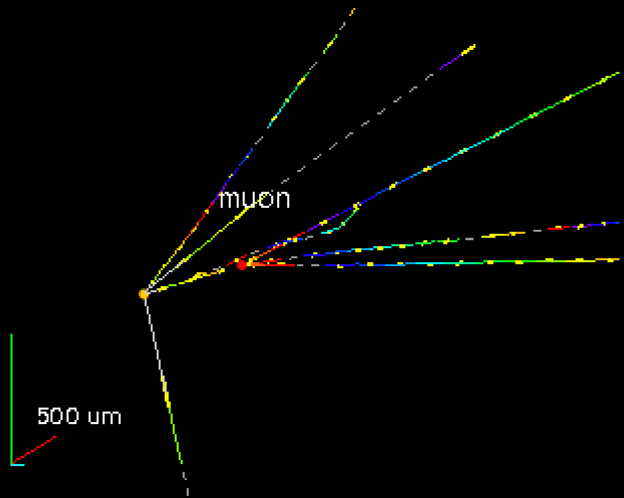
Observation of events with decay topologies in the OPERA experiment



On behalf of the OPERA Collaboration

Giovanni De Lellis

University "Federico II" of Naples and INFN

PHYSICS: from neutrino mixing to oscillations

3x3 Unitary Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric terms **Unknown terms** **Solar terms**

$c_{ij} = \cos\theta_{ij}, \; s_{ij} = \sin\theta_{ij}$

OPERA

OPERA: first direct detection of neutrino oscillations in appearance mode

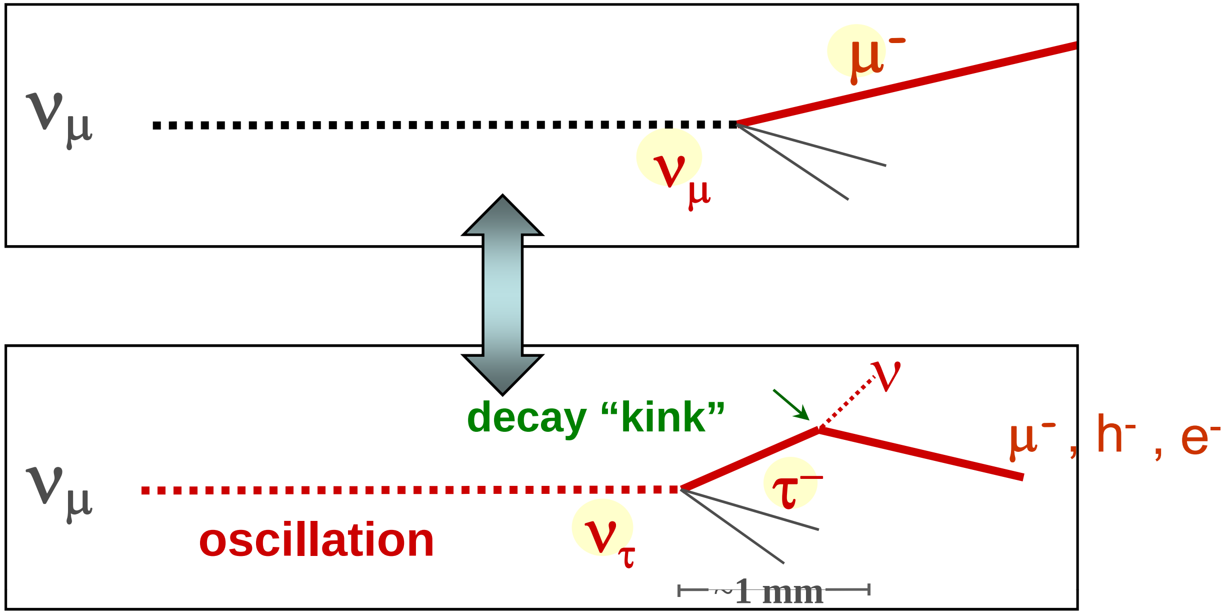
following the Super- Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams. An important, missing tile in the oscillation picture.

The PMNS 3-flavor oscillation formalism predicts:

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

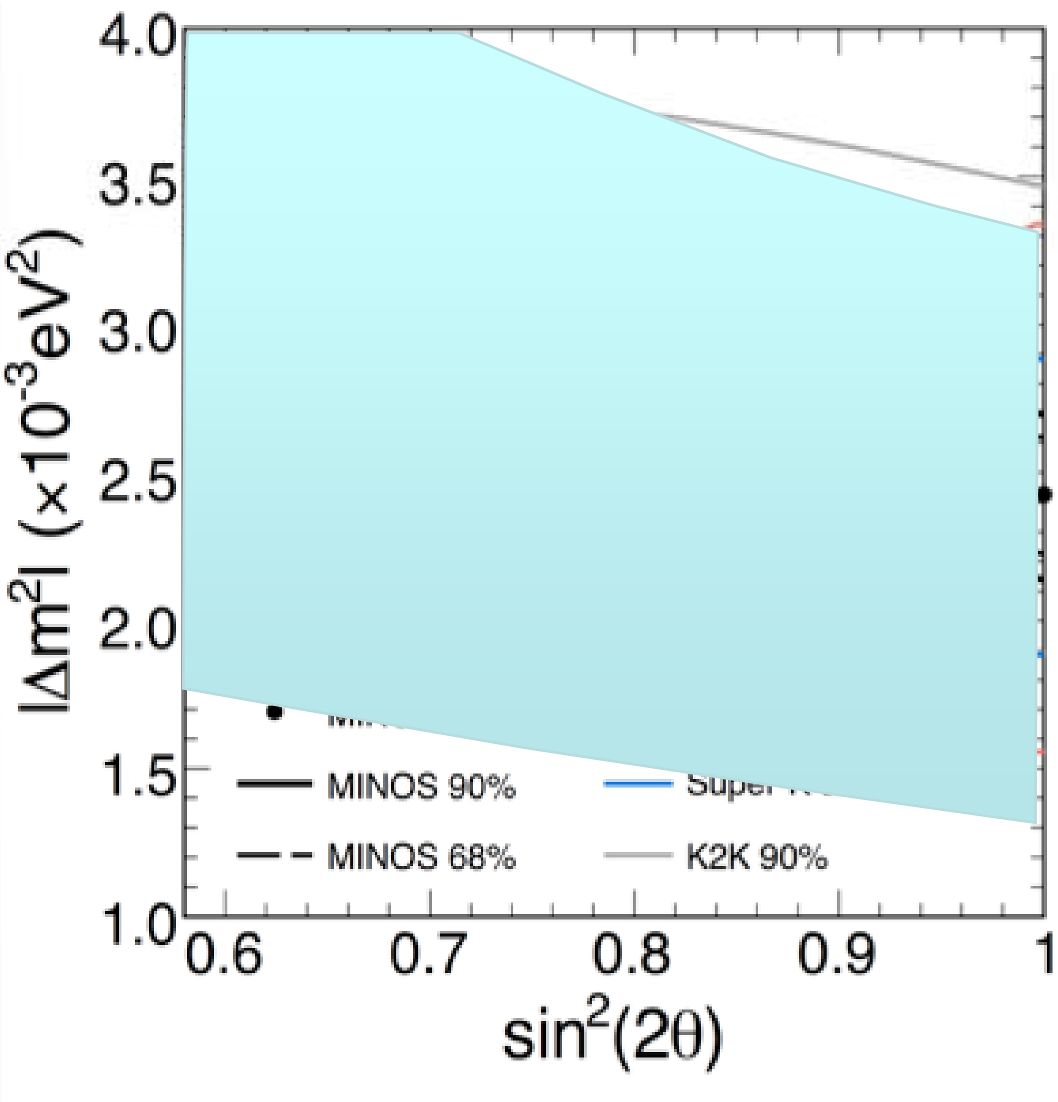
Requirements:

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



plus 3-prong decay modes

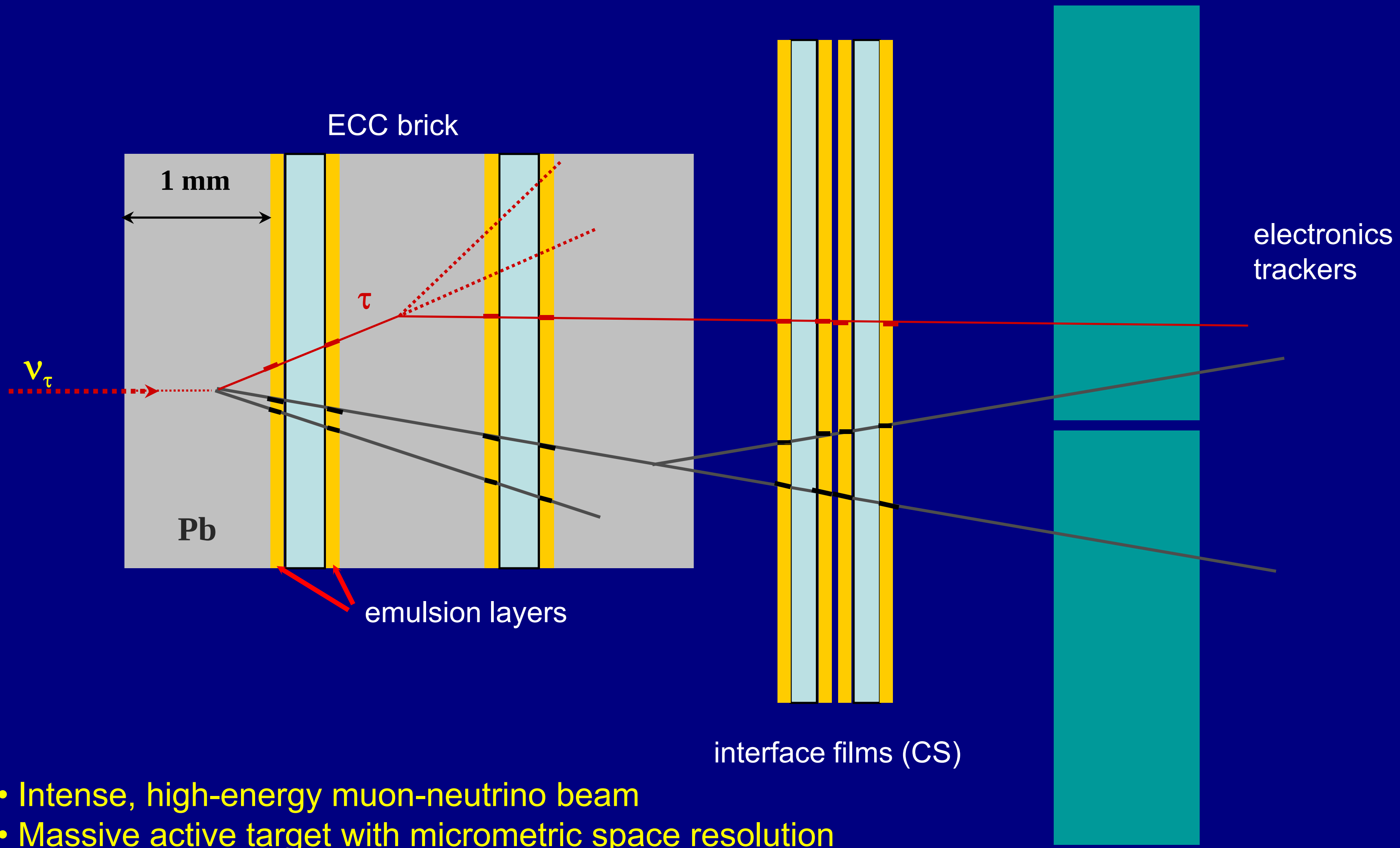
Measurement of the oscillation parameters in the atmospheric neutrino sector: present situation



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

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

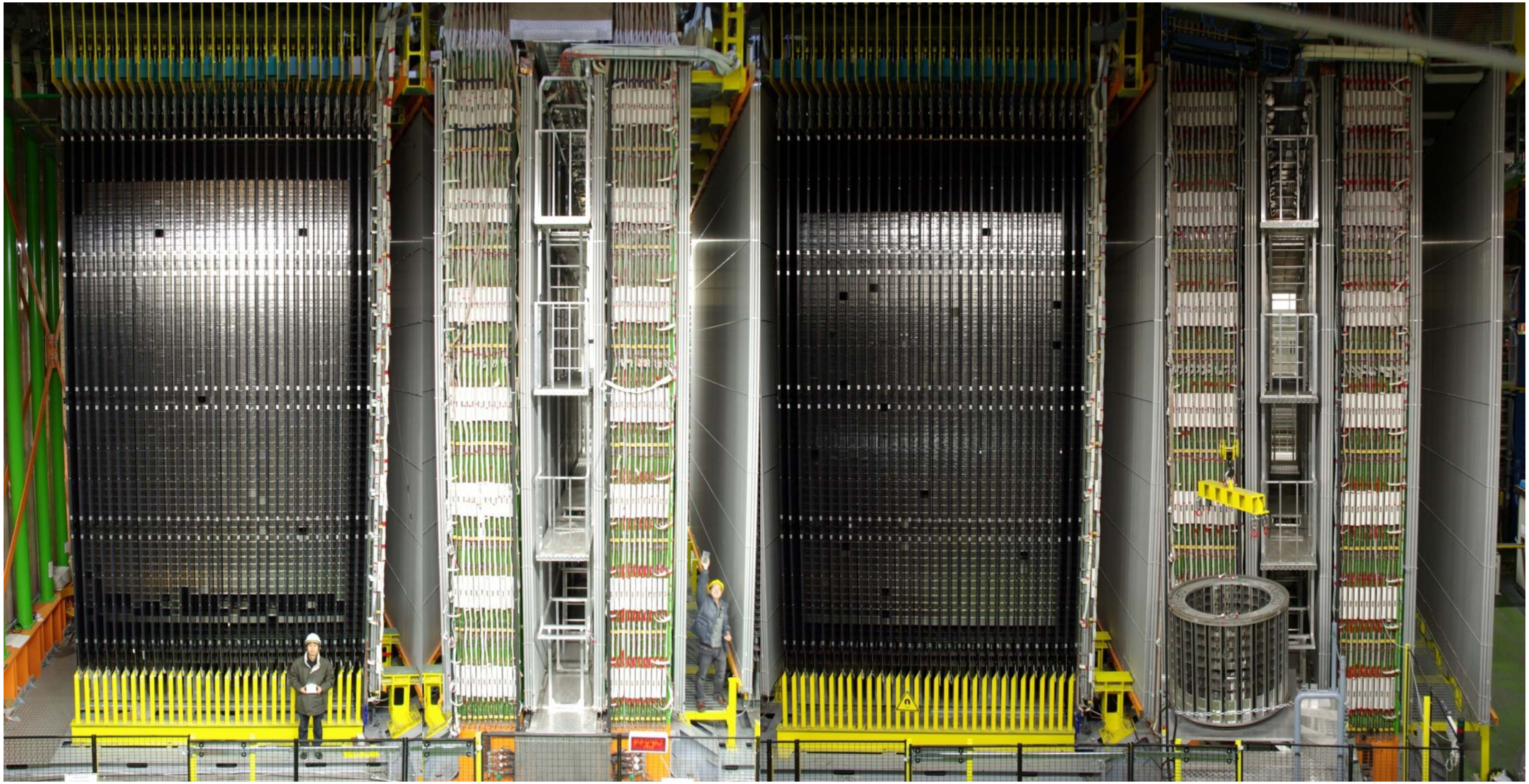
THE PRINCIPLE OF THE EXPERIMENT: ECC + ELECTRONIC DETECTORS



- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide "time resolution" to the emulsions and preselect the interaction region

THE IMPLEMENTATION OF THE PRINCIPLE

SM1 SM2



Target area Muon spectrometer

OPERA expected performance (Proposal)

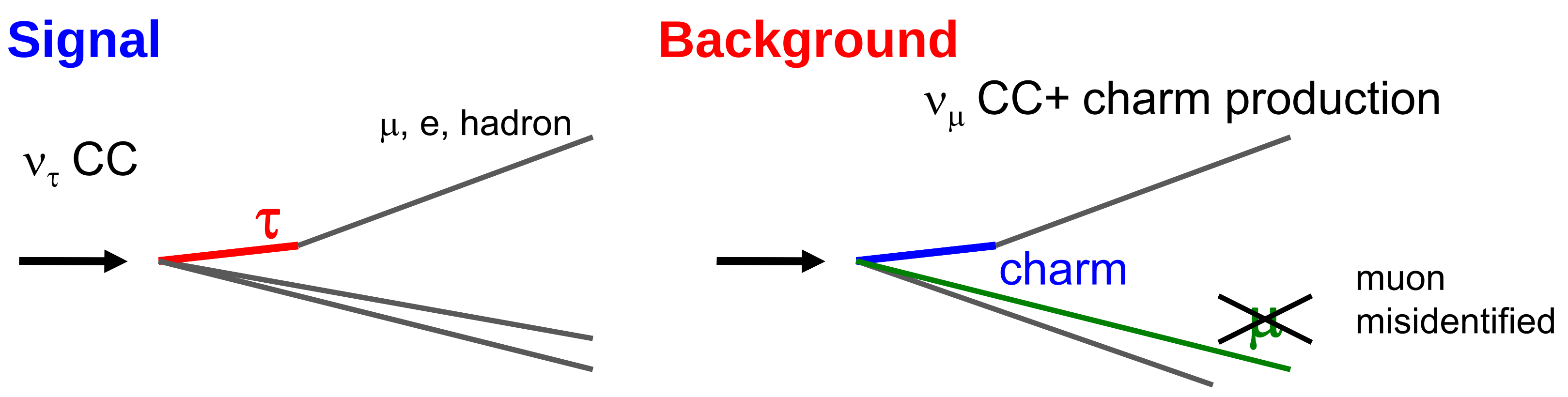
τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Background
$\tau \to \mu$	17.7	2.9	0.17
$\tau \to e$	17.8	3.5	0.17
$\tau \to h$	49.5	3.1	0.24
$\tau \to 3h$	15.0	0.9	0.17
Total		10.4	0.75

Main background sources:

- Production and decay of charmed particles
- Hadron reinteractions
- Large angle muon scattering

Assume 22.5×10^{19} pot

Example: charm BG to tau decays



HISTORY AND COLLABORATION

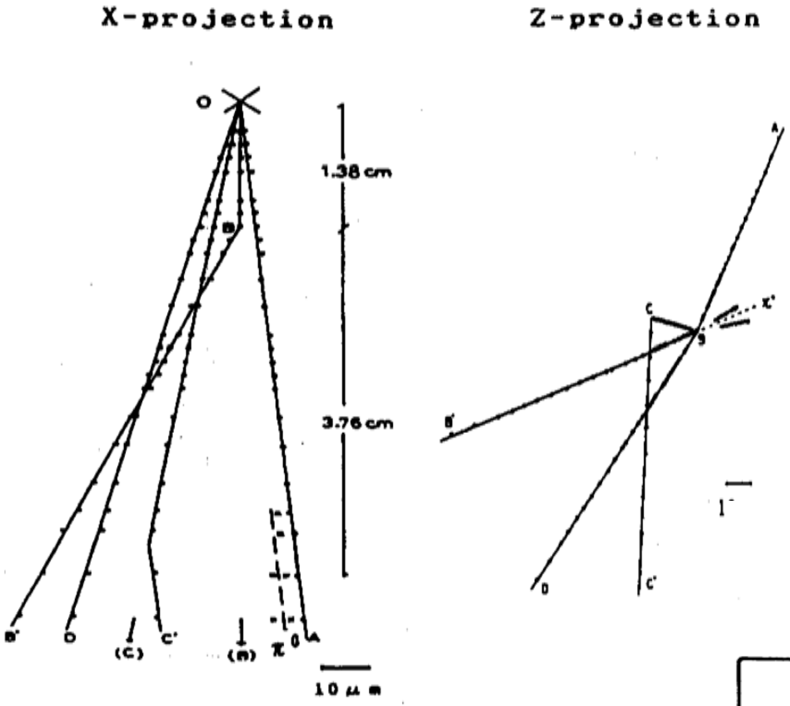
The ECC: evidence for charm in cosmic-rays by K. Niu (1971)

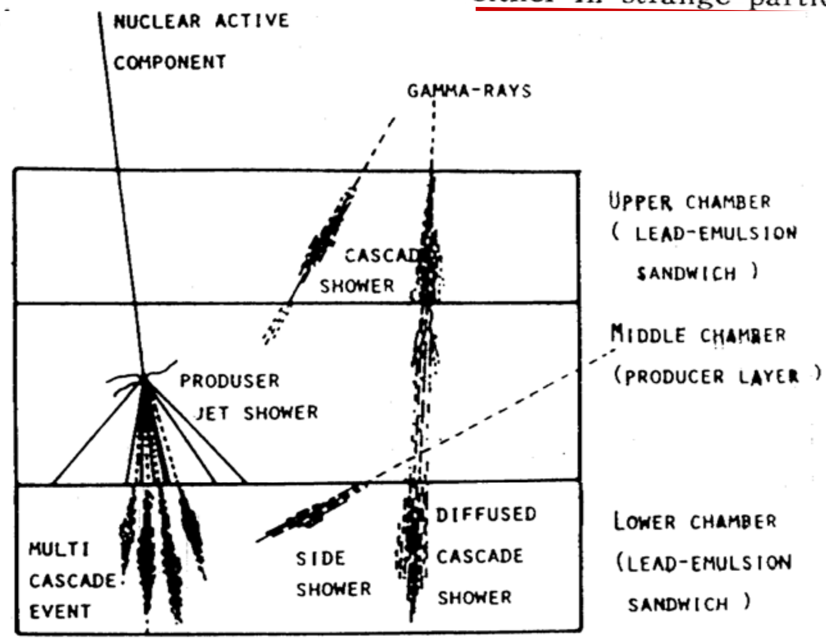
Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA

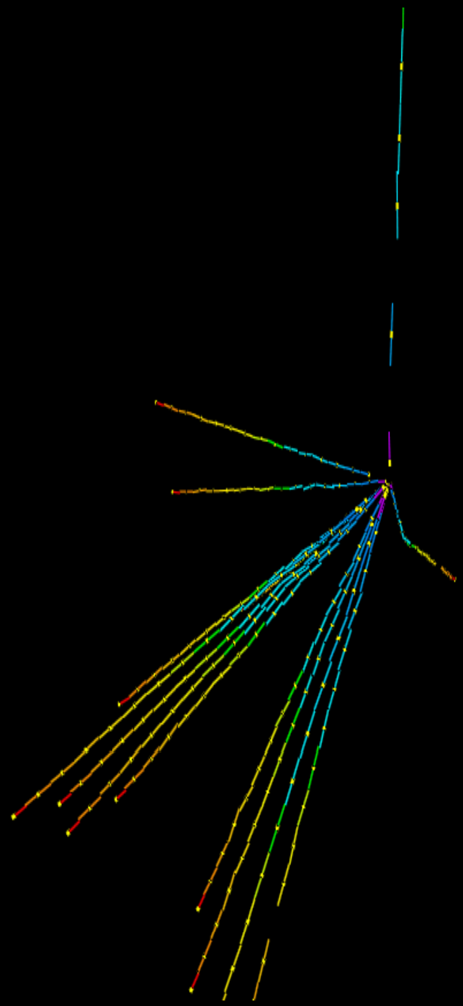
As for the characteristics of X particle, the transverse momentum of daughter π^0 meson, 627 ± 90 MeV/c, is much higher than the maximum momentum of decay products of the existing strange particles. The proper life time of X particle is several times 10^{-14} seconds, and this is extremely longer than those of resonance particles. Therefore, our X particle could not be included either in strange particle or in resonance

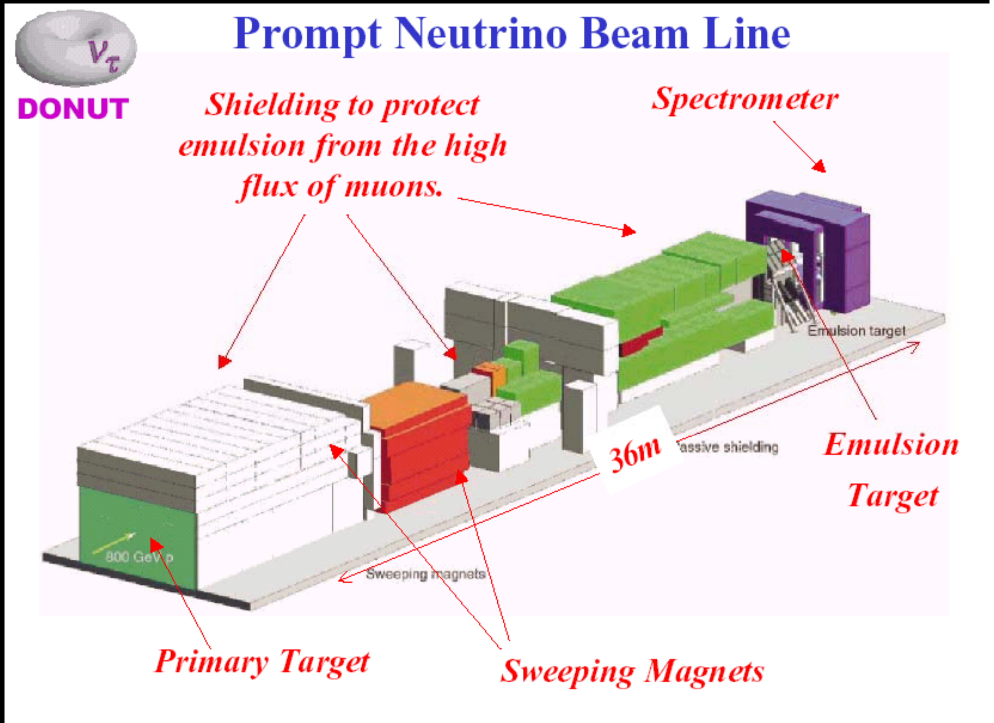




DONUT experiment at FERMILAB: first detection of ν_τ with an ECC based detector (K. Niwa and collaborators): 9 τ events, 1.5 BG.

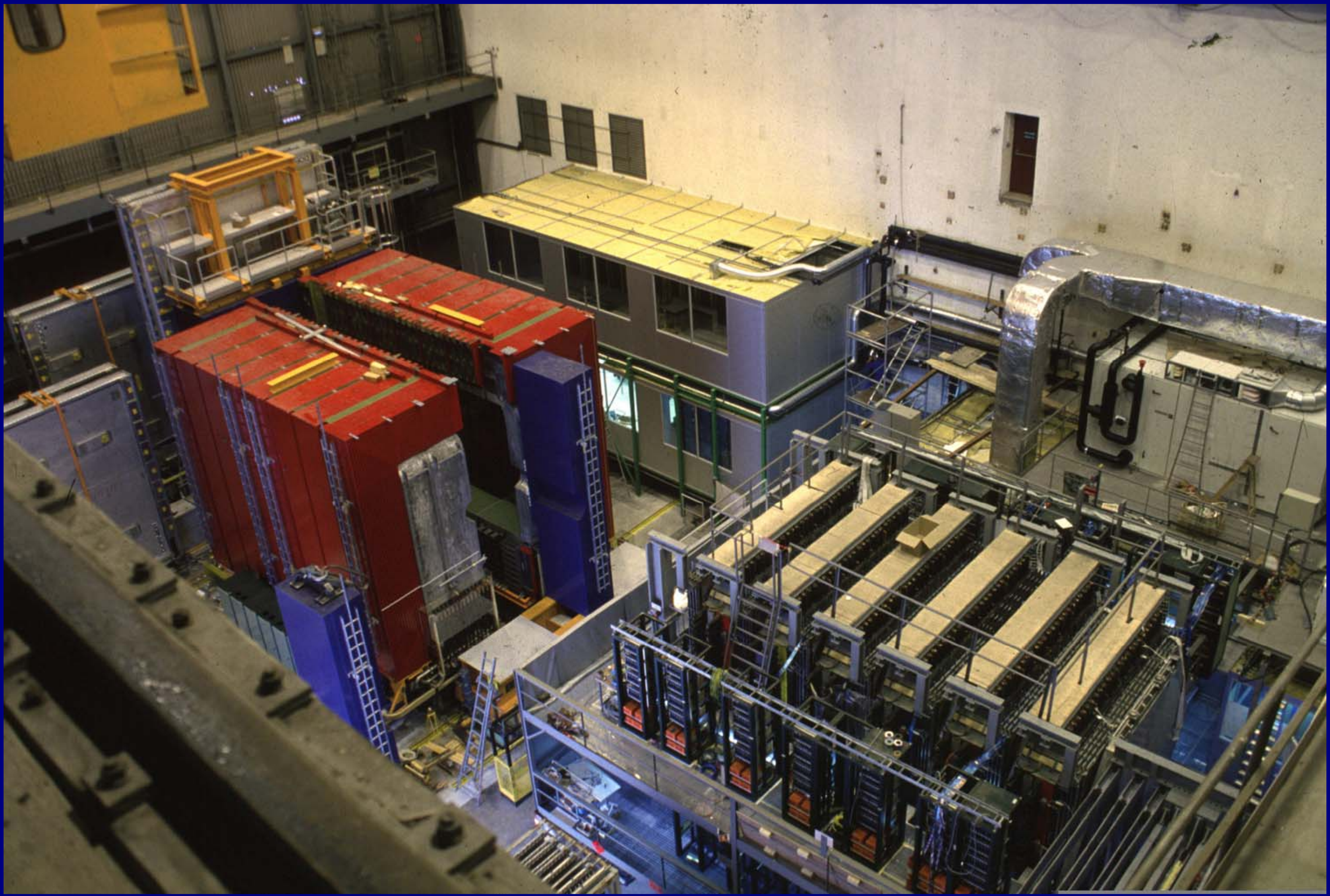
K. Kodama et al. (DONuT Collaboration), Phys. Lett. B 504, 218 (2001).





From CHORUS, NOMAD (and MACRO) to OPERA

Experience and participation from the three Collaborations



OPERA: the choice for appearance (reference papers)

A. Ereditato, K. Niwa and P. Strolin,
The emulsion technique for short, medium and long baseline $\nu_\mu \to \nu_\tau$ *oscillation experiments,*
INFN-AE-97-06, DAPNU-97-07, Jan 1997.

OPERA Collaboration, H. Shibuya et al., *Letter of intent: the OPERA emulsion detector for a long-baseline neutrino-oscillation experiment*,CERN-SPSC-97-24, LNGS-LOI-8-97.

OPERA Collaboration, M. Guler et al., *An appearance experiment to search for* $\nu_\mu \to \nu_\tau$ *oscillation in the CNGS beam: experimental proposal*, CERN-SPSC-2000-028.

OPERA Collaboration, R. Acquafredda et al., *First events from the CNGS neutrino beam detected in the OPERA experiment*, New J. Phys. 8 (2006) 303.

OPERA Collaboration, R. Acquafredda et al., *The OPERA experiment in the CERN to Gran Sasso neutrino beam*, JINST 4 (2009) P04018.

OPERA Collaboration, N. Agafonova et al., *The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment*. JINST 4 (2009) P06020

The present OPERA Collaboration:
170 physicists, 33 institutions in 12 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg
Münster
Rostock

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
L'Aquila,
LNGS
Napoli
Padova
Roma
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

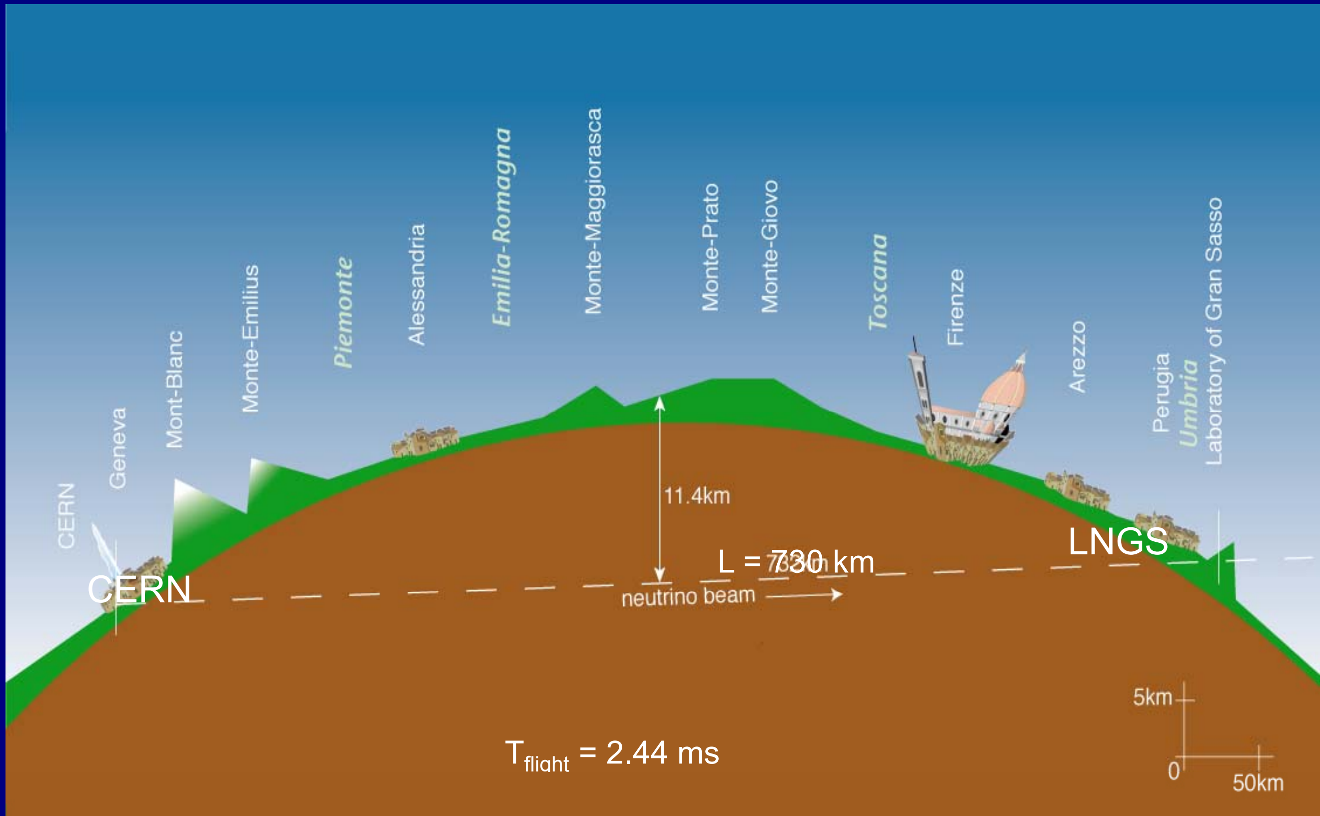
Tunisia
CNSTN Tunis

Turkey
METU Ankara

OPERA: CERN CNGS1 and LNGS experiment http://operaweb.lngs.infn.it/

CNGS BEAM AND LNGS

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

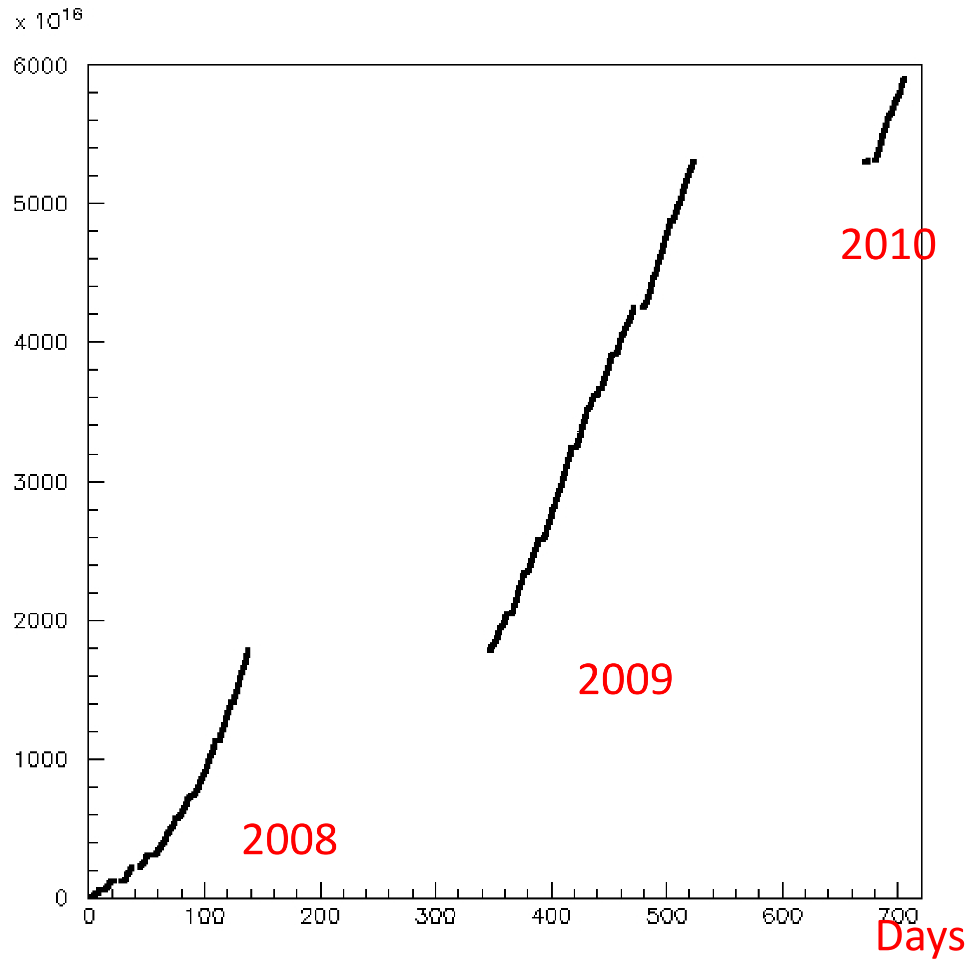


< E >	17 GeV
L	730 km
$(\nu_e + \overline{\nu}_e) / \nu_\mu$ (CC)	0.87%
$\nu_\mu / \overline{\nu}_\mu$ (CC)	2.1%
ν_τ prompt	negligible

Expected neutrino interactions for 22.5×10^{19} pot:
~ 23600 ν_μ CC + NC
~ 205 $\nu_e + \overline{\nu}_e$ CC
~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

CNGS performance

2006	0.076×10^{19} pot	no bricks	Commissioning
2007	0.082×10^{19} pot	38 ev.	Commissioning
2008	**1.78×10^{19} pot**	**1698 ev.**	**First physics run**
2009	**3.52×10^{19} pot**	**3693 ev.**	**Physics run**
2010	**0.60×10^{19} pot (23 May)**	**579 ev.**	**Physics run**



5970 events collected until 23 May 2010 (within 1σ in agreement with expectations)

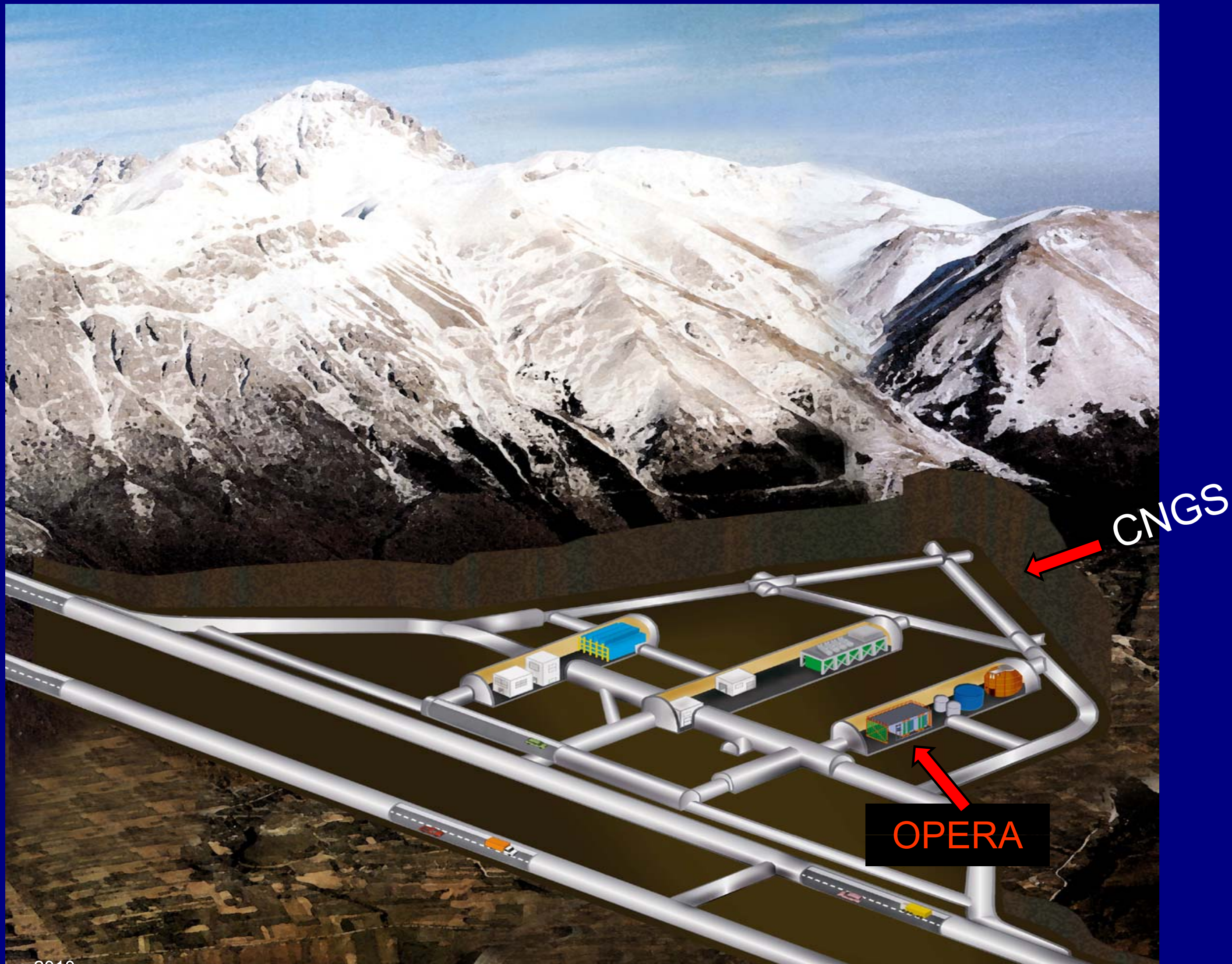
Improving features, high CNGS efficiency (97% in 2008-2009)

2010: close to nominal year;
Multi Turn Extraction routinely running

Aim at high-intensity runs in 2011 and 2012

LNGS of INFN, the world largest underground physics laboratory:

~180'000 m^3 caverns' volume, ~3'100 m.w.e. overburden, ~1 cosmic μ / (m^2 x hour), experimental infrastructure, variety of experiments. Perfectly fit to host detector and related facilities, caverns oriented towards CERN.

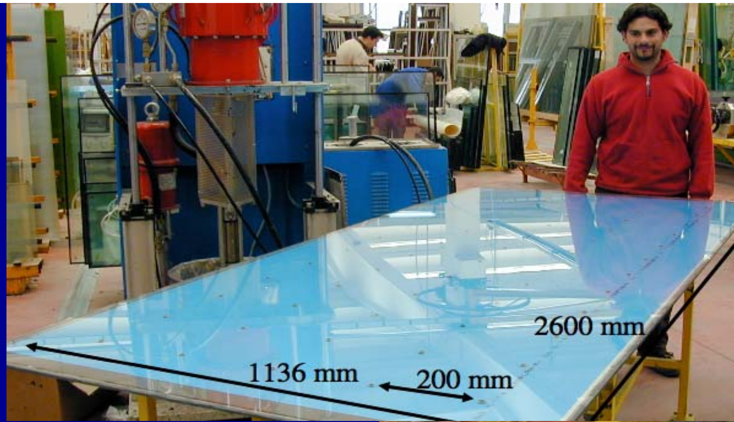


DETECTORS AND FACILITIES:

A very complex experiment…

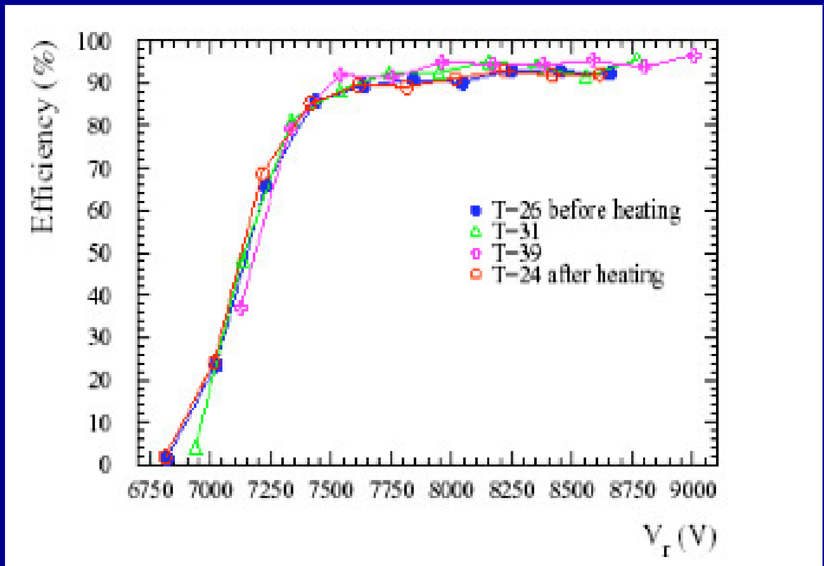
Two target super-modules, each with an iron spectrometer for muon detection (BG rejection and tau-into-muon decay channel)

VETO SYSTEM

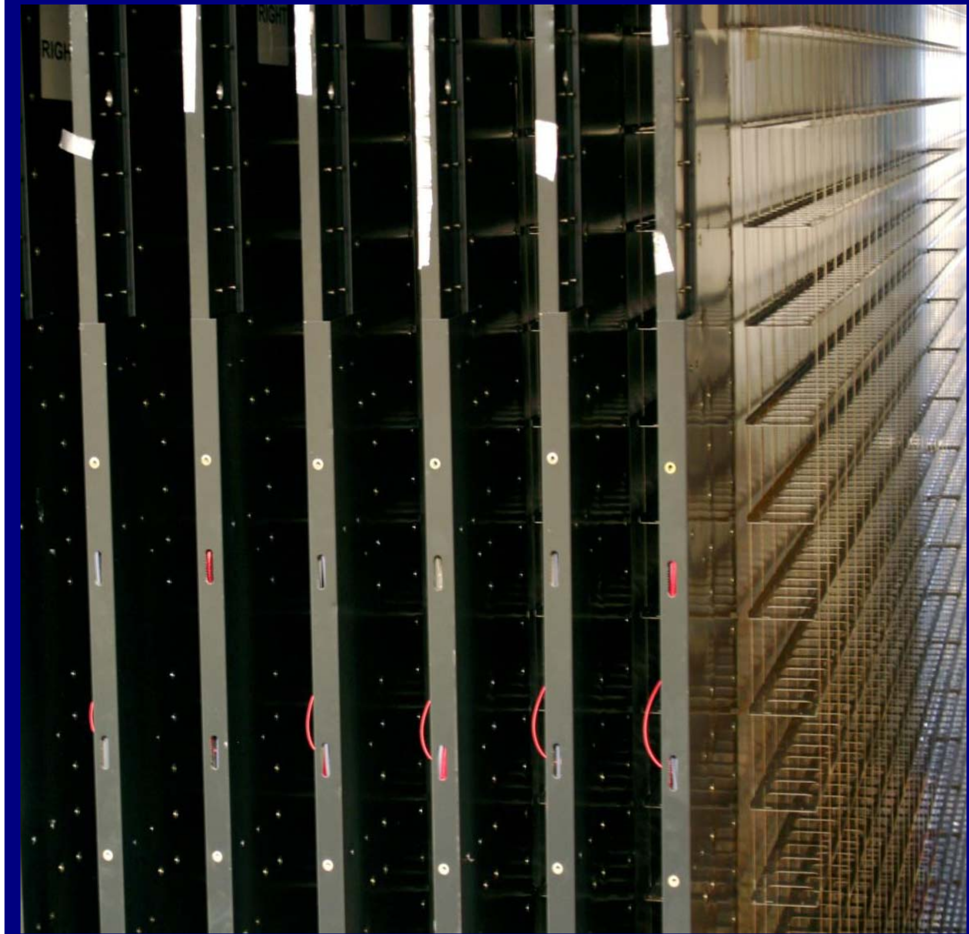


double layer of glass RPCs ~100 m^2

97% efficiency in streamer mode



SCINTILLATOR STRIPS TARGET TRACKER AND BRICK TRAYS



> 5 p.e. for a m.i.p.

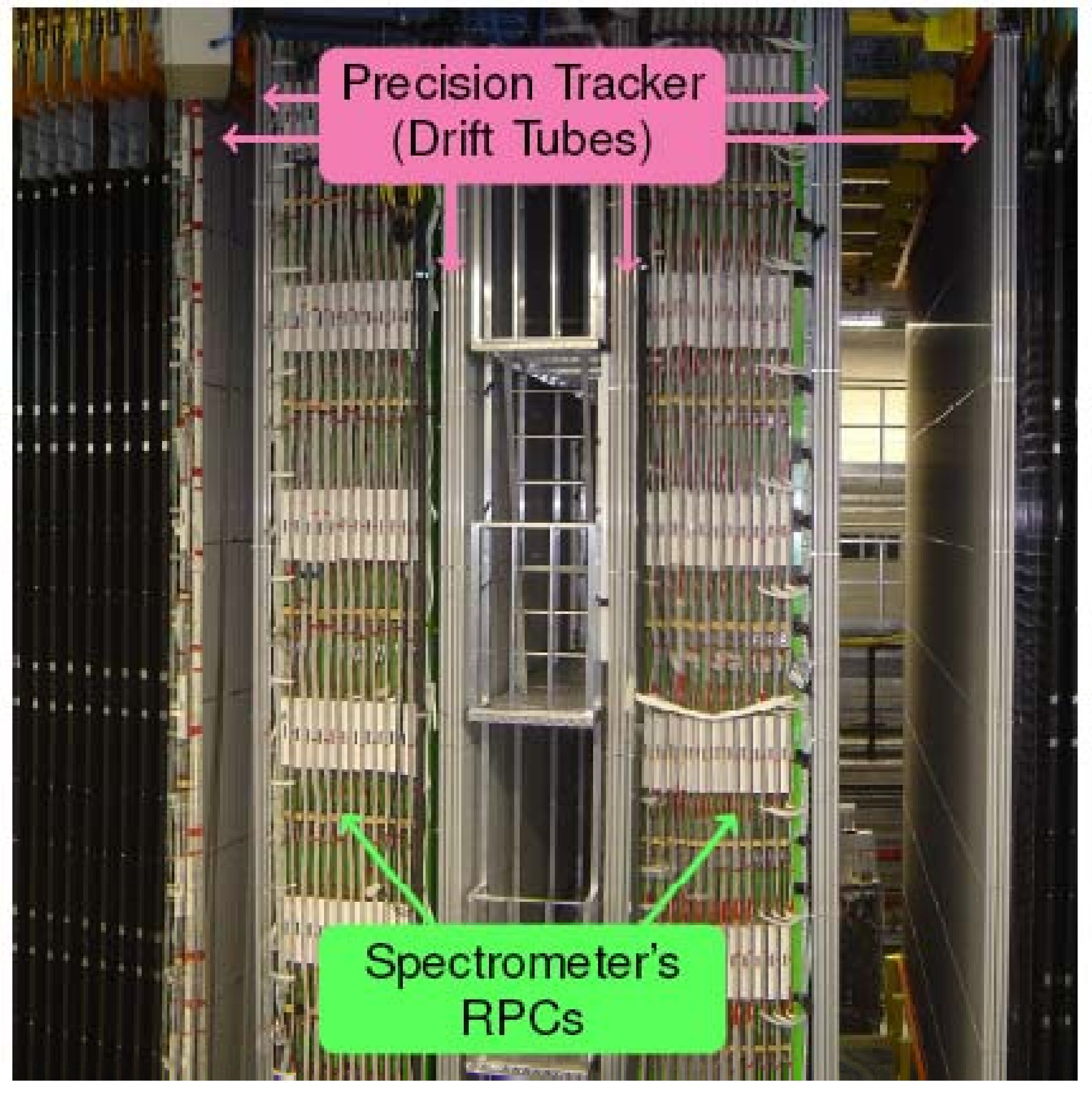
~ 99% detection efficiency ⇒ trigger

position accuracy: ~8 mm

angular accuracy: ~ 20 mrad

mechanical structure:
brick trays: only 0.5% of target mass

THE MAGNETIC SPECTROMETERS



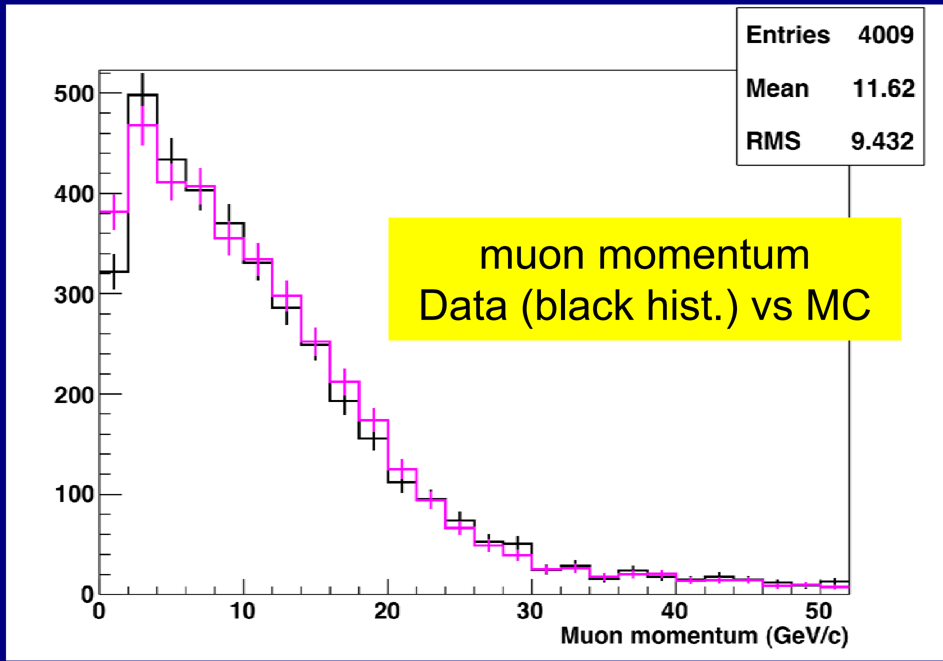
• 1.52 T magnetic field bending particles in the horizontal plane

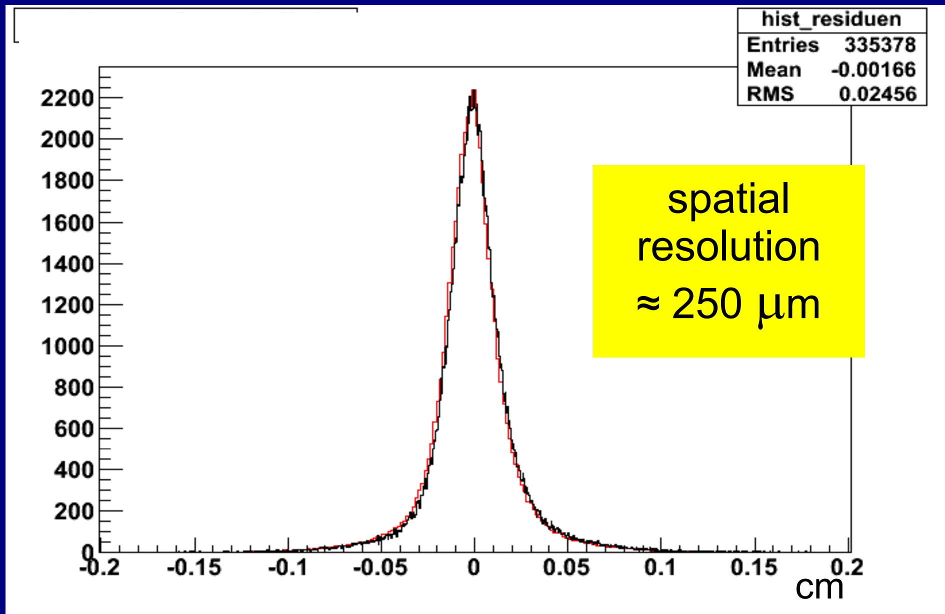
• 24 slabs of magnetized iron interleaved with 24 RPC planes

• 6 drift tube stations for precision measurement of the angular deflection

• momentum resolution:
20% below 30 GeV

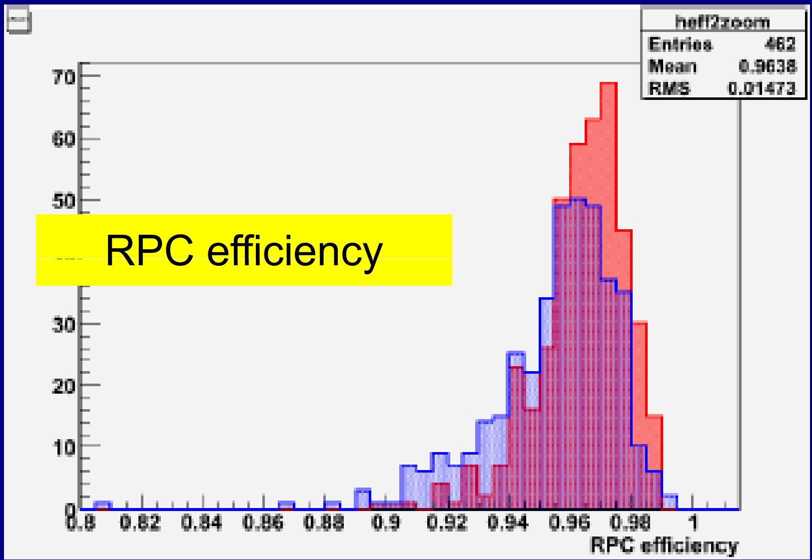
HIGH PRECISION TRACKERS (HPT)





RESISTIVE PLATE CHAMBERS (RPC)

- 3200 m^2 bakelite RPC's operated in streamer mode
- muon ID by range measurement
- hadronic energy reconstruction in the spectrometer
- trigger for the HPT
- coarse tracking of showers (~3 cm strip pitch)



DATA ACQUISITION

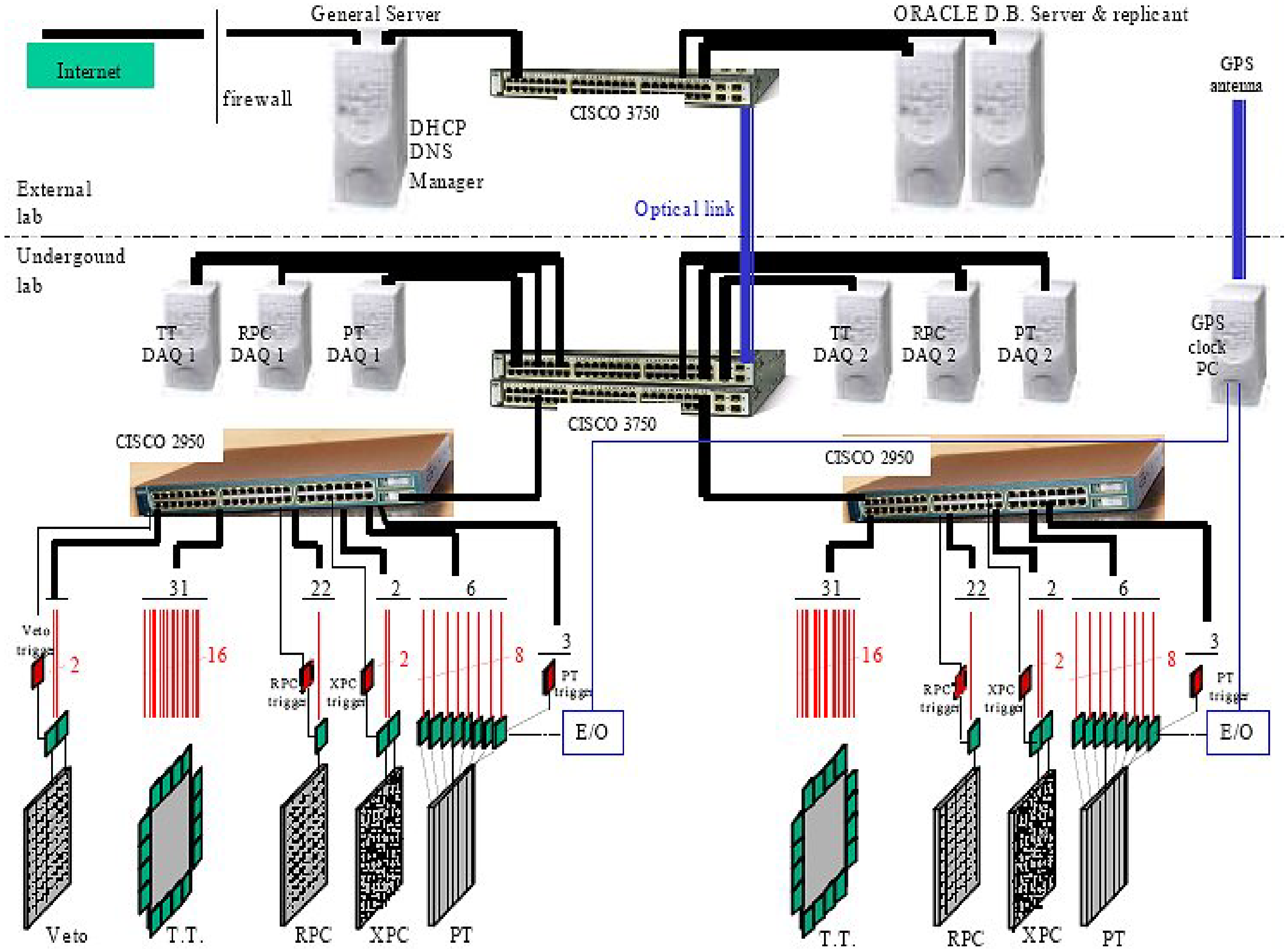
- Trigger-less scheme: hits from single detectors with GPS time stamp
- About 1200 sensors for controlling groups of pixels, strips or wires
- All hits recorded in the DB
- Events extracted offline from DB

Remote controls

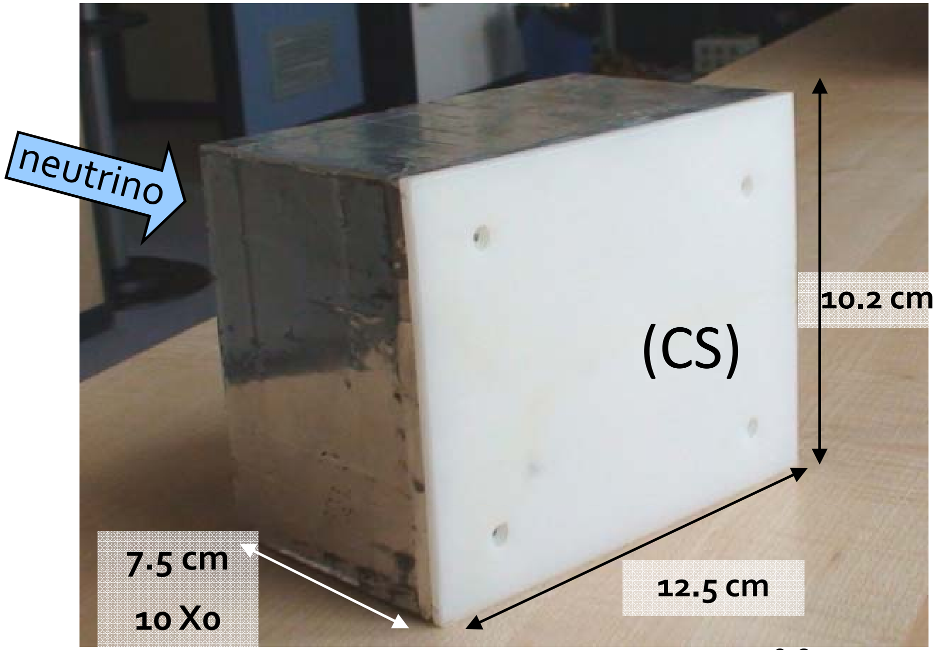
Ethernet switch

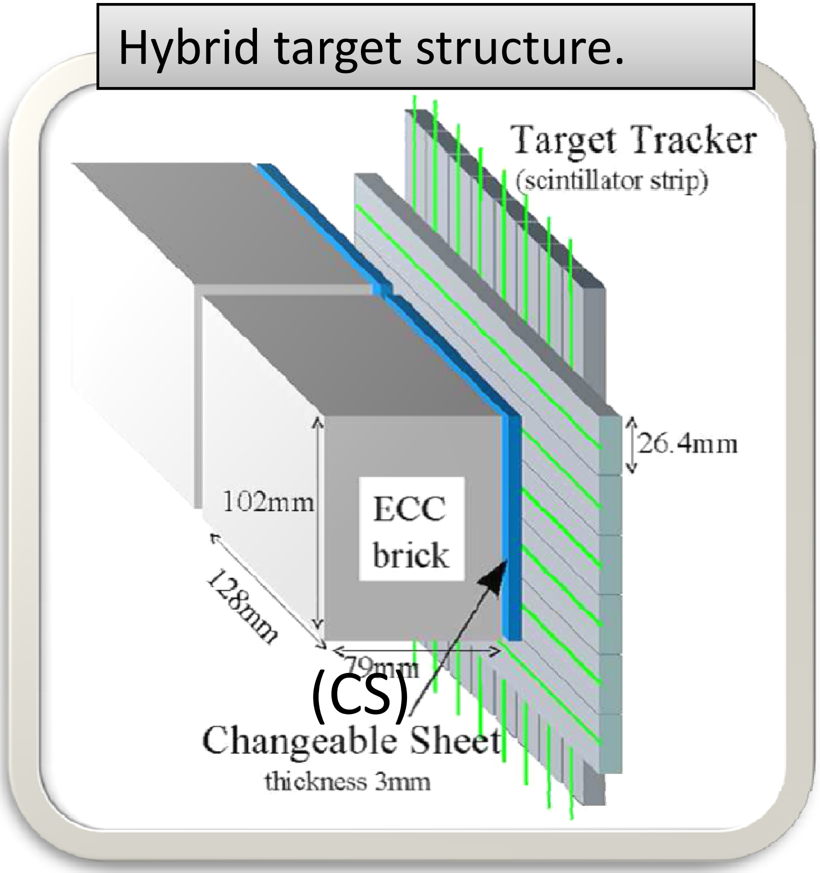
Sensors

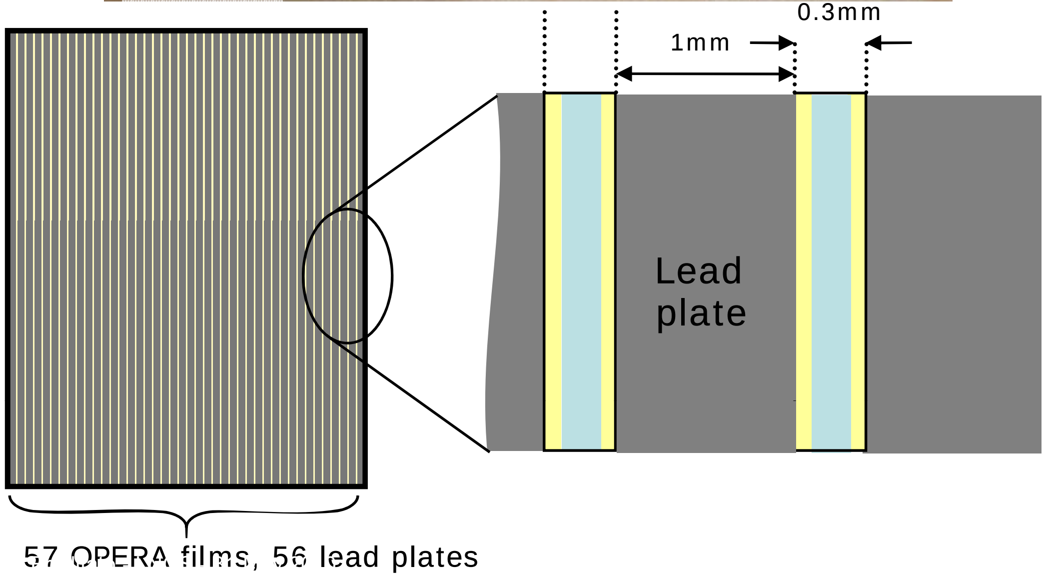
Detectors



The heart of the experiment:
THE ECC TARGET BRICKS







The OPERA target consists of 150’000 ECC bricks.

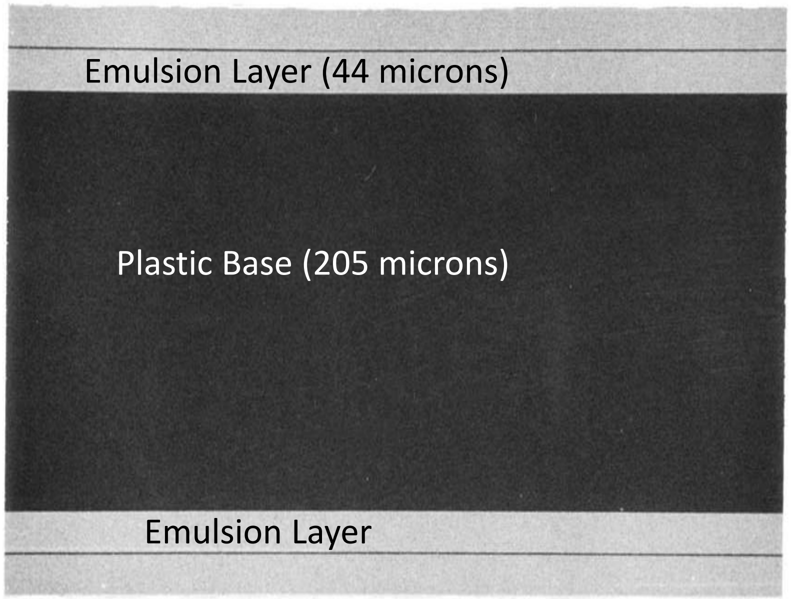
Total 105’000 m^2 of lead surface

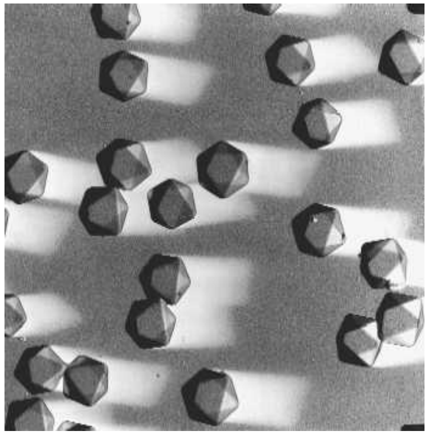
and 111’000 m^2 of film surface

(~ 8.9 million films)

Total target mass: 1.25 kton

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*





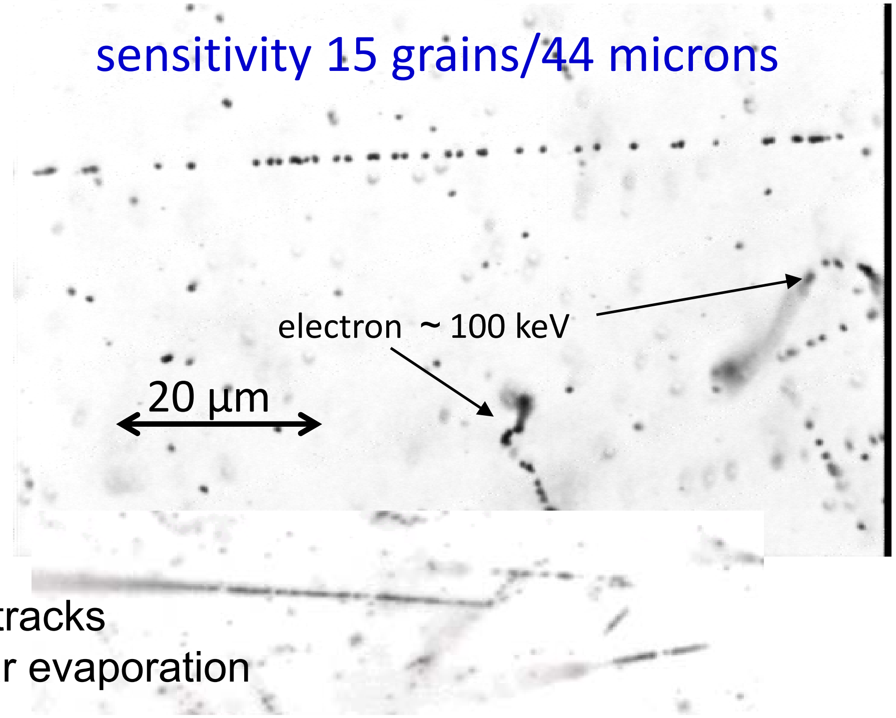
basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

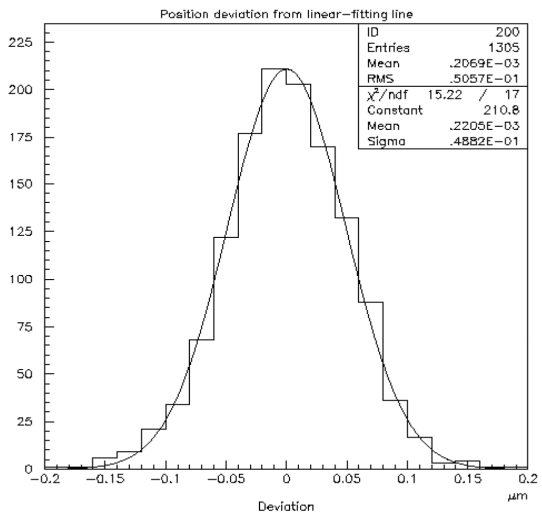
mip



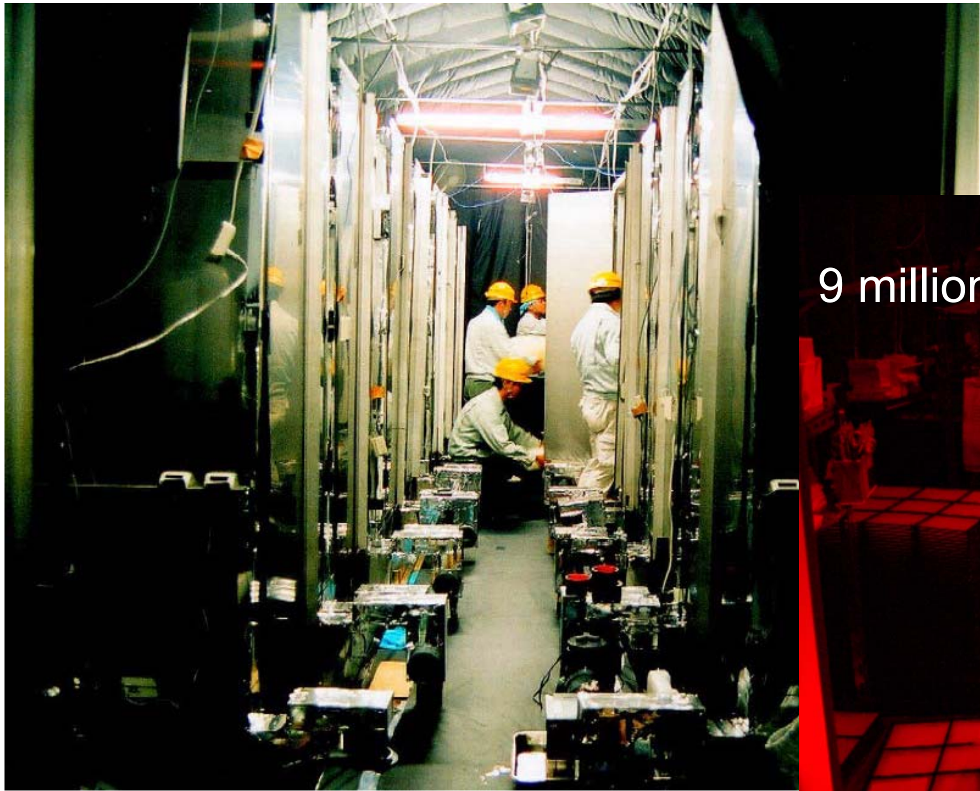
high dE/dx tracks
from nuclear evaporation

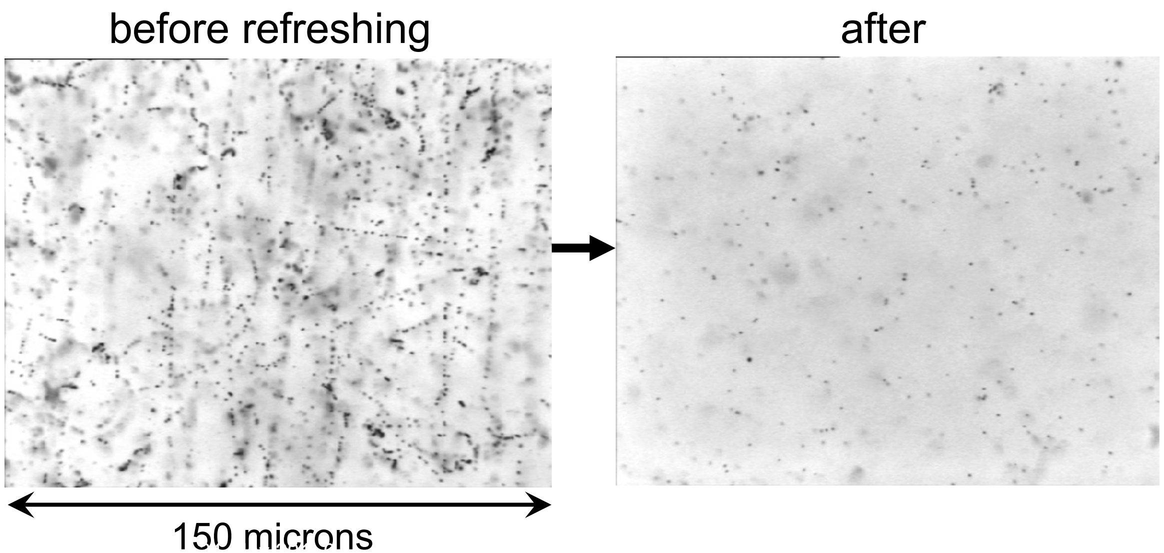
intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



Tono-mine film refreshing facility in Japan





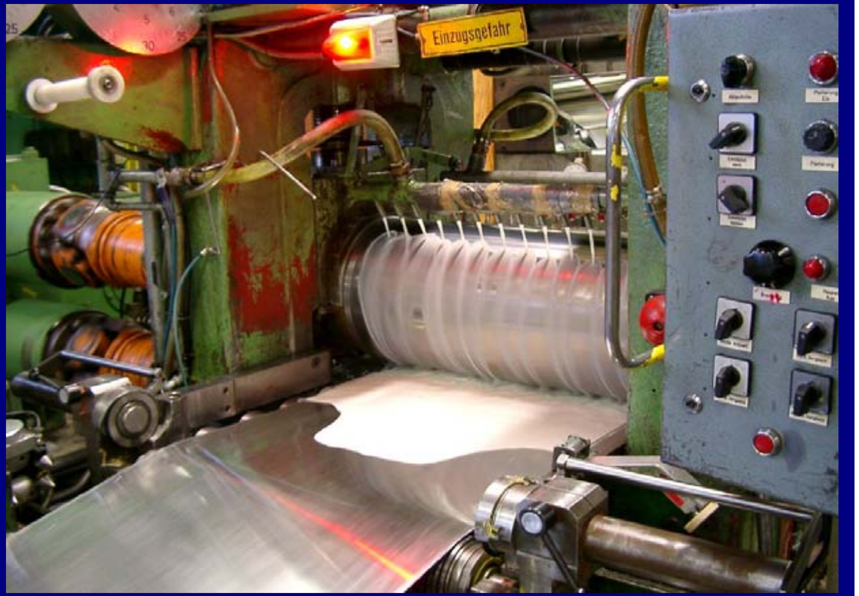
refreshing: erase cosmic-ray induced tracks accumulated during film production and storage at FUJI.

LEAD PLATE PRODUCTION AT JL-GOSLAR

Joint R&D effort and large industrial production:
9.2 million plates produced with 1'300 ton of lead

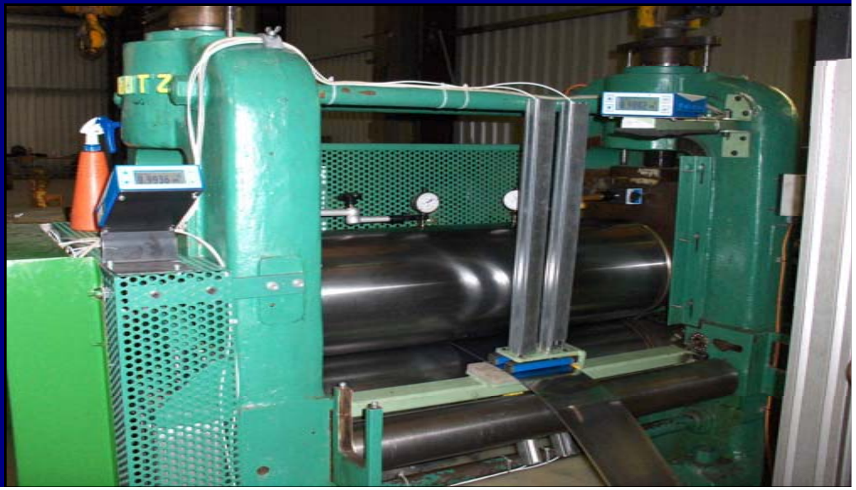
Low radioactivity primary lead (80 Bq/kg)

0.04% Ca alloy



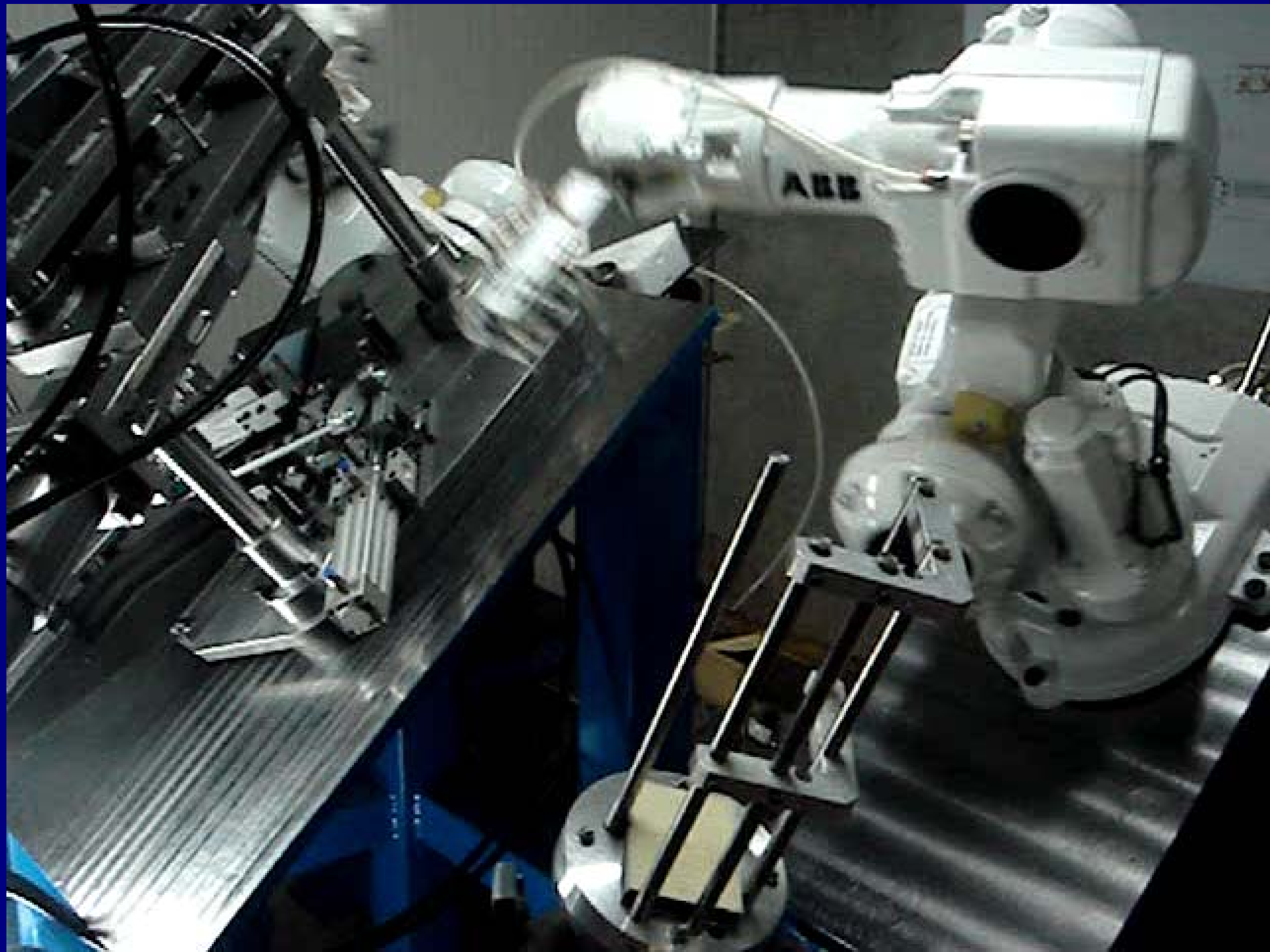
Specs (fulfilled):

- ± 5 μm planarity
- ± 5 μm thickness
- ± 50 μm transverse dimensions
- class 10000 cleanness
- no corrosion of surface
- not aggressive to emulsion

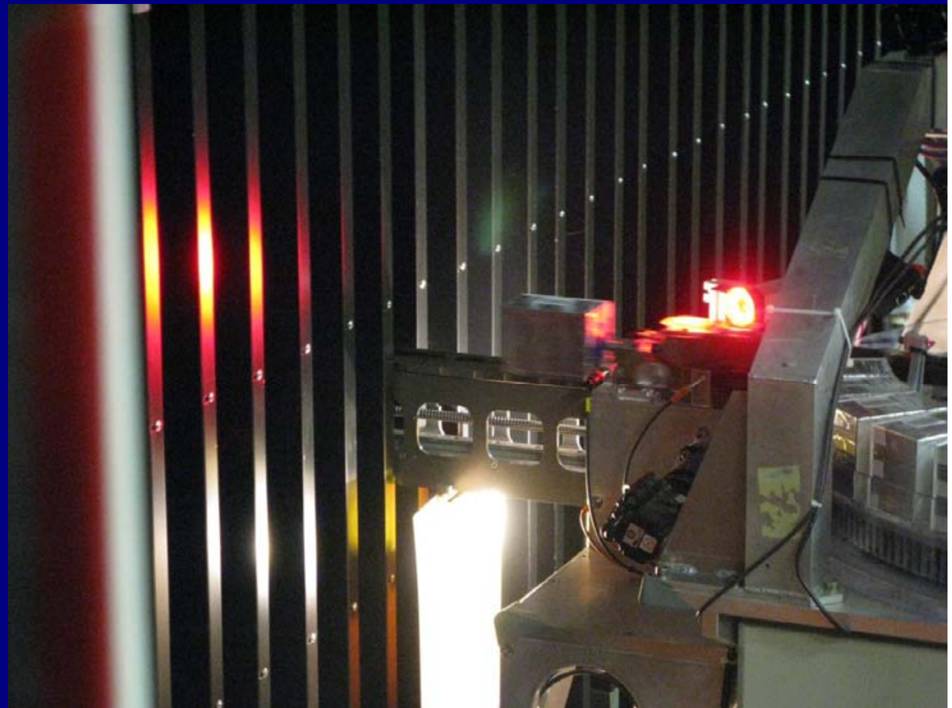


BRICK ASSEMBLY MACHINE (BAM)

Major engineering infrastructure: automatic production of 150’000 bricks (2006-2008)



BRICK MANIPULATOR SYSTEM (BMS)



Extraction of “hit” bricks in parallel with CNGS data taking:

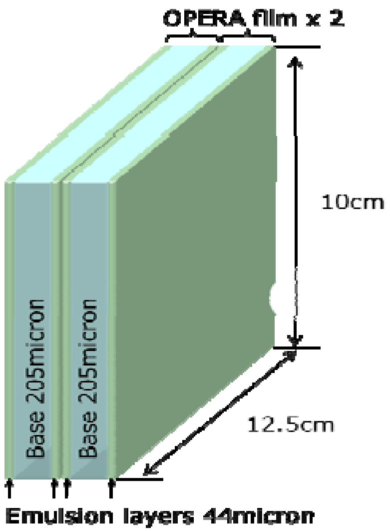
• initially used to fill the brick target (two twin devices at either detector sides)
• fully automatic extraction of 25 bricks/8 hour shift (neutrino interactions)
• ~90’000 bricks handled until 2009 for the extraction of ~7000 event related bricks

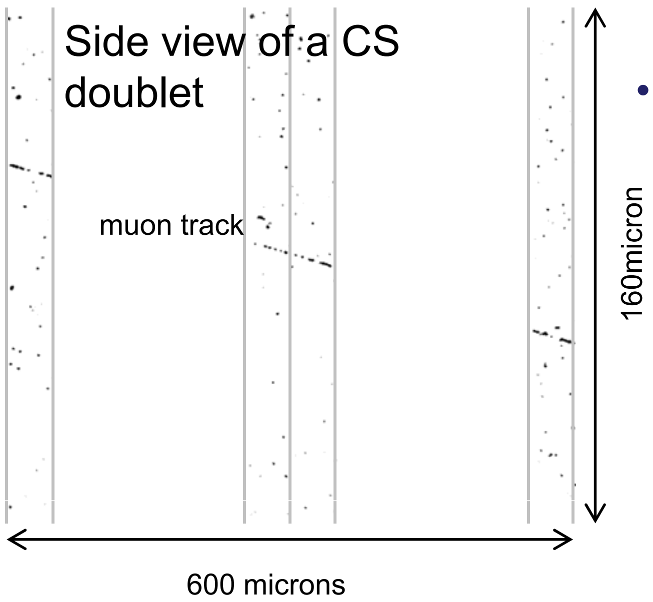
FILM DEVELOPMENT FACILITY

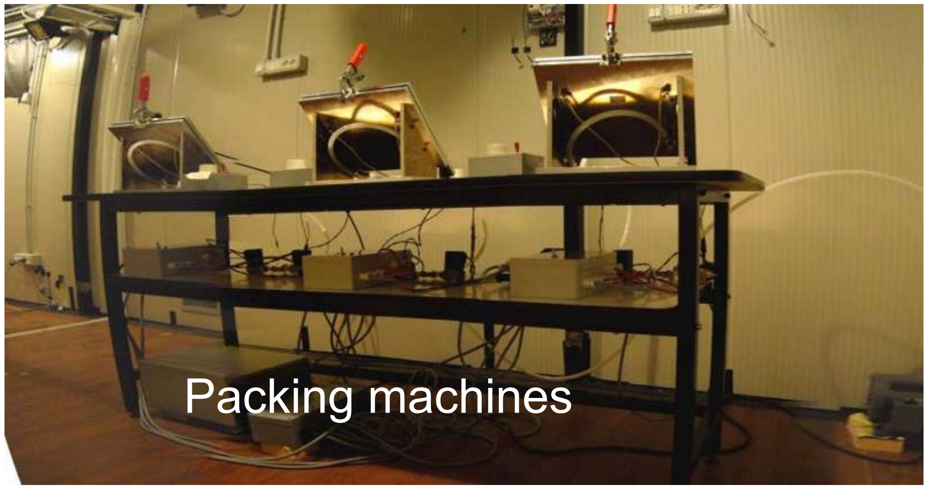
- 6 automatic lines running in parallel, in dark
- maximum rate: 150 bricks/week
- additional facility underground for CS: max 300 CS/week

Changeable Sheet (CS) assembly facility at LNGS underground

- To pick up event related tracks.
- On-site refreshing and doublet packing: very low background emulsion tracker.
- 160’000 CS produced in 2006-2008.







CHANGEABLE SHEET SCANNING STATIONS

High speed automatic microscopes:

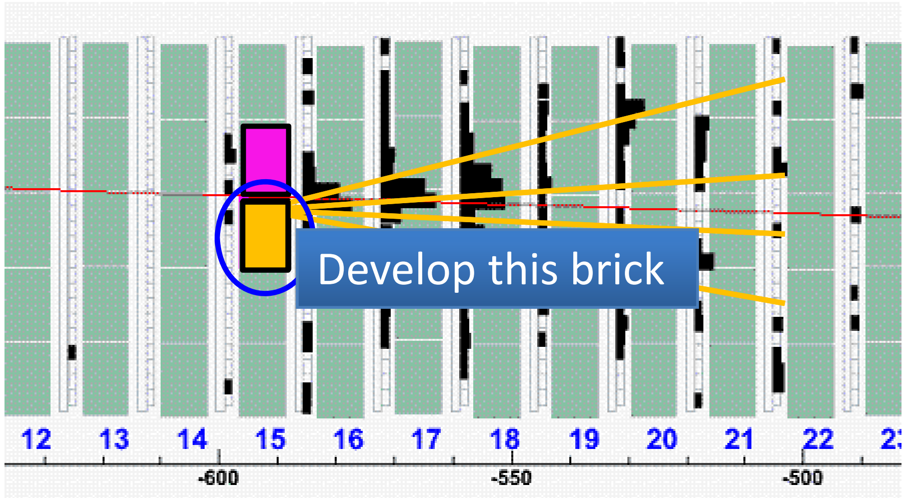
~ 200 cm^2 emulsion film surface/hour/facility

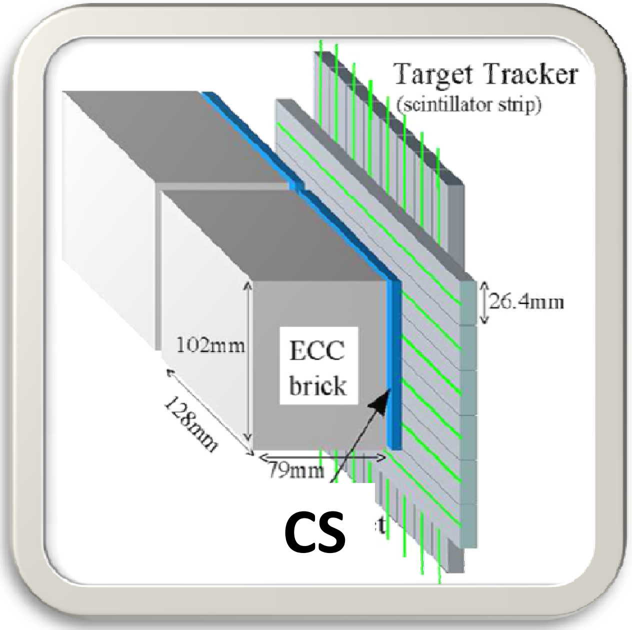
Based on state of the art technologies:

precision mechanics, stepping motors, CCD readout, pattern recognition, image analysis,…

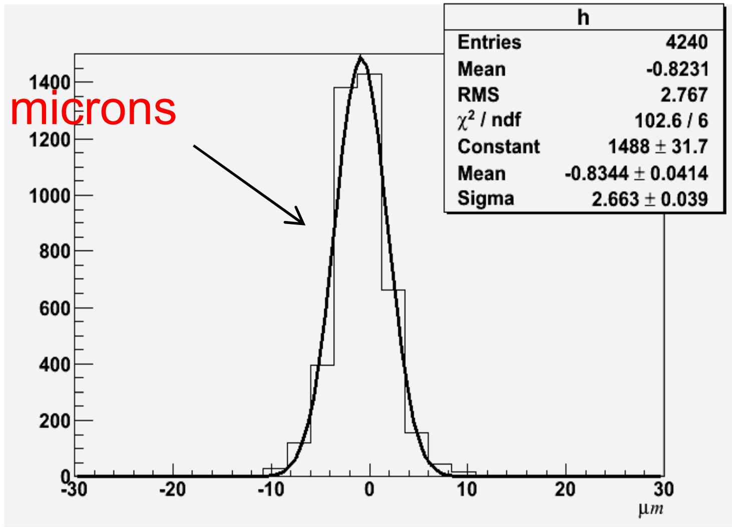
DETECTOR OPERATION

BRICK VALIDATION BY THE CS





CS doublet alignment by Compton electrons: 2.5 microns



Scanning effort/event: CHORUS 1x1 mm^2

DONUT 5x5 mm^2

OPERA 100x100 mm^2

So far, 640'000 cm^2 of CS surface have been scanned in OPERA

PARALLEL ANALYSIS OF BRICKS

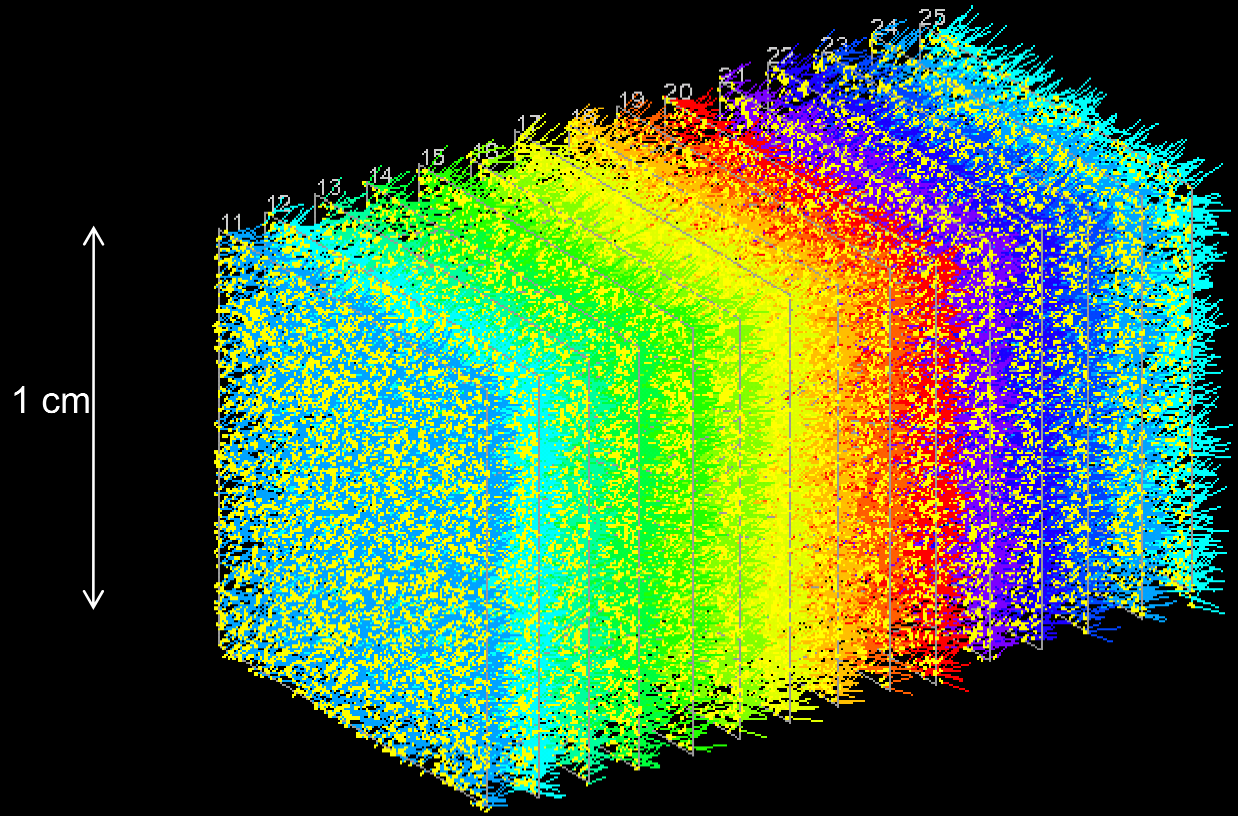
selected bricks sent to scanning labs (**presently 12**)

one of the brick scanning labs

Located neutrino interaction

Emulsions give 3D vector data, with micrometric precision of the vertexing accuracy.

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



Located neutrino interaction

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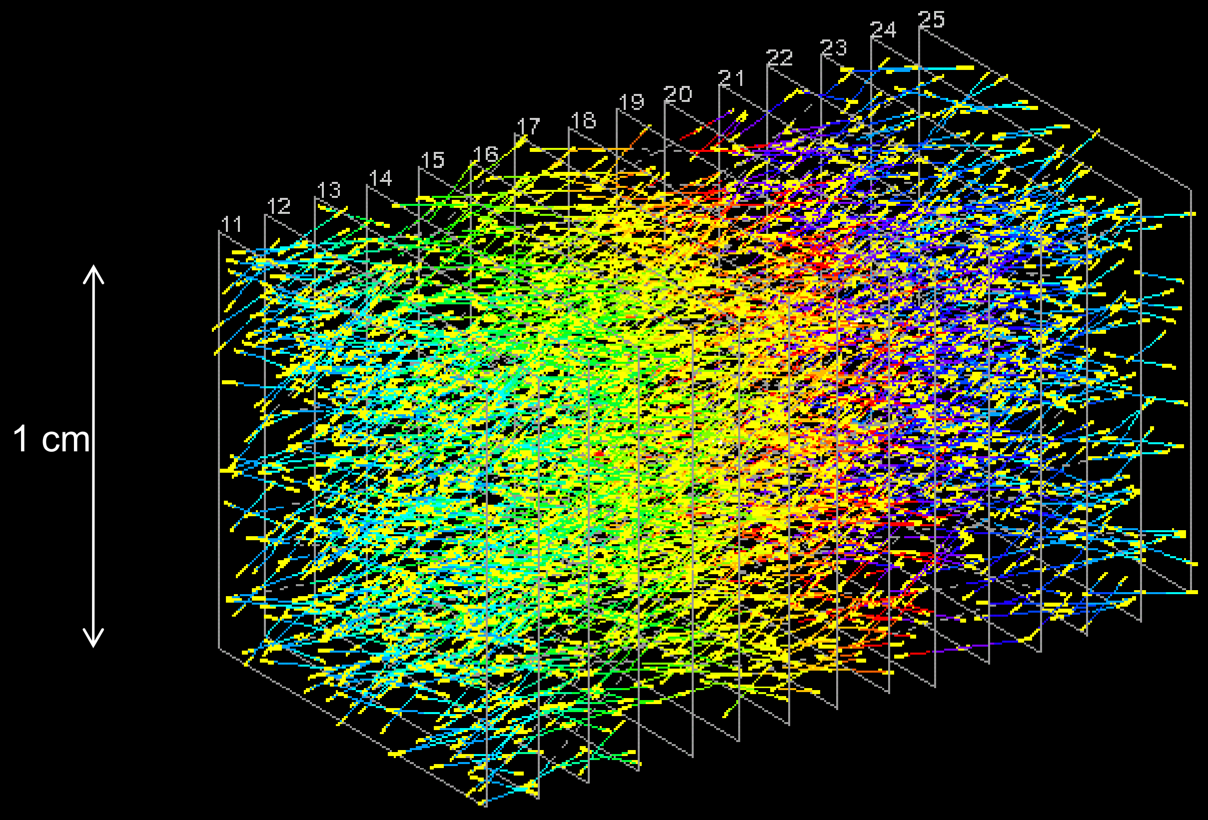

Located neutrino interaction

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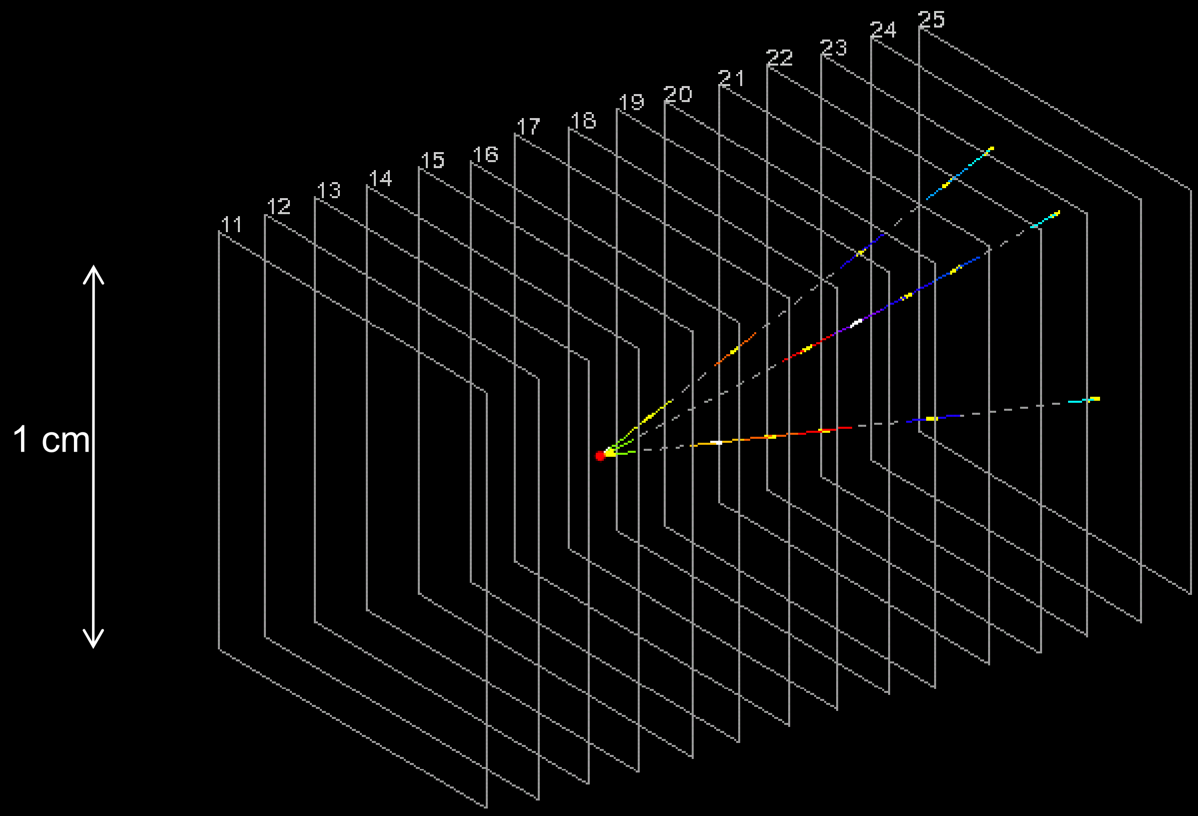
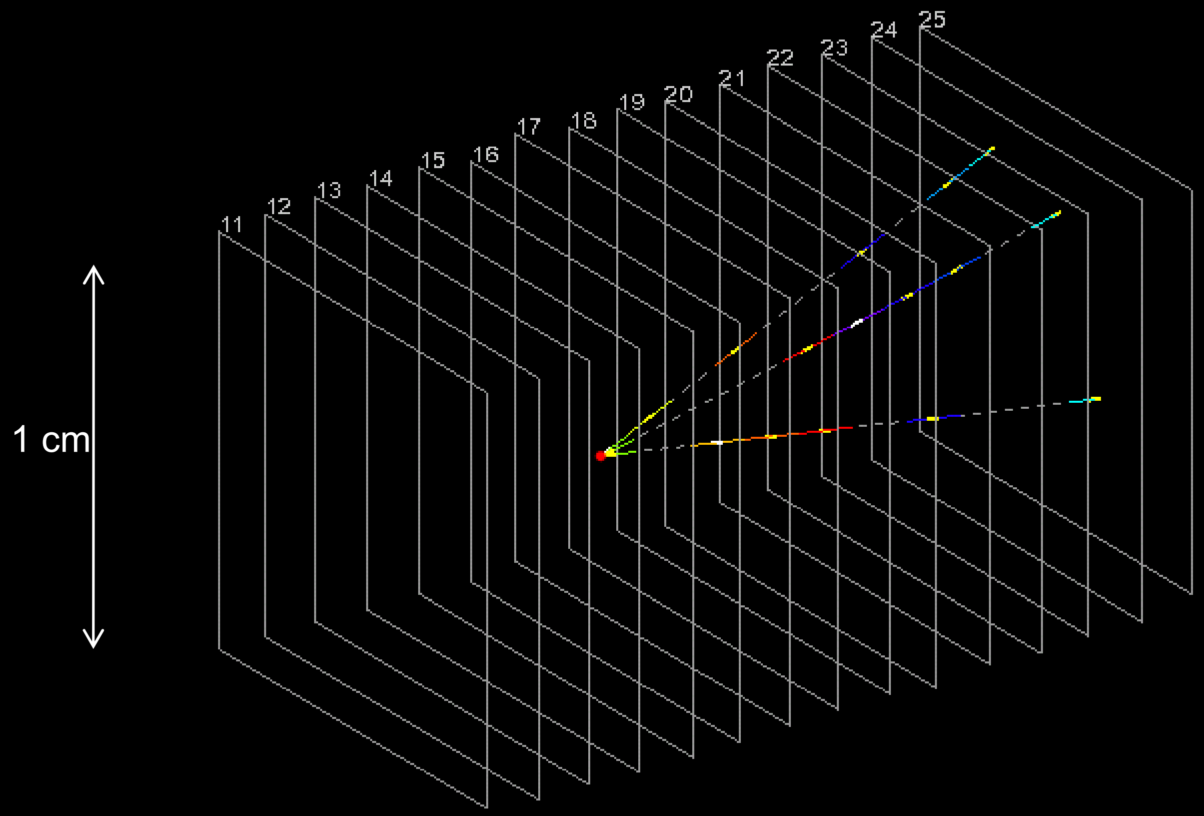


Located neutrino interaction

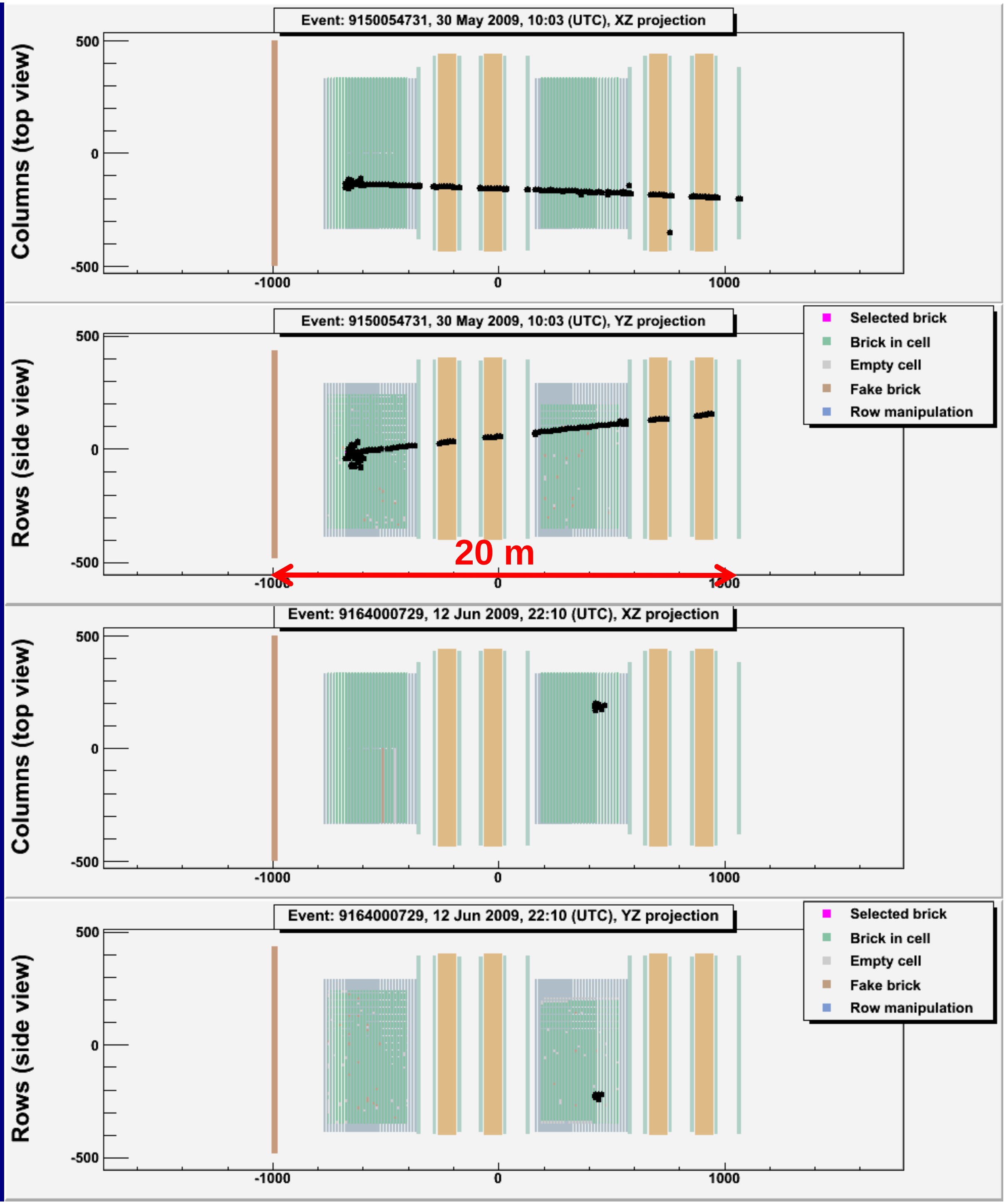
Emulsions give 3D vector data, with micrometric precision of the vertexing accuracy.

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



Typical ν_μ CC- and NC-like events

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



Event statistics

Brick tagging efficiency times vertex location efficiency: ~ 60%

Total found neutrino vertices: 1617

Events for which "decay search" was completed: 1088 (187 NC)

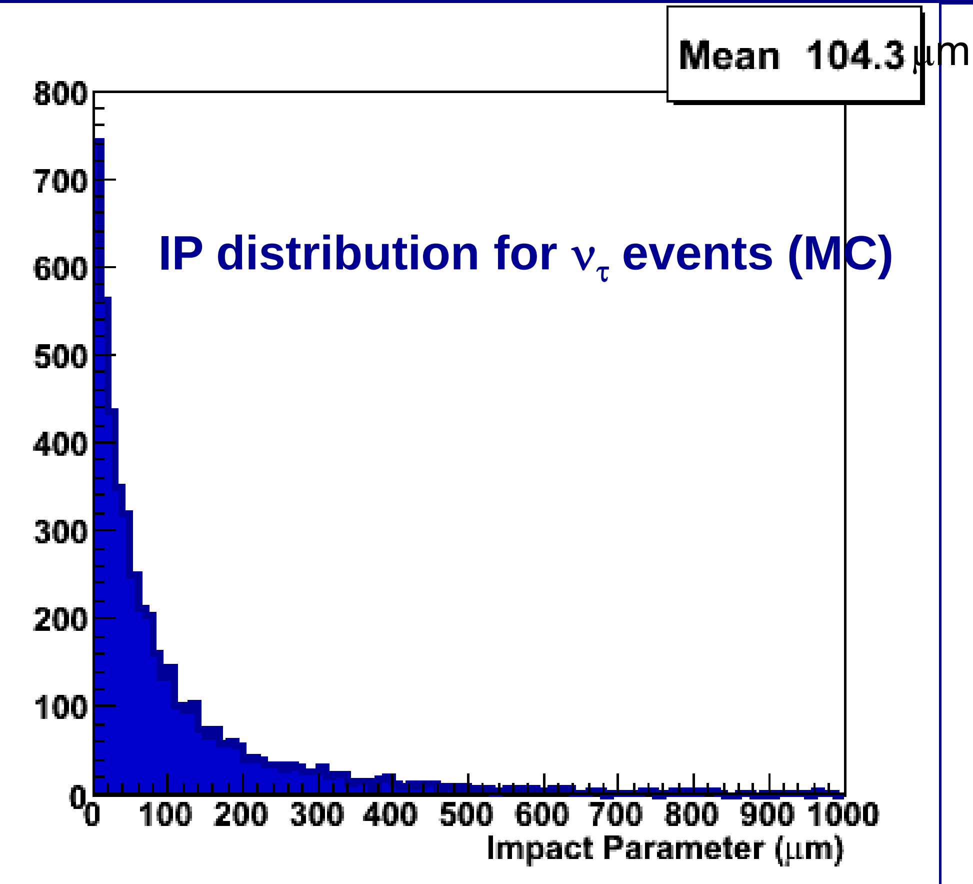
This is ~35% of the total 2008-2009 run statistics, corresponding to 1.85×10^{19} pot

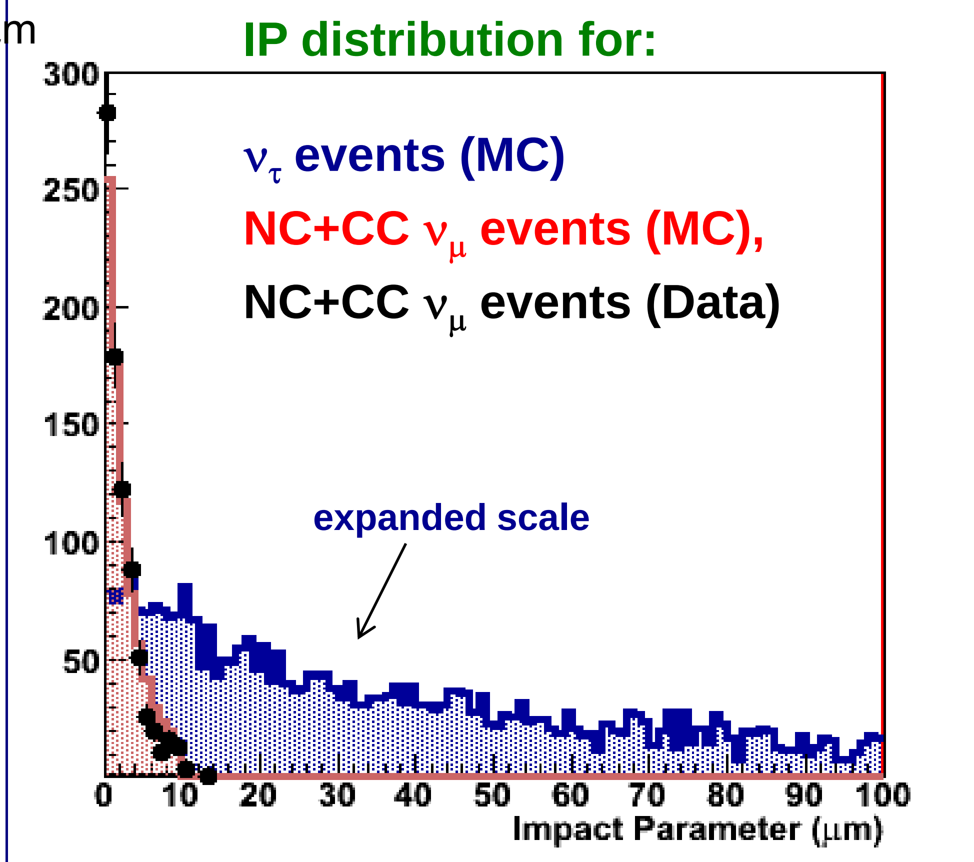
With the above statistics, and for $\Delta m^2_{23} = 2.5 \times 10^{-3}\ eV^2$ and full mixing, OPERA expects:

~ 0.5 ν_τ events

GLOBAL ANALYSIS PERFORMANCE

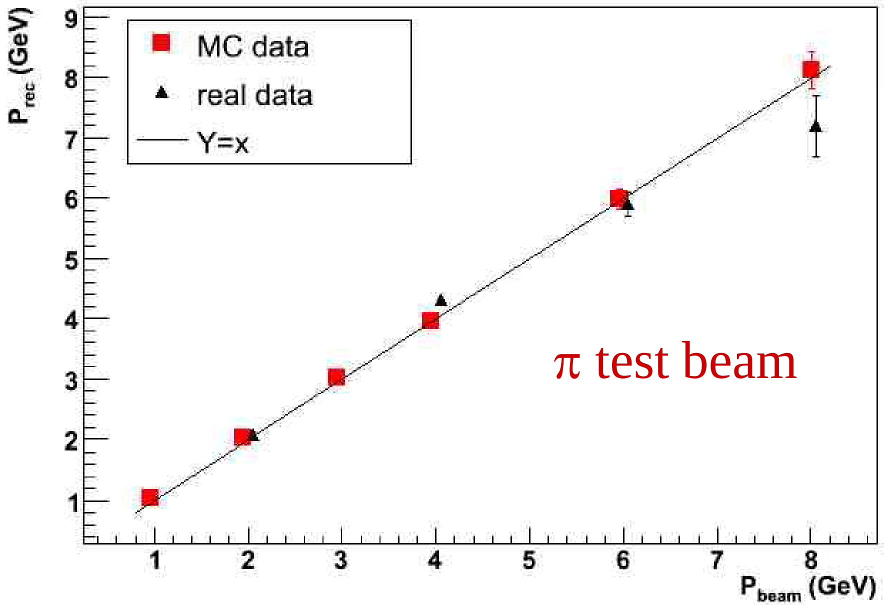
Impact parameter measurement

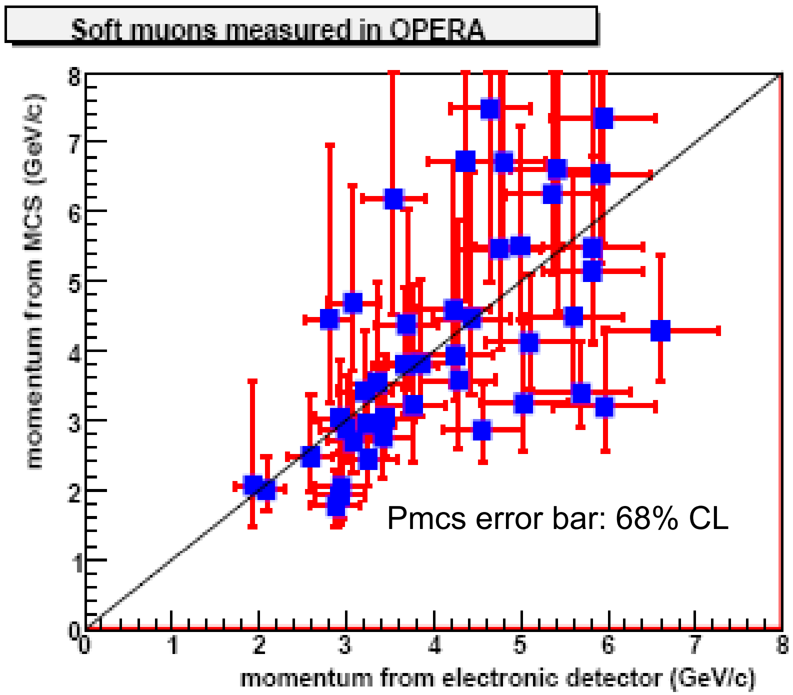


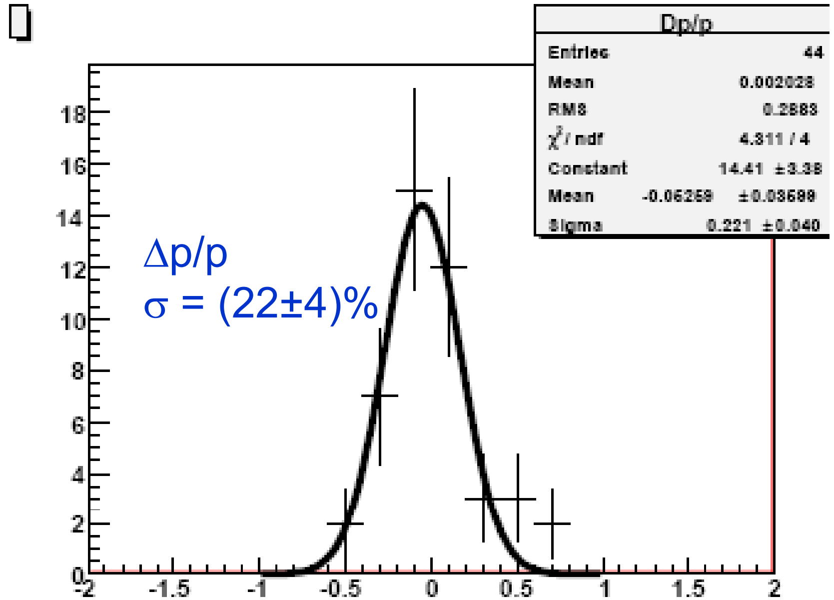


Momentum measurement by Multiple Coulomb Scattering…

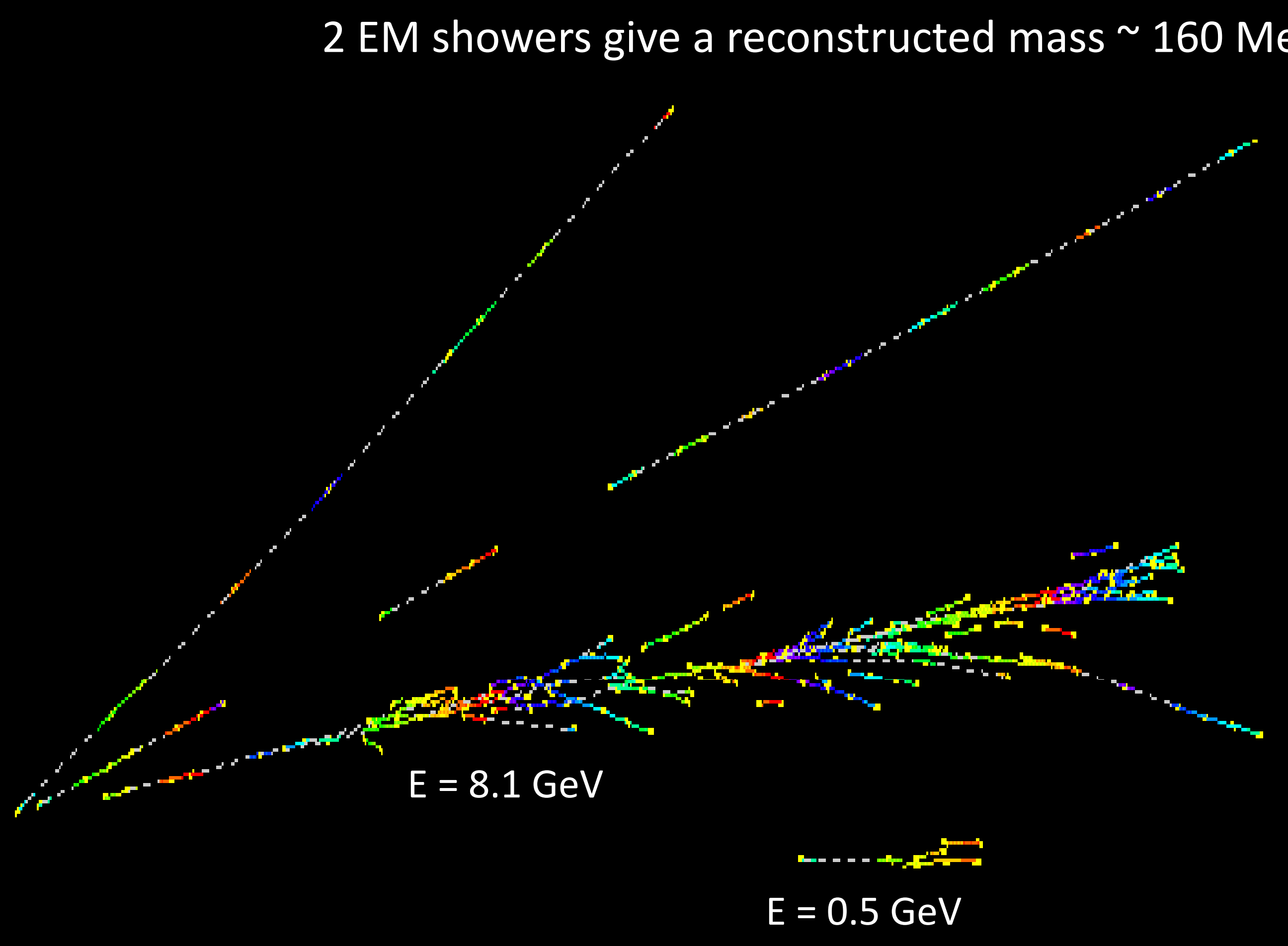
…in the lead/emulsion film sandwich and comparison with electronic detector measurements





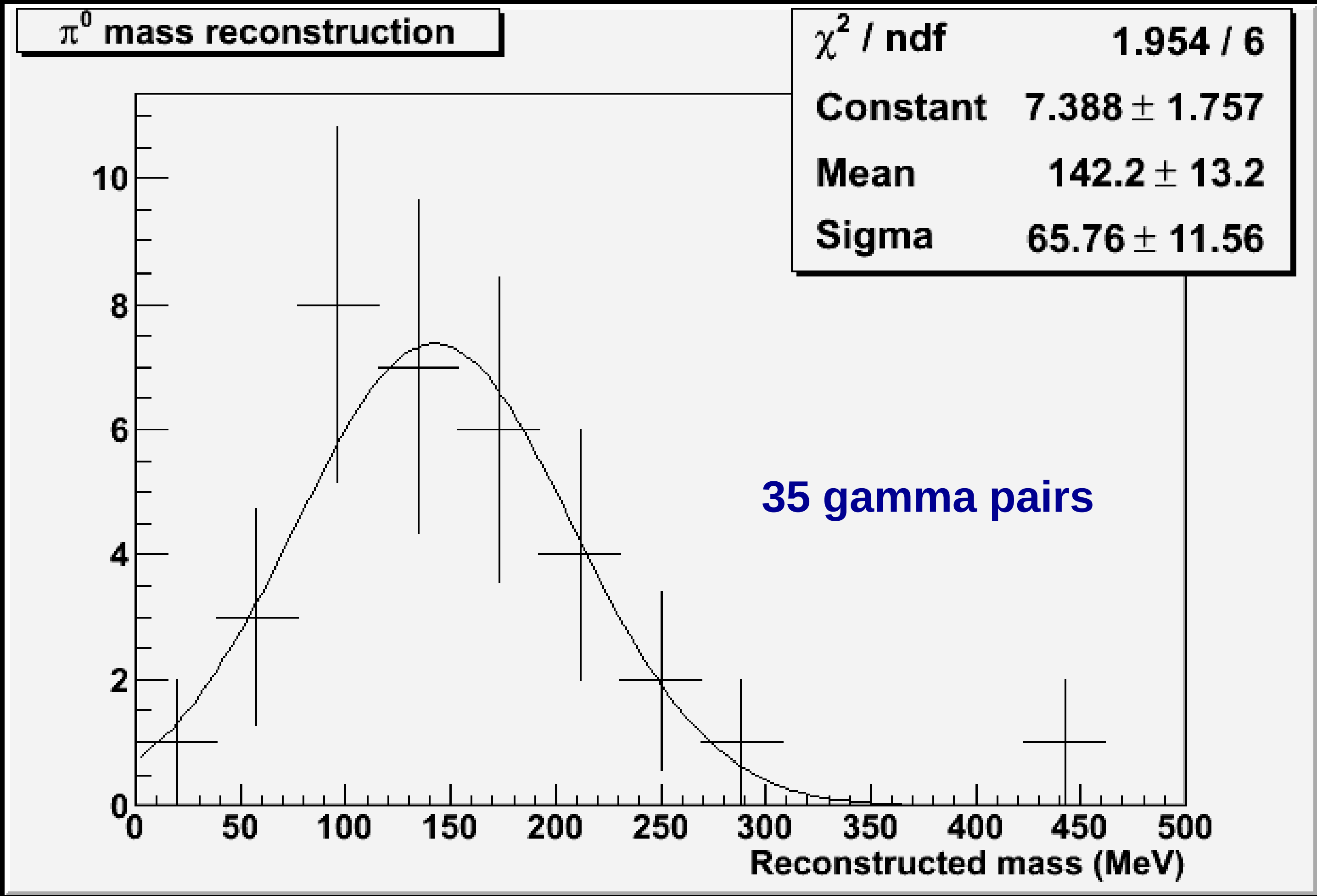


Gamma detection and π^0 mass reconstruction



EM shower energy measured by shower shape analysis and Multiple Scattering method

π^0 mass resolution (real data)

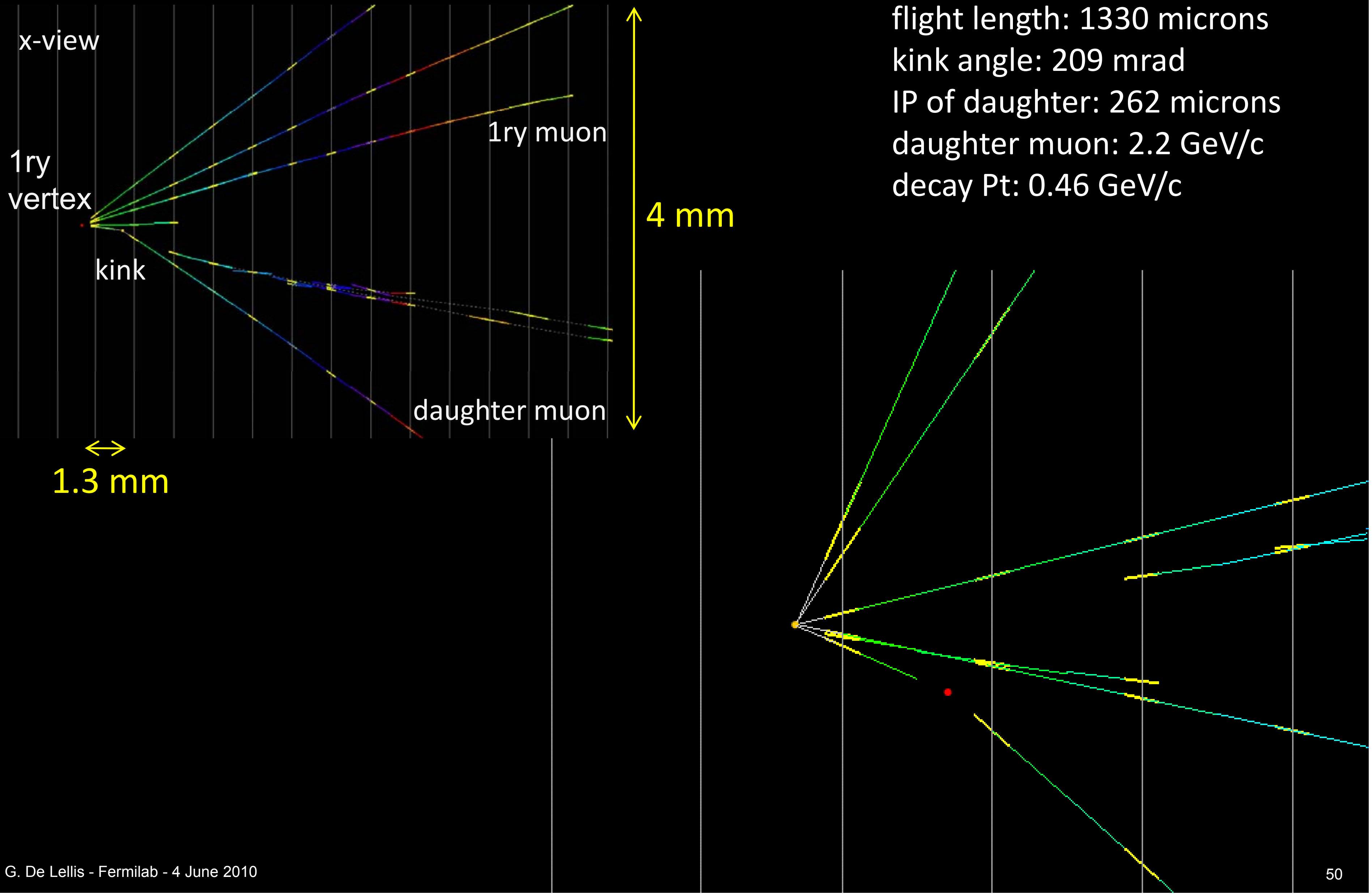


1 σ mass resolution: ~ 45%

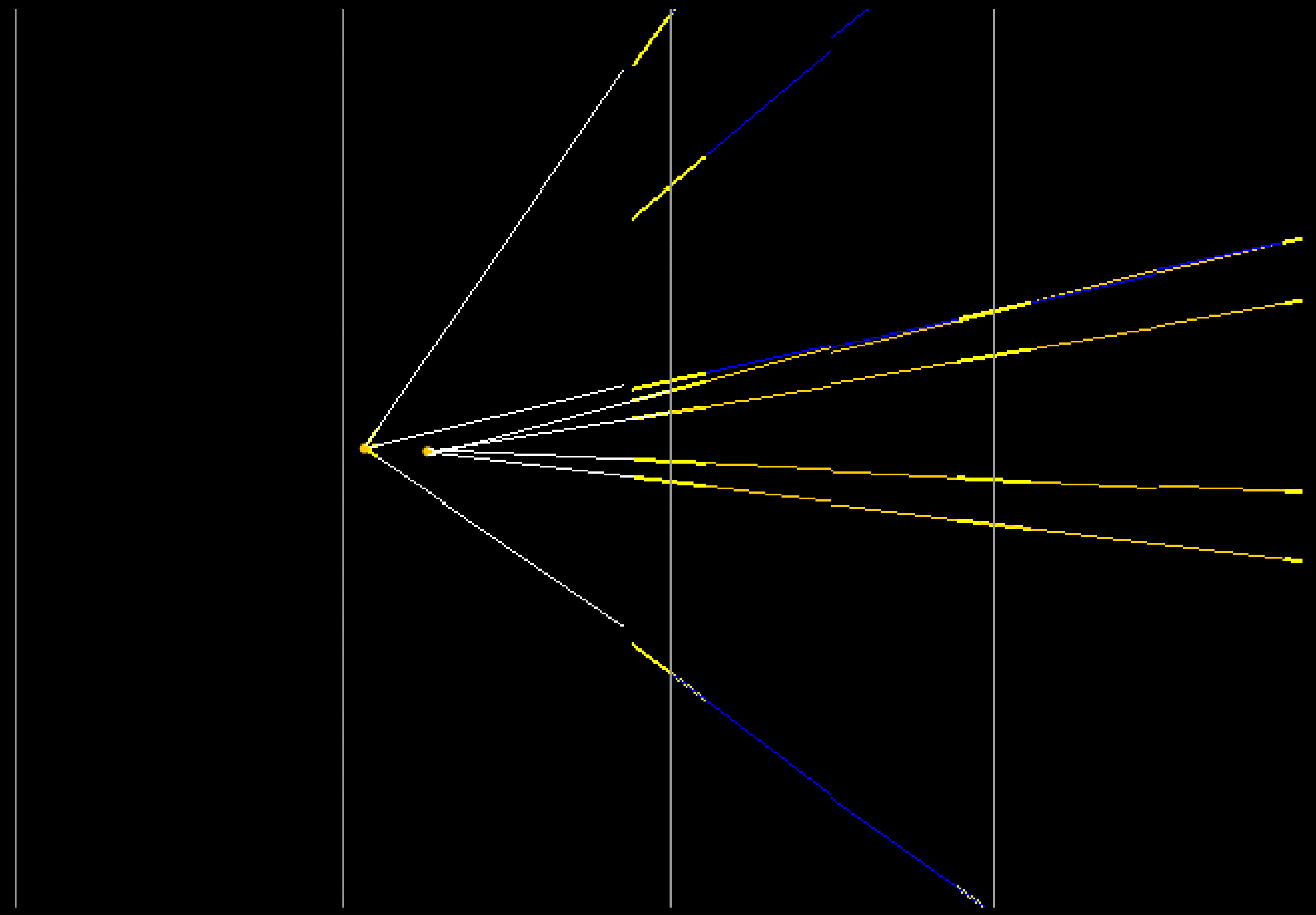
CHARM EVENTS

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, ϕ : 173.2^0, invariant mass: 1.7 GeV

Main kinematical cuts for charm events:

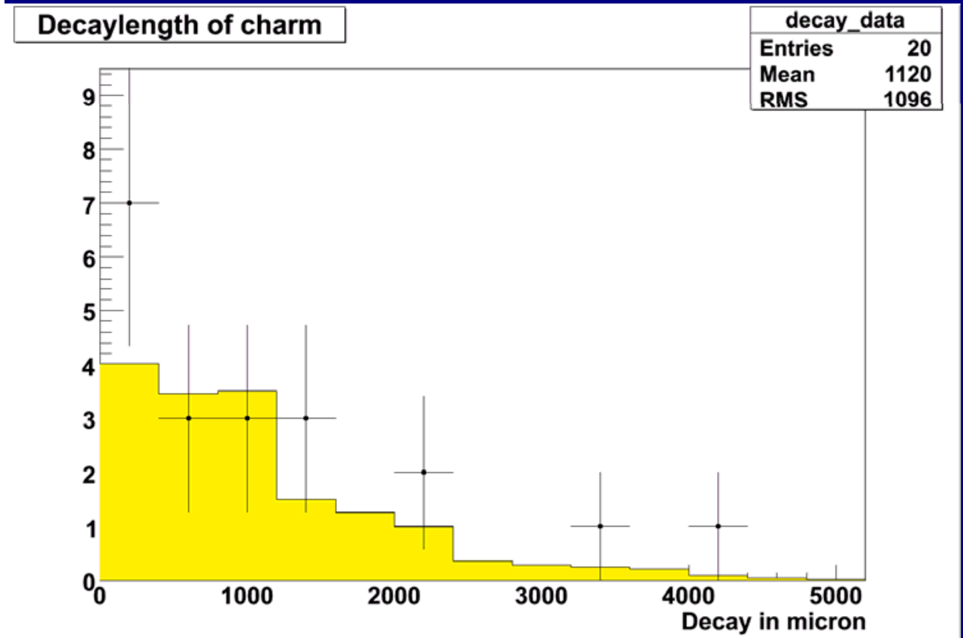
- P daughter >2.5 GeV/c, kink Pt > 0.5 GeV/c (for kink events)
- looser cuts for multi-prong events

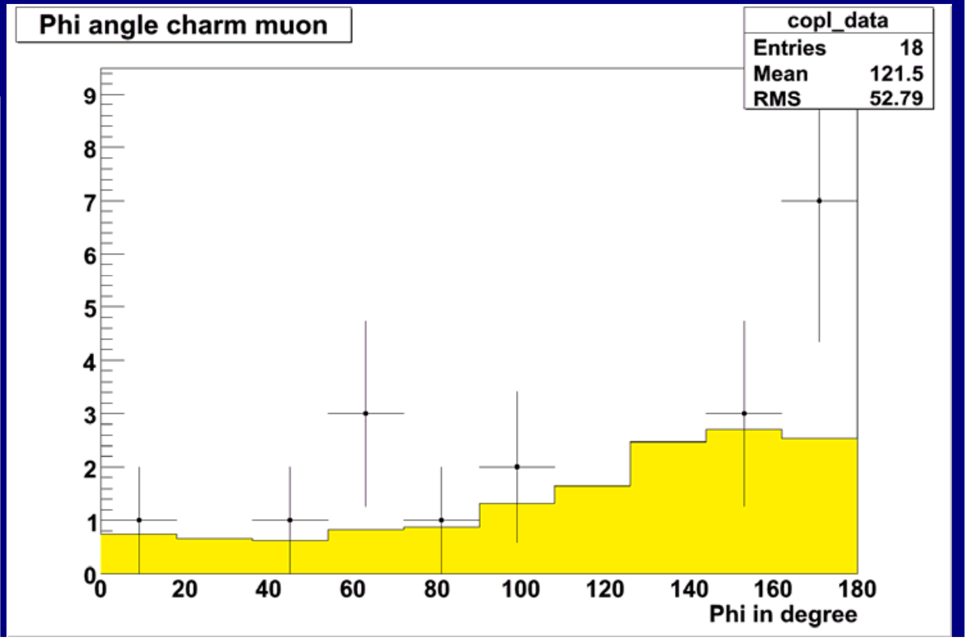
20 charm candidate events selected by the kinematical cuts,
3 of them with 1-prong kink topology.

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)

Examples of distributions:



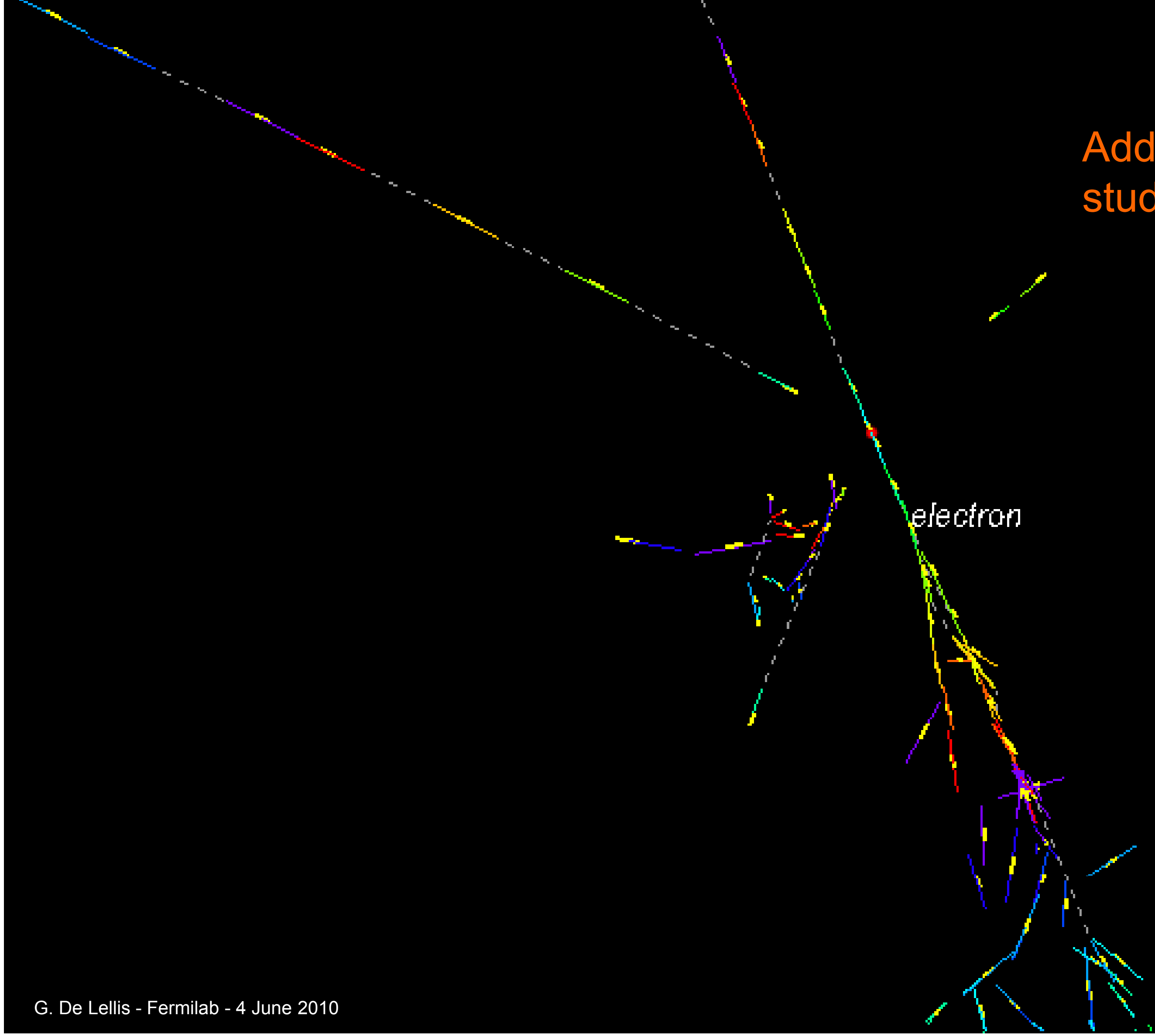


OTHER SPECIAL EVENTS

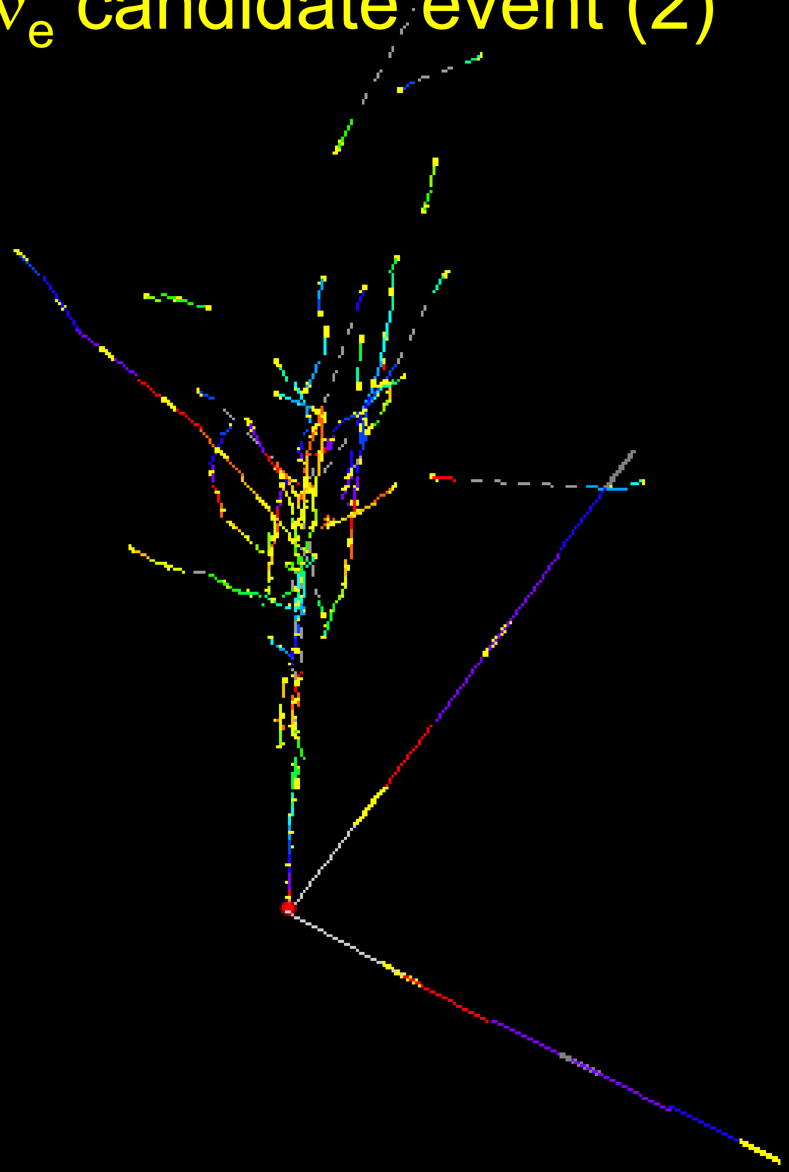
ν_e candidate event

From a subsample of ~ 800 located events we detected 6 ν_e candidates

Additional physics subject:
study $\nu_\mu \rightarrow \nu_e$ oscillations

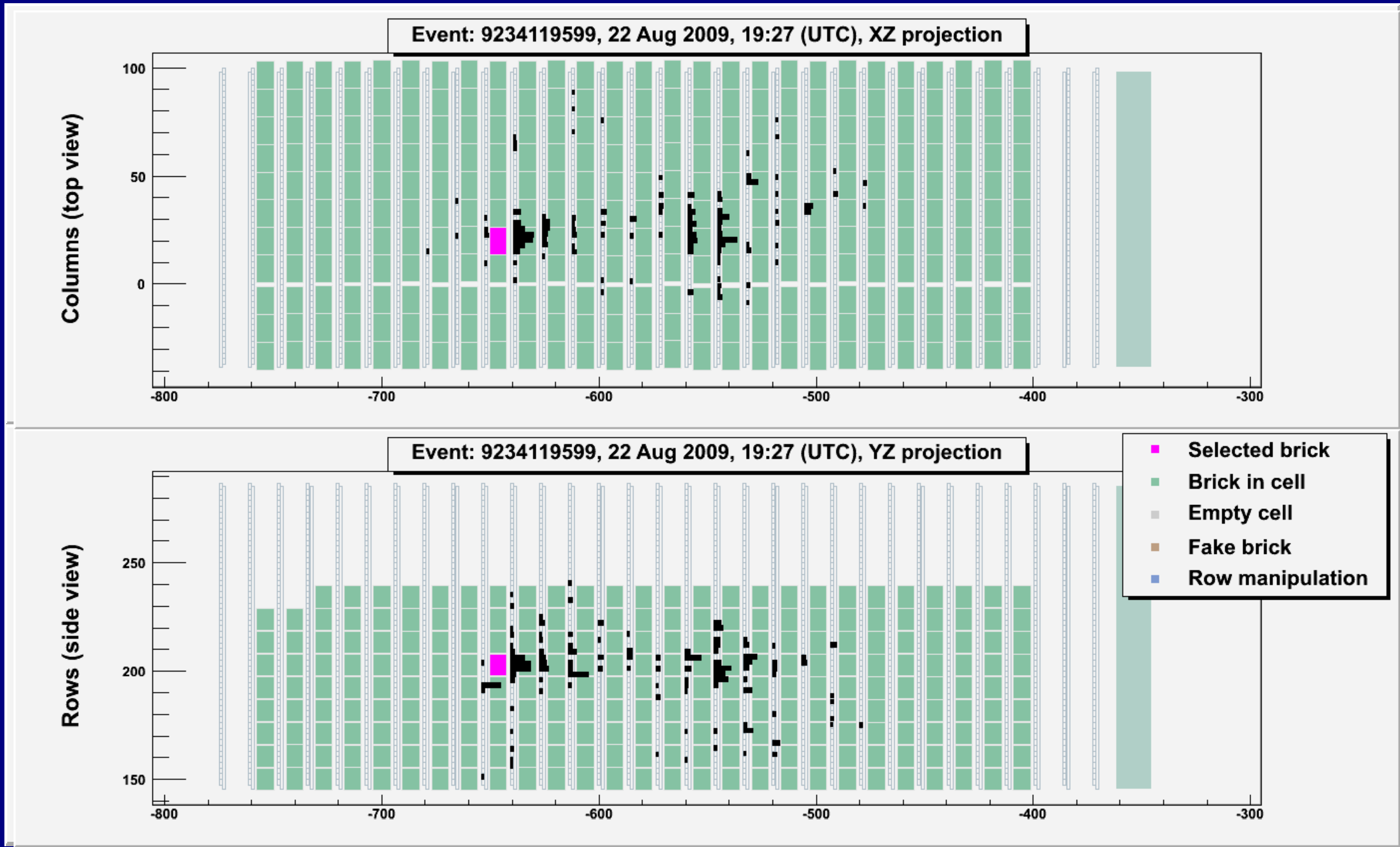


ν_e candidate event (2)



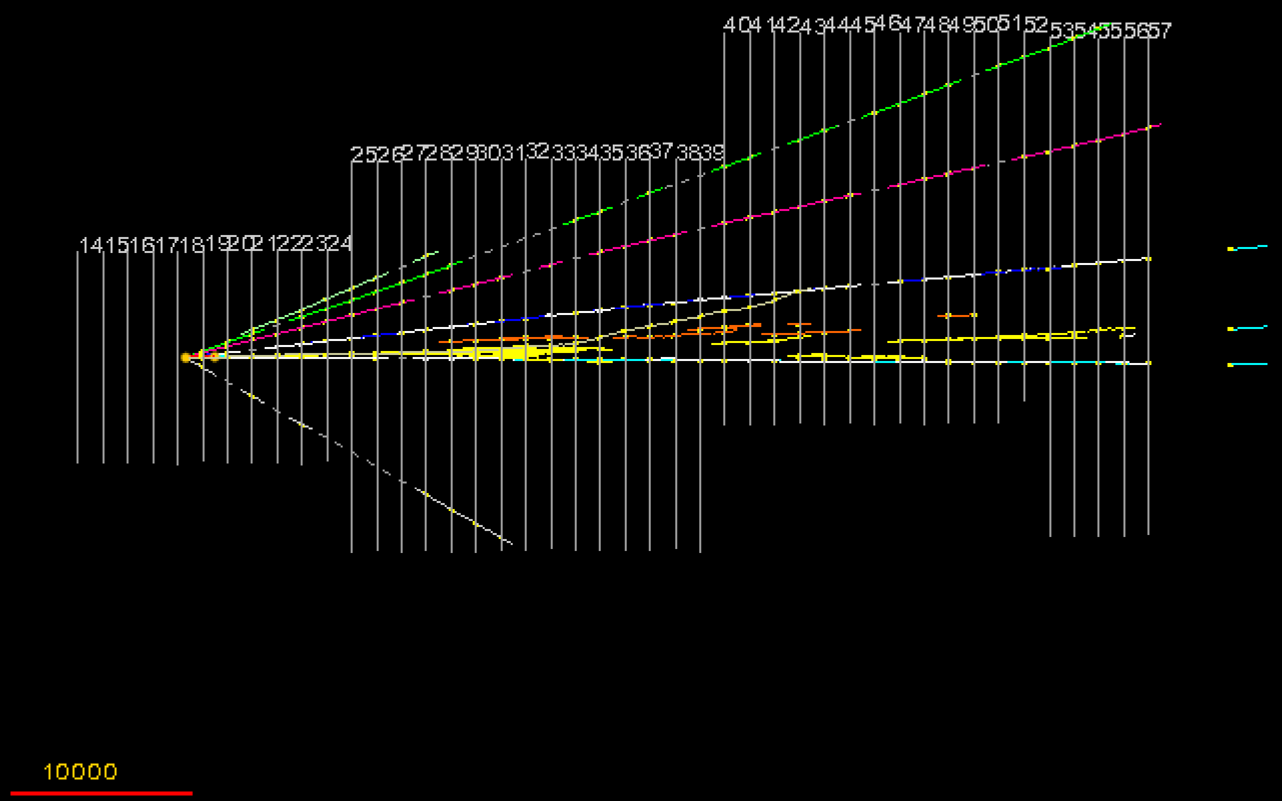
A VERY INTERESTING EVENT…

Muonless event 9234119599, taken on 22 August 2009, 19:27
(as seen by the electronic detectors)

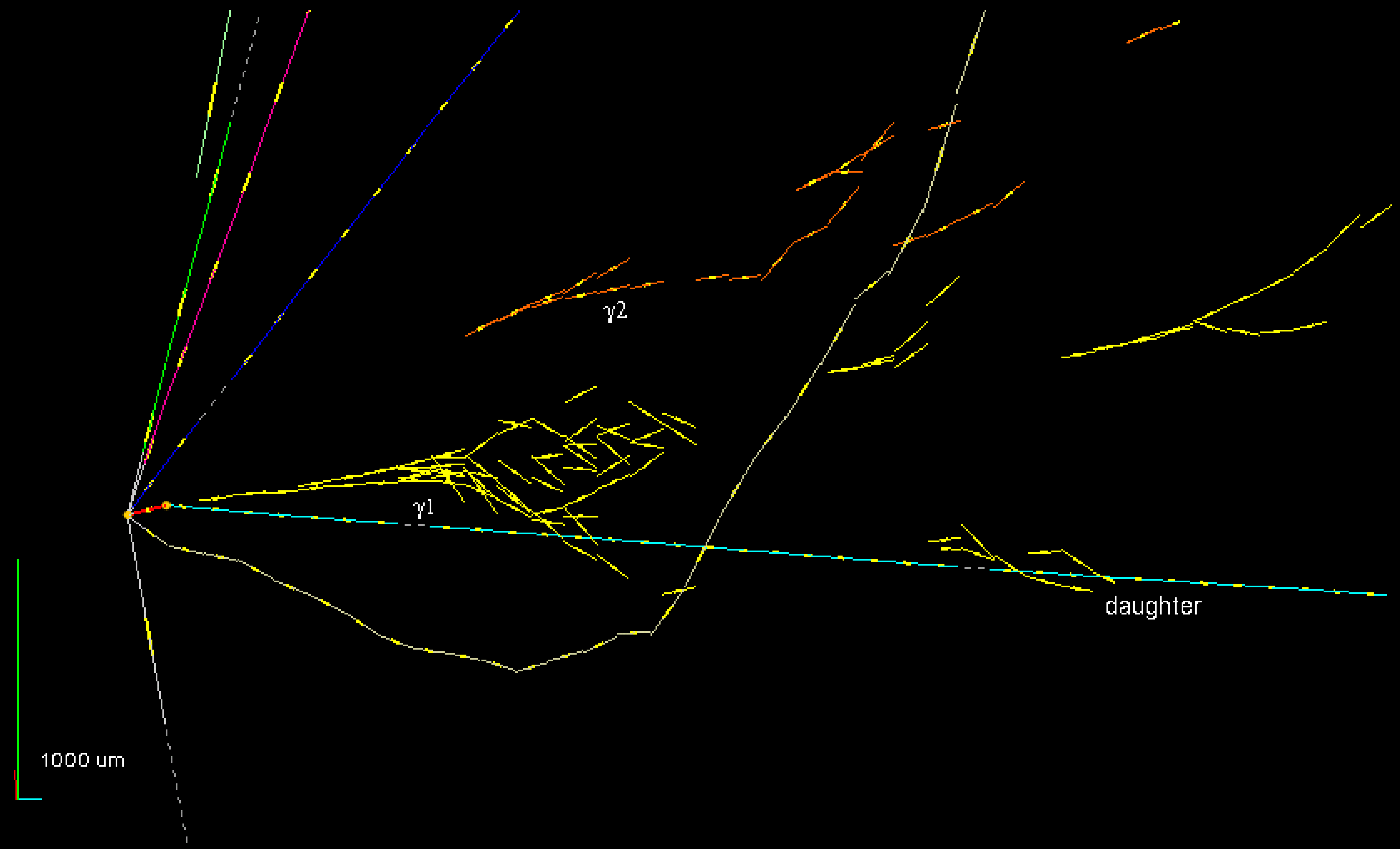


FROM CS TO VERTEX LOCATION

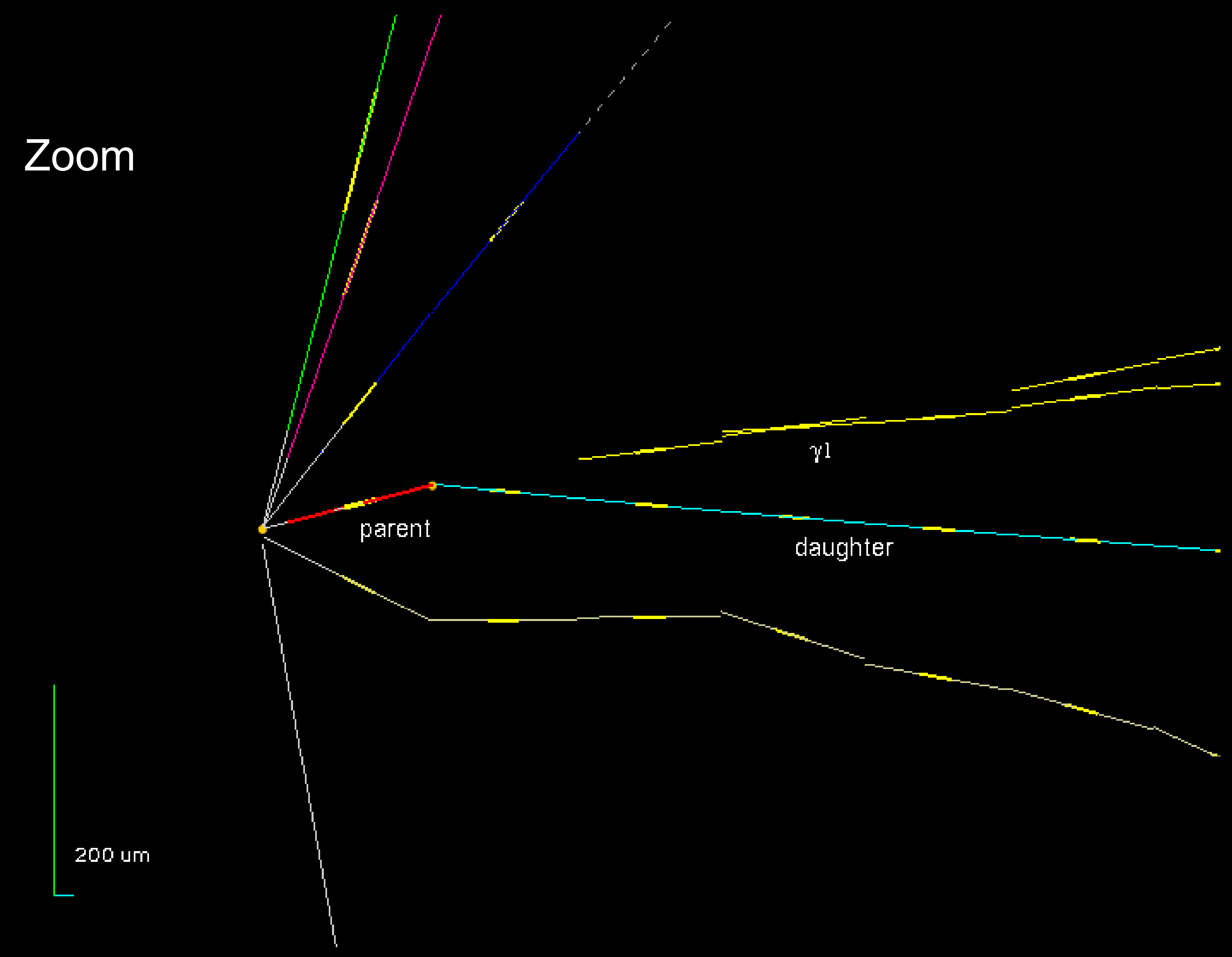
Large area scanning
Full reconstruction of vertices and gammas



Event reconstruction (1)

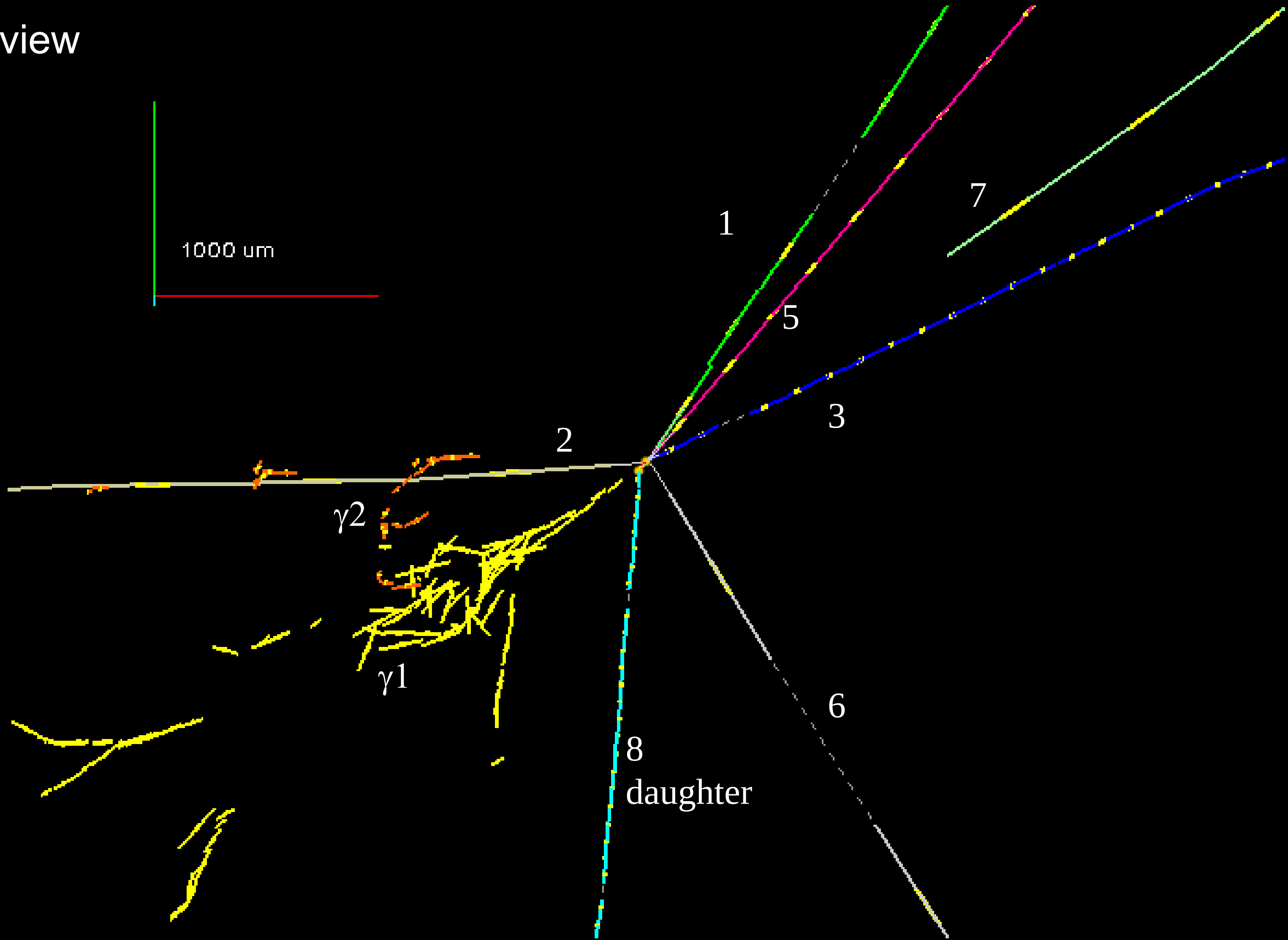


Event reconstruction (2)



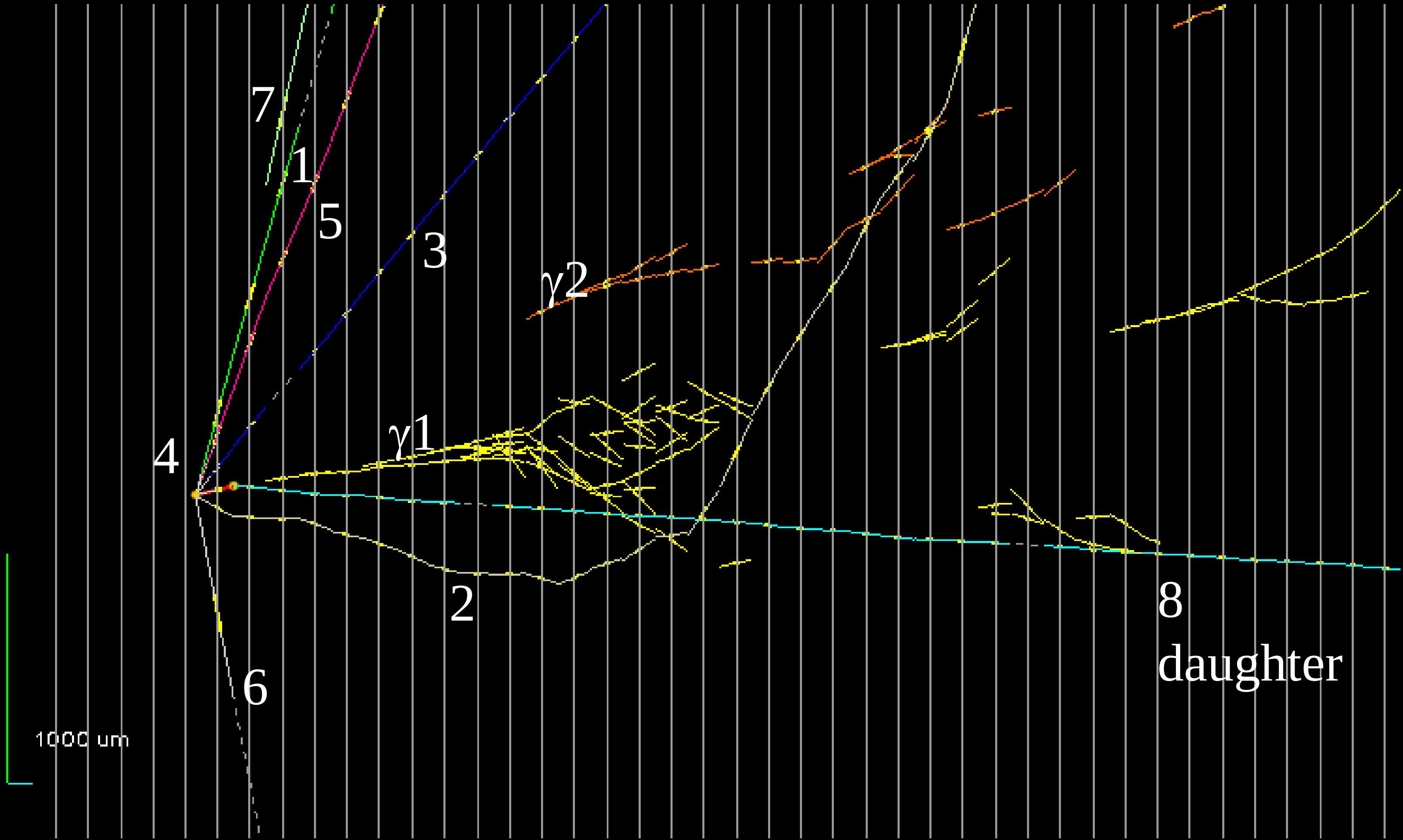
Event topological features (1)

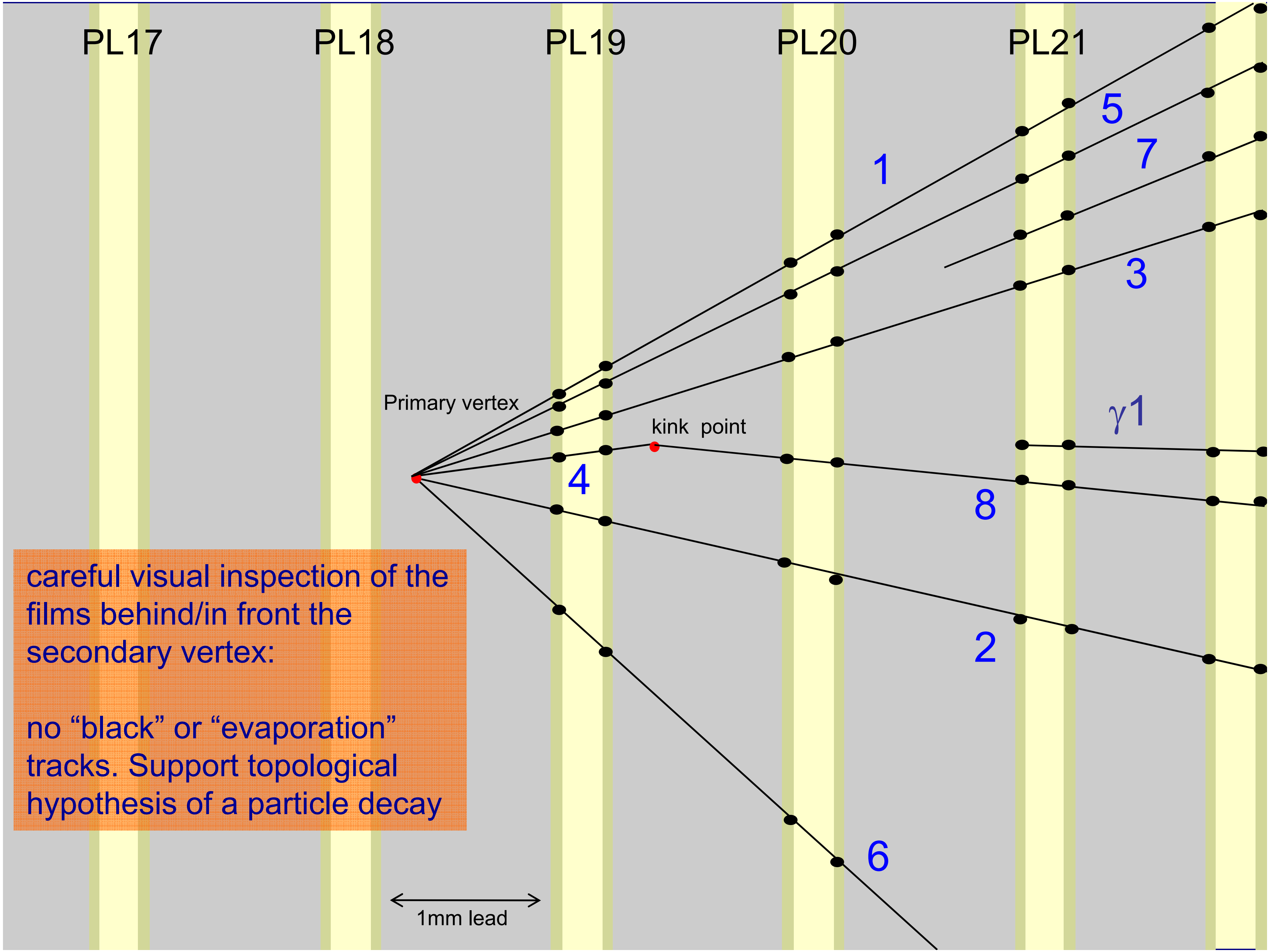
Beam view



Event topological features (2)

Side view





careful visual inspection of the films behind/in front the secondary vertex:

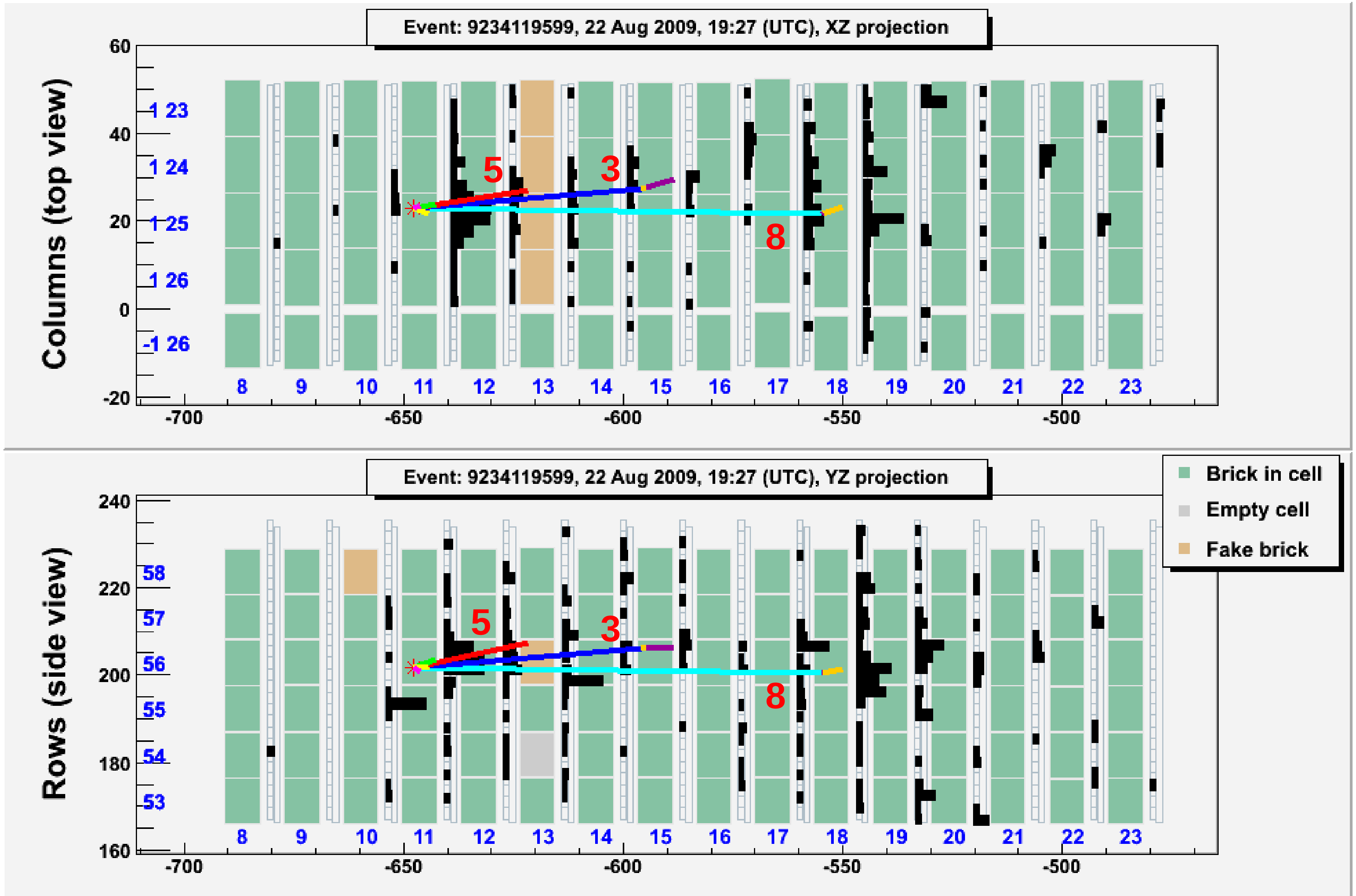
no “black” or “evaporation” tracks. Support topological hypothesis of a particle decay

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/emul=4.1/1.2 cm	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/emul=9.5/2.8 cm	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)

Vertex tracks followed down (through several bricks) to assess the muonless nature of the event. Residual probability of ν_μCC event (due to a possibly undetected large angle muon) ~1%. **“Nominal” value of 5% assumed**



ANALYSIS

OPERA nominal analysis flow applied to the hadronic kink candidates:

(more refined selection criteria being developed were not considered here not to bias our analysis)

- kink occurring within 2 lead plates downstream of the primary vertex

- kink angle larger than 20 mrad

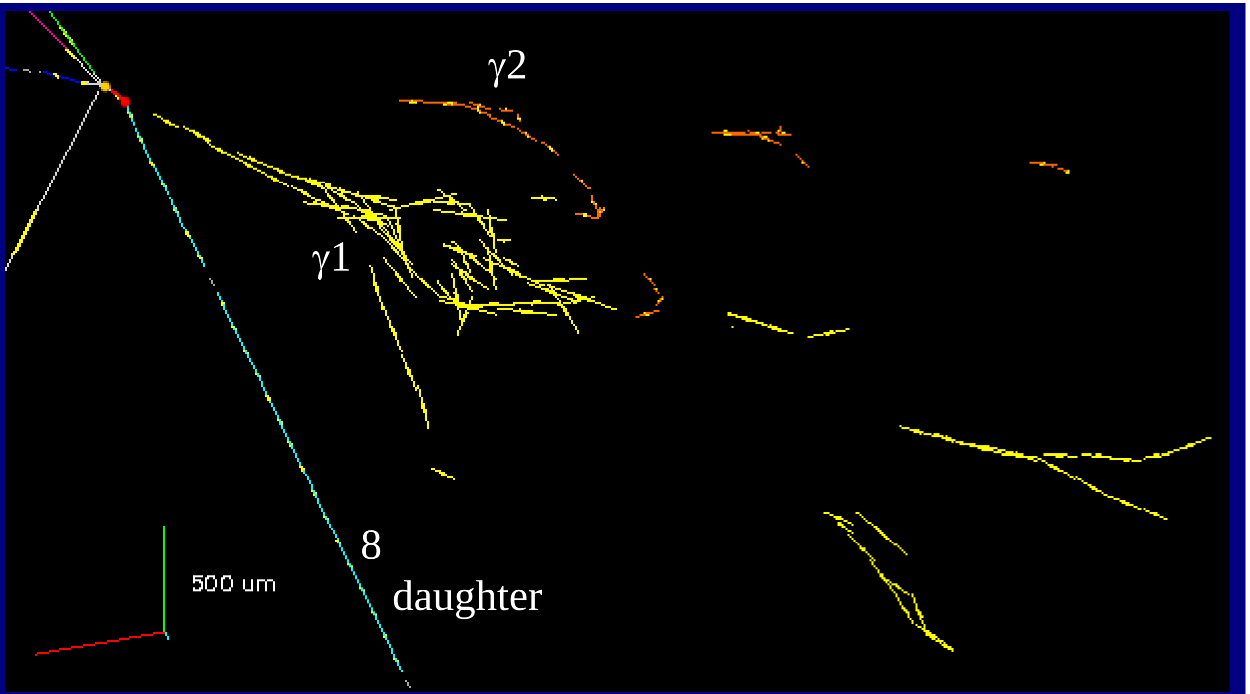
- daughter momentum higher than 2 GeV/c

- decay Pt higher than 600 MeV/c, 300 MeV/c if ≥ 1 gamma pointing to the decay vertex

- missing Pt at primary vertex lower than 1 GeV/c

- azimuthal angle between the resulting hadron momentum direction and the parent track direction larger than $\pi/2$ rad

γ detection



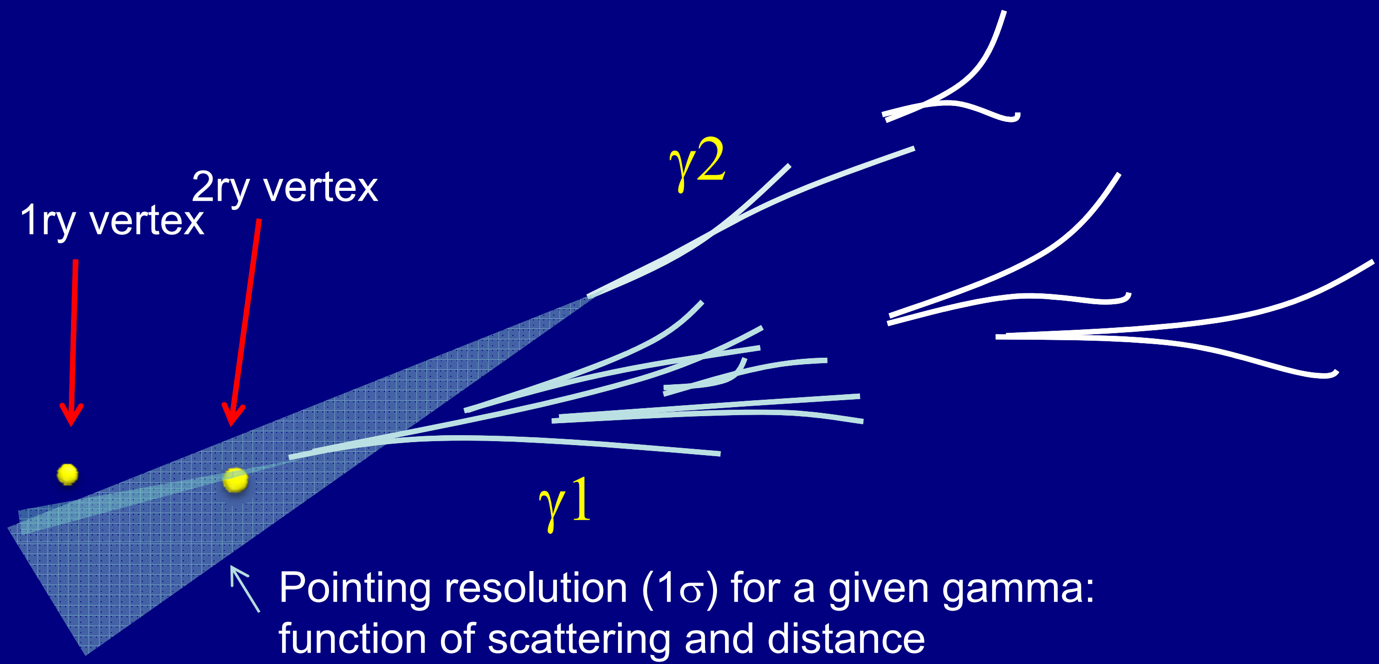
- total radiation length downstream the vertices: 6.5 X_0
- gamma search performed in the whole scanned volume
- careful visual scanning checks

	Distance from 2ry vertex (mm)	Energy (GeV)
1^{st} γ	2.2	5.6 ± 1.0 ± 1.7
2^{nd} γ	12.6	1.2 ± 0.4 ± 0.4

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



Kinematical variables

• The kinematical variables are computed by averaging the two sets of track parameter measurements

• We assume that:
$\gamma 1$ and $\gamma 2$ are both attached to 2^{ry} vertex

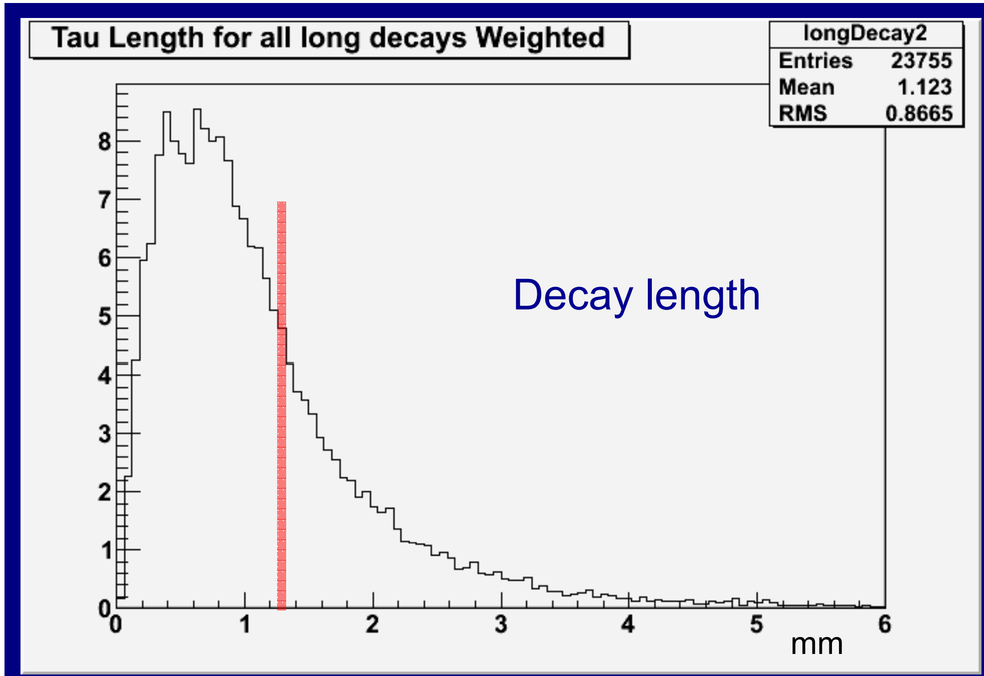
VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt (MeV/c)	**470^{+230}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**

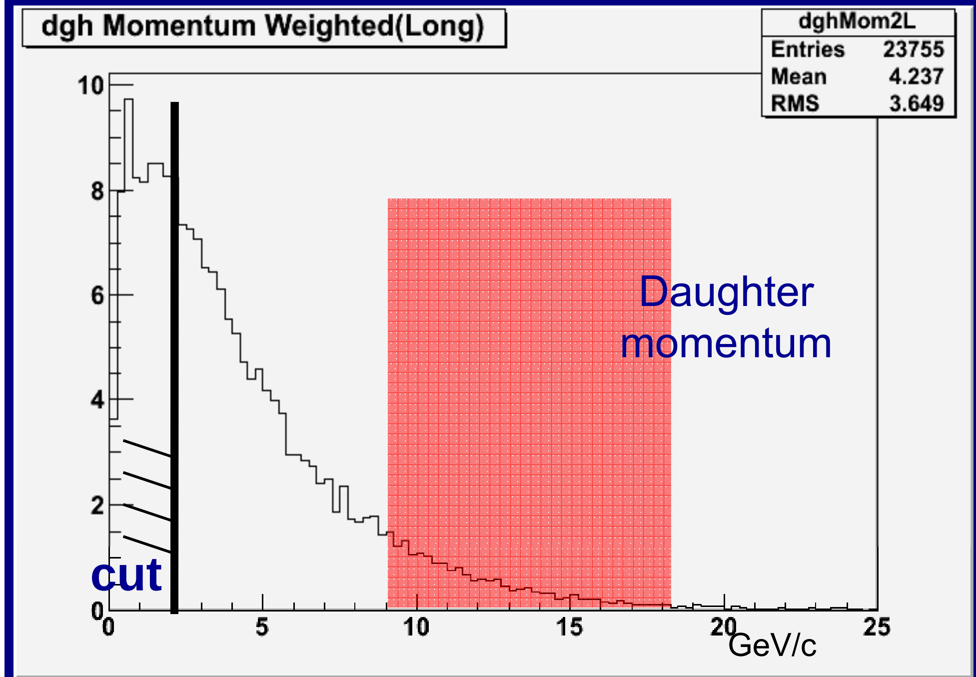
The average values are used in the following kinematical analysis

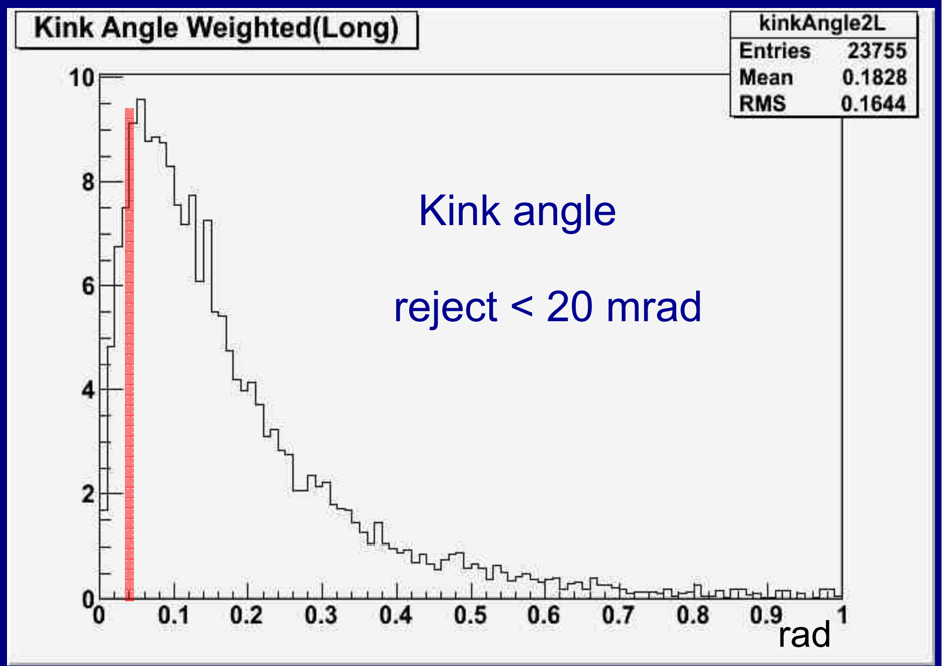
The uncertainty on Pt due to the alternative $\gamma 2$ attachment is < 50 MeV

Features of the decay topology

red bands: values for the “interesting” event with uncertainties

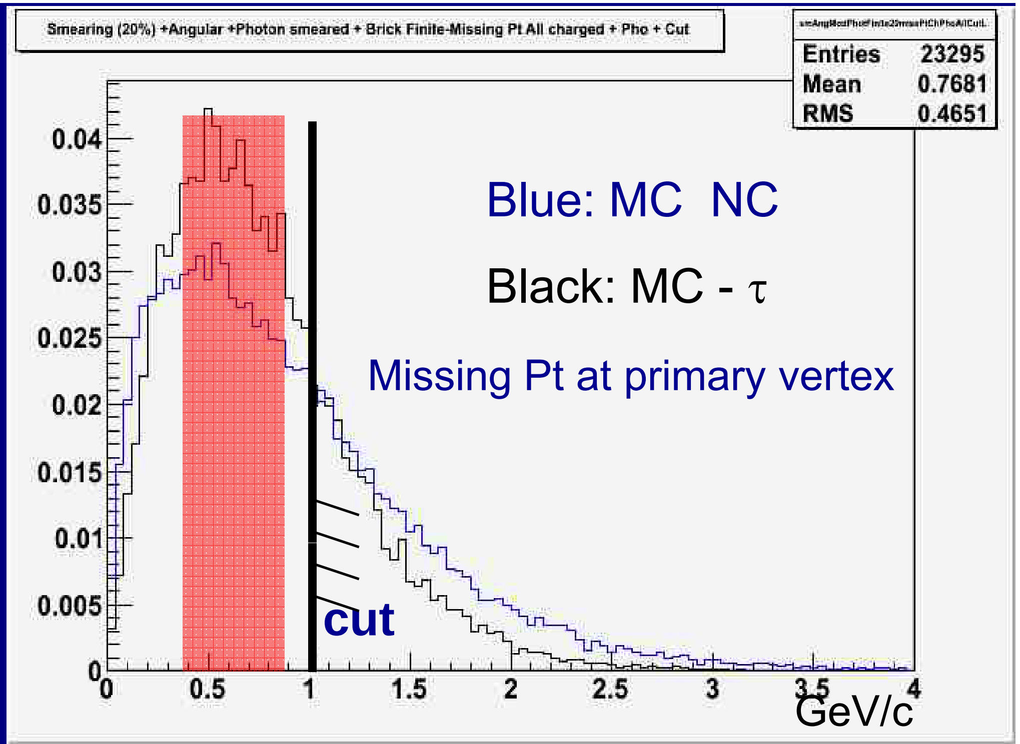




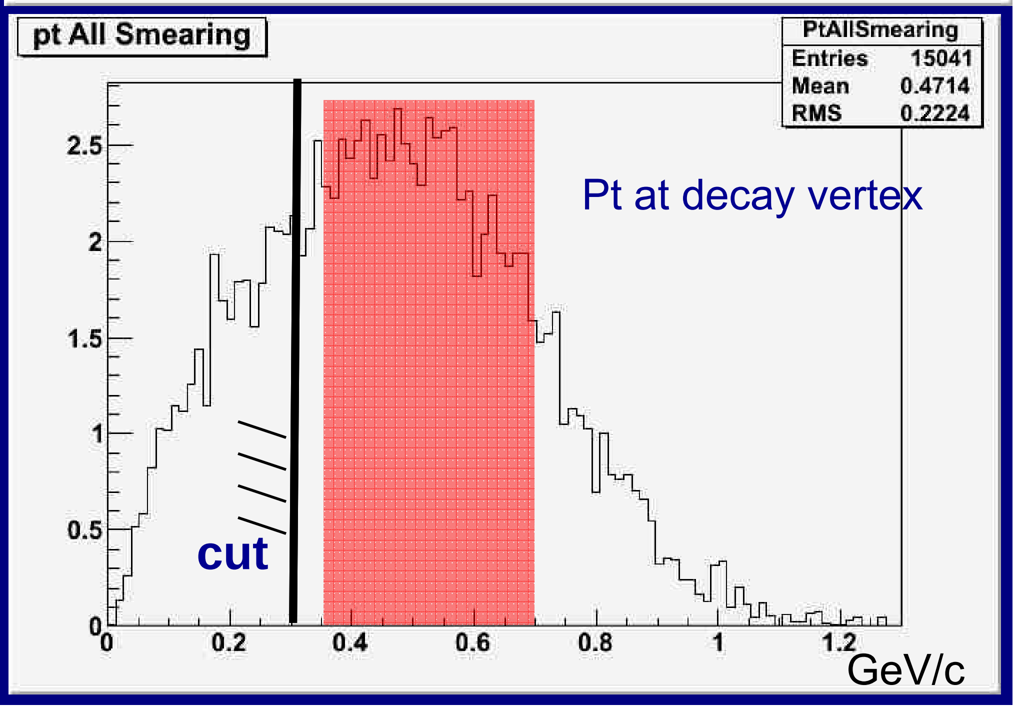


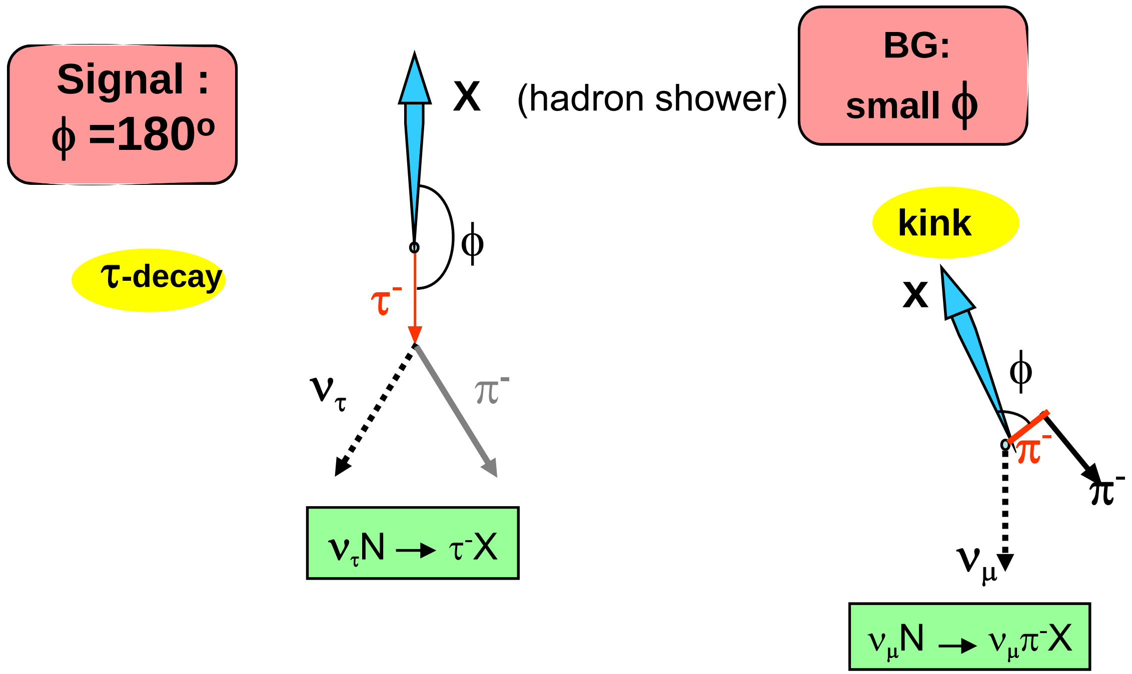
Kinematical cuts to be passed

Reject NC events with larger missing Pt (neutrino)

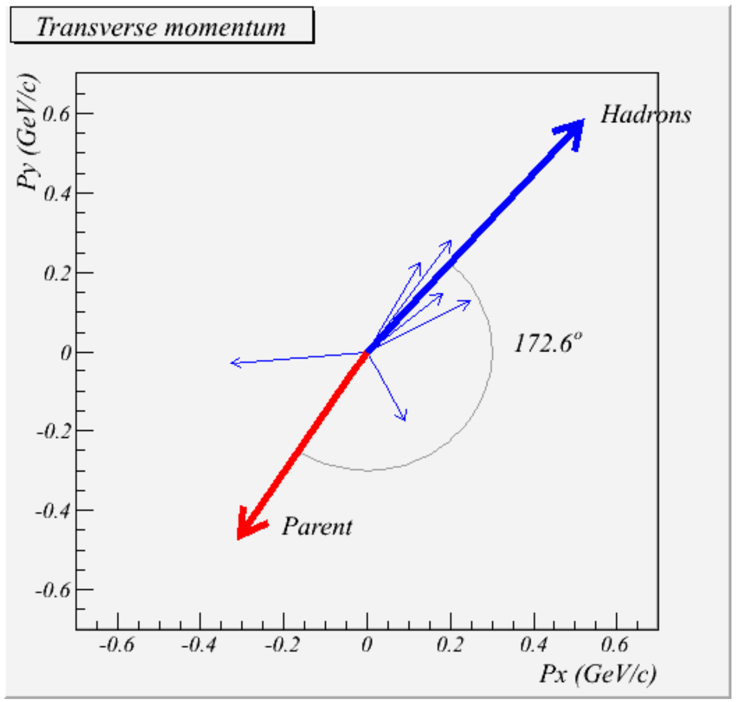


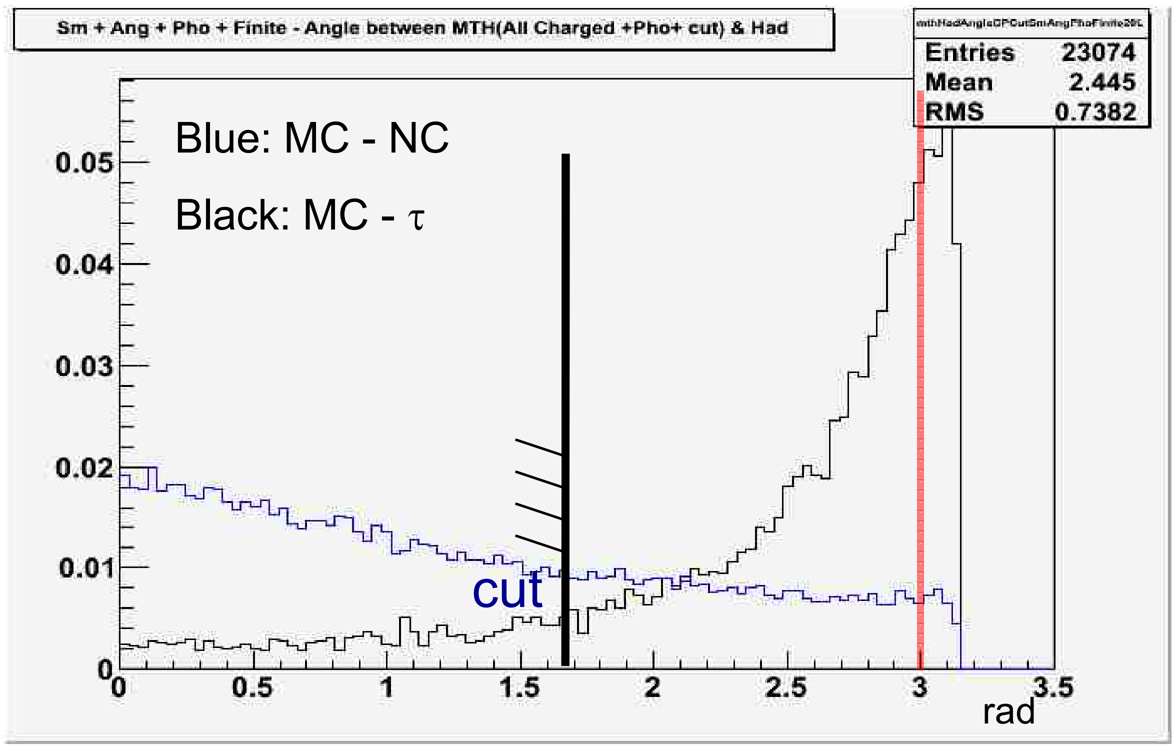
Reject hadron interactions





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





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-prong hadron decay mode.

• The invariant mass of the two detected gammas yields a mass 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^o mass	ρ mass
120 ± 20 ± 35 MeV	$640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

BACKGROUND SOURCES

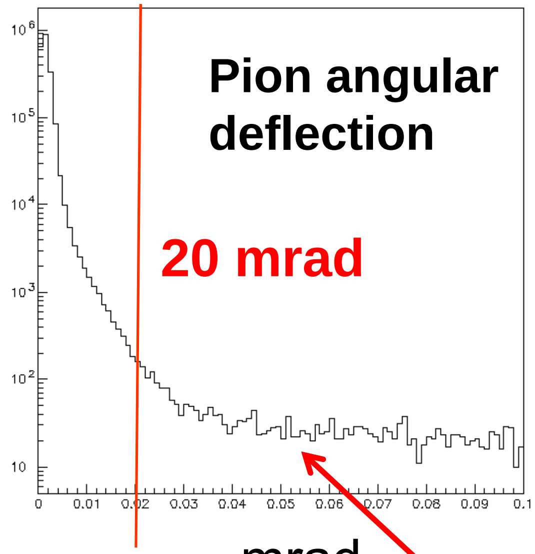
- Prompt ν_τ ~ 10^{-7}/CC
- Decay of charmed particles produced in ν_e interactions ~ 10^{-6}/CC
- Double charm production ~ 10^{-6}/CC

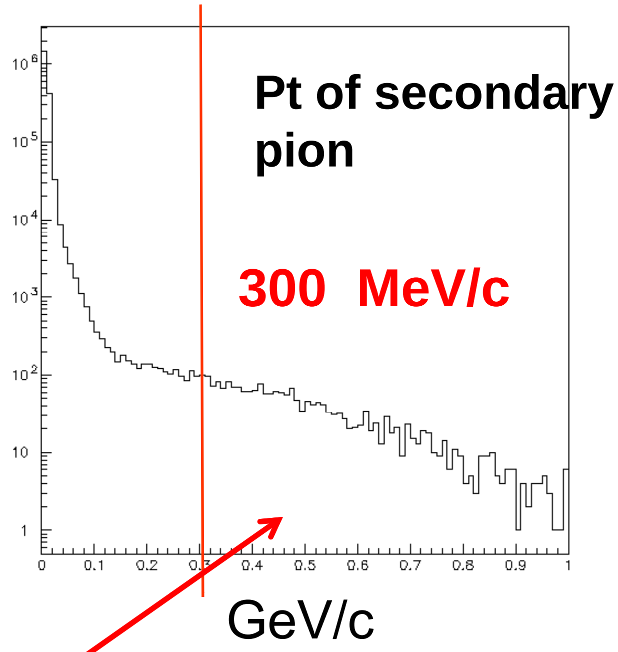
- Decay of charmed particles produced in ν_μ interactions ~ 10^{-5}/CC
- Hadronic reinteractions (UPDATE) ~ 10^{-5}/CC

Simulation of the reinteraction 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.

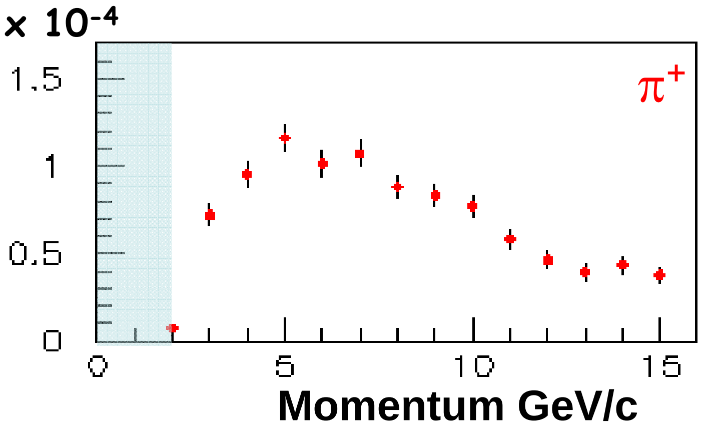
Typical scattering distributions for : 5 GeV π^+

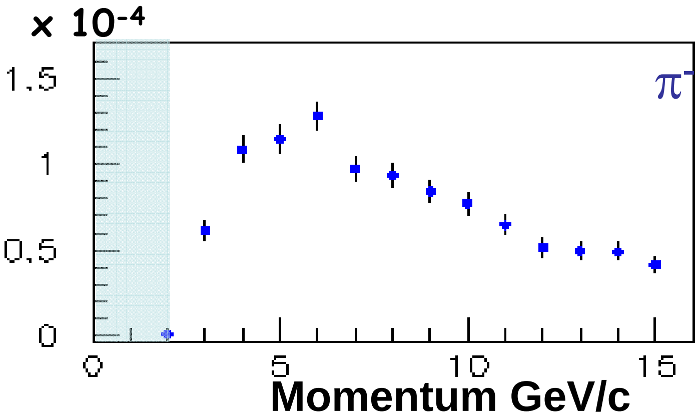


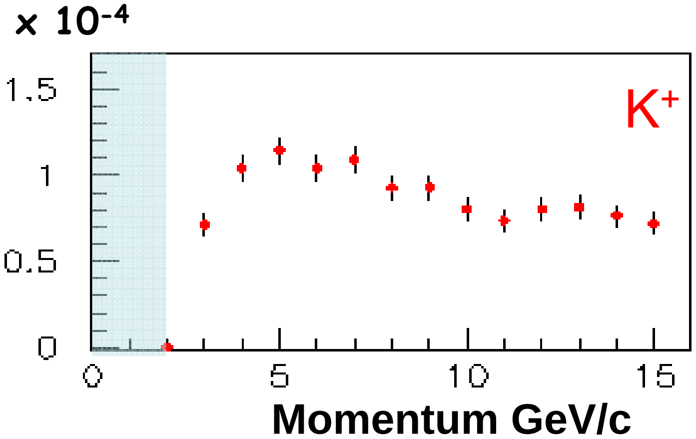


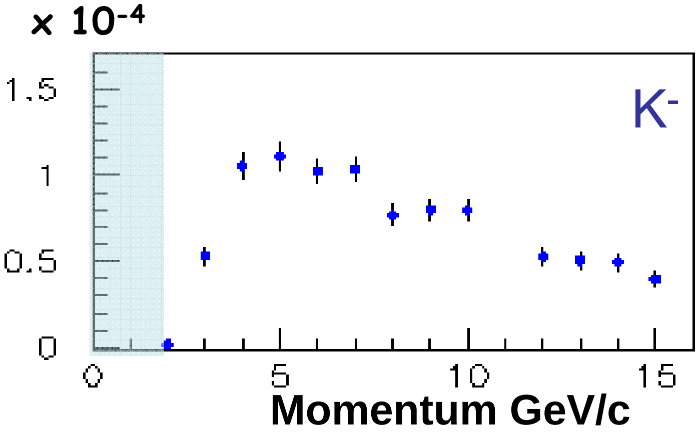
tails of the distributions

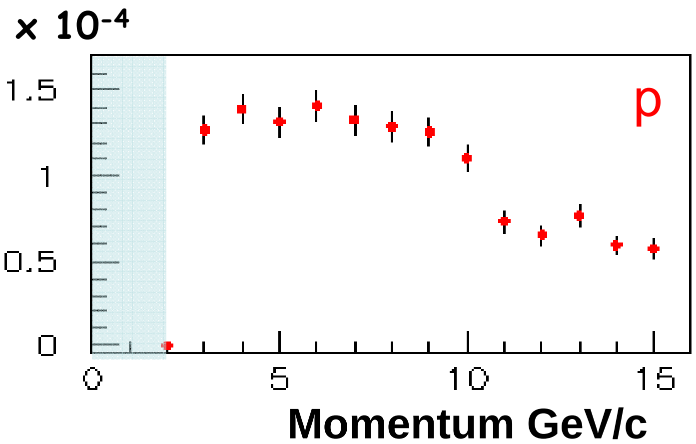
kink probabilities for 1 mm Pb











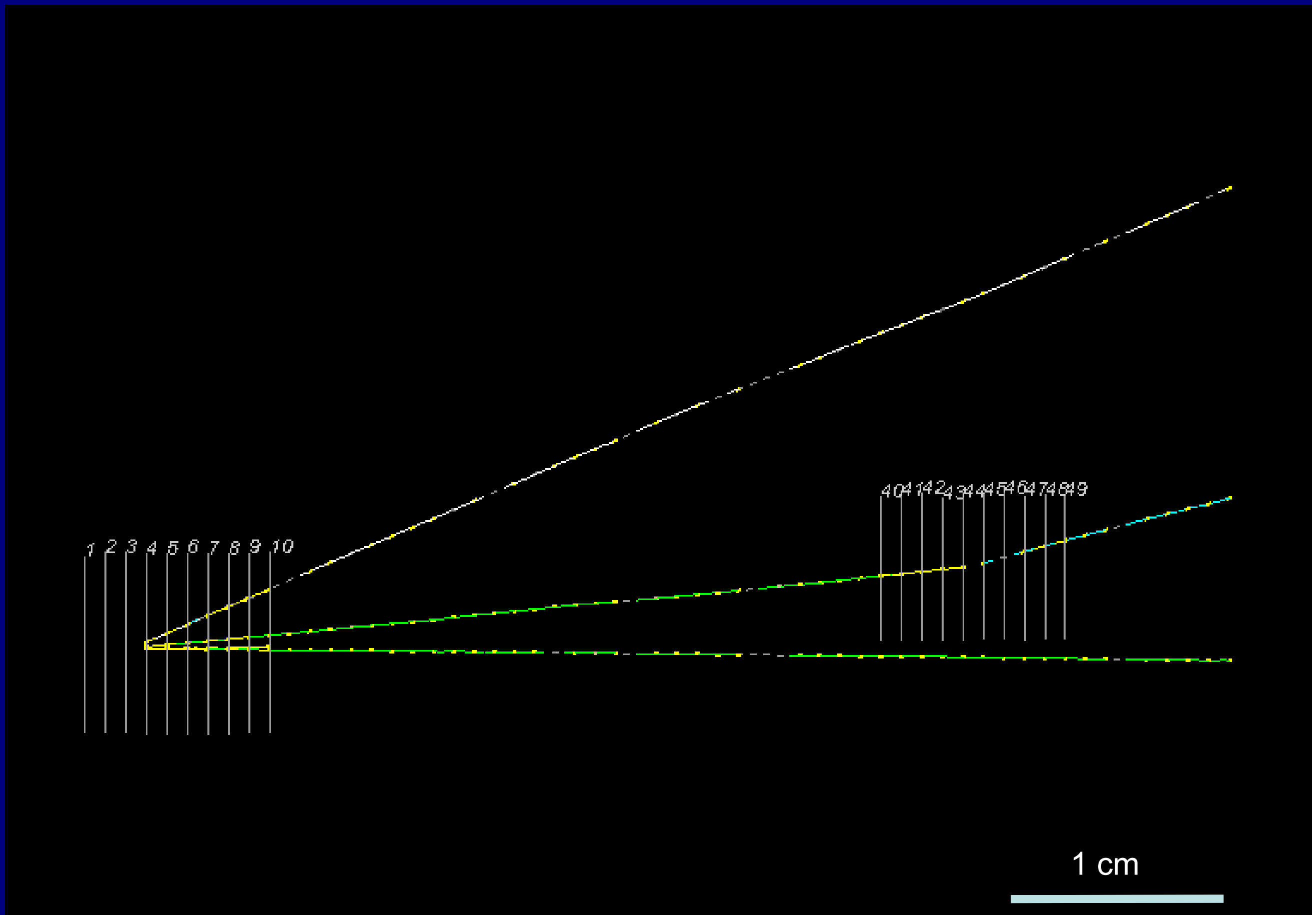
kink probabilities integrated over the ν_μ NC hadronic spectrum yield a BG probability of:

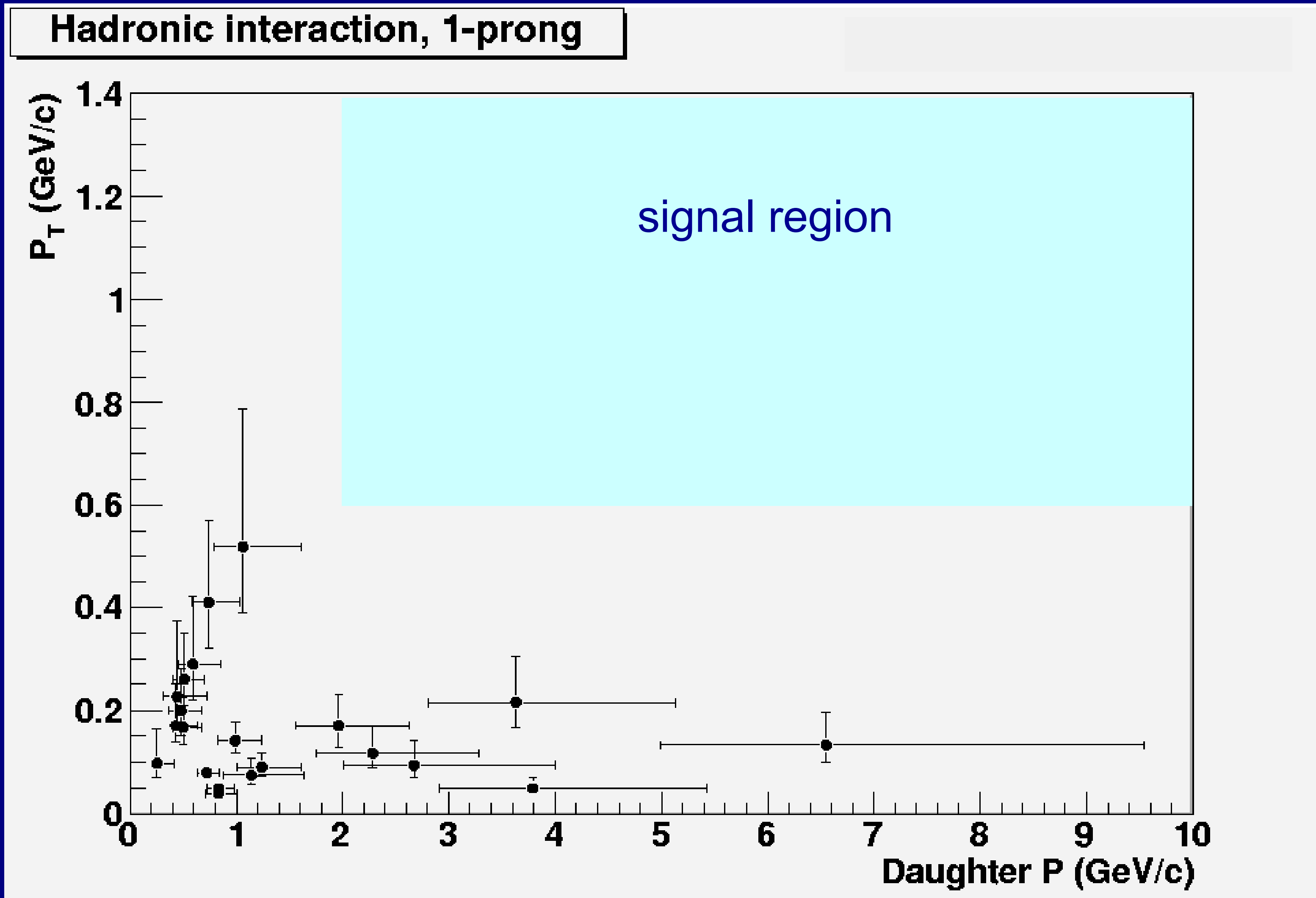
$(1.9 \pm 0.1) \times 10^{-4}$ kinks/NC (2 mm Pb)

Measure interaction BG far from the τ-decay region

• Search for "kinks" and interactions along a total of 9 m of hadron track measured for scanned events. This is about a factor 8 larger than the so far scanned track length for NC events (number of NC x hadron multiplicity x 2 mm decay length).

• Goal: ~100 m as needed to fully validate (eventually replace) the MC information





- no events in the signal region
- 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)

MC validation by beam test pion events

Brick exposed to 4 GeV/c pions: ~20 m of pion track scanned to search for interactions

Example →

kink interaction with back scattering

Daugther track
TX= 0.501
TY=0.359

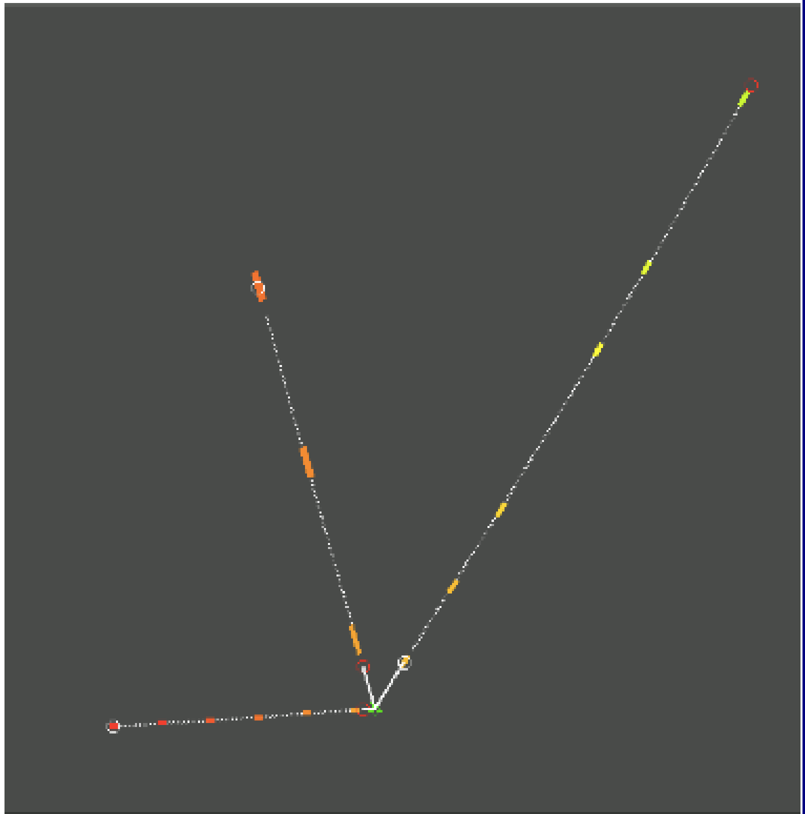
θ_{kink}=0.648 rad

P=$0.9^{+1.3}_{-0.4}$ GeV

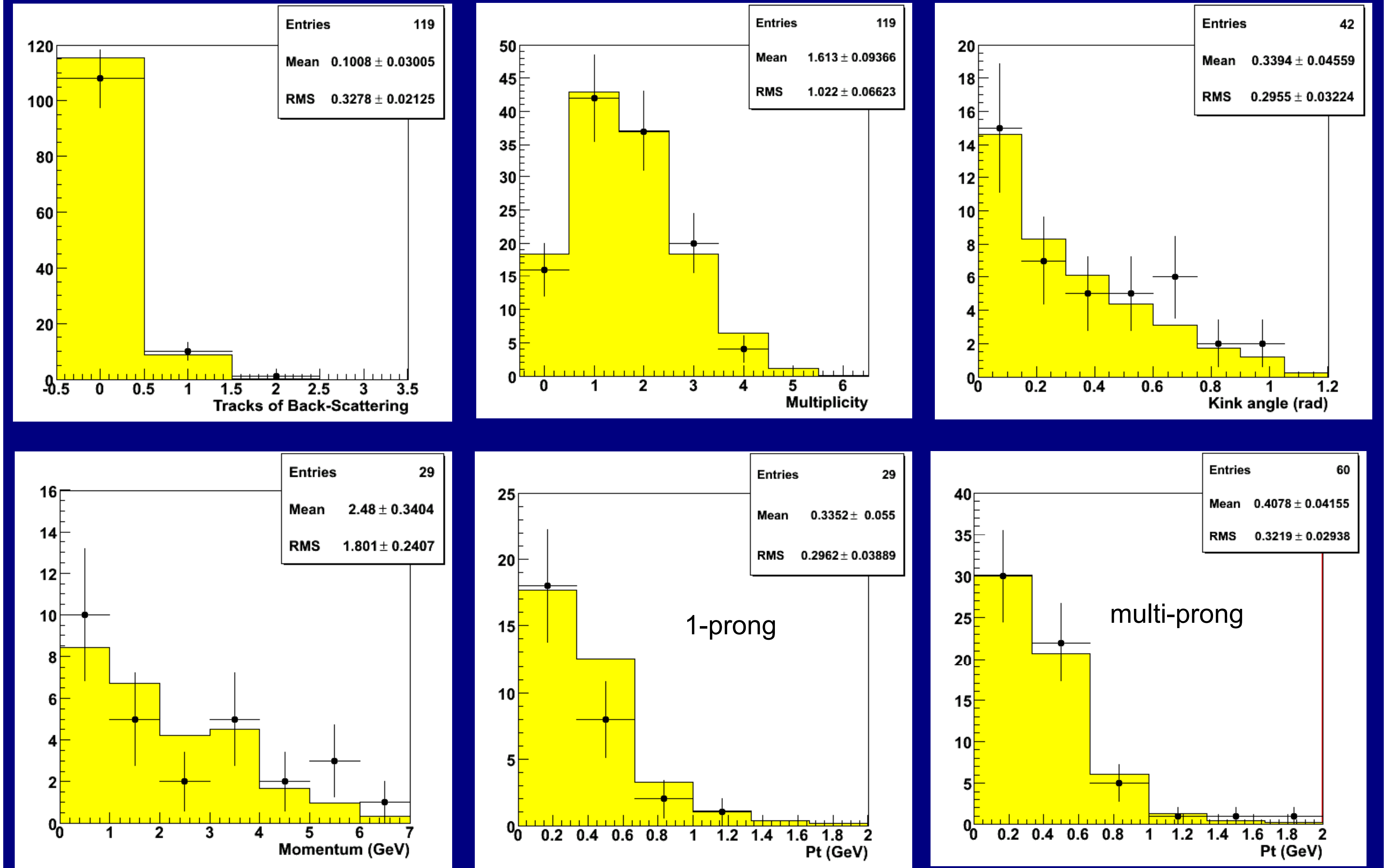
P_T=583 MeV

Back-scattered track

TX= 0.484 TY=-0.784

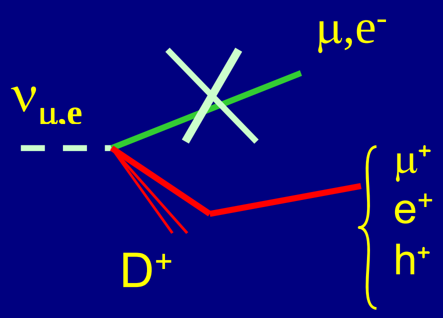


DATA/MC comparison: good agreement in normalization and shape



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.

STATISTICAL CONSIDERATIONS

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

0.011 events (reinteraction)
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

(here we add up the errors linearly)

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.

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)

CONCLUSIONS AND OUTLOOK (1)

• The OPERA experiment at LNGS is aimed at the first detection of neutrino oscillations in appearance mode through the study of the $\nu_\mu \rightarrow \nu_\tau$ channel.

• The Collaboration has conducted the analysis of a sub-sample of the neutrino data taken in the CERN CNGS beam in the 2008-2009 runs.

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

• One muonless event showing a τ ➔ 1-prong hadron decay topology has been detected and studied in detail. It passes all kinematical cuts required to reduce the physics background. It is the first ν_τ candidate event in OPERA.

CONCLUSIONS AND OUTLOOK (2)

• The observation of 1 candidate signal event within the analyzed sample allows us to exclude at the 90% CL Δm^2_{23} values > 7.5 x 10^{-3} eV^2 (full mixing).

• 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 decay modes 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.

• This result is an important step towards the long awaited discovery of neutrino oscillations in direct appearance mode.

• To meet this goal we will require to successfully complete data taking in the CNGS beam and perform the analysis of the full data sample.

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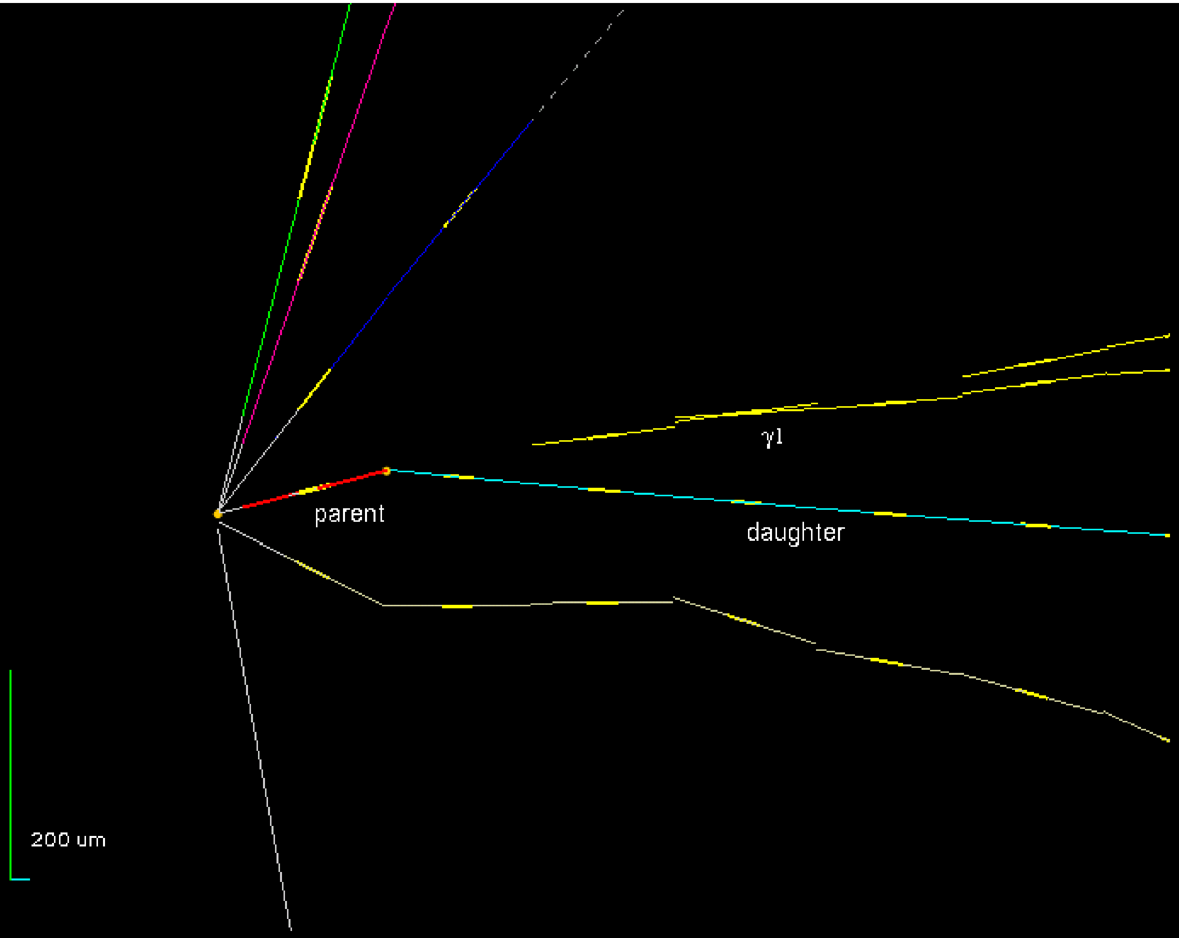

…and thank you for your attention!