Physics @ CNGS beam
Outline

- The CERN Neutrinos to Gran Sasso project
- $\nu_\tau$ hunting
- ICARUS at work (→ P. Sala’s talk in the afternoon)
- OPERA at work
The CERN Neutrinos to Gran Sasso project

CNGS Neutrino beam

proposed and developed to provide an unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillation in the parameter space allowed in the atmospheric sector

1979: Prof. A. Zichichi presents his vision to the “Commissione Lavori Pubblici”
1992: an internal report describes “CERN Beams for Long Baseline Neutrino experiments”
1999: CERN council approves the $\nu$, appearance CNGS program; a convention is signed between CERN and INFN, “concerning the CNGS facility”
2000: start of CNGS civil construction
2004: ceremony to mark the end of CNGS civil construction
2005: end of installation of equipment, start of hardware commissioning
2006: start CNGS commissioning with beam, first neutrinos at Gran Sasso
2007: very short run due a major problem in radiation shielding (3.6 nominal days)
2008 → now: CNGS runs delivering an increasing number of p.o.t. hopefully up to the nominal $4.5 \times 10^{19}$ p.o.t./year!
CERN Neutrinos to Gran Sasso: the beam

P+C → (interactions) → π⁺, K⁺ → (decay in flight) → μ⁺ + νₘ

~ 1 km, 2.5 m

conventional neutrino beam with a high intensity and high energy proton beam, intense short beam pulses and small beam spots (< 1 mm)

- 400 GeV/c protons from the CERN SPS on a graphite target
- 6 s cycle length, 2 extr. every 50 ms, 10.5 μs pulse length
- beam intensity 2.4 \times 10^{13} \text{ pot/extr}
- average power at the target 510 kW
- neutrinos from pions and kaons decaying in flight
Pr(\(\nu_\mu \rightarrow \nu_\tau\)) & \(\sigma_{\nu(\tau)CC}(E)\) convolution maximized \(\rightarrow\) high E beam

(“appearance”- optimized)

CERN Neutrinos to Gran Sasso: the beam

\[ <E_{\nu\mu}> \]

\[ (\nu_e + \overline{\nu}_e)/\nu_\mu \text{ CC} \]

\[ \overline{\nu}_\mu/\nu_\mu \text{ CC} \]

\[ \nu_\tau \text{ prompt} \]

p.o.t./year

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;(E_{\nu\mu})&gt;</td>
<td>17 GeV</td>
</tr>
<tr>
<td>((\nu_e + \overline{\nu}<em>e))/(\nu</em>\mu) CC</td>
<td>0.87%</td>
</tr>
<tr>
<td>(\overline{\nu}<em>\mu/\nu</em>\mu) CC</td>
<td>2.1%</td>
</tr>
<tr>
<td>(\nu_\tau) prompt</td>
<td>negligible</td>
</tr>
<tr>
<td>p.o.t./year</td>
<td>(4.5 \times 10^{19})</td>
</tr>
</tbody>
</table>

Shared SPS operation, 200 days/year
# CNGS 2008-2010

<table>
<thead>
<tr>
<th>run</th>
<th>days</th>
<th># p.o.t.*</th>
<th>extraction scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>123</td>
<td>1.8 \times 10^{19}</td>
<td>CT</td>
</tr>
<tr>
<td>2009</td>
<td>155</td>
<td>3.5 \times 10^{19}</td>
<td>CT (MTE commis.)</td>
</tr>
<tr>
<td>2010</td>
<td>187</td>
<td>2.7 \times 10^{19}</td>
<td>MTE + CT</td>
</tr>
</tbody>
</table>

*nominal value: 4.5 \times 10^{19} pot

CT = continuous turn
MTE = multi-turn extraction

2008: bad initial performance due to various problems occurred to the CERN accelerator complex. Then, during the last months of the run, SPS in semi-dedicated mode for CNGS.

2009: run has been smoother and more stable. MTE commissioning during the end of the run and the winter 2010 LHC run.

what about 2010 run?

[@2010/08/30, still running]
CNGS 2010: some details….

2010 run started with MTE and then switched back to CT due to some long term instabilities risk: long stop in the operation of the PS

at present: lower average intensities than 2009 due to MTE that was unstable above 1.8*10^{13} pot/extraction

Rough extrapolation of 2009 performance to number of days in 2010 would yield 4.25*10^{19} pot

hoping to get as close as possible to 4.5*10^{19} pot in 2010 and in the next future
CNGS: experimental signature for $\nu_\tau$ appearance

**goal:** proof $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode

\[ \nu_\mu \leftrightarrow \nu_\tau \rightarrow \tau^- + X \]

Two experiments take part to the CNGS project: **ICARUS** and **OPERA**

**ICARUS**
reveal $\tau$ decay topology in the electron decay channel by mean of kinematical criteria

**OPERA**
direct observation of the tau lepton decay topologies (kink signature)

Sept 7, 2010
A. Pastore, NOW2010
LNGS of INFN: the world largest underground physics laboratory

~180'000 m³ caverns’ volume, ~3’100 m.w.e. overburden, ~1 cosmic μ/ m²xhour, experimental infrastructure, variety of experiments. Perfectly fit to host detector and related facilities, caverns oriented towards CERN.
The ICARUS collaboration

Wroclaw University of Technology, Poland
Dipartimento di Fisica e INFN, Università di L’Aquila, Italy
Laboratori Nazionali del Gran Sasso (INFN), Italy
Dipartimento di Fisica e INFN, Università di Padova, Italy
Dipartimento di Fisica e INFN, Università di Milano, Italy
Dipartimento di Fisica Nucleare, Teorica e INFN, Università di Pavia, Italy
Dipartimento di Scienza Fisiche, INFN e Università Federico II, Napoli, Italy
H. Niewodniczanski Institute of Nuclear Physics, Poland
Laboratori Nazionali di Frascati (INFN), Italy
INR RAS, Moscow, Russia
University of Silesia, Poland
Warsaw University, Poland
A. Soltan Institute for Nuclear Studies, Poland
AGH University of Science and Technology, Poland
Dipartimento di Fisica, Università di Pisa, Italy
University of Technology, Poland
Department of Physics and Astronomy, University of California, Los Angeles, USA

Sept 7, 2010
A. Pastore, NOW2010
ICARUS : the first large scale LAr experiment

Based on the Liquid Argon Time Projection Chamber detection technique
[C. Rubbia: CERN-EP/77-08 (1977)]

ICARUS has a powerful detector capable of providing 3D imaging of any ionizing event

an ‘electronic bubble chamber’ with in addition:
- high granularity (~ 1 mm)
- self triggering capability
- continuous sensitivity
- excellent calorimetric properties
- particle ID capability (through dE/dx vs range)

[ ref: A. Guglielmi - Status and early events from ICARUS T600 – Neutrino ‘10-Athens, 15-06-2010 ]
ICARUS T600 physics @ CNGS

In the hypothesis of:

- CNGS delivering nominal $4.5 \times 10^{19}$ pot/year
- $\approx 2500$ ev/kton/year with 90% efficiency of collection
- a raw fiducial volume $\approx 480$ ton for ICARUS T600
  $\rightarrow$ $\approx 5000$ neutrino events for $18 \times 10^{19}$ pot

Goal of the experiment is the proof of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode, detecting $\tau$ decay with kinematical criteria

Studies to establish ICARUS T600 sensitivity in searching for sterile neutrinos in LSND parameter space are under way

In addition to CNGS physics, ICARUS has a potential vast non-accelerator based physics program thanks to the capability in triggering “low energy events” (solar neutrinos, SN neutrinos), atmospheric neutrinos and p-decay ($\rightarrow$ ICARUS talk, in the afternoon)

[ ref: A. Guglielmi - Status and early events from ICARUS T600 - Neutrino ‘10-Athens, 15-06-2010 ]
ICARUS T600: looking for $\nu_\tau$ signature

In order to prove $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode, the main reaction ICARUS is looking for is

$$\nu_\tau + Ar \rightarrow \tau^- + jet$$

$E_\nu = 20$ GeV and $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$, 4 yrs run @ nominal $4.5 \times 10^{19}$ pot/y

$\rightarrow$ 67 raw $\nu_\tau$ events expected @ T600

detection strategy: reveal $\tau$ decay topology in the electron decay channel

$$\tau \rightarrow e\nu\nu$$

Events characterized by a momentum unbalance (due to $\nu$ emission and a relatively low electron momentum) are selected by mean of kinematical criteria (eff. $\approx 50\%$)

$6 \pm 2.5$ unambiguous $\nu_\tau \rightarrow e\nu\nu$ events expected

[ ref: A. Guglielmi - Status and early events from ICARUS T600 - Neutrino ‘10-Athens, 15-06-2010 ]
ICARUS T600 at Gran Sasso National Laboratory is a major milestone towards the realization of a much more massive multikton LAr detector and acts as a full-scale test-bed located and working underground.

Since May 2010 the ICARUS experiment is taking data and CNGS neutrino interactions have been observed.

first CNGS neutrino interaction - ICARUS T600, May 28, 2010
The Oscillation Project with Emulsion tRacking Apparatus

34 INSTITUTIONS ~ 160 PHYSICISTS

IPNL, IPHC, LAPP
Hamburg, Münster, Rostock
IRB Zagreb
L’Aquila, Bari, Bologna, Napoli, Padova, Roma, Salerno, LNF, LNGS
Aichi, Toho, Kobe, Nagoya, Utsunomiya
METU Ankara

Technion Haifa
Bern, ETH Zurich
Jinju
CNSTN Tunis
JINR, INR-RAS, ITEP, LPI-RAS, SINP-MSU
IHE Bruxelles
OPERA: looking for $\nu_\tau$ signature

$$\nu_\mu \leftrightarrow \nu_\tau \rightarrow \tau^- + X$$

detector requirements: large mass, high resolution (for signal selection and background rejection)

@ 4.5$\times$10$^{19}$ p.o.t./year, 200 days/year for OPERA (~1.25 Kton) detector:
- $\sim 4700 \nu_\mu$ CC+NC / year
- $\sim 30 \nu_e + \bar{\nu}_e$ CC / year
- $\sim 25 \nu_\tau$ CC / year ($\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$)

expected neutrino interactions

<table>
<thead>
<tr>
<th></th>
<th>$\tau \rightarrow \mu$</th>
<th>$\tau \rightarrow e$</th>
<th>$\tau \rightarrow h$</th>
<th>$\tau \rightarrow 3h$</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal ($\Delta m^2=2.5 \times 10^{-3}$ eV$^2$)</td>
<td>2.9</td>
<td>3.5</td>
<td>3.1</td>
<td>0.9</td>
<td>10.4</td>
</tr>
<tr>
<td>bkgd</td>
<td>0.17</td>
<td>0.17</td>
<td>0.24</td>
<td>0.17</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Full mixing and $\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV$^2$

The grey band indicates the OPERA allowed region (90% CL) for the above parameter values for 22.5 $\times$ 10$^{19}$ pot

@22.5 $10^{19}$ pot
OPERA: the hybrid solution

OPERA: nuclear emulsions + electronic detectors

brick: 57 emulsion films
sandwiched between 1mm Pb plates

8.3 Kg
(10.2*12.5) cm²

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

1 Changeable Sheet doublet (CS)/brick:
two refreshed emulsion films, vacuum packed and glued onto the downstream brick face

~ 150000 bricks in the OPERA target (~ 1.25 kton)

physics in a brick:

- ν interactions and decay topology reconstruction
- measurement momenta by MCS
- e/π separation
- electromagnetic calorimetry

when electronic detectors enter the game:

- trigger for a neutrino interaction
- muon identification and momentum/charge measurement

Sept 7, 2010
The OPERA detector @ LNGS

[~3100 m.w.e. overburden, ~1 cosmic μ / m² x hour]

- Veto (RPC)
- Dipole magnet
  - 6 4-fold layers of drift tubes
  - 1.53 T
  - 22 XY planes of RPC
- muon spectrometer (8×10 m²)

- Target + Target Tracker (6.7m²)
  - Target/SM: ~75000 bricks
    (Pb – nuclear emulsions)
    Mass/SM 0.625 kt
  - Target tracker: 31 doublets XY
    (256 plastic scintillator strip + WLS fibres + multi-anodes PMT) for trigger,
    brick selection and calorimetry

[Ref. JINST 4 (2009) P04018]
A. Pastore, NOW2010
OPERA: steps to reach the goal

- on-line analysis of electronic data
OPERA: steps to reach the goal

- on-line analysis of electronic data
- brick finding algorithm for events ‘on time’ with the beam
OPERA: steps to reach the goal

- on-line analysis of electronic data
- brick finding algorithm for events ‘on time’ with the beam
- remove brick and scan CS: the interface between brick and TT ($\sigma_{\text{pos}} \approx 10$ mm, $\sigma_{\theta} \approx 20$ mrad)
OPERA: steps to reach the goal

- on-line analysis of electronic data
- brick finding algorithm for events ‘on time’ with the beam
- remove brick and scan CS: the interface between brick and TT ($\sigma_{\text{pos}} \approx 10$ mm, $\sigma_{\theta} \approx 20$ mrad)
- confirmation of the extracted brick

Sept 7, 2010
A. Pastore, NOW2010
OPERA: steps to reach the goal

• on-line analysis of electronic data

• brick finding algorithm for events ‘on time’ with the beam

• remove brick and scan CS: the interface between brick and TT ($\sigma_{\text{pos}} \approx 10 \text{ mm}, \sigma_{\theta} \approx 20 \text{ mrad}$)

• confirmation of the extracted brick

• development of the brick to be sent in a scanning Lab for ‘CS to brick connection’ ($\sigma_{\text{pos}} \approx 70 \mu\text{m}, \sigma_{\theta} \approx 8 \text{ mrad}$), event location, decay search studies, etc.

Sept 7, 2010  A. Pastore, NOW2010
OPERA films data taking: automatic microscopes

~ 20 bricks daily extracted from the target analyzed using high-speed automated systems (≥ 20 cm²/h)

European Scanning System
S-UTS (Japan)

Common Data Base for data sharing/publication

- Customized commercial optics and mechanics
- Asynchronous DAQ software modular, decentralized, approach

Piezo-controlled objective lens
High speed CCD Camera (3 kHz)

- Synchronization of objective lens and (constant speed) stage
- Hard-coded algorithms, custom electronics

~90% tracking efficiency
Spatial resolution < 1 µm and angular resolution < 2 mrad
OPERA: analysis performances (I)

Ip measurement:

IP distribution for $\nu_e$ events (MC)
NC+CC $\nu_\mu$ events (MC),
NC+CC $\nu_\mu$ events (Data)

expanded scale

particles momenta measurements by MCS

$\pi$ test beam
Measurements performed on several selected OPERA soft muon events.
**OPERA: analysis performances (II)**

**γ** detection and **π⁰** mass reconstruction

- **γ** → e-pair
  - e⁺
  - e⁻

70% of 1-prong hadronic **τ** decays include one or more **π⁰** → importance of gamma detection

**Gamma detection: how to...**
- detection of shower
- detection e-pair at start point

EM shower energy measured by shower shape analysis and Multiple Coulomb Scattering method

**2 em showers give a reconstructed mass 160±30 MeV/c²**

E = 0.5 GeV

E = 8.1 GeV

**χ² / ndf** 1.954 / 6
- Constant 7.388 ± 1.757
- Mean 142.2 ± 13.2
- Sigma 65.76 ± 11.56

1 σ mass resolution: ~ 45%

Sept 7, 2010
A. Pastore,
### OPERA: data analysis status

#### 3 physics runs

<table>
<thead>
<tr>
<th>run</th>
<th>days</th>
<th># p.o.t.*</th>
<th># events in the bricks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>123</td>
<td>$1.8 \times 10^{19}$</td>
<td>1698</td>
</tr>
<tr>
<td>2009</td>
<td>155</td>
<td>$3.5 \times 10^{19}$</td>
<td>3693</td>
</tr>
<tr>
<td>2010</td>
<td>187</td>
<td>$2.7 \times 10^{19}$</td>
<td>2828</td>
</tr>
</tbody>
</table>

$\text{5.3} \times 10^{19}$ pot $\approx 2 \tau$ expected

[@2010/08/30, still running]

* nominal value: $4.5 \times 10^{19}$ pot

- Data analysis for run 2008: Completed
- Data analysis for run 2009: Completed in few months
- Data analysis for run 2010: Going in parallel

**From 2008+2009 completed analysis:**

- Measured ratio of NC-like/CC-like events after muon ID and event location is ~20%, as expected from simulations
- 18 charm decay candidates (by kinematical cuts)
- 6 $\nu_e$CC candidates
- 1 $\nu_\tau$ candidate

Sept 7, 2010  A. Pastore
charm decays inside the OPERA target

Decay search procedure defined (ip evaluation, small angle kink search, extra-tracks search)

Decay Search extensively applied to located interactions data sample

Charm topology analogous to $\tau$: reference sample for the decay finding efficiency

18 charm candidate (by kinematical cuts)

3 of them with 1-prong kink topology.

Expected: $15.5 \pm 2.8$ out of which $0.79 \pm 0.22$ with kink topology

Expected BG: 1.7 events (loose cuts: work in progress to reduce BG)
$\nu_e$ CC interactions inside the OPERA target

6 electron neutrino interactions were found in a subsample of 800 CC located interactions.
 OPERA: the first $\nu_\tau$ candidate event (I)

Muonless event 9234119599
ED display

Scan-back in the brick for stopping point definition

CS confirmation of the brick

Large area scanning
Full reconstruction of vertices and gammas


http://arxiv.org/abs/1006.1623

A. Pastore, NOW2010 32
The primary neutrino interaction consists of 7 tracks of which one exhibits a visible kink.

[Diagram showing the primary neutrino interaction with 7 tracks, one of which exhibits a visible kink.]
**OPERA: the first $\nu_\tau$ candidate event (II)**

- The primary neutrino interaction consists of 7 tracks of which one exhibits a visible kink.
- Two electromagnetic showers caused by $\gamma$-rays, associated with the event, have been located (total radiation length downstream the vertices: $6.5 X_0$).

<table>
<thead>
<tr>
<th></th>
<th>Distance from 2ry vertex (mm)</th>
<th>Energy (GeV)</th>
<th>IP to 1ry vertex ($\mu$m)</th>
<th>IP to 2ry vertex ($\mu$m)</th>
<th>Prob. of attach. to 1ry vtx*</th>
<th>Prob. of attach. to 2ry vtx*</th>
<th>Attachment hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st $\gamma$</td>
<td>2.2</td>
<td>$5.6 \pm 1.0 \pm 1.7$</td>
<td>45.0 $&lt;11&gt;$</td>
<td>7.5 $&lt;7&gt;$</td>
<td>$&lt;10^{-3}$</td>
<td>0.32</td>
<td>2ry vertex</td>
</tr>
<tr>
<td>2nd $\gamma$</td>
<td>12.6</td>
<td>$1.2 \pm 0.4 \pm 0.4$</td>
<td>85.6 $&lt;56&gt;$</td>
<td>$22 &lt;50&gt;$</td>
<td>0.10</td>
<td>0.82</td>
<td>2ry vertex (favoured)</td>
</tr>
</tbody>
</table>

* probability to find an IP larger than the observed one
OPERA: the first $\nu_{\tau}$ candidate event (II)

- The primary neutrino interaction consists of 7 tracks of which one exhibits a visible kink
- Two electromagnetic showers caused by $\gamma$-rays, associated with the event, have been located (total radiation length downstream the vertices: 6.5 $X_0$)

- None of the tracks is compatible with being an electron track
- For tracks 1, 5 and 6 $P(\mu) < 10^{-3}$ (p-range consistency check)
- Remaining tracks are hadrons (interaction seen)
- Residual probability of $\nu_{\mu}$ CC event (possibly undetected large angle muon) is $\approx 1%$. “Nominal” value of 5% assumed

Sept 7, 2010  A. Pastore, NOW2010
OPERA: the first $\nu_\tau$ candidate event (III)

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>AVERAGE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>kink (mrad)</td>
<td>$41 \pm 2$</td>
</tr>
<tr>
<td>decay length ($\mu$m)</td>
<td>$1335 \pm 35$</td>
</tr>
<tr>
<td>$P$ daughter (GeV/c)</td>
<td>$12^{+6}_{-3}$</td>
</tr>
<tr>
<td>Pt decay (MeV/c)</td>
<td>$470^{+230}_{-120}$</td>
</tr>
<tr>
<td>missing Pt (MeV/c)</td>
<td>$570^{+320}_{-170}$</td>
</tr>
<tr>
<td>$\phi$ (deg)</td>
<td>$173 \pm 2$</td>
</tr>
</tbody>
</table>

Kinematical variables are **satisfying all selection criteria for hadronic kink** $\rightarrow$ **first $\nu_\tau$ candidate**!

defined in the proposal

candidate to the $\tau$ 1-prong hadron decay mode

- invariant mass of $\gamma$-rays 1 and 2:
  \[ 120 \pm 20 \text{ (stat)} \pm 35 \text{(syst)} \text{ MeV/c}^2 \]
  supporting the hypothesis $\pi^0 \rightarrow \gamma \gamma$

- assuming the charged decay product as $\pi^-$, the invariant mass of $\pi^-$ and 2 gammas:
  \[ 640^{+125}_{-80}^{+100}_{-90} \text{ MeV/c}^2 \]
  compatible with the $\rho(770)$ mass

\[ 2\text{ry vtx compatible with: } \tau \rightarrow h \ (n\pi^0) \nu_\tau \]

With the available statistics** ($\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$, full mixing) OPERA expected \~ 0.5 $\nu_\tau$ events

** at the time of observation
Evaluation of background sources:

- prompt $\nu_\tau$ ~ $10^{-7}$/CC
- decay of charmed particles produced in $\nu_\epsilon$ interactions ~ $10^{-6}$/CC
- double charm production ~ $10^{-6}$/CC
- decay of charmed particles produced in $\nu_\mu$ interactions ~ $10^{-5}$/CC
- hadronic reinteractions (UPDATE wrt Proposal) ~ $10^{-5}$/CC

For the 1-prong hadronic channel $0.007\pm0.004$ (syst) background events are expected for the analyzed statistics.

- Background evaluation by using state-of-the-art FLUKA code (upgrade wrt Proposal)
- Kink probabilities integrated over the $\nu_\mu$ NC hadronic spectrum yield (same cuts as for the tau analysis) a BG probability of $(1.9 \pm 0.1) \times 10^{-4}$ kinks/NC (2 mm Pb)
- First cross-checks of the simulation were performed on a scan-forth tracks sample and on dedicated test-beam data, showing a good agreement with the simulation, although still statistically limited
Background expectations 1-prong hadron $\tau$ decay channel:
($\sim 50\%$ syst. error for each component)

- 0.011 events (reinteractions)
- 0.007 events (charm, assuming standard mu ID)

---------------------------------

0.018 ± 0.007 (syst.) events 1-prong hadron

BCK for all decay modes: 1-prong hadron, 3-prongs + 1-prong $\mu$ + 1-prong $e$:
0.045 ± 0.020 (syst.) events total BG

Background fluctuation probabilities to 1 event:

1-prong hadron channel only: $P=1.8\% \rightarrow 2.36 \sigma$ significance
All tau decay modes included in search: $P=4.5\% \rightarrow 2.01 \sigma$ significance
Conclusions and outlook (I)

CNGS beam:

- 3rd physics run (CT extraction mode)
- hoping to get as close as possible to $4.5 \times 10^{19}$ pot in 2010 run
- aim at high-intensity runs in the future

ICARUS/CNGS2:

- The T600 detector at LNGS constitutes a major milestone towards the realization of a much more massive multikton LAr detector.
- Since May 2010 T600 is taking data.
- Neutrino interactions have been observed and data analysis is already on-going.

OPERA/CNGS1:

- The OPERA experiment is at its third physics run
Conclusions and outlook (II)

OPERA/CNGS1:

- the analysis of a sub-sample of the neutrino data taken in the CERN CNGS beam in the 2008-2009 runs lead to the reconstruction of a number of interesting topologies such as charm decays candidates and $\nu_e$CC interactions in agreement with the expectations.

- one muonless event showing a $\tau \to 1$-prong hadron decay topology has been detected and studied in detail. It passes all kinematical cuts required to reduce the physics background. It is the first $\nu_\tau$ candidate event in OPERA, with statistical significance of 2.36 $\sigma$ (1prong hadronic decay mode) and 2.01 $\sigma$ (all decay modes).

- analysis on 2008+2009 full sample data will be finished in few months, according with the present scanning speed. In this data set we expect $\approx 2$ $\nu_\tau$ CC interactions reconstructed in the target.

thank you for your attention!
backup
Expected neutrino flux @ LNGS

<table>
<thead>
<tr>
<th>Flux</th>
<th>$&lt; E_\nu &gt;$</th>
<th>$\nu_i/\nu_\mu$</th>
<th>$\nu_i/\nu_\mu$-CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu/cm^2/10^{19}pot)</td>
<td>[GeV]</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
<td>7.4 $\cdot$ 10^6</td>
<td>17.9</td>
<td></td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>2.9 $\cdot$ 10^5</td>
<td>21.8</td>
<td>3.9</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>4.7 $\cdot$ 10^4</td>
<td>24.5</td>
<td>0.65</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>6.0 $\cdot$ 10^3</td>
<td>24.4</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**CC event rate@ 4.5 $10^{19}$pot**

- 600 $\nu_\mu$ CC/kt/ $10^{19}$pot
- 5.5 $\nu_e$ CC/kt/ $10^{19}$pot
By assuming that $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$ and full mixing, we expected:

- $0.54 \pm 0.13 \text{ (syst)}$ $\nu_\tau$ CC events in all $\tau$ decay channels and
- $0.16 \pm 0.04 \text{ (syst)}$ $\nu_\tau$ CC events in the 1-prong hadron $\tau$ decay channel

and we observed 1 event.

This result allows us to exclude at the 90% CL

$\Delta m_{23}^2$ values $> 7.5 \times 10^{-3} \text{ eV}^2$ (full mixing)
## Event tracks’ features

<table>
<thead>
<tr>
<th>TRACK NUMBER</th>
<th>PID</th>
<th>Probability</th>
<th>MEASUREMENT 1</th>
<th>MEASUREMENT 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\tan \Theta_x$</td>
<td>$\tan \Theta_y$</td>
</tr>
<tr>
<td>1</td>
<td>HADRON range in Pb/emul=4.1/1.2 cm</td>
<td>Prob($\mu$)$\approx 10^{-3}$</td>
<td>0.177</td>
<td>0.368</td>
</tr>
<tr>
<td>2</td>
<td>PROTON range, scattering and dE/dx</td>
<td>-0.646</td>
<td>-0.001</td>
<td>0.60 [0.55,0.65]</td>
</tr>
<tr>
<td>3</td>
<td>HADRON interaction seen</td>
<td>0.105</td>
<td>0.113</td>
<td>2.16 [1.80,2.69]</td>
</tr>
<tr>
<td>4 (PARENT)</td>
<td></td>
<td></td>
<td>-0.023</td>
<td>0.026</td>
</tr>
<tr>
<td>5</td>
<td>HADRON: range in Pb/emul=9.5/2.8 cm</td>
<td>Prob($\mu$)$\approx 10^{-3}$</td>
<td>0.165</td>
<td>0.275</td>
</tr>
<tr>
<td>6</td>
<td>HADRON: range in Pb/emul=1.6/0.5 cm</td>
<td>Prob($\mu$)$\approx 10^{-3}$</td>
<td>0.334</td>
<td>-0.584</td>
</tr>
<tr>
<td>7</td>
<td>From a prompt neutral particle</td>
<td>0.430</td>
<td>0.419</td>
<td>0.34 [0.22,0.69]</td>
</tr>
<tr>
<td>8 (DAUGHTER)</td>
<td>HADRON interaction seen</td>
<td>-0.004</td>
<td>-0.008</td>
<td>12 [9,18]</td>
</tr>
</tbody>
</table>

Sept 7, 2010 A. Pastore, NOW2010 

muonless event (favored hypothesis)
OPERA Kinematical analysis

OPERA nominal analysis flow applied to the hadronic kink candidates:

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

10 years old criteria (@Proposal) → Blind 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 ≥ 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
Features of the decay topology...

- **Decay length**: 1335 ± 35 μm
- **Kink angle**: 141 ± 2 mrad
- **Daughter momentum**: 12 ± 6 GeV
- **Missing Pt at primary vertex**: rejection of NC events with larger missing Pt (neutrino)
- **Pt at decay vertex**: rejection of hadron interactions

Red bands: values for the “interesting” event with uncertainties

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Sept 7, 2010

A. Pastore, NOW
Charmed particles have decay topologies similar to the $\tau$ ones

- charm production in CC events represents a background source to all $\tau$ decay channels
- this background can be suppressed by identifying the primary lepton $\rightarrow$ $\sim$ 95% muon ID
- for the 1-prong hadronic channel $0.007 \pm 0.004$ (syst) background events are expected for the analyzed statistics
- further charm BG reduction is under evaluation by implementing the systematic follow-down of low energy tracks in the bricks and the inspection of their end-range, as done for the “interesting” event. For the latter we have 98-99% muon ID efficiency.
Simulation of the reinteraction BG with FLUKA…

- Background evaluation by using state-of-the-art FLUKA code, upgrade of the Proposal simulations.
- 160 million events (0.5-15 GeV/c) of $\pi^+,\pi^-,K^+,K^-,p$ impinging 1 mm of lead, equivalent to 160 km of hadronic track length.
- Kink probabilities evaluated by applying the same cuts as for the tau analysis.

\[ \text{kink probabilities integrated over the } \nu_\mu \text{ NC hadronic spectrum yield a BG probability of:} \]
\[ (1.9 \pm 0.1) \times 10^{-4} \text{kinks/NC (2 mm Pb)} \]

...cross check I (scan-forth data)

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

...cross check II (4GeV$\pi$ test-beam data)

- 8 times track length of tau search
- 18 times track length of tau search

- 1-prong
- multi-prong

Pastore
ICARUS

$\nu_\mu \rightarrow \nu_e$ appearance search summary

For $\Delta m^2_{23} = 2.5 \times 10^{-3}$

$$(\sin^2 2\theta_{13})_{\text{CNGS}} < 0.04 \quad \text{or} \quad \theta_{13} < 6^\circ$$

$$(\sin^2 2\theta_{13})_{\text{CHOOZ}} < 0.14 \quad \text{or} \quad \theta_{13} < 11^\circ$$

$$(\sin^2 2\theta_{13})_{\text{MINOS}} < 0.06 \quad \text{or} \quad \theta_{13} < 7^\circ$$

LIMITED BY STATISTICS OF CNGS!

ICARUS OFFERS THE BEST SENSITIVITY UNTIL JHF STARTS

CHIMP Forum - October 2, 2003

MINOS, 10 kton-years
ICARUS, 2.35 kton, 5 years CNGS, $\chi^2_{\nu_\mu} + 4.6$
JHF+SK, 22.5 kton, 5 years
**OPERA** $\nu_\mu \rightarrow \nu_e$ oscillation channel

- due to its good eID capability, OPERA is well suited for $\nu_\mu \rightarrow \nu_e$ searches
- main backgrounds:
  - $\nu_e$ beam contamination (larger contribution)
  - $\pi^0$ identified as electrons produced in $\nu_\mu$NC or $\nu_\mu$CC (+ $\mu$ misID)

<table>
<thead>
<tr>
<th>$\theta_{13}$</th>
<th>$\sin^2 2\theta_{13}$</th>
<th>signal</th>
<th>$\tau \rightarrow e$</th>
<th>$\nu_\mu$CC$\rightarrow\nu_\mu$NC</th>
<th>$\nu_\mu$NC</th>
<th>$\nu_e$CC beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>9°</td>
<td>0.095</td>
<td>9.3</td>
<td>4.5</td>
<td>1.0</td>
<td>5.2</td>
<td>18</td>
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<tr>
<td>8°</td>
<td>0.076</td>
<td>7.4</td>
<td>4.5</td>
<td>1.0</td>
<td>5.2</td>
<td>18</td>
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<tr>
<td>7°</td>
<td>0.058</td>
<td>5.8</td>
<td>4.6</td>
<td>1.0</td>
<td>5.2</td>
<td>18</td>
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<td>5°</td>
<td>0.030</td>
<td>3.0</td>
<td>4.6</td>
<td>1.0</td>
<td>5.2</td>
<td>18</td>
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<td>3°</td>
<td>0.011</td>
<td>1.2</td>
<td>4.7</td>
<td>1.0</td>
<td>5.2</td>
<td>18</td>
</tr>
<tr>
<td>eff</td>
<td></td>
<td>0.31</td>
<td>0.032</td>
<td>$0.34 \times 10^{-4}$</td>
<td>$7.0 \times 10^{-4}$</td>
<td>0.082</td>
</tr>
</tbody>
</table>

5 years nominal CNGS, target mass $\approx 2$kton
$\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$
full mixing

sensitivity is fully dominated by statistics

CNGS 5 years nominal beam

**Improvement of a factor 5 wrt CHOOZ**

**OPERA** interesting approach wrt $\theta_{13}$ studies due to:

- its detector
- different systematics (off-peak) wrt other experiments working on this item