Highlights from the OPERA experiment

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on behalf of the OPERA Collaboration

INFN - LNF

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OPERA Collaboration

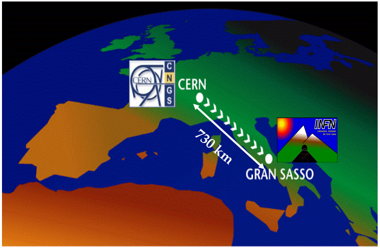
Outline

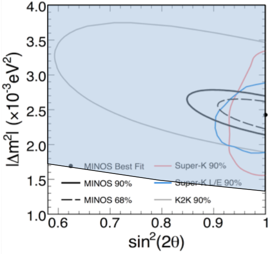
1. The OPERA experiment
   - Detection principle
2. Oscillation results
   - $\nu_\mu \rightarrow \nu_\tau$ search
   - $\nu_\mu \rightarrow \nu_e$ search
3. Non-Oscillation results
   - Neutrino velocity
4. Conclusions

OPERA experiment

Oscillation Project with Emulsion tRacking Apparatus

Aim: first direct $\nu_\mu \to \nu_\tau$ appearance detection





Full coverage of the parameter space for the atmospheric neutrino sector

- Long baseline neutrino oscillation experiment located in the CNGS (CERN Neutrinos to Gran Sasso) ν_μ beam
- Direct search for $\nu_\mu \to \nu_\tau$ oscillations detecting the τ lepton produced in ν_τ CC interactions (appearance mode)
- Search for the subdominant $\nu_\mu \to \nu_e$ oscillations

CNGS beam

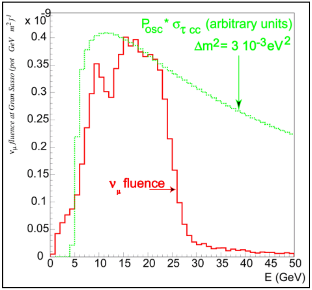
CNGS beam optimized for ν_τ appearance
$\Rightarrow$ maximize the number of ν_τ CC interactions

- τ production threshold (3.5 GeV) and ν_τ CC cross section
  $\longrightarrow$ high energy beam
- "off peak" w.r.t. maximum oscillation probability ($\sim$1.5 GeV)

Beam parameters

$< E_{\nu_\mu} >$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.89, 0.06 %
$\bar{\nu}_\mu/\nu_\mu$	2.1 %
ν_τ prompt	negligible
pot/year	4.5×10^{19}

Contaminations given in terms of interaction rates in OPERA

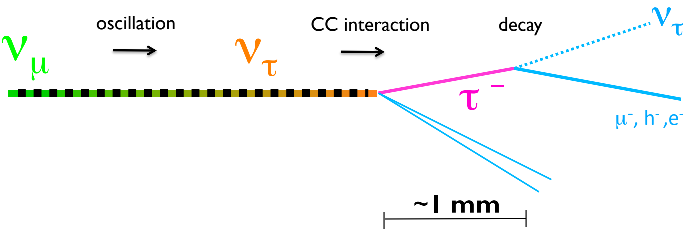


For 22.5×10^{19} pot $\longrightarrow$
Expected events: 7.6 signal, 0.8 bg

New J. Phys. 14 (2012) 033017

Appearance detection

Direct observation of $\nu_\mu \to \nu_\tau$ oscillation

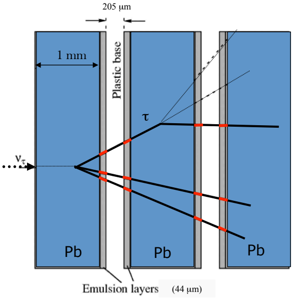


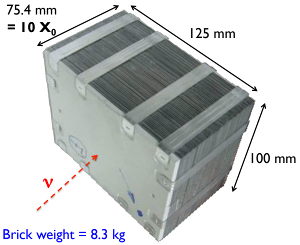
- Large mass [$\sim O$(kton)] due to small neutrino cross section $\to$ lead target
- High granularity [$\sim 1\mu$m] for signal selection/background rejection (clear identification of the "kink") $\to$ nuclear emulsions

Emulsion Cloud Chamber

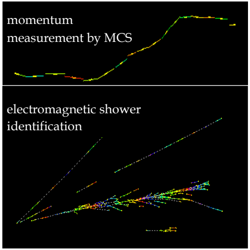
Neutrino interaction detector (ECC)

- Target basic unit: **brick** of 57 nuclear emulsions interleaved by lead plates + 2 interface emulsions (CS) → high resolution and large mass in a modular way
- unambiguous measurement of the kink





- "stand-alone" detector

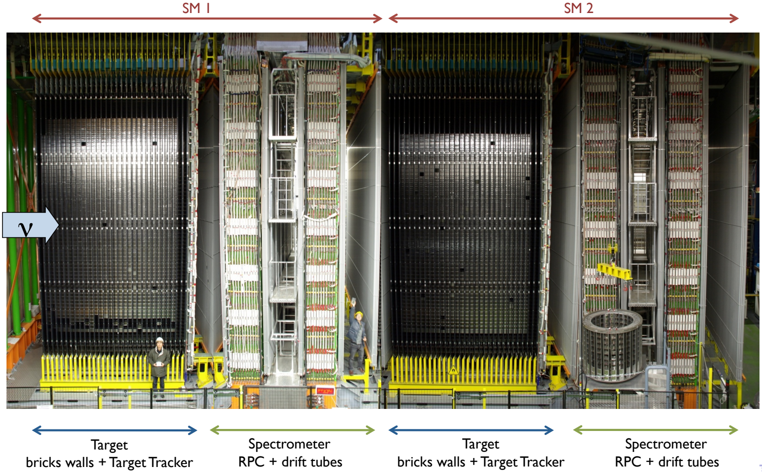


total OPERA target: ~150000 bricks → ~1.25 kton

OPERA detector

Electronic detectors: 1: "time resolution" to emulsions; 2: trigger and preselection of candidate bricks; 3: muon ID and momentum/charge measurement

OPERA: hybrid detector



CNGS data taking: status and outlook

POT and number of events

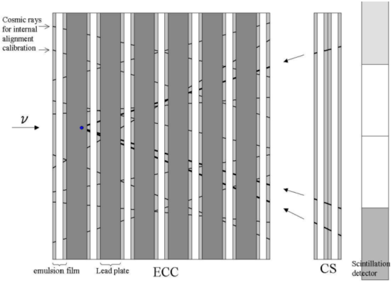
Year	Proton On Target POT	Number of Neutrino Interactions	Integrated POT / Proposal Value
2008	1.78×10^{19}	1698	7.9%
2009	3.52×10^{19}	3557	23.6%
2010	4.04×10^{19}	3912	41.5%
2011	4.84×10^{19}	4210	63.0%
2012	$(\sim 4.7 \times 10^{19})$	(~4050)	(~84%)

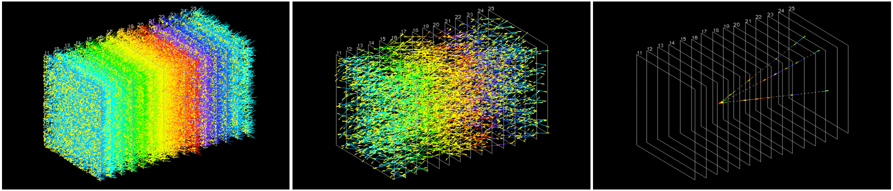
- 14.2×10^{19} POT up to 2011
- Good performance for current 2012 Run: 6.63×10^{18} POT up to 30/04, special Bunched Beam from 10/05 up to 24/05
- Expected POT after 2012 Run: 18.9×10^{19} (Proposal: 22.5×10^{19})

Scanning and analysis

Vertex location and event analysis in the OPERA brick

- Prediction scanning, driven by electronic detector tracks
- Define the stopping point
- Large area scan around the stopping point
- Interaction reconstruction and decay search



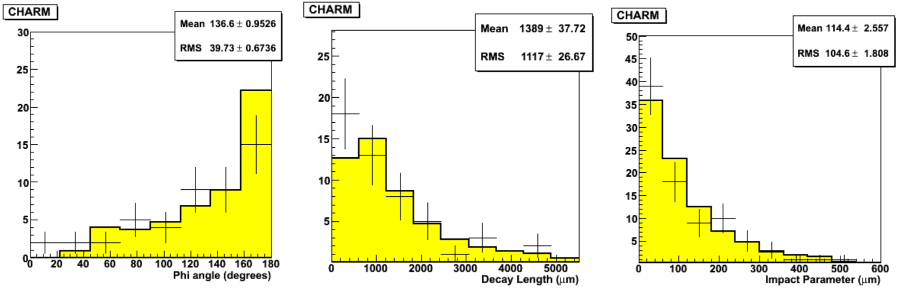


Data/MC comparison

Charm control sample: proof of the τ efficiency

Charm events

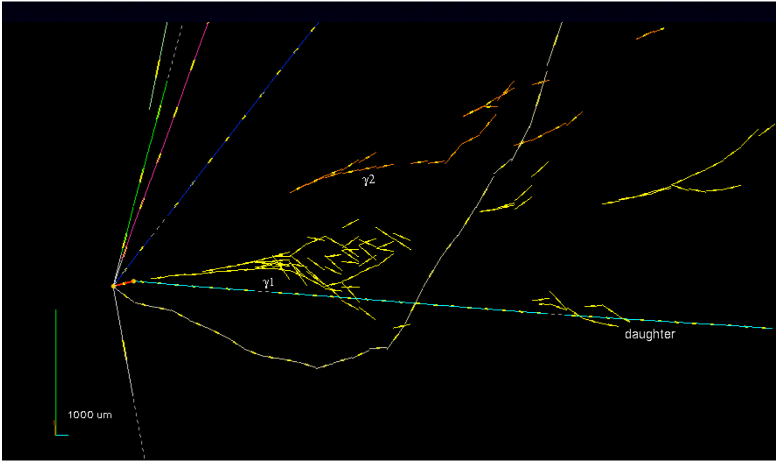
Detected: 49 events $\Leftrightarrow$ Expected: 51$\pm$7.5 events



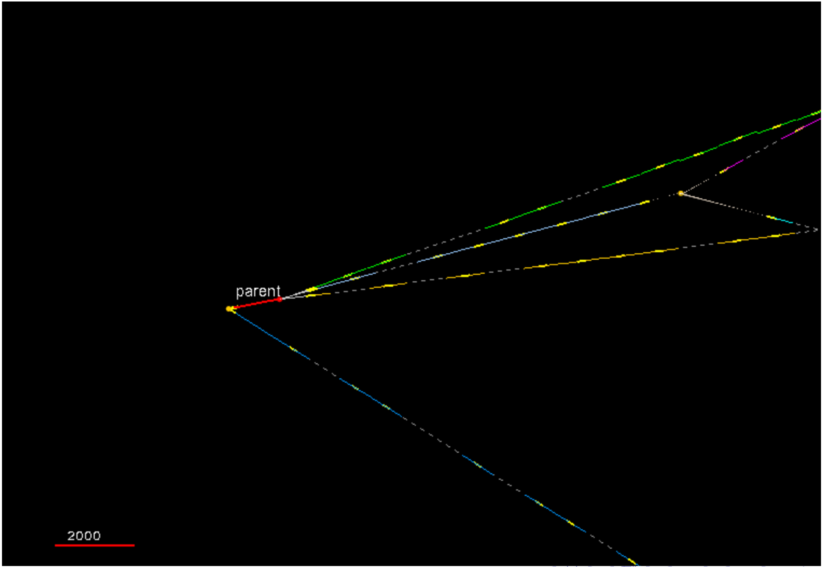
Phi angle — Decay length — Impact Parameter

Signal candidate

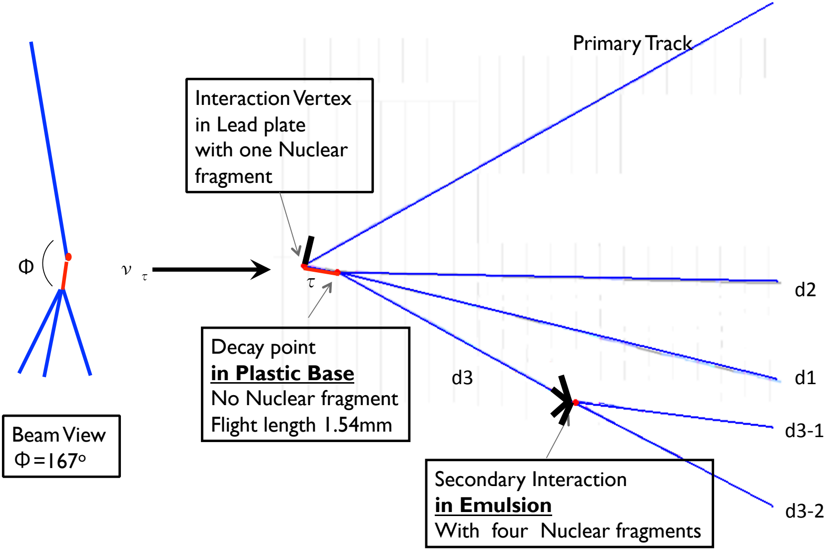
First ν_τ candidate found in the decay search of 2008 and 2009 Physics Runs
Released in June 2010 (Phys. Lett. B 691 (2010) 138)



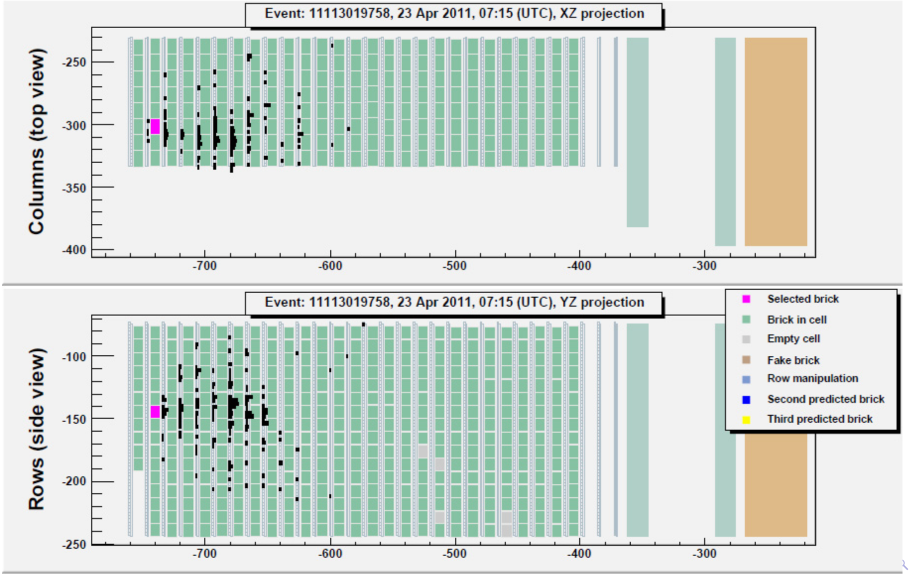
New ν_τ candidate event



Schematics of the event: $\tau \to 3h$



Electronic detector event display



Event kinematics

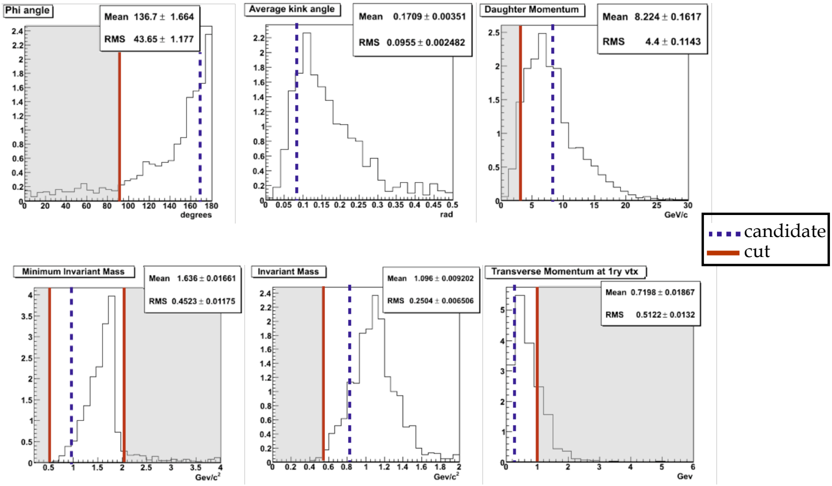
New candidate event

- no muons at the 1ry vertex
  primary track incompatible with muon hypothesis (p/range)
- fulfil the kinematic selections

	Cut	Value	Error
Phi (Tau - Hadron) [degree]	>90	167.8	± 1.1
average kink angle [mrad]	< 500	87.4	± 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4	± 1.7
Min Invariant mass [GeV/c²]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11

Event kinematics

New candidate event



Satisfying the specified criteria for $\tau \rightarrow 3$hadron decay

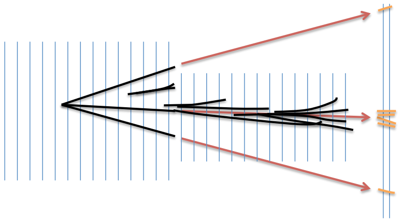
Status of the ν_τ search

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

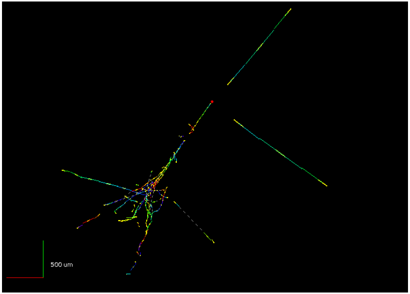
ν_e search

Systematic ν_e search in 0μ located events (NC-like) from 2008 and 2009 Runs

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



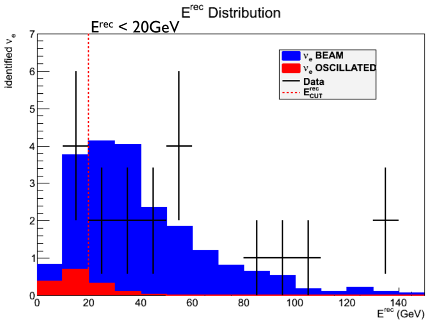
ν_e candidate event, $E_\nu = 15.6$ GeV



Result:

- 96 events selected
- 19 ν_e confirmed

Preliminary $\nu_\mu \to \nu_e$ oscillation result

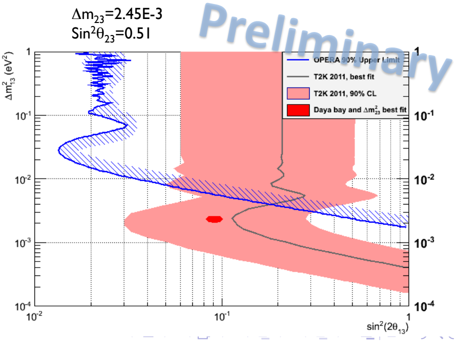


Expected events:
oscillated ν_e 1.5, BG-beam ν_e 19.2
Observed: 19 events

After low-energy selection ($E_\nu < 20$ GeV)

- Expected events:
  oscillated 1.1, beam-BG 3.7
- Observed events: 4 ν_e

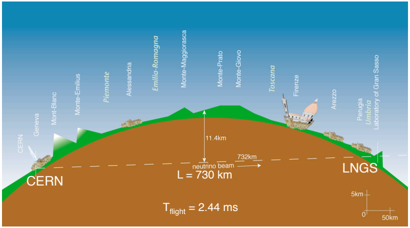
$\Rightarrow$ limit on oscillation parameters



Neutrino velocity

Neutrino TOF measurement:

- neutrino production time at CERN
- neutrino interaction time inside OPERA
- precise path length measurement (geodesy)
  - Distance (BCT-OPERA) $= (731278.0 \pm 0.2)$ m
- long baseline needed for high accuracy

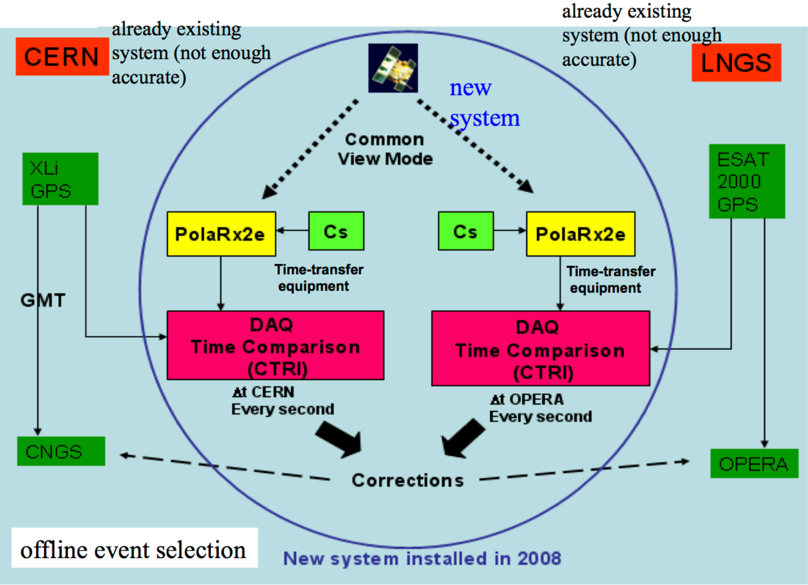


$$v_\nu = \frac{x_2 - x_1}{t_2 - t_1} = \frac{\Delta x}{\Delta t}$$

Key ingredients:

- CNGS-OPERA synchronisation at $\sim$1 ns (GPS common view mode)
- accurate calibration of the timing chains at CERN and OPERA
- precise ν time distribution at CERN through BCT proton waveforms

CNGS-OPERA synchronisation

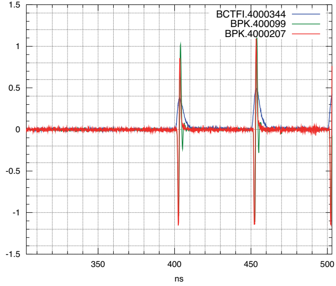


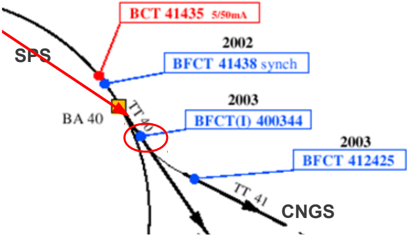
BCT calibration

Fast Beam Current Transformer (BCT)

- Proton pulse digitized by a waveform digitizer (WFD)

Result: signal comparison after Δt_{BCT} compensation





Dedicated beam experiment: BCT plus 2 pick-ups ($\sim$1 ns) using the LHC beam:

$$\Delta t_{BCT} = (583.7 \pm 1) \text{ ns}$$

(time difference between t_{WFD} and t_{BCT})

New measurement (May 2012)

Summary of calibration delays

Item	Result	Method
CERN UTC distribution (GMT)	10077.8 ± 1 ns	• Portable Cs • Two-ways
WFD trigger	26.6 ± 1 ns	Scope
BTC delay	583.7 ± 1 ns	• Portable Cs • Dedicated beam experiment
CERN-LNGS intercalibration	2.3 ± 1.7 ns	• METAS PolaRx calibration • PTB direct measurement
LNGS UTC distribution (fibers)	41067 ± 1 ns	• Two-ways • Portable Cs
OPERA master clock distribution	7046 ± 1 ns	• Two-ways • Portable Cs
FPGA latency, quantization curve	24.5 ± 1 ns	Scope vs DAQ delay scan (0.5 ns steps)
Target Tracker delay (Photocathode to FPGA)	50.2 ± 2.3 ns	UV picosecond laser
Target Tracker response (Scintillator-Photocathode, trigger time-walk, quantisation)	9.4 ± 3 ns	UV laser, time walk and photon arrival time parametrizations, full detector simulation

First four rows: ±1.8 ns (CERN)

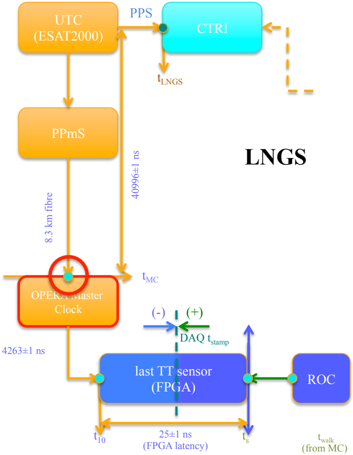
Last five rows: ±4.2 ns (OPERA)

PRELIMINARY

Two instrumental problems found after first data release

Test of the delay of the 8.3 km long optical fiber and of the DAQ internal delays

- Dedicated campaign (Dec 2011 - Feb 2012)
- Two identified issues in the timing chain at LNGS:
  - faulty connection of the optical fiber to the OPERA Master Clock
    $\Rightarrow$ artificial neutrino anticipation $\sim$74 ns
  - internal Master Clock frequency higher w.r.t. nominal value by $\Delta f/f = 1.24 \times 10^{-7}$ (124 ns/s)
    $\Rightarrow$ artificial neutrino delay $\sim$15 ns

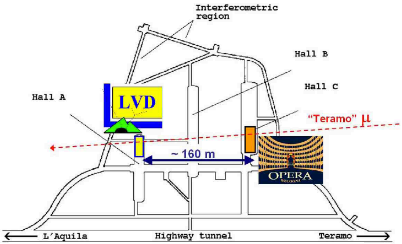


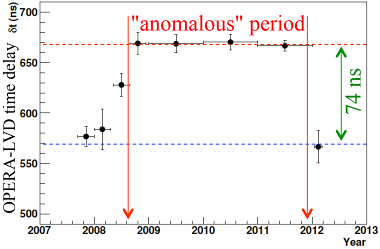
Investigation on when anomalous conditions occurred during the data taking and on their stability

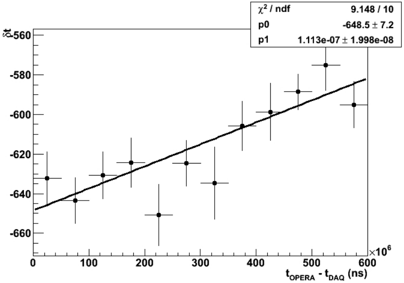
Systematics study with cosmic muons

Joint OPERA-LVD analysis

Coincidences using horizontal cosmic muons coming from the Teramo Valley



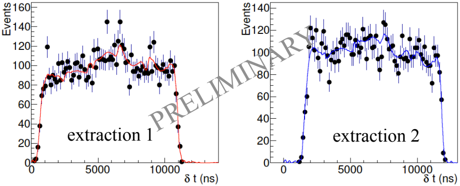




- fiber delay problem from 2008 and lasting in stable conditions up to end 2011
- inaccurate oscillator frequency since the beginning of the data taking, drift stable along the years

Preliminary 2011 result correction

2011 result corrected according to the new measured parameters

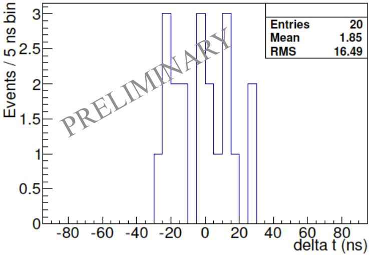


Statistical analysis:

- Likelihood approach, maximisation by varying $\delta t = TOF_c - TOF_\nu$
- $\delta t = (6.5 \pm 7.4(stat.)^{+9.2}_{-6.8}(syst.))$ ns

Bunched beam: event-by-event analysis

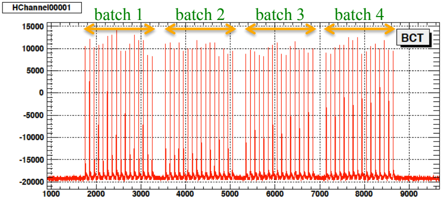
- 20 events detected by the TTs
- $\delta t = (1.9 \pm 3.7)$ ns
- excludes possible biases due to statistical analysis and to long proton pulses

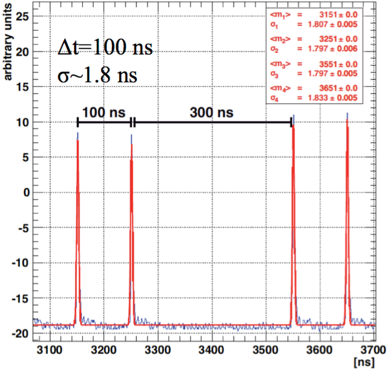


T. Adam *et al.* [arXiv:1109:4897] soon revised and resubmitted to JHEP

New measurements with a short-bunch narrow-spacing proton beam (May 2012)

Bunched beam from 10 to 24 May



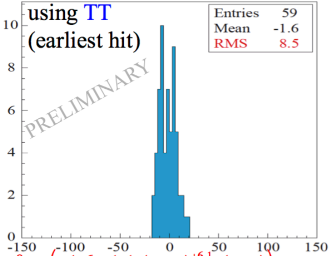


- 1 extraction per CNGS cycle
- 4 batches per extraction
- 16 bunches per batch
- POT: $\sim 2\times 10^{17}$ (2 weeks)

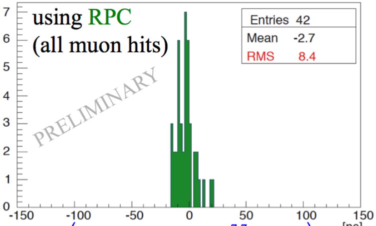
- Improved OPERA timing systems, redundant measurements
- 106 on time events (both external and contained)

New OPERA preliminary results

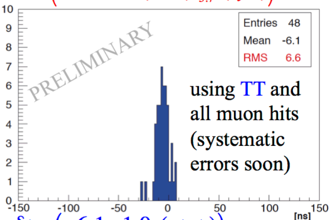
with new BCT values



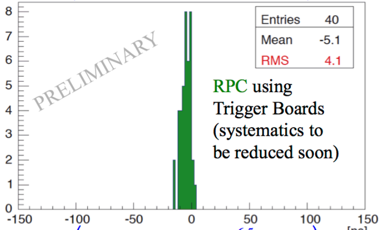
$\delta t = \left(-1.6 \pm 1.1\ (stat.)^{+6.1}_{-3.7}\ (sys.)\right)$ ns



$\delta t = \left(-2.7 \pm 1.3\ (stat.)^{+7.7}_{-7.4}\ (sys.)\right)$ ns



$\delta t = \left(-6.1 \pm 1.0\ (stat.)\right)$ ns



$\delta t = \left(-5.1 \pm 0.6\ (stat.)^{+6.5}_{-5.1}\ (sys.)\right)$ ns

Conclusions

- OPERA is successfully collecting CNGS events since 2008
- $\nu_\mu \to \nu_\tau$:
  - 2 ν_τ candidate events so far (2.1 expected, with 0.2 BG events)
  - estimation of detection efficiency and background in progress
- $\nu_\mu \to \nu_e$:
  - 19 events observed in 2008-2009 Run data, 4 surviving the selection cut (1.1 signal + 3.7 BG)
    $\Rightarrow$ set constraints in the high Δm^2 region
- Neutrino velocity:
  - two issues affecting previous analysis completely understood and corrected in 2011 result
  - preliminary 2012 results compatible with corrected 2011
    $\rightarrow$ picture clarified

By the end of 2012, we should (almost) reach the nominal statistics
τ search goes on, few more events under study... stay tuned!

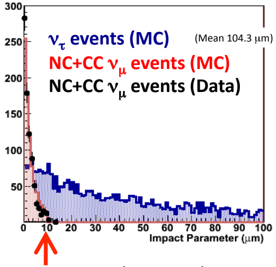
Thank you for your attention!

Backup

ν_τ decay modes

ν_τ CC Detection

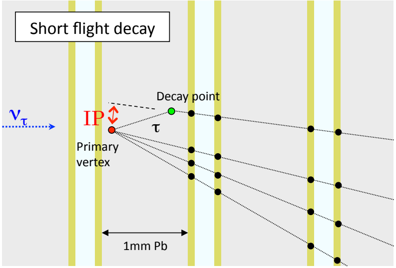
Impact Parameter distribution

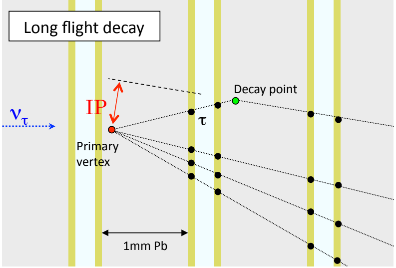


10 μm ↔ ($c\tau$ = 87μm)

τ Decay mode

Kink	$\tau^- \rightarrow e^-$	**17.8 %**
	$\tau^- \rightarrow \mu^-$	**17.4 %**
	$\tau^- \rightarrow h^-$	**49.5 %**
Trident	$\tau^- \rightarrow h^- h^- h^+$	**15.2 %**



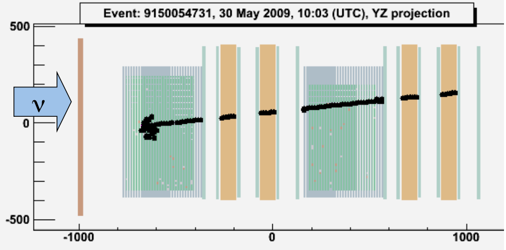


Neutrino interaction types

Detected Neutrino Interactions

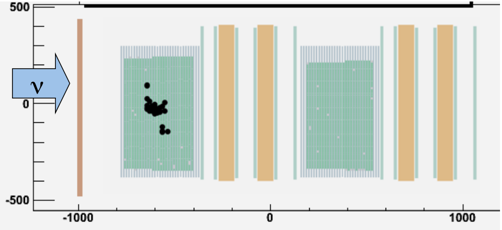
With μ

- ν_μ CC
- ν_τ CC, $\tau \rightarrow \mu$ (17.4%)



Without μ

- ν NC
- ν_τ CC, $t \rightarrow e$ (17.8%)
- ν_τ CC, $t \rightarrow h, 3h$ (64.8%)
- ν_e CC



Momentum measurement and particle ID of event tracks

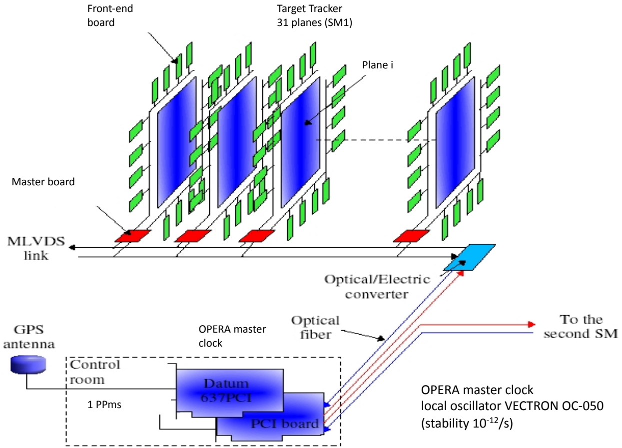
New ν_τ candidate

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 were carried out in two different labs

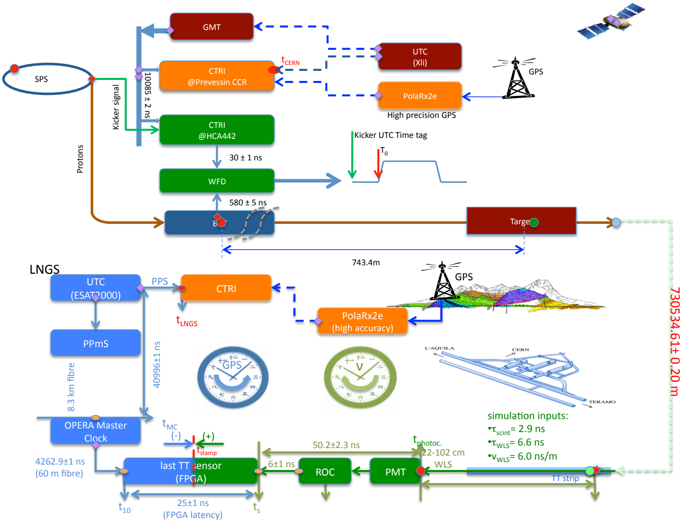
Clock distribution system

10 ns UTC time-stamp granularity

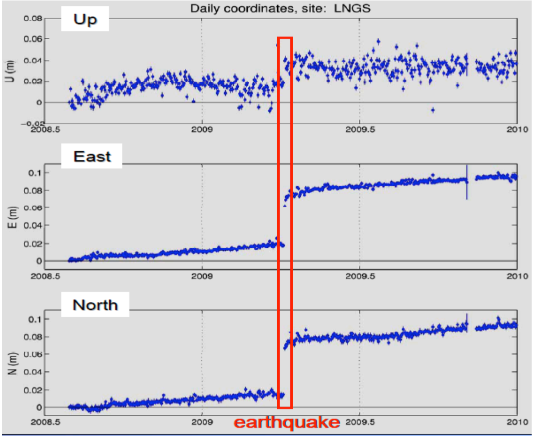


Mezzanine DAQ card common to all sub-detectors Front End nodes:
CPU, Memory, FPGA, clock receiver and ethernet

Timing chains at CERN and LNGS



LNGS position monitoring



Monitor continent drift and important geological events (e.g. 2009 earthquake)