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The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment

N. Agafonova,[a] A. Anokhina,[b] S. Aoki,[c] A. Ariga,[d] T. Ariga,[d] L. Arrabito,[e] D. Autiero,[e] A. Badertscher,[f] A. Bagulya,[g] F. Bersani Greggio,[h] A. Bertolin,[i] M. Besnier,[j,1] D. Bick,[k] V. Boyarkin,[a] C. Bozza,[l] T. Brugière,[e] R. Brugnera,[i,m] G. Brunetti,[n,o] S. Buontempo,[p] E. Carrara,[i,m,2] A. Cazes,[e] L. Chaussard,[e] M. Chernyavsky,[g] V. Chiarella,[h] N. Chon-Sen,[q] A. Chukanov,[p] M. Cozzi,[n] G. D'Amato,[l] F. Dal Corso,[i] N. D'Ambrosio,[r] G. De Lellis,[p,s,3] Y. Déclais,[e] M. De Serio,[t] F. Di Capua,[p] D. Di Ferdinando,[o] A. Di Giovanni,[u] N. Di Marco,[u] C. Di Troia,[h] S. Dmitrievski,[v] A. Dominjon,[e] M. Dracos,[q] D. Duchesneau,[j] S. Dusini,[i] J. Ebert,[k] O. Egorov,[w] R. Enikeev,[a] A. Ereditato,[d] L.S. Esposito,[r] J. Favier,[j] G. Felici,[h] T. Ferber,[k] R. Fini,[t] D. Frekers,[x] T. Fukuda,[y] C. Fukushima,[z] V.I. Galkin,[b] V.A. Galkin,[aa] A. Garfagnini,[i,m] G. Giacomelli,[n,o] M. Giorgini,[n,o] C. Goellnitz,[k] T. Goeltzenlichter,[q] J. Goldberg,[ab] D. Golubkov,[w] Y. Gornushkin,[v] G. Grella,[l] F. Grianti,[h] M. Guler,[ac] C. Gustavino,[r] C. Hagner,[k] K. Hamada,[y] T. Hara,[c] M. Hierholzer,[ad] K. Hoshino,[y] M. Ieva,[t] K. Jakovcic,[ae] B. Janutta,[k] C. Jollet,[q] F. Juget,[d] M. Kazuyama,[y] S.H. Kim,[af,4] M. Kimura,[z] N. Kitagawa,[y] B. Klicek,[ae] J. Knuesel,[d] K. Kodama,[ag] D. Kolev,[ah] M. Komatsu,[y] U. Kose,[ac,5] A. Krasnoperov,[v] I. Kreslo,[d] Z. Krumstein,[v] H. Kubota,[y] V.V. Kutsenov,[a] V.A. Kuznetsov,[a] I. Laktineh,[e] C. Lazzaro,[f] J. Lenkeit,[k] A. Ljubicic,[ae] A. Longhin,[m] G. Lutter,[d] A. Malgin,[a] K. Manai,[e] G. Mandrioli,[o] A. Marotta,[p] J. Marteau,[e] T. Matsuo,[z] V. Matveev,[a] N. Mauri,[n,o] E. Medinaceli,[o] F. Meisel,[d] A. Meregaglia,[q] M. Messina,[d] P. Migliozzi,[p,6] S. Miyamoto,[y] P. Monacelli,[u] K. Morishima,[y] U. Moser,[d] M.T. Muciaccia,[t,ai] N. Naganawa,[y] T. Naka,[y] M. Nakamura,[y] T. Nakano,[y] V. Nikitina,[b] K. Niwa,[y] Y. Nonoyama,[y] A. Nozdrin,[v] S. Ogawa,[z] A. Olchevski,[v] G. Orlova,[g] V. Osedlo,[b] D. Ossetski,[aa] M. Paniccia,[h] A. Paoloni,[h] B.D. Park,[af] I.G. Park,[af] A. Pastore,[t,ai] L. Patrizii,[o] E. Pennacchio,[e] H. Pessard,[j] V. Pilipenko,[x] C. Pistillo,[d] N. Polukhina,[g]

[1]Now at Laboratoire Leprince-Ringuet — École polytechnique, 91128 Palaiseau Cedex (France).
[2]Now at a private company.
[3]Supported by travel fellowship from the School of Sciences and Technology — University of Naples Federico II.
[4]Now at Chonnam National University.
[5]Supported by International PostDoctoral Research Scholarship Programme from "The Scientific and Technological Research Council of Turkey", TUBITAK.
[6]Corresponding author.

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M. Pozzato,[n,o] K. Pretzl,[d] P. Publichenko,[b] F. Pupilli,[u] R. Rescigno,[l] D. Rizhikov,[aa] T. Roganova,[b] G. Romano,[l] G. Rosa,[aj] I. Rostovtseva,[w] A. Rubbia,[f] A. Russo,[p,s] V. Ryasny,[a] O. Ryazhskaya,[a] A. Sadovski,[v] O. Sato,[y] Y. Sato,[ak] V. Saveliev,[aa] A. Schembri,[aj] W. Schmidt Parzefall,[k] H. Schroeder,[ad] H.U. Schütz,[d] J. Schuler,[q] L. Scotto Lavina,[p] H. Shibuya,[z] S. Simone,[t,ai] M. Sioli,[n,o] C. Sirignano,[l] G. Sirri,[o] J.S. Song,[af] M. Spinetti,[h] L. Stanco,[m] N. Starkov,[g] M. Stipcevic,[ae] T. Strauss,[f] P. Strolin,[p,s] V. Sugonyaev,[m] S. Takahashi,[y] V. Tereschenko,[v] F. Terranova,[h] I. Tezuka,[ak] V. Tioukov,[p] P. Tolun,[ac] V. Tsarev,[g] R. Tsenov,[ah] S. Tufanli,[ac] N. Ushida,[ag] V. Verguilov,[ah] P. Vilain,[al] M. Vladimirov,[g] L. Votano,[h] J.L. Vuilleumier,[d] G. Wilquet,[al] B. Wonsak,[k] V. Yakushev,[a] C.S. Yoon,[af] T. Yoshioka,[y] J. Yoshida,[y] Y. Zaitsev,[w] A. Zghiche[j] and R. Zimmermann[k]

[a] *INR-Institute for Nuclear Research of the Russian Academy of Sciences, RUS-117312 Moscow, Russia*

[b] *SINP MSU-Skobeltsyn Institute of Nuclear Physics of Moscow State University, RUS-119992 Moscow, Russia*

[c] *Kobe University, J-657-8501 Kobe, Japan*

[d] *Centre for Research and Education in Fundamental Physics, Laboratory for High Energy Physics (LHEP), University of Bern, CH-3012 Bern, Switzerland*

[e] *IPNL, Université Claude Bernard Lyon 1, CNRS/IN2P3, F-69622 Villeurbanne, France*

[f] *ETH Zurich, Institute for Particle Physics, CH-8093 Zurich, Switzerland*

[g] *LPI-Lebedev Physical Institute of the Russian Academy of Sciences, RUS-117924 Moscow, Russia*

[h] *INFN — Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati (Roma), Italy*

[i] *INFN Sezione di Padova, I-35131 Padova, Italy*

[j] *LAPP, Université de Savoie, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France*

[k] *Hamburg University, D-22761 Hamburg, Germany*

[l] *Dipartimento di Fisica dell'Università di Salerno and INFN, I-84084 Fisciano, Salerno, Italy*

[m] *Dipartimento di Fisica dell'Università di Padova, I-35131 Padova, Italy*

[n] *Dipartimento di Fisica dell'Università di Bologna, I-40127 Bologna, Italy*

[o] *INFN Sezione di Bologna, I-40127 Bologna, Italy*

[p] *INFN Sezione di Napoli, 80125 Napoli, Italy*

[q] *IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France*

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[r] INFN — Laboratori Nazionali del Gran Sasso,
I-67010 Assergi (L'Aquila), Italy
[s] Dipartimento di Fisica dell'Università Federico II di Napoli,
80125 Napoli, Italy
[t] INFN Sezione di Bari,
I-70126 Bari, Italy
[u] Dipartimento di Fisica dell'Università dell'Aquila and INFN,
I-67100 L'Aquila, Italy
[v] JINR-Joint Institute for Nuclear Research,
RUS-141980 Dubna, Russia
[w] ITEP-Institute for Theoretical and Experimental Physics,
RUS-117259 Moscow, Russia
[x] University of Münster,
D-48149 Münster, Germany
[y] Nagoya University,
J-464-8602 Nagoya, Japan
[z] Toho University,
J-274-8510 Funabashi, Japan
[aa] Obninsk State University, Institute of Nuclear Power Engineering,
RUS-249020 Obninsk, Russia
[ab] Department of Physics, Technion,
IL-32000 Haifa, Israel
[ac] METU-Middle East Technical University,
TR-06531 Ankara, Turkey
[ad] Fachbereich Physik der Universität Rostock,
D-18051 Rostock, Germany
[ae] IRB-Rudjer Boskovic Institute,
HR-10002 Zagreb, Croatia
[af] Gyeongsang National University,
900 Gazwa-dong, 660-300 Jinju, Korea
[ag] Aichi University of Education,
J-448-8542 Kariya (Aichi-Ken), Japan
[ah] Faculty of Physics, Sofia University "St. Kliment Ohridski",
BG-1000 Sofia, Bulgaria
[ai] Dipartimento di Fisica dell'Università di Bari,
I-70126 Bari, Italy
[aj] Dipartimento di Fisica dell'Università di Roma "La Sapienza" and INFN,
I-00185 Roma, Italy
[ak] Utsunomiya University,
J-321-8505 Tochigi-Ken, Utsunomiya, Japan
[al] IIHE, Université Libre de Bruxelles,
B-1050 Brussels, Belgium

E-mail: pmiglioz@na.infn.it

ABSTRACT: The OPERA neutrino detector in the underground Gran Sasso Laboratory (LNGS) was designed to perform the first detection of neutrino oscillations in appearance mode through the study of $\nu_\mu \rightarrow \nu_\tau$ oscillations. The apparatus consists of an emulsion/lead target complemented by electronic detectors and it is placed in the high energy long-baseline CERN to LNGS beam (CNGS) 730 km away from the neutrino source. Runs with CNGS neutrinos were successfully carried out in 2007 and 2008 with the detector fully operational with its related facilities for the emulsion handling and analysis. After a brief description of the beam and of the experimental setup we report on the collection, reconstruction and analysis procedures of first samples of neutrino interaction events.

KEYWORDS: Particle tracking detectors; Large detector systems for particle and astroparticle physics

Contents

1 Introduction

Neutrino oscillations were anticipated nearly 50 years ago [1] but they have been unambiguously observed only recently. Several experiments carried out in the last decades with atmospheric and accelerator neutrinos, as well as with solar and reactor neutrinos, contributed to our present understanding of neutrino mixing (see e.g. [2] for a review).

As far as the atmospheric neutrino sector is concerned, accelerator experiments can probe the same oscillation parameter region as atmospheric neutrino experiments [3]. This is the case of the OPERA experiment that has the main scientific task of the first direct detection of $\nu_\mu \rightarrow \nu_\tau$ appearance, an important missing tile in the oscillation scenario [4–6].

OPERA uses the long-baseline (L = 730 km) CNGS neutrino beam [7] from CERN to LNGS, the largest underground physics laboratory in the world. The challenge of the experiment is to measure the appearance of ν_τ from ν_μ oscillations in an almost pure muon-neutrino beam. Therefore, the detection of the short-lived τ lepton ($c\tau = 87.11\ \mu$m) produced in the charged-current (CC) interaction of a ν_τ is mandatory. This sets two conflicting requirements: a large target mass to collect enough statistics and an extremely high spatial accuracy to observe the short-lived τ lepton.

The τ is identified by the detection of its characteristic decay topologies either in one prong (electron, muon or hadron) or in three-prongs; its short track is measured with a large mass target made of 1 mm thick lead plates (target mass and absorber material) interspaced with thin nuclear emulsion films (high-accuracy tracking devices). This detector is historically called Emulsion Cloud Chamber (ECC). Among past applications it was successfully used in the DONUT experiment for the first direct observation of the ν_τ [8].

OPERA is a hybrid detector made of two identical Super Modules (SM) each consisting of a target section of about 625 tons made of emulsion/lead ECC modules (hereafter called “bricks”), of a scintillator tracker detector (TT) needed to trigger the read-out and localize neutrino interactions within the target, and of a muon spectrometer (figure 1). The detector is equipped with an automatic machine (the Brick Manipulator System, BMS) that allows the removal of bricks from the detector. Ancillary, large facilities are used for the handling, the development and the scanning of the emulsion films. Emulsion scanning is performed with two different types of automatic microscopes: the European Scanning System (ESS) [9, 10] and the Japanese S-UTS [11].

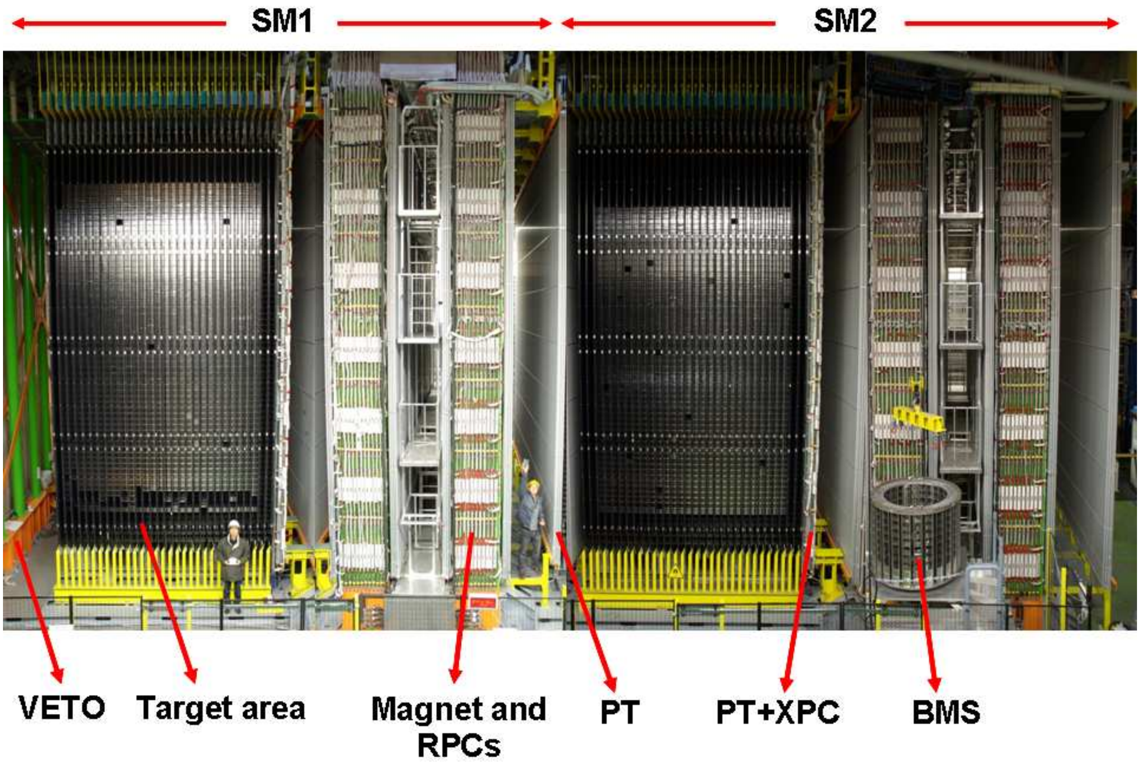

Figure 1. View of the OPERA detector; the neutrino beam enters from the left. The upper horizontal lines indicate the position of the two identical supermodules (SM1 and SM2). The "target area" is made of walls filled with ECC bricks interleaved with planes of plastic scintillators (TT). Arrows show the position of the VETO planes, the drift tubes (PT) pulled alongside the XPC, the magnets and the RPC installed between the magnet iron slabs. The Brick Manipulator System (BMS) is also visible. See [6] for more details.

A target brick consists of 56 lead plates of 1 mm thickness interleaved with 57 emulsion films [12]. The plate material is a lead alloy with a small calcium content to improve its mechanical properties [13]. The transverse dimensions of a brick are $12.8 \times 10.2\,\mathrm{cm}^2$ and the thickness along the beam direction is 7.9 cm (about 10 radiation lengths). The bricks are housed in a light support structure placed between consecutive TT walls. More details on the detector and on the ancillary facilities are given in [6].

In order to reduce the emulsion scanning load the use of Changeable Sheets (CS) film interfaces [14], successfully applied in the CHORUS experiment [15], was extended to OPERA. Tightly packed doublets of emulsion films are glued to the downstream face of each brick and can be removed without opening the brick. The global layout of brick, CS and TT is schematically shown in figure 2.

Charged particles from a neutrino interaction in the brick cross the CS and produce a signal in the TT scintillators. The corresponding brick is then extracted and the CS developed and analyzed in the scanning facilities at LNGS and in Nagoya. The information of the CS is then used for a precise prediction of the position of the tracks in the most downstream films of the brick, hence guiding the *scan-back* vertex finding procedure.

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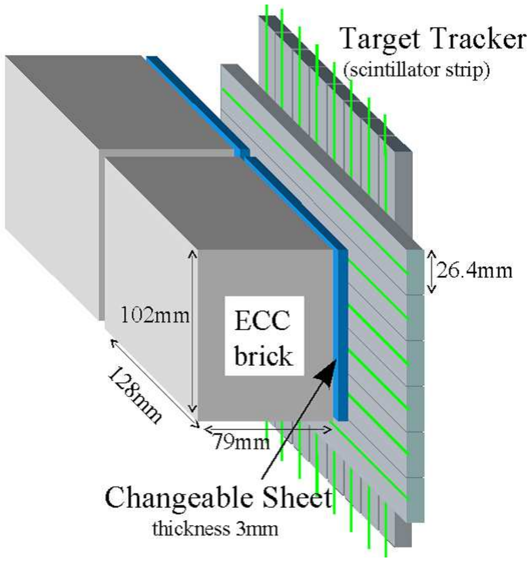

Figure 2. Schematic view of two bricks with their Changeable Sheets and target tracker planes.

A CC event reconstructed in emulsion is shown in the bottom panels of figure 3. The dimensions of the displayed volume are of the order of a few millimeters, to be compared with the ~ 10 m scale of the whole event reconstructed with the electronic detectors (top panels of figure 3).

First neutrino data were collected by OPERA in 2006 [5] with the electronic detectors alone, and then in 2007 and 2008, for the first time with target bricks installed. All steps from the prediction of the brick where the interaction occurred down to the kinematical analysis of the neutrino interactions are described in the following using as benchmark a sub-sample of the statistics accumulated during the CNGS runs. The procedure has proven to be successful. We are presently in the process of a quantitative evaluation of the different experimental efficiencies that are involved in the analysis procedure, profiting from the increasing statistics of the reconstructed neutrino events. The results presented in this paper are the first confirmation that OPERA is able to accomplish its task of selecting decay topologies in the emulsions from a large number of interactions triggered by the electronic detectors.

2 Real time detection of the CNGS beam

The CNGS neutrino beam [7] was designed and optimized for the study of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode by maximizing the number of CC ν_τ interactions at the LNGS site. After a short commissioning run in 2006 the CNGS operation started on September 2007 at rather low intensity. The first event inside the OPERA target was observed on October 3rd. Unfortunately, due to a fault of the CNGS facility, the physics run lasted only a few days. During this run 0.082×10^{19} protons on target (p.o.t.) were accumulated with a mean value of 1.8×10^{13} protons per extraction:[1] this corresponds to about ~ 3.6 effective nominal days of running. 465 events on time were recorded, of which about 35 in the target region.

[1] The 400 GeV proton beam is extracted from the CERN SPS in two 10.5 μs pulses, with design intensity of 2.4×10^{13} p.o.t.

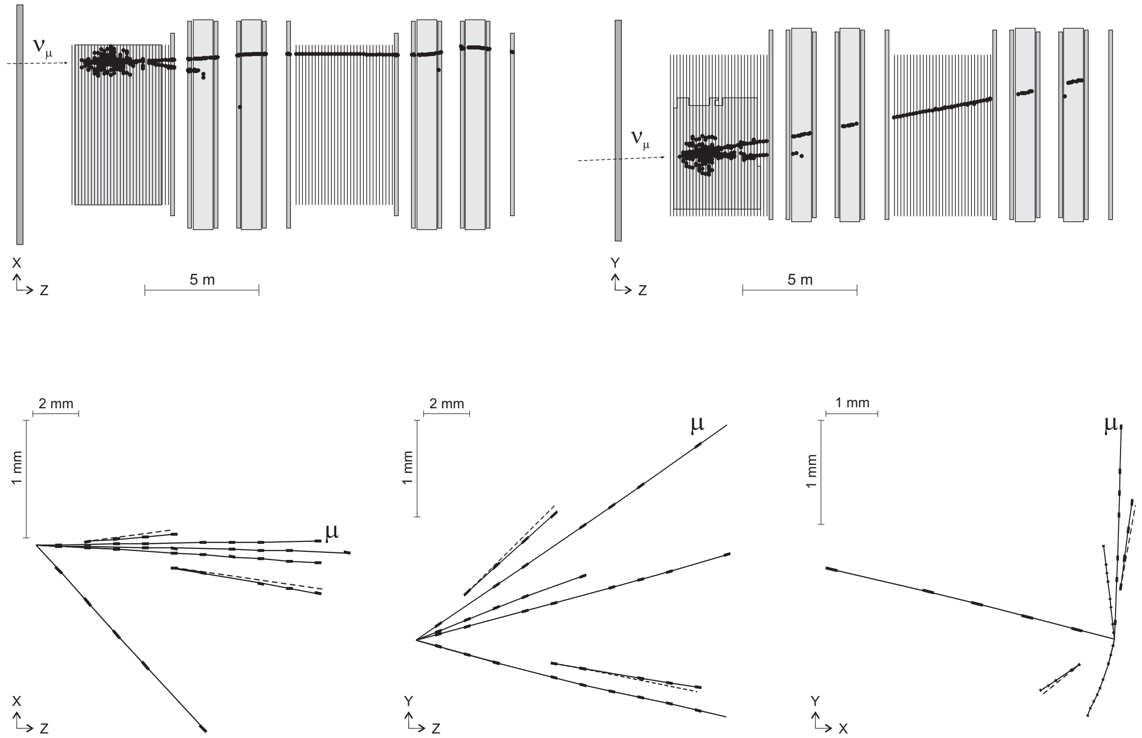

Figure 3. Top panels: on line display of an event seen by the OPERA electronic detectors (top and side views): a ν_μ interacts in one of the first bricks of the first supermodule (SM) yielding hadrons and a muon which is detected in both SMs and whose momentum is measured by the magnets of the two SMs. Bottom panels: the vertex of the same event observed in the emulsion films (top, side and front views). Note the two $\gamma \to e^+e^-$ vertices: the opening angle between them is about 300 mrad. By measuring the energy of the γ's one obtains a reconstructed invariant mass of $110 \pm 30\,\mathrm{MeV}/c^2$, consistent with the π^0 mass.

A much longer run took place in 2008 when 1.782×10^{19} protons were delivered on the CNGS target with a mean value of $\sim 2 \times 10^{13}$ protons per extraction. OPERA collected 10100 events on time and among them about 1700 interactions in the target region. The other events originated in the spectrometers, the supporting structures, the rock surrounding the cavern, the hall structures, etc. The run featured a poor initial efficiency of the CERN complex, of about 40% until reaching an average value of about 60%. In the last 6 weeks OPERA gathered the same number of events as during the first 11 weeks. The 2008 CNGS integrated p.o.t. intensity as a function of time is shown in figure 4.

During the 2007 and 2008 runs all electronic detectors were operational and the live time of the data acquisition system exceeded 99%. More than 10 million events were collected by applying a minimum bias filter. The selection of beam related events relies upon a time stamp, based on the time synchronization accuracy of 100 ns between the CERN beam GPS tagging and the OPERA timing system.

An automatic classification algorithm provides high efficiency in the selection of neutrino interactions inside the OPERA target both for CC and neutral-current (NC) events at the expenses of a slight contamination of neutrino interactions in the external material.

For the early 2007 run the algorithm selected 53 events as possibly occurring inside the target while expecting 50 including a contamination from neutrino interactions outside the target eval-

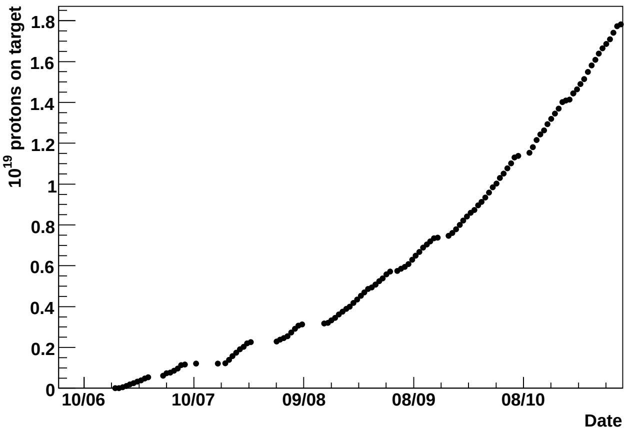

Figure 4. Integrated number of protons on target (p.o.t.) as a function of time for the 2008 CNGS run (June-November).

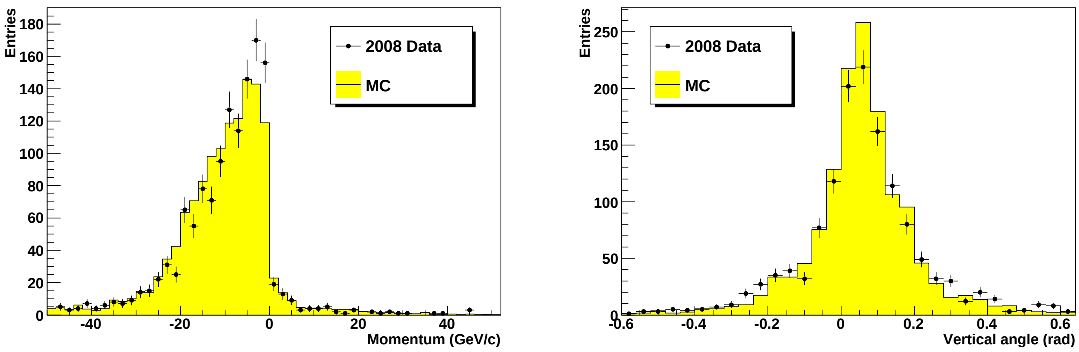

Figure 5. Left: momentum distribution of muons produced in CC neutrino interactions inside the OPERA target. Right: angular distribution of the muon tracks in the vertical (y-z) plane with respect to the horizontal (z) axis.

uated at 37% by Monte Carlo simulation. The low purity of the selected event sample was due to some sub-detectors still being in the commissioning phase and to the incomplete filling of the target. In the 2008 run 1663 events were classified as interactions in the target where 1723 were expected with a contamination from outside events of only 7%.

The muon momentum distribution for events classified as CC interactions in the target is shown in the left panel of figure 5. The distribution of the muon angle in the vertical (y-z) plane with respect to the horizontal (z) axis is shown in the right panel of figure 5; the beam direction angle is found to be tilted by 58 mrad, as expected from geodesy.

An extensive study of the beam monitoring is being performed by using neutrino interactions both in the whole OPERA detector and in the surrounding rock material. This will be the subject of a forthcoming publication.

3 Combined analysis of electronic detectors and nuclear emulsion film data

We describe in the following the breakdown of the different steps carried out to analyze neutrino interaction events from the identification of the "fired" brick up to the detailed kinematical analysis of the vertex in the emulsion films.

Before that we recall the procedure to obtain triggers from the electronic detectors. Their data are actually acquired in trigger less mode since the read out of the front-end electronics is asynchronous with the data time stamped with 10 ns clock. A minimum bias filter is applied at the level of sub-detector in order to reduce the detector noise. The event building is then performed by collecting all the hits in a sliding time window of 3000 ns. A cellular automaton algorithm reconstructs off line the tracks independently in the two projections. The two longest projections are merged to form a three dimensional track. Finally the momentum and the slope of the 3D tracks at the production vertex (starting point) are reconstructed with a Kalman filter algorithm.

Once a trigger in the electronic detectors is selected to be compatible with an interaction inside a brick the following procedure is applied [6]:

1. electronic detector data are processed by a software reconstruction program that selects the brick with the highest probability to contain the neutrino interaction vertex;

2. this brick is removed from the target wall by the BMS and exposed to X-rays for film-to-film alignment. There are two independent X-ray exposures: the first one ensures a common reference system to the CS film doublet and the most downstream film of the brick (frontal exposure); the second one produces thick lateral marks on the brick edges, used for internal alignment and film numbering within the brick;

3. after the first X-ray exposure the CS doublet is detached from the brick and developed underground, while the brick is kept in a box made of 5 cm thick iron shielding to reduce the radioactivity background;

4. if the CS scanning detects tracks compatible with those reconstructed in the electronic detectors the second X-ray exposure (lateral marking) is performed and the brick is brought to the surface laboratory. The brick is then exposed to cosmic-rays for about 24 hours in a dedicated pit in order to select high-energy cosmic muons to provide straight tracks for a refined (sub-micrometric) film-to-film alignment;

5. the brick emulsion films are then developed and dispatched to the various scanning laboratories in Europe and Japan.

The procedure described above has proven to be successful. As an example, in figure 6 we show the number of bricks extracted by the BMS per week, about one hundred. This is matched by the 100 CS developed and scanned per week in the LNGS (Italy) and Tono (Japan) scanning stations.

Brick Finding and Changeable Sheet interplay. The efficiency for selecting the "fired" brick is the convolution of several effects and measurements. Here we discuss the two most important ones, the Brick Finding procedure and the Changeable Sheet measurement, for which preliminary results have been obtained from the analysis of partial samples of already scanned events.

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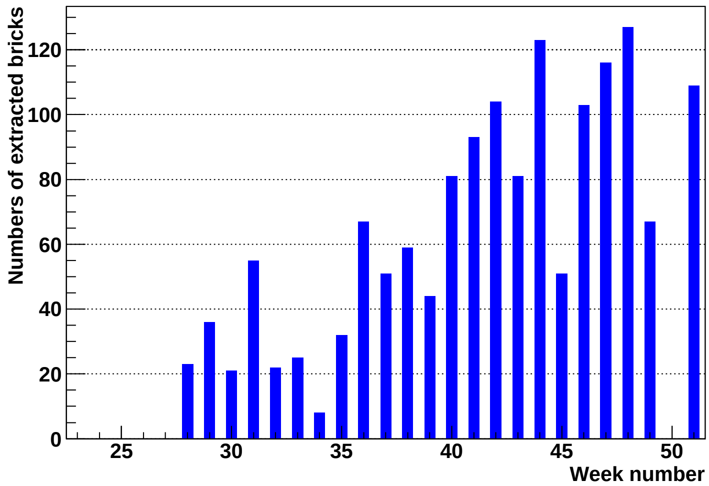

Figure 6. The number of bricks extracted per week by the BMS in 2008.

The brick finding algorithm exploits the tracking capabilities of the OPERA electronic detectors and, by combining this information with the output of a Neural Network for the selection of the most probable wall where the interaction occurred, provides a list of bricks with the associated probability that the interaction occurred therein. A preliminary estimate of the brick finding efficiency, limited to the extraction of the first most probable brick (for about 700 events) and not considering the small fraction ($< 5\%$) of events for which the present electronic detector reconstruction fails, is compatible with the Monte Carlo estimate of 70% computed for a standard mixture of CC and NC events. A higher efficiency can be obtained by extracting also bricks ranked with lower probabilities.

The tracking efficiency of single emulsion films can be measured by an exposure to high-energy pion beams and amounts to about 90% [10]. However, the measurement of the CS doublet efficiency in situ, in the OPERA detector, is by far more challenging, given the coarse resolution in the extrapolation of tracks from the electronic detectors to the CS.

At present, we are studying the CS tracking efficiency by two independent approaches: (a) all tracks produced in already located neutrino vertices are followed downstream and searched for in the corresponding CS doublet; (b) muon tracks reconstructed by the electronic detectors and found in the CS are properly normalized to the total number of CC events where at least one track (not necessarily the muon) is found in the CS. The two methods yield a preliminary efficiency for finding a track in both films of the CS doublet which is compatible with the conservative expectation of 90% on a single film [10]. The experimental efficiency has been evaluated on a sample of 100 events scanned in both the European and the Japanese laboratories. We are presently working in order to further increase this efficiency by employing more advanced analysis techniques.

So far, 1248 first and 134 second extracted CS have been analyzed and 79% of the events have at least a track found that can be extrapolated and searched for in the ECC brick. In order to evaluate the brick finding efficiency from this raw number, we should carefully evaluate fiducial volume effects, the percentage of interactions in the dead material and so on. Nonetheless, aiming

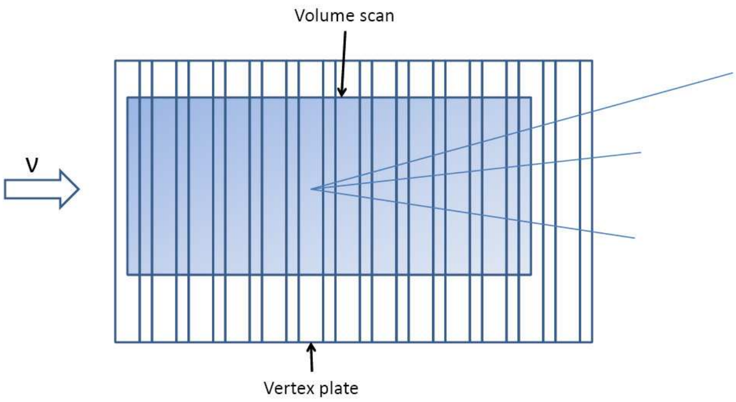

Figure 7. Schematic view of the volume scan performed around the stopping point of the track.

at the highest possible efficiency, we are also thinking of removing additional bricks in case the event would not be found using the first 2 CS.

Vertex analysis. All tracks measured in the CS are sought in the most downstream films of the brick and followed back until they are not found in three consecutive films. The stopping point is considered as the signature either for a primary or a secondary vertex. The vertex is then confirmed by scanning a volume with a transverse size of 1 cm^2 for 11 films in total, upstream and downstream of the stopping point (see figure 7). The vertex location analysis of some of the events found in the CS is still in progress. Under the two extreme hypotheses that none or all the events still under analysis will be found the vertex location efficiency ranges in the intervals 90%-95% and 74%-83% for CC and NC , respectively. These preliminary estimates of the vertex location efficiency are in agreement with the Monte Carlo expectations of 90% and 80% for CC and NC events, respectively.

The track impact parameter distribution of the muon in CC events with respect to the reconstructed vertex position and the event track multiplicity distribution are shown in figure 8. As expected, the impact parameter distribution is peaked at zero and has a mean value of 2.5 μm. The multiplicity distribution shows the anticipated enhancements for even track numbers due to the preferred interaction of neutrinos with neutrons.

As an example, in figures 9 and 10 we show a NC and a CC event, respectively, fully reconstructed in the brick. A very "peculiar" event is shown in figure 11: the neutrino interaction occurred in the bottom layer of an emulsion film. Therefore, the associated nuclear fragments (large angle heavy ionizing tracks) are also visible in the film containing the vertex.

Decay topologies. Charm production and decay topology events have a great importance in OPERA for two main reasons. On the one hand in order to certify the observation of τ events one should prove the ability of observing charm events at the expected rate. On the other hand, since charm decays exhibit the same topology as τ decays, they are a potential source of background if the muon at the primary vertex is not identified (see figure 12). Therefore, searching for charm-decays in events with the primary muon correctly identified provides a direct measurement of this background.

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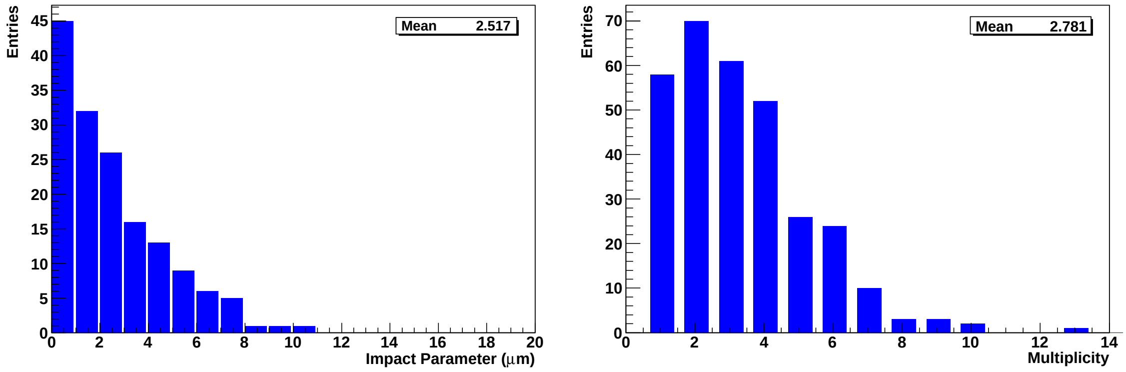

Figure 8. Left panel: impact parameter distribution of the muon track in CC events with respect to the reconstructed vertices. Right panel: charged track multiplicity distribution of the events.

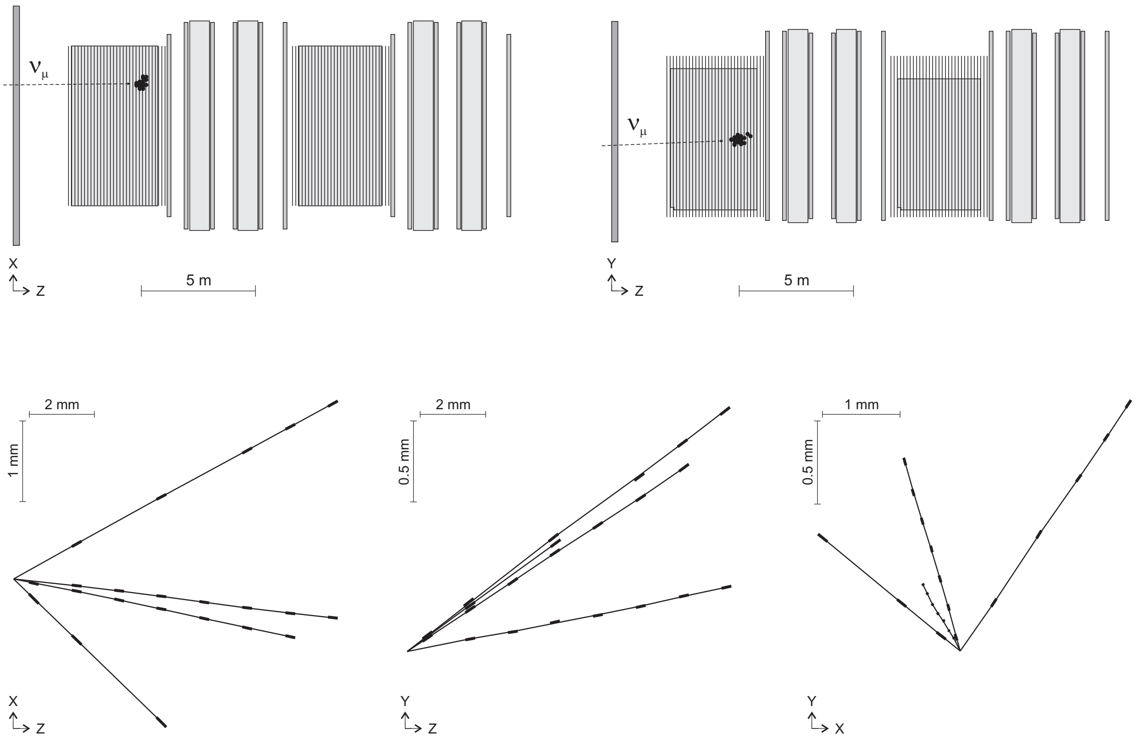

Figure 9. Top panels: online display of one NC event seen by the OPERA electronic detectors. The regions filled with bricks are highlighted. Bottom panels: emulsion reconstruction top view (bottom left), side view (bottom center), front view (bottom right).

Charm decay topologies were searched for in the sample of located neutrino interactions. Two events with charm-like topologies were found. From the neutrino-induced charm-production cross-section measured by the CHORUS experiment [16] about 3 charged-charm decays are expected to be observed in this sample.

The event in figure 13 has high track multiplicity at the primary vertex and one of the scan-back tracks shows a kink topology. The measured decay angle is 204 mrad and the flight length

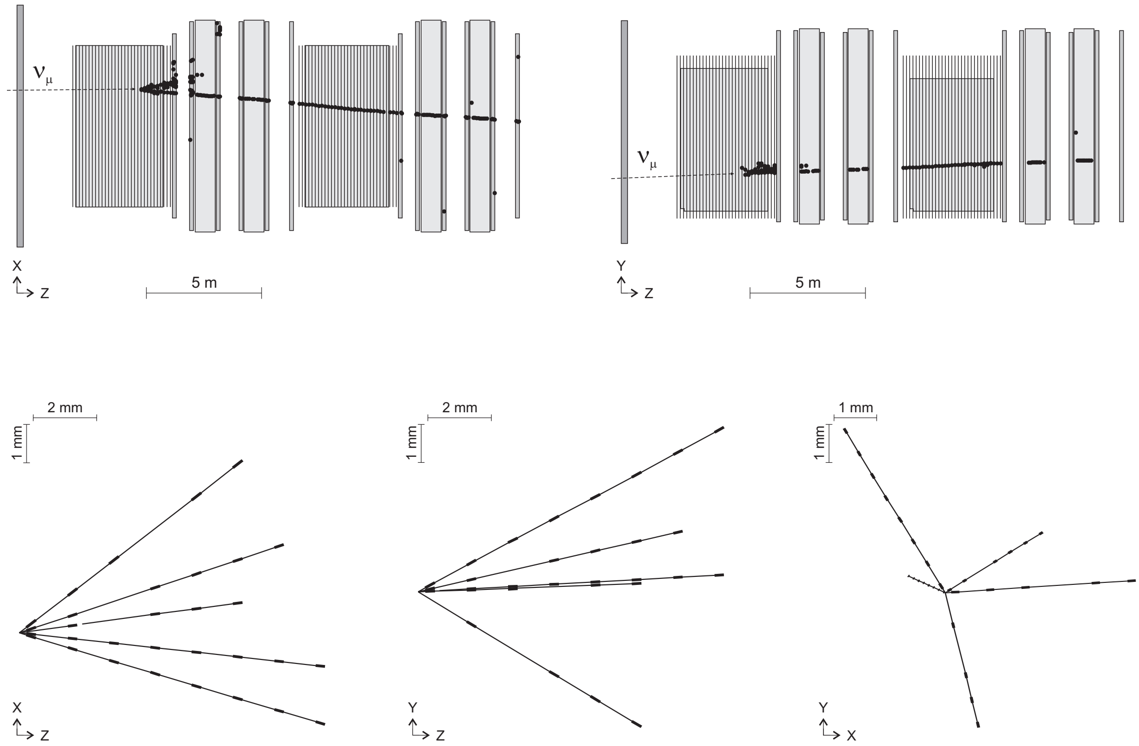

Figure 10. Top panels: online display of one CC event seen by the OPERA electronic detectors. Bottom panels: emulsion reconstruction top view (bottom left), side view (bottom center), front view (bottom right).

of the decaying particle is 3247 μm. The decay occurred in the third lead plate downstream of the interaction plate. No large angle tracks are produced at the decay vertex. This allows to further rule out the hadronic interaction hypothesis. The muon track and the charm candidate track lie in a back-to-back configuration ($\Delta\phi \simeq 165^\circ$) as one would expect for charm production [17]. The daughter momentum, measured by using the Multiple Coulomb Scattering technique [18] is $3.9^{+1.7}_{-0.9}$ GeV/c at the 90% C.L. Therefore, at the 90% C.L. the transverse momentum ranges between 610 MeV/c and 1140 MeV/c.

The daughter particle being a hadron, we computed the probability that a hadron interaction mimics a hadronic charm decay. According to the FLUKA Monte Carlo [19] the probability that a hadron interaction mimics a charm-decay with transverse momentum larger than 610 MeV/c is only 4×10^{-4}. We stress that the actual selection and background rejection procedure we will apply to the events in order to select signal decay topologies is the subject of detailed studies that we are conducting with the use of simulated events and real data.

The second charm-like topology is shown in figure 14. A 4-prong primary vertex is observed originating at a depth of about 30 μm in the upstream lead plate. The charmed hadron track points to a 3-prong decay vertex located at a distance of 1150 μm from the primary vertex (200 μm inside the lead). All tracks have a clear CS tag. The interaction occurs downstream in the brick and the tracks only cross four emulsion films and the CS doublet (the two most downstream hits in the figure). The muon track and the charm candidate track lie in a back-to-back configuration ($\Delta\phi \simeq 150^\circ$). The Lorentz γ of the charmed parent has been roughly estimated as the inverse of the

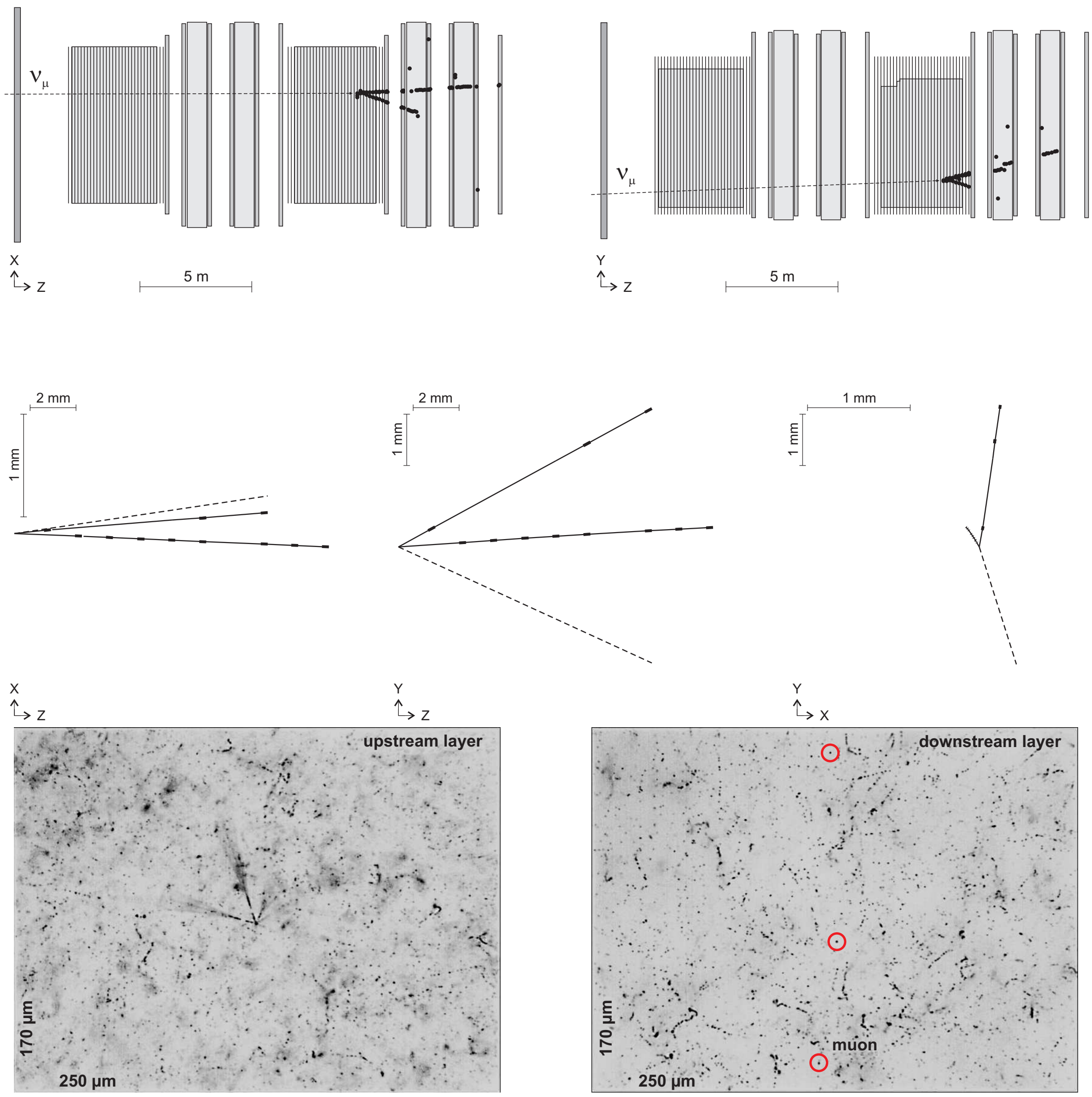

Figure 11. Display of the OPERA electronic detector of a ν_μ CC interaction, top and side views. The emulsion reconstruction is shown in the middle panels: top view (left), side view (center), frontal view (right). The dashed line shows a track that has been validated manually. Bottom left panel: picture of the interaction vertex as seen by the microscope CMOS camera. The nuclear fragments produced in the interaction are visible. Bottom right panel: picture taken about 200 micron far from the interaction vertex. The minimum ionizing particles produced in the interaction are indicated by a circle. The muon track is also indicated.

average angle in space that the daughter tracks form with it [20]. This leads to a γ value of about 8.6, implying a parent high momentum of ~ 16 GeV/c (assuming the D^+ mass). The momenta of the daughter tracks have also been measured by extracting the downstream brick and using the Multiple Coulomb Scattering technique. The measured values are $p_1 = 2.4^{+1.3}_{-0.6}$, p_2=$1.3^{+0.4}_{-0.3}$ and $p_3 = 1.2^{+1.7}_{-0.4}$ GeV/c (transverse momenta of about 610, 90 and 340 MeV/c, total momentum: $4.8^{+2.2}_{-0.8}$ GeV/c), at the 90% C.L. The probability of a hadron interaction has been evaluated using FLUKA and amounts to 10^{-6}. Assuming a $D \to K\pi\pi$ decay, an invariant mass of $1.1^{+0.2}_{-0.1}$ GeV/c^2

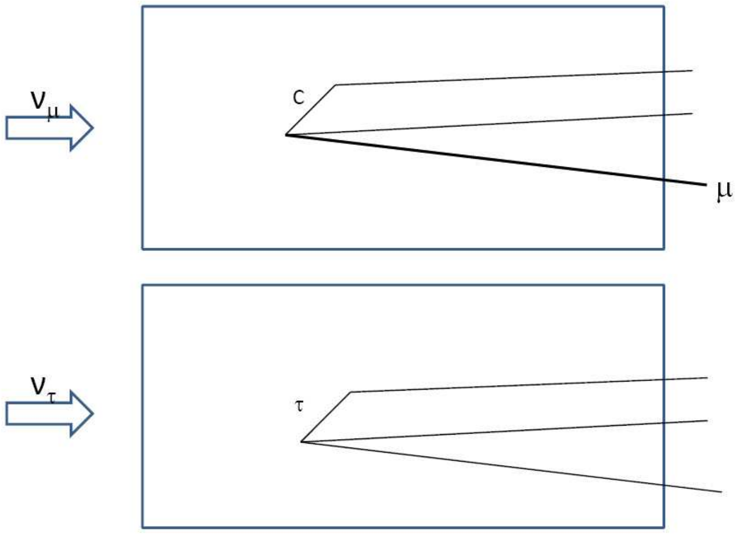

Figure 12. Schematic view of the charm and tau decay topologies.

is obtained. On the other hand assuming a $D_s \rightarrow KK\pi$ decay an invariant mass of $1.5^{+0.4}_{-0.1}$ GeV/c^2 is derived. In the latter case the invariant mass is consistent with the mass of a charmed hadron while in the first case the consistency is marginal. The probability of a decay in flight of a K is about 10^{-3}.

4 Conclusions

The 2007 and 2008 CNGS runs constitute an important milestone for the LNGS OPERA experiment searching for $\nu_\mu \rightarrow \nu_\tau$ oscillations. Initial samples of neutrino interaction events have been collected in the emulsion/lead target and allowed to check the complete analysis chain starting from the trigger down to the neutrino vertex location in the emulsions and to the topological and kinematical characterization of the event.

In this paper we reported on the capability in performing an online identification, extraction and development of the bricks where the neutrino interaction occurred, vertex location and kinematical reconstruction. The overall performance of the experiment during the running phase and through the analysis chain can be summarized by stating that:

- all electronic detectors performed excellently allowing the precise localization of the brick hit by the neutrino;
- the electronic detector event reconstruction was tuned to the brick finding procedure which operated for the first time with real neutrino events providing good results;
- all experimental activities from brick removal upon identification to the X-ray and cosmic-ray exposures, brick disassembly and emulsion development, have been successfully accomplished. At present more than 100 bricks per week can be routinely handled;
- the scanning of the Changeable Sheets can be performed with the expected detection efficiencies;

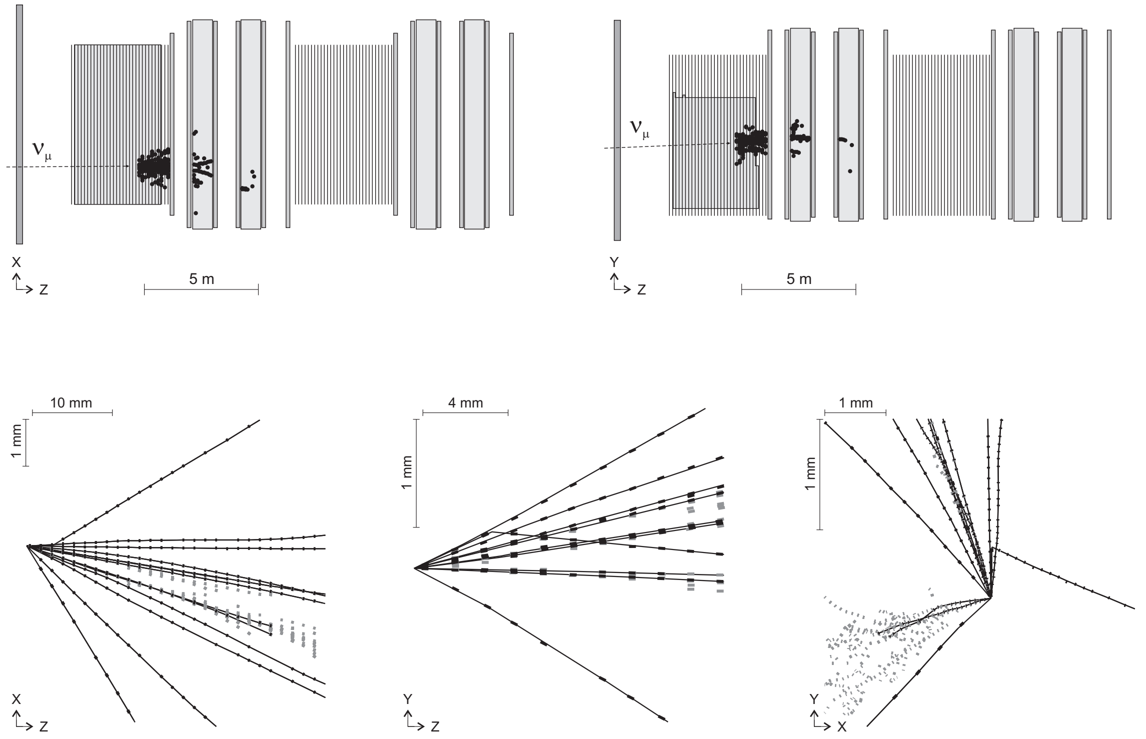

Figure 13. Online display of the OPERA electronic detector of a ν_μ charged-current interaction with a charm-like topology (top panels). The emulsion reconstruction is shown in the bottom panels where the charm-like topology is seen as a track with a kink: top view (bottom left), side view (bottom center), frontal view (bottom right). The dots visible in the left and right lower panels are due to an electromagnetic shower.

- vertex location was successfully attempted for both CC and NC events;
- the topological and kinematical analyses of the vertices were successfully exploited and led to an unambiguous interpretation of neutrino interactions. In particular two events with a charm-like topology were found so far in the analyzed sample. This is fully consistent with expectations based on the known neutrino-induced charm production cross-section.

The results presented in this paper are the first confirmation that OPERA is able to accomplish its task of selecting decay topologies in the emulsions from a large number of interactions triggered by the electronic detectors and that the scene has been set for the discovery of ν_τ appearance. Detailed studies currently in progress with simulated events and real data will allow to assess the experimental efficiencies, backgrounds and sensitivity; this will be the subject of a forthcoming publication.

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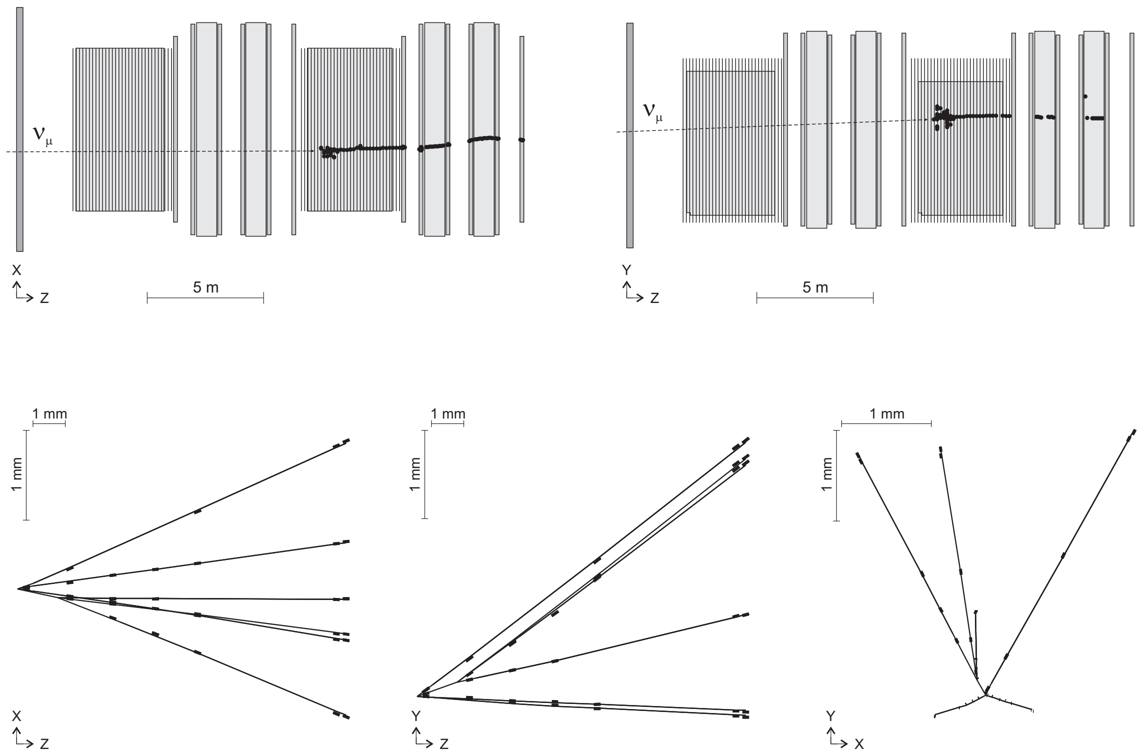

Figure 14. Online display of the OPERA electronic detector of a ν_μ charged-current interaction with a charm-like topology (top panels). The emulsion reconstruction is shown in the bottom panels where the charm-like topology is seen as a three-prongs secondary vertex: top view (bottom left), side view (bottom center), frontal view (bottom right).

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