SEARCH FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS:

STATUS OF THE OPERA EXPERIMENT

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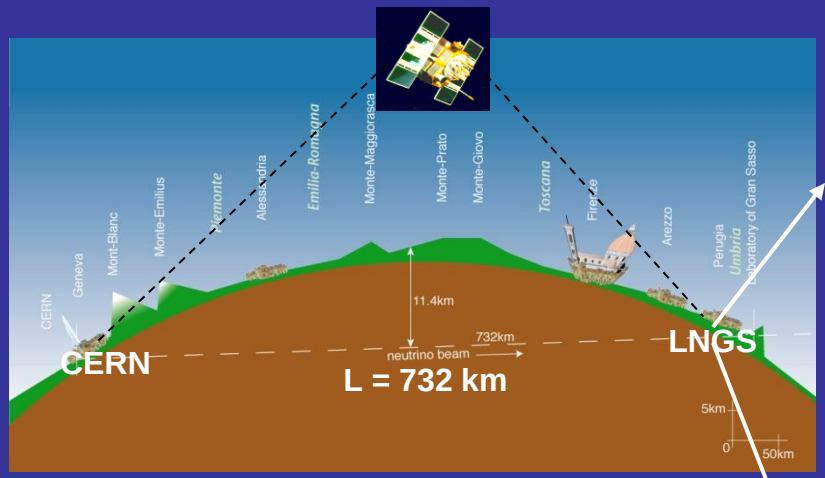
On behalf of the OPERA Collaboration

SEARCH FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS:

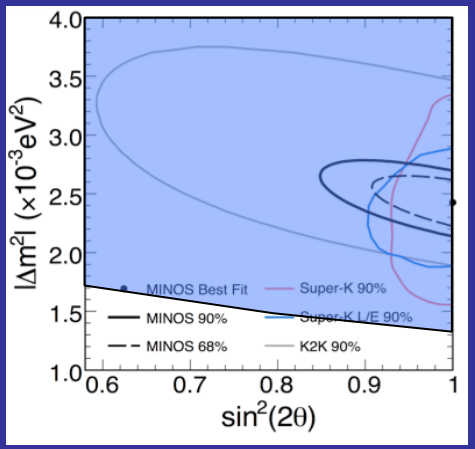
STATUS OF THE OPERA EXPERIMENT

- ✓ The OPERA experiment:
  - ➢ Physics goal
  - ➢ ν_τ detection principle
  - ➢ Detector
  - ➢ Status of data-taking and analysis
- ✓ $\nu_\mu \rightarrow \nu_\tau$ oscillation results
- ✓ Preliminary results on $\nu_\mu \rightarrow \nu_e$ oscillation search

OPERA: Oscillation Project with Emulsion tRacking Apparatus

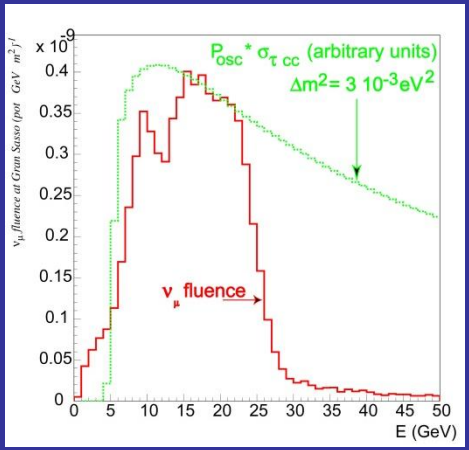


- Long baseline neutrino oscillation experiment
- Aim: Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode covering the whole interesting region of the parameter space indicated by atmospheric neutrino data
- CNGS (CERN Neutrinos to Gran Sasso) ν_μ beam optimised for ν_τ appearance



CNGS beam

Conventional ν_μ beam



Beam parameters

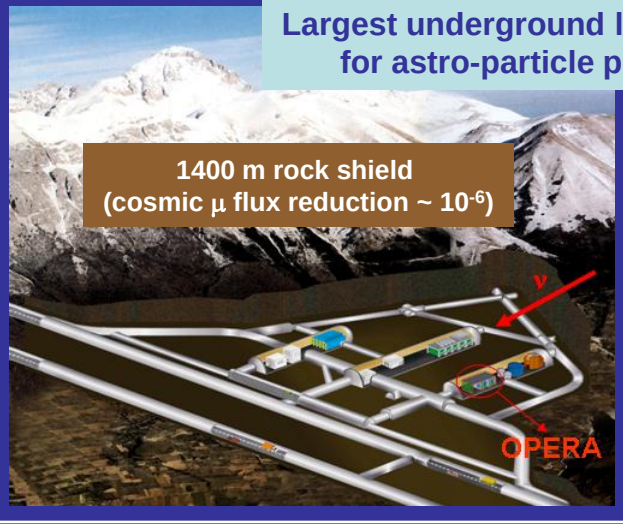
$< E_{\nu_\mu} >$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.89, 0.06 %
$\bar{\nu}_\mu/\nu_\mu$	2.1 %
ν_τ prompt	negligible
pot/year	4.5×10^{19}

Contaminations given in terms of interaction rates in OPERA

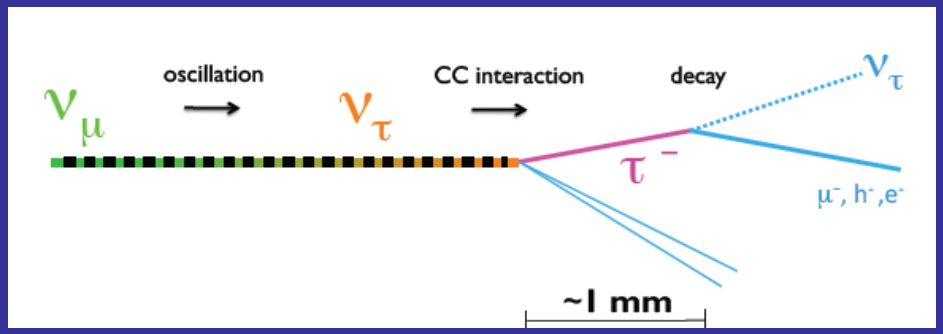
Nominal intensity: 22.5 x 10^{19} p.o.t.
Expected events: 7.6 signal, 0.8 background
[New Journal of Physics 14 (2012) 033017]

Gran Sasso National Laboratory

Largest underground laboratory for astro-particle physics



ν_τ detection principle



τ decay channel	B.R. (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	15.0

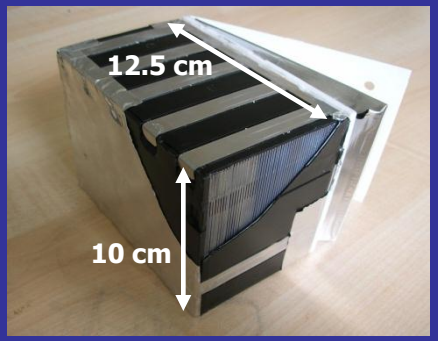
➢ Event-by-event separation of ν_τ CC interactions from dominant ν_μ interactions by direct observation of τ lepton decay

Requirements:

➢ Large target mass to compensate for *small* neutrino interaction cross-section

➢ Micrometric resolution to observe τ decay *kink*

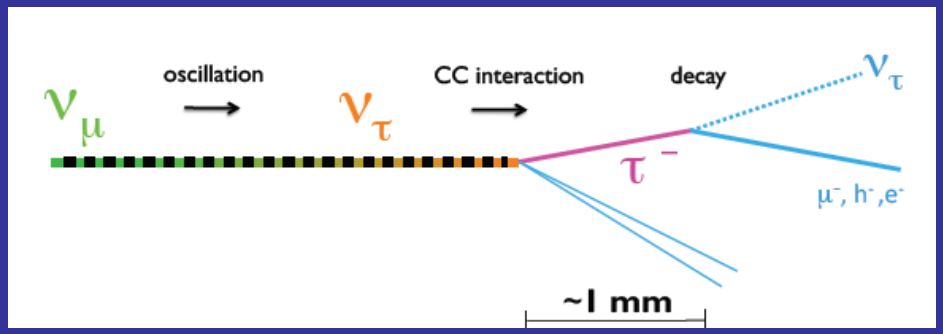
⇒ Nuclear emulsions



Target segmented into basic units called *bricks*.
Brick: *sandwich* of 57 emulsion films interleaved with 1mm-thick lead plates

Total target mass ~ 1.25 kt
(about 150000 bricks)

ν_τ detection principle



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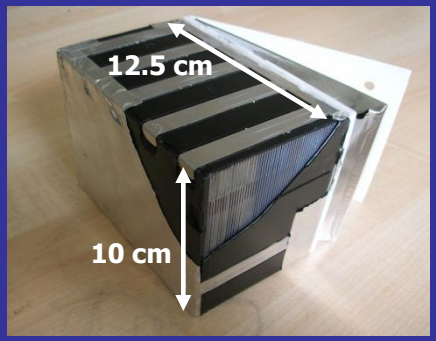
➢ Micrometric resolution to observe τ decay *kink*

⇒ Nuclear emulsions

➢ High muon identification efficiency to reduce charm background; event region pre-selection

⇒ Electronic detectors



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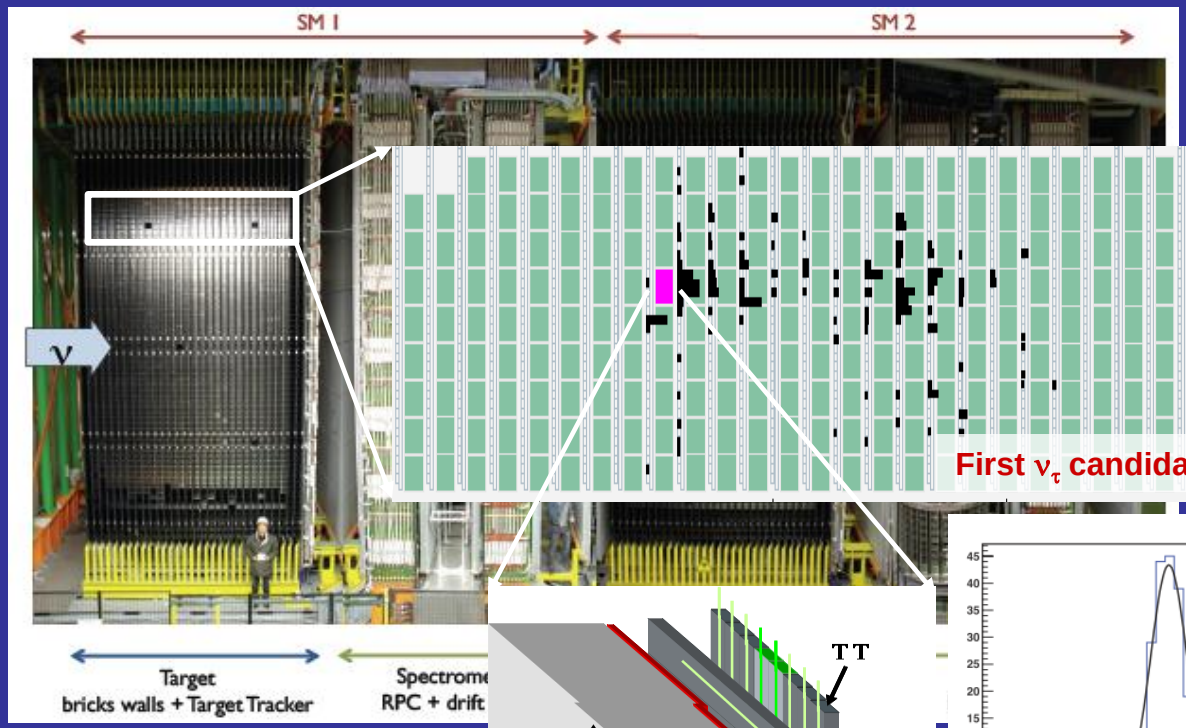
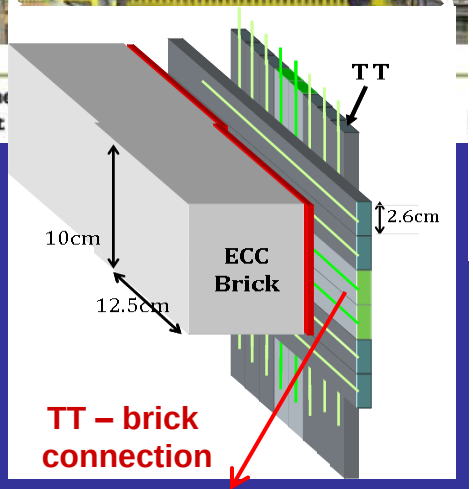
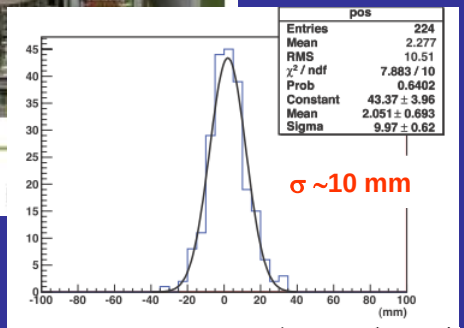
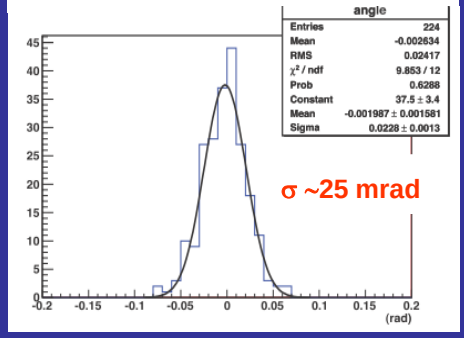
OPERA detector





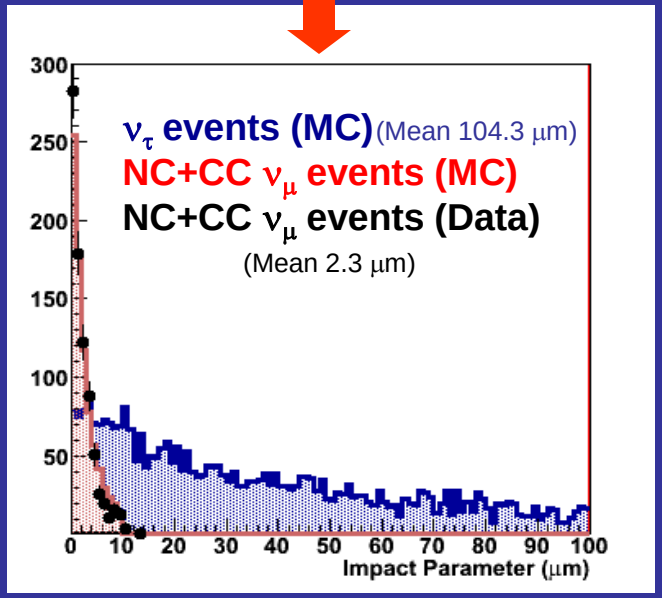


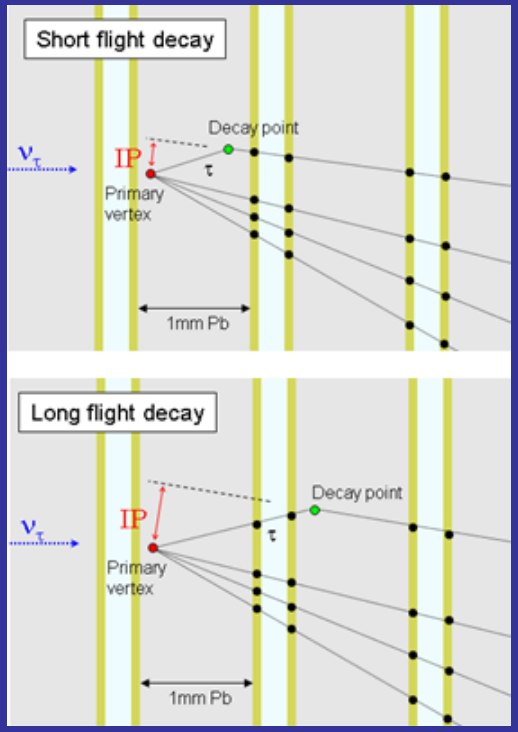


Changeable Sheets (CS): pair of emulsion films acting as TT – brick interface

OPERA detector

Each brick is a stand-alone detector with sub-micrometric resolution.



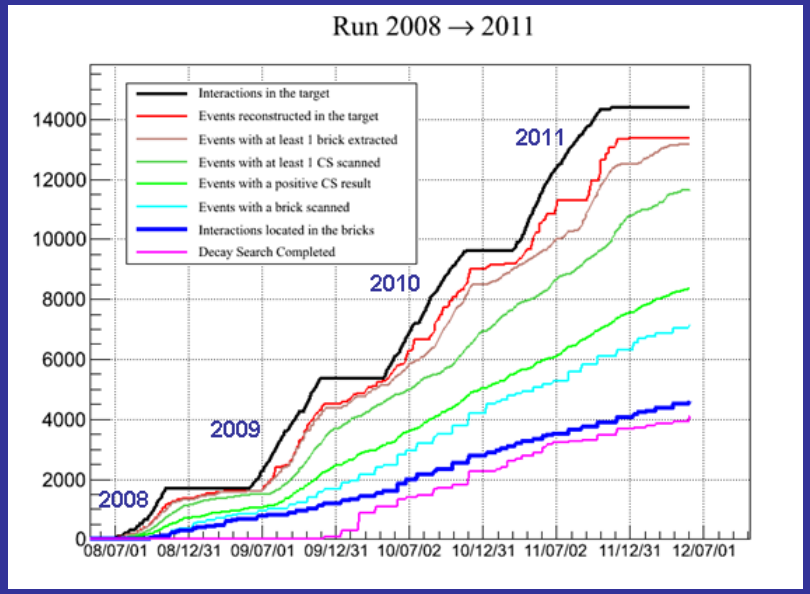


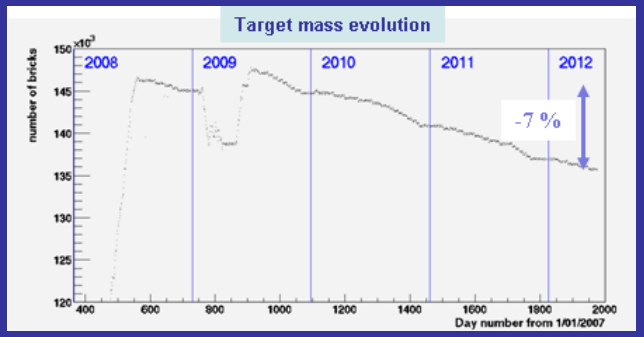
- Momentum measurement by multiple Coulomb scattering
- E.m. shower detection and energy measurement
- Detection of highly-ionizing nuclear fragments produced in hadronic interactions **(discrimination between interactions and decays)**

Status of the experiment

Run	Protons on target	SPS efficiency	In-target events
2008	1.78×10^{19}	61%	1698
2009	3.52×10^{19}	70%	3557
2010	4.04×10^{19}	81%	3912
2011	4.84×10^{19}	78%	4210

Run 2012 in progress.
Foreseen integrated intensity at the end of the run:
18.9×10^{19} p.o.t.
(~ 84% of nominal intensity)



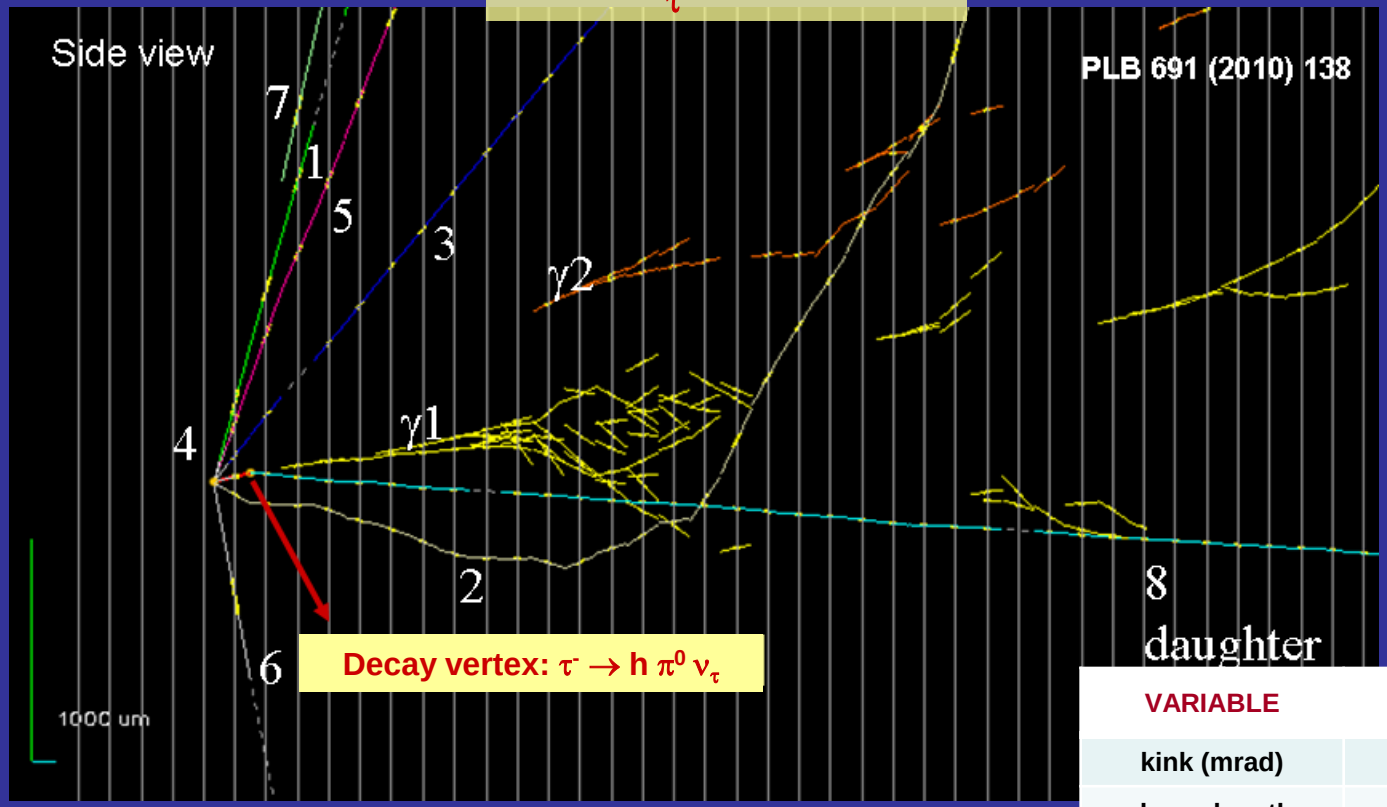


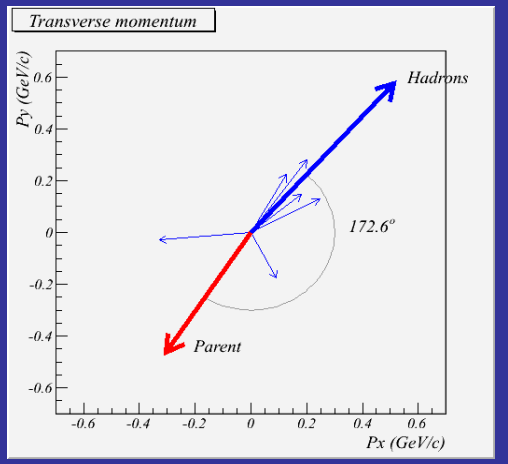
Located neutrino interactions	4611
Fully analysed events	4126
ν_τ candidate events	2

compatible with the expectations for the analysed sample

$\nu_\mu \rightarrow \nu_\tau$ oscillation search

First ν_τ candidate



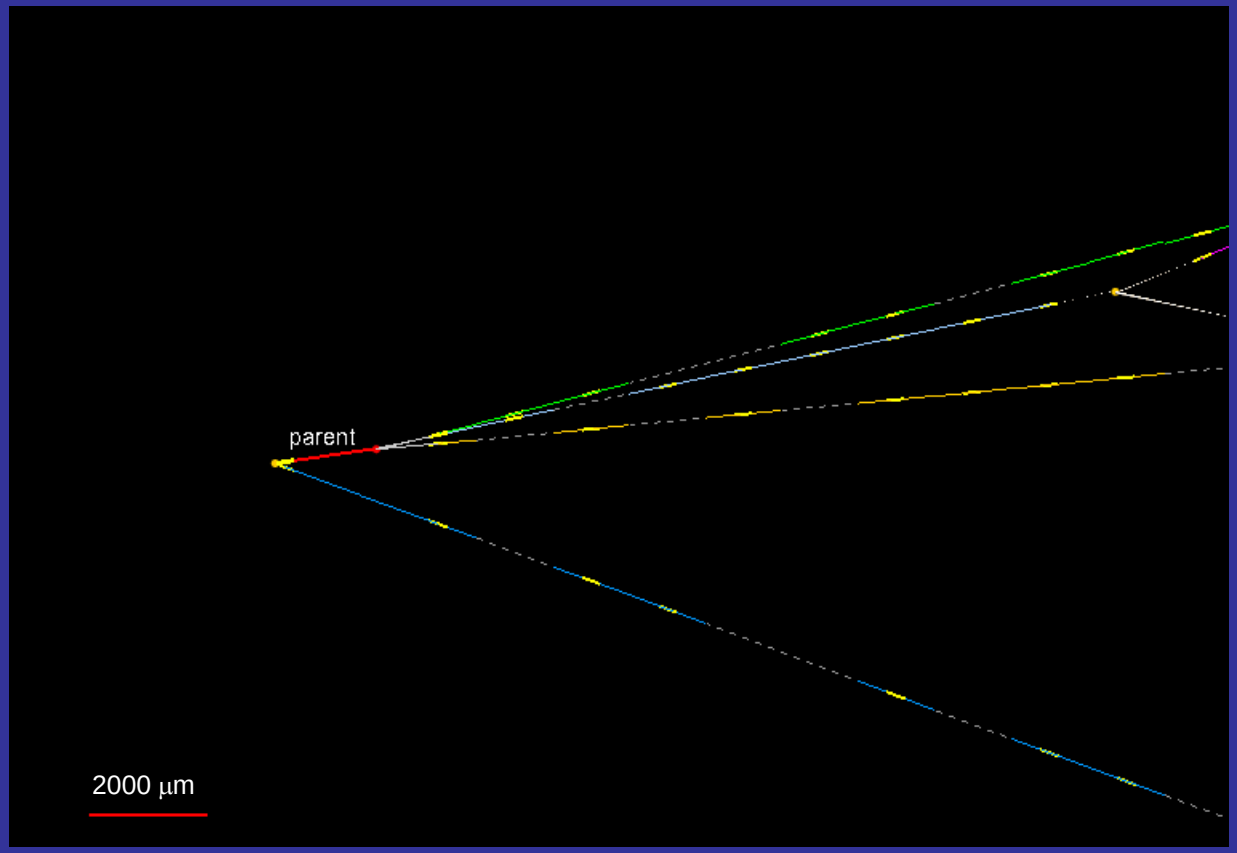


VARIABLE	AVERAGE	Selection criteria
kink (mrad)	41 ± 2	>20
decay length (μm)	1335 ± 35	within 2 lead plates
P daughter (GeV/c)	$12\ ^{+6}_{-3}$	>2
Pt (MeV/c)	$470\ ^{+230}_{-120}$	>300 (γ attached)
missing Pt (MeV/c)	$570\ ^{+320}_{-170}$	<1000
ϕ (deg)	173 ± 2	>90

First direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode

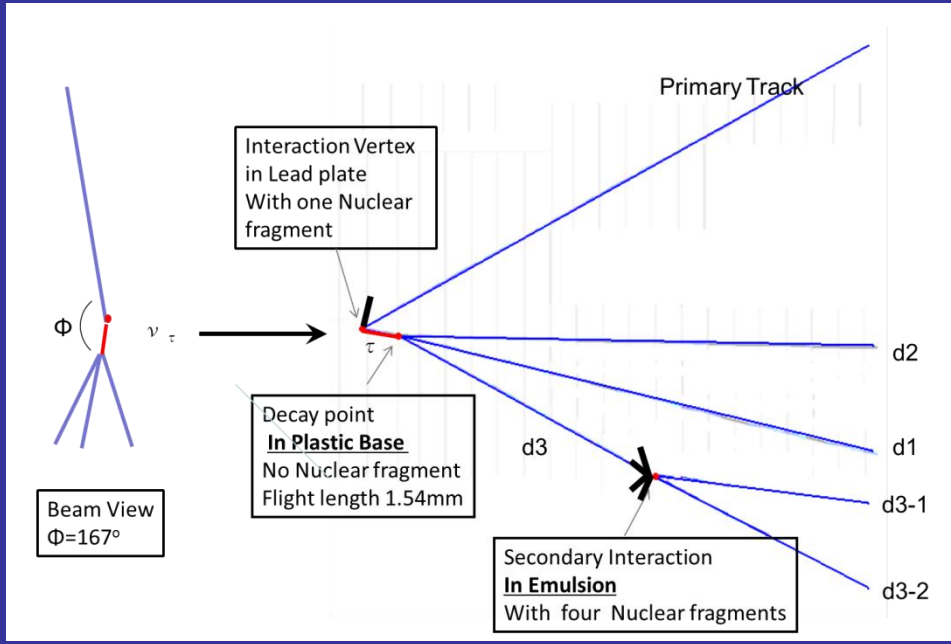
$\nu_\mu \rightarrow \nu_\tau$ oscillation search

New ν_τ candidate

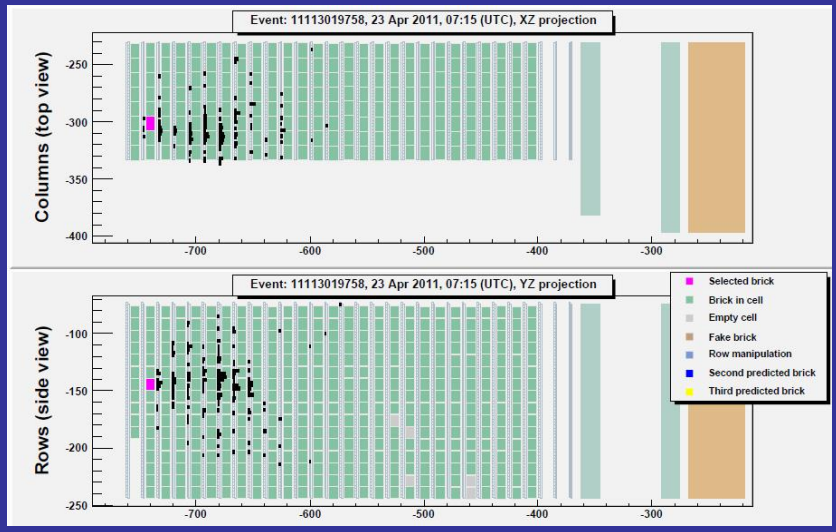


2-prong ν interaction with one track showing a secondary vertex compatible with the hypothesis of $\tau^- \rightarrow h^+ h^- h^- \nu_\tau$

$\nu_\mu \rightarrow \nu_\tau$ oscillation search



New ν_τ candidate



No muon detected at the primary vertex:

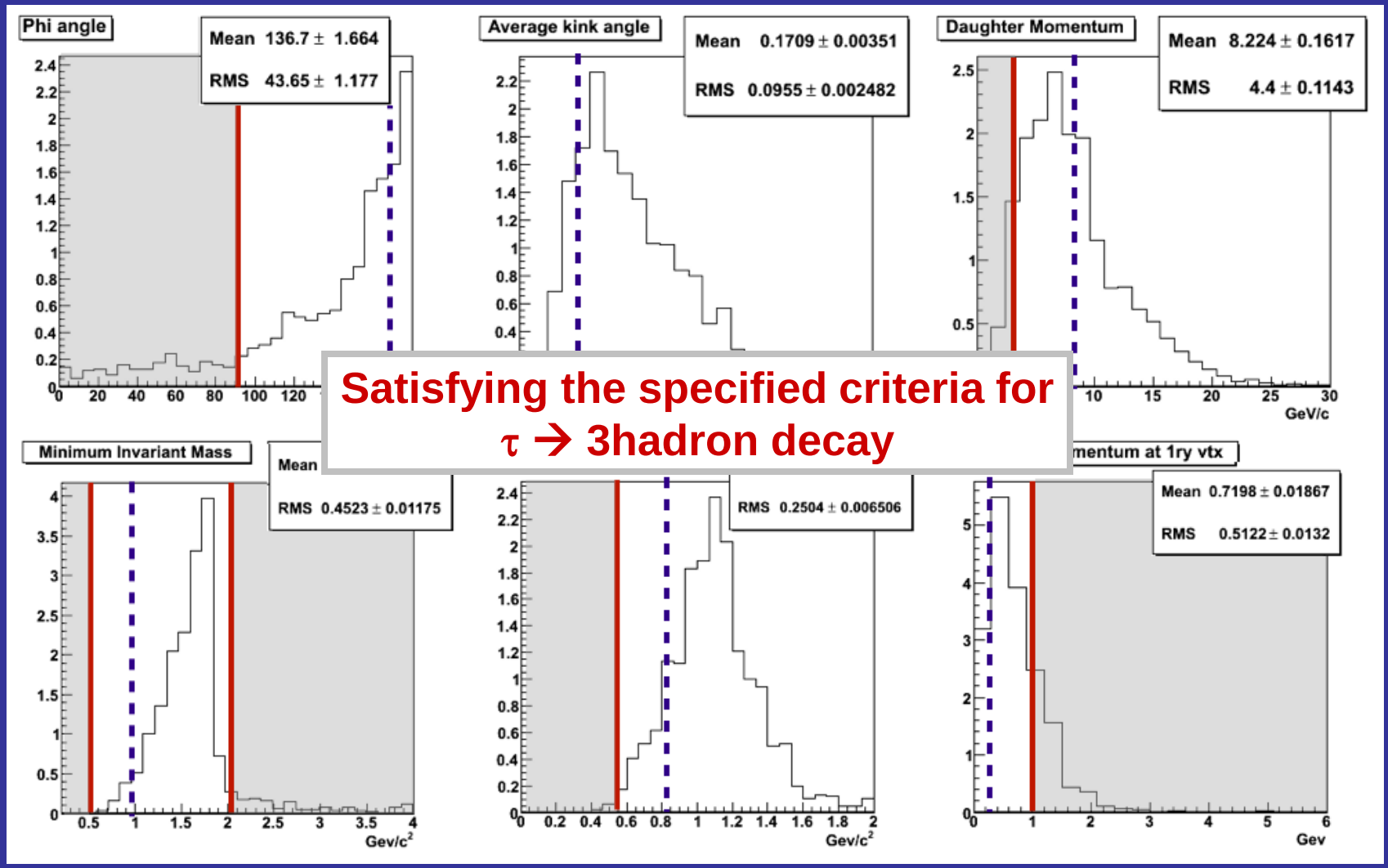
track other than τ lepton candidate not compatible with muon hypothesis based on momentum – range correlation

Event kinematics

	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/c^2]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c^2]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11

$\nu_\mu \rightarrow \nu_\tau$ oscillation search

New ν_τ candidate



candidate
cut

$\nu_\mu \rightarrow \nu_\tau$ oscillation search: summary

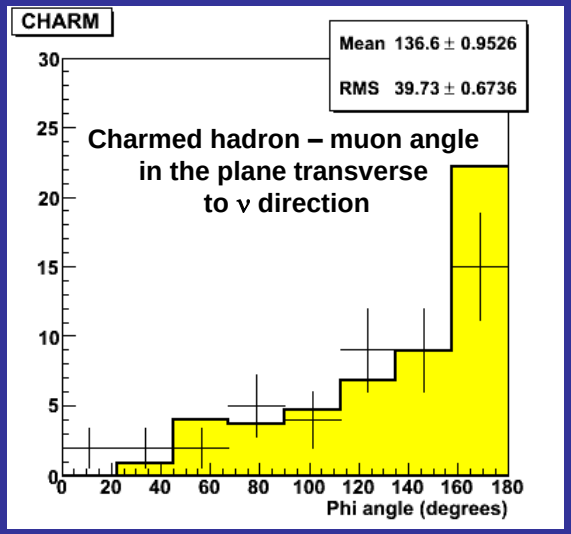
Run	Status	Number of analysed events	Expected ν_τ events (Preliminary)	Observed ν_τ candidate events	Expected BG (Preliminary)
2008 - 2009	Finished	2783		1	
2010 - 2011	Analysis in progress	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

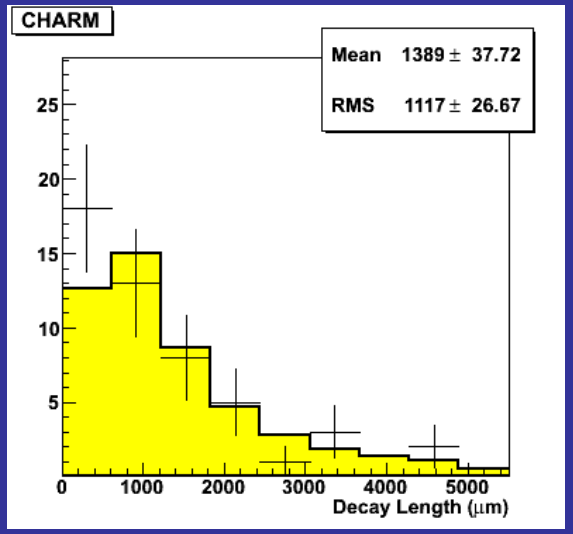
Preliminary

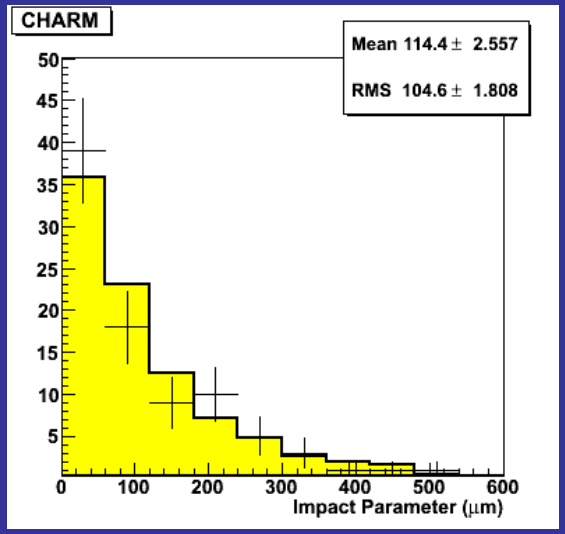
$\nu_\mu \rightarrow \nu_\tau$ oscillation search: control sample

Control sample for ν_τ detection efficiency:

charm production and decay (flight length and decay topologies similar to those of the τ lepton)





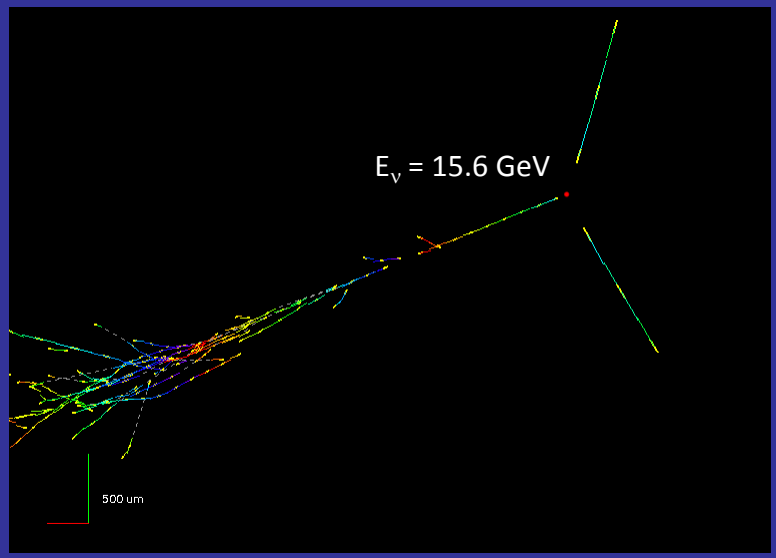


Expected events: 51 ± 7.5
Observed events: 49

$\nu_\mu \rightarrow \nu_e$ oscillation search

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

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



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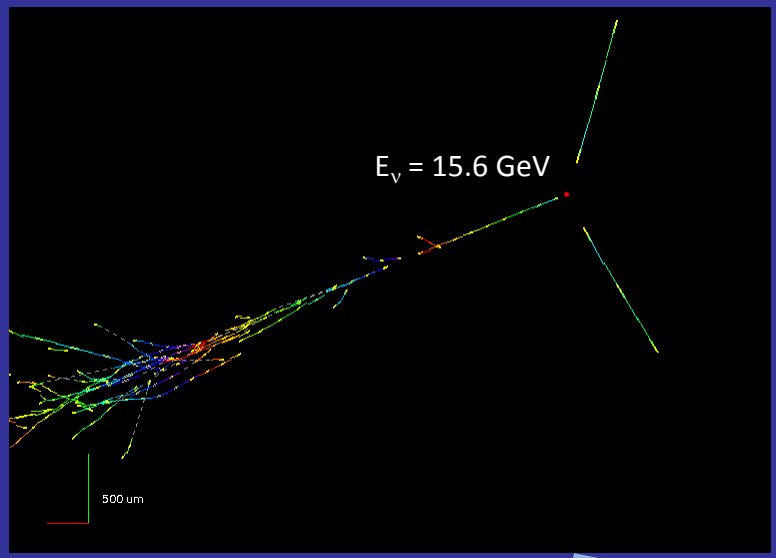
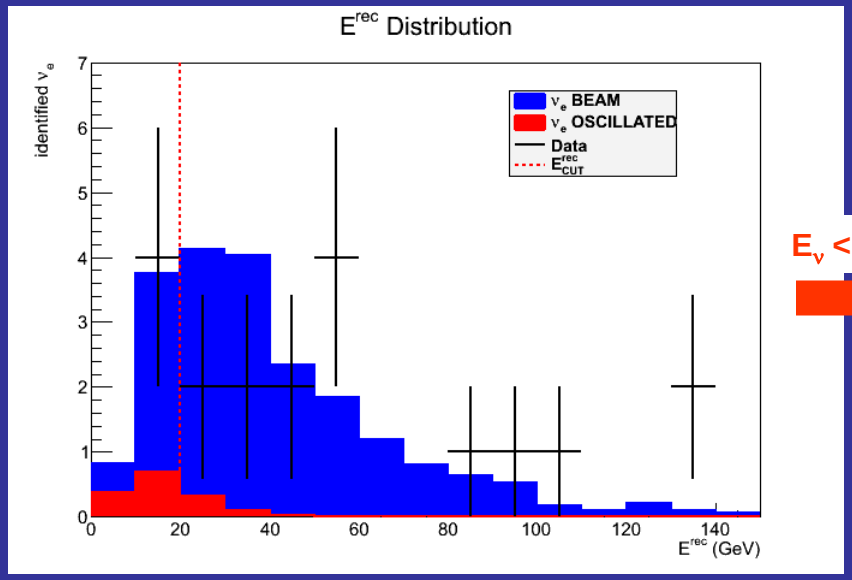
Expected events: 19.2 (beam) + 1.5 (oscillated)
Observed events: 19

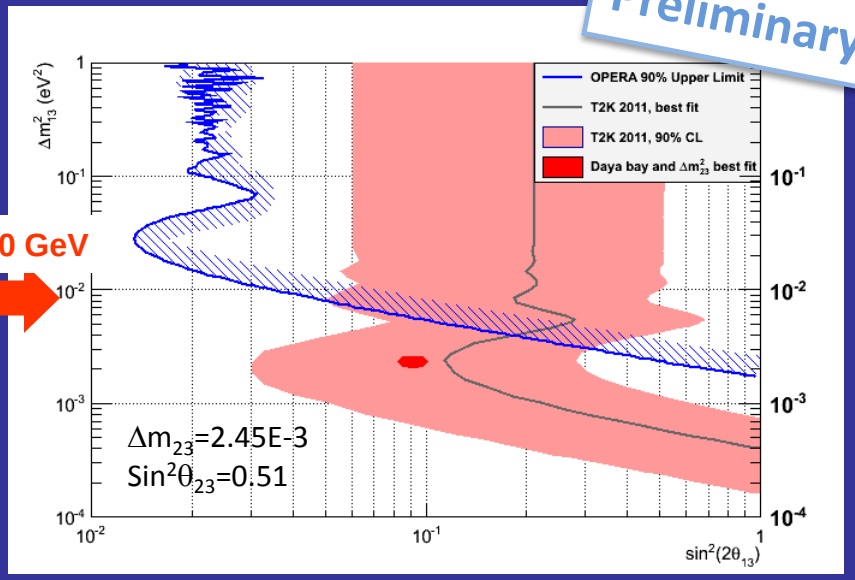
E_ν < 20 GeV (improve S/N ratio)

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





E_ν < 20 GeV



Conclusions and Outlooks

- **OPERA is successfully collecting data since 2008.**

We expect to reach 18.9 x 10^{19} integrated p.o.t.
by the end of 2012 run,
corresponding to ~ 84% of the nominal intensity.

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

2 ν_τ candidate events observed so far

(expected: 2 signal, 0.2 BG – preliminary -)

A few more events are under study.

- **$\nu_\mu \rightarrow \nu_e$ oscillation search:**

- **19 ν_e events observed in 2008 – 2009 statistics,**

4 with E_ν < 20 GeV (expected: 1.1 oscillated, 3.7 BG).

Statistics will be improved by a factor of ~ 3

$\Rightarrow$ set constraints in the high Δm^2 region

Thank you!

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis 2008-2009

New Journal of Physics 14 (2012) 033017

2738 located and fully analysed events
($\Leftrightarrow$ 4.8 x 10^{19} p.o.t.)

1 ν_τ candidate observed in the $\tau \rightarrow$ h channel

Expected: 0.49±0.12 signal events,
0.05±0.01 background events

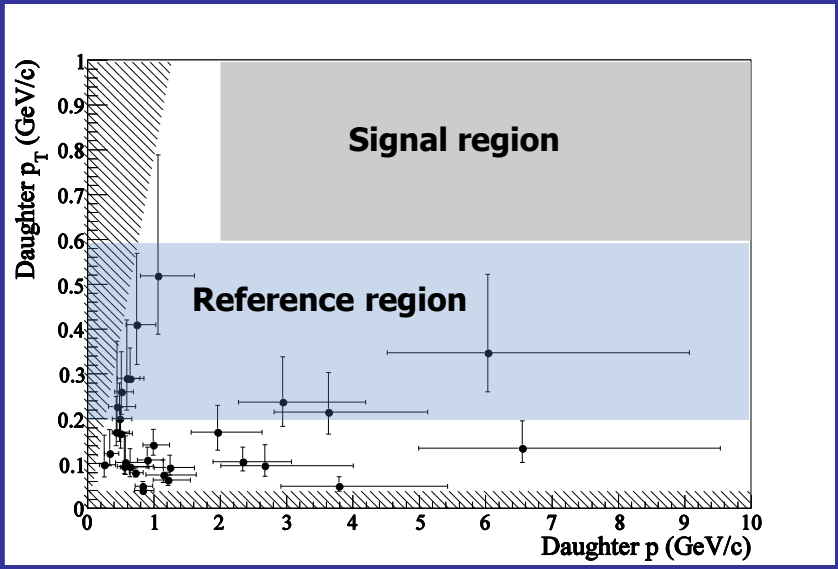
Expected (all decay channels):
1.65±0.41 signal events,
0.16±0.03 background events

Control sample: charm events
(flight length and decay topologies similar to those of the τ)

Topology	Observed events	Expected events		
		Charm	Background	Total
Charged 1-prong	13	15.9	1.9	17.8
Neutral 2-prong	18	15.7	0.8	16.5
Charged 3-prong	5	5.5	0.3	5.8
Neutral 4-prong	3	2.0	<0.1	2.1
Total	39	39.1±7.5	3.0±0.9	42.2±8.3

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis 2008-2009

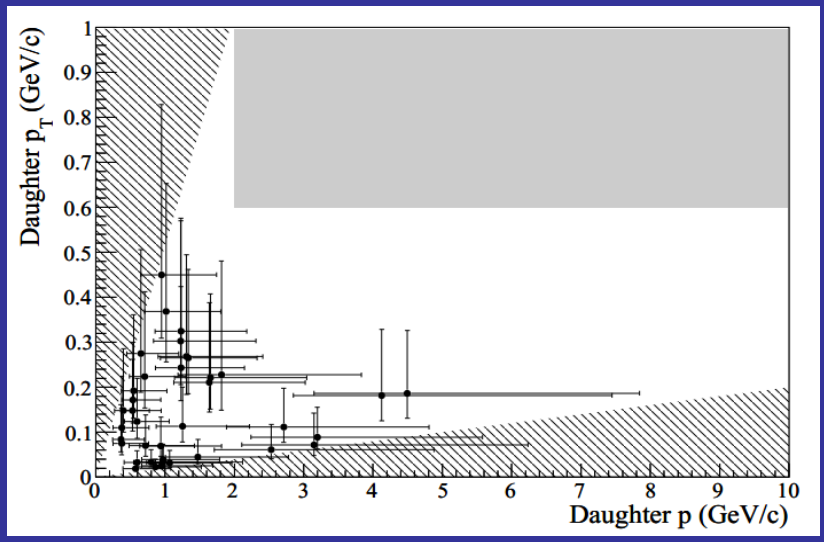
Hadronic interaction background



Hadronic tracks produced in ν interactions showing kink topology:

- **14 m of tracks scanned**
- **No events in the signal region**
- **10 events in reference region (P_t 200 ÷ 600 MeV/c), 10.8 expected**

90% C.L. upper limit of 1.0×10^{-3} kinks/NC event



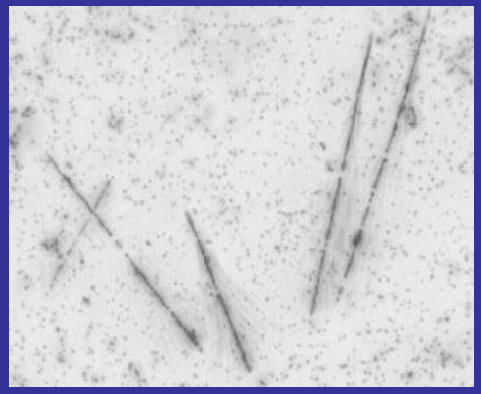
4 GeV/c pion interactions in test beam bricks:

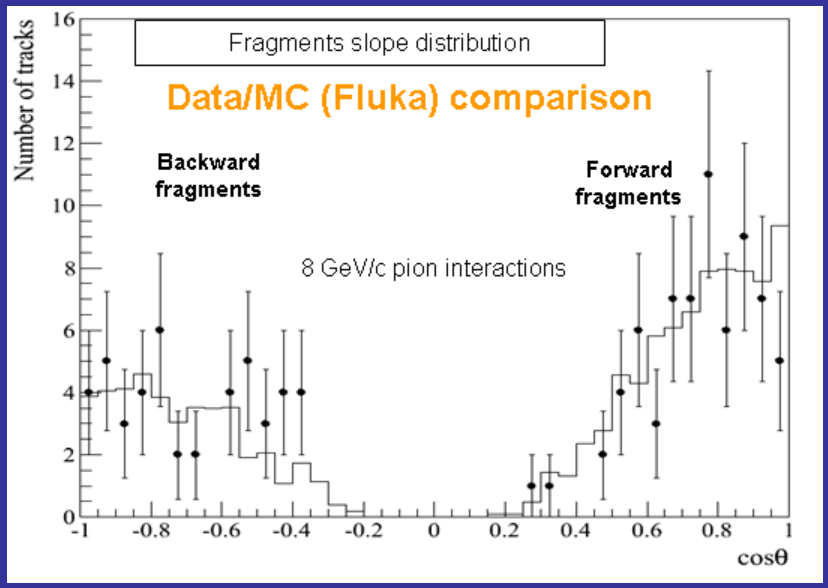
- **190 m of tracks scanned**
- **534 interactions found**
- **214 kinks detected**
- **No events in the signal region**

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis 2008-2009

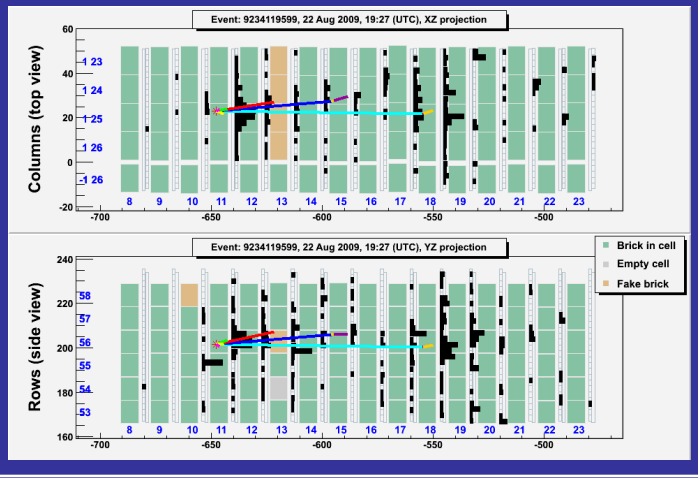
Background reduction: black track search

Highly ionizing nuclear fragments produced in hadronic interactions





Background reduction: track follow-down



Tracks produced in potentially interesting ν interactions are followed in downstream bricks to detect secondary interactions and/or apply momentum-range consistency checks:

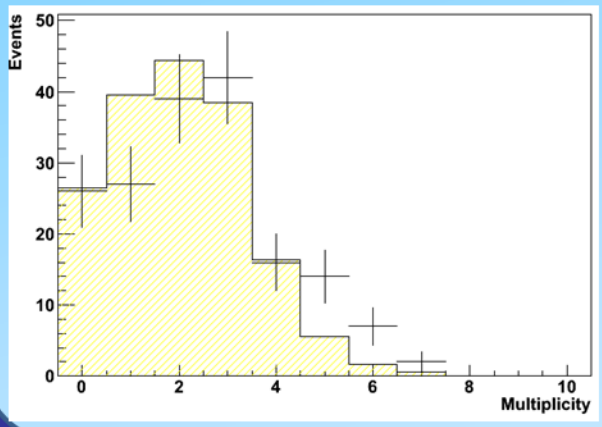
- **Misidentified muons from charm events: 5% $\rightarrow$ 3.3%**
- **Factor 100 BG reduction in $\tau \rightarrow \mu$ channel due to muon mismatch in CC and NC interactions**

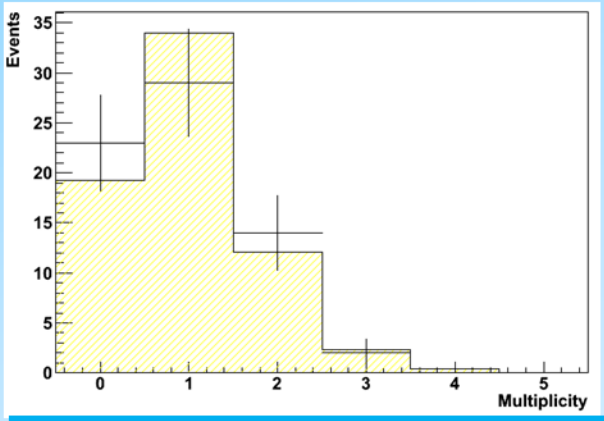
$\nu_\mu \rightarrow \nu_\tau$ oscillation search: study of hadronic interactions

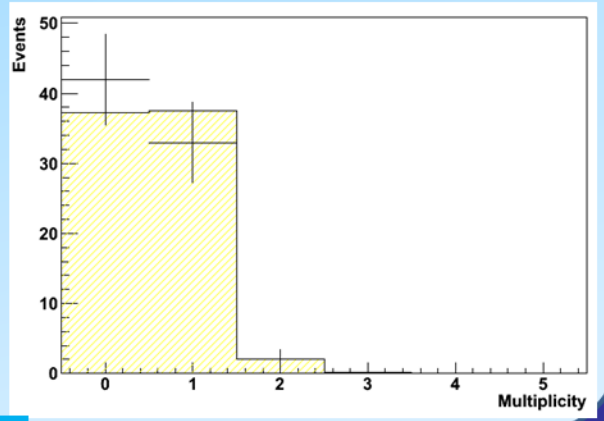
Comparison between data and MC (Fluka)

10GeV/c | 4GeV/c | 2GeV/c

Multiplicity

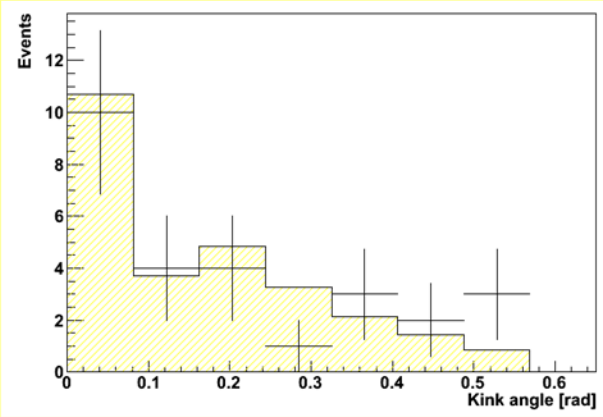


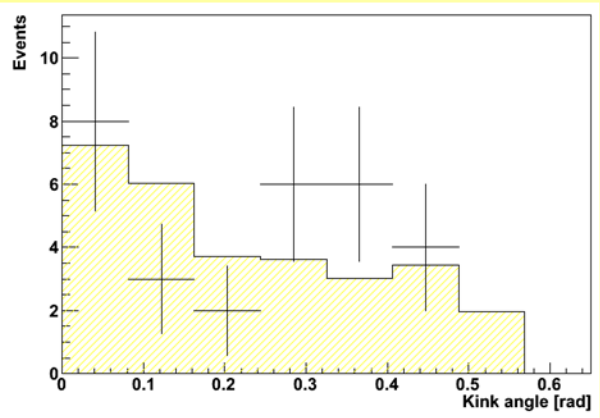


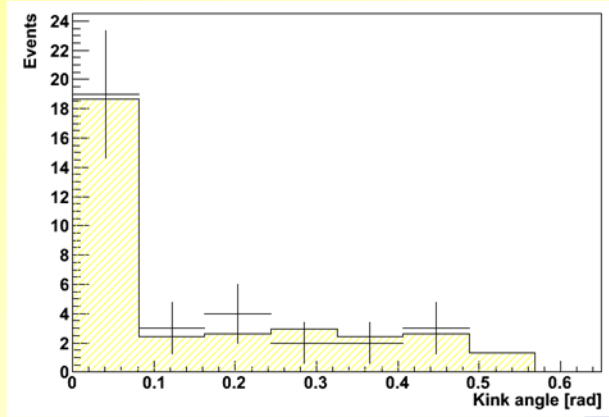


Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)





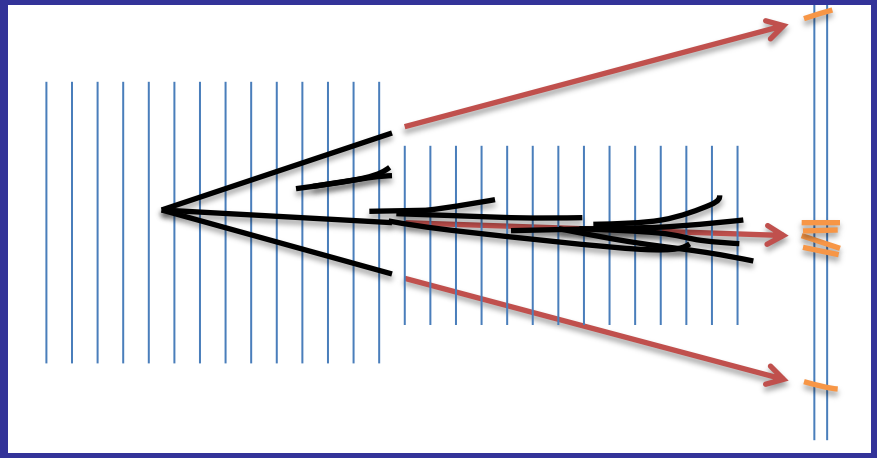


$\nu_\mu \rightarrow \nu_e$ oscillation search

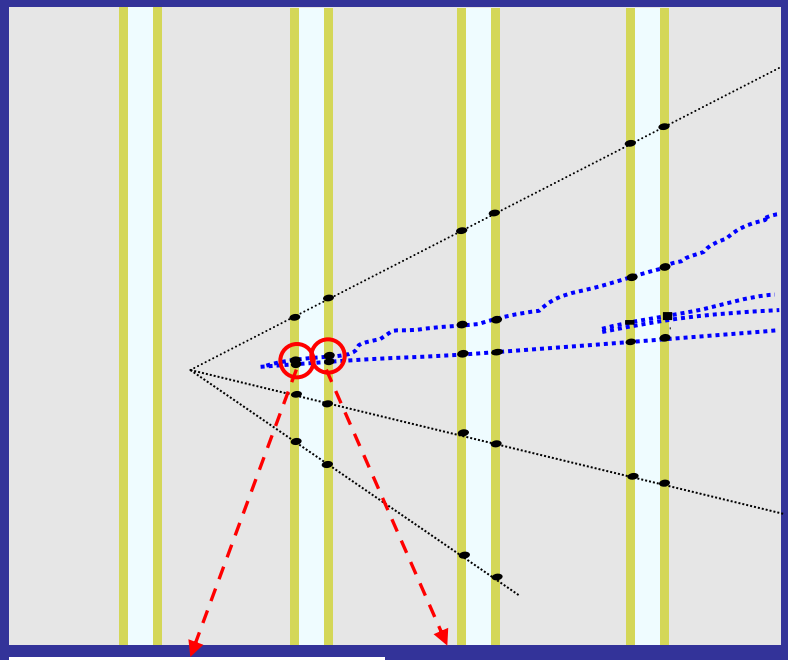
- Event sample :
  – 505 NC-like events (runs 2008 and 2009)

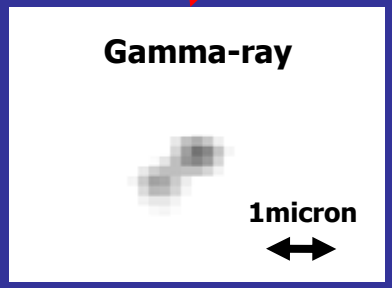
- For each event:
  – Extrapolate 1ry tracks to CS
  – For each track, search for shower signal in CS
  – If shower-like tracks are found, measure additional volume around 1ry track.

  - Results:
  – 96 events selected
  – 19 ν_e interactions confirmed

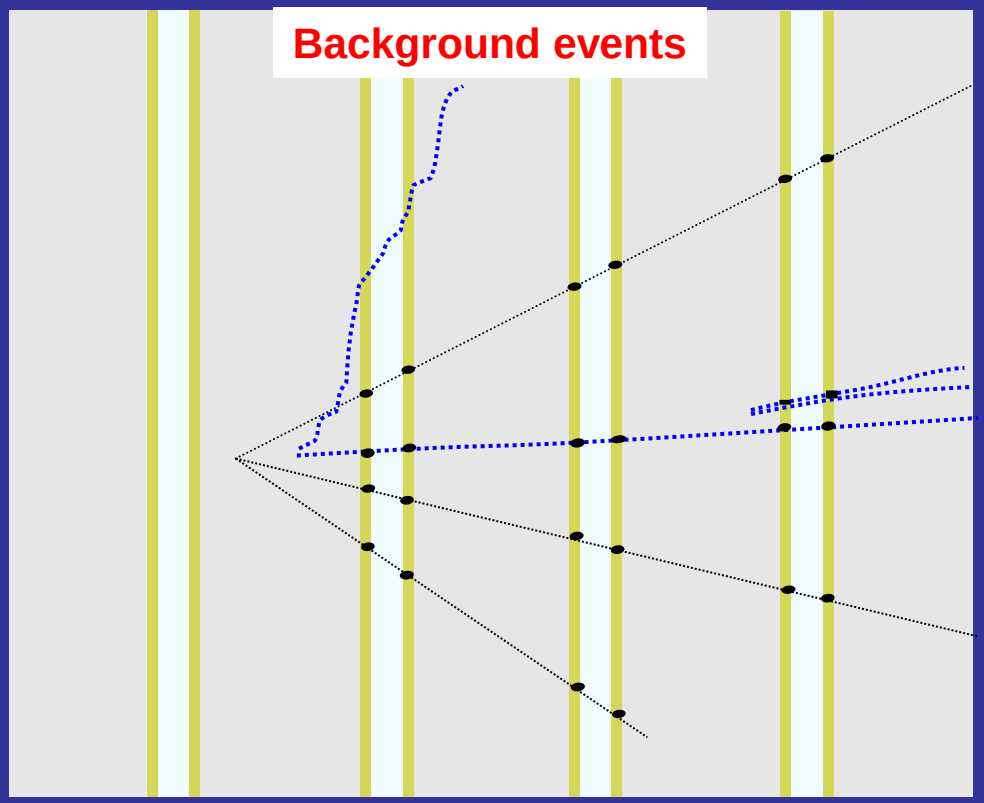


$\nu_\mu \rightarrow \nu_e$ oscillation search





A close-up of an electron pair as seen in emulsion



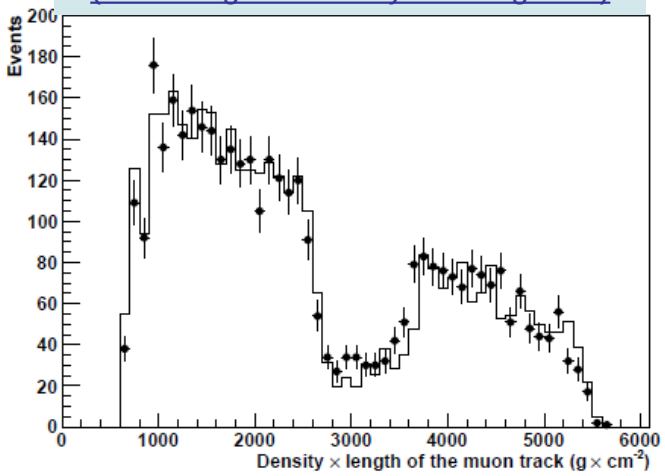
Low-energy electrons produced in gamma conversion are difficult to recognise in emulsion
⇒ Background source

Estimated background in 2008-2009 sample:

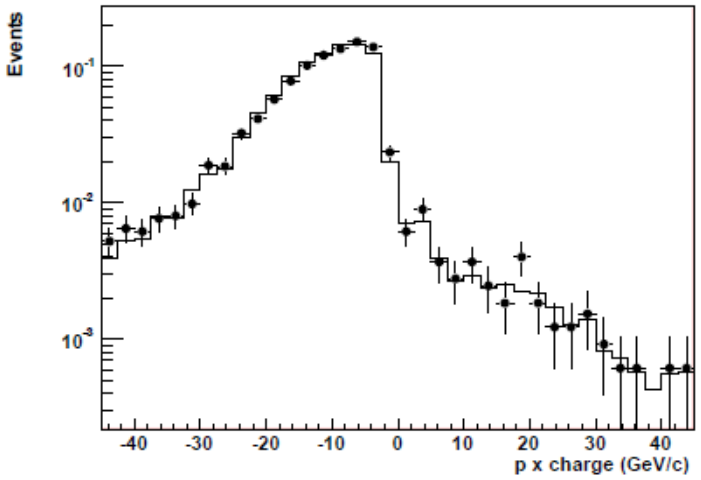
0.16 events

Performance of the Electronic detectors

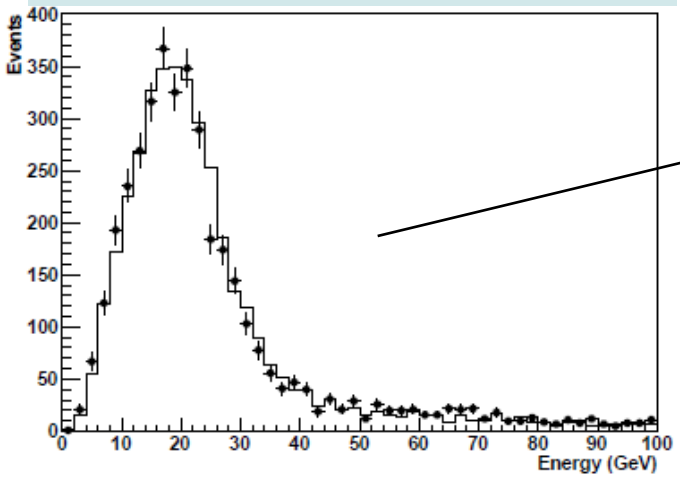
Muon identification efficiency ~ 95%
(track length × density > 660 g cm^{-2})

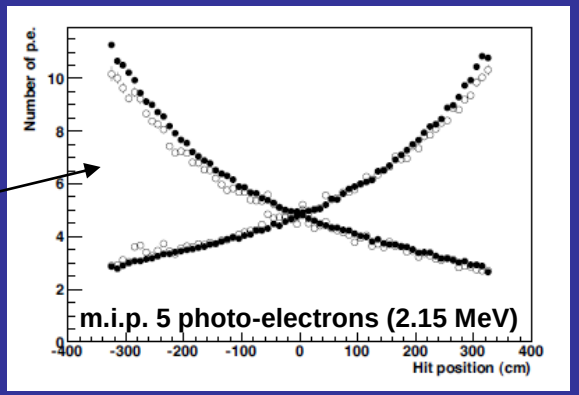


Muon momentum reconstruction



Deposited energy in the TT – CC events





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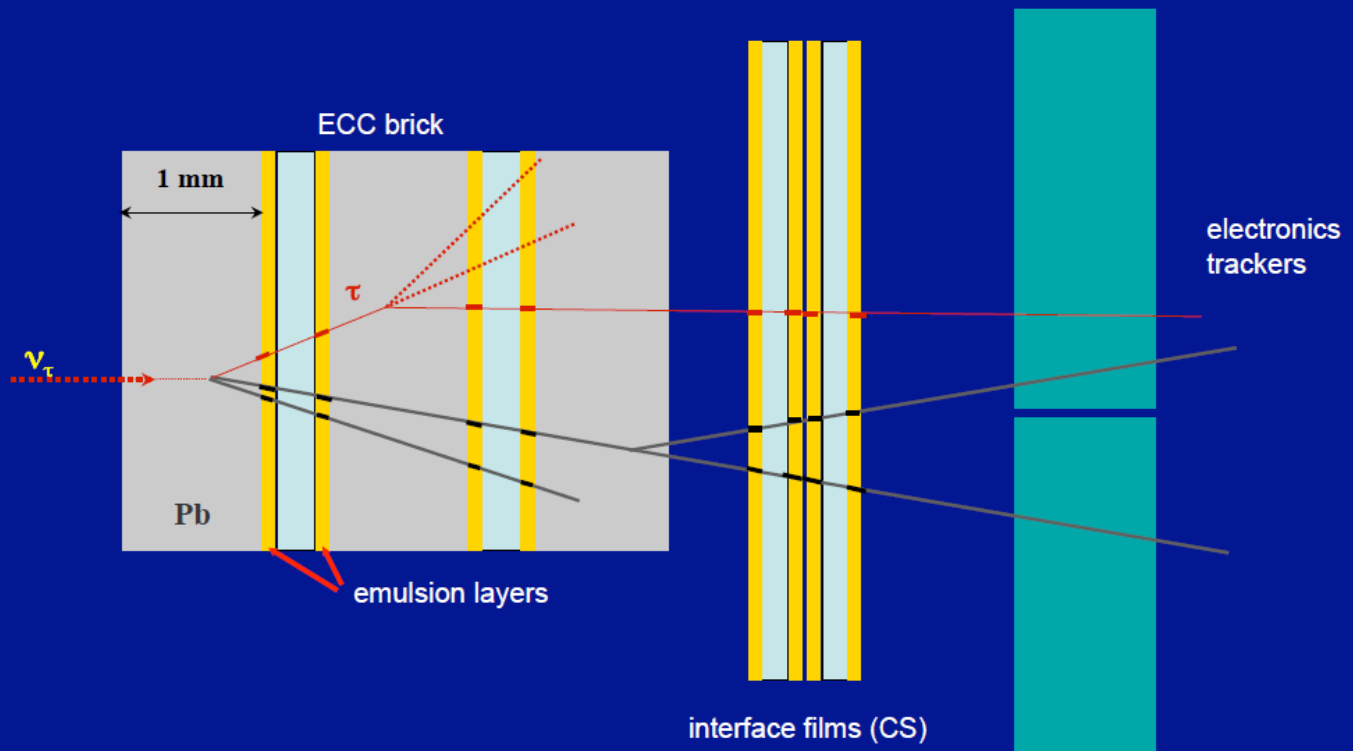
THE PRINCIPLE OF THE EXPERIMENT: ECC + ELECTRONIC DETECTORS



- 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