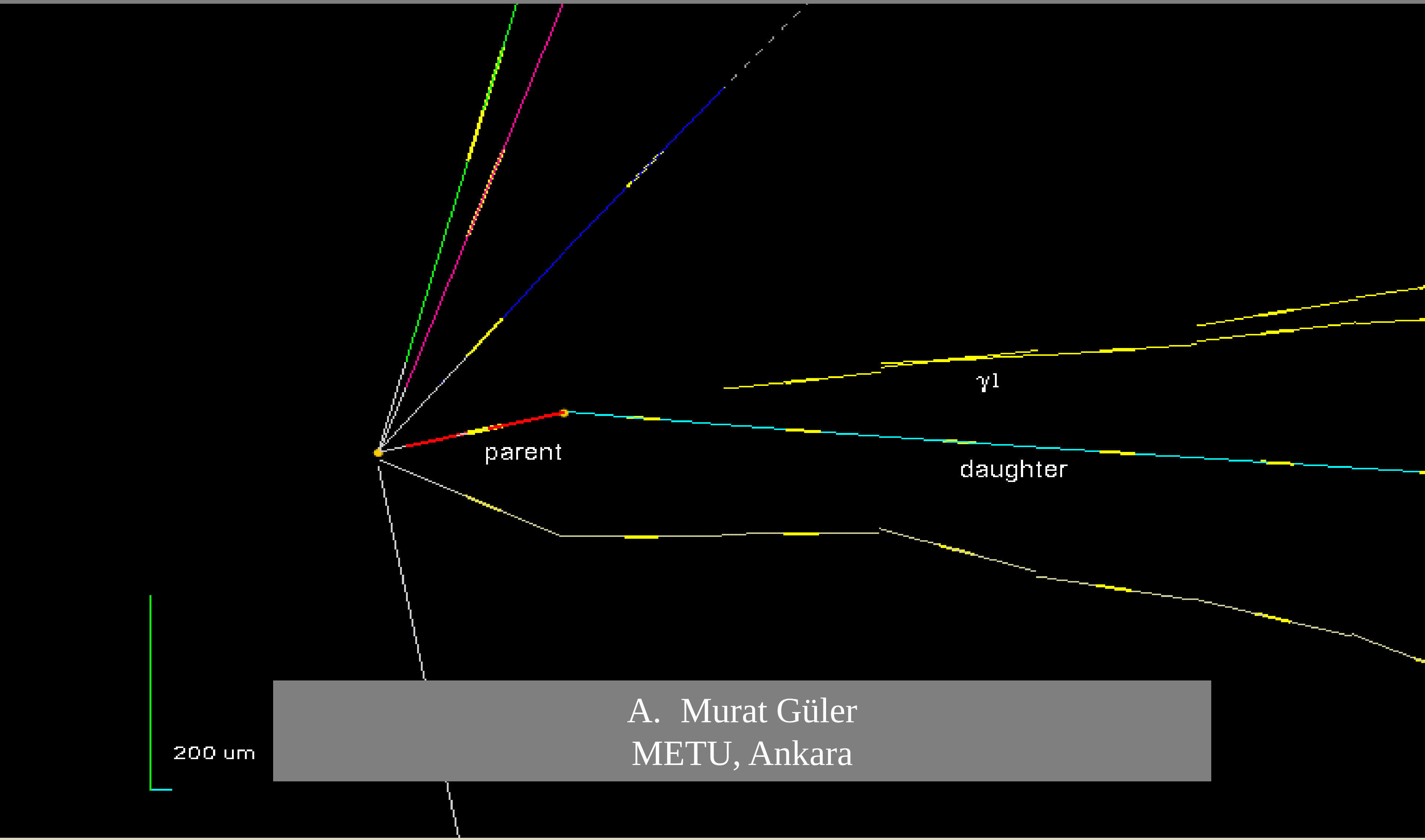
OPERA Results



A. Murat Güler
METU, Ankara

OPERA Experiment

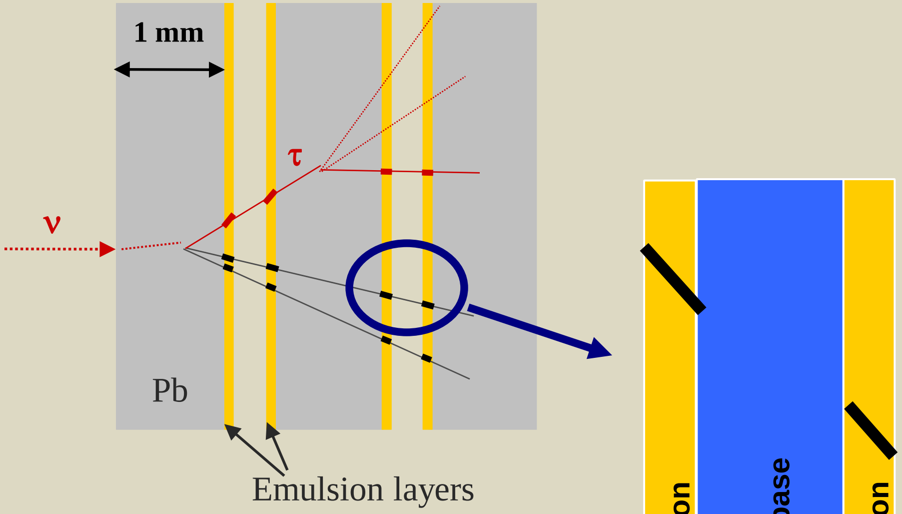
$$P(\nu_\mu \to \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \Delta m^2_{23} \cdot \frac{L}{E}\right) \sim 1.7\%$$

- Direct search for $\nu_\mu \to \nu_\tau$ oscillations by looking at the appearance of ν_τ in a pure ν_μ beam
- Requirements:

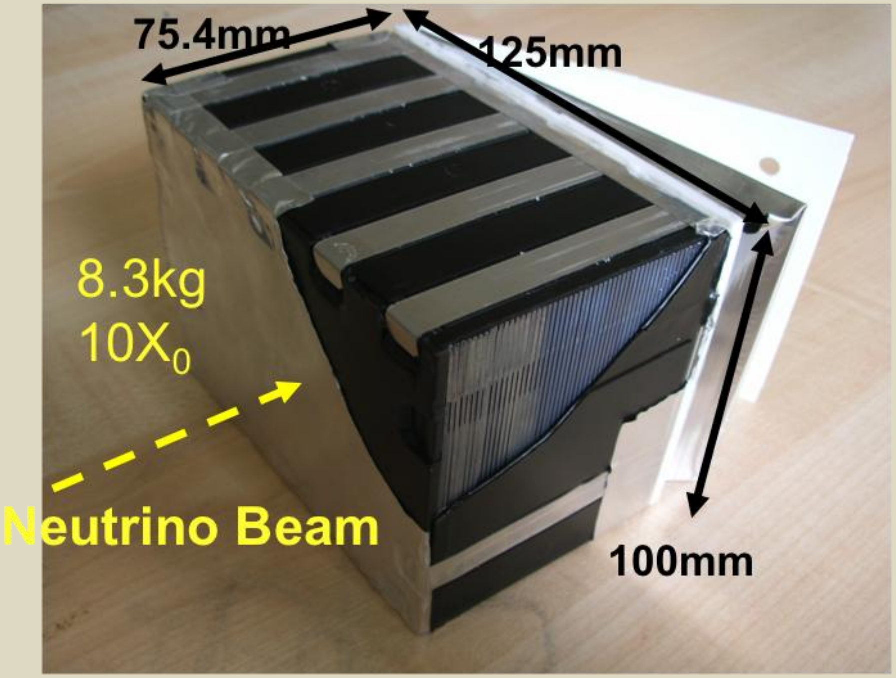
1) long baseline, 2) high neutrino energy, 3) high beam intensity,
4) large mass, 5) detect short lived τ's

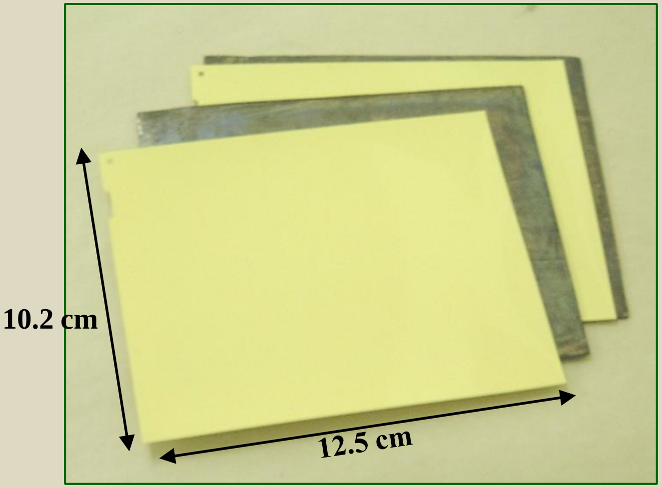
Detection Principle

➢ 1 mm thick Pb plate interleaved with emulsion film; 2 emulsion layers 44 µm thick poured on a 205 µm plastic base.



arranged in a “BRICK”:
- 57 emulsion films
- 56 Pb layers

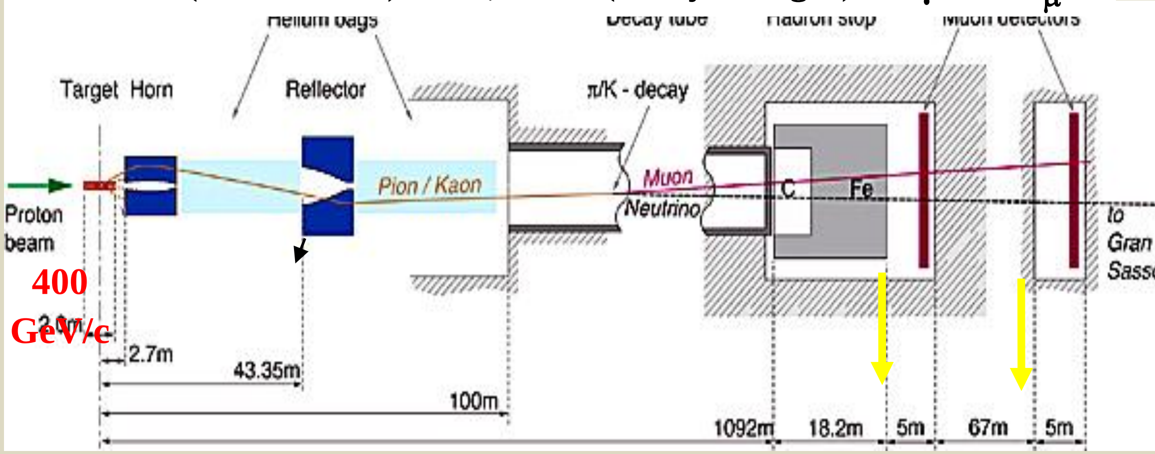




➢Track reconstruction accuracy inside emulsion film: $\Delta x \sim 1\ \mu m$ $\Delta\theta \sim 2$ mrad.

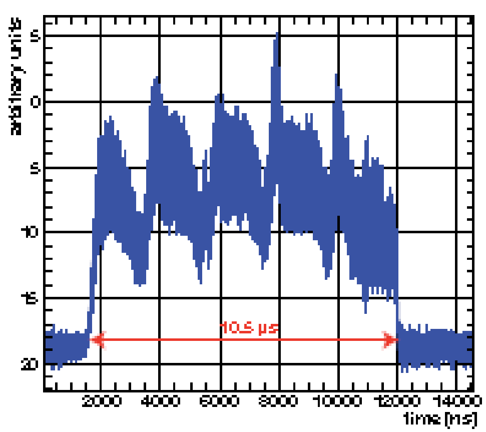
CNGS Beam

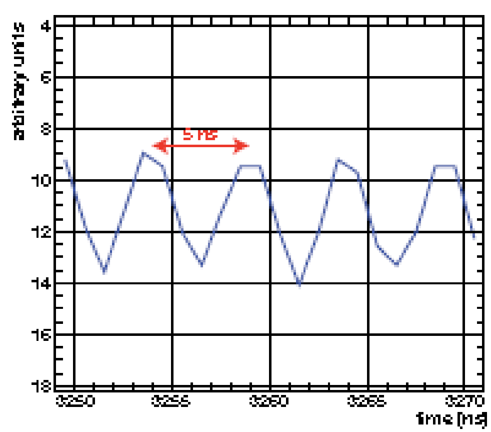
P+C → (interactions) → π^+, K^+ → (decay in flight) → $\mu^+ + \nu_\mu$

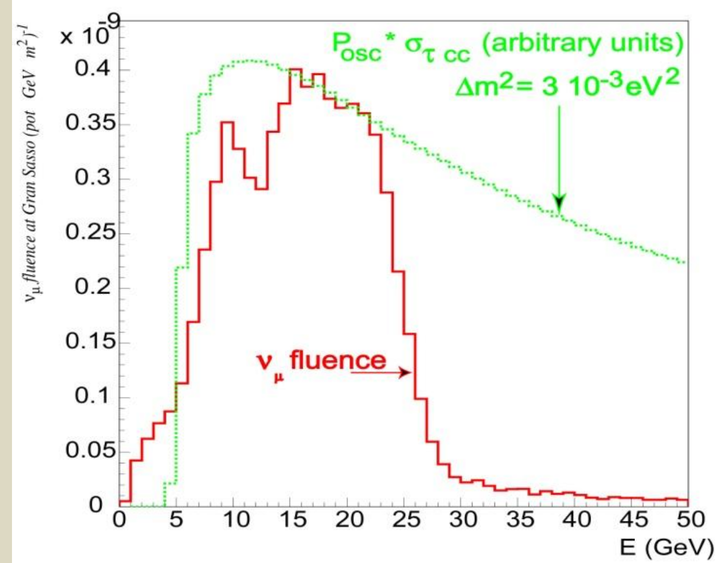


$<E\nu_\mu>$	17 Gev
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu / \nu_\mu$	4 %
ν_τ prompt	negligible
Total p.o.t	22.5x 10^{19}
ν_μ CC + NC	~23600
$\nu_e + \bar{\nu}_e$ CC	~170
ν_τ	~115

- 400 GeV/c protons from the CERN SPS on a graphite target
- 6 s cycle length, 2 extraction every 50 ms, 10.5 μs pulse length







CNGS Performance

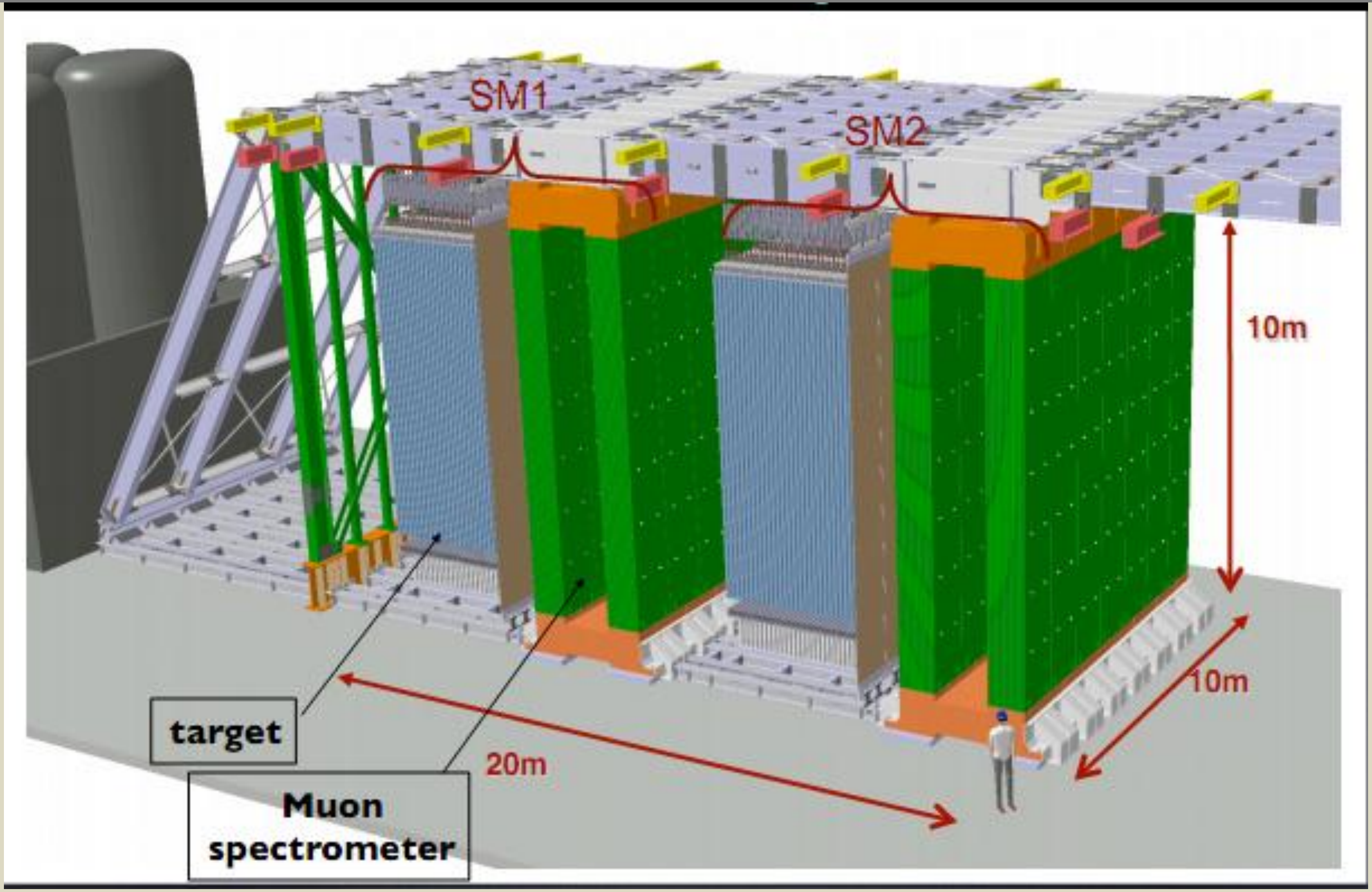
- Goal of the experiment: 22.5×10^{19} pot .

Run	POT	Integrated POT/Proposal	Accumulated event
2008	1.78×10^{19}	7.9%	1698
2009	3.52×10^{19}	23.6%	3557
2010	4.04×10^{19}	41.5%	3912
2011	4.84×10^{19}	63.0%	4210
2012	$\sim 4.00 \times 10^{19}$	～80%	～4000

- Expected POT at the end of 2012 RUN : 18.2×10^{19}

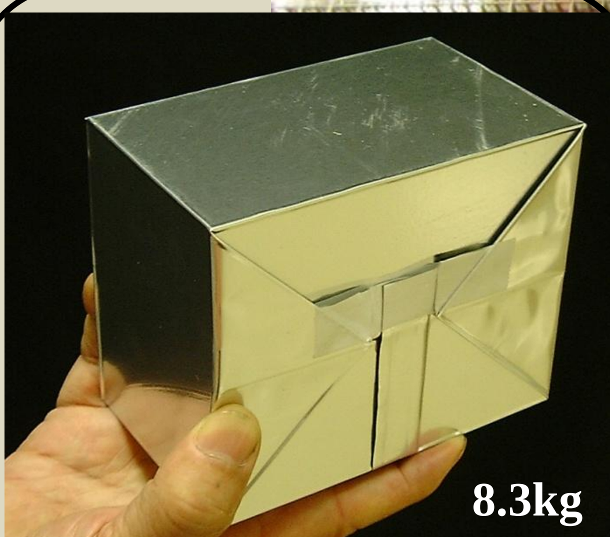
OPERA Detector

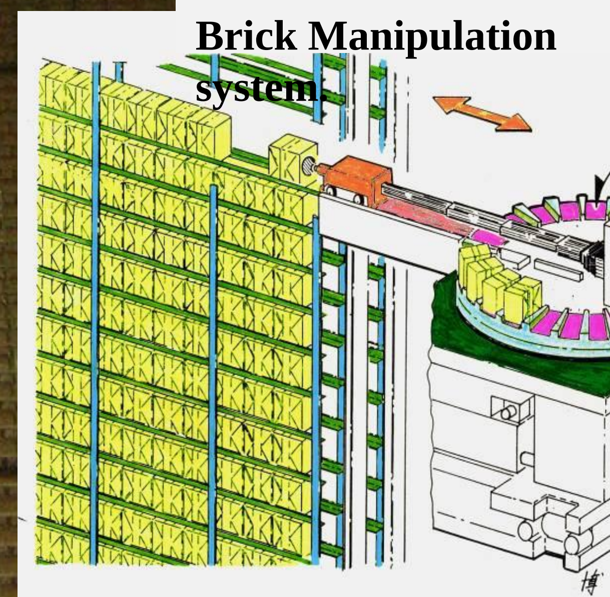
Hybrid detector (electronic + emulsions) with a modular structure:
2 supermodules = 2*(31 walls + 1 spectrometer)
↳ 31 walls = 31*(56*64 bricks + 2 scintillator tracker planes)
The total target mass = 1.25 kton



OPERA Target

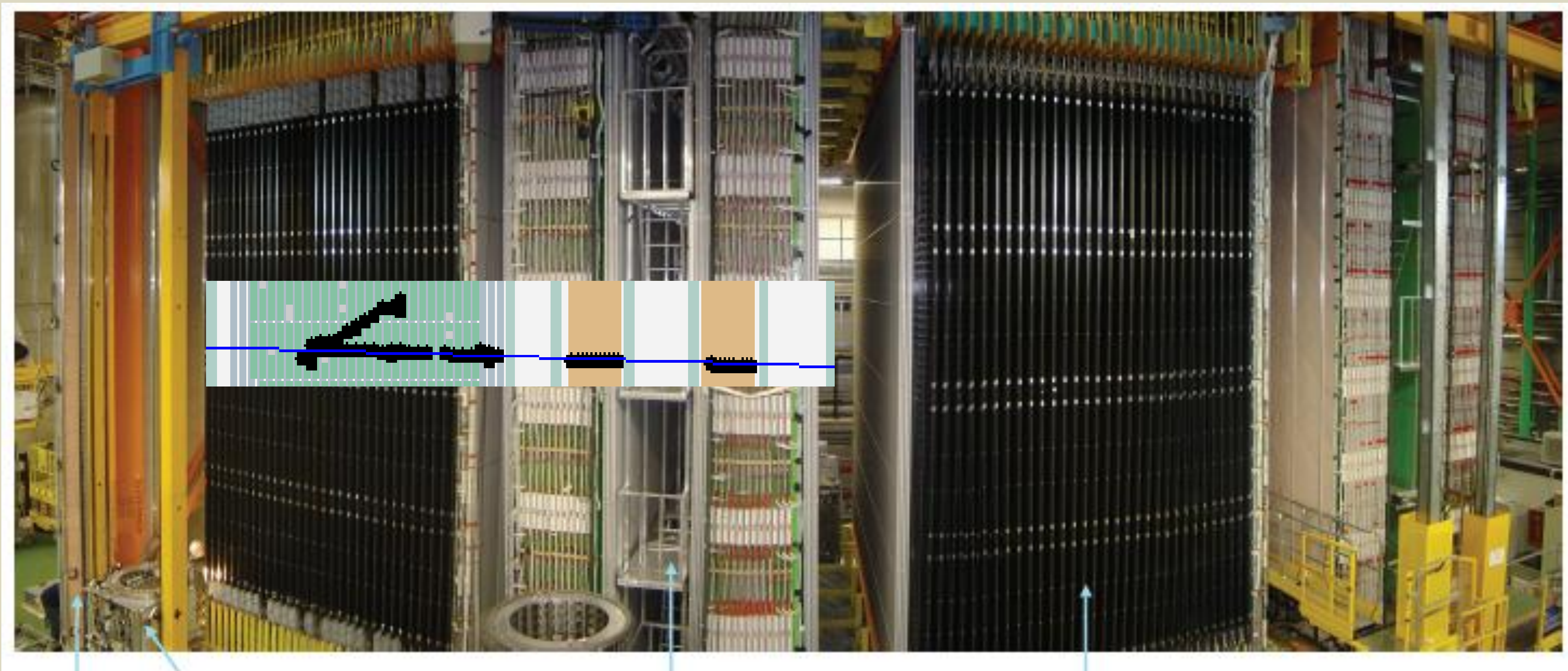
- Brick filling is finished in 2008.
- ~150,000 bricks with ~8 millions of nuclear emulsions films.
- Bricks assembling was technologically challenging. The small mechanical industry installed underground and worked in the red-light dark room





Brick Wall and Brick Manipulation system.

The OPERA Electronic Detectors



Target Tracker

- Made of plastic scintillation strips with wavelength shifting fiber s.p.e/mip > 5
- Detection efficiency: 99 %
- Brick finding efficiency: ~80 %

Muon spectrometer

- RPC and drift tubes in 1.5T magnet
- charge miss id (<25 GeV/c): <1%
- $\Delta P/P$ (<50GeV/c) ~ 20%
- μ id (with TT) ~ 95%

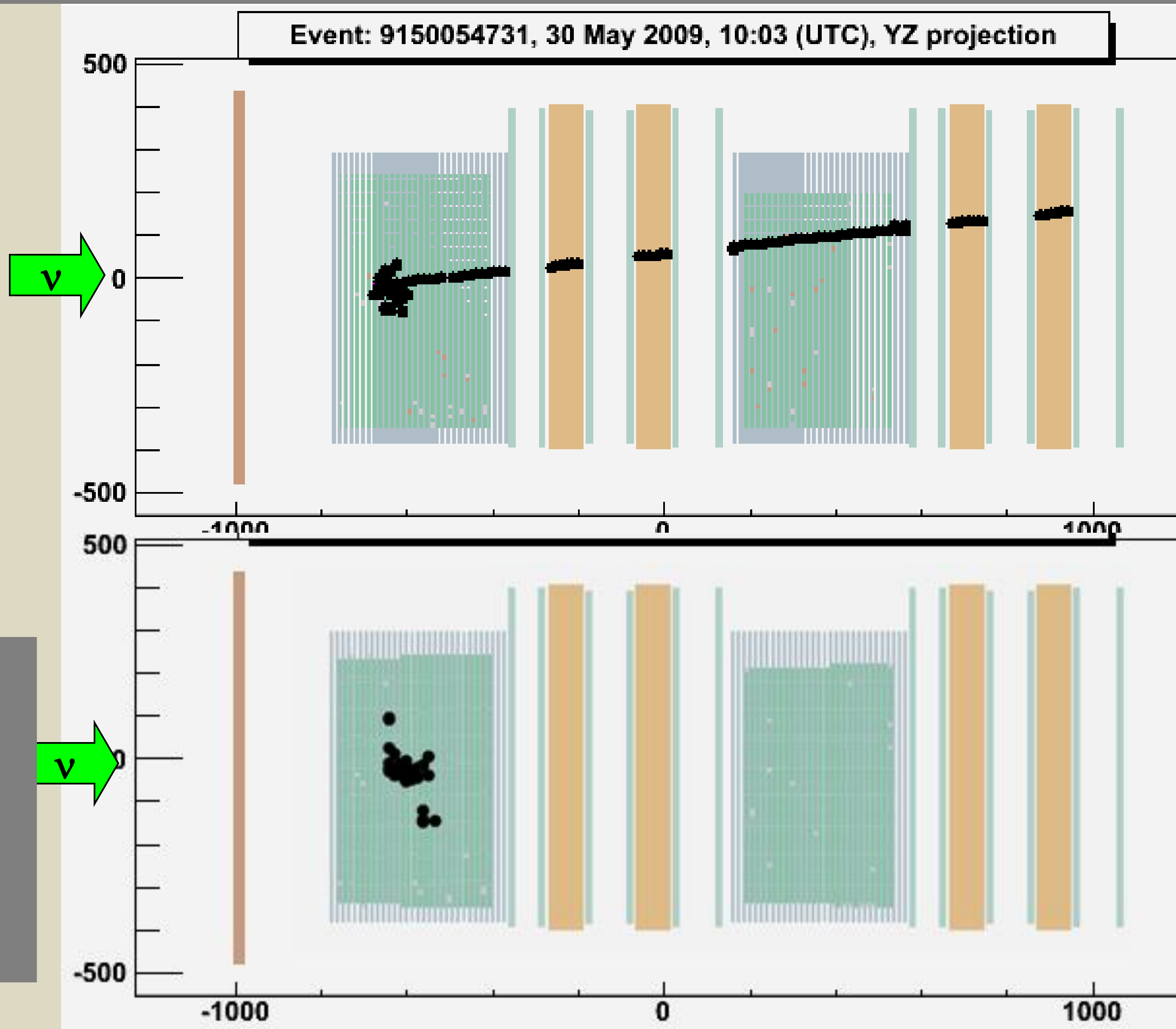
Neutrino Interactions

Muon identified

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

No muon identified

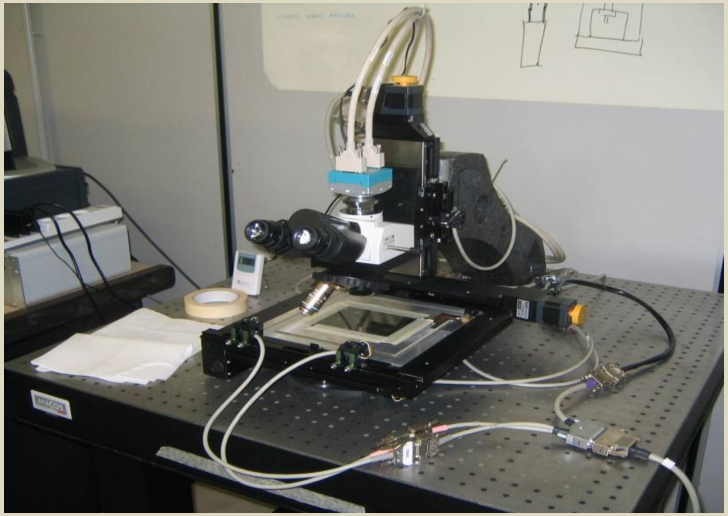
ν_μ NC
ν_e CC
ν_τ CC,
$\tau \rightarrow e$ (17.8%)
$\tau \rightarrow h, 3h$ (64.8%)



Automatic Scanning System

➢The mean area to be scanned is ~ 200 cm^2 per each OPERA event cconsidering 20000 events to process the full area to be scanned is 400 m^2 of the emulsion surface.

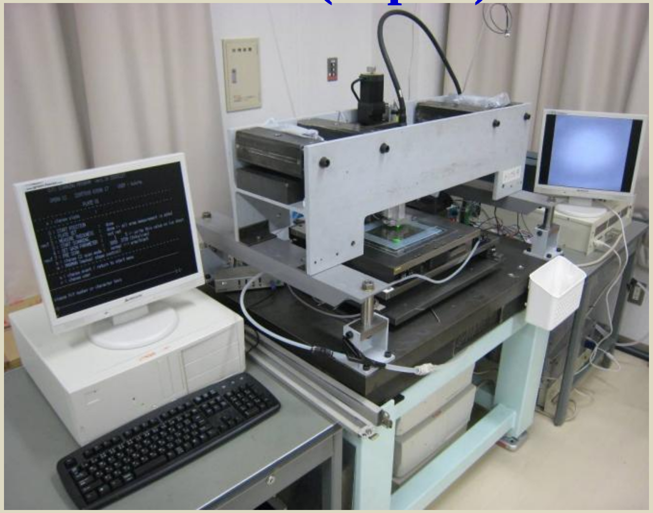
European Scanning System



➢Customized commercial optics and mechanics.

➢Scanning speed: 20 cm^2/h.

S-UTS (Japan)



➢High speed CCD Camera (3 KHz)

➢Objective lens moved by piezo-element.

➢Hard-coded algorithms.

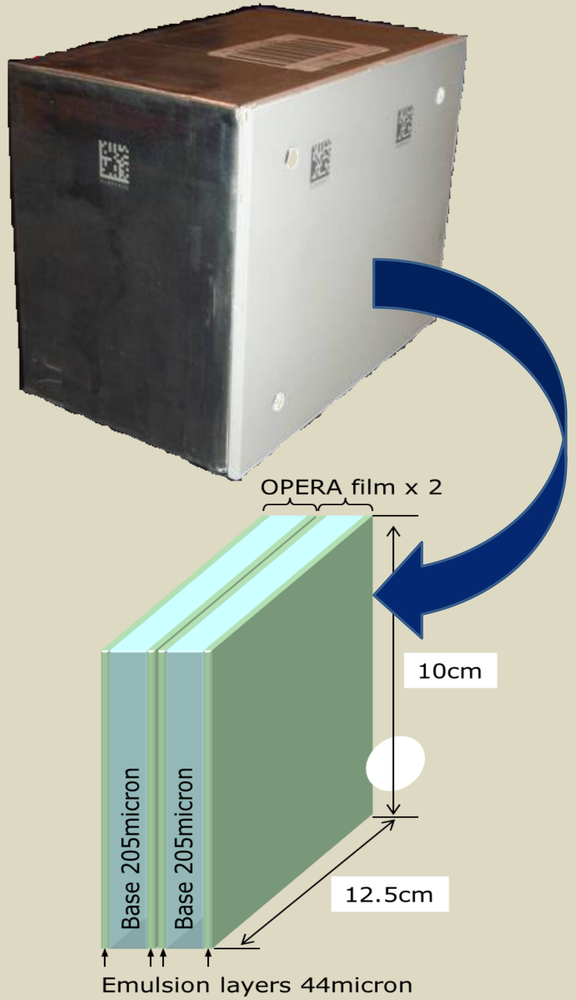
➢Scanning speed: 75 cm^2/h.

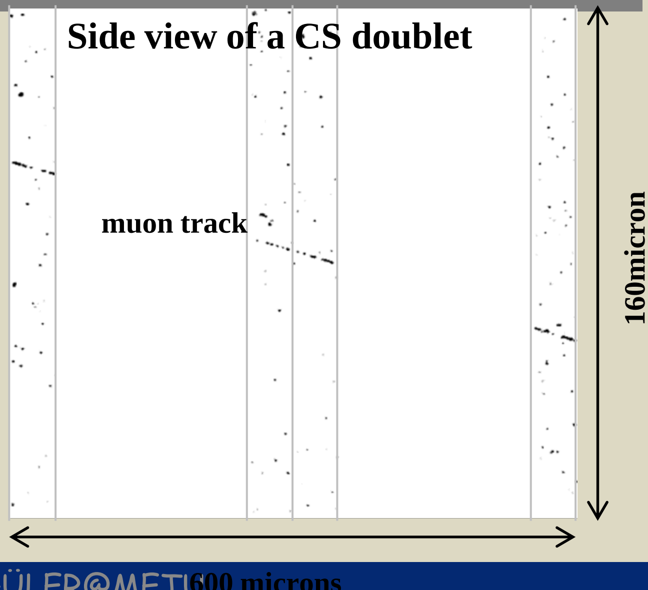
Changeable Sheet (CS)

From meters to microns:

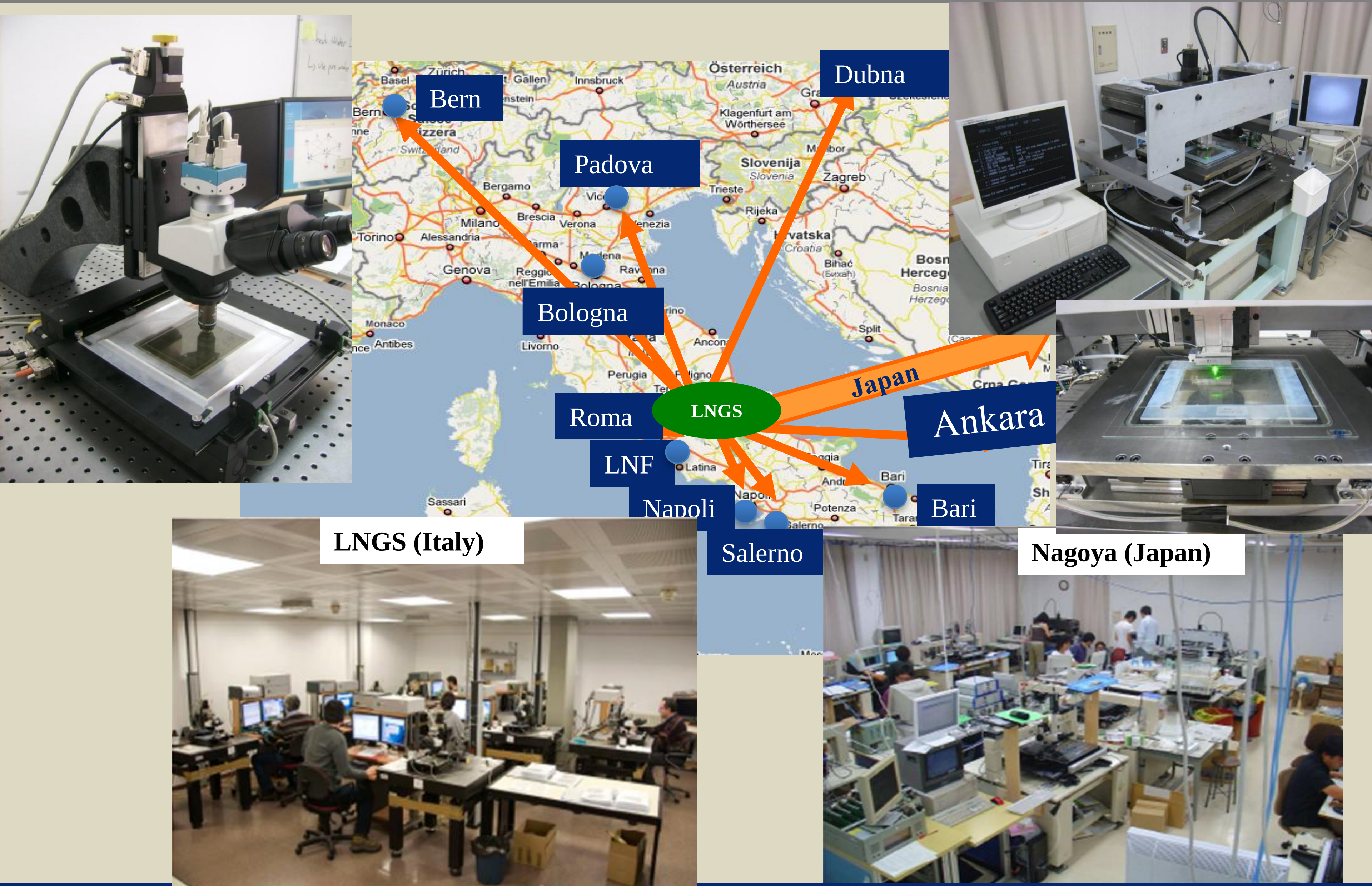
- **OPERA: 10x10 m^2**
- **TT – indicate brick ~1 cm accuracy**
- **CS – ~100 microns**
- **Inside brick near the vertex ~1 micron**

- **CS background requirements:**
  1 track/10x10 cm^2
- **Doublet film for coincidence**



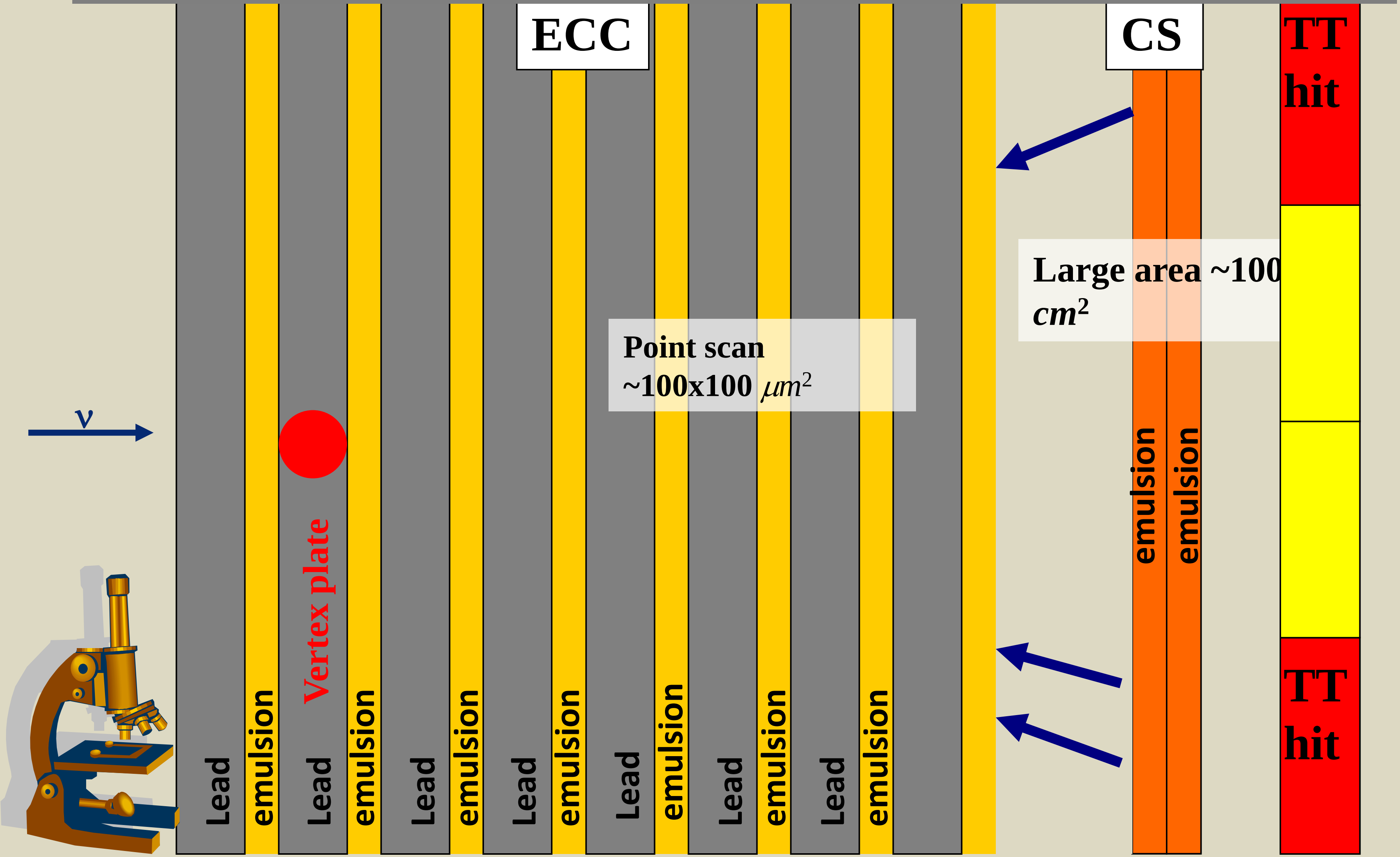


Emulsion Scanning



Emulsion Data Reconstruction

- Track following: TT->CS-Brick upstream till the vertex .



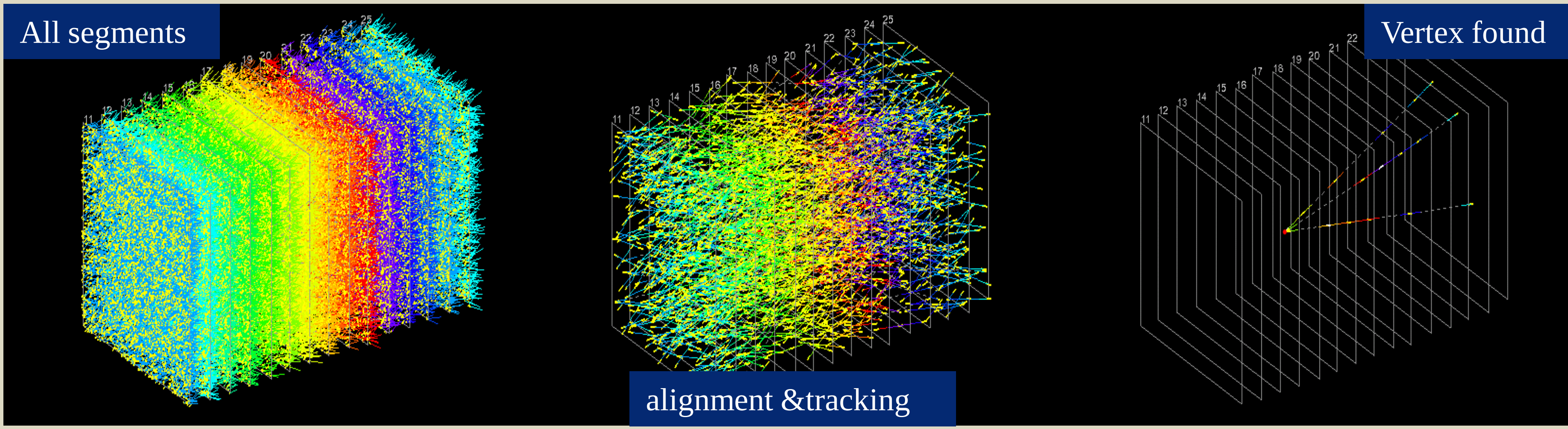
Emulsion Data Reconstruction

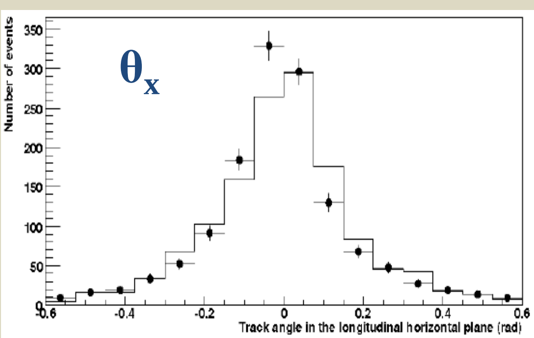
- Volume scan and reconstruction of all tracks around the expected vertex position

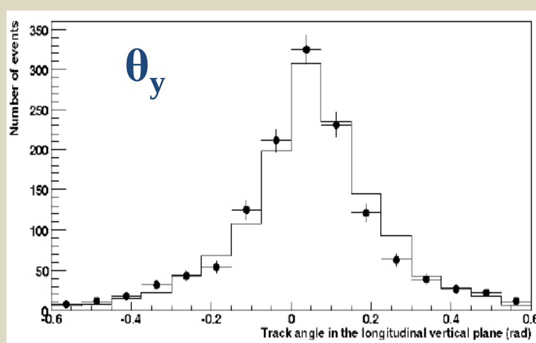
All segments

alignment &tracking

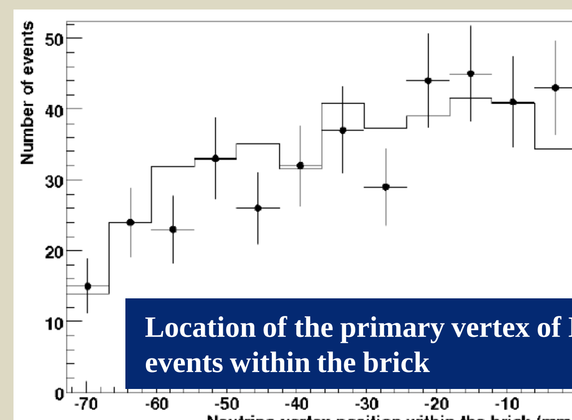
Vertex found







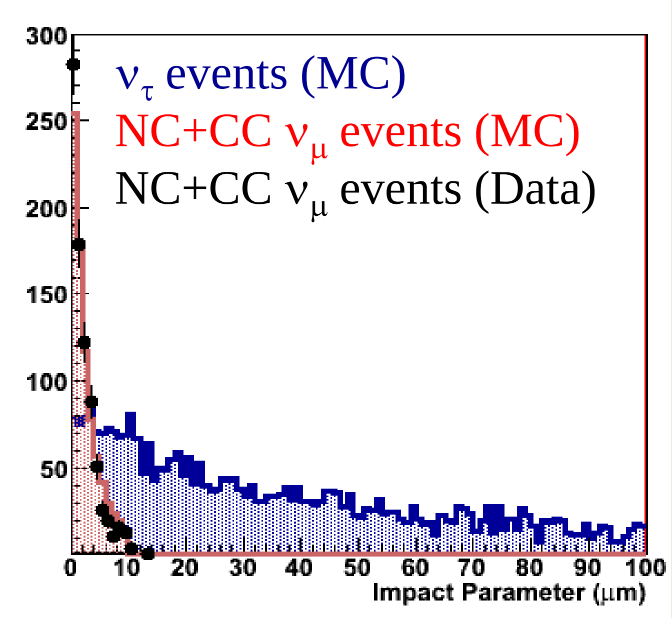
Angular distribution of tracks attached to the vertex



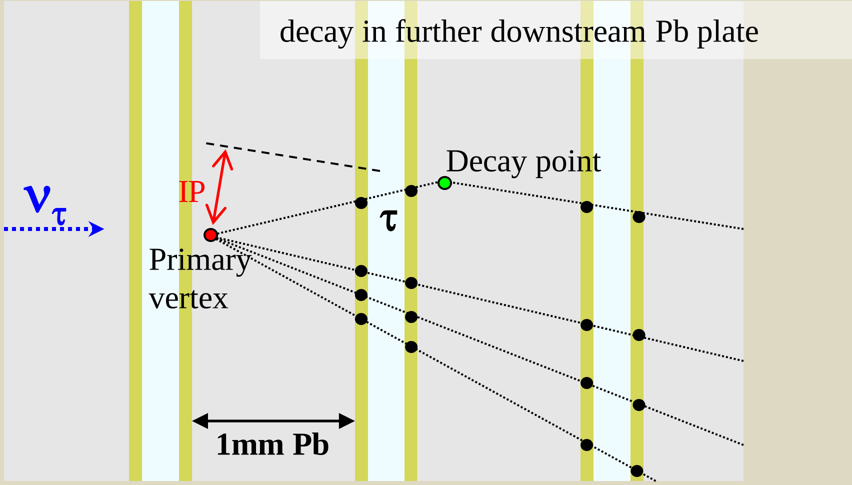
Location of the primary vertex of NC events within the brick

Decay Search

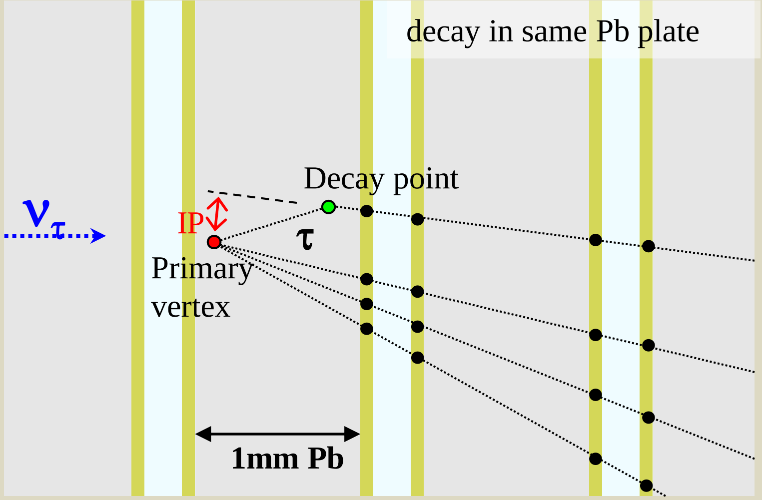
Impact Parameter distribution



Long flight decay



Short flight decay

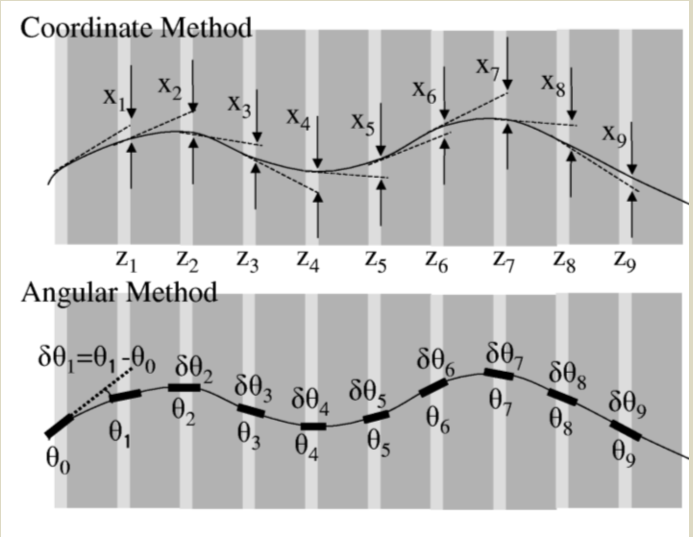


τ decay topology

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

Event Kinematics

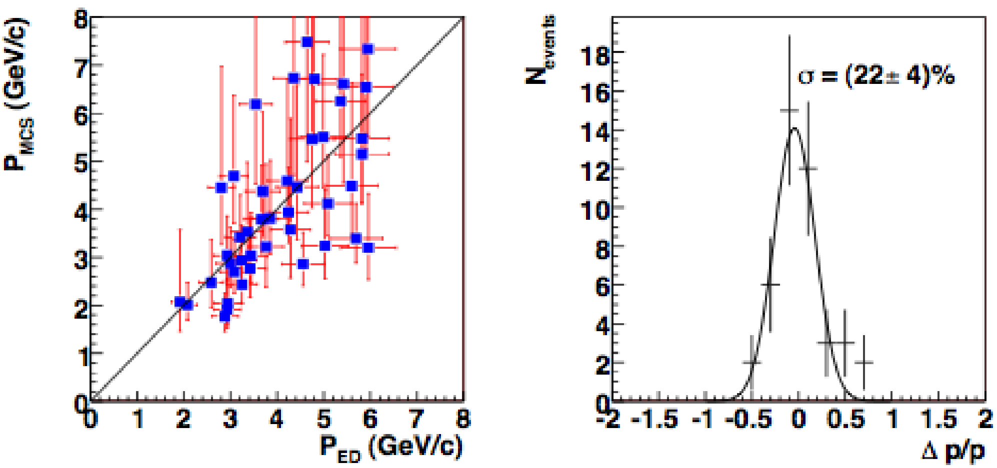
- ➢Particle ID is possible in ECC by dE/dx. (hadron or muon or electron)
- ➢Measurement of the position or angular displacement caused by the Multiple Coulomb Scattering



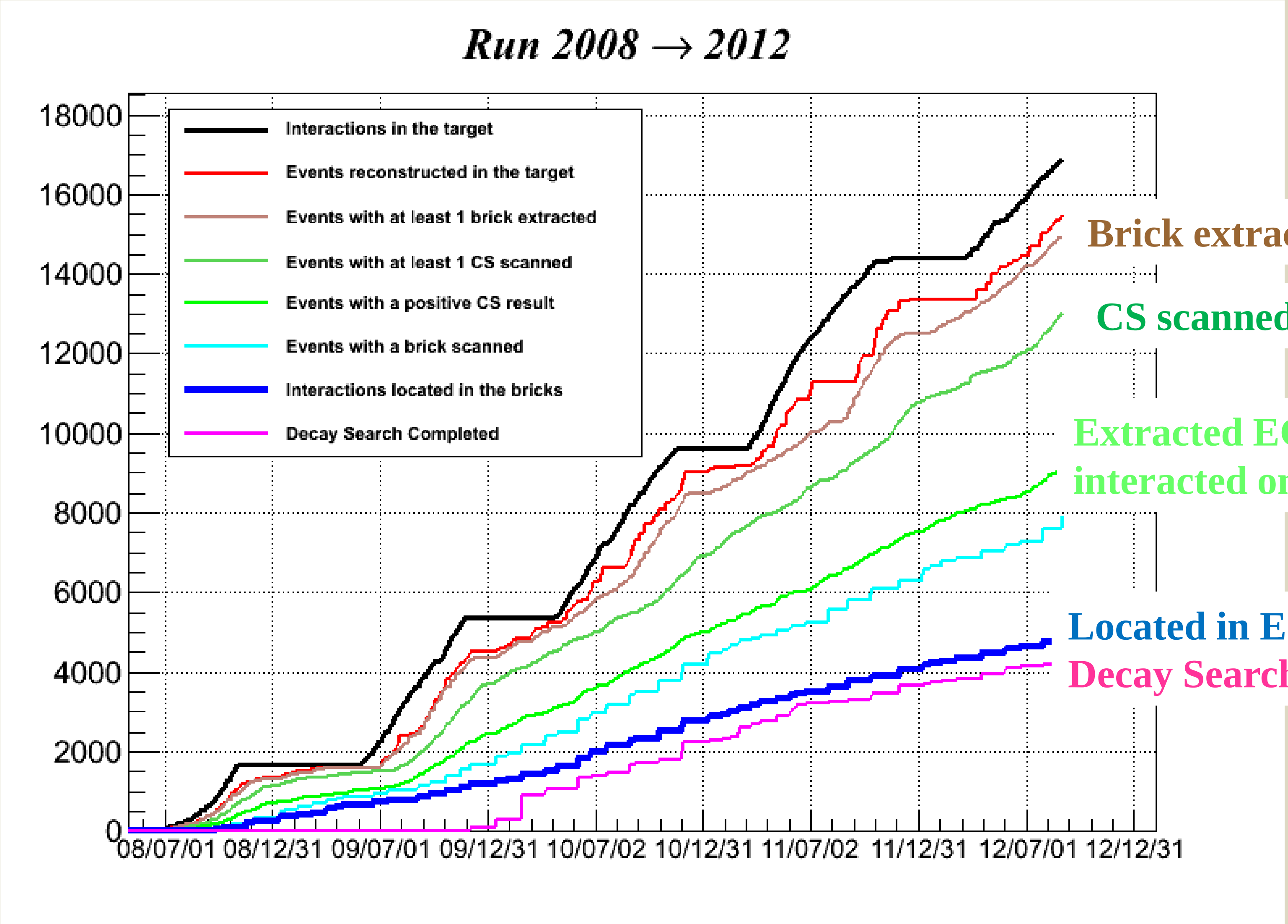
$$d\theta^{RMS} = \frac{13.6}{pc\beta} z \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right)$$

Soft data sample

- ➢**Muon momenta measured by MCS as a function of the momenta obtained from the electronic detectors.**



Located Events in ECC



Brick extraction

CS scanned

Extracted ECC was interacted one

Located in ECC 4898

Decay Search 4190

Analysis of 2008-2009 Data

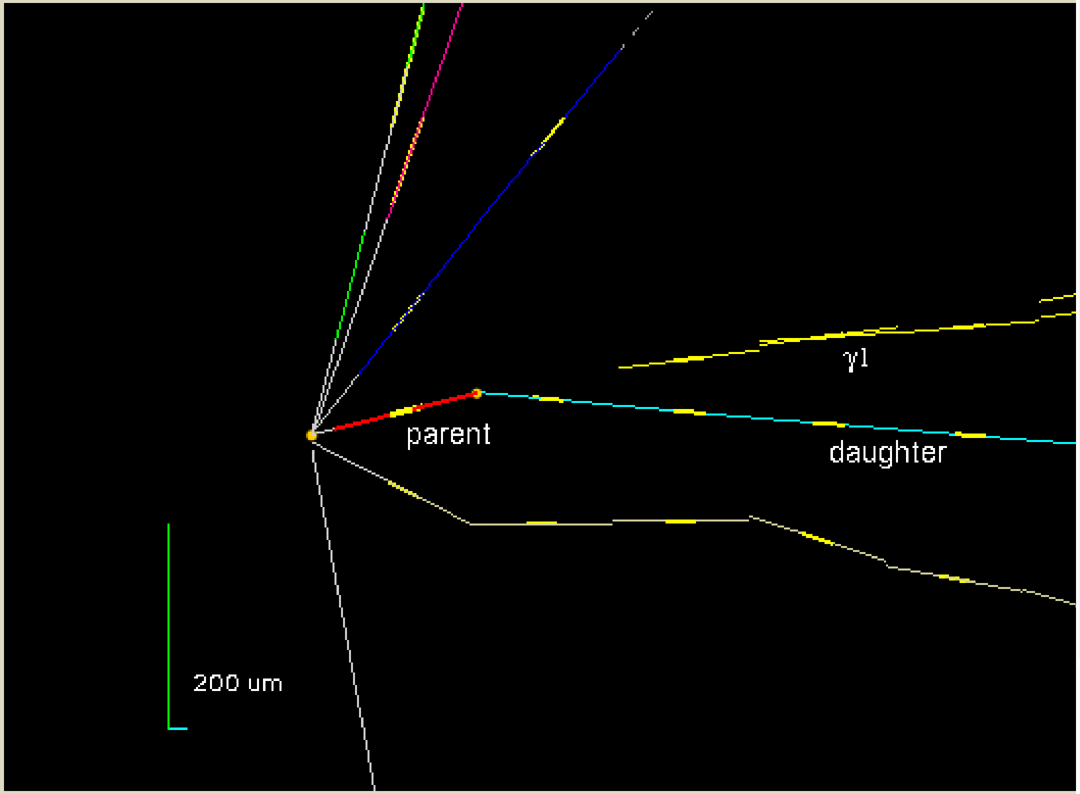
- Minimum bias analysis
  - no kinematical pre-selection.
  - 2825 interactions : located in ECC.
  - 2738 interactions : decay search was applied.

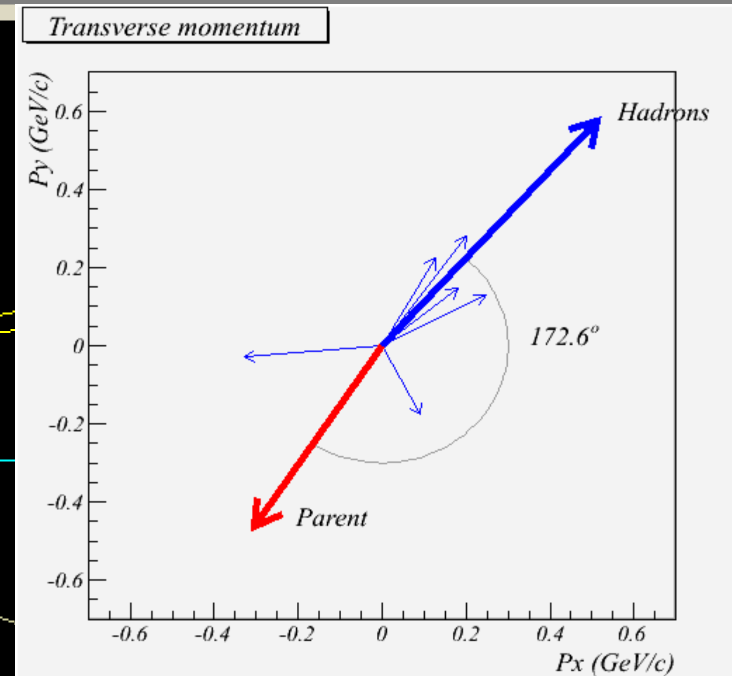
- Results
  - 1st tau neutrino event was found. *Published in PLB 691(2010)138*
  - Systematic electron neutrino search .

    19 electron neutrino candidate events was identified

    （to be submitted soon).

The First τ Candidate





Variable	Estimate	Cut
kink	$41 \pm 2\ mrad$	$> 20\ mrad$
decay length	$1335 \pm 35\ \mu m$	< 2 *lead plates* $(\sim 2600\ \mu m)$
daughter P	$12^{+6}_{-3} GeV/c$	$> 2 GeV/c$
decay Pt	$620^{+310}_{-155}\ MeV$	$> 300 MeV/c$ (600 *if no* γ *at decay vtx*)
missing Pt	$530^{+300}_{-160}\ MeV$	$< 1\ GeV/c$
ϕ (angle btw. had. system and tauon)	$173° \pm 2°$	$> 90°$

➢Interpretation of the event

$\tau \to \rho \nu_\tau$ candidate

$\rho \to \pi^- \pi^0$ $(\pi^0 \to \gamma\gamma)$

$m(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV

$m(\pi^- \gamma\gamma) = 640^{+125}_{-80}{}^{+100}_{-90}$ MeV

$Br(\tau \to \rho \nu_\tau) \sim 25\%$

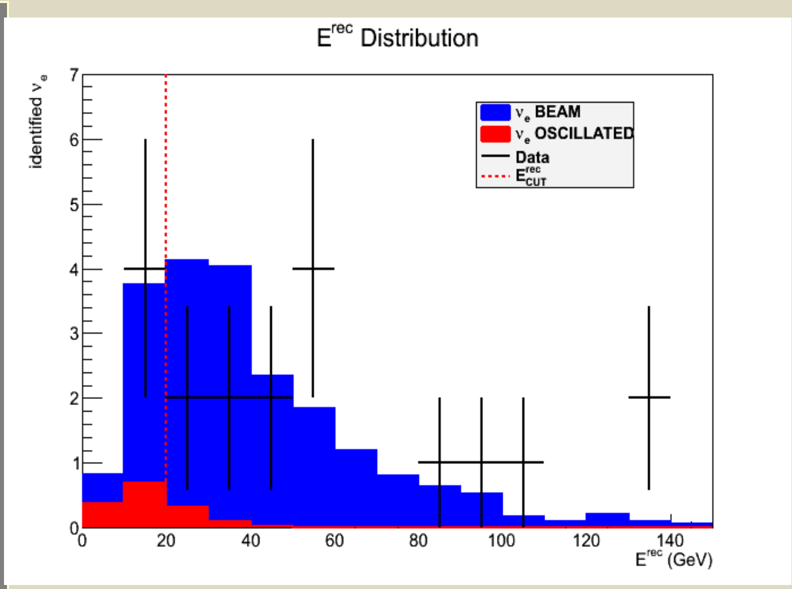
$\nu_\mu \rightarrow \nu_e$ Oscillation Search

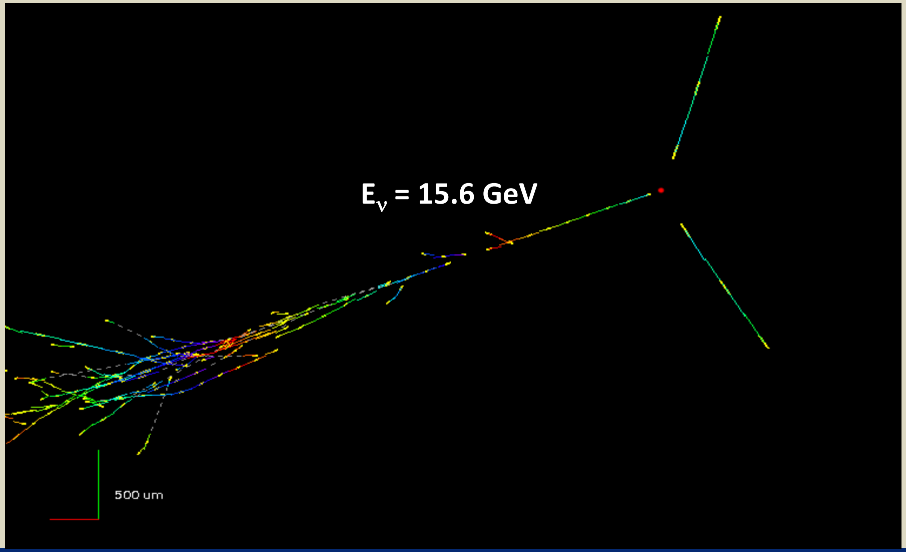
- Systematic search for electron neutrinos applied to 505 events without muon in the final state (2008 – 2009 data)

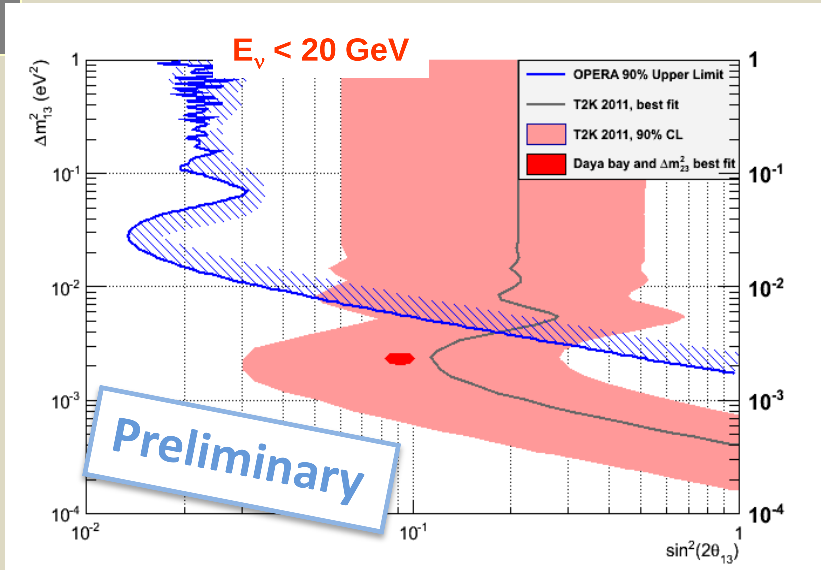
- Expected events: 19.2 (beam) + 1.5 (oscillated)
- Observed events: 19

- E_ν < 20 GeV (improve S/N ratio)

- Expected events: 3.7 (beam) + 1.1 (oscillated)
- Observed events: 4







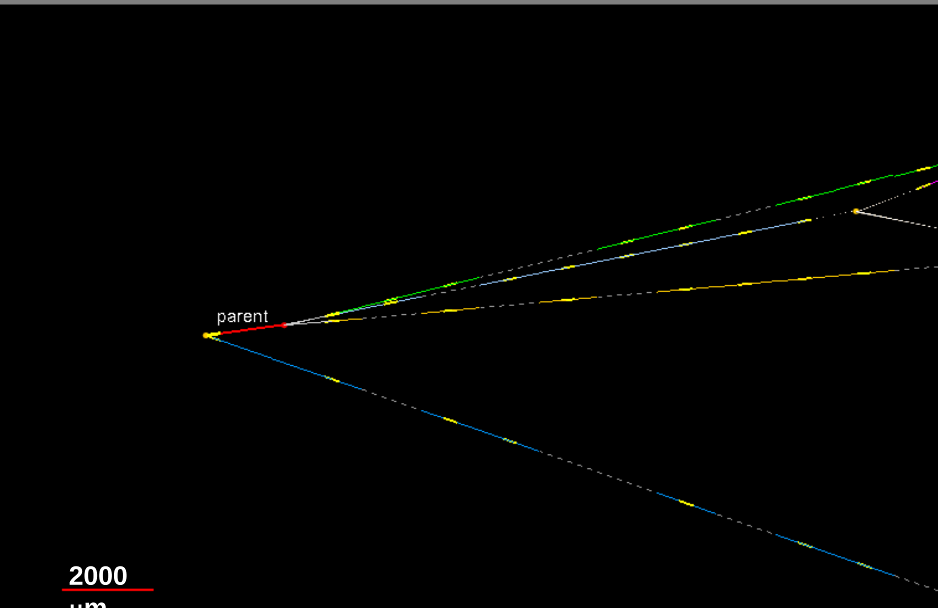
Analysis Status 2010-2012

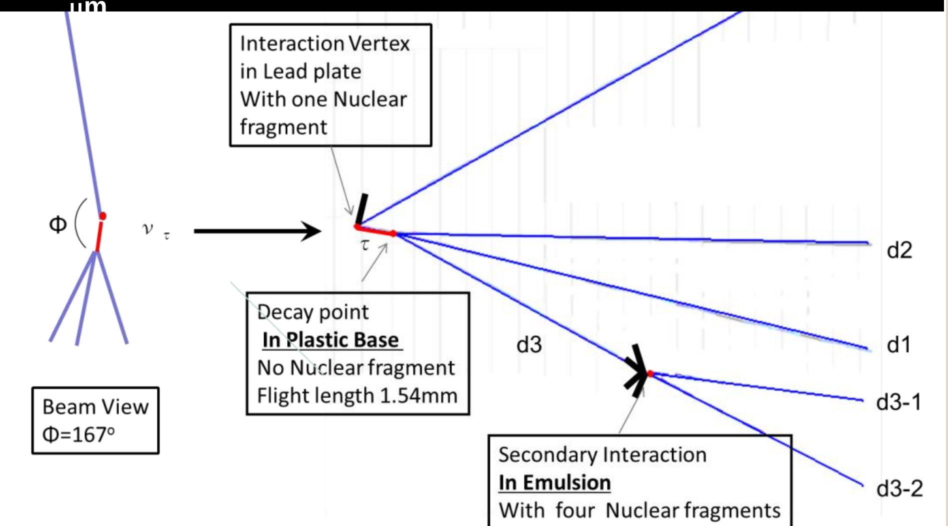
- Pre-selection for oscillation analysis:
  - 1mu events with muon momentum < 15 GeV/c

    (30 % reduction of 1mu events)
  - All 0mu events

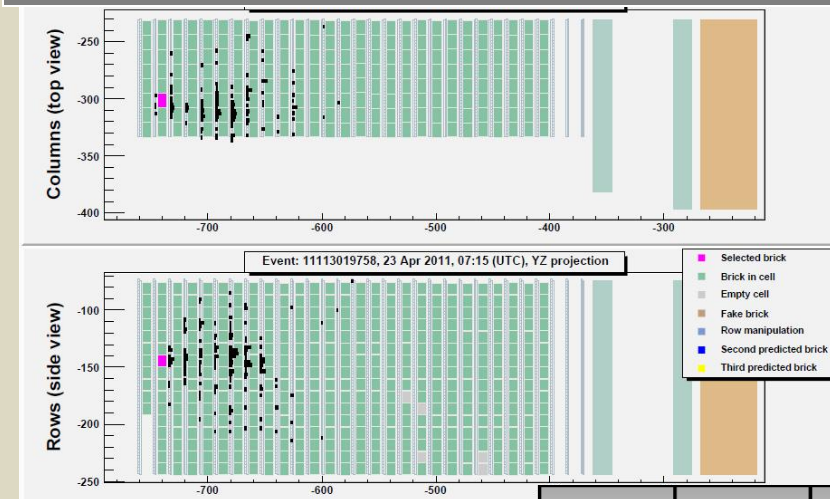
- Status:
  - 1343 interactions were located and decay search was done.
  - 2nd tau neutrino event was found

The Second τ Candidate





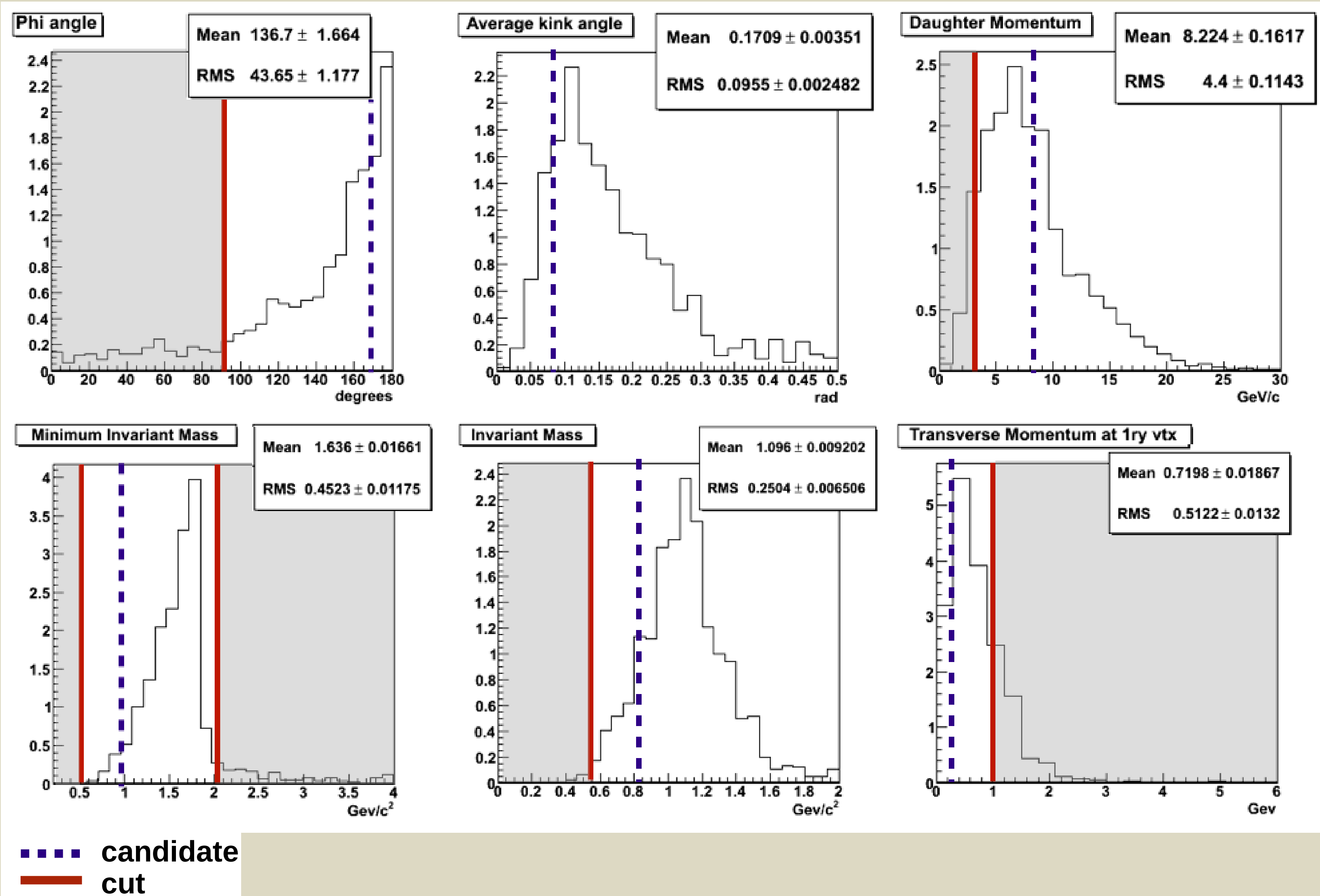
➢No muon detected at the primary vertex:



	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

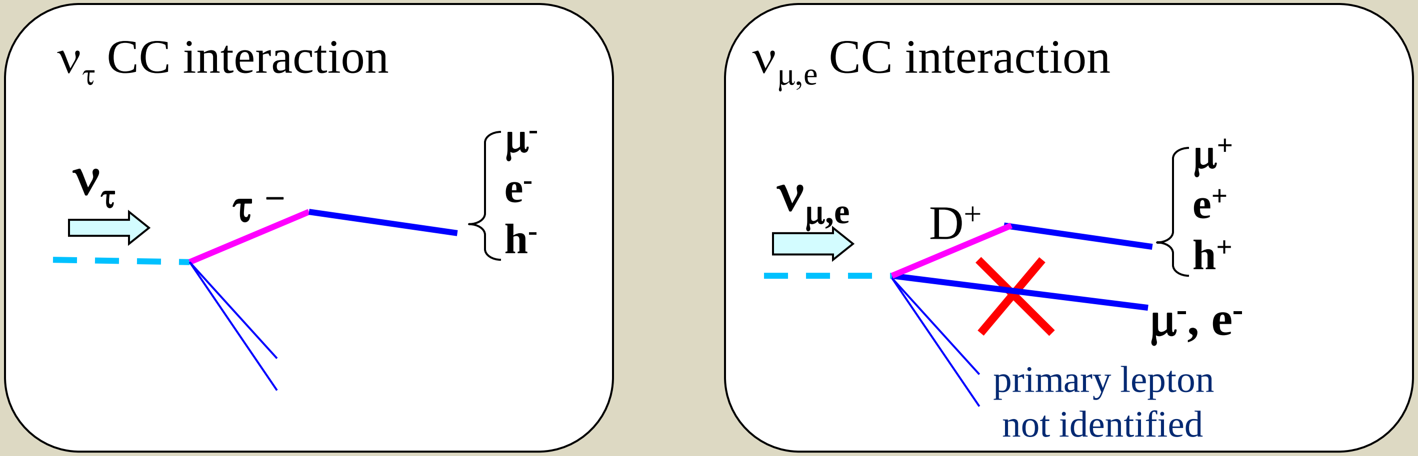
➢2-prong ν interaction with one track showing a secondary vertex compatible with the hypothesis of $\tau^- \rightarrow h^+ h^- h^- \nu_\tau$

The Second τ Candidate



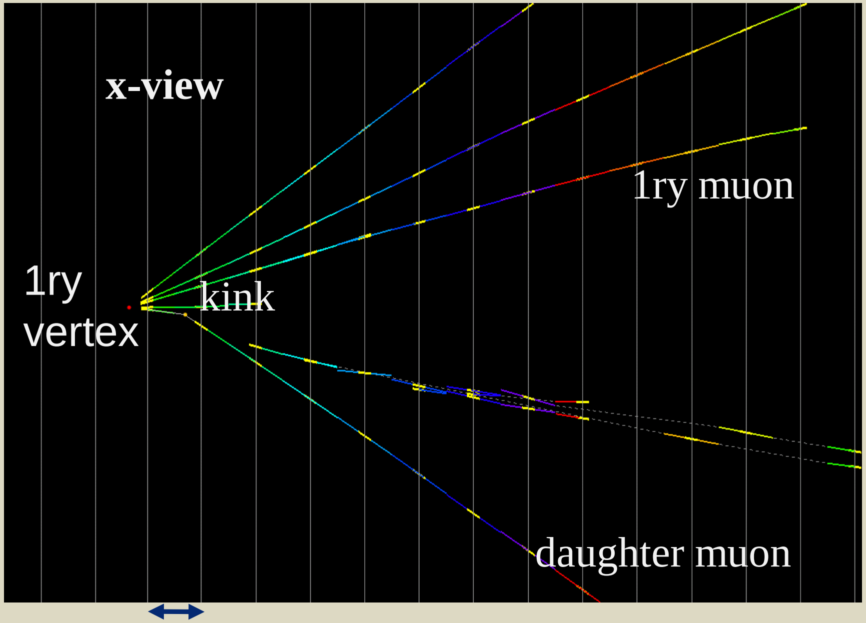
Background Sources for ν_τ

- Charmed particles have similar decay topologies to the τ.



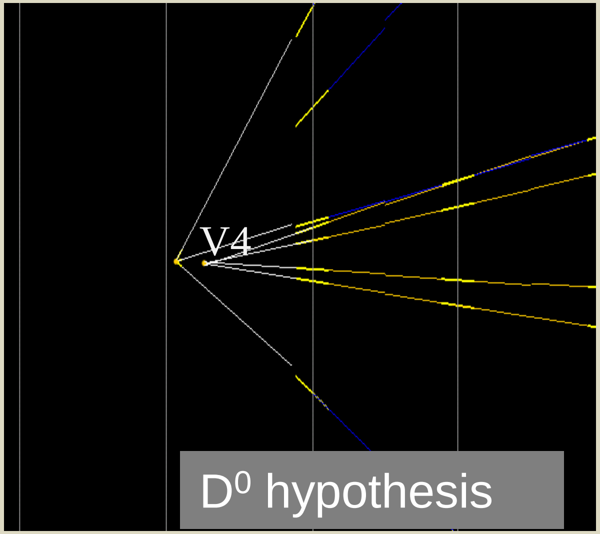
- Charm production in CC events represents a background source to all tau decay channels.
- This background can be suppressed by identifying the primary lepton.

Charm Candidate



1.3 mm

FL: 1330 μm
kink angle: 209 mrad
IP : 262 μm
daughter muon: 2.2 GeV/c
Pt: 0.46 GeV/c



FL: 313.1 μm,

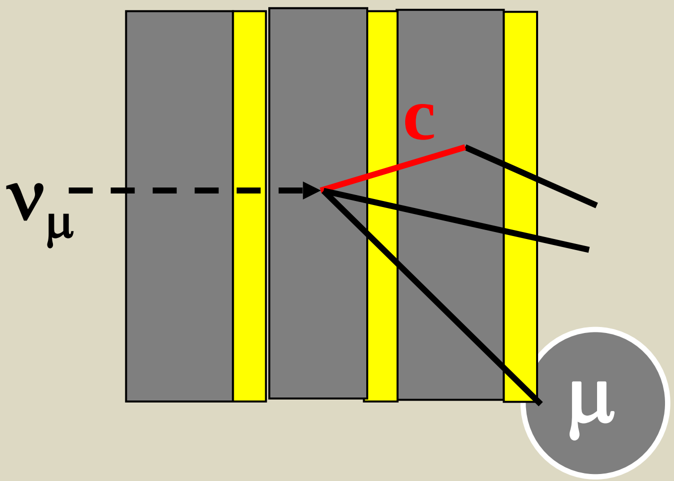
ϕ : 173.2^0,

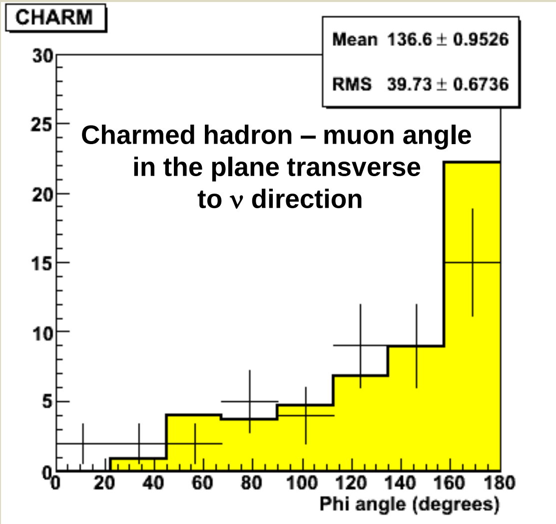
invariant mass: 1.7 GeV

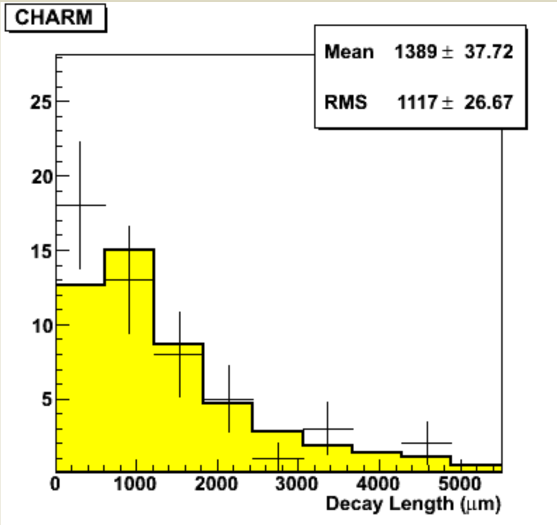
Charm Sample

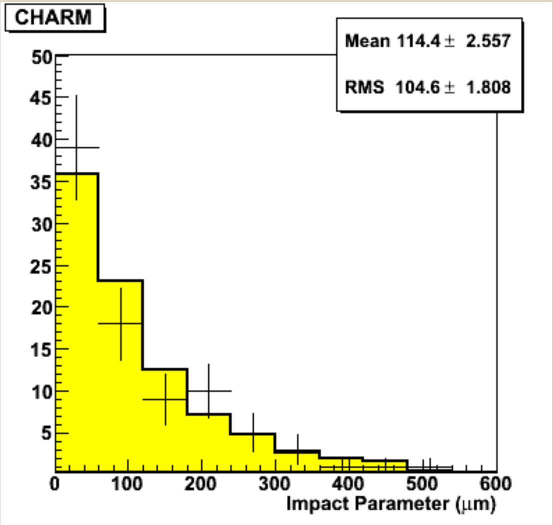
➢Charged Charm's life time and its decay topology are similar with tau.
→Tau detection efficiency validation sample

Expected events: 51 ± 7.5
Observed events: 49



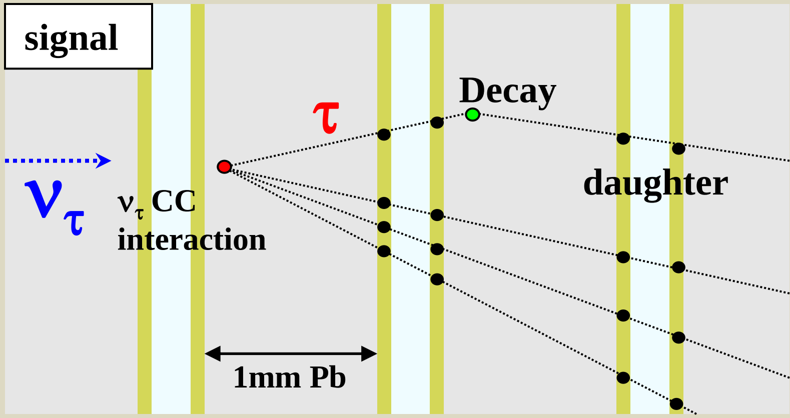


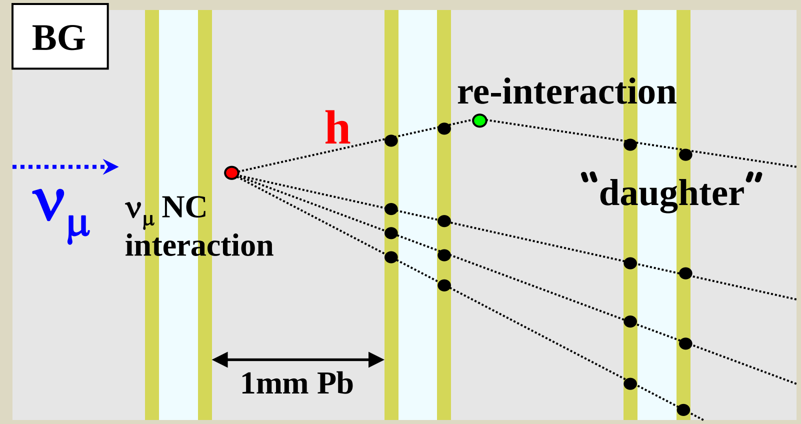




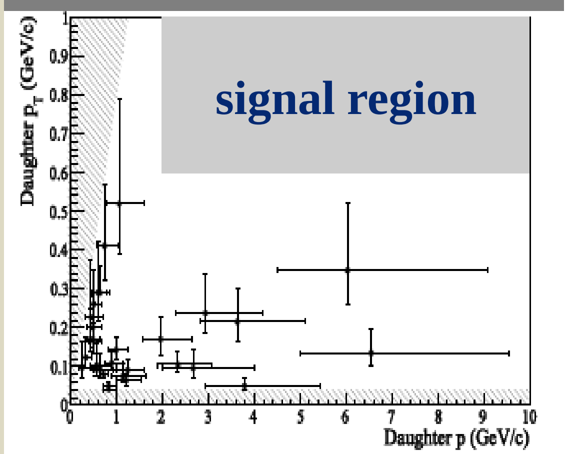
Background Sources for ν_τ

➢Interactions of hadrons produced in ν_μ interactions

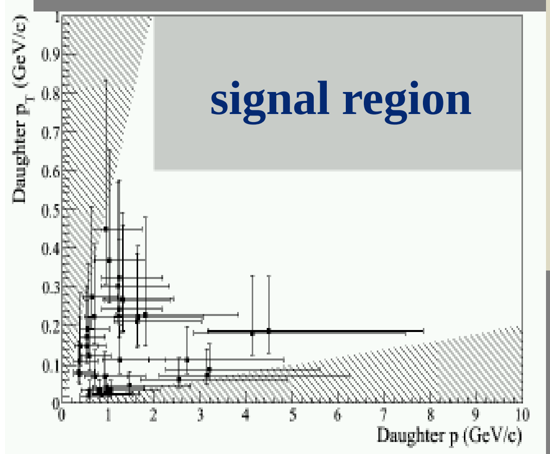




Hadronic tracks in neutrino interactions



Hadronic interactions in test beam



14 m, equivalent to 2300 NC events

signal, BG separation

Kinematical cut
- "daughter" momentum (p) > 2 GeV/c
- "daughter" transverse momentum (P_T) > 0.6 GeV/c

(If gamma attached: P_T > 0.3 GeV/c)

Expected Background

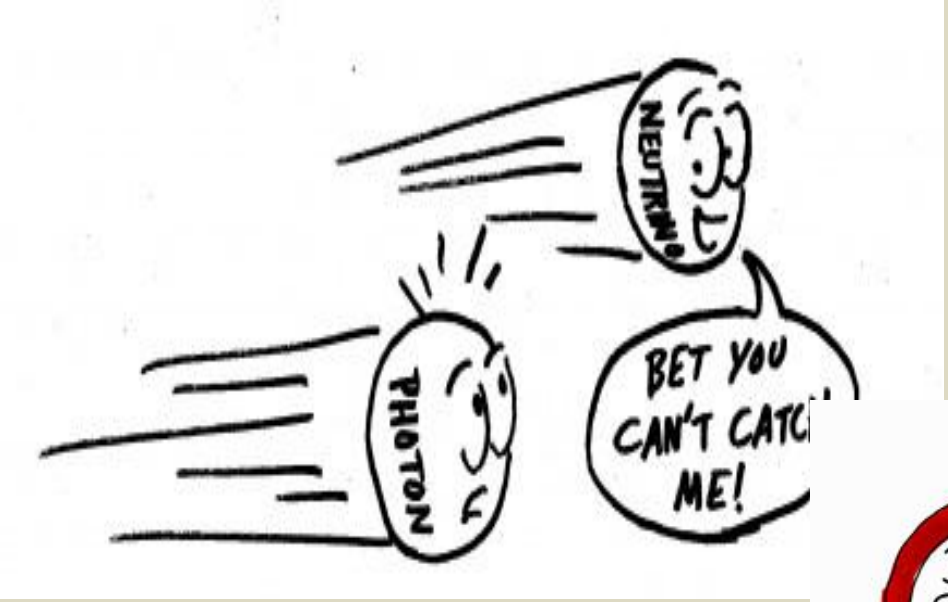
preliminary

	Signal	Bck	Charm	Mu scattering	Hadrons
Tau→mu	0,49	0,02	0,01	0,02	0,00
Tau→e	0,68	0,05	0,05	0,00	0,00
Tau→h	0,56	0,06	0,03	0,00	0,03
Tau→3pi	0,18	0,05	0,05	0,00	0,00
total	1,91	0,18	0,14	0,02	0,03

Conclusions I

- 4898 neutrino interactions were located in ECC.
  - 2 tau neutrino events found .
  - 49 charm associating CC event were found with good agreement to MC expectations.
  - 19 electron neutrino events (2008-2009) were identified and a limit for $\nu_\mu \rightarrow \nu_e$ oscillations was set .

Neutrino Velocity



Past Experimental Results

- FNAL experiment (*Phys. Rev. Lett. 43 (1979) 1361*)
 high energy (E_ν > 30 GeV) short baseline experiment.
Tested deviations down to $|v-c|/c \leq 4\times10^{-5}$
(comparison of muon-neutrino and muon velocities).

- MINOS (*Phys. Rev. D 76 (2007) 072005*)
muon neutrinos, 730 km baseline, E_ν peaking at ~3 GeV with a tail extending above 100 GeV. $(v-c)/c = 5.1 \pm 2.9\times10^{-5}$ (1.8 σ).

- SN1987A (see e.g. *Phys. Lett. B 201 (1988) 353*)
electron (anti) neutrinos, 10 MeV range, 168'000 light years baseline.
 $|v-c|/c \leq 2\times10^{-9}$. Performed with observation of neutrino and light arrival time.

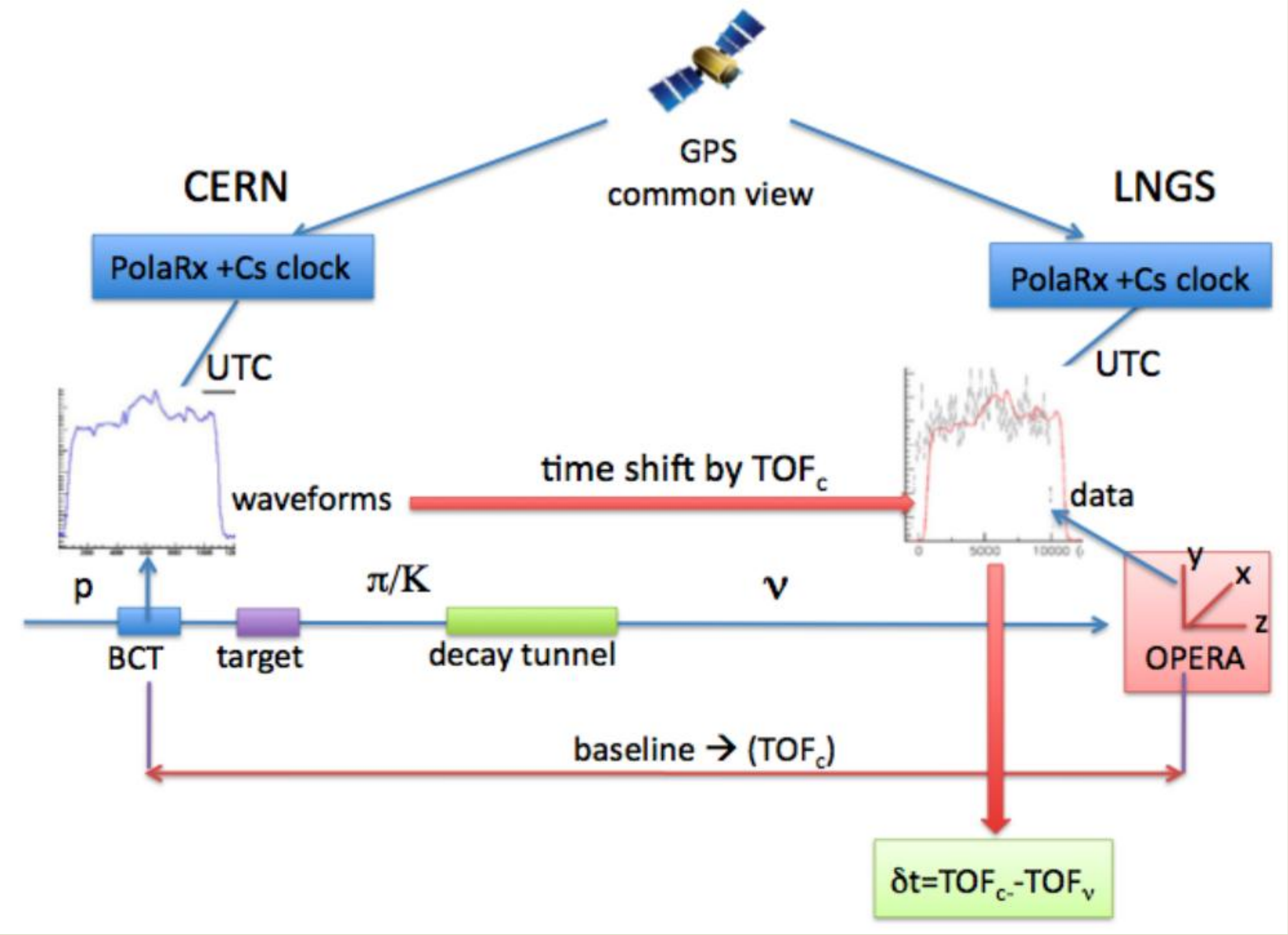
Principle of Measurement

- Definition of neutrino velocity:

  baseline / time of flight

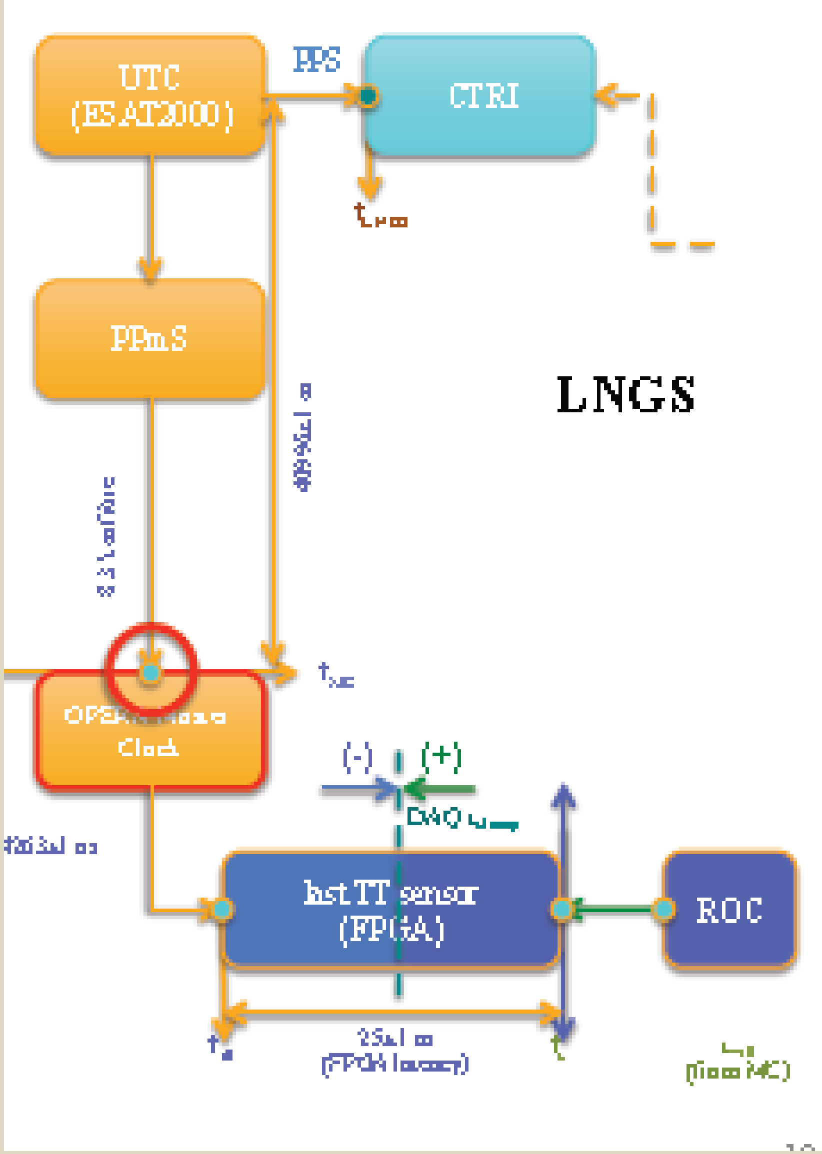
- Key ingredients:
  - High statistics.
  - Sophisticated timing system .
  - Accurate calibrations of the timing chains at CERN and OPERA.
  - Preciese measurement of the ν time distribution at CERN through proton waveforms.
  - Measurement of the baseline by geodesy.

Principle of Measurement

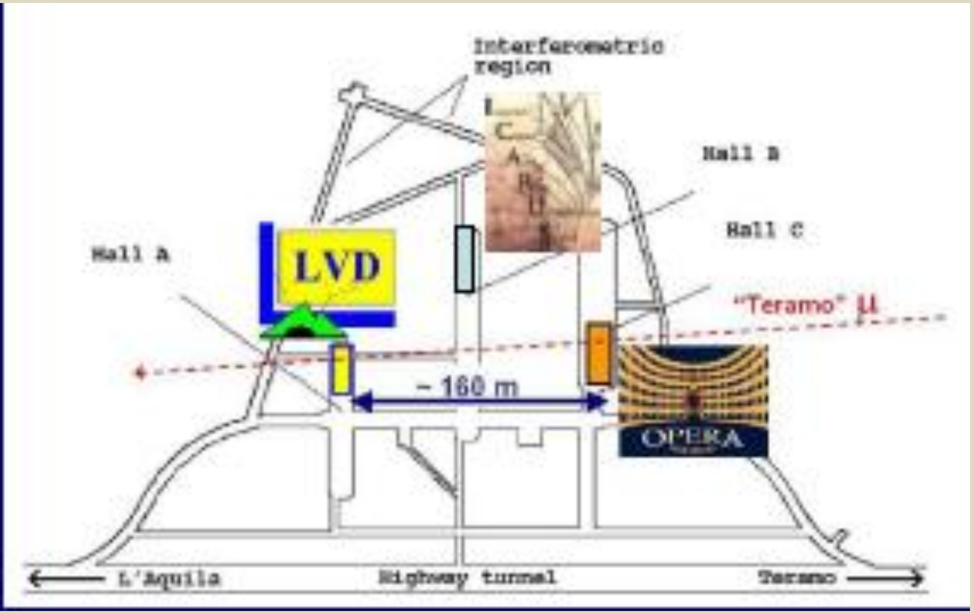


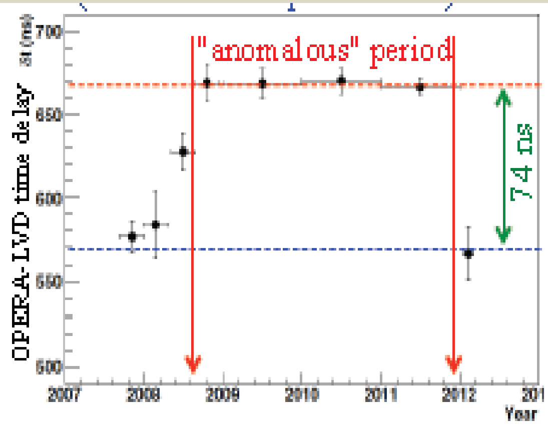
Two Unknown Systematic Errors

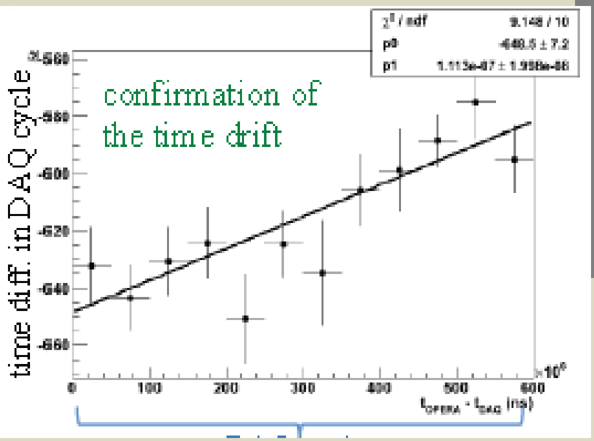
- Not proper connection of the fiber to the OPERA Master Clock causes an artificial time delay of the 8.3 km fiber in LNGS.
  - Re-measurements show that time delay is increased by 73.2 ns.
- Internal Master Clock frequency off by $\Delta f/f = 1.24\times10^{-7}$ (124ns/s) which artificially decrease the neutrino anticipation by ~15ns.
- These anamolous conditions subsected to futher investigation in the period of December 2011 - Feburary 2012



Further Investigation of Anomalous Conditions







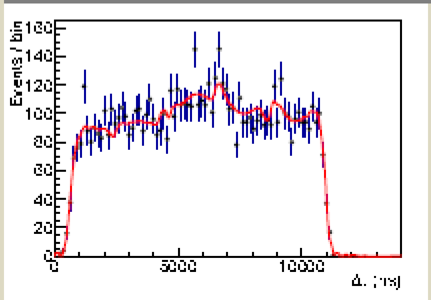
- ➢The fiber connection problem started in 2008 and lasted end of 2011 after it was correctly connected to the OPERA Master Clock.

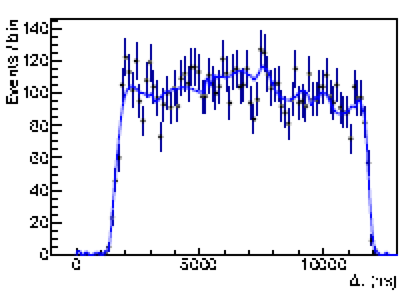
- ➢Wrong oscillator frequency was there all the time in a stable way.

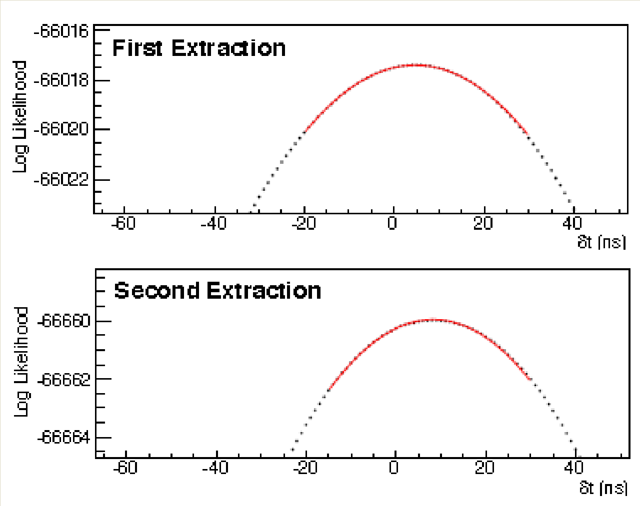
- ➢The following 2011 results have been corrected according to new measured parameters and new systematic errors have been evaluated.

Analysis Method

- For each neutrino event → Proton waveform of the corresponding extraction.
- Sum up and normalise → form PDF→ Seperate likelihood for each extraction.







Data Sample

- 15223 events are selected
  - 7235 internal events
  - 7988 external events

Results

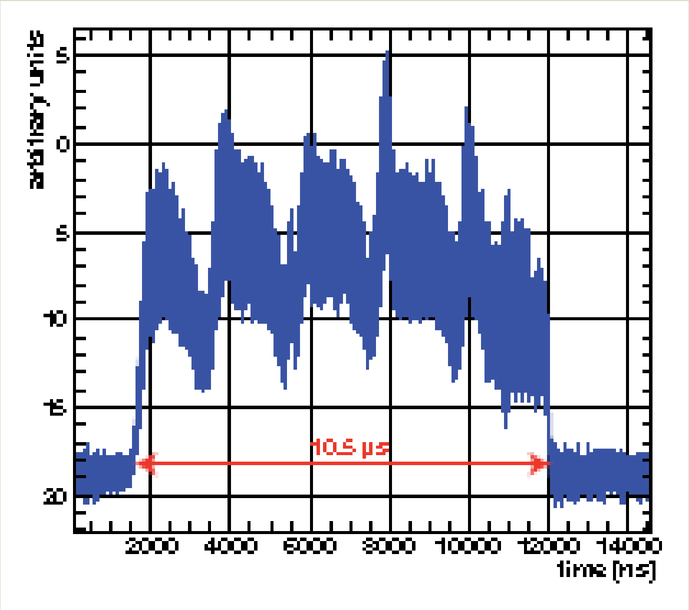
- No day/night effect
- No seasonal effect
- No energy dependence
- No beam intensity effect

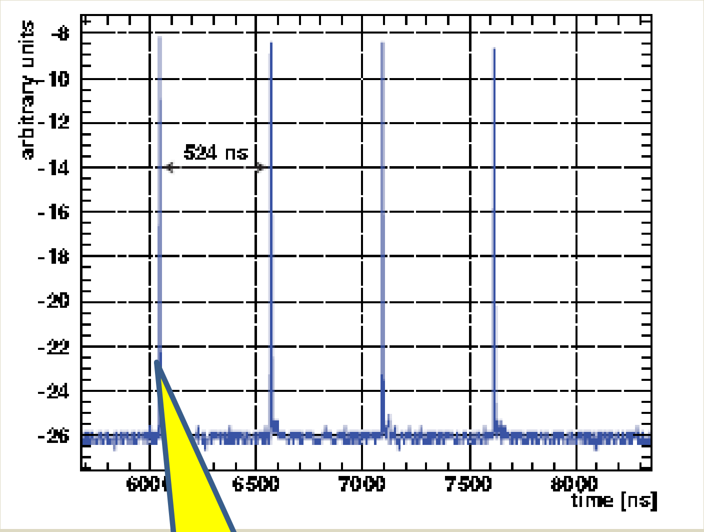
Results

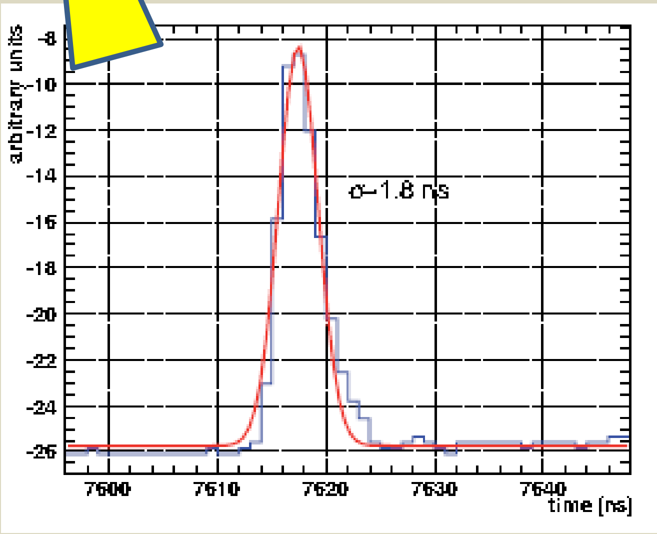
$$\Delta t = TOF_c - TOF_\nu = 6.5 \pm 7.4(\text{stat})\,{}^{+8.3}_{-8.0}(\text{sys.})\text{ ns}$$

$$\frac{v-c}{c} = \frac{\delta t}{TOF_c - \delta t} = 2.7 \pm 3.1(\text{stat.})\,{}^{+3.4}_{-3.3}(\text{sys.})\times 10^{-6}$$

Bunched Beam Analysis



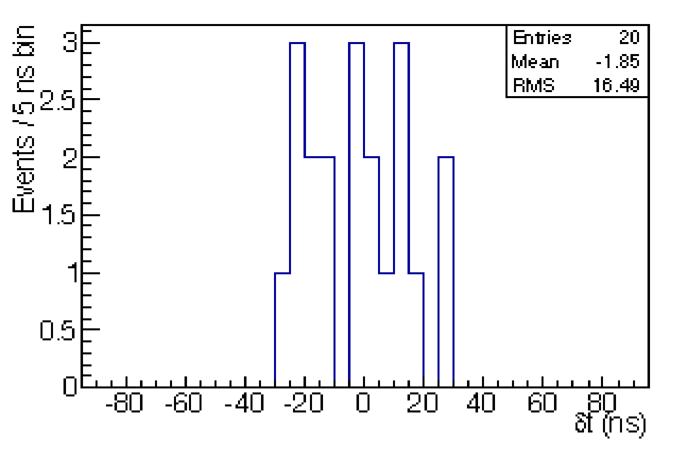




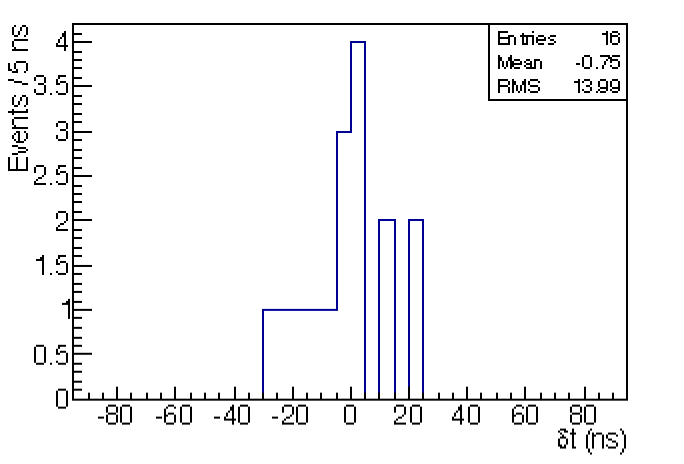
- TOF_v for each detected neutrino
  - $4x10^{16}$ pot in total
  - 6 internal events
  - 14 external events
  - events evenly distributed in the four bunches of the extraction mode.

Bunched Beam Analysis

- Short bunched beam is designed for OPERA to exclude possible biases effecting the statistical analysis based on the proton PDF.



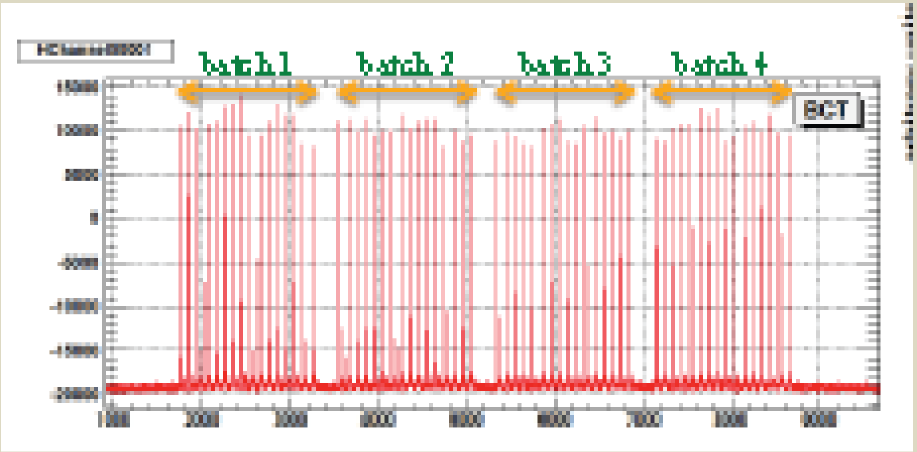
- Result is consistent with the main analysis
  - With TT $\delta t = -1.9 \pm 3.7(\text{stat.})$ ns
  - With RPC $\delta t = -0.8 \pm 3.5(\text{stat.})$ ns

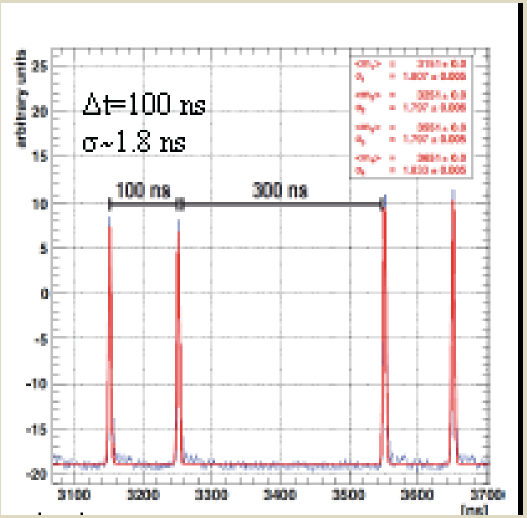


T. Adam et al. [arXiv: 1109.4897] will appear in JHEP

Bunched Beam in May 2012

- Mainly designed to get conclusive result
  - 1 extraction per CNGS cycle
  - 4 batches per extraction
  - 16 bunches per batch
  - 2×10^{17} pot in total (for two weeks)

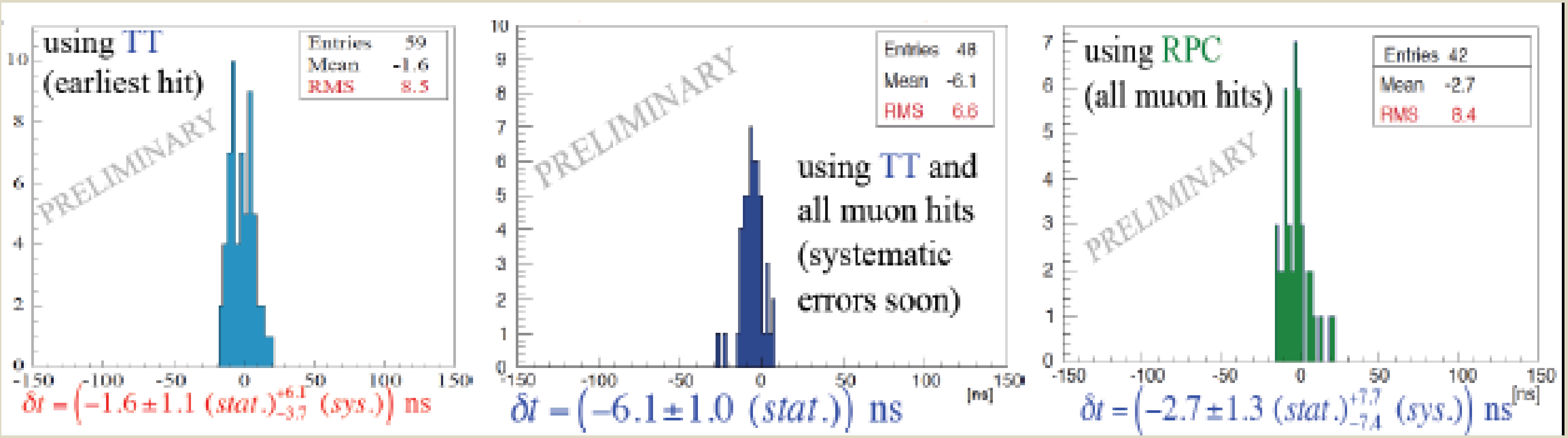




New OPERA results (Bunched Beam in May)

- 106 events collected and 59 events are selected.

- Muon Selection Criteria
  - CERN-LNGS time-link
  - WFD
  - Well identified muon
  - No isolated earliest hits



Conclusions II

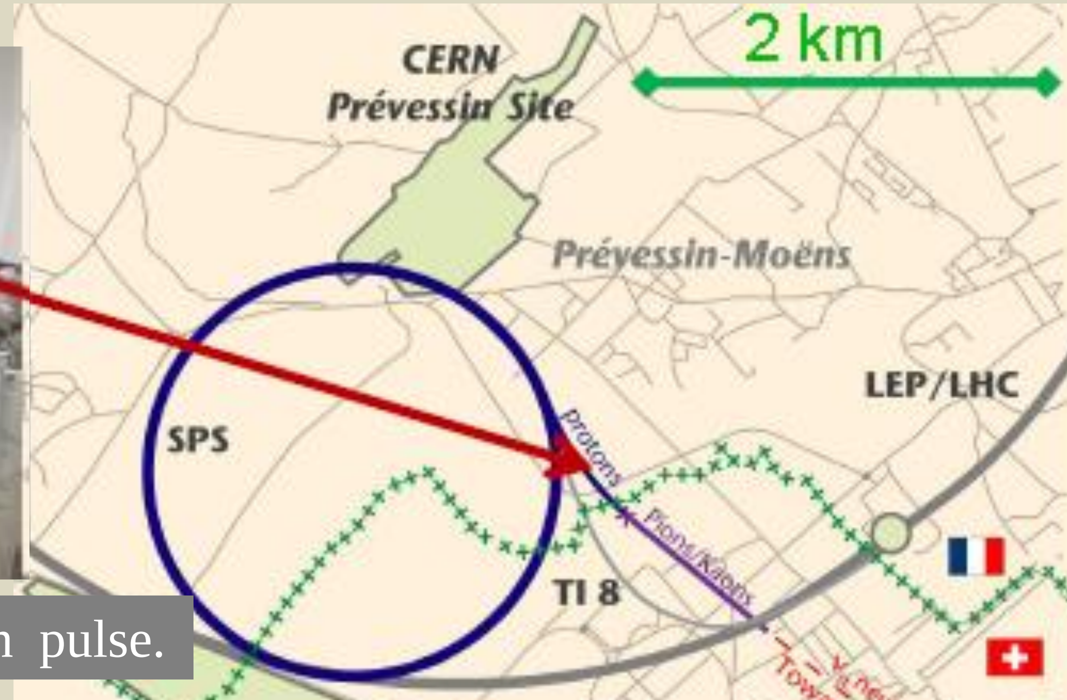
- OPERA found the source of the anomaly announced last year and corrected the result.
- Neutino velocity measurement performed in OPERA by using different beam and different sub-detectors are in agreement with the speed of light.
- Combination of all the different experimental results in progress.

Thank you !

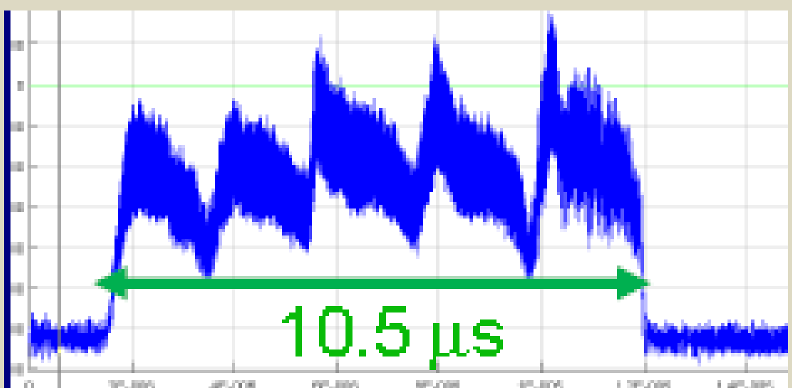
Moteşekkirem!

Back up

Proton Timing



- ➢ Wave Form of recorded proton pulse.



- ➢Proton pulse digitized by a 1GS/s.
- ➢Wave Form Digitilizer(WFD) triggered by a replica the Kicker signal.
- ➢Waveforms are UTC time-stamped and stored in CNGS database for offline analysis.

GPS common view mode

- GResolves (x,y,z,t) with ≥4 satellite observations

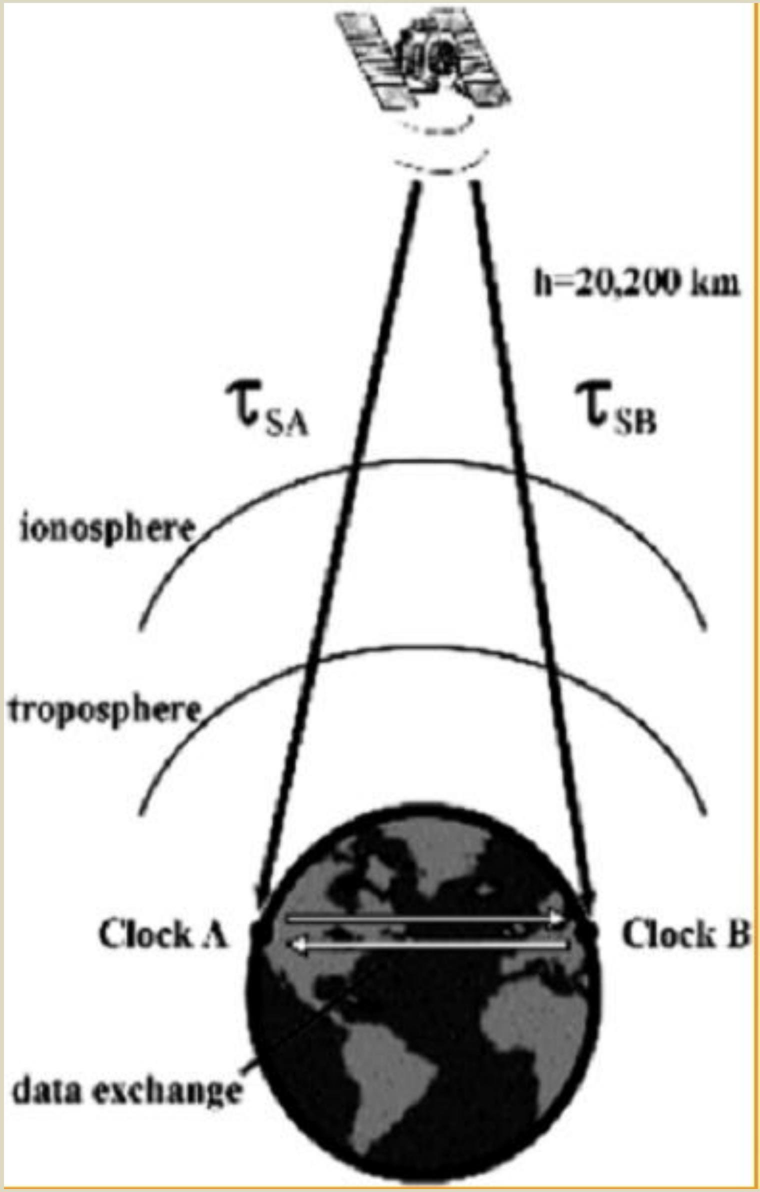
- GPS common-view mode.

- Same satellite visible of the sites from former dedicated measurements → determine time difference of local clocks w.r.t. the satellite by off-line data exchange.

- Advantage: 730 km << 20000 km (satellite height) →similar paths in ionosphere error cancellation.

- Standard technique for high accuracy time transfer.

- Permanent time link (~1 ns) between reference points at CERN at CERN and OPERA.

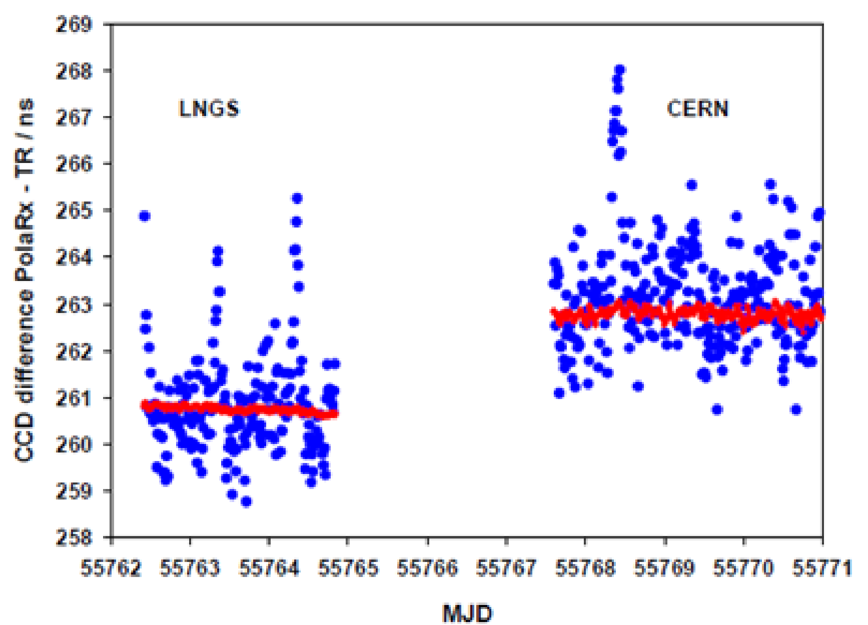


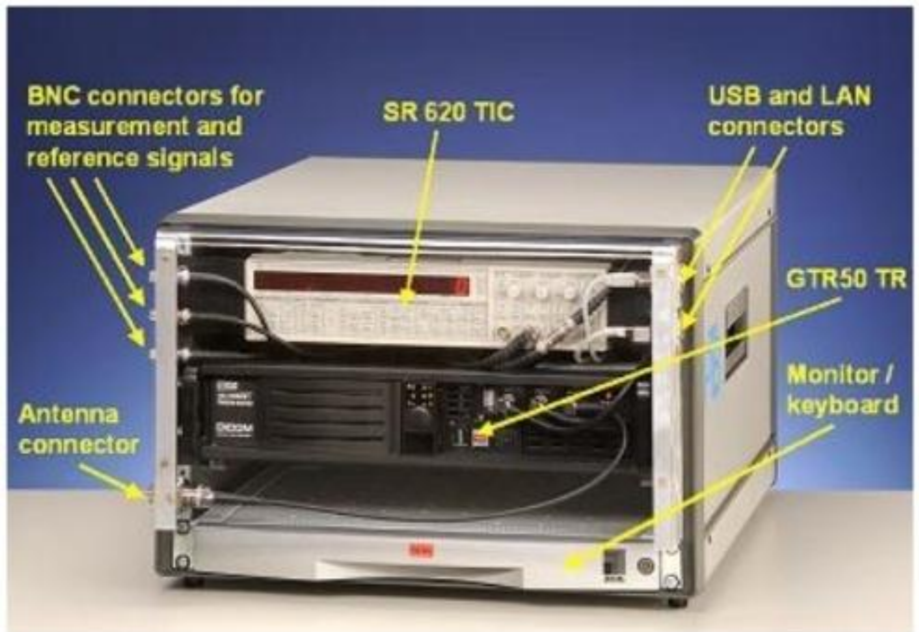
Timing-Inter-calibration

Independent twin-system calibration by the Physikalisch-Technische Bundesanstalt (PTB)

High accuracy/stability portable time-transfer setup @ CERN and LNGS

GTR50 GPS receiver, thermalised, external Cs frequency source, embedded Time Interval Counter





Correction to the time-link:

$t_{CERN} - t_{OPERA} = (2.3 \pm 0.9)$ ns

Geodesy

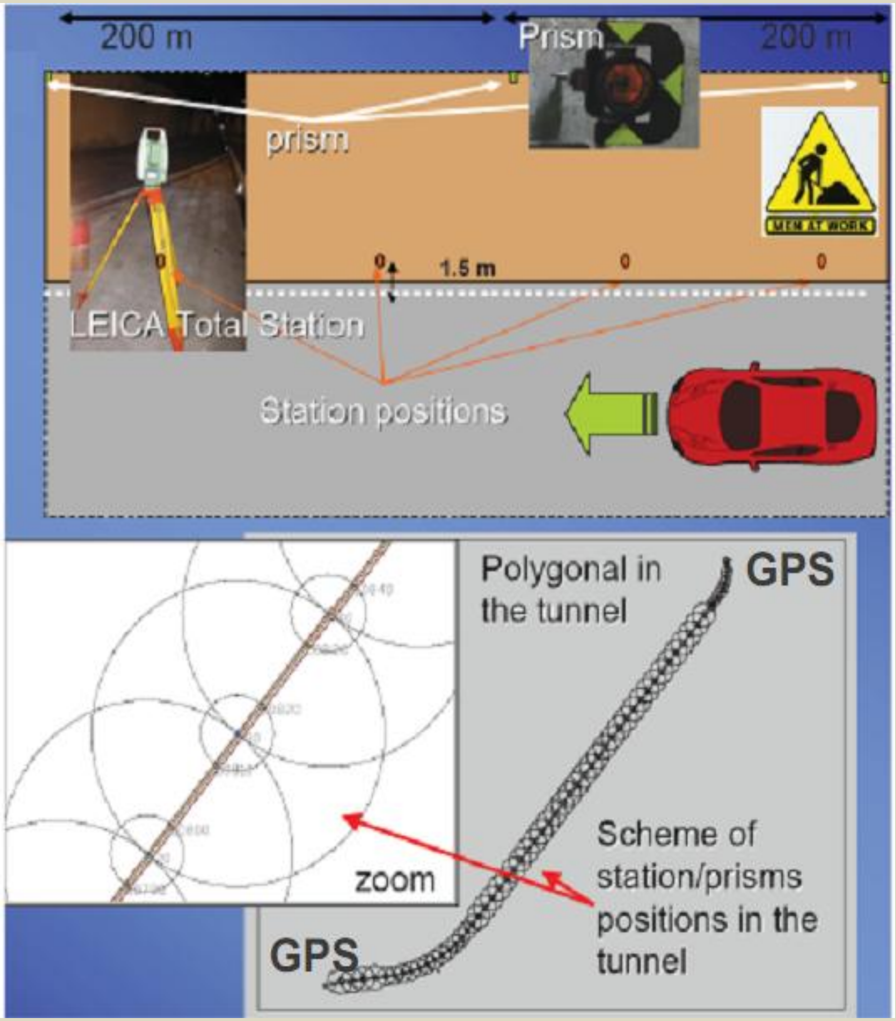
LNGS

➢Dedicated measurements July-September 2010.

➢2 new GPS benchmar.ks on each side of the 10 km highway tunnel

➢CERN measurements (taken in different periods) combined in the ETRF200 European Global system accounting for earth dynamics.

➢Cross-check in June 2011: simultaneous CERN-LNGS measurement of GPS benchmarks.



Distance (BCT-OPERA reference frame) = (731278.0±0.2)m

New Calibration Delays

Item	Result	Method
CERN UTC distribution (GMT)	10077.8 ± 1 ns	• Portable Cs • Two-ways
WFD trigger	26.6 ± 1 ns	Scope
BCT delay	$\boxed{583.7 \pm 1 \text{ ns}}$	• 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

±1.8 ns (CERN)

±4.2 ns (OPERA)

PRELIMINARY