OPERA HIGHLIGHTS

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On behalf of

The OPERA collaboration

Outline

- OPERA
  - physics goal
  - detector
  - physics results
    - Oscillation
    - Neutrino speed
  - conclusion

The OPERA Collaboration

160 physicists, 30 institutions, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

http://operaweb.lngs.infn.it/scientists/?lang=en

Neutrino propagation

- Neutrinos are created as weak eigenstate, but propagate as mass eigenstate

$$|\nu\rangle = \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} \qquad |\nu'\rangle = \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- When we detect them after their travel, we can detect their current weak eigenstate

$$|\nu'(t)\rangle = e^{-iH't}|\nu'(0)\rangle \qquad |\nu(t)\rangle \ ?$$

- This leads to a possible flavour change of neutrinos during their travel, which was observed for solar (Davis, SNO) and atmospheric neutrinos (Super KAMIOKANDE)

Neutrino oscillation – theoretical description

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 angles θ_{ij}; the fraction of ν_1, ν_2 or ν_3 in a flavor eigenstate
1 phase δ; CP violation (for Dirac neutrinos)
atmospheric (23) and solar (12)

$c_{ij}=\cos\theta_{ij}$
$s_{ij}=\sin\theta_{ij}$

Oscillation probability in the three neutrinos scenario

$$P(\nu_\ell \to \nu_{\ell'}) = |\sum_i U_{\ell i} U^*_{\ell' i} e^{-i(m_i^2/2E)L}|^2$$

$$= \sum_i |U_{\ell i} U^*_{\ell' i}|^2 + \Re \sum_i \sum_{j \neq i} U_{\ell i} U^*_{\ell' i} U^*_{\ell j} U_{\ell' j} e^{i\frac{|m_i^2 - m_j^2|L}{2E}}$$

Δm^2

L

E

2 mass differences $\Delta m^2_{12} << \Delta m^2_{23}$

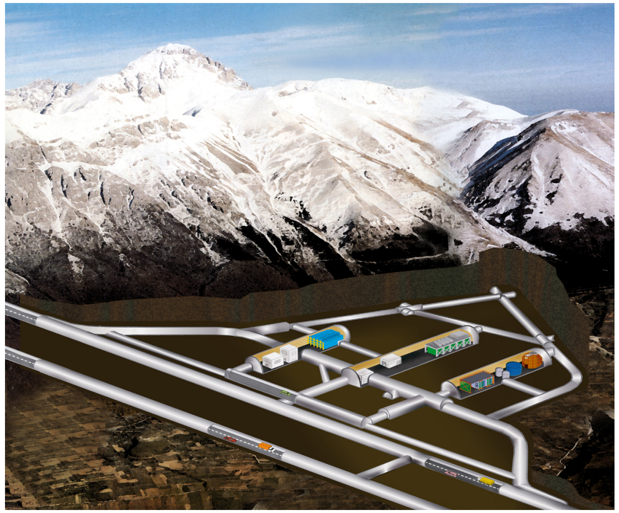
2 neutrino approximation:

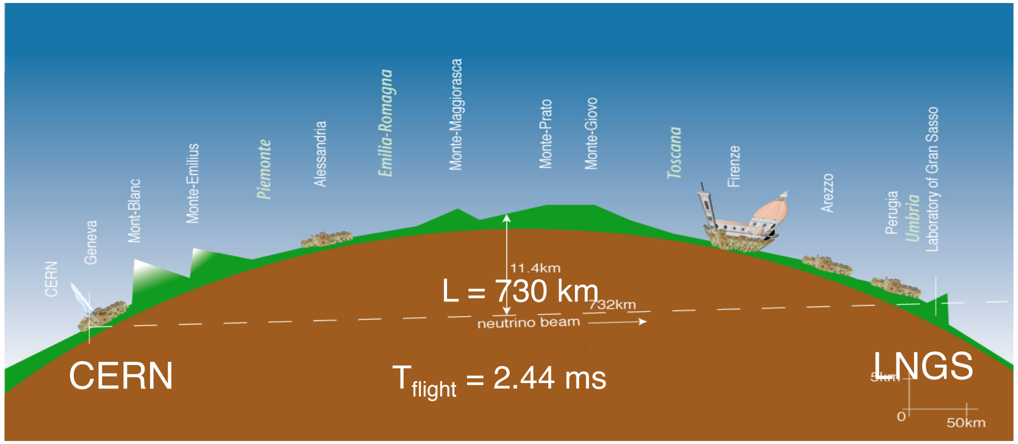
$$P(\nu_\mu \to \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(\Delta m^2_{23} L/4E)$$

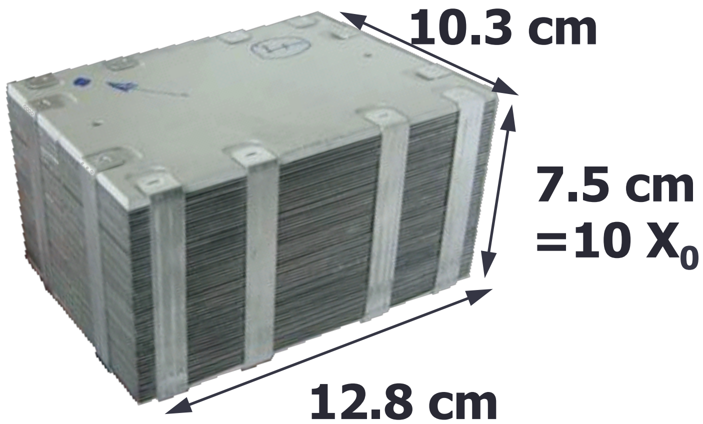
~1

Physics goal of Opera

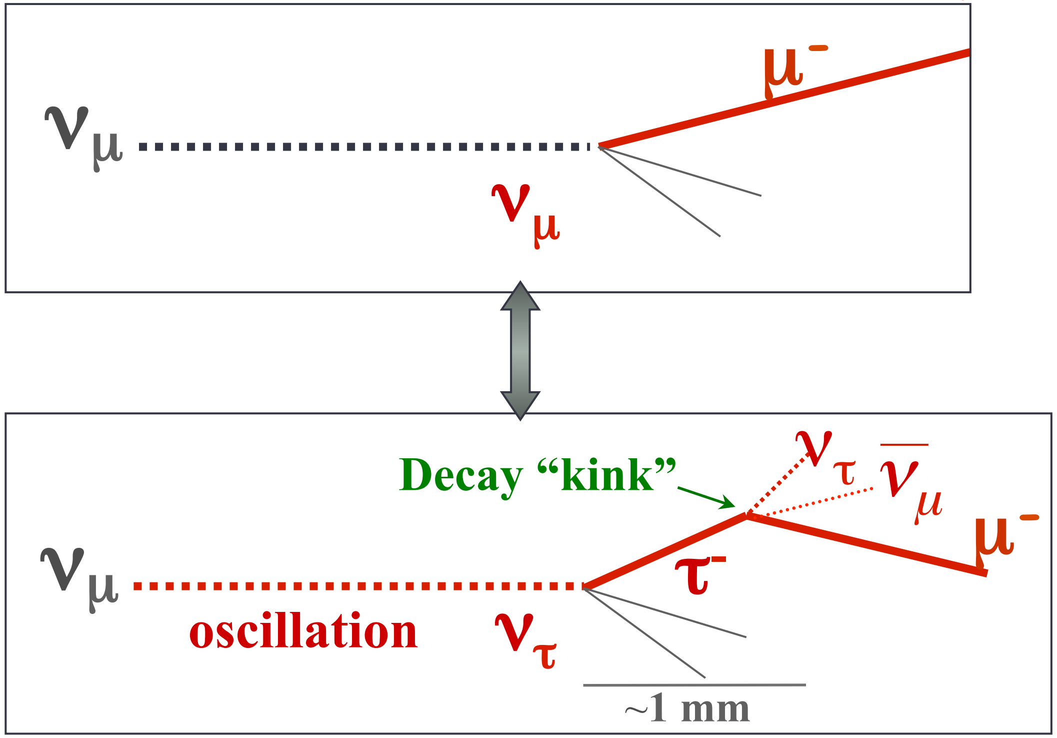
- First detection of neutrino oscillation in direct appearance mode via the ν_μ to ν_τ channel.
- Detection of the ν_τ by the τ decay topology
- Low cross section leads to a large mass
  - Emulsion Cloud Chamber: Lead brick, interleaved with emulsion
- Low background requirement: LNGS
- Neutrino beam optimized for detection



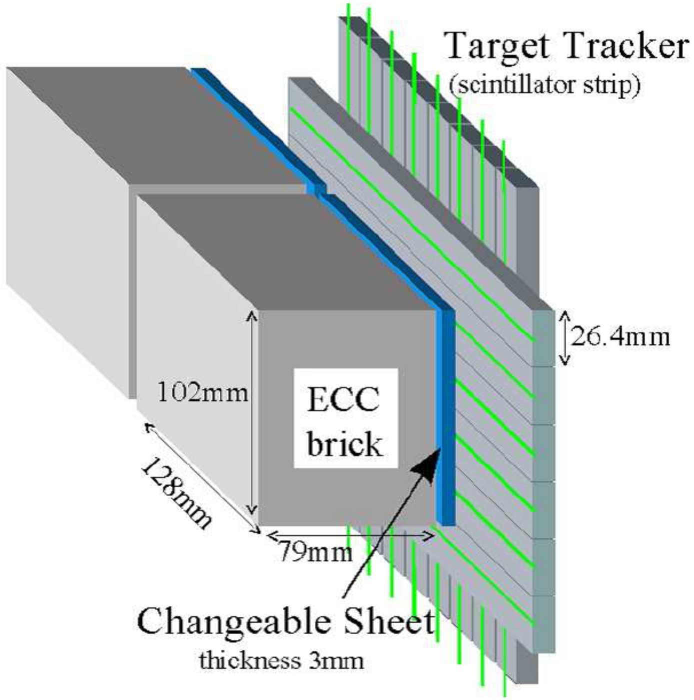




The direct probe for $\nu_\mu \rightarrow \nu_\tau$ appearance



leptonic, 1 + 3-prong decay modes



Two conflicting requirements:

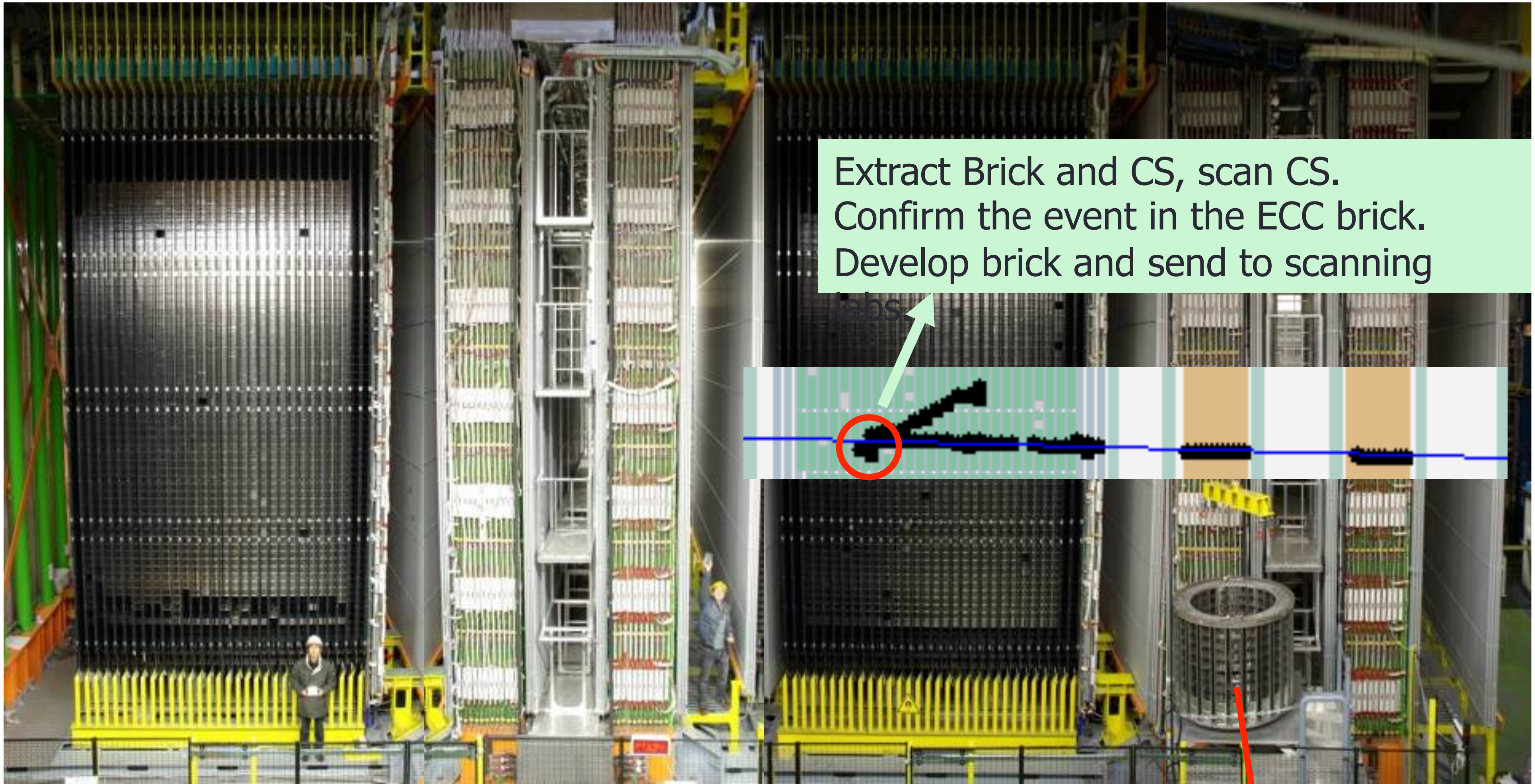
- **Large mass (low Xsection)**
- **High spatial resolution**
  - ➡ signal selection
  - ➡ background rejection

Target: ~1250 tons,
22.5E19 pot during 5 years

- >20000 neutrino interactions
- ~100 ν_τ interactions
- ~10 ν_τ identified
- <1 background event

The OPERA detector

SM1 SM2

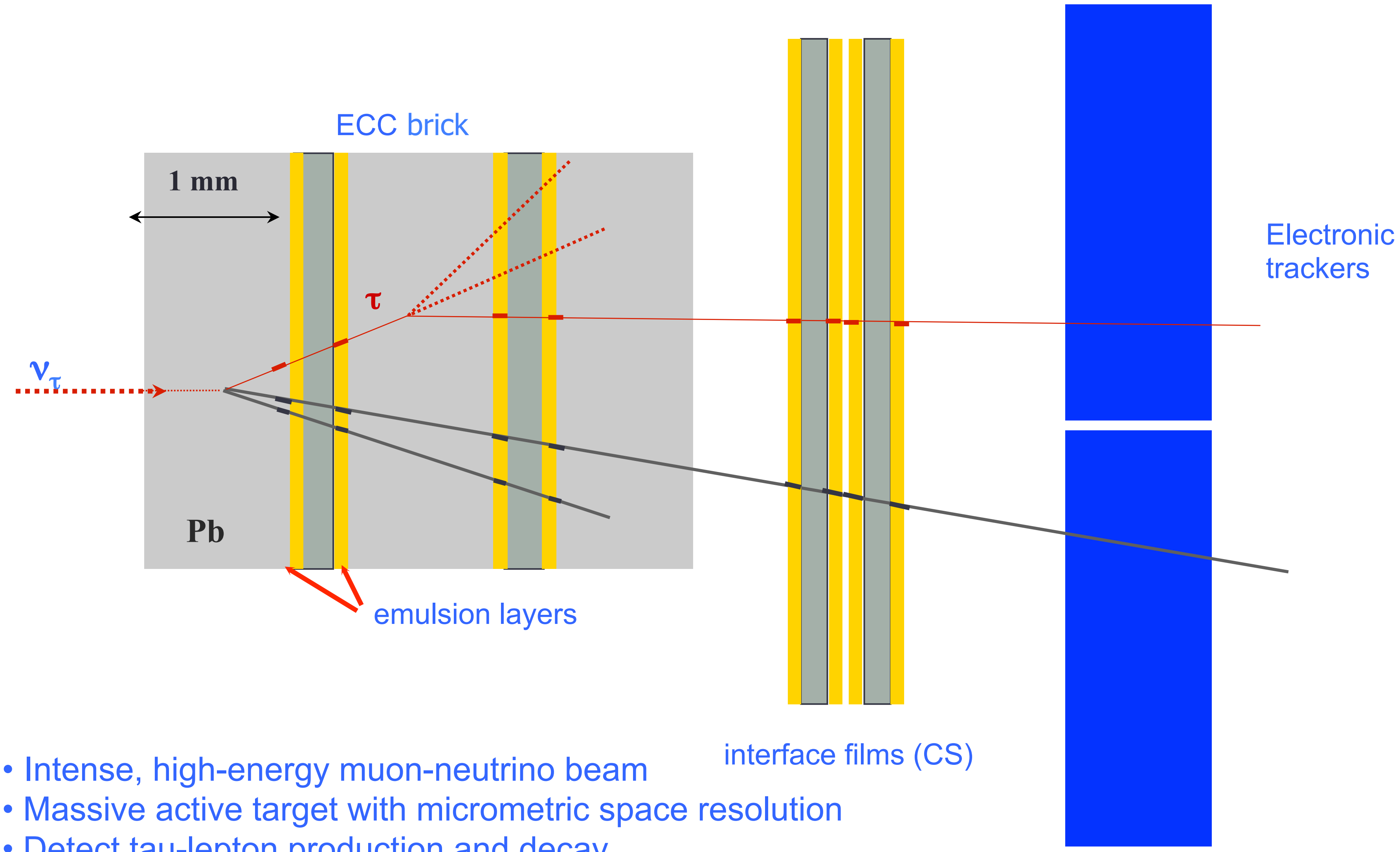


Target area (ECC + CS + TT)

Muon spectrometer (Magnet+RPC+PT)

Brick Manipulator System

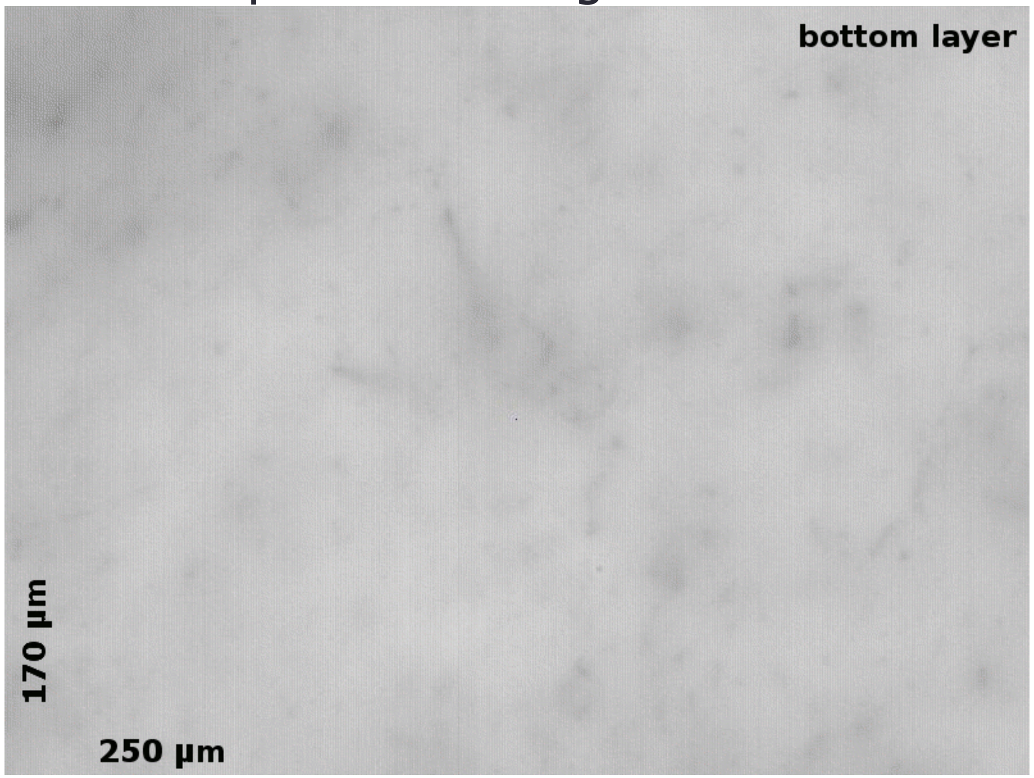
ECC combined with electronic detector

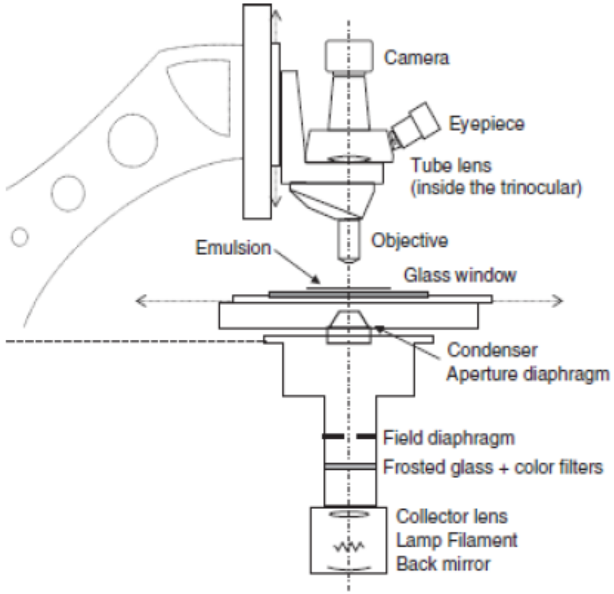


- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region

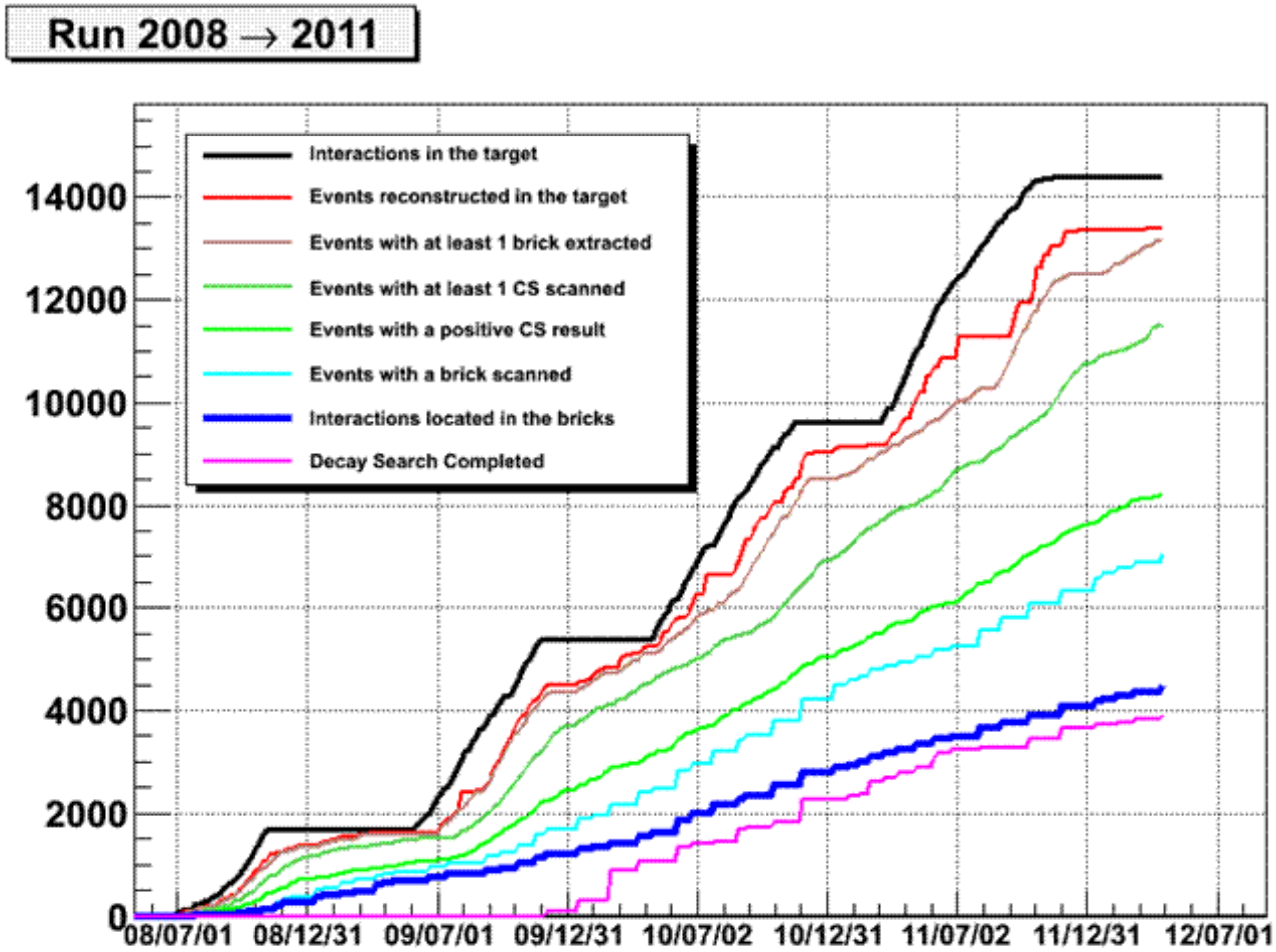
Emulsion Scanning

- Scanning Labs in Europe and Japan
  - 50% sharing
  - European CS scanning at LNGS
  - Data storage of scanned data in DB
  - Example of neutrino vertex
  - Example of scanning station at Bern



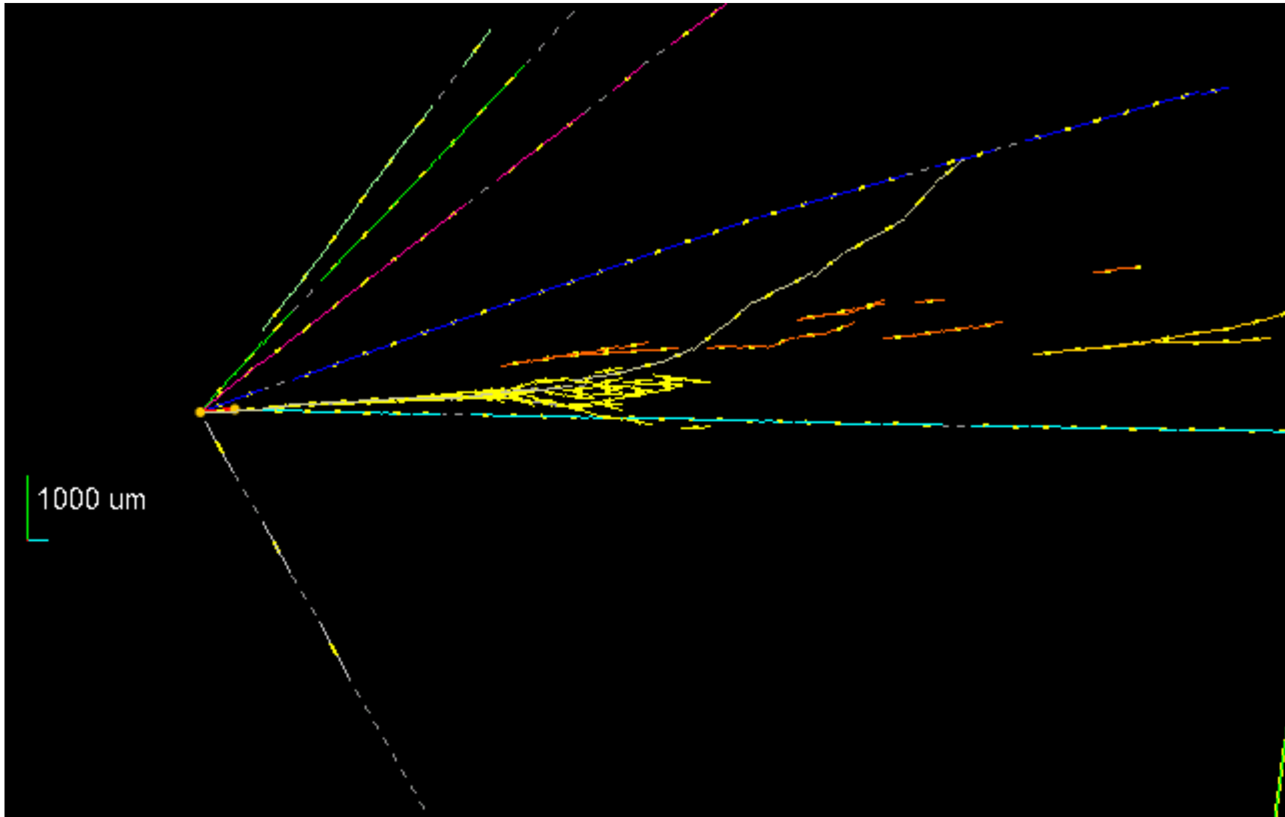


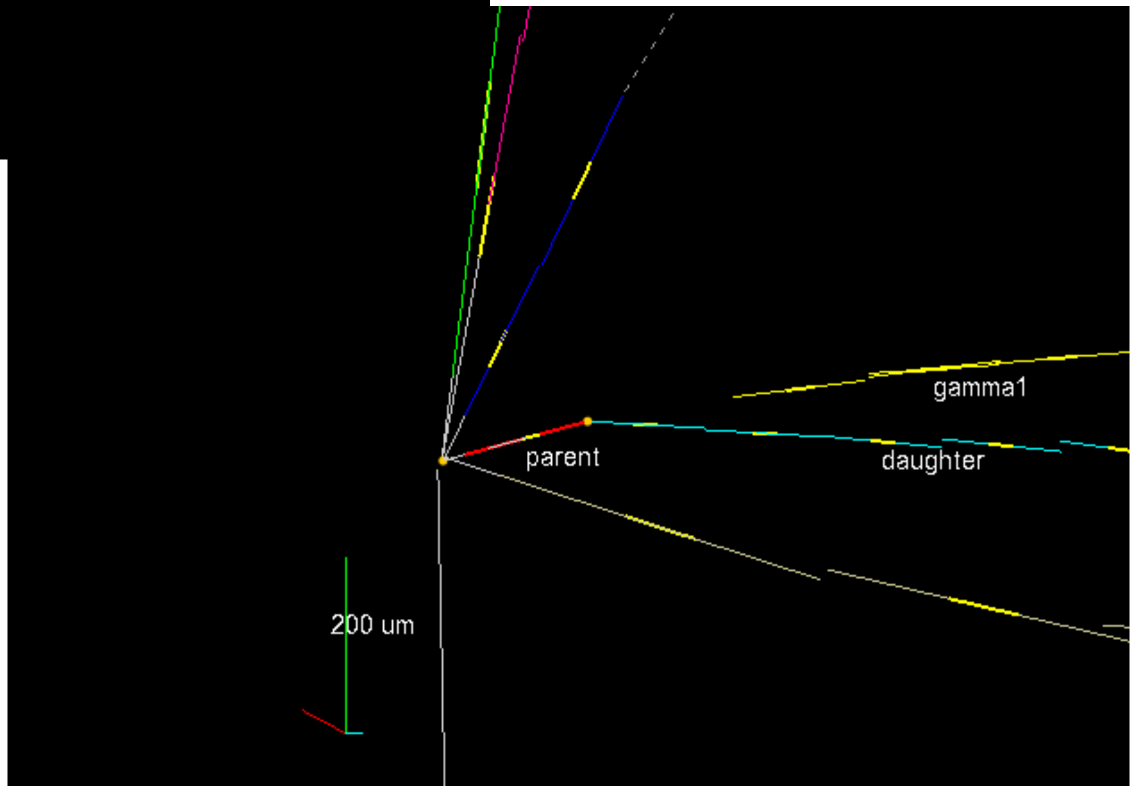
Event collection



Run 2012 is started, currently “bunched beam” mode for ν velocity measurement

First ν_τ candidate





- PLB 691 (2010) 138
- No μ found in spectrometer
- All tracks followed till stopping point or reinteraction (no μ found)
- In agreement with expectation
- Compatible with a hadronic τ decay: $\tau^- \to h^- (n\pi^0)\, \nu_\tau$

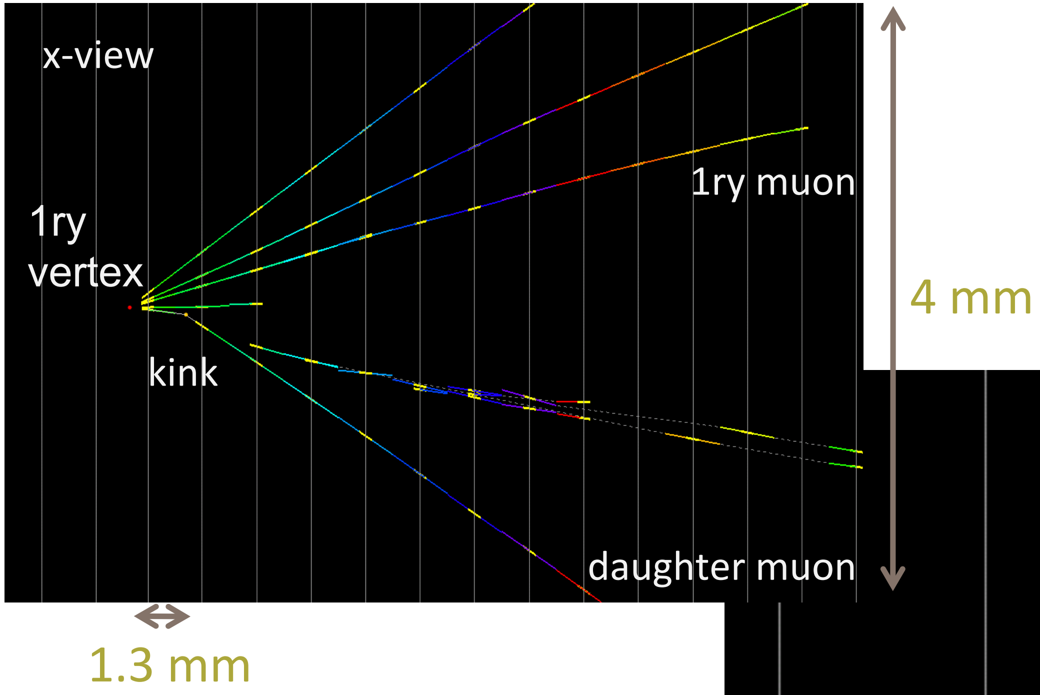
- Full update for Neutrino 2012
    - New Candidates
    - New Background estimation

About the first ν_τ event

- All cuts defined at the proposal time applied, event passed the selection.
- Current expectation 1.7 events in all tau channels (0.5 in singleprong)
- Propability for a background event 5%, expected background so far only 0.16 (0.05) for 4.9×10^{19} pot

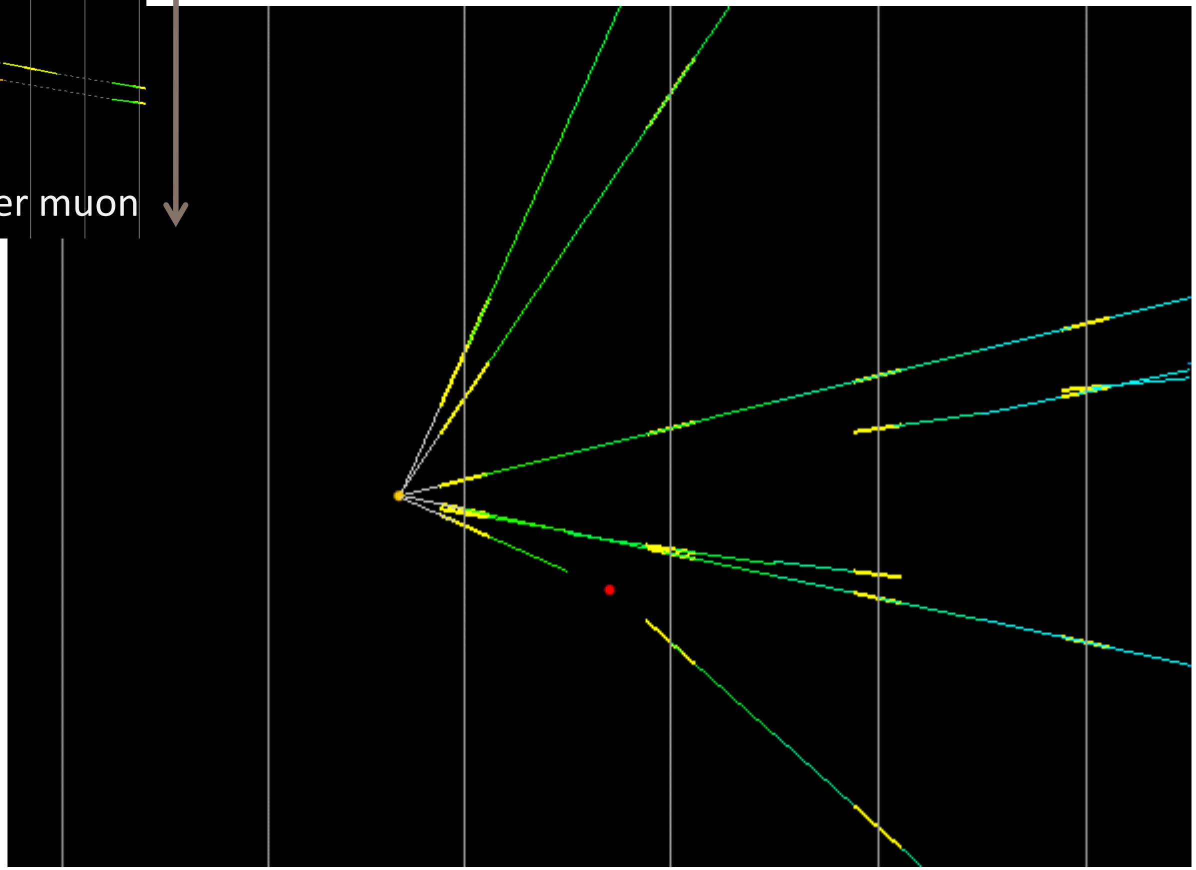
- What else can we do except for τ decay
  - Other rare events: charm
  - electron neutrinos
  - Timing of neutrino events

Charm event

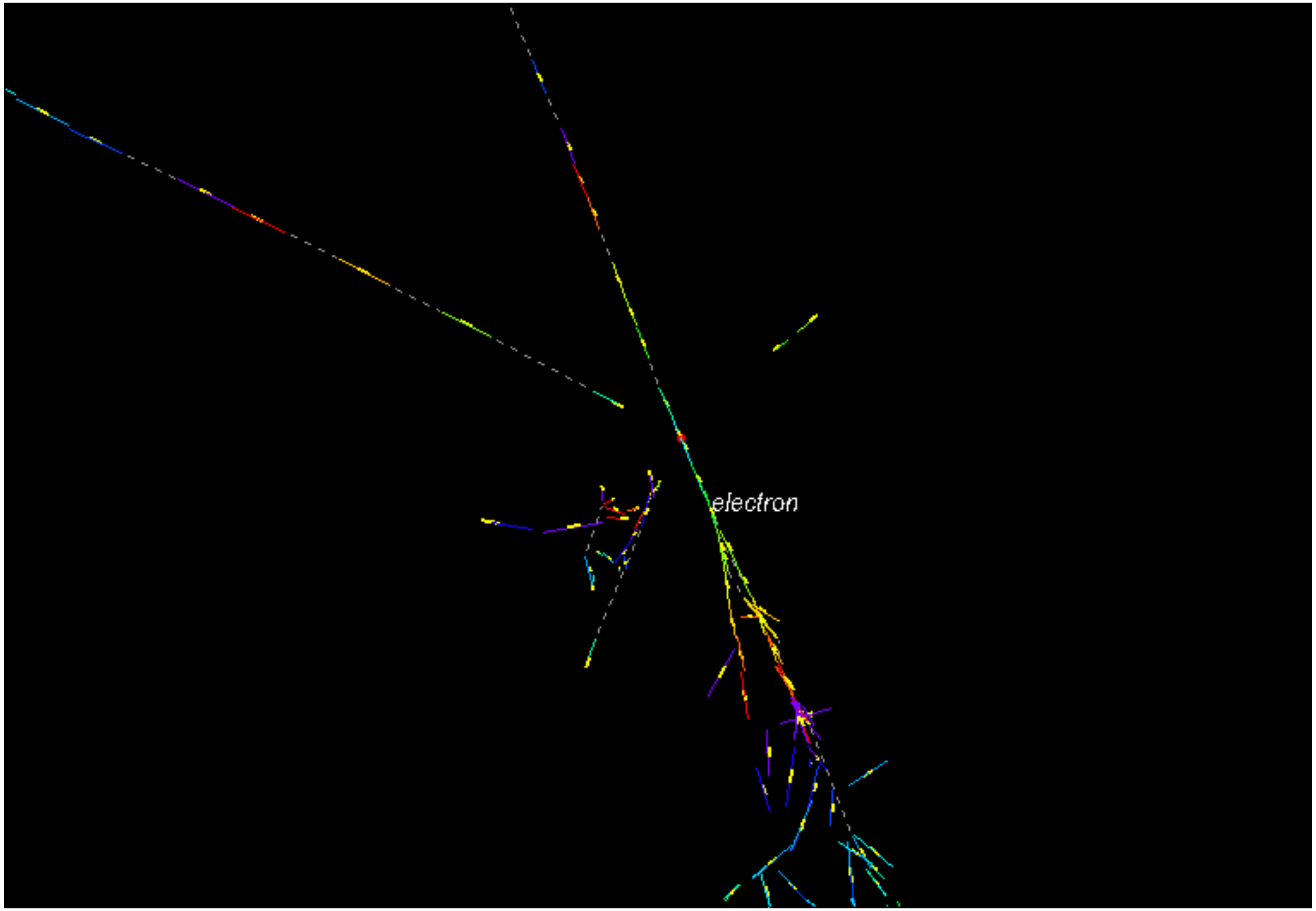


flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay P_t: 0.46 GeV/c

Di muon candidate
μ^+ and μ^- in spectrometer



ν_e candidate



Neutrino velocity measurement

- Just a brief description of technics and concept, more details and new numbers will come at Neutrino 2012
- TOF: Time of flight $TOF_{\nu} = t_B - t_A - t_{delay}$
  - t_A – prodcution time
  - t_B - detection time
- Distance: between source (CNGS) and detector (Opera)
- Velocity: distance / TOF_{ν}
- Statistical analysis on neutrino events collected 2009-2011
- Special bunched beam mode end of 2011 and in may 2012 for direct comparison event by event

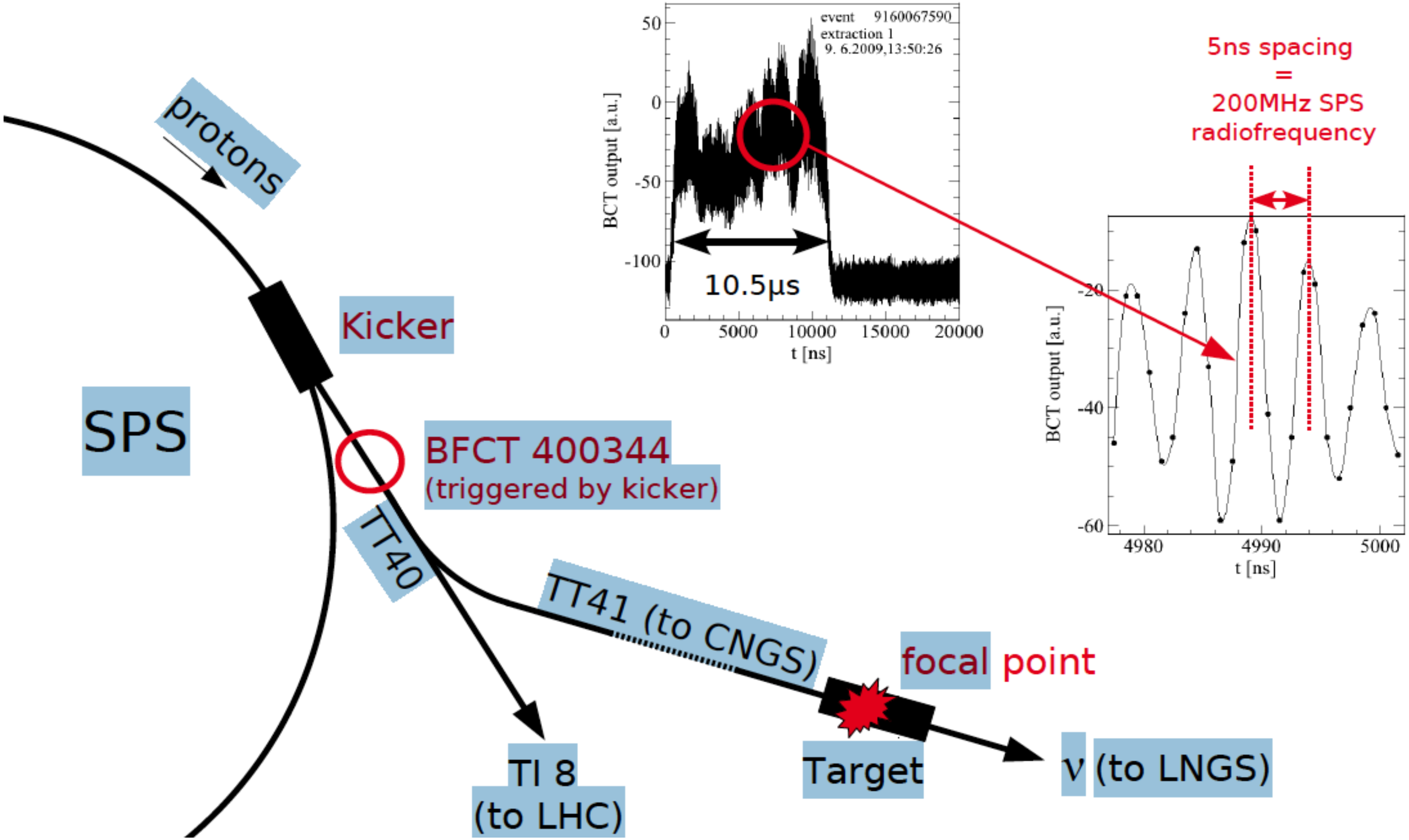
Previous measurements

- 1979: FNAL **(Phys. Rev. Lett. 43 (1979) 1361)**
- short distance, 30 GeV ν_μ, comparison of ν_μ and μ TOF
- $|v-c|/c \leq 4x10^{-5}$
- 1988: SN1987A **(Phys. Lett. B 201 (1988) 353)**
- very long distance (168.000 light years), 10 MeV anti-ve,
- comparison of ν and photon arrival time (not SN mod.-dep.)
- $|v-c|/c \leq 2x10^{-9}$
- 2007: MINOS **(Phys. Rev. D 76 (2007) 072005)**
- 730km distance, ~3 GeV v_μ, near detector comparison
- $(v-c)/c = (5.1 \pm 2.9)x10^{-5}$
- 2011: OPERA
- 730km distance, ~17 GeV v_μ, proton – BCT comparison

CERN production timestamp creation t_A

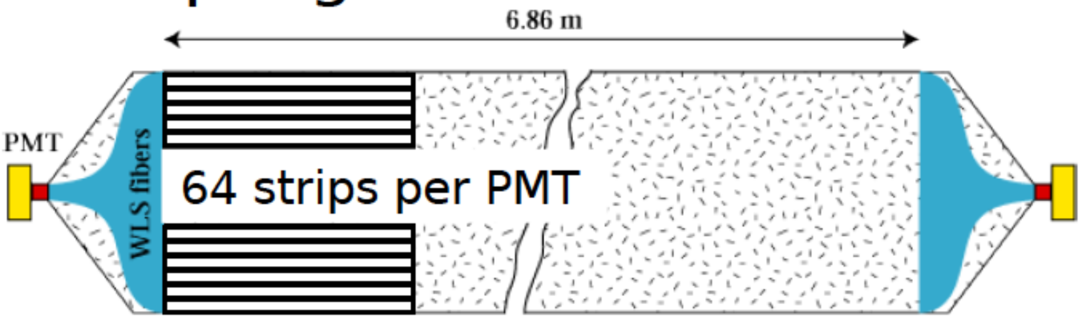
- protons accelerated in SPS@CERN
- protons extracted to TT40 transfer tunnel by kicker magnets (“global t0”)
- two extractions per SPS filling separated by 50ms, each 10.5μs long, consist of thousands of 2ns-long “bunches”
- proton distribution after kicker measured by fast beam current transformer (BFCT) and read-out by a waveform digitizer (WFD)
- protons focused on graphite target
- Proton interaction: subsequent pion (kaon) decay into neutrinos

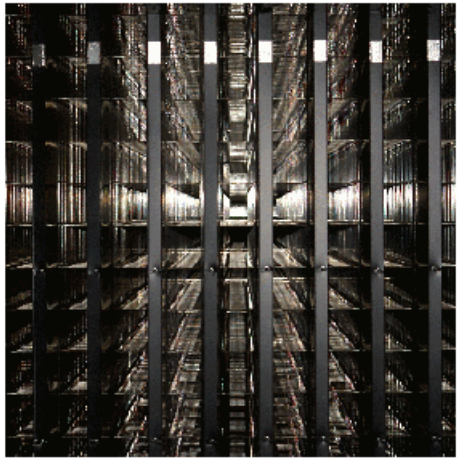
CERN production timestamp creation t_A

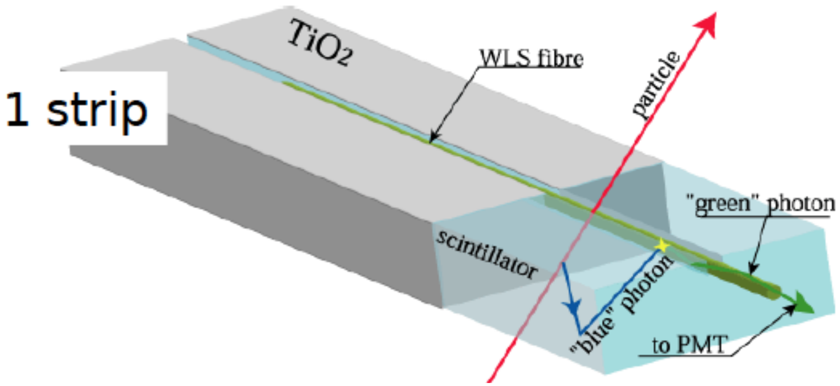


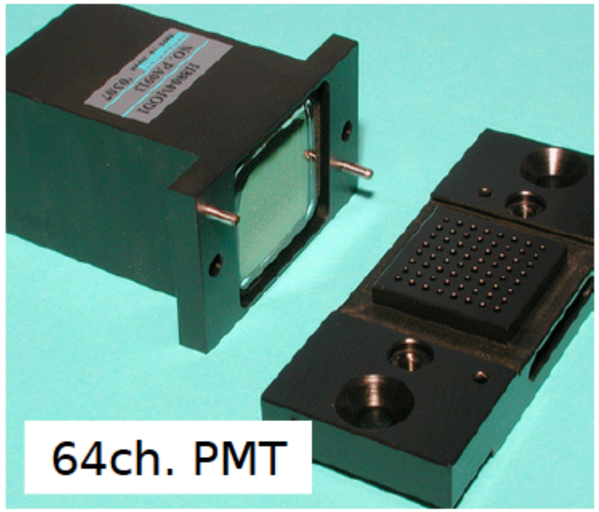
OPERA detection time t_B (LNGS)

- use plastic scintillators only
- first hit in target trackers is the stop signal

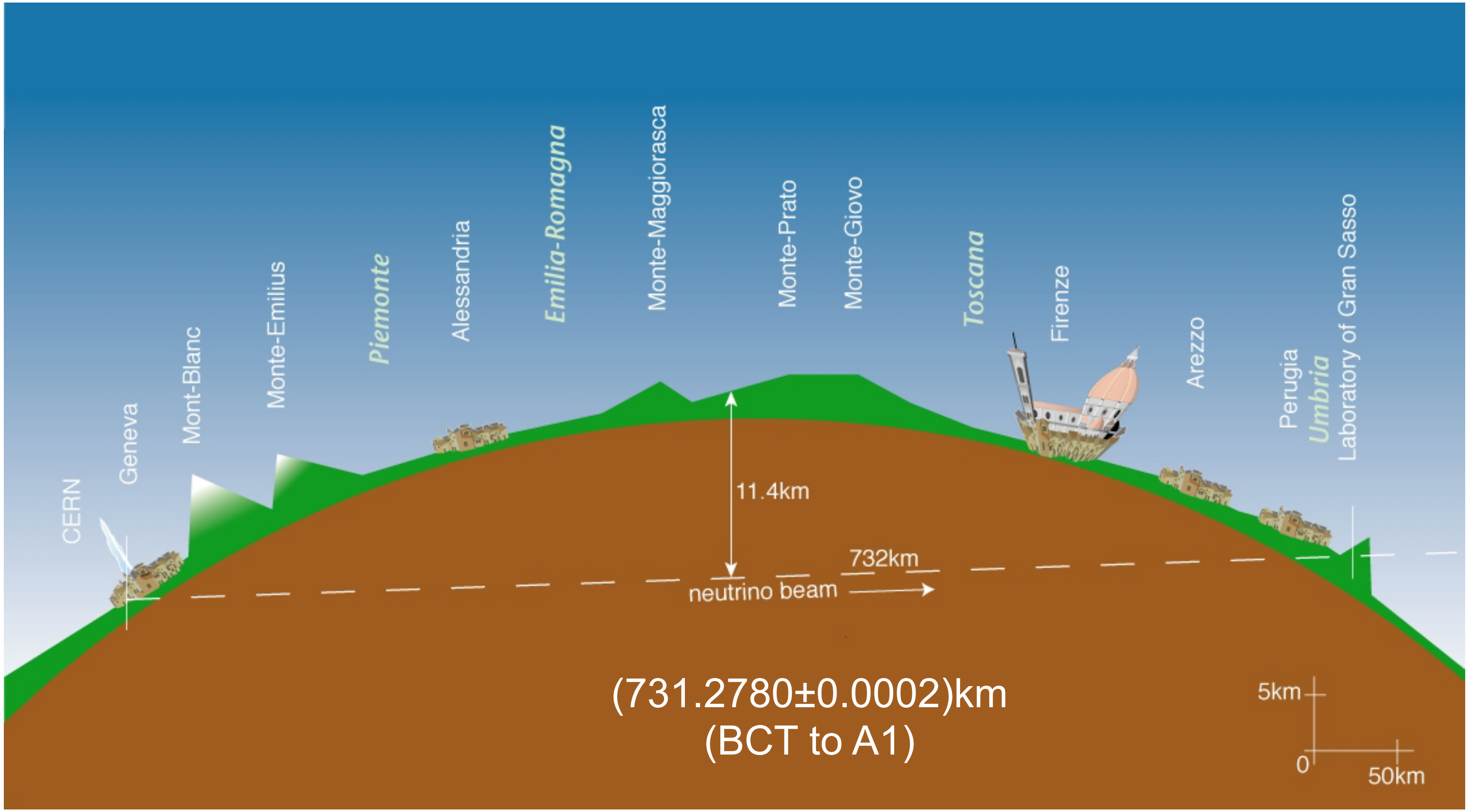






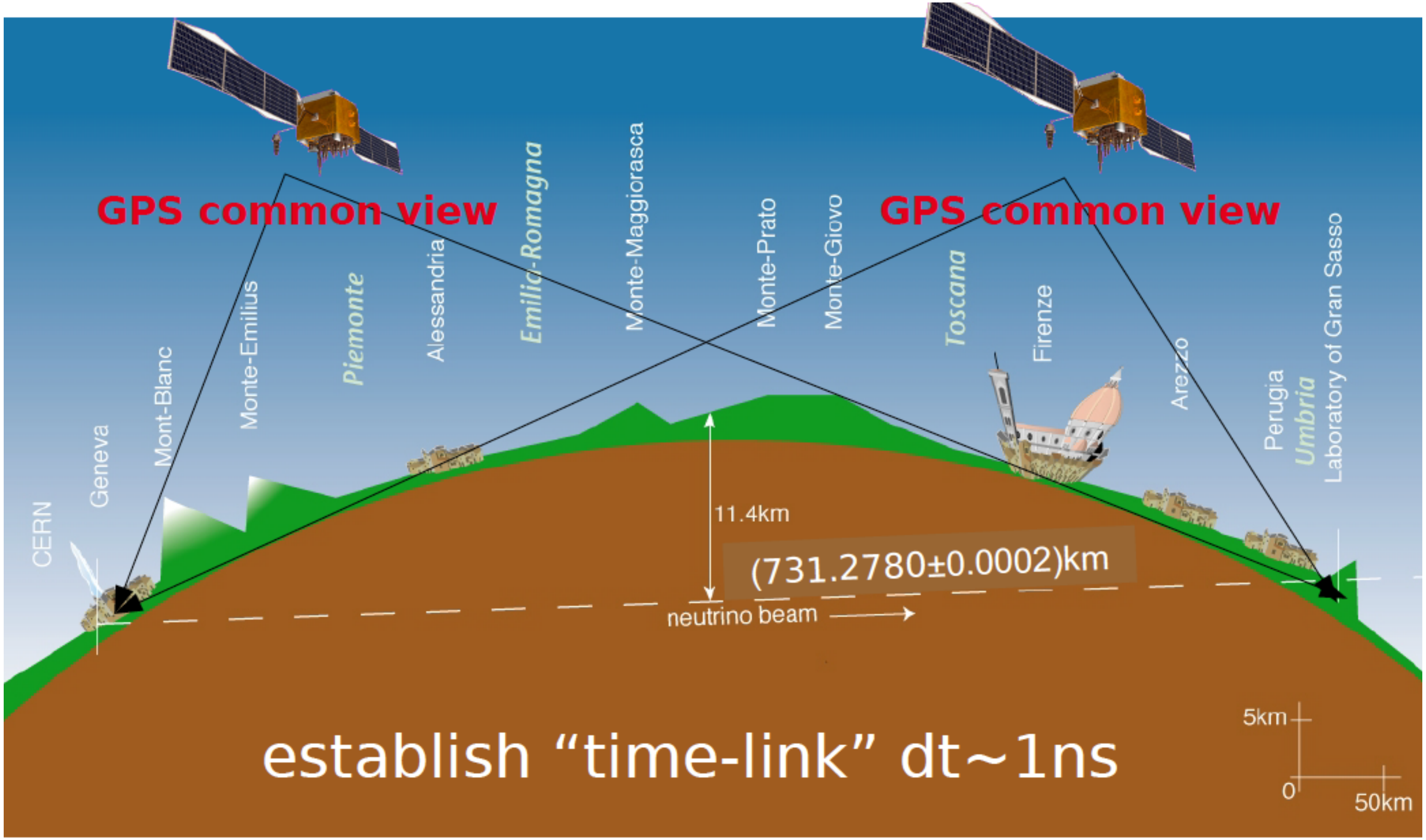


Distance measurement CNGS – LNGS

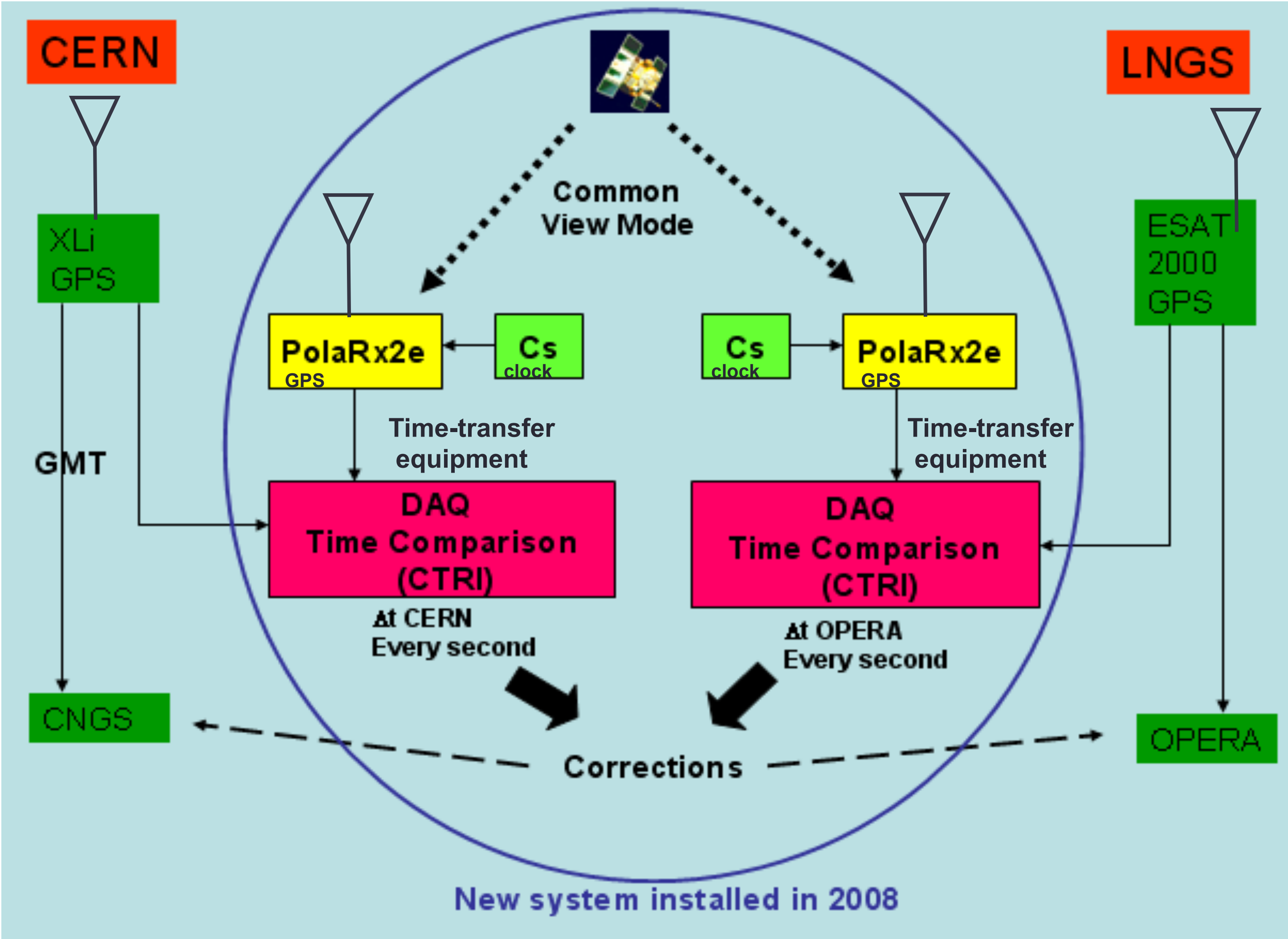


(731.2780±0.0002)km
(BCT to A1)

Time link between LNGS and CERN



Time link between LNGS and CERN



Data selection for statistical analysis Sep. 2011

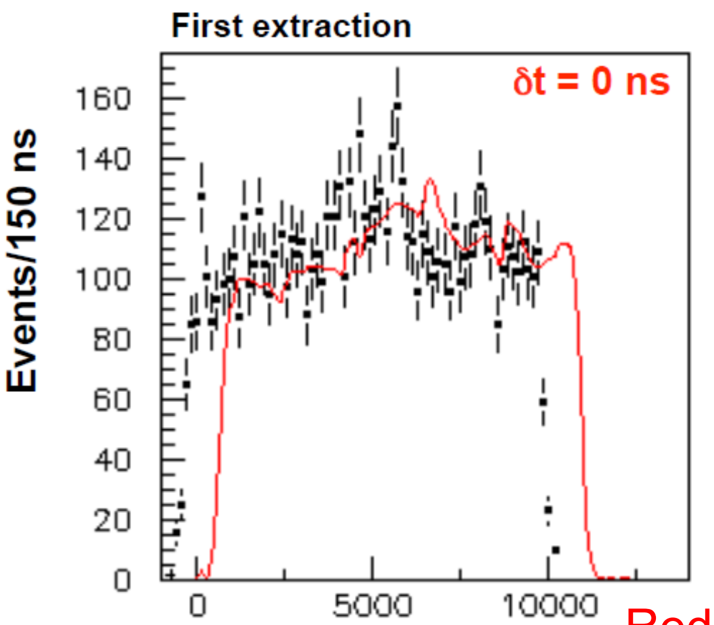
- selection of neutrino events
- internal events (within fiducial volume, same as for the oscillation search): 7586
- external events (interactions in rock) with reconstructed 3D muon track: 8525 (±2ns additional uncertainty)
- at least 4 GPS satellites in common view
- first hit not isolated in time or space
- if neutrino event passes selection:
  - select the corresponding BCT waveform
- 7235 internal and 7988 external events

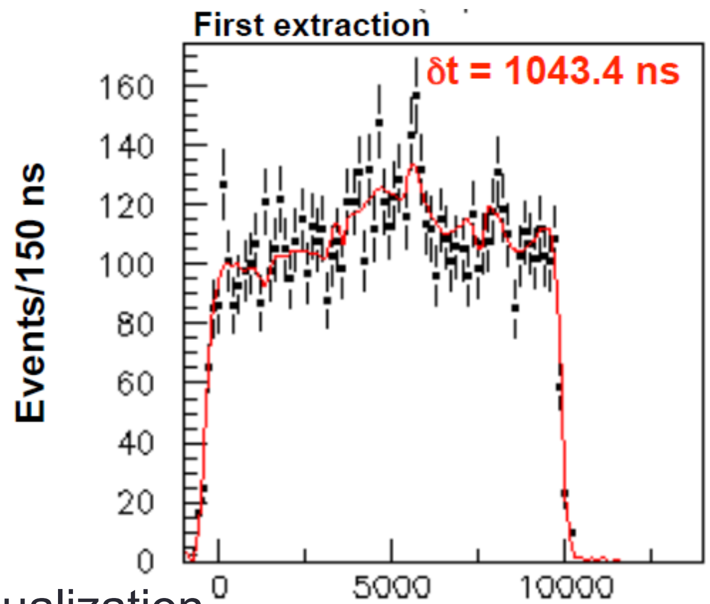
Statistical anlysis

- Build a likelihood from the sum of the waveforms
  - All waveforms/ only waveform of events which were selected

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

- measurement of delay δt for Opera

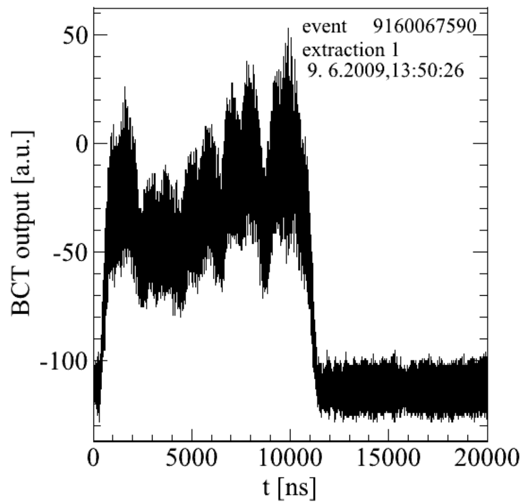


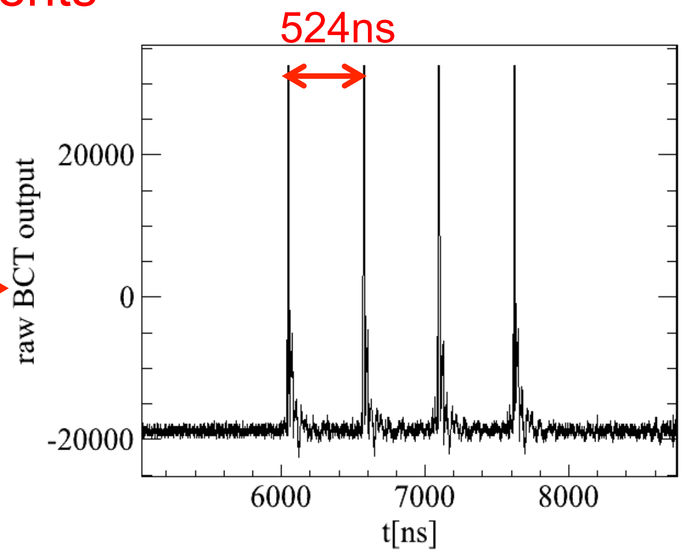


Red curve only visualization

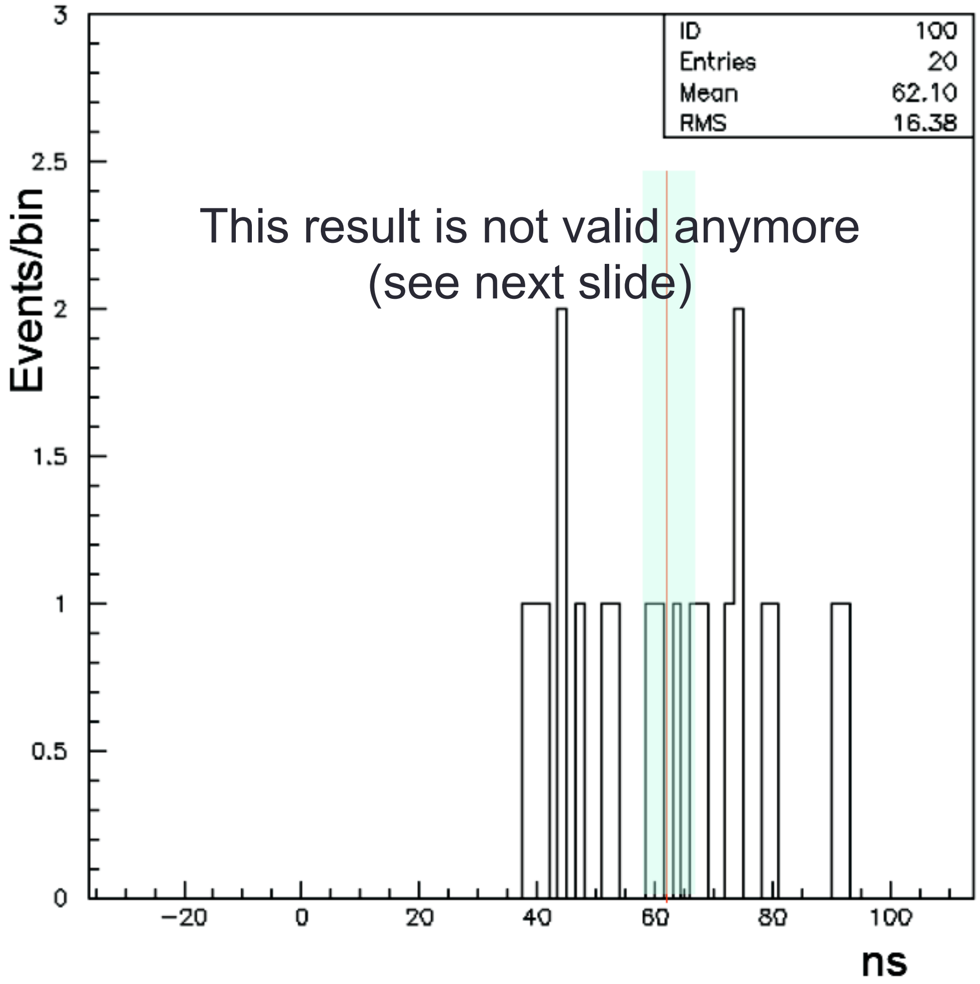
Bunched beam 2011

- bunched beam: instead of 10.5μs extractions:
- 4 single, 3ns-wide bunches, separated by 524ns
  → single-event TOF measurement!
- October 22 to November 6, 2011
- beam intensity lower than nominal (~1/60)
- collected 35 events, same selection criteria,
- same delay corrections
  → 14 external and 6 internal events





Bunched beam 2011



This result is not valid anymore
(see next slide)

The story of δt

- “The OPERA Collaboration **[...]** has identified two issues that could significantly affect the reported result**.**
  - **[...] the** oscillator used to produce the events time-stamps **[...]**
  - **[...] the** connection of the optical fiber **[...]” (Feb. 23rd 2012)**

- Taken into account these correction, the time of flight could be in agreement with the speed of light.

- Currently a new bunched beam mode (different settings, to increase statistics, all LNGS experiments taking data)
- New preliminary results to be expected at Neutrino 2012

Conclusions

- Opera is the first experiment that observed muon to tau neutrino oscillation appearance by identifying the event candidates by the topological characterization of the tau decay
- Opera is detecting other rare decays as charm decays and is detecting electron neutrino interactions
- Opera is able to measure the time of flight for neutrinos with a higher precision than any previous earth based experiment
- A lot of more exiting news will be released in 2 weeks time, stay tuned

Questions?