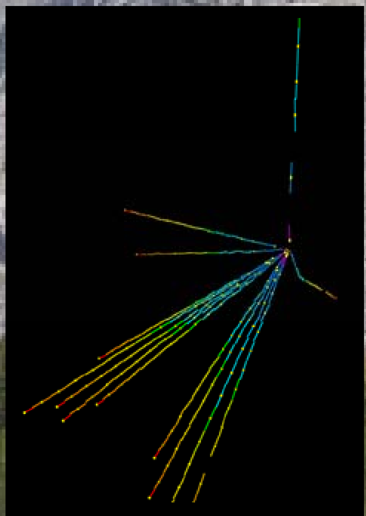
Neutrino Oscillations Studies with the Opera Experiment at CNGS Beam

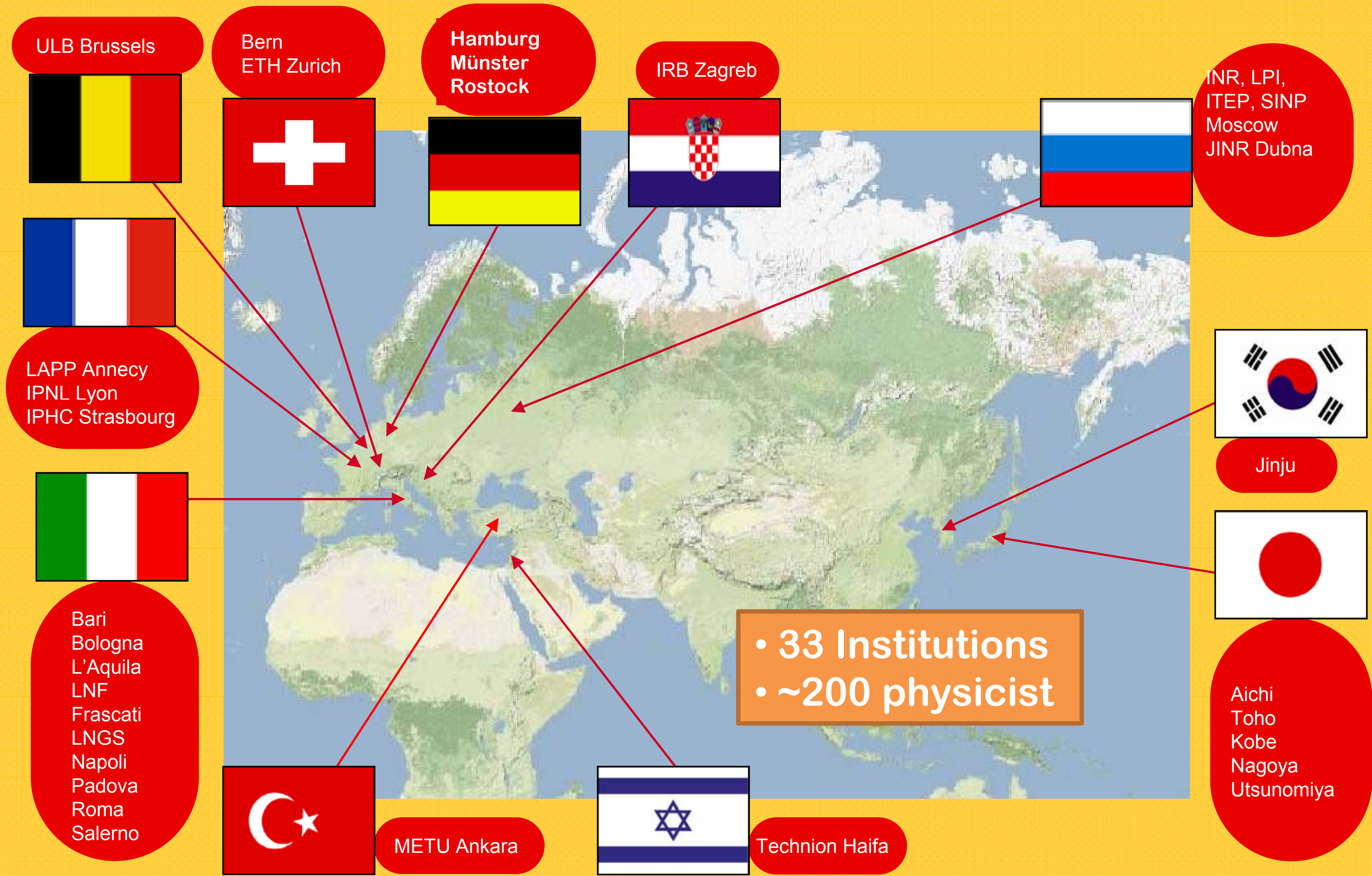


Elisabetta Pennacchio, IPN Lyon,
on behalf of OPERA Collaboration

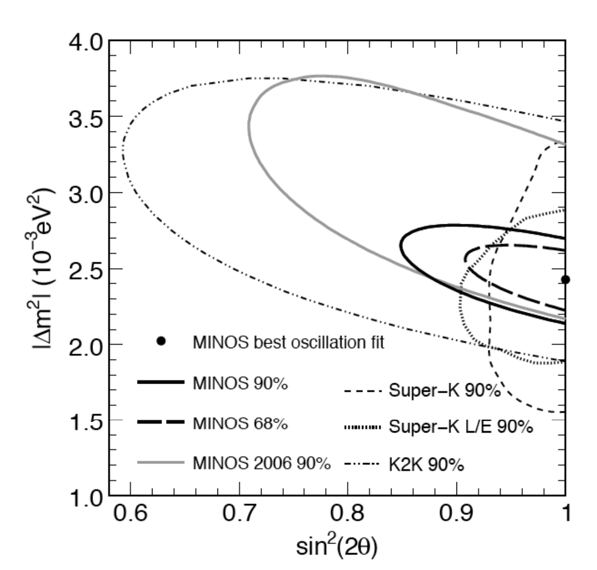
Outline :

- The OPERA collaboration
- Physics motivation
- CNGS beam
- Topological tau detection
- The OPERA detector
- Analysis Flow chart
- Physics results
- Conclusions

The OPERA collaboration



Physics motivation



- CHOOZ (1997): $\nu_\mu \rightarrow \nu_e$ oscillations excluded as dominant process responsible for atmospheric neutrino disappearance
- SK (1998): atmospheric neutrino anomaly interpretable as $\nu_\mu \rightarrow \nu_\tau$ oscillations
- (2004-2009) K2K, MINOS energy modulated disappearance measurements

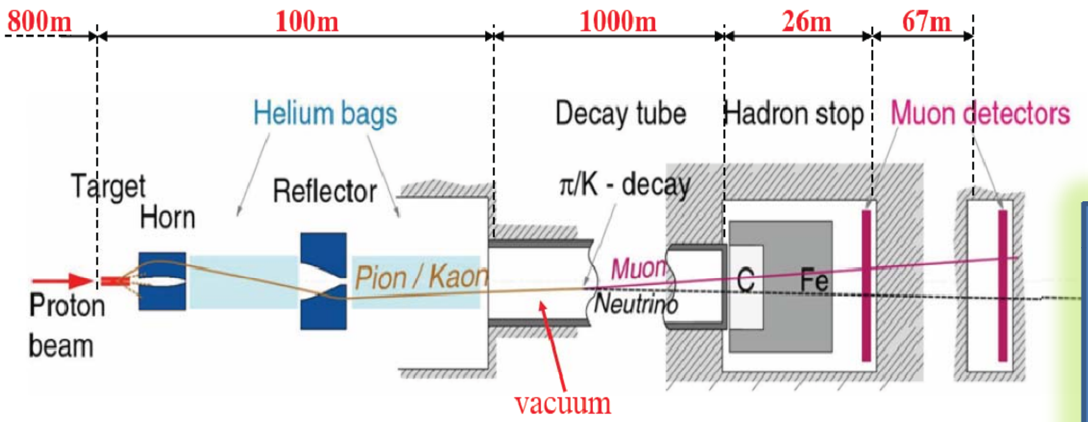
In ν oscillations there is not yet a direct evidence of new flavour APPEARANCE tagged by identification of the charged lepton produced in charged current interactions

OPERA

(Oscillation Project with Emulsion tRacking Apparatus) long baseline neutrino oscillation experiment aiming the direct observation of the ν_τ appearance in an initially pure ν_μ beam through the ν_τ CC interactions.

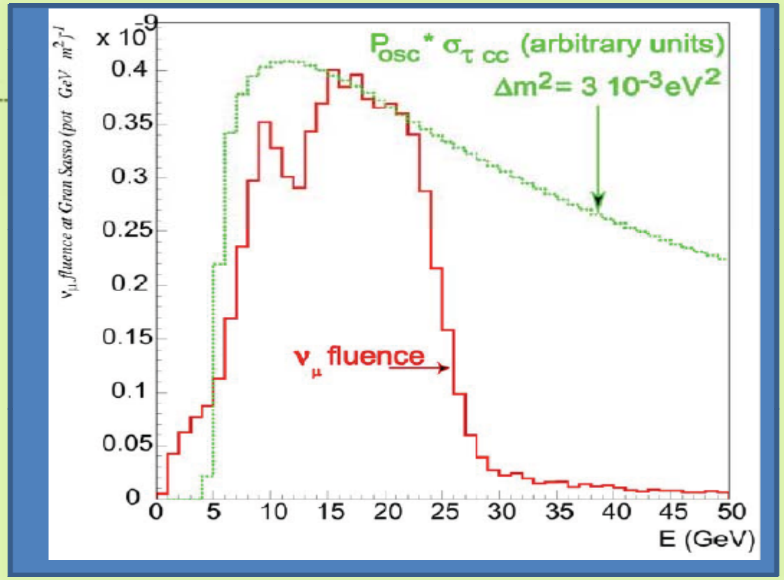
The sub-leading oscillation $\nu_\mu \rightarrow \nu_e$ is also studied

CNGS (CERN Neutrino To Gran Sasso) beam



- Protons from SPS: 400 GeV/c
- Cycle length: 6 s
- 2 extractions separated by 50 ms
- Pulse length: 10.5 μs
- Beam intensity: 2.4 10^{13} proton/extr.
- Expected performance: 4.5 · 10^{19} pot/year

Flux optimized to produce the max. number of ν_τ CC



<E (ν_μ)>	17 GeV
L	730 km
L/E	43 Km/GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$ cc	0.87%
$\bar{\nu}_\mu / \nu_\mu$ cc	2.1%
ν_τ prompt	negligible

- Nominal beam performance (4.5*10^{19} pot/y)
- Target mass of 1.25 kton

→ Expected number of interactions in 5 years running:

~ 23600 ν_μ CC+NC
~ 170 ν_e + $\bar{\nu}_e$ CC
~ 115 ν_τ CC (Δm^2 =2.5 x 10^{-3} eV^2)

After efficiencies, 10 tau decays are expected to be observed , with <1 background events

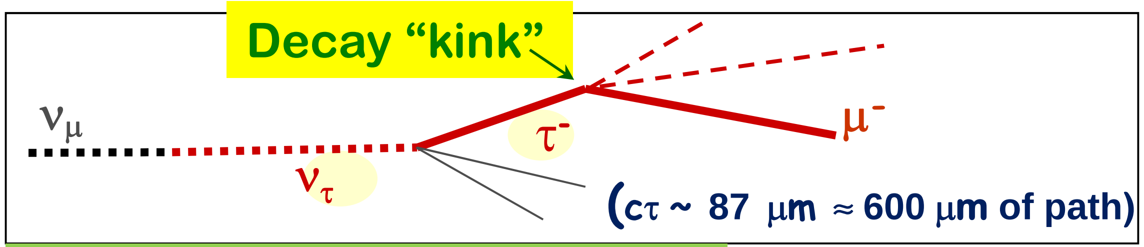
Principle of topological τ detection

ν_τ CC interaction:

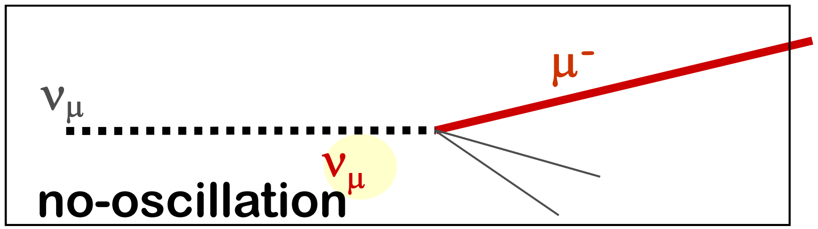
$\nu_\mu \Rightarrow \nu_\tau + N \rightarrow \tau^- + X$

oscillation

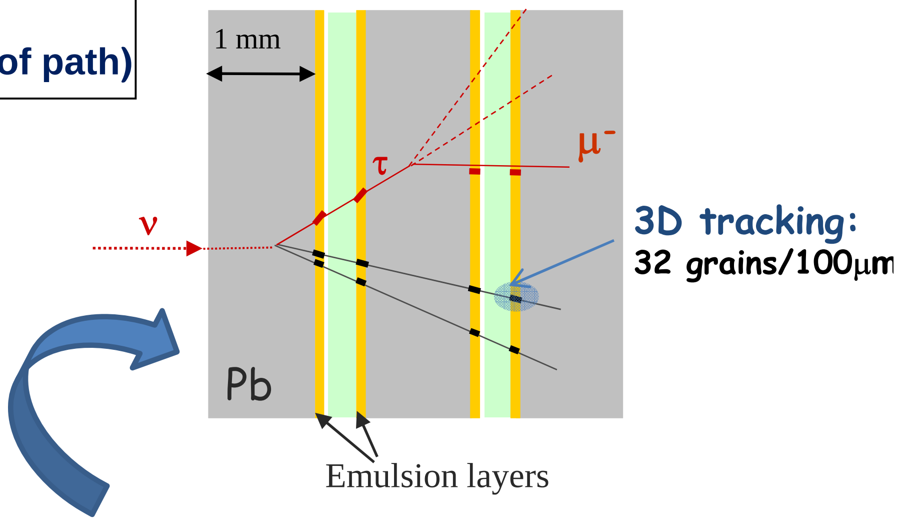
$$\tau^- \rightarrow \begin{cases} \mu^- \ \nu_\tau \ \bar{\nu}_\mu & \text{B. R.} \sim 17\% \\ h^- \ \nu_\tau \ n(\pi^o) & \text{B. R.} \sim 49\% \\ e^- \ \nu_\tau \ \bar{\nu}_e & \text{B. R.} \sim 18\% \\ \pi^+ \pi^- \pi^- \ \nu_\tau \ n(\pi^o) & \text{B. R.} \sim 15\% \end{cases}$$



(35% of Non-Scaling QE and 65% DIS)



(11% of Non-Scaling QE and 89% DIS)



2 conflicting requirements:

✓Target mass O(kton)
(low ν interaction cross-section)

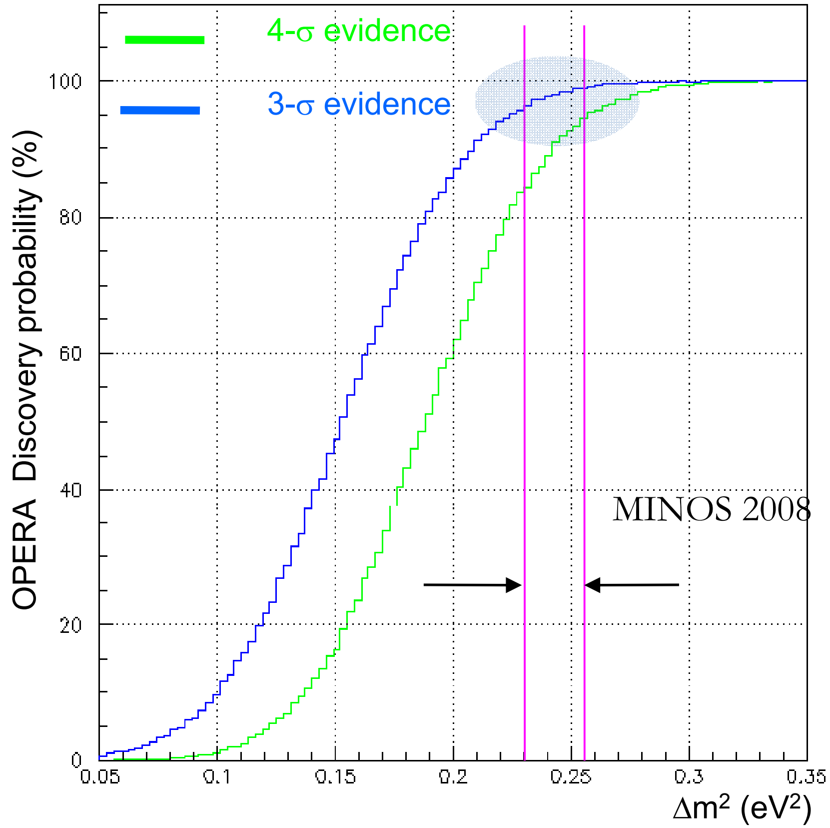
✓High granularity : signal identification
background rejection

ECC (Emulsion Cloud Chamber) concept:
thin metal plates interleaved with nuclear photographic emulsions on films

OPERA sensitivity

5 years of nominal beam 4.5 ^{E}19 pot/year:

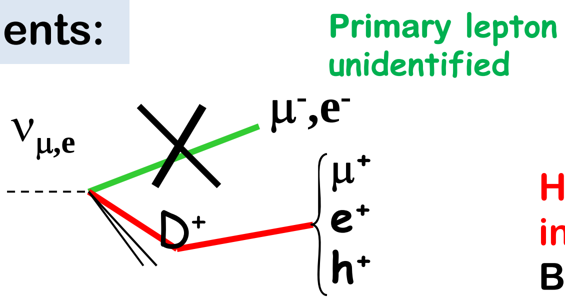
τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10\text{-}3\ eV^2$	Background
$\tau \to \mu$	17.7	2.9	0.17
$\tau \to e$	17.8	3.5	0.17
$\tau \to h$	49.5	3.1	0.24
$\tau \to 3h$	15.0	0.9	0.17
All	BR*eff =10.6%	10.4	0.75



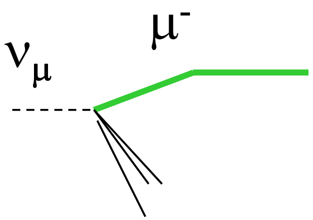
The number of signal events goes as $(\Delta m^2)^2$

Background components:

Production of charmed particles in CC interactions (all decay channels)

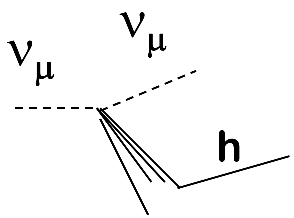


Coulombian large angle scattering of muons in lead
Bck. to $\tau \to \mu$



Hadronic interactions in lead:
Bck. to $\tau \to h$

or to $\tau \to \mu$
(if hadron misid. as muon)

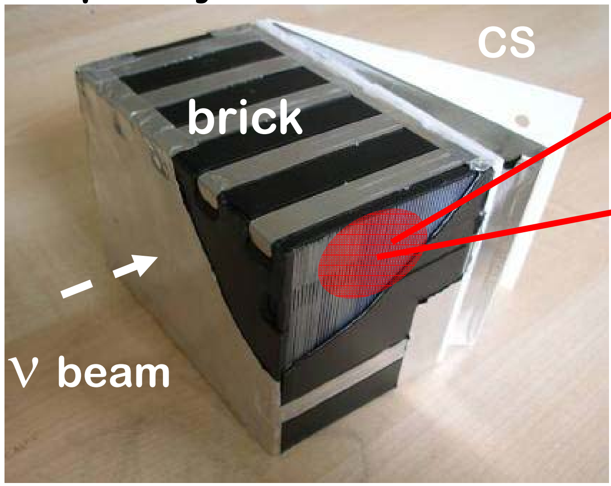


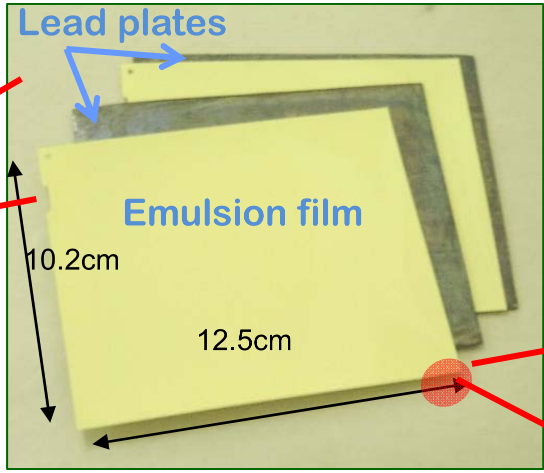
The OPERA basic unit: the « Brick »

Based on the concept of the **E**mulsion **C**loud **C**hamber :

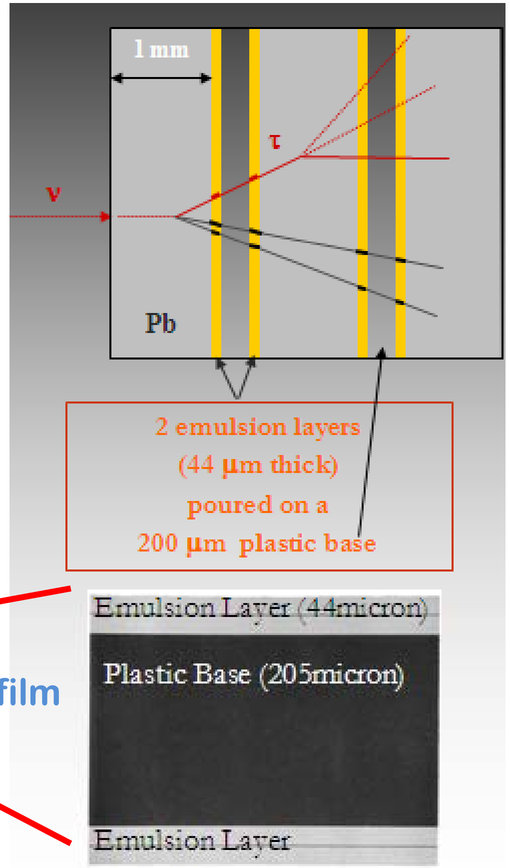
- 57 emulsion films+ 56 Pb plates
- a box with a removable pair of films (Changeable Sheets) interface to the electronic detectors

→ High space resolution in a large mass detectors with a completely modular scheme





Emulsion film

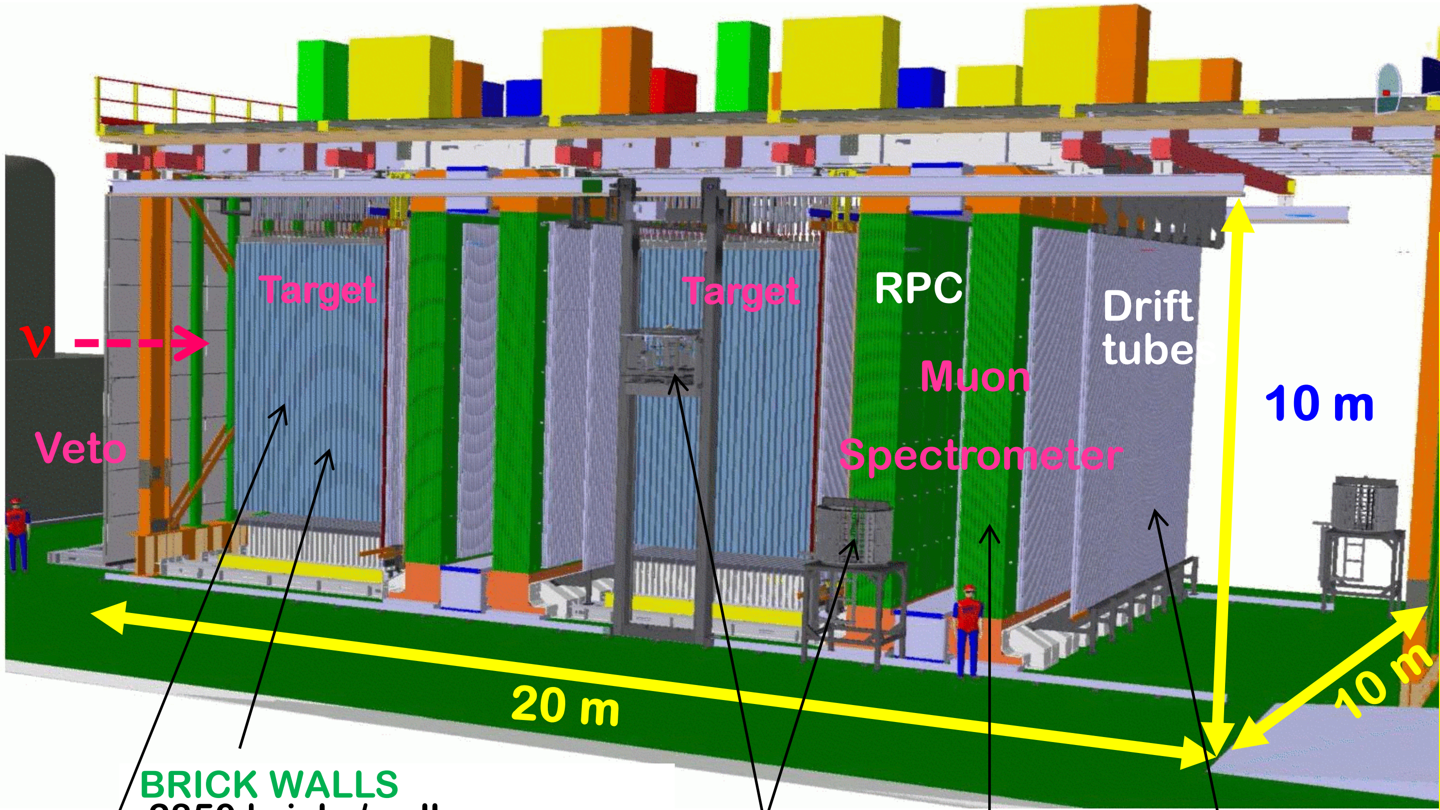


Track reconstruction accuracy in emulsions:
$\Delta x \approx 0.3\ \mu m \quad \Delta\theta \approx 2$ mrad

Bricks are completely stand-alone detectors:

- Neutrino interaction vertex and kink topology reconstruction
- Measurement of hadrons momenta by multiple scattering
- dE/dx pion/muon separation at low energy (at end of range)
- Electron identification and measurement of the energy of electrons and gammas

The OPERA hybrid detector



The **bricks** are stand-alone passive detectors

→ **Electronic Detectors** are needed for:

- Triggering, Timing
- Neutrino interactions Location
- Calorimetry
- Muon I.D. and Spectrometry

BRICK WALLS
2850 bricks/wall
- 53 walls
- 150000 bricks ~ 1.25 kton

BMS
Brick Manipulator System

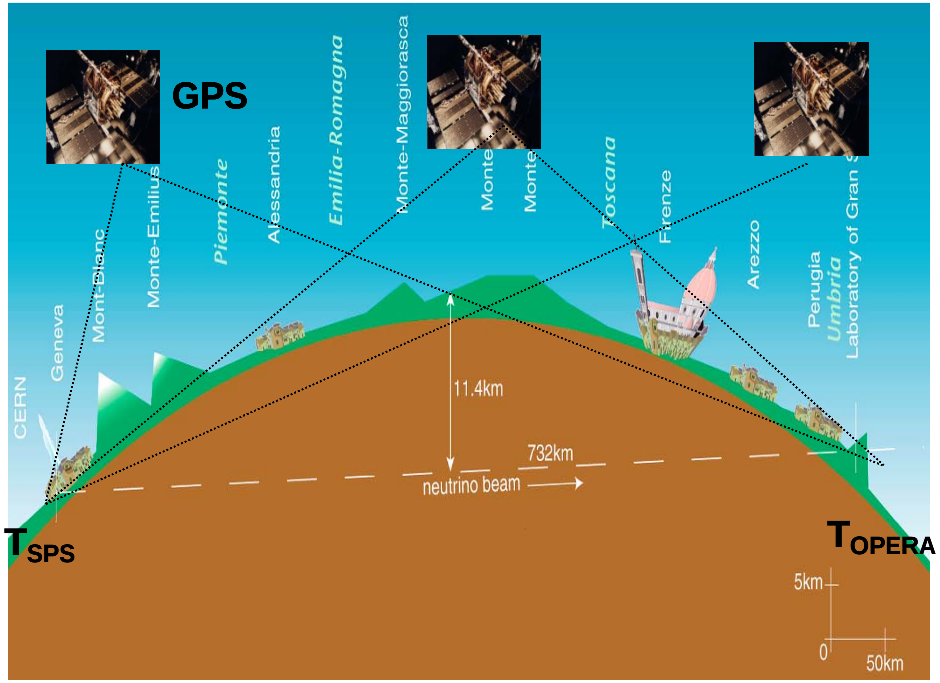
HIGH PRECISION TRACKERS
6 drift-tube layers/spectrometer
spatial resolution < 0.5 mm

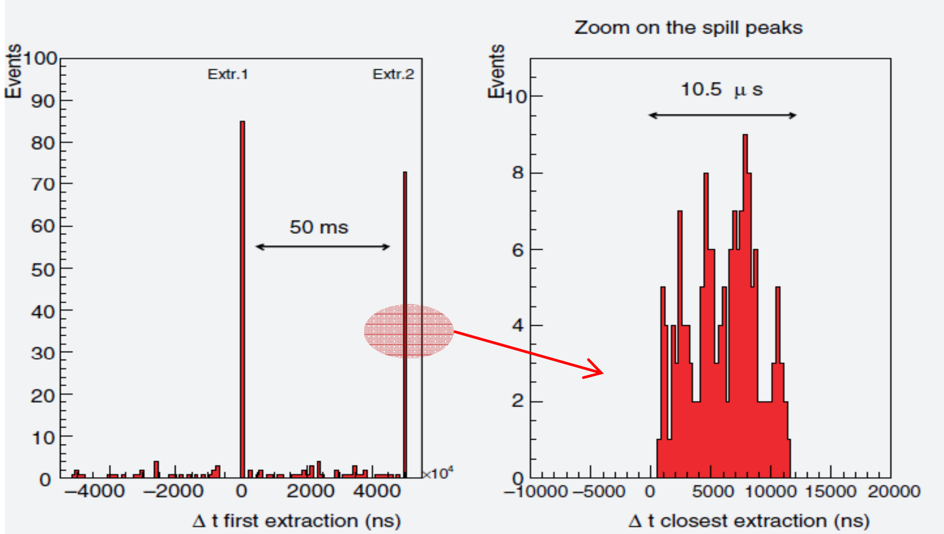
TARGET TRACKERS
- 2x31 scintillator strips walls
- 256+256 X-Y strips/wall
- WLS fiber readout
- 64-channel PMTs
- 63488 channels
- 0.8 cm resololution, 99% ε
- rate 20 Hz/pixel @1 p.e.

INNER TRACKERS
- 990-ton dipole magnets
(B= 1.55 T) instrumented with 22 RPC planes
- 3050 m^2, ~1.3 cm res.

OPERA as real time experiment

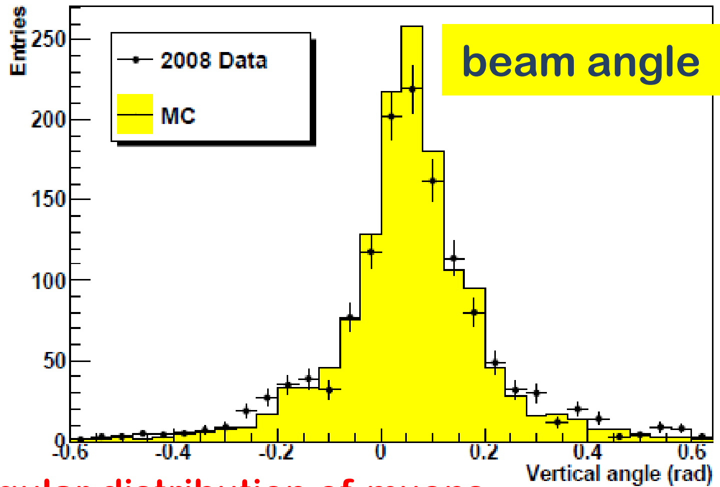
- CNGS events are selected on a delayed time coincidence between proton extractions from SPS and the events in OPERA.
- The synchronization is based on GPS with precision of ~100 ns (can be improved to 10ns)
- DAQ livetime during CNGS is 98.8%
- Real time detection of neutrino interaction in target and in the rock surrounding OPERA





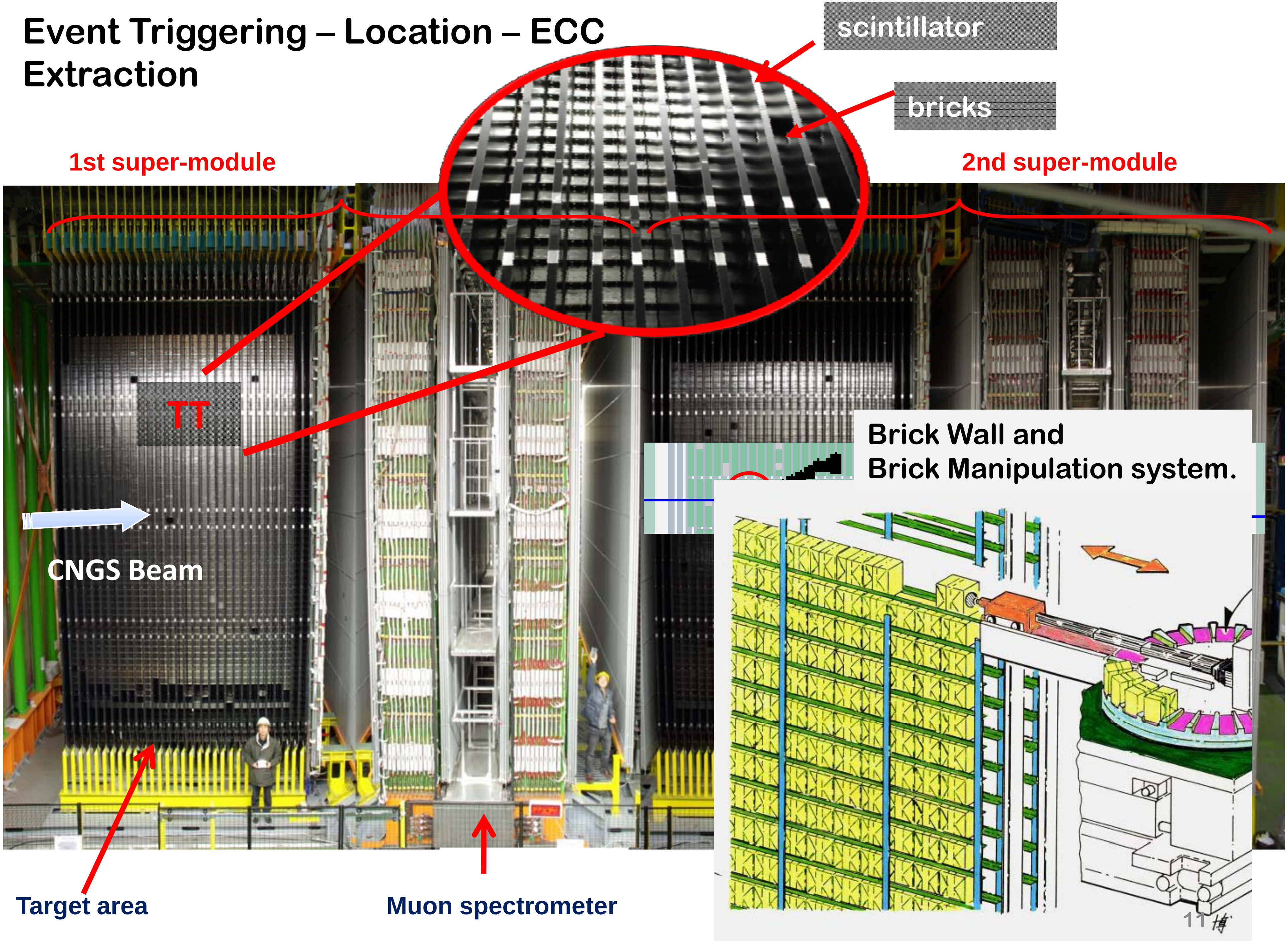
Time distribution of events in the neutrino run.

Event time difference wrt the closest extraction



Angular distribution of muons produced by ν interactions in the rock

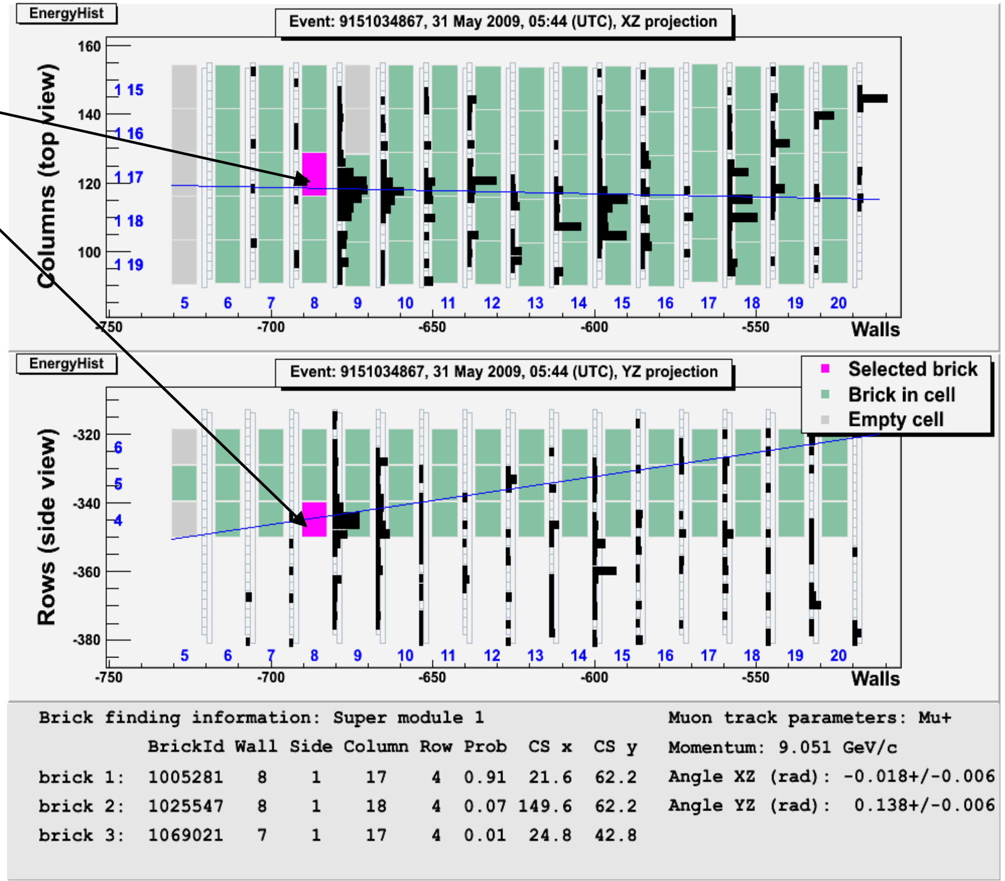
Event Triggering – Location – ECC Extraction



OPERA event analysis step by step

1. Trigger on events"on time" with CNGS and selection of the brick with ν interaction using electronic detectors information (brick finding algorithm)

Brick location

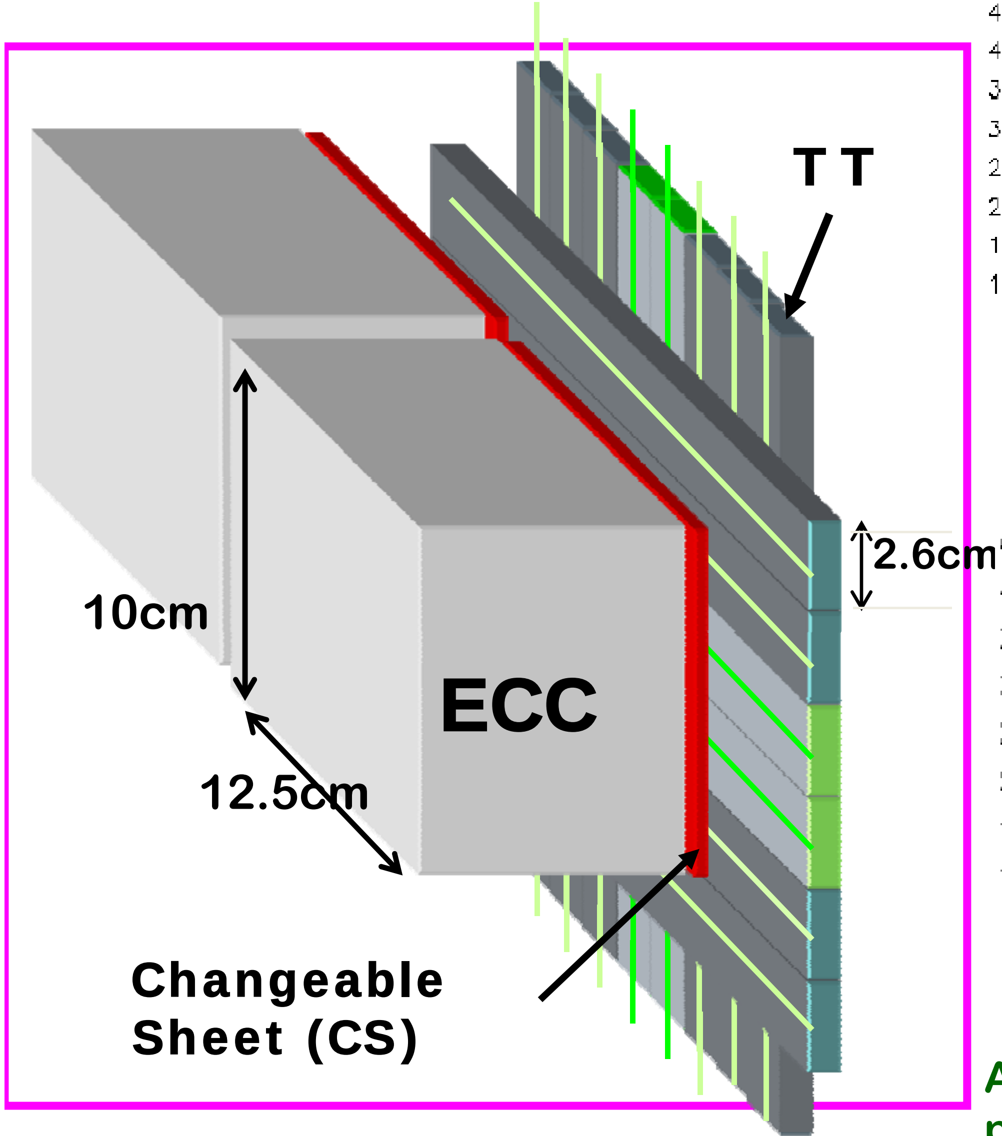


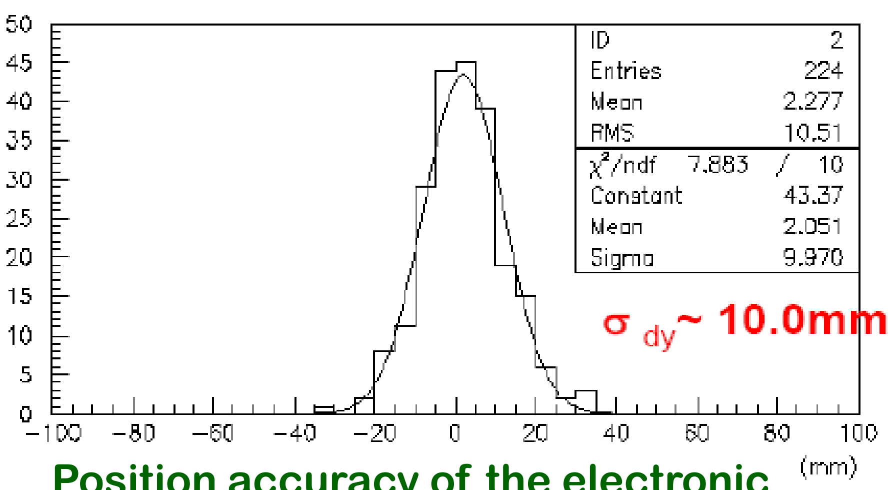
2. Brick removed by BMS (brick manipulator system)

- Semi-online ECC target analysis
- Minimize the target mass loss

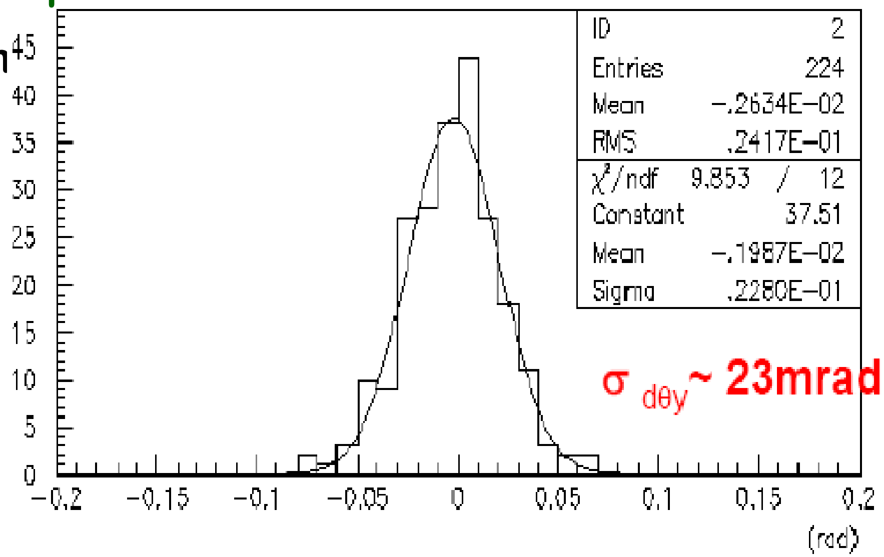
3. The emulsion interface films (CS), are separated from the brick and scanned looking for a connection with respect to the electronic detectors predictions

→ **high signal/noise ratio for event trigger and scanning time reduction**





Position accuracy of the electronic predictions



Angular accuracy of the electronic predictions

4. If tracks are found in the CS, the brick is exposed to X-rays beam and to cosmic rays for sheets alignment .

5. The brick is disassembled and the emulsion films are developed and sent to one of scanning labs

EUROPE :

Brick emulsion scanning: 9 labs
LNGS is CS scanning center

European Scanning System

CMOS camera

Scanning speed 20 cm^2/h

JAPAN:

Brick emulsion scanning: 2 labs
Nagoya is CS scanning center

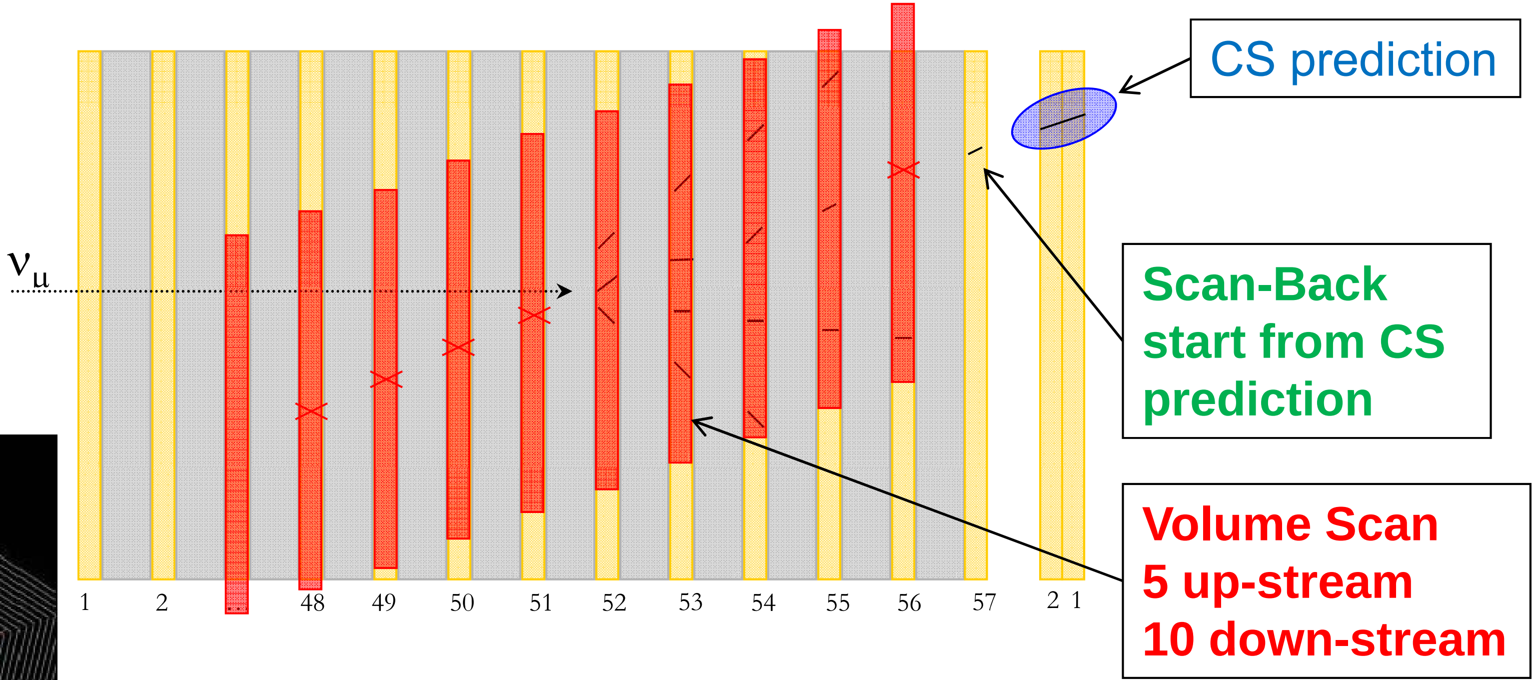
Super-UltraTrackSelector

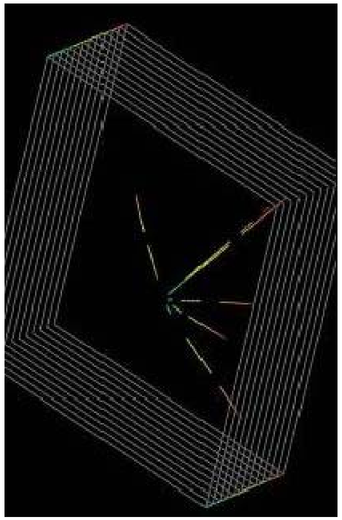
High speed CCD camera (3 kHz)

Scanning speed up to 75 cm^2/h

6. Brick Scanning and neutrino interaction vertex location

Tracks found in CS are followed in the most downstream films of the brick up to their stopping point : Scan-back procedure





Volume scan: a zone of ~ 1 cm^2 in several films is measured around track disappearance point(s) to confirm the presence of the interaction

7. Vertex tracks may be followed in the forth direction for kinematical measurements

Data are published on the central DataBase

Offline treatment of emulsion data

- Emulsion data (scanback,volume scan, scanforth) stored in the DB are extracted to produce root ntuple for offline analysis O(Gb/event data volume)

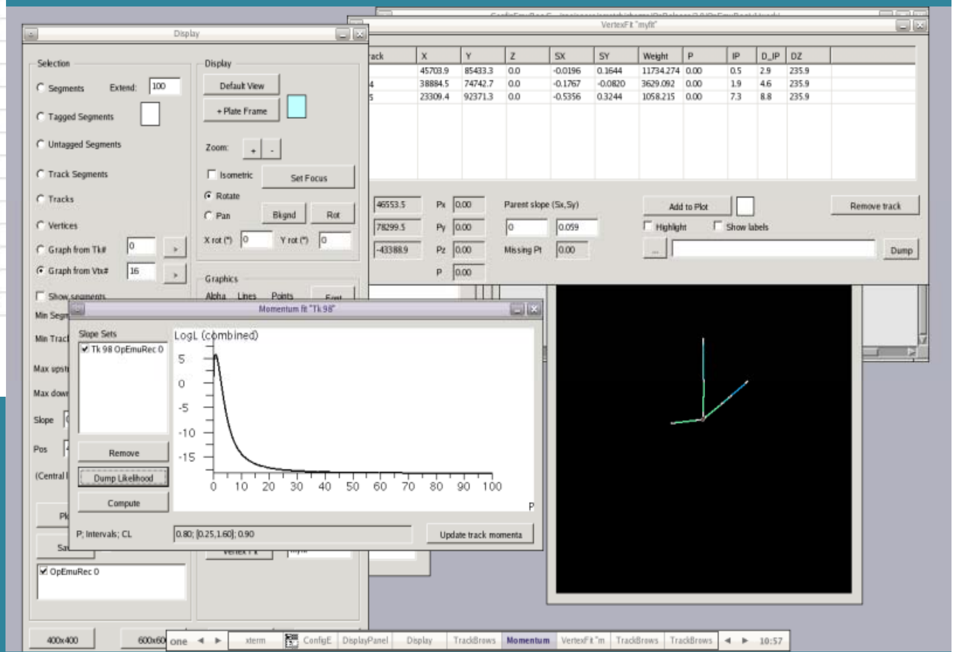
- Operational for alignment-tracking-vertexing

- MC output integrated in the framework, mixing with real data background from scanned empty volumes

- Integrated interactive display

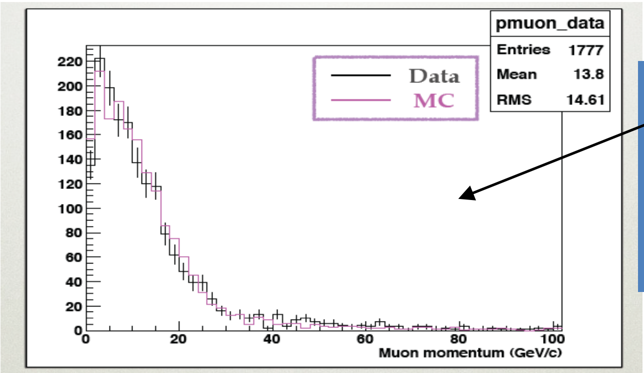
Memory utilisation (MB)
*This value is **stable** during job execution*

Processing time



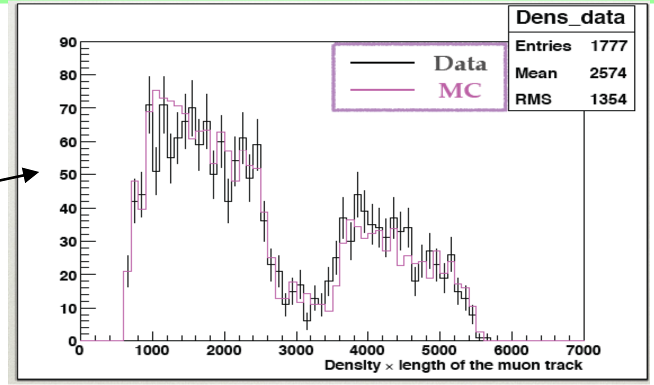
ν_μ CC events : quantities measured in the ED

Muon reconstruction and hadronic showers behaviour in reasonable agreement data/MC for ν_μ CC events



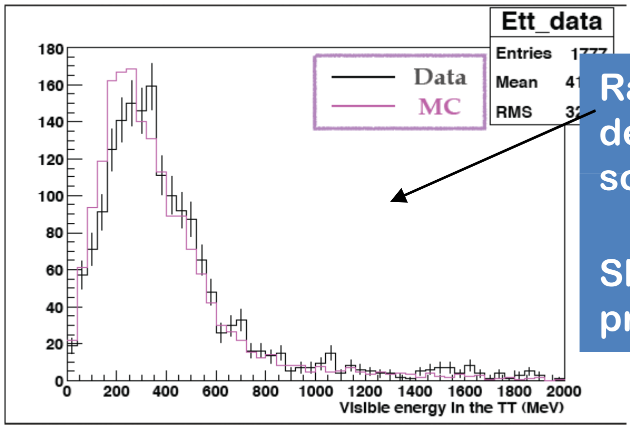
Muon momentum

Track length x density (range for muon id)



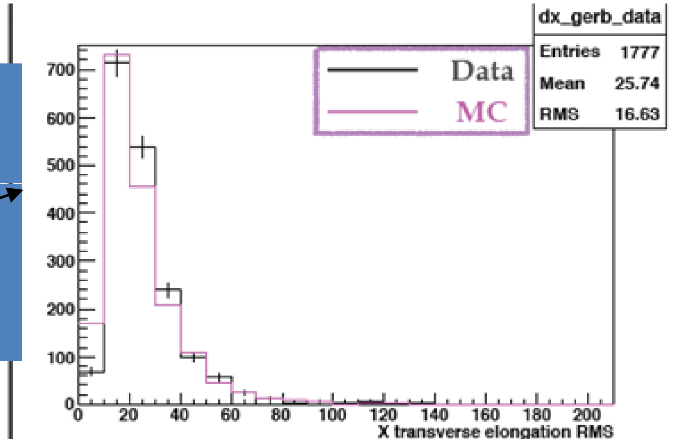
Muon identification:

- ✓Range cut
- ✓Range vs momentum measured in bricks with MCS
- ✓Best brick-ED angular matching



Raw hadronic energy deposited in TT scintillator (MeV)

Shower transverse profile

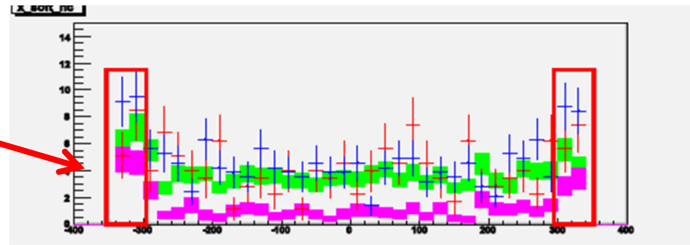


NC/CC ratio measurement after removal of external bck accumulation at target borders:

Data 2008: NC/CC= 0.230 ± 0.014 (stat.)

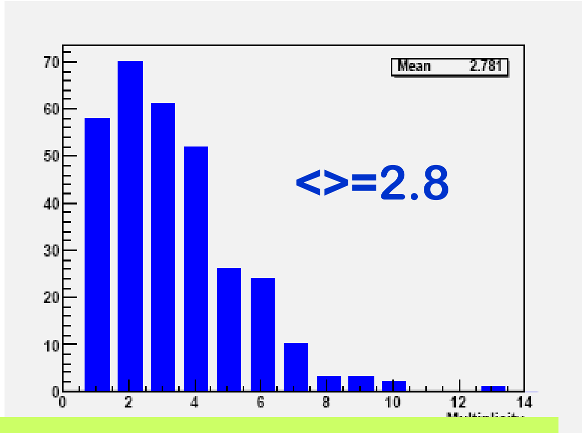
Data 2009: NC/CC= 0.230 ± 0.009 (stat.)

MC: NC/CC= 0.236 ± 0.005 (stat.)

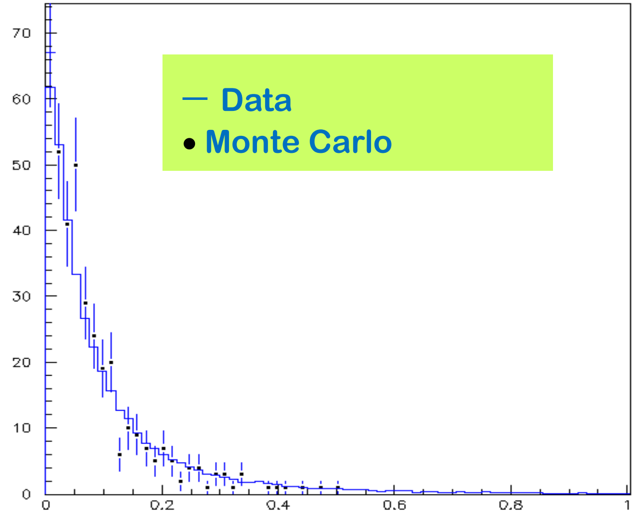


Reconstructed tracks and momenta in bricks

Reconstructed tracks at the primary vertex for ν_μ CC events



Event track multiplicity distribution

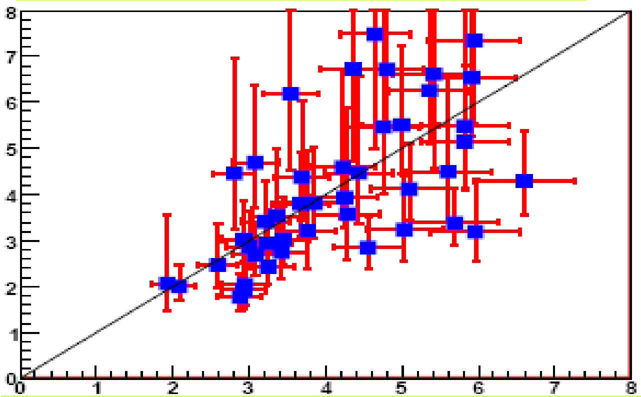


Track slope (rad)

Muon slopes measured at primary vertex compared to MC (at generator level !)

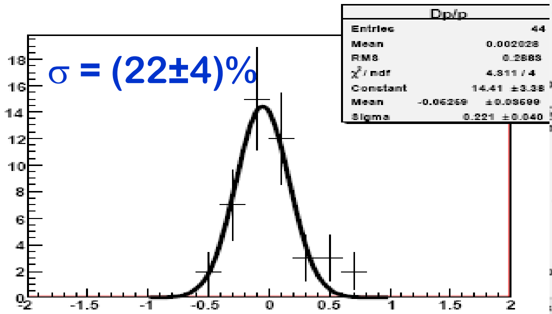
MCS measurement of soft muons (p<6 GeV) in order to validate the technique for kinematical measurements and compare to momentum from ED

Soft muon measured in OPERA



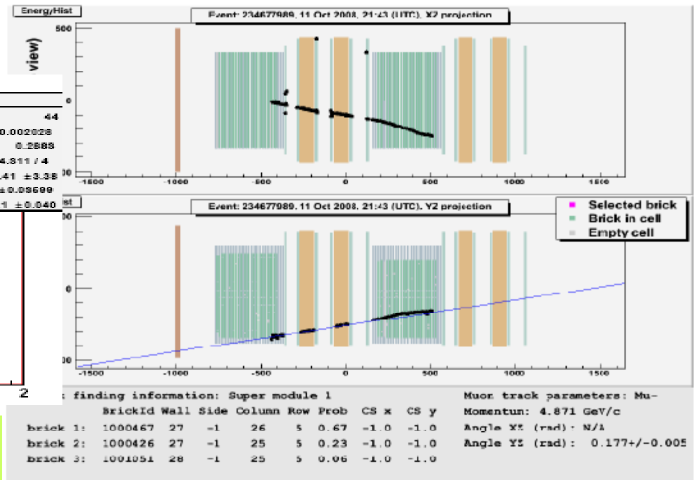
Momentum from MCS (GeV/c)

Momentum from electronic detector (GeV/c)



$\frac{\text{Pmcs-Pspectro}}{\text{Pspectro}}$

$\frac{\Delta p}{p}$



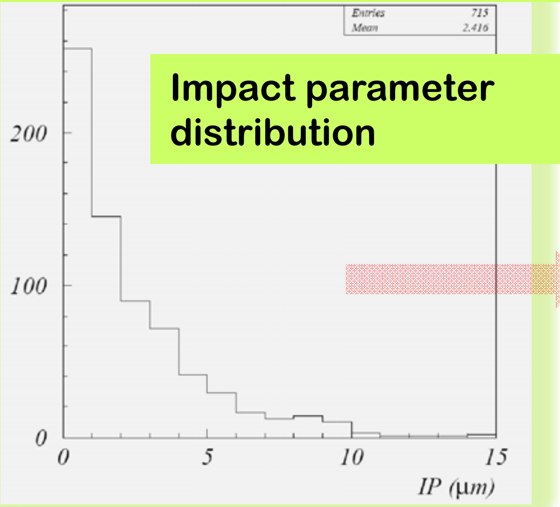
Decay search

Scanning activities (till fall 2009) were focused on vertex location

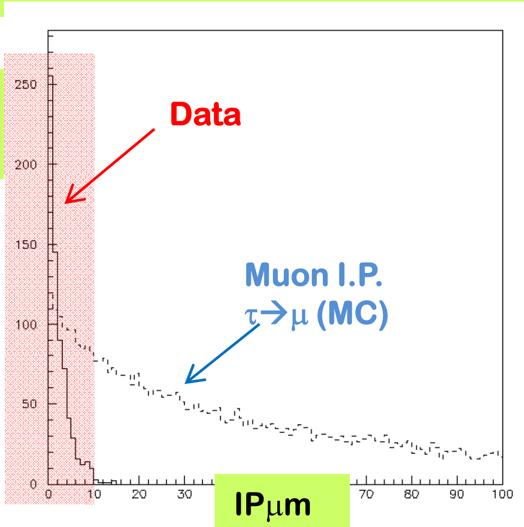
→ A systematic DECAY SEARCH was started on 2008 and 2009 data in order to find all possible decay topologies

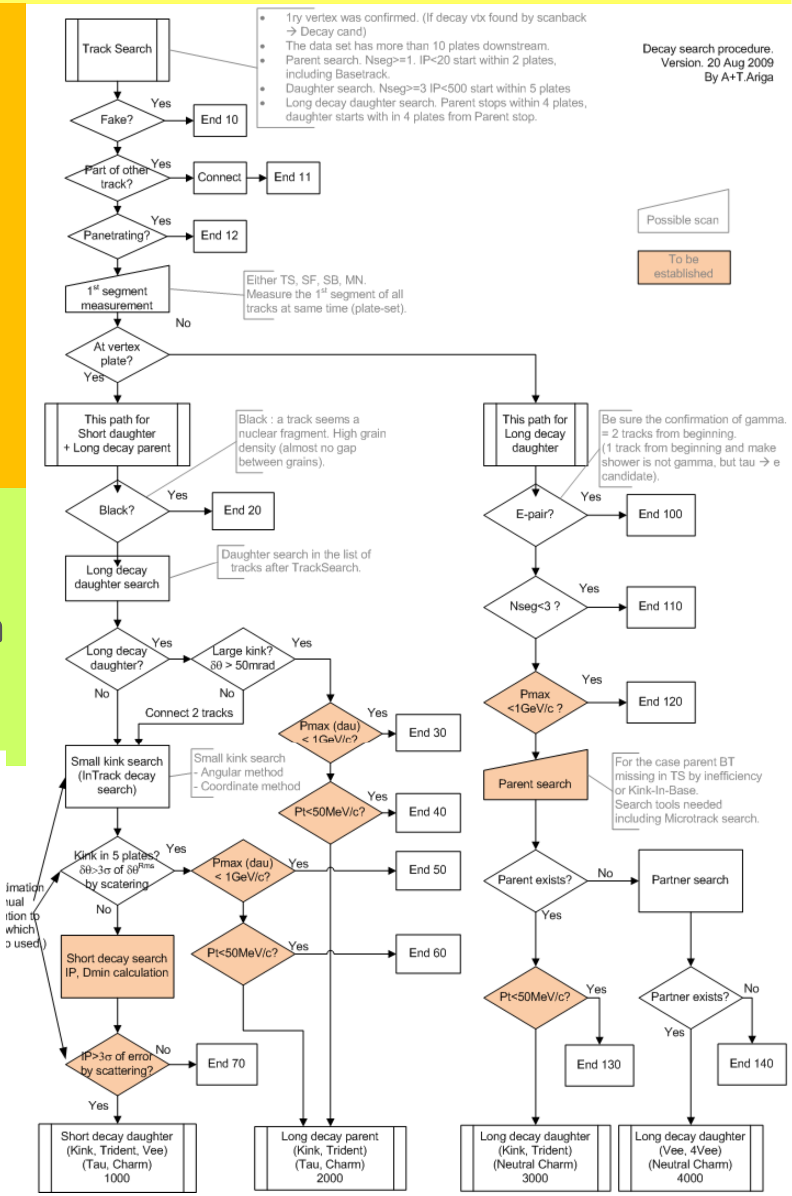
1) improvement of the vertex definition and IP distribution
2) detection of possible kink topologies (on tracks attached to primary vertex)
3) search for extra tracks from decays not attached to primary vertex

20 charm candidates were found so far (in good part with the scan-back and vertex location procedures).
Charm events are the control sample for decay search
→ completion of systematic decay search for final evaluation



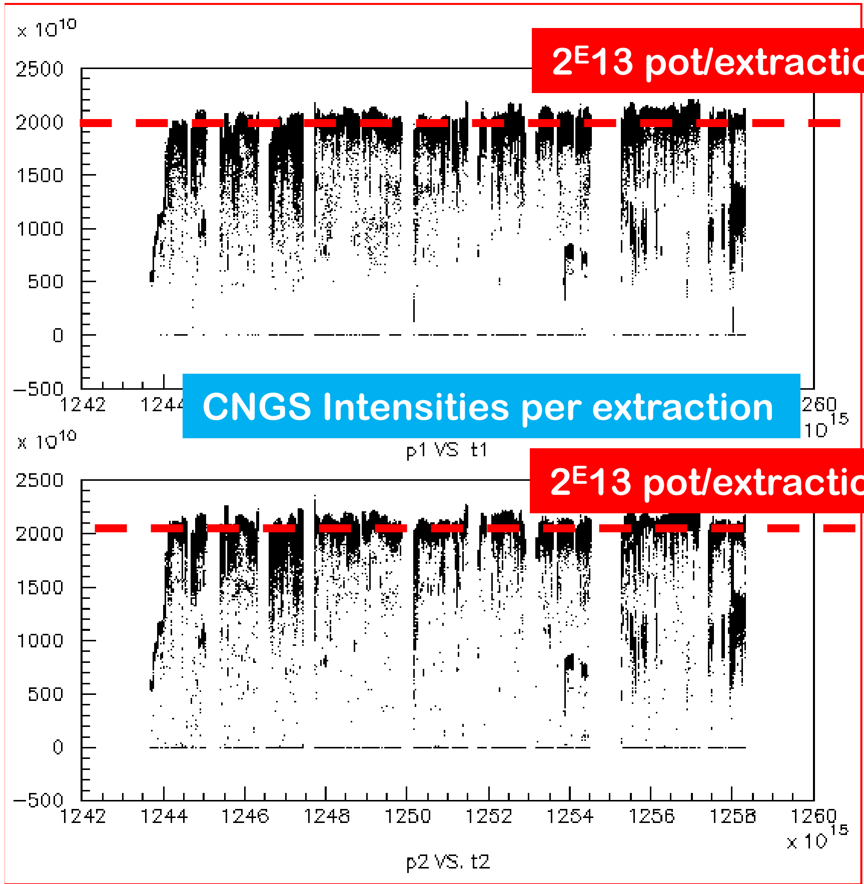
Impact parameter distribution

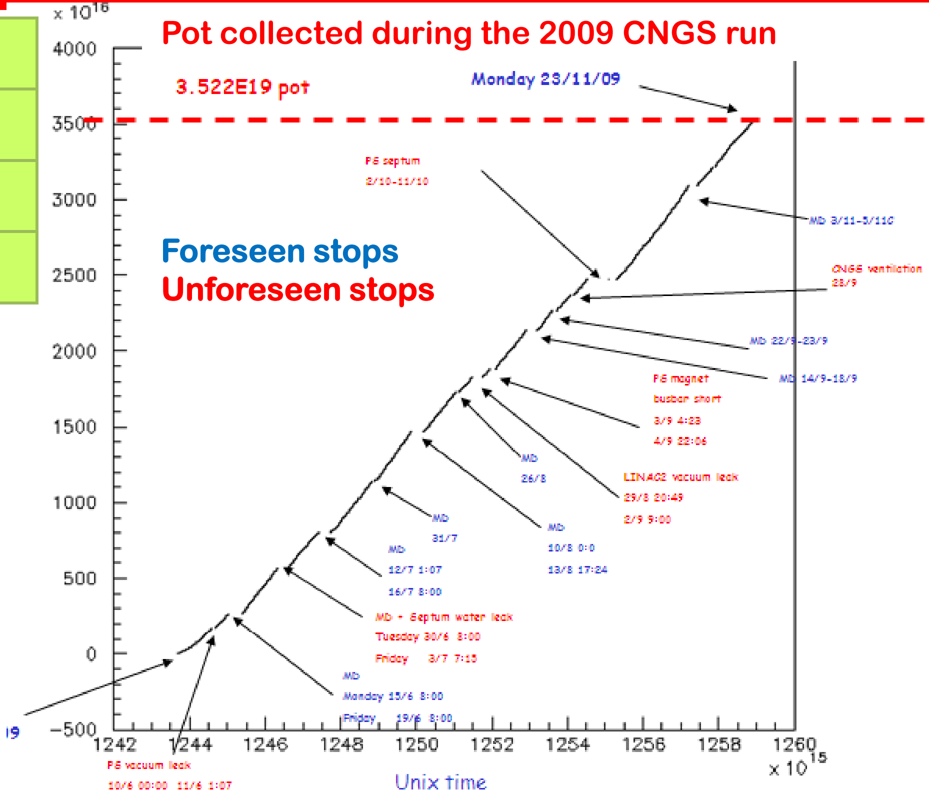


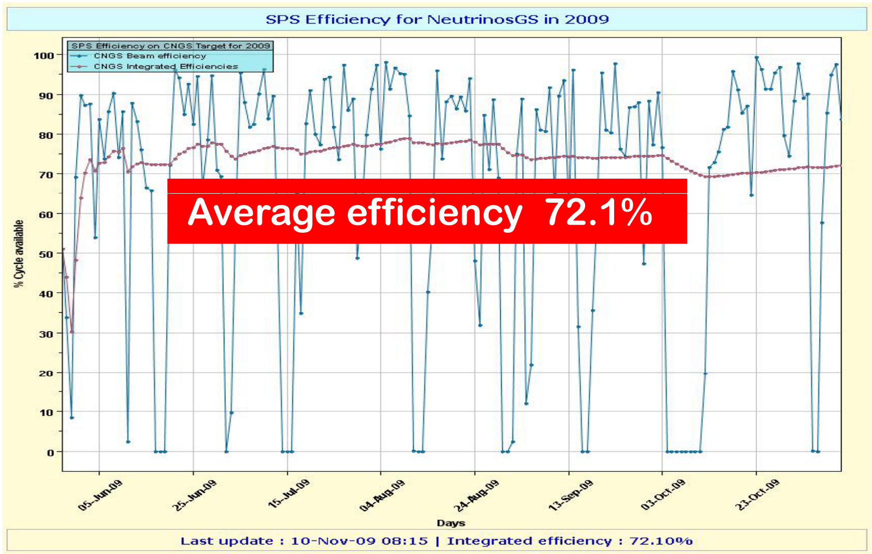


CNGS beam performance

	2008 run	2009 run
total	1.782E19 pot	3.522E19 pot
On-time events	10122	21428
candidate in the target	1698	3693







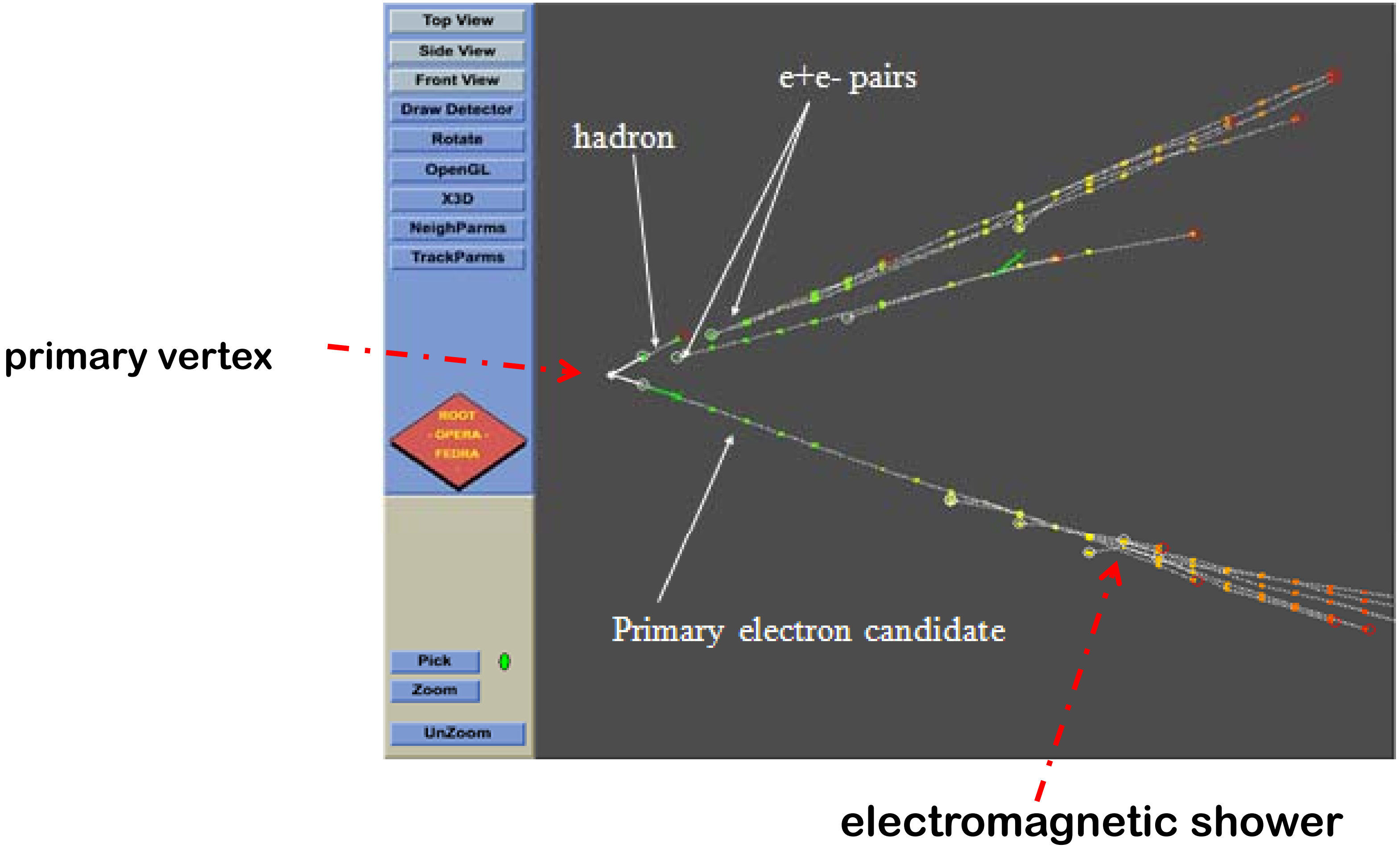
Events location summary for 2008 run

	0mu	1mu	All
Events predicted by the electronic detector	406	1292	1698
Found in CS	271	1045	1316
Vertices located in bricks	151	792	943
Vertices located in dead materials	6	38	44
Interactions in the upstream brick	6	33	39

Events location summary for 2009 run

	0mu	1mu	All
Events predicted by the electronic detector	865	2297	3162
Extracted CS	829	2211	3040
CS Scanned	666	1802	2468
Found in CS	376	1139	1515
Vertices located in bricks	67	371	438
Vertices located in dead materials	2	11	13
Interactions in the upstream brick	3	36	39

A ν_e candidate:

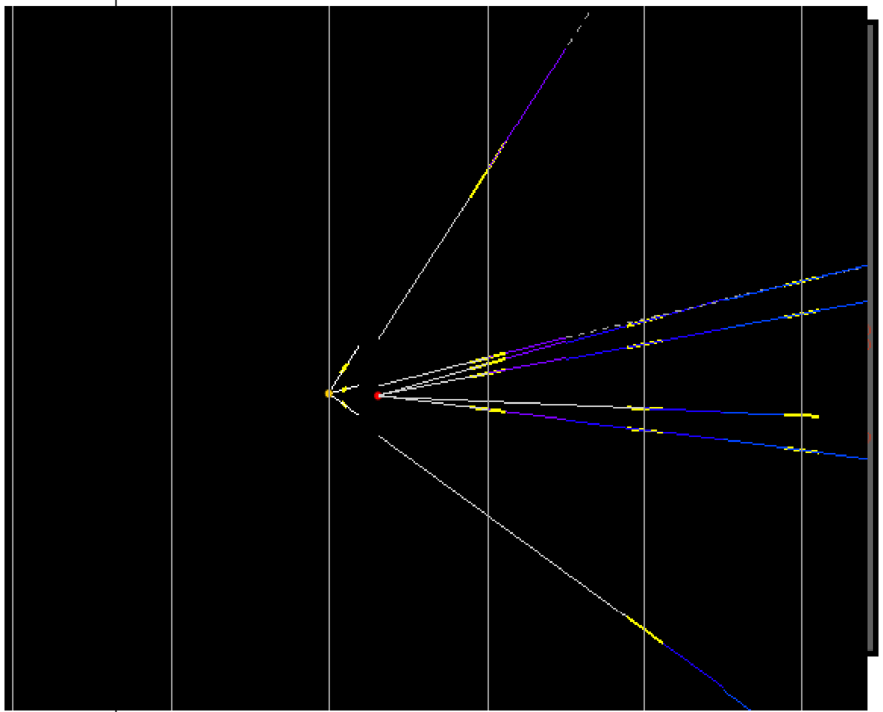


Topological identification and kinematical confirmation of a charm event

All units are in microns

Event 234654975

Brick 85405



VERTEX 1

	Impact Parameter
Track 1	1,36
Track 2	0,88
Track 7	0,51

X	66716,60
Y	49892,8
Z	90,9

Primary vertex

VERTEX 2

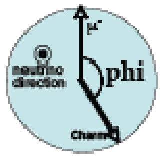
	Impact Parameter
Track 3	1,13
Track 4	1,81
Track 5	1,99
Track 6	1,39

X	66710,10
Y	49899
Z	403,9

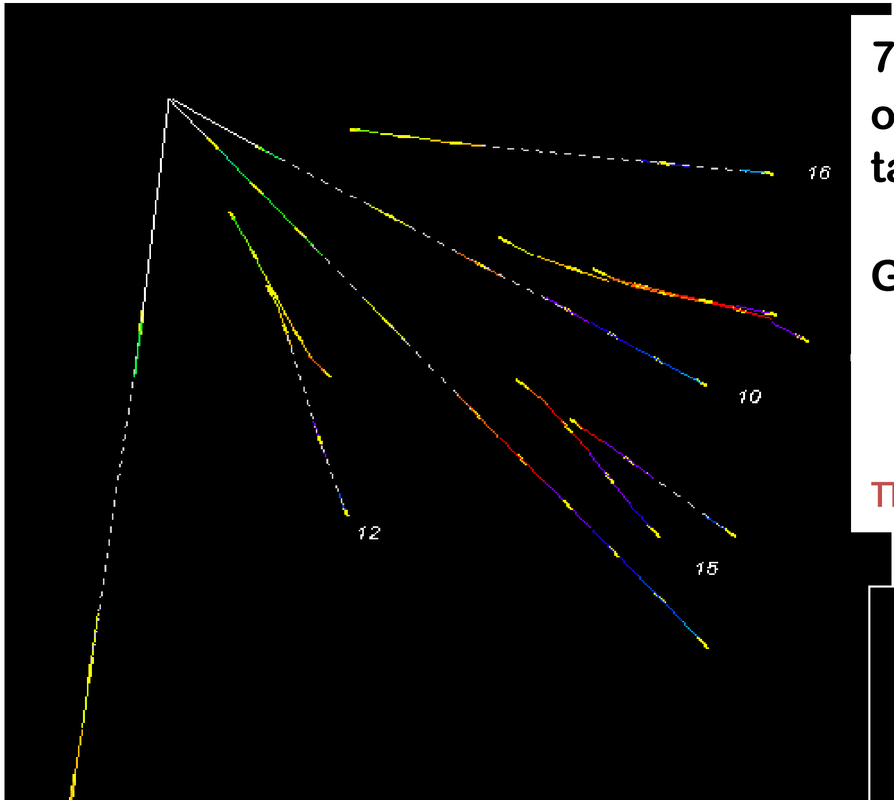
Decay vertex

D^0

Tx	Ty	Flight Length (μm)	phi	minimum mass (GeV/c²)
-0,0207	0,0198	313,1	173,2°	1,7



γ detection and π^0 reconstruction

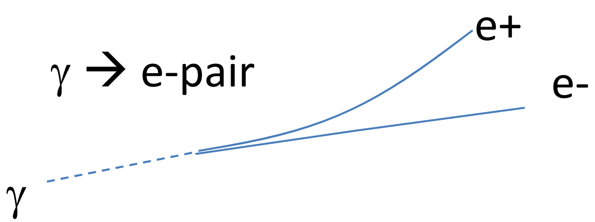


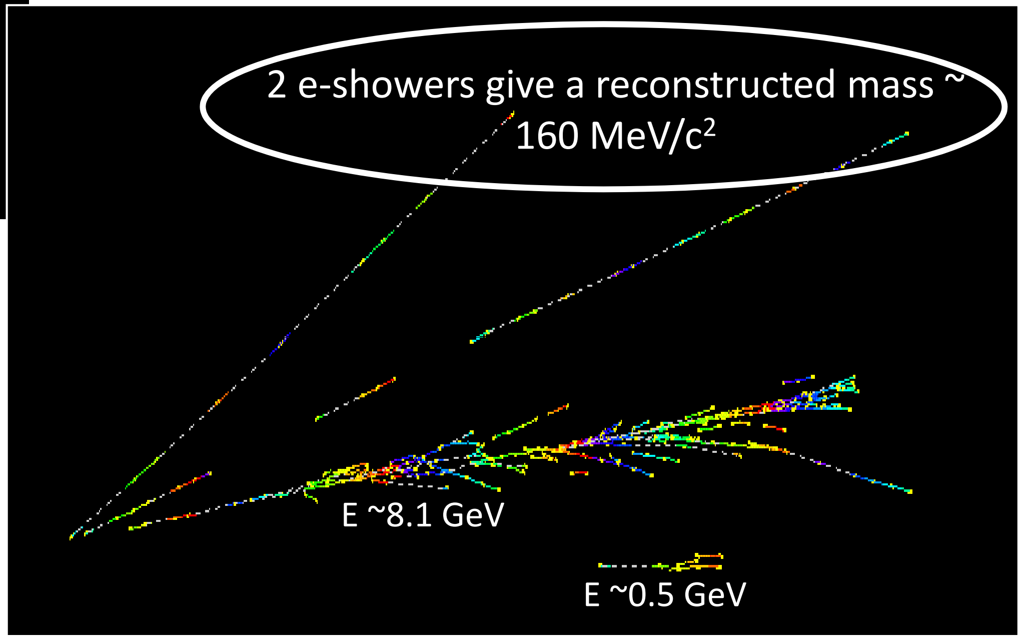
70% of 1-prong hadronic τ decays include one or more π^0. Important to detect gamma from tau decay to improve S/N.

Gamma detection

- detection of shower
- detection e-pair at start point

π^0 reconstruction is in progress.

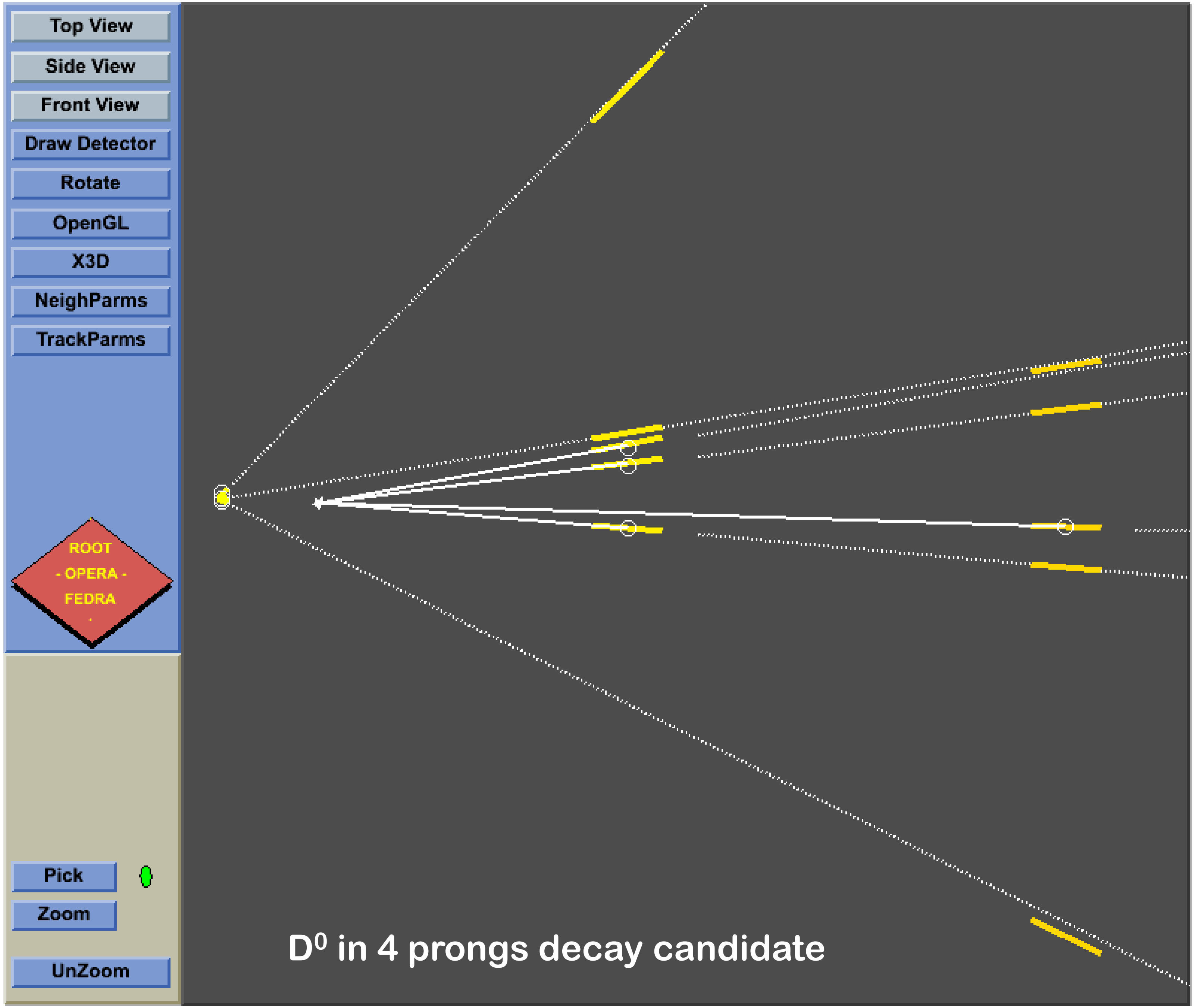




Conclusions :

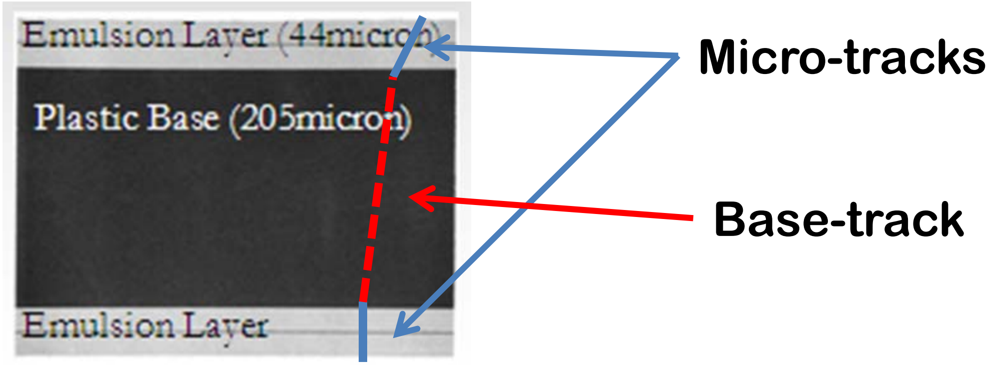
- OPERA has taken data in 2008 and 2009 for 5.3E19 pot, proving the full chain of events handling/analysis
- Electronic detectors performance reliable and well understood
- A systematic decay search was started on all 2008 (and then 2009) events in order to find all possible decay topologies
- Several charm events found as expected
- Global analysis well in progress, ongoing studies on kinematics and hadronic interactions
- The 2010 run will start soon. Hoping to achieve nominal CNGS performance
- No tau signal yet, stay tuned "estote parati" !!!

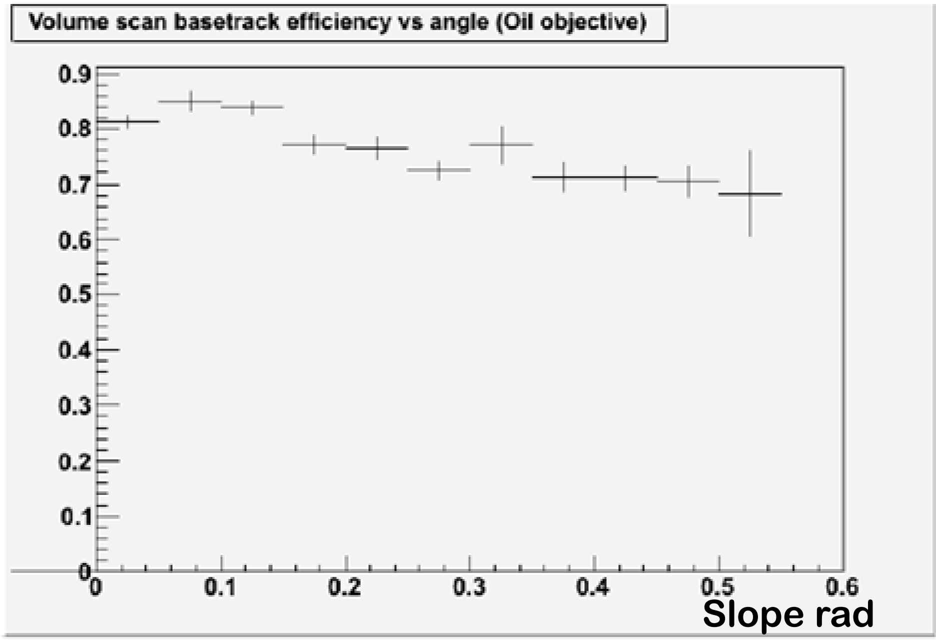
SPARES

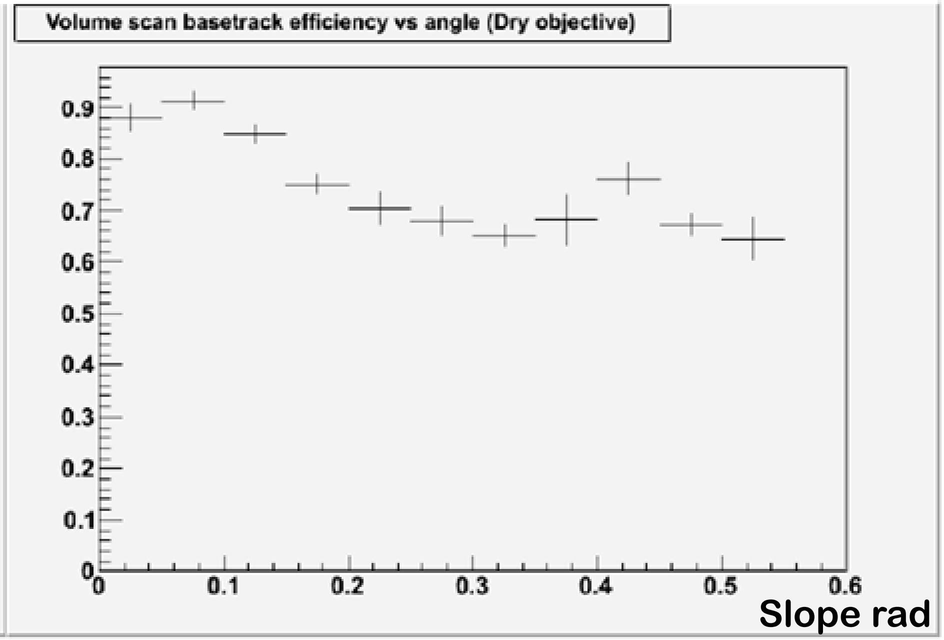


D^0 in 4 prongs decay candidate

Scanning efficiency (single emulsion film base-track reconstruction efficiency) with different methods (oil immersion objectives, dry objectives)

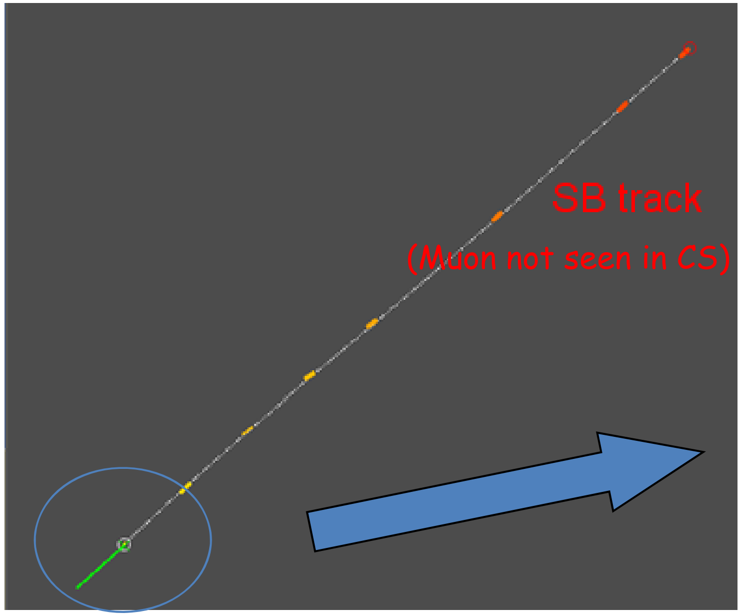


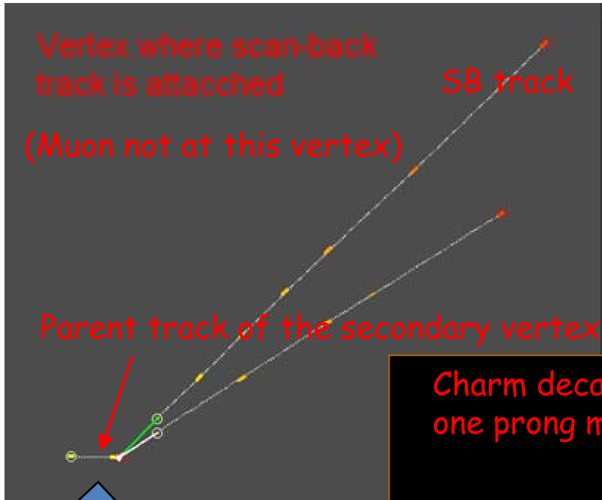


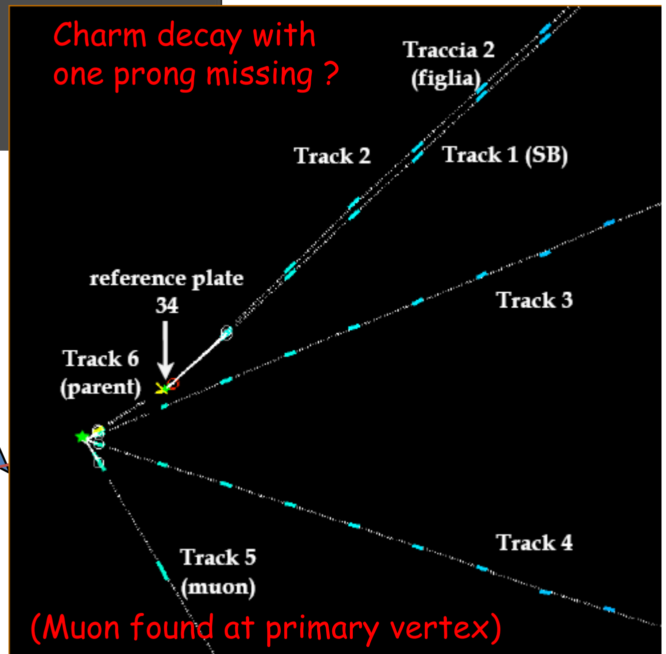


Parametrizations taken into account at the simulation level

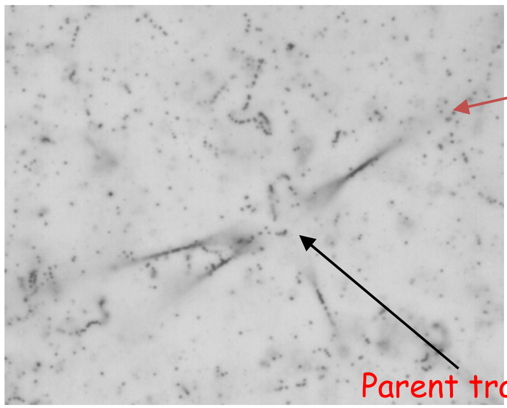
Example of decay search procedure with recovery of the vertex topology







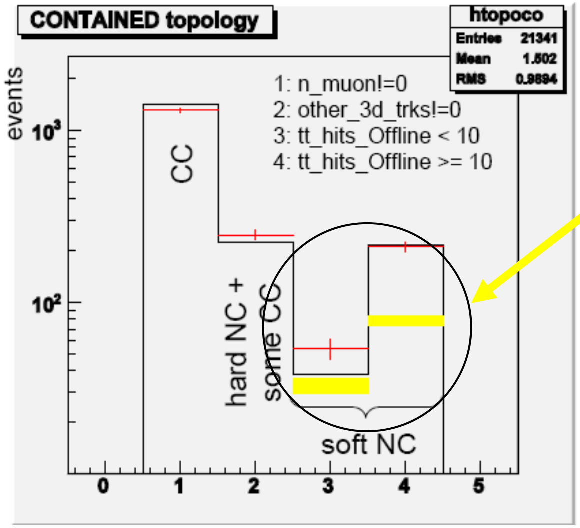
Charged charm candidate with one prong not reconstructed or hadronic interaction (large angle) ?



For this particular event an unforeseen extra handle allows to clarify its nature: the decay vertex is just at the surface of the downstream lead plate, nuclear fragments backscattered are visible in the emulsion upstream

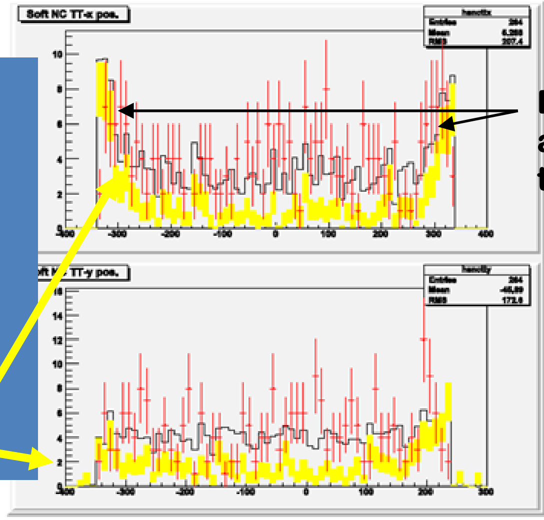
→ It is an hadronic interaction and not a charm

Finalization of events selection and validation of the background from external neutrino interactions in the soft NC candidates sample

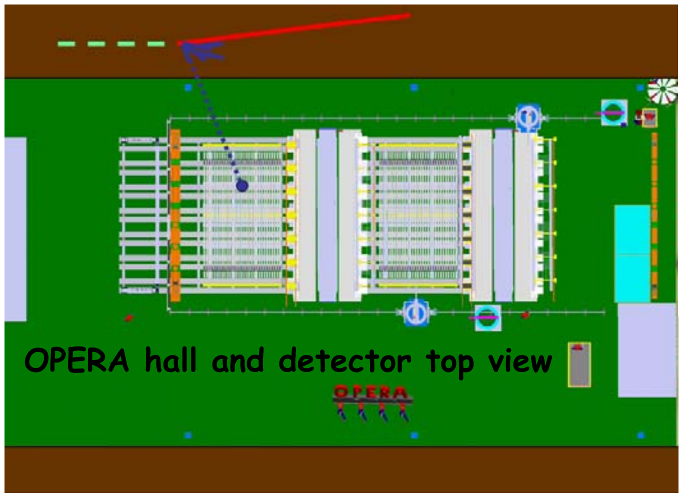


Event categories
Soft NC BCK

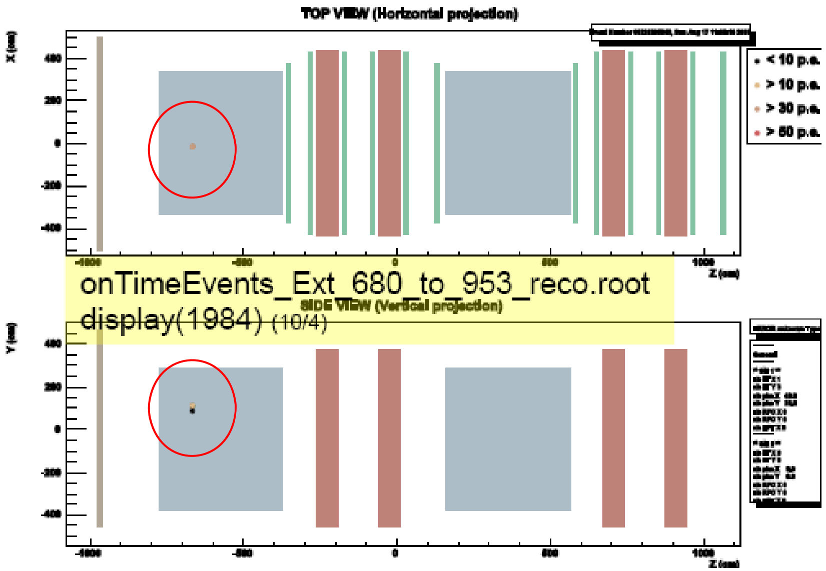
Space distribution of soft NC sample:
Data, Total MC,
External Bck MC



Bck accumulation at the borders of the target



OPERA hall and detector top view



Contamination due to interactions of neutrals produced in neutrino interactions external to the target (about 200 events for 2009) affects NC/CC ratio →

NC/CC

NC/CC ratio

To be independent of the tracking efficiency, an event is identified as CC if the number of touched planes is more than 14.

	CC identified	CC misidentified	NC identified	NC misidentified
MC	96.1%	3.9%	69.0%	31.0%

	OpCarac (fiducial volume) efficiency CC	OpCarac (fiducial volume) efficiency NC
MC	96.9%	88.2%

	CC identified	NC identified
Data	(1928) 78.0%	(545) 22.0%

OpCarac efficiency for CC; CC identified efficiency; True number of CC; OpCarac efficiency for NC; NC misidentified efficiency; True ratio NC/CC = 0.29

$$CC_{measured} = \epsilon_{OpCarCC} \times eff_{CC} \times n_{CC} + \epsilon_{OpCarNC} \times ineff_{NC} \times \epsilon_{NC/CC} \times n_{CC}$$

$$NC_{measured} = \epsilon_{OpCarCC} \times ineff_{CC} \times n_{CC} + \epsilon_{OpCarNC} \times eff_{NC} \times \epsilon_{NC/CC} \times n_{CC}$$

MC NC/CC = 21.2%
Data NC/CC = 28.3%

We find more NC events in the data, which are due to interacting neutrons coming from a neutrino interaction in the rock or materials in front of the detector. Characterisation of this «noise» under study!

15

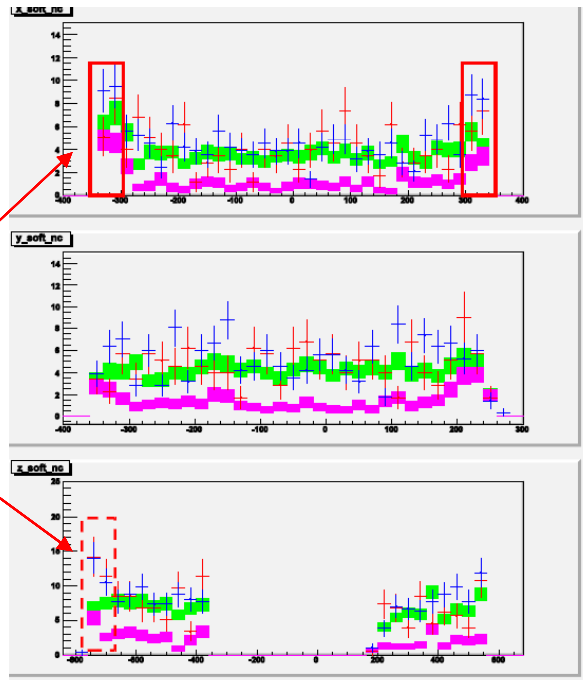
Visible NC/CC takes into account:

- ✓NC/CC true ratio (0.3)
- ✓Target interactions sele. Eff. (OpCarac
- ✓Muon ID efficiencies
- ✓Events migrations due to misidentification CC↔NC

Visible NC/CC full target:
MC: NC/CC= 21.7%
Data: NC/CC= 28.3%

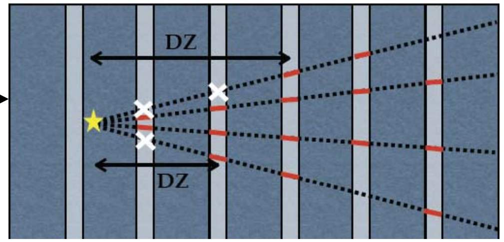
❖ NC excess in data described by MC when including BCK due to external interactions:
→ MC including external BCK full simulation 27.1%

❖ Full MC well reproduces BCK reduction and NC/CC ratio by <u>cutting harder</u> on the fiducial volume:



Visible NC/CC fid. Volume:
Data 2008: NC/CC= **0.230 ± 0.014 (stat.)**
Data 2009: NC/CC= **0.230 ± 0.009 (stat.)**
MC: NC/CC= **0.236 ± 0.005 (stat.)**

1st Step VERTEX DEFINITION



Automatic search for microtracks in order to compensate BT inefficiency

Improvement in the vertex definition and IP distribution

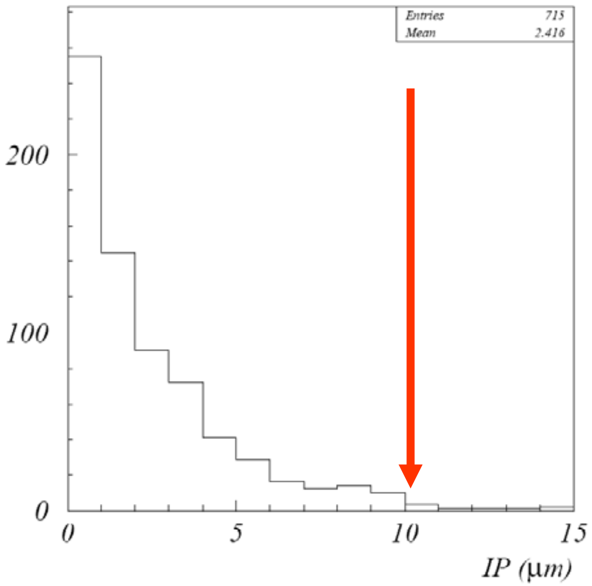
2nd Step ALL TRACKS ANALYSIS

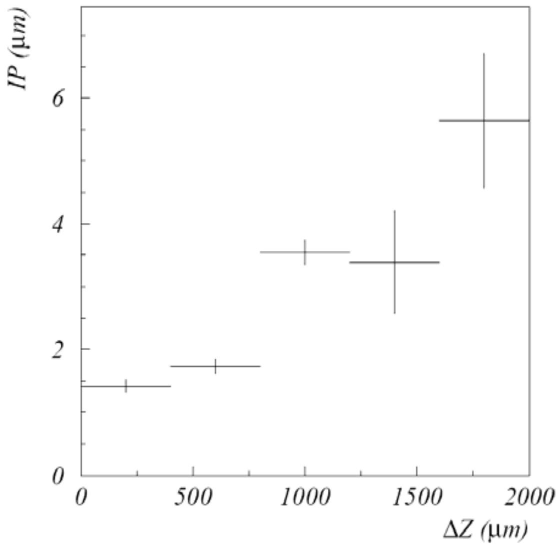
ATTACHED TO VERTEX ?

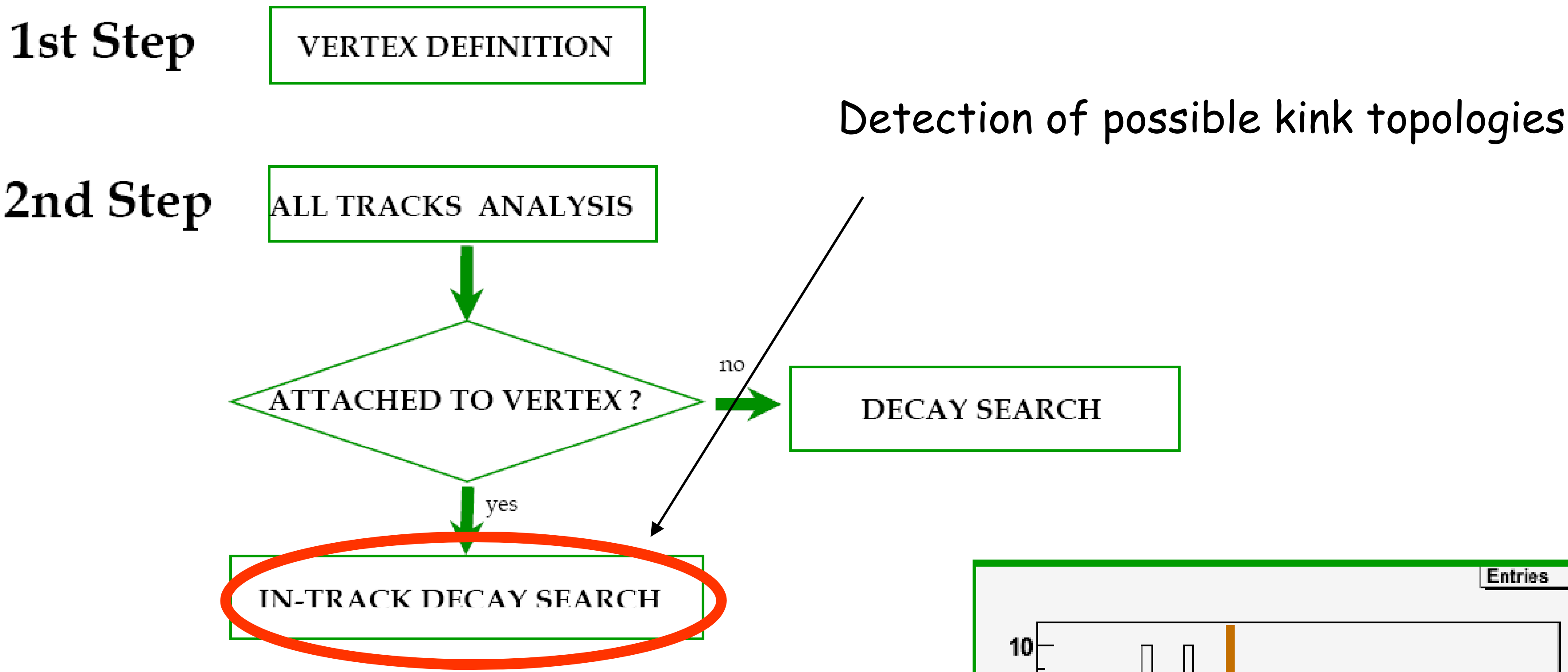
no → DECAY SEARCH

yes → IN-TRACK DECAY SEARCH

Background to automatic mictrotracks search ~0.2 %

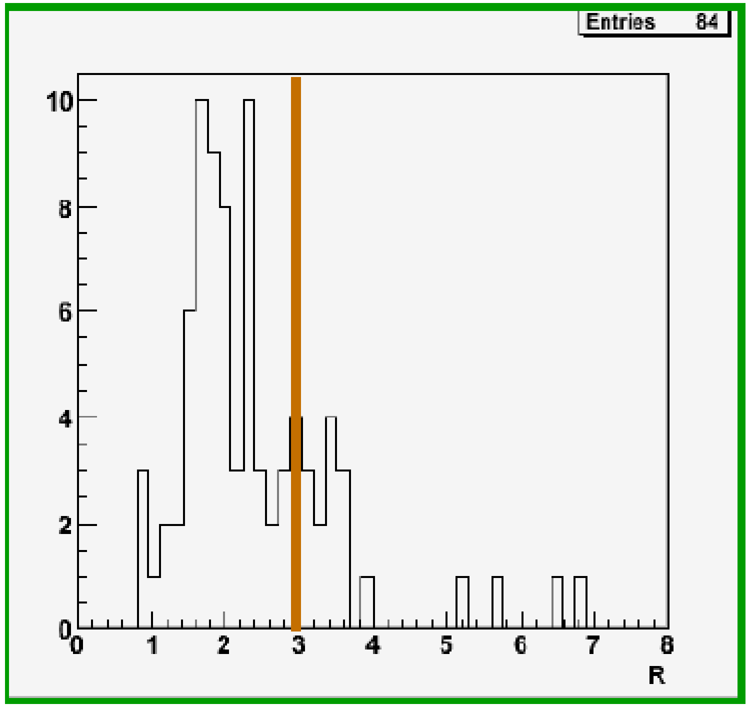






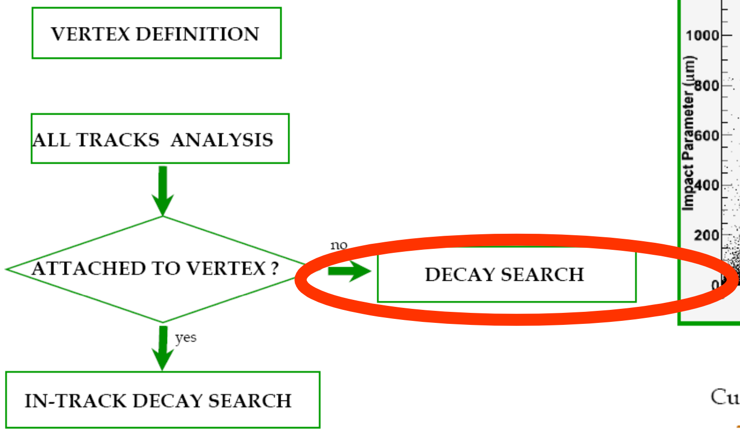
$$\Delta\theta^{RMS}{}_{kink} = \sqrt{\frac{\sum_{i!=kink}^{N-1} \Delta\theta^2{}_i \ /(\Delta npl)_i}{N-1}}$$

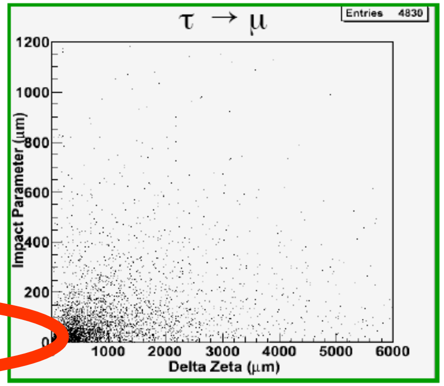
Compare the kink angle to average angular deviations due to MCS, cut at 3 (example on 30 events)



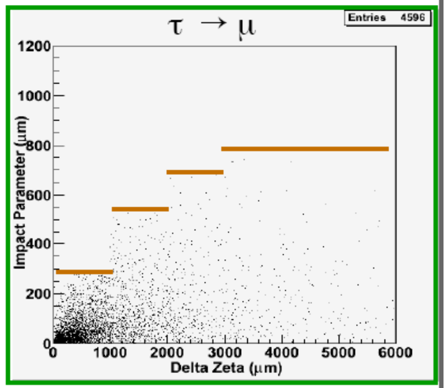
1st Step

2nd Step





τ → μ
MC true



Cut on Impact Parameter as a function of ΔZeta:

- ΔZeta ϵ [0 - 1000] → IP < 280
- ΔZeta ϵ [1000 - 2000] → IP < 540
- ΔZeta ϵ [2000 - 3000] → IP < 680
- ΔZeta ϵ [3000 - 6000] → IP < 800

→ Selection: 95% of signal

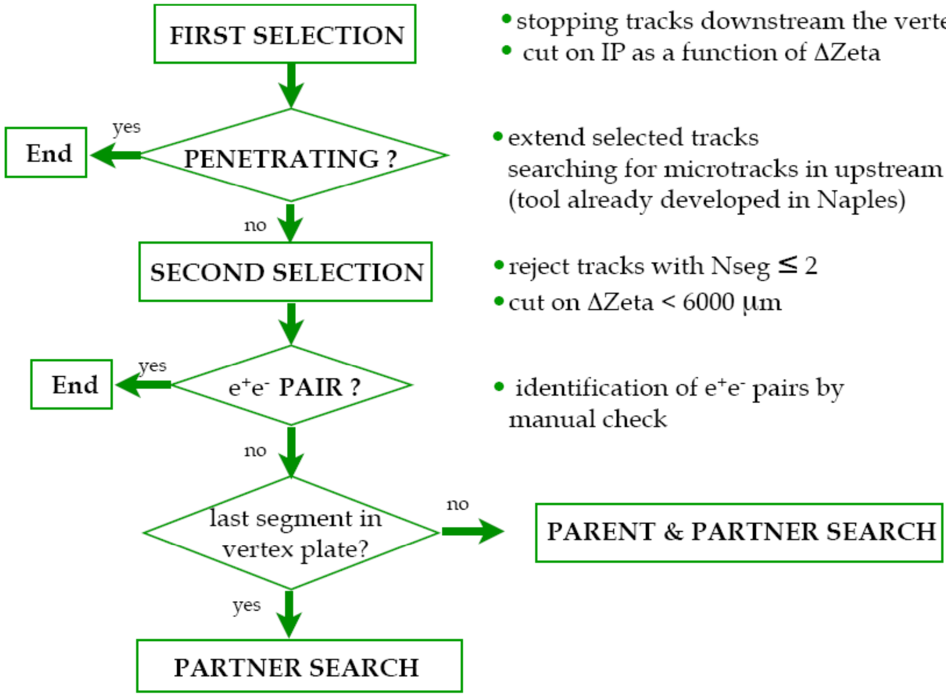
Tracks not attached to primary vertex:

Evaluation of IP vs DZ

Sample cleaning

Decay Search

Procedure



- stopping tracks downstream the vertex
- cut on IP as a function of ΔZeta

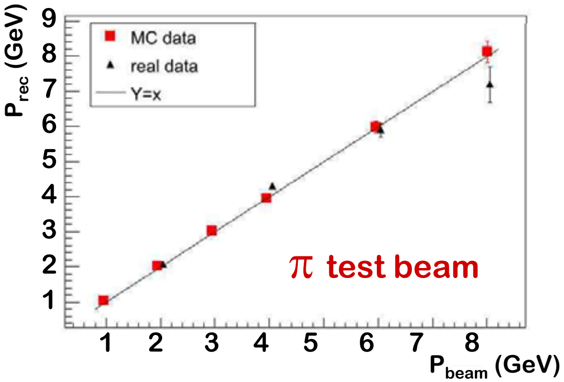
- extend selected tracks searching for microtracks in upstream plates (tool already developed in Naples)

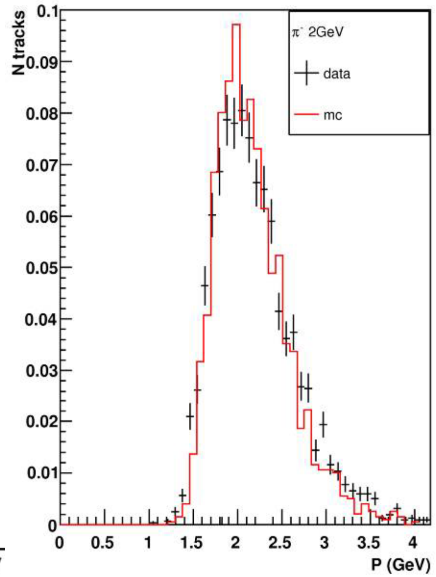
- reject tracks with Nseg ≤ 2
- cut on ΔZeta < 6000 μm

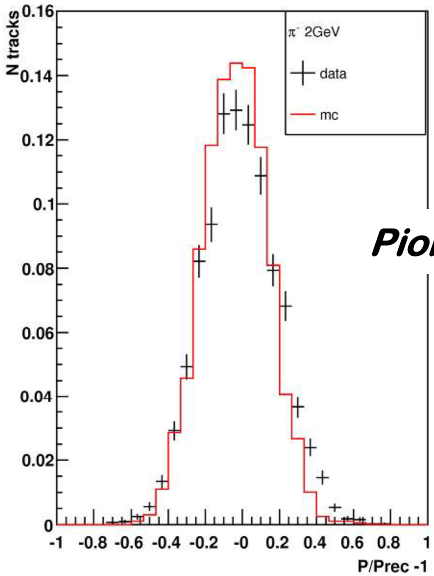
- identification of e^+e^- pairs by manual check

Test beam data samples of pions and several MC samples were produced and used for the development of the method.

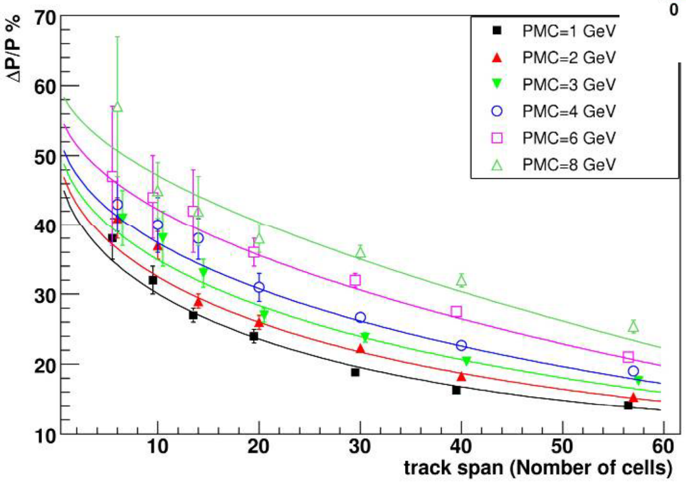
Very detailed results are given and should be considered as reference ones for further MCS investigations.



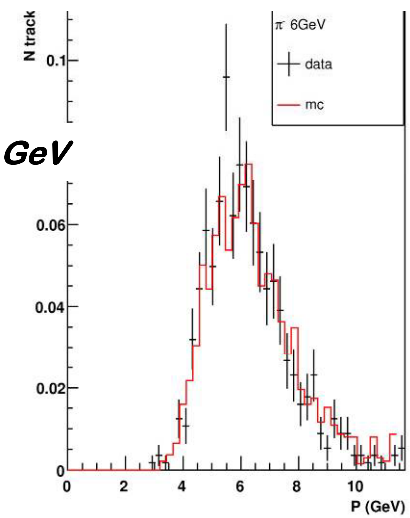


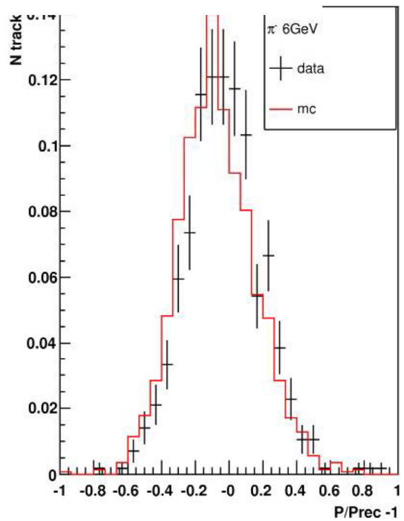


Pion 2 GeV



Pion 6 GeV



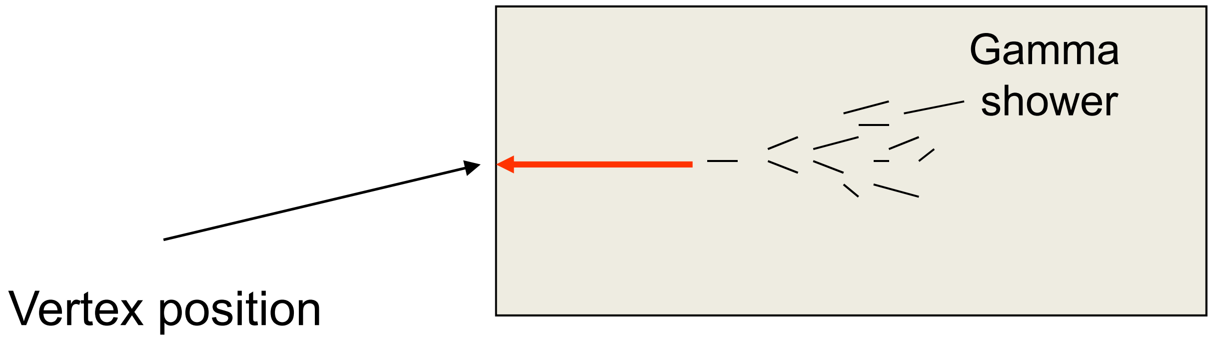


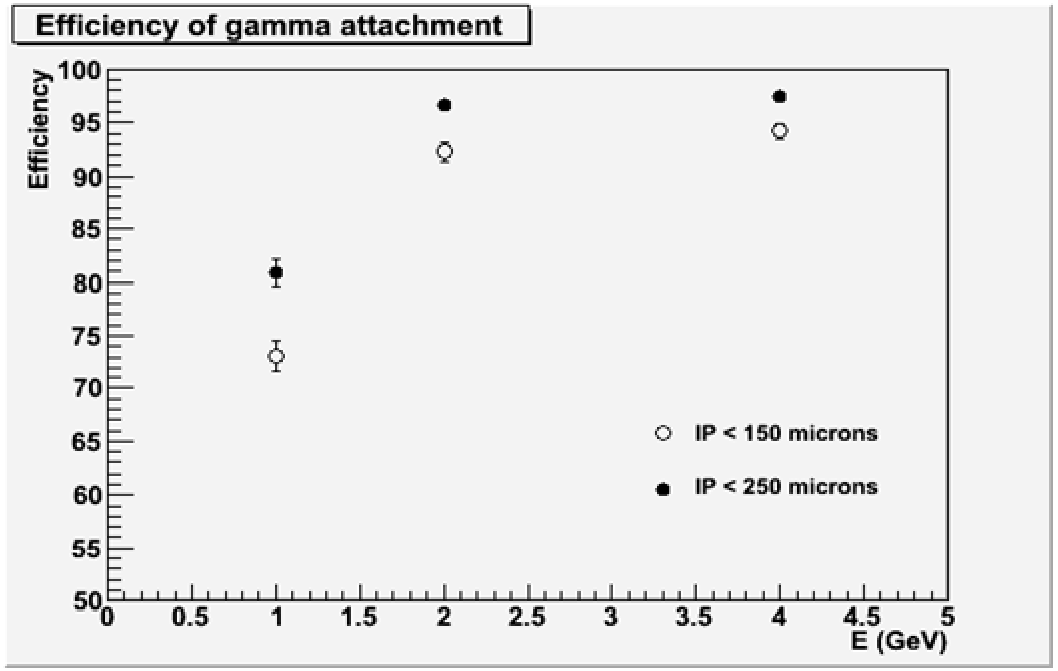
Ref: OPERA internal note #92

Gamma/electrons

-Gamma attachment to primary/secondary vertices (tau→rho)

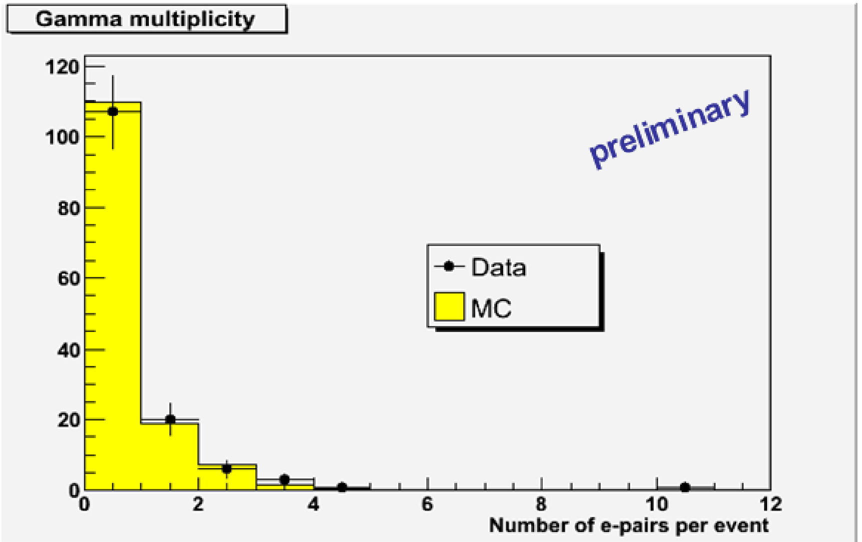
By extrapolating the first base-track of the shower





Purely attachment efficiency (does not include the probability that the gamma converts in the volume scan)

Data vs MC for γ reconstruction



Comparison data/MC for the Gamma multiplicity in ν_μ CC+NC events

Volume scan of 20 plates downstream vertex and area of 1 cm^2