

Neutrino Flavour Appearance at LNGS: Results and Perspectives

Lucia Votano - LNGS

Gran Sasso Laboratory

3 main halls A B C $\sim 100 \times 20 \text{ m}^2$ (h 20 m)



External facilities

Muon Flux

$$3.0 \cdot 10^{-4} \mu \text{ m}^{-2} \text{ s}^{-1}$$

Neutron Flux

$$2.92 \cdot 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \quad (0-1 \text{ keV})$$

$$0.86 \cdot 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1} \quad (> 1 \text{ keV})$$

Depth: 1400 m (**3800 m w.e.**)

Surface: 17800 m^2

Volume: **180000 m^3**

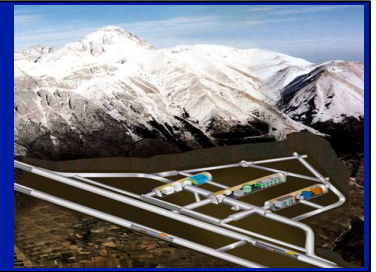
Rn in air: 20-80 Bq/m^3

ISO 14001

Ventilation: 1 Lab volume/3 h

Electrical power: 1300 kW

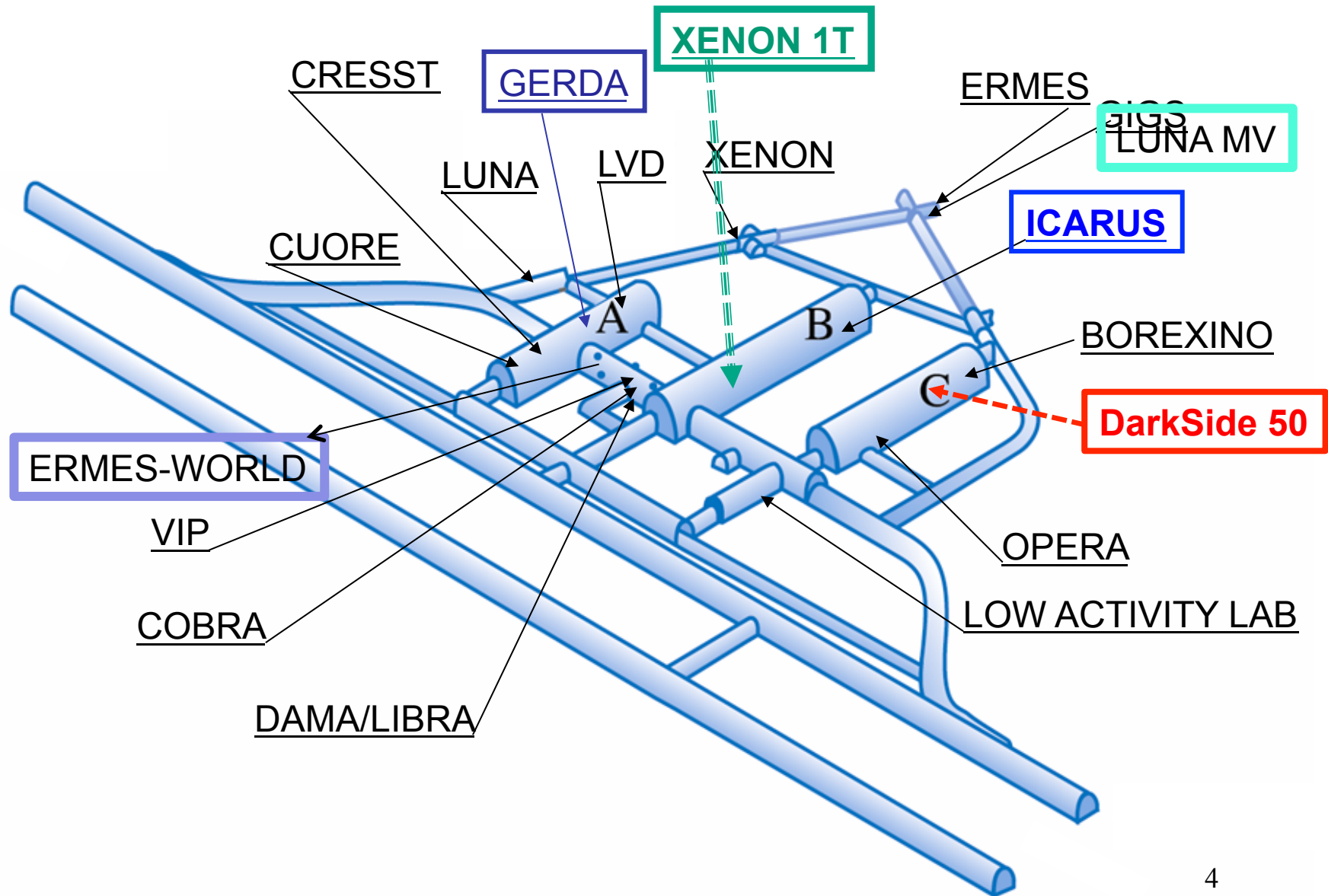
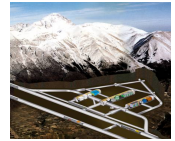
Access: horizontal



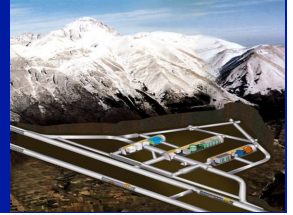
Research activities:

- Dark matter searches
- Neutrino physics
- Nuclear Astrophysics
- Associate Sciences:
Environmental Radioactivity for Earth Sciences,
Geophysics, Fundamental Physics, Biology

OCCUPANCY



Neutrino Physics: open questions



- *Solar, atmospheric, accelerator and reactor neutrino experiments show that the usual three active neutrinos have mass and that flavour mixing concerns the leptonic sector;*
- *Massive neutrinos are the only experimental evidence of phenomena beyond the SM of particle physics;*
- *The main goals of neutrino physics for the next decades:*
 - ① The determination of the neutrino mass hierarchy and the assessment and measurement of CP violation in the leptonic sector

New scenarios opened by the recent measurements and the relative large value of θ_{13}

 - ② The discrimination of the Dirac/Majorana nature of neutrinos,
 - ③ Beyond 3 ν ??
- *Neutrinos from cosmos are very important messengers for our comprehension of the stars and of the Universe evolution.*

Neutrino physics @ LNGS

- Basic neutrino properties
 - $0\nu\text{DBD}$
- Solar neutrinos (Borexino)
 - ^7Be the main target
 - ^8B , pep first evidence, CNO limit, and possibly pp
- Geo anti-neutrinos (Borexino)
- SuperNova neutrinos
 - LVD, Borexino and ICARUS
 - LVD and Borexino are in the SNEWS network
- CernNeutrinoGranSasso neutrinos
OPERA and ICARUS

CNGS beam: CERN Neutrino to Gran Sasso

High Energy ν_μ beam ≈ 17 GeV:
optimized for ν_τ CC interactions
Goal: prove definitely the neutrino
oscillations in appearance mode

Project INFN-CERN: approved in 1999,
started in 2006

ν_μ beam produced at CERN and detected
at LNGS

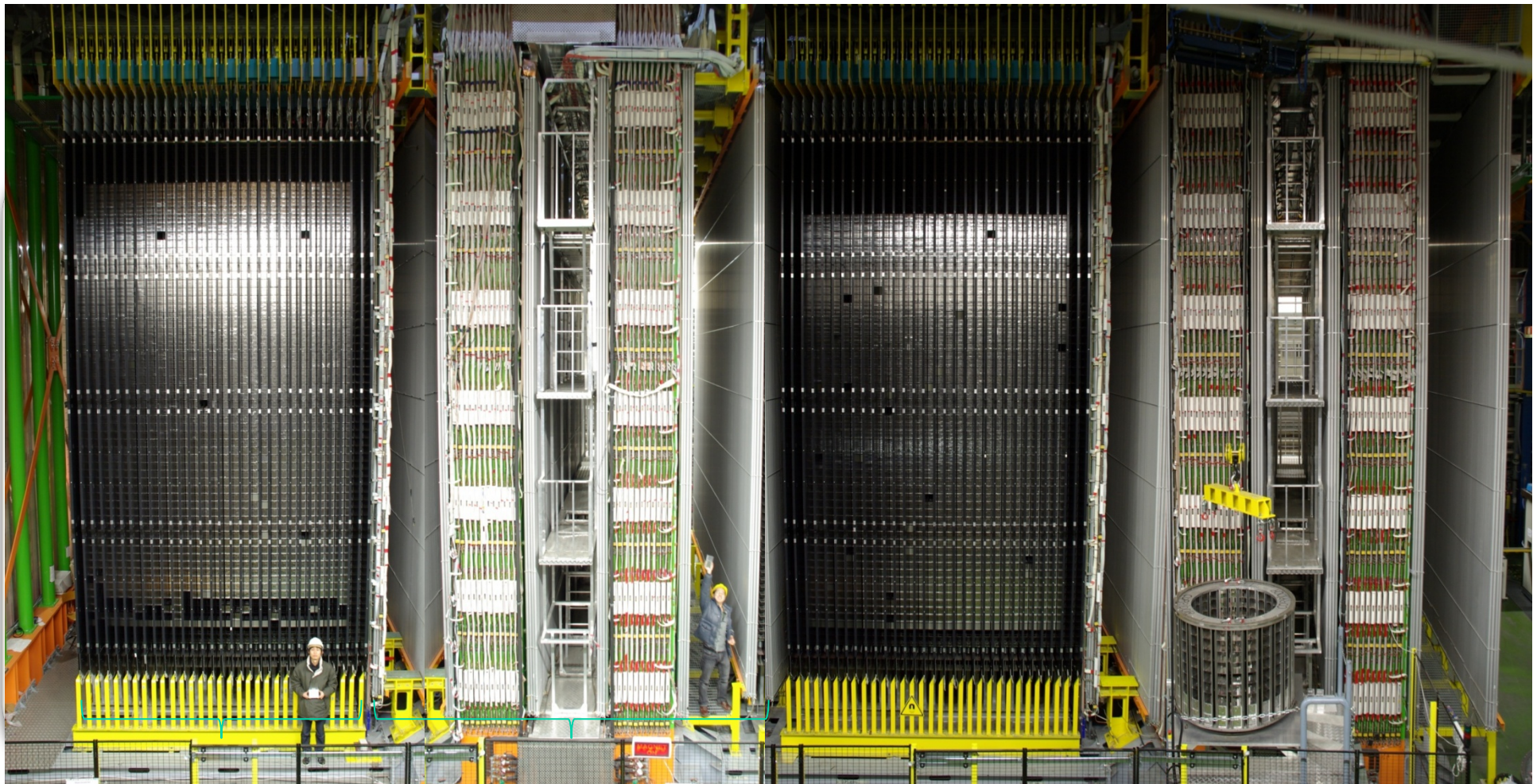
Experimental halls designed in the CERN
direction

OPERA running since 2006
ICARUS running since 2010



OPERA: Oscillation Project with Emulsion tRacking Apparatus

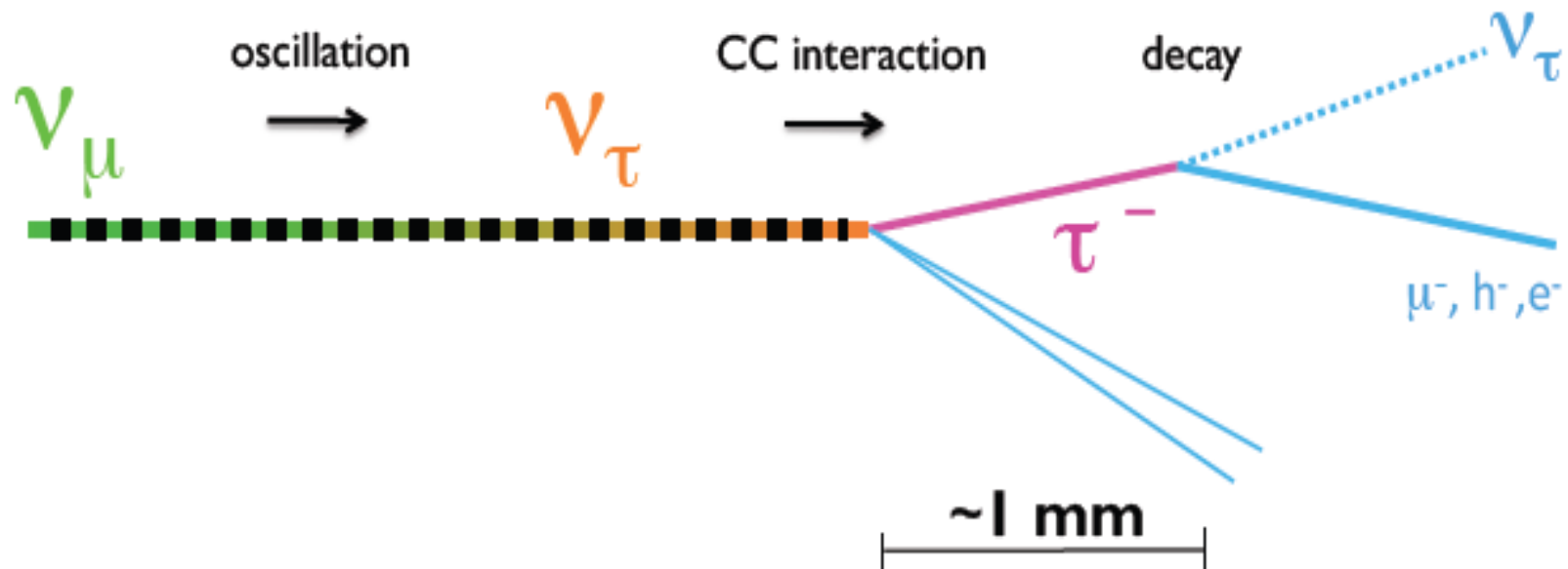
- Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations by looking at the **appearance** of ν_τ in a pure ν_μ beam
- Search for the sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations for Θ_{13} measurement



OPERA

The direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations by looking at the **appearance** of ν_τ implies opposite requirements to the detector:

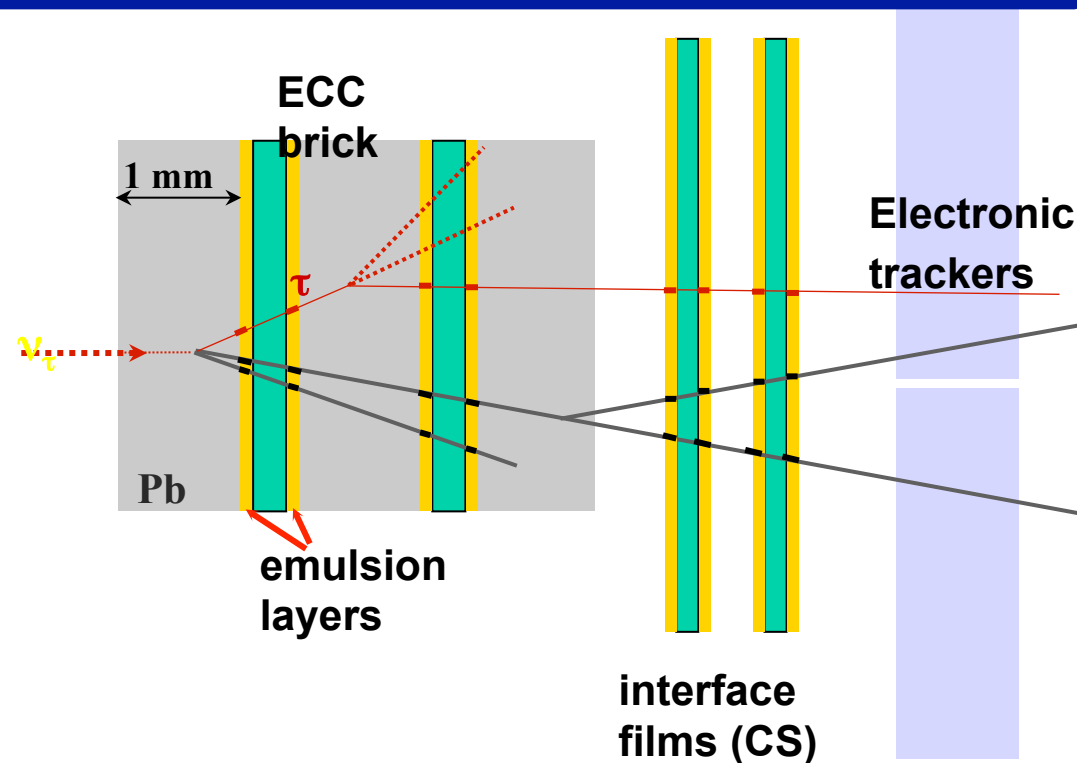
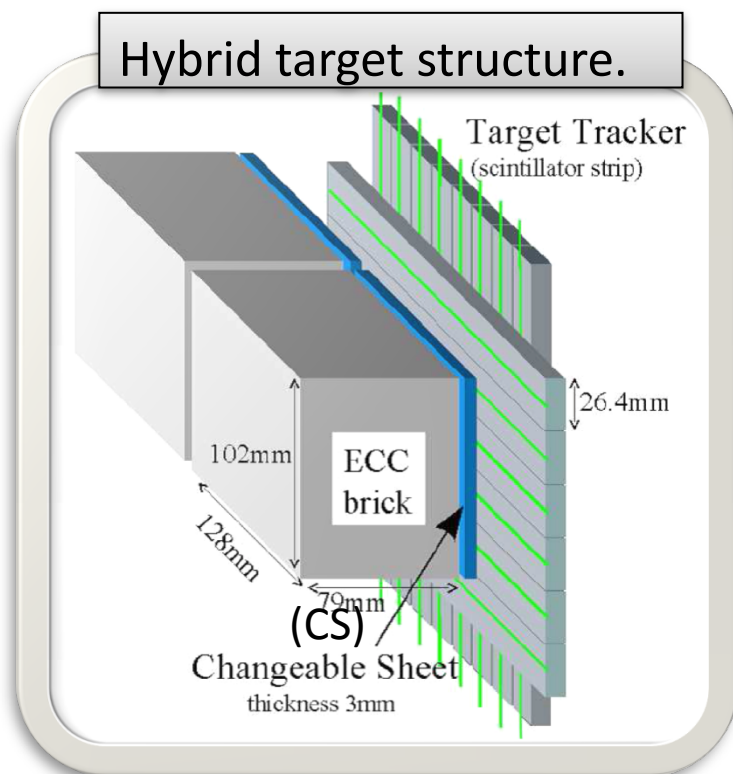
- Large mass [O(kton)] due to small neutrino $\sigma \rightarrow$ lead target
- High granularity [1μ] for clear identification of the “kink signal” and background rejection $\rightarrow$ **nuclear emulsions**



OPERA

OPERA Hybrid detector:

- **EmulsionCloudChamber BRICKS:** Nuclear emulsion interleaved with lead plates
- Electronic detectors for trigger and pre-selection of candidate bricks and for time resolution to emulsions
- **Magnet spectrometers** for muon ID and momentum/charge measurement



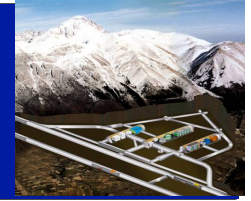
OPERA

	Signal $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$	Background
Counts for $22.5 \times 10^{19} \text{ pot}$	7.6 New J. Phys. 14 (2012) 033017	0.8

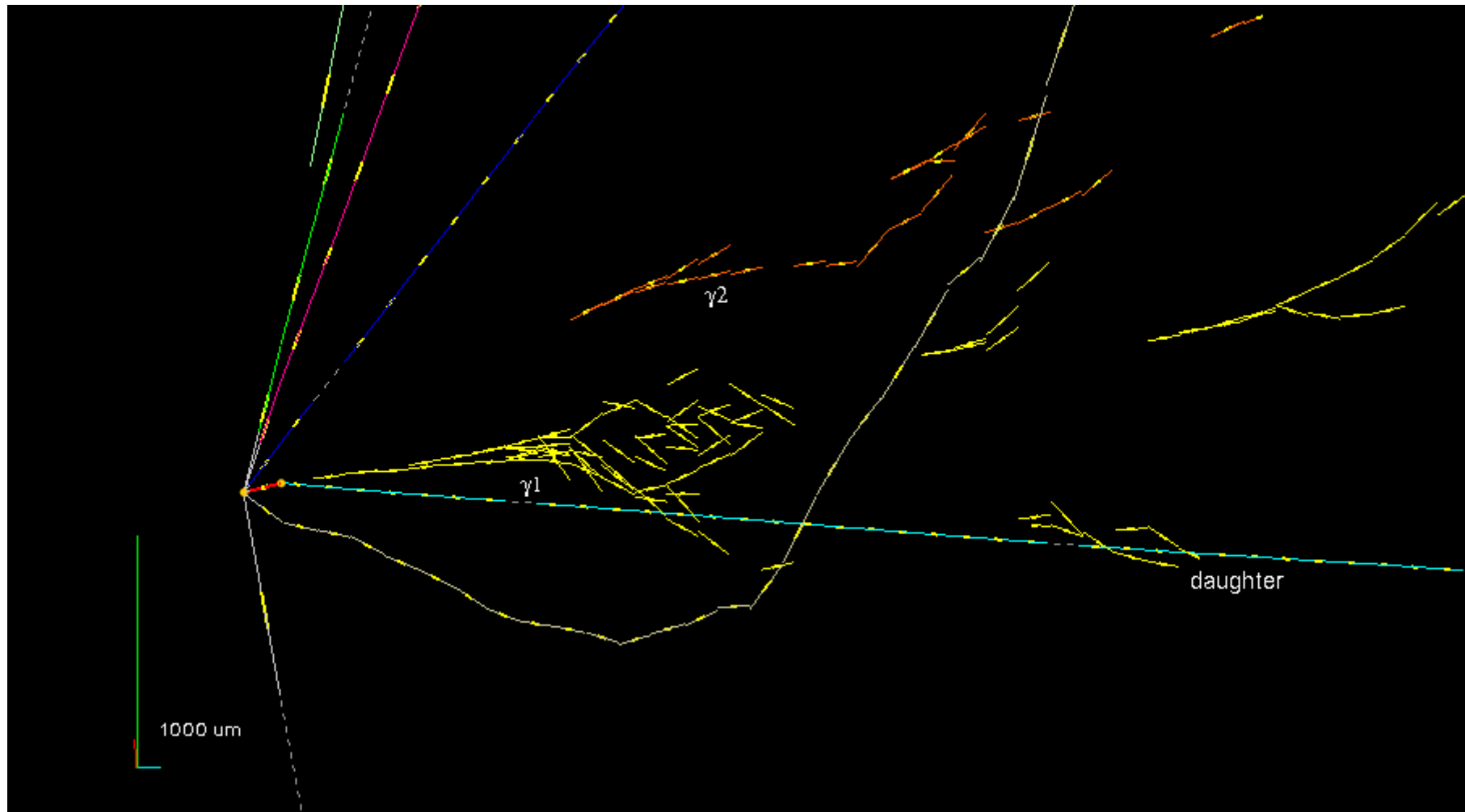
Year	Proton On Target POT	Number of Neutrino Interactions	Integrated POT / Proposal Value
2008	1.78×10^{19}	1698	7.9%
2009	3.52×10^{19}	3557	23.6%
2010	4.04×10^{19}	3912	41.5%
2011	4.84×10^{19}	4210	63.0%
2012	$(\sim 4.7 \times 10^{19})$	(~ 4050)	$(\sim 84\%)$

Expected total POT after 2012 Run: 18.9×10^{19}

Neutrino Oscillations: OPERA



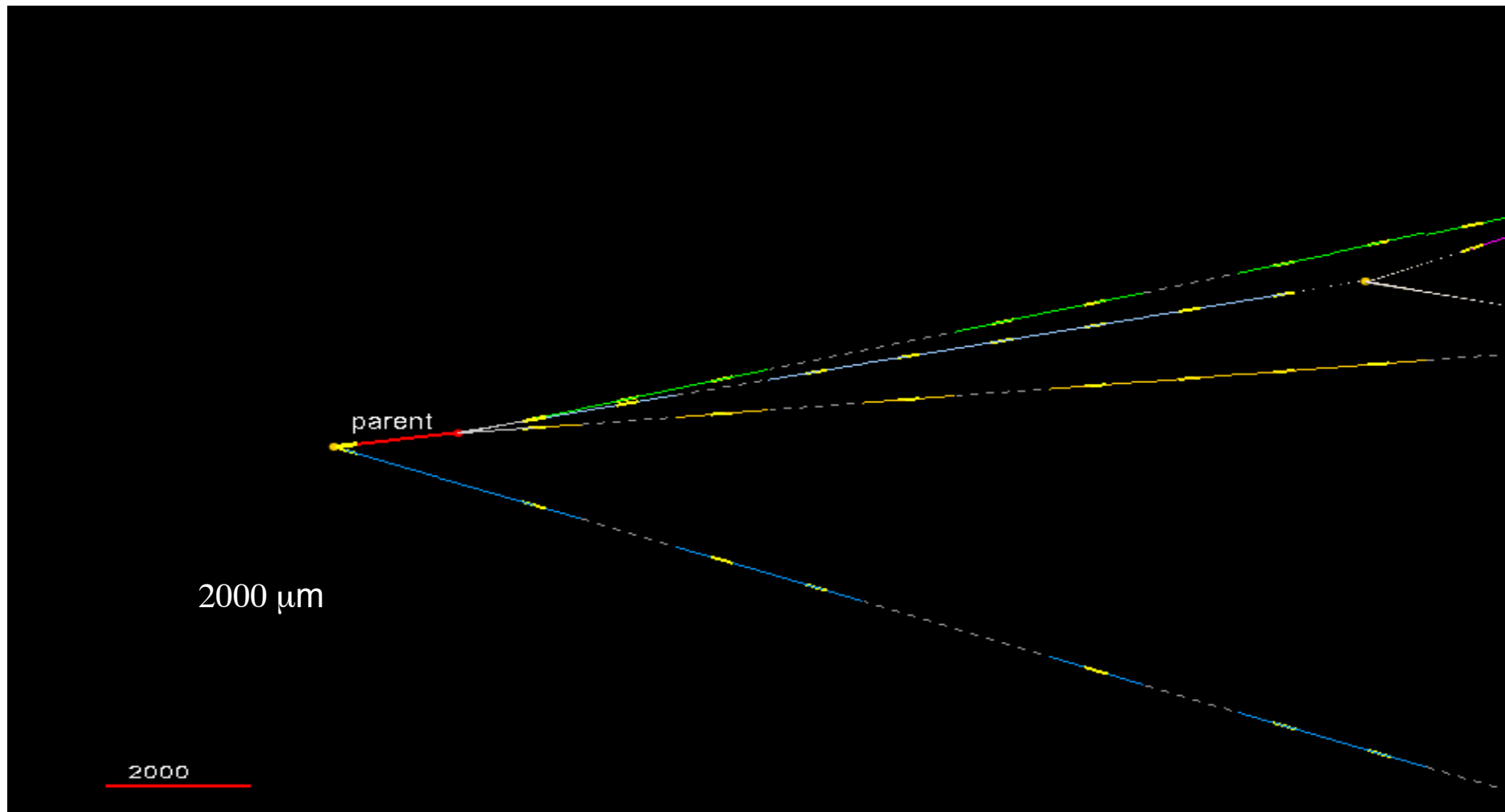
- In 2010 at LNGS the **first evidence** of direct detection of $\nu_\mu \rightarrow \nu_\tau$ **oscillation** in **appearance** mode. Event found in the decay search of 2008 and 2009 Physics Runs (Phys. Lett. B 691 (2010) 138)



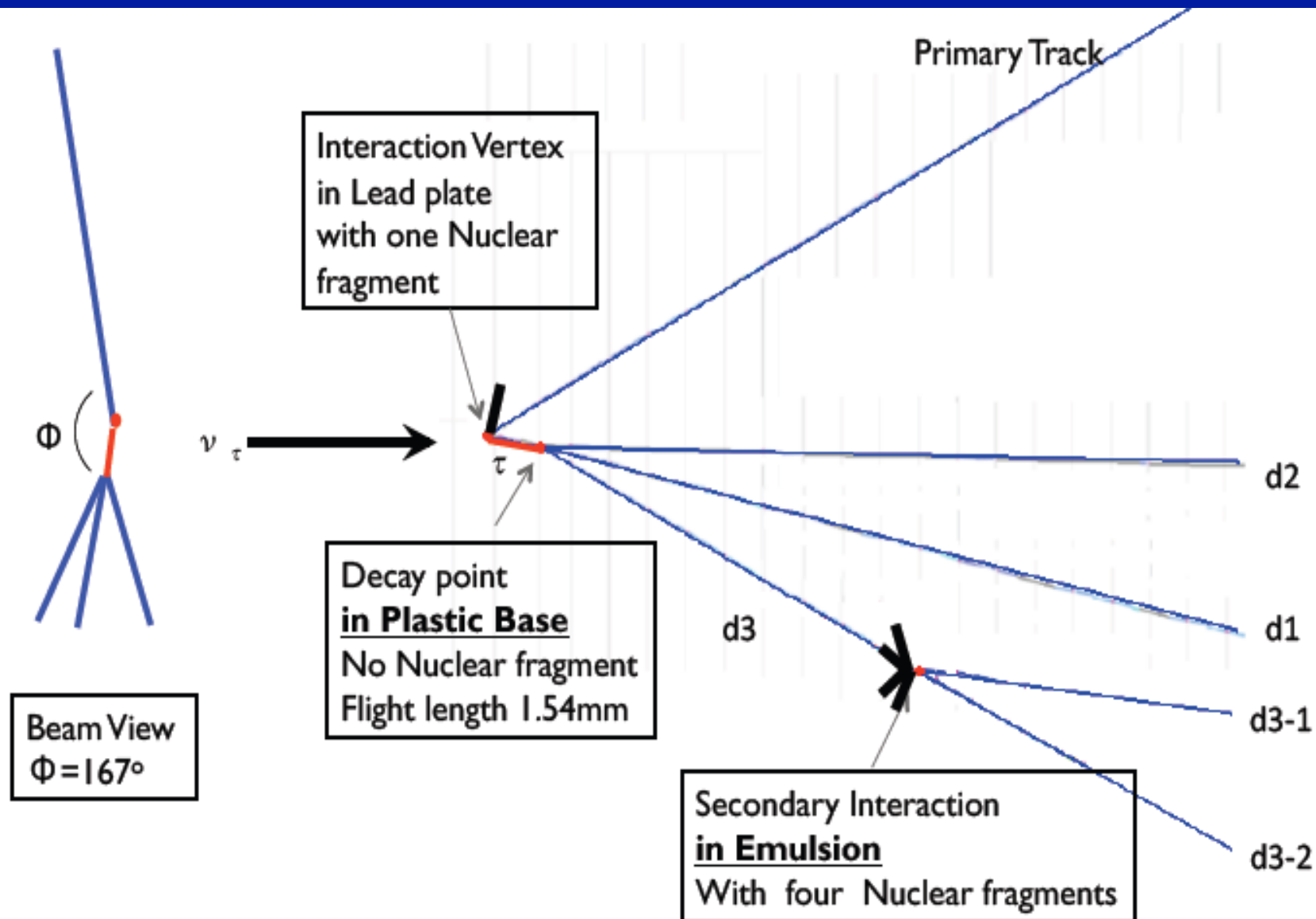
Neutrino Oscillations: OPERA

In 2012 the second ν_τ candidate. Event taken on April 2011

Topology and reconstruction



OPERA second ν_τ candidate: Layout of the event



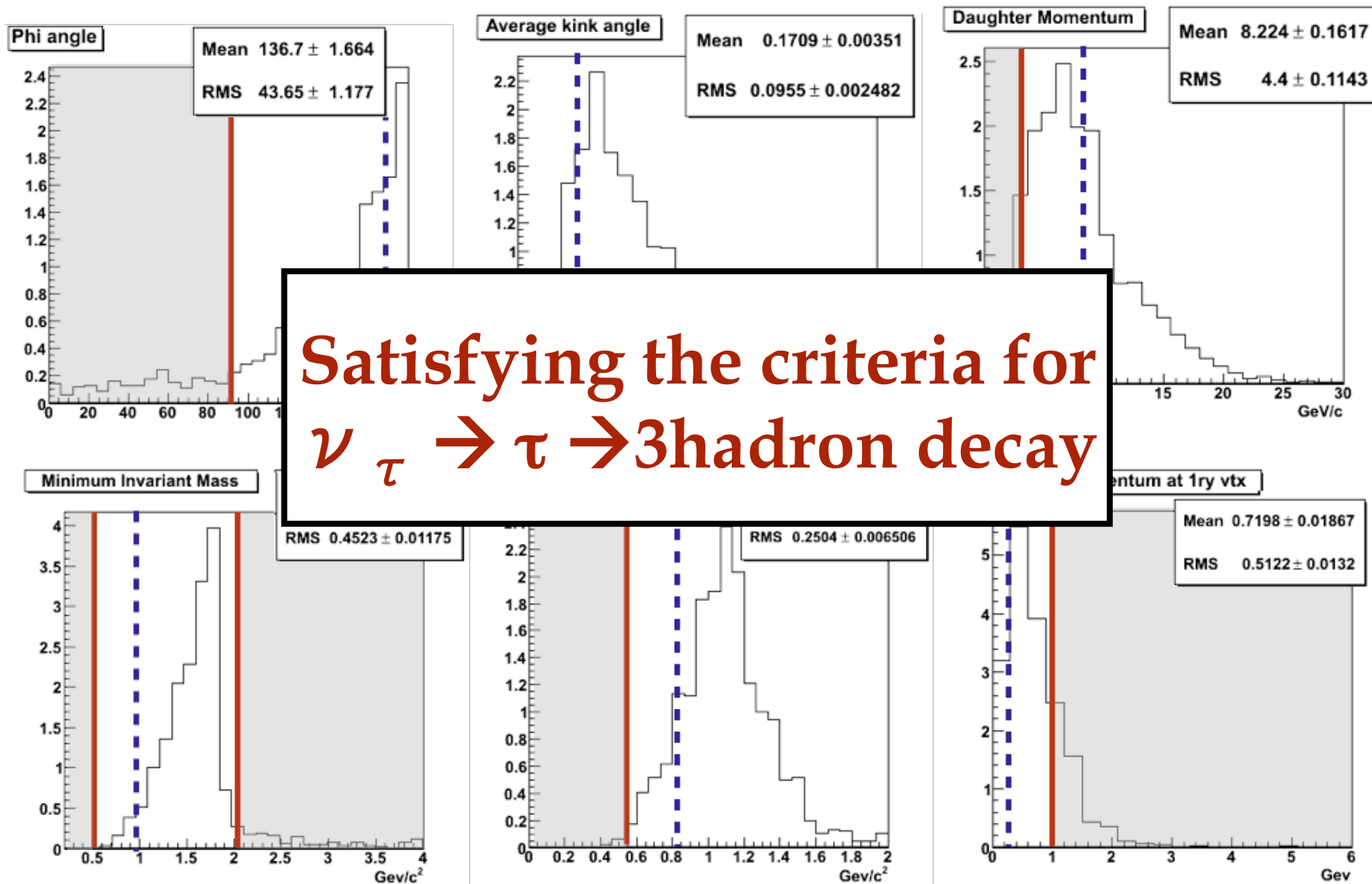
Momentum measurement and particle identification of event tracks

Track#	Momentum (1σ interval) [GeV/c]	Particle ID	Method / Comments
Primary	2.8 (2.1-3.5)	Hadron	Momentum-Range Consistency Check Stops after 2 brick walls. Incompatible with muon (26÷44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	Momentum-Range Consistency Check
d2	1.3 (1.1 -1.5)	Hadron	Momentum-Range Consistency Check
d3	2.0 (1.4 - 2.9)	Hadron	Interaction in the Brick @ 1.3cm downstream

Independent momentum measurements carried out in two labs

Kinematics of the New Candidate Event

.... candidate
— cut



OPERA status of the ν_τ candidate search

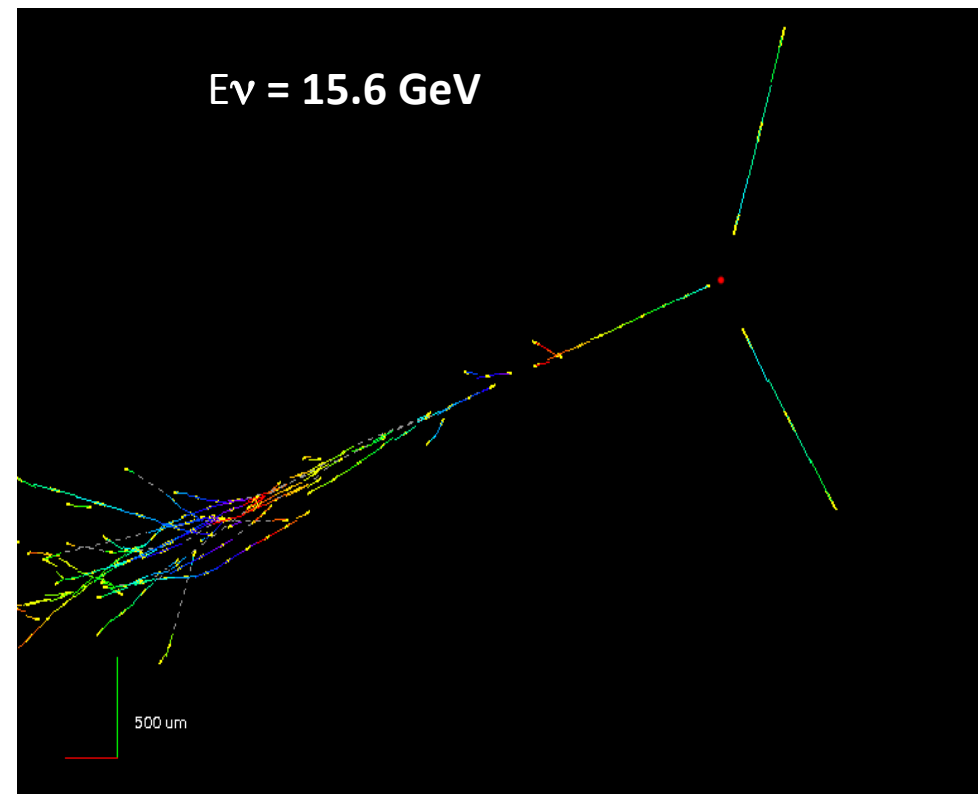
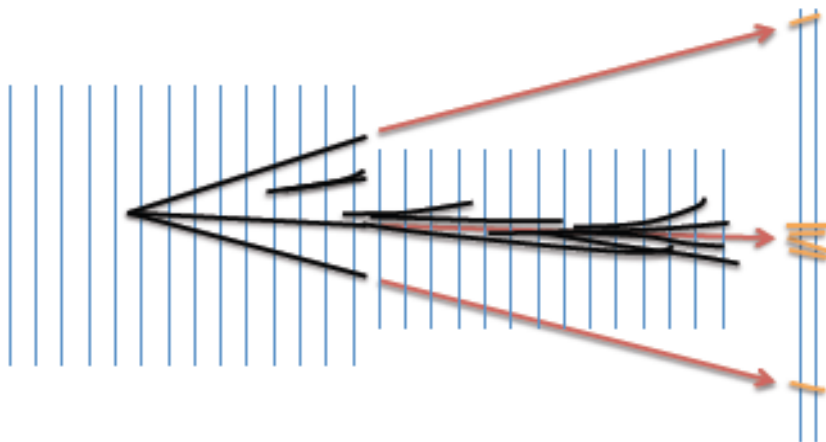
Years	Status	# of events for Decay search	Expected ν_τ (Preliminary)	Observed ν_τ candidate events	Expected BG for ν_τ (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

Neutrino Oscillations: OPERA

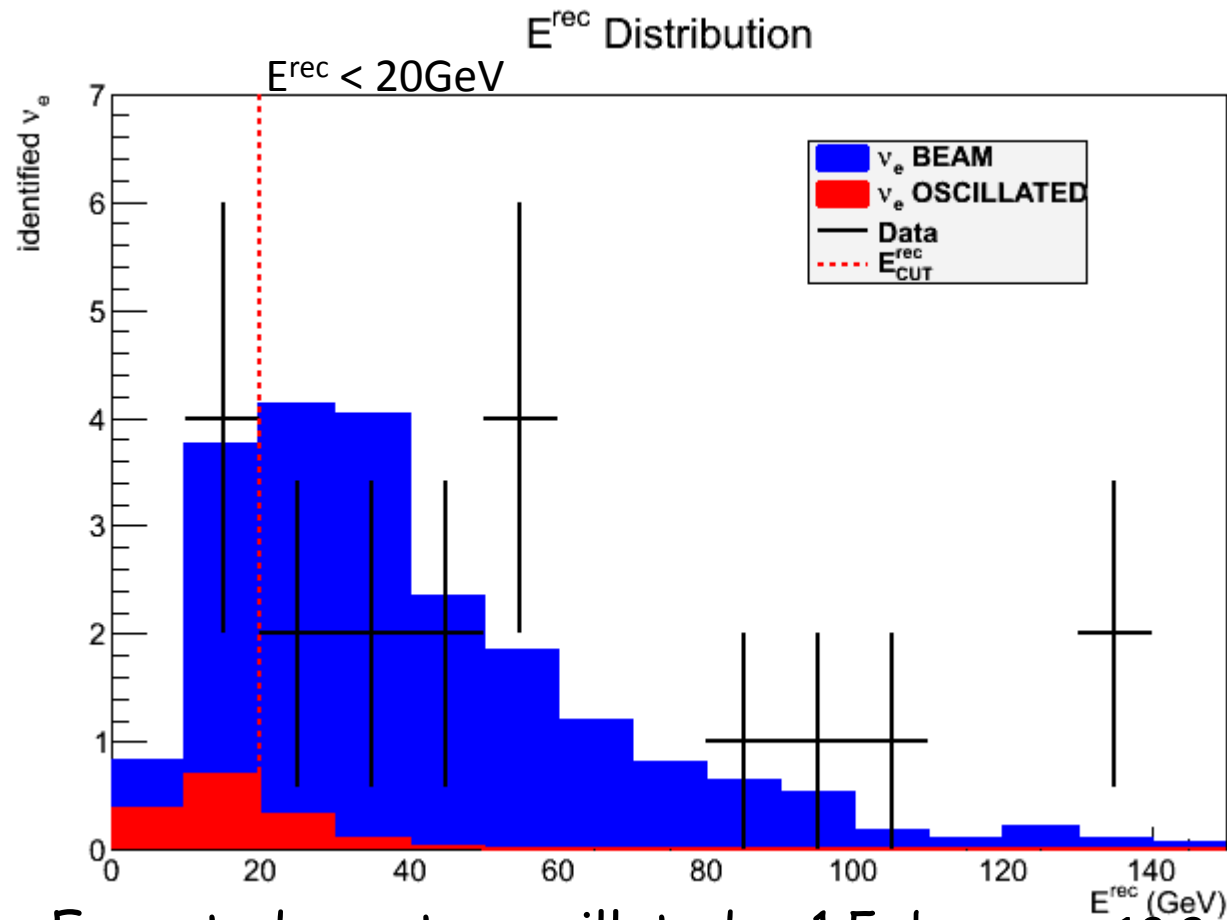
ν_e search

Systematic ν_e search in 0μ located events (NC-like)
2008 and 2009 Runs ($5.3 \cdot 10^{19}$ pot)

- Extrapolate primary tracks to CS
- Search for **shower hints on CS**
- If shower hints, open additional volume



Event energy distribution



Expected events: oscillated ν_e 1.5, beam ν_e 19.2

Observed ν_e : 19 events

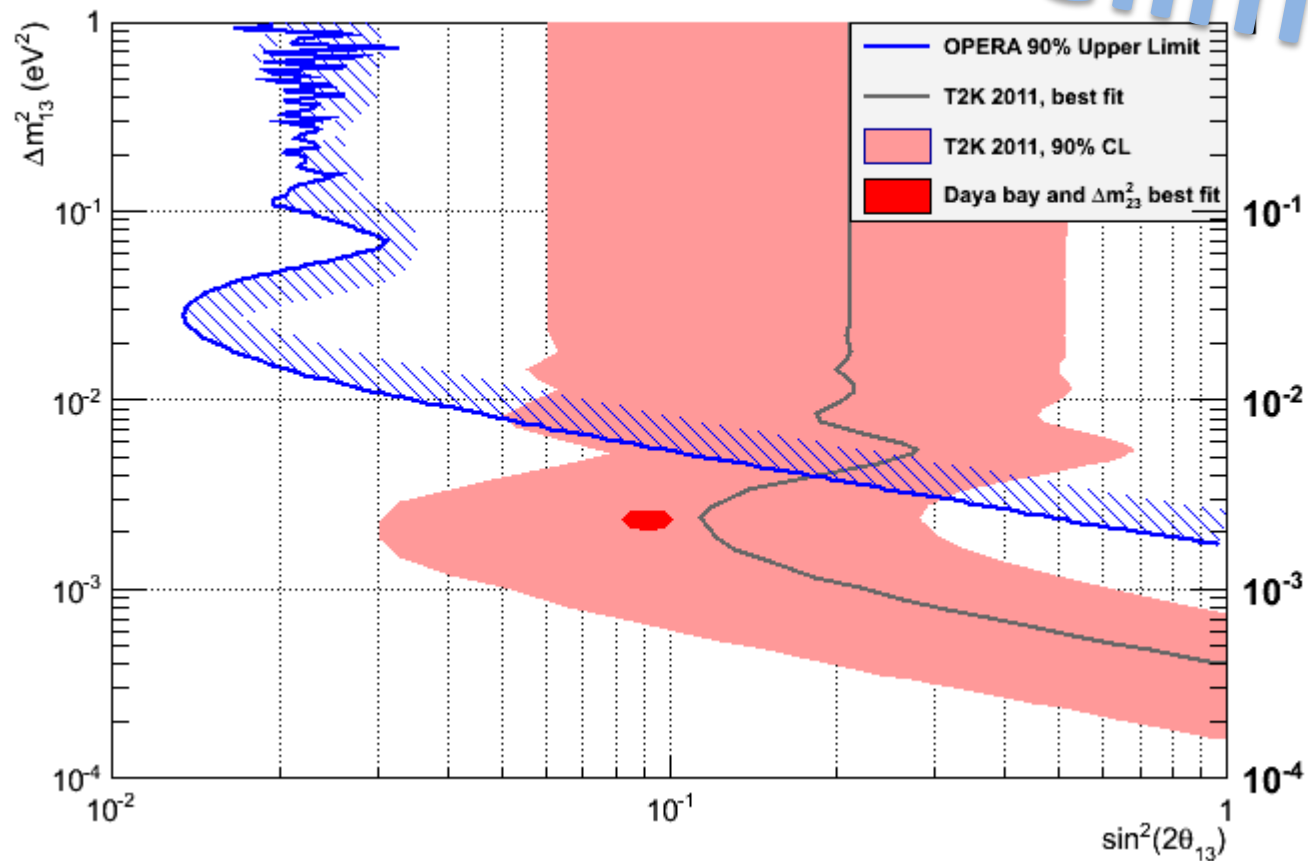
After low-energy selection ($E^{\text{rec}} < 20\text{GeV}$)

Expected events: **oscillated** ν_e **1.1**, **beam** ν_e **3.7**

Observed ν_e : **4 events**

OPERA $\nu_\mu \rightarrow \nu_e$ oscillation result

Preliminary

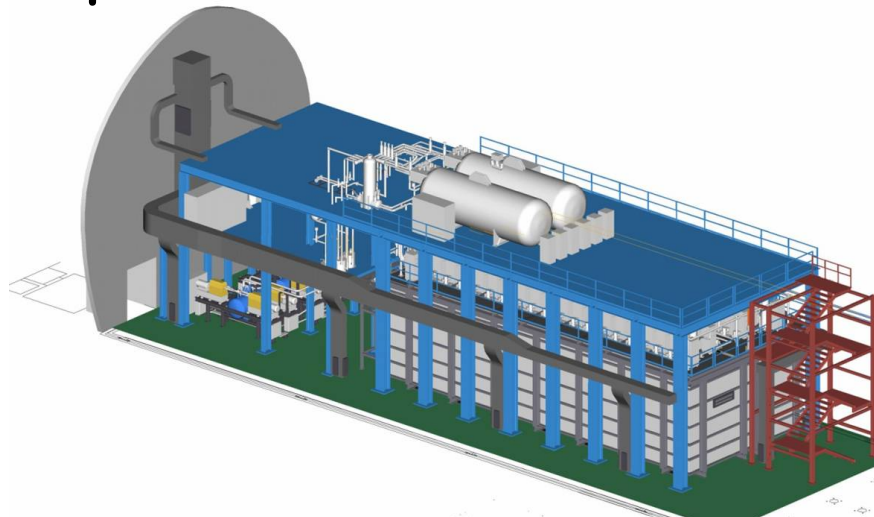


$$\Delta m_{23}^2 = 2.45 \text{E-}3$$
$$\sin^2 \theta_{23} = 0.51$$

- 1) Statistics will be Increased $\times 3$
- 2) Improvement of the efficiency

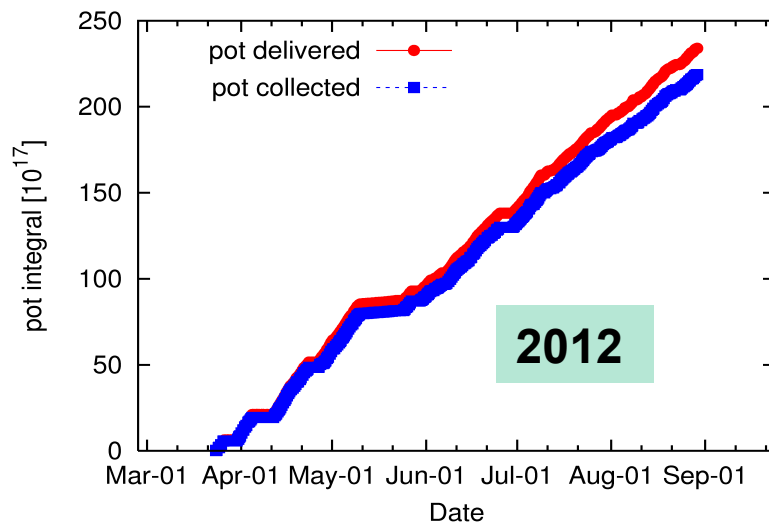
ICARUS T600 @ LNGS

Two identical modules
 $3.6 \times 3.9 \times 19.6 \approx 275 \text{ m}^3$ each
 Liquid Ar active mass: $\approx 476 \text{ t}$

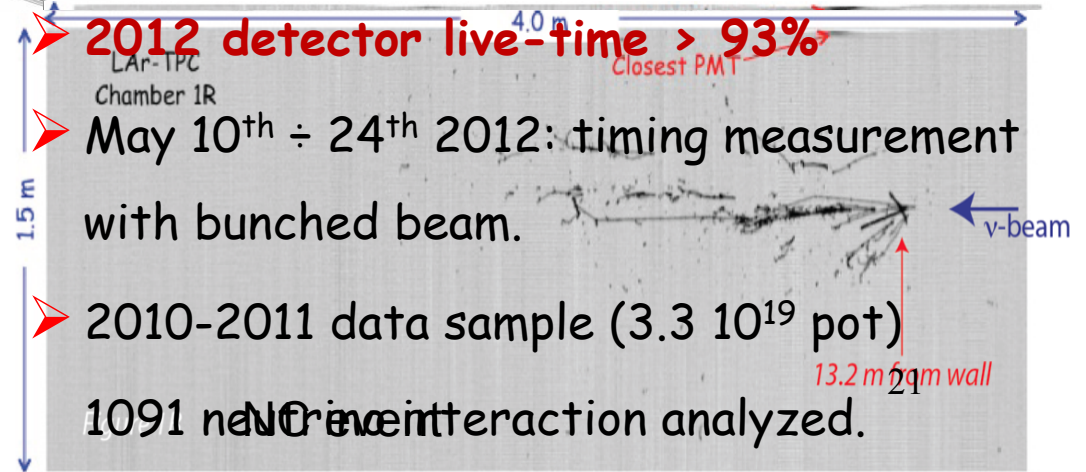


Conceived as a Multi-purpose detector: atmospheric, solar ($>8 \text{ MeV}$), supernovae neutrinos, nucleon decay searches in "exotic" channels, CNGS beam

The most important Milestone towards a multi-kton LAr detector with unique imaging capability, and spatial/calorimetric resolutions



CNGS neutrino events



ICARUS T600 @ LNGS

- The unique imaging capability of ICARUS, its spatial/calorimetric resolutions, and e/π^0 separation allow “to see” events in a new way
- The detector is collecting “bubble chamber like” CNGS events since October 2010: for 10^{20} pot (expected until November 2012)
 - CC event expected ≈ 2800 ev
 - NC event expected ≈ 900 ev
 - Muons from upstream GS rock ≈ 12000 ev (≈ 8200 on TPC front face)
 - Intrinsic beam ν_e CC ≈ 26 ev
 - $\nu_\mu \Rightarrow \nu_\tau$ detecting τ decay with kinematical criteria (~ 2 event $\tau \rightarrow e$).
 - Search for sterile neutrinos in LSND parameter space, with e-like CC events excess at $E > 10\text{GeV}$ (0 – 55 events CC depending on θ , max calculated for $\Delta m^2 = 0.2 \text{ eV}^2$, $\sin^2(2\theta)=0.04$, bottom corner of exclusion)
- The T600 is also collecting simultaneously “self triggered” events:
 - ≈ 100 ev/year of atmospheric ν CC interactions.
 - Proton decay with 3×10^{32} nucleons, zero bkg. in some of the channels

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See Rubbia's talk
(Arxive 1209.0122)

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Progress on data analysis in 2012

- ✓ CNGS events analysis → ongoing
- ✓ Cosmic-ray analysis → automatic reconstruction of deposited energy in agreement with expectations
- ✓ Development / optimization of analysis tools in terms of performance, calibrations and event reconstruction.

Progresses in:

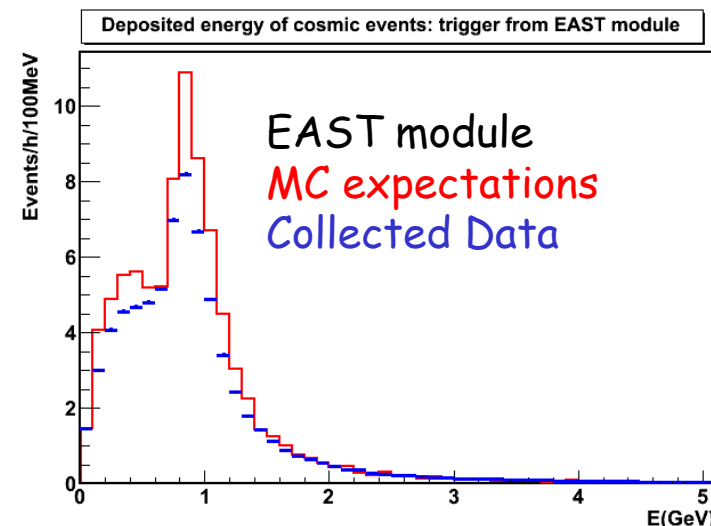
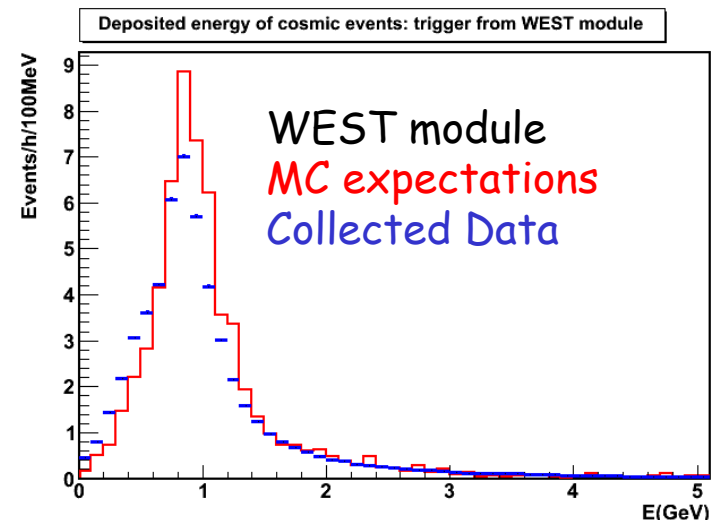
- 3D reconstruction, leading to better performance especially for horizontal tracks
- Muon momentum measurement by M.S. under refinement
- Particle Identification Algorithm
- Automatic reconstruction: vertex finding, clustering, track finding
- Developments on tools for Calorimetric reconstruction

Cosmic ray muon spectrum

Cosmic Rays : ~ 130 cosmic events/h

- Coincidence of PMT sum signals of two adjacent chambers (50% cathode transparency). Signal threshold ~ 100 (200) phe West (East) cryostat
- CR data automatically filtered:
 - Skip fake triggers
 - Find "good" muons for purity
 - First reconstruction
- Exposure: 0.25 kton*y in 2011, expected total ~ 0.6 kton*y by the end of 2012.

Good agreement of energy spectrum with MC expectation is found (MC simulation includes light collection and trigger conditions).



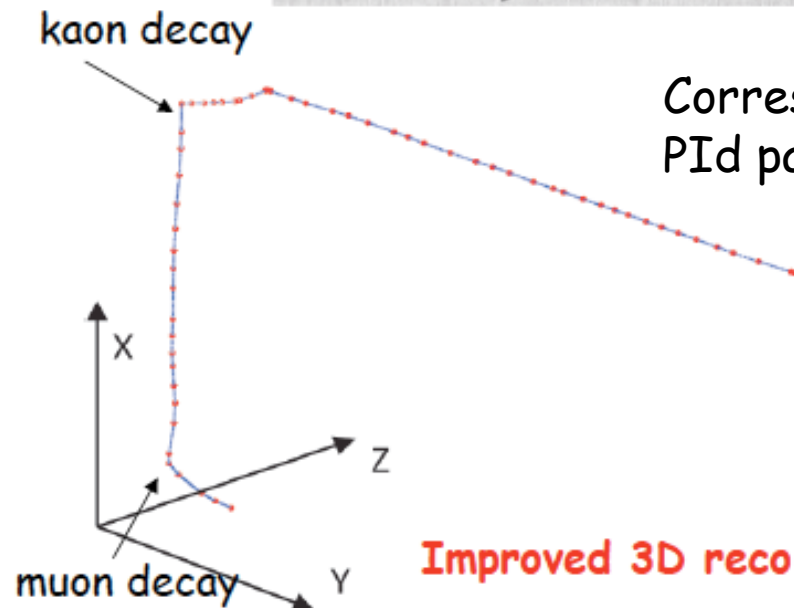
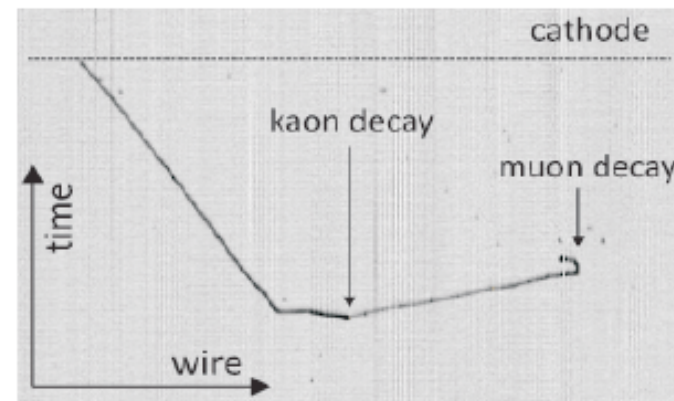
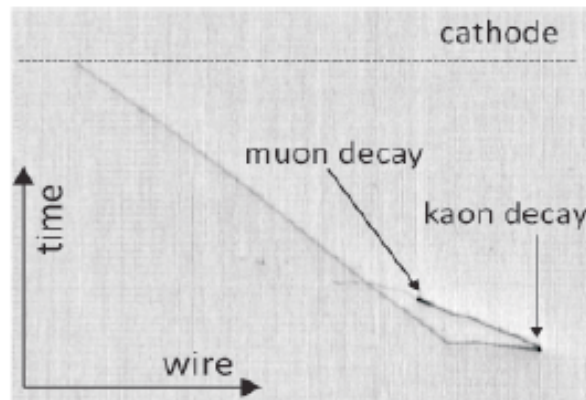
April-July 2012: 0.13 kton*y sample

Since March 2012 an additional trigger based on charge deposition on TPC wires is active to push forward the trigger performance at low energy (Super-Daedalus).

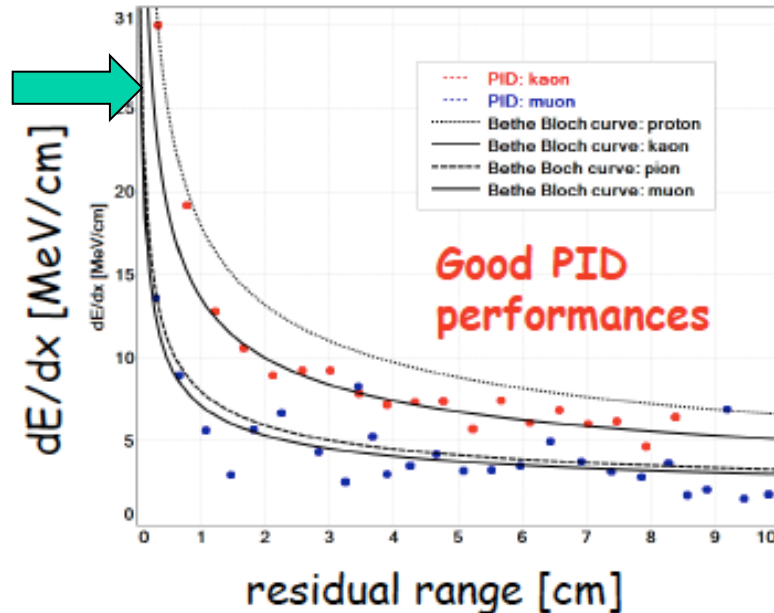
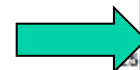
3D and calorimetric reco: real decaying kaon

REAL EXAMPLE FROM CNGS EVENT

Important for nucleon decay channels with K in final state

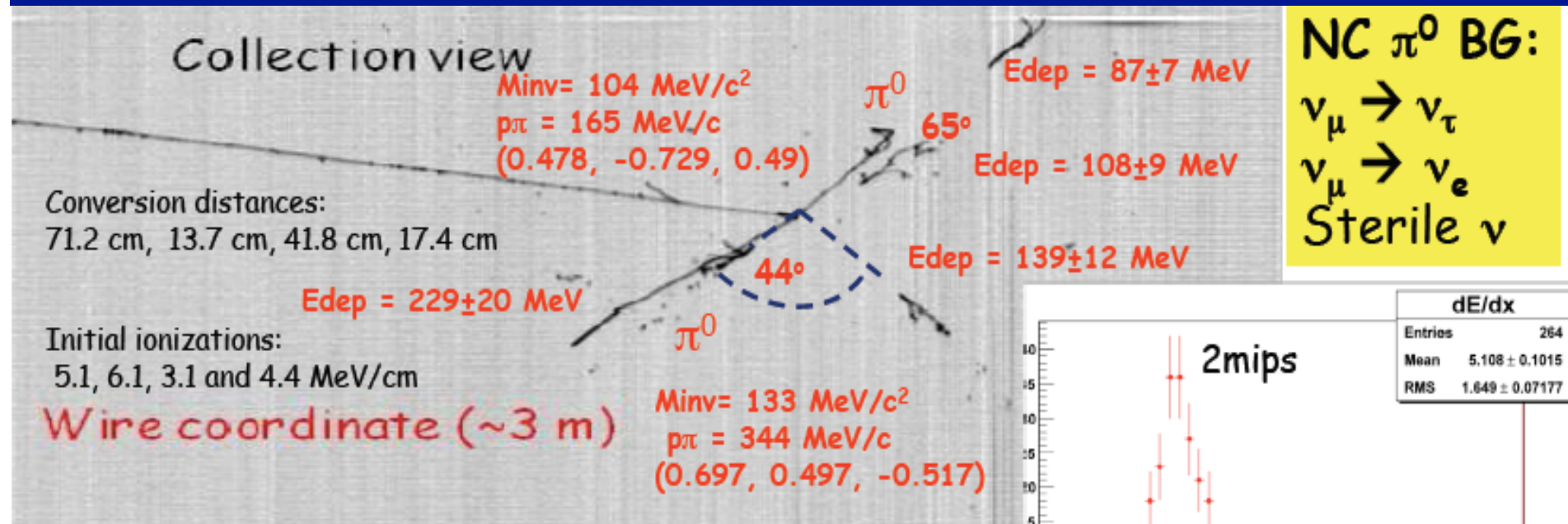


Corresponding
PID patterns



Improved 3D reco

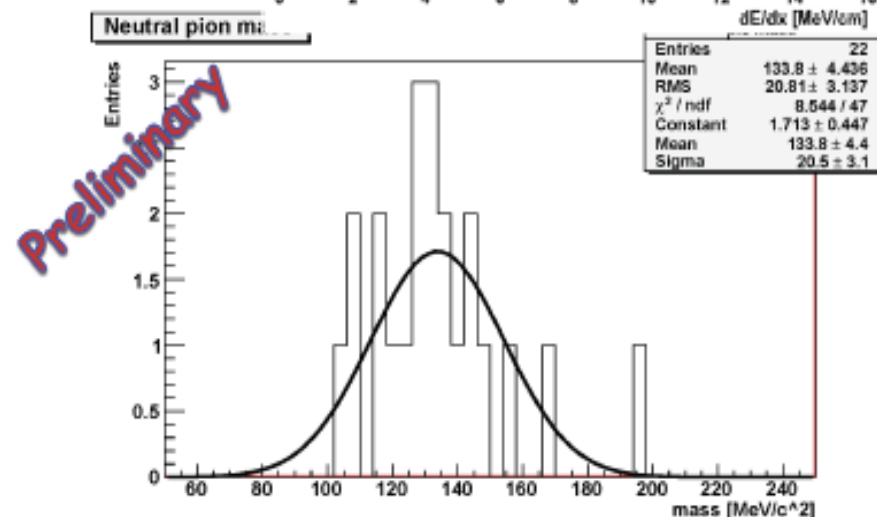
π^0 reconstruction in CNGS event



π^0 -showers identified by

- 2γ conversion separated from primary vertex
- Reconstruction of $\gamma\gamma$ invariant mass
- Ionization in the first segment of showers (1 mip or 2 mips)

Mean: $133.8 \pm 4.4(\text{stat}) \pm 4(\text{syst})$ MeV/ c^2
 $\sigma = 20.5$ MeV



Perspectives at LNGS for neutrino physics

Question marks:

1. Besides the $0\nu\text{DBD}$ search, will LNGS continue to play a significant role in the neutrino physics sector????
2. Will be there any space available in the future for new experiments ??
3. What about future experiments on the search for sterile neutrinos, LBL or atmospheric neutrinos ??

Sterile neutrino proposals

@ LNGS

A proposal for a short baseline sterile neutrino search experiment in the Borexino detector has been submitted to the LNGS SC in April 2012

ν ^{51}Cr Source under the detector

Antiv ^{144}Ce - ^{144}Pr inside the detector

@ CERN

The proposal ICARUS -NESSiE:

Large mass LAr-TPC, now running @LNGS,
moved to CERN

Complemented with magnetic spectrometers for the
charge determination

Spaces @ LNGS

➤ Currently at underground Laboratory:

Since the end of the CNGS program (2013-2015), and before next decade, large underground space could be made available:

- the entire Hall B (110 m long, 17K m³)
- there may be additional 40 m in Hall C

LNGS may host in future new detectors for neutrino physics searches. Enough underground space for:

1. $\approx(7-10)$ Kt Liquid Argon TPC detector
2. ≈ 100 Kt magnetized iron scintillator detector
See "Monolith" ($13 \times 14.5 \times 30 \text{ m}^3 = 34\text{Kt}$)

For CPV and mass hierarchy with LBL and/or atmospheric ν

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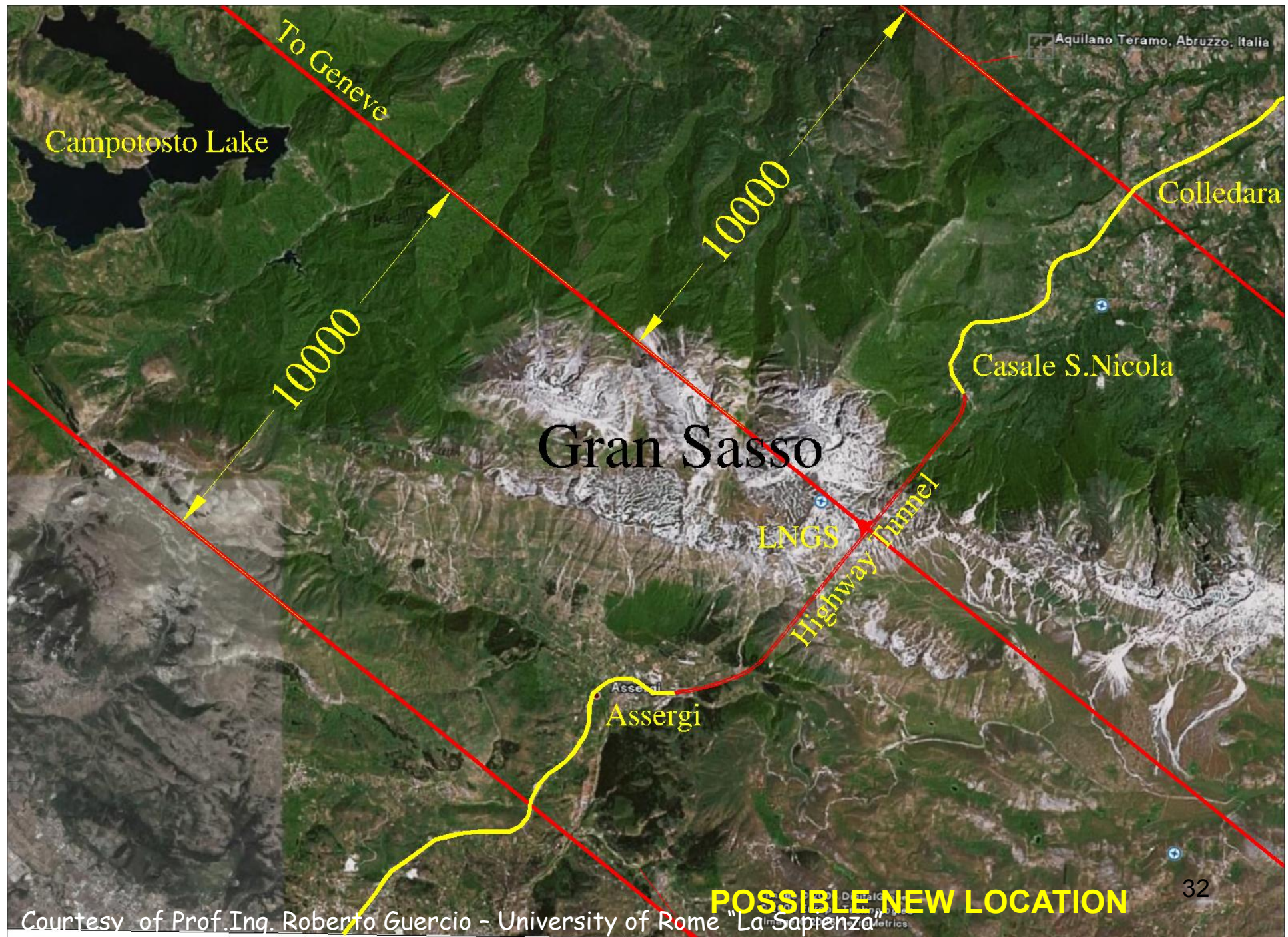
- the entire Hall B (110 m long, 17K m³)
- there may be additional 40 m in Hall C

➤ New halls in the present site can hardly be excavated

➤ LNGS-B proposal:

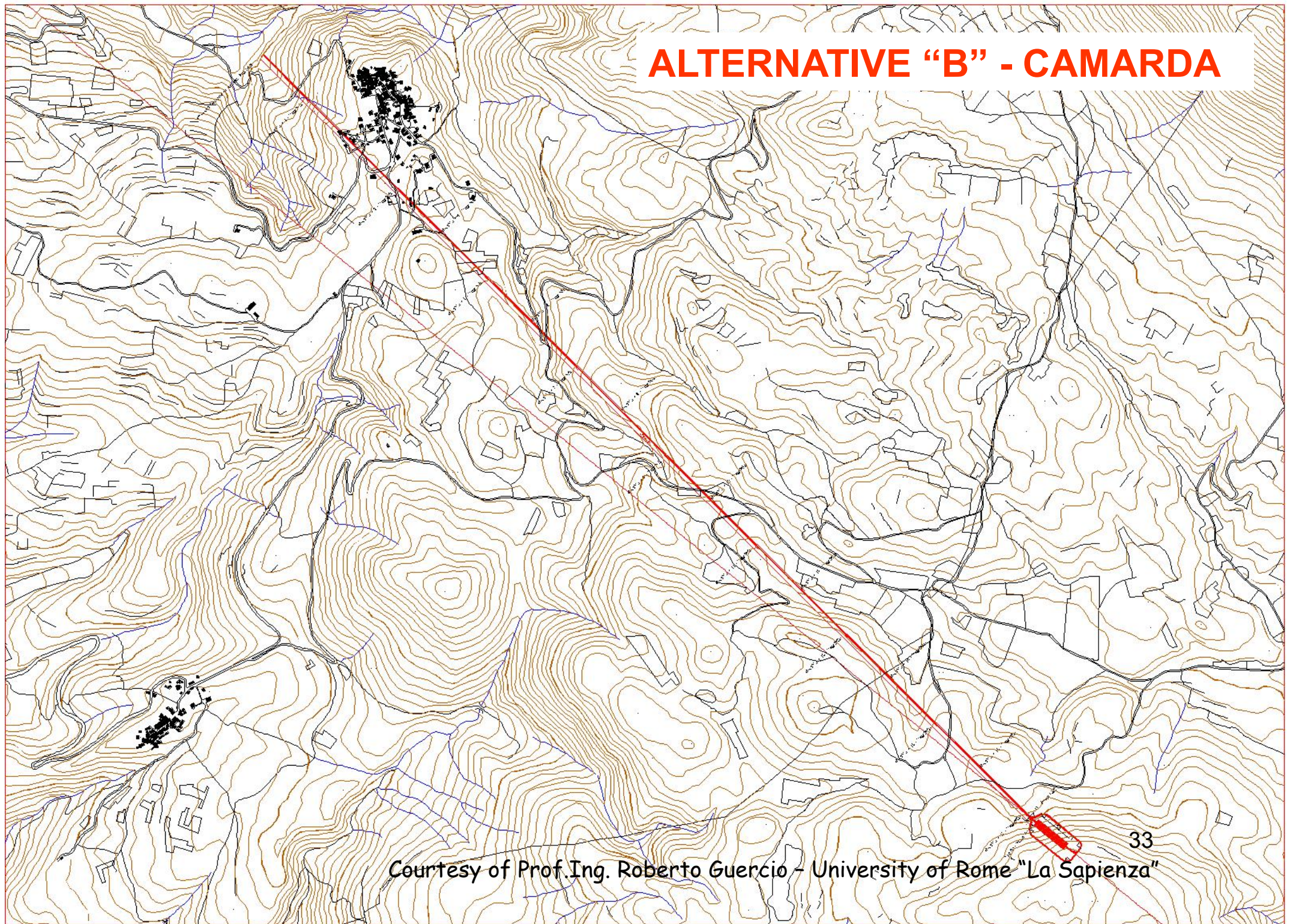
A shallow depth (1.2 Km w.e.) new laboratory

- 2 possible sites, 7-12 Km off axis CNGS
- Out of the protected area of the Gran Sasso Park
- Any presence of significant Uwater
- Contributions from Regional funds may be possible



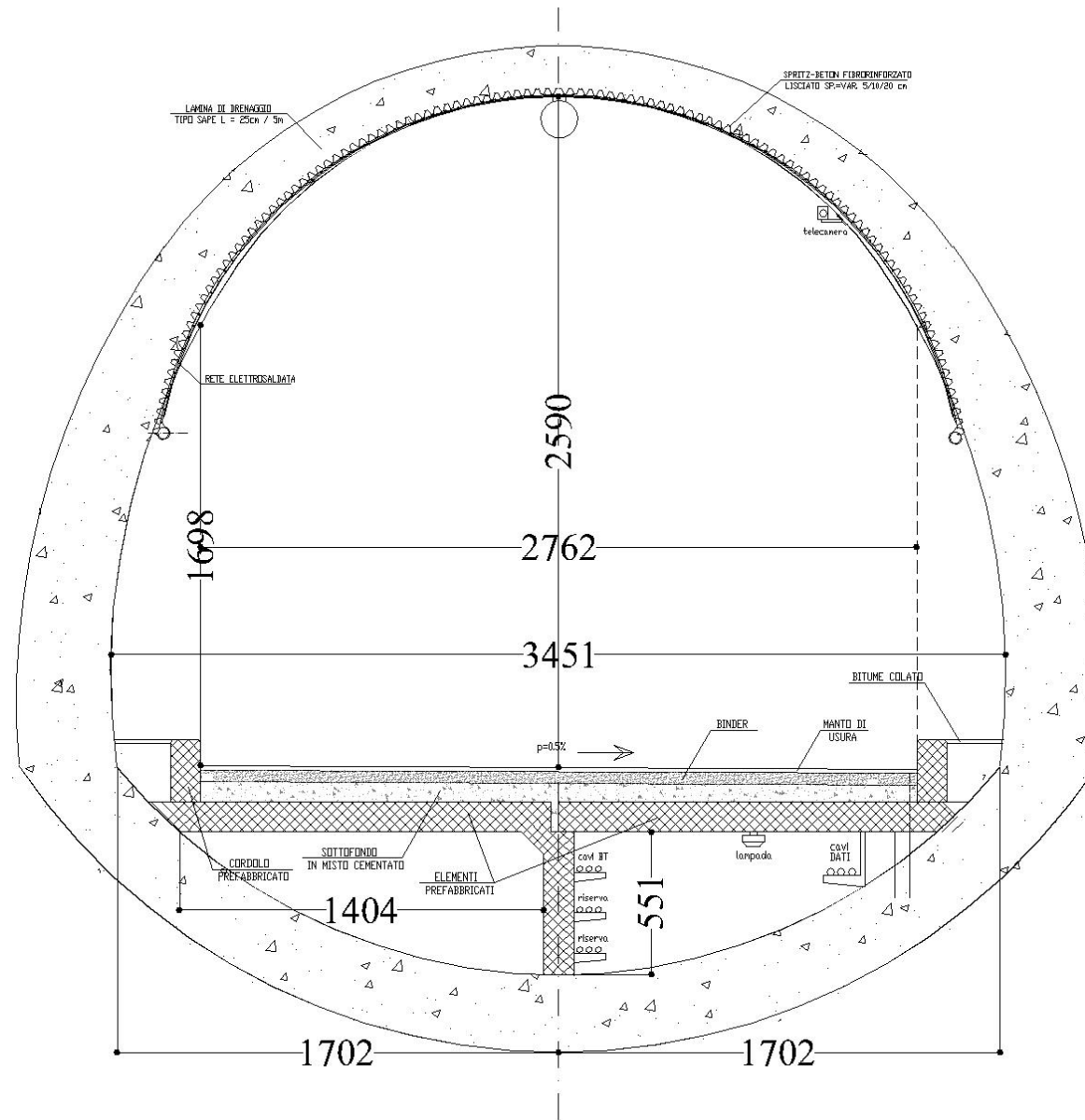
Courtesy of Prof. Ing. Roberto Guercio - University of Rome "La Sapienza"

ALTERNATIVE "B" - CAMARDA



Courtesy of Prof. Ing. Roberto Guercio - University of Rome "La Sapienza"

NEW LABORATORY SECTION



RECEIVED: *November 14, 2008*ACCEPTED: *January 16, 2009*PUBLISHED: *February 26, 2009*

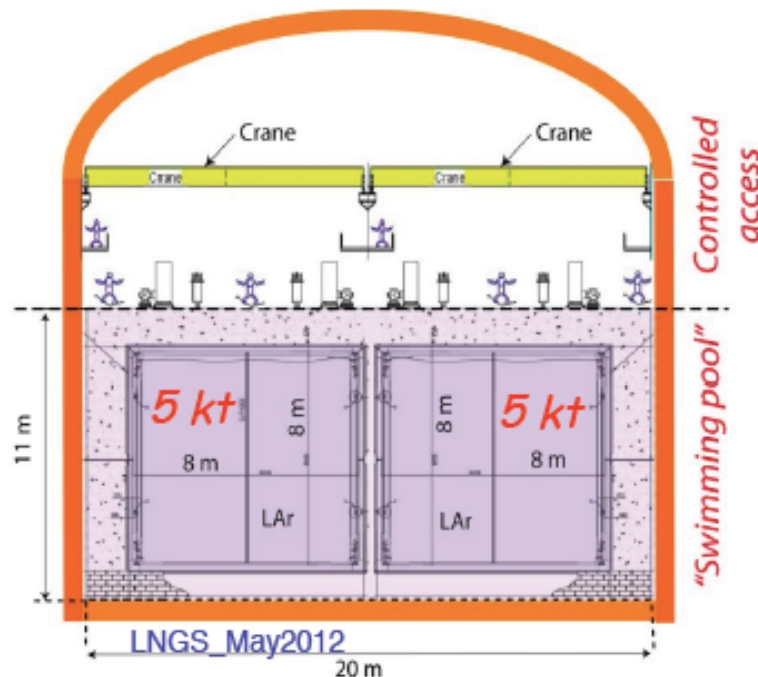
Towards a new Liquid Argon Imaging Chamber for the MODULAR project

D. Angeli,^a B. Baibussinov,^b M. Baldo Ceolin,^{cb} G. Battistoni,^d P. Benetti,^{ef}
A. Borio,^e E. Calligarich,^f M. Cambiaghi,^{ef} F. Cavanna,^{gh} S. Centro,^{cb} K. Cieslik,^b
A. G. Cocco,ⁱ R. Dolfini,^{ef} A. Gigli Berzolari,^{ef} C. Farnese,^{cb} A. Fava,^{cb} A. Ferrari,^k
G. Fiorillo,^{ji} D. Gibin,^{cb} A. Guglielmi,^b G. Mannocchi,^{lm} A. Menegolli,^{ef} G. Meng,^b
C. Montanari,^f S. Muraro,^d O. Palamara,^h L. Periale,^l P. Picchi,^m F. Pietropaolo,^b
A. Rappoldi,^f G.L. Raselli,^f M. Rossella,^f C. Rubbia,^{hk*} P. Sala,^d G. Satta,^m
F. Varanini,^{cb} S. Ventura^b and C. Vignoli,^f

The MODULAr detector

- Each gap is a scaled-up version of ICARUS ($\times 2.66^3$):
 - 8 X 8 m² LAr cross section and about 60 m length
 - Two gaps within a same cryogenic volume: 10'740 ton
 - 4 m drift (2.66 ms), $E_{\text{drift}} = 0.5$ kV/cm, H.V.: -200 kV
 - 3-D imaging like ICARUS, 6 mm pitch (~ 50000 chs)
 - PM's will extract the trigger and timing LAr signal.

MODULAr: 8 x 8 m²



ICARUS: 3 x 3 m²



Slide# : 11

Daya Bay and RENO have recently observed a large θ_{13} neutrino mixing angle which confirms the early results from T2K, Double-Chooz and MINOS, as well as from global neutrino data analyses.

This finding offers an unprecedented opportunity to study the leptonic mixing matrix with artificial neutrino beams, addressing the major challenges in this field, as the occurrence of CP violation in the leptonic sector, the determination of the neutrino mass hierarchy and the measurement of θ_{23} .

The meeting will evaluate the experimental perspectives of such a “large θ_{13} ” scenario.

The talks and discussions will target the opportunities offered by the existing and new facilities and in particular by the long-baseline experiments.

ν TURN 2012

The new opportunities offered by a large theta 13. A workshop to examine the

Neutrino at the Turning Point LNGS 8-10 May 2012

A principal aim was to clarify which type of neutrino beams, detectors and which laboratories are best suited to investigate the neutrino properties, in order to outline a realistic European roadmap for the next decade.

ν TURN 2012 workshop: Considerations on mass hierarchy

✓ There is a possibility that the neutrino mass pattern might be measured in less than a decade with a significance of $\approx 3\sigma$ by a combination of the presently running experiments (T2K, MINOS, Double Chooz, Daya Bay, RENO) or going to take data (Nova). However none of them guarantees a safe coverage of the CP-violation parameter space, especially for conservative assumptions on the performances of the facilities.

✓ An ultimate answer well beyond 3σ for any value of CP phase requires a dedicated facility.

Many proposals on the floor:

HyperK, LBNE, LAGUNA-LBNO, PINGU, Daya Bay II

✓ Besides the reactor experiments, the exploitation of matter effects remains the most promising approach to determine mass hierarchy

The CERN-LNGS baseline is not well suited in this context.

ν TURN 2012 workshop: Considerations on mass hierarchy

ICAL@INO could also be able to determine mass hierarchy before 2025 irrespective to the CP value with a significance of $\approx 3\sigma$ under optimistic assumptions on the calorimeter resolutions.

At LNGS a ≈ 100 Kt magnetized iron scintillator detector could be envisaged.
However a significantly better granularity than ICAL@INO would be necessary to reach conclusive ($> 3\sigma$) sensitivities on the mass pattern

ν TURN 2012 workshop: Considerations on CP-violating phase δ

✓ The assessment of CP violation and the precise measurement of δ is still a major challenge even in presence of the relative large value of θ_{13} :

Three new projects on the floor: LAGUNA-LBNO, LBNE/LAr, Hyper-K

✓ It's well known that baselines in the approximate range of 1000 Km are well suited for CP violation

✓ LNGS offer a baseline of 730Km for Superbeams from CERN and of 1500Km for a neutrino factory (RAL-LNGS)

The CERN-LNGS baseline hypothesis has been deeply analyzed during the NUTURN 2012 workshop @LNGS

Considered beams from CERN

- off-axis configurations: the SPS at 400 GeV
- on-axis configurations: a 50 GeV machine

Why? Using a 400 GeV p-driver it is difficult to efficiently populate the low energy region (see for example hep-ph/0609106v1)

We will show results as a function (MW Mt 10^7 s) thus allowing to "read" the combination of mass and beam needed to get a certain coverage.

Anyway we set some reasonable benchmarks to allow an easier "reading" of the plots :

- SPS at 400 GeV
 - × 1.2×10^{20} pot/year = 2.7 nominal CNGS ~ 770 kW + variable mass
 - × Same pot/year as in the MODULAR study
- 50 GeV machine (as assumed in the context of LAGUNA):
 - × $0.77 \rightarrow 2.4$ MW + 10 kt mass (could fit in existing LNGS)

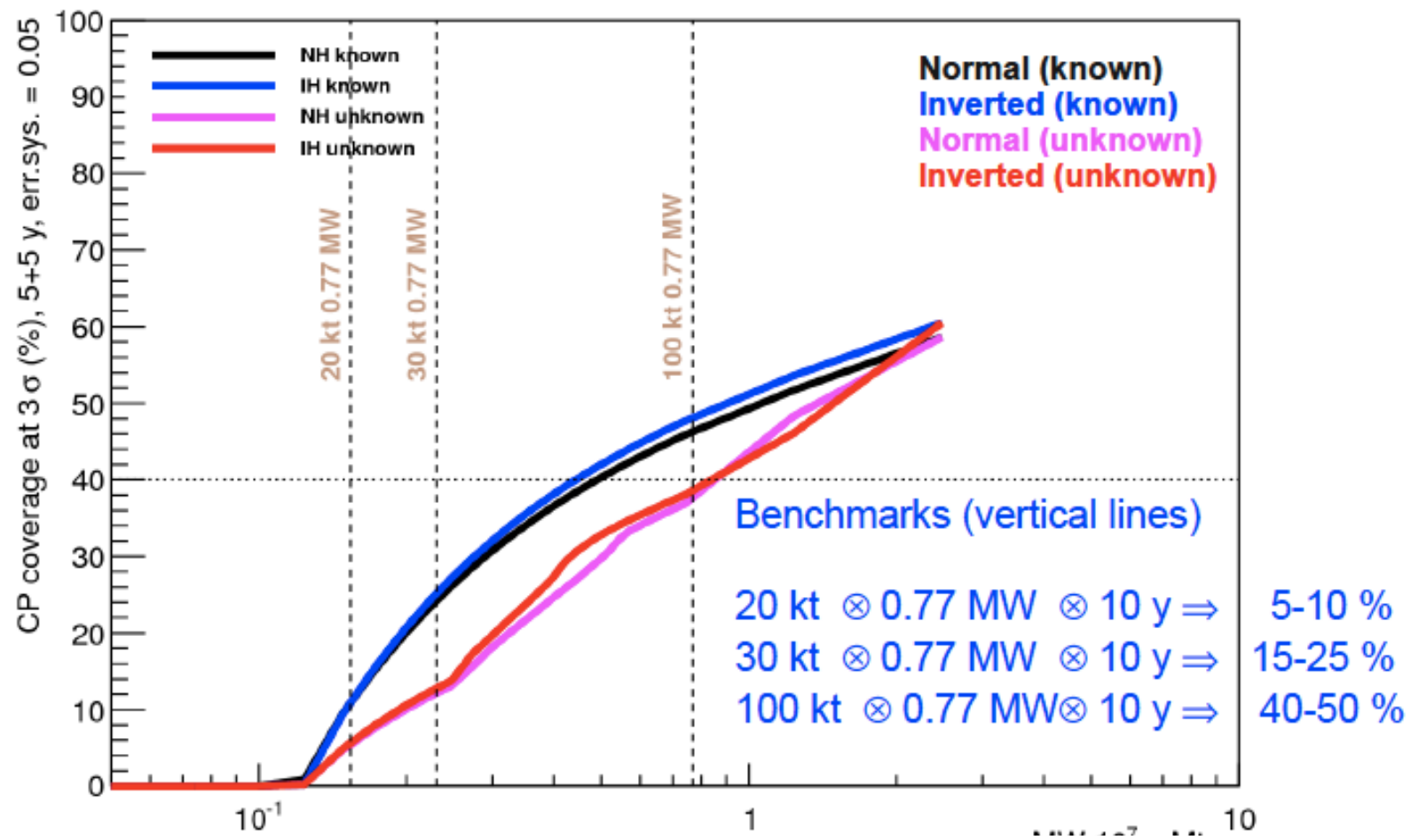
We use a run sharing of: 5 years of ν + 5 years of anti- ν

CPV coverage (off-axis 7 km 400 GeV)

5% systematic error on flux normalization

5 ν + 5 $\bar{\nu}$ years

CP coverage at 3σ (%), 5+5 y, err.sys. = 0.05 OFFAXIS7



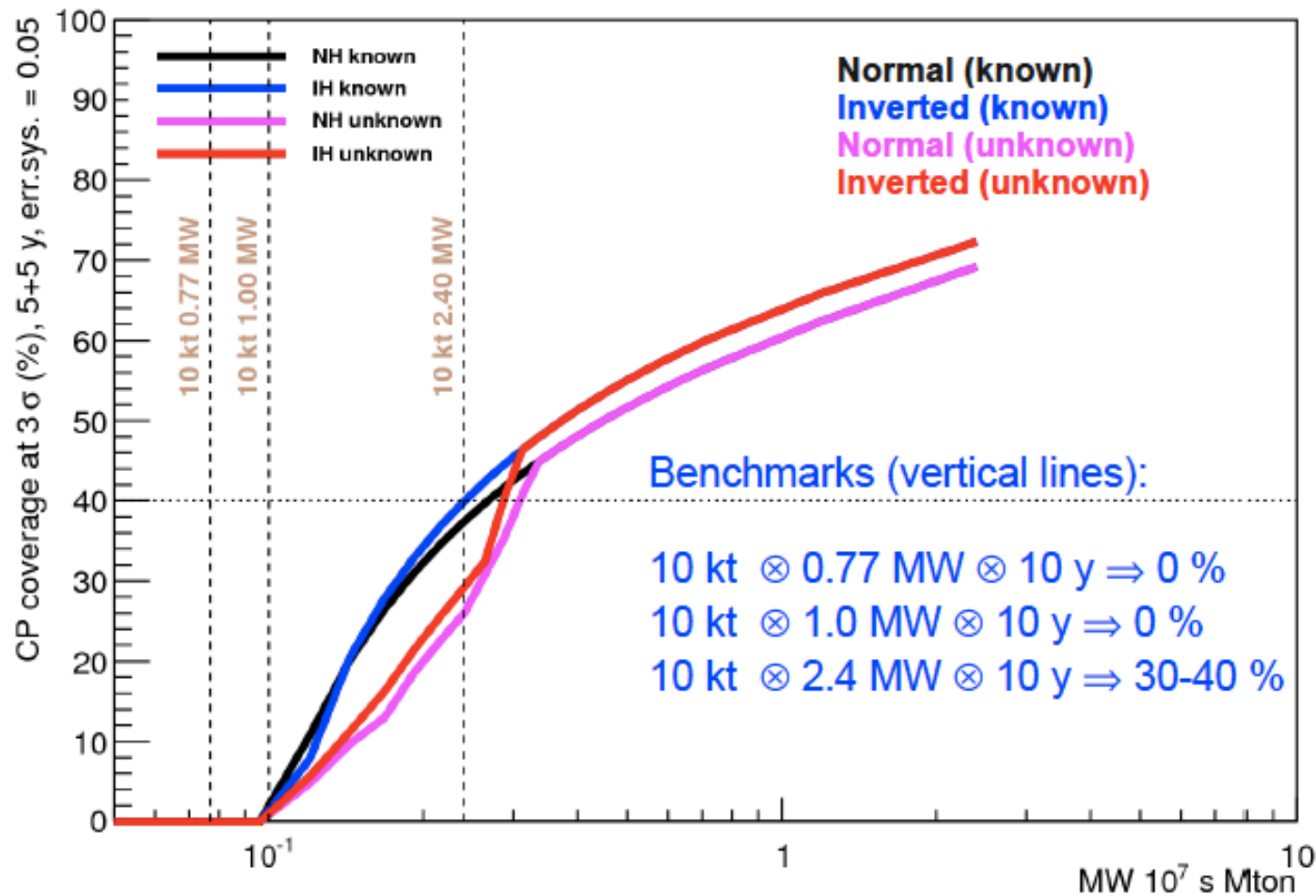
- **CPV**: for each δ value claim 3σ discovery if the CP conserving cases ($\delta = 0, \pi$) can be excluded (for both hypotheses on MH, unless it is assumed known)

CPV coverage (on-axis 50 GeV)

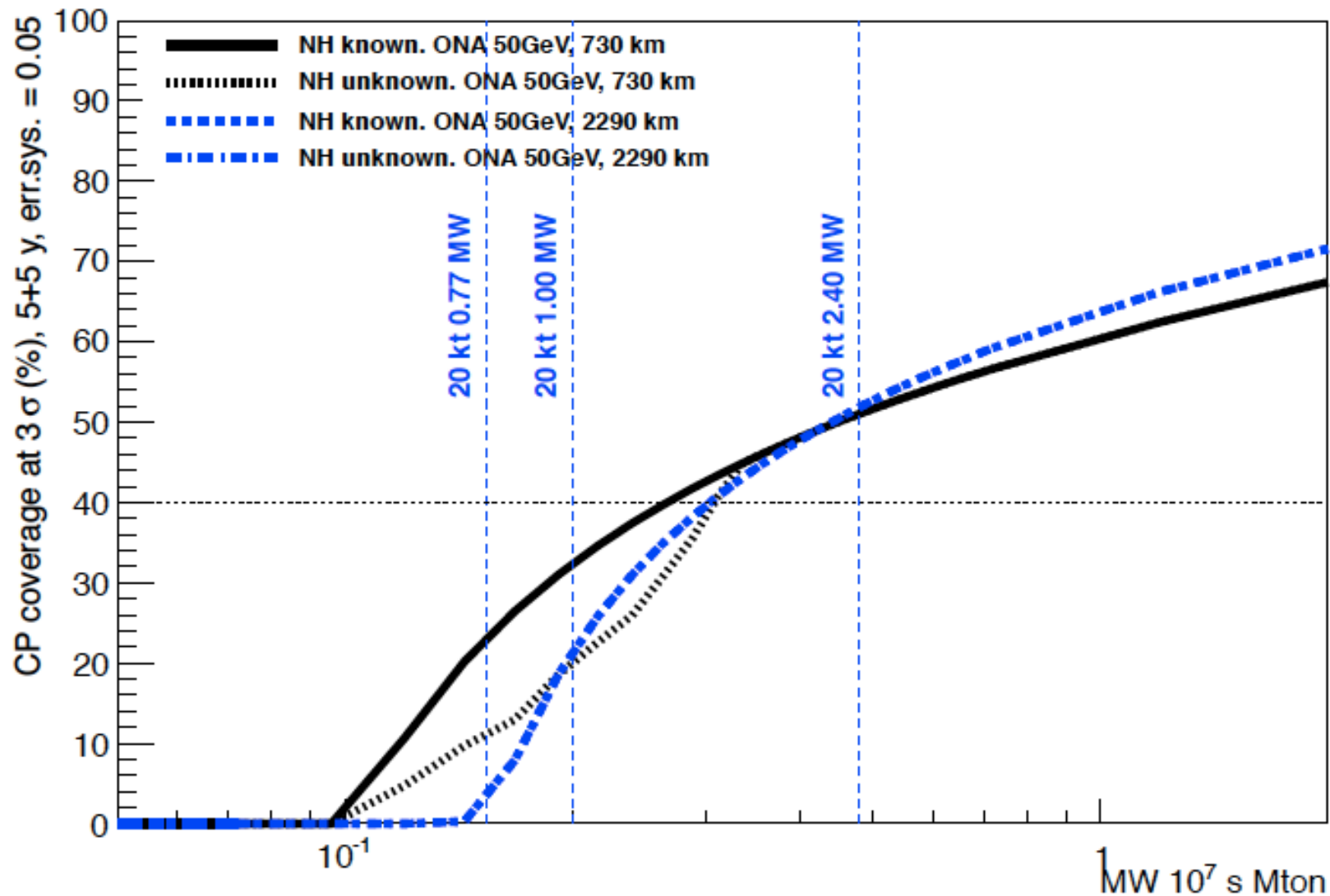
5% systematic error on flux normalization

5 ν + 5 $\bar{\nu}$ years

CP coverage at 3σ (%), 5+5 y, err.sys. = 0.05 ONAXIS



CP coverage at 3σ (%), 5+5 y, err.sys. = 0.05



Comparison 2290 Km, 50 GeV p-driver ↔ 730 Km, 50 GeV p-driver

Courtesy of Longhin

Conclusions on LNGS perspectives

- After the end of the CNGS program (2013-2015), large underground space **could be made available @LNGS**
- LNGS-B: a shallow depth new laboratory **can be envisaged**
- New proposals on the floor:
 1. Search for sterile neutrino with Borexino
 2. Search for CPV with Modular
- A possible scenario CERN-LNGS-B, dedicated high power proton driver (2.4MW) and a very large LAr detector **are worth further studies for CP violation**