Status and results from the OPERA experiment

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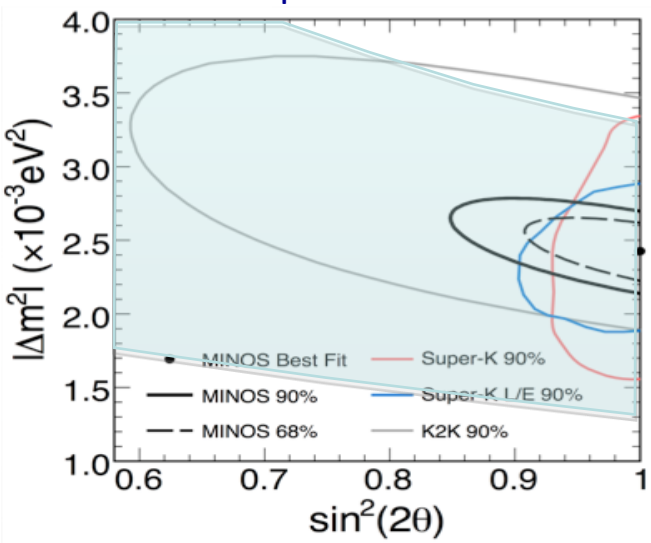
OPERA

- Aiming the first direct detection of neutrino oscillations in appearance mode.

Oscillation parameters in the atmospheric neutrino sector

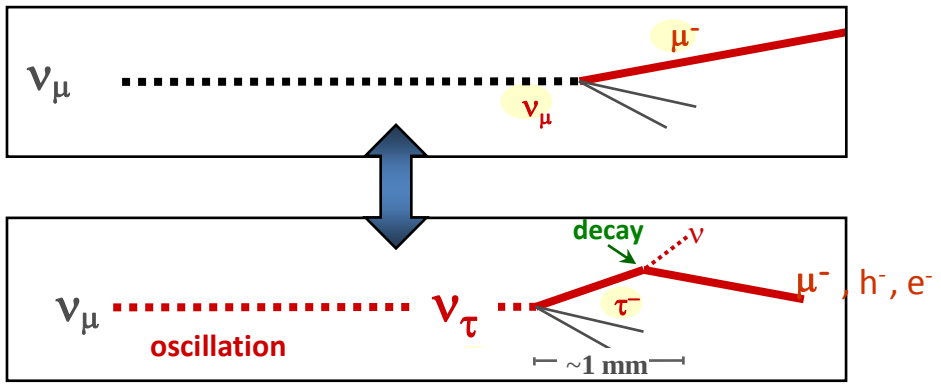


Full mixing and $\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2

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

  - Beam line: CNGS long base-line ν_μ beam

- Direct observation of ν_τ events in nuclear emulsion detectors.
  - Sub-micron resolution
  - 1.25 kton of target mass



CNGS beam

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

* Interaction rate at LNGS

Expected interactions for 22.5×10^{19} pot (nominal pot in 5 years):

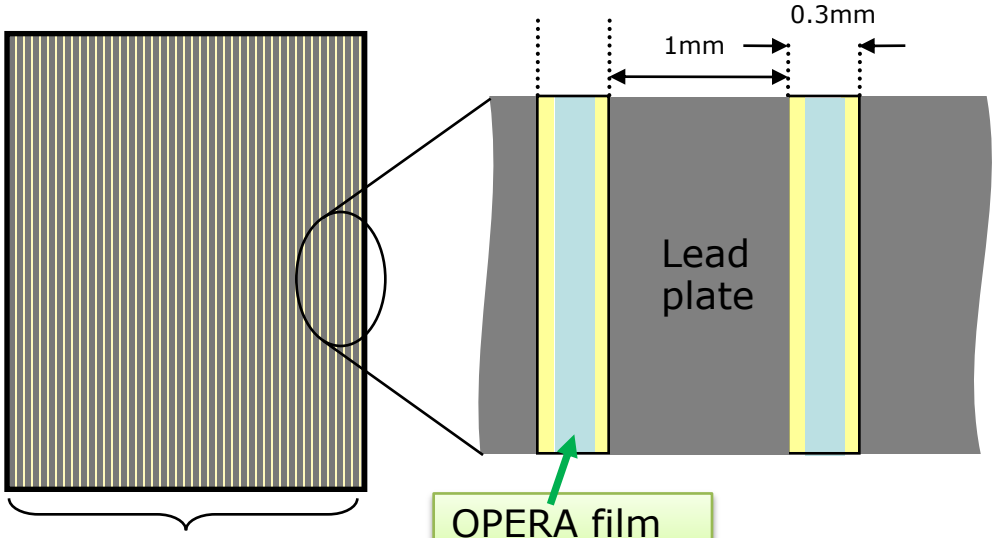
~23600 ν_μ CC + NC

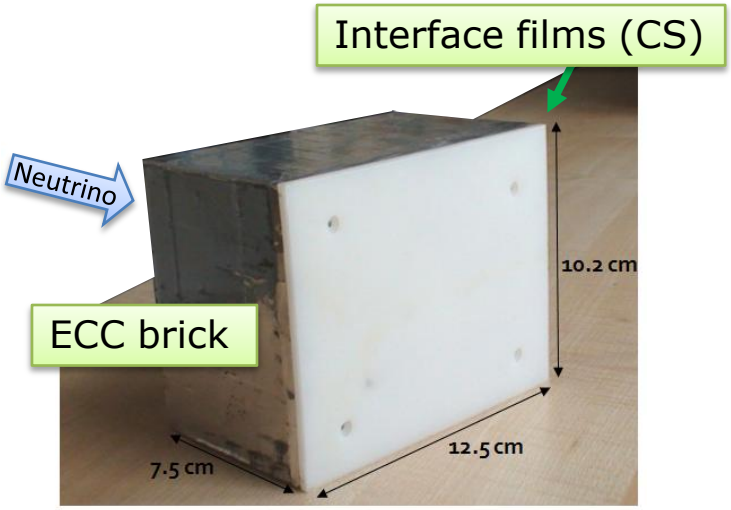
~160 $\nu_e + \overline{\nu}_e$ CC

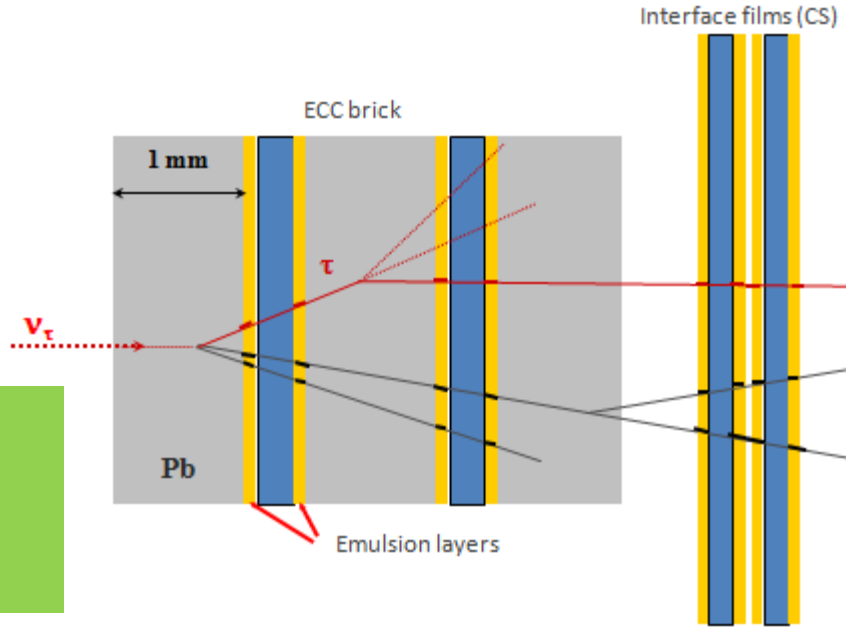
~115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

~10 tau decays are expected to be observed (BG<1)

ECC brick



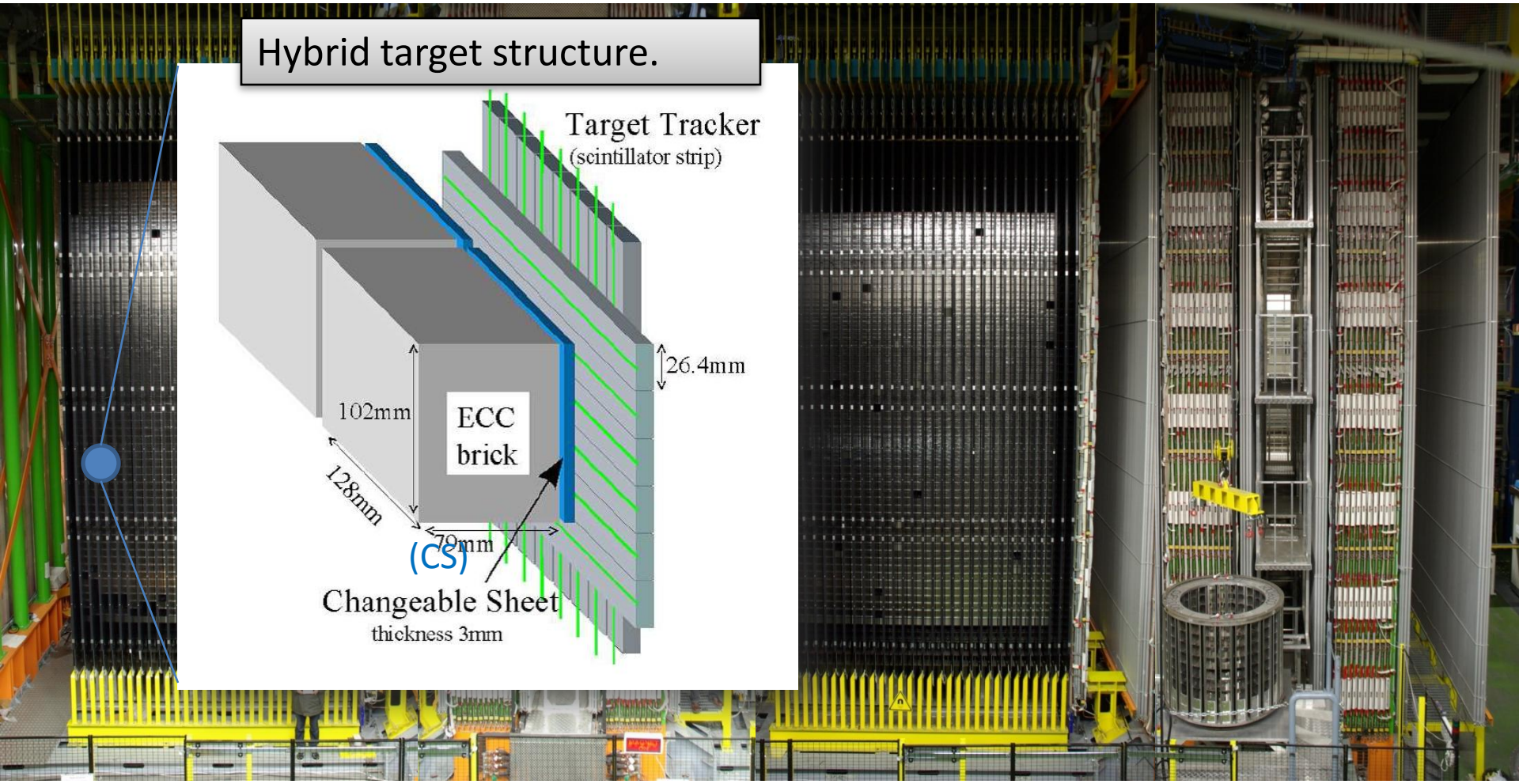




The OPERA target consists of about 150,000 bricks.

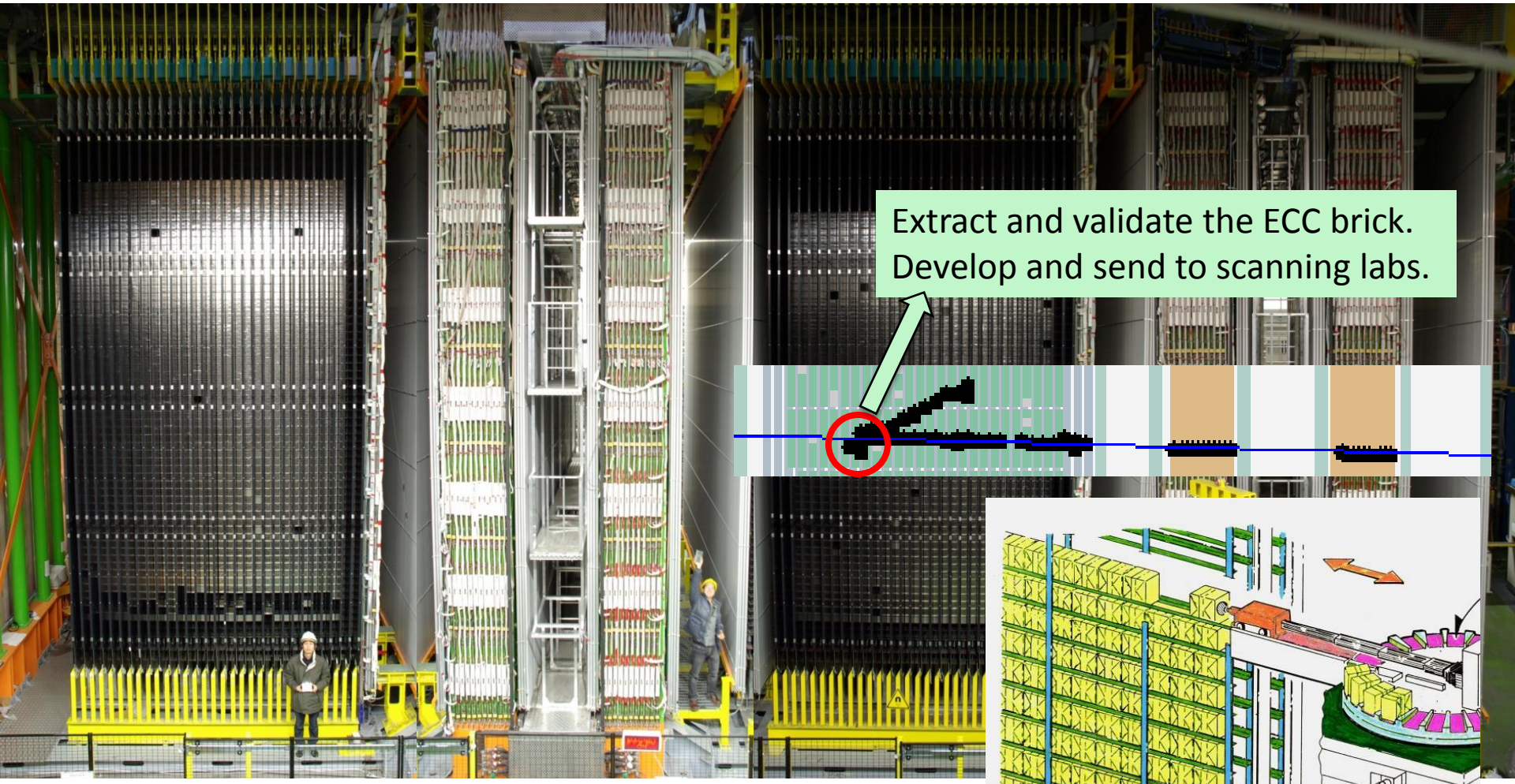
Total target mass: 1.25 kton

OPERA detector



Target area **Muon spectrometer**

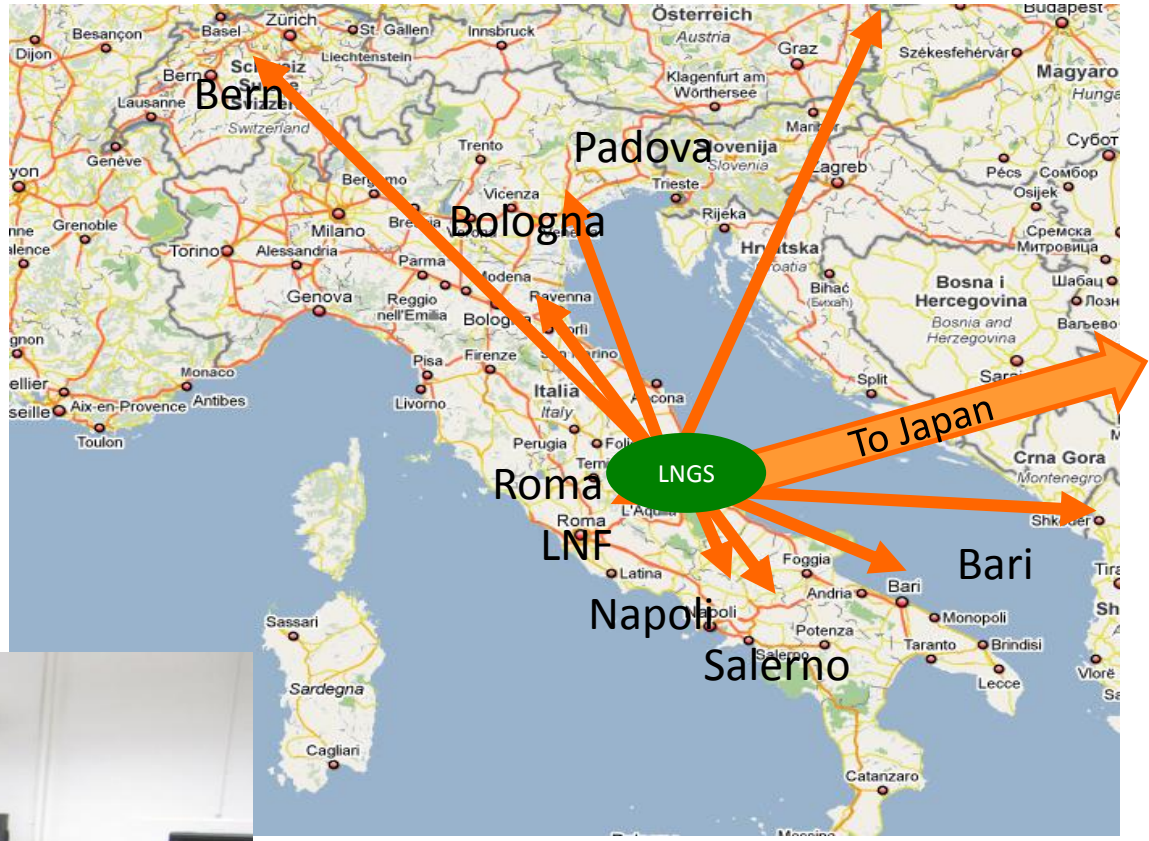
OPERA detector



Target area **Muon spectrometer**

ECC brick scanning

Parallel analysis in ~10 labs.
Number of labs is increasing.

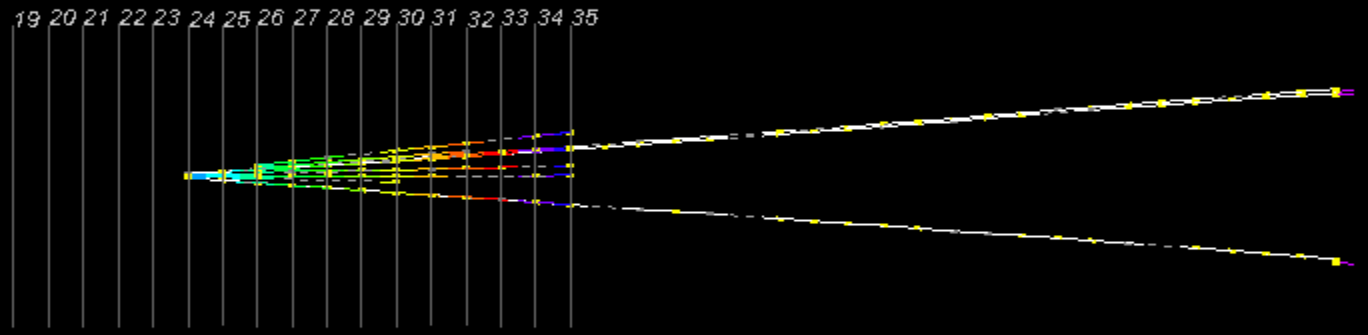


One of the brick scanning labs

For example, Swiss scanning station in Bern
• 5 microscopes with automatic plate changers.

Event analysis in ECC brick

Event reconstruction



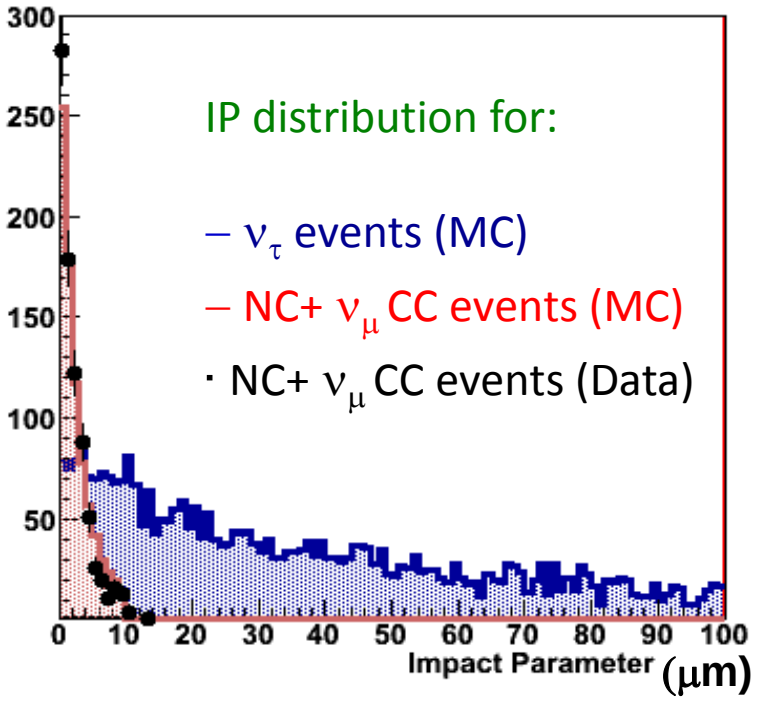
5 mm

Emulsion gives 3D vector data, with a few micron precision of the vertex accuracy.

The frames correspond to scanning area. Yellow short lines are measured tracks. Other colored lines are interpolation or extrapolation.

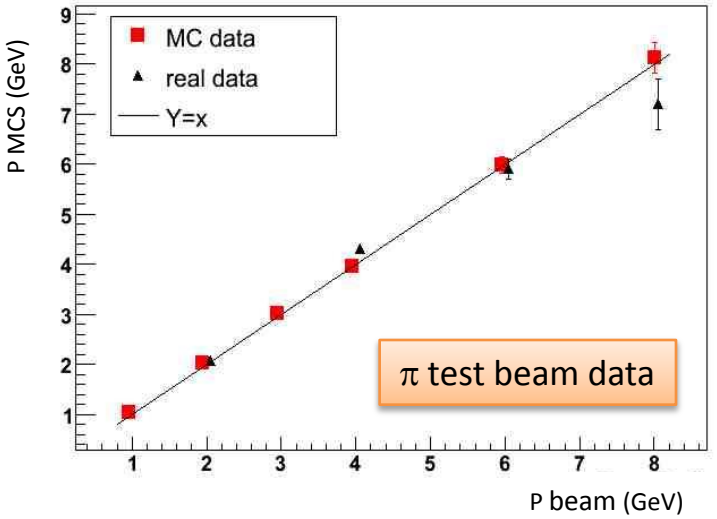
Performance of ECC brick

IP measurement

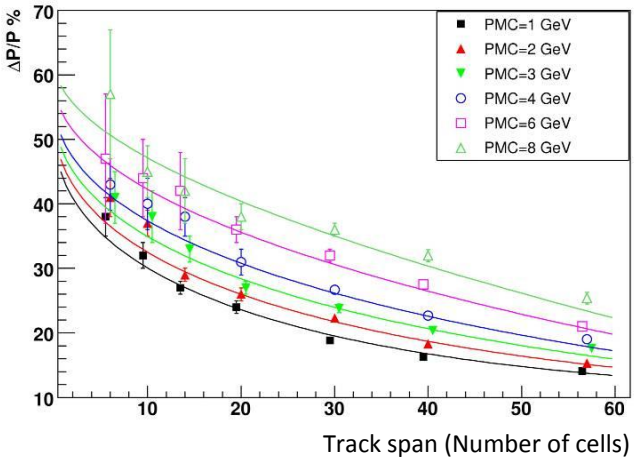


Momentum measurement by MCS

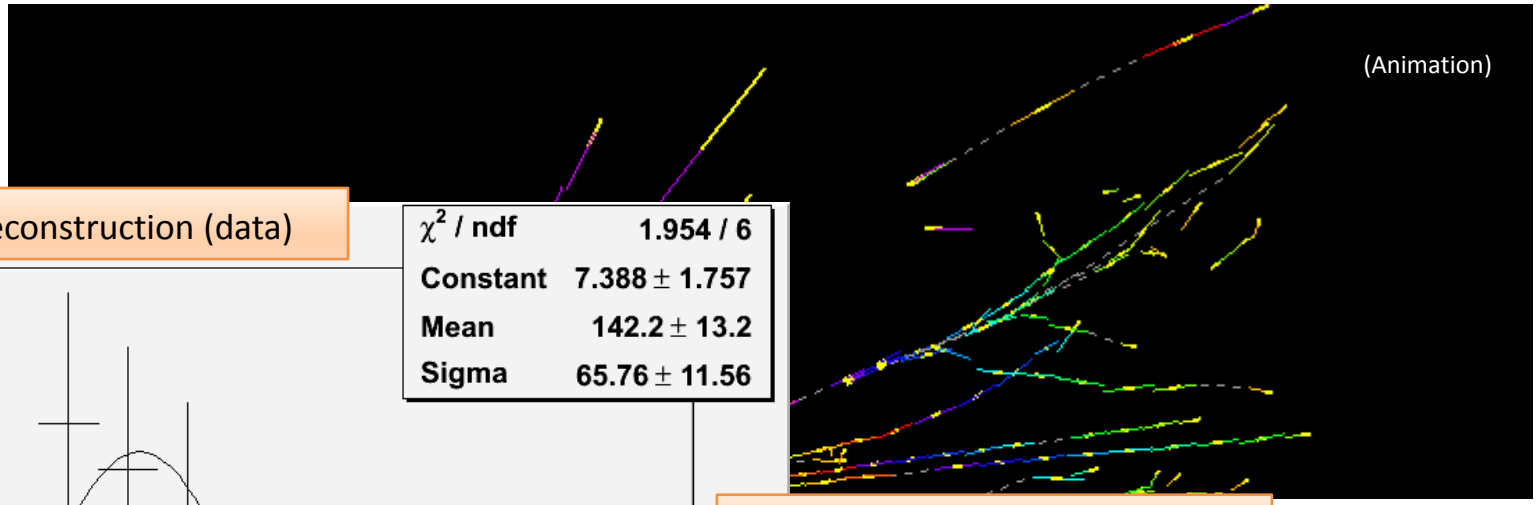
Linearity of momentum center



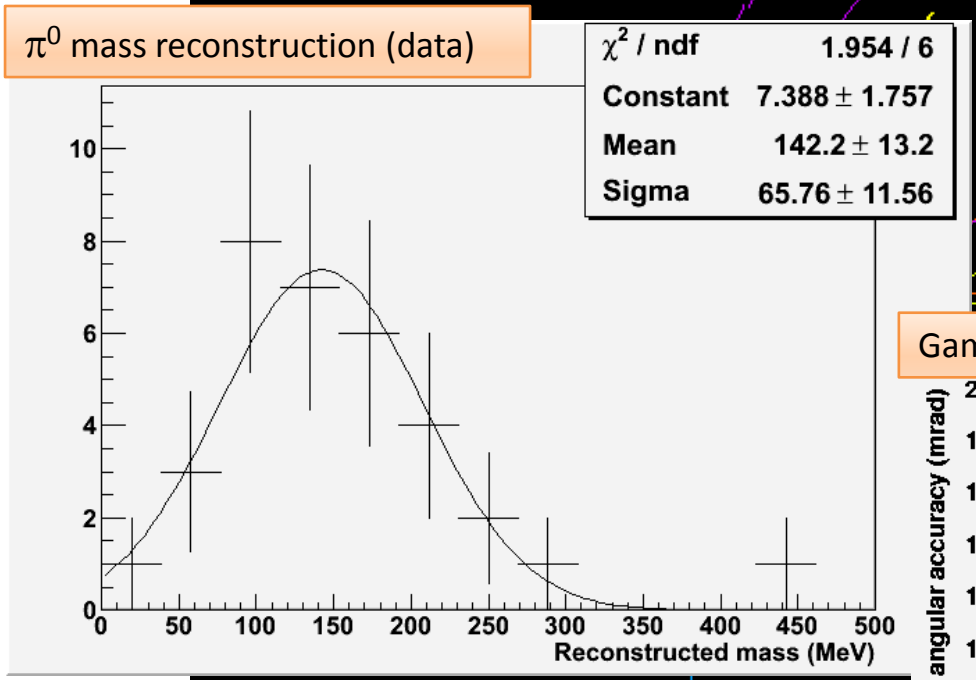
Resolution



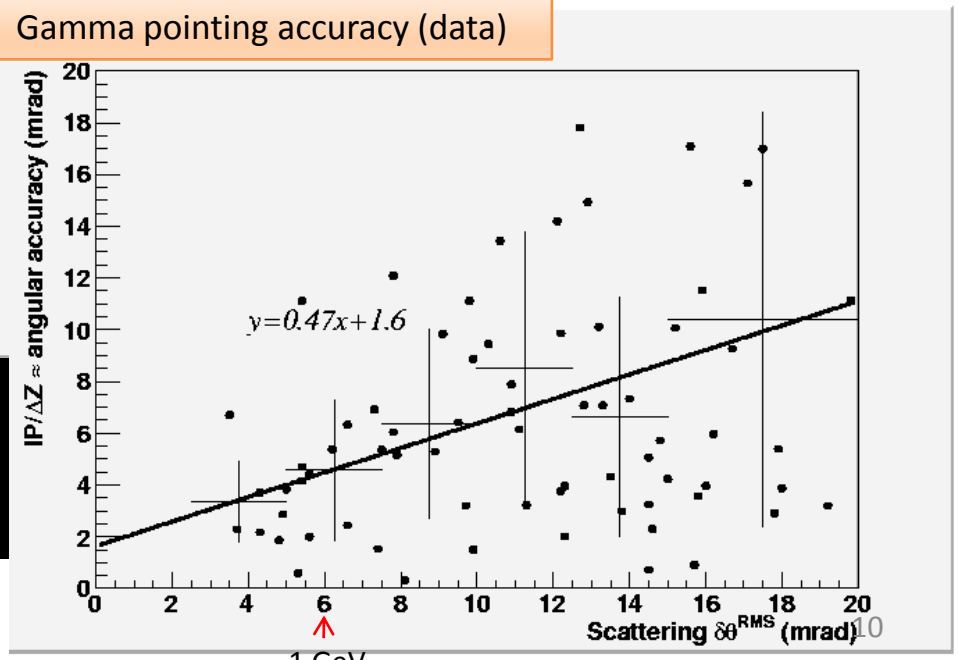
Gamma reconstruction analysis in ECC brick



π^0 mass reconstruction (data)

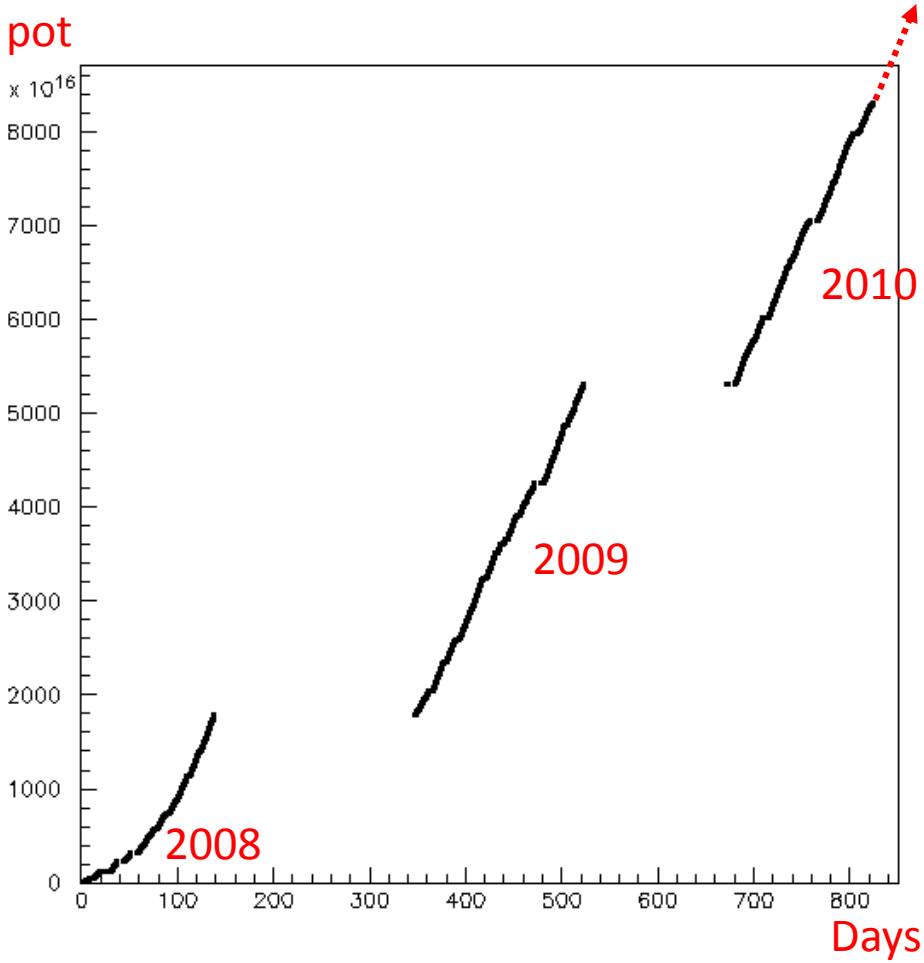


Gamma pointing accuracy (data)



Progress of CNGS runs

Year	Beam days	Protons on target	Events in the bricks
2008	123	1.78×10^{19}	1698
2009	155	3.52×10^{19}	3693
2010	(187)	3.55×10^{19} (18 Oct.)	3713 (18 Oct.)



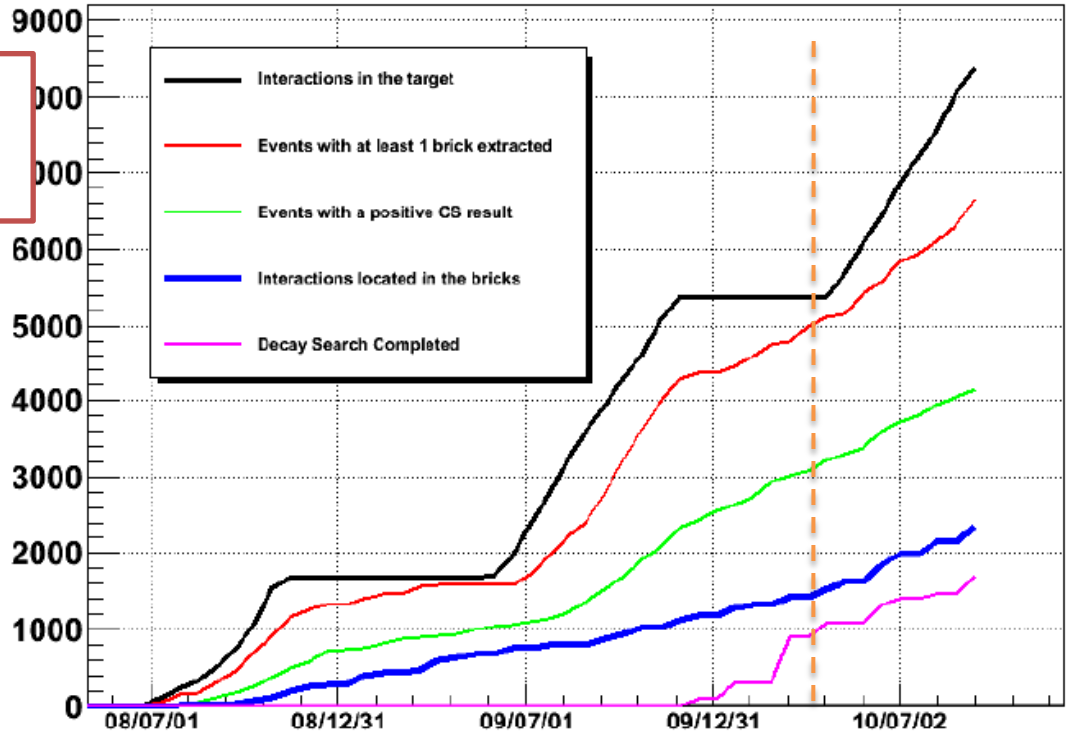
9104 events have been collected until 18/10/2010

2010: hoping to get as close as possible to nominal year (4.5×10^{19} pot)

Extrapolating average performance
→ get around 4.2×10^{19} by the end of the run

Analysis status in ECC brick

2367 neutrino interactions located.



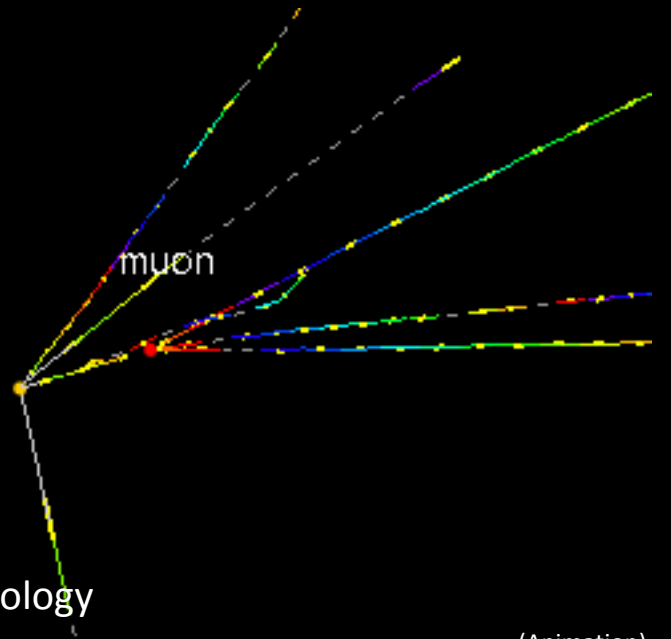
The analysis of a sub-sample of the data taken in the 2008-2009 runs was completed.

Number of events completed: 1088 (187 NC)

This is ~35% of the total 2008-2009 run statistics, corresponding to 1.85 x 10^{19} pot

With the above statistics, and for Δm^2_{23} = 2.5 x10^{-3} eV^2 and full mixing, OPERA expects:
~ 0.5 ν_τ events

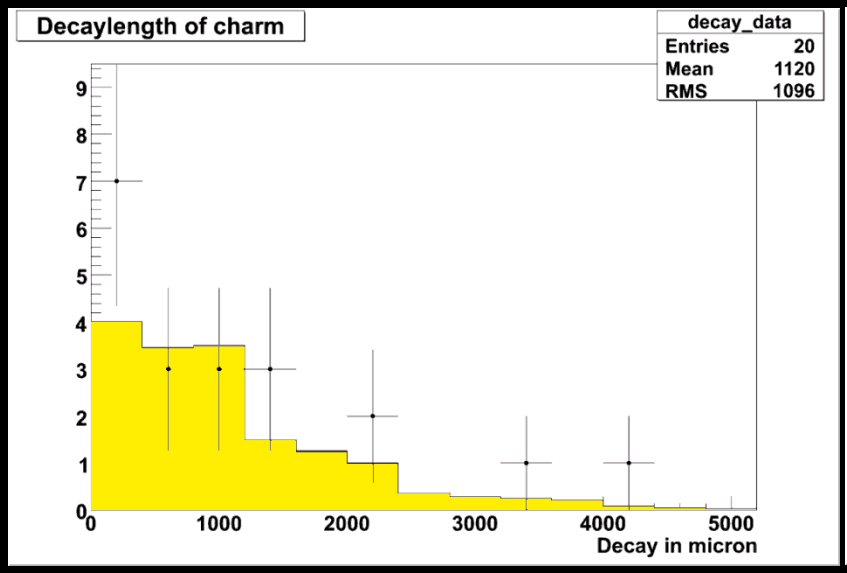
Charm candidate events
-- proof of the efficiency for τ --

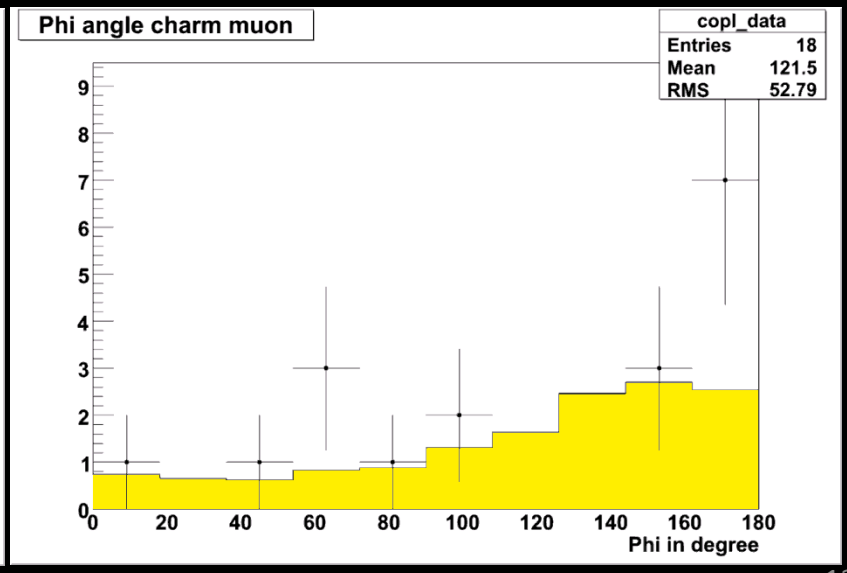


- 20 charm candidate events selected by the kinematical cuts.
- 3 of them with 1-prong kink topology.

- Expected: 16.0 ± 2.9 out of which 0.80 ± 0.22 with kink topology
- Expected BG: ~2 events (loose cuts: work in progress to reduce BG)

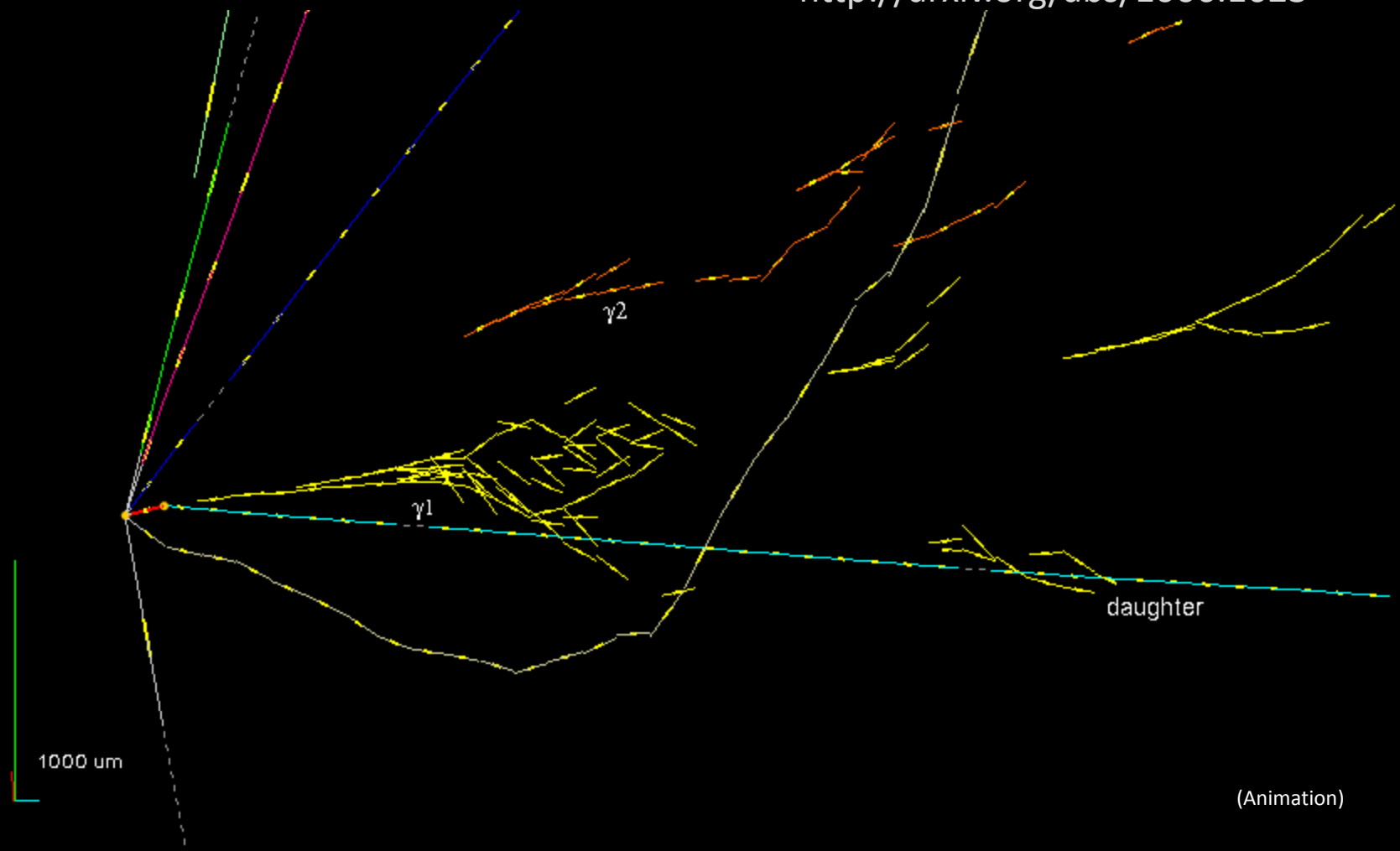
(Animation)





The first ν_τ candidate event

Physics Letters B 691 (2010) 138-145
http://arxiv.org/abs/1006.1623



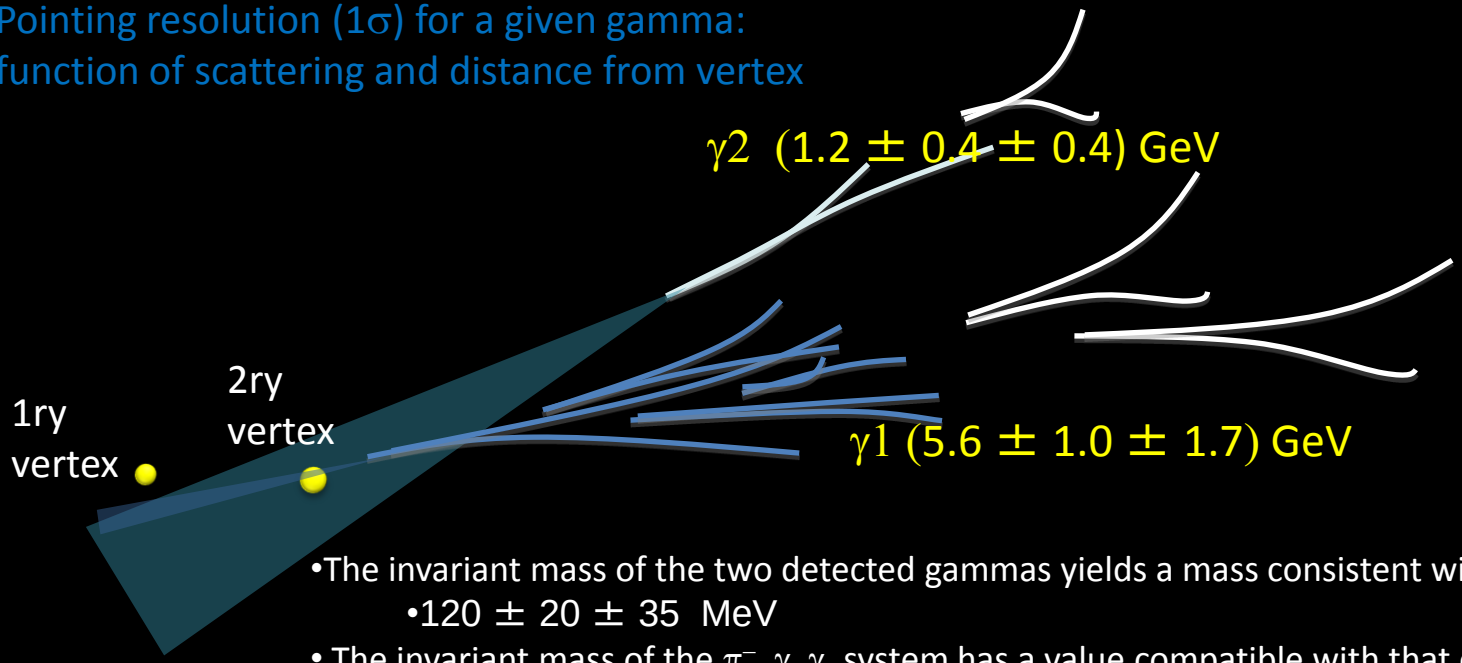
(Animation)

γ attachment to the vertices

	Distance from 2ry vertex (mm)	IP to 1ry vertex (μm) <resolution>	IP to 2ry vertex (μm) <resolution>	**Prob. of attach. to 1ry vtx***	**Prob. of attach. to 2ry vtx***	**Attachment hypothesis**
1st γ	2.2	45.0 <11>	7.5 <7>	**$<10^{-3}$**	**0.32**	**2ry vertex**
2nd γ	12.6	85.6 <56>	22 <50>	**0.10**	**0.82**	**2ry vertex (favored)**

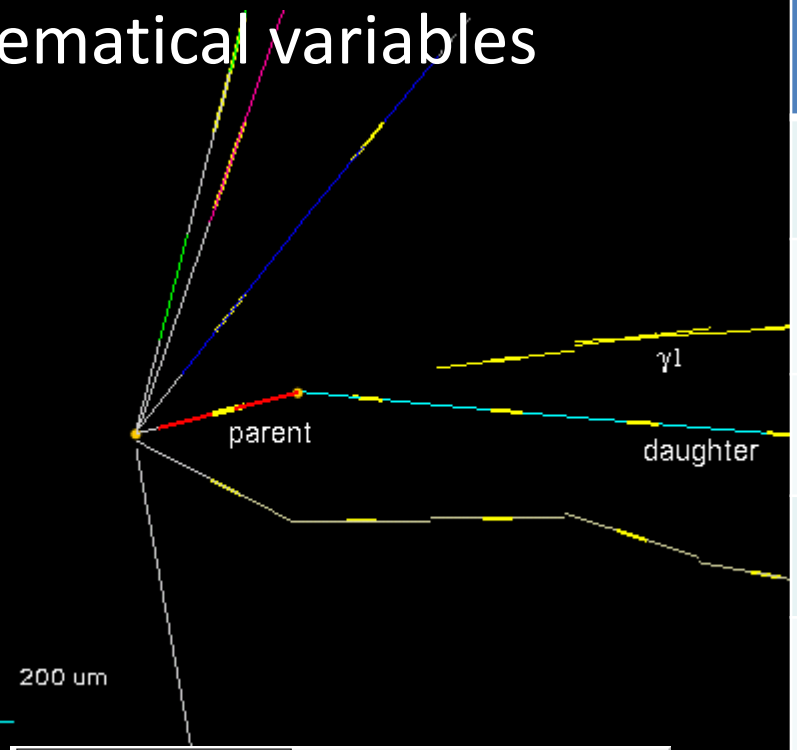
* probability to find an IP larger than the observed one

Pointing resolution (1σ) for a given gamma: function of scattering and distance from vertex



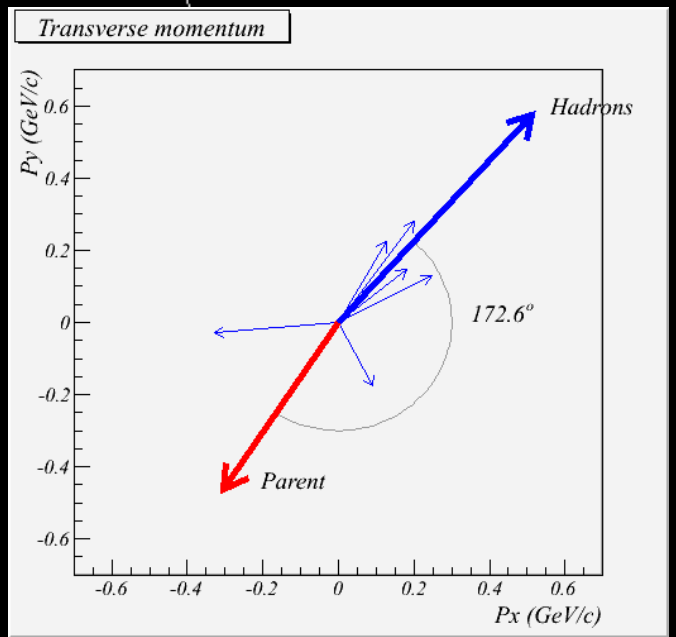
- The invariant mass of the two detected gammas yields a mass consistent with the π^0 mass value.
  - 120 ± 20 ± 35 MeV
- The invariant mass of the π^- γ γ system has a value compatible with that of the ρ (770).
  - $640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV
  - The ρ appears in about 25% of the τ decays: $\tau \rightarrow \rho\ (\pi^-\ \pi^0)\ \nu_\tau$.

Kinematical variables



(Animation)

VARIABLE	Measured	Selection criteria
Kink (mrad)	**41 ± 2**	**>20**
Decay length (μm)	**1335 ± 35**	**Within 2 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**



The uncertainty on Pt due to the alternative γ2 attachment is < 50 MeV.

The event passes all the kinematical cuts required.

Background sources

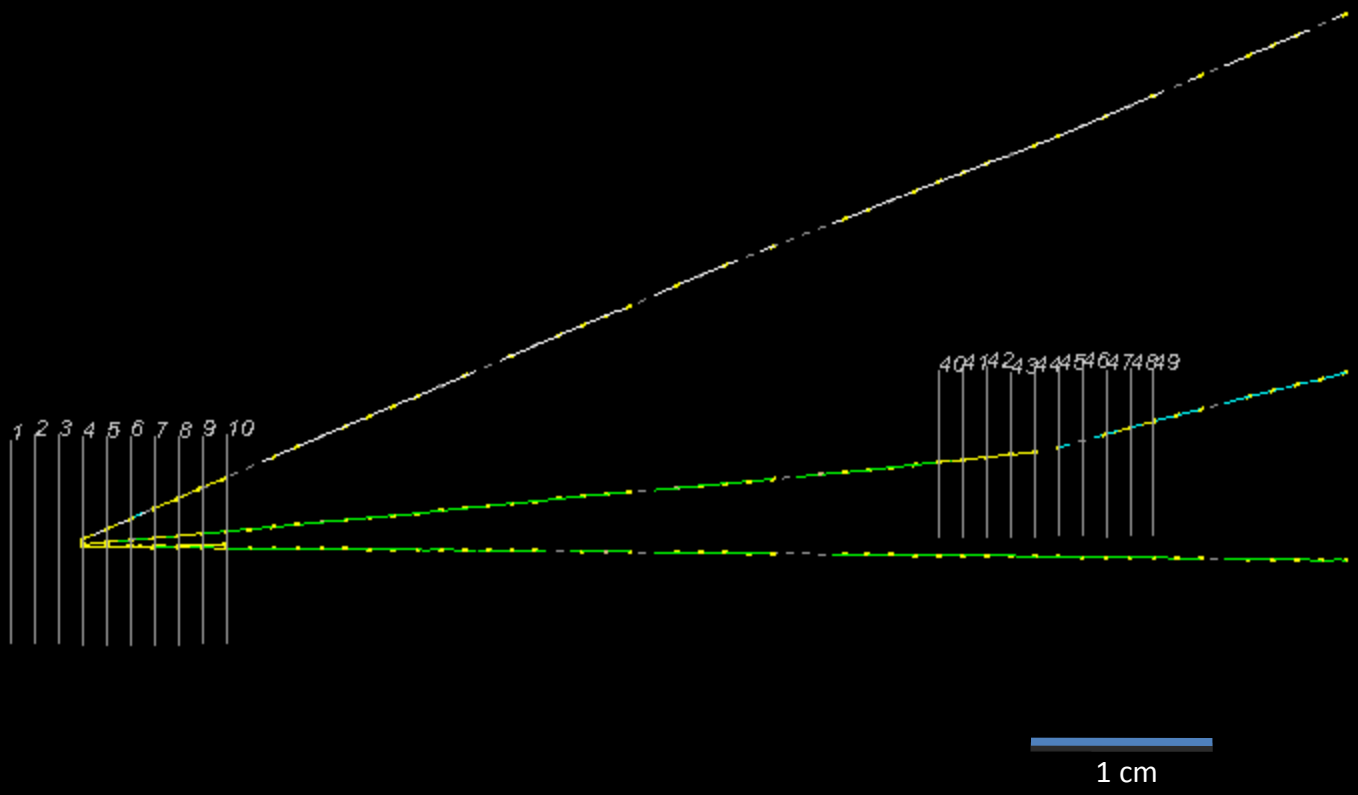
- Prompt ν_τ ~ 10^{-7}/CC
- Decay of charmed particles produced in ν_e interactions ~ 10^{-6}/CC
- Double charm production ~ 10^{-6}/CC

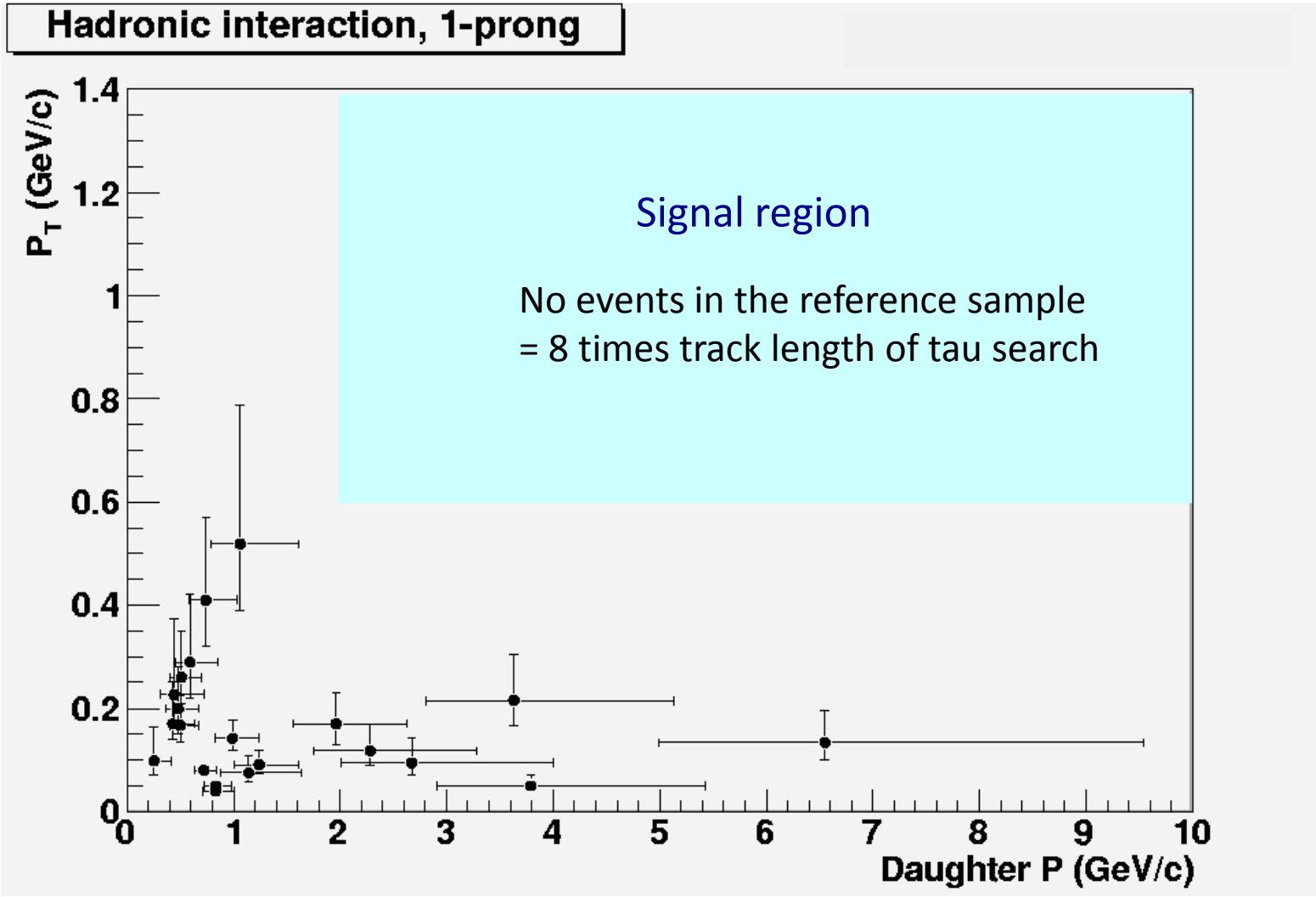
- Decay of charmed particles produced in ν_μ interactions ~ 10^{-5}/CC
- Hadronic interactions ~ 10^{-5}/CC

Evaluation by using state-of-the-art FLUKA code, updated wrt the Proposal simulations.
kink probabilities integrated over the ν_μ NC hadronic spectrum yield a BG probability of:
$(1.9 \pm 0.1) \times 10^{-4}$ kinks/NC (2 mm Pb)

Hadronic interaction background study in OPERA data

- Search for “decay-like” interactions along total 9 m of hadron track. This is about a factor 8 larger than the so far scanned track length for NC events.
- Goal: ~100 m as needed to fully validate (eventually replace) the MC information.





- 90% CL upper limit of 1.54 x 10^{-3} kinks/NC event
- The number of events outside the signal region is confirmed by MC (within the ~30% statistical accuracy of the measurement)

Statistical significance

We observe 1 event in the 1-prong hadron τ decay channel,
with a background expectation (~ 50% error for each component) of:

0.011 events (hadronic interactions)
0.007 events (charm)

⇩

0.018 ± 0.007 (syst) events 1-prong hadron

all decay modes: 1-prong hadron, 3-prongs + 1-prong μ + 1-prong *e :*

0.045 ± 0.020 (syst) events total BG

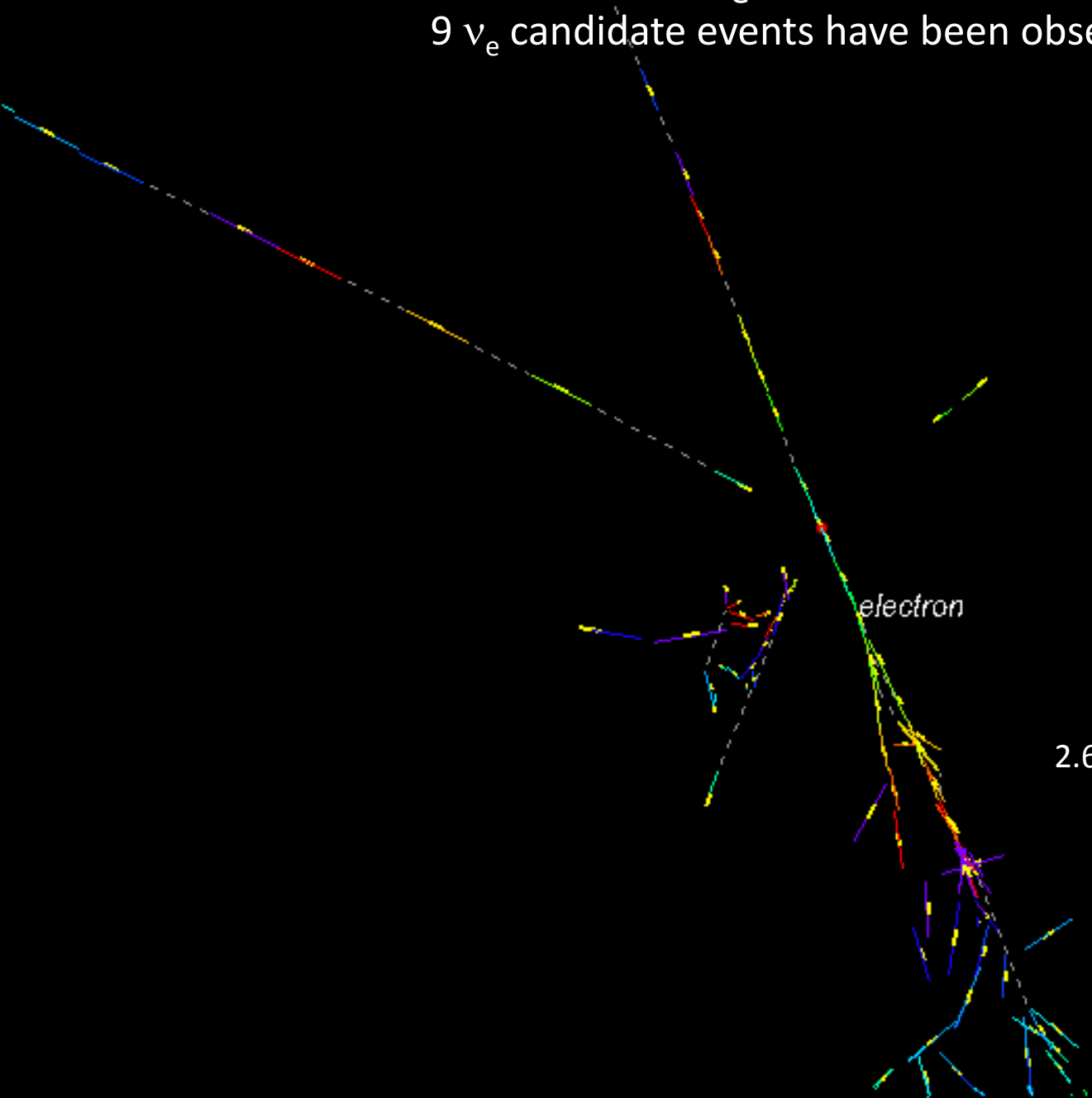
By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 σ on the measurement of a first ν_τ candidate event in OPERA.

If one considers all τ decay modes which were included in the search, the probability to observe 1 event for a background fluctuation is 4.5%.
This corresponds to a significance of 2.01 σ.

ν_e events

9 ν_e candidate events have been observed.

(Animation)



2.6 ± 0.8 GeV

Summary and prospect

• The OPERA experiment is aimed at the first detection of neutrino oscillations in appearance mode through the study of the $\nu_\mu - \nu_\tau$ channel.
•The data taking in CNGS beam is going smoothly.

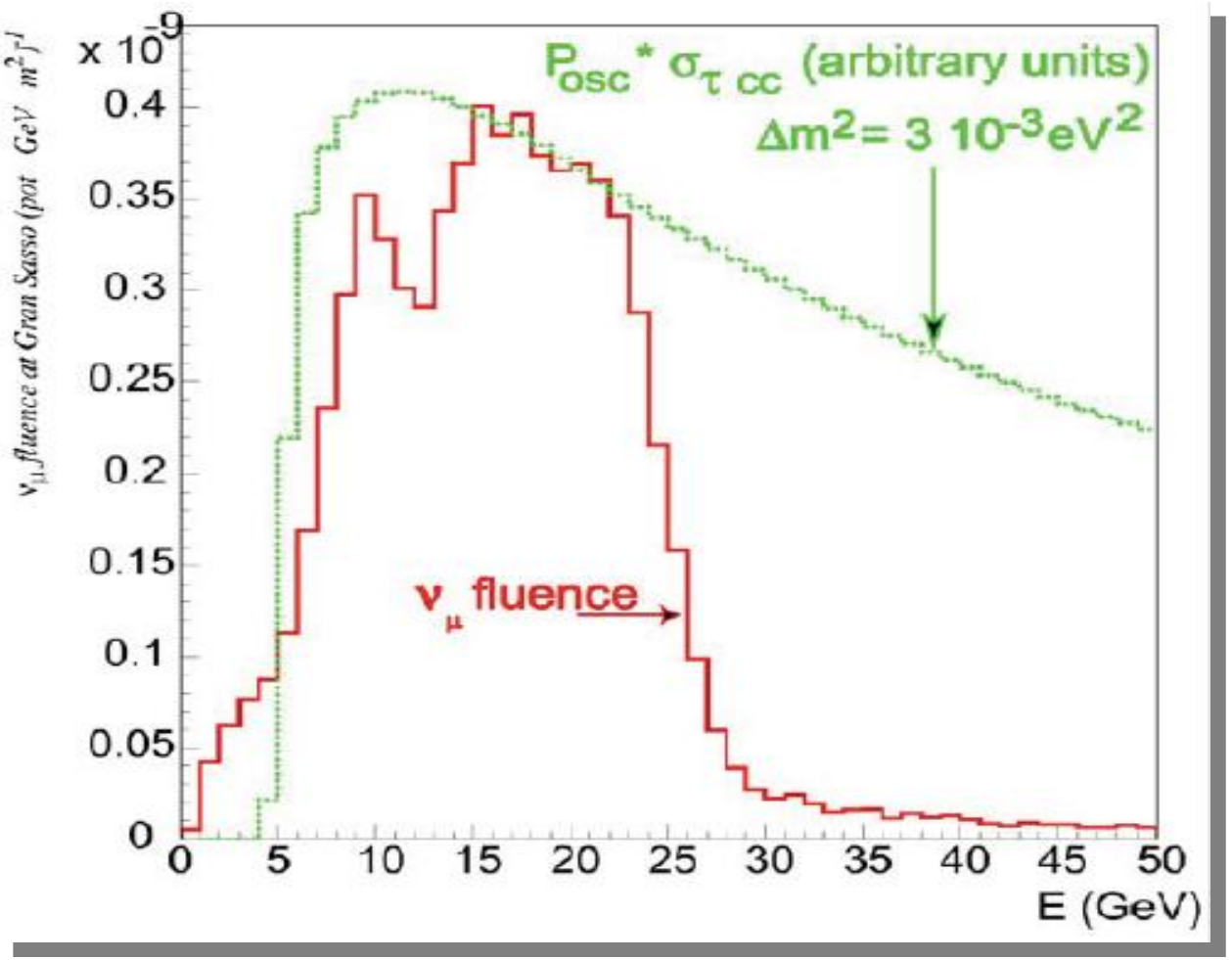
• The analysis of a sub-sample of the neutrino data taken in the CNGS in the 2008-2009 runs was completed, corresponding to 1.85×10^{19} pot out of 22.5×10^{19} proposed pot.

• Decay topologies due to charmed particles have been observed in good agreement with expectations, as well as several events induced by ν_e present as a contamination in the ν_μ beam.

• One muonless event showing a τ ➔ 1-prong hadronic decay topology has been detected. It is the first ν_τ candidate event in OPERA, with a statistical significance of 2.36 σ (1-prong hadronic decay mode) and 2.01 σ (all decay modes).

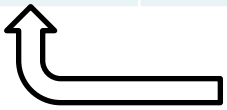
•Analysis on 2008+2009 full sample will be completed early next year. Analysis of 2010 events is being performed in parallel.

BACKUP


x 10^-9
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
40
45
50
E (GeV)
ν_μ fluence at Gran Sasso (pot GeV m^2)$^{-1}$
$P_{osc} * \sigma_{\tau\,cc}$ (arbitrary units)
$\Delta m^2 = 3\ 10^{-3} eV^2$
ν_μ fluence

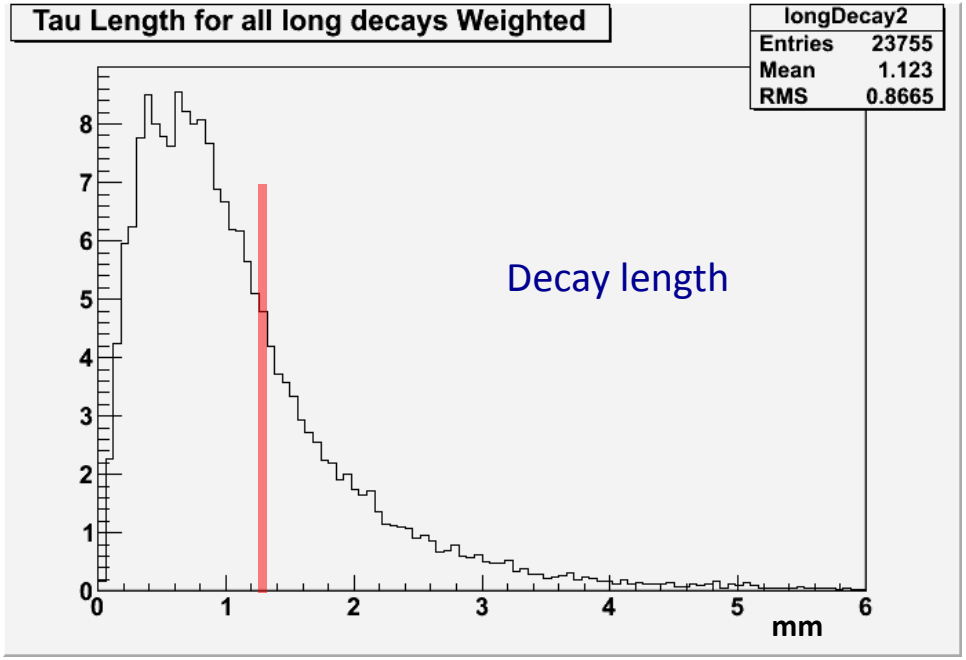
Event tracks' features

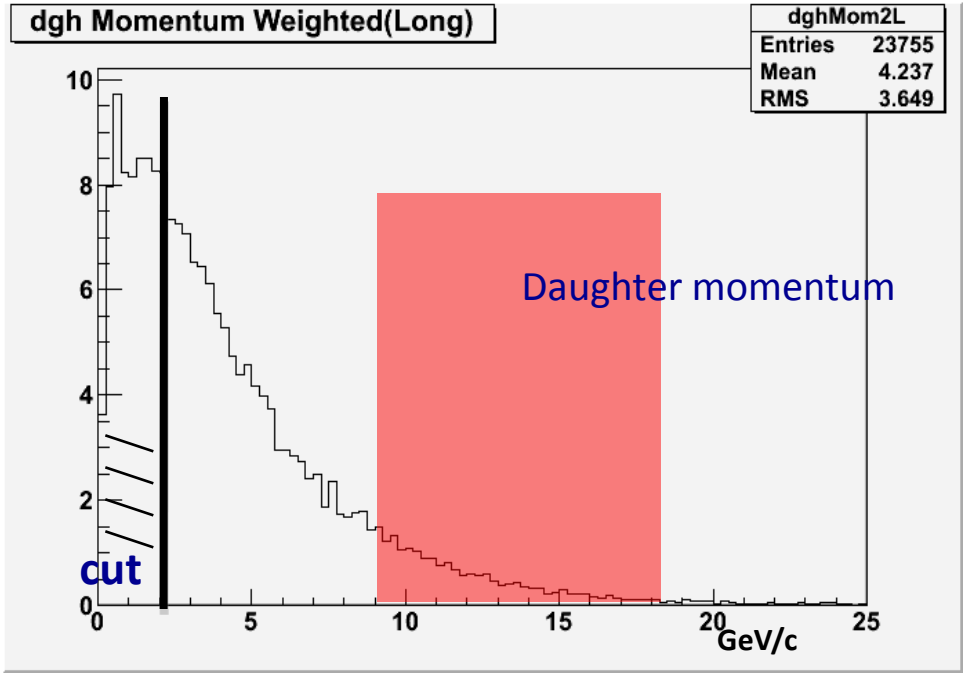
TRACK NUMBER	PID	Probability	MEASUREMENT 1			MEASUREMENT 2		
			tan Θ_X	tan Θ_Y	P (GeV/c)	tan Θ_X	tan Θ_Y	P (GeV/c)
1	HADRON range in Pb/em=4.1/1.2cm	Prob(μ)≈10^{-3}	0.177	0.368	0.77 [0.66,0.93]	0.175	0.357	0,80 [0.65,1.05]
2	PROTON	range, scattering and dE/dx	-0.646	-0.001	0.60 [0.55,0.65]	-0.653	0.001	
3	HADRON	interaction seen	0.105	0.113	2.16 [1.80,2.69]	0.110	0.113	1,71 [1.42,2.15]
4 (PARENT)			-0.023	0.026		-0.030	0.018	
5	HADRON: range in Pb/em=9.5/2.8cm	Prob(μ)≈10^{-3}	0.165	0.275	1.33 [1.13,1.61]	0.149	0.259	1,23 [0.98,1.64]
6	HADRON: range in Pb/emul=1.6/0.5 cm	Prob(μ)≈10^{-3}				0.334	-0.584	0,36 [0.27,0.54]
7	From a prompt neutral particle		0.430	0.419	0.34 [0.22,0.69]	0.445	0.419	0.58 [0.39,1.16]
8 (DAUGHTER)	HADRON	interaction seen	-0.004	-0.008	12 [9,18]	-0.009	-0.020	

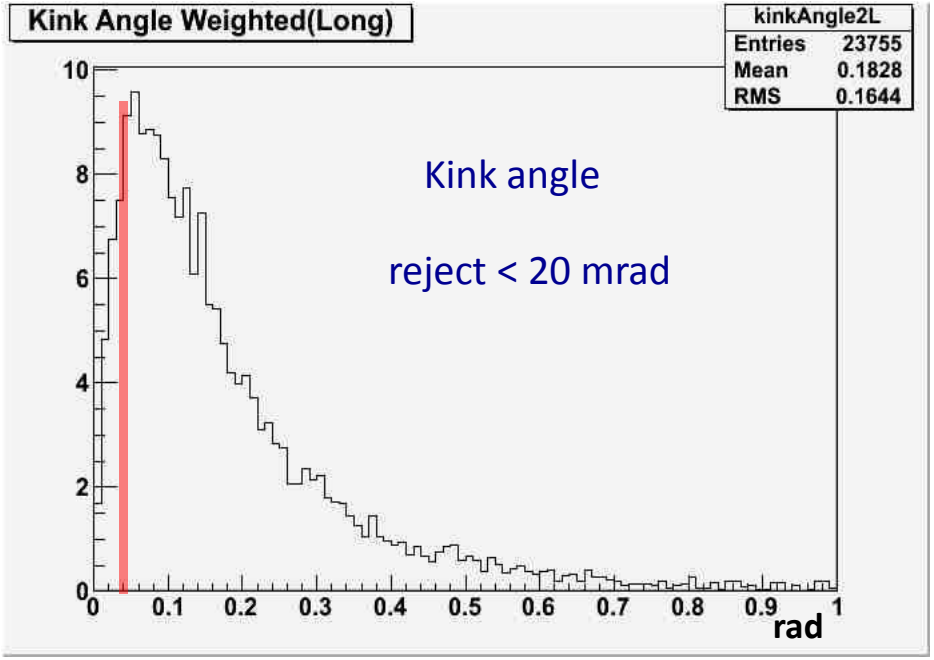


muonless event (favored hypothesis)

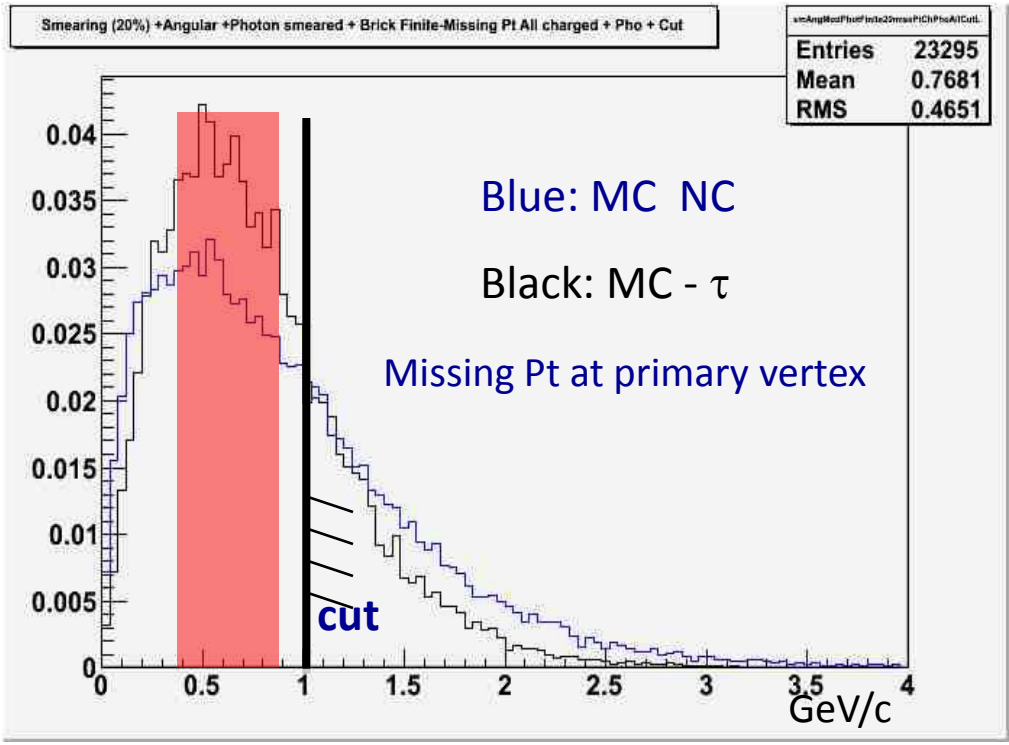
Features of the decay topology

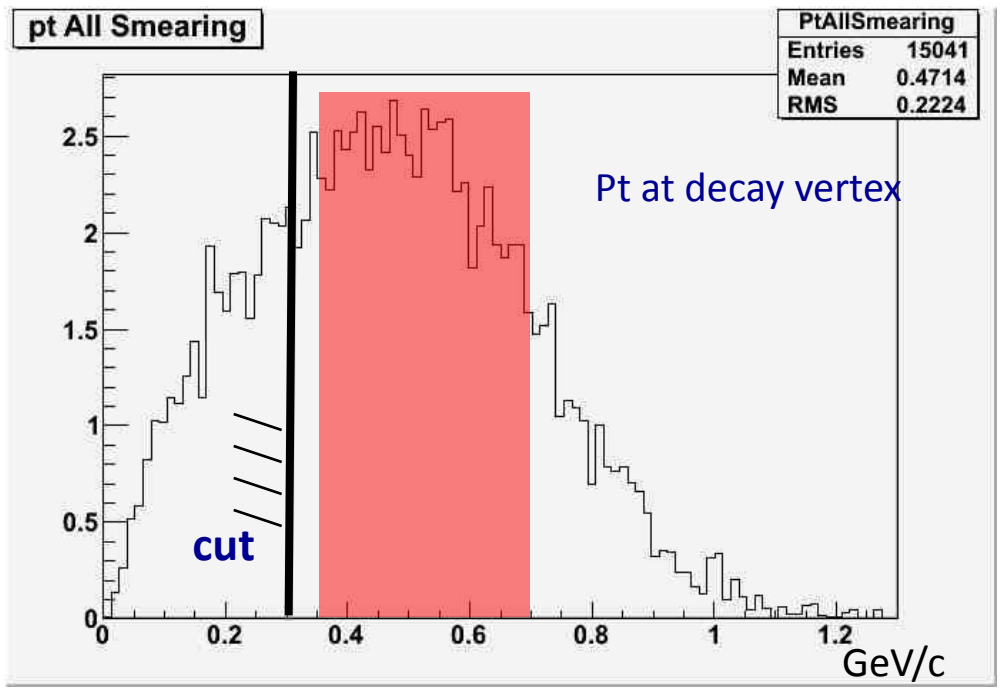




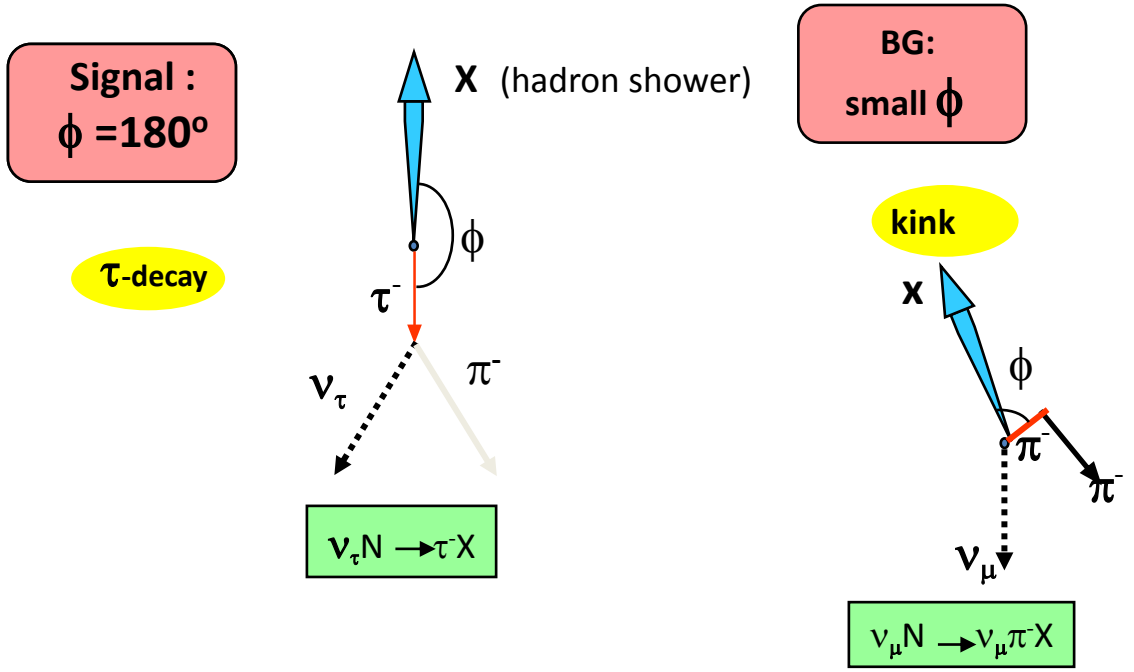


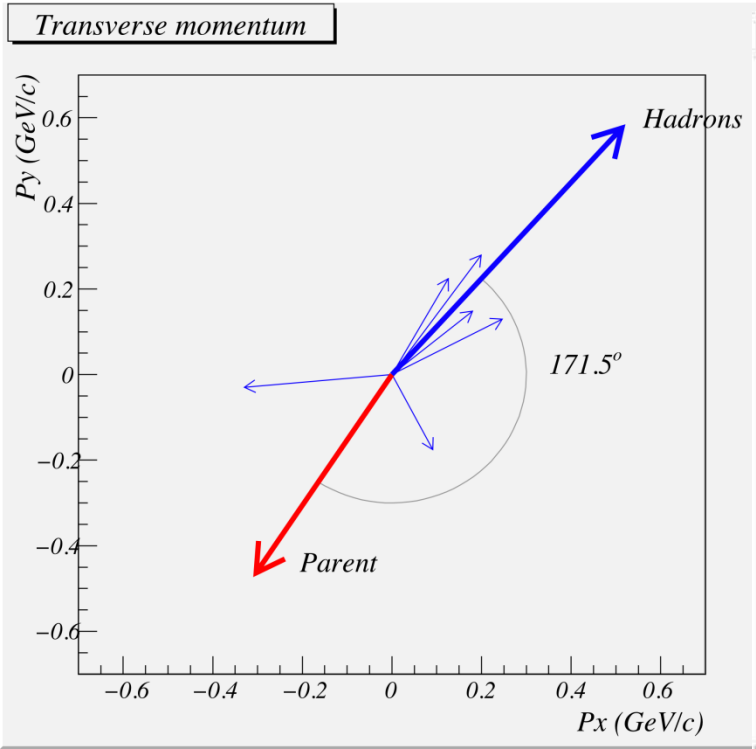
Kinematical cuts to be passed

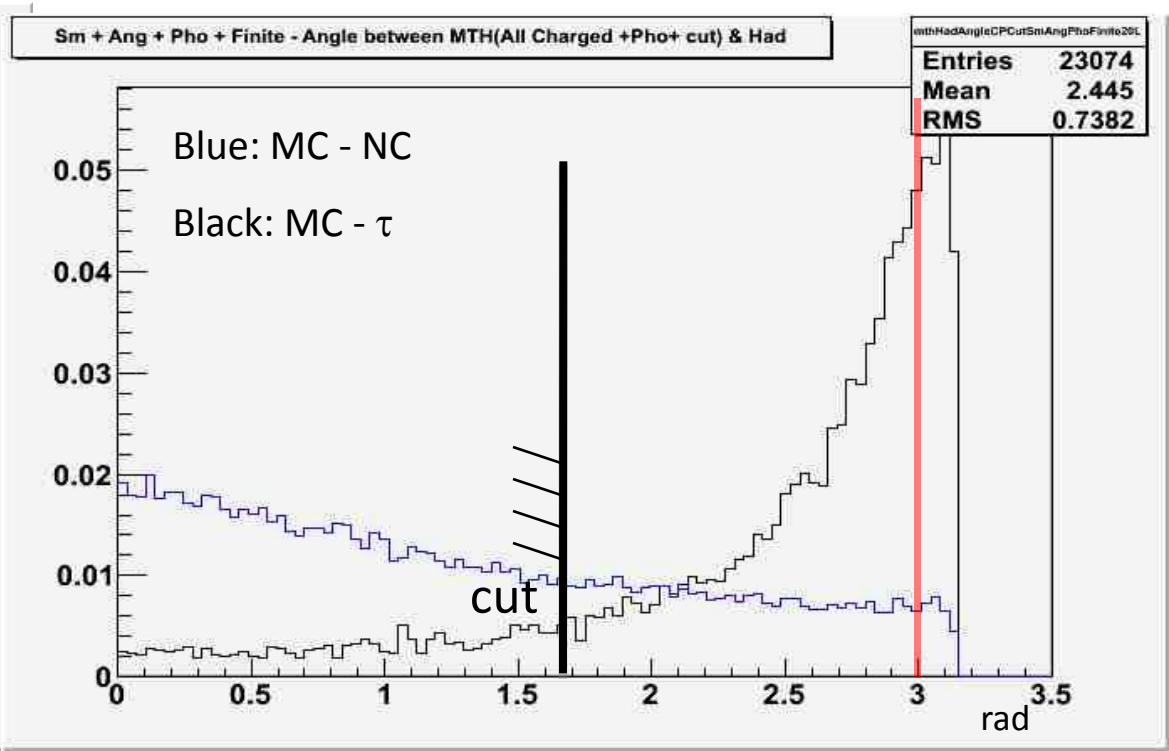




Azimuthal angle between
the resulting hadron momentum
direction and the parent track
direction

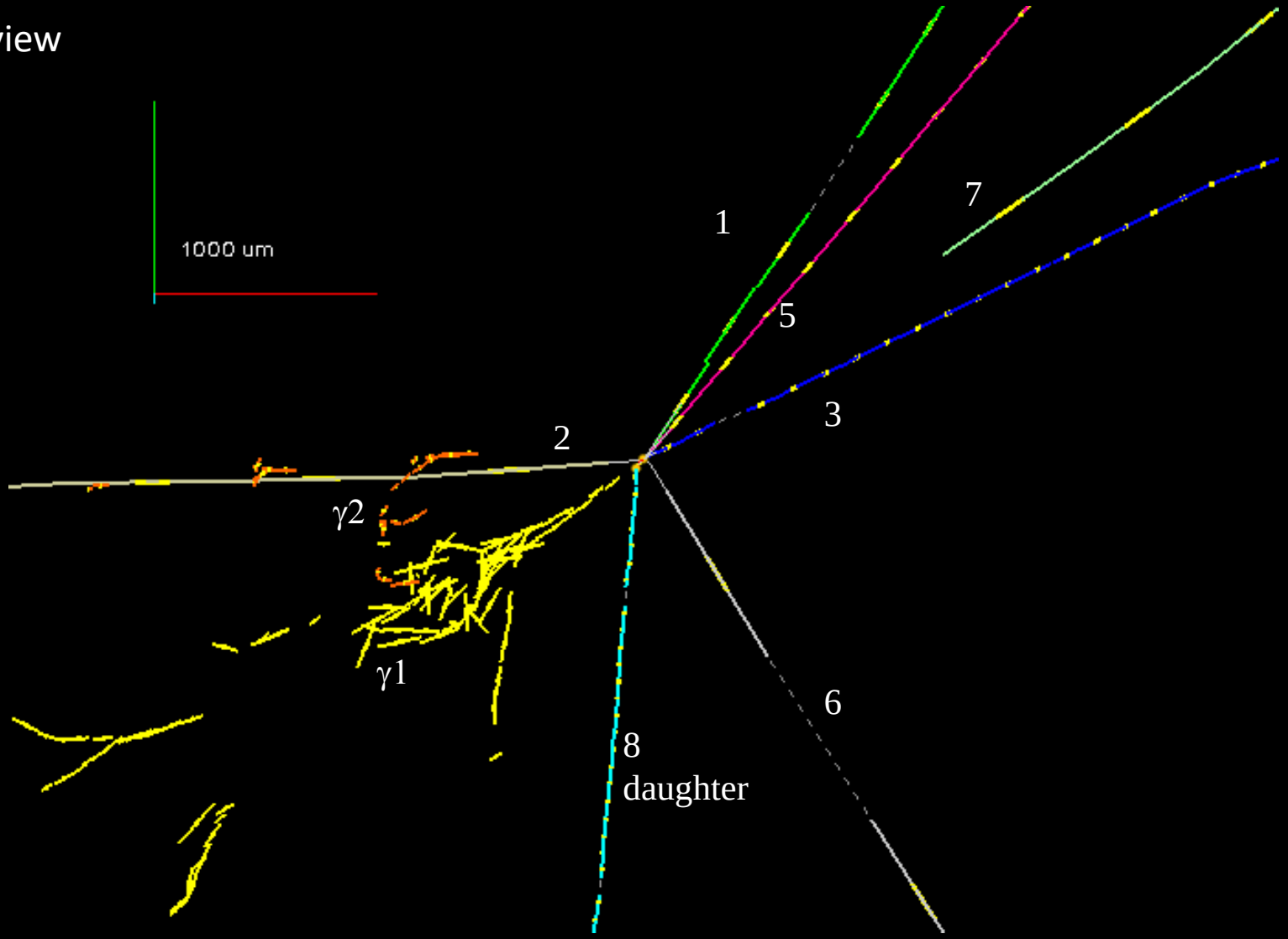






Event topological features (Beam view)

Beam view



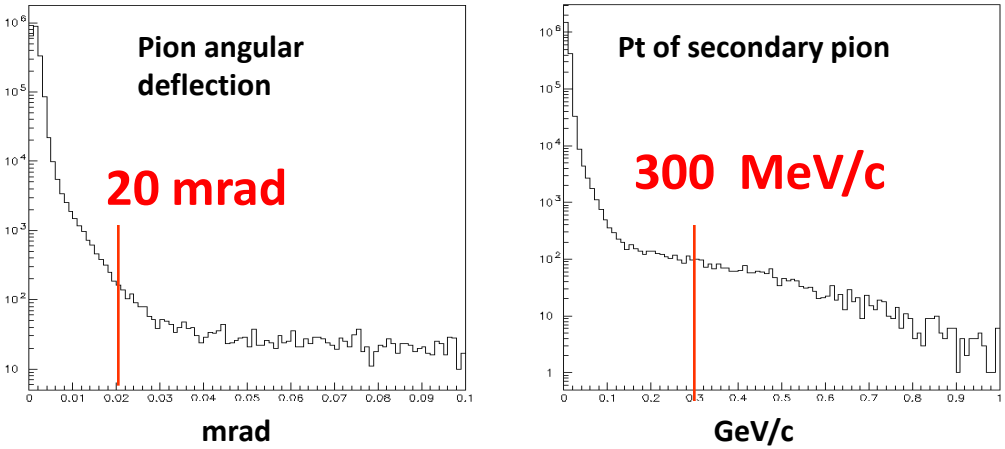
Simulation of the hadronic interaction BG

- Background evaluation by using state-of-the-art FLUKA code, upgrade of the Proposal simulations.
- 160 million events (0.5-15 GeV/c) of π^+,π^-,K^+,K^-,p impinging 1 mm of lead, equivalent to 160 km of hadronic track length.
- Kink probabilities evaluated by applying the same cuts as for the tau analysis.

kink probabilities integrated over the ν_μ NC hadronic spectrum yield a BG probability of:

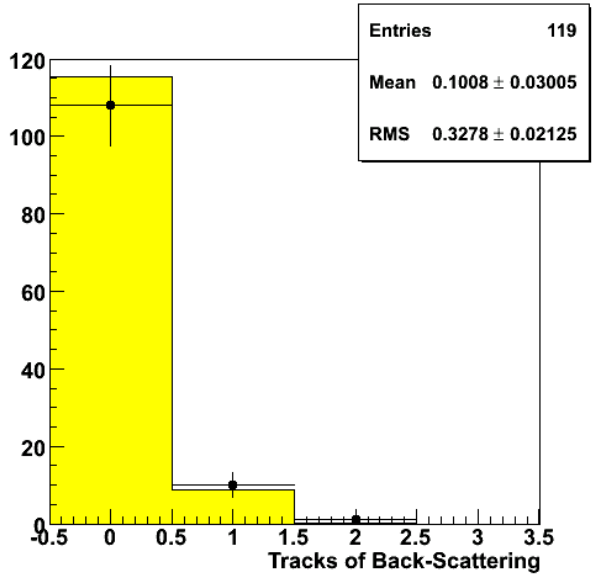
$(1.9 \pm 0.1) \times 10^{-4}$ kinks/NC (2 mm Pb)

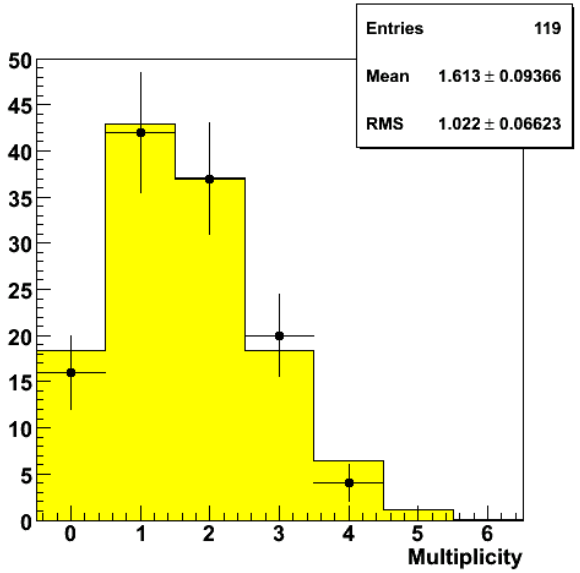
Typical scattering distributions for : 5 GeV π^+

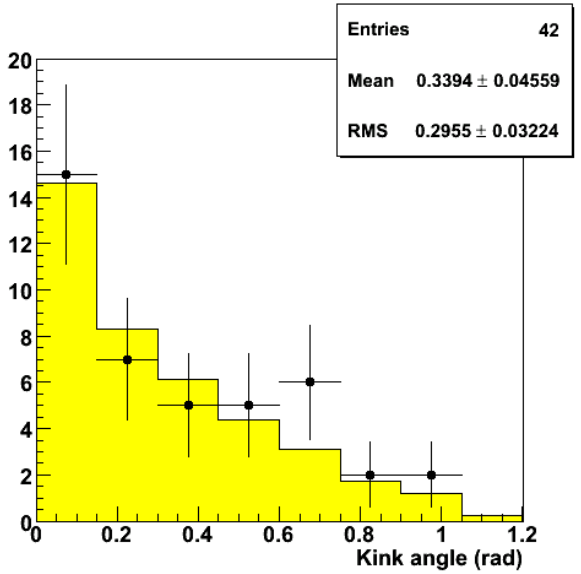


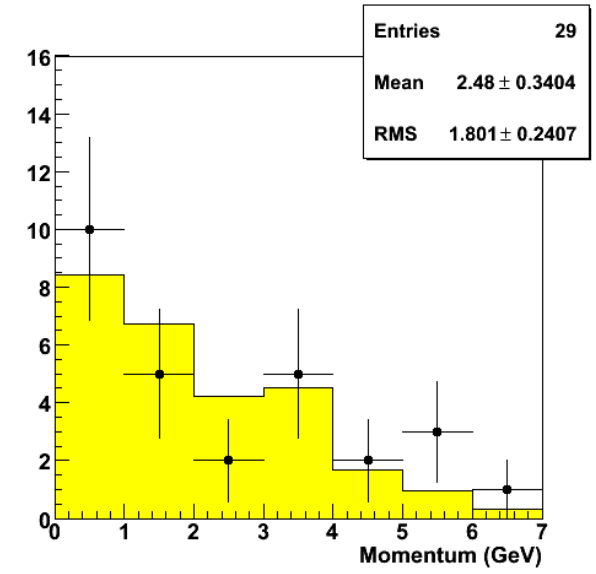
DATA/MC comparison: good agreement in normalization and shape

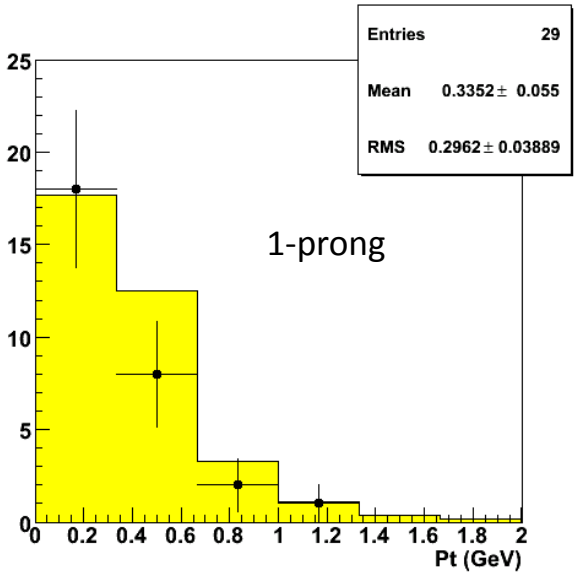
Beam test 4GeV pion 18 times track length (20m) of tau search.

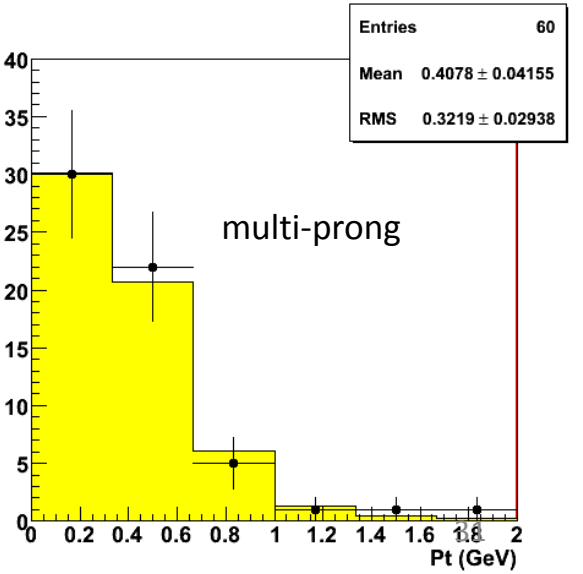






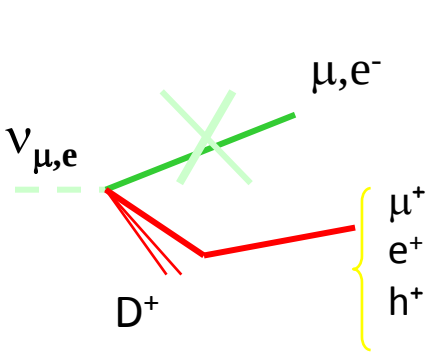






Charm background

Charmed particles have similar decay topologies to the τ



• Charm production in CC events represents a background source to all tau decay channels

• This background can be suppressed by identifying the primary lepton
→ ~ 95% muon ID

• For the 1-prong hadronic channel 0.007±0.004 (syst.) background events are expected for the analyzed statistics

• Further charm BG reduction is under evaluation by implementing the systematic follow-down of low energy tracks in the bricks and the inspection of their end-range, as done for the "interesting" event. For the latter we have 98-99% muon ID efficiency.

By assuming that $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and full mixing, we expected:

0.54 ± 0.13 (syst) ν_τ CC events in all τ decay channels and

0.16 ± 0.04 (syst) ν_τ CC events in the 1-prong hadron τ decay channel

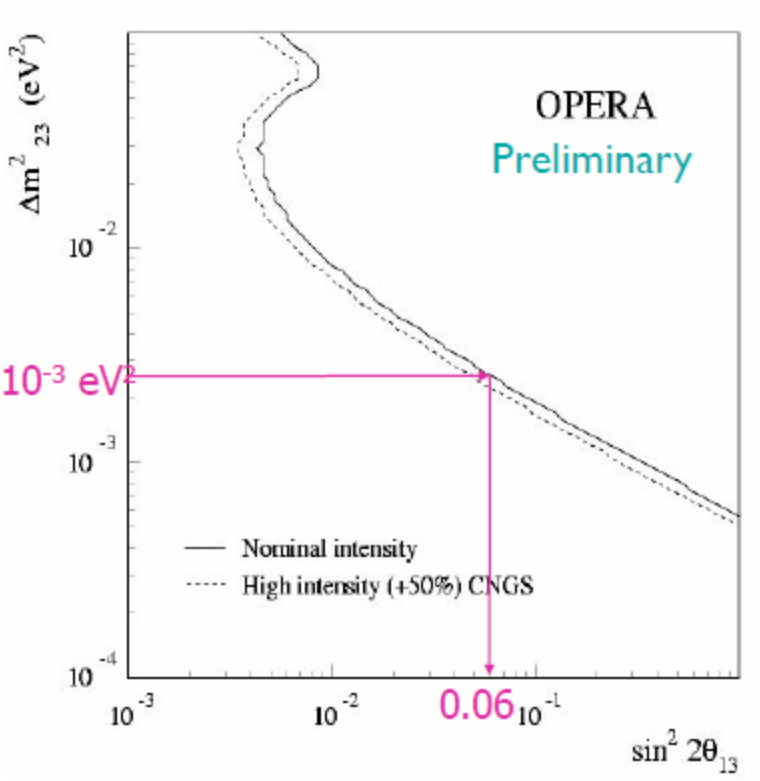
and we observed 1 event.

This result allows us to exclude at the 90% CL

Δm^2_{23} values > 7.5×10^{-3} eV^2 (full mixing)

Sensitivity to Θ_{13}

Simultaneous fit on:
E_e, missing p_T and visible energy



full mixing, 5 years run @ 4.5×10^{19} pot / year

Θ_{13} (deg)	Signal $\nu_\mu \to \nu_e$	Background			
		$\tau \to e$	ν_μCC	ν_μNC	ν_eCC beam
9	9.3	4.5	1.0	5.2	18
7	5.8	4.5	1.0	5.2	18
5	3.0	4.5	1.0	5.2	18

Limits at 90% CL for
$\Delta m^2 = 2.5\times10^{-3}$ eV^2 full mixing

	$\sin^2 2\Theta_{13}$	Θ_{13}
CHOOZ	<0.14	11°
OPERA	<0.06	7.1°