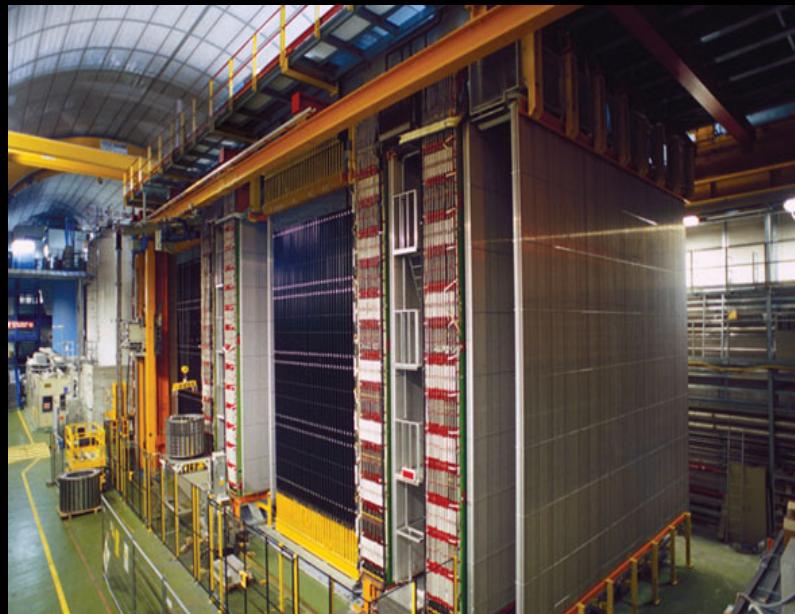


The quest of oscillation appearance: OPERA



International Symposium on Neutrino Physics and Beyond

Shenzhen, 23- 26 September 2012

Antonio Ereditato
University of Bern

From PMNS matrix to oscillations

OPERA



$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Measured with atm and LBL } \nu}$$

Measured with
atm and LBL ν

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

$$\underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Measured with reactor and LBL } \nu}$$

Measured with reactor
and LBL ν

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

$$\underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Measured with solar, reactor } \nu}$$

Measured with
solar, reactor ν

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

Oscillation formula (3-neutrino scheme)

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

Dominant terms

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



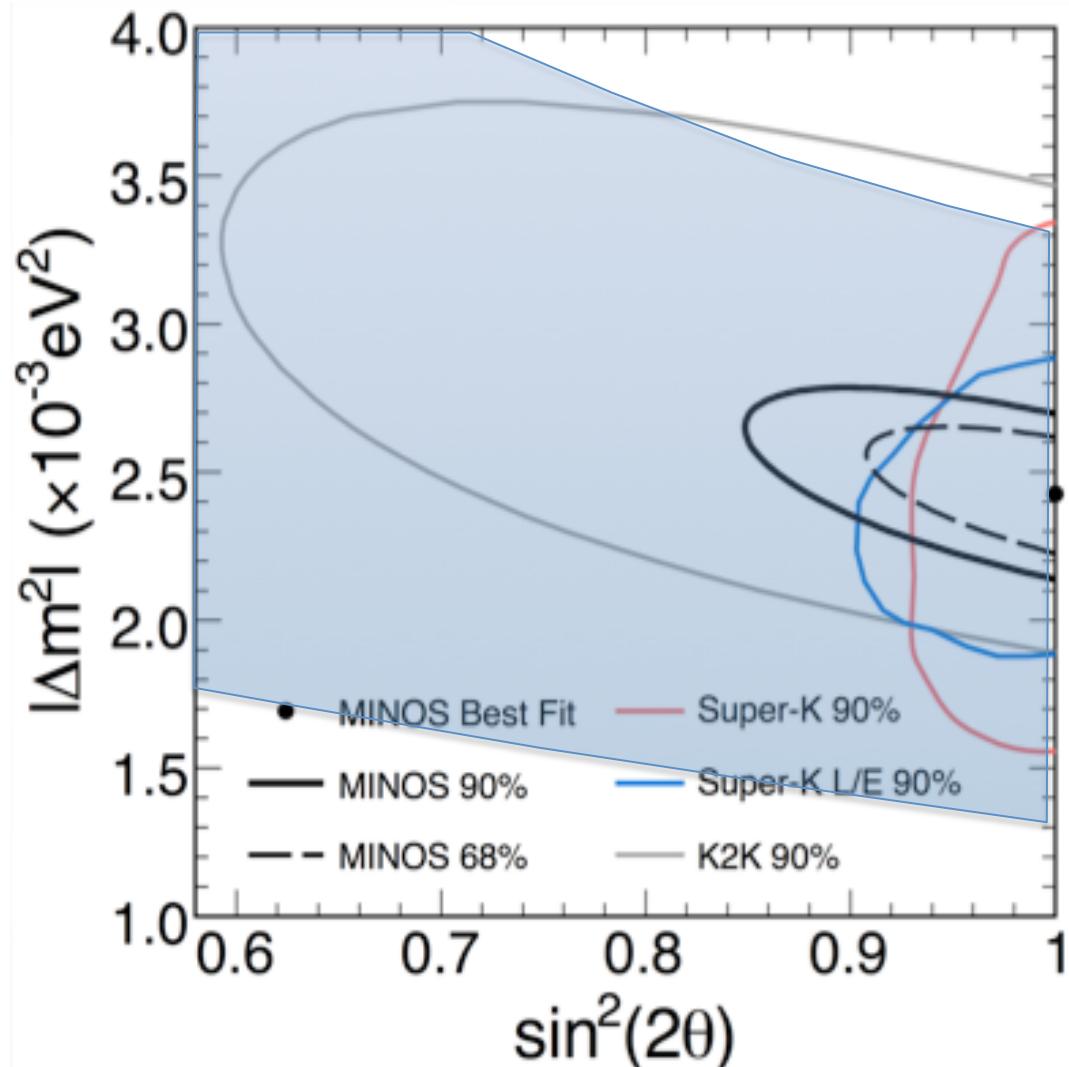
OPERA

direct detection of neutrino oscillations in appearance mode

Requirements:

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

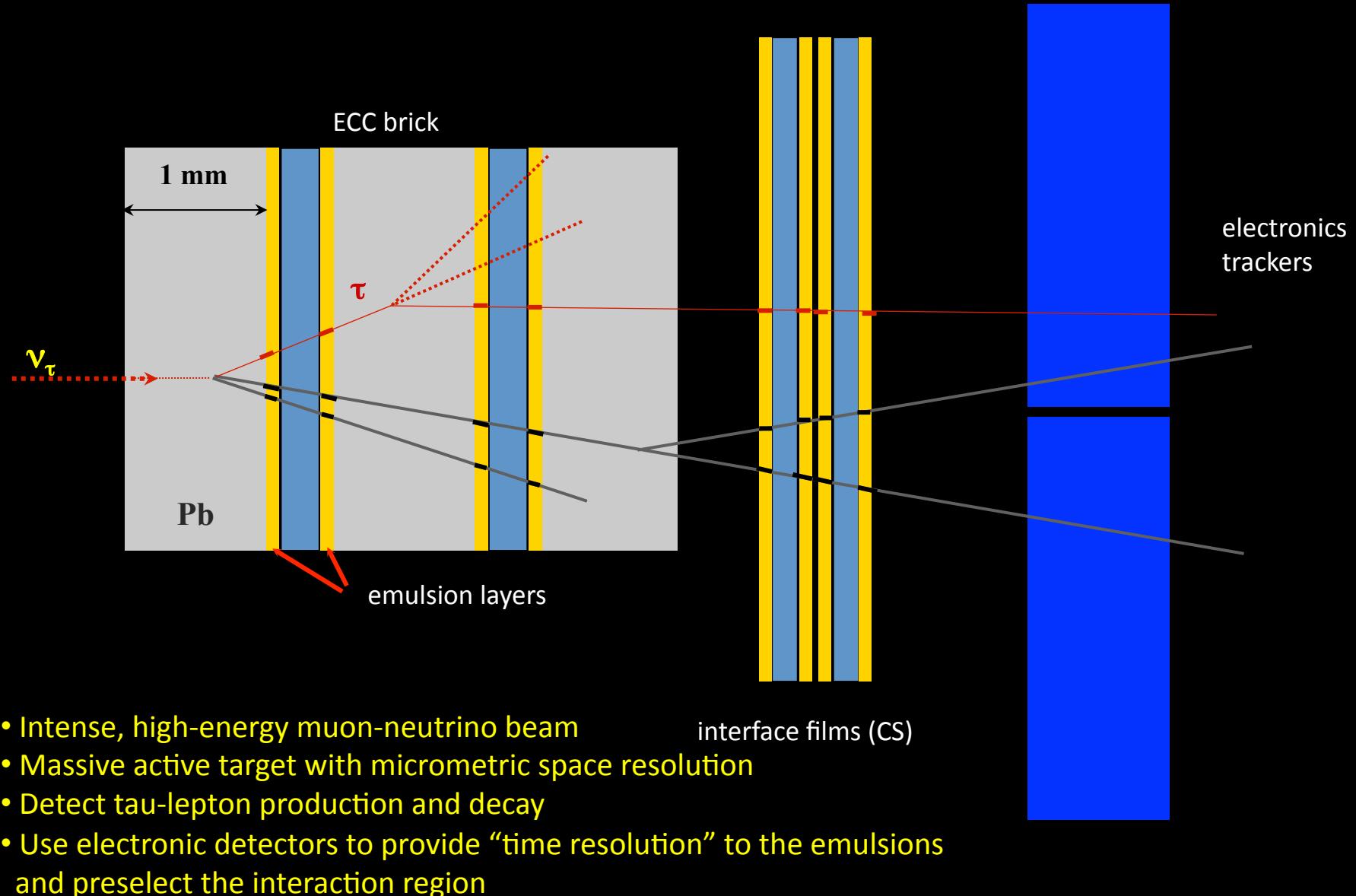
Oscillation parameter sensitivity



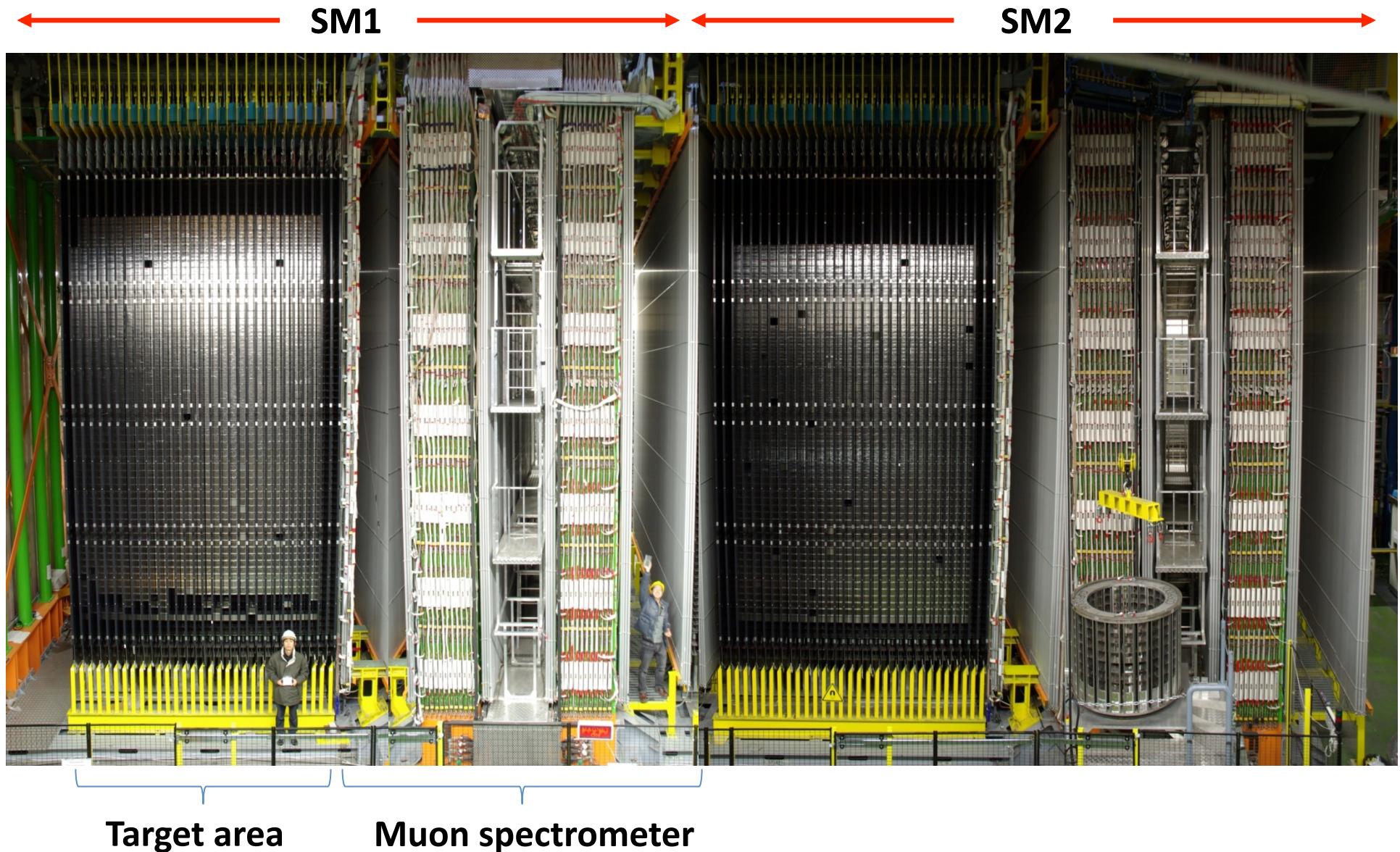
Full mixing and
 $\Delta m^2_{23} \sim 2.4 \times 10^{-3} \text{ eV}^2$

The grey band indicates
the OPERA allowed region
(90% CL) for the above
parameter values for
 22.5×10^{19} pot

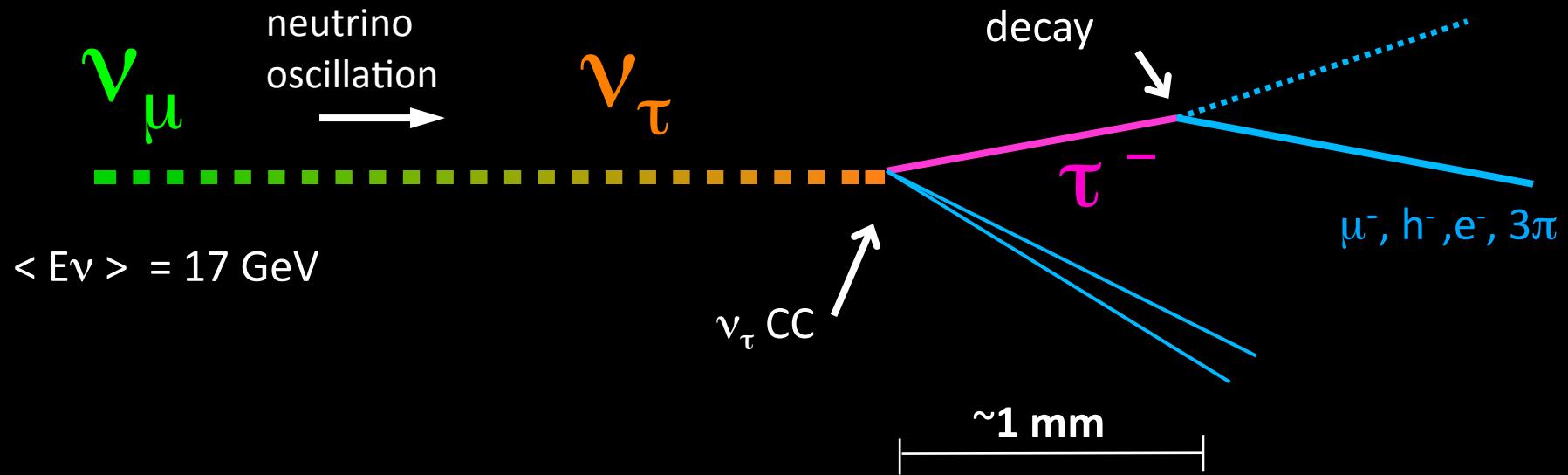
THE PRINCIPLE OF THE EXPERIMENT: ECC + ELECTRONIC DETECTORS



THE IMPLEMENTATION OF THE PRINCIPLE

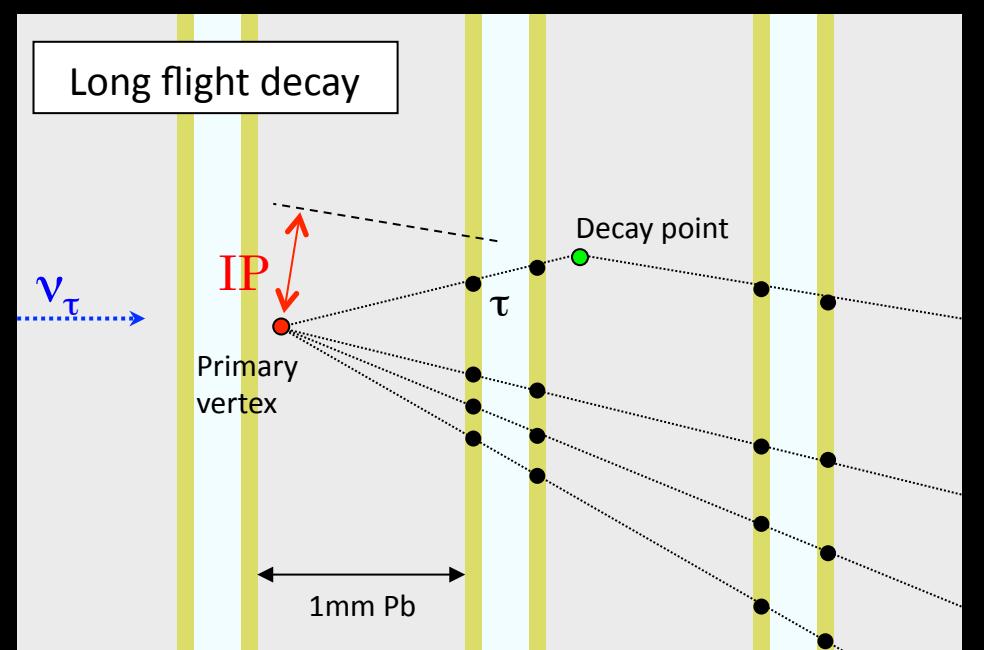
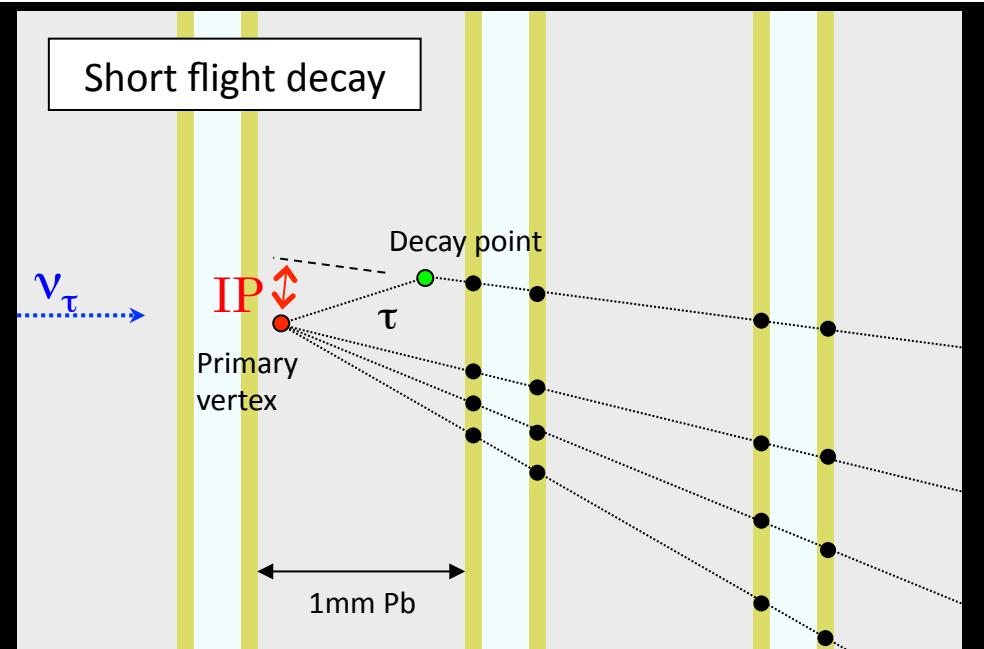


τ decay modes



Topology	decay mode	BR	exp. evts. (22.5×10^{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

ν_τ CC detection





2012: 15 years since the conceptual design of the experiment...



ELSEVIER

Nuclear Physics B (Proc. Suppl.) 66 (1998) 423–427

P63

SUPPLEMENTS

A. Ereditato, K. Niwa, P. Strolin:

THE EMULSION TECHNIQUE FOR SHORT, MEDIUM AND LONG BASELINE $\nu_\mu - \nu_\tau$ OSCILLATION EXPERIMENTS

INFN/AE-97/06
27 Gennaio 1997
DAPNU-97-07

The emulsion technique for short, medium and long baseline $\nu_\mu - \nu_\tau$ oscillation experiments

ISTITUTO NAZIONALE DI FISICA NUCLEARE

INFN – Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

Sezione di Napoli

INFN/AE-97/06
27 Gennaio 1997
DAPNU-97-07

INFN/AE-97/06
27 Gennaio 1997

DAPNU-97-07

OPERA: an emulsion detector for a long baseline $\nu_\mu - \nu_\tau$ oscillation search

A. Ereditato^{a*}, K. Niwa^b and P. Strolin^a

^aUniversità "Federico II" and INFN, Naples, Italy

^bUniversity of Nagoya, Japan

In this paper we outline the design of a new experiment for the search of $\nu_\mu - \nu_\tau$ oscillation in a long-baseline configuration. The apparatus exploits a novel application of nuclear emulsion for the direct detection of the lepton, allowing for an unambiguous signature of the neutrino oscillation. The experiment, sensitive to the oscillation parameter region indicated by the atmospheric neutrino anomaly, will be located at the Gran Sasso Laboratory, in the foreseen beam from the CERN SPS.

A. Ereditato, INFN-AE-97/06
2012



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



Korea
Jinju



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



Japan
Aichi edu.
Kobe
Nagoya
Toho
Utsunomiya



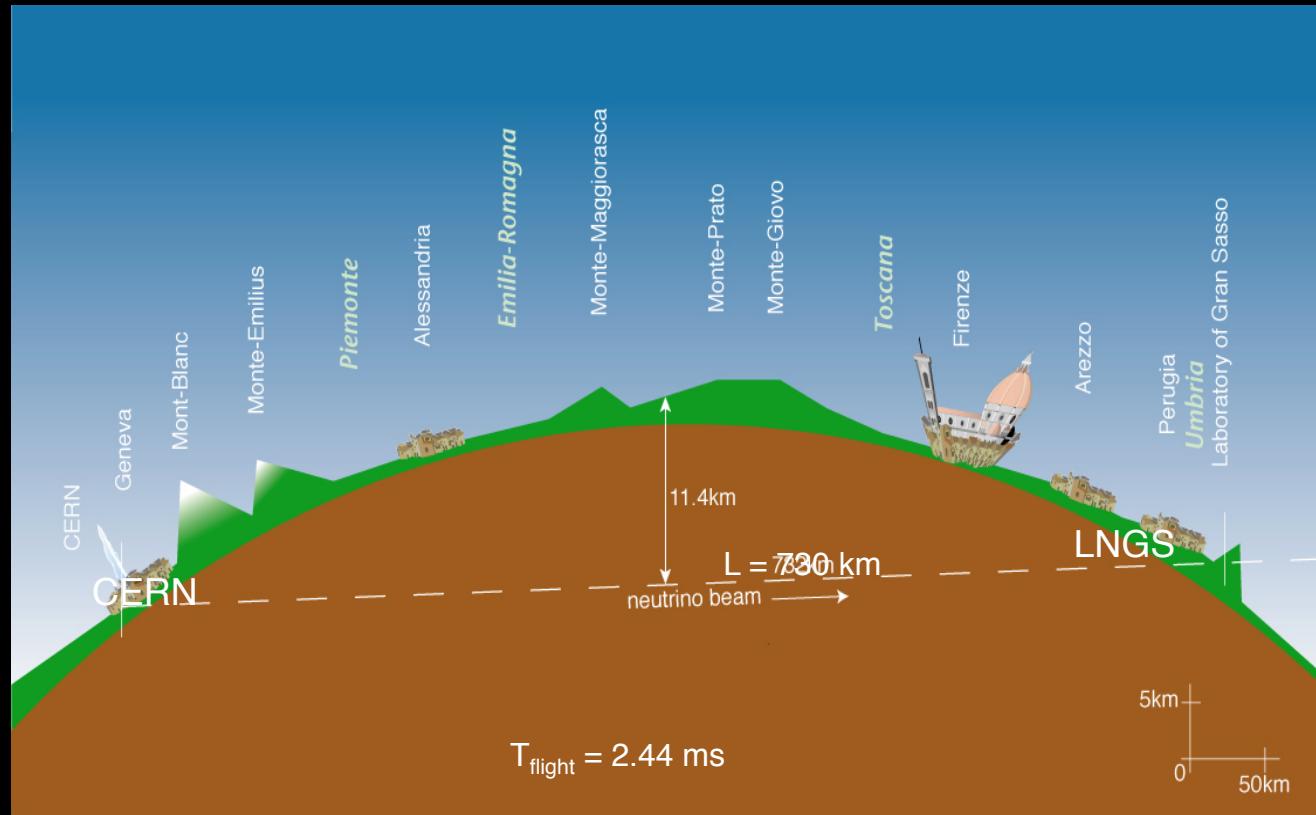
Switzerland
Bern
ETH Zurich



Turkey
METU Ankara



CNGS beam: tuned for ν_τ -appearance at LNGS (730 km away from CERN)



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

Expected neutrino interactions for 22.5×10^{19} pot:

- ~ 23600 ν_μ CC + NC
- ~ 160 $\nu_e + \bar{\nu}_e$ CC
- ~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$)

Neutrino velocity update

arXiv-1109.4897v4 - accepted by JHEP

The results of the study using CNGS muon neutrinos with an average energy of 17 GeV indicate a neutrino arrival time compatible within errors to the one computed by assuming the speed of light in vacuum:

$$\delta t = (6.5 \pm 7.4 \text{ (stat.)} {}^{+8.3}_{-8.0} \text{ (sys.)}) \text{ ns.}$$

The corresponding relative difference of the muon neutrino velocity and the speed of light is:

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

A dedicated CNGS beam was generated by an SPS proton beam set up for the purpose of the neutrino velocity measurement. The modified beam consisted of a single extraction including four bunches about 3 ns long (FWHM) separated by 524 ns. With an integrated beam intensity of 4×10^{16} protons on target a total of 20 TT and 16 RPC events were retained, leading to a value of δt measured from the average of the TT distribution of (-1.9 ± 3.7) ns and (-0.8 ± 3.5) ns from the RPC, in agreement with the value of (6.5 ± 7.4) ns obtained with the main analysis.

Status of the CNGS data taking (oscillation analysis)

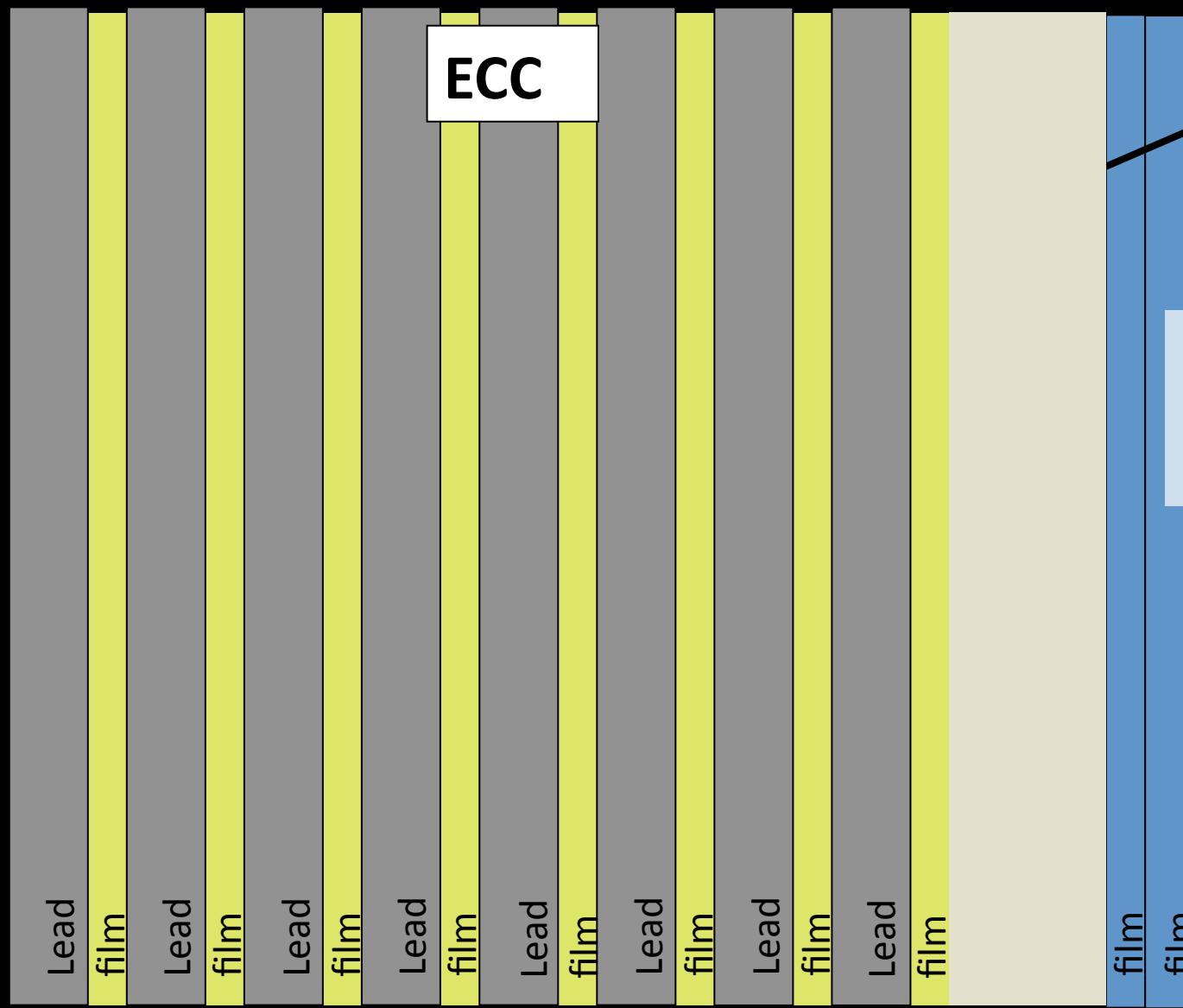
Year	Protons on target (pot)	Number of neutrino Interactions	Integrated pot /proposal value
2008	1.78×10^{19}	1698	7.9%
2009	3.52×10^{19}	3557	23.6%
2010	4.04×10^{19}	3912	41.5%
2011	4.84×10^{19}	4210	63.0%
2012	$(\sim 4.7 \times 10^{19})$	(~ 4050)	$(\sim 84\%)$

14.2×10^{19} pot up to 2011

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

Event Location in the ECC

Changeable Sheet

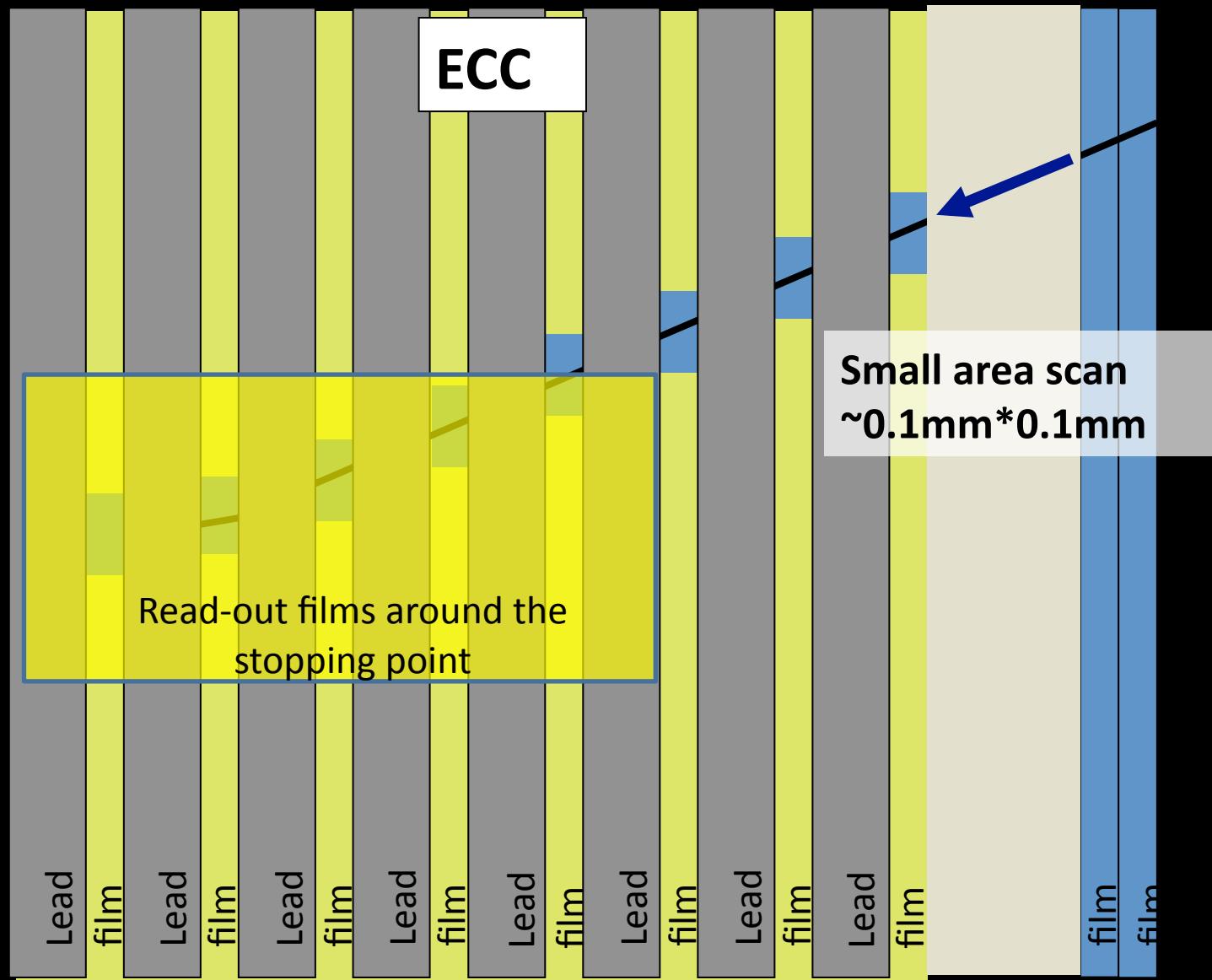


Large Area Scanning

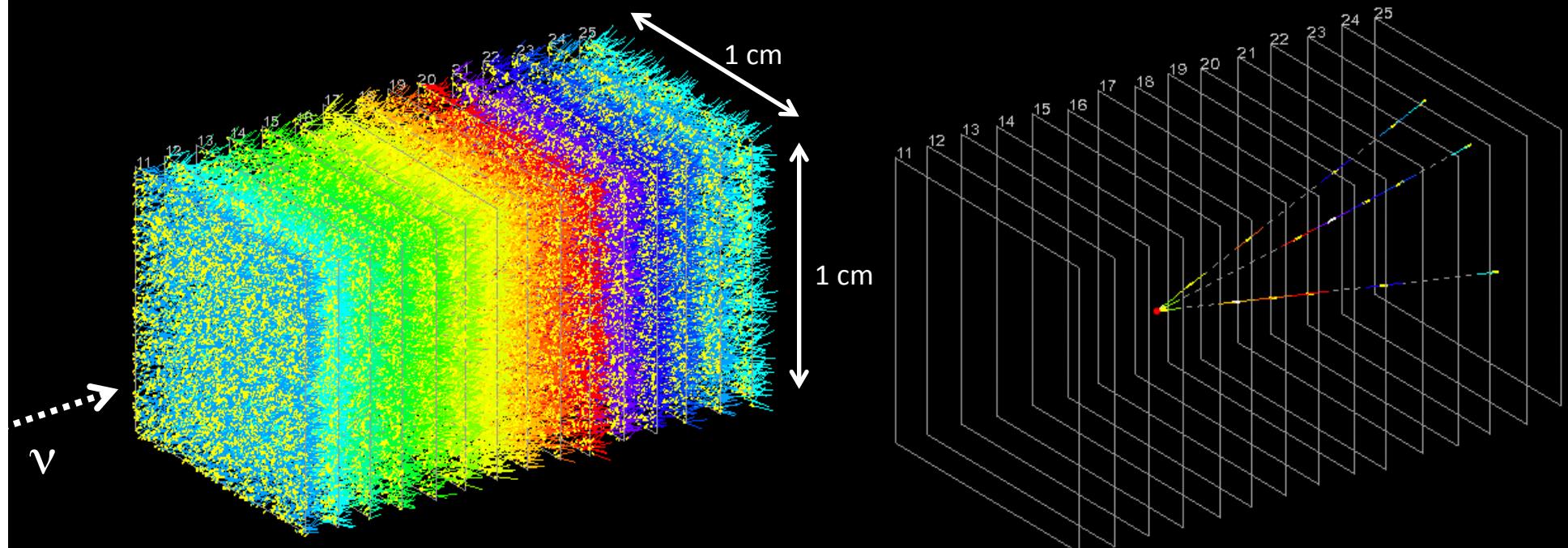
~5cm x 5cm

Event Location in the ECC

Changeable Sheet



Interaction vertex confirmation & decay search

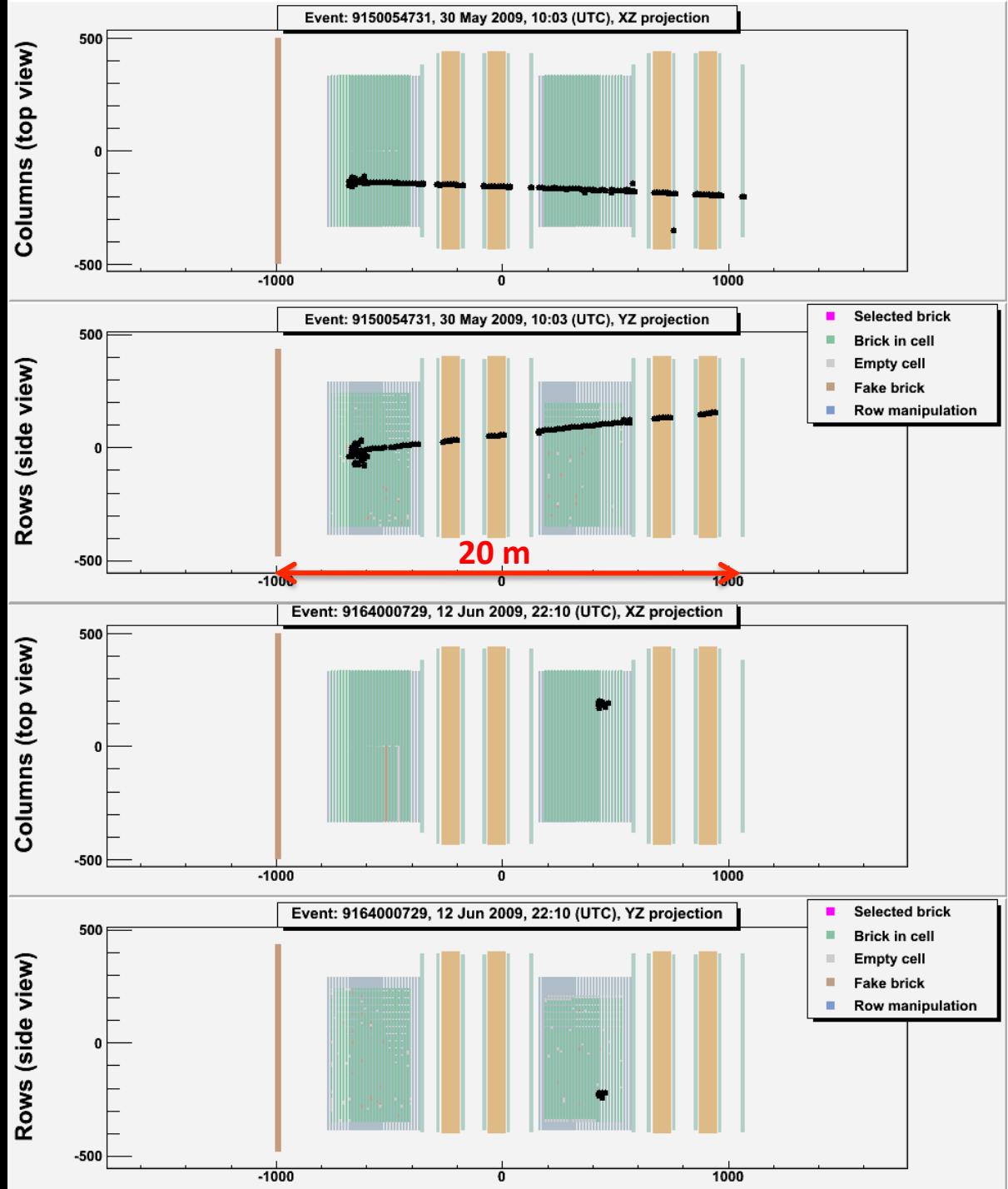


Cloud of low energy tracks

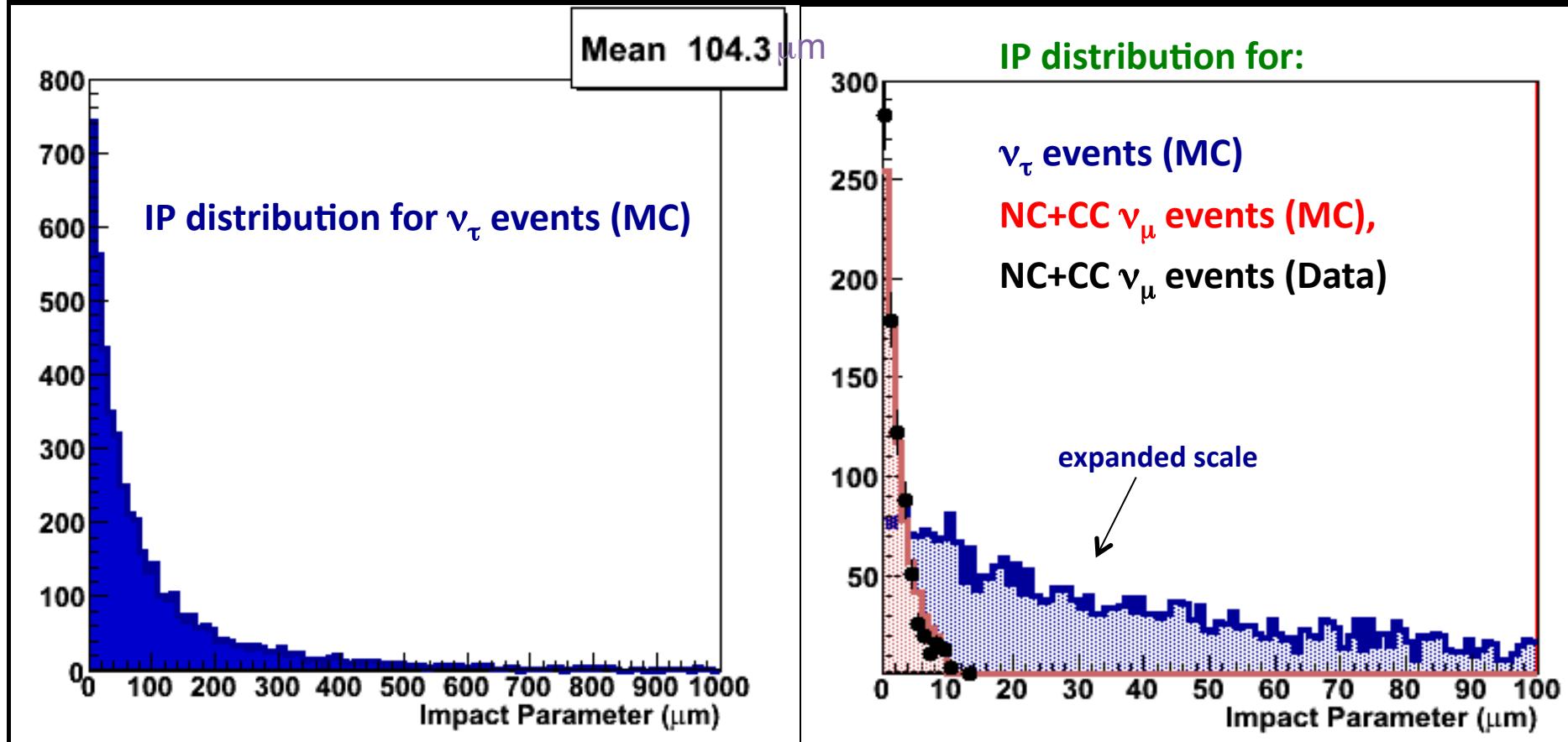
After the selection of high energy tracks
connecting across the lead

Typical ν_μ CC- and NC-like events

The measured ratio of NC-like/CC-like events after muon ID and event location is $\sim 20\%$, as expected from simulations

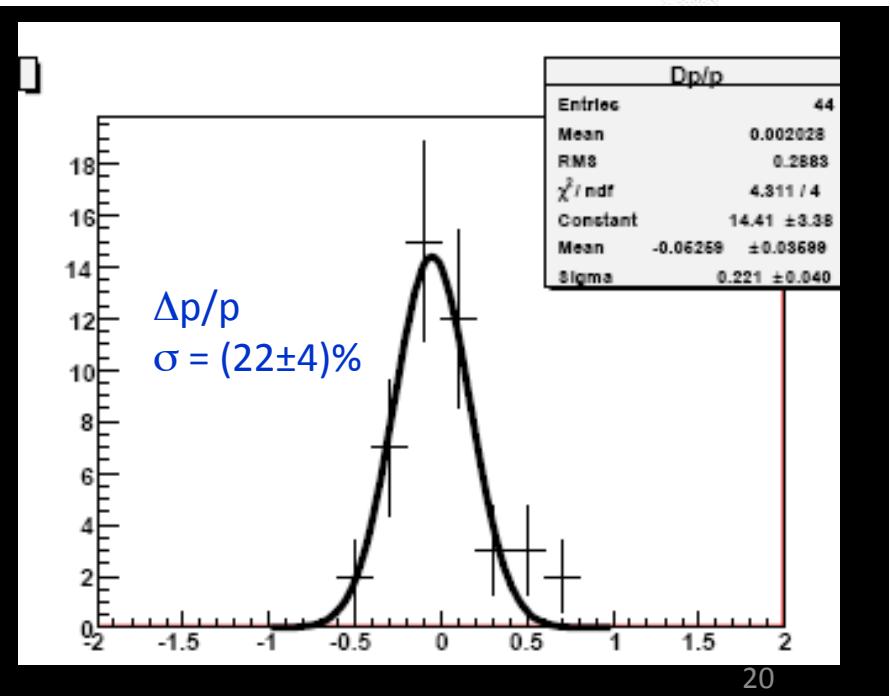
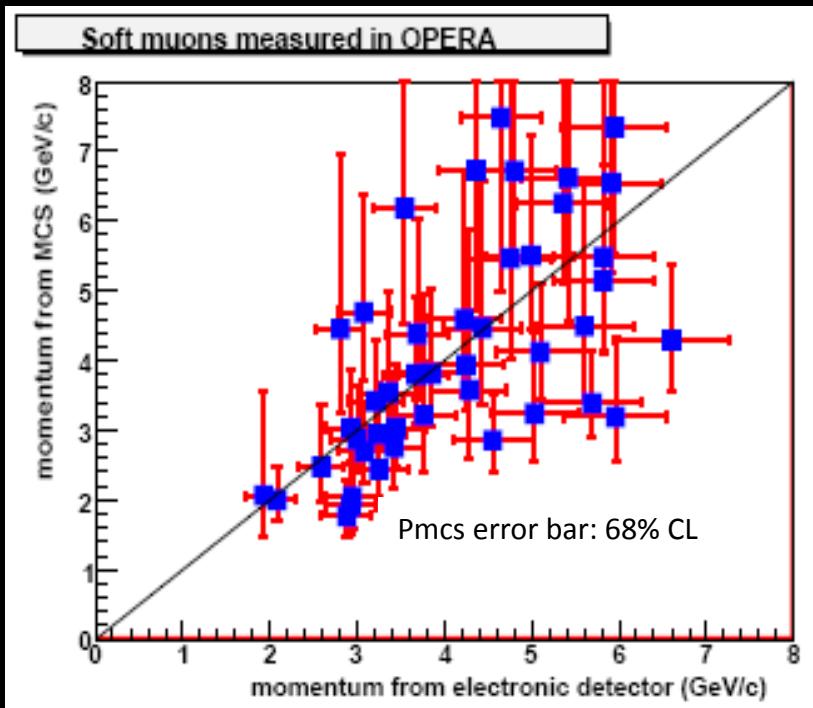
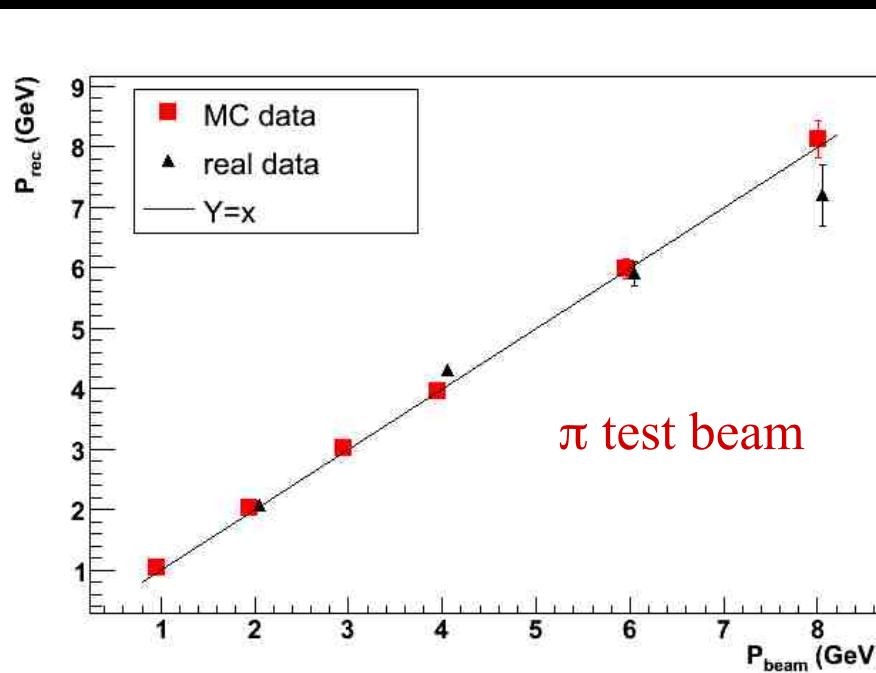


Impact parameter measurement



Momentum measurement by Multiple Coulomb Scattering...

...in the lead/emulsion film sandwich and
comparison with electronic detector
measurements



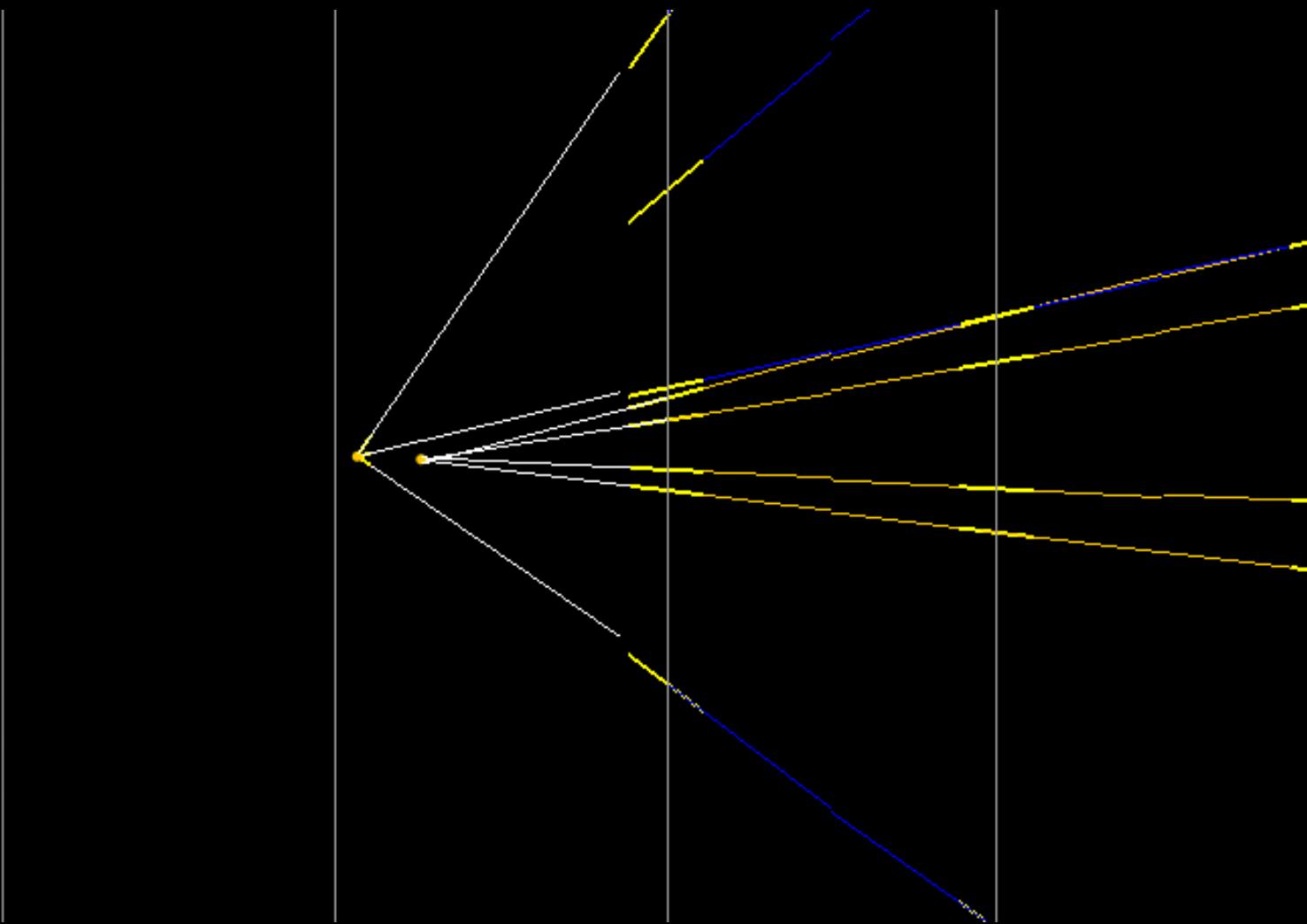
CHARM EVENTS: a test sample and a physics BG

Charm candidate event (dimuon)



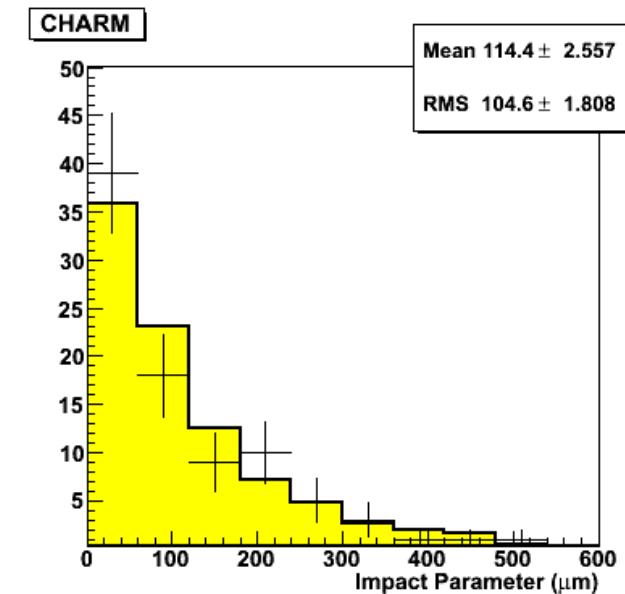
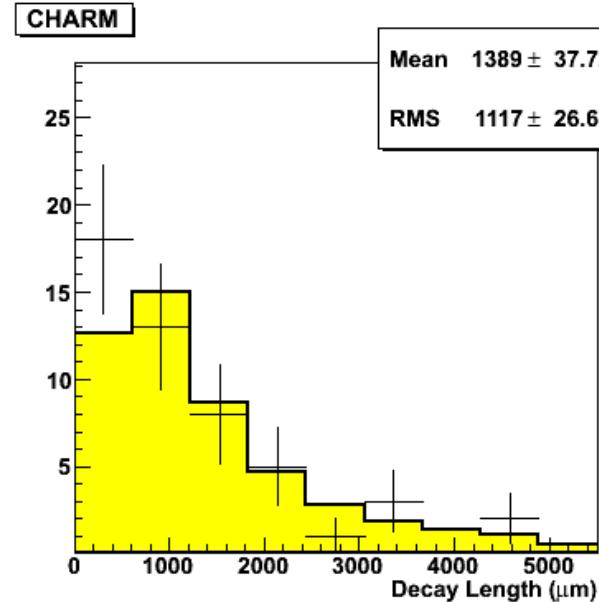
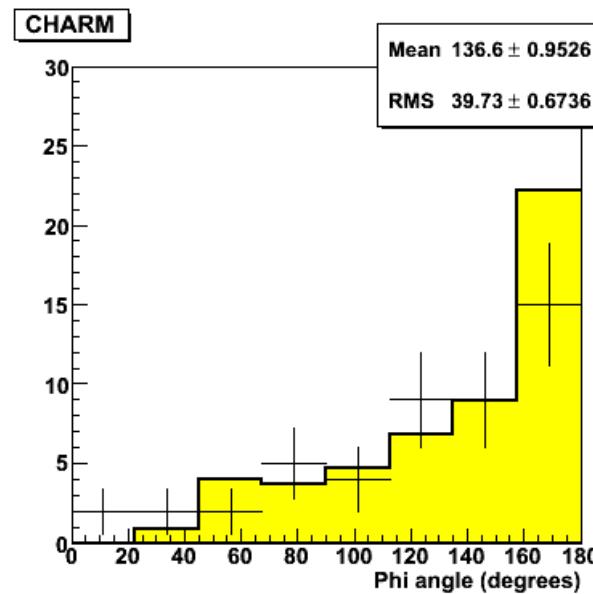
flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay Pt: 0.46 GeV/c

Charm candidate event (4-prong)



D_0 hypothesis: F.L.: 313.1 μm , $\phi : 173.2^\circ$, invariant mass: 1.7 GeV

CHARM events: detected 49, expected 51 ± 7.5



Phi angle

Decay length

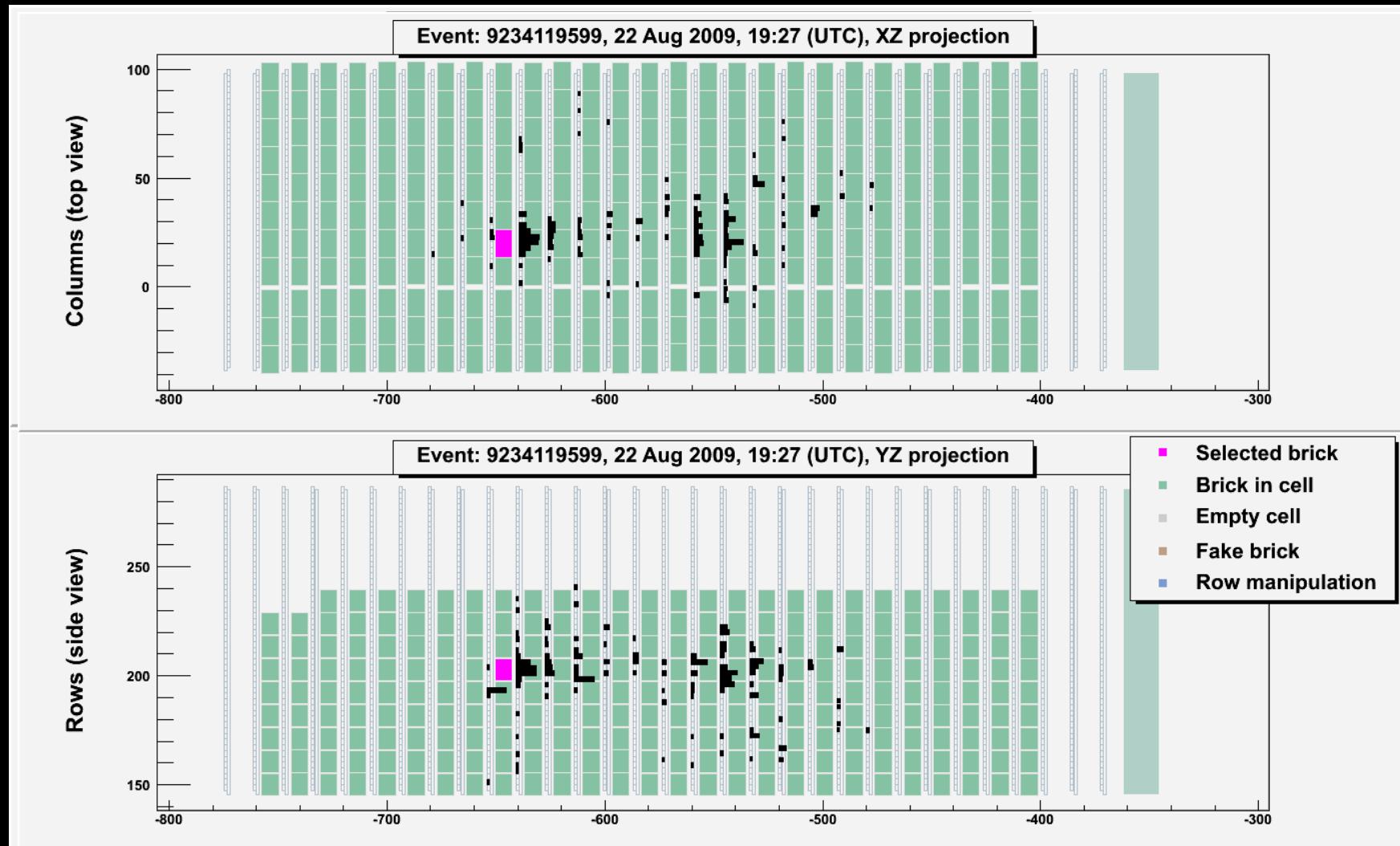
Impact Parameter

ν_τ CANDIDATE EVENTS

Present statistics (NEUTRINO12 conference)

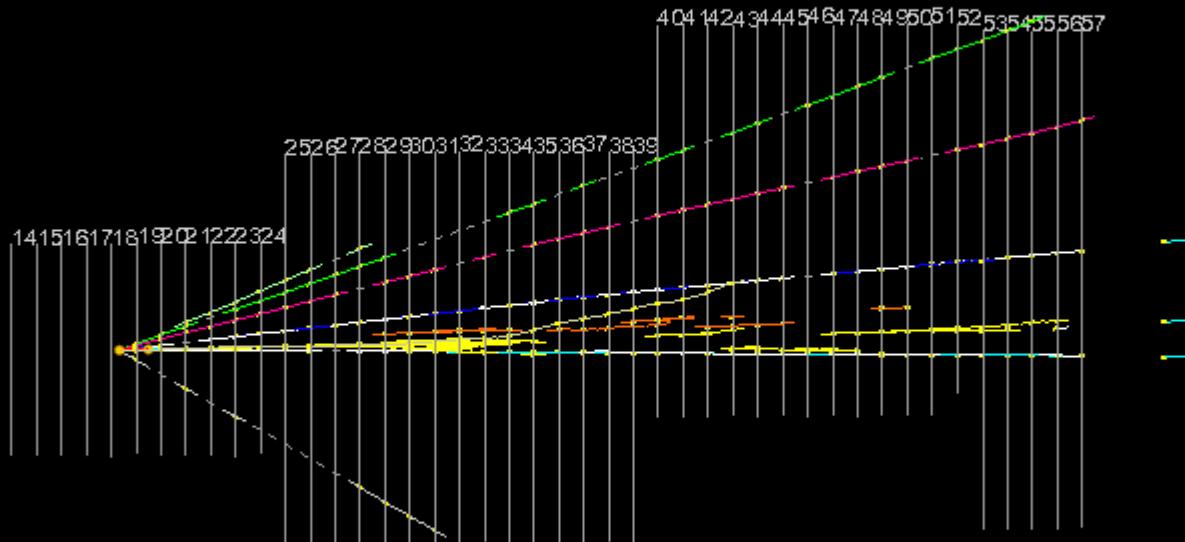
Years	Status of analysis	# of events for decay search	Expected ν_τ events (Preliminary)	Observed ν_τ candidate events	Expected BG for ν_τ (Preliminary)
2008-2009	completed	2783		1	
2010-2011	in progress	1343		1	
2012	started				
Total		4126	2.1	2	0.2

Electronic detectors' display: first ν_τ candidate event

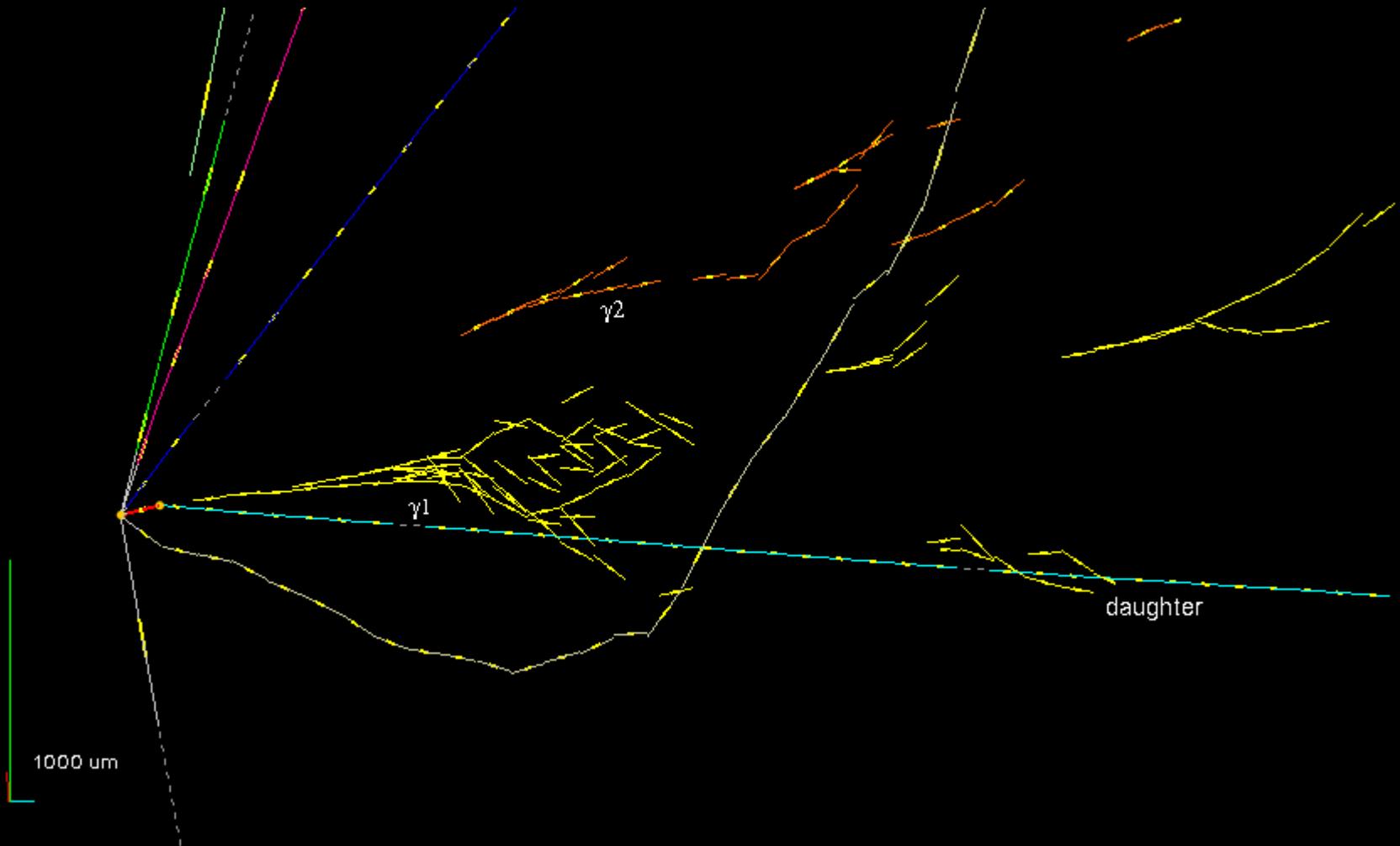


From CS to vertex location

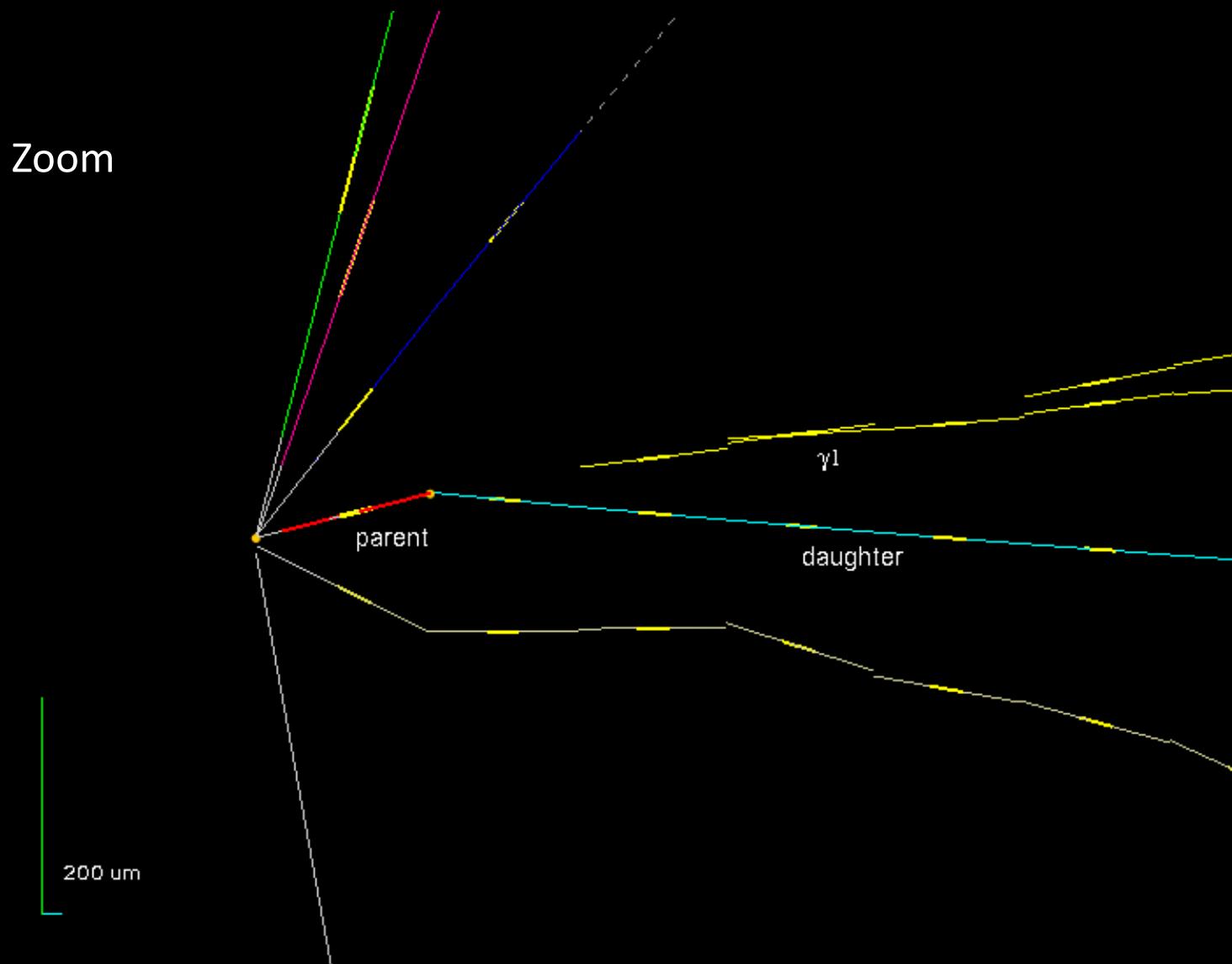
Large area scanning
Full reconstruction of vertices and gammas



Event reconstruction (1)



Event reconstruction (2)



Event nature and invariant mass reconstruction

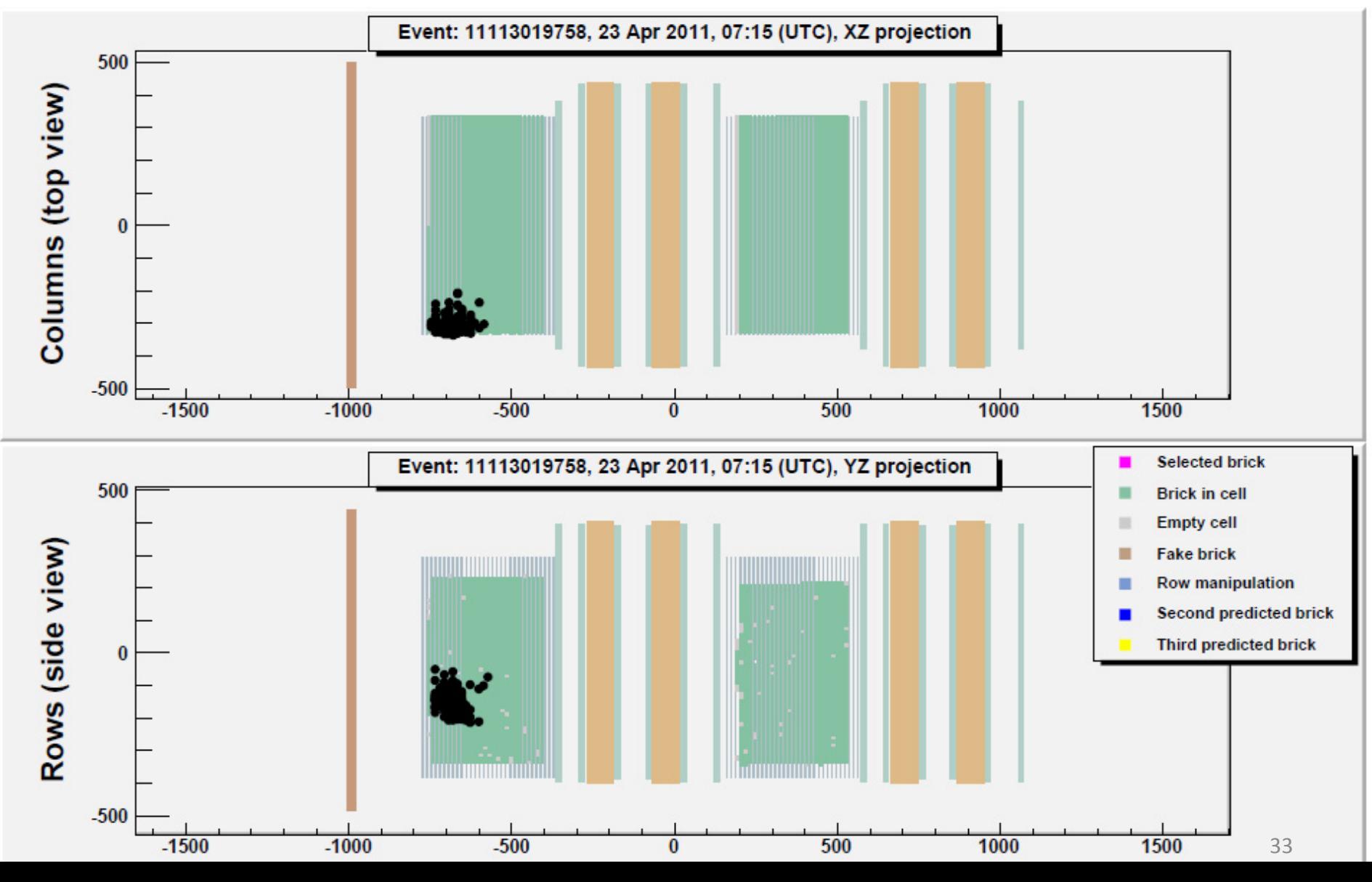
- The event passes all cuts, with the presence of at least 1 gamma pointing to the secondary vertex, and is therefore a candidate to the $\tau \rightarrow 1\text{-prong}$ hadron decay mode.
- The invariant mass of the two detected gammas is consistent with the π^0 mass value (see table below).
- The invariant mass of the $\pi^- \gamma \gamma$ system has a value (see below) compatible with that of the ρ (770). The ρ appears in about 25% of the τ decays: $\tau \rightarrow \rho (\pi^- \pi^0) \nu_\tau$.

π^0 mass	ρ mass
$120 \pm 20 \pm 35$ MeV	$640^{+125}_{-80} {}^{+100}_{-90}$ MeV

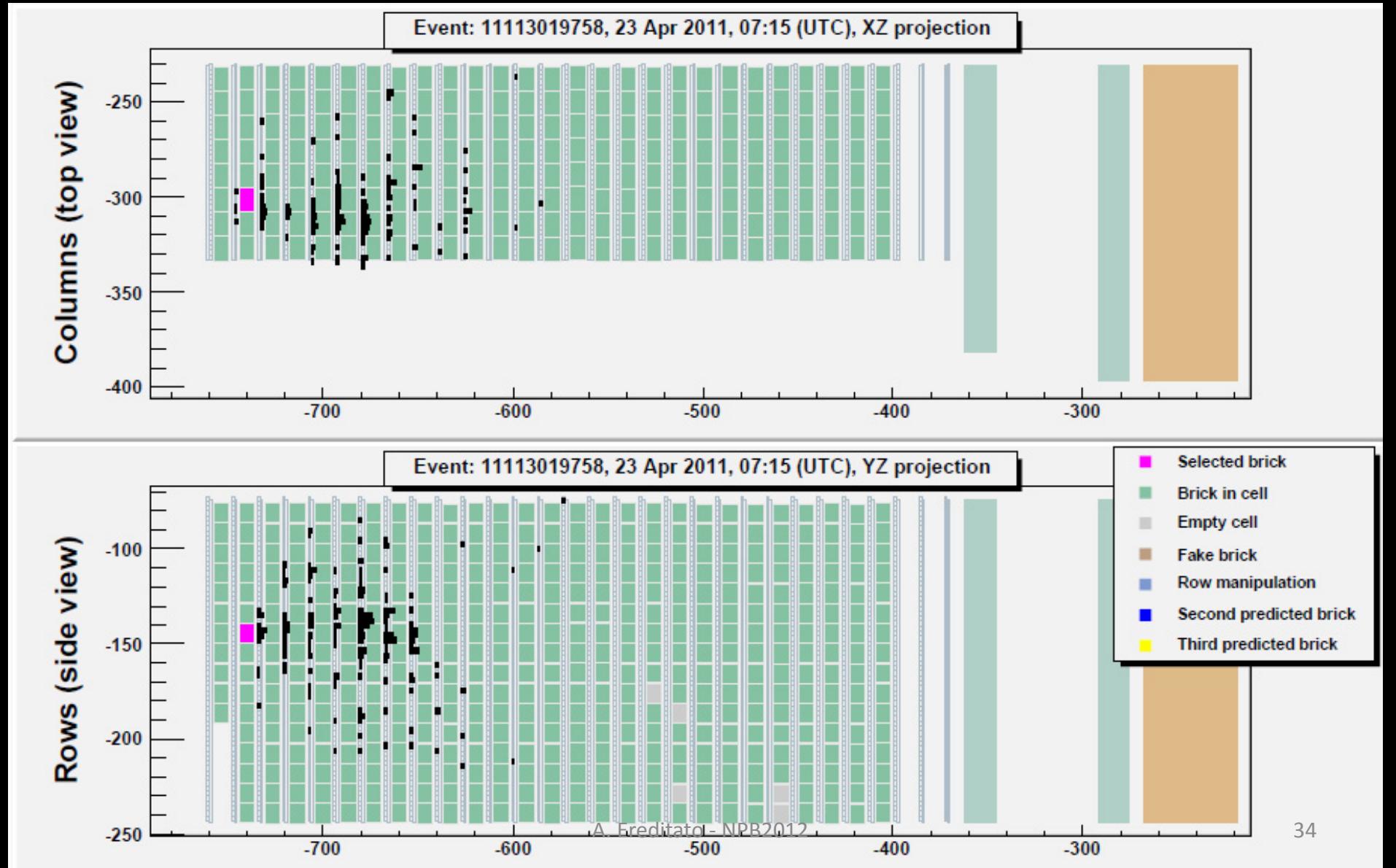
BACKGROUND SOURCES

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

Electronic detectors' display: second ν_τ candidate event



Electronic detectors' display: second candidate event (zoom)



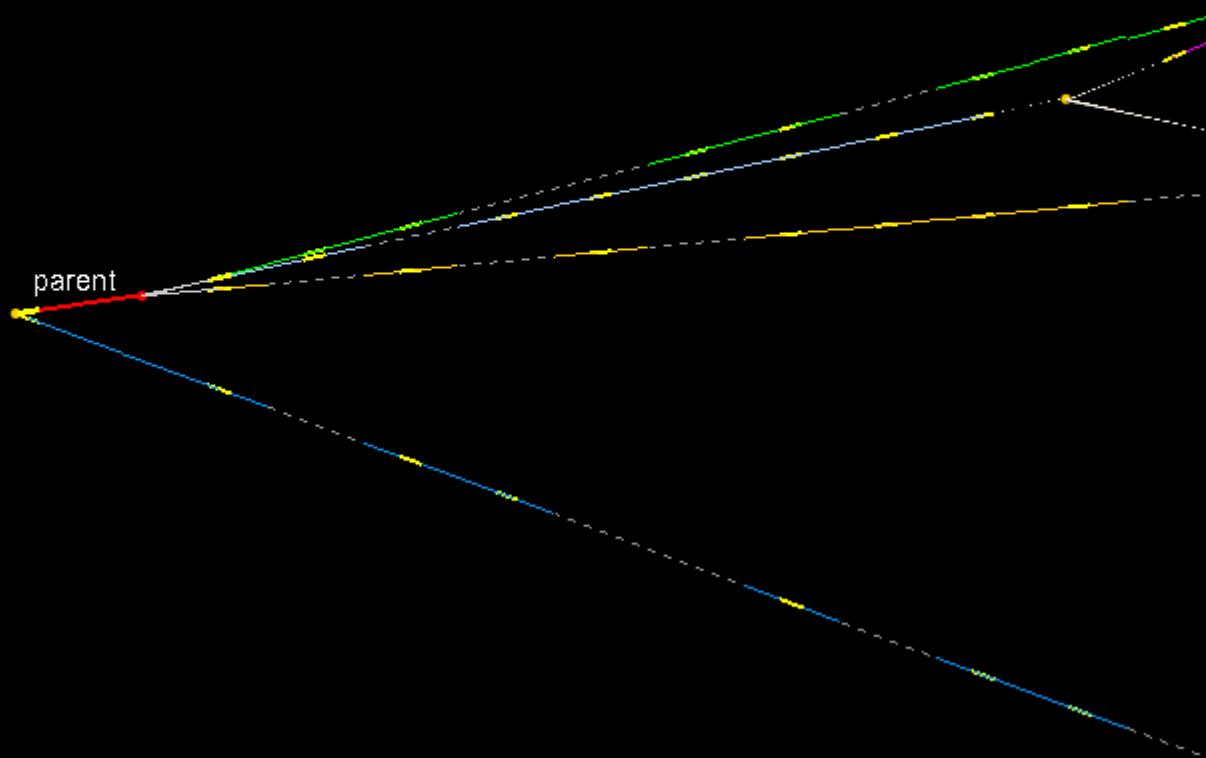
Previously defined brick information: Super module 1

BrickId Wall Side Column Row Prob CS_x CS_y

Muon track parameters:

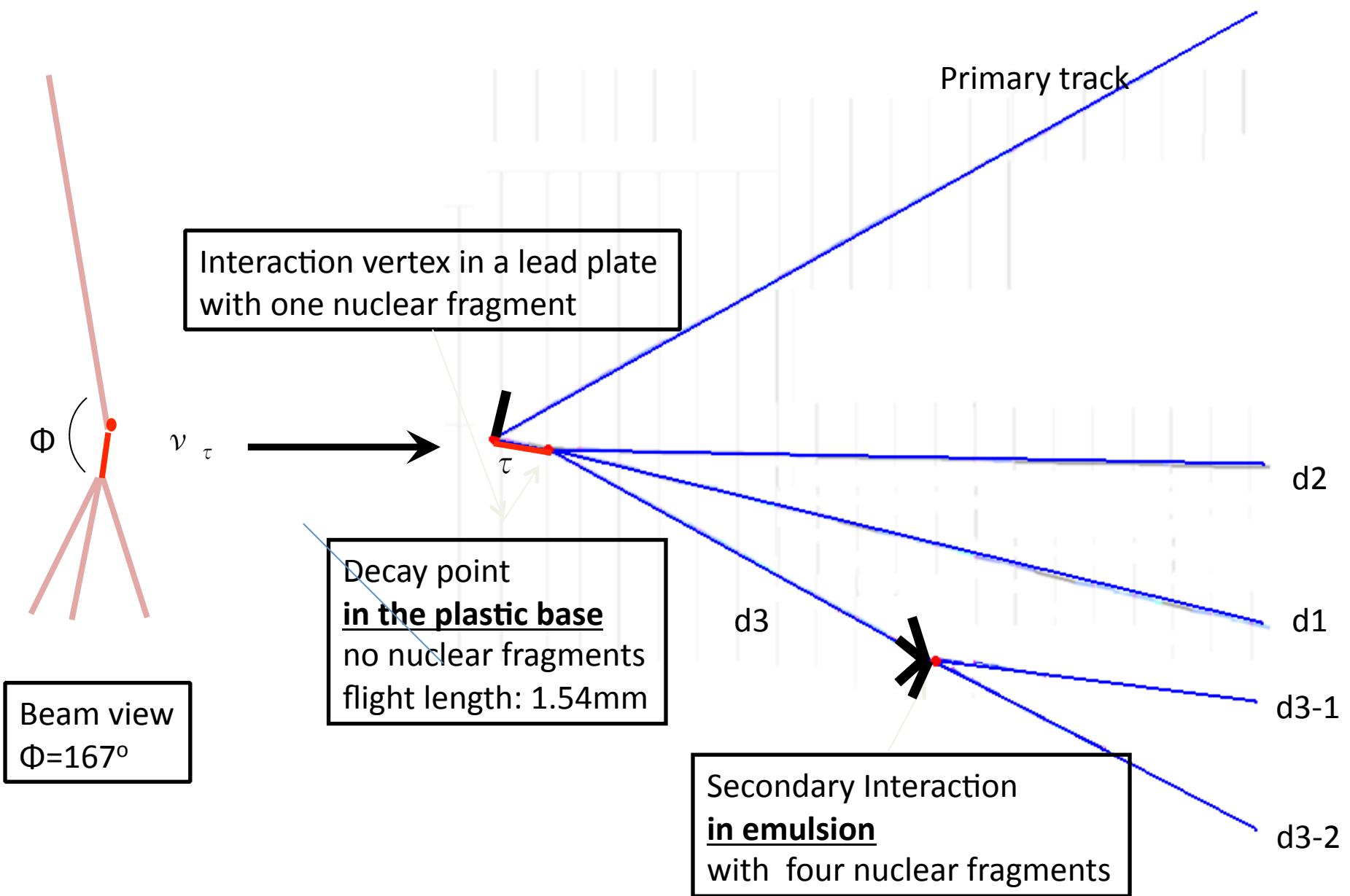
Momentum: N/A

Event reconstruction



$2000 \mu\text{m}$

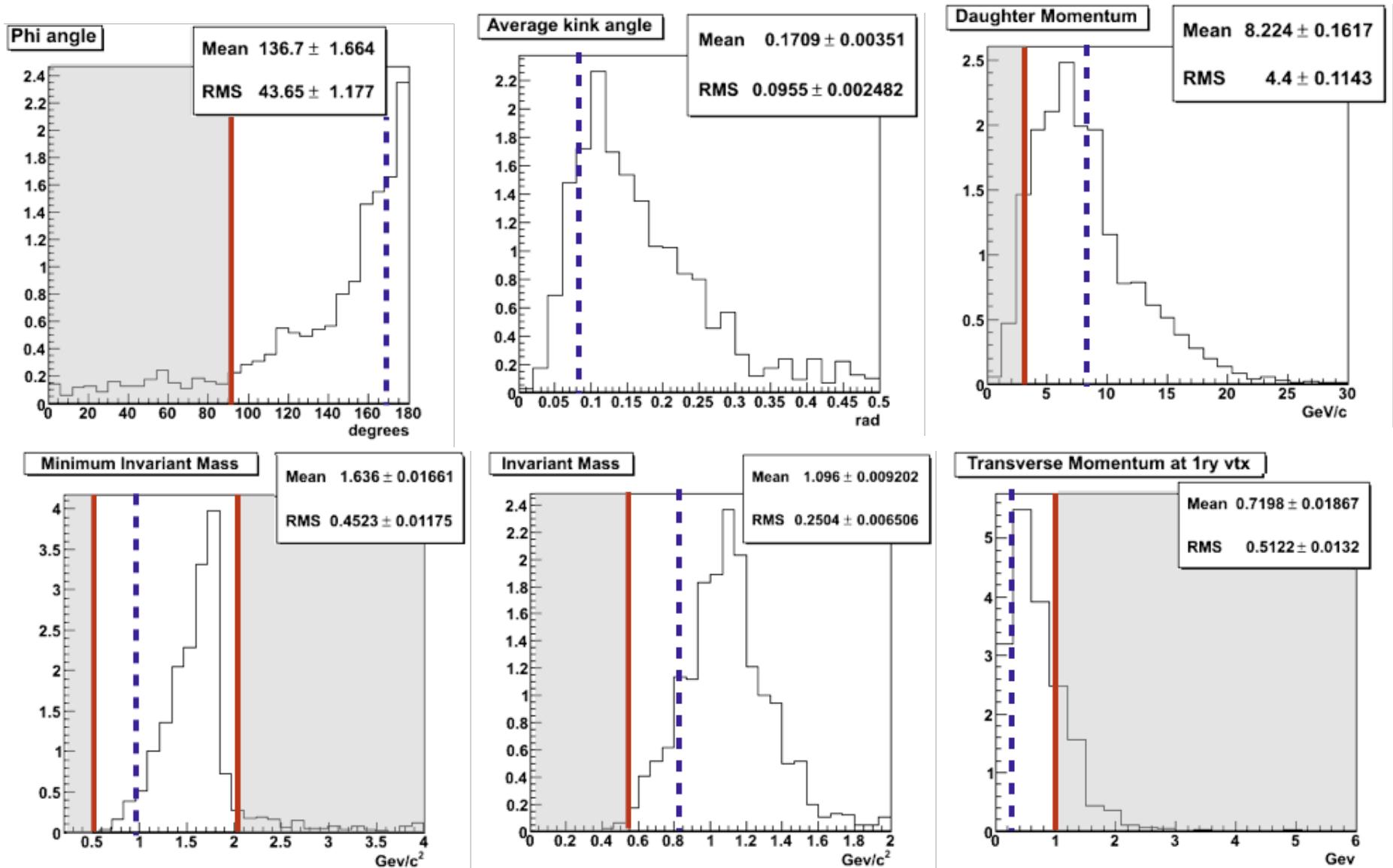
Event topology



Event tracks' features

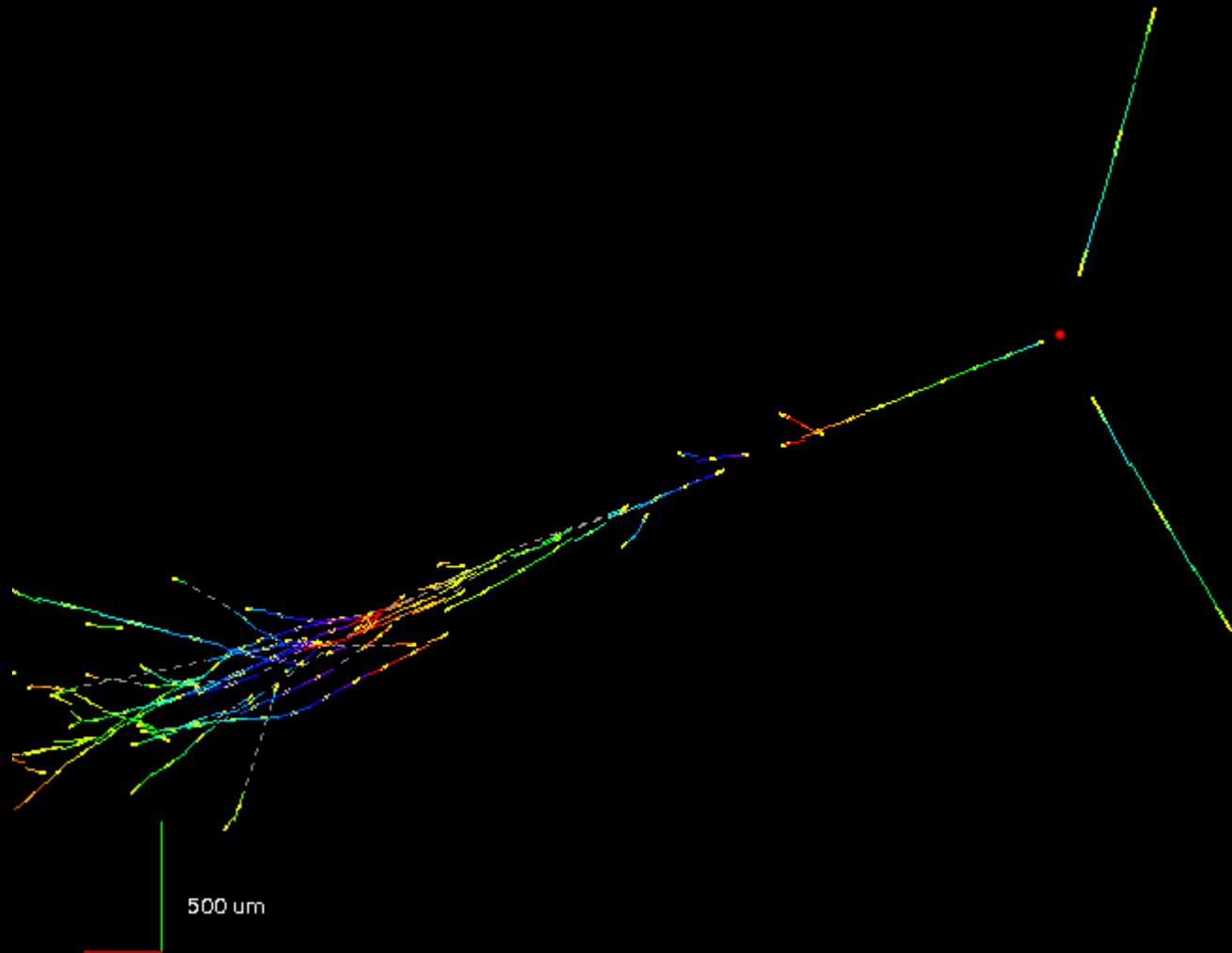
Track	Momentum (1σ interval) [GeV/c]	Particle ID	Method / comments
Primary	2.8 (2.1-3.5)	Hadron	Momentum-range consistency Stops after 2 brick walls Incompatible with a muon (26~44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	Momentum-range consistency
d2	1.3 (1.1 -1.5)	Hadron	Momentum-range consistency
d3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

Kinematical cuts to be passed

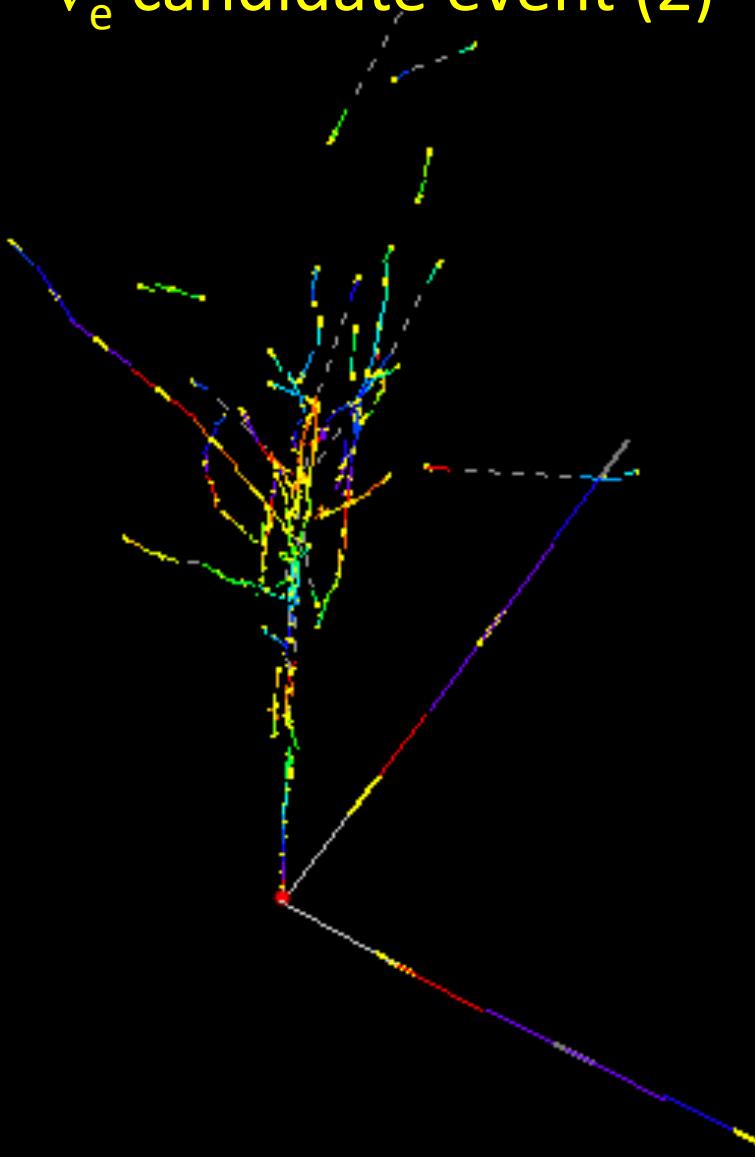


*AN INTERESTING BY-PRODUCT: SEARCH FOR
 ν_e APPEARANCE*

ν_e candidate event (1)



ν_e candidate event (2)



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

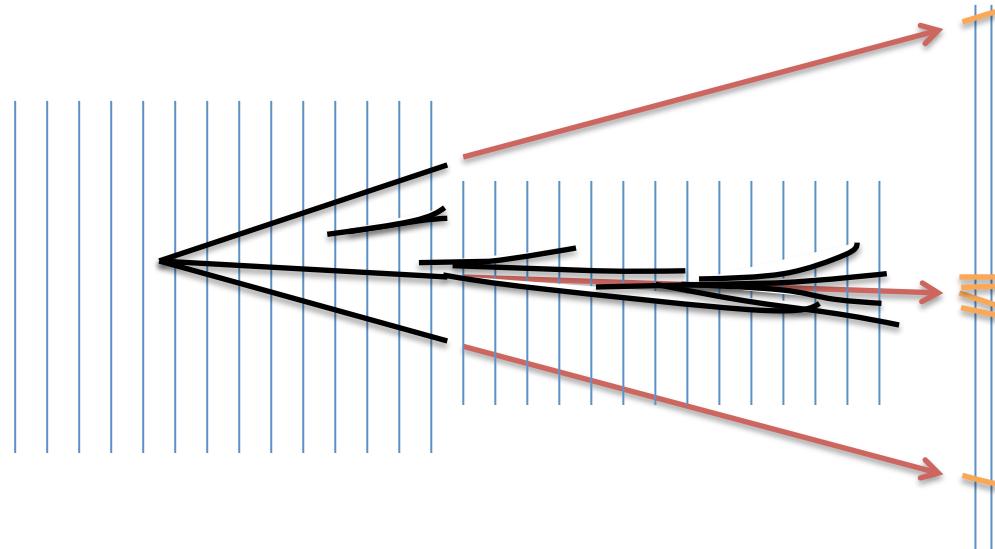
Event sample: 505 NC-like events in 2008 and 2009

For each located event

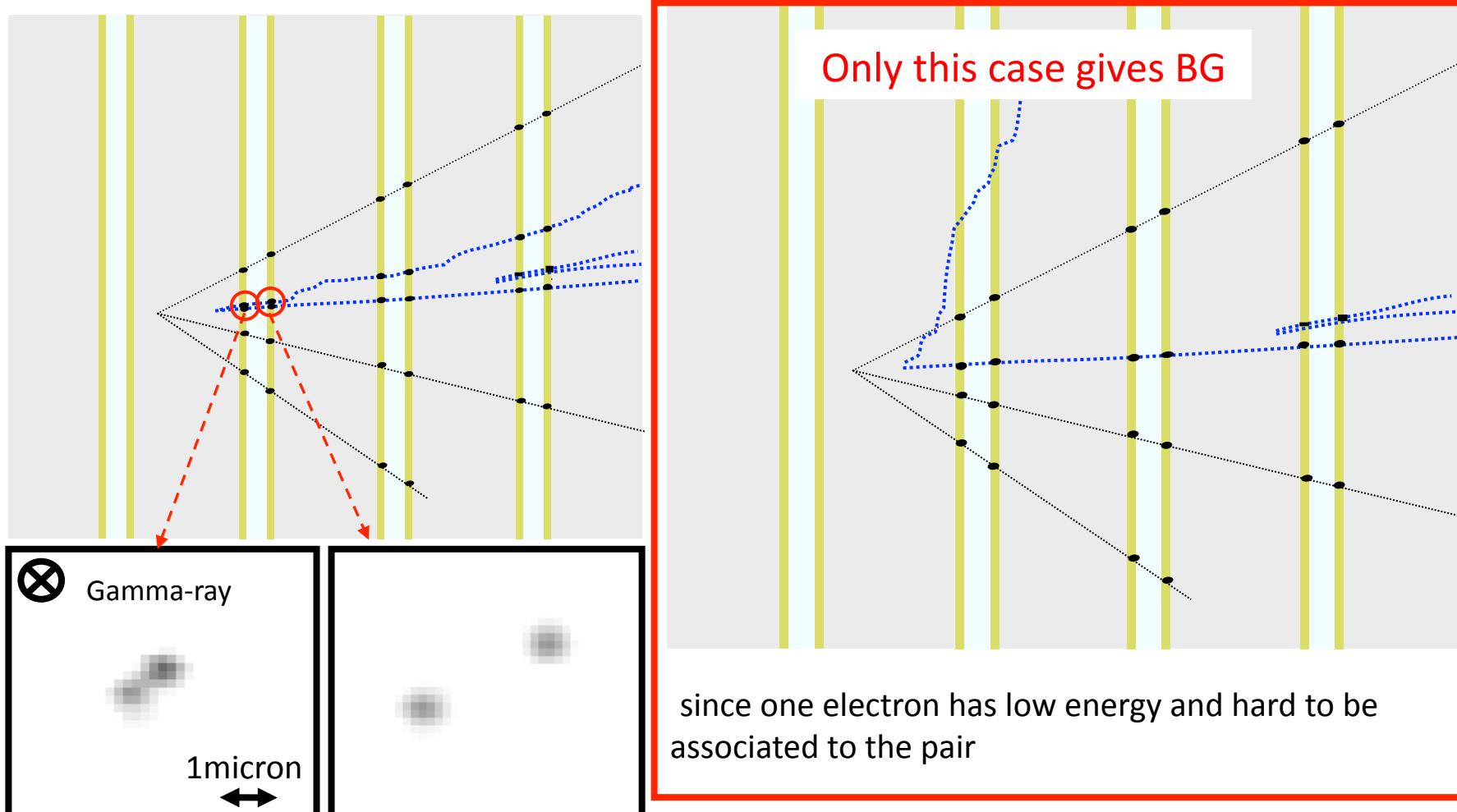
- Extrapolate 1ry tracks to CS.
- Search shower on CS
- If shower-like tracks are found on CS, open additional volume.

As a result

- 96 events are selected
- Total 19 ν_e confirmed

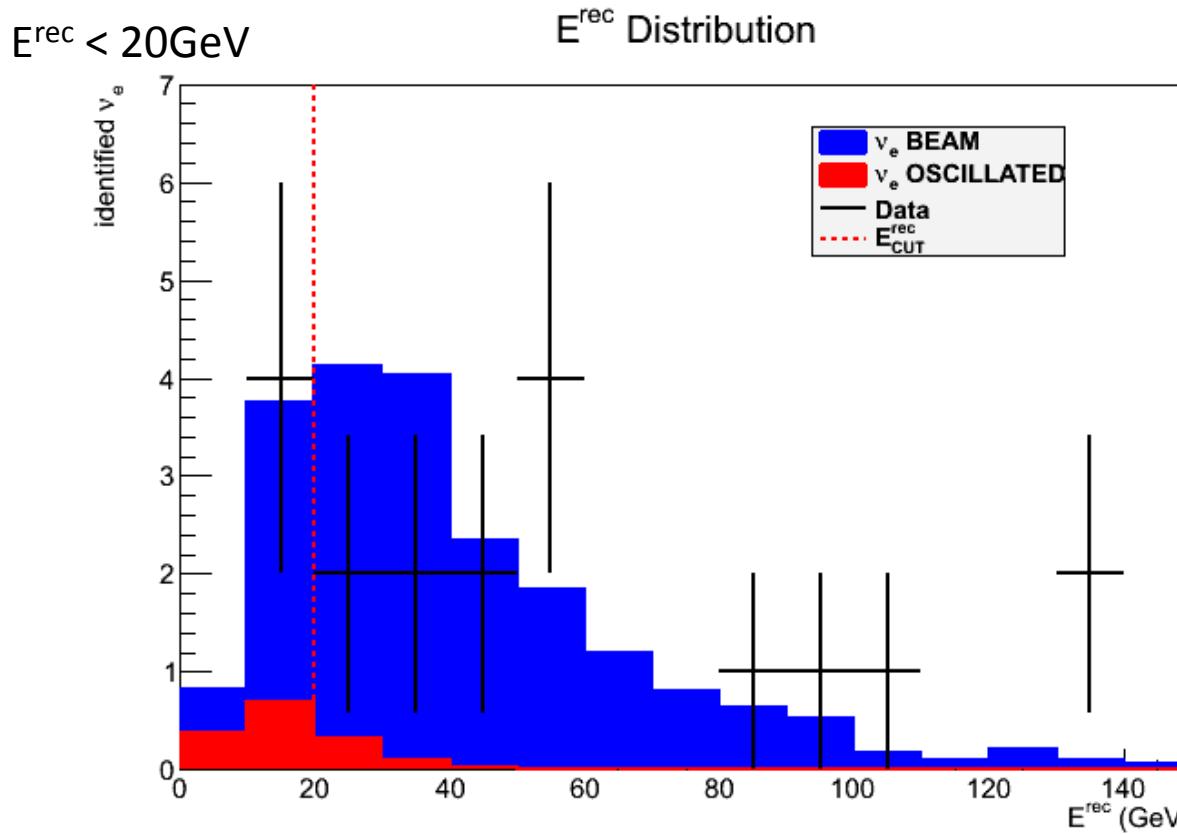


Background from $\nu_\mu NC$ ($\pi^0 \rightarrow 2\gamma$)



BG for 2008+2009 statistics : **0.16** events

Event energy distribution



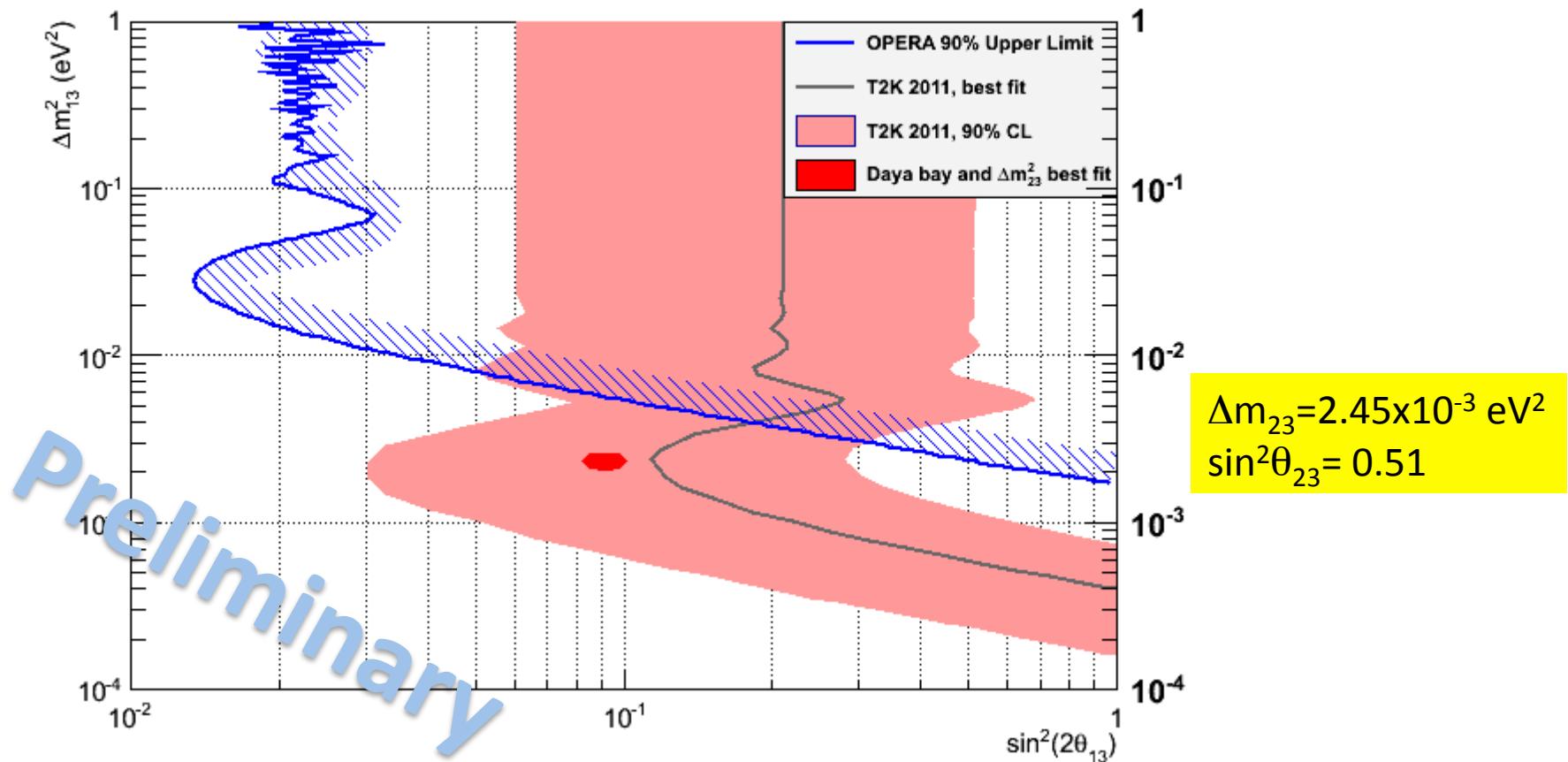
expected events:
oscillated ν_e 1.5
beam ν_e BG 19.2
observed ν_e : 19

After low-energy event selection ($E\nu < 20\text{GeV}$):

Observed events: 4

Expected events: oscillated 1.1, beam BG 3.7

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



Future improvements:

- 1) Statistics increased by x3
- 2) better efficiency



Thank you for the attention!