RECENT RESULTS OF THE OPERA EXPERIMENT

Giulia Brunetti

OUTLINE

- **OPERA experiment**

  Oscillation Project with Emulsion tRacking Apparatus

  → **Neutrino oscillations**

  in **APPEARANCE MODE** **on a** **LONG BASELINE**

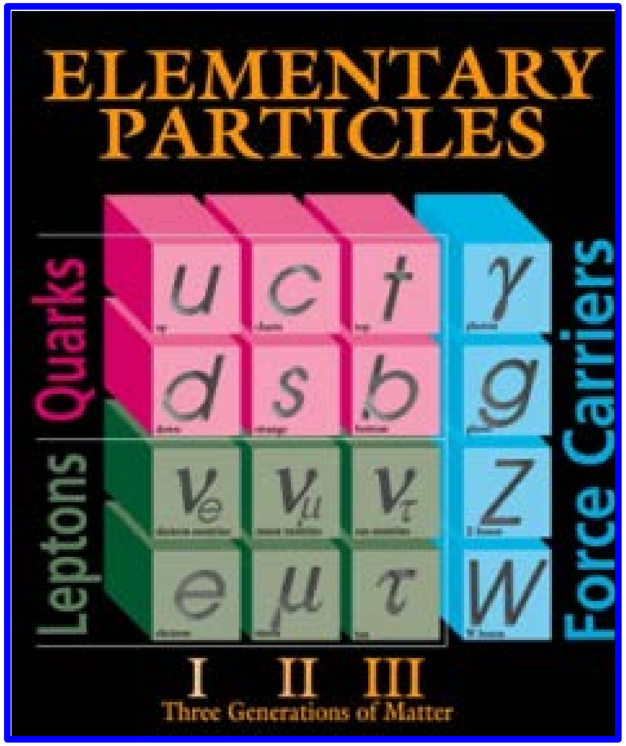
- **$\nu_\mu \rightarrow \nu_\tau$ oscillation**

  → **τ decays, candidate events**

- **Complemetary analysis**

  → **$\nu_\mu \rightarrow \nu_e$ oscillation analysis**

  → **Neutrino velocity measurement**



NEUTRINOS in the STANDARD MODEL

- Neutral, MASSLESS fermions;
- 3 neutrinos, one for each of the 3 charged leptons;
- The lepton number is conserved separately for each of the 3 lepton families (e, ν_e), (μ, ν_μ), (τ, ν_τ);
- Neutrinos and antineutrinos are distinct

... BUT

Weak neutrinos:

ν_e, ν_μ, ν_τ

Mass eigenstates:

ν_1, ν_2, ν_3

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{PMNS} : Pontecorvo-Maki-Nakagawa-Sakata matrix

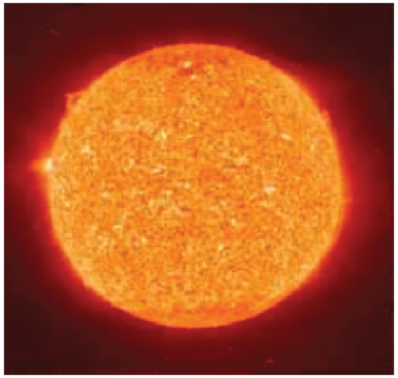
If neutrinos have mass: $|\nu_\ell\rangle = U_{\ell i} \, |\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

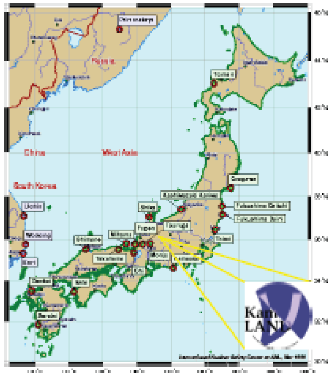
Where $c_{ij} = \cos\theta_{ij}$ *and* $s_{ij} = \sin\theta_{ij}$

Various neutrino sources and vastly different energy and distance scales

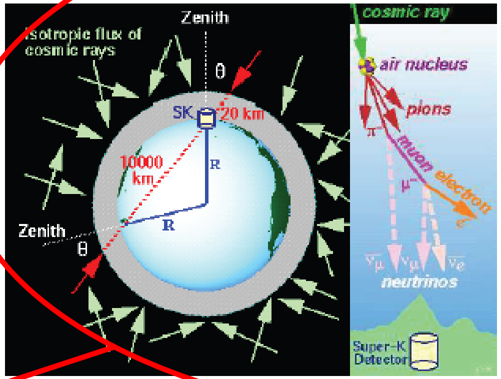
sun



reactors



atmosphere



accelerators

OPERA

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}\underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}s_{13} & 0 & c_{13} \end{pmatrix}}\underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

Measured with atm and LBL ν

Measured with reactor and LBL ν

Measured with solar, reactor ν

$\theta_{23} \approx \pi/4$

$\theta_{13} \approx \pi/20$

$\theta_{12} \approx \pi/6$

Neutrino oscillations parametrized by

- mass squared differences Δm^2_{ij}
- mixing angles θ_{ij}
- CP phase δ_{CP}

For instance, 2-flavor case:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

L(km), E(GeV)

Oscillation formula (3-neutrino scheme)

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_\tau) \sim & \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta_{atm} \\ & - \Delta_{sol}\cos^2\theta_{13}\sin^2 2\theta_{23}(\cos^2\theta_{12} - \sin^2\theta_{13}\sin^2\theta_{12})\sin 2\Delta_{atm} \\ & - \Delta_{sol}\cos\delta\cos^2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos 2\theta_{23}\sin 2\Delta_{atm}/2 \\ & + \Delta_{sol}\sin\delta\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin^2\Delta_{atm} \end{aligned}$$

Dominant terms

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23}\cos^4\theta_{13}\sin^2(\Delta m^2_{23} L/4E)$$

Direct detection of neutrino oscillations in <u>APPEARANCE MODE</u>:

ν_τ CC interactions by direct observation of τ lepton decay

→ OPERA experiment

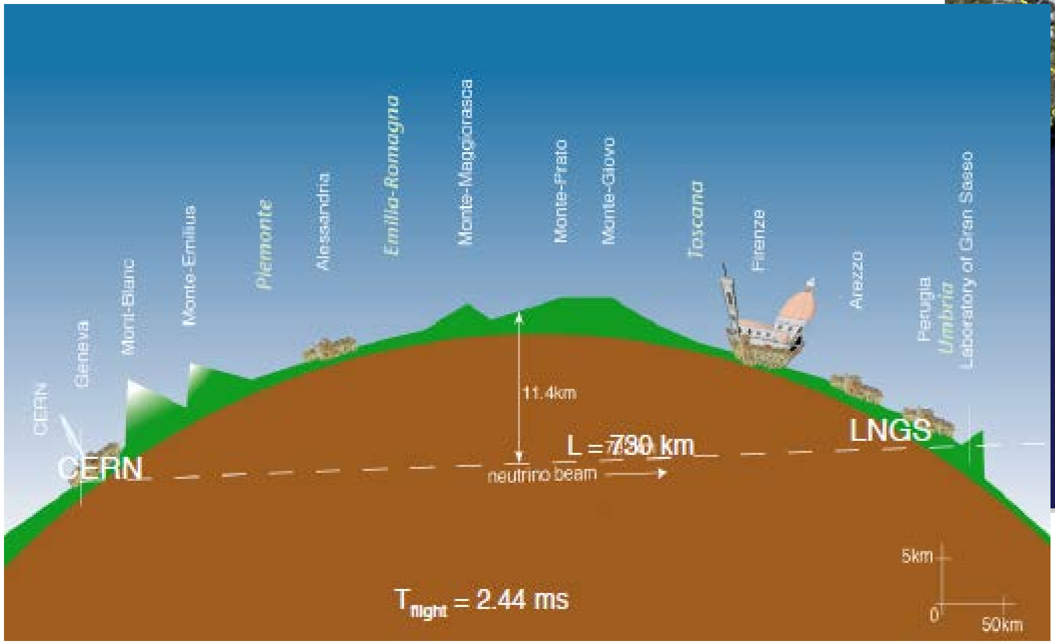
(Oscillation Project with Emulsion tRacking Apparatus)

Requirements:

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

CNGS ν_μ BEAM

Tuned for ν_τ-appearance at LNGS
(730 km away from CERN)



‹E›	17 GeV
L	730 km
$(\nu_e + \bar{\nu}_e)/\nu_\mu$ (CC)	0.87%
$\bar{\nu}_\mu/\nu_\mu$ (CC)	2.1%
ν_τ prompt	negligible

For 22.5×10^{19} POT $\rightarrow$ Expected Events
7.6 Signal, 0.7 Background
Ref: New Journal of Physics 14(2012)033017

OPERA collaboration

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi edu.
Kobe
Nagoya
Toho
Utsunomiya

Korea
Jinju

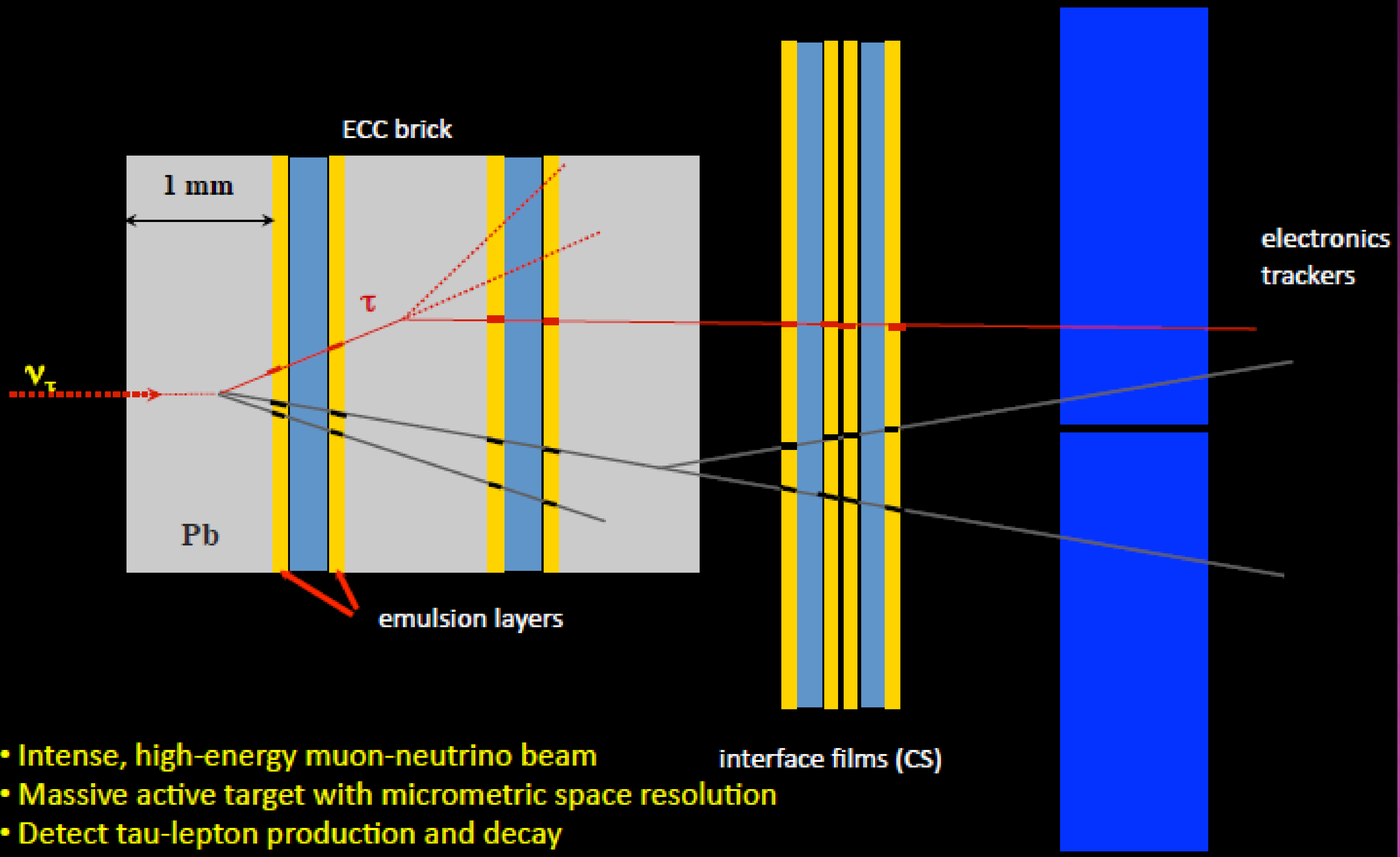
Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

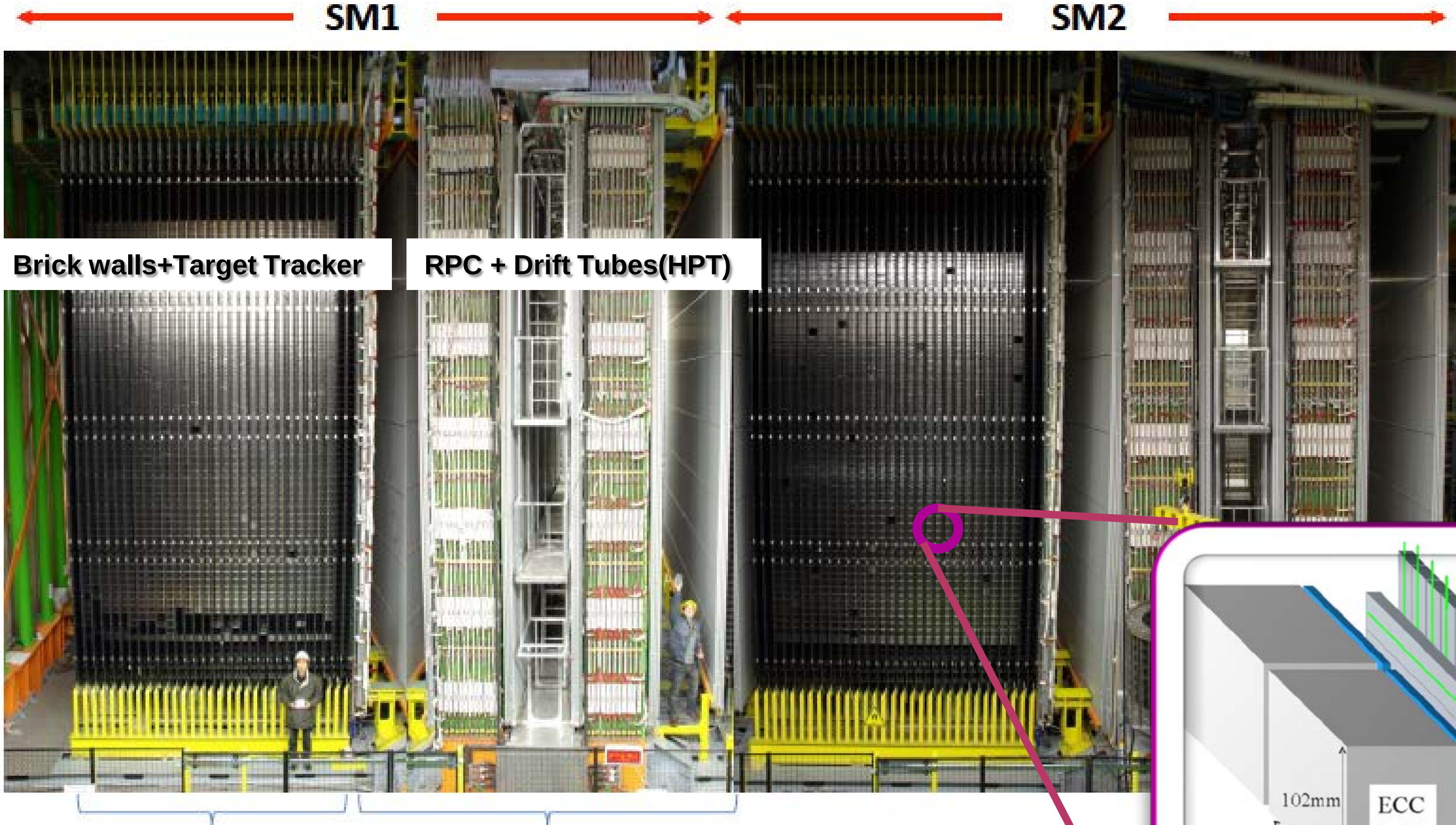
（11 countries,30 Institutes,~160 researchers）

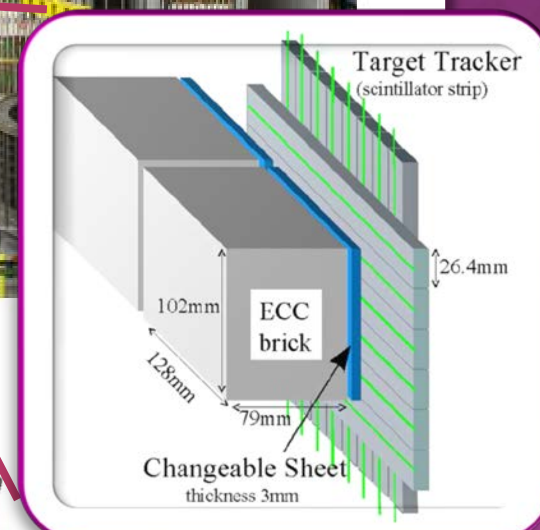
THE PRINCIPLE OF THE EXPERIMENT: ECC + ELECTRONIC DETECTORS



- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region

THE IMPLEMENTATION OF THE PRINCIPLE





Target area

Total OPERA Target
~150000 bricks → 1.25 kton

Muon Spectrometer

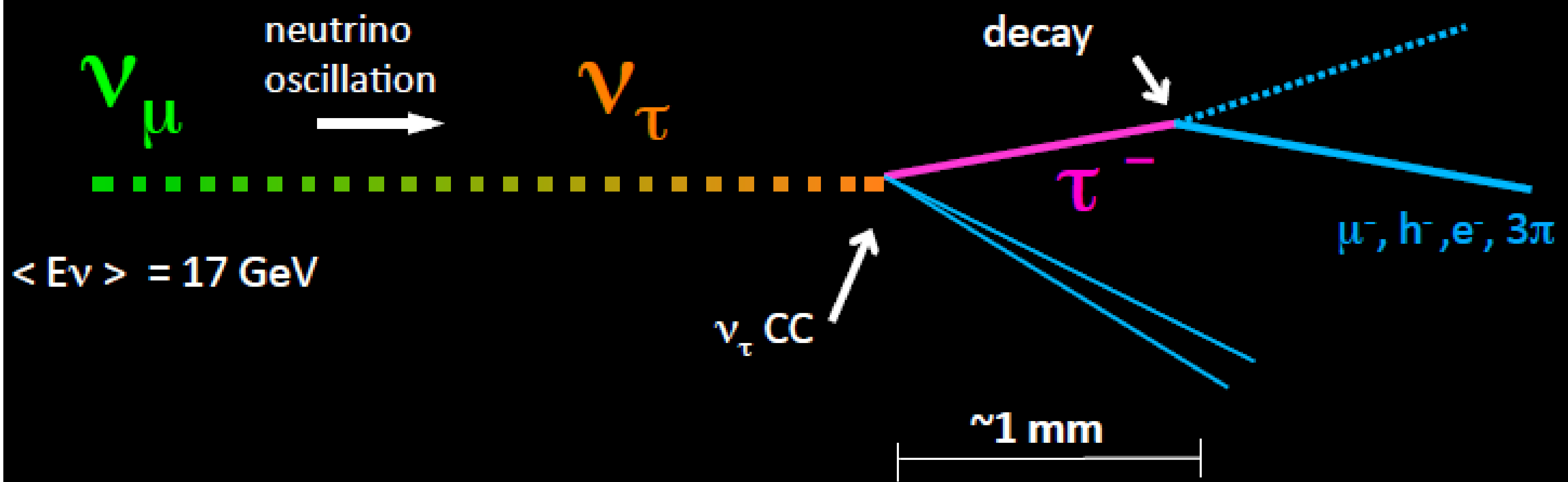
Muon ID, Momentum and charge measurement

56pb plates + 57films + 2 interface emulsions (CS) = 8 Kg (10 X_0)

Each brick wall is followed by a plane of plastic scintillator strips in X/Y direction

Target Trackers (TT) → interaction trigger, brick localization

τ decay modes



Topology	decay mode	BR	exp. evts. (22.5x10^{19} pot)	BG events
Kink	$\tau^- \rightarrow e^-$	17.8 %	1.8	0.09
	$\tau^- \rightarrow \mu^-$	17.4 %	2.9	0.22
	$\tau^- \rightarrow h^-$	49.5 %	2.2	0.24
Trident	$\tau^- \rightarrow h^- h^- h^+$	15.2 %	0.7	0.18
Total			7.6	0.73

Detected Neutrino Interactions

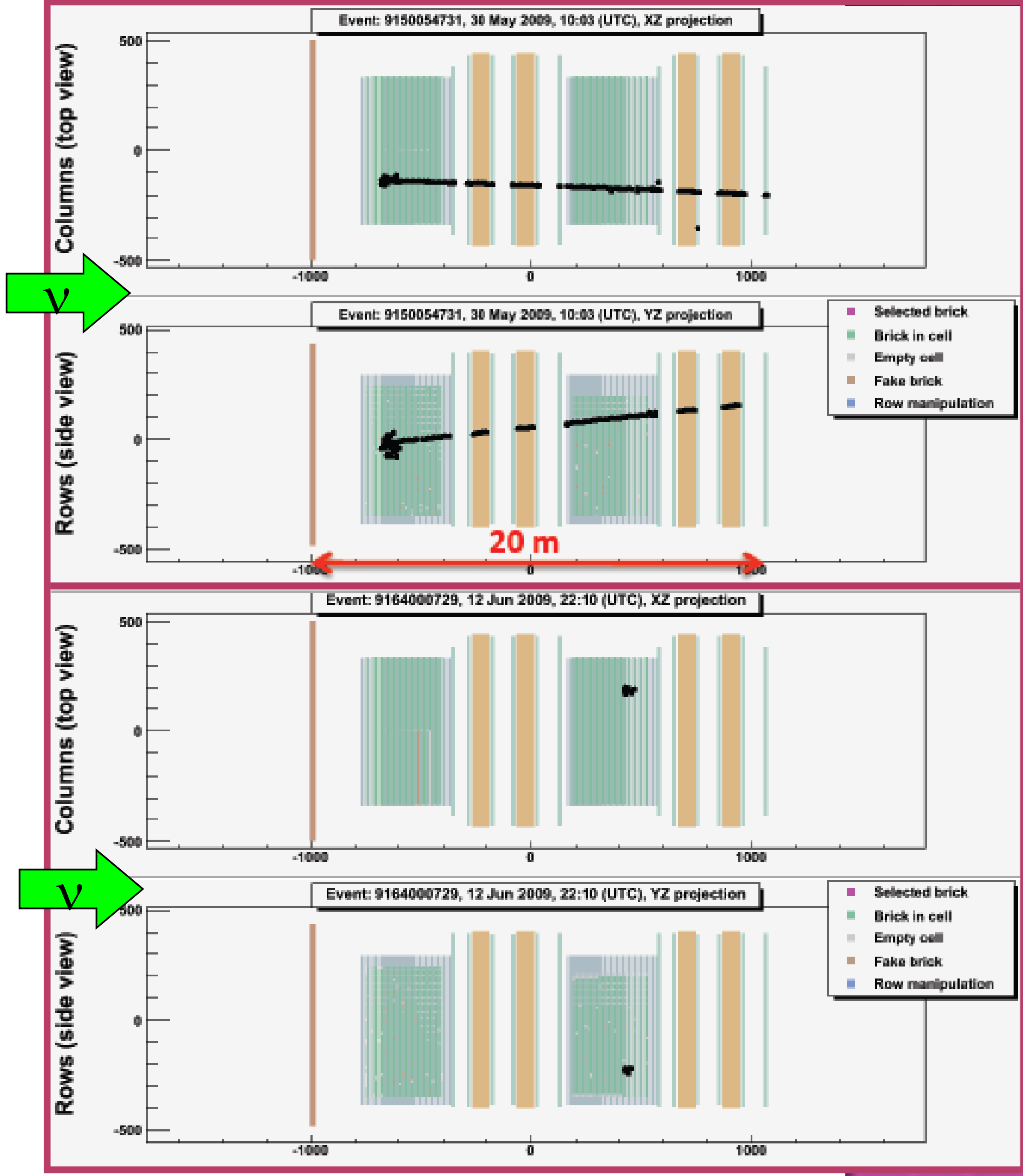
With μ

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

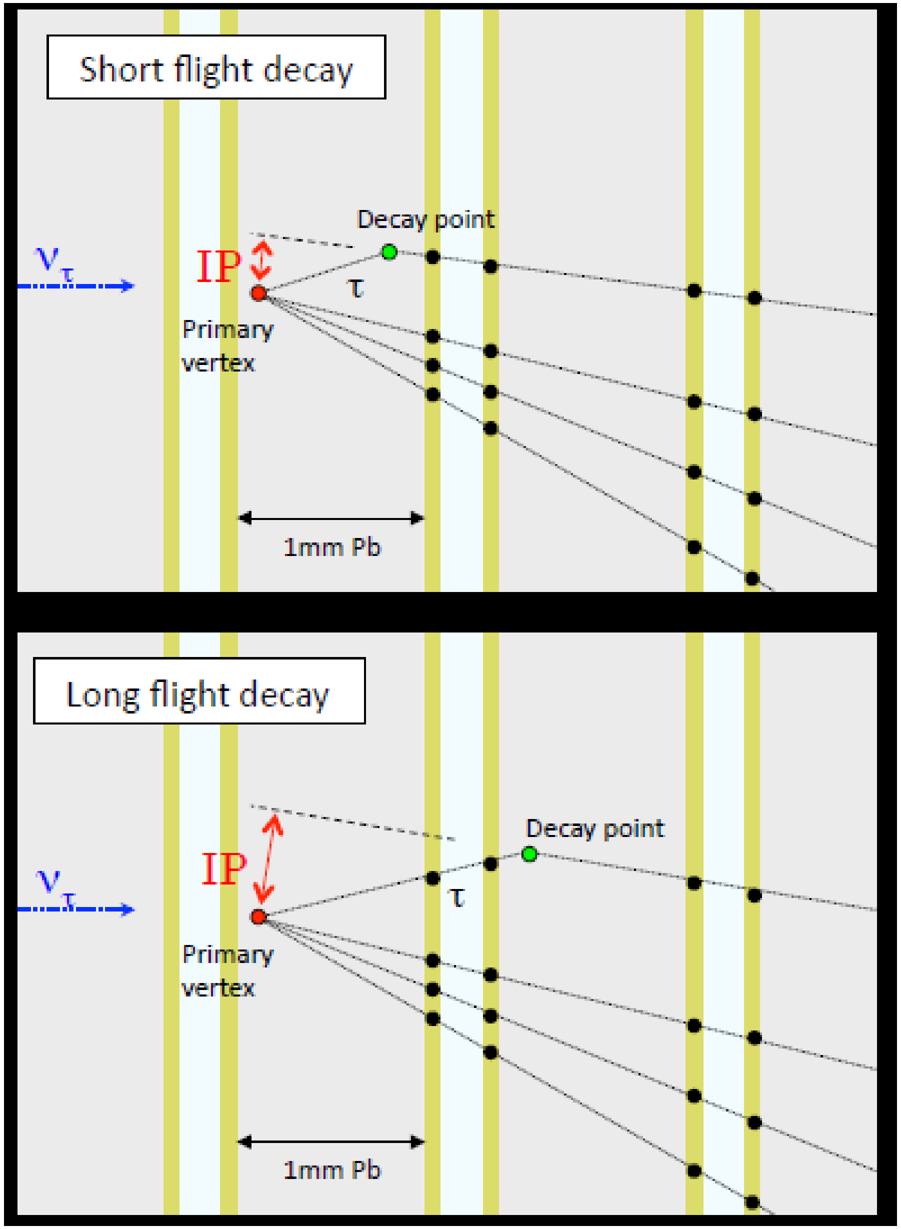
Without μ

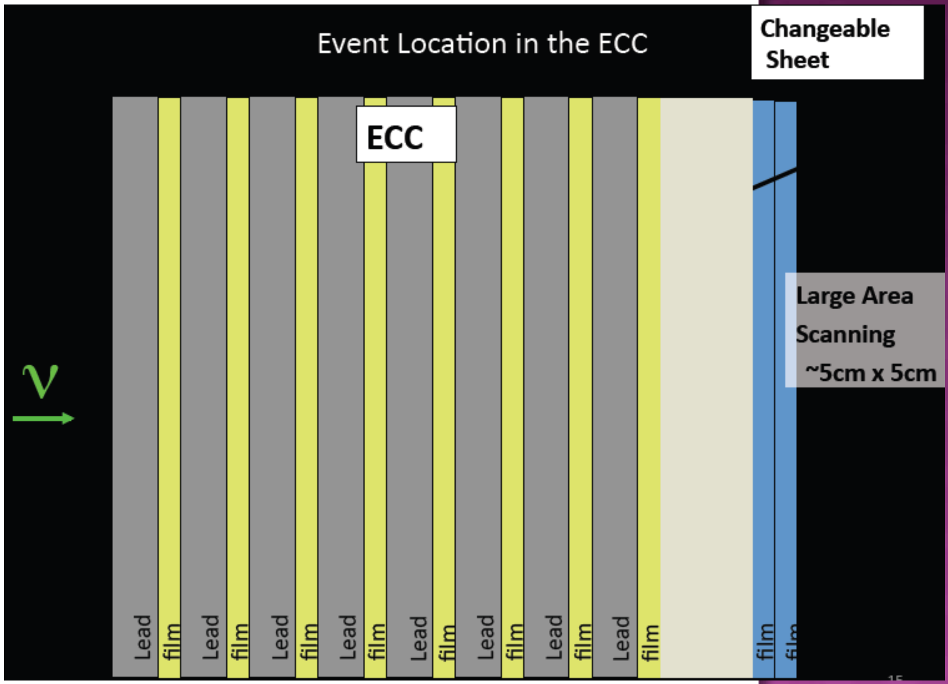
- ν **NC**
- ν_τ CC, $\tau \rightarrow e$ (17.8%)
- ν_τ CC, $\tau \rightarrow h$, 3h (64.8%)

- ν_e **CC**

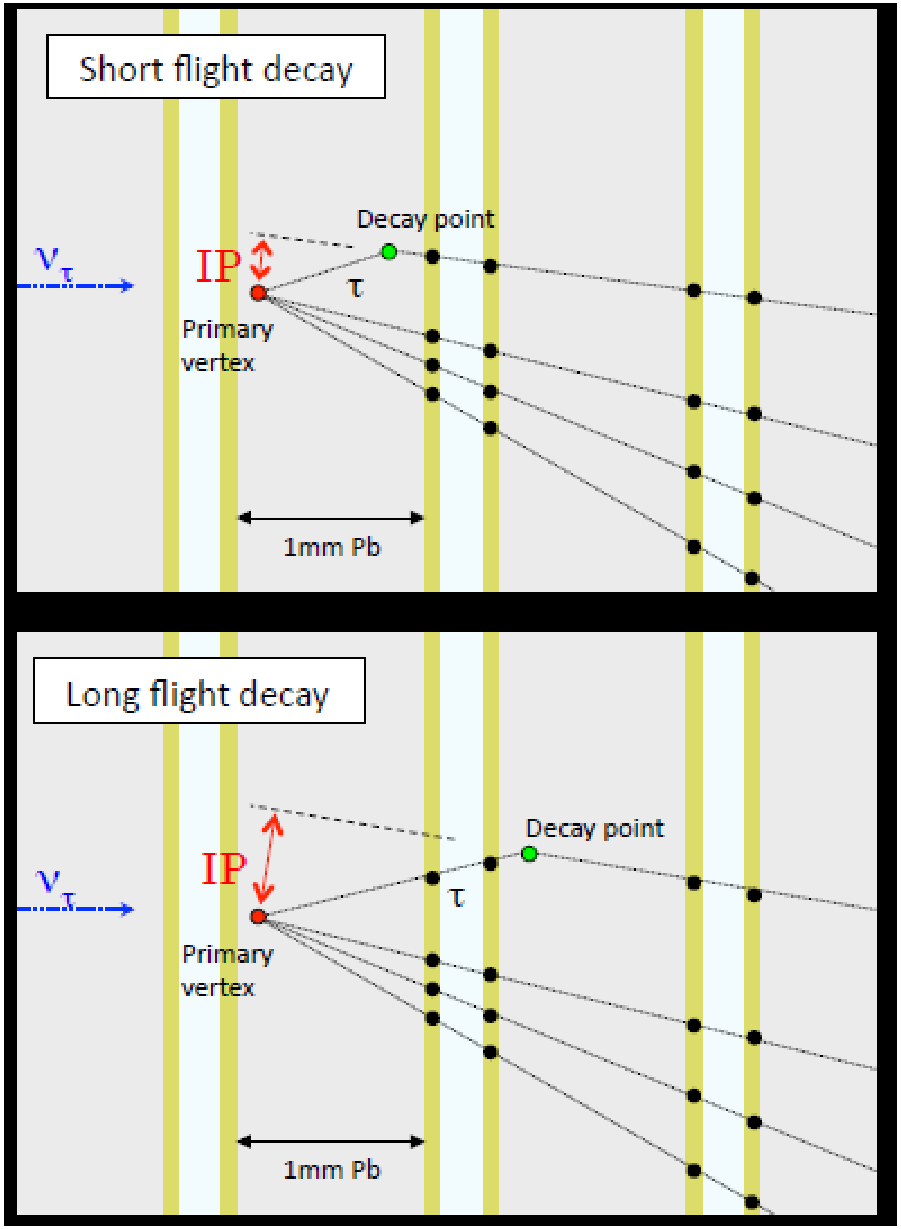


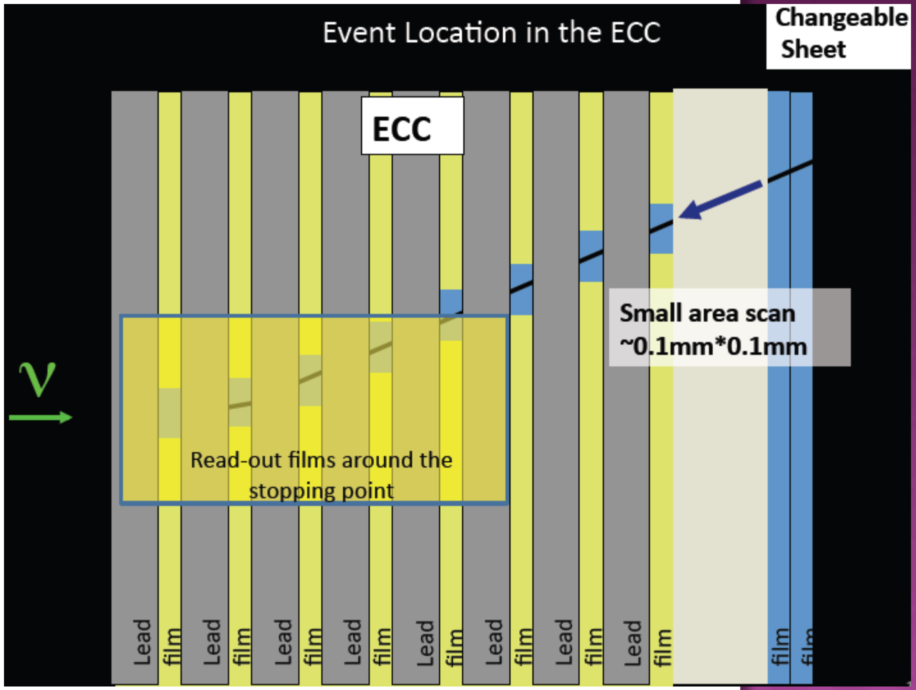
ν_τ CC detection



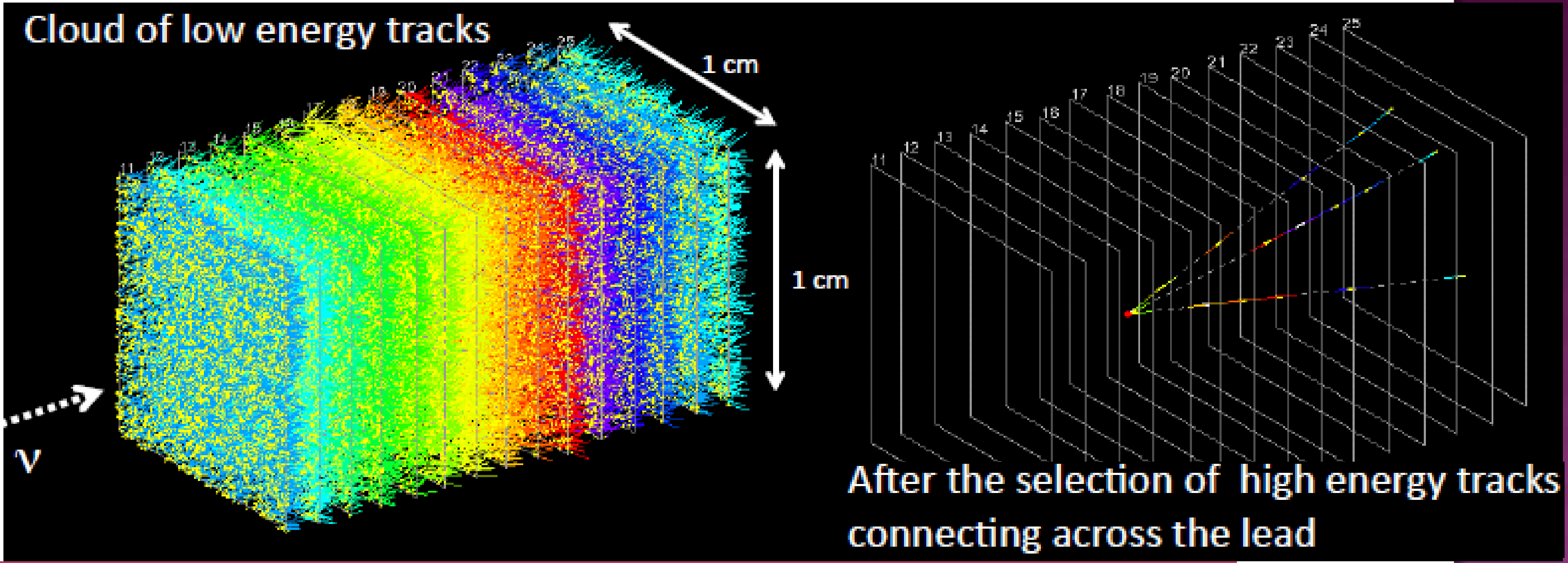


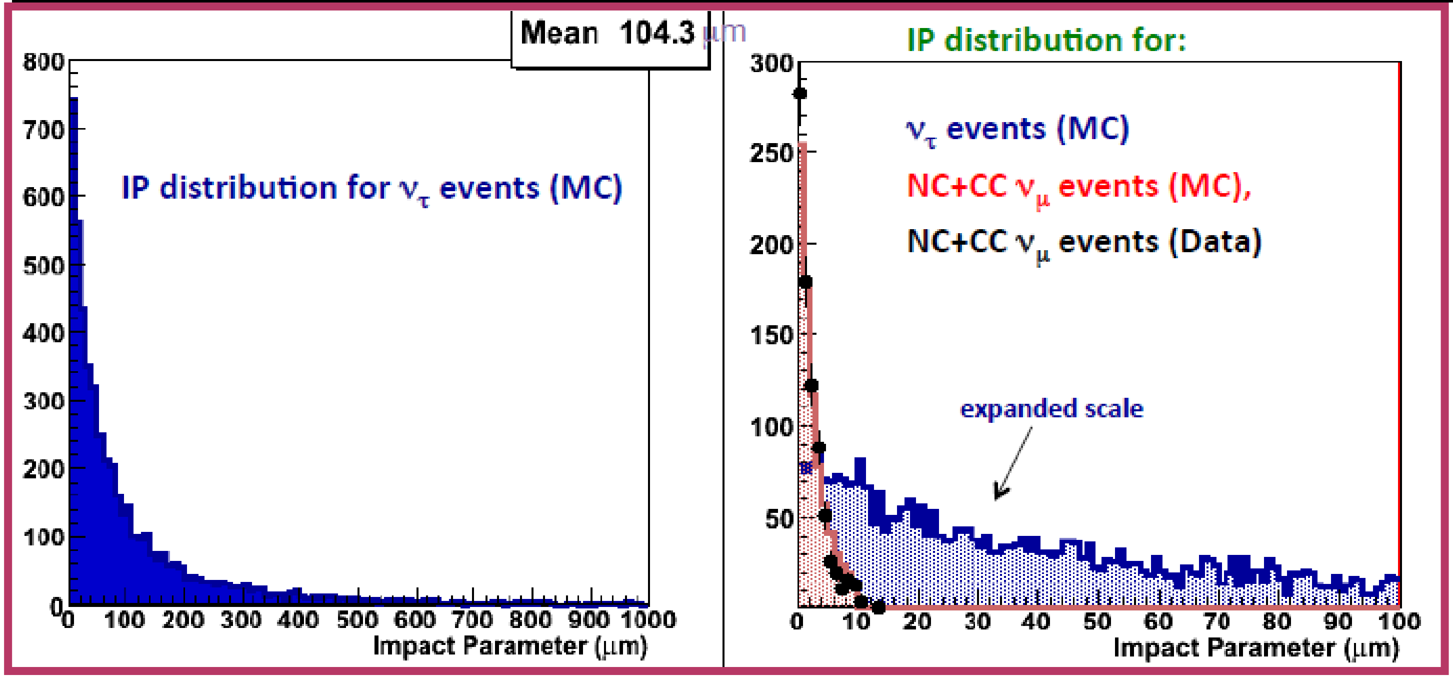
ν_τ CC detection





Interaction vertex confirmation & decay search



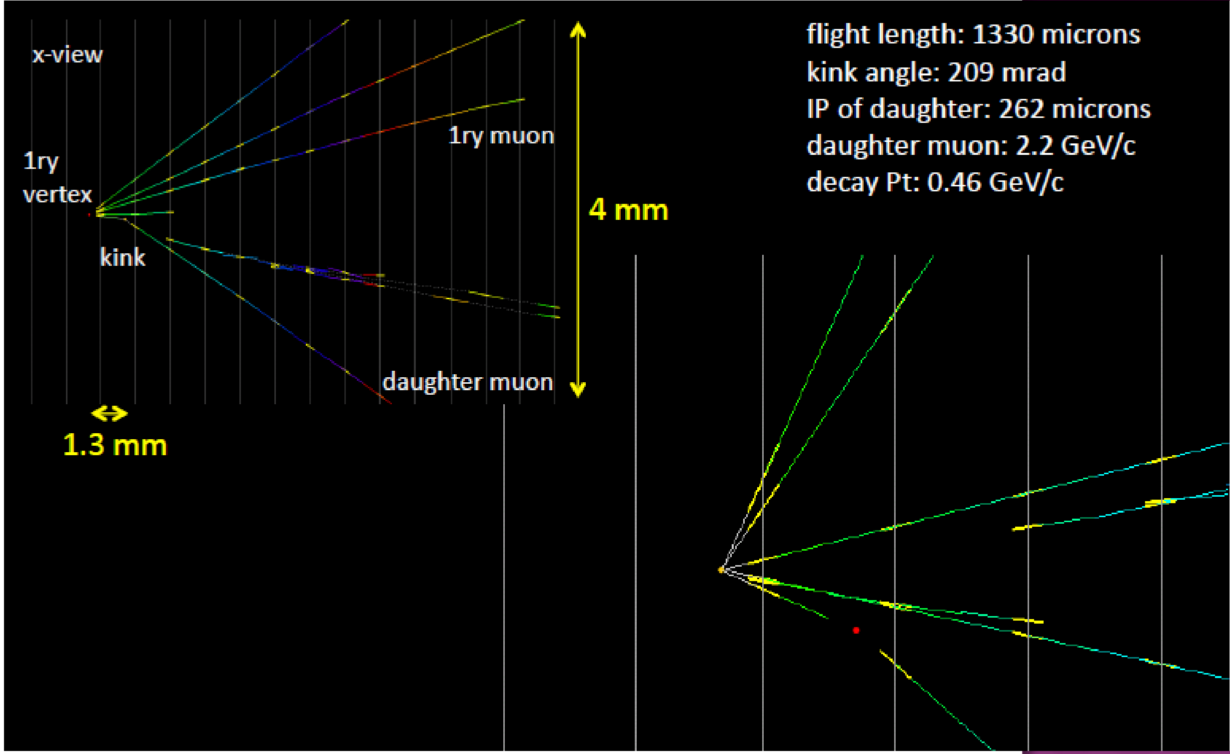


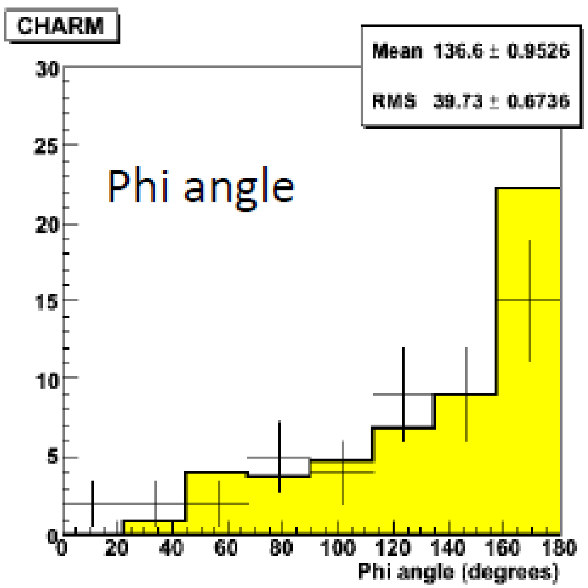
Impact Parameter Measurement

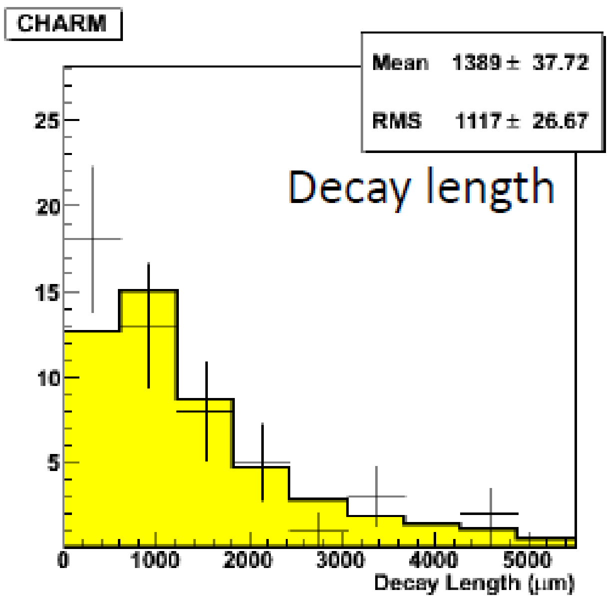
CHARM EVENTS: A test sample and a physics BG

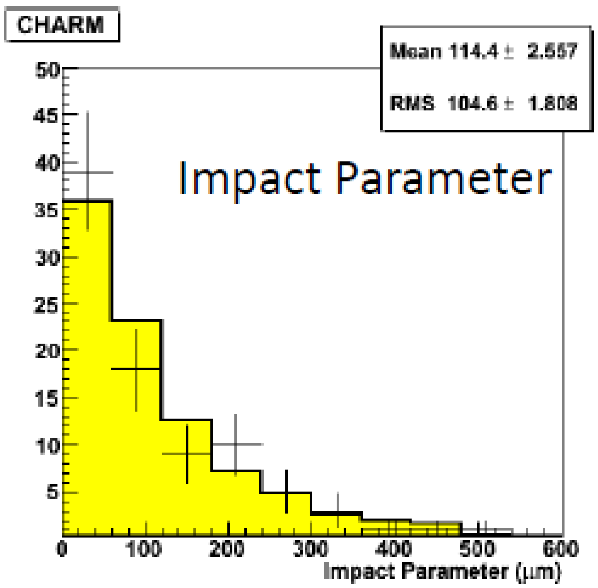
Charm Data-MC comparison:
Proof of the τ efficiency

Detected: 49 events
Expected: 51± 7.5 events









Status of the CNGS data taking (oscillation analysis)

Year	Protons 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

Expected pot after 2012 run
18.9×10^{19} (22.5×10^{19} proposal)

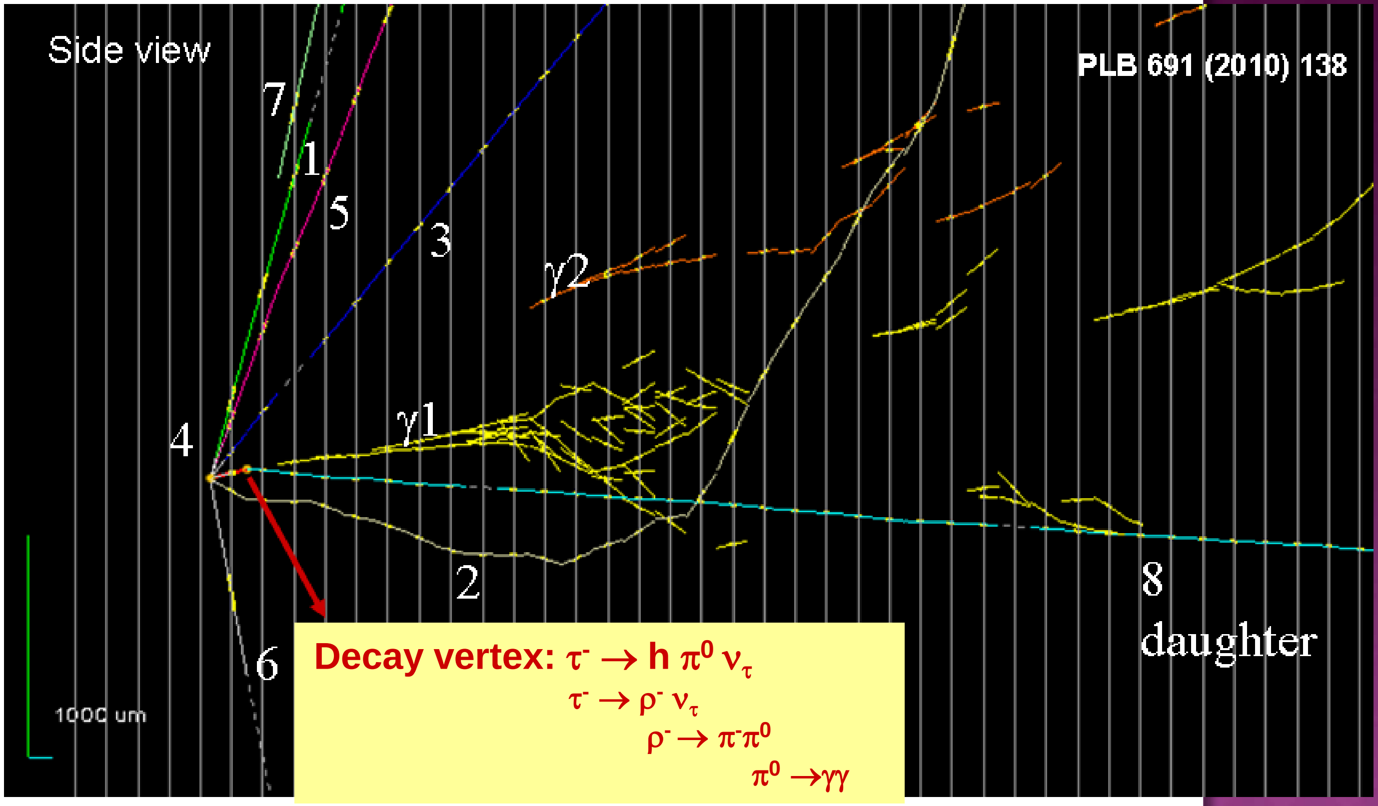
ν_τ CANDIDATE EVENTS

Years	Status of analysis	# of events for decay search	Expected ν_τ events (Preliminary)	Observed ν_τ candidate events	Expected BG for ν_τ (Preliminary)
2008-2009	completed	2783		1	
2010-2011	in progress	1343		1	
2012	started				
Total		4126	2.1	2	0.2

PRESENT STATISTICS

(NEUTRINO2012 conf.)

First ν_τ candidate



VARIABLE	AVERAGE	Selection criteria
kink (mrad)	41 ± 2	>20
decay length (mm)	1335 ± 35	within 2 lead plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt (MeV/c)	470^{+230}_{-120}	>300 (g attached)
missing Pt (MeV/c)	570^{+320}_{-170}	<1000
ϕ (deg)	173 ± 2	>90

Event nature and invariant mass reconstruction

- The event passes all cuts, with the presence of at least 1 gamma pointing to the secondary vertex, and it is therefore candidate to the

$\tau \rightarrow$1 prong hadron decay mode

- The invariant mass of the two detected gammas is consistent with the

π^0 mass value: $120 \pm 20 \pm 35$ MeV

- The invariant mass of the $\pi^- \gamma \gamma$ system has a value compatible with that of the

ρ(770) mass value: $640^{+125}_{-80}{}^{+100}_{-90}$ MeV

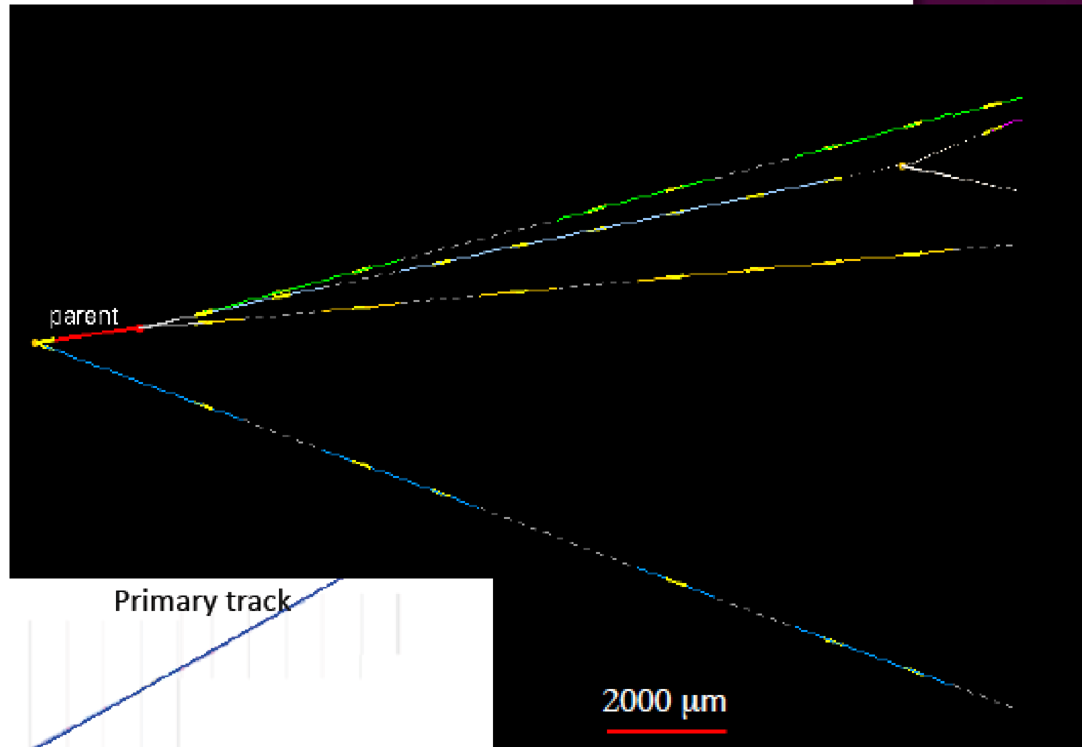
The ρ appears in about 25% of the τ decays:

$\tau \rightarrow \rho(\pi^- \pi^0)\nu_\tau$

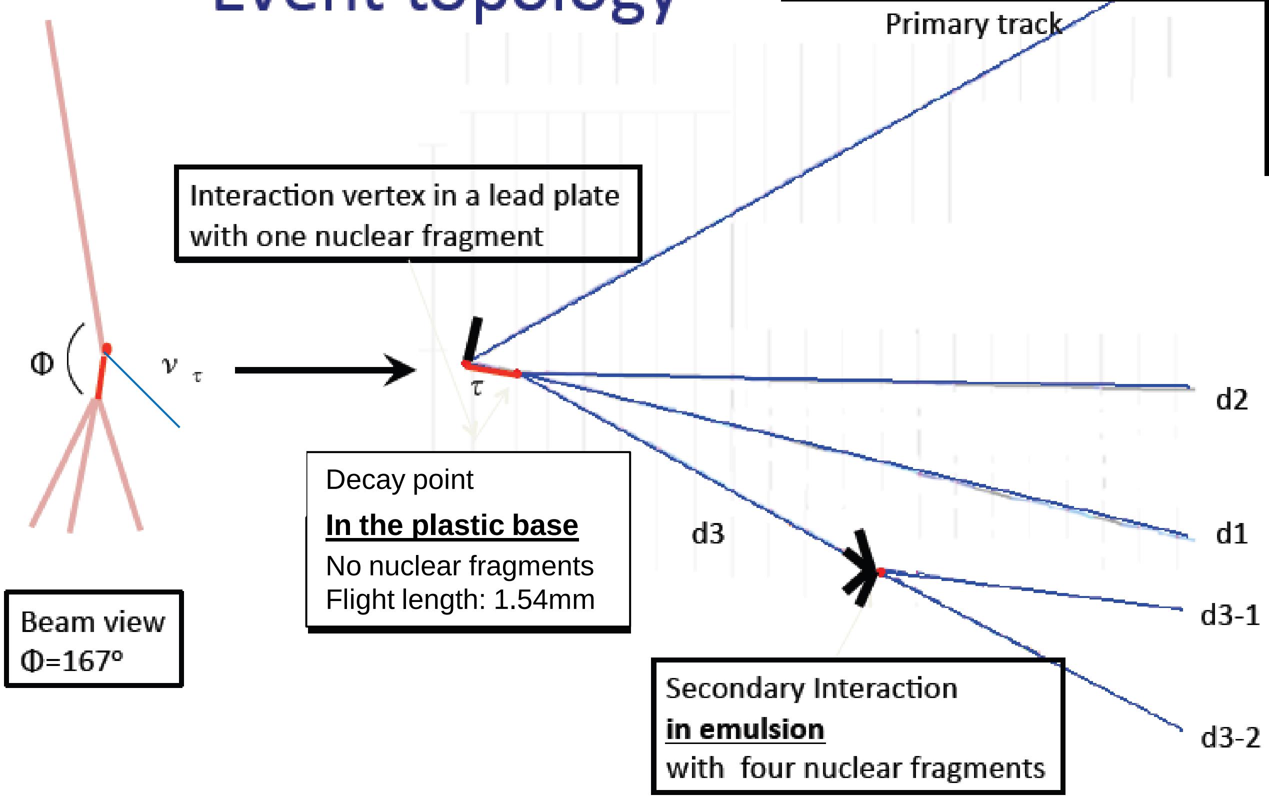
BACKGROUND SOURCES:

• Prompt ν_τ	$\sim 10^{-7}$/CC
• Decay of charmed particles produced in ν_e interactions	$\sim 10^{-6}$/CC
• Double charm production	$\sim 10^{-6}$/CC
• Decay of charmed particles produced in ν_μ interactions	$\sim 10^{-5}$/CC
• Hadronic reinteractions	$\sim 10^{-5}$/CC

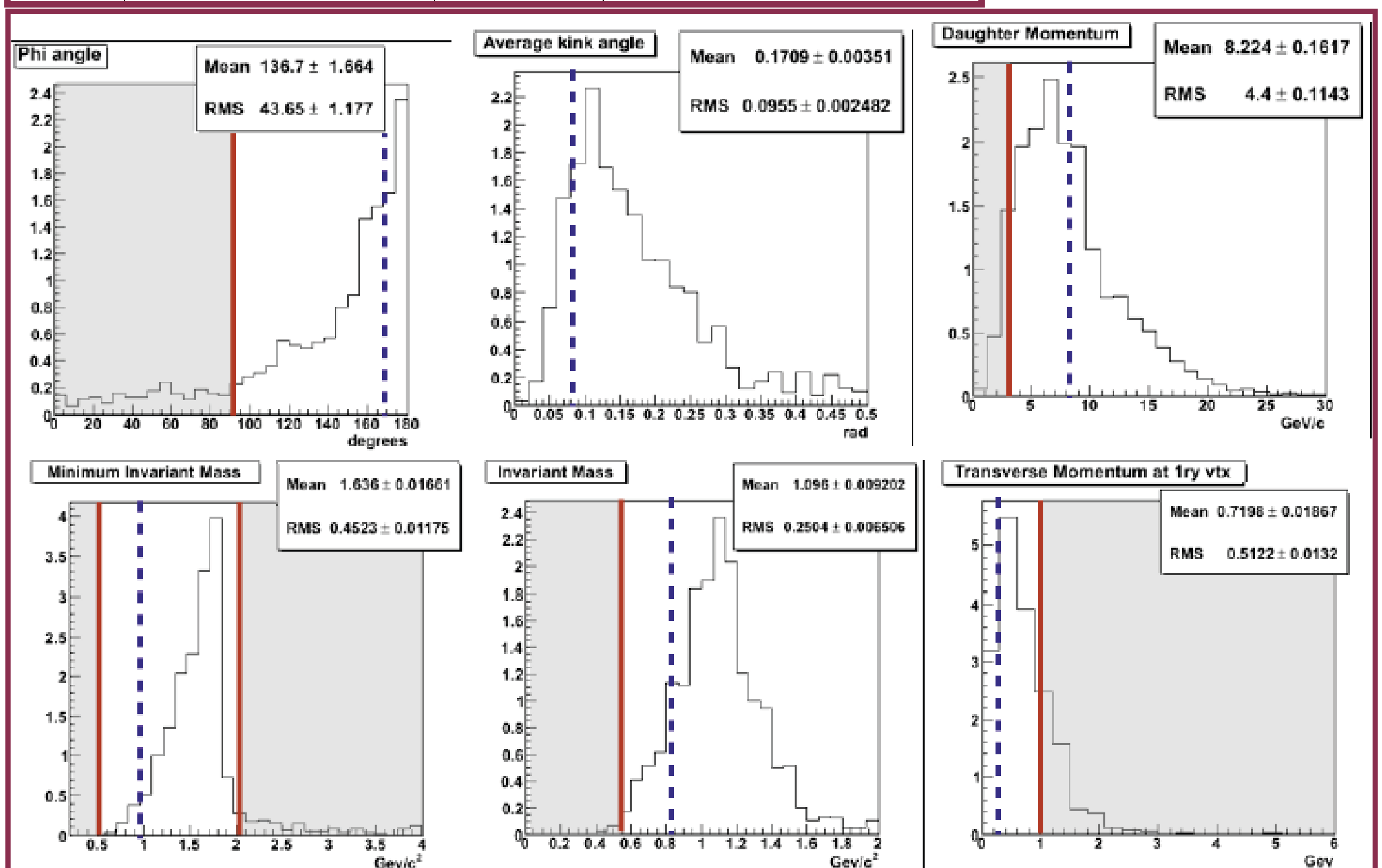
Second ν_τ candidate



Event topology

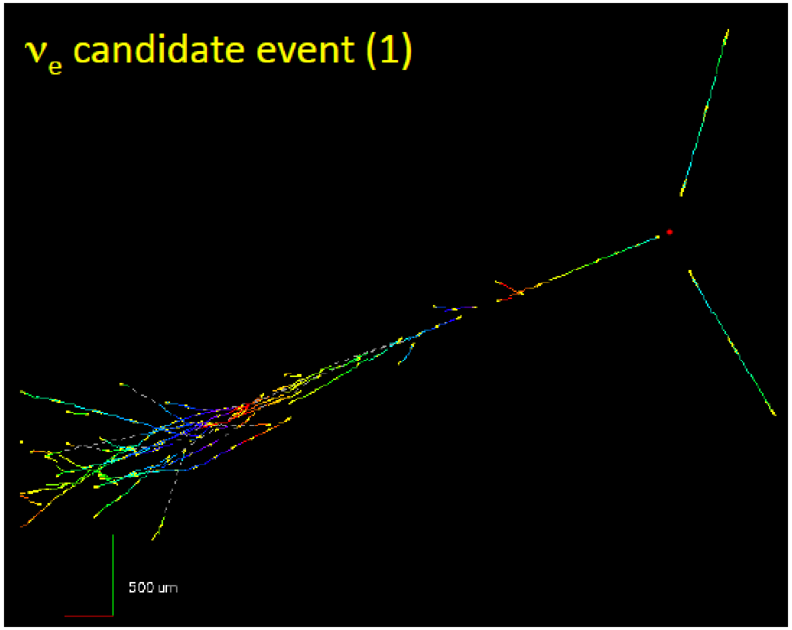


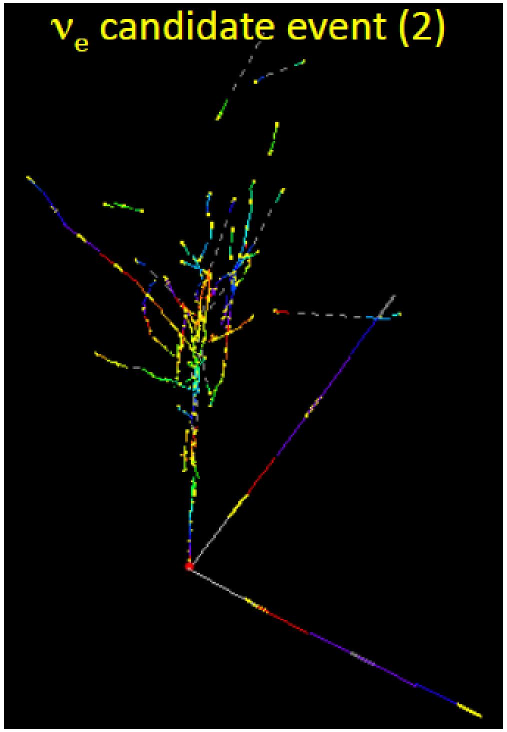
Track	Momentum (1σ interval) [GeV/c]	Particle ID	Method / comments
Primary	2.8 (2.1-3.5)	Hadron	Momentum-range consistency Stops after 2 brick walls Incompatible with a muon (26~44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	Momentum-range consistency
d2	1.3 (1.1 -1.5)	Hadron	Momentum-range consistency
d3	2.0 (1.4 - 2.9)	Hadron	Interaction in the brick @ 1.3 cm downstream



Kinematical Cuts to be passed

An Interesting by-product: search for ν_e appearance

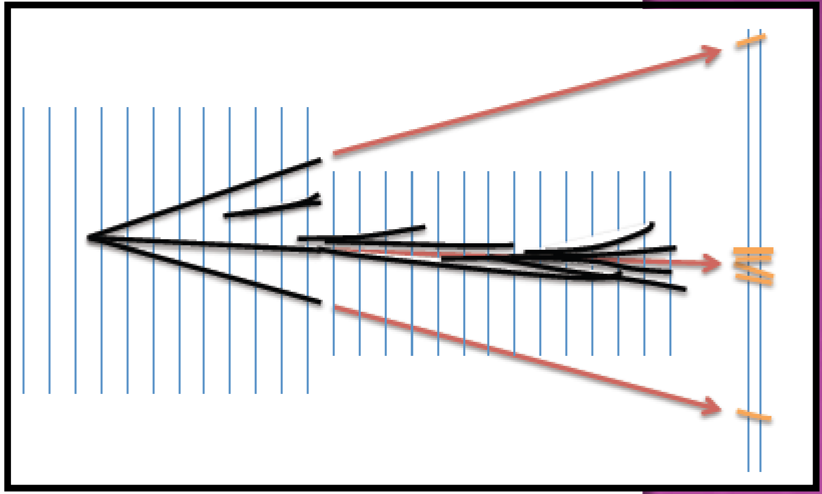




Systematic ν_e search for 2008/2009 located events (preliminary result presented at NEUTRINO 2012)

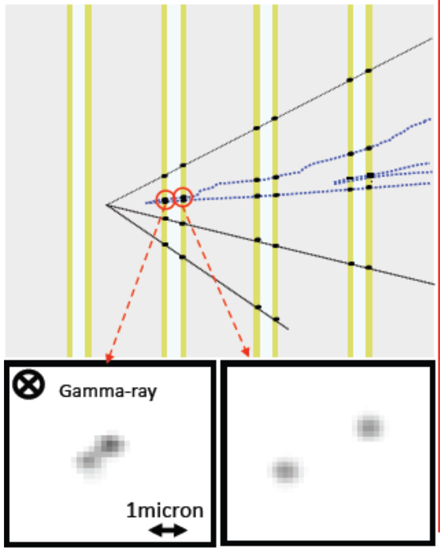
Event sample: 505 NC-like events in 2008-2009

For each located event:
- Extrapolated 1ry track to CS
- Search shower on CS
- If shower-like tracks are found on CS, open additional volume

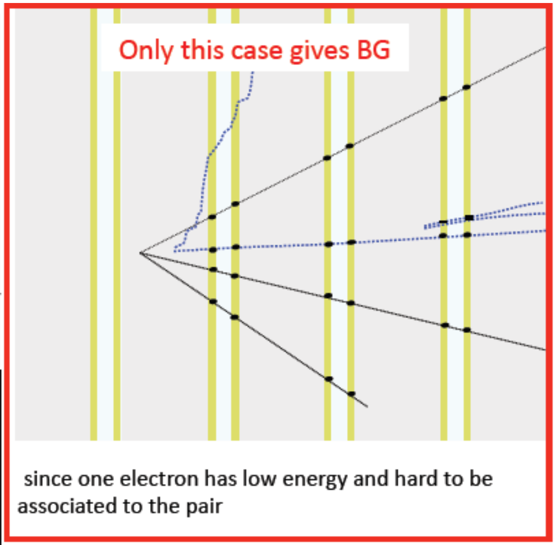


As a result: 96 events selected, total 19 ν_e confirmed

Background from ν_μNC ($\pi^0 \to 2\gamma$)

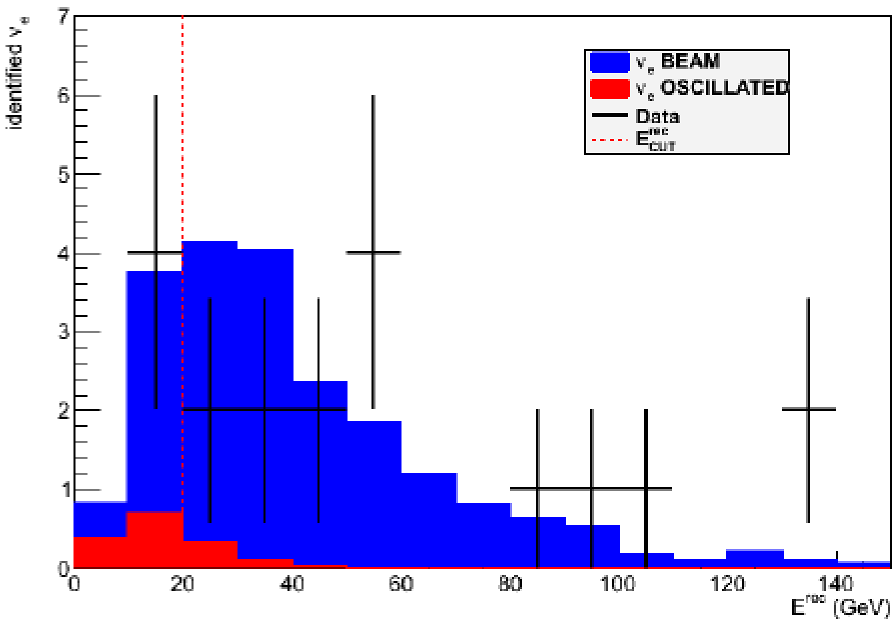


Close-up of an electron pair



BG for 2008+2009 statistics: 0.16 events

Event Energy Distribution

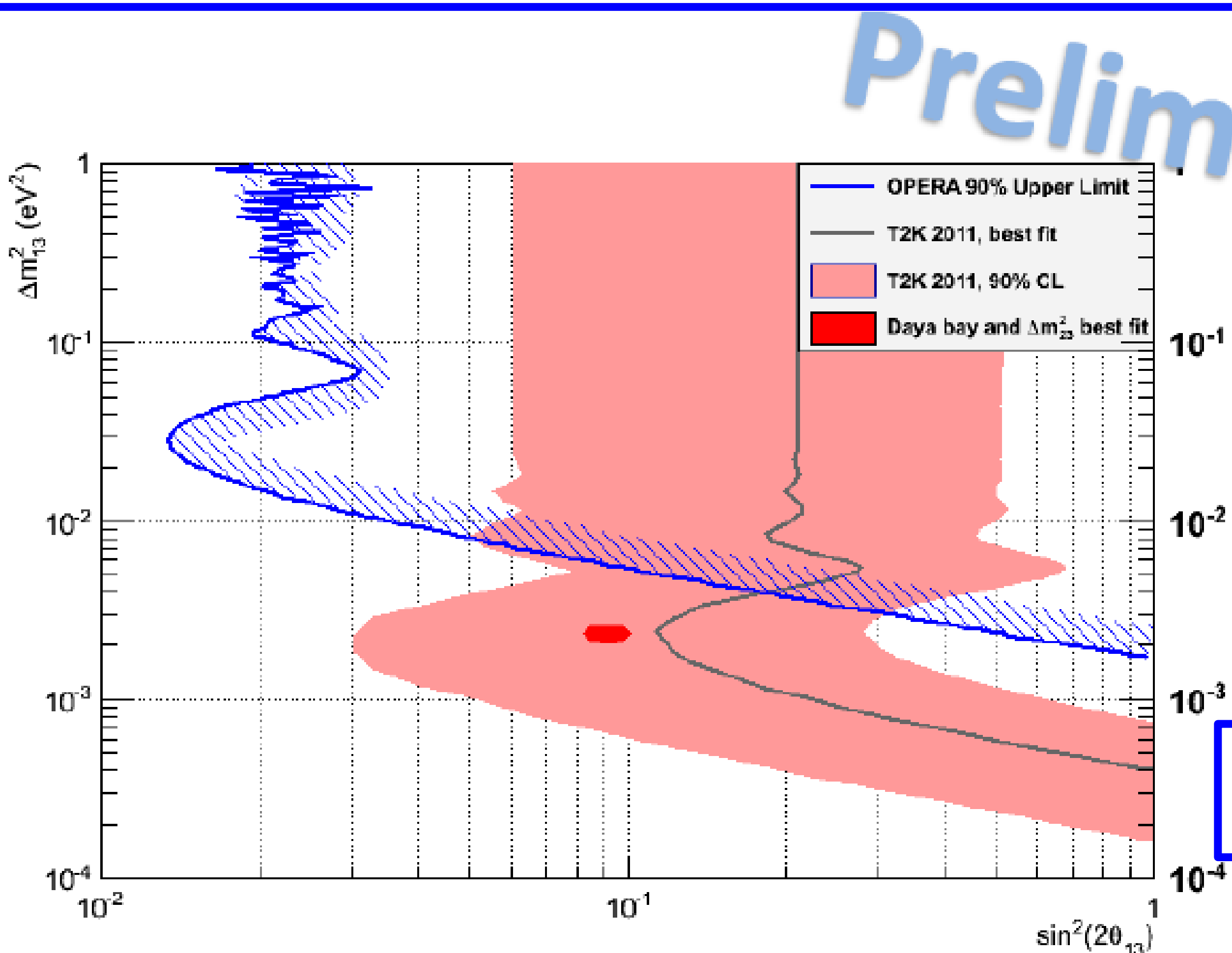


Expected events:

Oscillated ν_e : 1.5
Beam ν_e BG: 19.2
Observed ν_e : 19

After low-energy event selection ($E\nu$ < 20 GeV):
Observed events: **4**
Expected event: **oscillated 1.1**,
beam BG 3.7

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



Δm_{23}=2.45E-3
$\sin^2\theta_{23}$=0.51

Kyoto Neutrino2012

WORK IN PROGRESS…

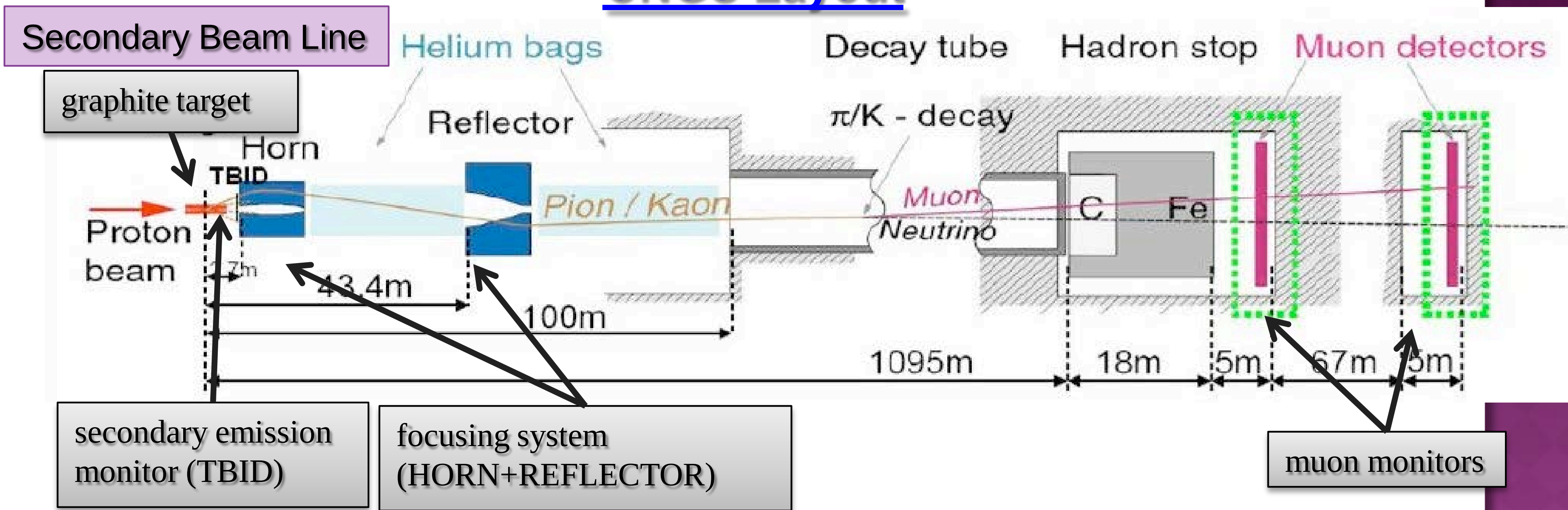
→ **Better sensitivity evaluation as a function of E_{cut}**

→ **Optimization of E_{cut}**

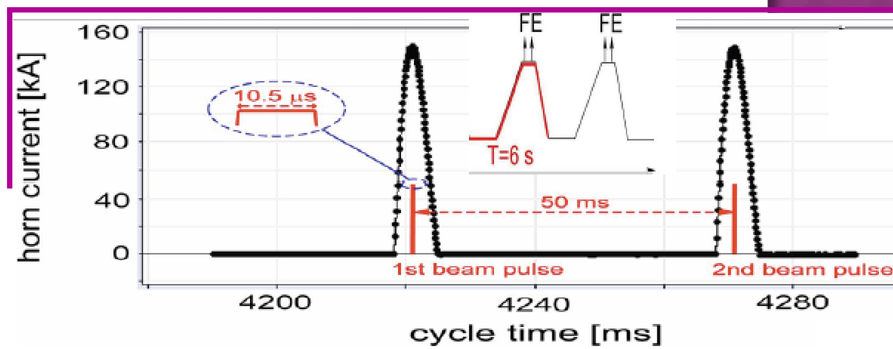
→ **New Result Soon…**

Neutrino Velocity Measurement

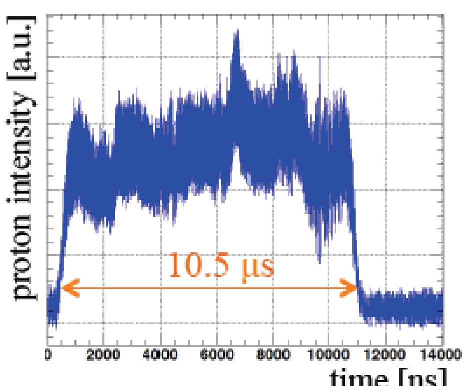
CNGS Layout



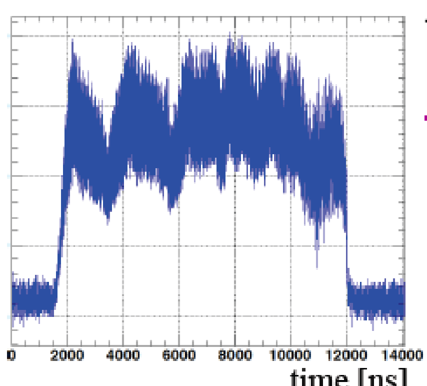
- **2 Fast Extractions**
- **10.5 μs**
- **50 ms separation**



extraction 1



extraction 2

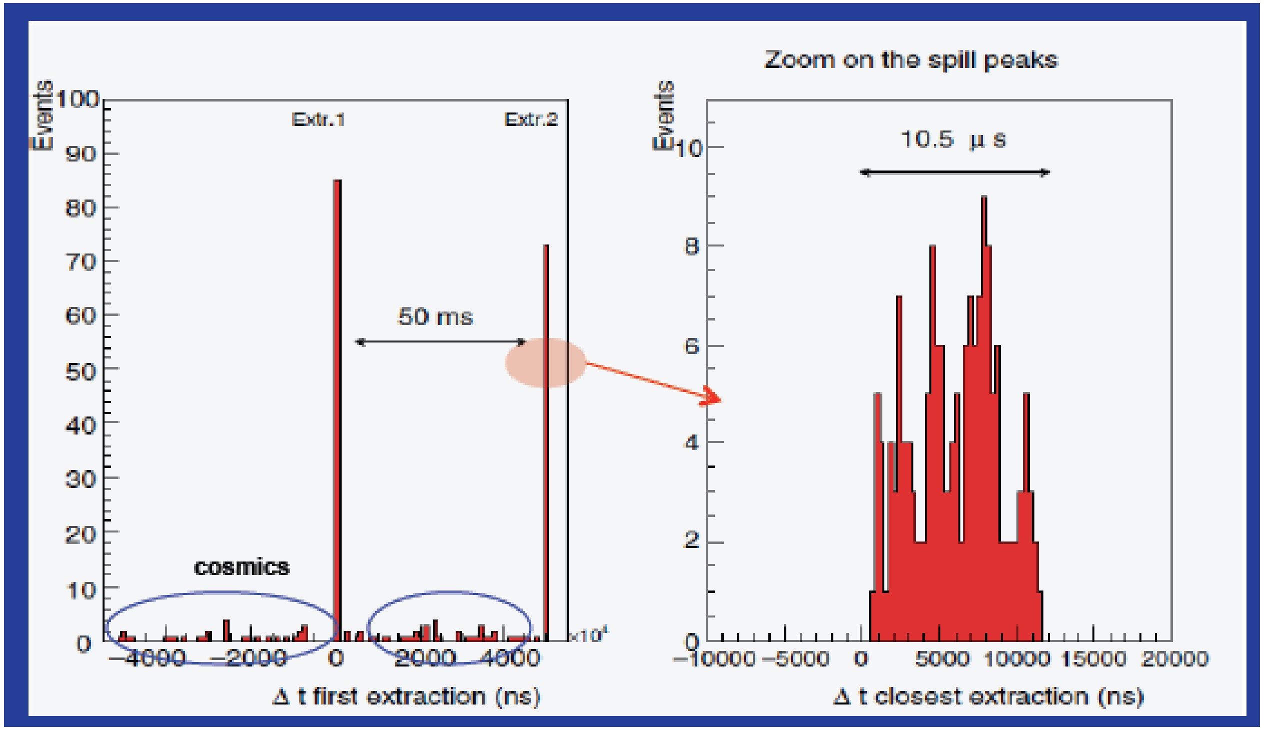


CNGS event selection – ON TIME events

Offline coincidence of SPS proton extractions (kicker time-tag) and OPERA events

$$|T_{OPERA} - (T_{kicker} + TOFc)| < 20\ \mu s$$

Synchronisation with standard GPS system ~100 ns (not adequate for our purposes)



OPERA data: narrow peaks of the order of the spill width (10.5 μs)

Negligible cosmic-ray background: $O(10^{-4})$

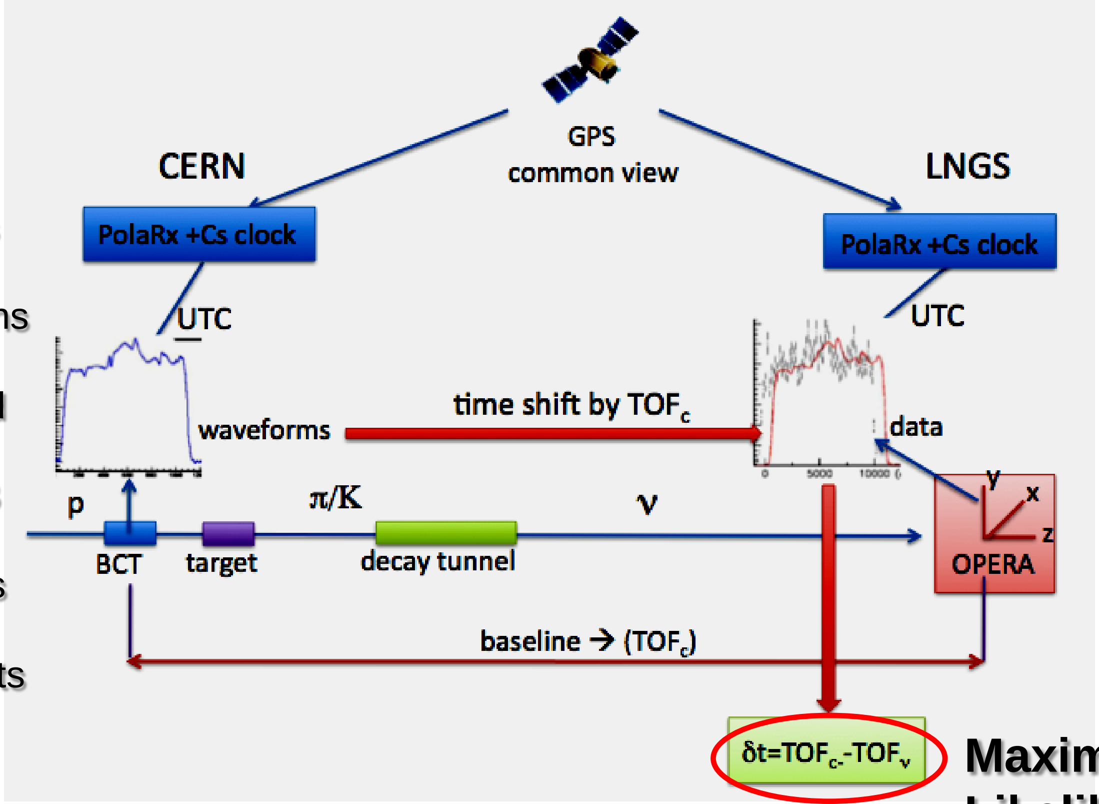
Selection procedure kept unchanged since first events in 2006

Summary of the principle

- ✓ Tagging of neutrino production time
- ✓ Tagging of neutrino interaction by a far detector
- ✓ Accurate determination of the baseline
- ✓ Blind Analysis

CNGS
- Proton pulses individually measured (1 ns sampling)
- Time stamped and logged in the CERN DB

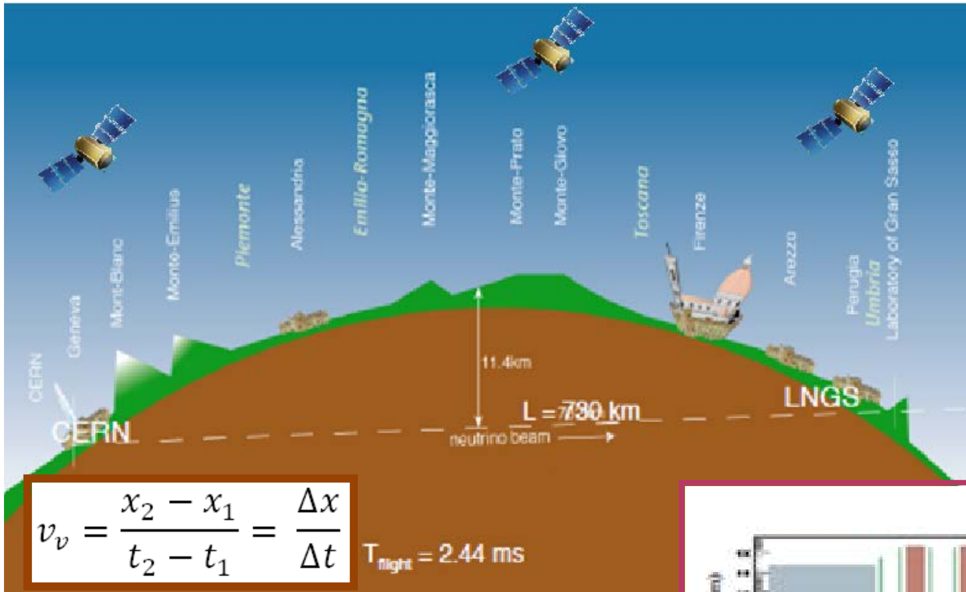
→PDF functions to predict the neutrino events distributions



Synchronization
- 2 TWIN high accuracy timing system
- Common View Mode

OPERA
- Time distributions of the ON TIME events

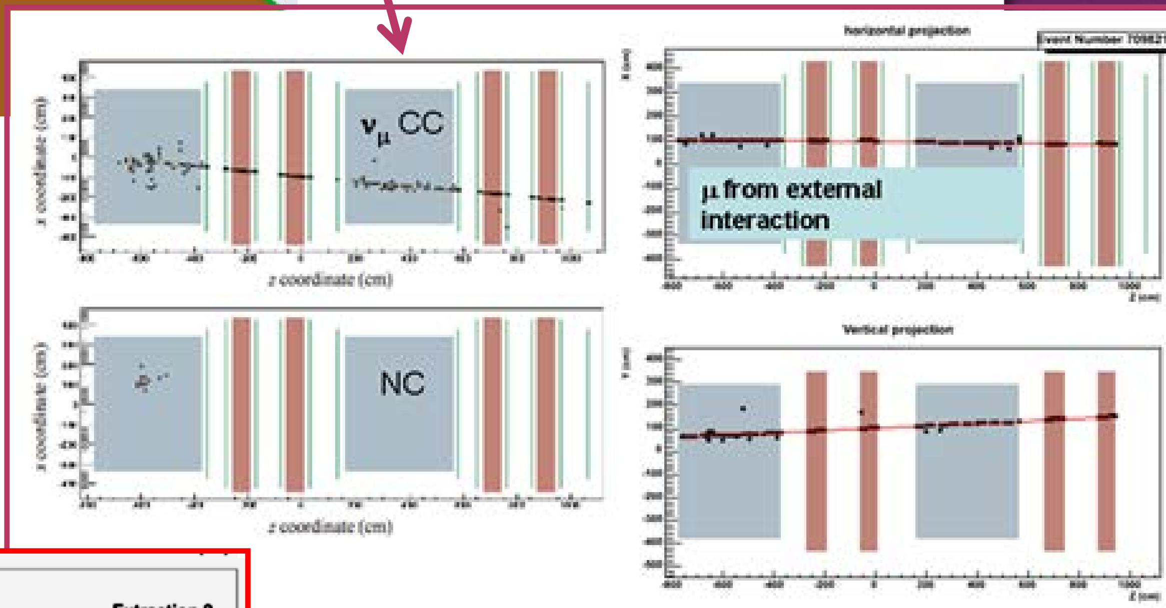
Maximum Likelihood



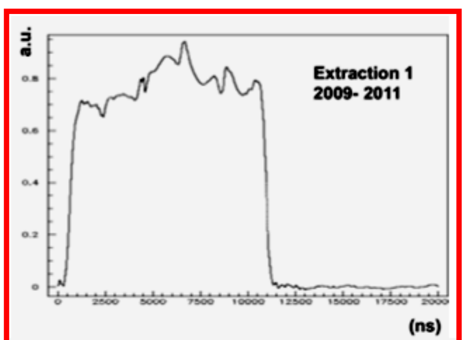
$$v_\nu = \frac{x_2 - x_1}{t_2 - t_1} = \frac{\Delta x}{\Delta t}$$

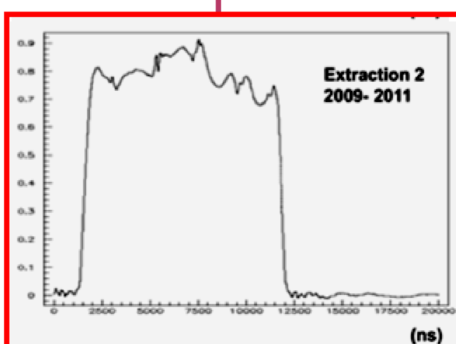
$T_{flight} = 2.44$ ms

- Long Baseline needed for high accuracy
- The shape of the two extraction is not the same → treat each extration separately
- Event time-stamped with the first digit of the OPERA electronic detectors
- Internal and External Events used, 3 years of data → high statistic

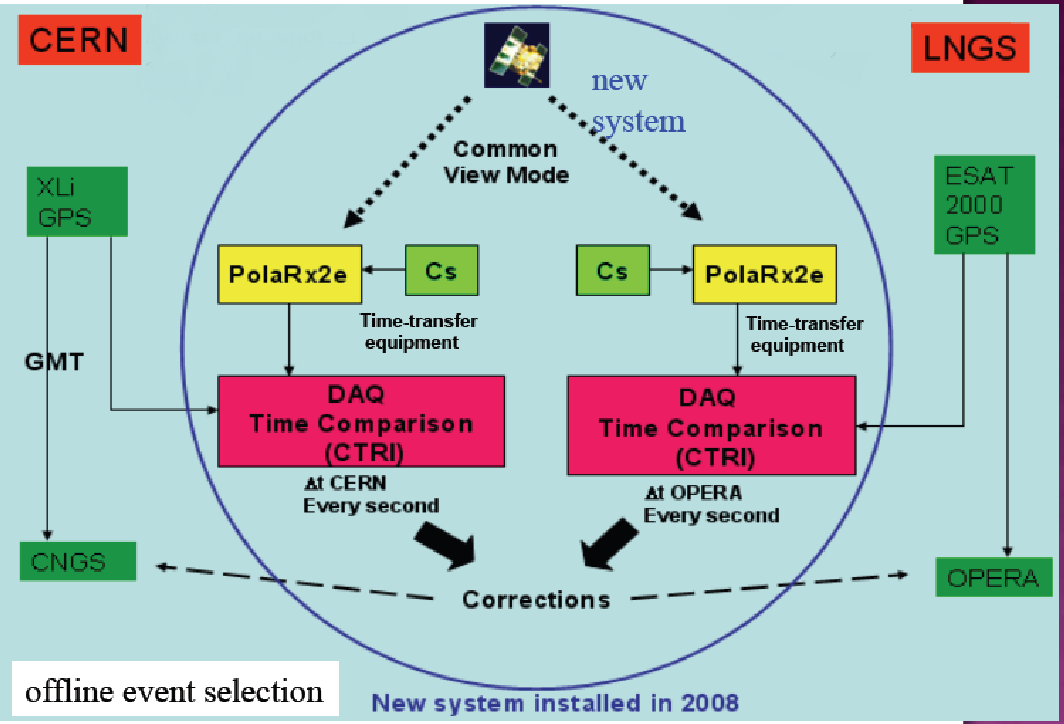


- For each neutrino event in OPERA → proton waveform of the corresponding extraction
- Sum up and normalise → PDF w(t) → separate likelihood for each extraction





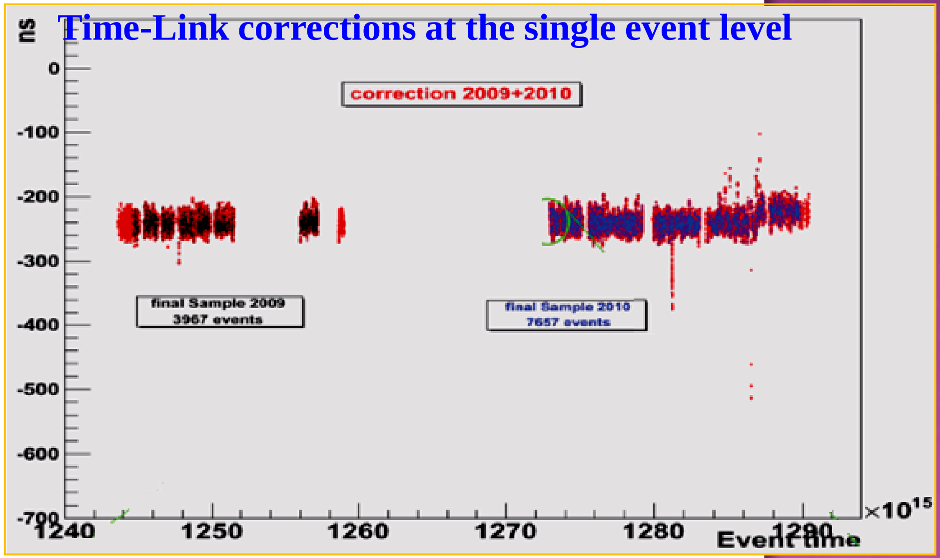
CNGS-OPERA Synchronization



→ **Data processing** of the twin high accuracy timing system

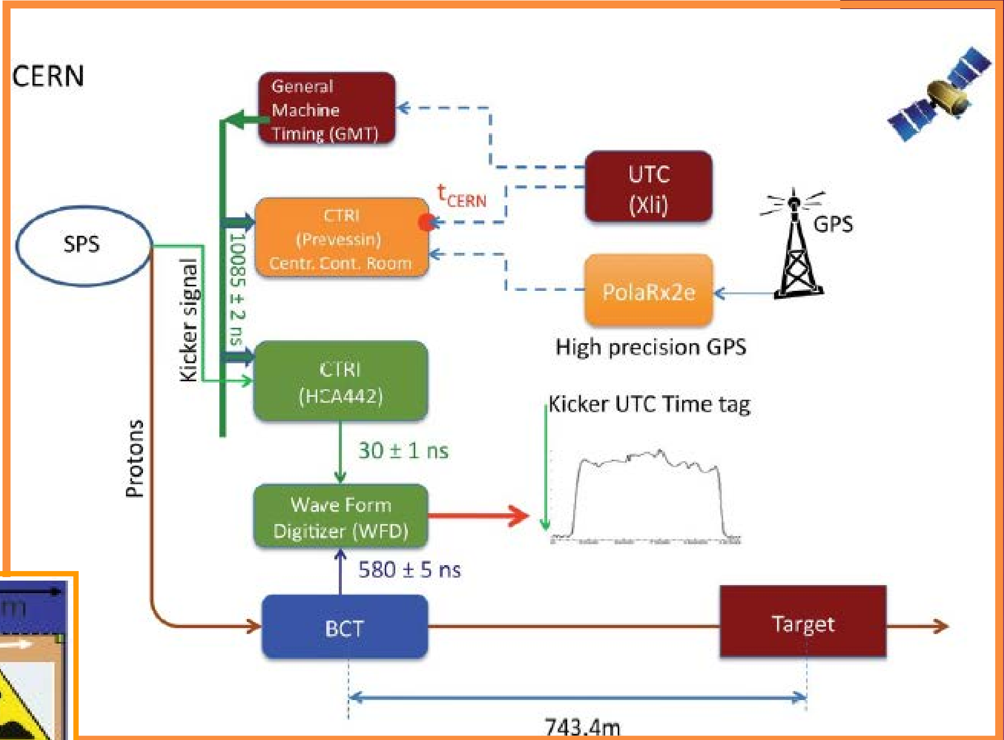
- **Comparison old/new timing system every second**
- **Satellites in common view mode**

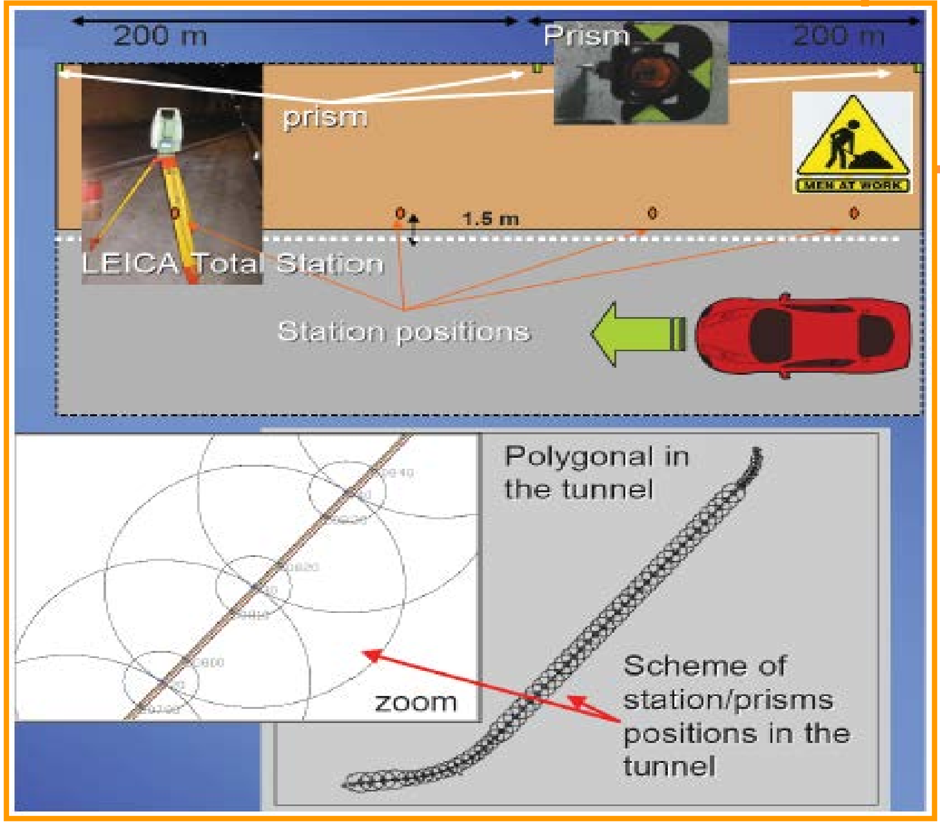
TIME LINK VALUES at single event level



→ **Timing chains calibrations**

Every path delays of the timing chains has been calibrated more then once, using different techniques (Portable Cs clock, 2-ways, Scope meas., laser, dedicated beam … …)

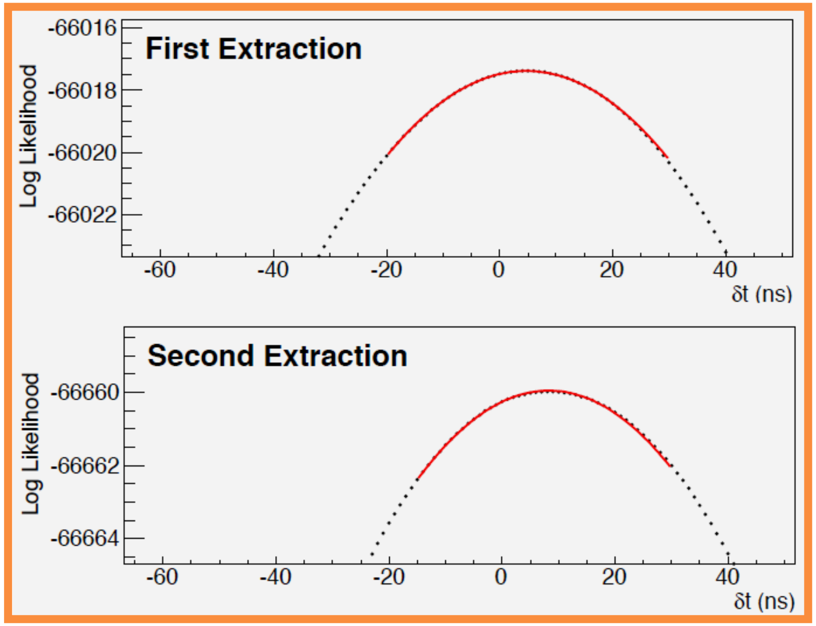




→ **Geodesy measurements to link the OPERA detector position underground to GPS benchmarks**

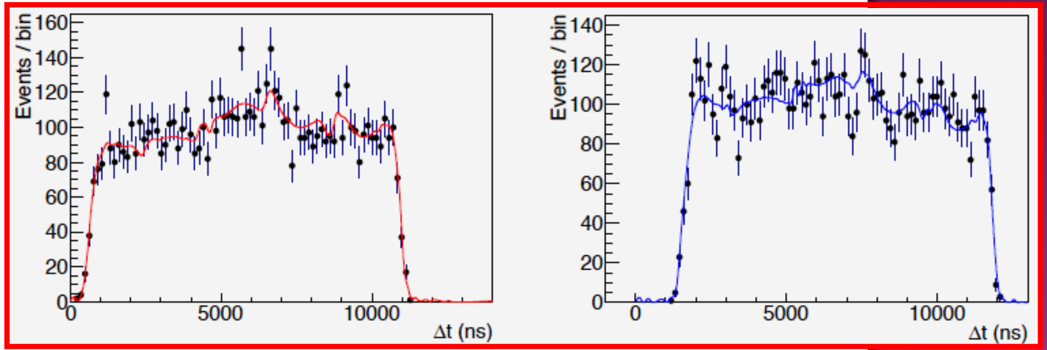
20 cm accuracy over ~730 km

$\rightarrow$ Statistical Analysis



$$L_k(\delta t_k) = \prod_j w_k(t_j + \delta t_k) \quad k = 1,2 \text{ extractions}$$

- maximisation by varying $\delta t = TOF_c - TOF_\nu$
- statistical error evaluated from the log likelihood curves



$$\delta t = \mathrm{TOF}_c - \mathrm{TOF}_\nu = (6.5 \pm 7.4 \ (\mathrm{stat.}) \ ^{+8.3}_{-8.0} \ (\mathrm{sys.}))\,\mathrm{ns}$$

$$(v - c)/c = \delta t/(\mathrm{TOF}'_c - \delta t) = (2.7 \pm 3.1 \ (\mathrm{stat.}) \ ^{+3.4}_{-3.3} \ (\mathrm{sys.})) \times 10^{-6}$$

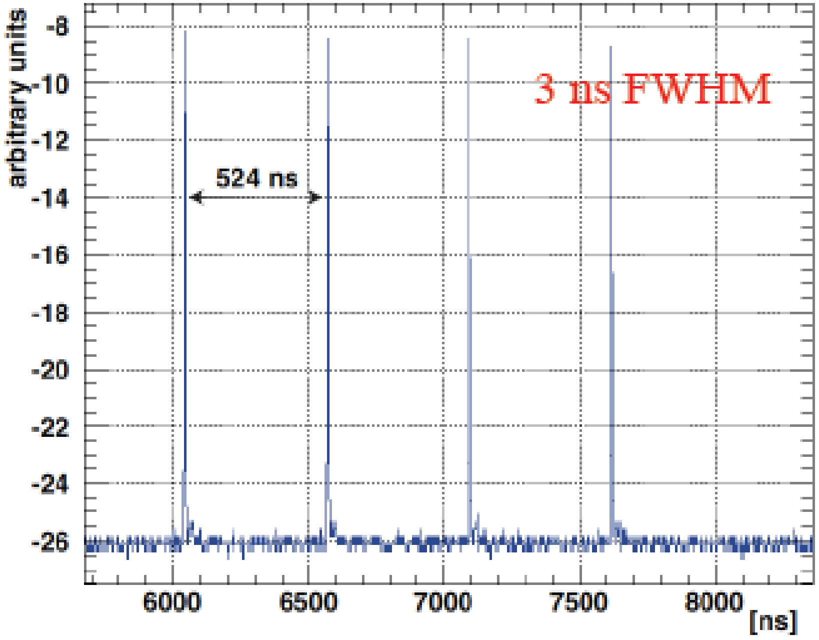
- **No seasonal effect**
- **No day/night effect**
- **No energy dependence**
- **No beam intensity dependence**
- **No difference between internal and external events (agreement with MC)**

Measurement with a short-bunch narrow-spacing proton beam

→ **2011: By associating each event to its own bunch: check on possible biases due to:**

- **Statistical treatment of data**
- **Response of the beamline components to long-lasting pulses**

October 22 to November 6 (2011)

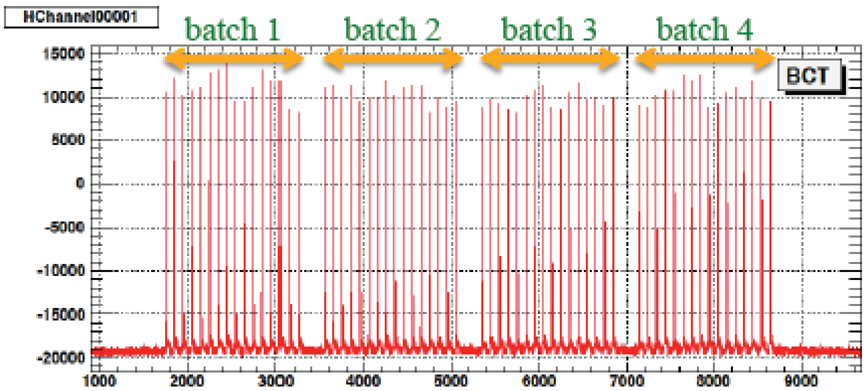


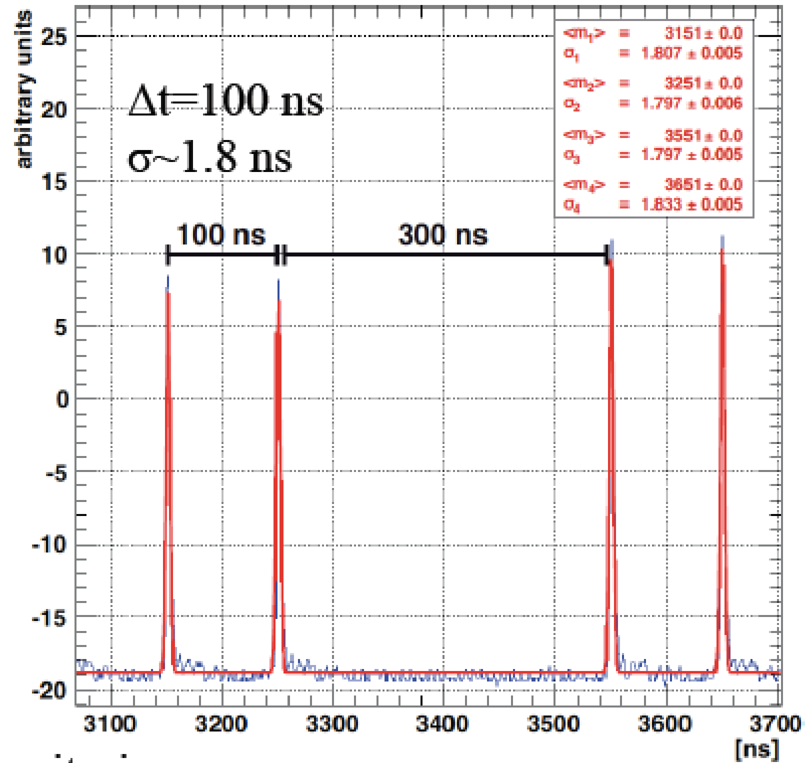
- **TOFν for each detected neutrino**
- **6 internal events**
- **14 external events**
- **events evenly distributed in the 4 bunches of the extraction**

Result compatible with the previous measurement

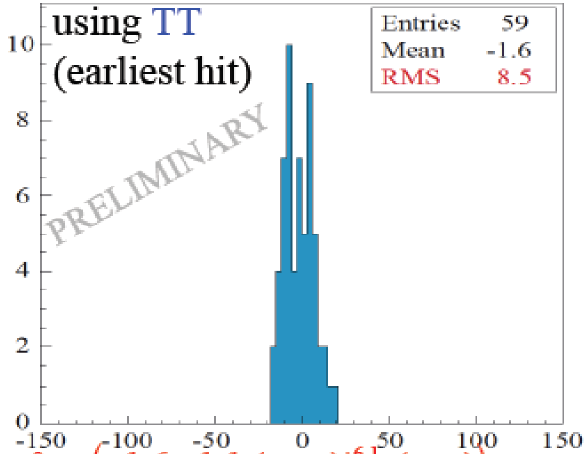
→New measurement in 2012

10 to 24 May 2012

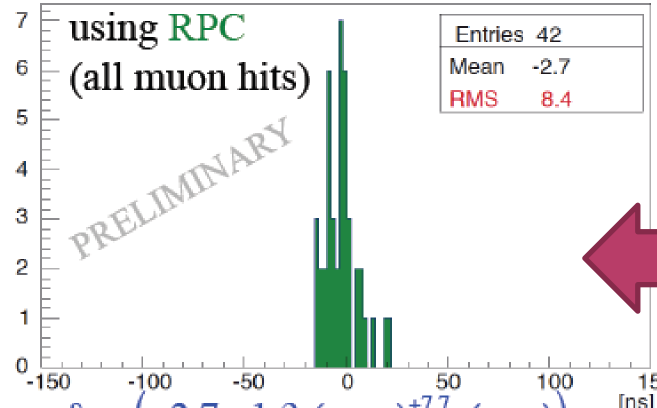




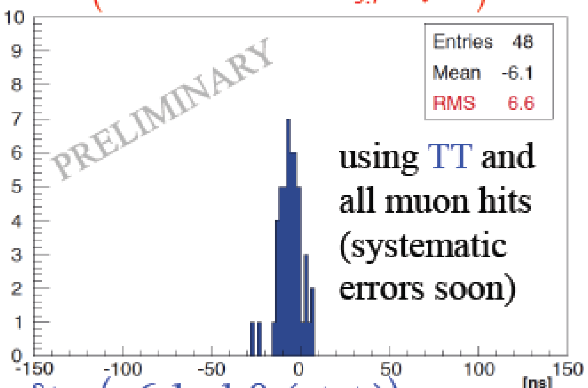
- 1 extraction per CNGS cycle
- 4 batches per extraction
- 16 bunches per batch
- p.o.t.: ~2 x 10^{17} (2 weeks)
- CERN White Rabbit system for delay monitoring
- **improved OPERA timing system (including both TT and RPC)**
- **106 on time events (external + contained)**



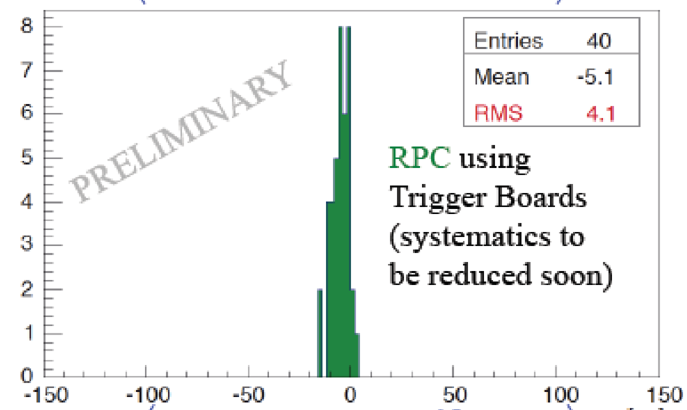
$$\delta t = \left(-1.6 \pm 1.1\ (stat.)^{+6.1}_{-3.7}\ (sys.)\right)\ \text{ns}$$



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



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



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

- **Data analysed with 4 different methods …**

+

- **New calibration delays …**

PRELIMINARY result from 2012 data is:

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

$$\frac{v-c}{c} = \frac{\delta t}{TOF_c - \delta t} = (-0.7 \pm 0.5\ (\text{stat.})^{+2.5}_{-1.5}\ (\text{sys.})) \times 10^{-6}$$

Kyoto Neutrino2012

- **New Result Soon**
- **Neutrino TOF computed for ν and $\bar{\nu}$ indipendently**

SUMMARY

- **OPERA** experiment: Direct detection of neutrino oscillations in **<u>APPEARANCE MODE</u>**
  - **$\nu_\mu \rightarrow \nu_\tau$ → τ decays**
    → High energy almost pure ν_μ beam (CNGS)
    → High spatial resolution + high target mass → hybrid detector: ECC and lead (brick walls) + electronic detectors

Year	Protons 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%)

- **2 candidate events**:
  - $\tau \rightarrow 1$ prong: $\tau \rightarrow \rho(\pi^- \pi^0)\nu_\tau$
  - $\tau \rightarrow 3$ h

Exp. Evts. ($22.5 \, 10^{19}$ pot)	BG events
7.5	0.73

- Preliminary result on the **$\nu_\mu \rightarrow \nu_e$ oscillation** analysis
  - 19 events observed, 4 with energy < 20 GeV (expected osc. Signal 1.1, BG 3.9)
    → constraints in the high Δm^2 region
  - **New improved result soon**

- **Neutrino velocity measurement**
  - Long baseline
  - Sophisticated timing system (common view mode GPS)
  - Geodesy
  - **2012 bunched beam preliminary result:**

$$\delta t = -1.6 \pm 1.1 \, ^{+6.1}_{-3.7} \rightarrow (v-c)/c = (-0.7 \pm 0.5 \, ^{+2.5}_{-1.5})10^{-6}$$

√ Techniques not commonly used in high energy physics

THANK YOU!