Recent results of the OPERA search for $\nu_\mu \rightarrow \nu_\tau$ oscillations

T. OMURA

On behalf of The OPERA Collaboration

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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Bologna
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Naples
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JINR Dubna

Switzerland
Bern

Turkey
METU Ankara

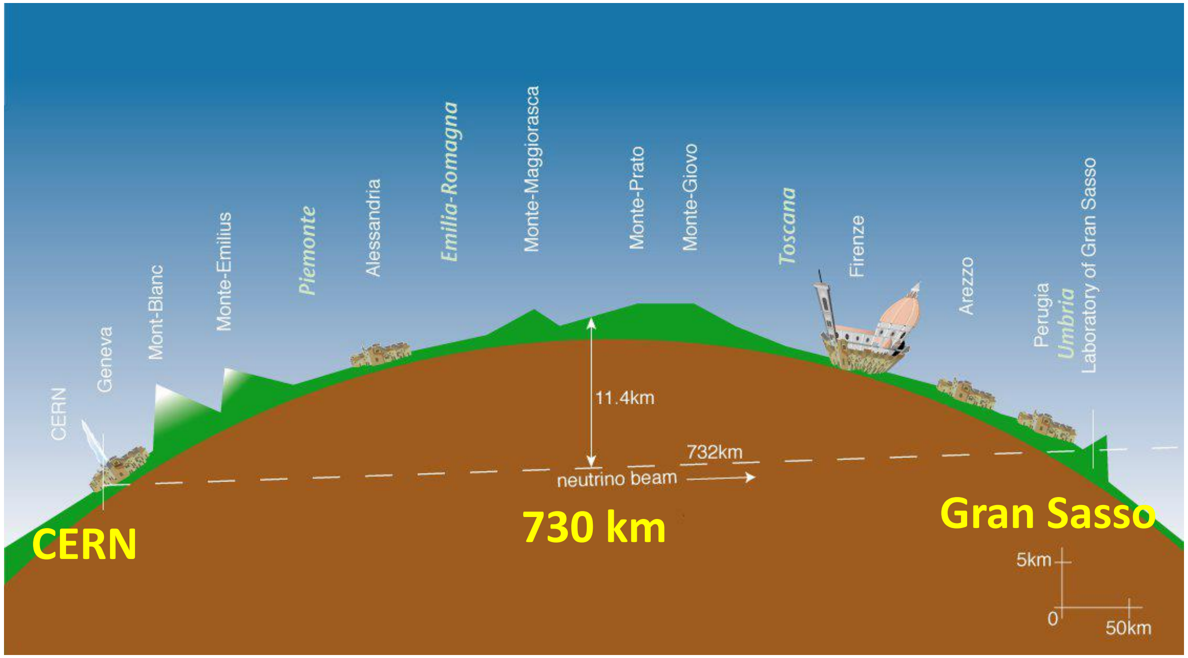
Goal of OPERA

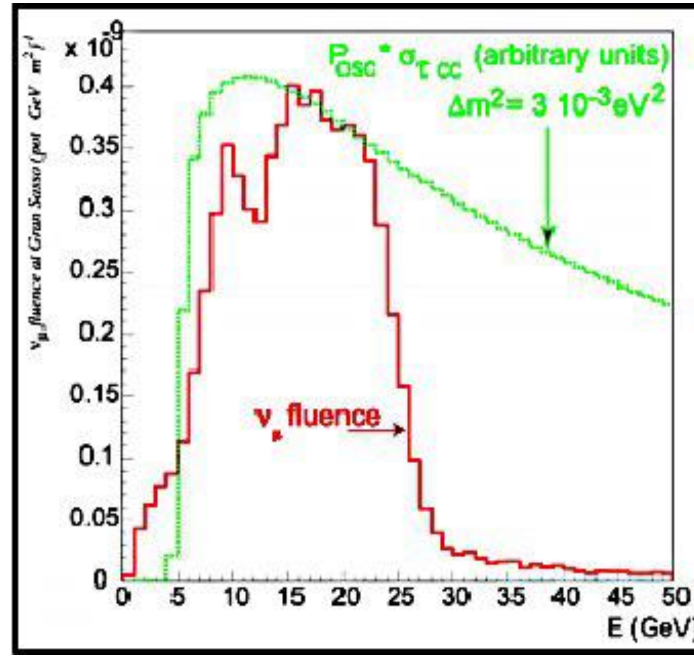
Prove the $\nu_\mu \rightarrow \nu_\tau$ oscillation by direct detection of ν_τ CC interaction in pure ν_μ beam

Requirements:

- High energy ν beam for tau production
- High intensity and large target mass for statistics
- Long base line for oscillation
- Micrometric resolution to identify τ kinematics

CERN Neutrino to Gran Sasso





Optimized to maximize ντ CC cross section

Beam property

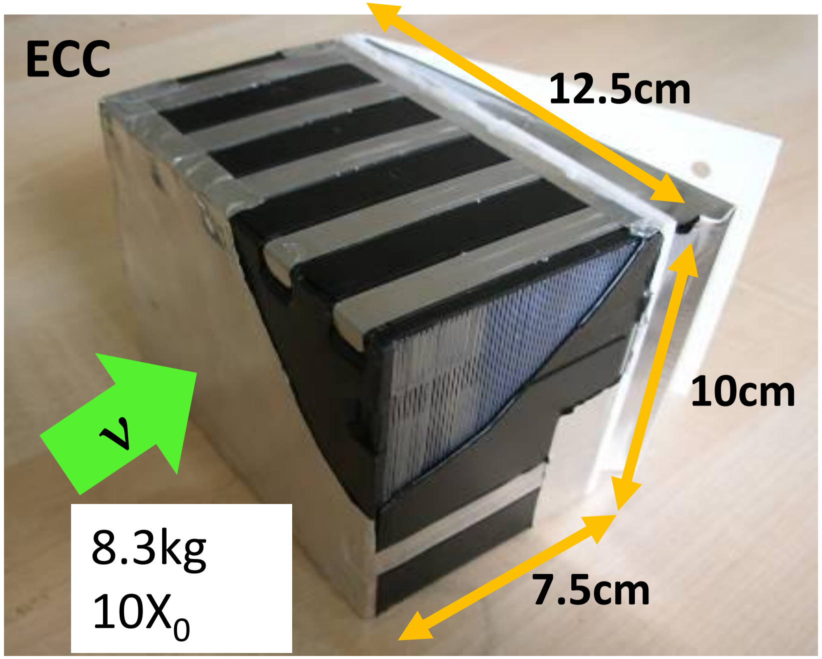
<Eν>	17 GeV
(νe + $\overline{\nu e}$) / νμ	0.87 %
$\overline{\nu\mu}$ / νμ	2.1 %
ντ prompt	Negligible

Oscillation probability (2ν model)

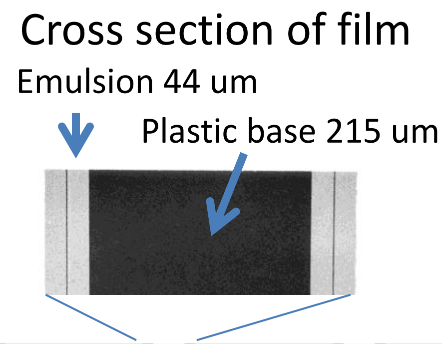
$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \Delta m^2_{23} \cdot \frac{L}{E}\right) \sim 1.7\%$$

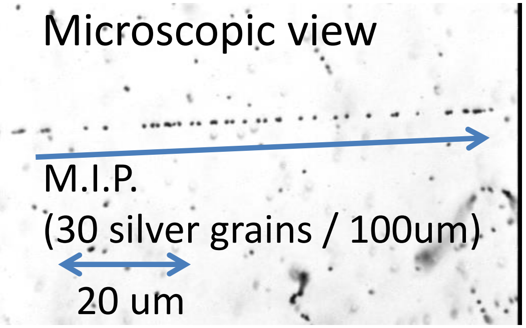
(Assuming $\Delta m^2_{23} = 2.43 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$)

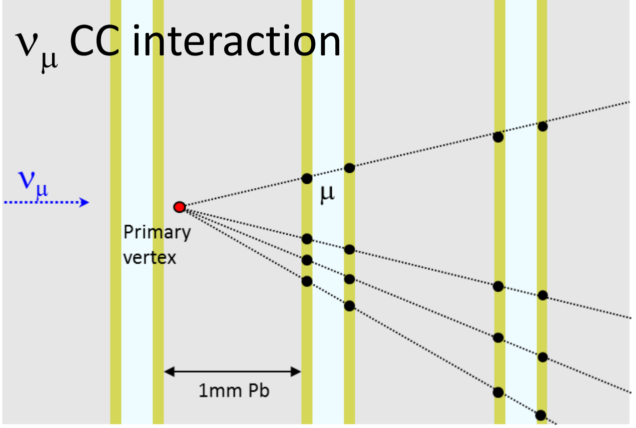
Emulsion Cloud Chamber

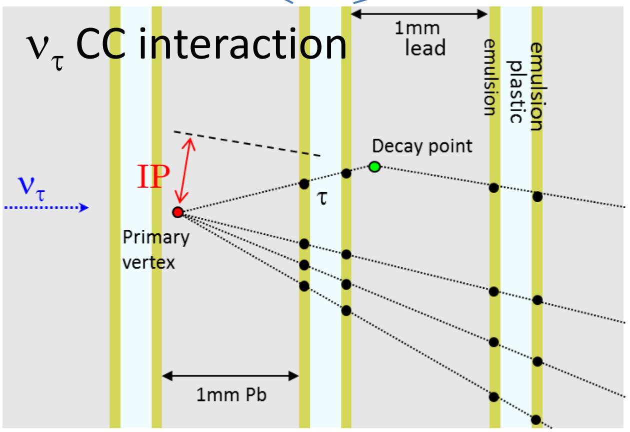


- Main target and detector unit
- 56 lead plates (1mm) + 57 emulsion photographic films (0.3 mm)
- 3D track reconstruction with micrometric resolution
- Momentum measurement by MCS







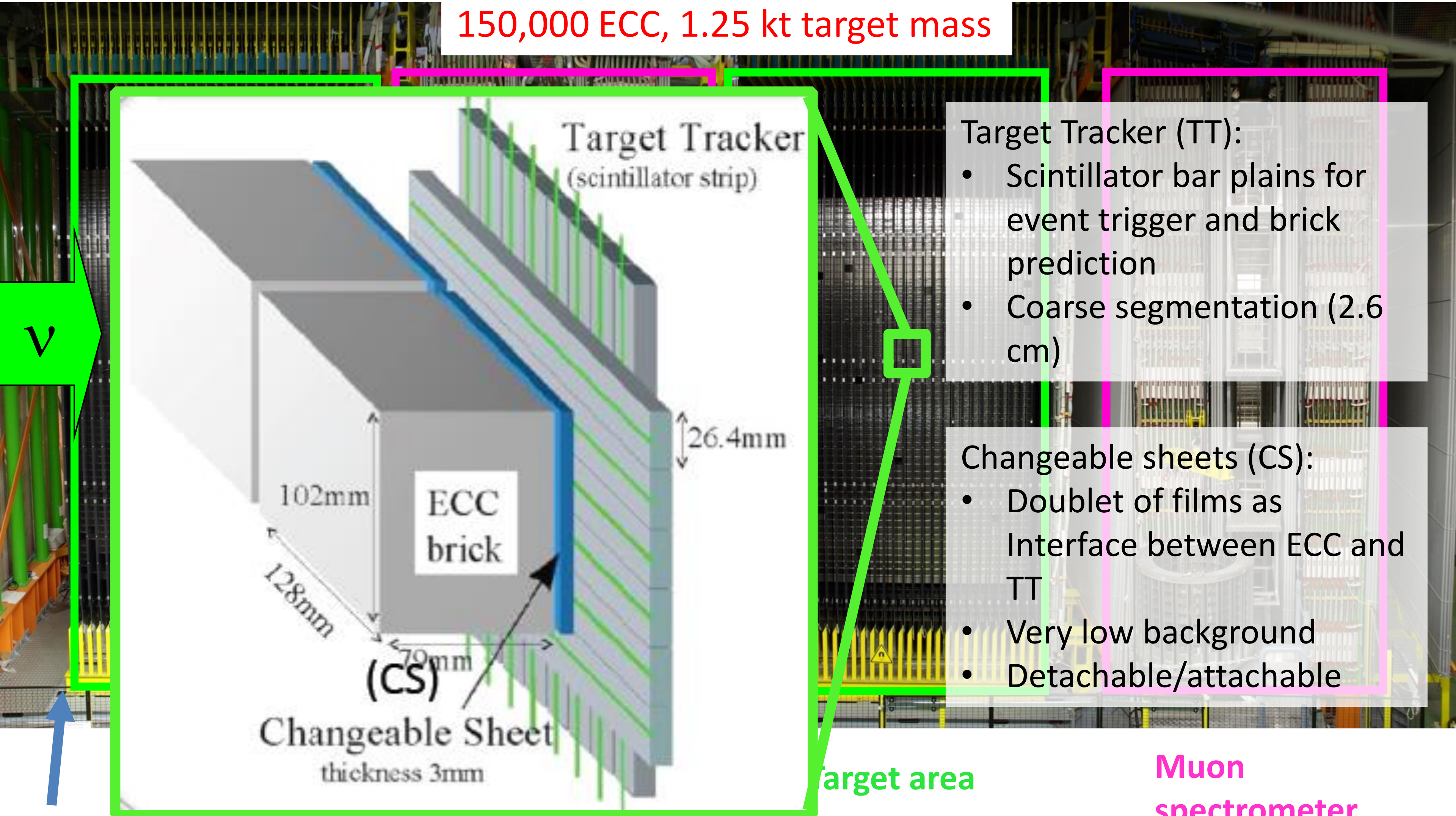


τ decay channel	B.R. (%)
τ → h	49.5
τ → 3h	15.0
τ → e	17.8
τ → μ	17.7

No other lepton at the vertex

The OPERA Detector

150,000 ECC, 1.25 kt target mass



Target Tracker (TT):

- Scintillator bar plains for event trigger and brick prediction
- Coarse segmentation (2.6 cm)

Changeable sheets (CS):

- Doublet of films as Interface between ECC and TT
- Very low background
- Detachable/attachable

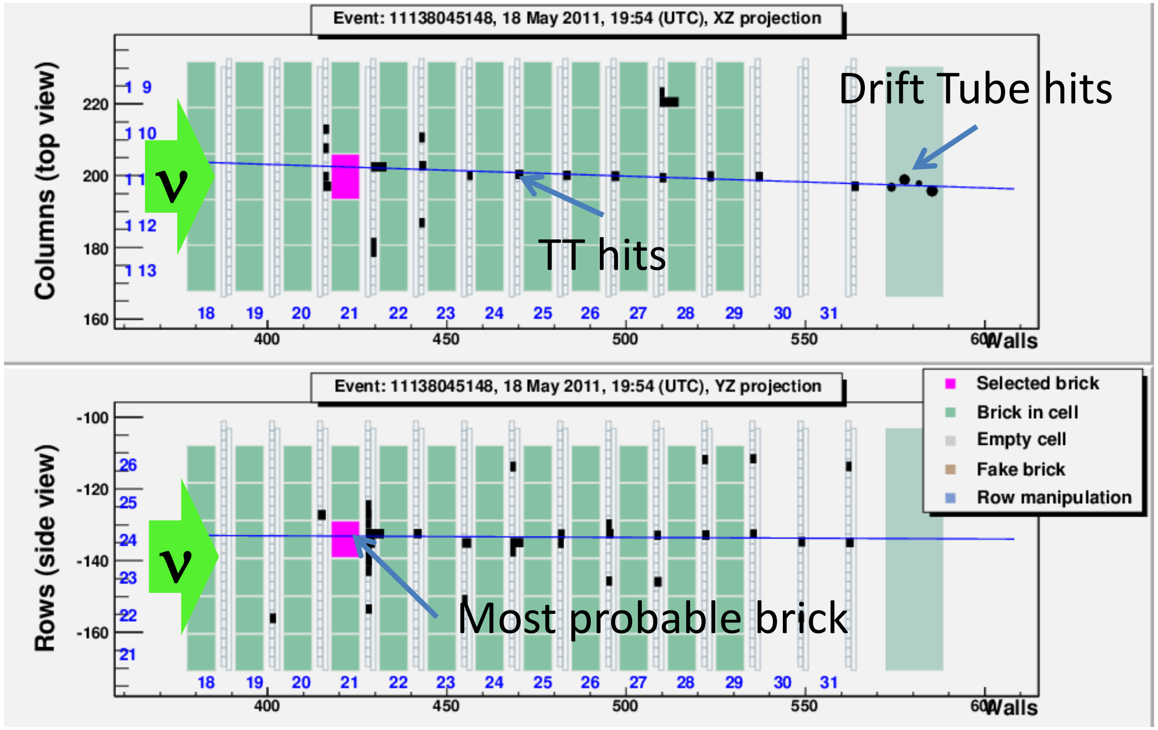
Veto

Target area

(Drift Tube + RPC + Magnet)

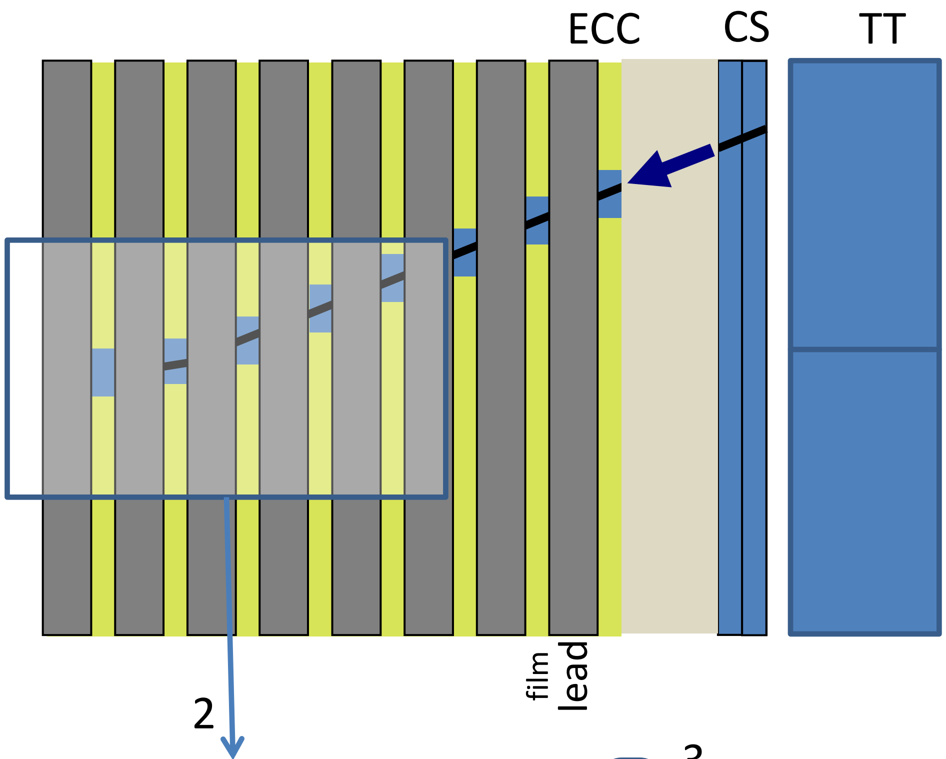
Muon spectrometer

Location step (1) Brick Finding

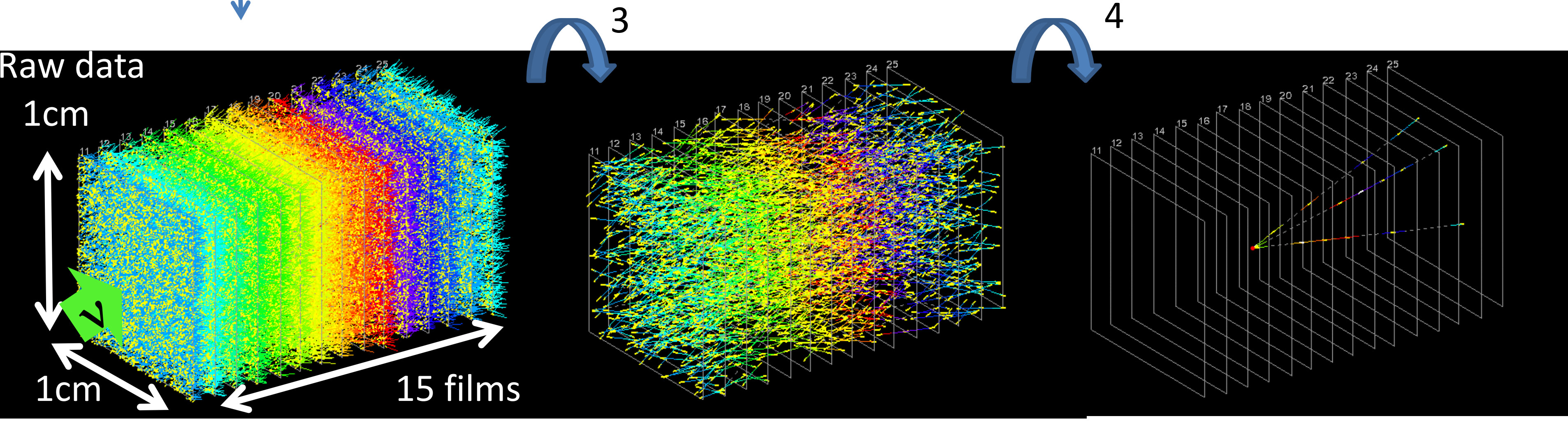


1. Event trigger & brick prediction by TT
2. Extract most probable brick by Brick Manipulator System
3. Detach CS from ECC and develop it
4. Validation by scanning CS searching tracks from ν interaction (automatic scanning system)
   - Track found → Develop ECC films
   - Not found → extract the 2nd probable brick…

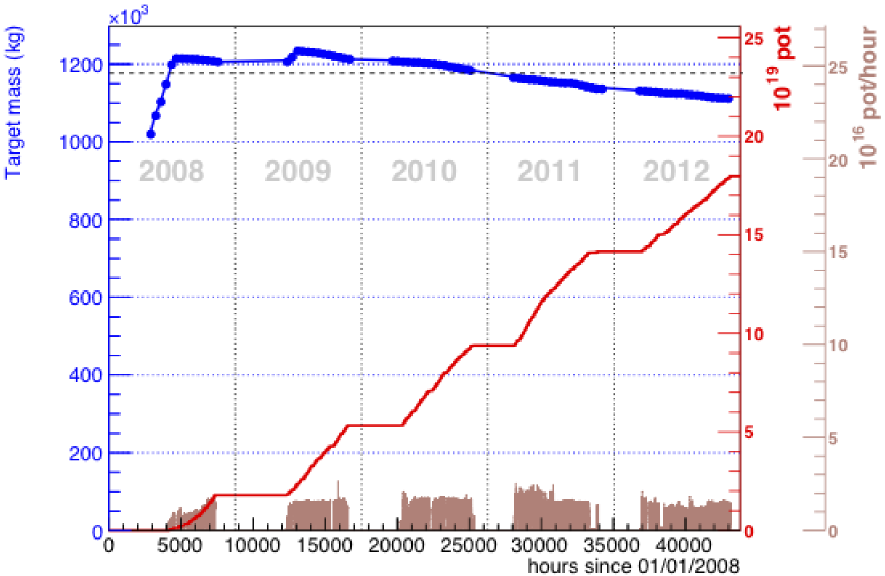
(2) Scanback & Decay search



1. Extrapolate track to upstream film by film from CS until stopping point (Scanback)
2. Volume scan around stopping point
3. Reconstruct high energy tracks
4. Vertexing with the scanback track
5. Decay daughter search with large impact parameter w.r.t. the vertex



Data taking



17.97 x 10^{19} POT

Analysis is on going

6604 events were located

6148 decay searched

(+ ~1000 from XXIXth conference)

1^{st} ν_τ (2009): $\tau \rightarrow h$

NEUTRINO2010
Phys. Lett. B691 (2010) 138

2^{nd} ν_τ (2011): $\tau \rightarrow 3h$

2012 NEUTRINO2012
JHEP 11 (2013) 036

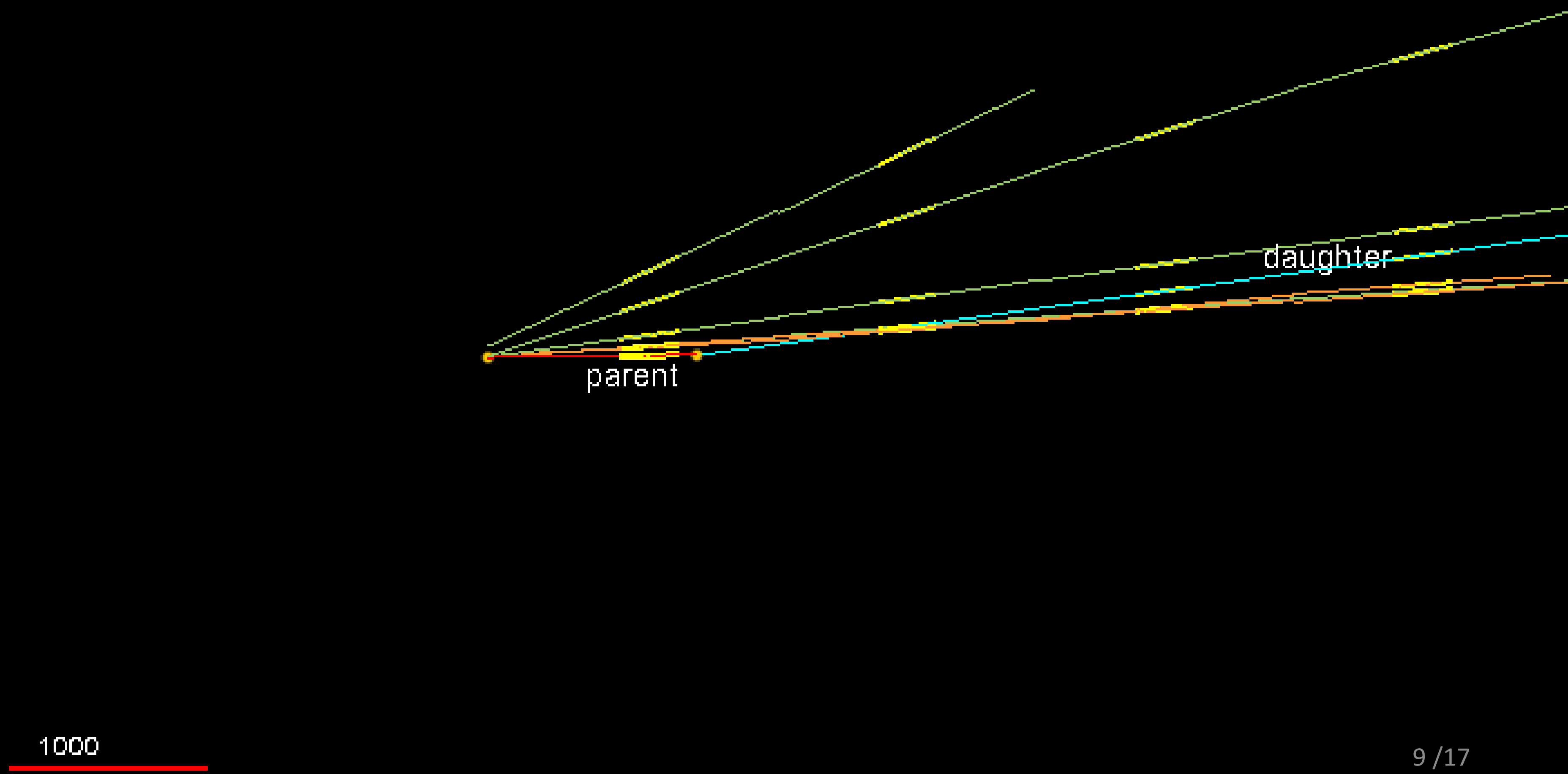
3^{rd} ν_τ (2011): $\tau \rightarrow \mu$

JPS 2013 Spring
Phys. Rev. D 89 (2014) 051102(R)

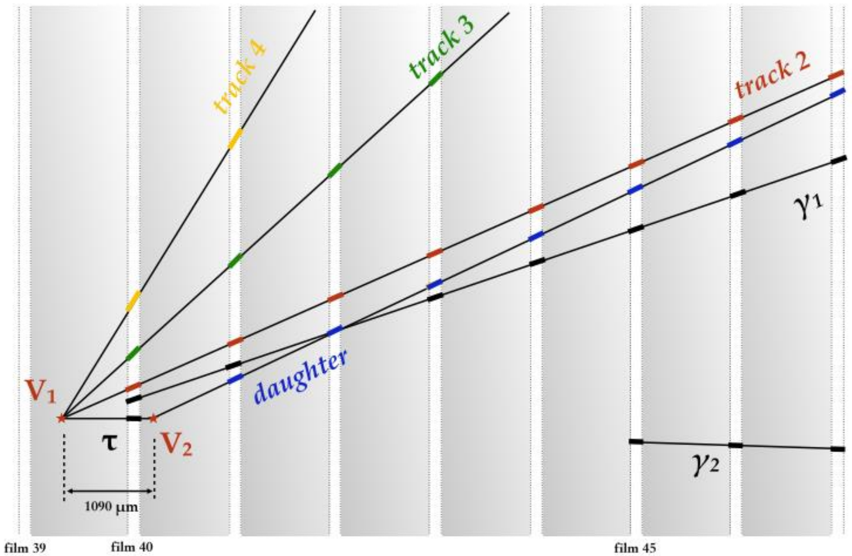
4^{th} ν_τ (2012): $\tau \rightarrow h$ **NEW**

Seminar @ Gran Sasso (2014 March)
JPS 2014 Spring
NEUTRINO2014

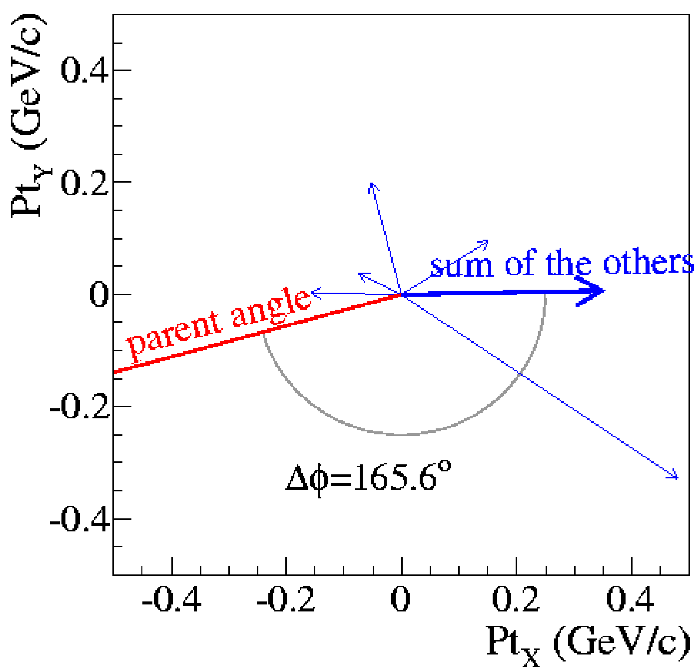
The 4th ν_τ event ($\tau \rightarrow h$)



Kinematics



	ID	Slopes	P (GeV/c)
1ry	1 parent	**-0.144, 0.020**	**-**
	2	**-0.046, 0.078**	**1.9 [1.7, 2.2]**
	3	**0.131, 0.146**	**1.1 [1.0, 1.2]**
	4	**-0.082, 0.352**	**0.7 [0.6, 0.8]**
	γ1	**-0.234, 0.062**	**0.7 [0.6, 0.9]**
	γ2	**0.113,-0.024**	**4.0 [2.6, 8.7]**
2ry	daughter	**-0.088, 0.147**	**6.0 [4.8, 8.2]**

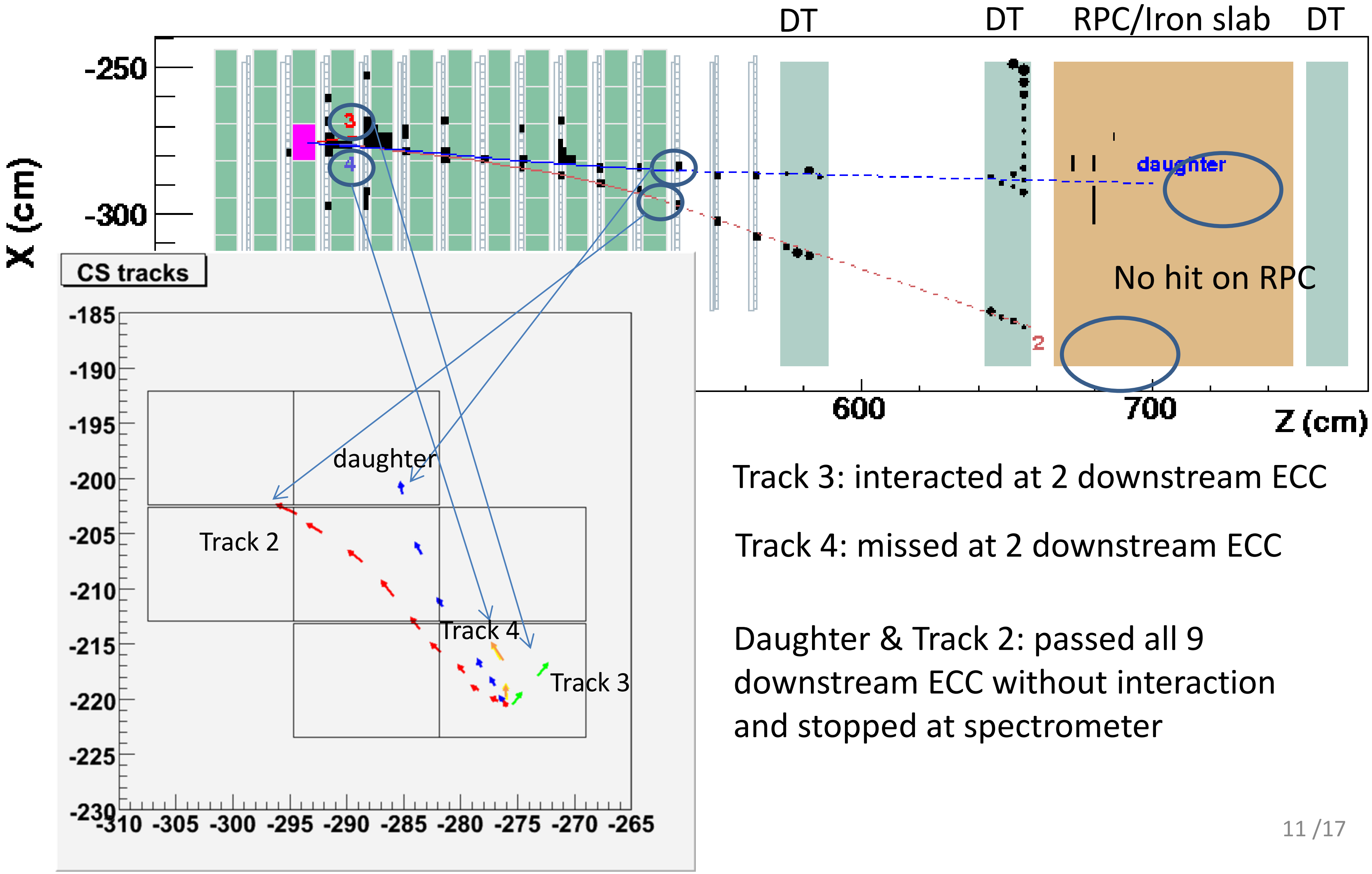


Good picture as tau:
Large phi angle (back-to-back)
Large Pt at kink (0.82 GeV/c).

Particle ID is important to reject backgrounds from nm CC interaction and determine decay channel

Particle ID

Track follow down was performed on relevant ECC for all tracks

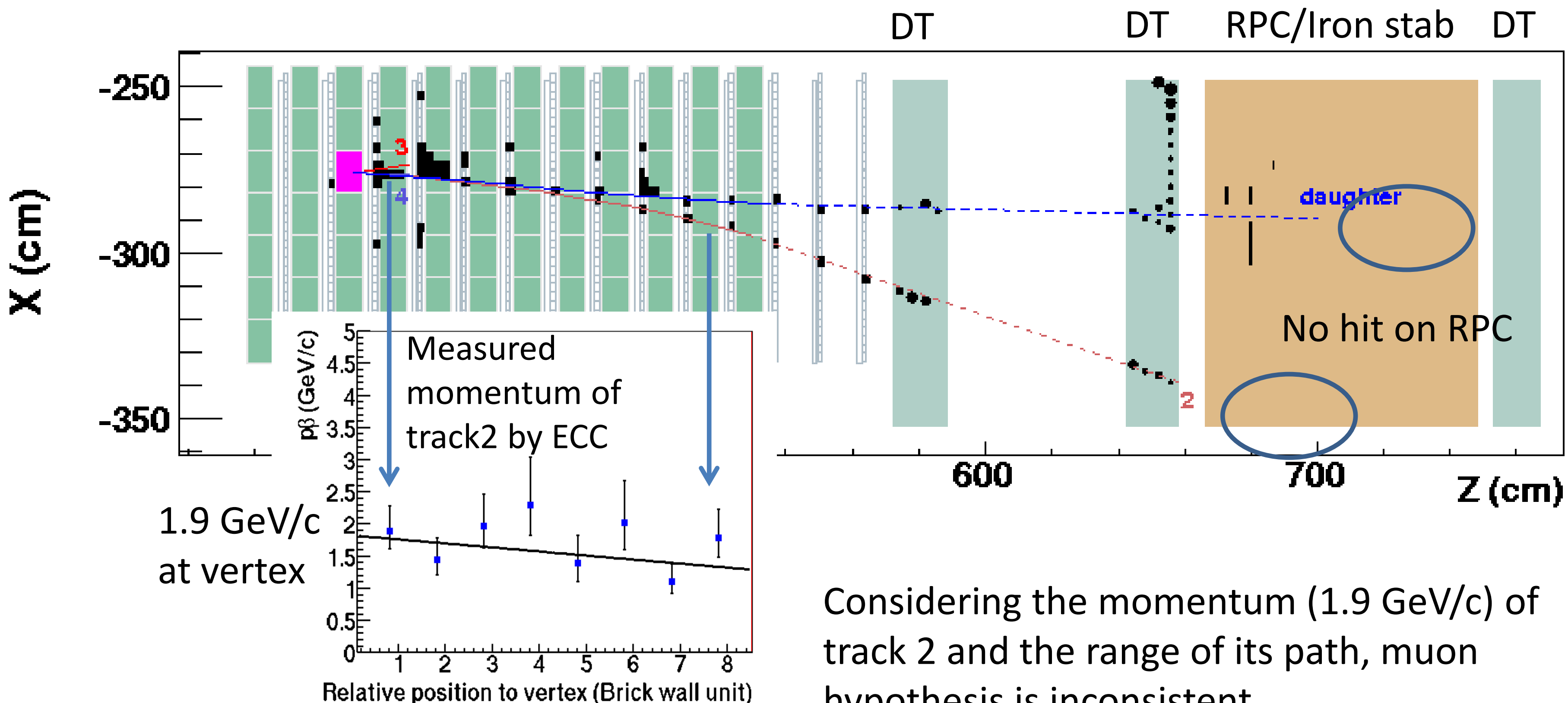


Track 3: interacted at 2 downstream ECC

Track 4: missed at 2 downstream ECC

Daughter & Track 2: passed all 9 downstream ECC without interaction and stopped at spectrometer

Particle ID



Considering the momentum (1.9 GeV/c) of track 2 and the range of its path, muon hypothesis is inconsistent.

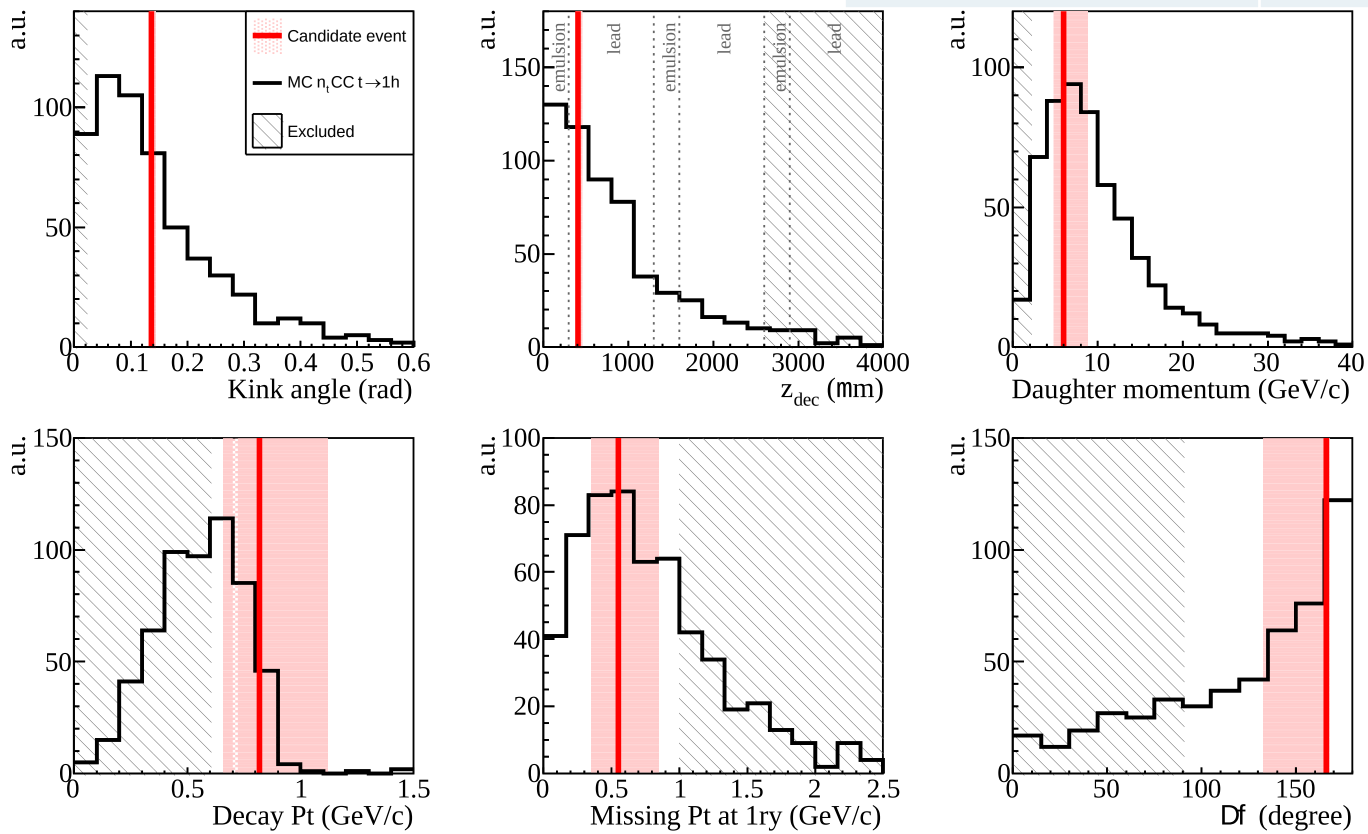
Track 2 is hadron.
Daughter also was judged as hadron by same analysis

→ No muon at 1ry vertex

Criteria

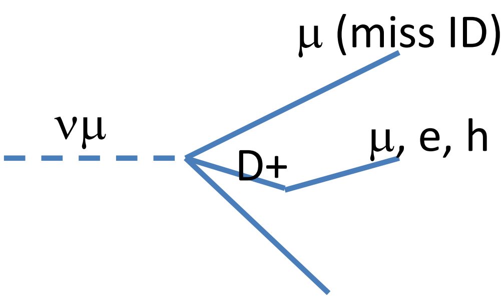
Passed all the cut for $\nu\tau$

	Using the mean values	Selection criteria
P daughter (GeV/c)	$6.0^{+2.2}_{-1.2}$	>2
P_t at kink (GeV/c)	$0.82^{+0.30}_{-0.16}$	>0.6
P_t miss at 1ry (GeV/c)	$0.55^{+0.30}_{-0.20}$	<1
Phi (deg)	166^{+2}_{-31}	>90
Kink angle (deg)	137 ± 4	>20
Flight length (um)	1090 ± 30	<2600

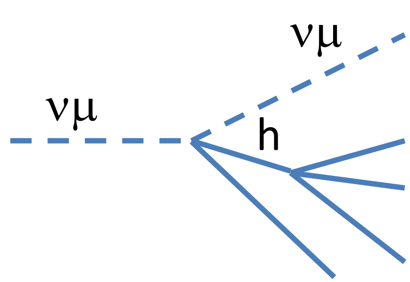


Background source

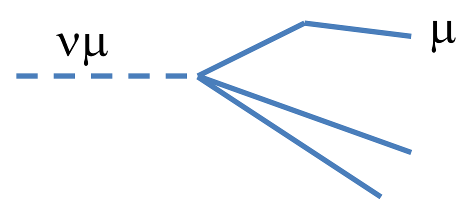
1. Charmed hadron with missed muon



2. Hadronic interaction



3. Large angle scattering of muon



Estimation by MC
Validation by OPERA data or test beam.

Oscillation analysis

Data samples
4686 events (979 0μ + 3707 1μ)

2008 – 2009: 1st brick + 2nd brick
2010 – 2012: 1st brick

Decay channel	Signal expectation	Total background	Observed events
t → h	0.4 ± 0.08	0.033 ± 0.006	2
t → 3h	0.57 ± 0.11	0.155 ± 0.03	1
t → m	0.52 ± 0.1	0.018 ± 0.007	1
t → e	0.61 ± 0.12	0.027 ± 0.005	0
Total	**2.1 ± 0.42**	**0.23 ± 0.04**	**4**

Combination of four single channel p-value was calculated in order to take account the difference of background with decay channels

P-value = $p^{\star} = \prod_{i=1}^{4} p(n_i, b_i) = \prod_{i=1}^{4} e^{-b_i} \sum_{j=n_i}^{\infty} \frac{b_i^j}{j!}$ = 1.03×10^{-5}

➔ No oscillation was excluded with 4.2σ significance

Observation of ν_τ appearance

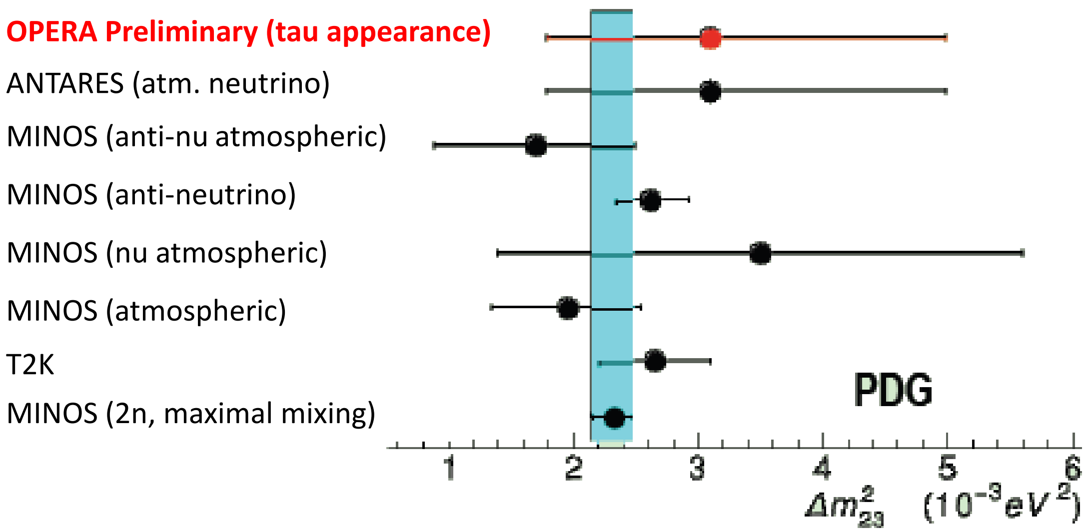
Oscillation parameter from ν_τ appearance

First measurement by ν_τ appearance

$$n_{exp}(\Delta m^2) = \int \Phi(E) \cdot \sigma(E) \cdot oscprob(\Delta m^2, E) \cdot \varepsilon(E)\, dE$$

flux — cross section — detection efficiency

90 % C.L. intervals on Δm^2_{23} by Feldman & Cousin method: $[1.8 - 5.0] \times 10^{-3}\ eV^2$
(assuming full-mixing)



Consistent with other experiments

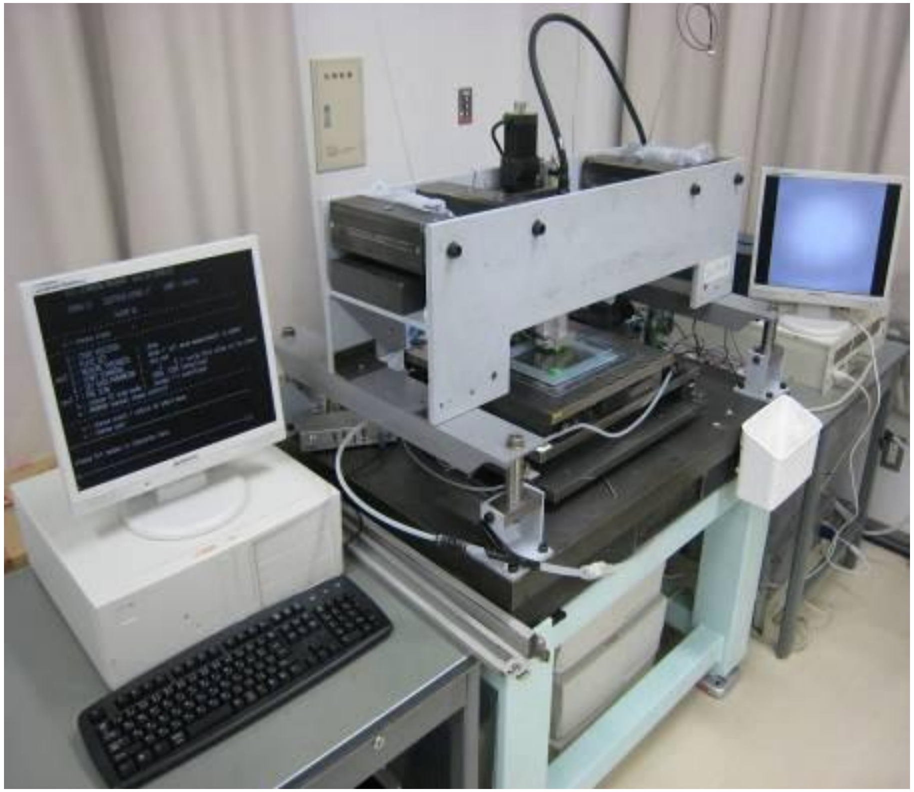
Conclusions

- OPERA aims direct observation of ν_τ from the $\nu_\mu \rightarrow \nu_\tau$ oscillation .
- 17.97 x 10^{19} POT (80% or proposal) of neutrinos were delivered to the detector from 2008 to 2012.
- The analysis on ECC is on going, 6604 neutrino interactions were located up to now.
- The 4th ν_τ candidate was newly found.
- Observation of oscillation at 4.2σ significance.
- The first measurement of Δm^2_{23} by appearance mode was done. The value [1.8 – 5.0] x 10^{-3} (90 % C.L.) is consistent with other experiments.

Backup

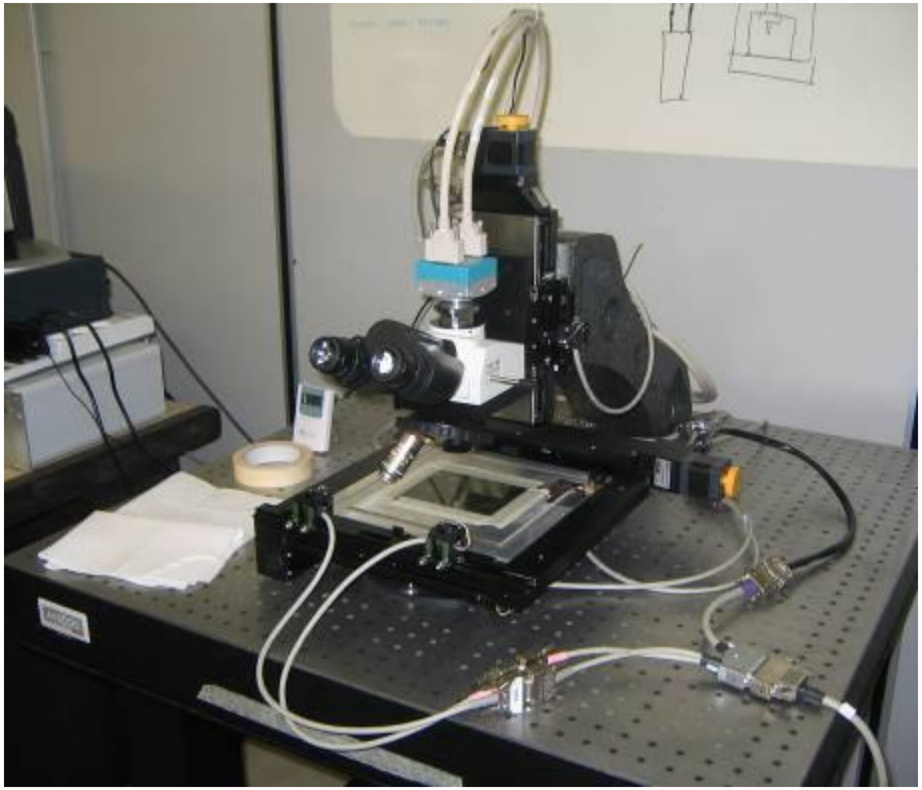
Automatic scanning system

Japanese Scanning System (S-UTS)



Scanning speed/system: 75cm2/h
x 5 system

European Scanning System (ESS)

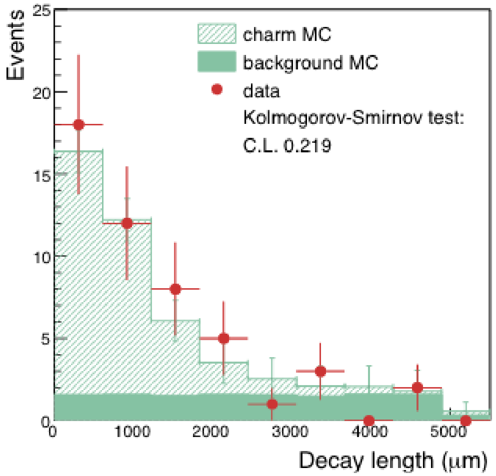


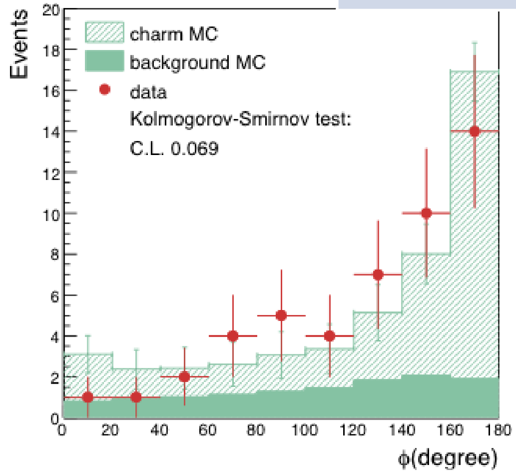
Scanning speed/system: 20cm2/h
x 10 system

The Scanning analysis is divided half-and-half to Japanese and European lab.

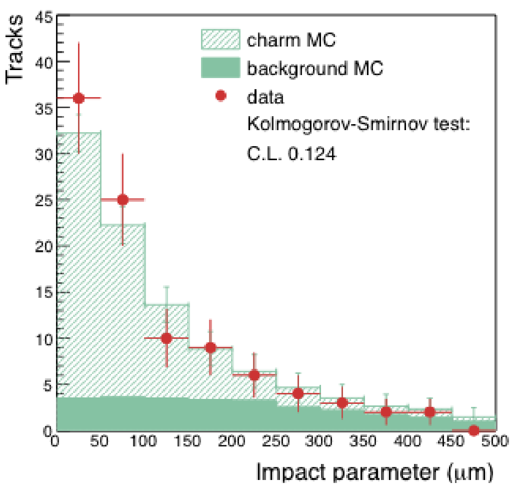
Charm control sample

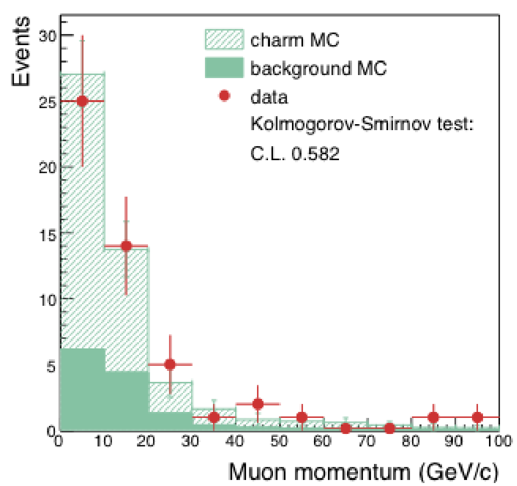
	expected	Data
1 prong	30 ± 4	19
2 prong	18 ± 2	22
3 prong	5 ± 1	5
4 prong	0.9 ± 0.2	4
toal	54 ± 4	50





Phi: The angle between 1ry muon and charm in transverse plain



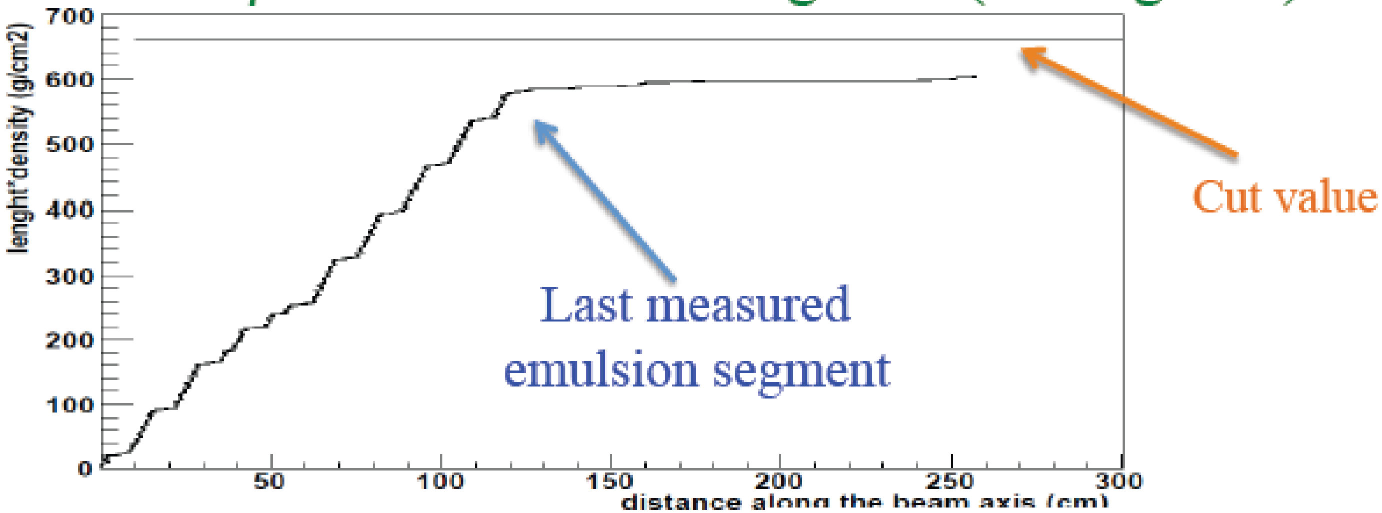


Charm hadrons have near mass and lifetime as tau

Guarantee Decay search efficiency

Measured length x density, Lρ

Lρ for the track = 604 g/cm² (<660 g/cm²)



$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.40^{+0.04}_{-0.05}$$

- Prob. for a μ to cross ≤ 12 planes ~ 0.35%
- Prob. for a π to cross ≥ 12 planes ~ 10.2%