# ICARUS and status of Liquid Argon Technology 

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- The ICARUS detector.
- Event reconstruction.
- Preliminary results from data taken during run 2010.
- Physics perspectives.
- Summary.


## The ICARUS Collaboration

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## The detection technique

- The Liquid Argon Time Projection Chamber [C. Rubbia: CERN-EP/77-08 (1977)] first proposed to INFN in 1985 [ICARUS: INFN/AE-85/7] capable of providing a 3D imaging of any ionizing event (electronic bubble chamber) with in addition:
- continuously sensitive, self triggering;
- high granularity (spatial resolution of the detector $\sim 1 \mathrm{~mm}$ );
- excellent calorimetric properties.

- Electrons from ionizing track are drifted in LAr by uniform electric field. They traverse transparent wire arrays oriented in different directions where induction signals are recorded. Finally electron charge is collected by collection plane.
Key feature: LAr purity. Impurities form electro-negative molecules ( $\mathrm{O}_{2}, \mathrm{H}_{2} \mathrm{O}, \mathrm{CO}_{2}$ ).
Target: 0.1 ppb $\mathrm{O}_{2}$ equivalent $=3 \mathrm{~ms}$ lifetime ( 4.5 m drift @ $\mathrm{E}_{\text {drift }}=500 \mathrm{~V} / \mathrm{cm}$ ).


## ICARUS T600@LNGS

## A novel instrument for neutrino physics

- Two identical T300 modules
(2 TPC chambers for each module).
- LAr active mass 476 t :
- ( $17.9 \times 3.1 \times 1.5$ for each TPC) m³;
- drift length $=1.5 \mathrm{~m}$;
- $E_{\text {drift }}=0.5 \mathrm{kV} / \mathrm{cm} ; \mathrm{v}_{\text {drift }}=1.6 \mathrm{~mm} / \mu \mathrm{s}$.
- 3 readout wire planes/chamber at $0^{\circ},+-60^{\circ}, 3 \mathrm{~mm}$ plane spacing:
- $\approx 53000$ wires, 3 mm pitch;
- two induction planes, 1 collection.

PMT for scintillation light (128 nm):

- $(20+54)$ PMTs.

The ICARUS is collecting events of the CNGS neutrino beam from CERN to Gran Sasso.


LAr purity time evolution


- Electronegative impurities (mainly $\mathrm{O}_{2}, \mathrm{H}_{2} \mathrm{O}$ ) can attenuate e- signal: high purity is crucial!
- Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.
$\tau_{\text {ele }}[\mathrm{ms}]=0.3 / \mathrm{N}\left[\mathrm{ppb} \mathrm{O}_{2}\right.$ equivalent] currently: $\tau_{\text {ele }}>6[\mathrm{~ms}]: \sim 50 \mathrm{ppt}$
$\tau_{R^{\prime}}$ recirculation time for a full detector volume $k_{I}$ and $\tau_{I}$ : related to the total degassing internal rate $k$ : related to the external leaks $d N / d t=-N / \tau_{R}+k+k_{I} \exp \left(-t / \tau_{I}\right)$ $\tau_{R^{\prime}}: 2 \mathrm{~m}^{3} / \mathrm{h}$ (per cryostat) corresponding to $\approx 6$ day cycle time


## CNGS trigger

- At every CNGS cycle protons are extracted in 2 spills lasting $10.5 \mu$ s each, 50 ms apart. CNGS "Early Warning" signal sent 80 ms before the proton extraction with the expected absolute time for next extraction.
- Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within $60 \mu \mathrm{~s}$ wide beam gate.
- 80 events per day are recorded with a trigger rate of about 1 mHz .


- Offset value ( 2.40 ms ) in agreement with vt.o.f. ( 2.44 ms ) with the addition of $40 \mu \mathrm{~s}$ fiber transit time from external LNGS lab absolute clock to Hall B (8 km).

CNGS CC v interaction with both TPC signal


## Muon from $v$ beam interaction in the rock



Predicted number of collected interactions in the rock: $7.8 \times 10^{-17} /$ po $\dagger$


CNGS CC $v$ interation with $\pi^{0}$ production


The total deposited energy ~ $1 \mathbf{G e V}$

## CNGS NC $v$ interaction candidate



## ICARUS LAr TPC performances

## CASCADES:

- The total energy of cascades is measured by charge integration with recombination correction.

Very good e/ $\pi^{0}$ separation by means of $\mathrm{dE} / \mathrm{dx}$ in the first part of the cascade.
$v_{\mu}$ NC background rejected at $0.1 \%$ level while keeping $90 \%$ of $v_{e}$ CC

ENERGY RESOLUTIONS:
Low energy electrons $\quad \sigma(E) / E=11 \% / \mathrm{VE}(\mathrm{MeV})+2 \%$
Electromagnetic showers $\sigma(\mathrm{E}) / \mathrm{E}=3 \% / \mathrm{VE}(\mathrm{GeV})$
Hadron shower (pure LAr) $\quad \sigma(\mathrm{E}) / \mathrm{E} \sim 30 \% / \mathrm{VE}(\mathrm{GeV})$


## TRACKS:

- Momentum of escaping muons is measured via multiple scattering: $\Delta p / p \sim 10-15 \%$ depending on track length and $p$.
- Stopping particles energy is measured by charge integration with recombination correction
require good spatial
reconstruction
- Stopping particle identification by means of $d E / d x$ vs $E$.


## Spatial reconstruction

1. Hit finding: wire ADC pulse position (drift time) and charge reconstruction (in collection).
2. Forming 2D objects (tracks, cascades) from hits.
3. 3D reconstruction: combining 2D objects in different views.



## Stopping particle identification (Neural Network based)

- Particle identification is based on:
- $\mathrm{d} E / \mathrm{d} x=\mathrm{f}(E)$ dependency
- reconstructed 3D track segments: $\mathrm{d} x$
- charge deposition on the track segment: $\mathrm{d} E$
- Classify single $i^{t h}$ segment of the track

$$
\mathbf{p}_{i}:[E, \mathrm{~d} E / \mathrm{d} x] \rightarrow \mathrm{nn}_{j}:[\mathrm{P}(p), \mathrm{P}(K), \mathrm{P}(\pi), \mathrm{P}(\mu), \mathrm{P}(\text { other })]
$$ neural network output vector

- Average $k$ output vectors for the track segments

$$
\mathbf{N N}=\Sigma_{i=1 . . M}\left(\mathbf{n n}_{i}\right) / k
$$

- Identify track as a particle corresponding to max(NN)
- NN training patterns based on MC tracks:
- with quenching simulation
- simulated with full angular distribution
theoretical $\mathrm{d} E / \mathrm{d} x(E)$ curves


Efficiency > 85\% for kinetic energy around 30 MeV and higher

- reconstructed with the same algorithms as prepared for real data

Examples of stopping particles in the $v_{\mu}$ CC CNGS events

## Run 9809 Event 651

Stopping particle identification

|  | Track | $E_{\text {dep }}$ [MeV] | range <br> [cm] |
| :---: | :---: | :---: | :---: |
|  | 1(p) | $185 \pm 16$ | 15 |
|  | 5(p) | $192 \pm 16$ | 20 |
| 5 | 7(p) | $142 \pm 12$ | 17 |
| 11 | 8( $\pi$ ) | $94 \pm 8$ | 12 |
|  | 9(p) | $26 \pm 2$ | 4 |
|  | 10(p) | $141 \pm 12$ | 23 |
| 6 protons and 1 pion which decays at rest muon: $7.1 \pm 1.3[\mathrm{GeV} / \mathrm{c}]$ | 11(p) | $123 \pm 10$ | 6 |

## Examples of stopping particles in the $v_{\mu}$ CC CNGS events

## Run 9808 Event 250



Example of fully reconstructed CNGS neutrino interation


Collection
ALL PARTICLES RECONSTRUCTED IN 3D + DEPOSITED ENERGY MEASUREMENT

Primary vertex :

- Long muon - not contained (1) - $10.5 \mathrm{GeV} / \mathrm{c}$ from MS.
- EM cascade (2), identified as $\pi^{0}$.
- Charge pion (3).

Secondary vertex:
The longest track (5) is a muon coming from stopping K (6)

- muon decay is observed.

The conversion distances are: $6.9 \mathrm{~cm}, 2.3 \mathrm{~cm}$.
$\mathrm{M}^{*} \gamma \gamma=125 \pm 15 \mathrm{MeV} / \mathrm{c}^{\mathbf{2}}$
Induction2

## CNGS runs in 2010

- ICARUS fully operational for CNGS events since October $1^{\text {st }} 2010$.
- $5.9 \times 10^{18}$ pot collected in 2010; Number of $v$ interactions agrees with expectations.


| EVENT TYPE | COLLECTED | EXPECTED |
| :--- | :--- | :--- |
| $v_{\mu} \mathrm{CC}$ | 114 | 129 |
| $v_{\mu} \mathrm{NC}$ | 46 | 42 |
| $\nu \mathrm{XC}$ (further analysis needed) | 7 | - |
| Total | 167 | 171 |

## $v_{\mathrm{e}}$ event candidate



- Total deposited energy 45 GeV .
- Single high energy EM shower ( 37 GeV ) measured by charge integration, partially overlapped to hadronic jet.



## Preliminary results of CNGS 2010 CC $v$ interactions

Measurement of muon momentum from multiple scattering

Calorimetric measurement of the deposited energy

CNGS CC 2010

$E_{\text {dep }}[G e V]$

## Preliminary results of first CNGS 2010 run

 Reconstruction of muon from $v$ interaction in the rockDirection of muons w.r.t. the vertical:
Muon azimuth:
Reconstruction of muon direction (from rock $\mu$ ) Agrees with expectations (allowing for Earth curvature)
$\theta=86.7^{\circ}, \varphi=0^{\circ}$





## CNGS runs in 2011

- Beam restarted on March 19th.
- $2.8 \times 10^{19}\left(2.5 \times 10^{19}\right)$ pot delivered (collected) up to July 14 th.
- Detector live-time improved ( $\sim 93 \%$ ) due to more stable running conditions.
- Trigger: photomultiplier signal summed for each chamber (100 phe threshold), within $60 \mu \mathrm{~s}$ beam gate.



## ICARUS T600 physics potential

- CNGS $v$ events collection (beam intensity $4.5 \times 10^{19}$ pot/year, $\mathrm{En} \sim 17.4 \mathrm{GeV}$ ):
- $1200 v_{\mu}$ CC event/year;

■ ~ $8 v_{\mathrm{e}}$ CC event/year;

- observation of $v_{\tau}$ events using kinematical criteria for selection of $\tau$ decay in the electron channel;
- search for sterile $v$ in LSND parameter space (deep inelastic $v_{\mathrm{e}}$ CC events excess).
- Self triggered events collection:
- ~80 events/year of unbiased atmospheric $v$ CC;
- practically zero background proton decay with $3 \times 10^{32}$ nucleons for exotic channels.


## Conclusions

- ICARUS T600 @ LNGS is taking data with CNGS beam since October 2010.
- The successful assembly and operation of the LAr-TPC is the experimental proof that this technique is well-suited for large scale experiments.
- The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, allow to reconstruct and identify events in a new way w.r.t previous/current experiments.
- The 2011-2012 run with CNGS $\nu_{\mu}$ beam will allow to possibly detect few $\nu_{\tau}$ appearance events. Interesting physics perspectives also for solar and atmospheric neutrinos, sterile neutrino and proton decay.
- The ICARUS experiment at the Gran Sasso Laboratory is so far the major milestone towards the realization of a much more massive LAr detector.

THANKYOU!

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## Sterile neutrino search with ICARUS T600

- Sensitivity region, in terms of standard deviations, for 3000 raw CNGS muon neutrino events.
- The potential signal is above the background generated by the intrinsic $v_{\mathrm{e}}$ beam contamination, in the deep inelastic interval $10-30 \mathrm{GeV}$.
- Largely complementary to the Fermi-lab program in terms of energy and baseline.
$\mathrm{v}_{\mathrm{H}}-\rightarrow \mathrm{v}_{\mathrm{e}}$ appearance search in T600 in LSND parameter space



## 2011-2012 CNGS run: physics perspectives

- 2011-2012 run with dedicated SPS periods @ high intensity: expected $10^{20}$ pot.
- For $1.1 \times 10^{20}$ pot: 3000 beam related $v_{\mu}$ CC events expected in ICARUS-T600.
- At the effective neutrino energy of 20 GeV and $\Delta \mathrm{m}^{2}=2.5$ $10^{-3} \mathrm{eV}^{2}, \mathrm{P}\left(v_{\mu} \rightarrow v_{\tau}\right)=1.4 \%$
- 17 raw CNGS beam-related $v_{\tau}$ CC events expected
- $P(\tau \rightarrow e v \nu)=18 \% \Rightarrow 3$ electron deep inelastic events with visible energy $<20 \mathrm{GeV}$.
Background
Signal
- $\tau \rightarrow$ evv events characterized by momentum unbalance ( $2 v$ emission) and relatively low electron momentum. Selection criteria suggest a sufficiently clean separation with kinematic cuts opening the possibility to identify $1-2 v_{\tau}$ CNGS events in the next 2 years, only in this gold channel.
- Currently collected CC/NC data will be used to tune the selection criteria in order to optimize the sensitivity for $\tau$ search.


## Nucleon decay expectations



- With $1.2 \times 10^{34}$ nucleons, MODULAr is well suited for channels not accessible to Cherenkov detectors due to the complicated event topology, or if the emitted particles are below the Cherenkov (e. g. $\mathrm{K}^{+}$).
(pdg 90\% CL)
$\mathrm{p} \rightarrow \quad \mathrm{v} \pi^{+}$
$1.1 \times 10^{32}$
$2.5 \times 10^{31}$
$\mathrm{p} \quad \rightarrow \quad \mu^{-} \pi^{+} \mathrm{K}^{+}$
$2.7 \times 10^{32}$
$2.5 \times 10^{32}$


$$
\mathrm{p} \rightarrow \mathrm{~K}^{+}+\bar{v}
$$



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## Polygonal 3D Line Algorithm



## 3D track reconstruction

- Associating the track's hits in each 2D view.
- Track fitting with Polygonal Line Algorithm (PLA):
- hits sorted along the track;
- hit projections to the track fit;
- available for 3D matching;
- 3D: matching hit projections from two 2D views:
- matching hits with corresponding drift time - may be ambiguous, therefore:
- using order of hits sorted with PLA and hit-to-hit 3D distance criteria;
- Supplement 3D track with unmatched Collection hits.




## Particle identification: efficiency and purity vs particle energy



- 500 tracks per species (proton, kaon, pion, muon).
- Full angular distribution.
- Tracks simulated with kinetic energy: 100 MeV .
- Identification performed with varying range from the track end (corresponding to different deposited energy $\mathrm{E}_{\text {dep }}$ ).
- Purity / Efficiency dependance on used sample shown with error bars.

| Results for max $E_{\text {dep }}=60 \mathrm{MeV}:$ |  |  |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| MC $\backslash$ PID | proton | kaon | pion | muon | other | purity | efficiency |
| proton: | 498 | 2 | 0 | 0 | 0 | 0.984 | 0.996 |
| kaon: | 8 | 490 | 1 | 1 | 0 | 0.996 | 0.980 |
| pion: | 0 | 0 | 436 | 64 | 0 | 0.950 | 0.872 |
| muon: | 0 | 0 | 22 | 478 | 0 | 0.880 | 0.956 |

