Recent results from the OPERA experiment

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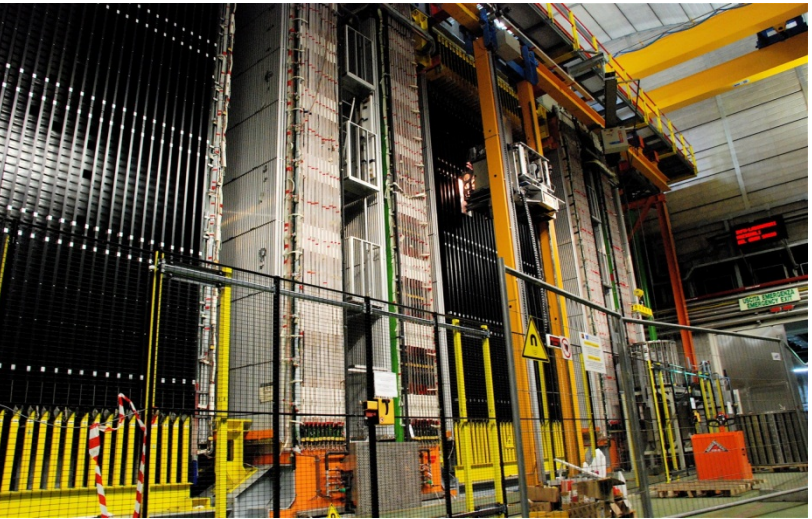
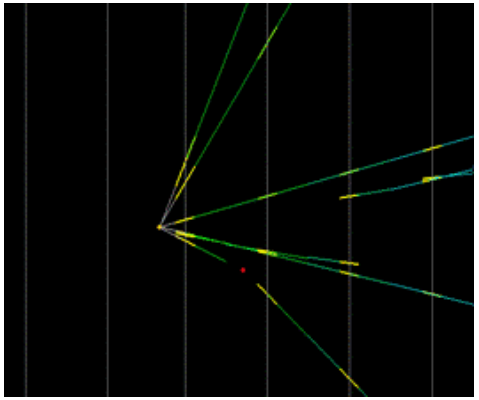
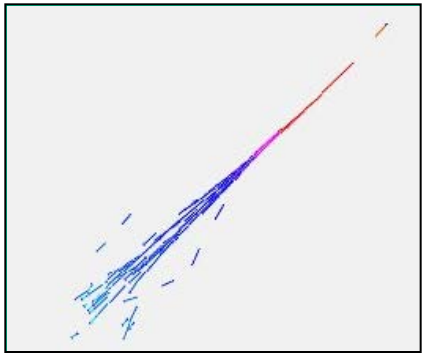
On behalf of the OPERA Collaboration

- Introduction
- Experimental setup: CNGS and detector
- Data Analysis and Oscillation search
- Conclusions







TAUP 2013, Asilomar

September 9th 2013

The OPERA collaboration

~ 140 physicists, 28 institutes, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

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

Switzerland
Bern

Turkey
METU Ankara

- July 2000: Experiment proposal
- May 2003: start construction at LNGS
- summer 2006: 1st run with cosmics and CNGS beam to Gran Sasso
- autumn 2007: 1st CNGS beam with ν interactions seen in the target
- July 2008: Emulsion target completed: start of ν physics run
- Dec. 2012: End of ν physics run

CNGS/OPERA: European Long Base-line ν project:

- motivated by the **atmospheric ν disappearance** results and the discovery of neutrino oscillation in 1998
- 3-flavour oscillation formalism (PMNS matrix) describes with success the major results from solar, atmospheric, reactor and neutrino beam experiments
  - ➢ Most results from ν disappearance (ν_e, ν_μ, $\bar{\nu}_\mu$, $\bar{\nu}_e$)

  => Oscillation picture should be tested in **different ν flavour appearance mode**

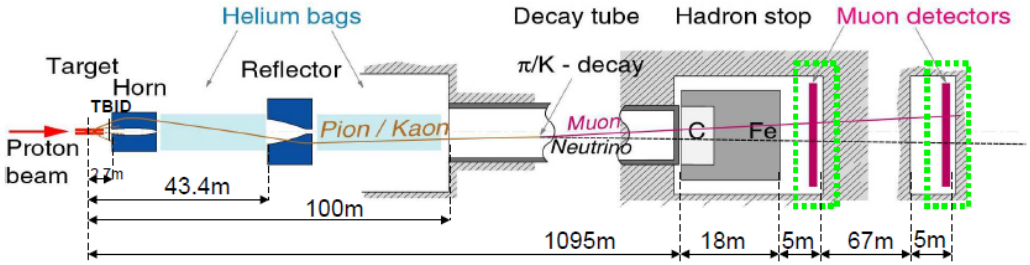
In the CERN high energy ν_μ beam (CNGS):

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \cos^4(\theta_{13})\sin^2(2\theta_{23})\sin^2\left(1.27\frac{\Delta m^2_{23} L}{E}\right)$$

- search for direct ν_τ appearance at the Gran Sasso underground laboratory (730 km from CERN)

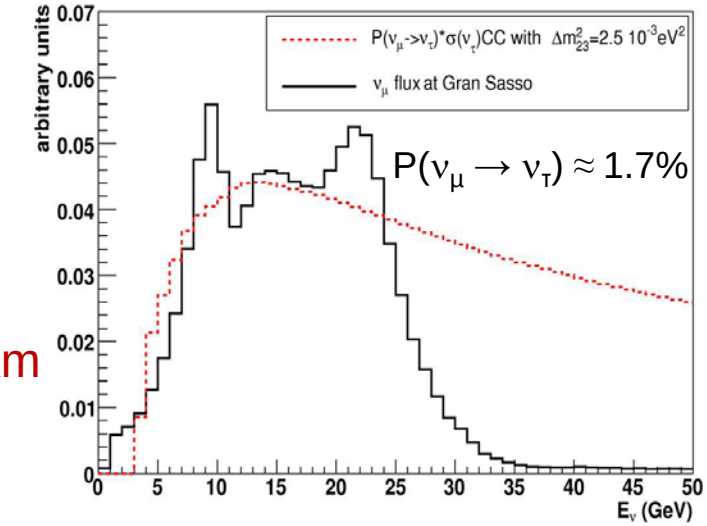
- search for $\nu_\mu \rightarrow \nu_e$ and put constraints on non standard oscillation

CNGS: CERN Neutrinos to Gran Sasso



ν to Gran Sasso

L=730 km

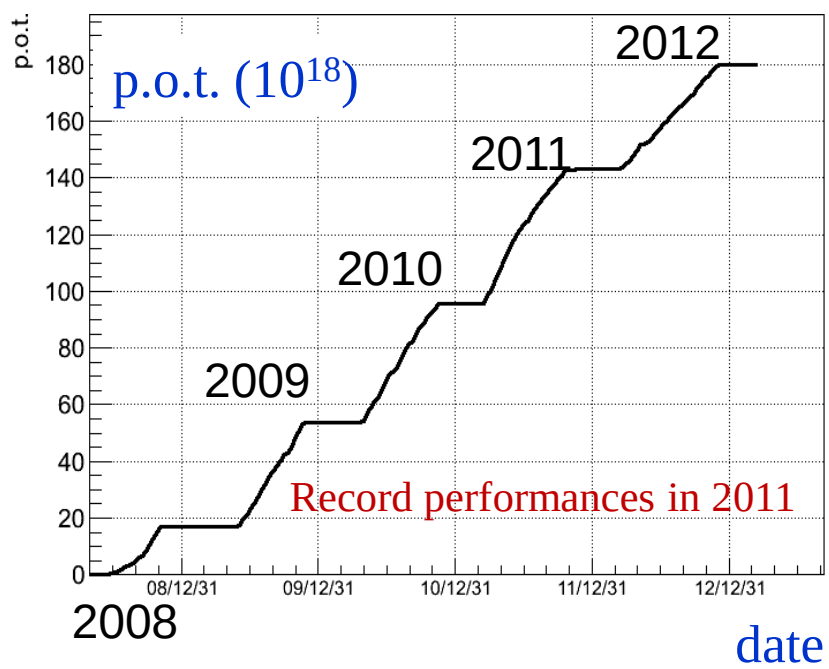


Conventional ν beam: 400 GeV protons from SPS

- 2 fast extractions (10.5 μs), separated by 50 ms / SPS cycle (6 s) => 2 10^{13} protons/extraction

=> Average beam power: 160 kW (peak: 480 kW)

ν_μ flux optimized to maximize the ν_τ charged current interactions



$< E >_\nu$	**17 GeV**
$(\nu_e + \bar{\nu}_e)CC$ / $\nu_{\mu CC}$	**0.9 %**
$\bar{\nu}_{\mu\ CC}$ / $\nu_{\mu\ CC}$	**2.1 %**
ν_τ **prompt**	**negligible**

CNGS operation: 2008 => 2012

total intensity delivered:

18.08 x10^{19} p.o.t.

LNGS: Gran Sasso National Laboratory (Italy, 120 km from Rome)

Underground laboratory:

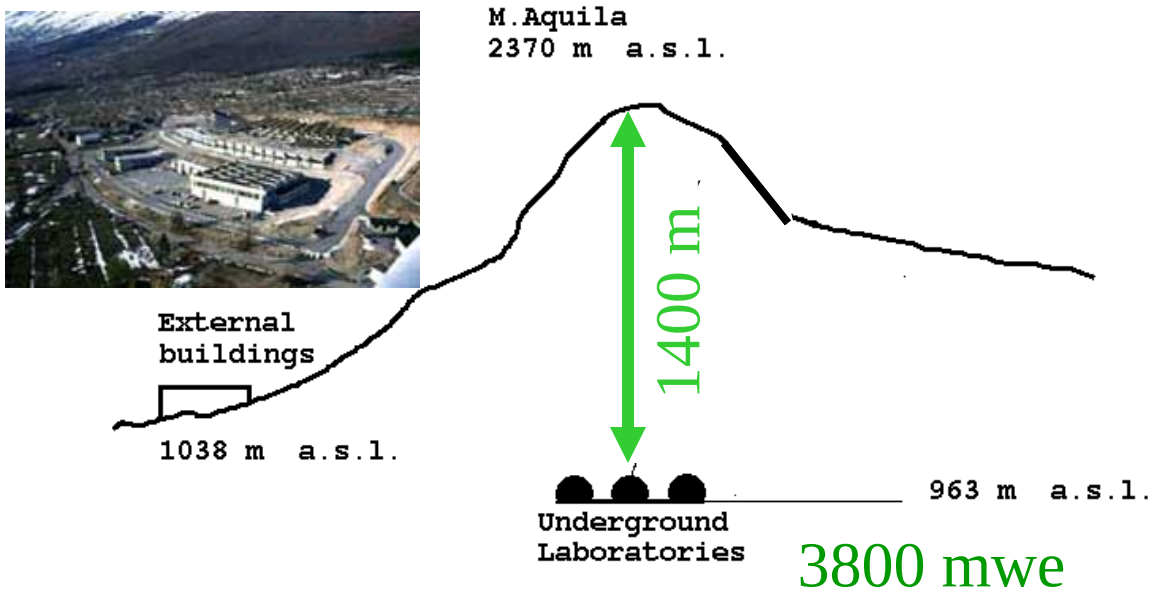
good cosmic ray shielding

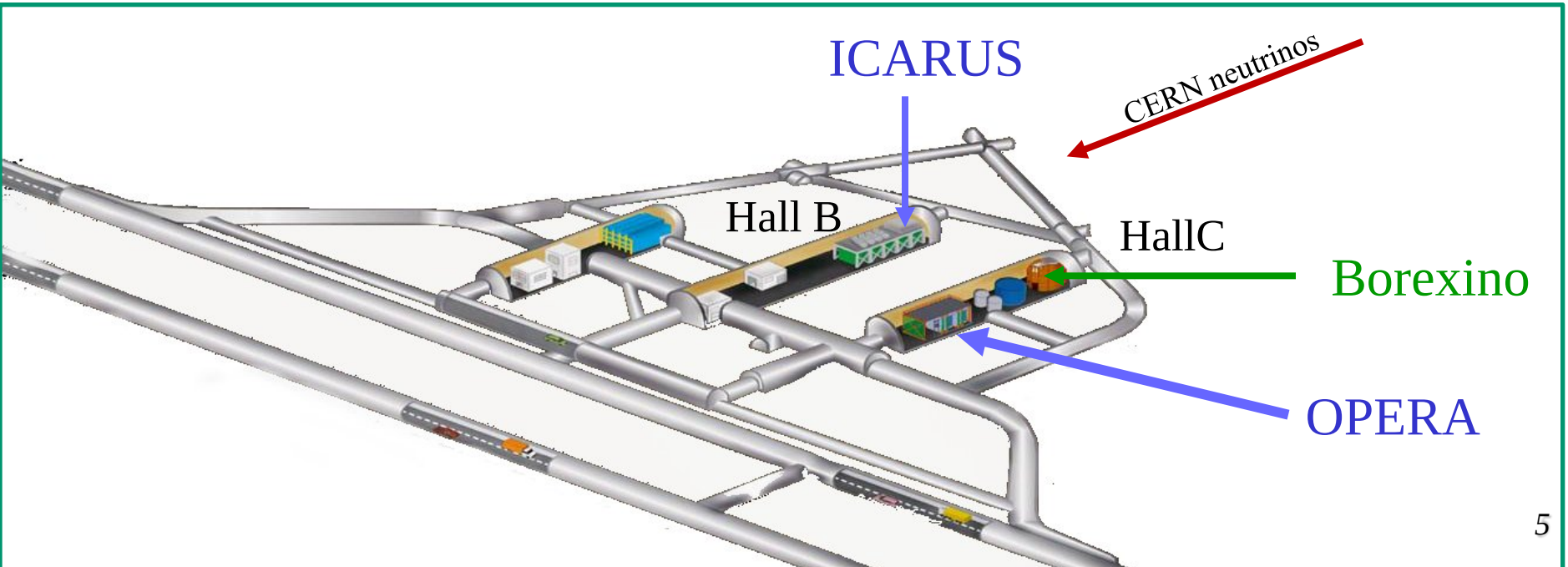
1 cosmic/m^2/hr

3 large experimental halls

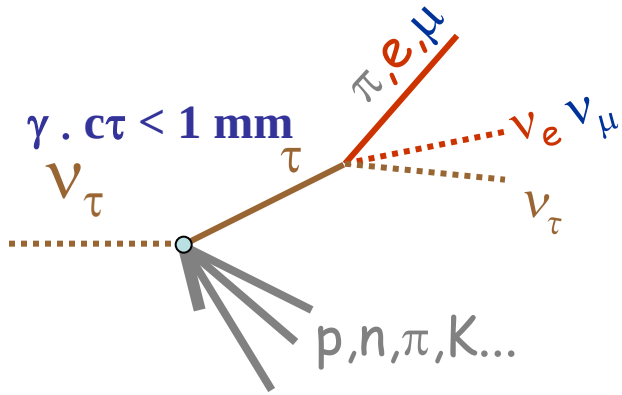
(100 m x 20 m x 18 m)

directed towards CERN





Experimental signature for ν_τ appearance:



τ decay modes:

$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$	BR 17.4 %
$h^- \ \nu_\tau \ n\pi^o$	49.5 %
$e^- \ \nu_\tau \ \bar{\nu}_e$	17.8 %
$h^+ \ h^- \ h^- \ \nu_\tau \ n\pi^o$	15.2 %

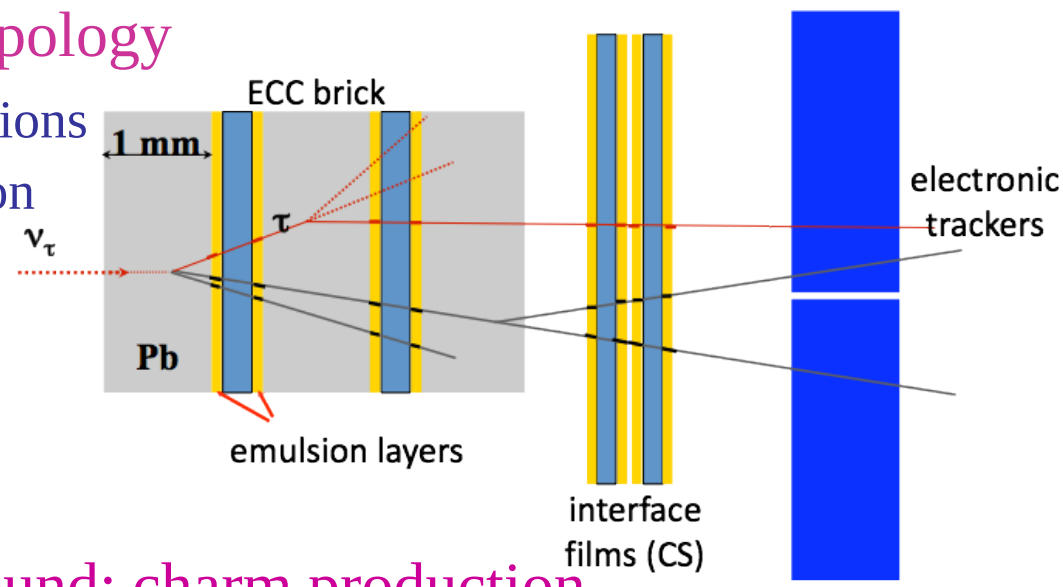
→ detect and identify the ν_τ charged current (CC) events

OPERA Principle: hybrid detector with modular structure

direct observation of τ decay topology

→ μm resolution: photographic emulsions

→ large target mass: alternate emulsion films with lead sheets



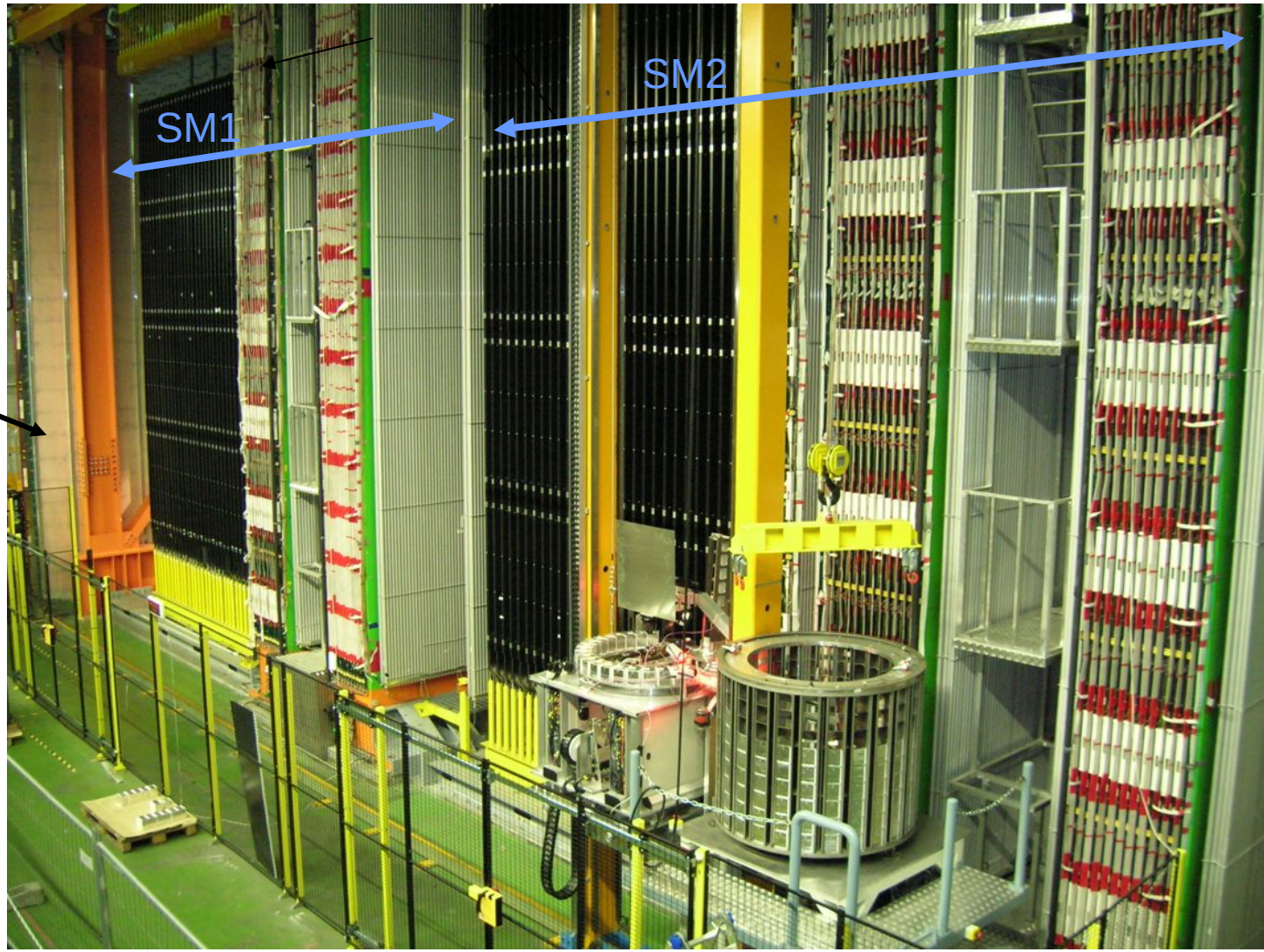
reject main topological background: charm production

→ good muon id and charge: use electronic detectors also for trigger and event localisation

1.25 kton detector at Gran Sasso (Hall C)

2 identical
Super Modules (SM)

Veto plane
(glass RPC)



JINST 4(2009) p04018

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Super Modules (SM)

Veto plane
(glass RPC)

Target and Target Tracker (6.7*m*)^2

- **Target : 74500 bricks, 26 walls**
- **Target tracker : 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT**

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High precision tracker
- **6 4-fold layers of drift tubes**

Instrumented dipole magnet
- **1.53 *T***
- **22 XY planes of RPC**

Muon spectrometer (8×9 *m*^{2})

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see also poster
from A. Hollnagel

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Δp/p (<50 GeV/c)	~ 20%
μ ID (with TT)	~ 95%

JINST 4(2009) p04018

High precision tracker
- **6 4-fold layers of drift tubes**

Instrumented dipole magnet
- **1.53 *T***
- **22 XY planes of RPC**

see also poster
from A. Hollnagel

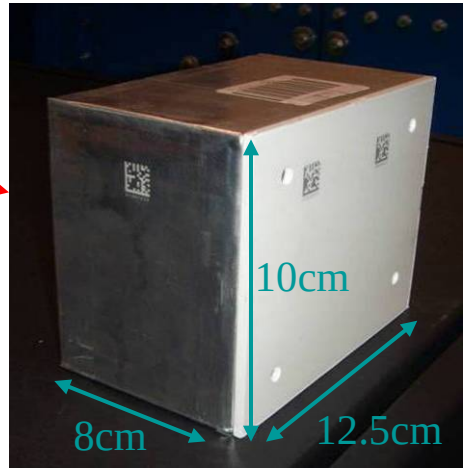
Muon spectrometer (8×9 *m*^{2})

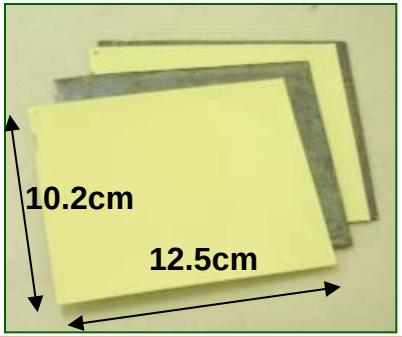
OPERA target: Modular detector: basic unit brick

56 Pb sheets (1mm) + 57 FUJI emulsion films +1 changeable sheet doublet (CS)

8.3 kg
$10X_0$

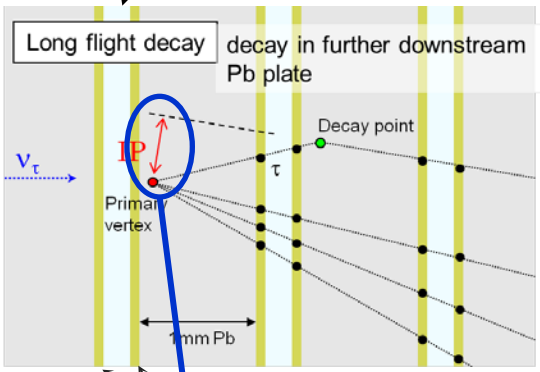
ν





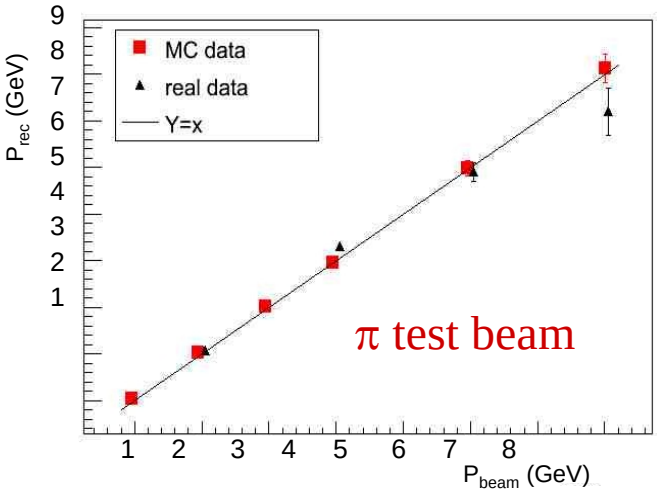
Track segment resolution:
σ(angle) = 2.1 mrad
σ (position) = 0.21 μm

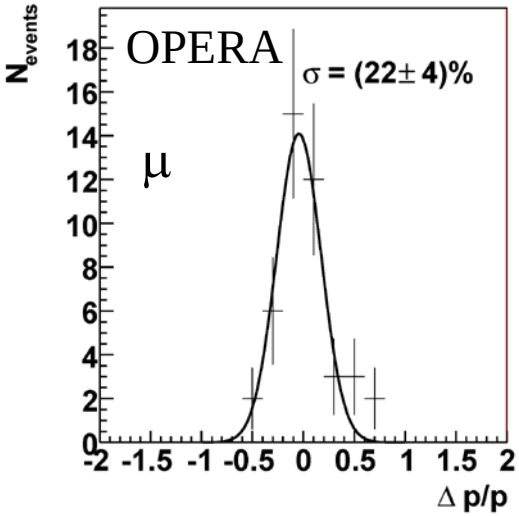
plastic base 200 μm thick

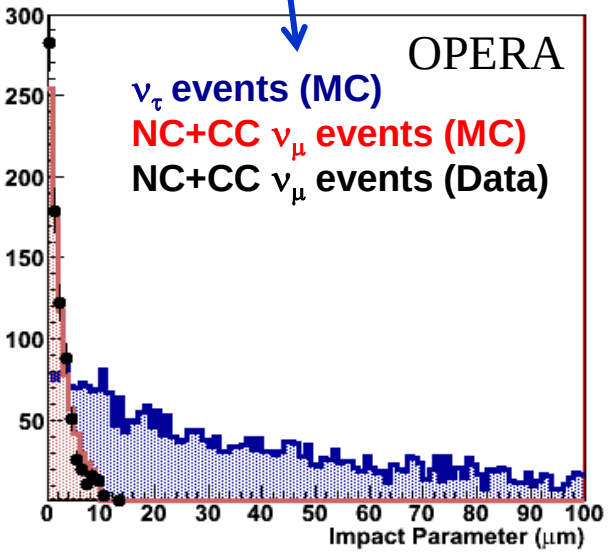


emulsion layers (44 μm thick)

Measurement of particle **momentum** by Multiple Coulomb Scattering in lead NJP 14 (2012) 013026

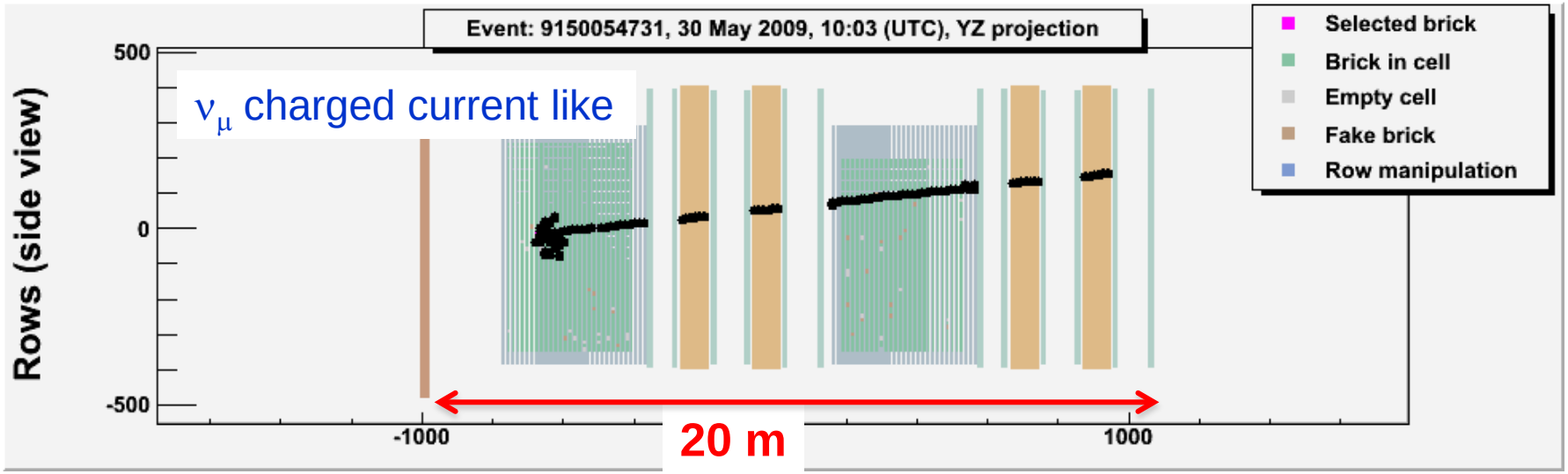






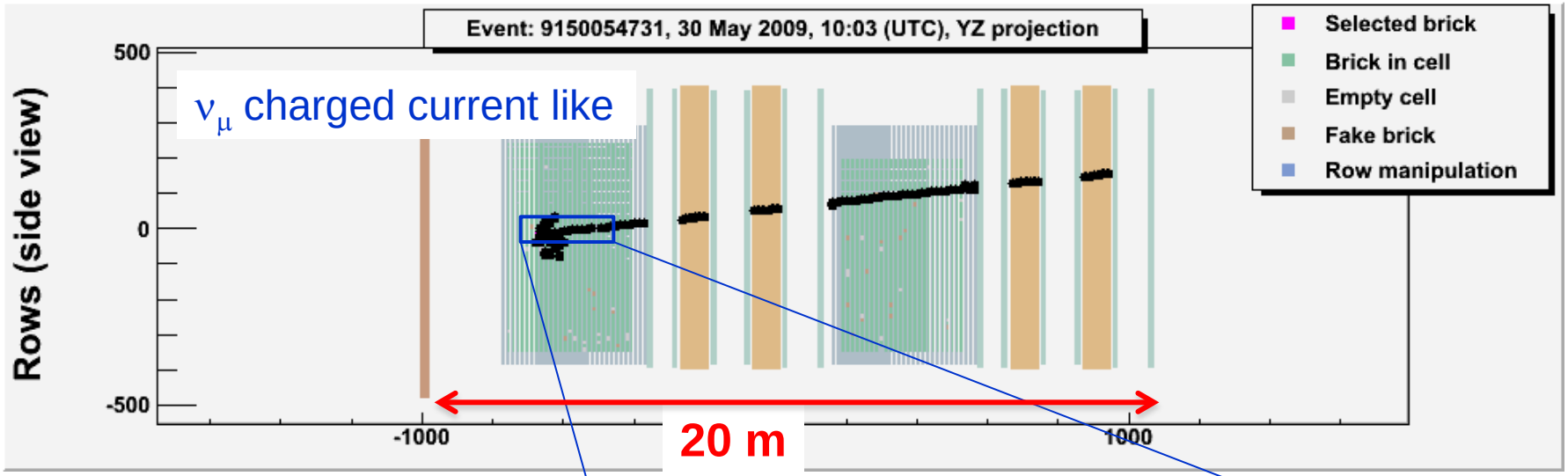
Vertex position resolution : ~1μm in transverse plane

OPERA Event analysis

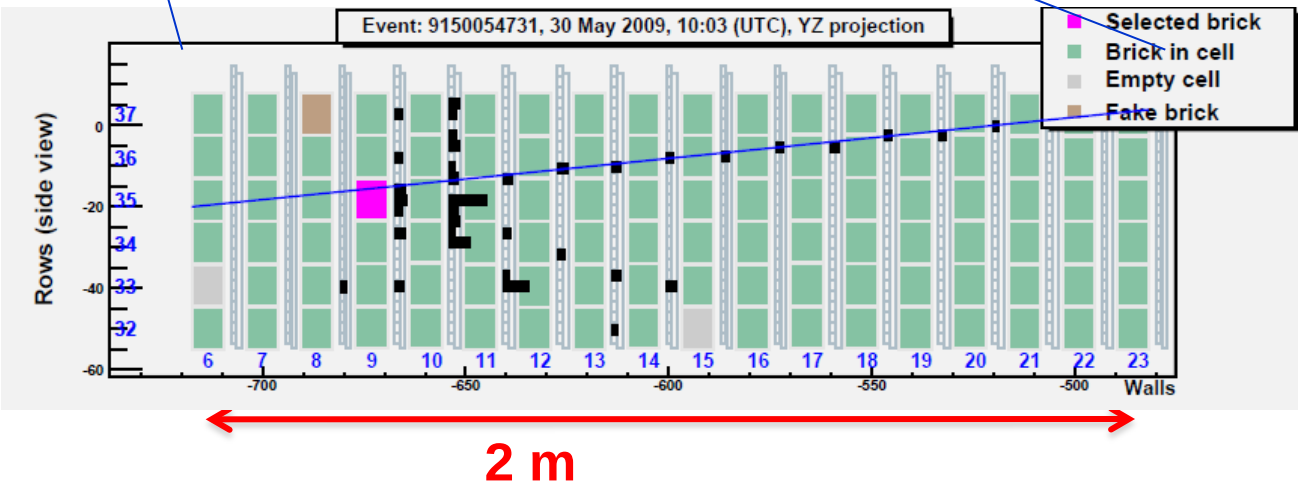


- Beam on time event
  DAQ: trigger, selection
- Electronic detector
  reconstruction

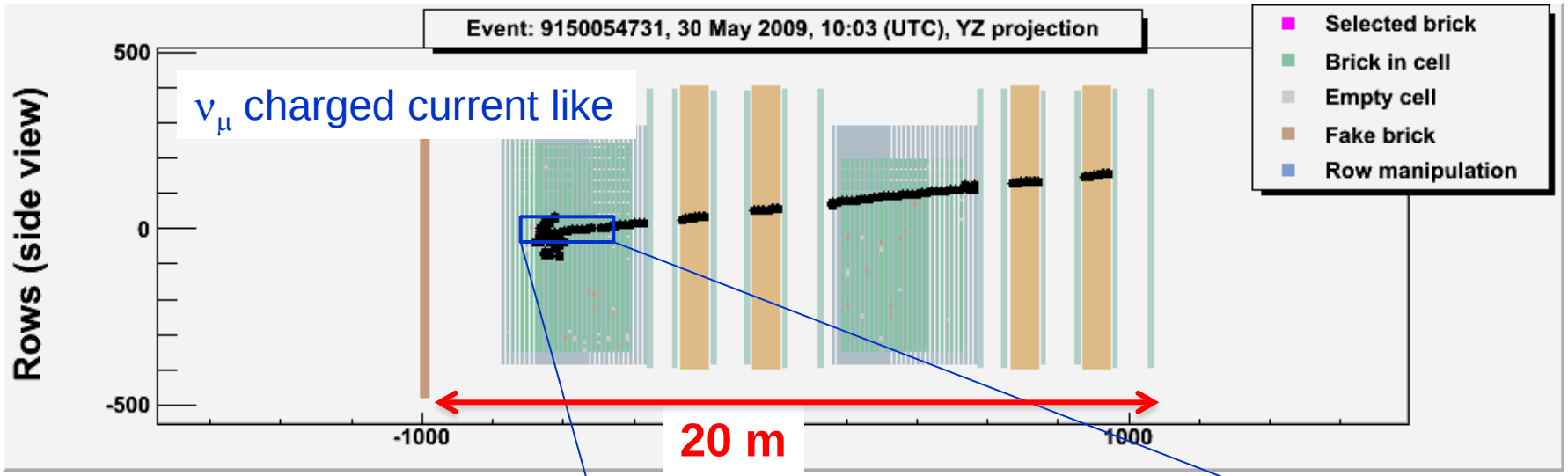
OPERA Event analysis



- Beam on time event DAQ: trigger, selection
- Electronic detector reconstruction
  - Brick Finding



OPERA Event analysis



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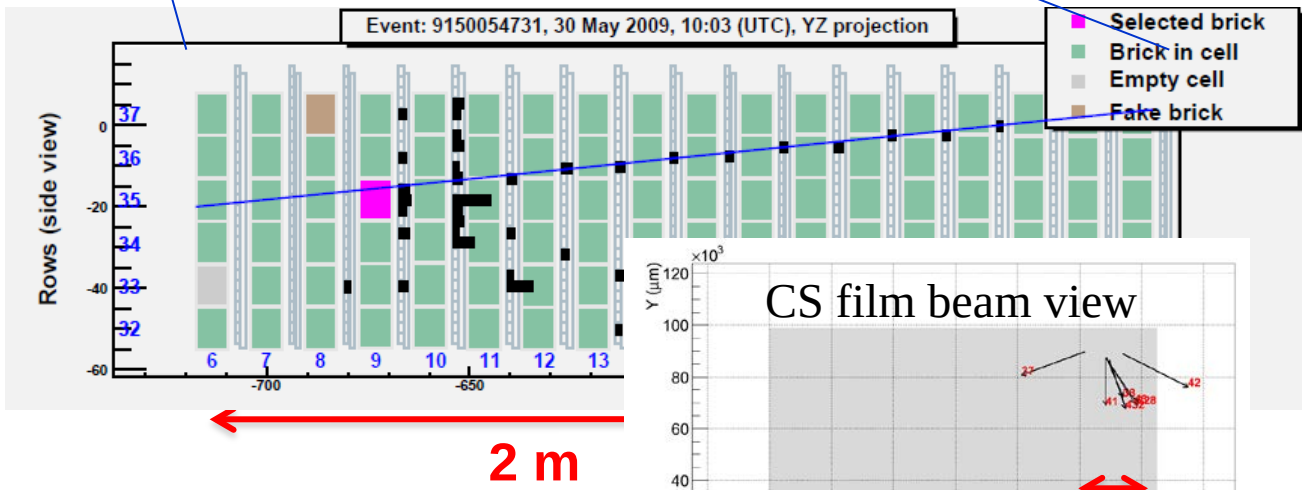

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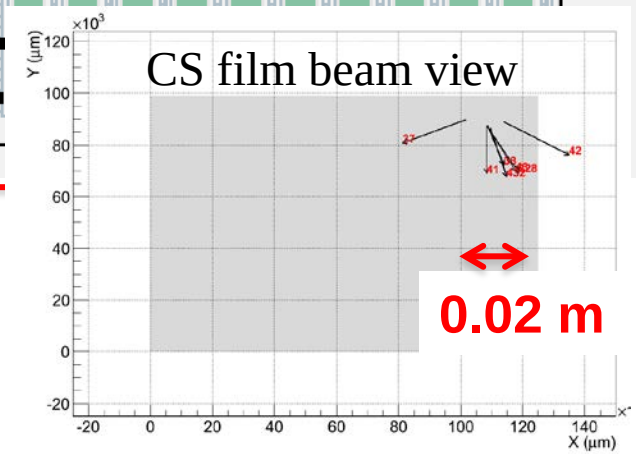
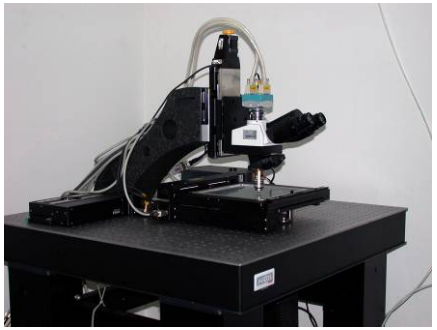


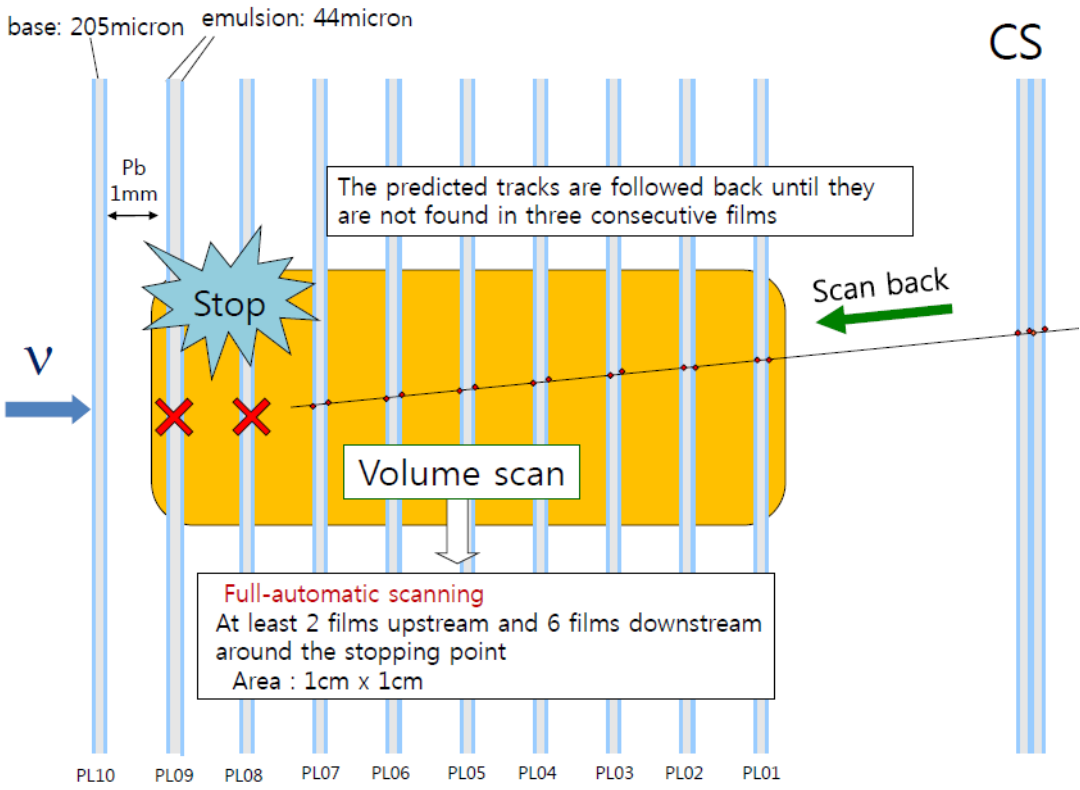
- CS scanning and brick validation
- Send Brick to development
- Emulsion scanning

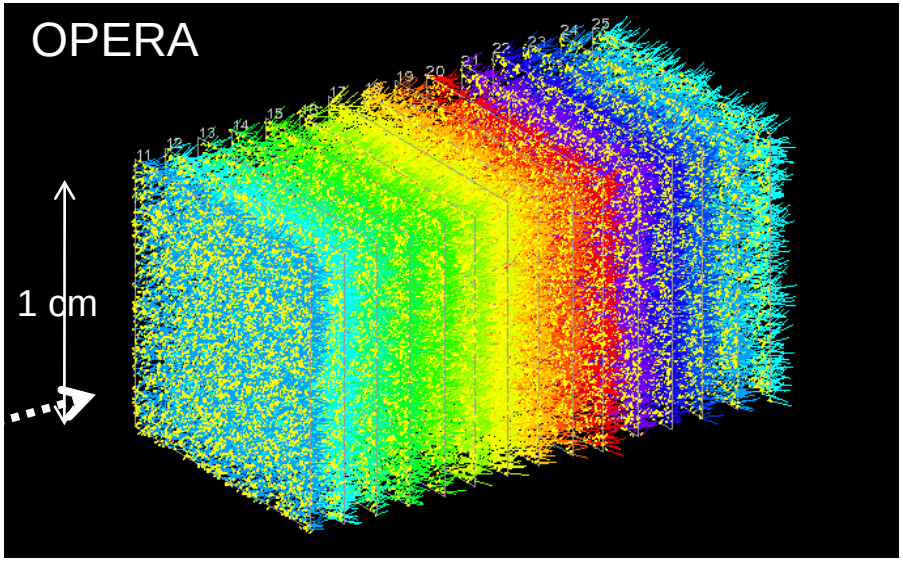
Interaction location and vertex reconstruction

Emulsion analysis: 40 automated microscopes in Japan in Europe



Volume scan (~2 cm^3) around each stopping point





Scan about 10 films around vertex: Track reconstruction in several films

Interaction location and vertex reconstruction

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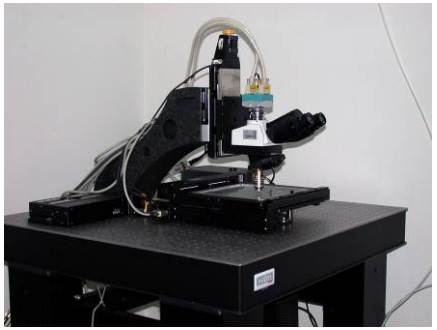

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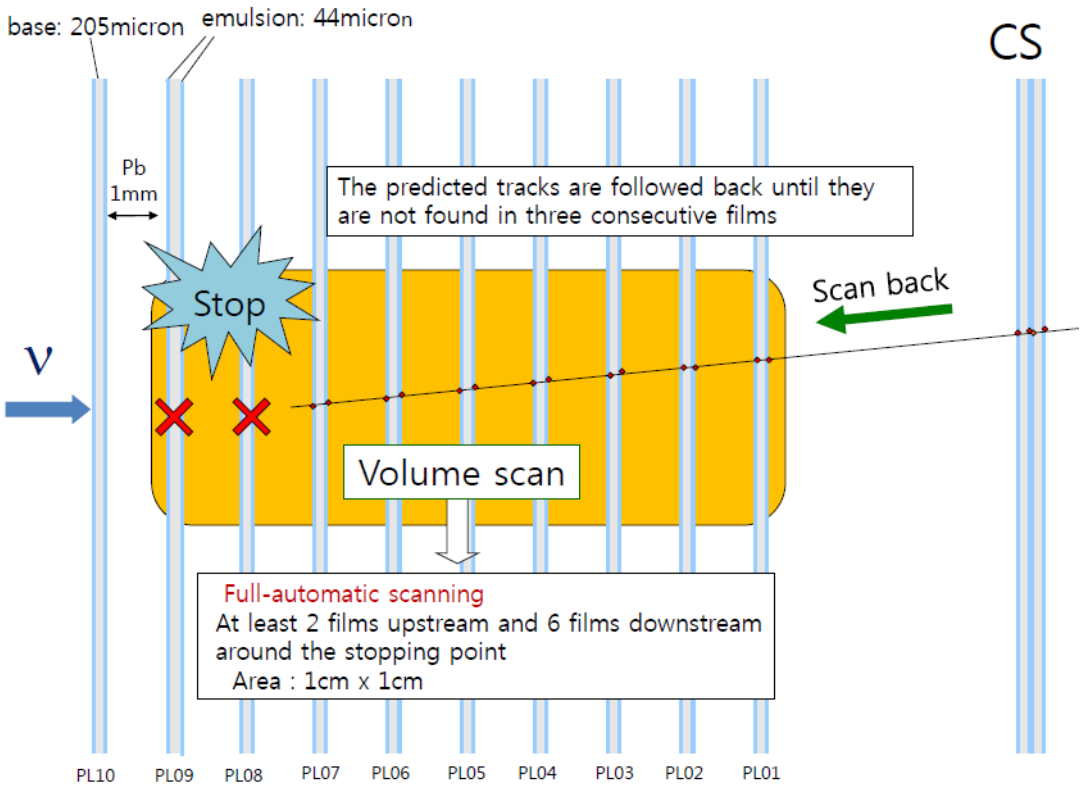

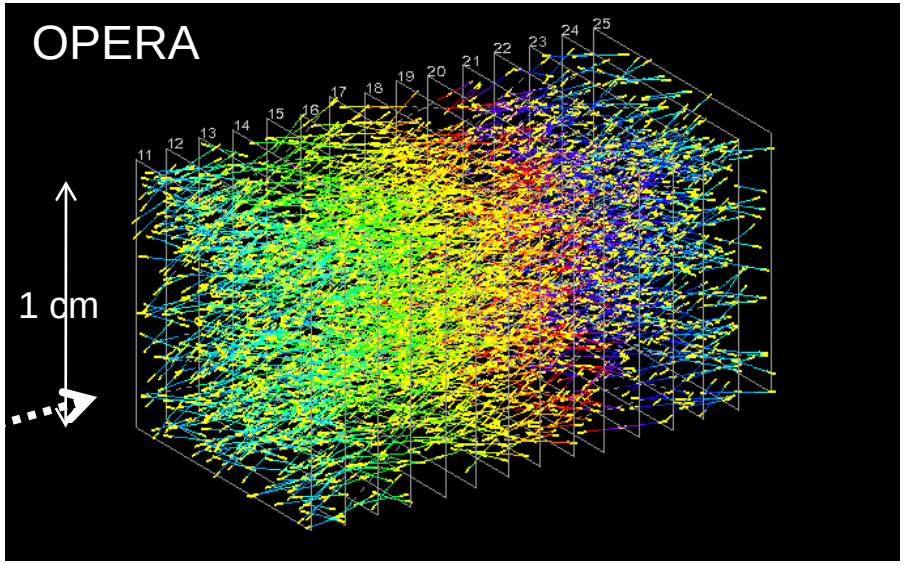

Scan about 10 films around vertex: Track reconstruction in several films

Reject passing through and short tracks

Interaction location and vertex reconstruction

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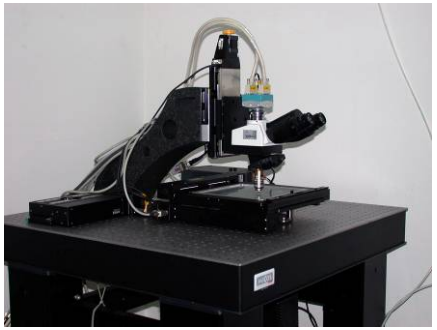
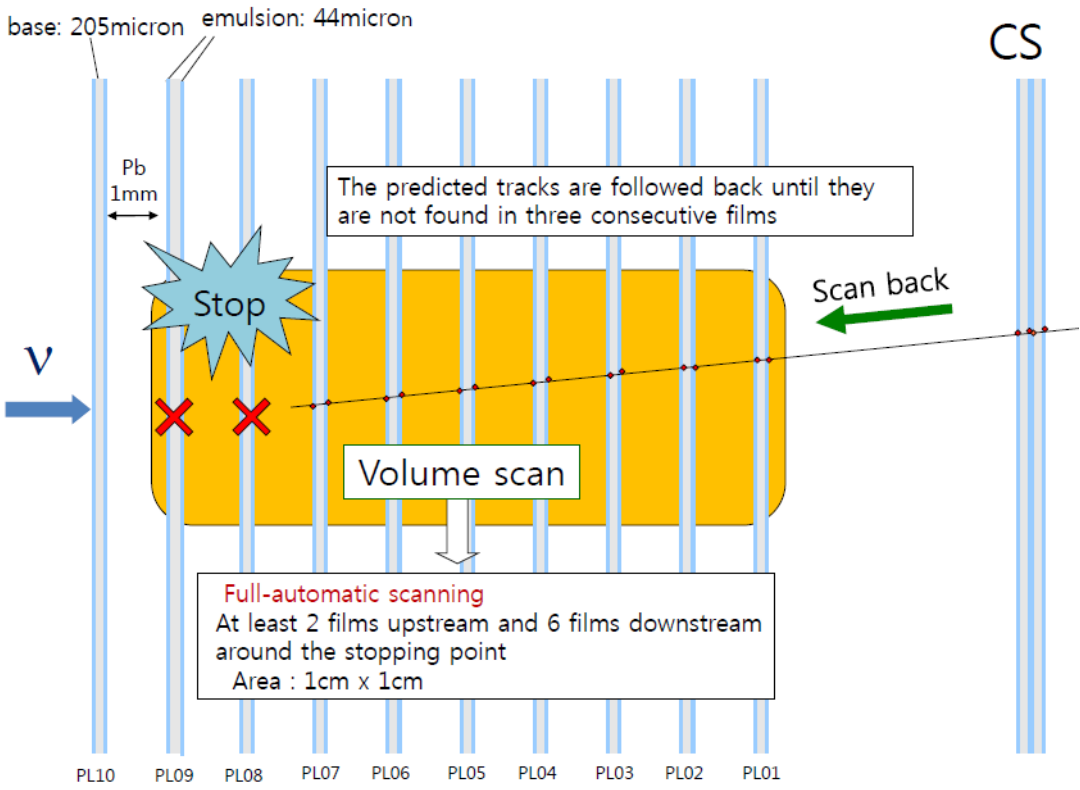
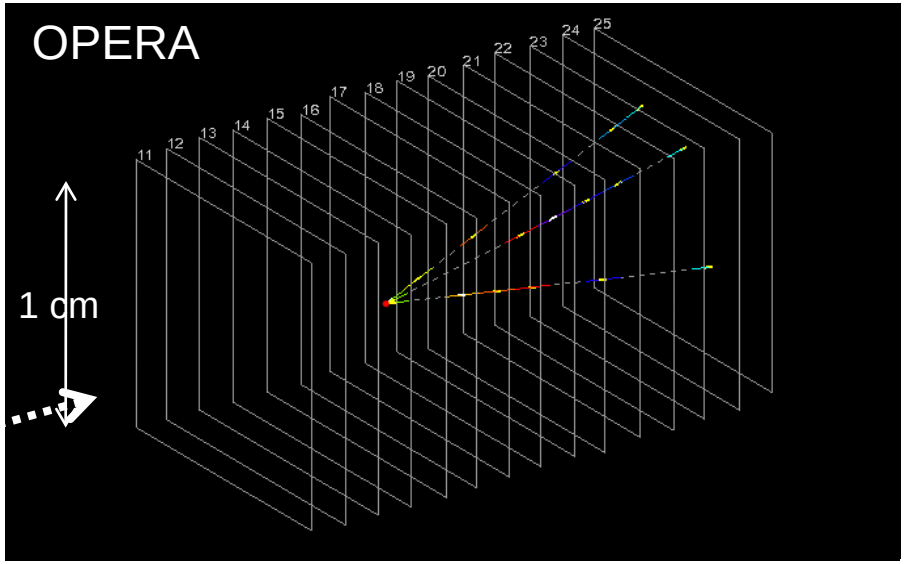


Vertex location efficiency:

74% CC

48% NC





Scan about 10 films around vertex:
Track reconstruction in several films

Reject passing through and short tracks

Search tracks pointing to an interaction vertex
→ Decay Search procedure

Status of data analysis

total intensity collected: 17.97×10^{19} p.o.t.

Year	Protons on target	SPS Eff.	Beam days	ν interactions
2008	1.74×10^{19}	61%	123	1931
2009	3.53×10^{19}	73%	155	4005
2010	4.09×10^{19}	80%	187	4515
2011	4.75×10^{19}	79%	243	5131
2012	3.86×10^{19}	82%	257	3923

20% less than the experiment proposal value ($22.5\ 10^{19}$ p.o.t.)

$\varepsilon_{trigger} = 99\%$

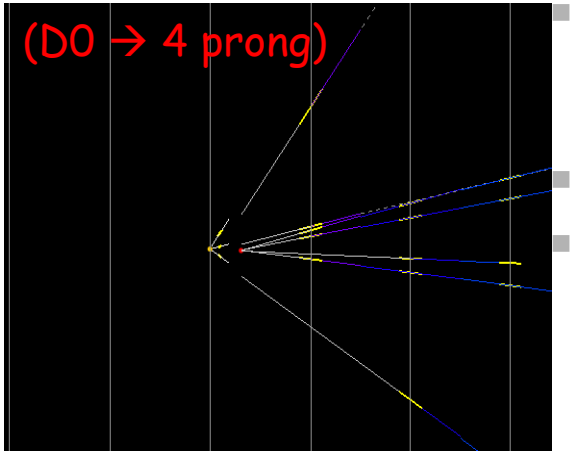
- 106 422 on time events recorded
- 60% are external rock events
- 20% are spectrometer interactions

19505 recorded ν interactions in the OPERA target

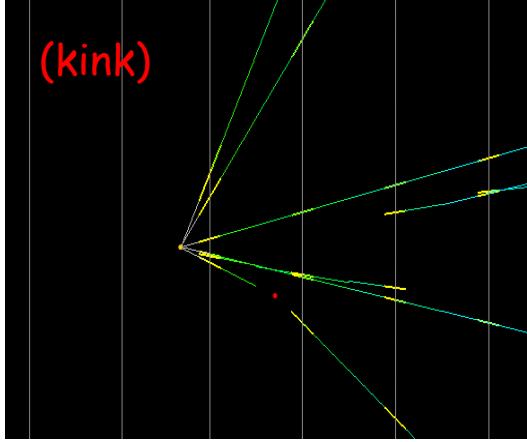
83% are reconstructed in the target

Years	p.o.t. ($\times 10^{19}$)	Status	Selected Data sample	# of Decay Searched events
2008-2009	5.27	Completed	mutli-bricks + all $P\mu$	2783
2010-2011-2012	12.7	In progress	1 brick + $P_\mu < 15$ GeV	2186
Total	18.0		~64%	4969

Charmed hadron production



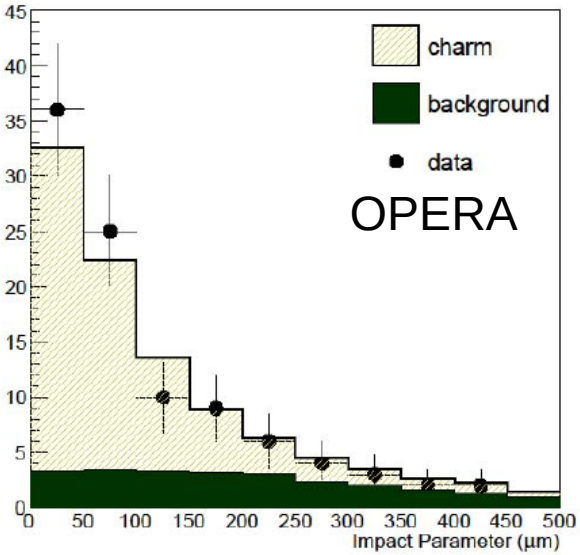
- Charm topology similar to τ (decay modes and lifetime) but μ at interaction vertex
- Control sample for decay search and ε
- Background, mostly from hadronic interactions



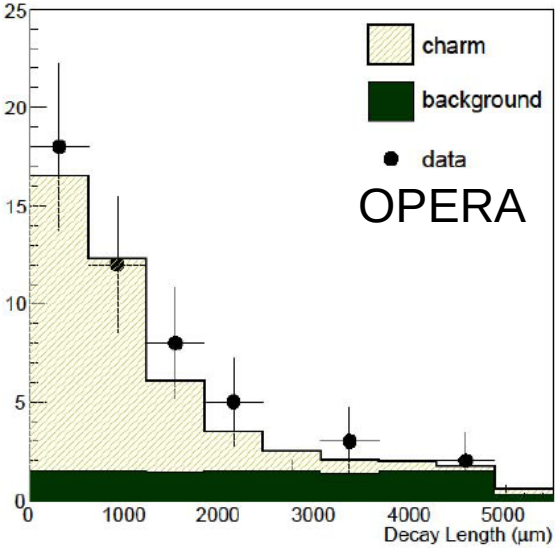
2008-2010 data analysis

Topology	Observed events	Expected events		
		Charm	Background	Total
Charged 1-prong	**19**	20 ± 3	9 ± 3	**29 ± 4**
Neutral 2-prong	**22**	15 ± 2	3.8 ± 1.1	**19 ± 2**
Charged 3-prong	**5**	5 ± 1	1.0 ± 0.3	**6 ± 1**
Neutral 4-prong	**4**	0.8 ± 0.2	<0.1	**0.8 ± 0.2**
Total	**50**	41.1±4	14±3	**55±5**

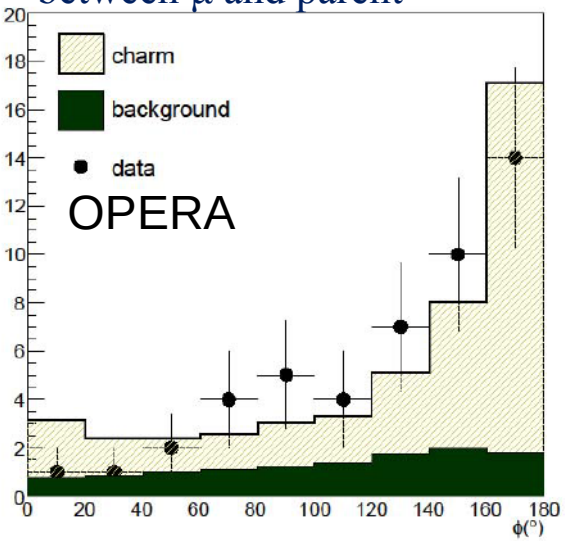
Impact parameter



Decay length



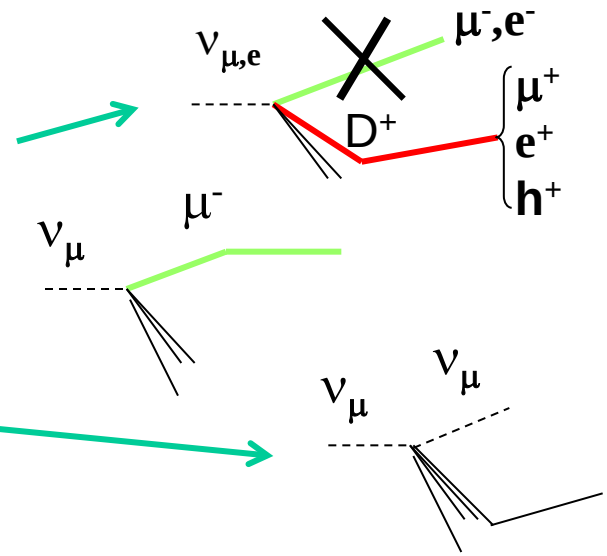
Angle in the transverse plane between μ and parent



$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis:

Background

- ν_μ CC charm production (4% of CC), with μ mis-id'd (similar lifetime, missing E_T decays)
- large angle coulomb scattering of μ
- nuclear interactions of hadrons (0.2% of NC)



Kinematical analysis

variables to reduce background:

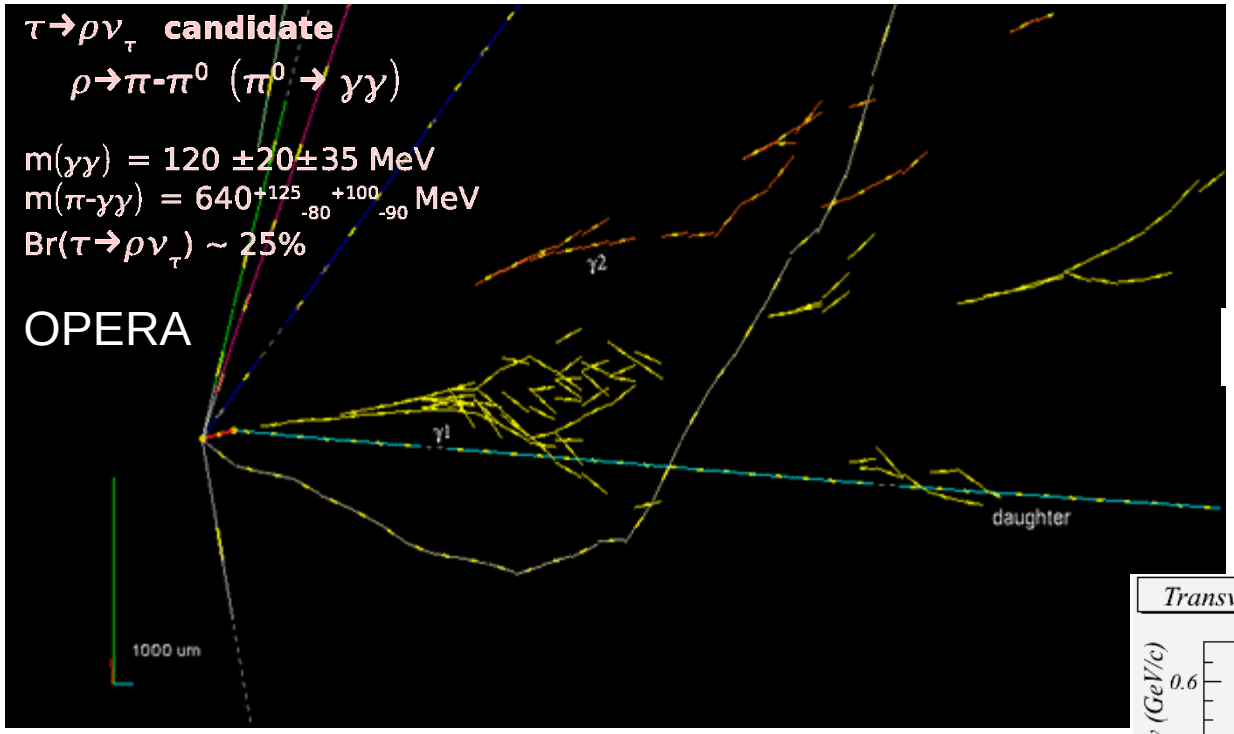
- Flight length
- Total p_T of τ daughters wrt τ direction
- Missing p_T at 1ary vertex
- φ = angle of τ wrt hadronic shower in transverse plane to beam

Decay channel	expected signal events $\Delta m^2 = 2.32 \times 10^{-3}\ eV^2$		PRELIMINARY	
	Full sample 18×10^{19} p.o.t.	Analysed sample	background analysed sample	Observed events
$\tau \rightarrow \mu$	0.90	0.56	0.026	1
$\tau \rightarrow e$	1.06	0.49	0.065	
$\tau \rightarrow h$	0.70	0.66	0.045	1
$\tau \rightarrow 3h$	0.99	0.51	0.090	1
Total	3.65	2.22	0.216	3

Probability to be explained by background fluctuation $p = 7.3.10^{-4}$

No oscillation hypothesis excluded at 3.2 σ

First ν_τ candidate (event 9234119599, taken on 22/08/2009)



- In 2010 OPERA has published the first candidate based on the analysis of 35% of 2008/2009.

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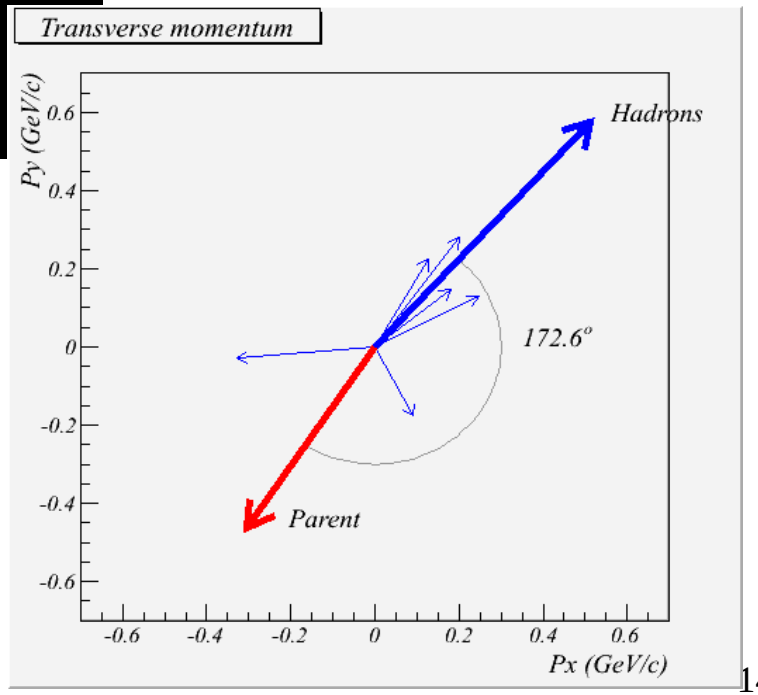
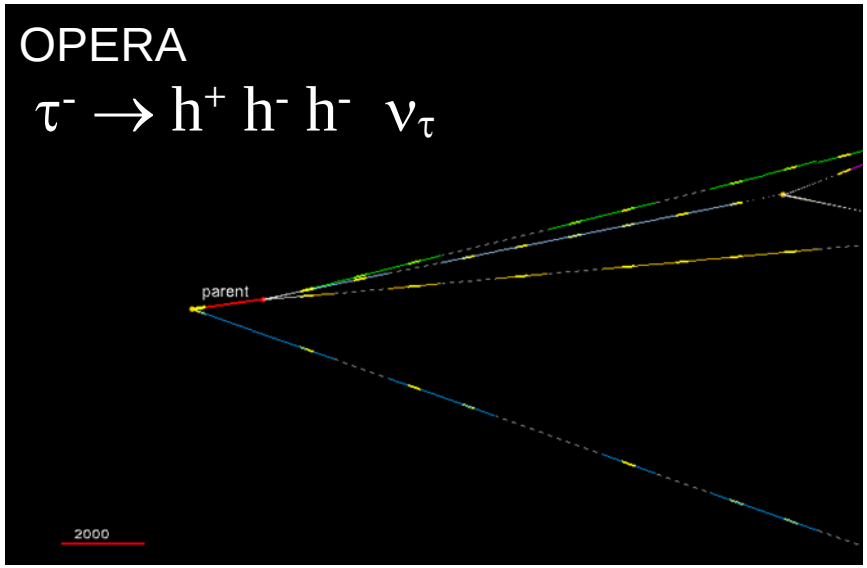
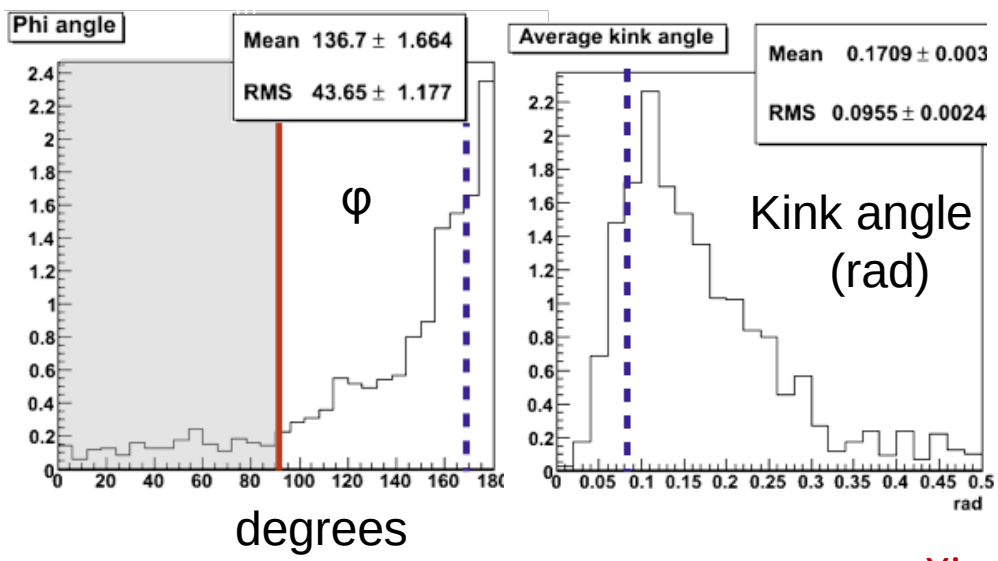
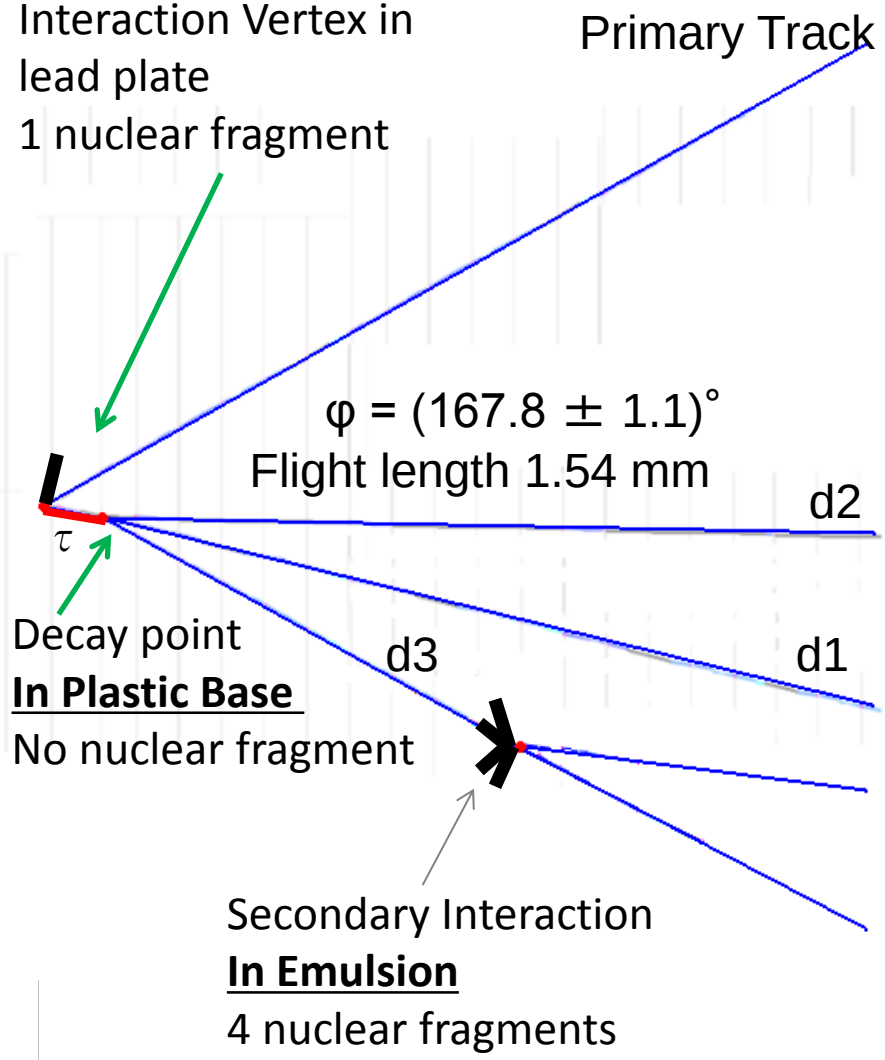
VARIABLE	Measured	Selection criteria
Kink (mrad)	**41 ± 2**	**>20**
Decay length (μm)	**1335 ± 35**	**Within 2 plates**
P daughter (GeV/c)	**12^{+6}_{-3}**	**>2**
P_T daughter (MeV/c)	**470^{+230}_{-120}**	**>300 (γ attached)**
Missing P_T (MeV/c)	**570^{+320}_{-170}**	**<1000**
ϕ (deg)	**173 ± 2**	**>90**



Second ν_τ candidate (event 11113019758, taken on 23/04/2011)

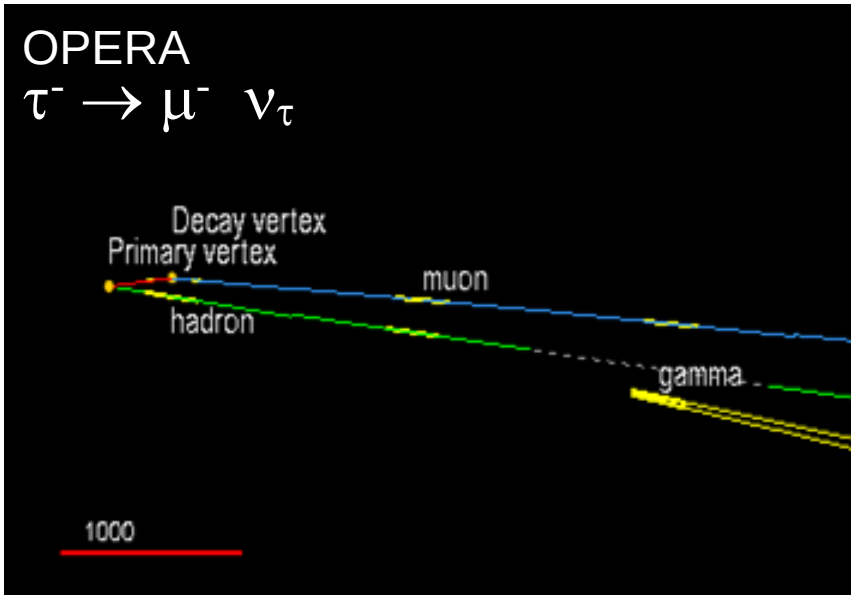


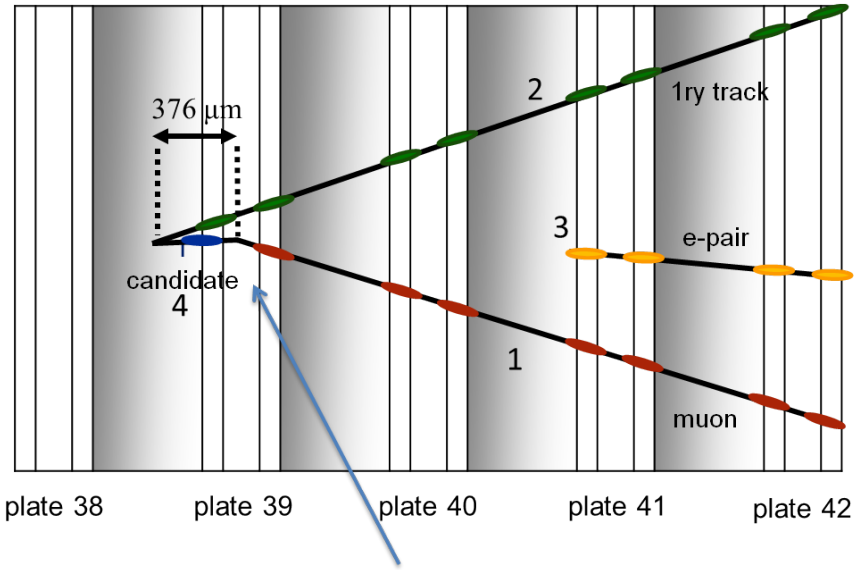




arXiv:1308.2553 submitted to JHEP

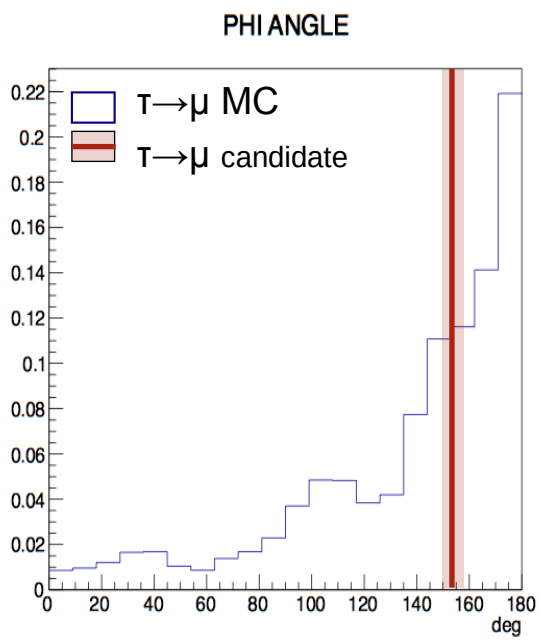
Third ν_τ candidate (event 12123032048, taken on 2/05/2012)

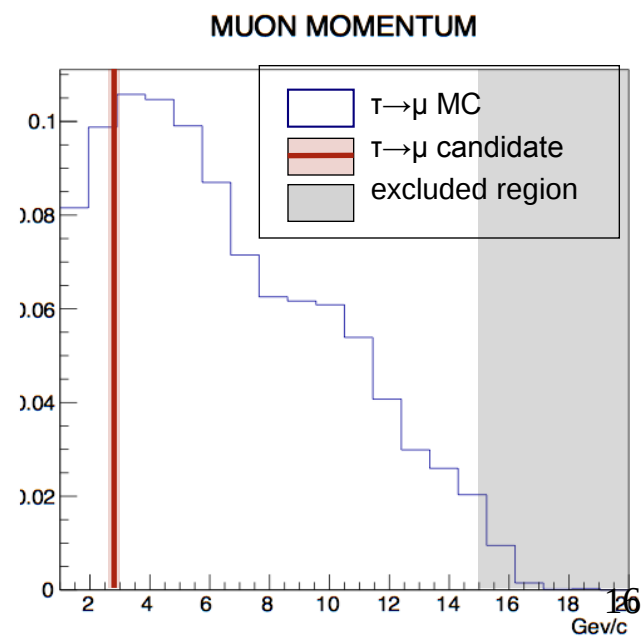




Decay in the plastic base

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**





ν_e appearance search

2008+2009 sample (5.25 x 10^{19} p.o.t.)

→ Observed 19 ν_e events

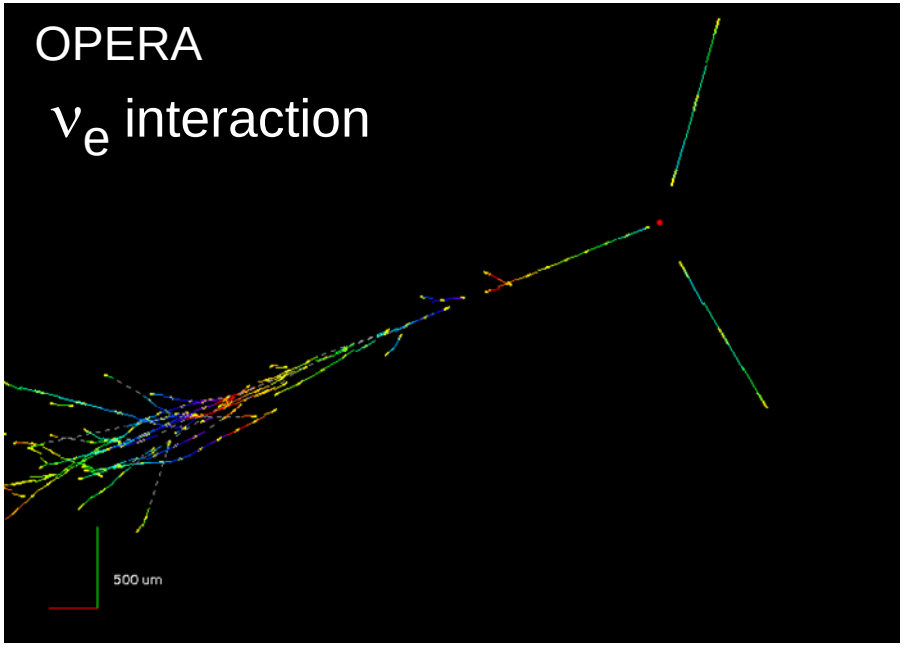
Expected ν_e events :

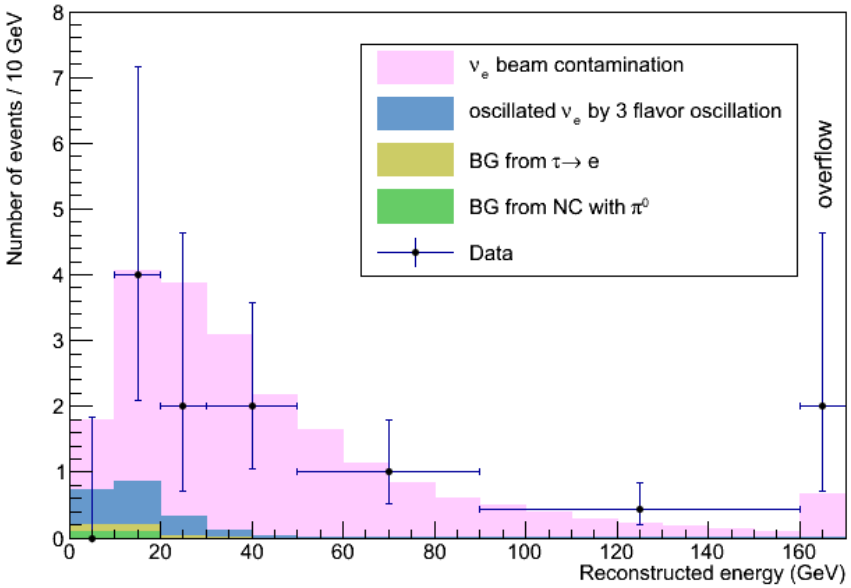
ν_e beam contamination 19.3 ± 2.8

Background $\tau \rightarrow e$ + mis-id'd π^0 0.5 ± 0.2

From 3-flavour oscillation:

$\nu_\mu \rightarrow \nu_e$ 1.4 evts ($\sin^2(2\theta_{13}) = 0.098$)





=> Observation compatible with non oscillation hypothesis

To increase signal to background ratio:
E < 20 GeV
4 observed events with 4.6 background expected
=> $\sin^2(2\theta_{13}) < 0.44$ @ 90% CL

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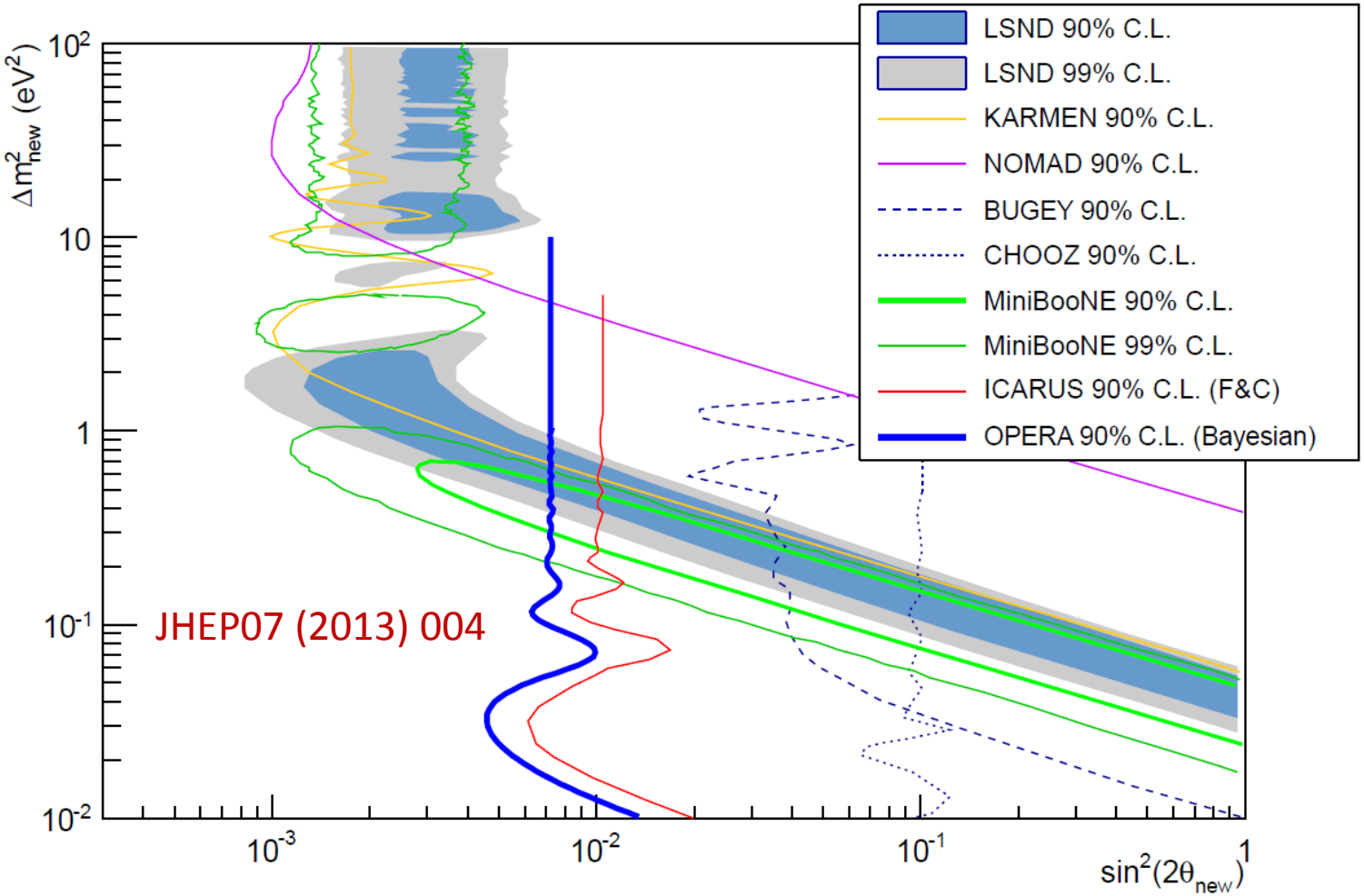
ν_e appearance search 2008+2009 sample (5.25 x 10^{19} p.o.t.)

→ Observed 19 ν_e events with 19.8 ± 2.8 expected



→ Upper limit on non standard ν oscillations $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ 90% CL

where $P = \sin^2(2\theta_{new}) \sin2(1.27\, \Delta m^2_{new}\, L/E)$

Summary and Conclusions

- OPERA has recorded events corresponding to 18.0 x 10^{19} p.o.t. delivered by the CNGS beam from 2008 to 2012 (80% of the nominal)
- Scanning ("second data-taking") and analysis ongoing. ~64% completed!

- $\nu_\mu \rightarrow \nu_\tau$ oscillation analysis:
  3 candidates observed for 2.2 signal + 0.22 background expected
  3.2 σ significance with simple counting approach

- $\nu_\mu \rightarrow \nu_e$ oscillation search:
  19 ν_e events observed for 19.4 expected
  non standard ν oscillation bound: $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ @ 90% CL

- Analysis on-going: More statistics expected and some interesting events under investigation.

The end