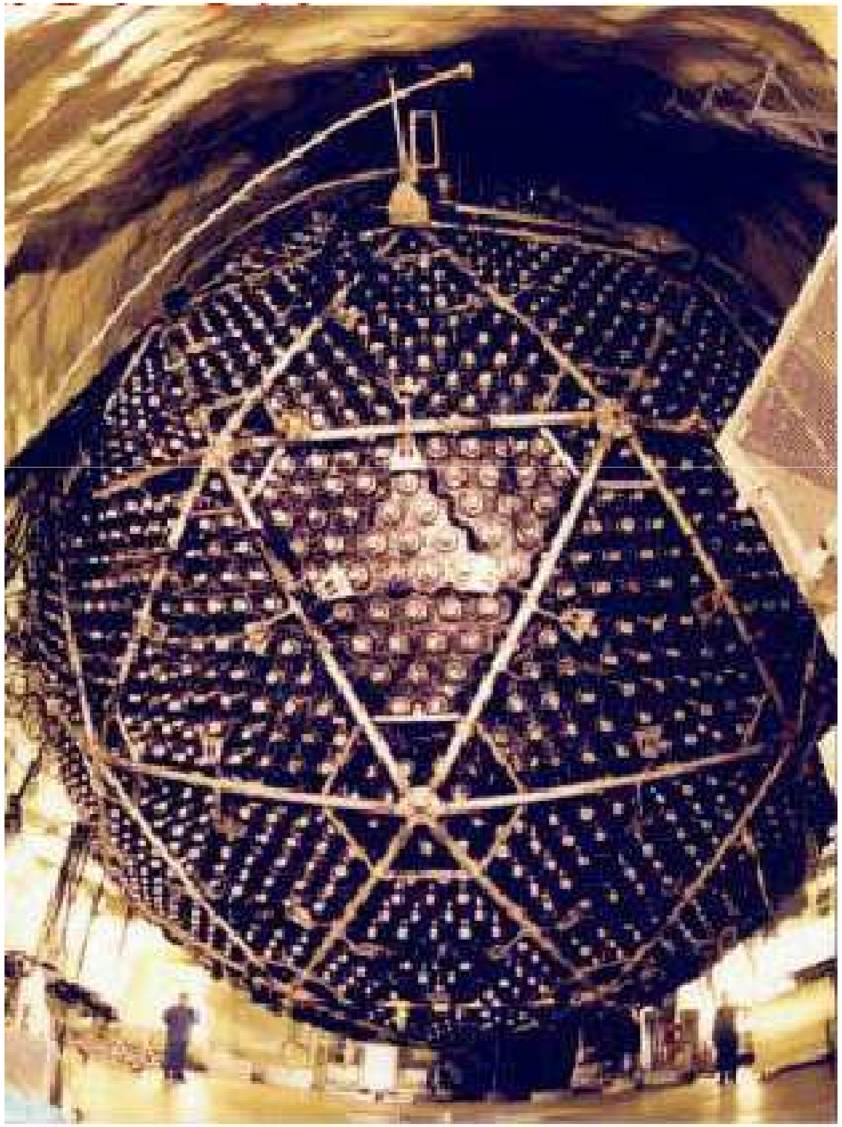


Able to photograph the Sun with neutrinos, but not to understand it....

In 2000 the SNO experiment solved the long standing solar problem



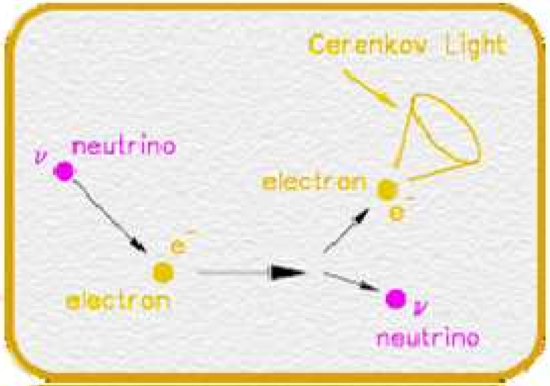




Signals in SNO

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

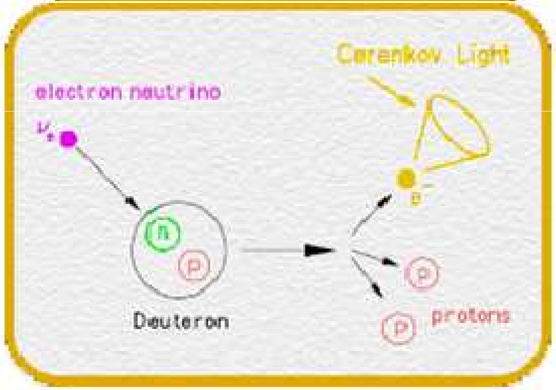
- Strong directional sensitivity



CC $\nu_e + d \Rightarrow p + p + e^-$

- Good measurement of ν_e energy spectrum
- Weak directional sensitivity ∝ 1-1/3cos(θ)

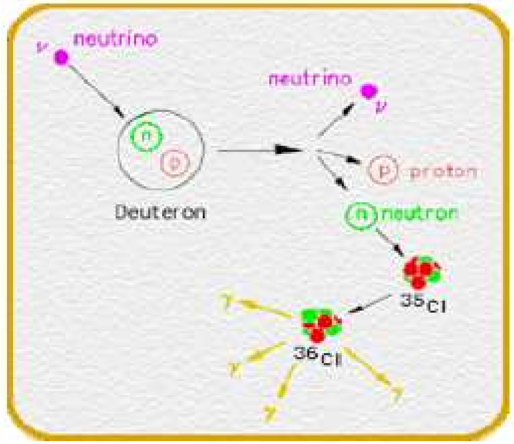
- ν_e ONLY



NC $\nu_x + d \Rightarrow p + n + \nu_x$

- Measure total ^8B ν flux from the sun.

- Equal cross section for all ν types

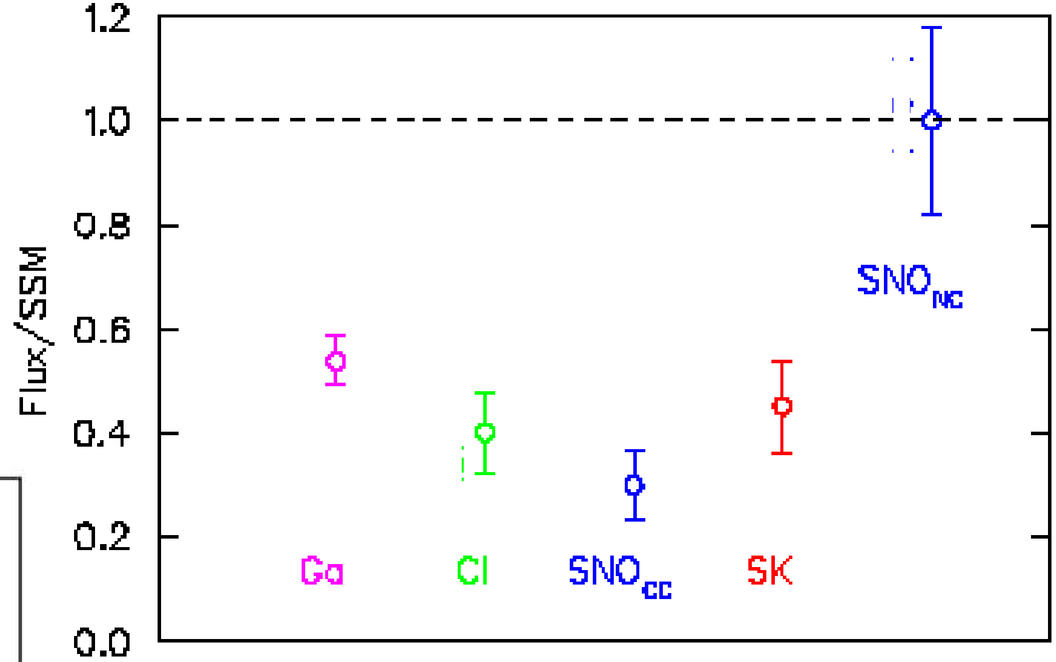


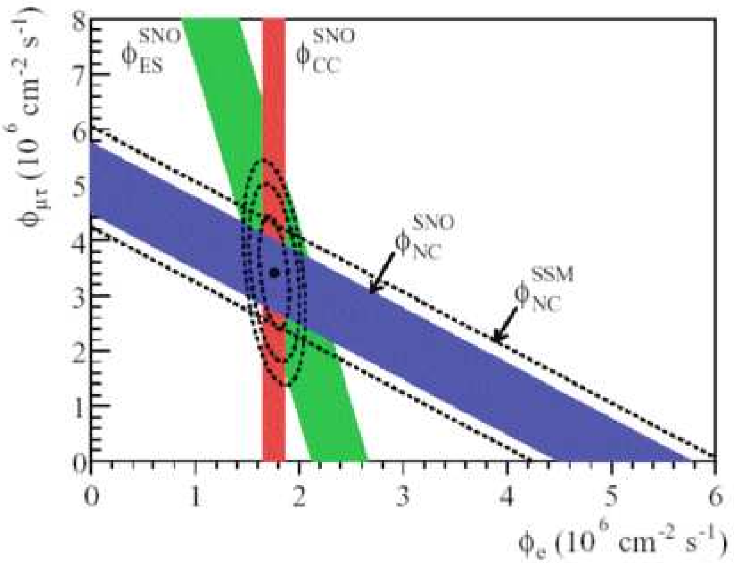
The SNO results

CC $\nu_e + d \Rightarrow p + p + e^-$

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$

NC $\nu_x + d \Rightarrow p + n + \nu_x$





So the Sun is shining the expected number of neutrinos but many of them are ν_μ and/or ν_τ!

Not only Davis, but also Bahcall was right!

The Golden Age of Neutrino oscillation from 1998 to 2006: the PDG Indicator

PDG 1997 edition

Neutrinos 5pg
No. of Light Neutrino Types from Collider Expts. 2pg
Massive Neutral Leptons & Effects of Nonzero Neutrino Masses 5pg
Limits from Neutrinoless Double-beta Decay 2pg
Solar neutrinos 8pg

PDG 1999 edition

Neutrino mass	16pg
No. of Light Neutrino Types from Collider Expts.	2pg
Searches for Massive Neutrinos	5pg
Limits from Neutrinoless Double-beta Decay	2pg
Solar neutrinos	8 pg

PDG 2000 edition

Neutrino mass	17 pg
No. of Light Neutrino Types from Collider Expts.	2 pg
Searches for Massive Neutrinos	(5 pages)
Two-flavor Oscillation Parameters and Limits	(2 pages)
Limits from Neutrinoless Double-beta Decay	(3 pages)
Solar neutrinos	(11 pages)

PDG 2002 edition

Electron, muon, and tau neutrinos (New)	3pg
Neutrino Physics as Explored by Flavor Change (New)	24pg
Understanding Two-Flavor Oscillation Parameters and Limits (Rev.)	6pg
Two-Flavor Oscillation Parameters and Limits (plots) (Rev.)	4pg
No. of Neutrino Types from Collider Expts. (Rev.)	2pg
Solar neutrinos (Rev.)	14pg
Limits from Neutrinoless Double-beta Decay (Rev.)	4pg

PDG 2004 edition

Electron, muon, and tau neutrinos (Rev.)	3pg
Neutrino mass, mixing, and flavor change (Rev.)	24pg
Number of Light Neutrino Types from Collider Expts.	2pg
Understanding Two-Flavor Oscillation Parameters and Limits	5pg
Limits from Neutrinoless Double-beta Decay (Rev.)	4pg
Solar neutrinos (Rev.)	18pg

PDG 2006 edition

Standard Model and Related Topics

Quantum chromodynamics (Rev.) errata	(25 pages)
Electroweak model and constraints on new physics (Rev.) errata	(50 pages)
Cabibbo-Kobayashi-Maskawa quark-mixing matrix (New) erratum	(20 pages)
CP violation (Rev.)	(28 pages)
Neutrino mass, mixing, and flavor change (Rev.)	(23 pages)
Quark model (Rev.) erratum	(20 pages)
Grand Unified Theories (Rev.)	(20 pages)
Structure Functions (Rev.; see below for more figures)	(15 pages)
Structure Functions--additional figures (Rev.; see above) errata	(8 pages)
Fragmentation Functions (Rev.)	(26 pages)
Tests of Conservation Laws (Rev.) errata	(5 pages)
CPT Invariance Tests in Neutral Kaon Decay (Rev.)	(4 pages)
CP Violation in K_S -> 3pi	(1 page)
CP Violation in K_L Decays (Rev.)	(12 pages)
V(ud), V(us), Cabibbo Angle, and CKM Unitarity (New)	(11 pages)
Determination of V(cb) and V(ub) (New)	(39 pages)

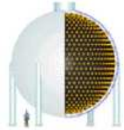
Constraints from a global 3ν analysis

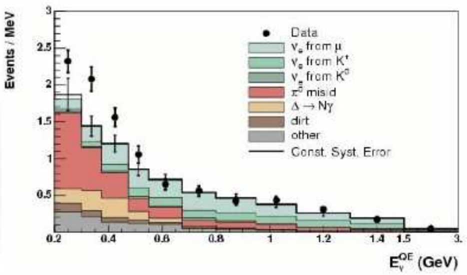
M. C. Gonzalez-Garcia, M. Maltoni and J. Salvado, ``Updated global fit to three neutrino mixing: status of the hints of theta13 > 0,'' arXiv:1001.4524 [hep-ph].

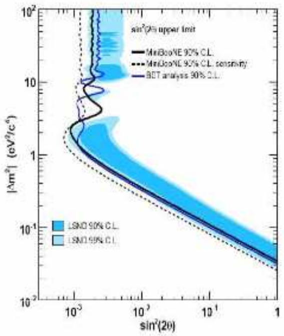
High-Z	GS98 with Gallium cross-section from [17]	Low-Z and SAGE meas.	AGSS09 with modified Gallium cross-section [13]	
	$\Delta m^2_{21} = 7.59 \pm 0.20 \; \left({}^{+0.61}_{-0.69}\right) \times 10^{-5} \text{ eV}^2$		Same	(<10%)
	$\Delta m^2_{31} = \begin{cases} -2.40 \pm 0.11 \; \left({}^{+0.37}_{-0.39}\right) \times 10^{-3} \text{ eV}^2 \text{ (inverted)} \\ +2.51 \pm 0.12 \; \left({}^{+0.39}_{-0.36}\right) \times 10^{-3} \text{ eV}^2 \text{ (normal)} \end{cases}$		Same	(~15%)
	$\theta_{12} = 34.4 \pm 1.0 \; \left({}^{+3.2}_{-2.9}\right)$		$34.5 \pm 1.0 \; \left({}^{+3.2}_{-2.8}\right)$	(~10%)
	$\theta_{23} = 42.3\,^{+5.3}_{-2.8} \; \left({}^{+11.4}_{-7.1}\right)$		Same	(~30%)
	$\theta_{13} = 6.8\,^{+2.6}_{-3.6} \; (\leq 13.2)$ $\theta_{13} \neq 0$ at 1.9σ	$\theta_{13} \neq 0$ at 1.5σ	$5.7\,^{+3.0}_{-3.9} \; (\leq 12.7)$	
	$\left[\sin^2\theta_{13} = 0.014\,^{+0.013}_{-0.011} \; (\leq 0.052)\right]$		$\left[0.010\,^{+0.013}_{-0.009} \; (\leq 0.049)\right]$	
	$\delta_{CP} \in [0, 360]$		Same	

The LSND saga (from 1995 on...)

Appearance results (neutrino mode)



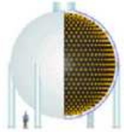


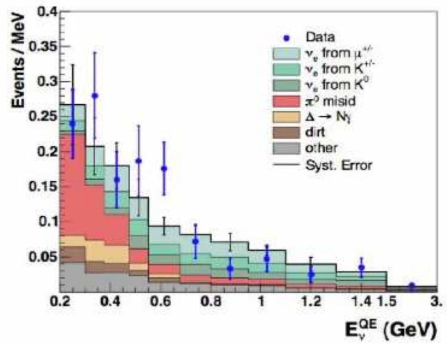


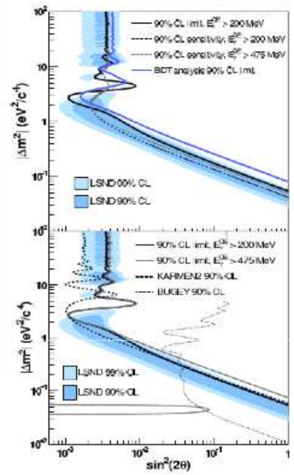
- Analysis based on 6.46E20 POT
- No oscillations at LSND L/E region (> 475 MeV)
- Observed 3σ excess of events in low-energy region (< 475 MeV)

Lett. 102, 101802 (2009)

Appearance results (anti-neutrino mode)







- Analysis based on 3.386E20 POT
- No low energy excess
- Currently work on combined $\nu - \bar{\nu}$ analysis
- More data will provide additional information

Phys. Rev. Lett. 103, 111801 (2009)

Anomaly Mediated Neutrino-Photon Interactions
Harvey, Hill, & Hill, arXiv:0905.029

CP-Violation 3+2 Model
Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301

Lorentz Violation
Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009

CPT Violation 3+1 Model
Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

VSBL Electron Neutrino Disappearance
Giunti and Laveder arXiv:0902.1992

New Gauge Boson with Sterile Neutrinos
Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

MicroBooNE @FNAL on the BooNE and NUMI beams, DoubleLAr recently proposed to run on a refurbished PS neutrino beam. OscSNS will exploit the SNS neutrino beam with a oil–scintillator detector to check the LSND signal

The importance of pursuing neutrino oscillation studies

- Neutrino oscillations are the sole body of experimental evidence for physics beyond the Standard Model
- The observed tiny mass and the large flavour mixing are believed to be consequences of phenomena occurred at the Bing Bang
  - Neutrino oscillation physics is complementary to high-energy collider physics
- The precision measurement of the oscillation parameters and the discovery of LCPV will have important consequences on astrophysics and cosmology
- Furthermore, if the presence of massive sterile neutrinos is proved, it will contribute to clarify the Dark Matter problem
- For a detailed discussion of these topics we refer to arXiv:0710.4947 and references therein (The ISS Working Group); hep-ph/0606054 A. Strumia and F. Vissani

What about OPERA?

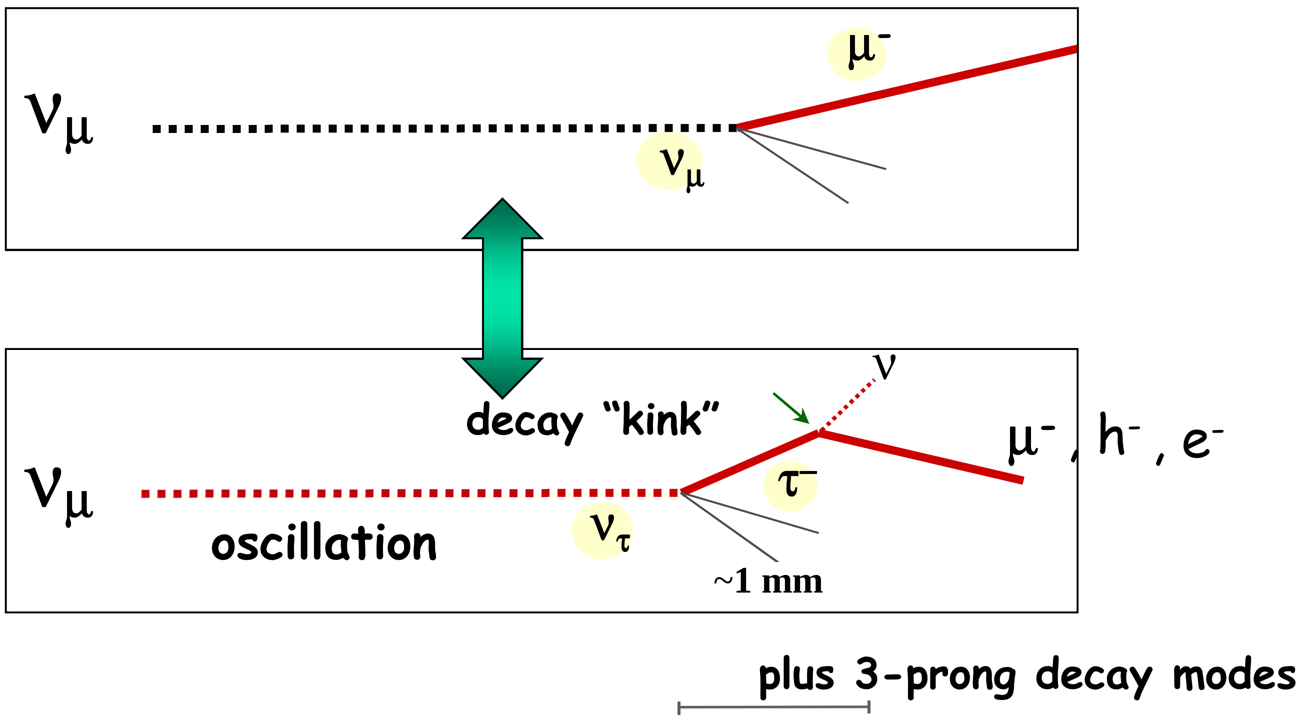
- None of the experiments showing an evidence for neutrino oscillations gave DIRECT evidence for the "appearance of an unexpected" flavour after a given distance
- LSND, Karmen and MiniBoone exploited the appearance but the results are rather controversial...
- These are the motivations that in 1997, but still valid, led to the proposal of the OPERA experiment

OPERA: first direct detection of neutrino oscillations in appearance mode

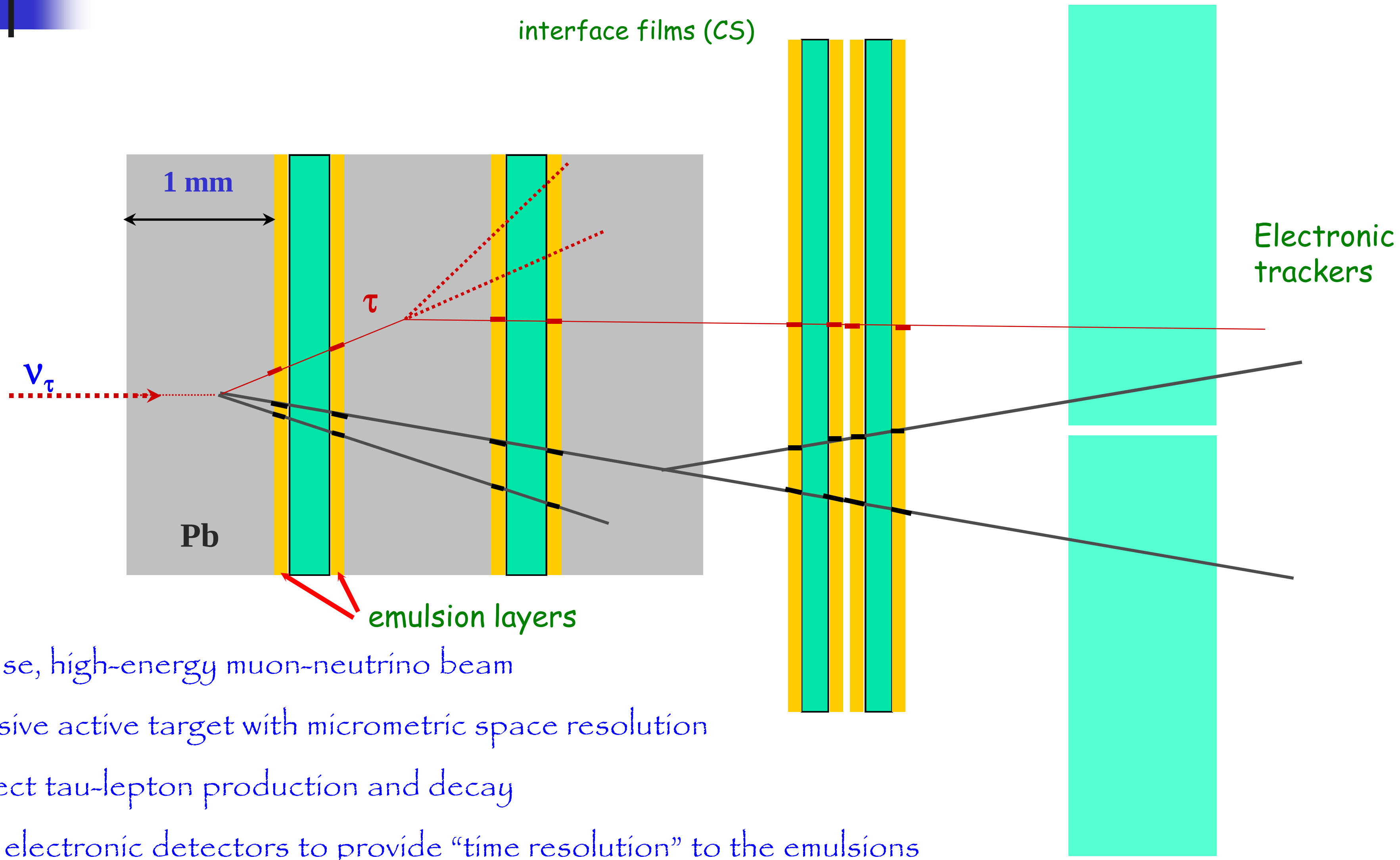
following the Super- Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams. Important, missing tile in the oscillation picture.

Requirements:

1) long baseline, 2) high neutrino energy, 3) high beam intensity, 4) detect short lived τ's



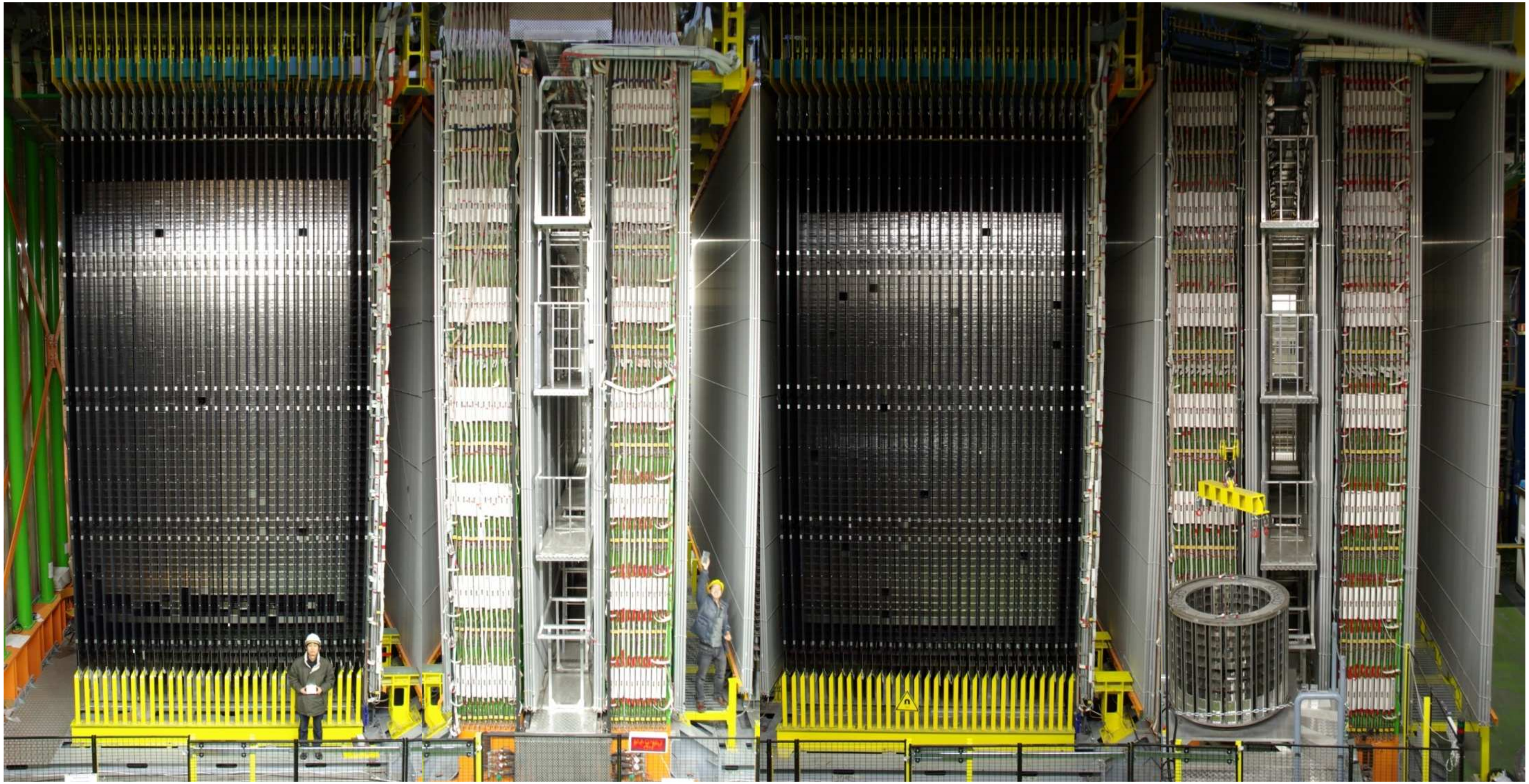
Experiment principle: ECC + Electronic Detectors



- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide "time resolution" to the emulsions and preselect the interaction region

THE IMPLEMENTATION OF THE PRINCIPLE

SM1 SM2



Target area Muon spectrometer

The OPERA Collaboration

180 physicists, 33 institutions in 12 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg
Münster
Rostock

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

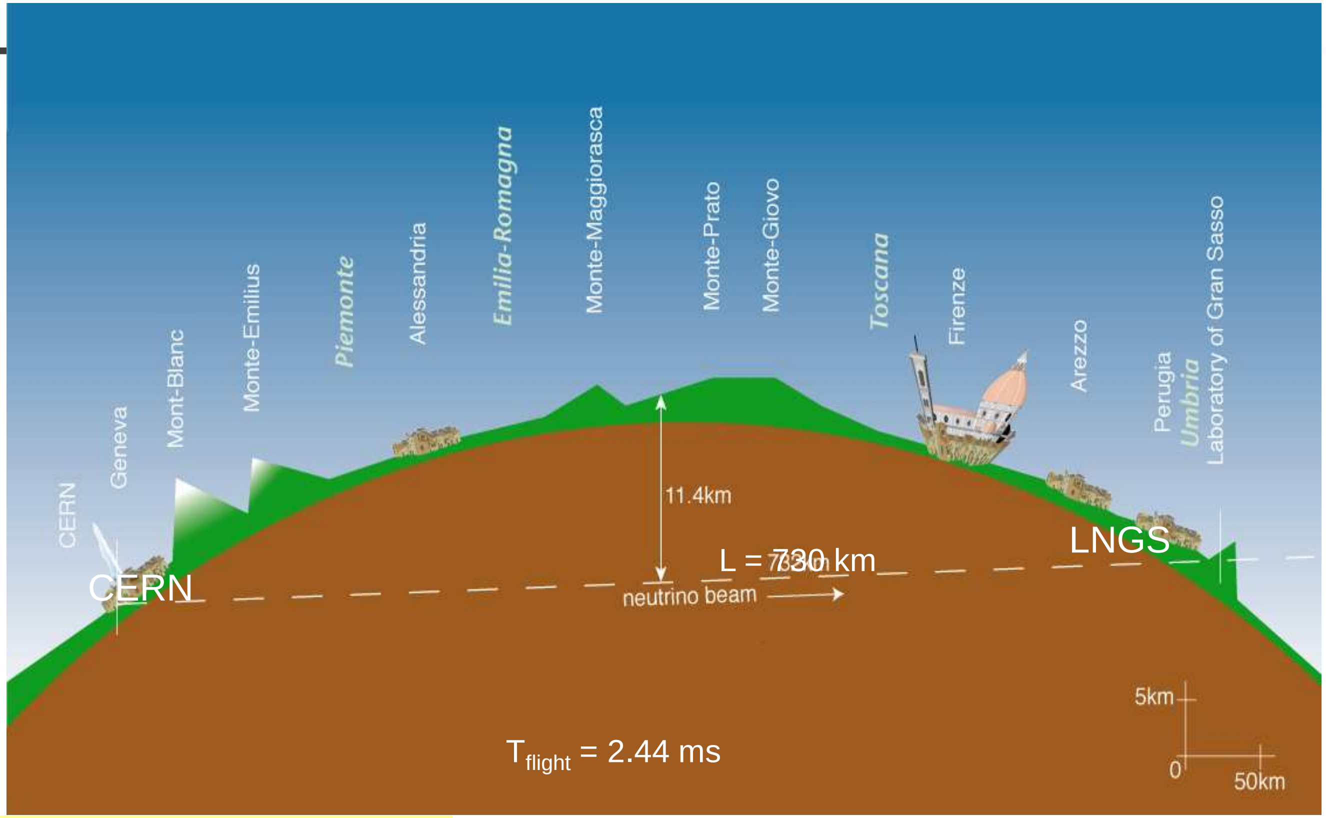
Switzerland
Bern
ETH Zurich

Tunisia
CNSTN Tunis

Turkey
METU Ankara

http://operaweb.web.cern.ch/operaweb/index.shtml

CNGS beam: tuned for ν_τ-appearance at LNGS (730 km away from CERN)



< E >	17 GeV
_ L	730 km
$(\nu_e + \nu_e) / \nu_\mu$ (CC)	0.87%
$\nu_\mu / \bar{\nu}_\mu$ (CC)	2.1%
ν_τ prompt	negligible

Expected neutrino interactions for 22.5×10^{19} pot:

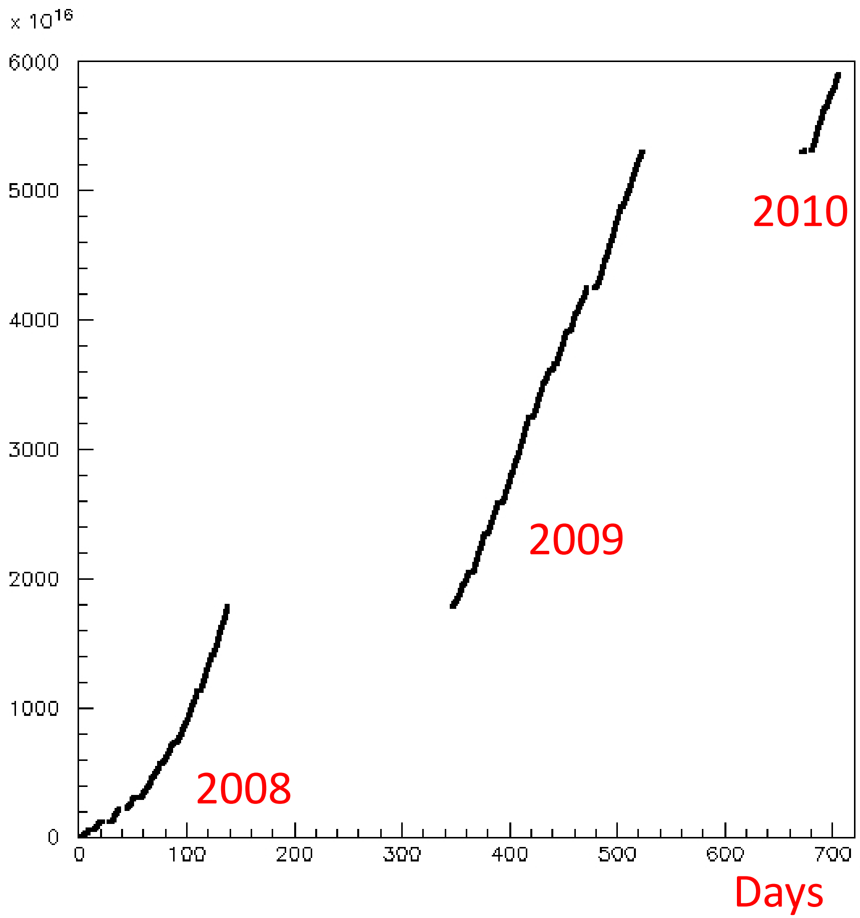
~ 23600 ν_μ CC + NC

~ 160 $\nu_e + \bar{\nu}_e$ CC

~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

CNGS performance

2006	0.076x10^{19} pot	no bricks	Commissioning
2007	0.082x10^{19} pot	38 ev.	Commissioning
2008	**1.78x10^{19} pot**	**1698 ev.**	**First physics run**
2009	**3.52x10^{19} pot**	**3693 ev.**	**Physics run**
2010	**0.60x10^{19} pot (23 May)**	**579 ev.**	**Physics run**



5970 events collected until 23 May 2010 (within 1σ in agreement with expectations)

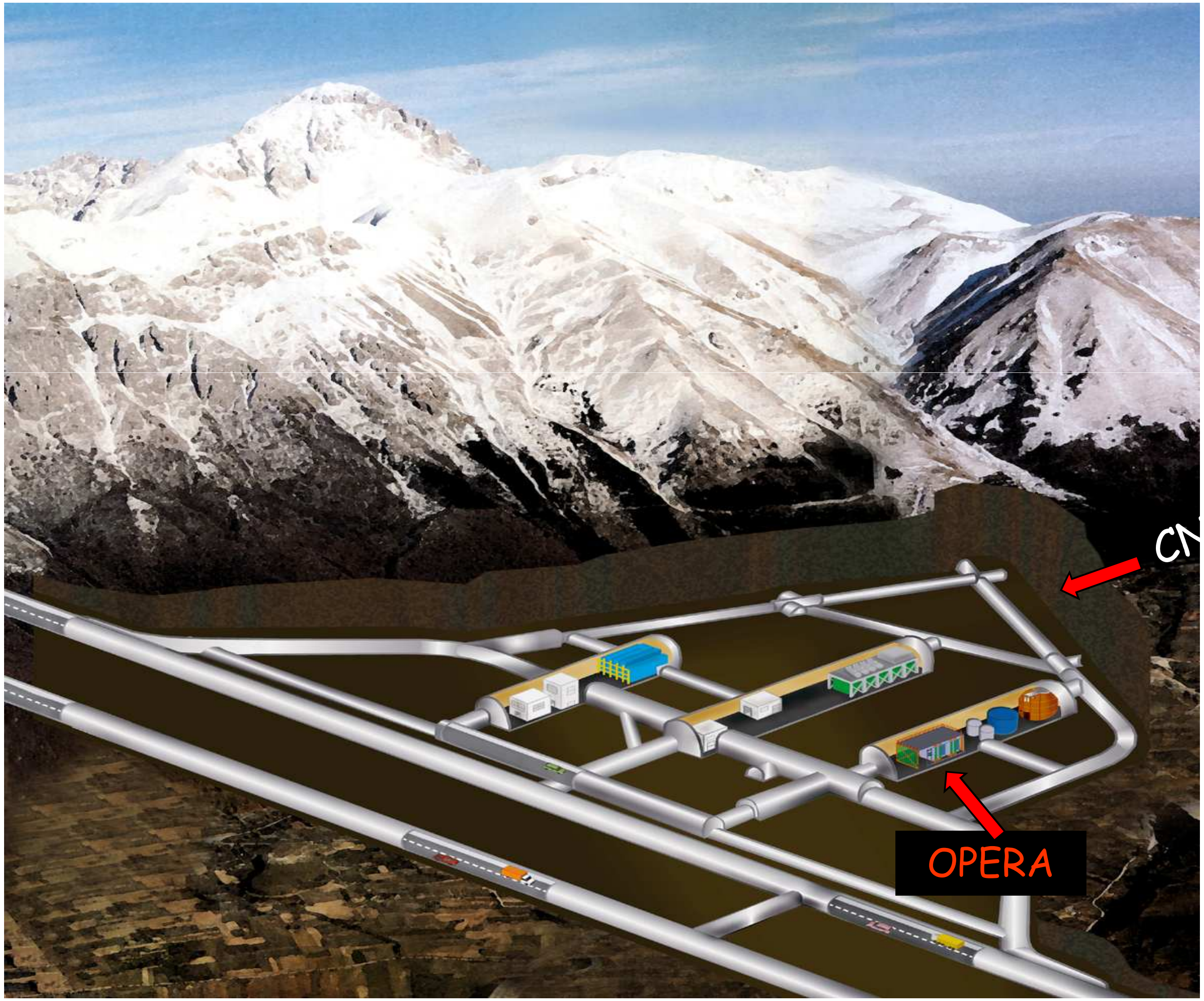
Improving features, high CNGS efficiency (97% in 2008-2009)

2010: close to nominal year;

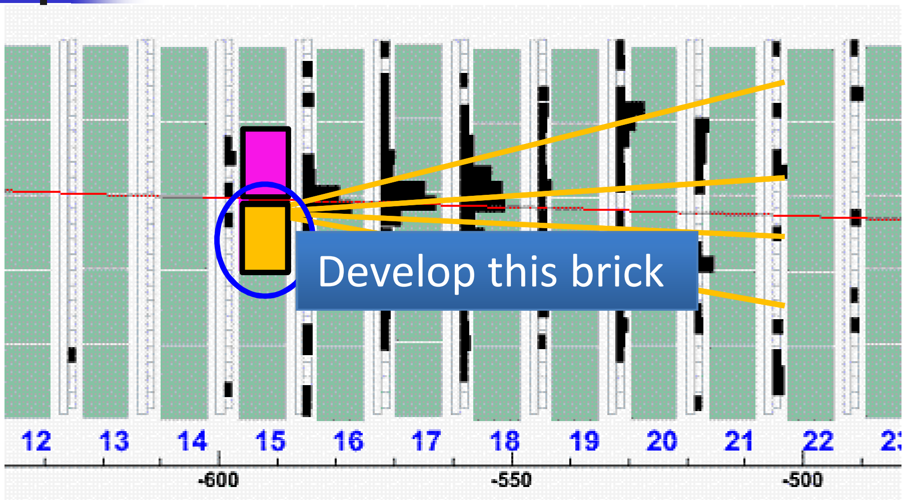
Aim at high-intensity runs in 2011 and 2012

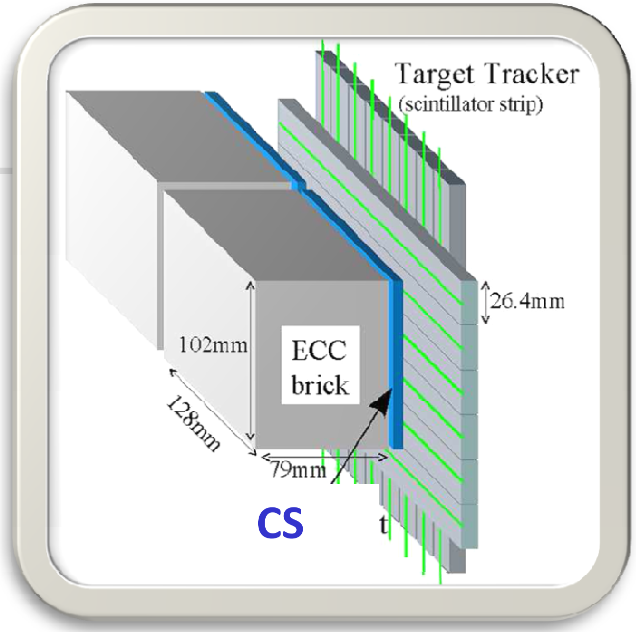
LNGS of INFN, the world largest underground physics laboratory:

~180'000 m^3 caverns' volume, ~3'100 m.w.e. overburden, ~1 cosmic μ / m^2 x hour, experimental infrastructure, variety of experiments. Perfectly fit to host detector and related facilities, caverns oriented towards CERN.

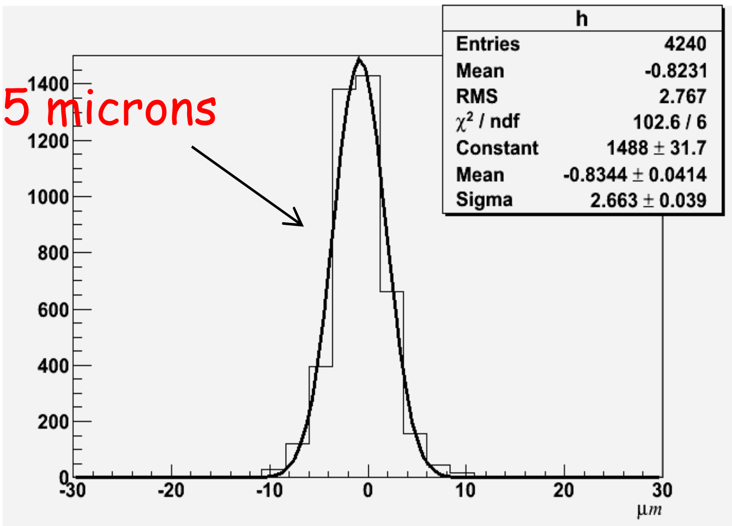


VALIDATION BY THE CS





CS doublet alignment by Compton electrons: 2.5 microns



Scanning effort/event: CHORUS 1x1 mm^2

DONUT 5x5 mm^2

OPERA 100x100 mm^2

So far, 640'000 cm^2 of CS surface have been scanned in OPERA

PARALLEL ANALYSIS OF BRICKS

selected bricks sent to scanning labs (presently 12)

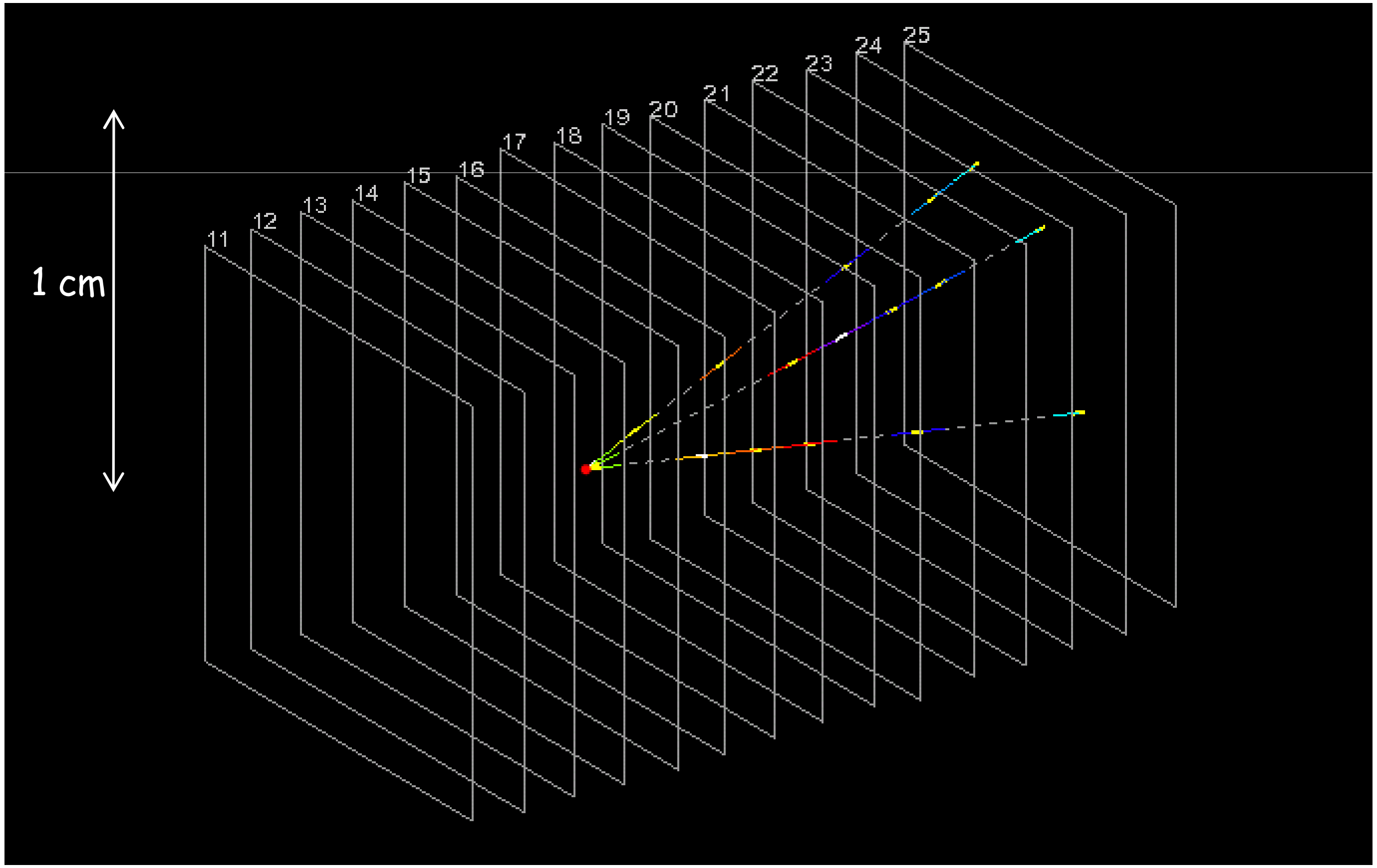
Napoli brick scanning labs

Located neutrino interaction

Emulsions give 3D vector data, with micrometric precision of the vertexing accuracy.

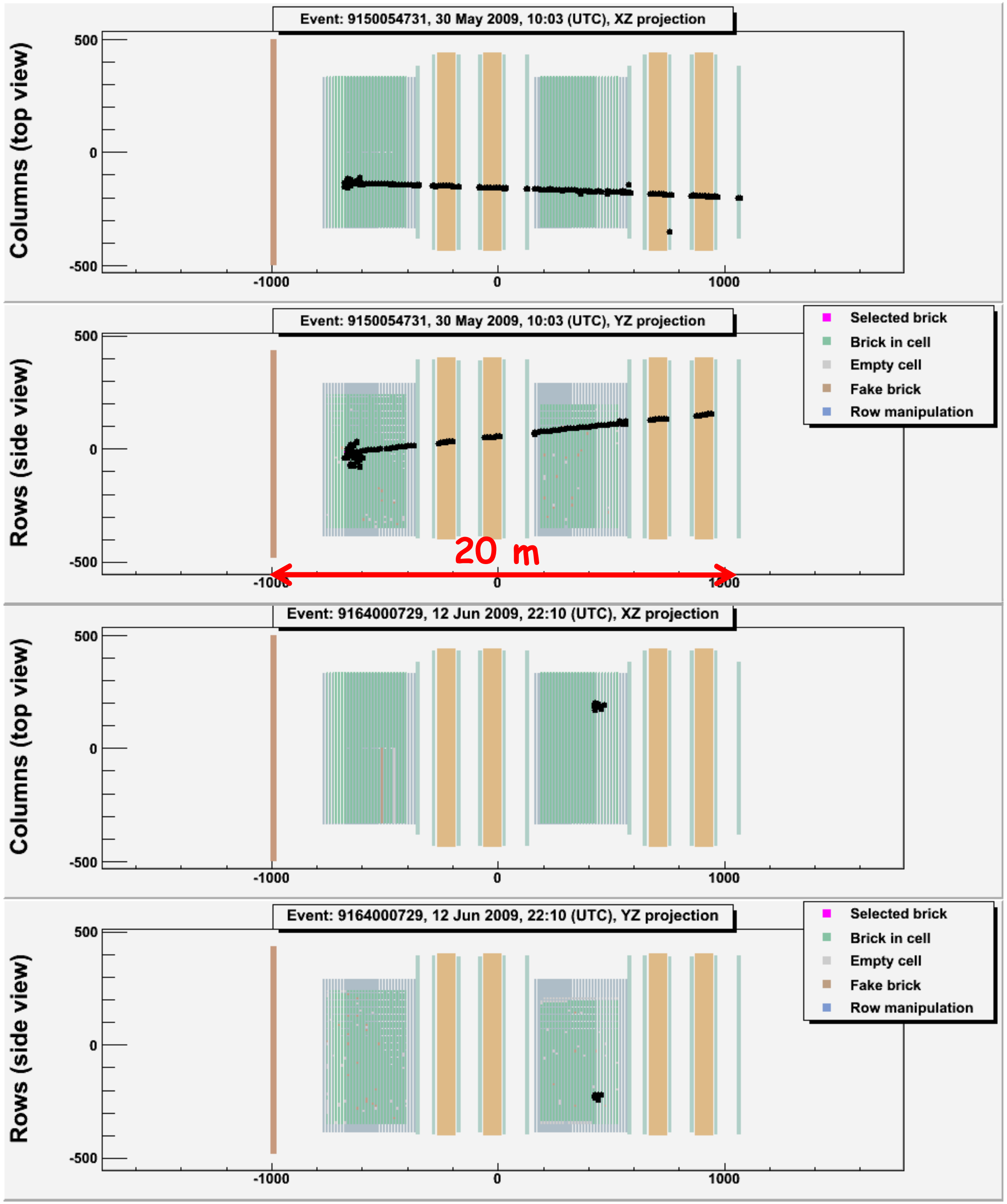
The frames correspond to the scanning area. Yellow short lines → measured tracks.

Other colored lines → interpolation or extrapolation.

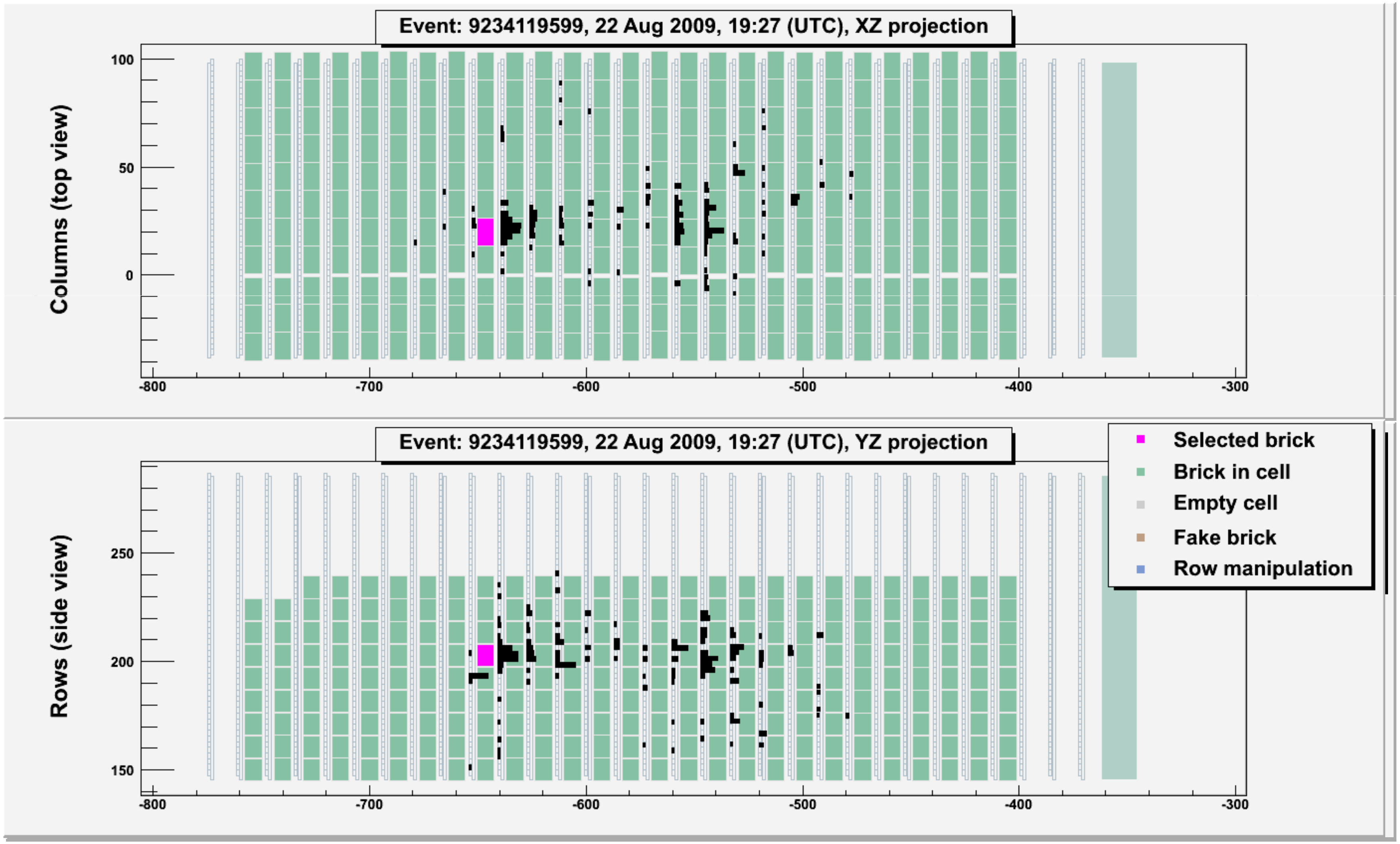


Typical ν_μCC- and NC-like events

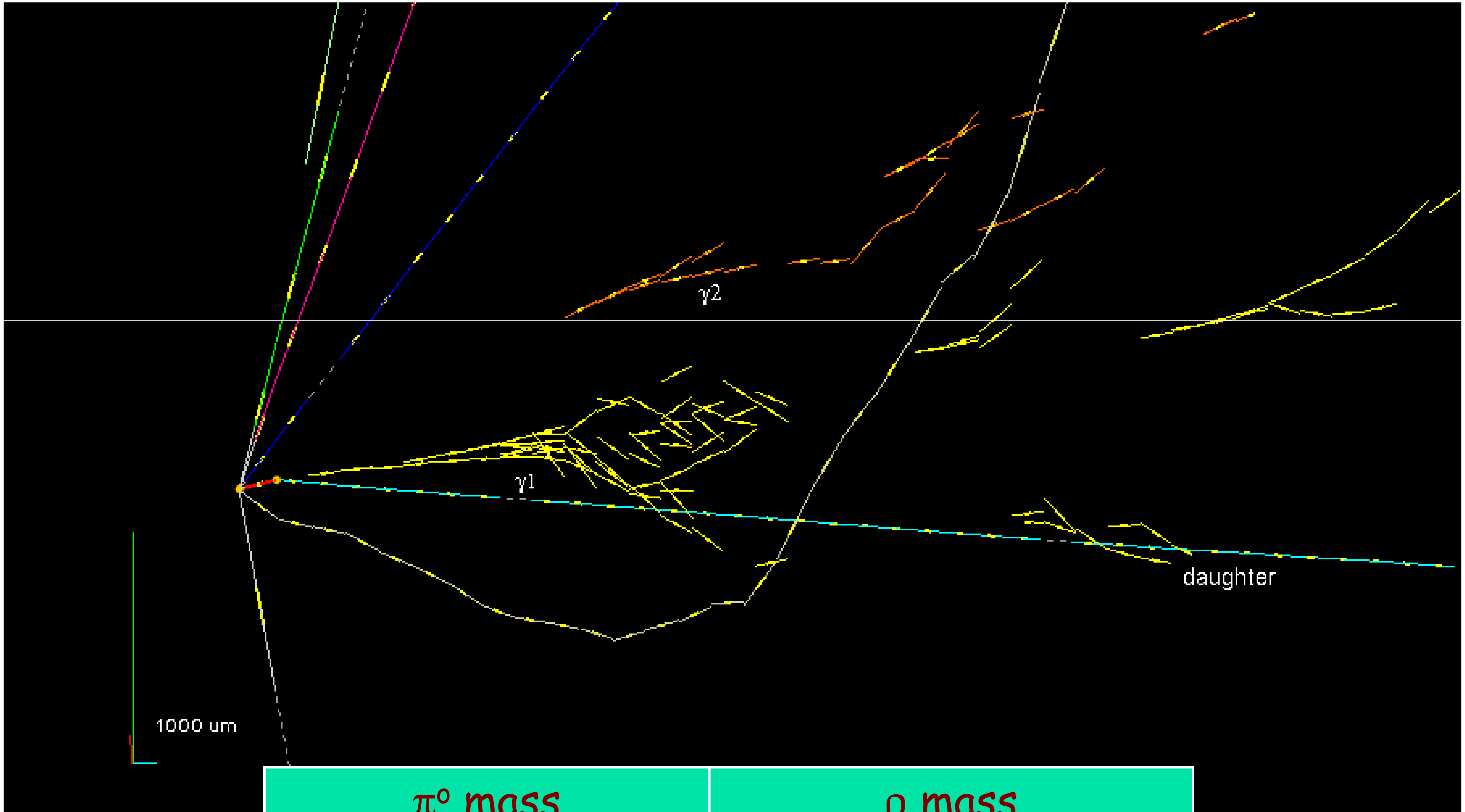
The measured ratio of NC-like/CC-like events after muon ID and event location is ~20%, as expected from simulations



Muonless event 9234119599, taken on 22 August 2009, 19:27 (UTC) (as seen by the electronic detectors)

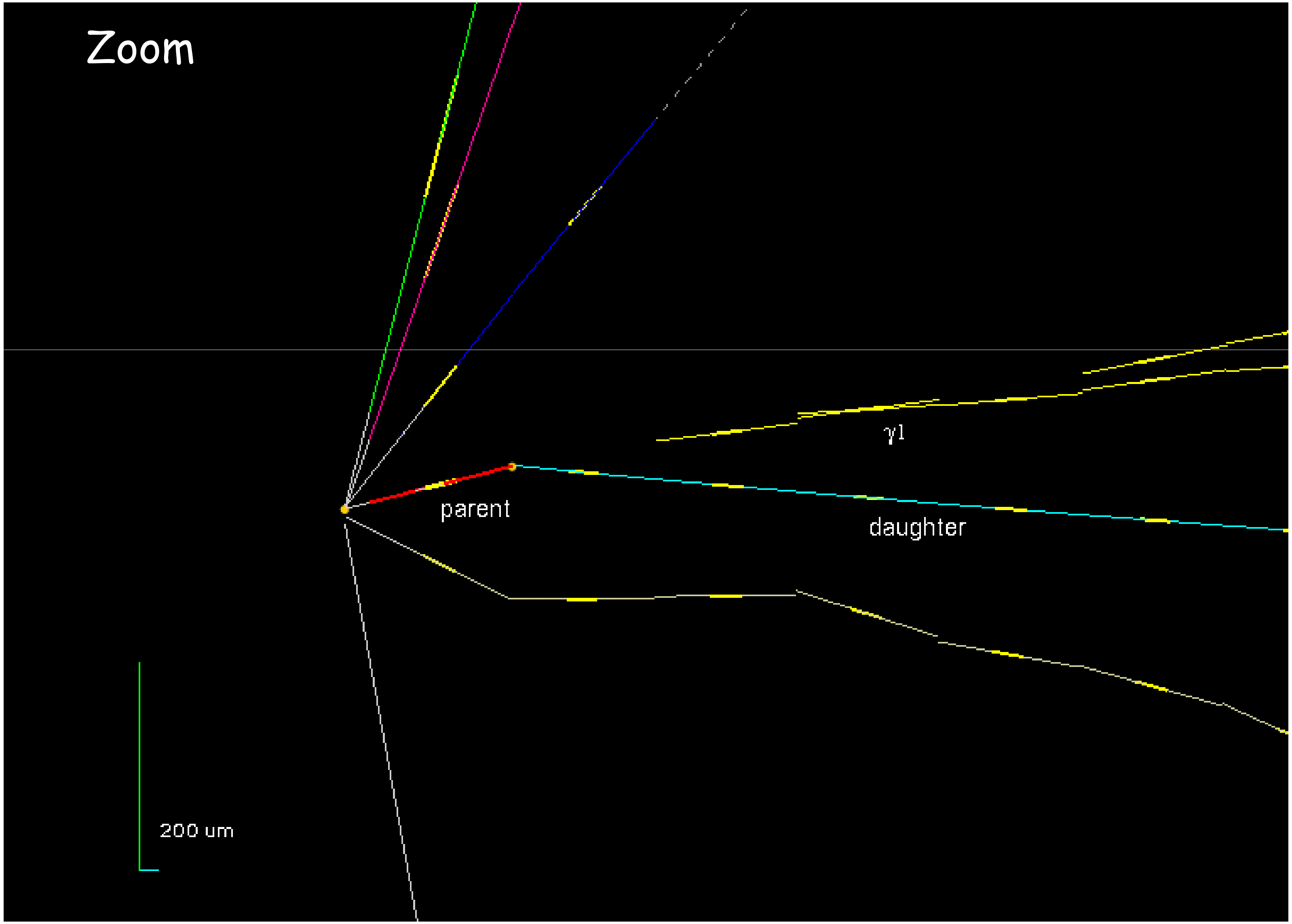


Event reconstruction (1)



π^0 mass	ρ mass
120 ± 20 ± 35 MeV	$640^{+125}_{-80}\,^{+100}_{-90}$ MeV

Event reconstruction (2)



Kinematical analysis

OPERA nominal analysis flow applied to the hadronic kink candidates:

(more refined selection criteria being developed were not considered here not to bias our analysis)

- kink occurring within 2 lead plates downstream of the primary vertex
- kink angle larger than 20 mrad
- daughter momentum higher than 2 GeV/c
- decay Pt higher than 600 MeV/c, 300 MeV/c if $\geq$ 1 gamma pointing to the decay vertex
- missing Pt at primary vertex lower than 1 GeV/c
- azimuthal angle between the resulting hadron momentum direction and the parent track direction larger than $\pi/2$ rad

Kinematical variables

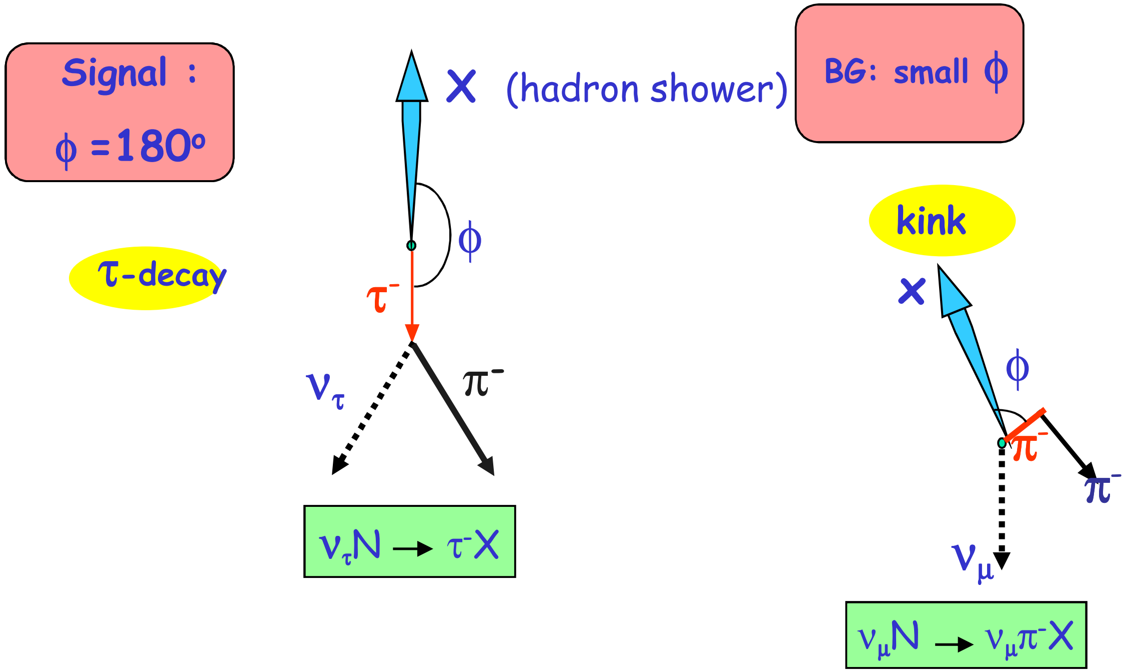
- The kinematical variables are computed by averaging the two sets of track parameter measurements
- We assume that:

$\gamma 1$ and $\gamma 2$ are both attached to 2^{ry} vertex

VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt daughter (MeV/c)	**470^{+230}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**

The average values are used in the following kinematical analysis

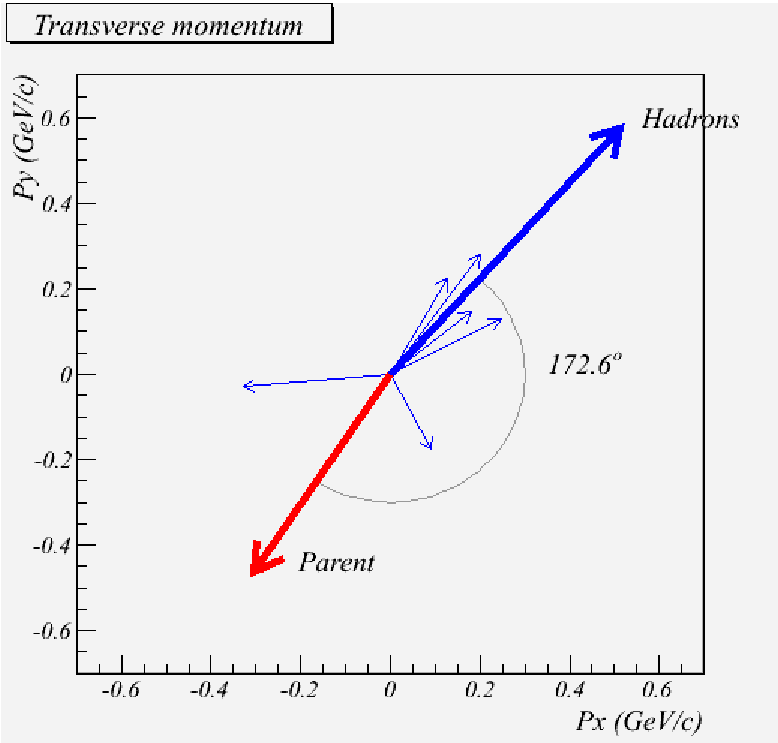
The uncertainty on Pt due to the alternative $\gamma 2$ attachment is < 50 MeV

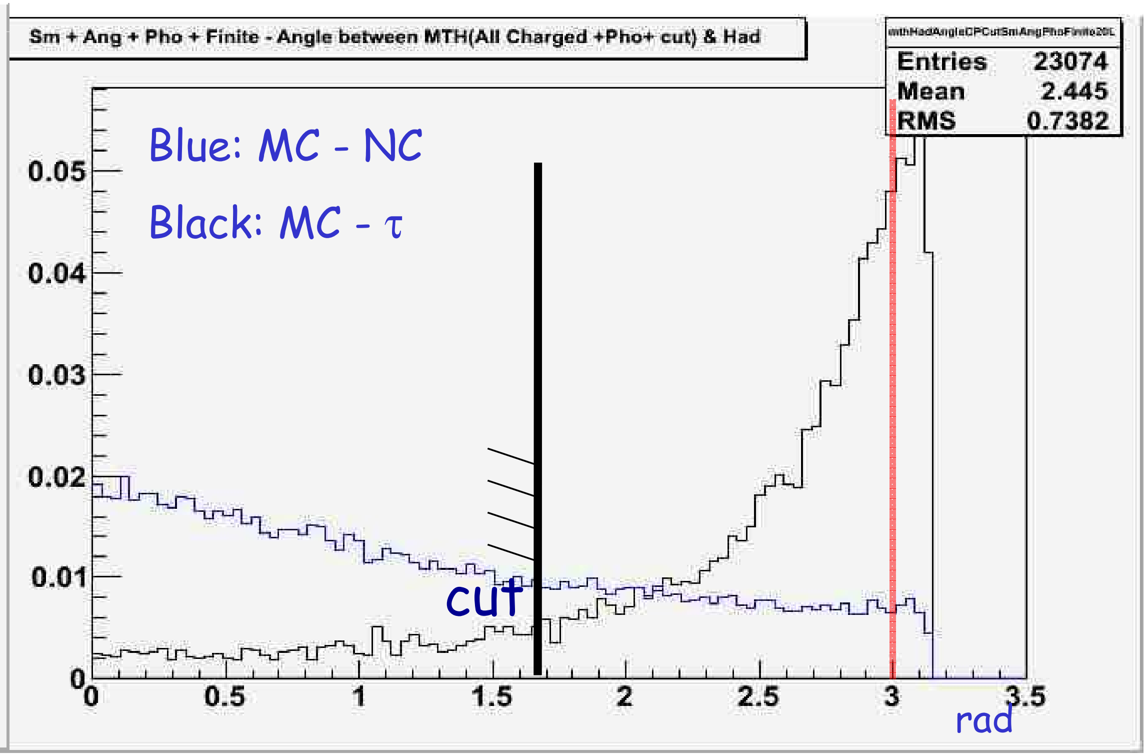


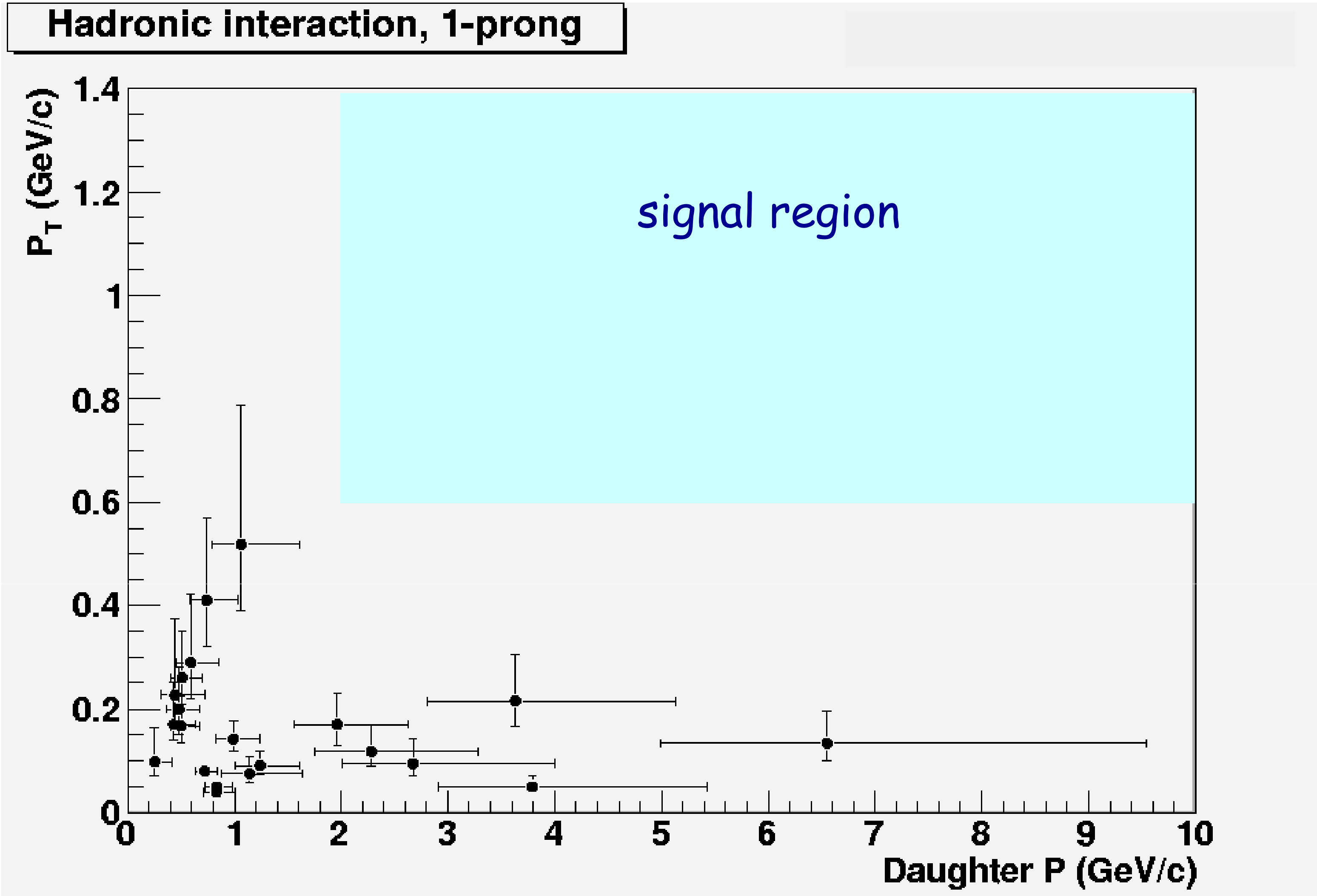
Azimuthal angle between

the resulting hadron momentum

direction and the parent track direction

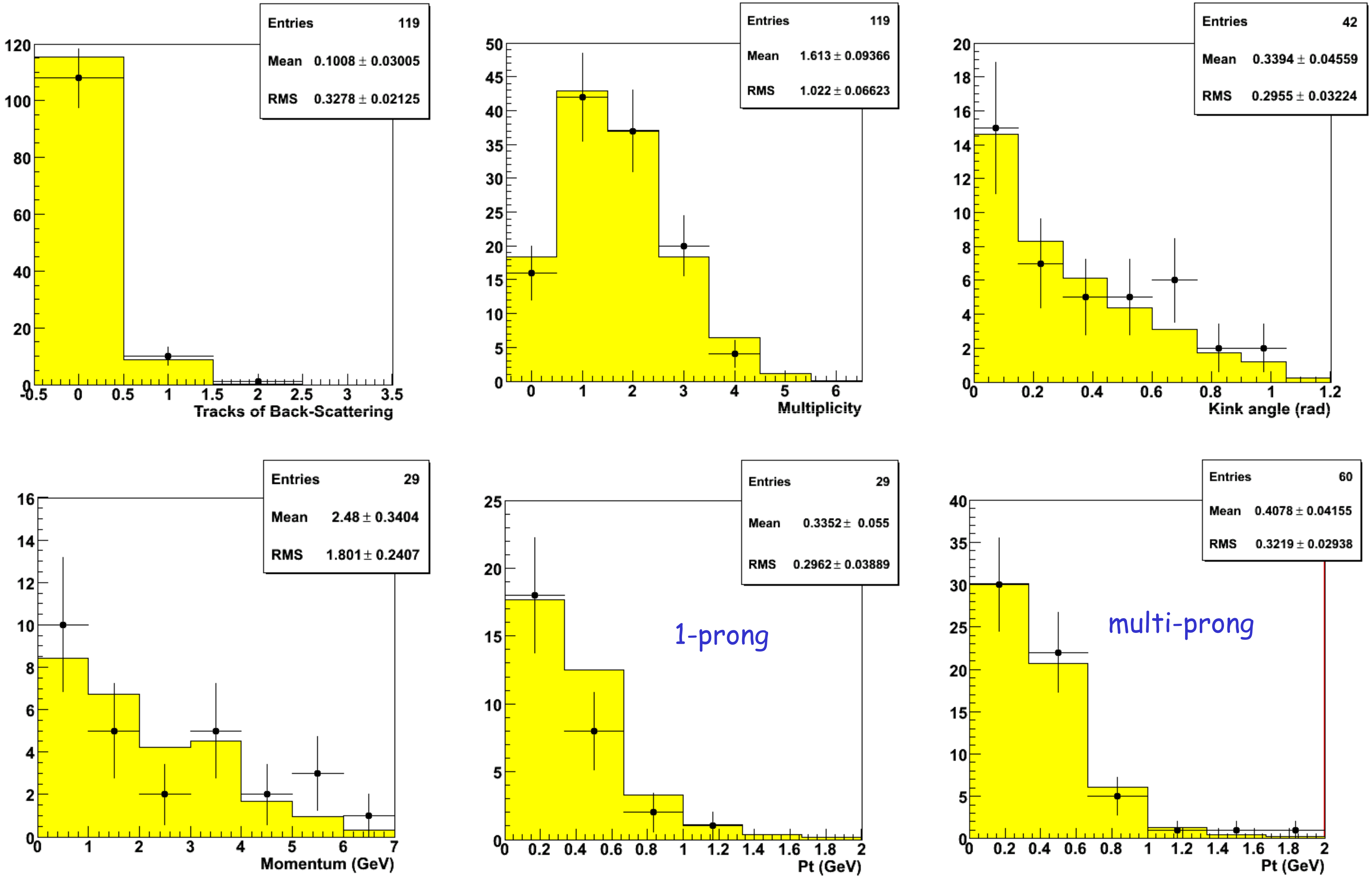






- no events in the signal region
- 90% CL upper limit of 1.54×10^{-3} kinks/NC event
- the number of events outside the signal region is confirmed by MC (within the ~30% statistical accuracy of the measurement)

DATA/MC comparison: good agreement in normalization and shape



Statistical significance

We observe 1 event in the 1-prong hadron τ decay channel, with a background expectation (~ 50% error for each component) of:

0.011 events (reinteractions)

0.007 events (charm)

⬇

0.018 ± 0.007 (syst) events 1-prong hadron

all decay modes: 1-prong hadron, 3-prongs + 1-prong μ + 1-prong *e* :

0.045 ± 0.020 (syst) events total BG

By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 σ on the measurement of a first ν_τ candidate event in OPERA.

If one considers all τ decay modes which were included in the search, the probability to observe 1 event for a background fluctuation is 4.5%.

This corresponds to a significance of 2.01 σ.

Napoli Group contribution

A. Ereditato, K. Niwa and P. Strolin, *The emulsion technique for short, medium and long baseline ν_{μ}□ν_{t} oscillation experiments* INFN-AE-97-06, DAPNU-97-07, Jan 1997.

Paolo Strolin ha avuto la responsabilità dell'esperimento come primo Spokesperson, carica poi passata al fisico francese Yves Déclais e ora affidata ad Antonio Ereditato.

Pasquale Migliozzi è ora vice-Spokesperson ed è stato Physics Coordinator avendo così tra l'altro una speciale responsabilità nella difficile compito di una valutazione preventiva delle prestazioni dell'esperimento.

Salvatore Buontempo è stato Technical Coordinator per la realizzazione dell'intero apparato sperimentale e in particolare ha diretto la costruzione, mediante un complesso sistema di robot, del grandissimo numero (150.000) di moduli elementari ("mattoni") in cui è suddiviso il bersaglio.

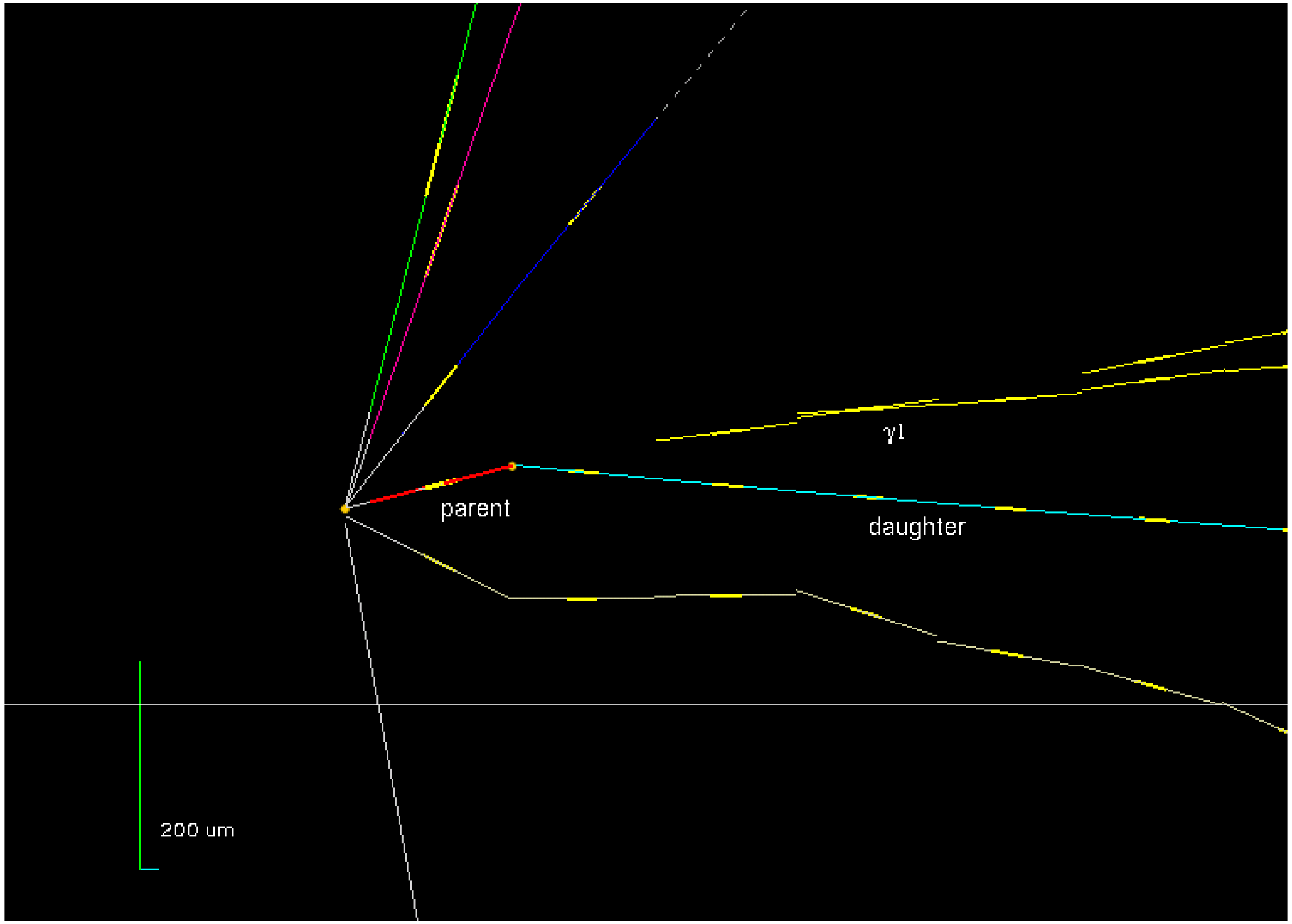
Giovanni De Lellis è stato profondamente impegnato nella messa a punto della tecnica delle emulsioni fotografiche, coordina ora la loro analisi e ha avuto in essa un ruolo personale importantissimo.

Nel gruppo di Salerno, Giovanni Rosa (ora a Roma La Sapienza) e Cristiano Bozza assieme a Nicola D'Ambrosio (ora al Laboratorio del Gran Sasso) e Valeri Tioukov del gruppo di Napoli hanno avuto un ruolo fondamentale nello sviluppo dei microscopi automatici ultra-veloci necessari per l'analisi della tante emulsioni fotografiche in cui cercare il fatidico neutrino tau.


THE NOBEL PRIZE IN PHYSICS 2002
Antonia Di Crescenzo
Francesco Di Capua
Andrea Russo

Ringraziamenti

- Il gruppo di Napoli (e tutta la Collaborazione) vuole ringraziare l'INFN per aver fortemente contribuito alla realizzazione del fascio CNGS e dell'esperimento OPERA
- I direttori INFN che si sono succeduti dal 2000 ad oggi (Profs B. D'Ettorre Piazzoli e L. Merola) per il continuo supporto fornitoci
- I servizi della sezione di Napoli per il loro essenziale contributo nella fase di realizzazione e di presa dati dell'esperimento
- Tutti gli studenti e i ricercatori italiani e stranieri che negli ultimi 10 anni hanno fatto parte del gruppo OPERA di Napoli



... neutrinos induce courage in theoreticians and perseverance in experimenters

Maurice Goldhaber, 1974