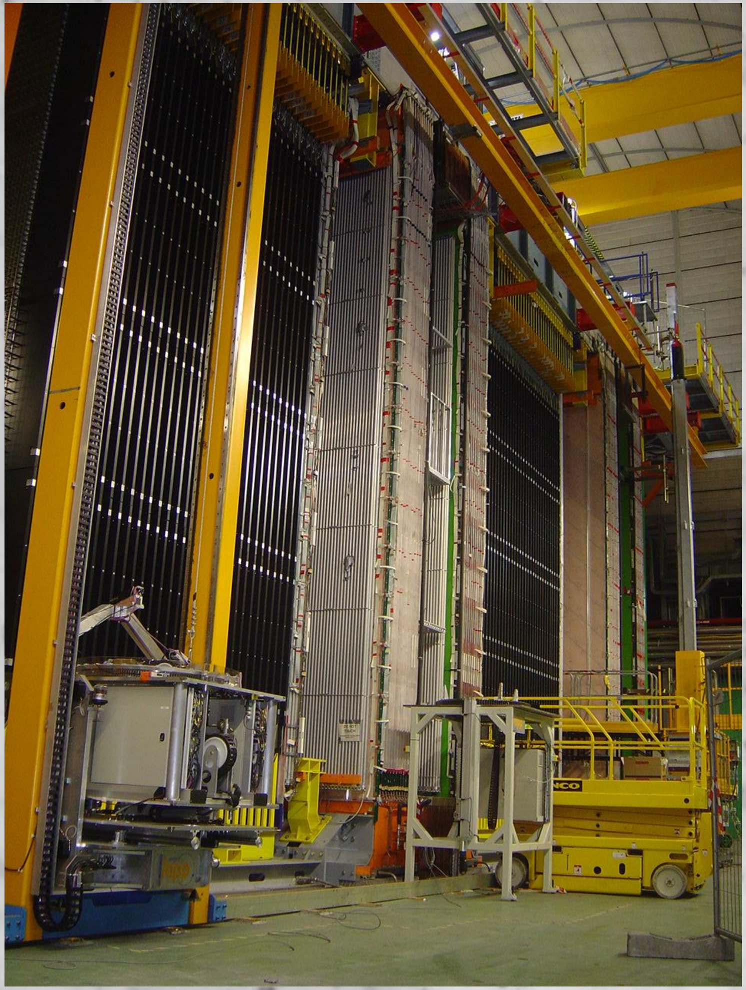
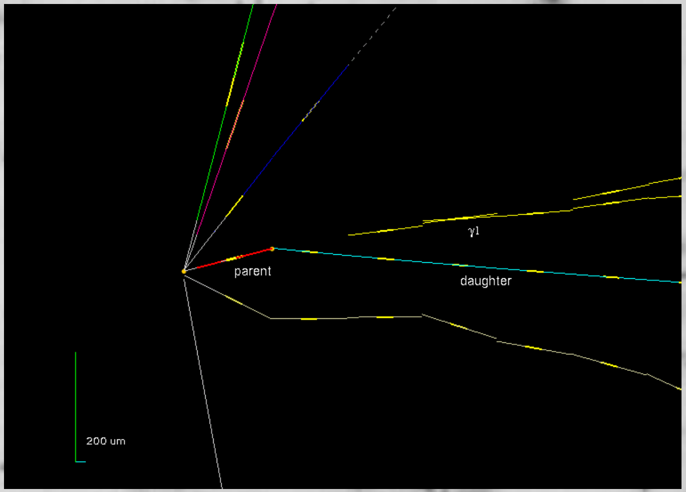
“Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode in the OPERA experiment“





Yuri Gornushkin (JINR, Russia)

On behalf of the members of OPERA Collaboration present at the school

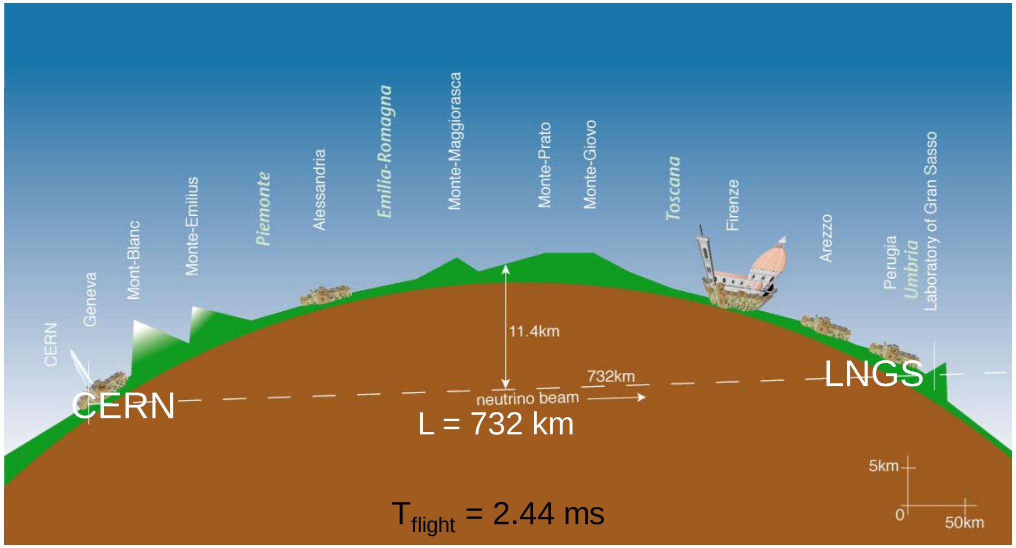
OPERA physics goals

First direct detection of $\nu_\mu \rightarrow \nu_\tau$ 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.

Important, missing tile in the oscillation picture.

CNGS – a long baseline, high energy νbeam

$< E \nu_\mu >$	17 GeV
L	730 km
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87%
$\bar{\nu}_\mu / \nu_\mu$	4%
ν_τ prompt	negligible

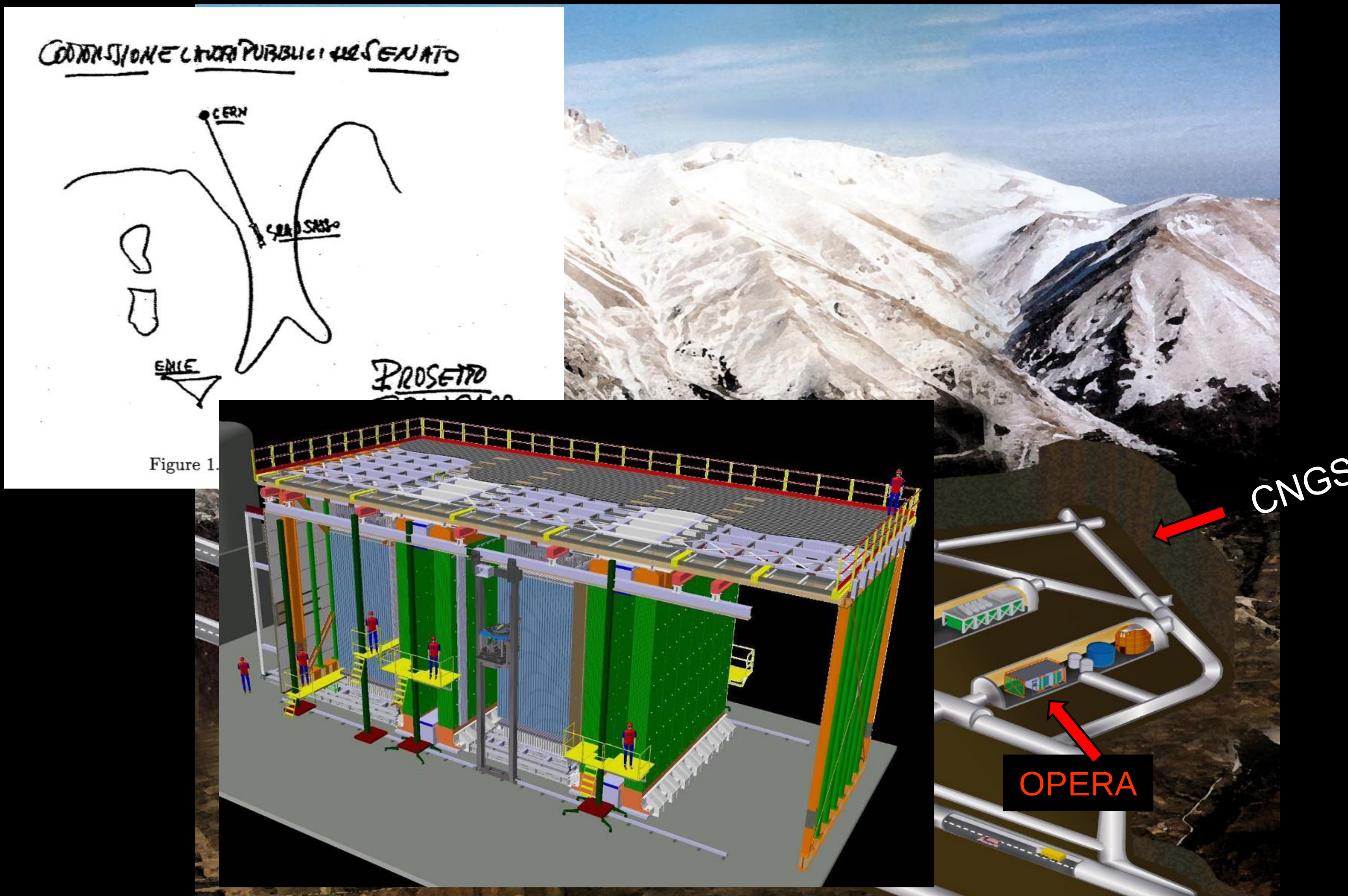


Expected produced interactions (22.5×10^{19}):
~25400 ν_μ CC + NC
~170 $\nu_e + \bar{\nu}_e$ CC
~125 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)

~10 tau decays are expected to be observed
Less than 1 background after 5 years running

LNGS: the world largest underground physics laboratory:

~100’000 m^3 caverns’ volume, ~3’100 m.w.e. overburden



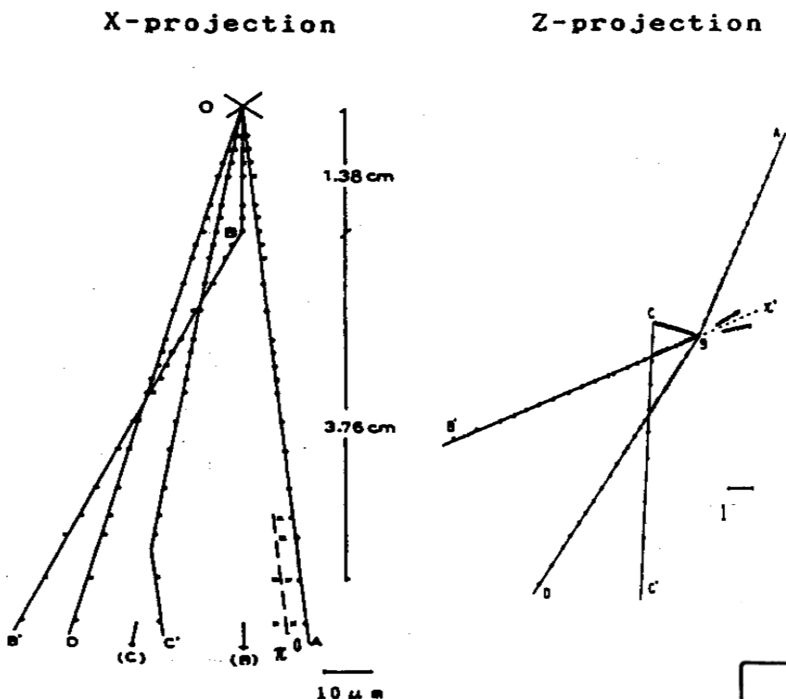
The ECC: evidence of charm in cosmic-rays by K. Niu (1971)

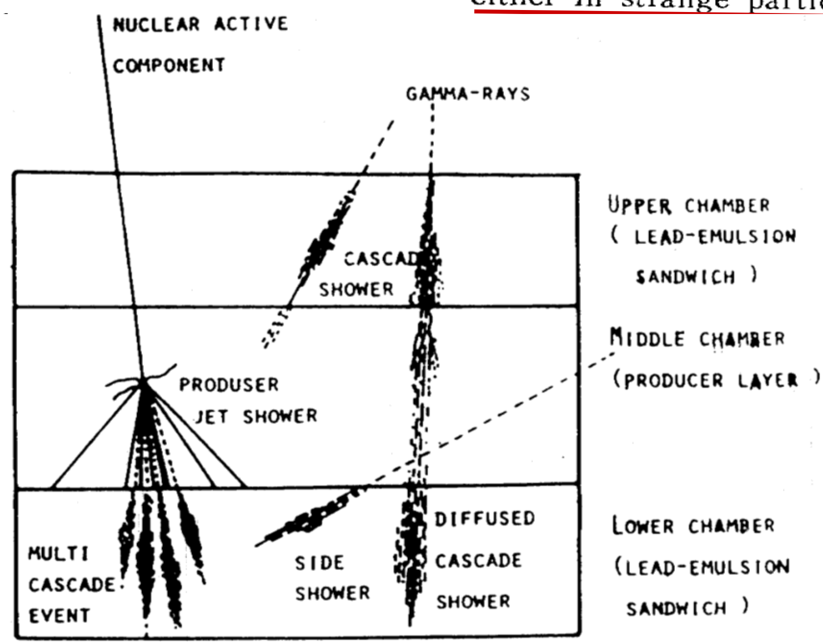
Prog. Theor. Phys. Vol. 46 (1971), No. 5

A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA

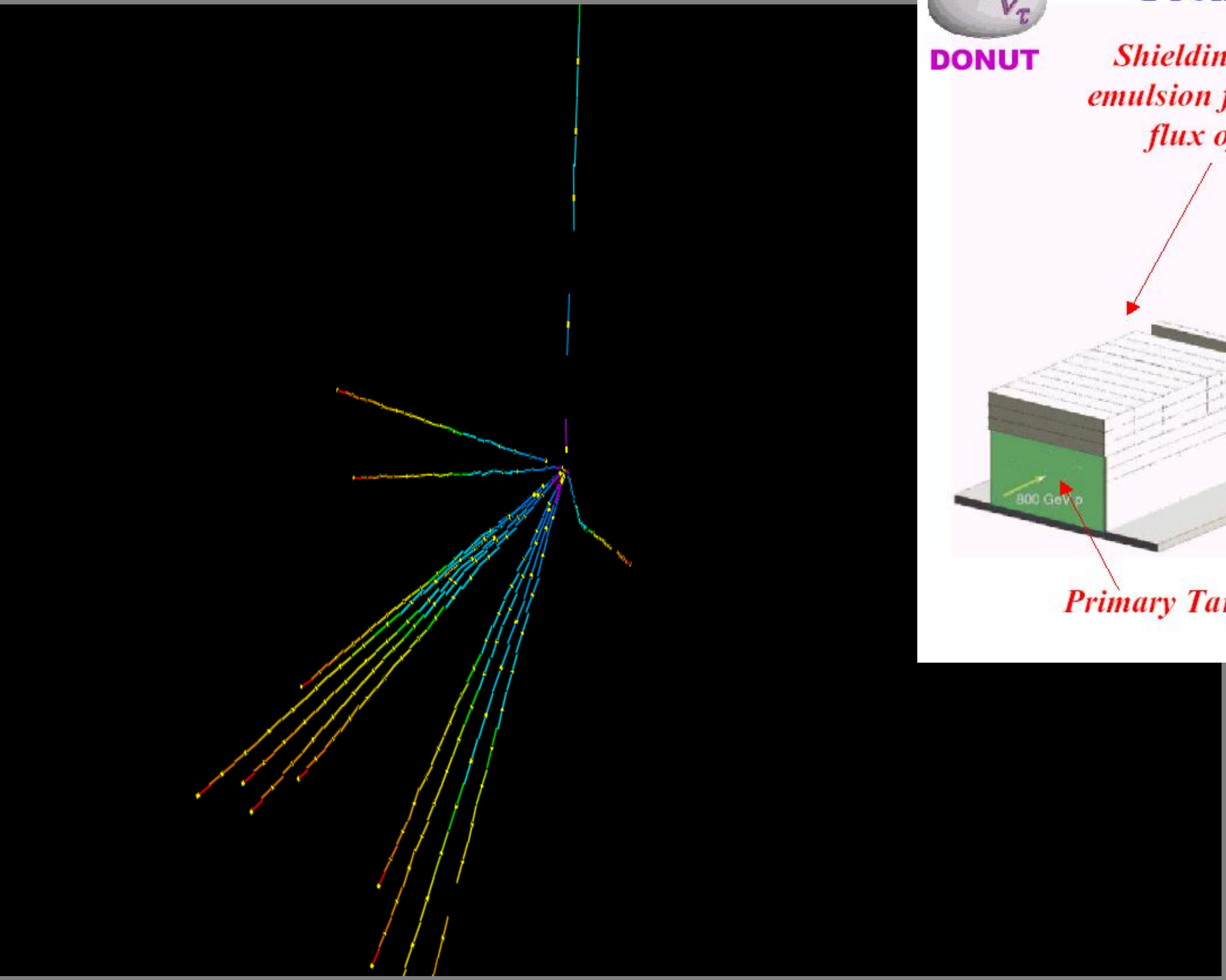
As for the characteristics of X particle, the transverse momentum of daughter π^0 meson, 627 ± 90 MeV/c, is much higher than the maximum momentum of decay products of the existing strange particles. The proper life time of X particle is several times 10^{-14} seconds, and this is extremely longer than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

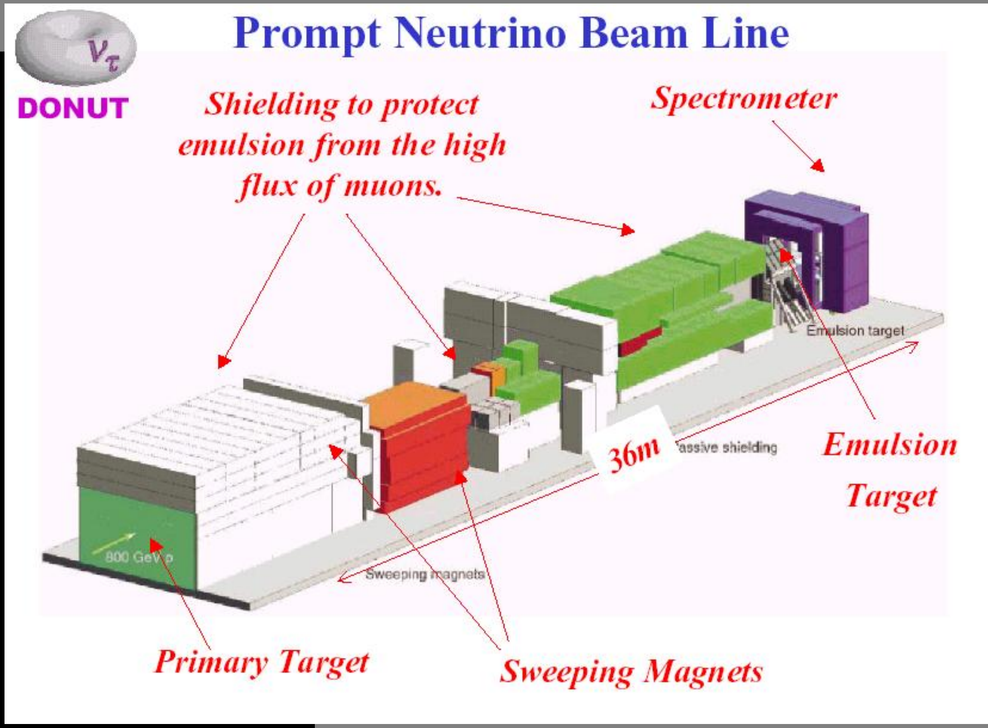




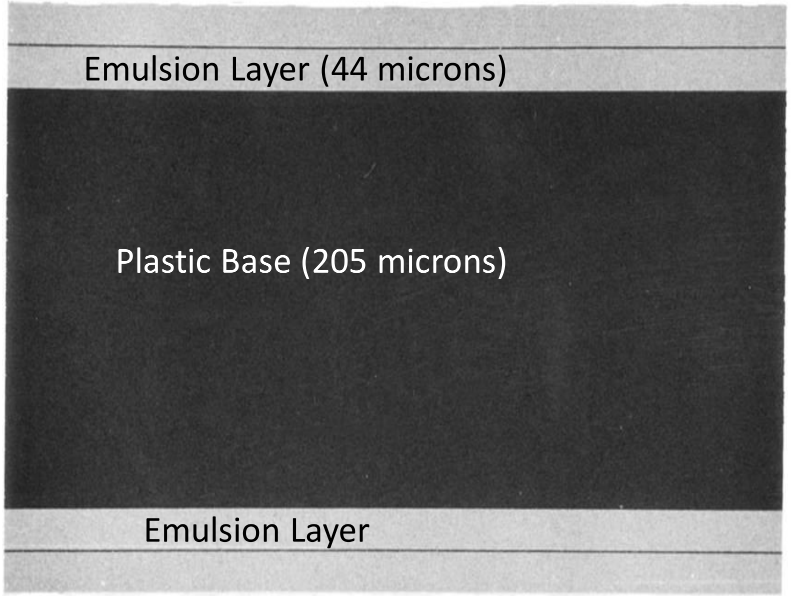
DONUT experiment at FERMILAB: first detection of ν_τ with an ECC based detector (K. Niwa and collaborators): 9 τ events, 1.5 BG.

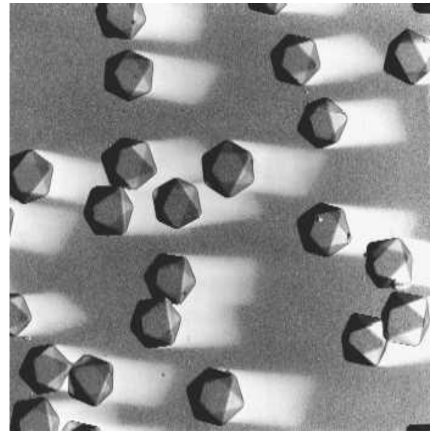
K. Kodama et al. (DONuT Collaboration), Phys. Lett. B 504, 218 (2001).





INDUSTRIAL EMULSION FILMS BY *FUJI FILM*





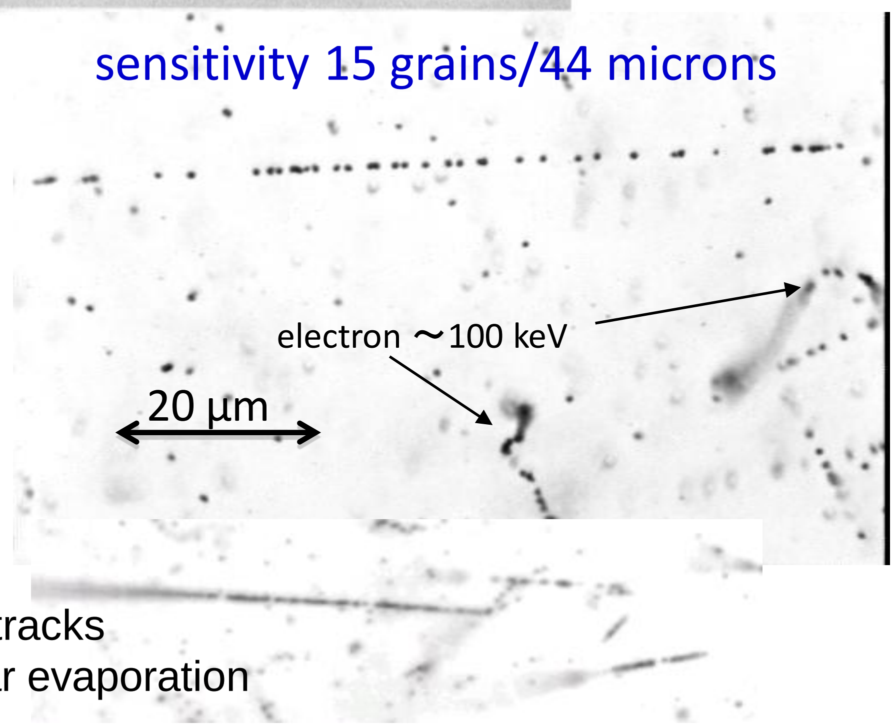
basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

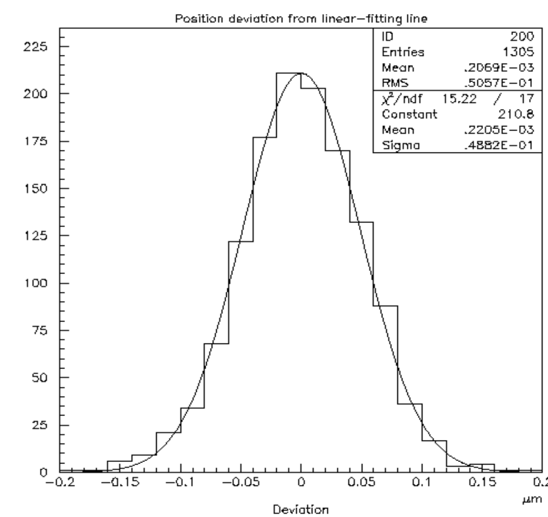
mip



high dE/dx tracks
from nuclear evaporation

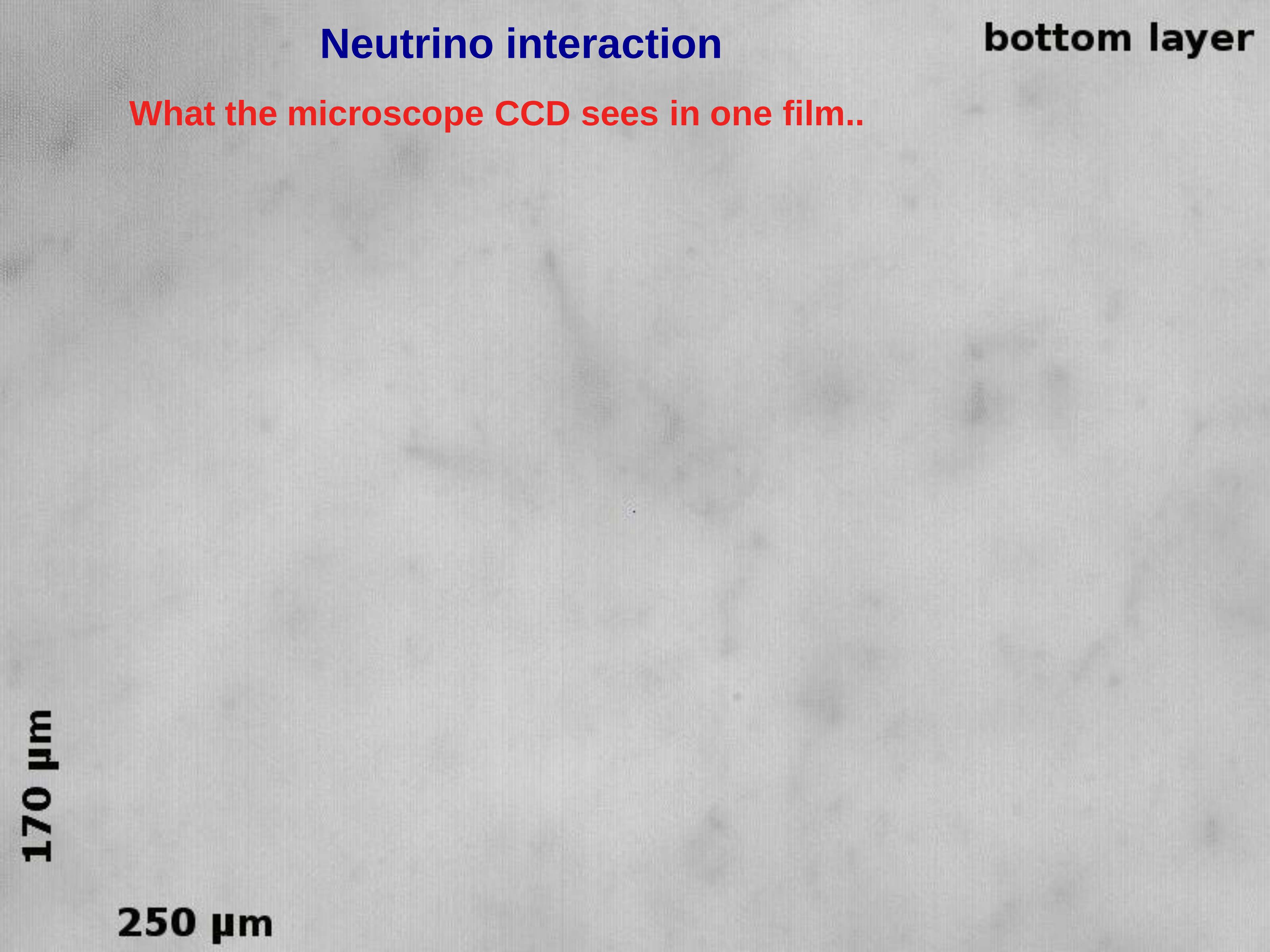
intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



Neutrino interaction

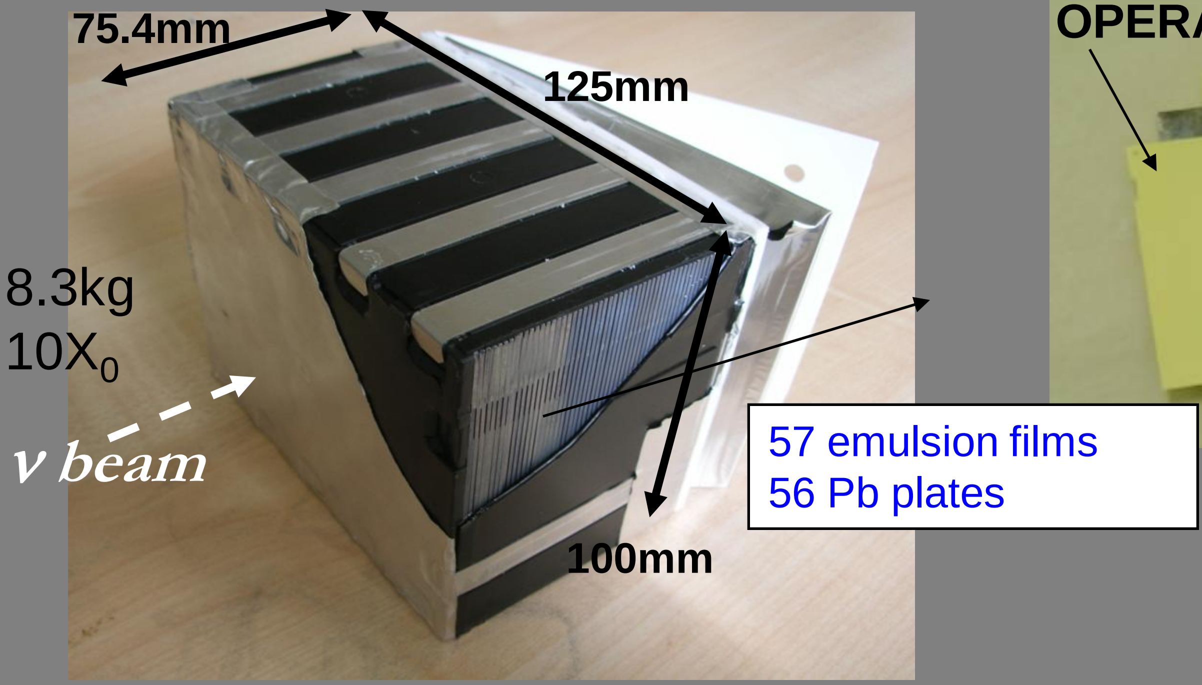
What the microscope CCD sees in one film..

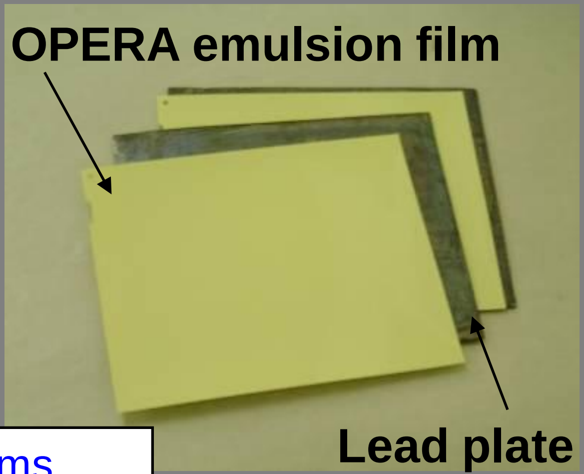


OPERA FILM, SUTS読み出しの情報量 (DVD Blu-ray Diskとの比較)

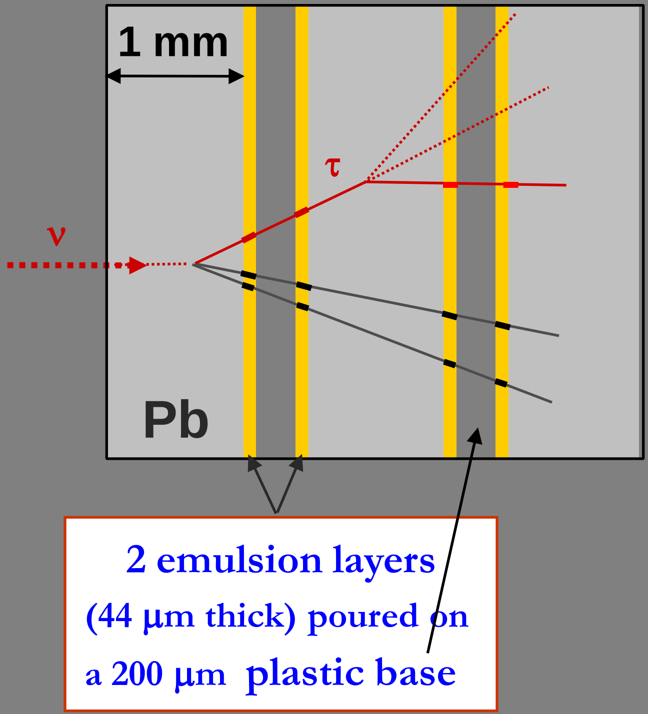
	大きさ	容量	読み出し
DVD	12cm Disk	8.5GB 2層	177Mbps 規格上の最高速度(11倍速)
Blu-ray Disc	12cm Disk	50GB 2層	216Mbps 規格上の最高速度(6倍速)
OPERA Film	**12.5×10cm**	**556GB相当** (0.3um^2)/(100mm*125mm) *16layer * 両面	**839Mbps** SUTSで毎秒200視野

OPERA ECC brick





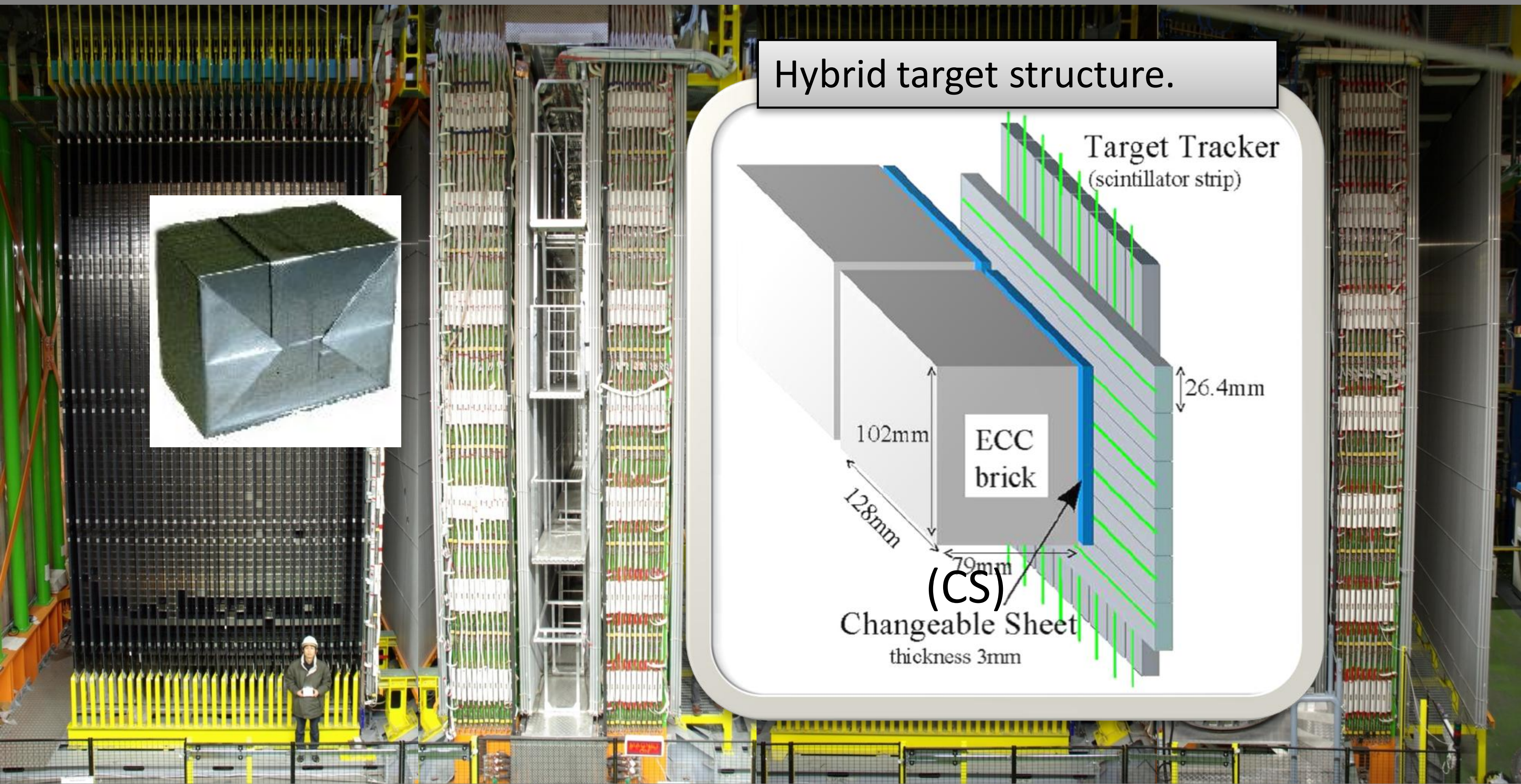
“Emulsion Cloud Chamber”



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

OPERA hybrid detector: **150000 bricks, 1.25 kT, 3100 m.w.e., 1 m/m2/h**

SM1 **SM2**



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

- Target : 77500 bricks, 29 walls
- Target tracker : 31 XY doublets of 256 scintillator strips

+ WLS fibres + multi-anodes PMT for
  - Vertex brick identification
  - Calorimetry

JINST 4 (2009) P04018

Muon spectrometer (8×10 *m*2)

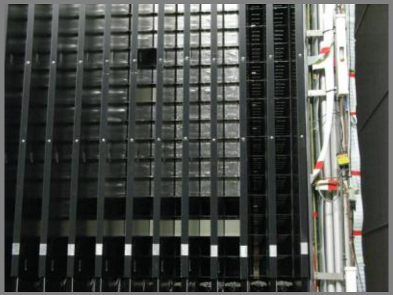
Instrumented dipole magnet

- 1.53 *T*
- 22 XY planes in both arms

High precision tracker

6 4-fold layers of drift tubes

OPERATIONS ON BRICKS



Waiting for neutrinos in the target…

Extracted by the Brick Manipulator System

X-ray exposure for alignment

Stored underground (waiting for the CS response)

Exposed to cosmic-rays for precision film alignment

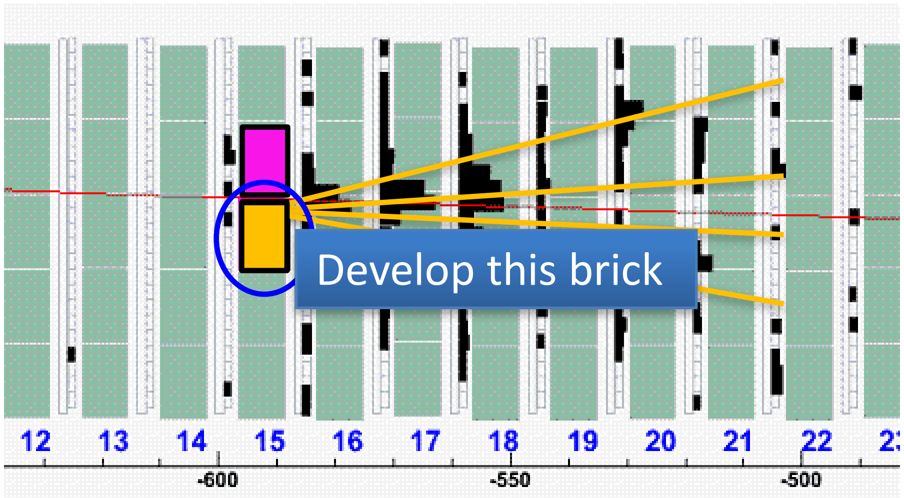
Films developed at surface

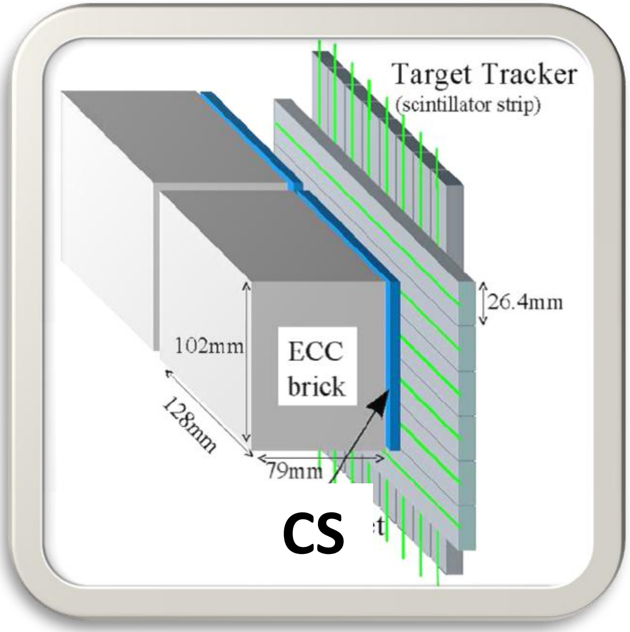
PARALLEL ANALYSIS OF BRICKS

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

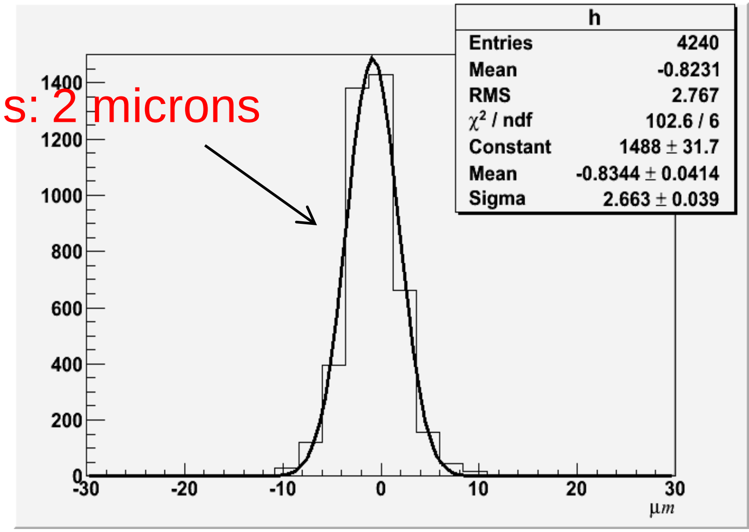
one of the brick scanning labs

BRICK VALIDATION BY THE CS





CS doublet alignment by Compton electrons: 2 microns



Scan only bricks containing neutrino interactions
(save analysis time, minimize the loss of target mass)

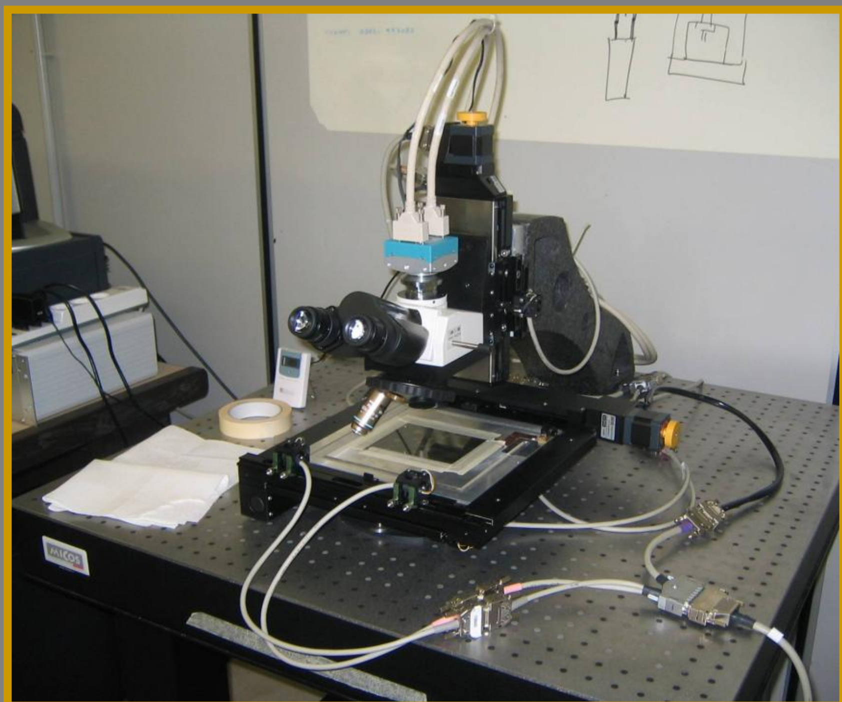
Scanning effort/event: CHORUS 1x1 mm^2
DONUT 5x5 mm^2
OPERA 100x100 mm^2

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

Emulsion scanning stations

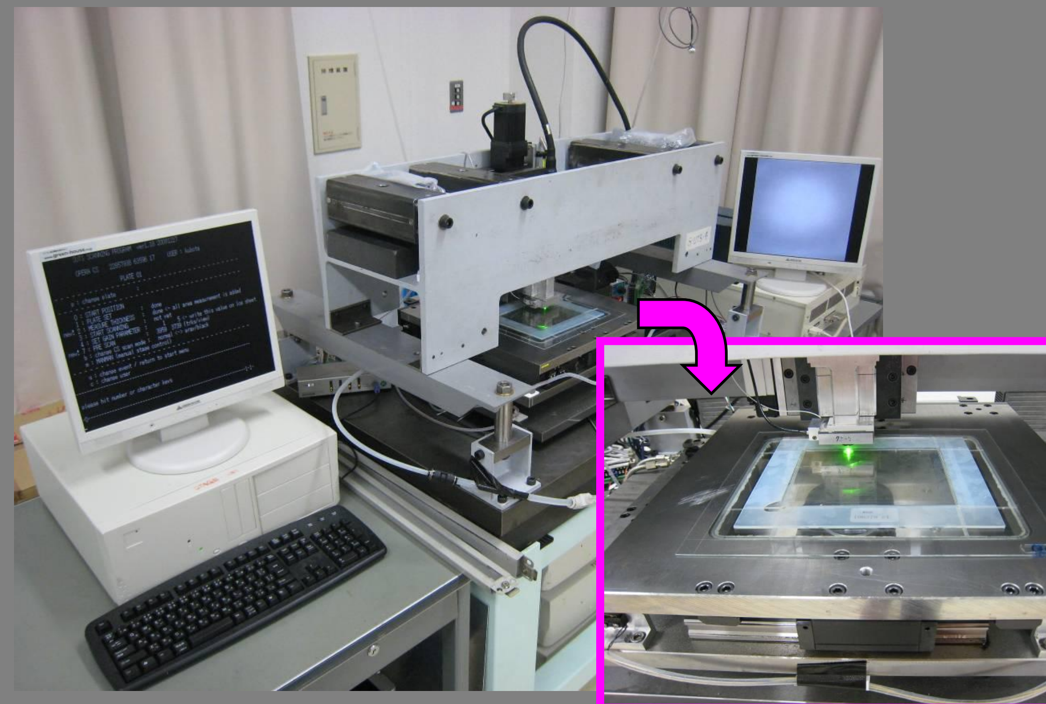
extract 3-D tracking information from emulsions

EU: ESS
(European Scanning System)



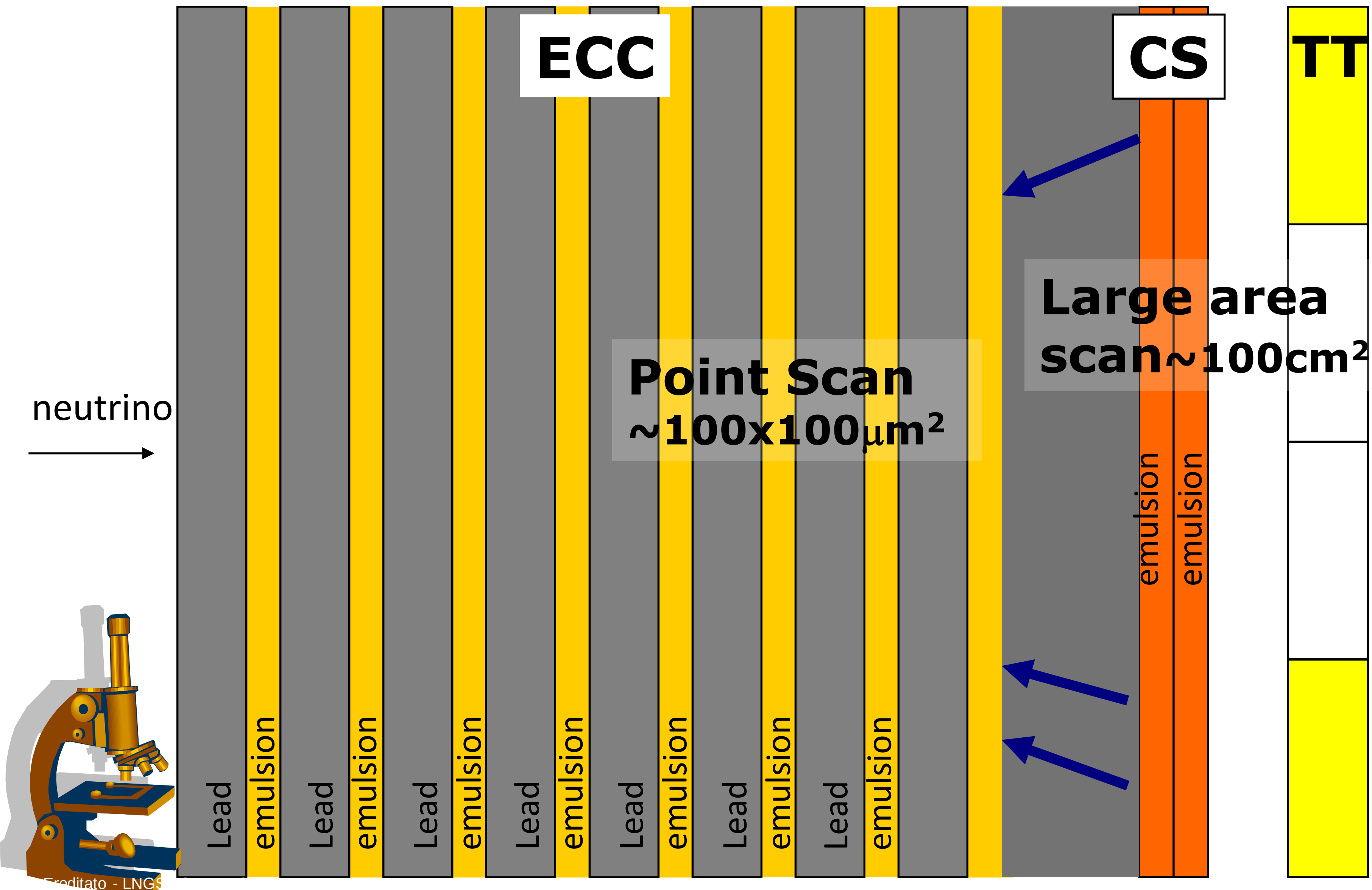
- **Scanning speed/system: 20cm^2/h**
- **Customized commercial optics and mechanics**
- **Asynchronous DAQ software**

Japan: SUTS
(Super Ultra Track Selector)

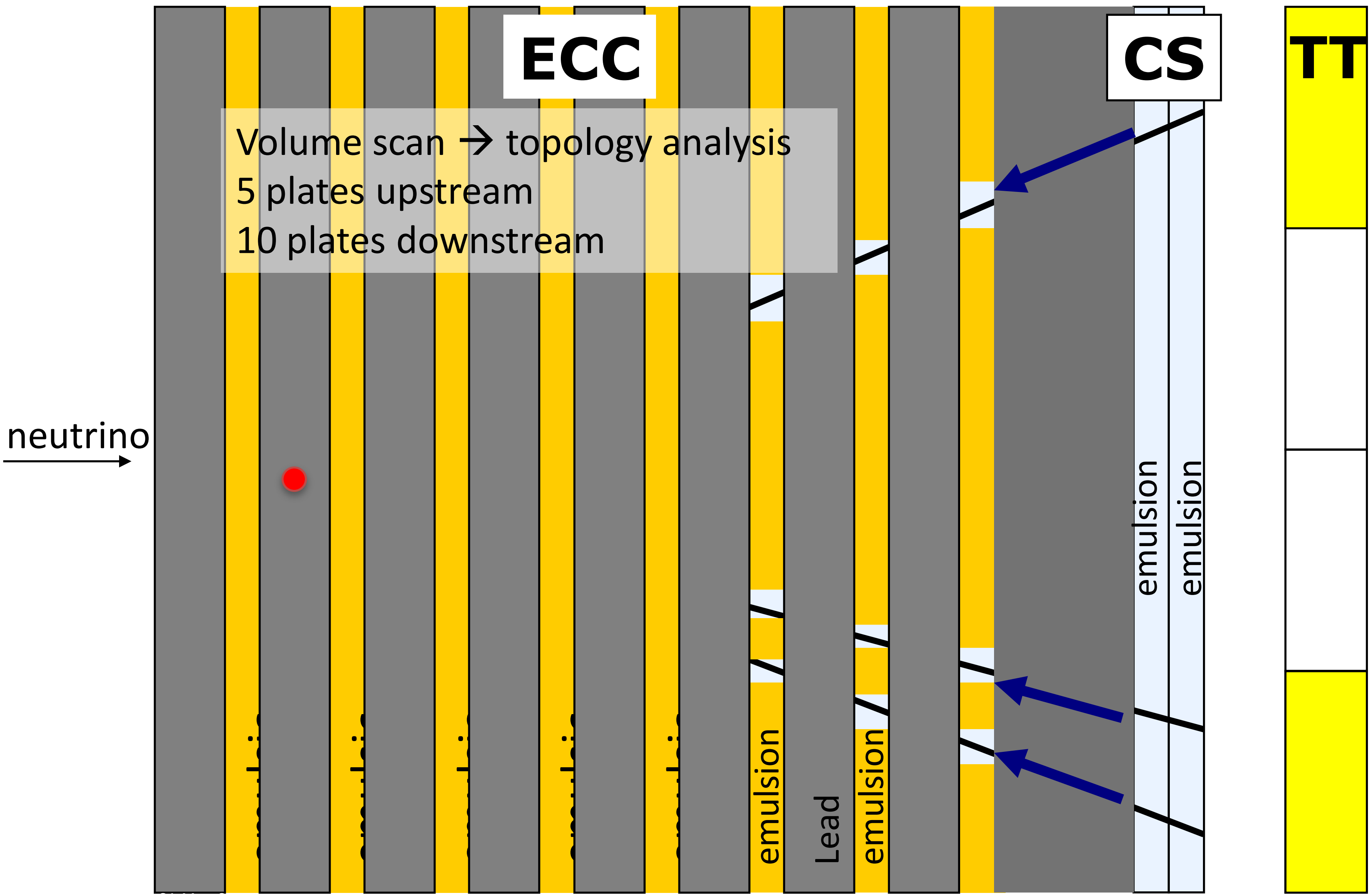


- **Scanning speed/system: 75cm^2/h**
- **High speed CCD camera (3 kHz), Piezo-controlled objective lens**
- **FPGA Hard-coded algorithms**

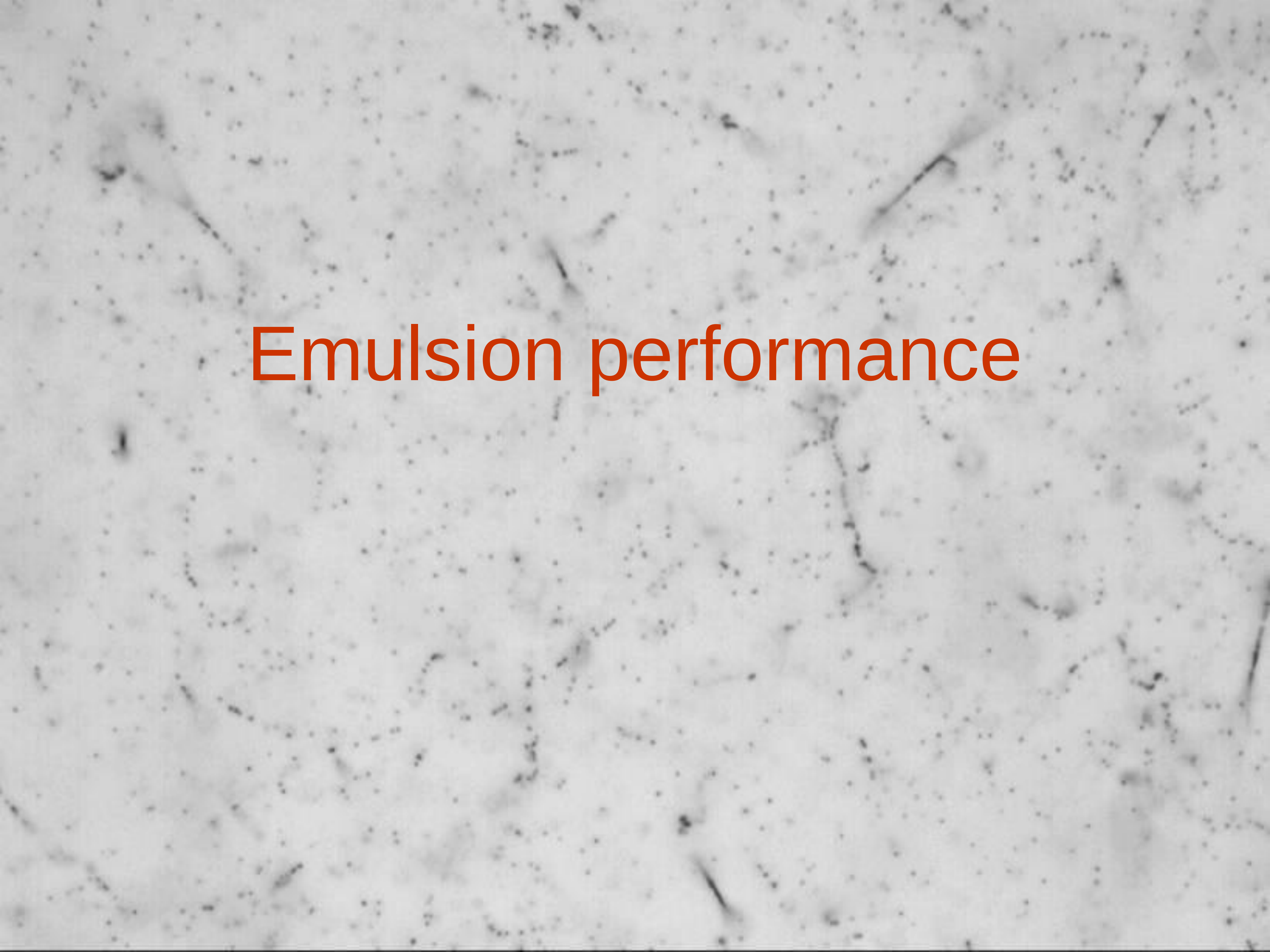
Vertex location procedure



Volume Scan

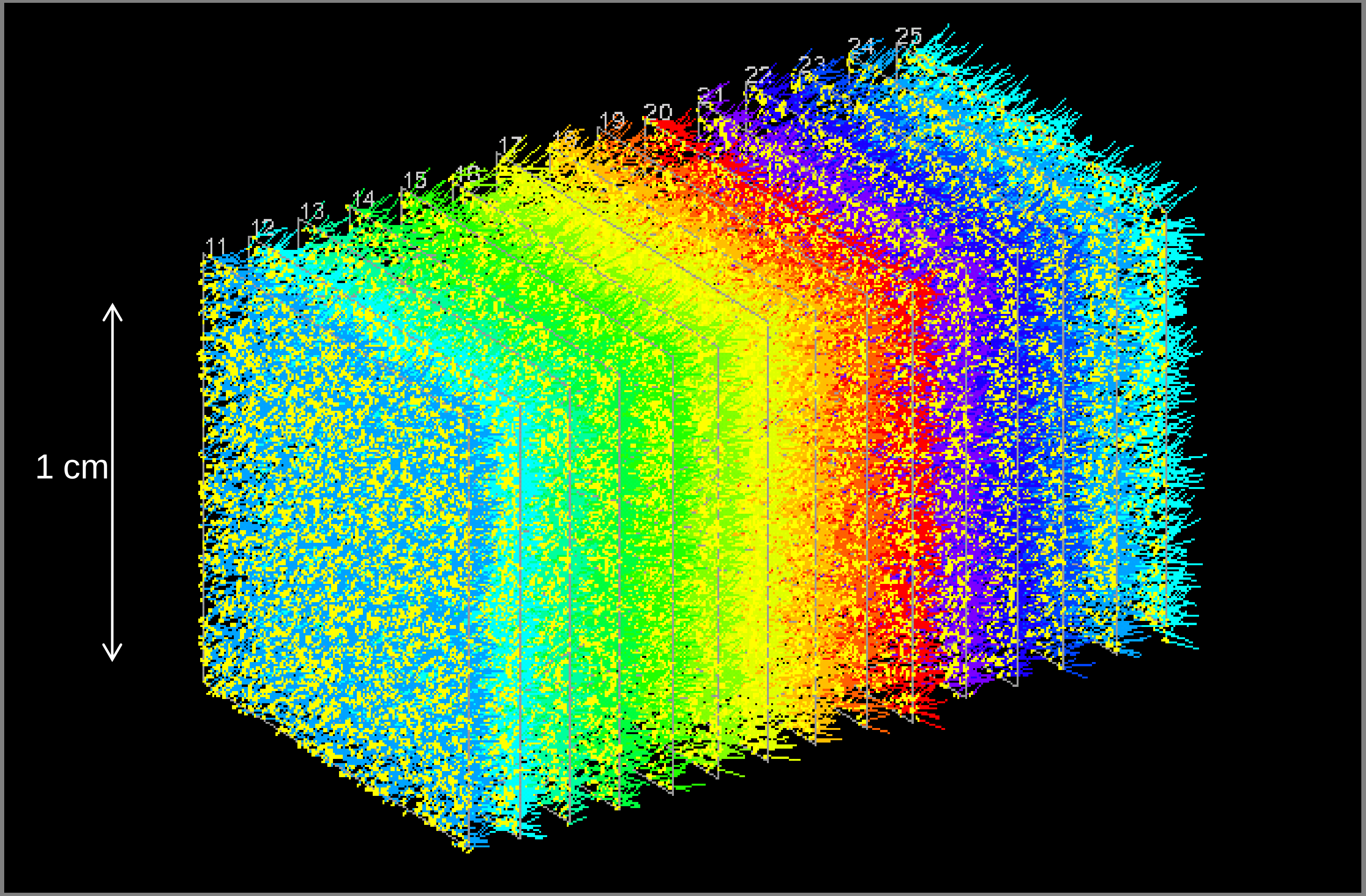

ECC
CS
TT
Volume scan → topology analysis
5 plates upstream
10 plates downstream
neutrino
emulsion
Lead
emulsion
emulsion
emulsion

Emulsion performance

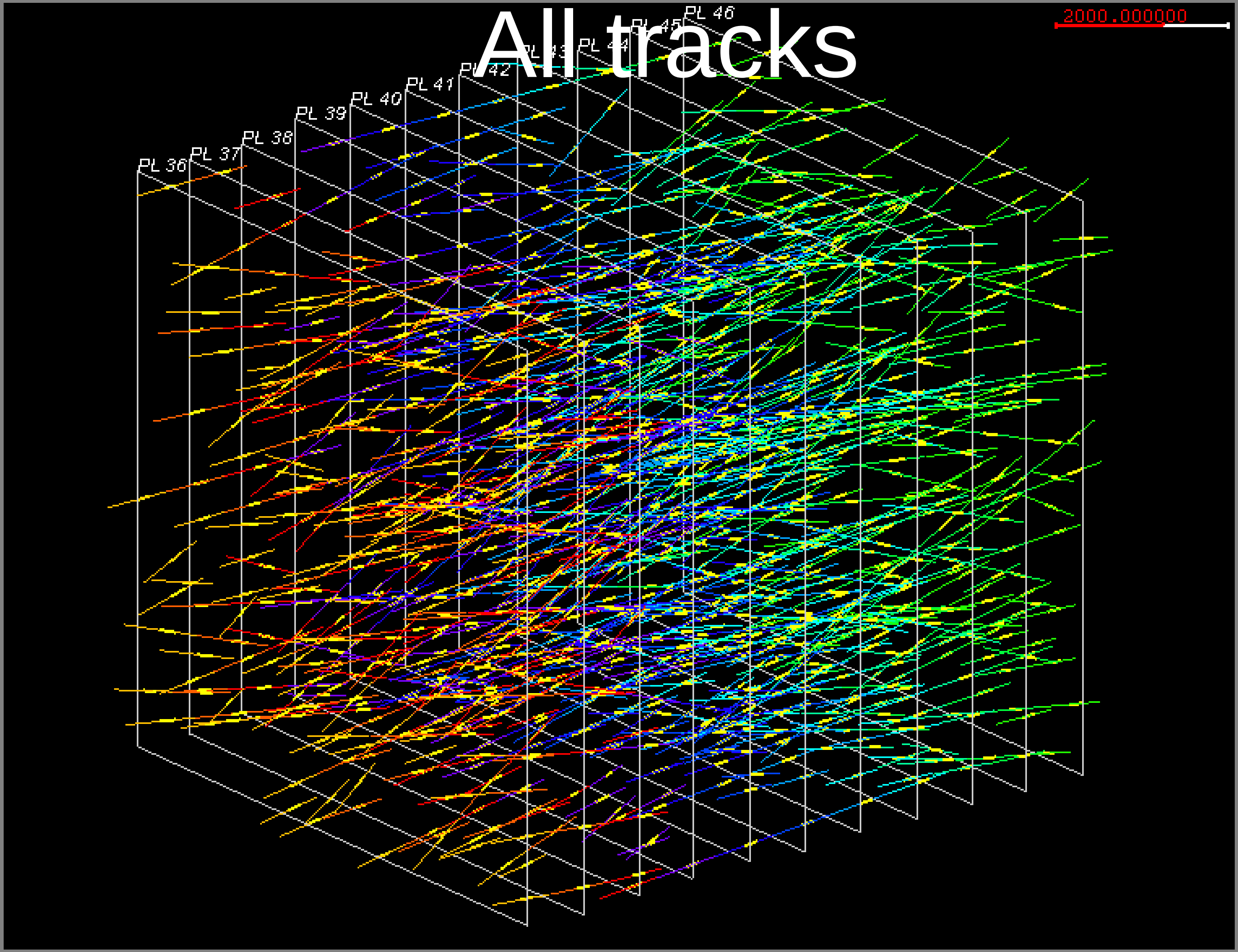


Emulsions give 3D vector data, with micrometric precision of the vertexing accuracy.

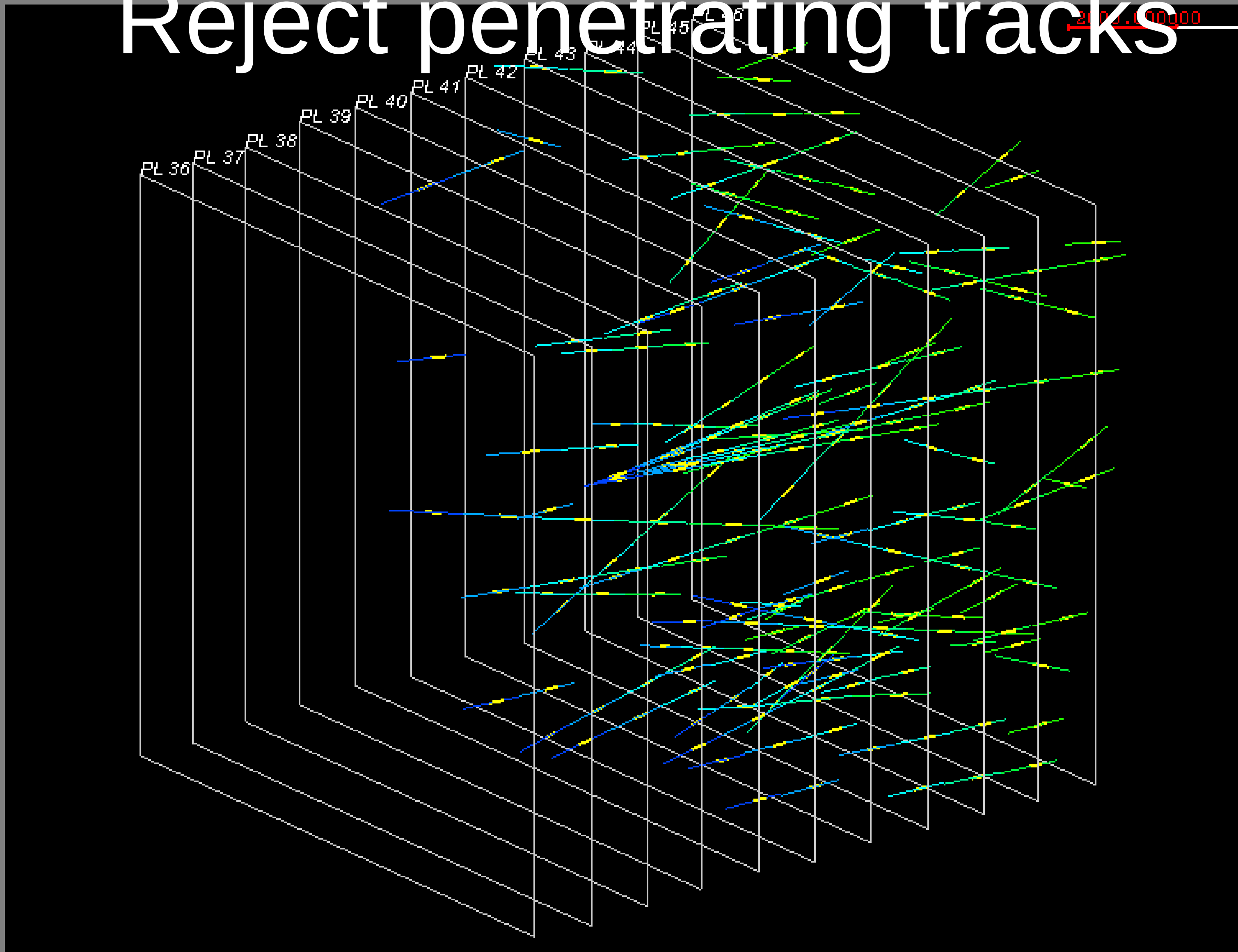
The frames correspond to the scanning area. Yellow short lines → measured tracks.
Other colored lines → interpolation or extrapolation.



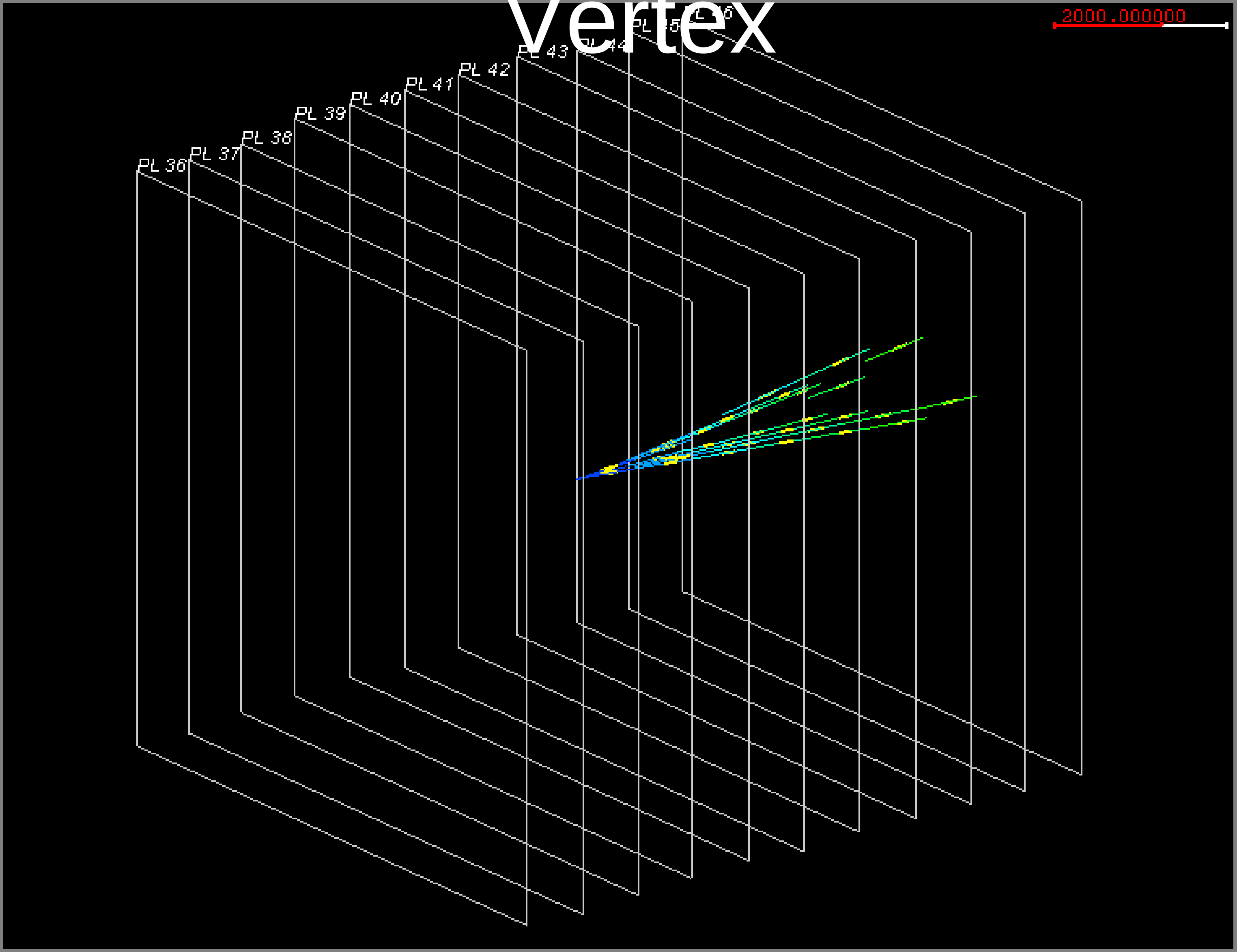
All tracks



Reject penetrating tracks

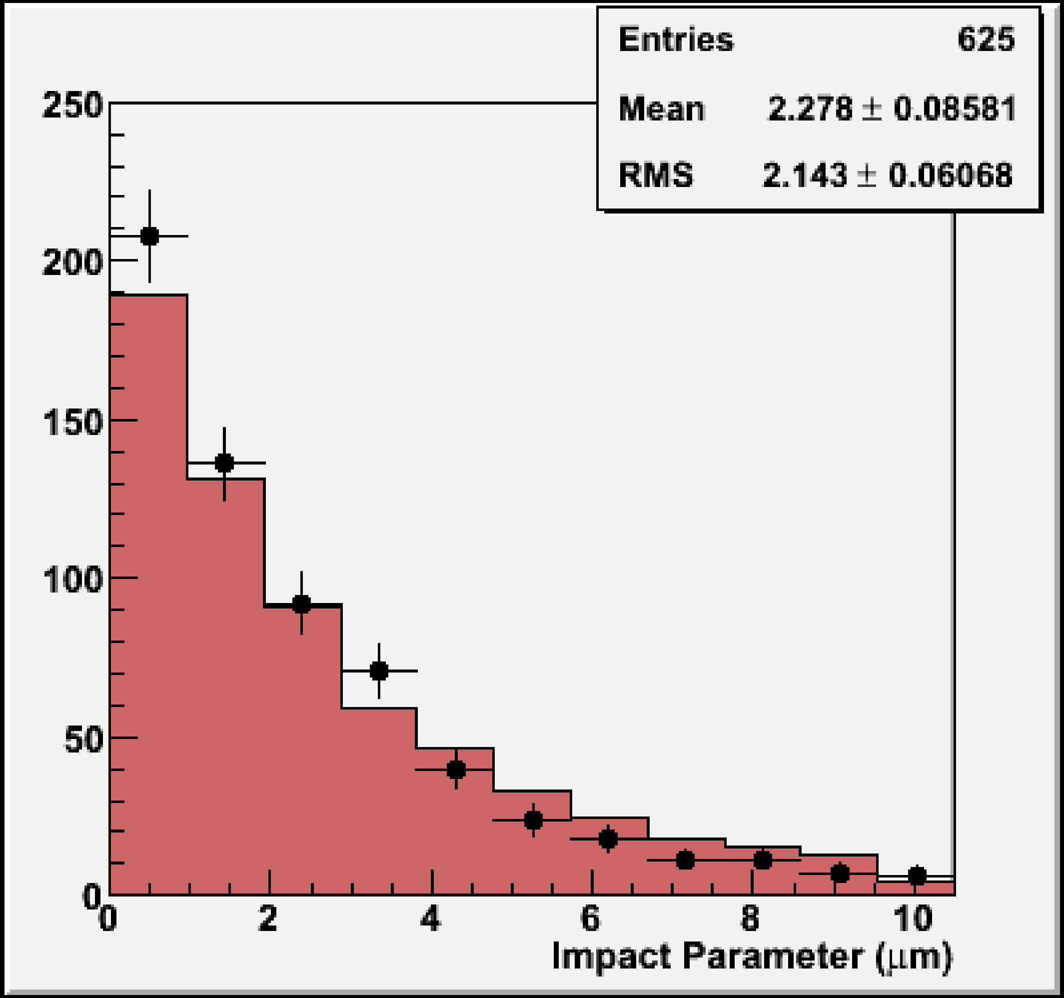


Vertex



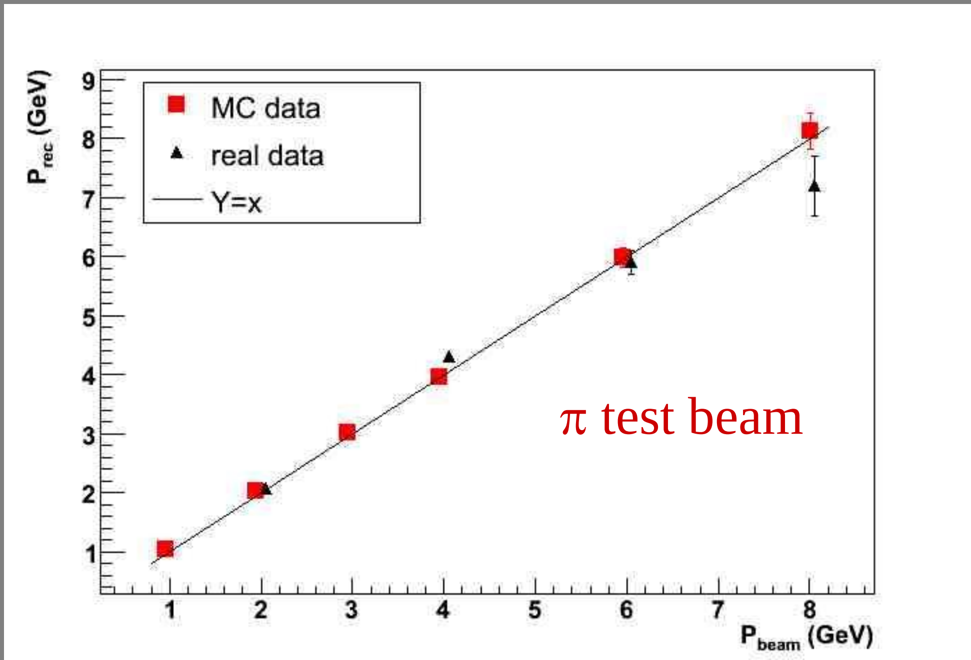
Impact parameter measurement

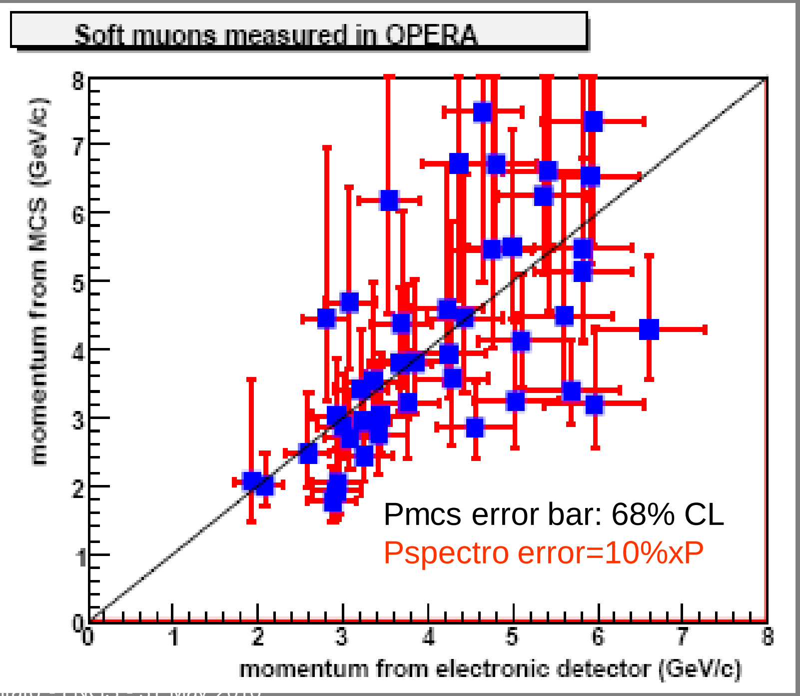
NC+CC event tracks from primary vertices (DATA vs MC)

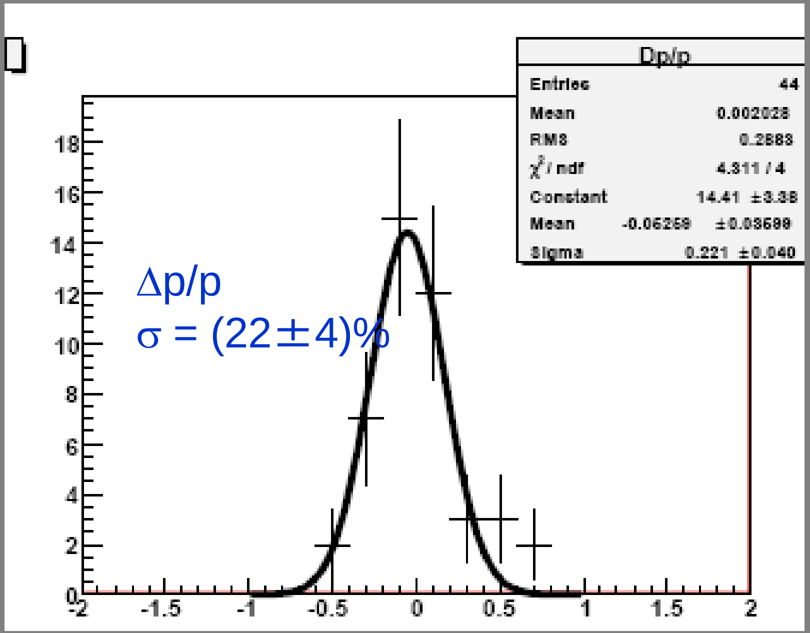


Momentum measurement by Multiple Coulomb Scattering…

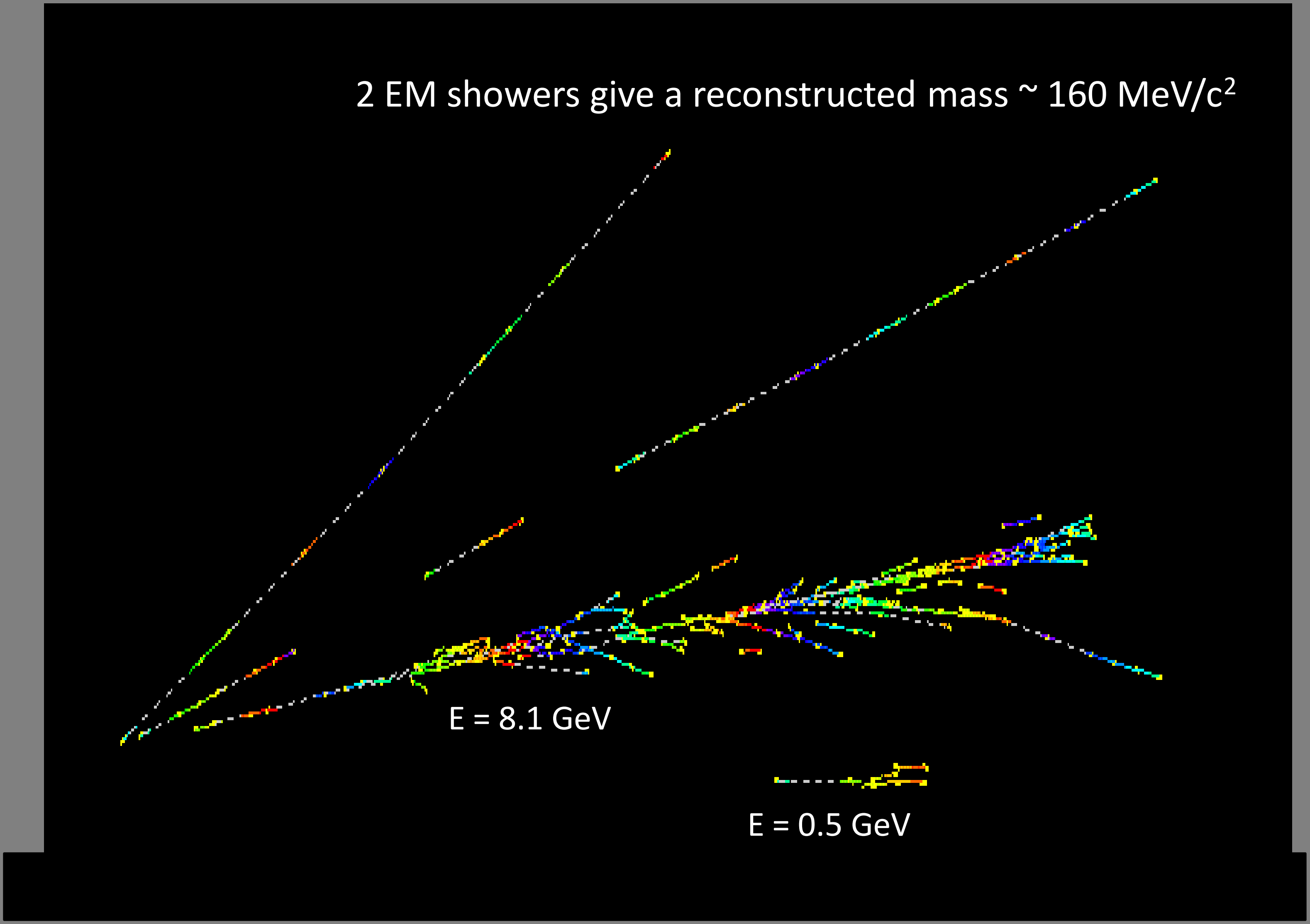
…in the lead/emulsion film sandwich and comparison with electronic detectors' measurements





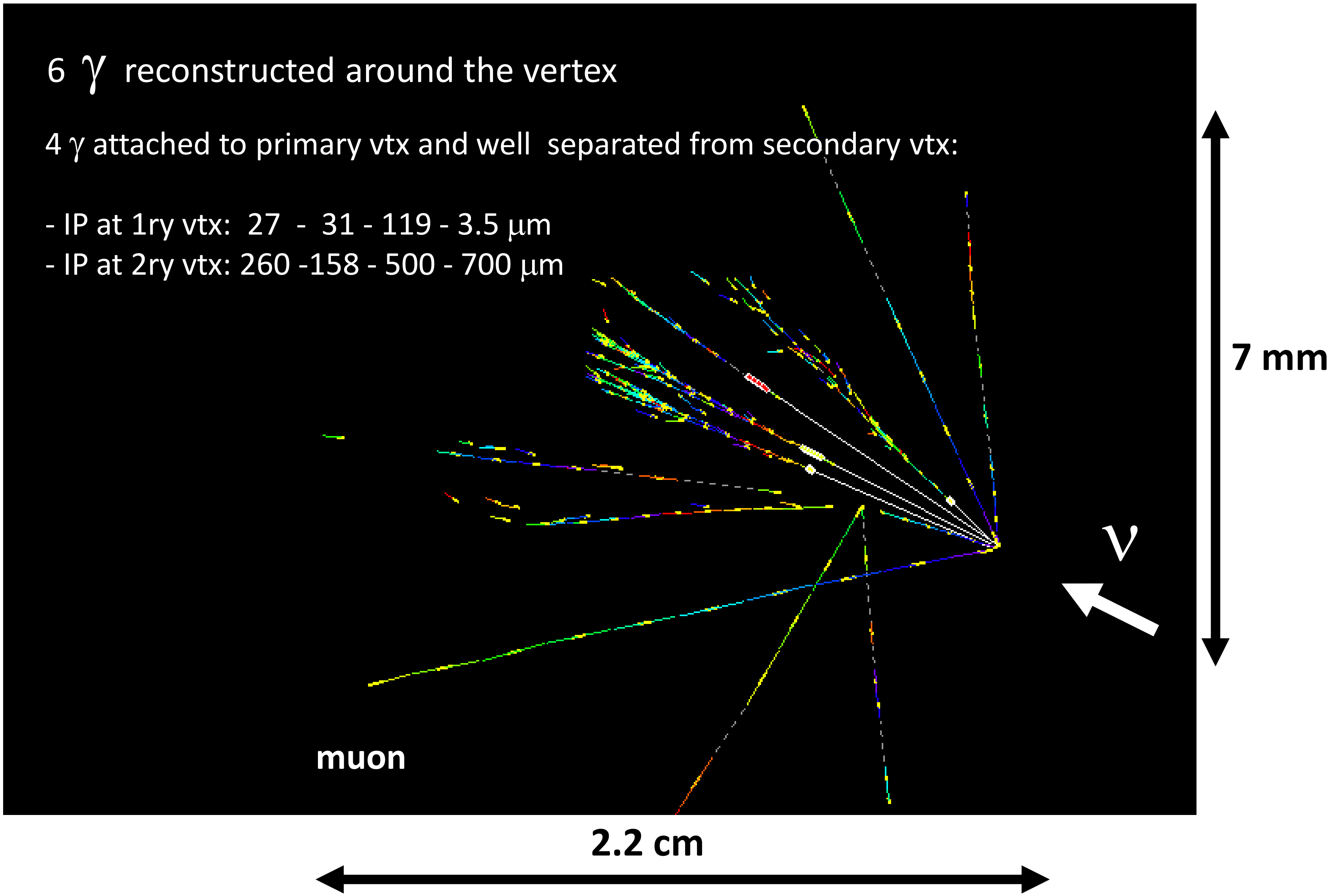


Gamma detection and π^0 mass reconstruction

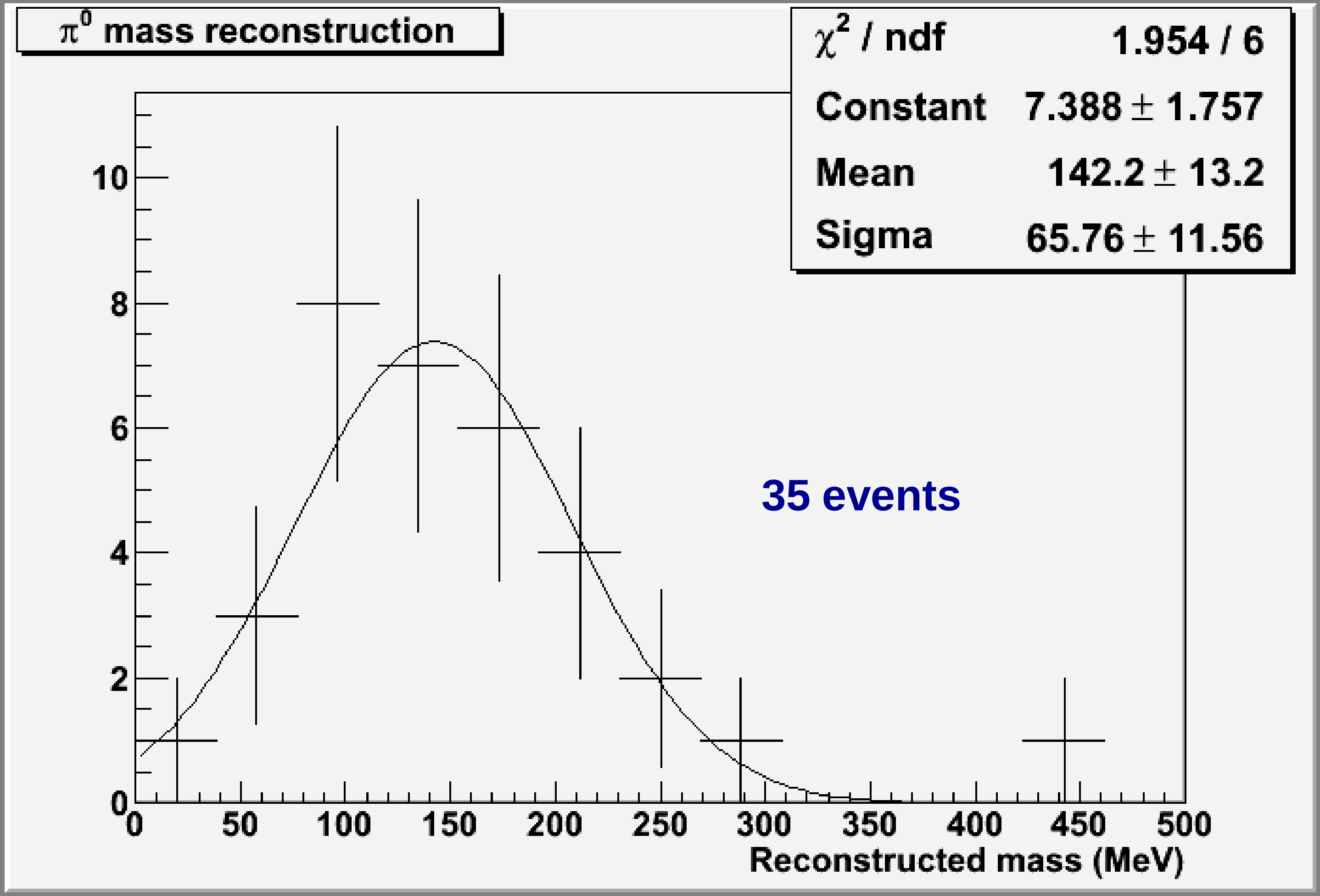


EM shower energy measured by a Neural Network algorithm

Example of Gamma to vertex attachment



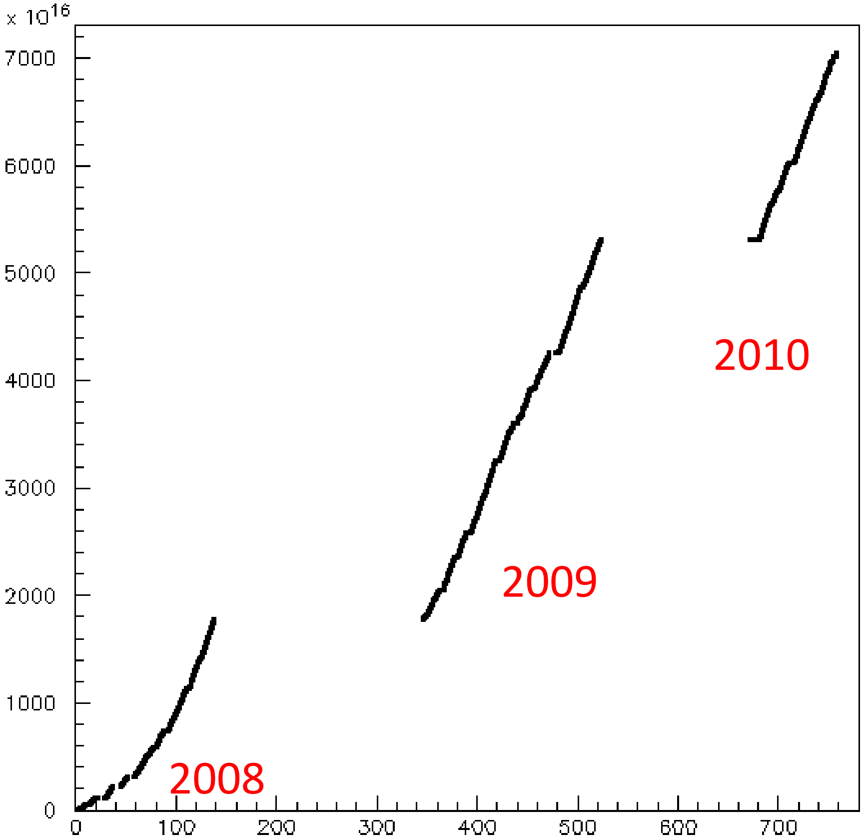
π^0 mass resolution (real data)



mass resolution: ~45%

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	**1.74×10^{19} pot (19 July)**	**1856 ev.**	**Physics run**



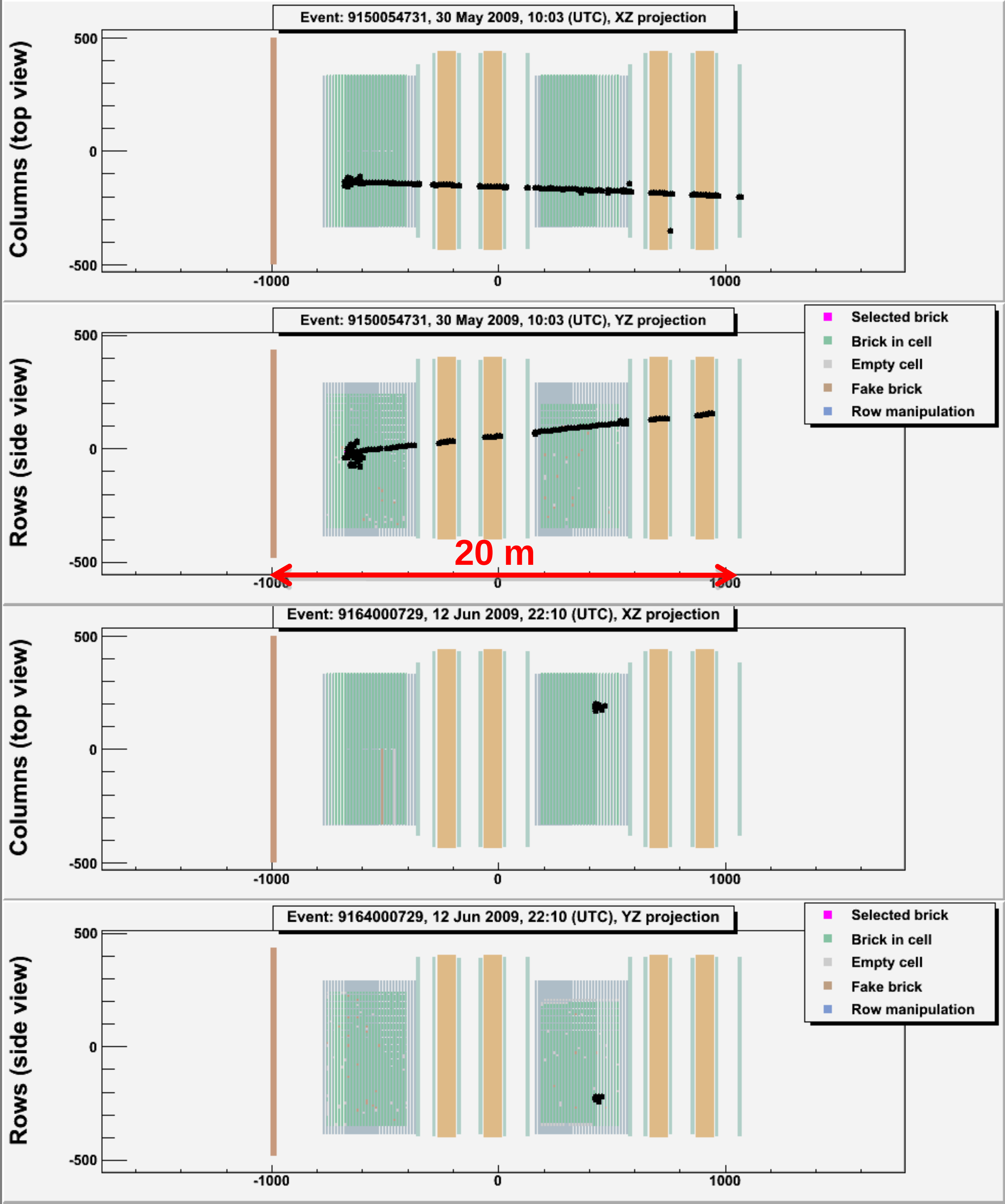
Improving features, high CNGS efficiency (97% in 2008-2009)

2010: close to nominal year;

Aim at high-intensity runs in 2011 and 2012

Typical ν_μ CC- and NC-like events

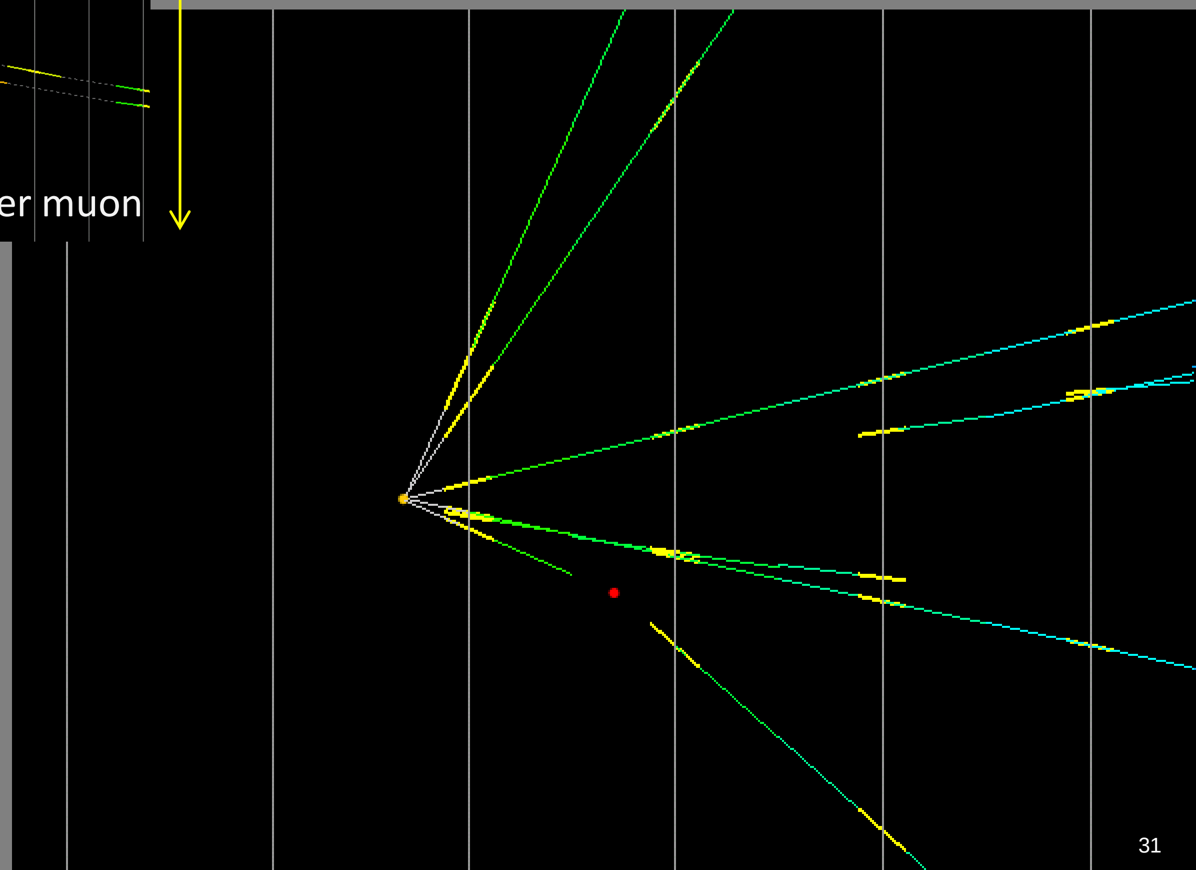
The measured ratio of NC-like/CC-like events after muon ID and event location is ~20%, as expected from simulations



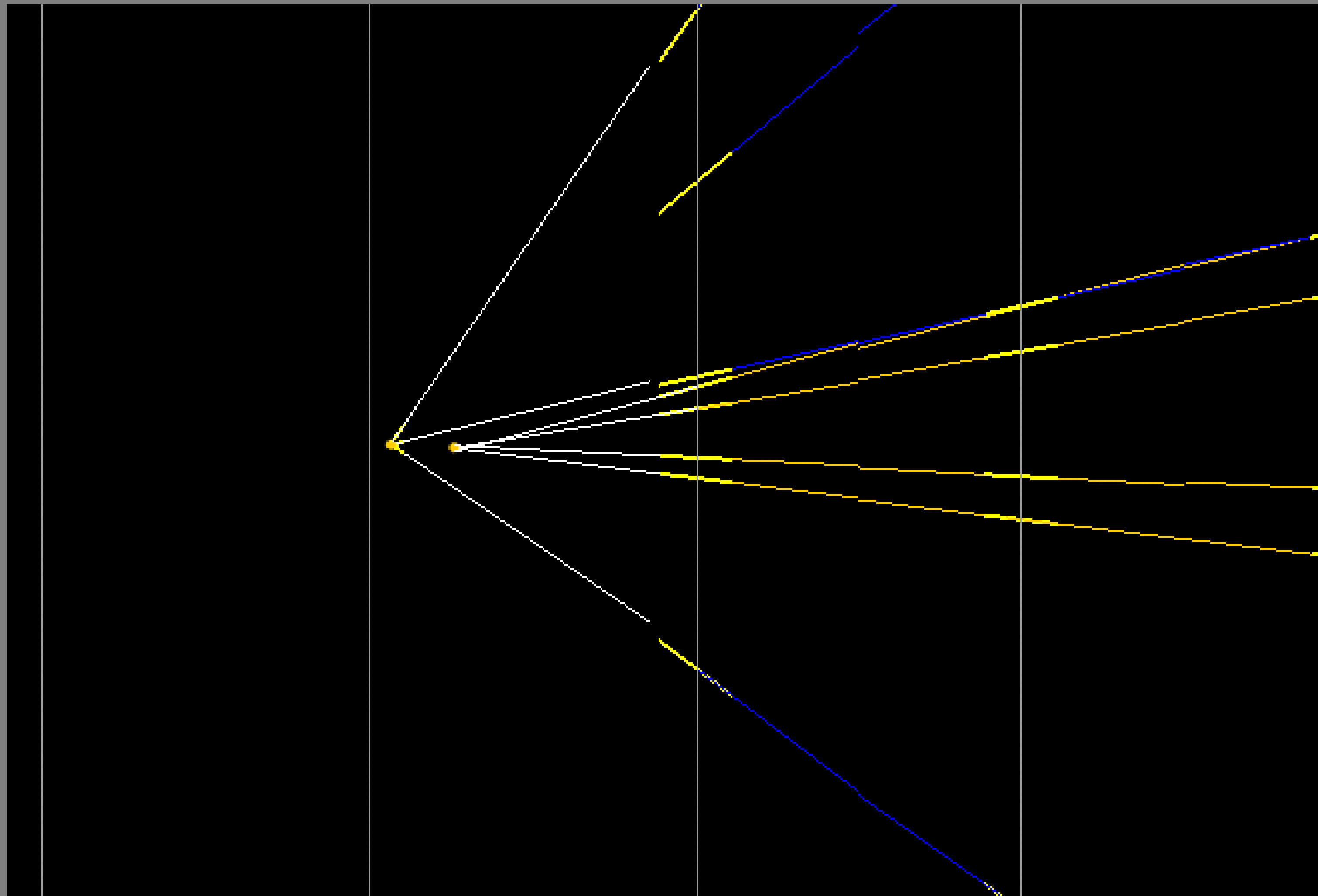
CHARM EVENTS

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

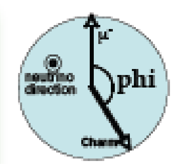


Charm candidate event (4-prong)



D^0

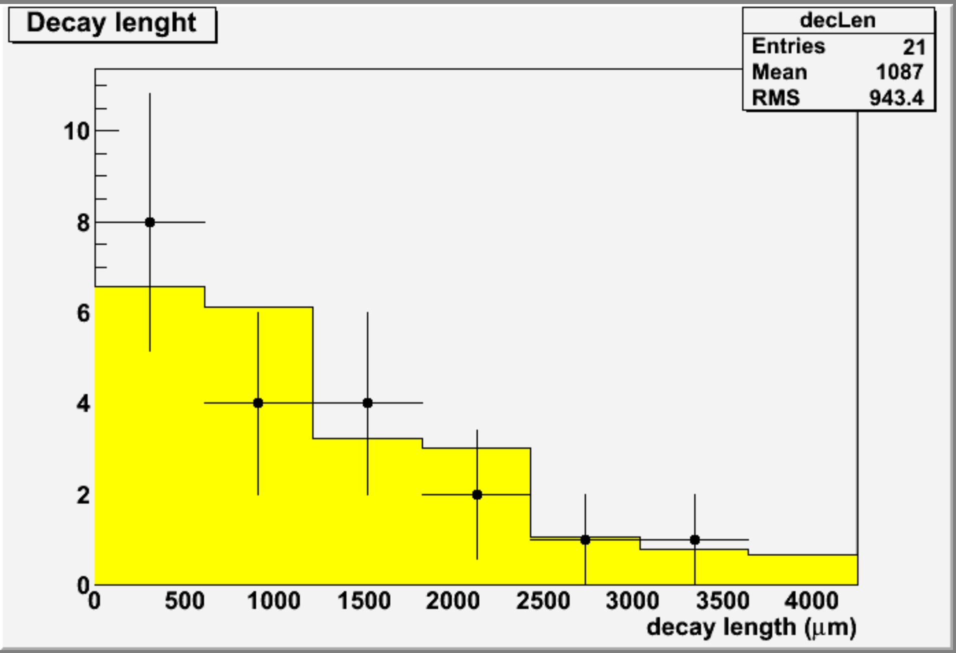
Tx	Ty	Flight Length (μm)	phi	minimum mass (GeV/c²)
-0,0207	0,0198	313,1	173,2°	1,7

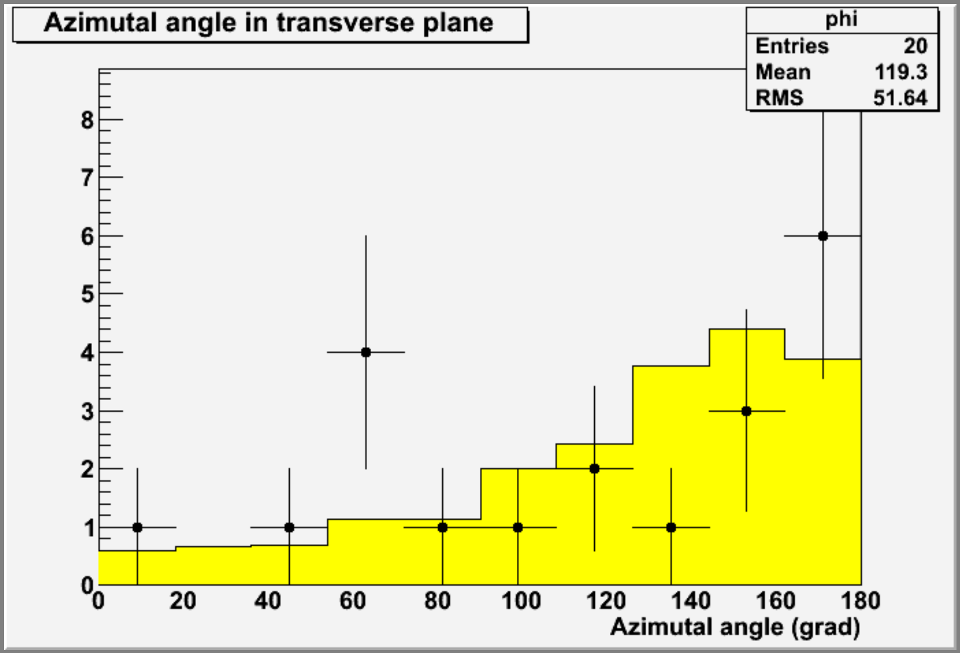


21 charm candidate events selected with kinematical cuts, 3 of them with 1-prong “kink” topology

Expected: 21.8 out of which 1.2 with kink topology

Examples of distributions:



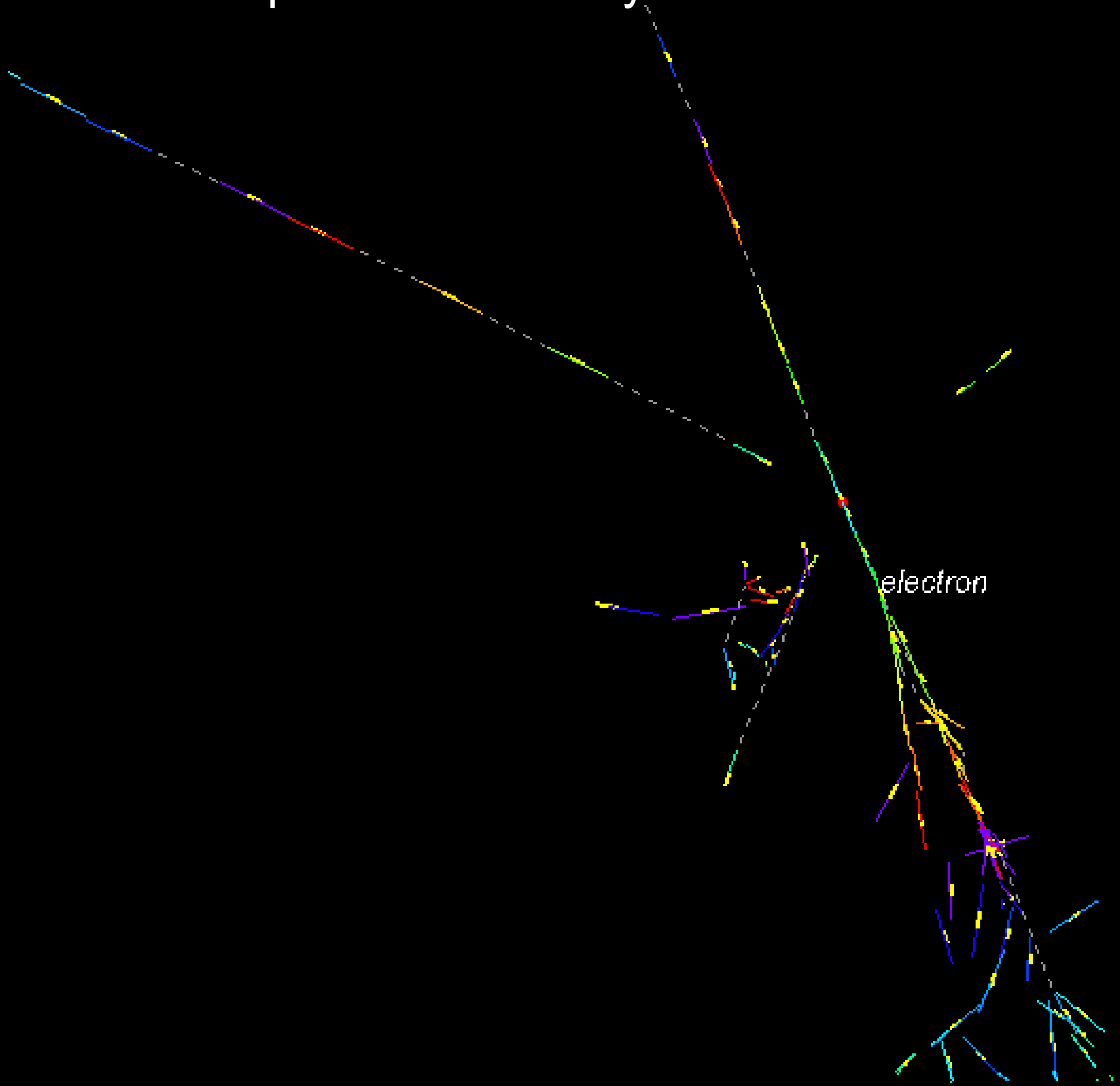


OTHER SPECIAL EVENTS

ν_e candidate event

For a subsample of 773 “decay-searched” events:

expected 6.2
detected 6



Event statistics

Events collected by 2008-2009 run 5391

Brick tagging efficiency times vertex location efficiency: ~ 60%

Total found neutrino vertices: 1921

This is ~60% of the total 2008-2009 run statistics .

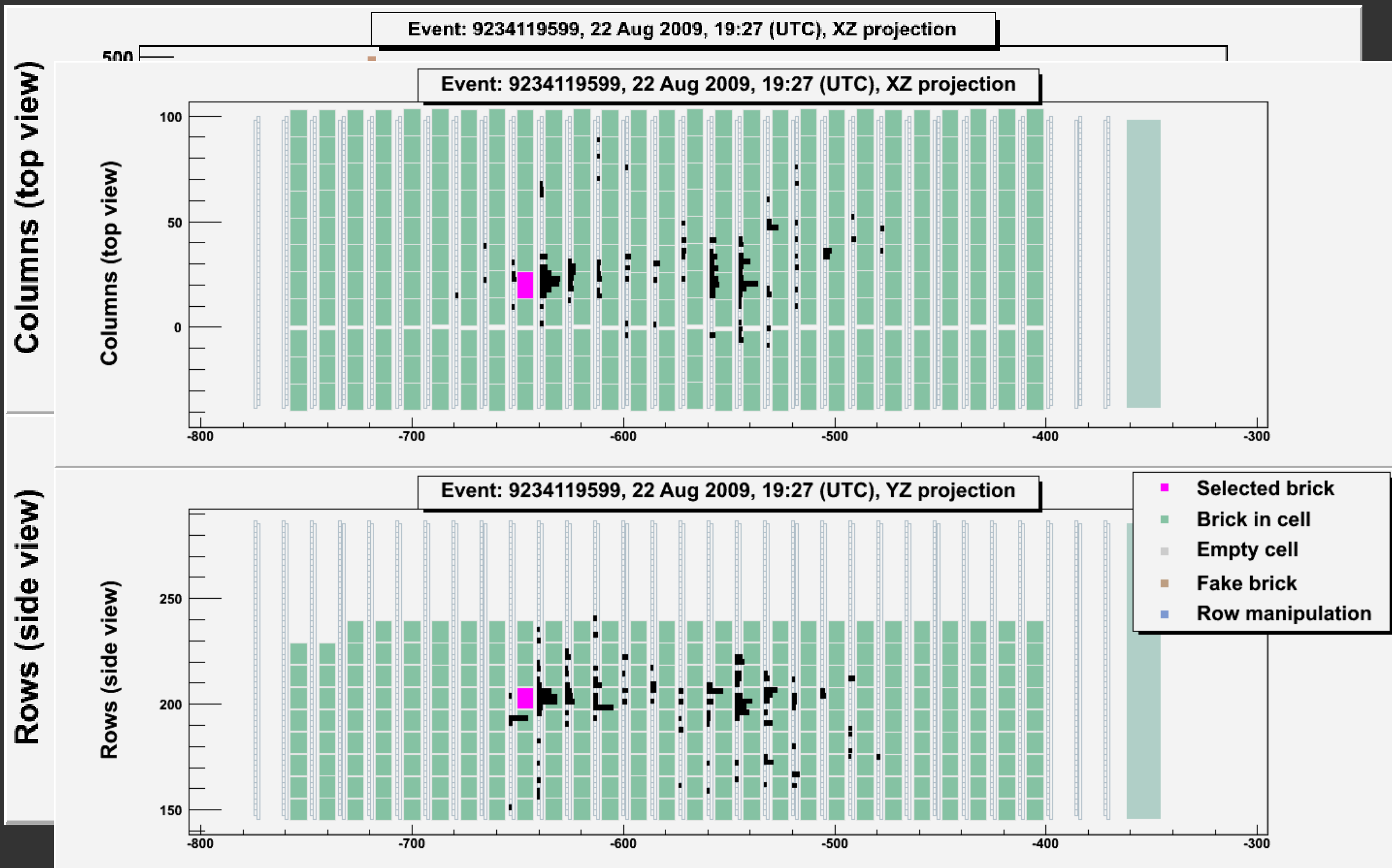
Events for which "decay search" was completed: 1088 (187 NC)

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:

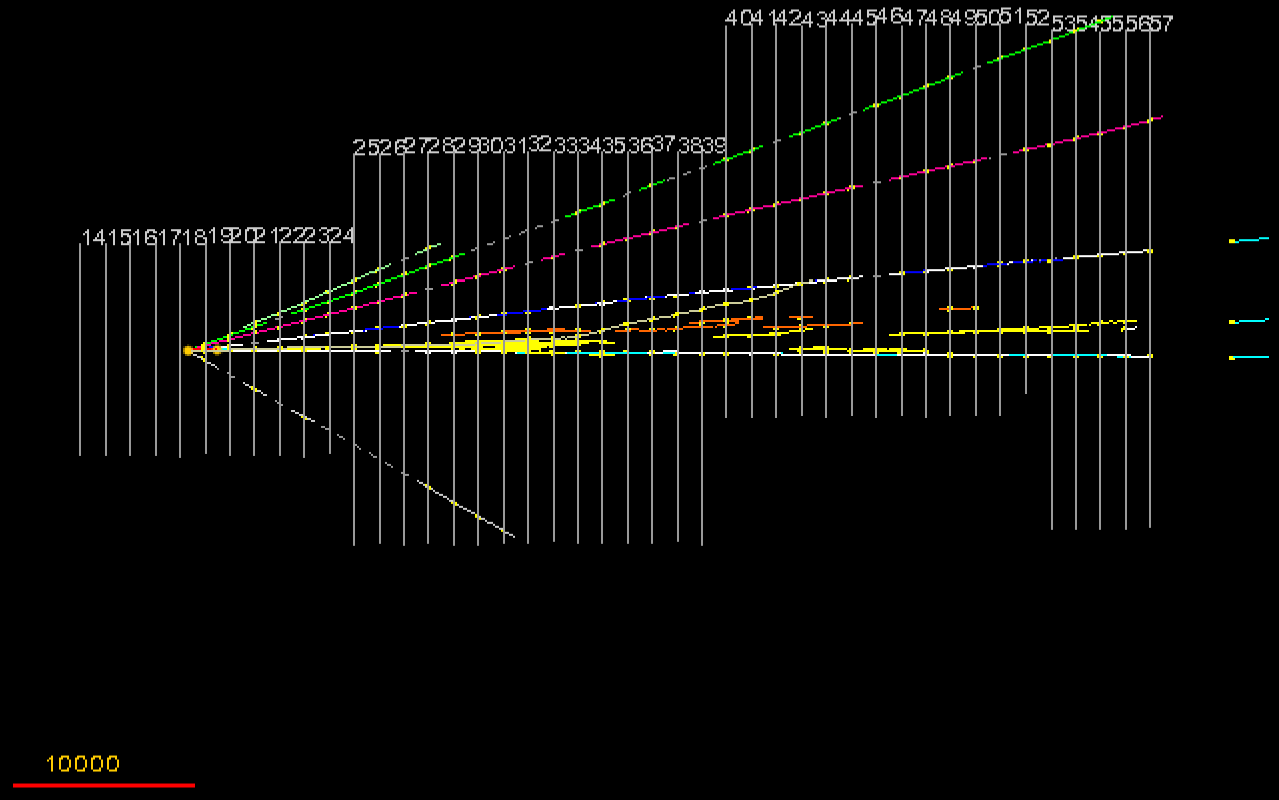
~ 0.5 ν_τ events

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

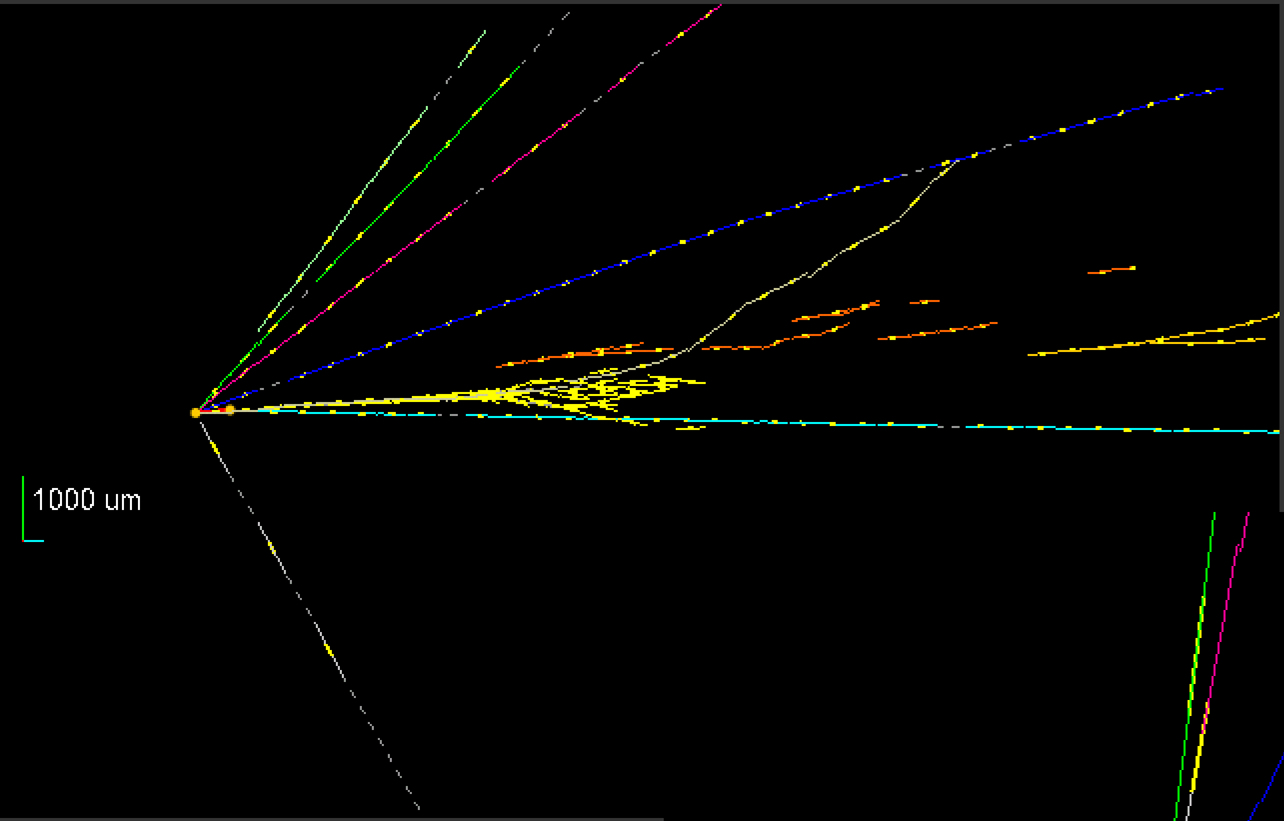


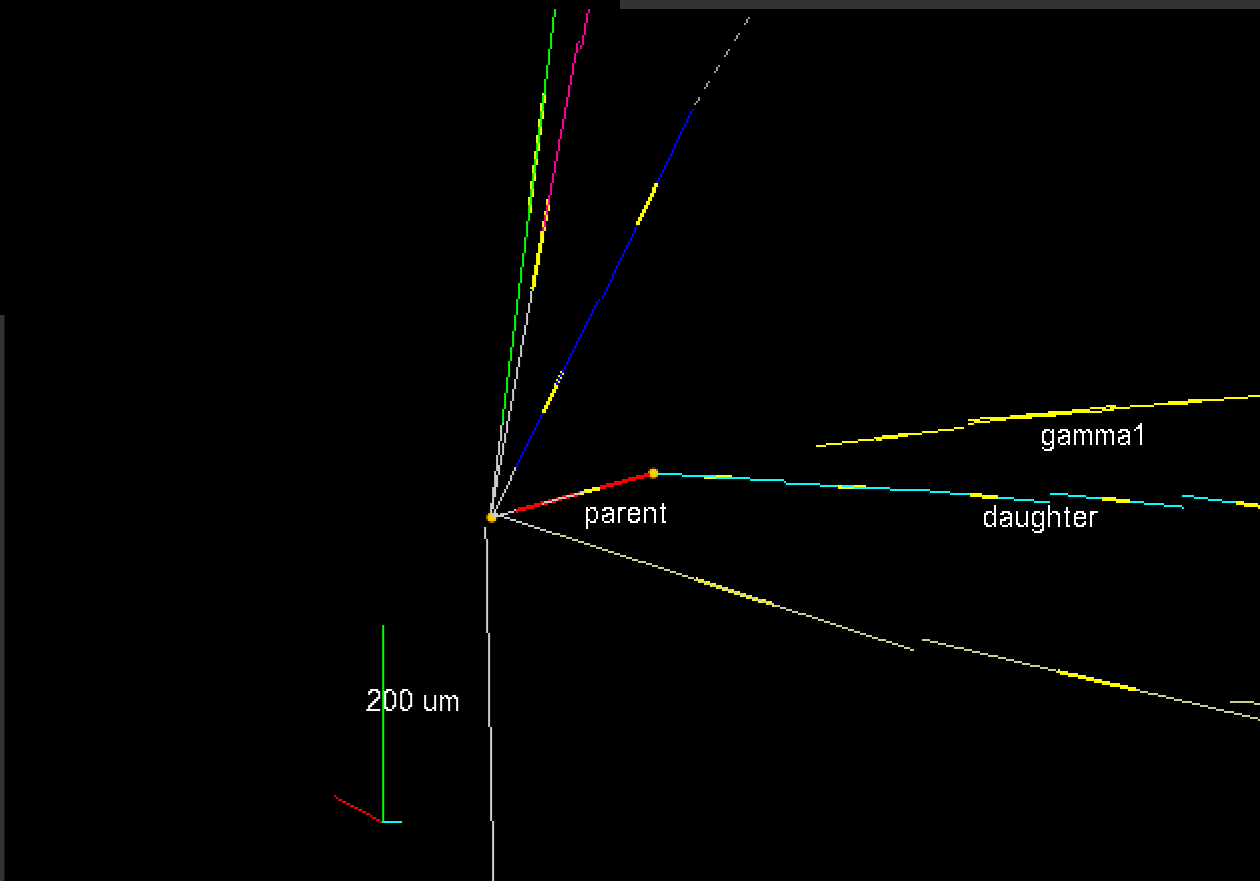
FROM CS TO VERTEX LOCATION

Large area scanning
Full reconstruction of vertices and gammas

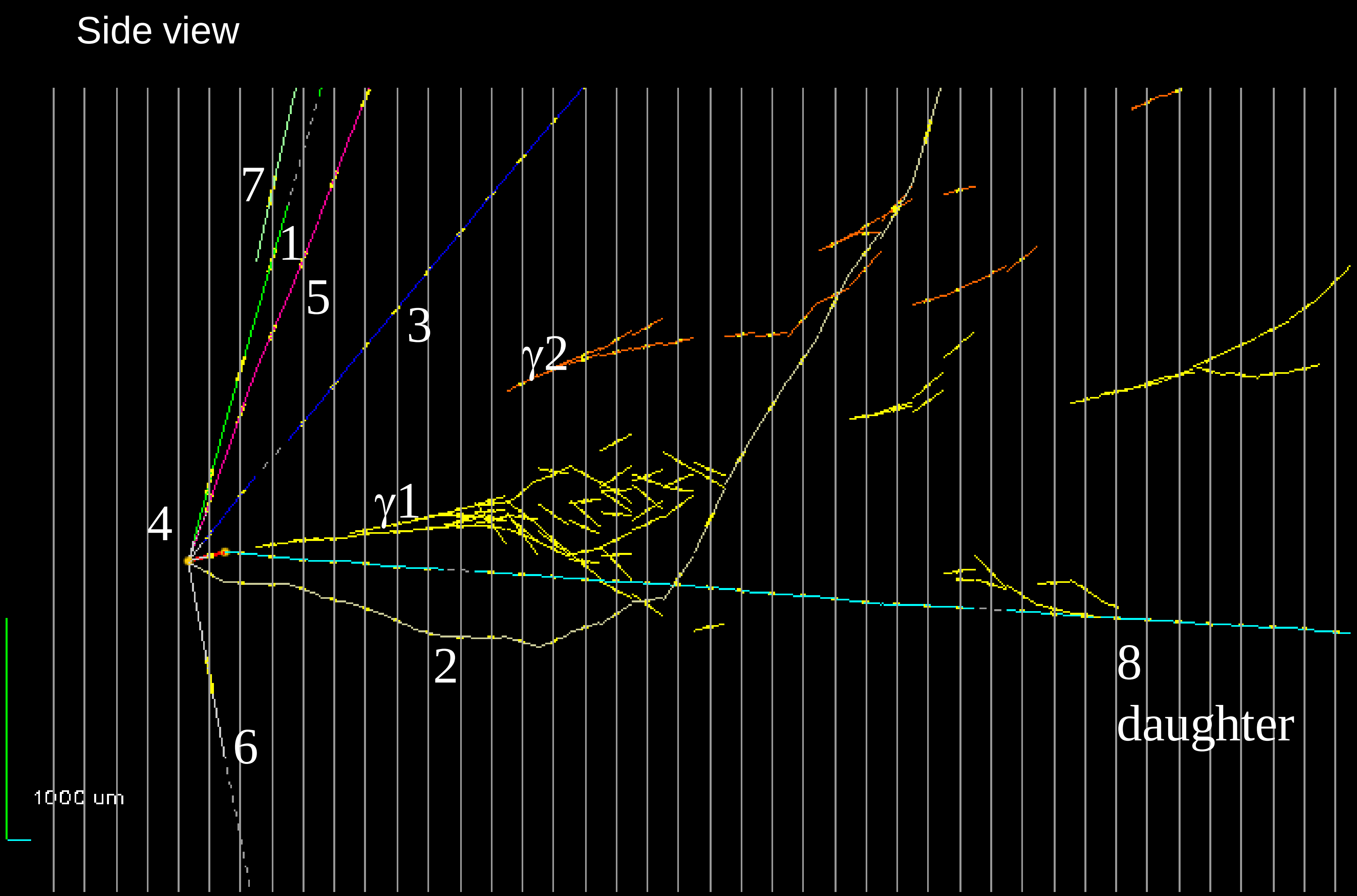


Event reconstruction

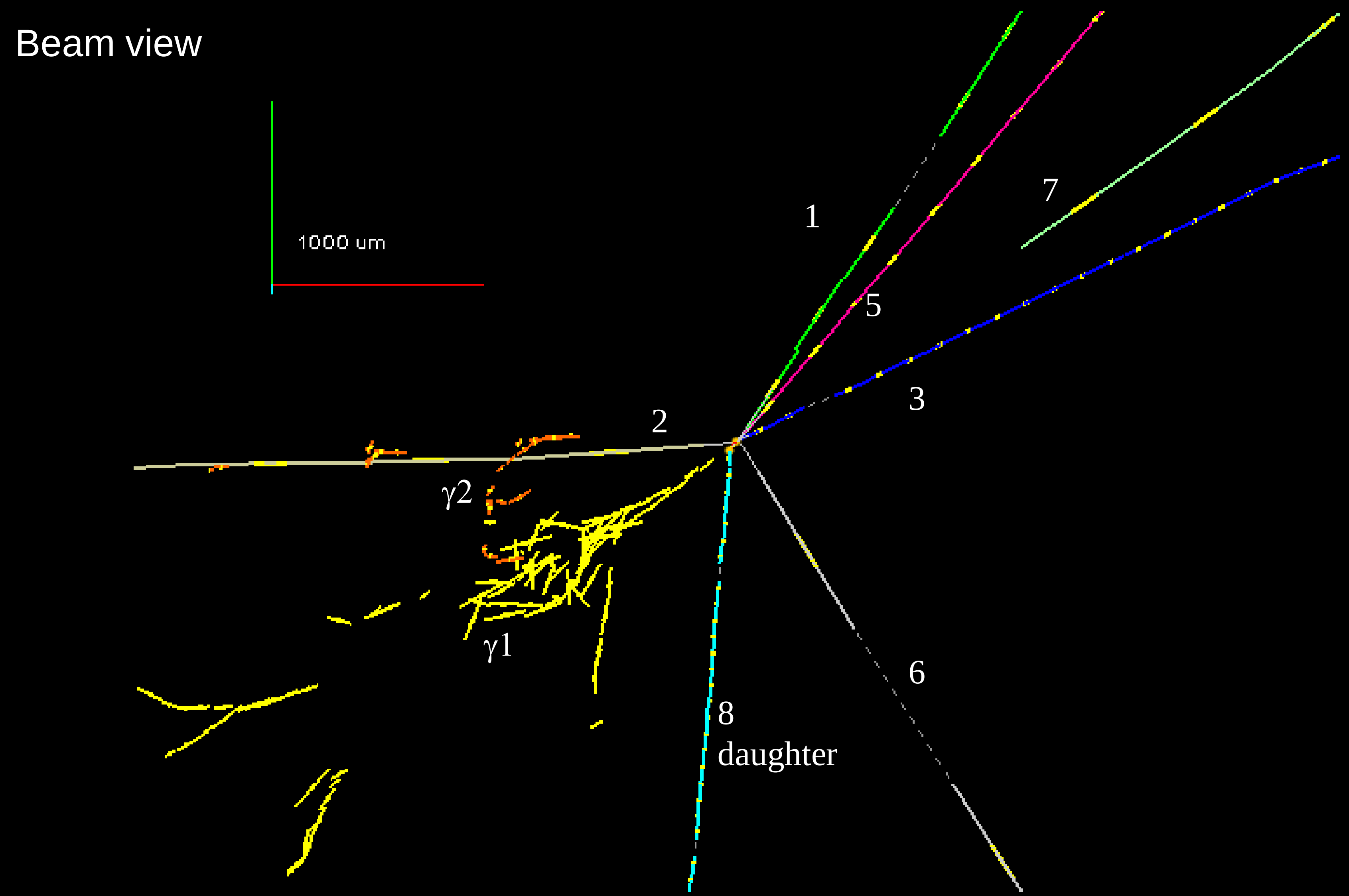




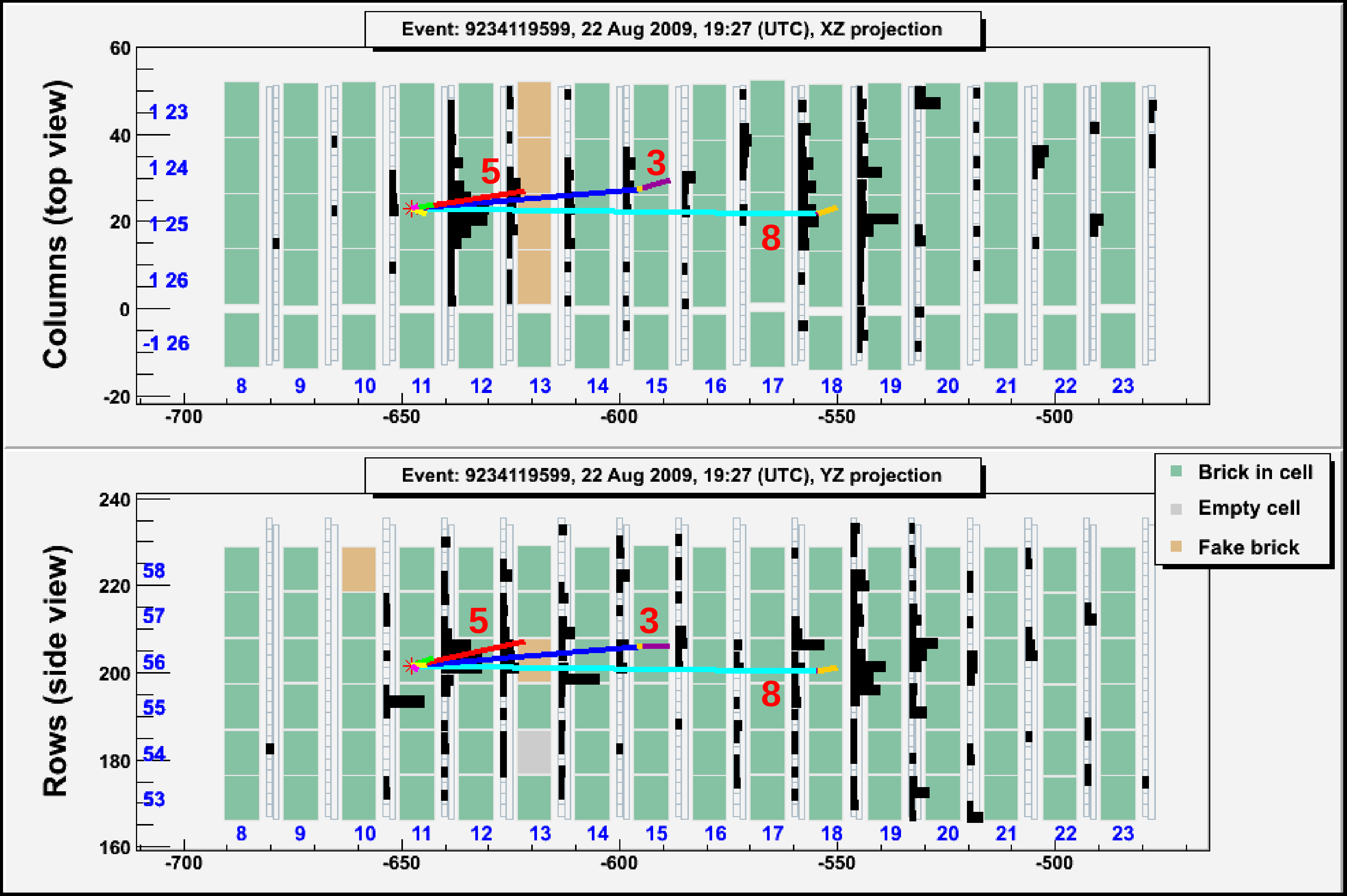
Event topological features (side view)



Event topological features (Beam view)



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**



Event tracks' features

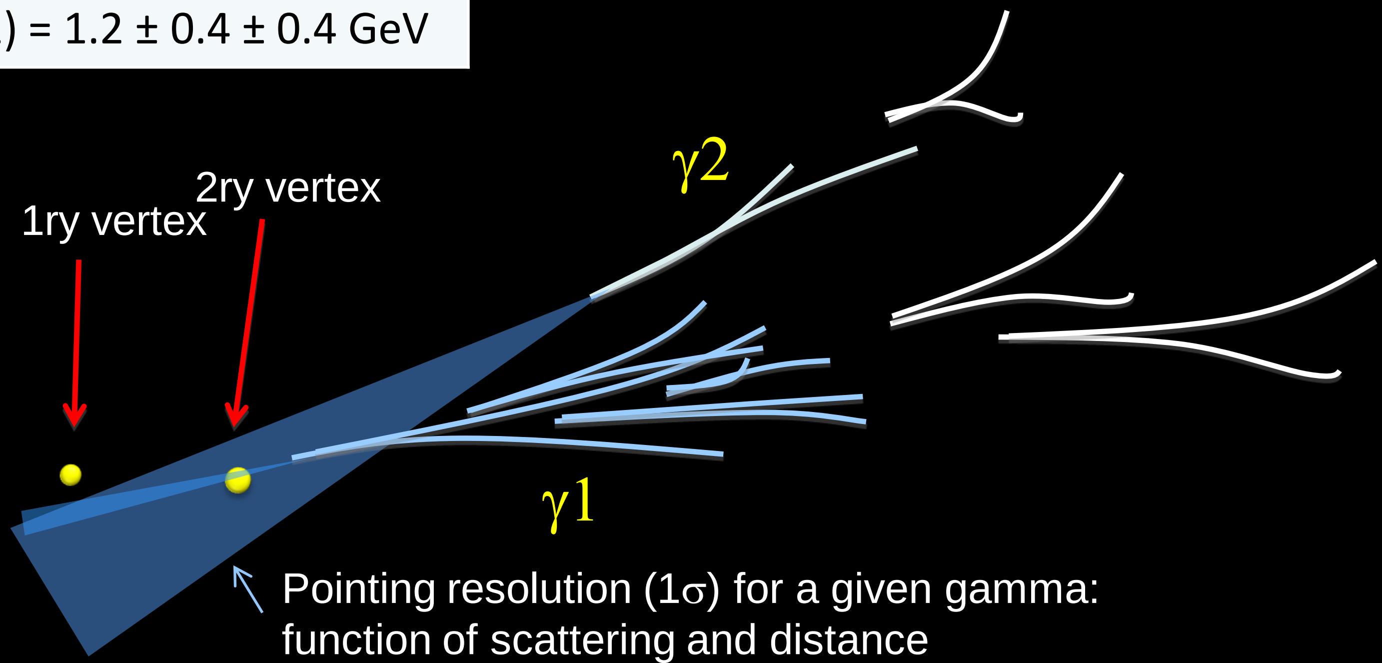
TRACK NUMBER	PID	Probability	MEASUREMENT 1			MEASUREMENT 2		
			Θ_X (RAD)	Θ_Y (RAD)	P (GEV)	Θ_X (RAD)	Θ_Y (RAD)	P (GEV)
1	**HADRON range in Pb/emul=4.1/1.2 cm**	Prob(μ)≈10^{-3}	**0.177**	**0,368**	**0,77 [0.66,0.93]**	**0,175**	**0,357**	**0,80 [0.65,1.05]**
2	**PROTON**	range, scattering and dE/dx	**-0.646**	**-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**		**0.445**	**0.419**	**0.48 [0.34,0.66]**
8 (**DAUGHTER**)	**HADRON**	interaction seen	**-0.004**	**-0.008**	**12 [9,18]**	**-0,009**	**-0,020**	

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
1^{st} γ	2.2	45.0 <11>	**7.5** <7>	$<10^{-3}$	**0.32**	**2ry vertex**
2^{nd} γ	12.6	85.6 <56>	**22** <50>	0.10	**0.82**	**2ry vertex** (favored)

E(γ 1) = 5.6 ± 1.0 ± 1.7 GeV
E(γ2) = 1.2 ± 0.4 ± 0.4 GeV

* probability to find an IP larger than the observed one

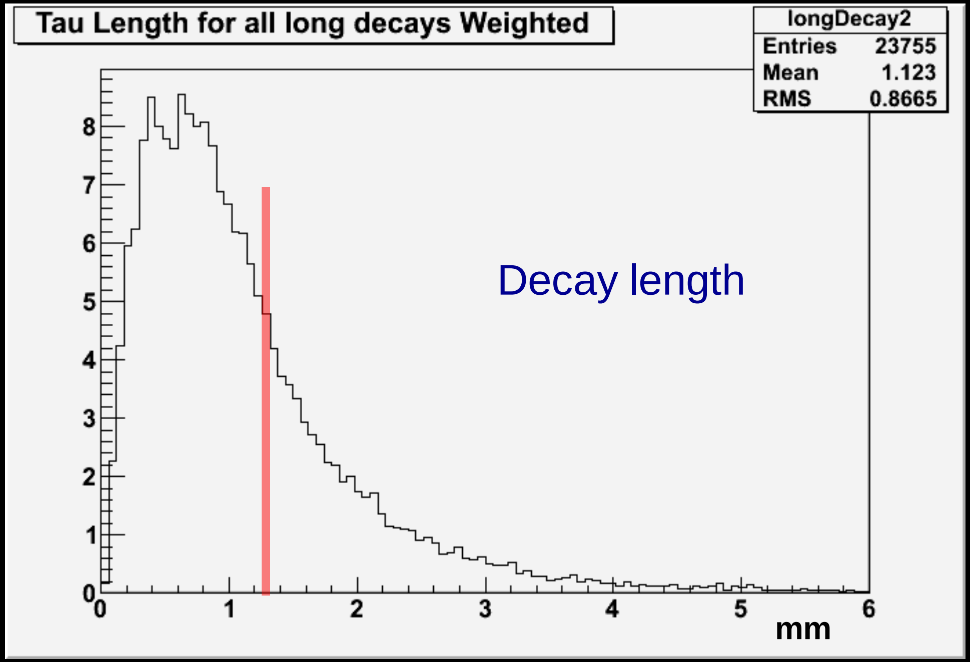


Kinematical analysis

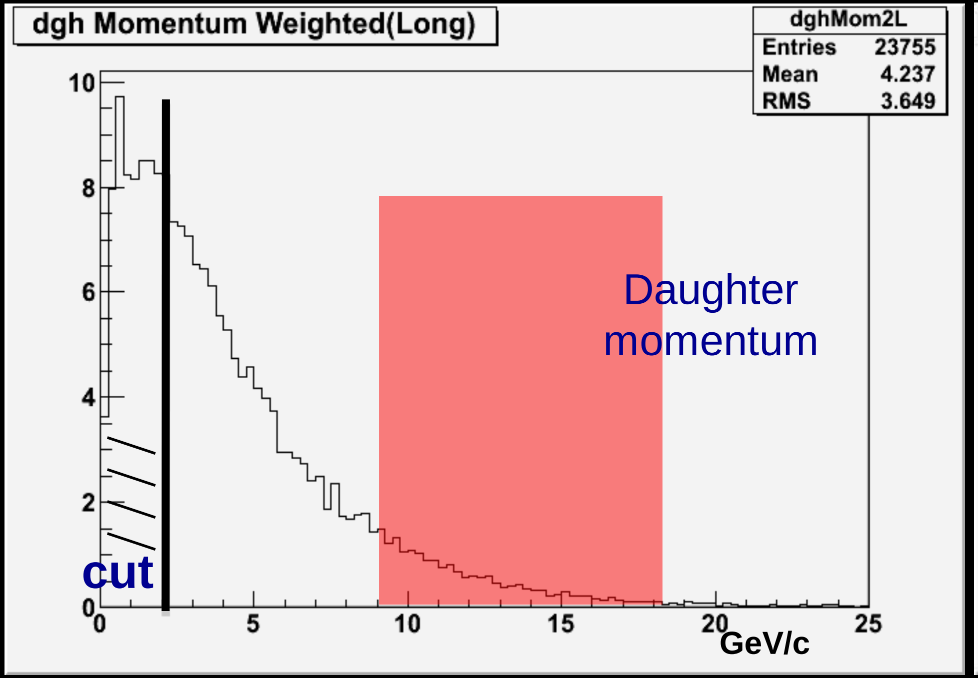
VARIABLE	AVERAGE	Selection criteria
kink (mrad)	**41 ± 2**	**>20**
decay length (μm)	**1335 ± 35**	**within 2 lead plates**
P daughter (GeV/c)	**12^{+6}_{-3}**	**>2**
Pt (MeV/c)	**470^{+230}_{-120}**	**>300 (γ attached)**
missing Pt (MeV/c)	**570^{+320}_{-170}**	**<1000**
⎞ (deg)	**173 ± 2**	**>90**

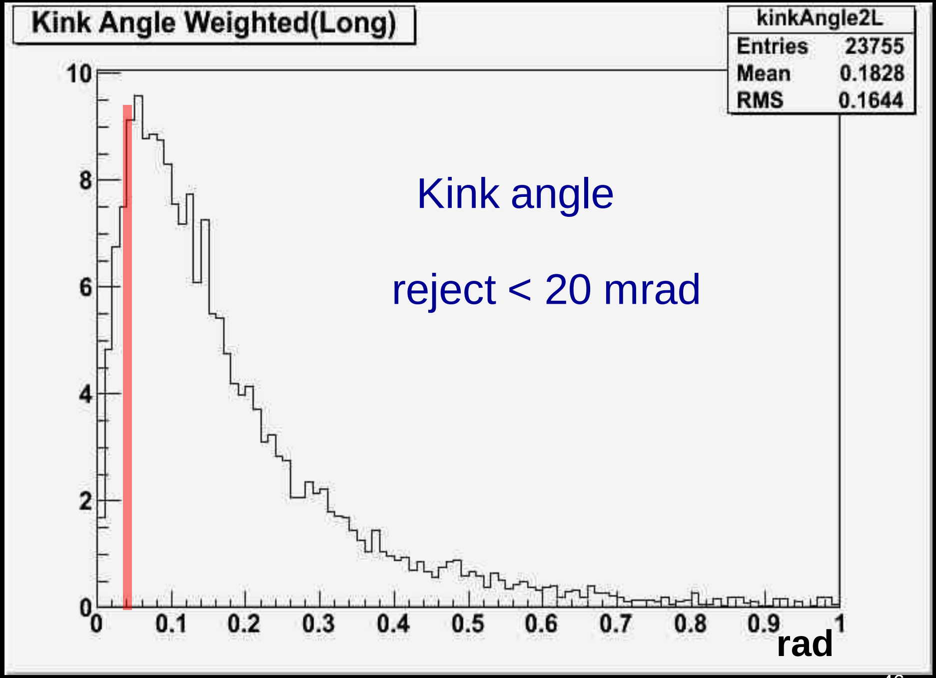
γ1 and γ2 are both assumed as attached to 2^{ry} vertex
The uncertainty on Pt due to the alternative γ2 attachment is < 50 MeV

Features of the decay topology



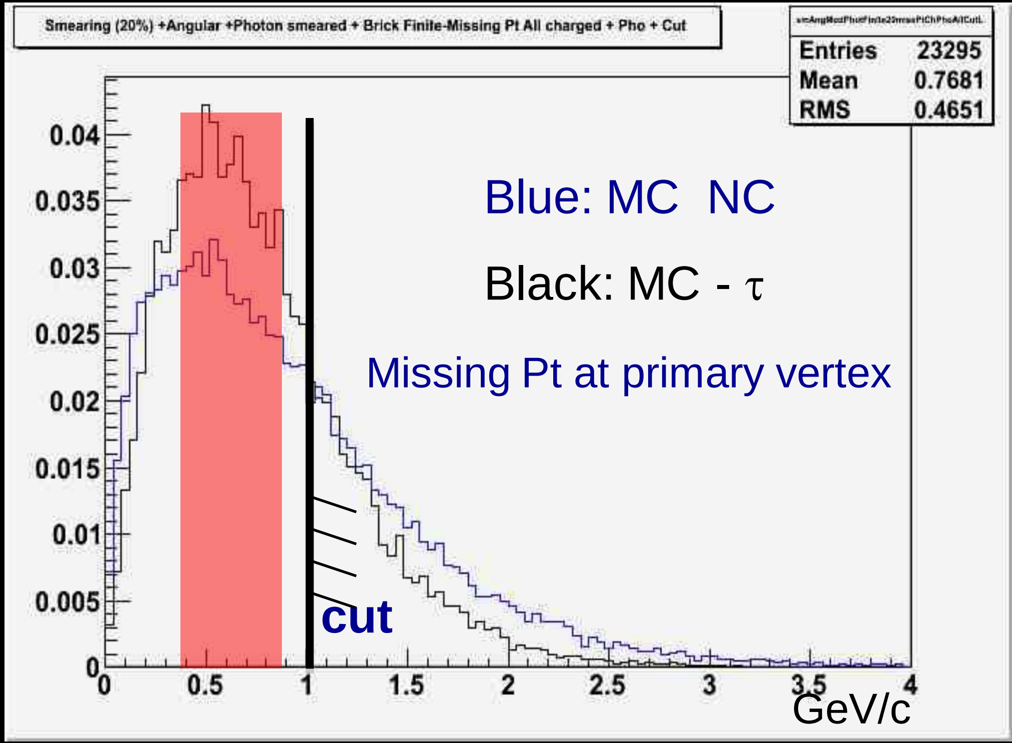
red bands: values for the “interesting” event with uncertainties



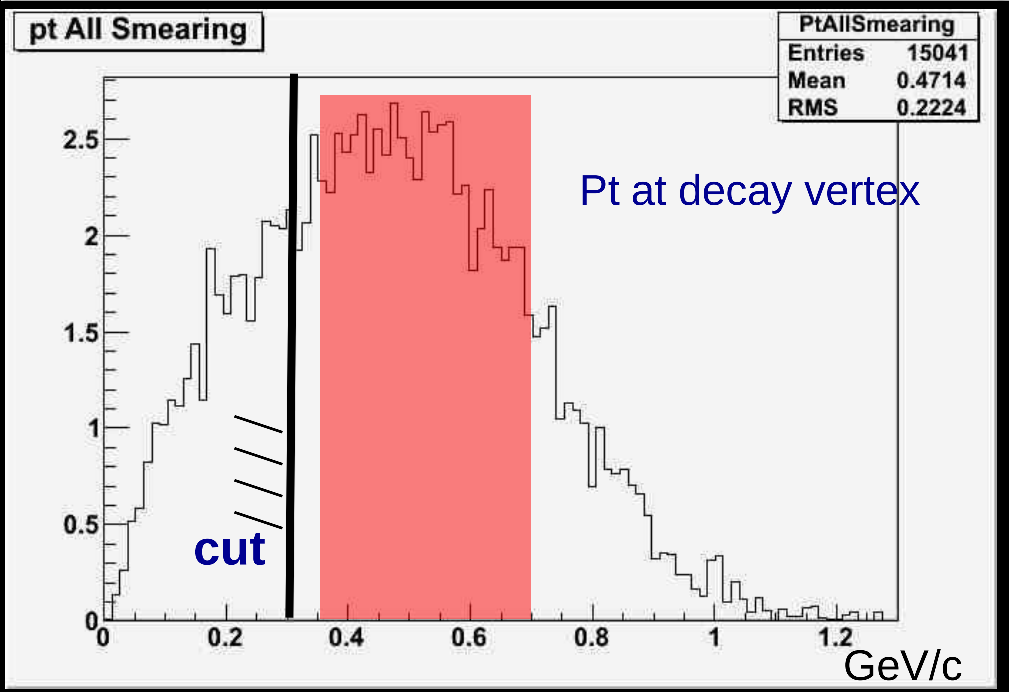


Kinematical cuts to be passed

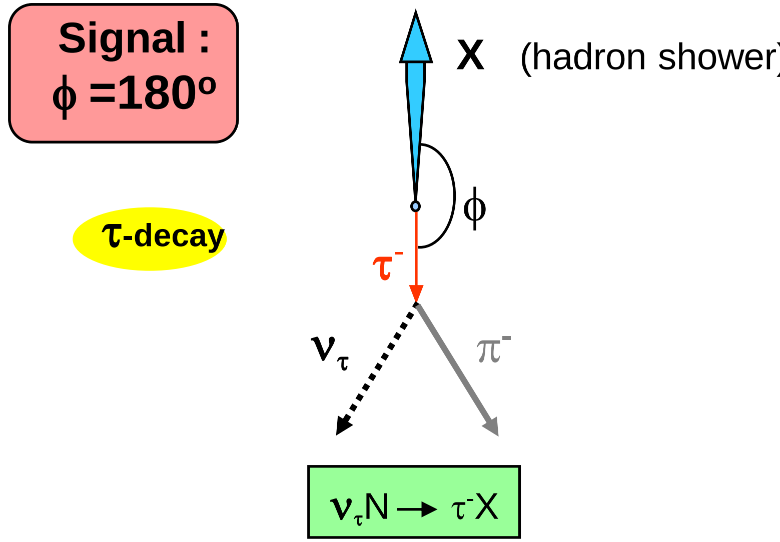
Reject NC events with larger missing Pt (neutrino) →

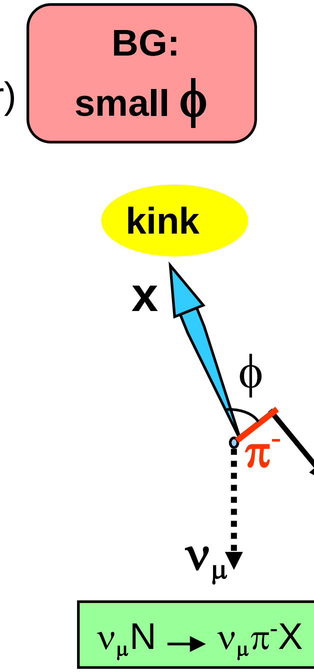


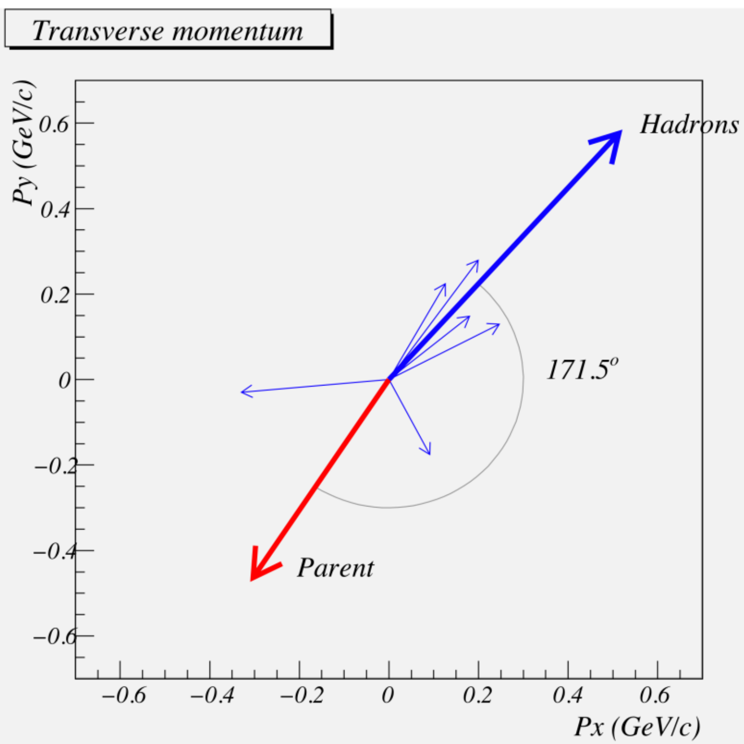
Reject hadron interactions →

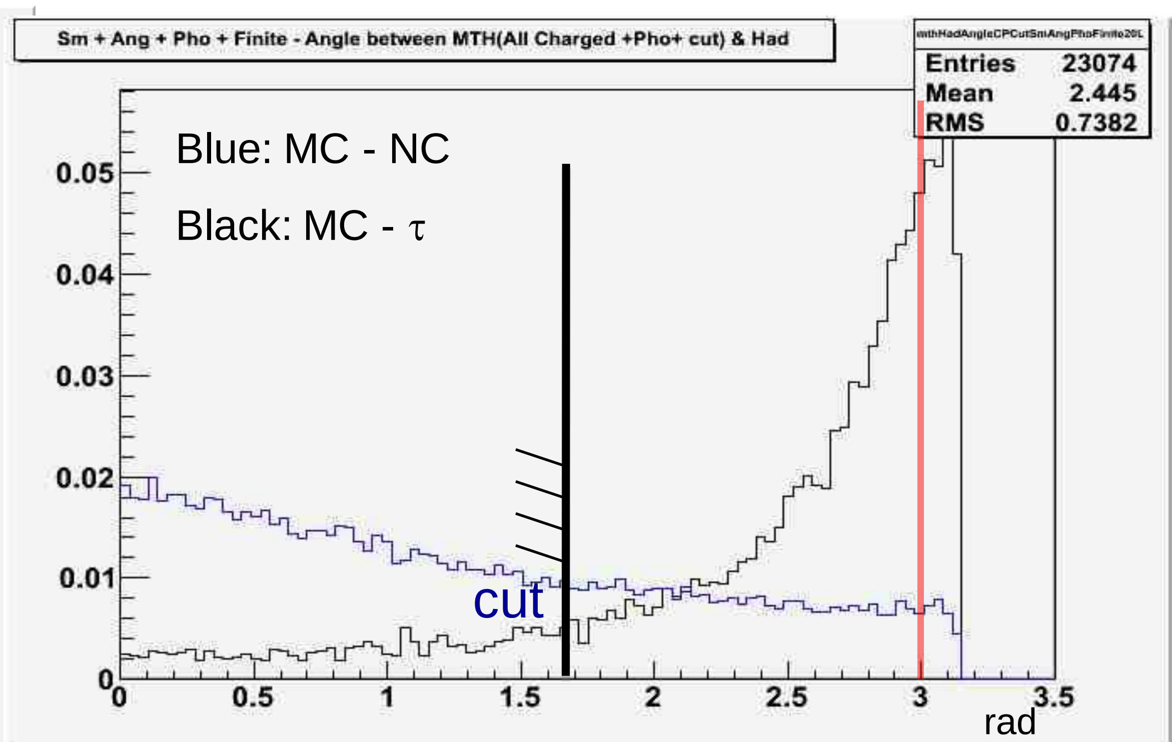


Azimuthal angle between the resulting hadron momentum direction and the parent track direction









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.

• A fit of 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^0 mass	ρ mass
$120 \pm 20 \pm 35$ MeV	$640 ^{+125}_{-80} {}^{+100}_{-90}$ MeV

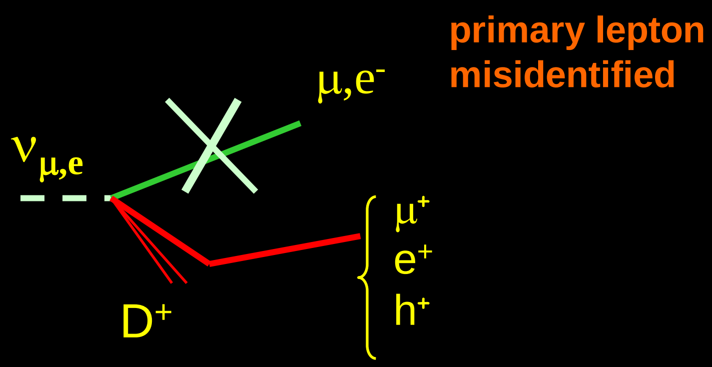
BACKGROUND SOURCES

- 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 ~ 10^{-5}/CC

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

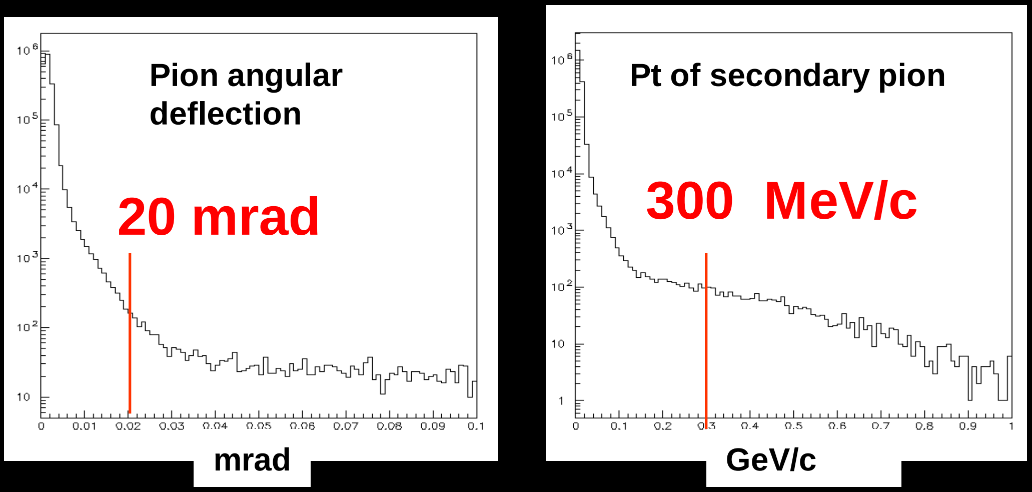
• further charm BG reduction is under evaluation by implementing the systematic follow-down of low energy tracks in the bricks and the inspection of their end-range, as done for the "interesting" event. For the latter we have 98-99% muon ID efficiency.

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.

kink probabilities integrated over the ν_μ NC hadronic spectrum yield
a BG probability of: **$(1.9 \pm 0.1) \times 10^{-4}$ kinks/NC** (2 mm Pb)

Typical scattering distributions for : 5 GeV π^+



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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

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.

CONCLUSIONS AND OUTLOOK

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.

• One muonless event showing a τ ➔ 1-prong hadron decay topology has been detected and studied in details. It passes all kinematical cuts required to reduce the physics background. It is the first ν_τ candidate event in OPERA.
(Phys.Lett.B691(2010), 138-145)

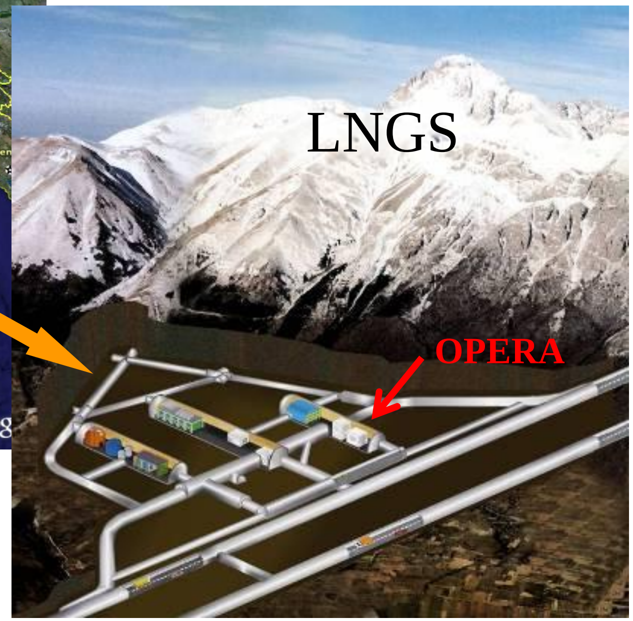
•By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 s on the measurement of a first nt candidate event in OPERA.

• 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

Back up

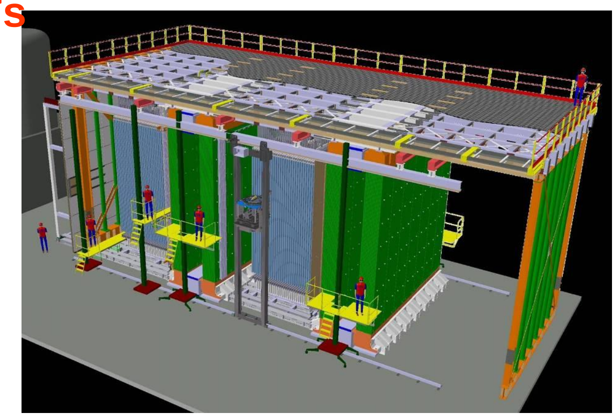
CNGS neutrino beam: long baseline, high energy to maximize number of ν_τCC events

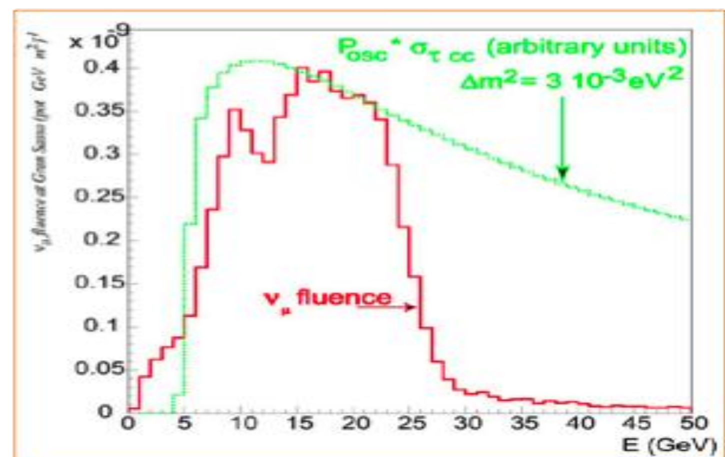


$< E_{\nu_\mu} >$	17 GeV
ν_μ(CC + NC)/year	~4700
ν_τ CC/year	~20
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87%
$\bar{\nu}_\mu / \nu_\mu$	4%
ν_τ prompt	negligible

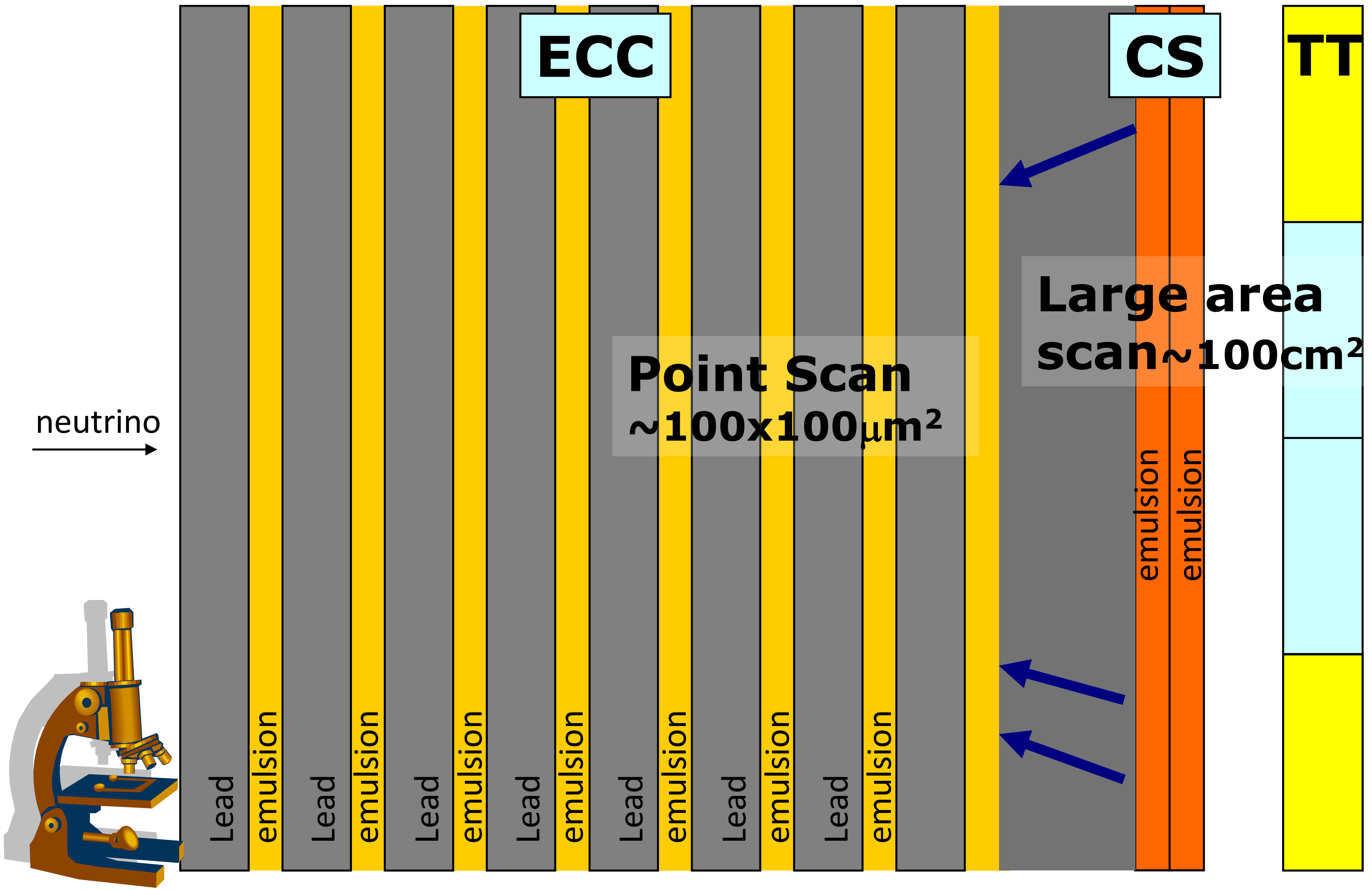
OPERA: large mass/high spatial resolution

able to detect short lived **τs**



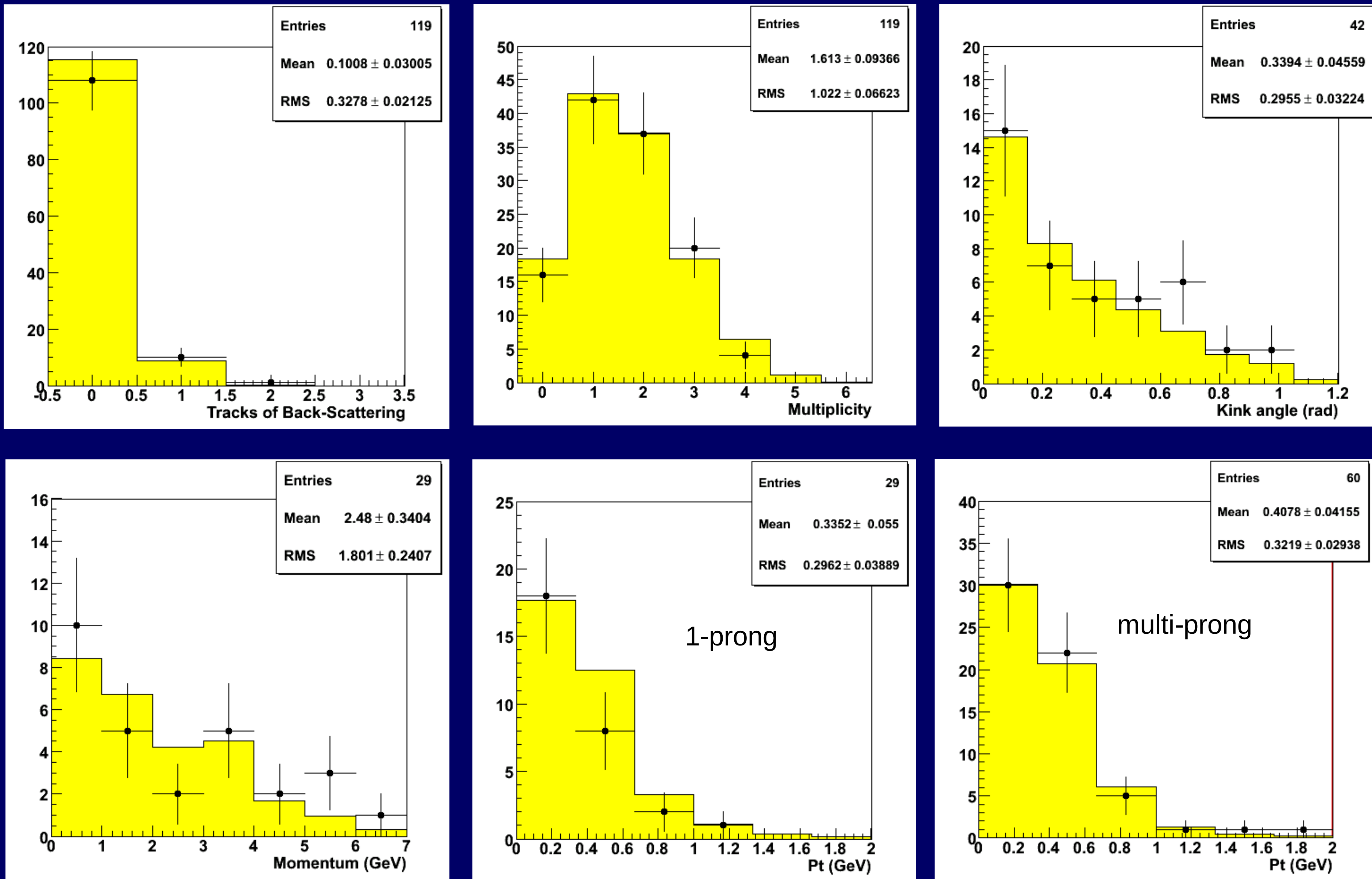


Decay Search Procedure



DATA/MC comparison: good agreement in normalization and shape

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



Main kinematical cuts for charm events:

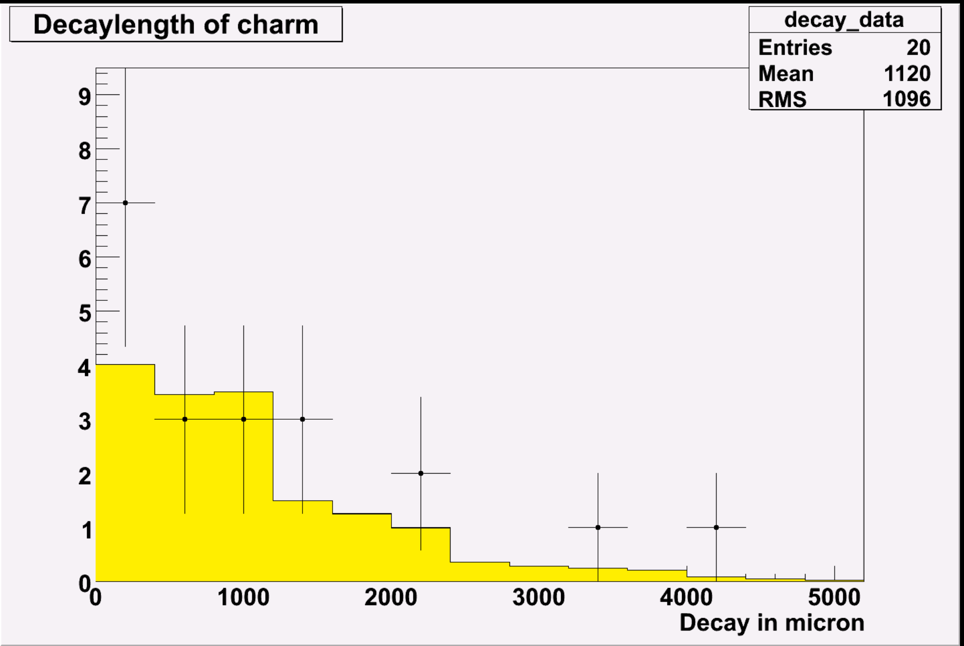
- P daughter >2.5 GeV/c, kink Pt > 0.5 GeV/c (for kink events)
- looser cuts for multi-prong events

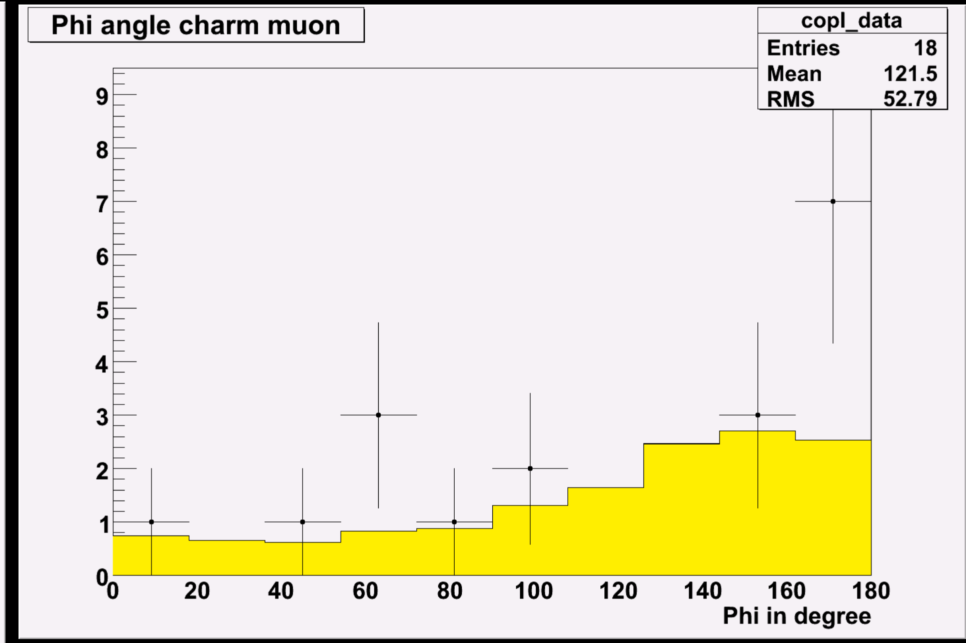
20 charm candidate events selected by the kinematical cuts,
3 of them with 1-prong kink topology.

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:





Charm candidate event (dimuon)

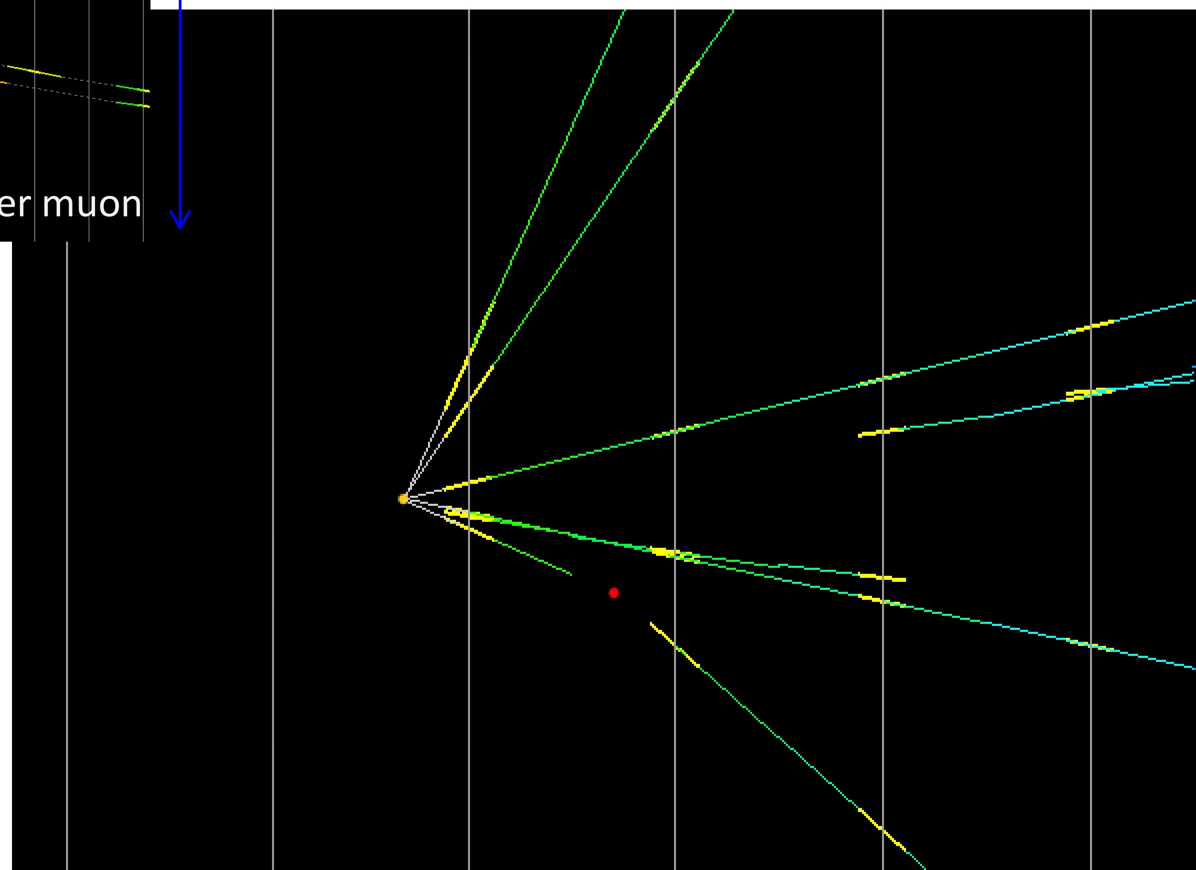
flight length: 1330 microns

kink angle: 209 mrad

IP of daughter: 262 microns

daughter muon: 2.2 GeV/c

decay Pt: 0.46 GeV/c



ν_e candidate event

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

Additional physics subject:

study ν_μ-ν_e oscillations