Tsutomu Fukuda, Toho University, Japan
on behalf of the OPERA Collaboration

PASCOS 2013, 20-26 Nov. 2013, Taipei, Taiwan

140 physicists, 28 Institutions from 11 countries

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

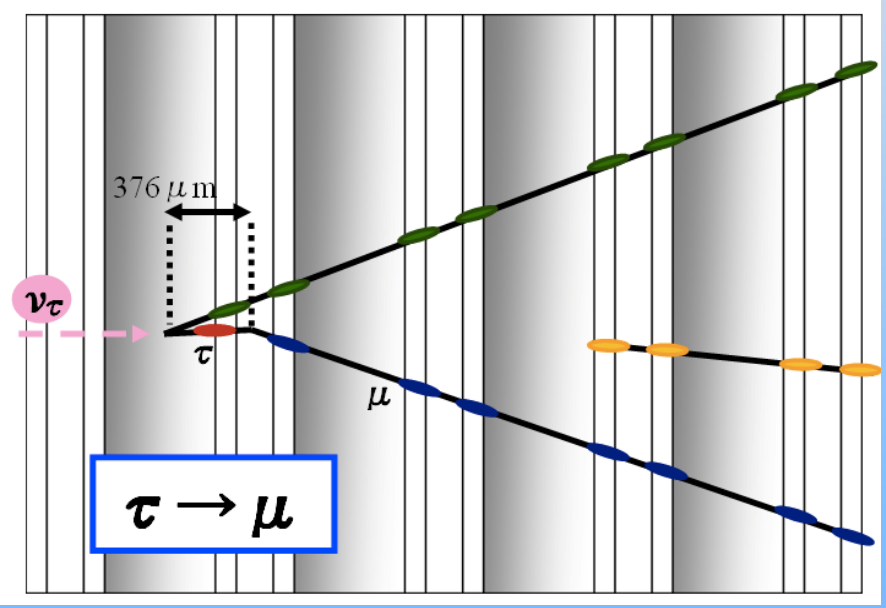
Japan
Aichi edu.
Kobe
Nagoya
Toho
Nihon

Korea
Jinju

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

Switzerland
Bern

Turkey
METU Ankara



Evidence of ν_τ appearance in a ν_μ beam with the OPERA experiment

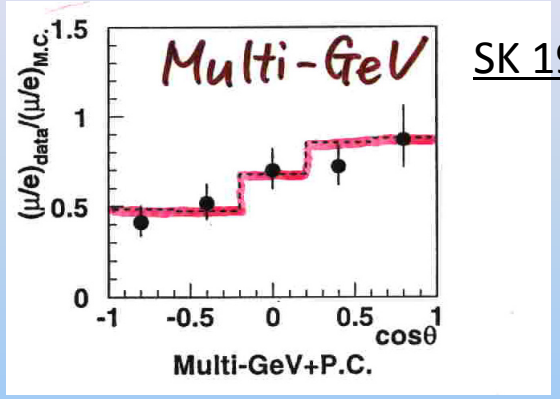
Purpose:

Oscillation Project with Emulsion tRacking Apparatus

Direct observation of $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation in appearance mode

Motivation:

Observation of ν_τ appearance from ν_μ oscillation at atmospheric scale (SK 1998).



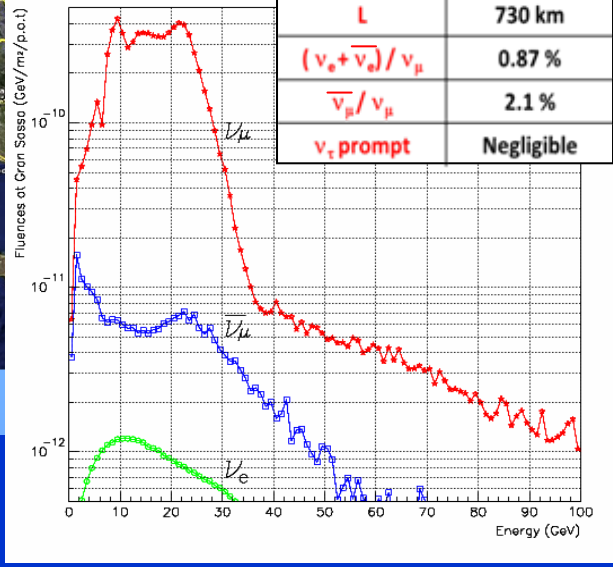
SK 1998

Requirements:

1) Long baseline
2) High neutrino energy
3) Large target mass
4) High spatial resolution (τ detection capability)

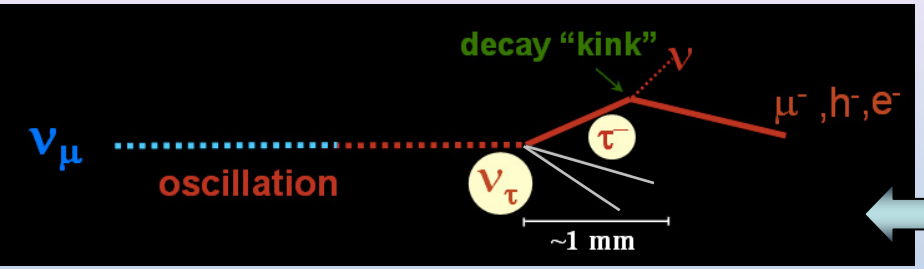
CNGS neutrino beam

$<E_\nu>$	17 GeV
L	730 km
$(\nu_e+\bar{\nu}_e)/\nu_\mu$	0.87 %
$\bar{\nu}_\mu/\nu_\mu$	2.1 %
ν_τ prompt	Negligible

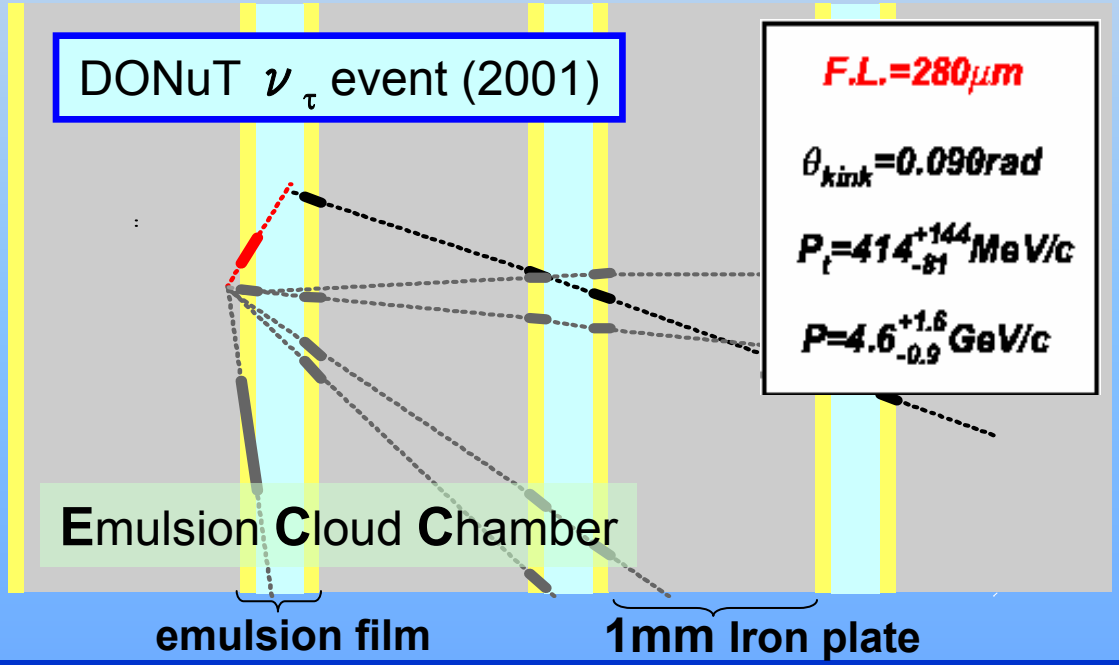


$\nu_\mu \rightarrow \nu_\tau$

Search for τ decay topology on an event by event basis.



plus 3-prong decay modes



Decay mode	BR (%)
$\tau^- \rightarrow \mu^- \nu_\mu \overline{\nu}_\tau$	17.36
$\tau^- \rightarrow e^- \nu_e \overline{\nu}_\tau$	17.85
$\tau^- \rightarrow h^-(n\pi^0) \overline{\nu}_\tau$	49.52
$\tau^- \rightarrow 2h^-h^+(n\pi^0) \overline{\nu}_\tau$	15.19

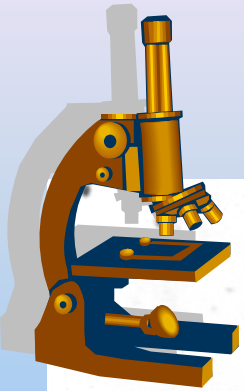
Direct observation of ν_τ using emulsion technology

Phys. Lett. B 504 (2001) 218

ν_τ detection

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau + N \rightarrow \tau^- + X$$

- Nuclear Emulsion is a special photographic film.
  : AgBr micro crystal semiconductor
- Signal is amplified by chemical process (development).



1896 (A.H.Becquerel)
Discovery of Radioactivity

1947 (C.Powell et al.)
Discovery of π

1971 (K.Niu et al.)
Discovery of charm particle in cosmic-ray

2001 (K.Niwa et al.)
Direct observation of ν_τ

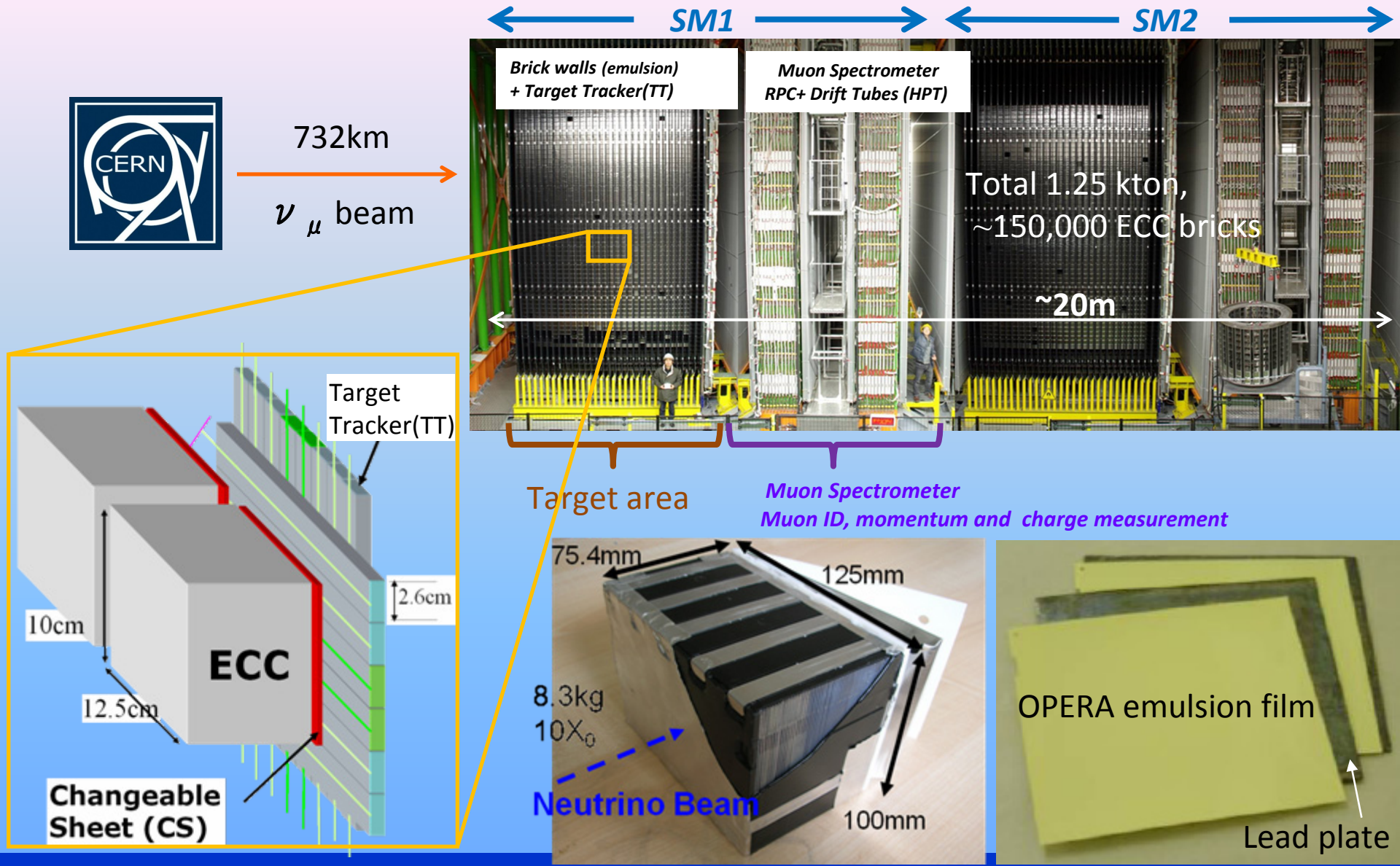
Nuclear emulsion

Sub micron resolution 3D tracker

Target mass

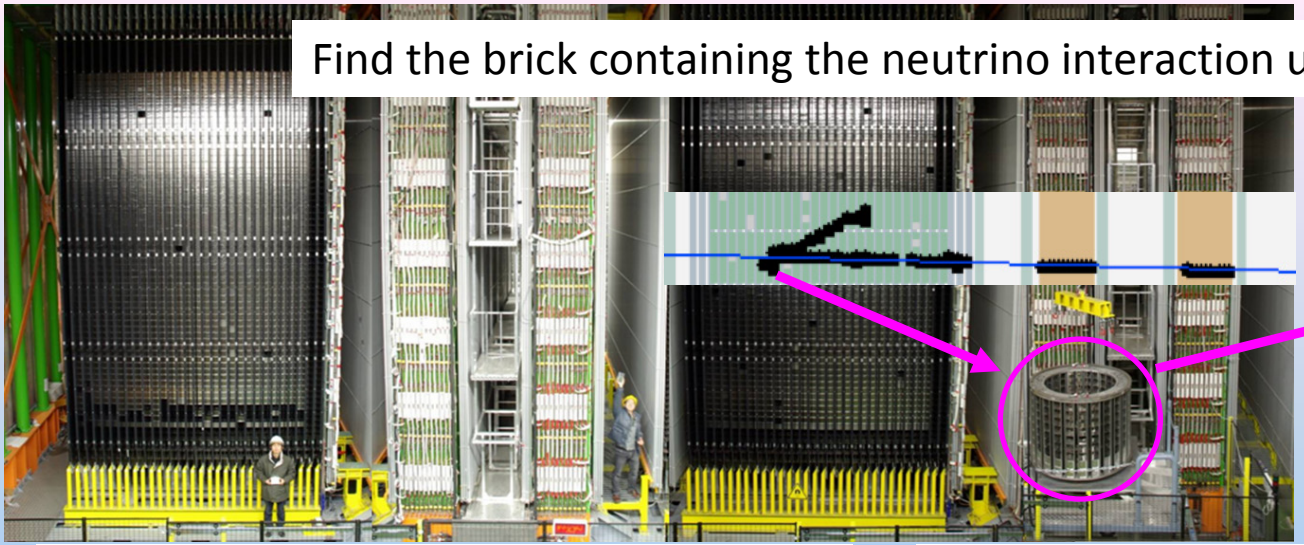
- **1978-1983 Fermilab E531** ~ 100kg
  charm physics, $\nu_\mu \rightarrow \nu_\tau$ oscillation
- **1990-2000 CERN WA95 CHORUS** ~ 1 ton
  $\nu_\mu \rightarrow \nu_\tau$ oscillation, charm physics
- **1994-2001 Fermilab E872 DONuT** ~ 1 ton
  First ν_τ observation
- **2008- CERN CNGS01 OPERA** **1250 ton**
  $\nu_\mu \rightarrow \nu_\tau$ oscillation, $\nu_\mu \rightarrow \nu_e$ oscillation

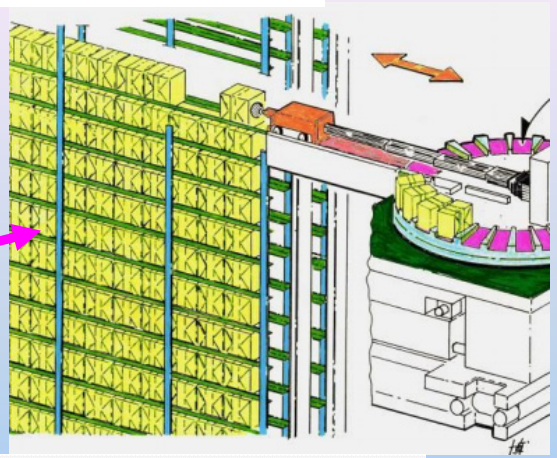
Long history of emulsion in neutrino physics

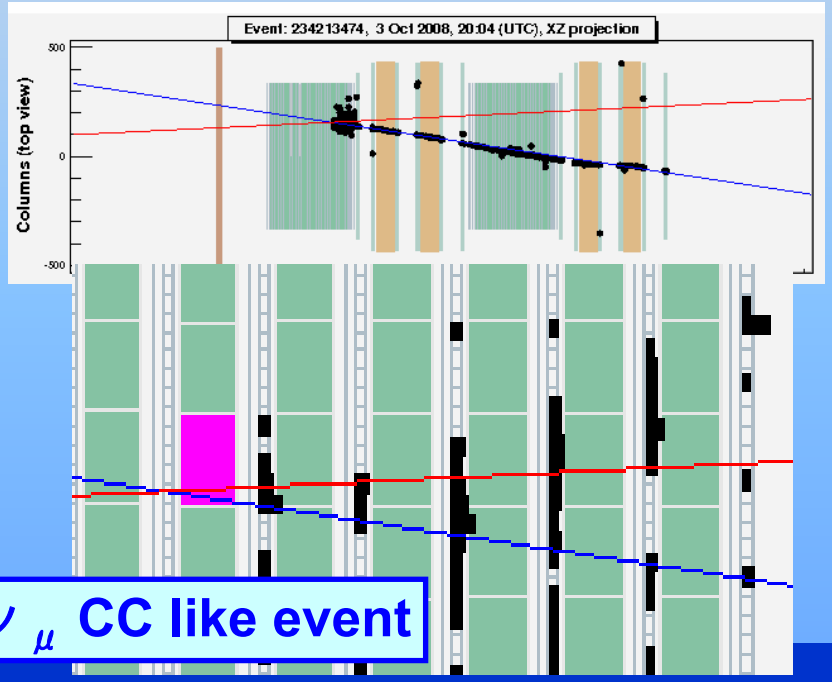


The OPERA detector

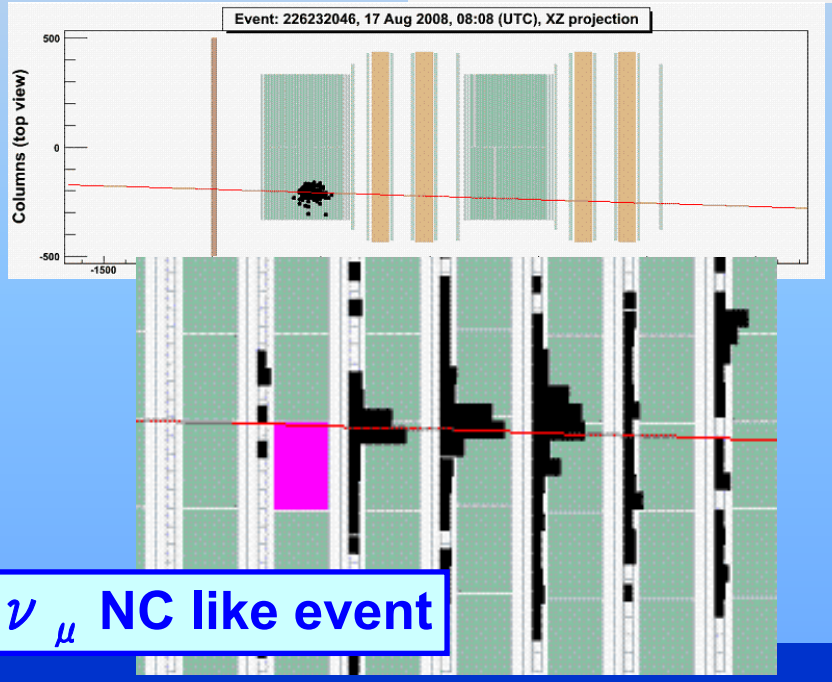
Find the brick containing the neutrino interaction using TT hits







ν_μ CC like event



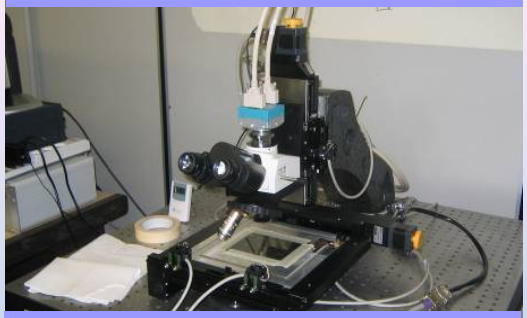
ν_μ NC like event

Event analysis – Brick finding –

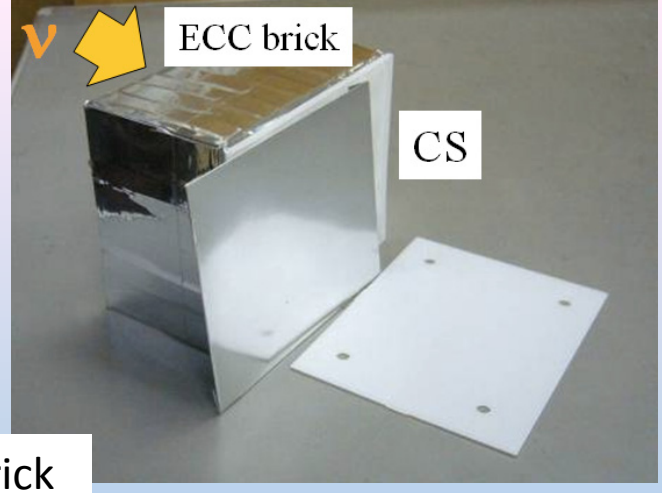
Japanese Scanning System

Scanning speed : 75cm²/h

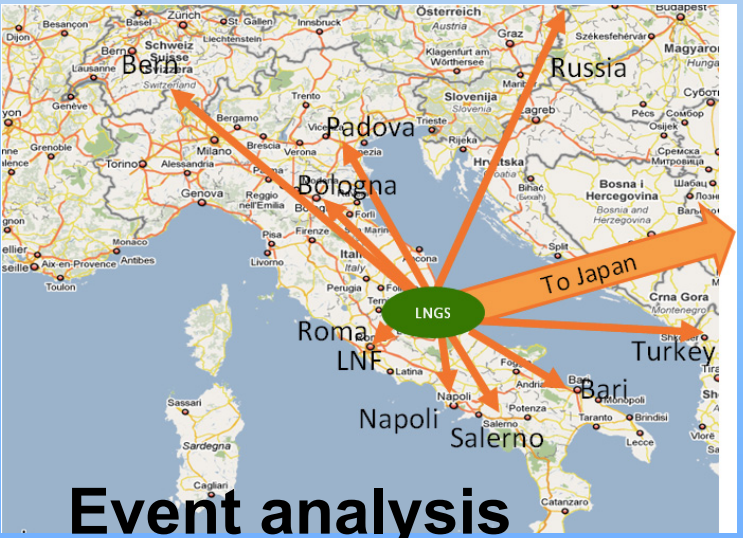
European Scanning System



Scanning speed : 20cm²/h

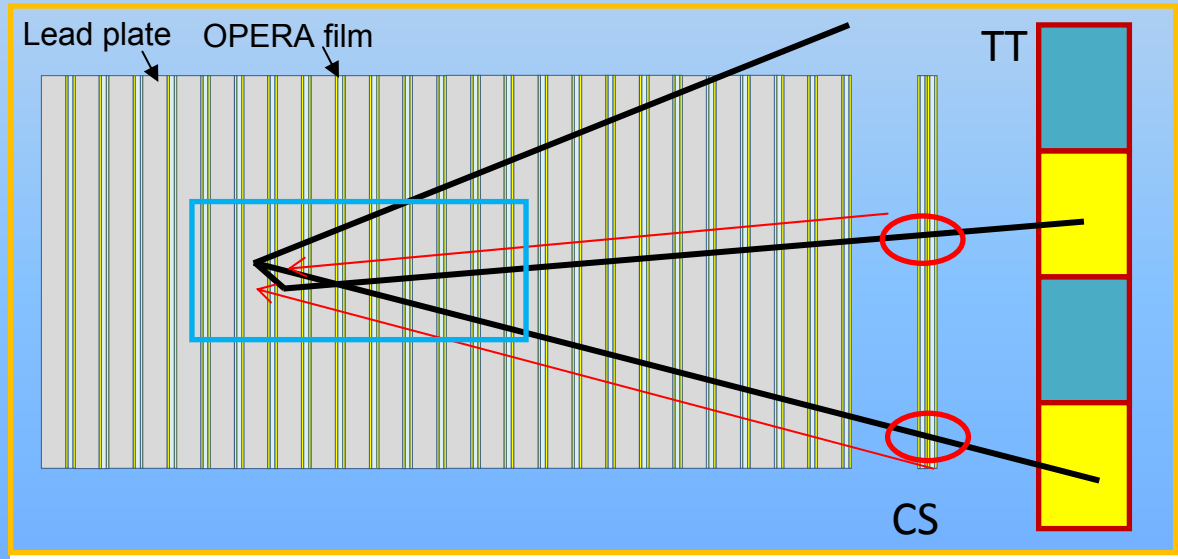


1. Full area CS scan and check tracks to confirm the brick
2. Connect tracks found at CS to ECC brick



Event analysis

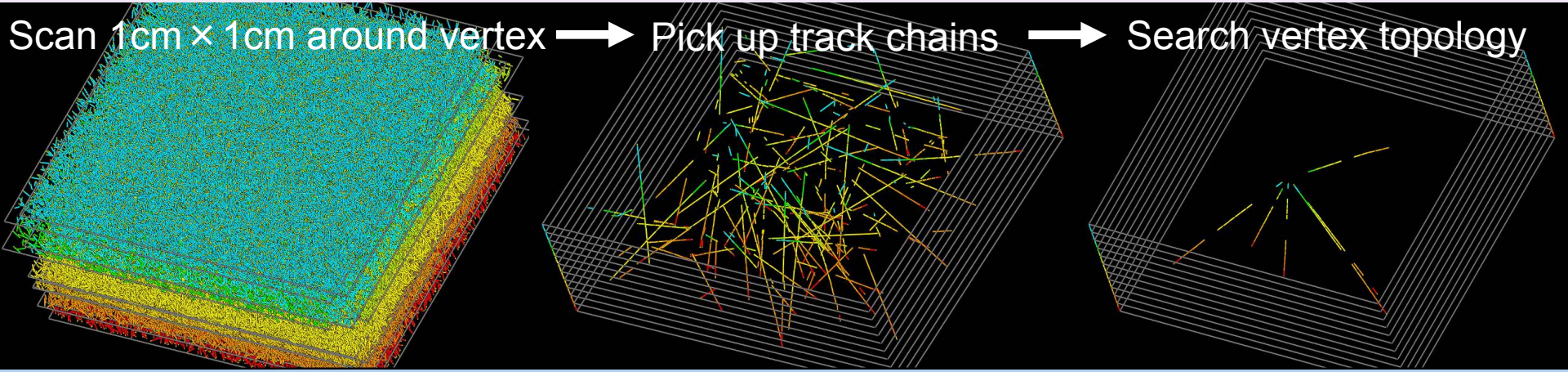
→ JP : EU = 50 : 50



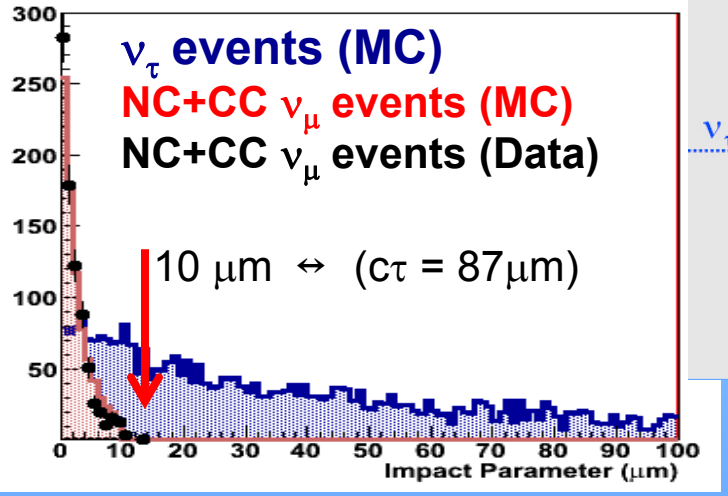
3. Follow up tracks to interaction vertex in the ECC brick
4. Scan 10 films around interaction vertex (blue box)

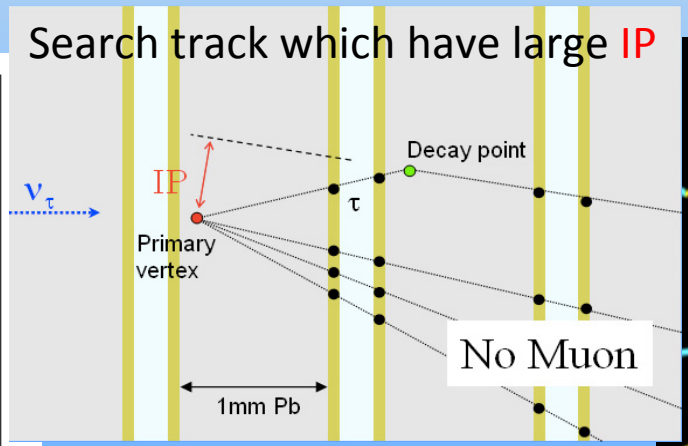
Event analysis – Location –

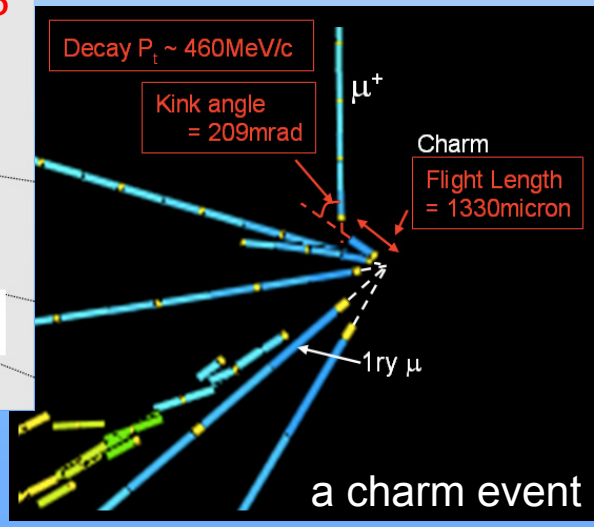
Neutrino event reconstruction in emulsion detector



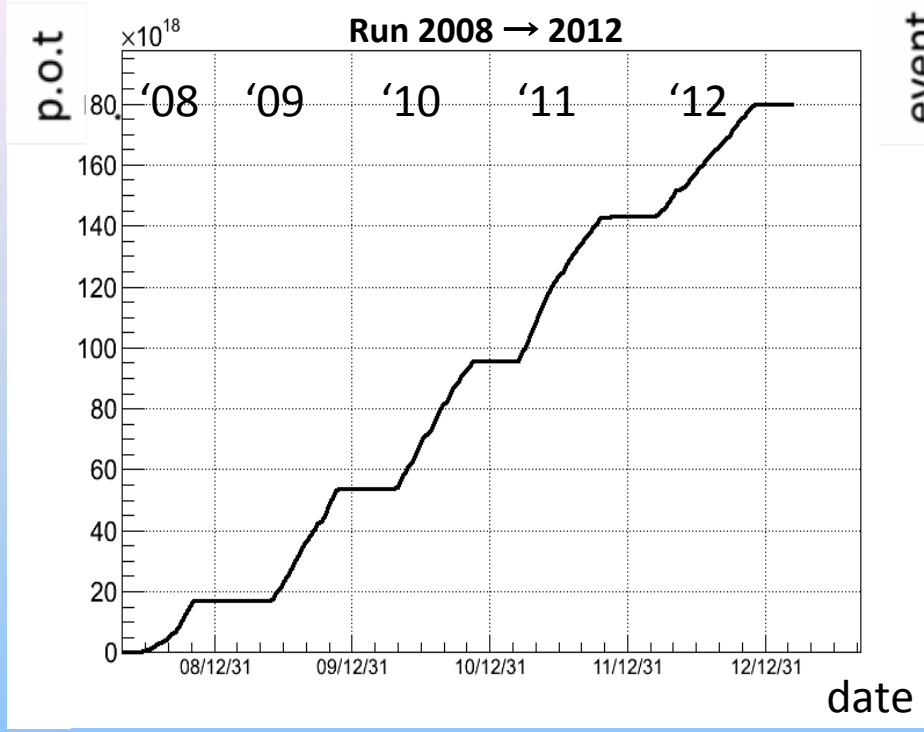
Impact Parameter distribution

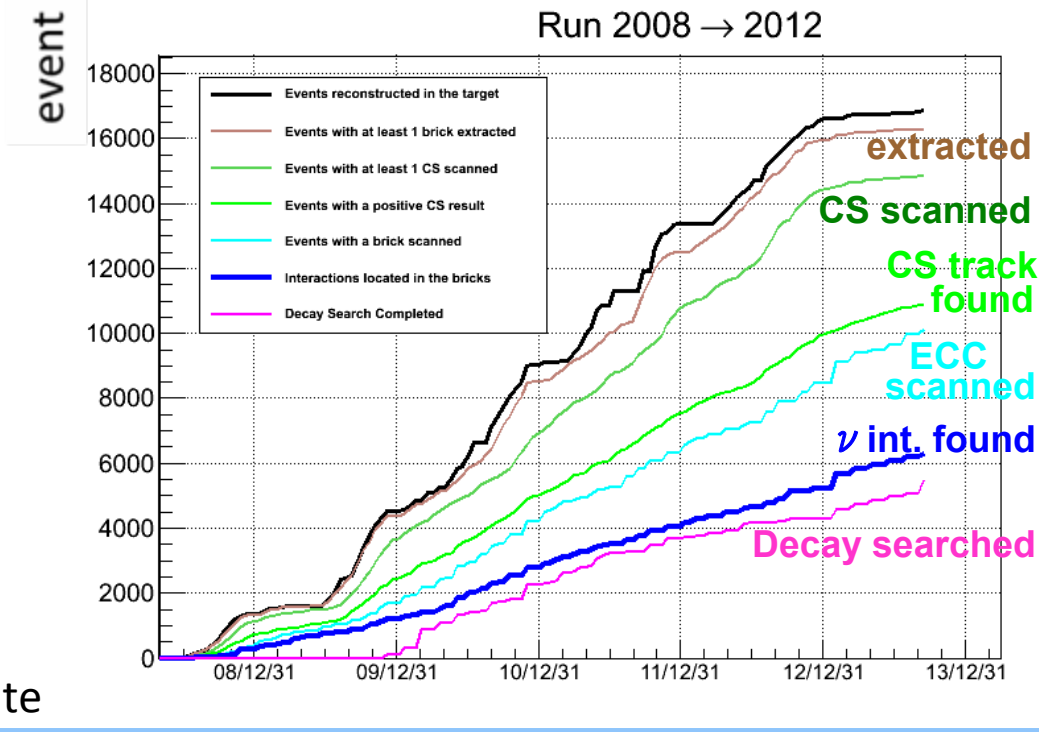






Event analysis – Decay search –





Beam: 5years (965days)

17.97×10^{19} protons on target

Overall 80% of the Proposal value

(22.5×10^{19} p.o.t.)

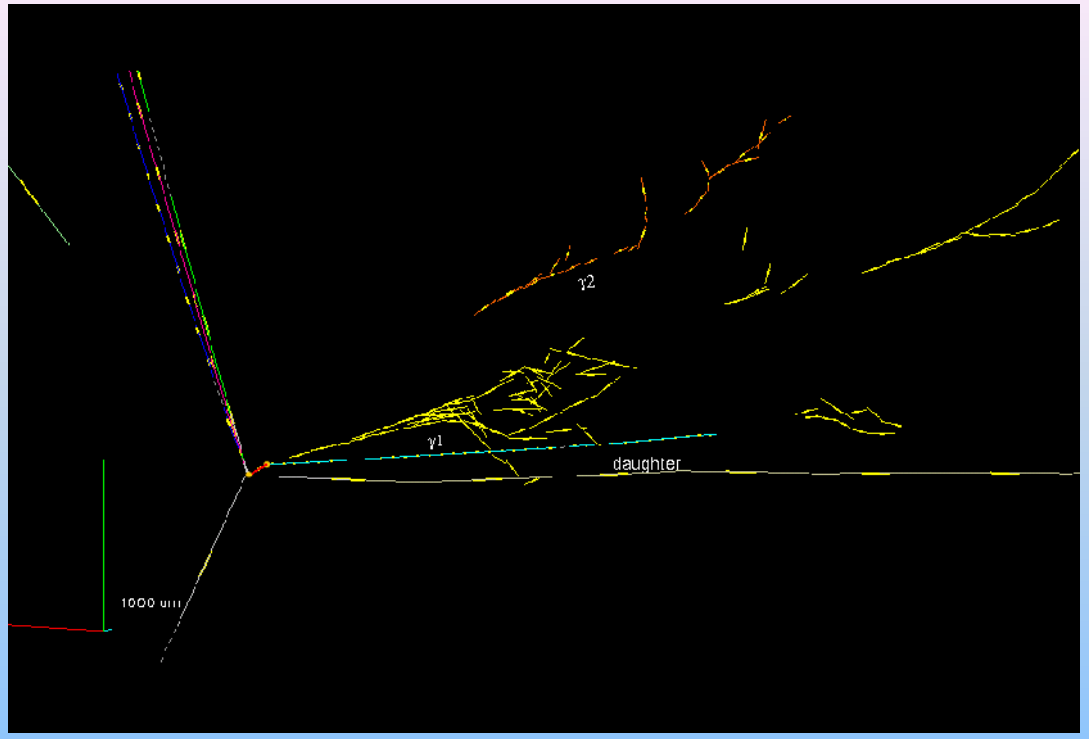
Event analysis completed: 2008, 2009

2010-12 on going with optimised strategy

Located: 6299, Decay search: 5497

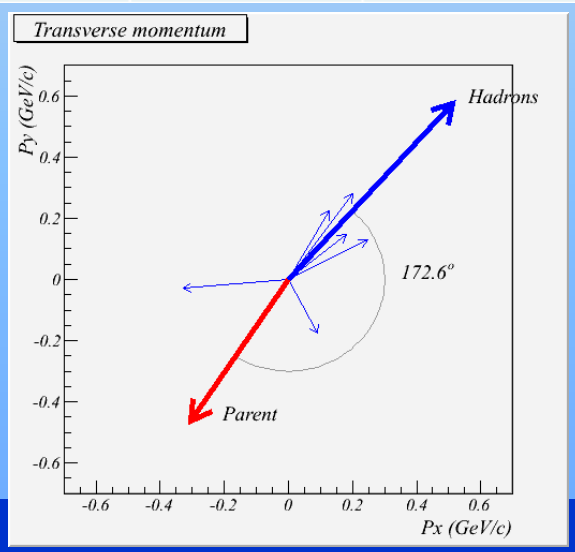
~67% located of expected value

Beam exposure and analysis status



Event Kinematics

VARIABLE	Measured	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 daughter (MeV/c)	470^{+230}_{-120}	>300 (γ attached)
Missing Pt (MeV/c)	570^{+320}_{-170}	<1000
φ (deg)	173 ± 2	>90



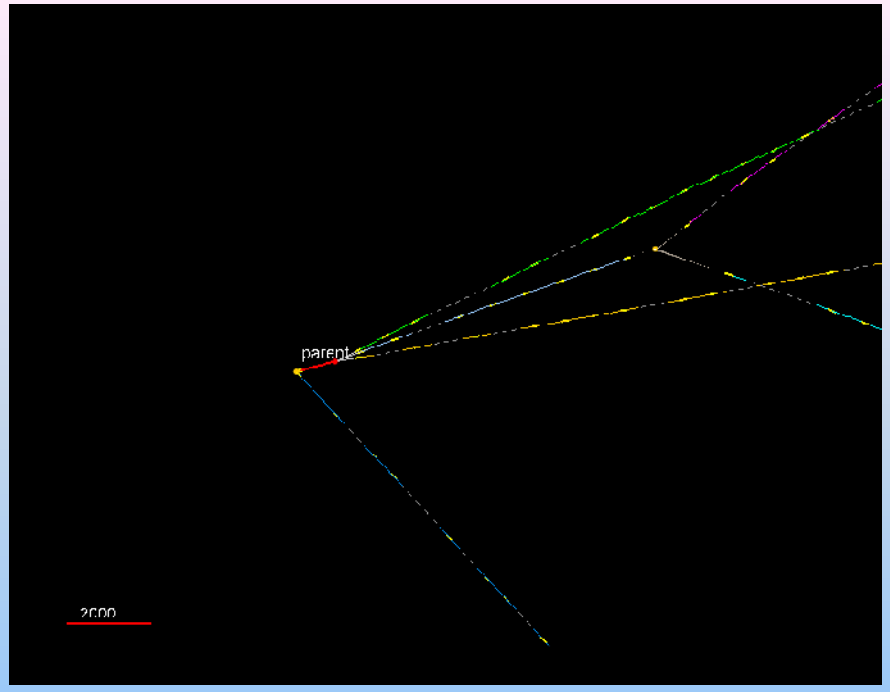
First detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode

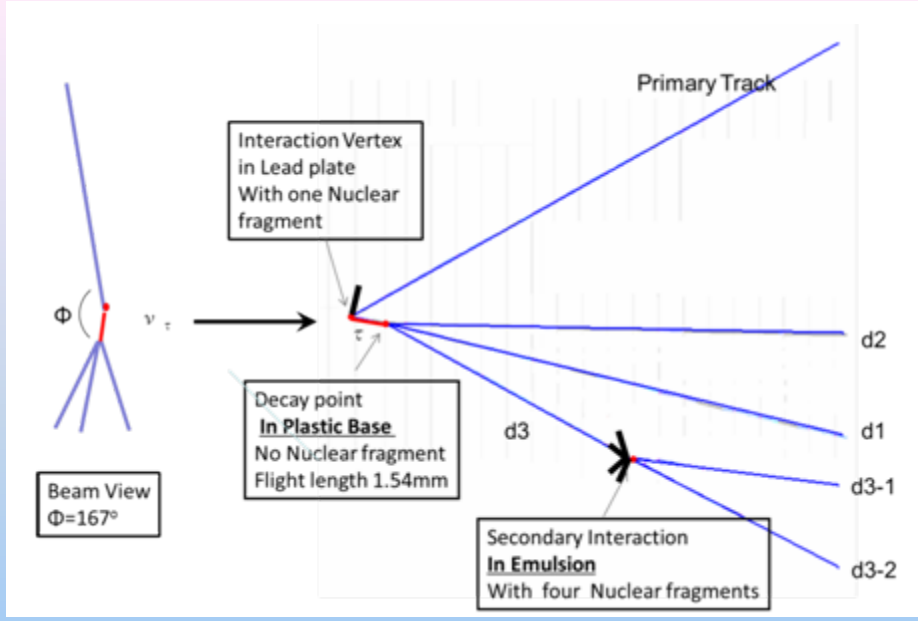
Reported in May 2010

Decay channel: $\tau \rightarrow$ 1h

Phys. Lett. B 691 (2010) 138

The first ν_τ "appearance" candidate





All tracks other than τ were identified as hadrons.
Decay in plastic base.

Reported in June 2012

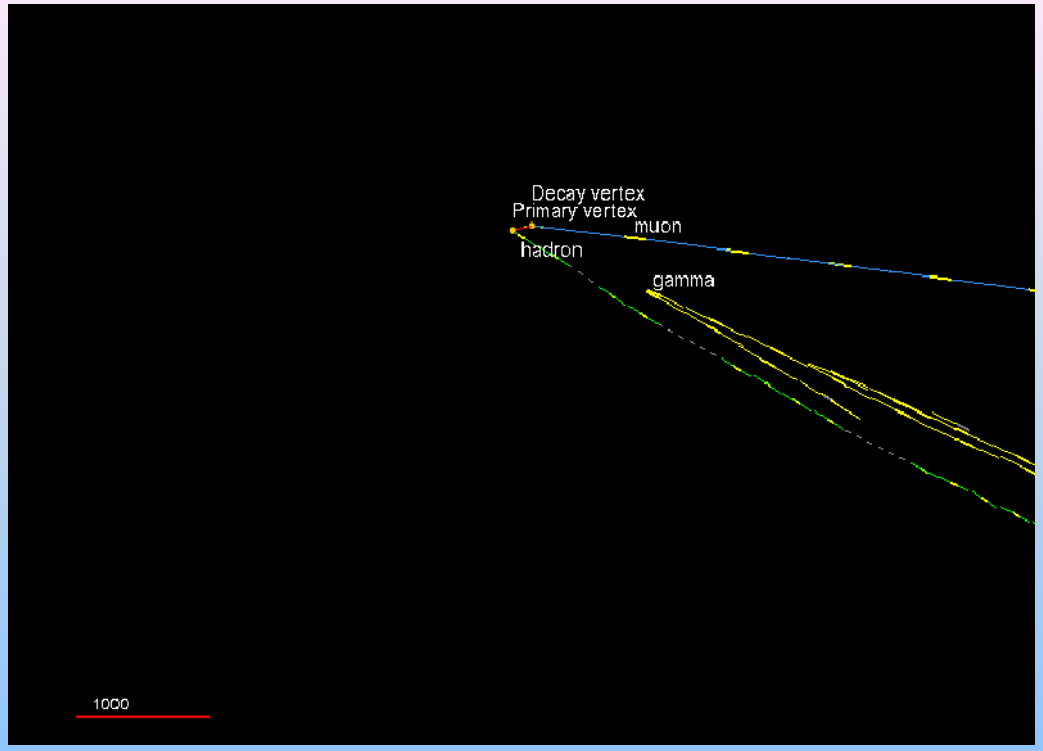
NEUTRINO 2012
June 3-9 2012 Kyoto, Japan

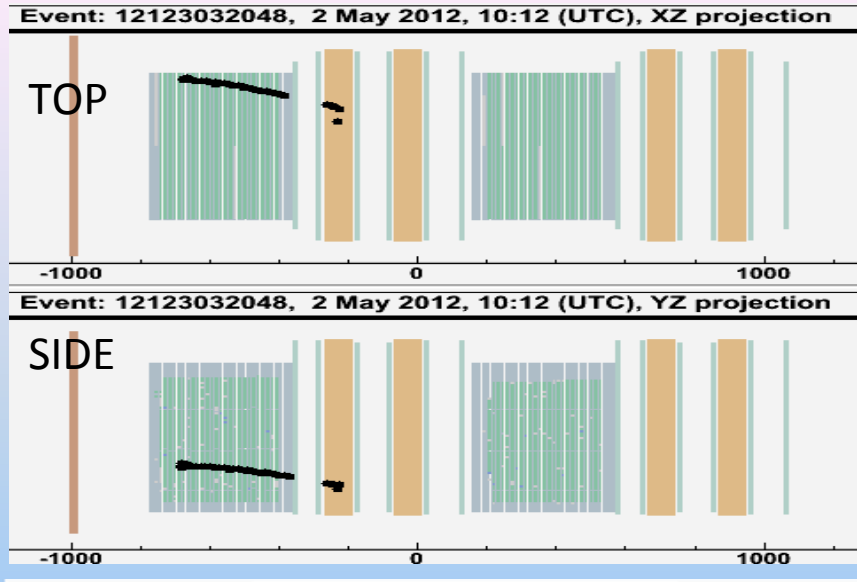
Decay channel: $\tau \rightarrow 3h$

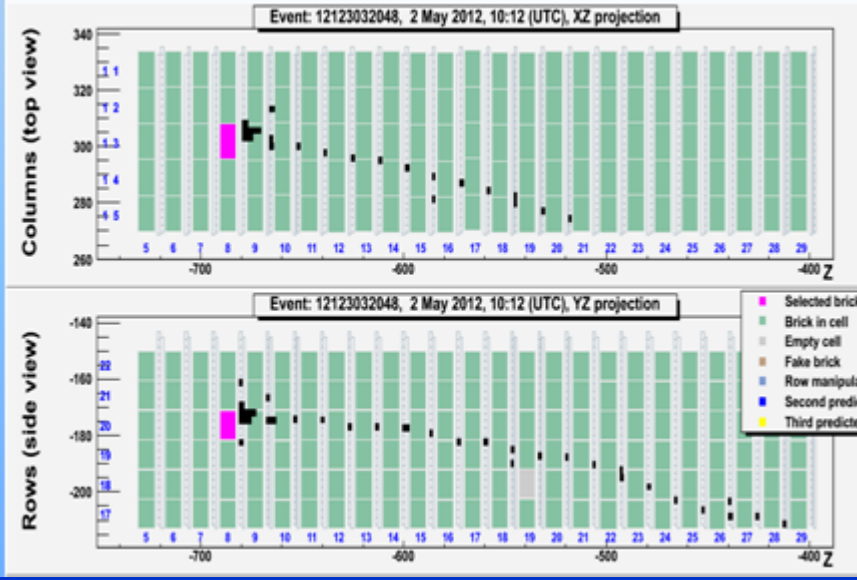
JHEP 11 (2013) 036

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/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

The second ν_τ candidate







Decay daughter was identified as a muon because of its high penetrability.

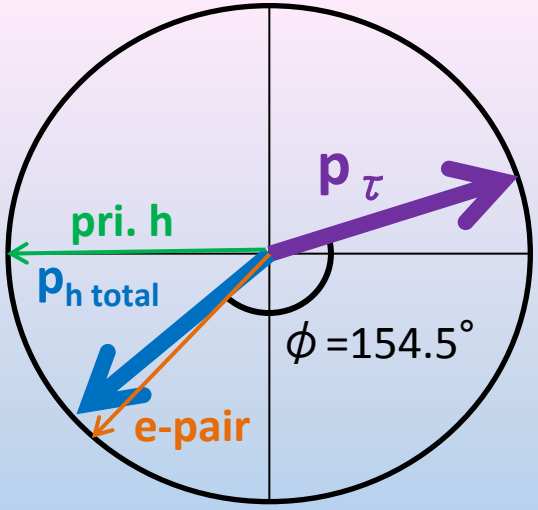
Reported first in March 2013

Decay channel: $\tau \rightarrow \mu$

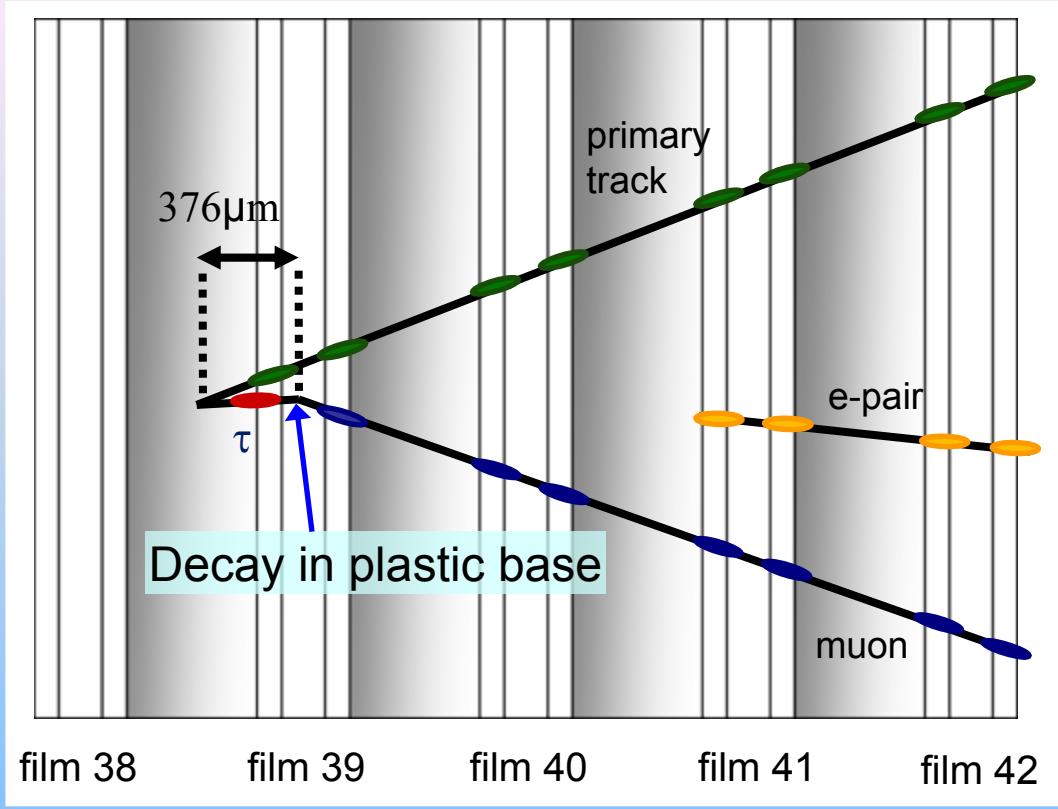
Submitted to Phys. Rev. Lett. this month

The third ν_τ candidate

First leptonic decay



VARIABLE	AVERAGE
Kink angle (mrad)	245 ± 5
decay length (μm)	376 ± 10
Pμ (GeV/c)	2.8±0.2
Pt (MeV/c)	690±50
ϕ (degrees)	154.5 ± 1.5

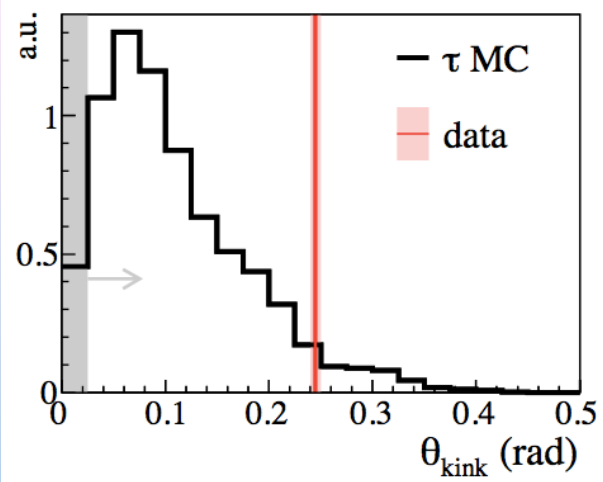


γ is attached to the primary vertex.

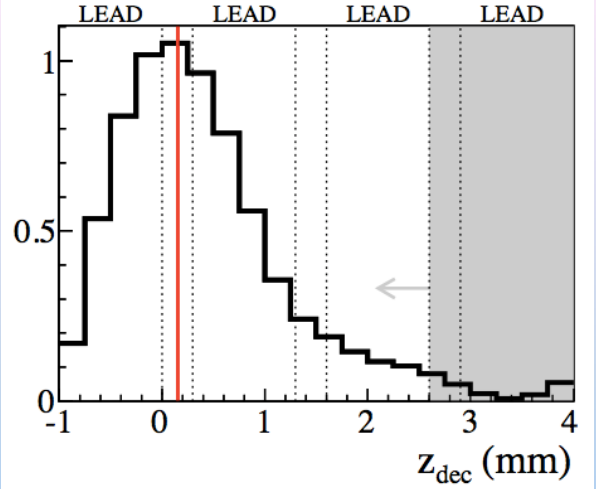
	$\delta\theta_{RMS}$ (mrad)	DZ (mm)	Measured IP (μm)	IP resolution (μm)	ATTACHMENT
1ry vertex	6	3.1	18.2	13.6	OK
2ry vertex	6	2.8	68.7	12.2	EXCLUDED

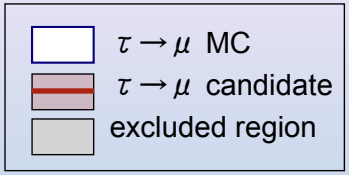
The 3rd ν_τ cand. – event kinematics –

KINK ANGLE

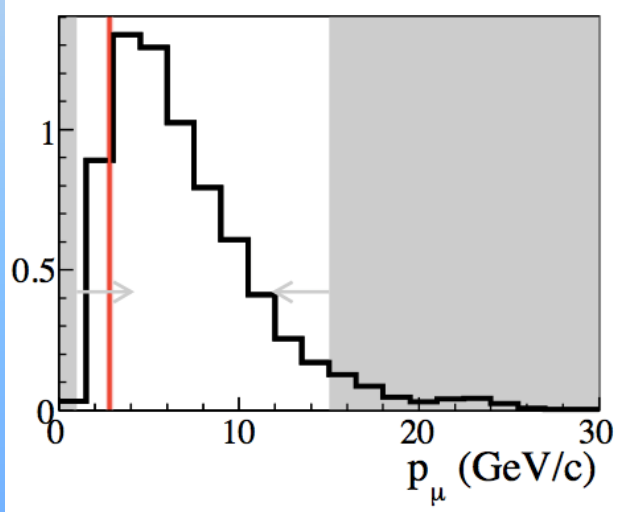


DECAY LENGTH

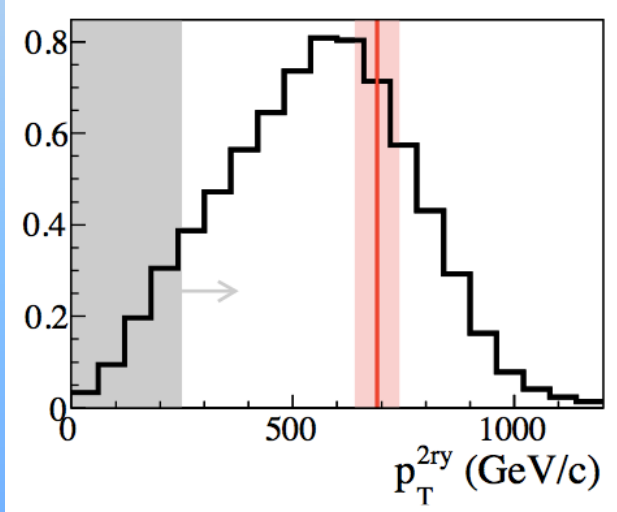




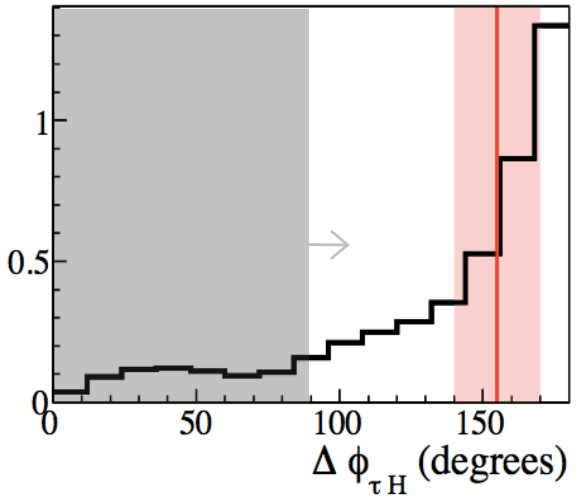
MUON MOMENTUM



TRANSVERSE MOMENTUM AT 2RY VTX

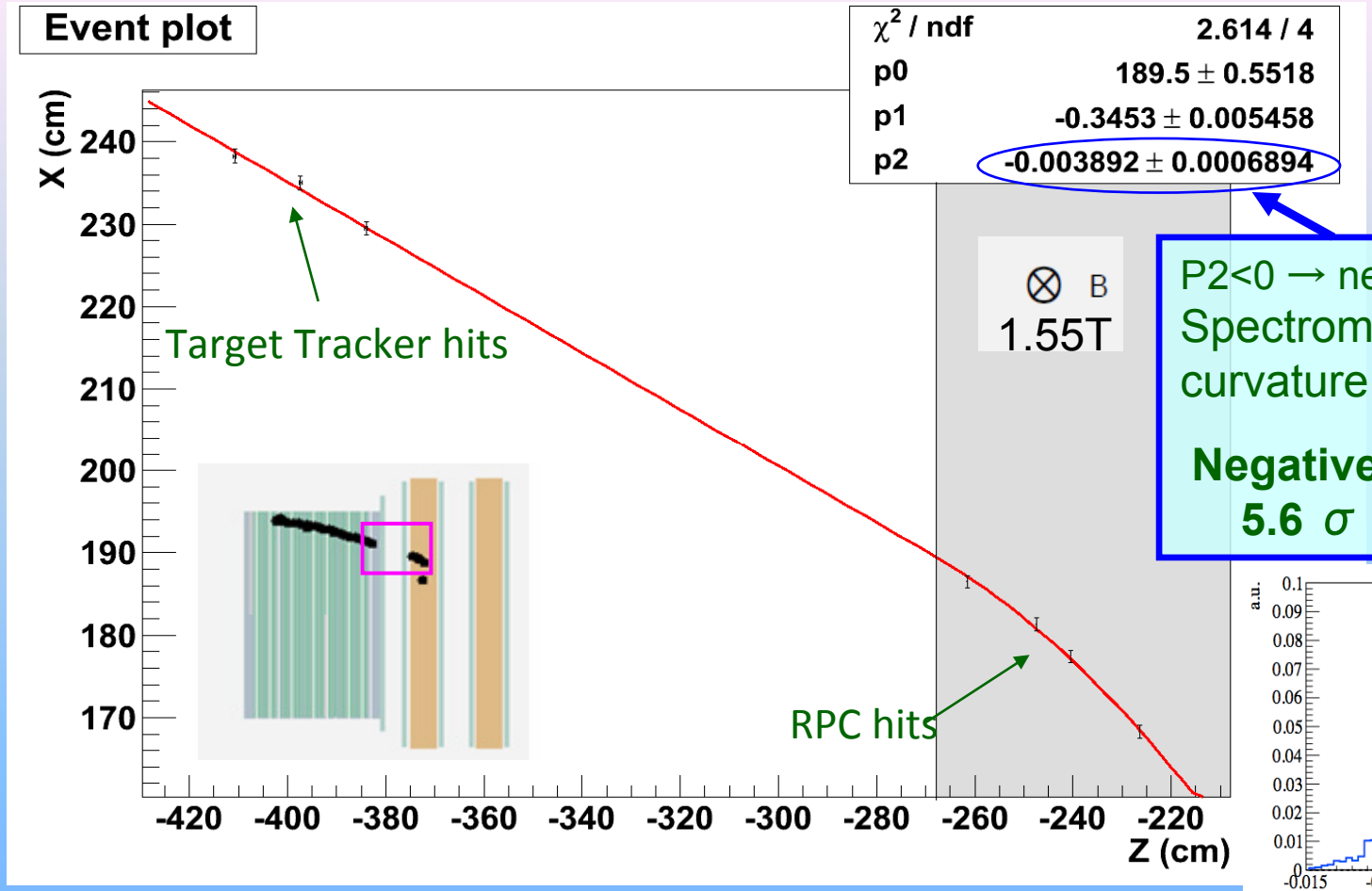


PHI ANGLE



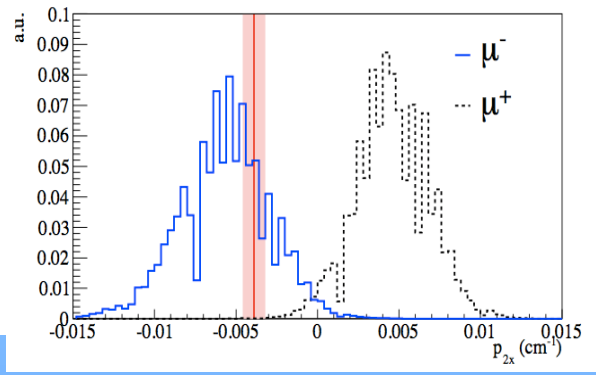
All variables passed the kinematical cuts

The 3rd ν_τ cand. – event kinematics –



P2<0 → negative charge
Spectrometer 4hits
curvature radius ~ 85cm

Negative μ :
5.6 σ significance



$\nu_\tau \rightarrow \tau^-$: identification of oscillated ν_τ interaction ($\neq \overline{\nu}_\tau$)

The 3rd ν_τ cand. – Lepton number identification –

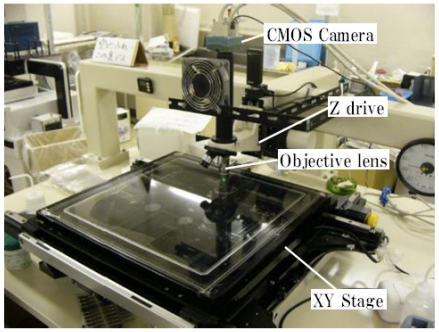
Expected number of Signal & BG events for 5272 analyzed sample

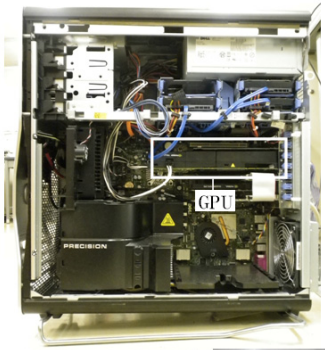
	Signal	Background	Charm	μ scattering	had int
$\tau \rightarrow h$	0.31	0.027	0.011		0.016
$\tau \rightarrow 3h$	0.43	0.12	0.11		0.0021
$\tau \rightarrow \mu$	0.54	0.021	0.0044	0.017	
$\tau \rightarrow e$	0.46	0.020	0.020		
Total	1.74	0.184	0.145	0.017	0.018

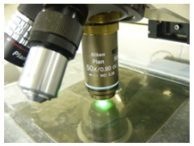
- Three ν_τ candidates were found,
  1st : $\tau \rightarrow h$, 2nd : $\tau \rightarrow 3h$, 3rd : $\tau^- \rightarrow \mu^-$.
- Probability explained by only background ~ 2.9×10^{-4}
- The significance value : 3.4 σ of non-null observation
- **This means an evidence for $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillation in appearance mode.**

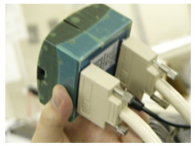
$\nu_\mu \rightarrow \nu_\tau$ oscillation search

New automatic emulsion scanning system with wide-angle acceptance





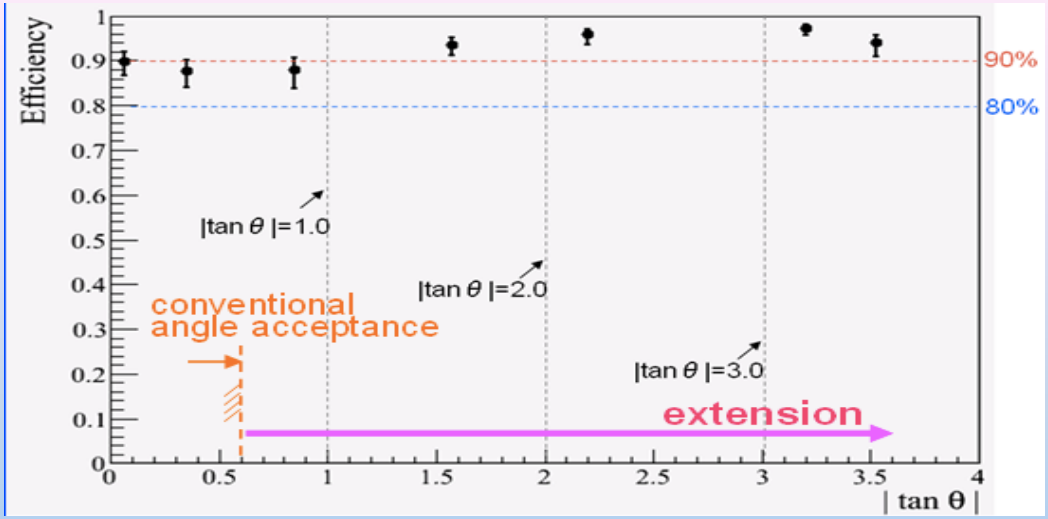




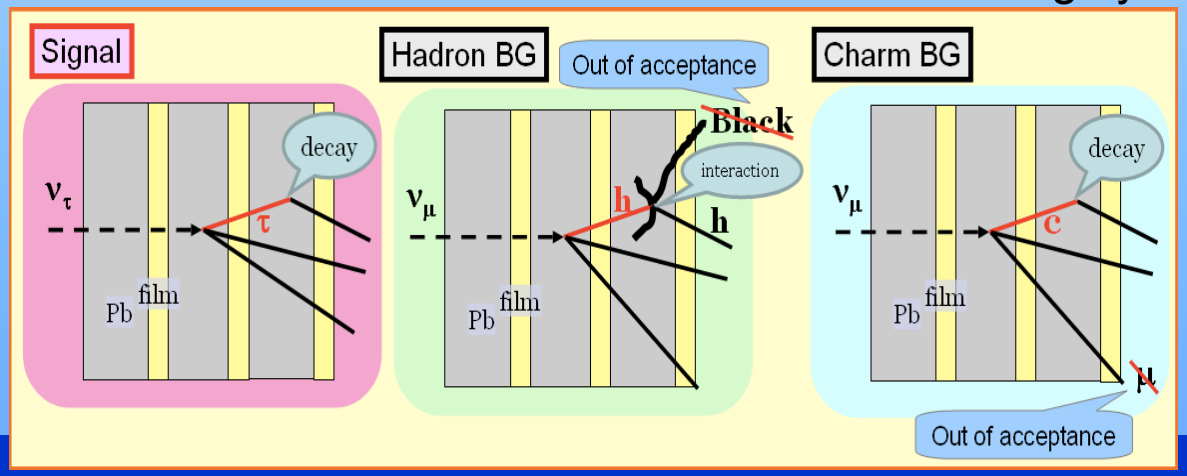
Objective lens
Nikon CFI Plan x50
oil immersion lens

CMOS Camera
Mikrotron
Eosens MC 1362

Graphics Processing Unit (GPU)
NVIDIA Tesla C2050



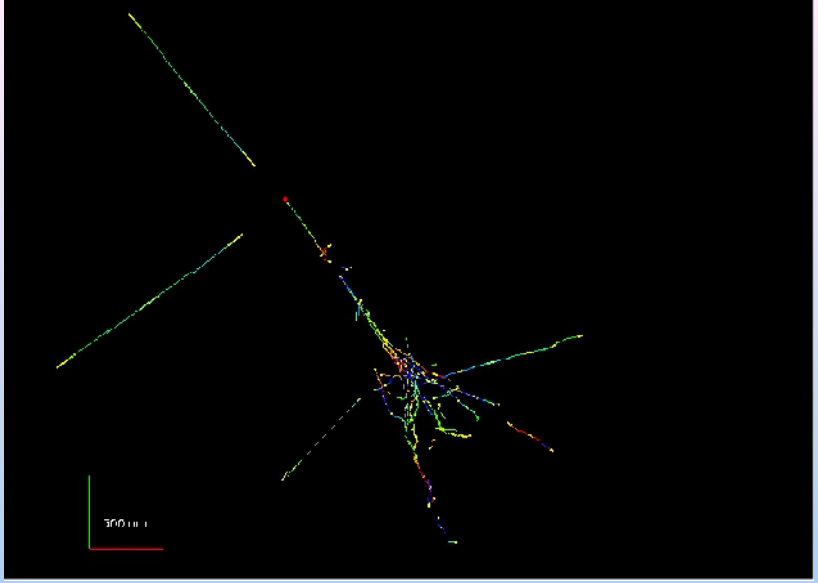
New automatic emulsion scanning system was developed to detect large angle tracks which are out of angle acceptance of a conventional scanning system.



for Hadron BG: already applied
→ 30% BG reduction

for Charm BG: under study

New developments & BG reduction



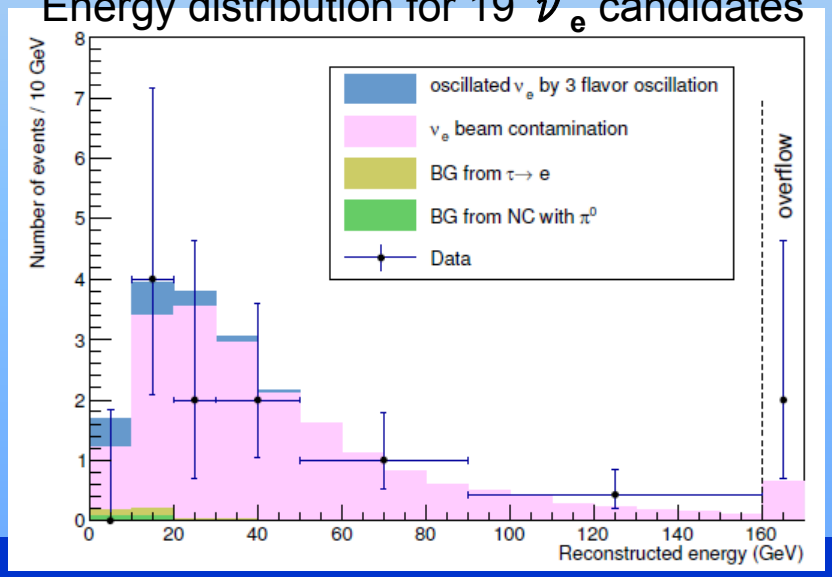
E_ν = 15.6 GeV

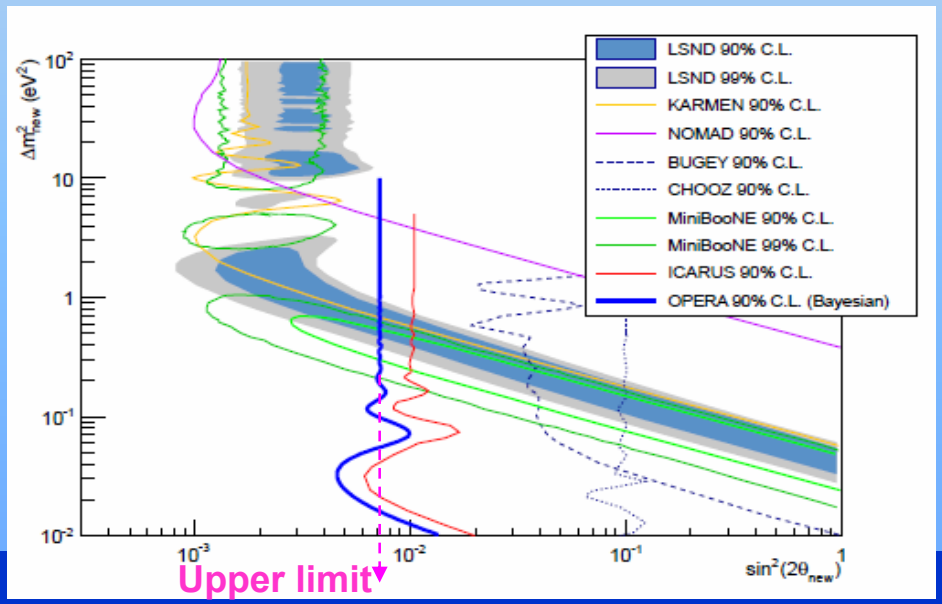
- 19 ν_e candidate events observed, compatible with background hypothesis expectation of 19±2.8 (sys) events in 2008-2009 data sample.
- Applying Energy cut (E<20GeV) to increase S/N, 4 observed events wrt 4.6 expected.

  $\sin^2(2\theta_{13}) < 0.44$ (90% C.L.)
- Search for non-standard oscillations at large Δm^2 values. We observed 6 events below 30GeV with 9.4±1.3 expected events.

  Upper limit : 7.2 x 10^{-3} (90% C.L.) on $\sin^2(2\theta_{new})$

Energy distribution for 19 ν_e candidates





$\nu_\mu \to \nu_e$ oscillation search

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- The OPERA experiment is pursuing the observation of $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations in appearance mode.

- OPERA successfully collected data from 2008 to 2012. A total number of **17.97 x 10^{19} p.o.t.** integrated (~80% of the nominal value). Analysis is on-going.

- **3 ν_τ candidate events** were found with 1.74 signal and 0.18 background events expected in the analyzed sample.

- Significance of the observation is **3.4 σ**
  → **Evidence of ν_τ appearance** in the CNGS beam.

- Effort ongoing to improve the significance by extending the analysis and improving of background rejection.

Conclusions