OPERA and its Tau Neutrino Candidate

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- Neutrino mass, mixing and neutrino oscillations
- OPERA experiment
- Detector performance
- Special events: charm, ν_e
- **ν_τ candidate**
- Outlook

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Neutrino Mass and Mixing

$$\Delta m^2_{solar} = m_2^2 - m_1^2 \approx 8 \cdot 10^{-5} eV^2,$$

$$|\Delta m^2_{atm}| = |m_3^2 - m_2^2| \approx 2 \cdot 10^{-3} eV^2$$

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

θ_{atm} θ_{13}, δ θ_{sol}

$\theta_{23} \approx 45^o$ $\theta_{13} < 13^o, \delta$? $\theta_{12} \approx 33^o$

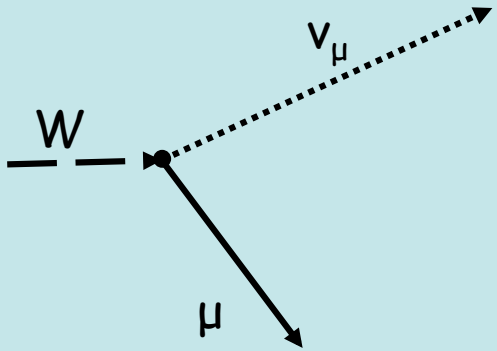
Neutrino Oscillations (simplified)

Flavor eigenstates ν_μ, ν_τ with $\theta_{23} \approx 45^\circ$

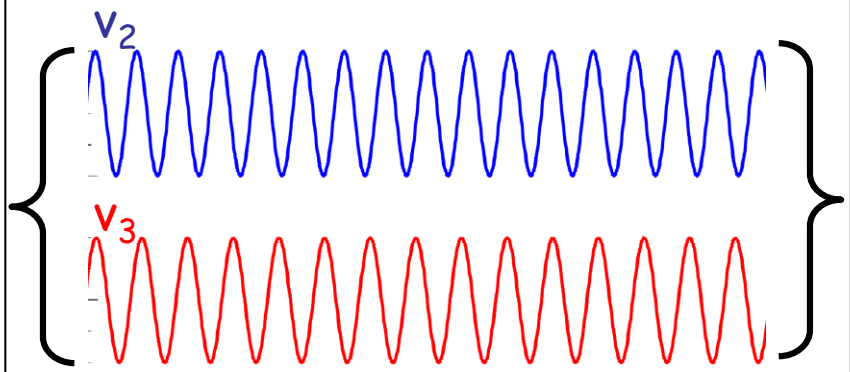
$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates ν_2,ν_3

source creates flavor-eigenstates



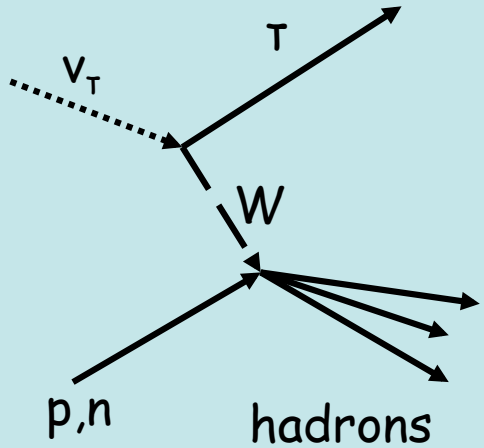
propagation determined by mass-eigenstates



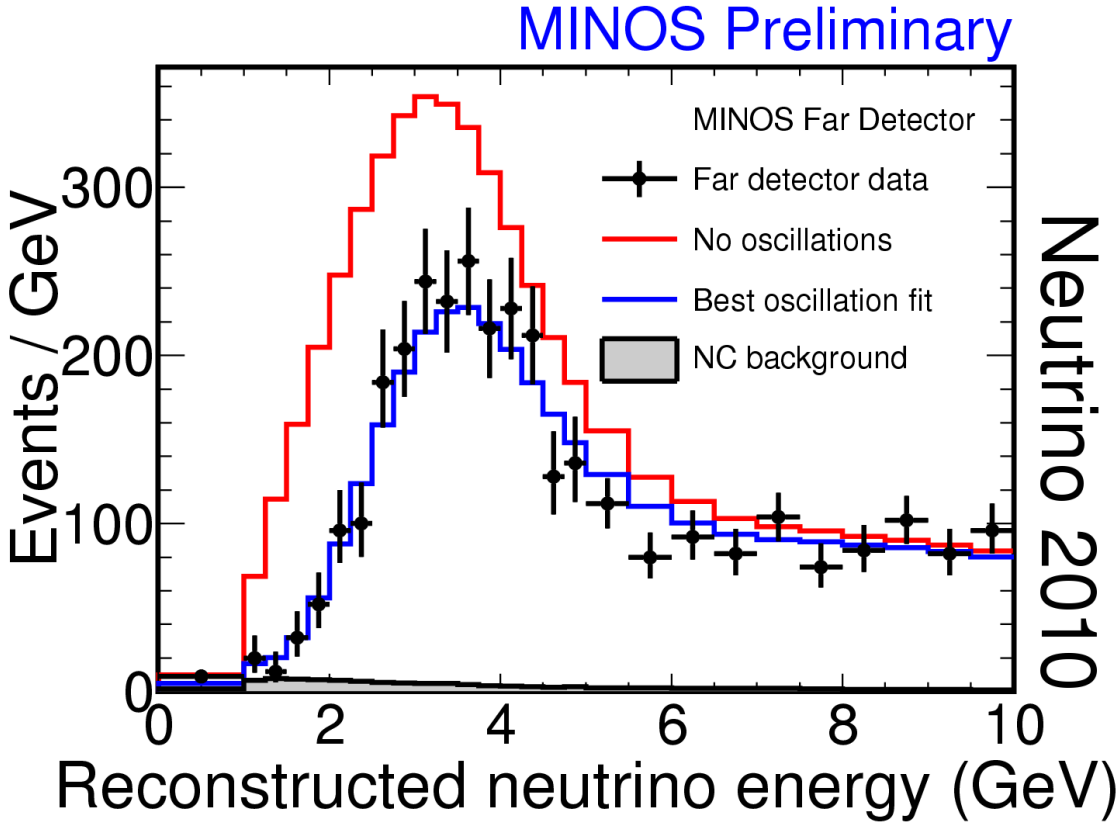
$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

slightly different frequencies
→ phase difference changes

detector sees flavor-eigenstates



MINOS Results: Fit to Oscillation Hypothesis



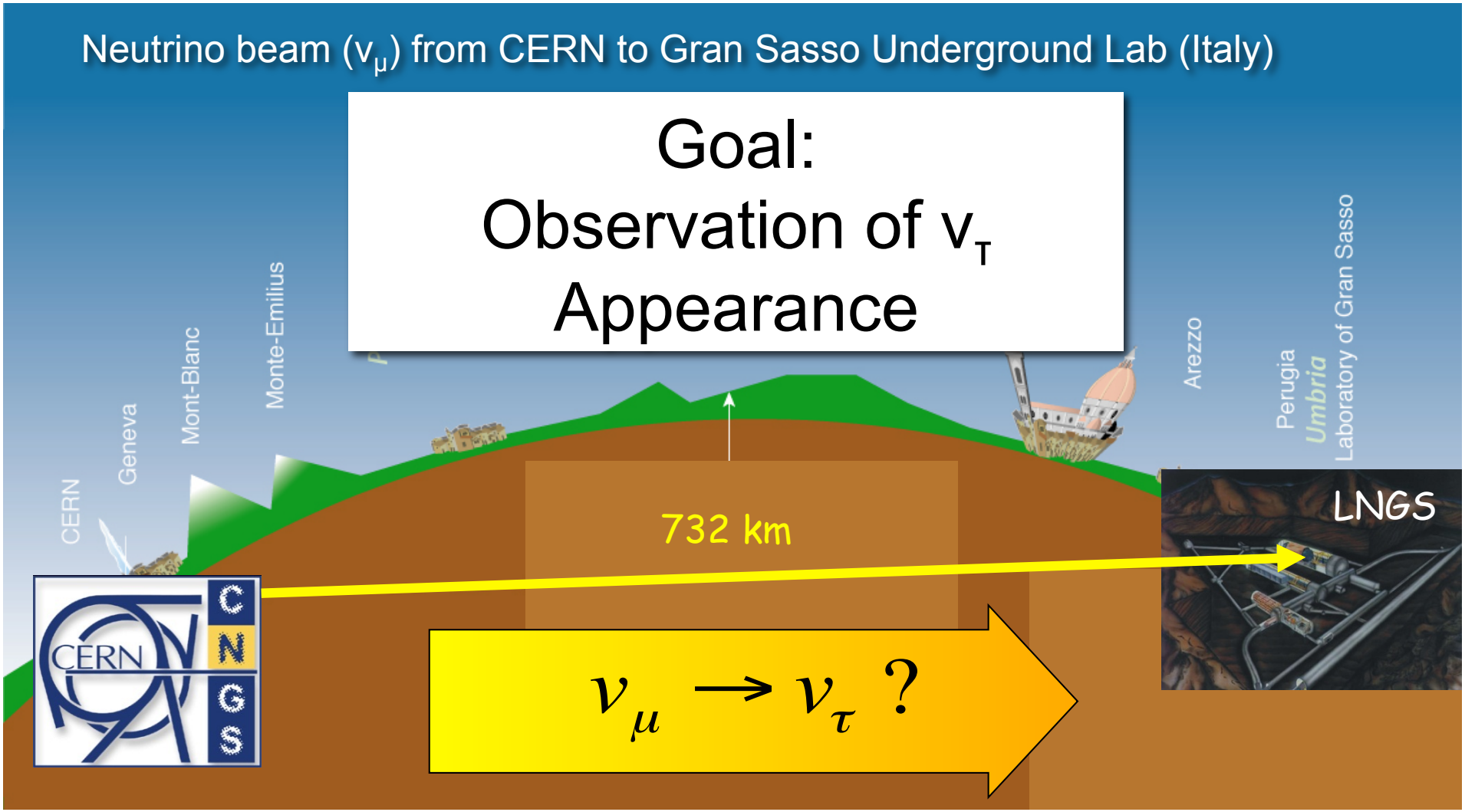
$$\left|\Delta m^2_{32}\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2 \quad (68\%\mathrm{CL})$$

$$\sin^2 2\theta_{23} > 0.91 \quad (90\%\mathrm{CL})$$

(for $7.2 \cdot 10^{20}$pot)

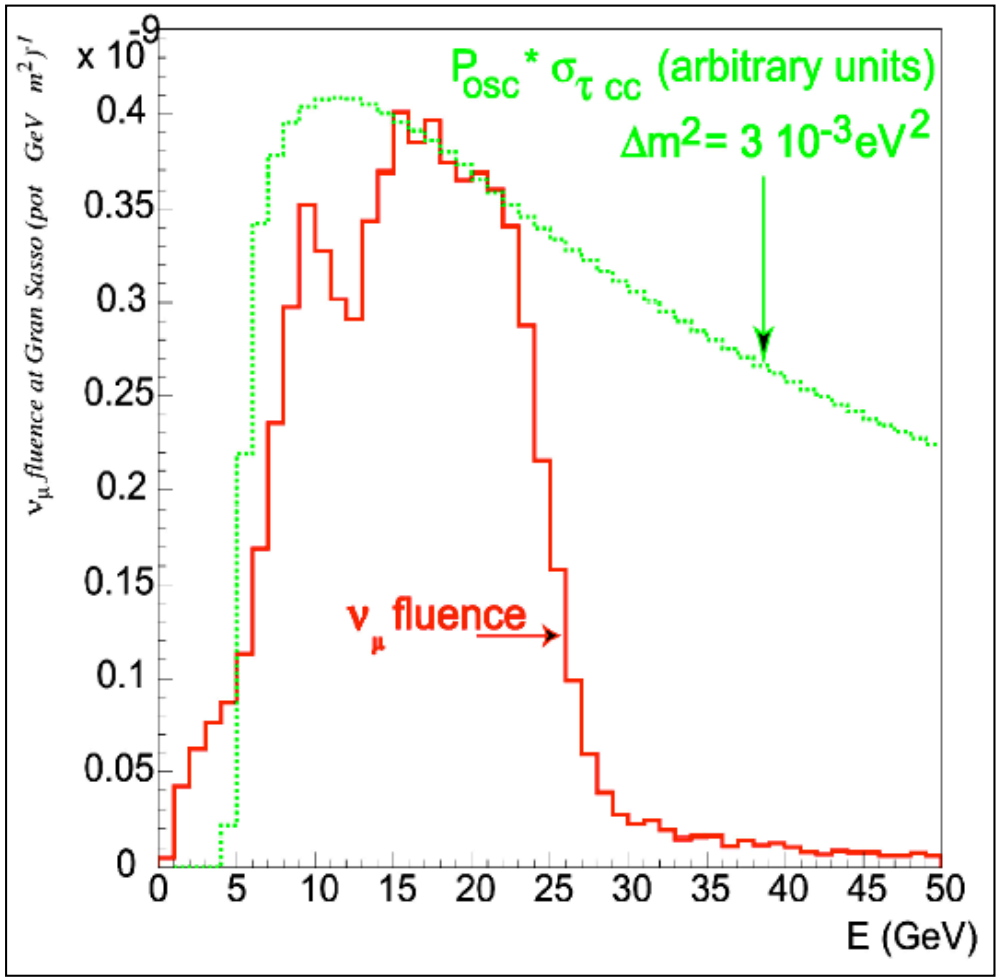
(best fit)

OPERA:
Oscillation Project with Emulsion tRacking Apparatus



Physics runs: 2008 and 2009 completed, 2010 ongoing

CNGS beam ("pure" ν_μ)



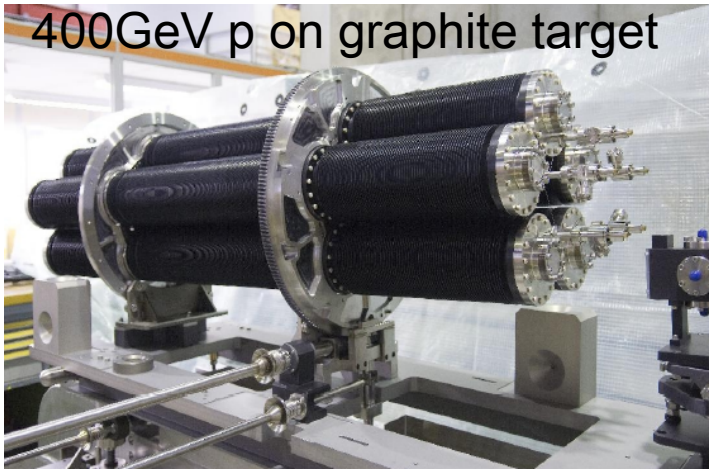
$$\langle E_\nu \rangle = 17\text{GeV}$$

comparison of CC-event rates:

$$\bar{\nu}_\mu / \nu_\mu = 2.1\%$$

$$(\bar{\nu}_e + \nu_e) / \nu_\mu = 0.87\%$$

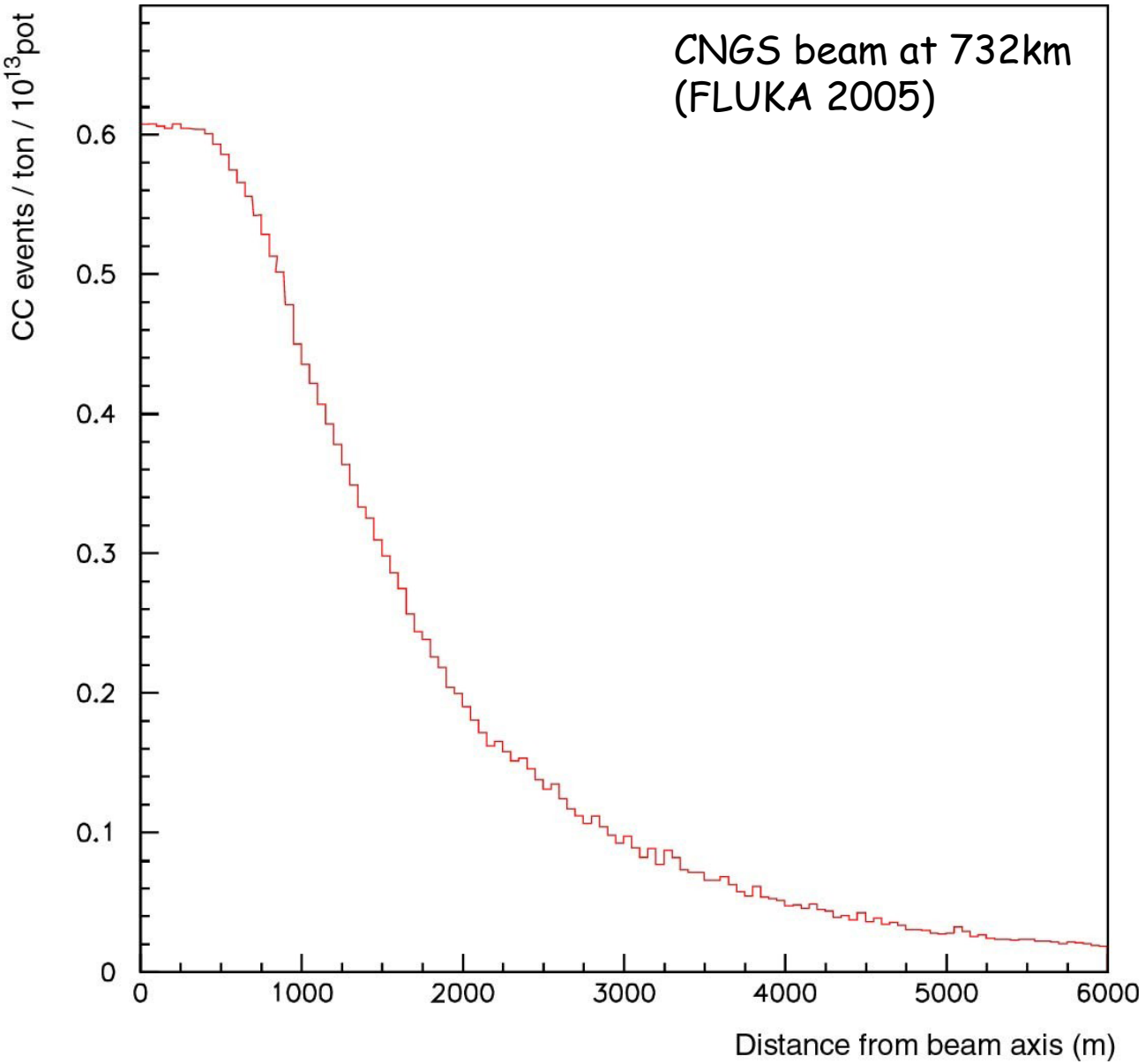
Prompt ν_τ negligible (≈ 10^{-7})



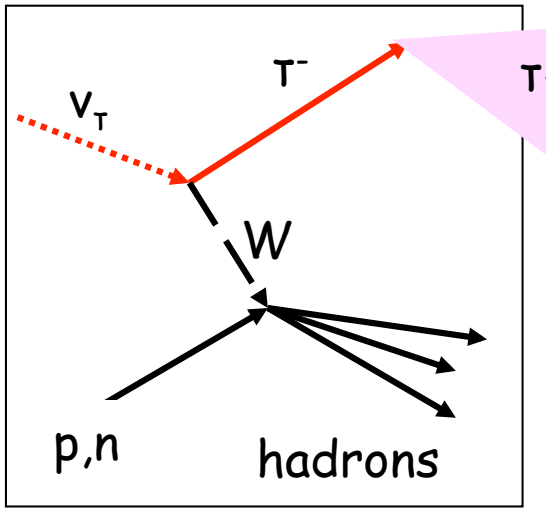
Total exposure expected: 22.5·10^{19} pot

4.5·10^{19}pot/year

Profile of neutrino beam @ LNGS



OPERA: ν_τ detection



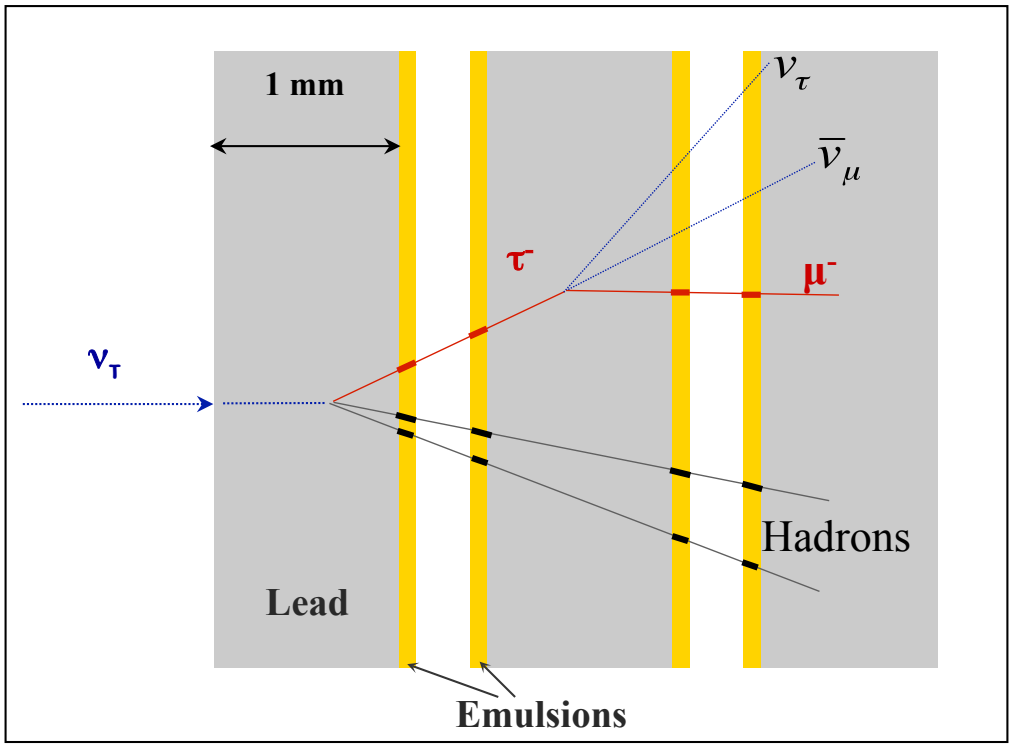
τ-decay:

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \quad 17.4\%$$
$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \quad 17.8\%$$
$$\tau^- \to \text{hadron} + \nu_\tau \quad 49.5\%$$
$$\tau^- \to \pi^-\pi^-\pi^+(n\pi^0) + \nu_\tau \quad 15.2\%$$

kink

trident

Typical topology of τ-decay:
"Kink" within 1mm from vertex

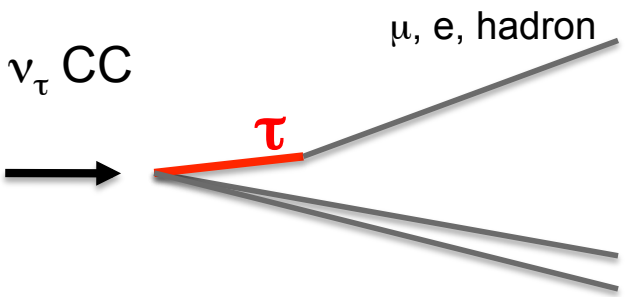


Background Processes

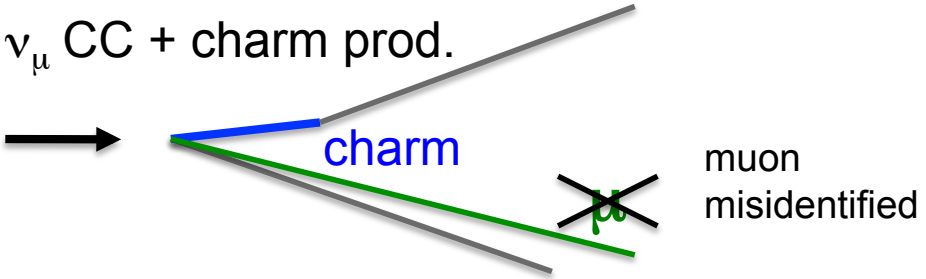
Most important background processes:

- Charm production and decay
- Hadron re-interactions in lead
- Large angle myon scattering in lead

Signal



Background



Expected Signal

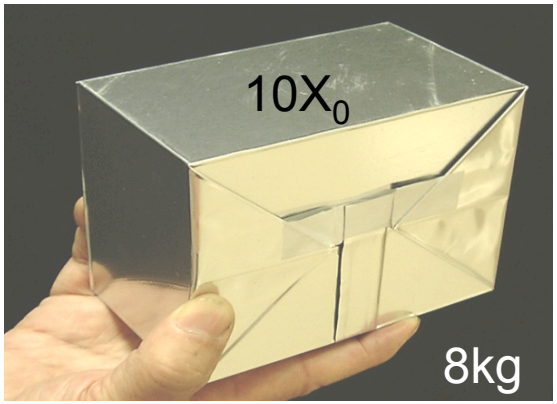
Assume: Maximal mixing, 22.5×10^{19}pot (=5years @ 4.5×10^{19}pot/year)

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

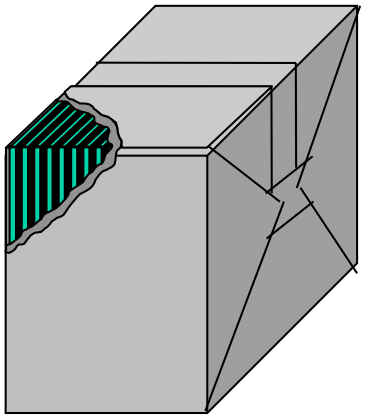
Expected events:

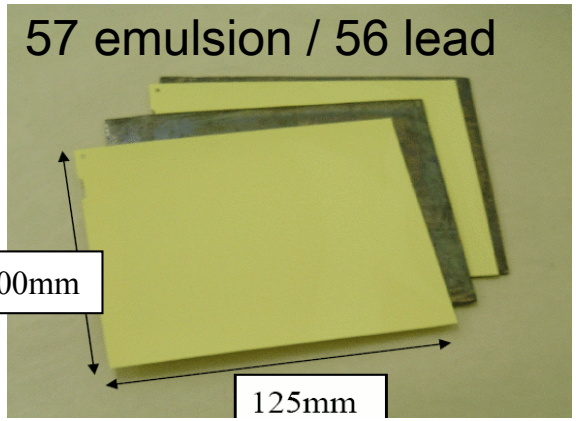
~ 23600 ν_μ CC+NC interactions
~ 160 ν_e interactions
~ 115 ν_τ CC interactions
~ 10 identified ν_τ
< 1 background

OPERA target: lead-emulsion-bricks



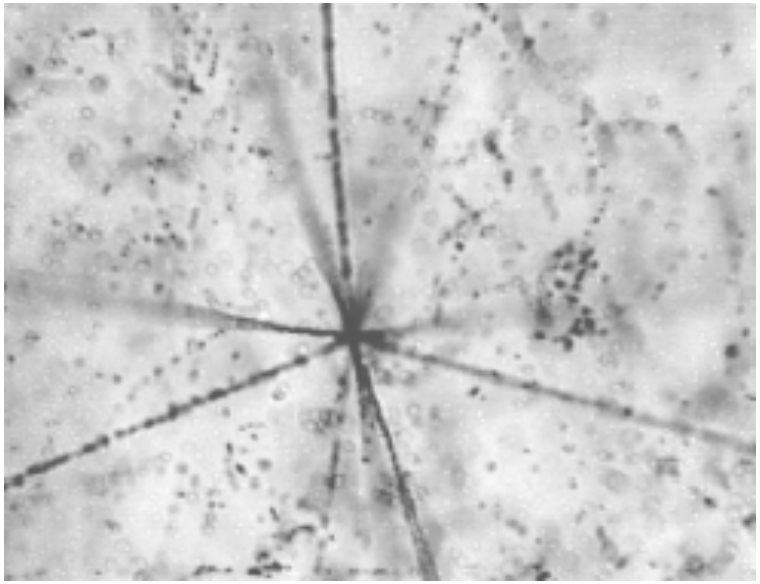
lead-emulsion-brick
(total ≈ 150.000)





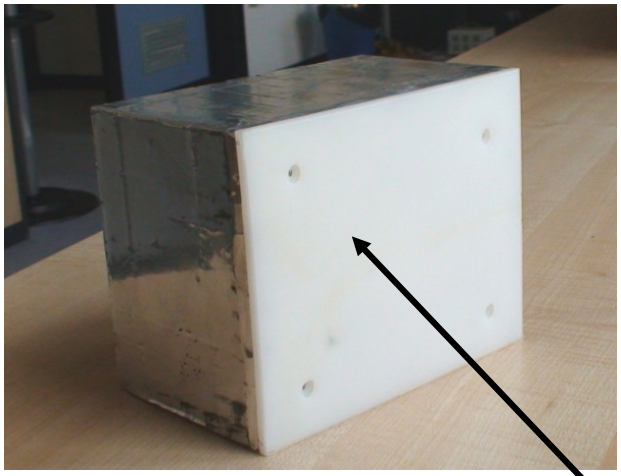
target mass:
≈ 1,35 kton

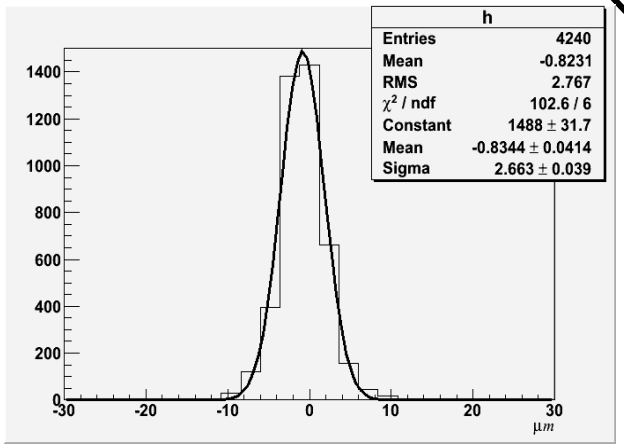
105000 m^2 of lead surface
111000 m^2 of film surface
(9 million films)



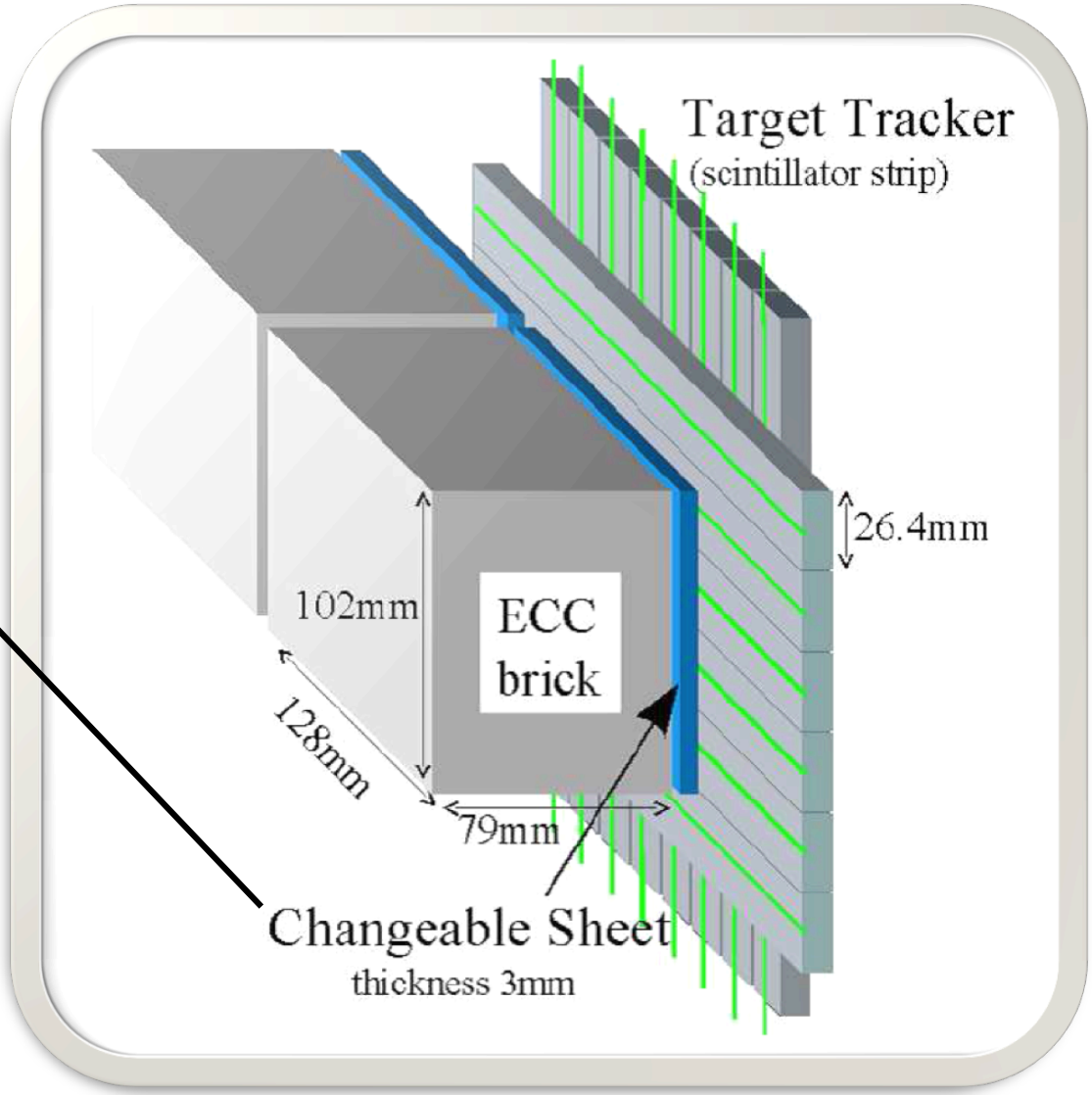
„Emulsion Cloud Chamber“ (ECC)

Hybrid Target Structure

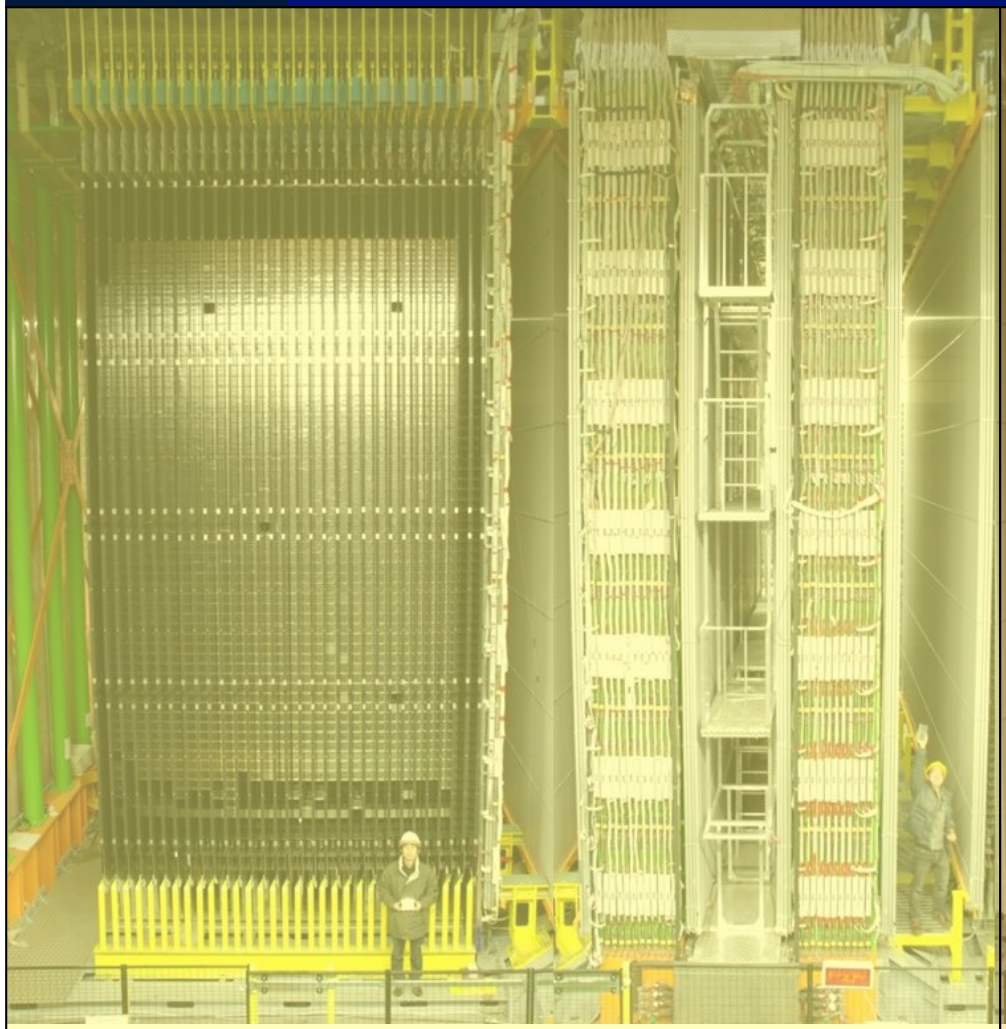




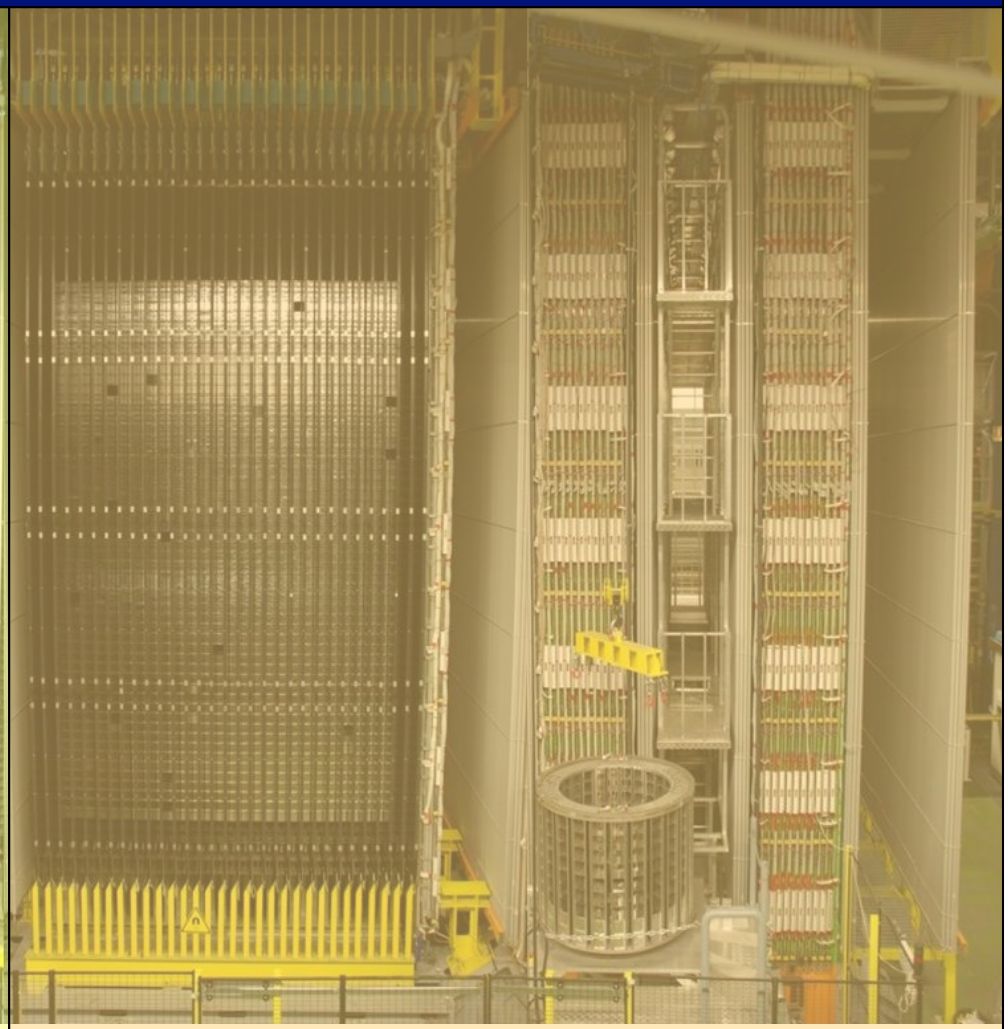
CS doublet alignment
by Compton electrons:
2.5 microns



OPERA - Detector

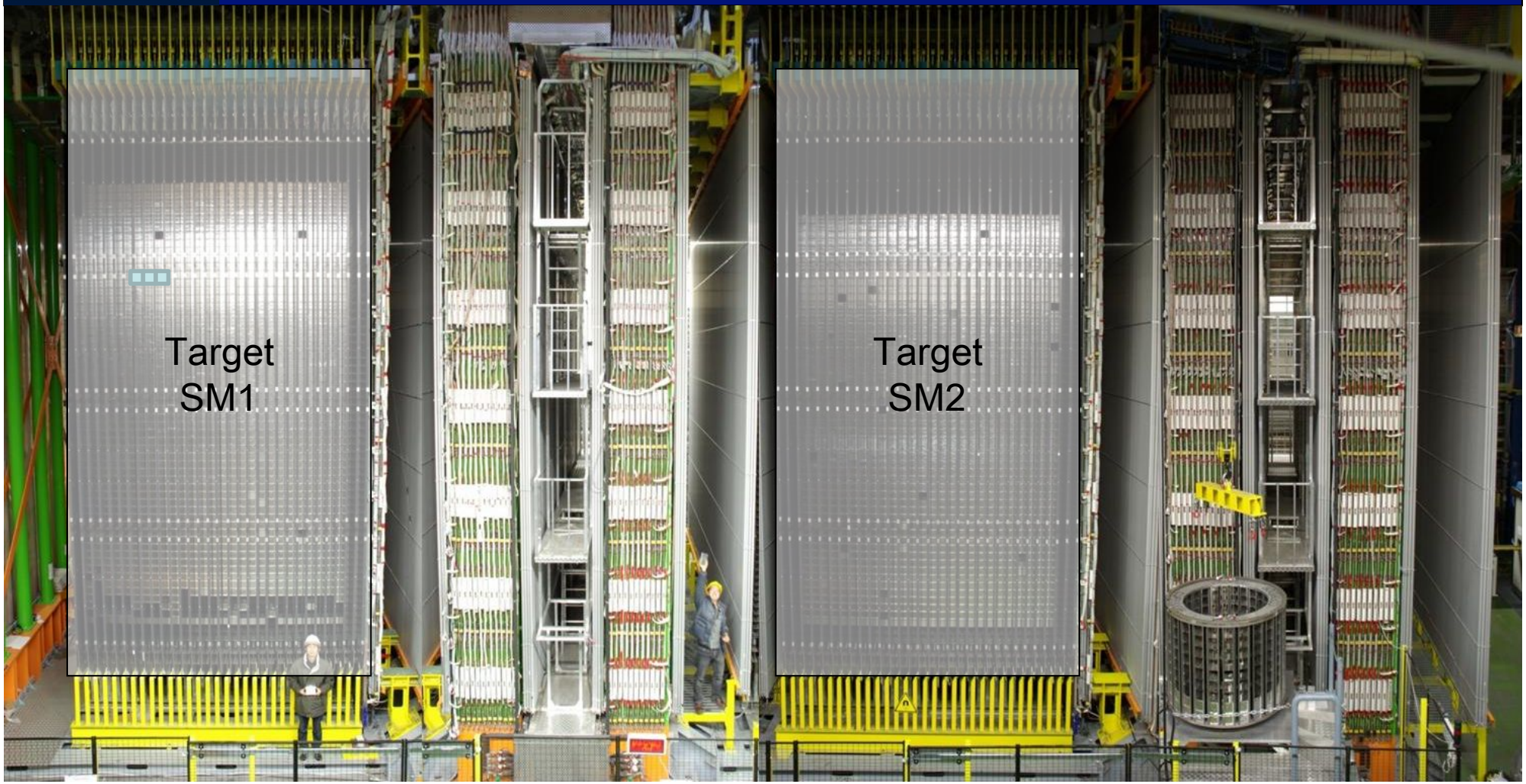


Supermodule 1



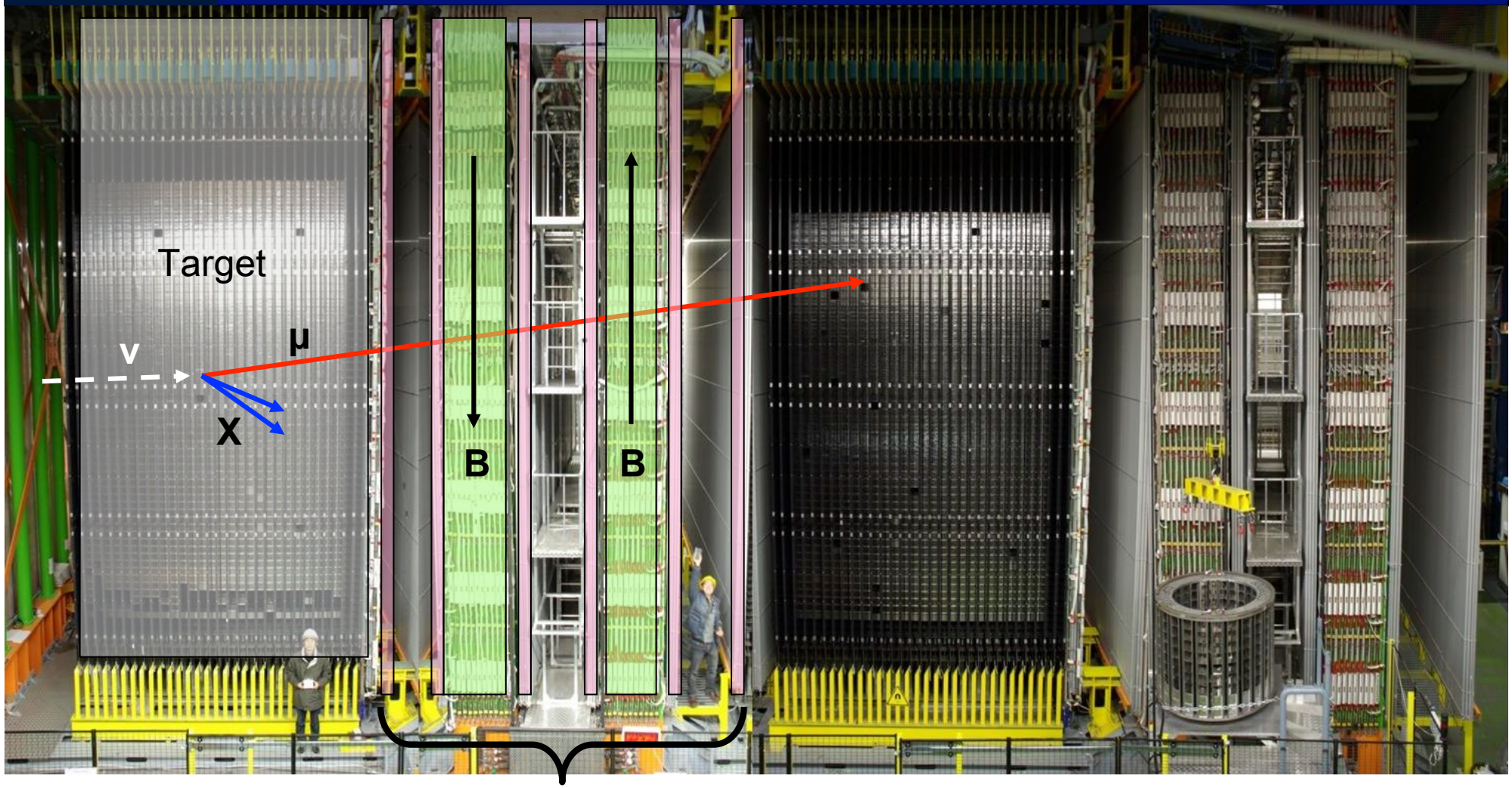
Supermodule 2

OPERA - Detector



Target Region:
- Target Tracker (Scintillator)
- Lead/Emulsion Bricks (75.000 per Supermodule)

OPERA - Detector

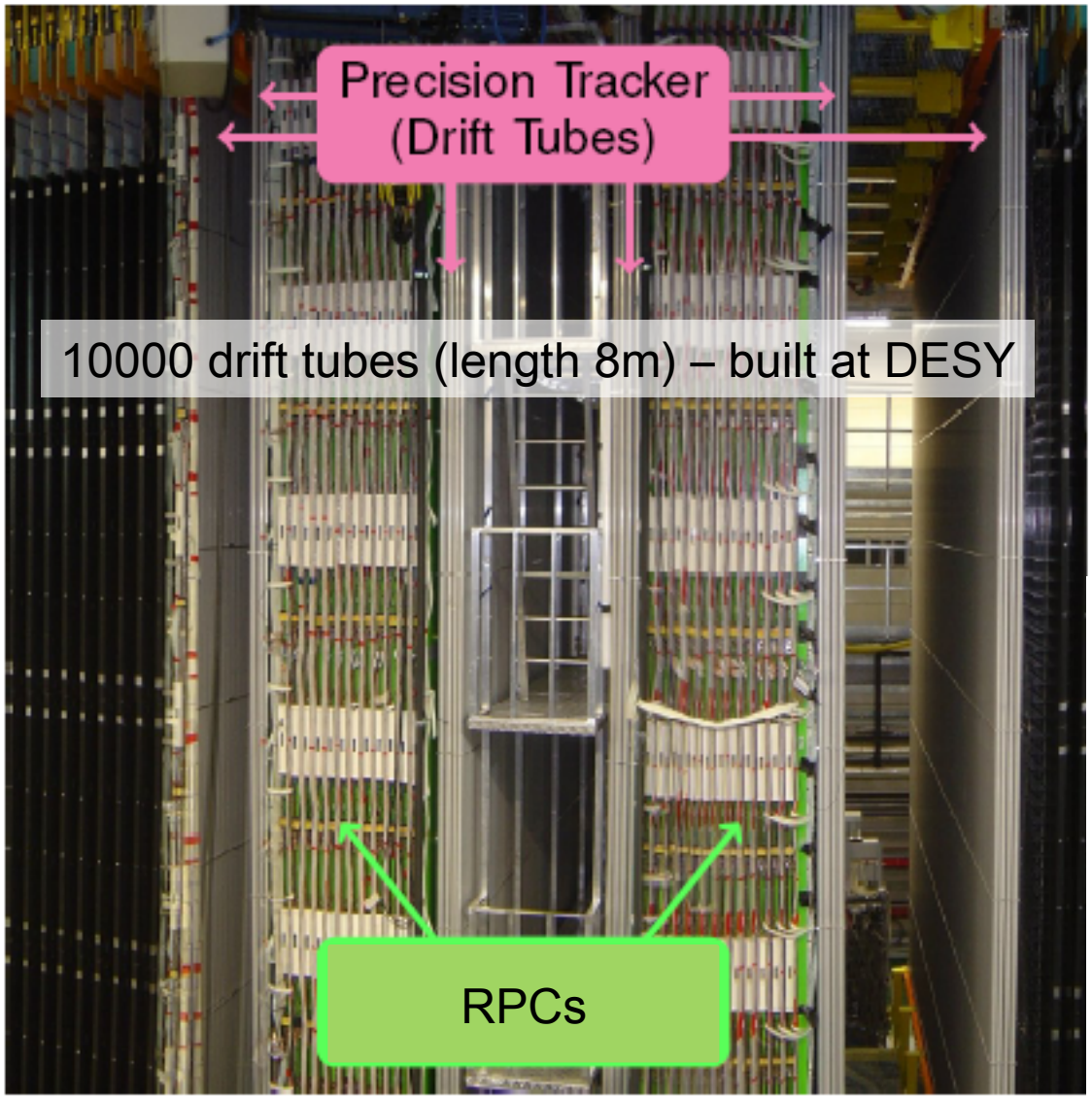


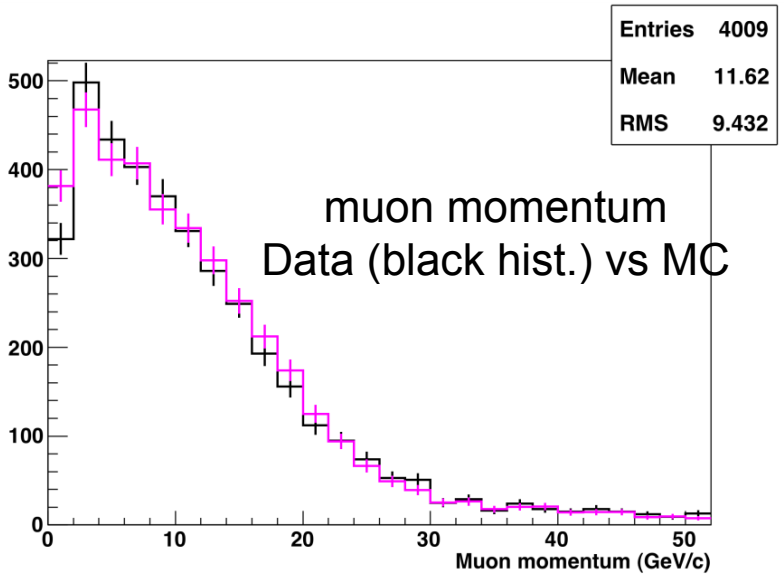
Magnetic Spectrometer:

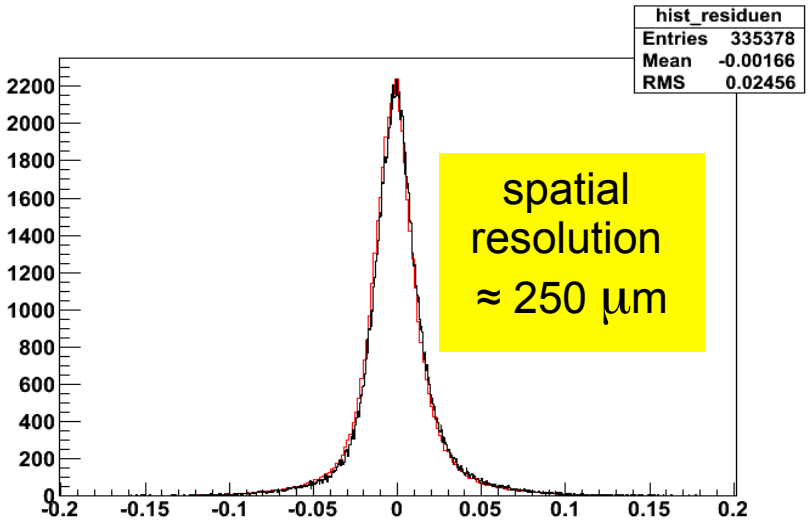
Magnet-Region: Iron & RPCs	Precision Tracker: 6 Planes of Drifttubes

The Electronic Detectors

Magnetic Spectrometer

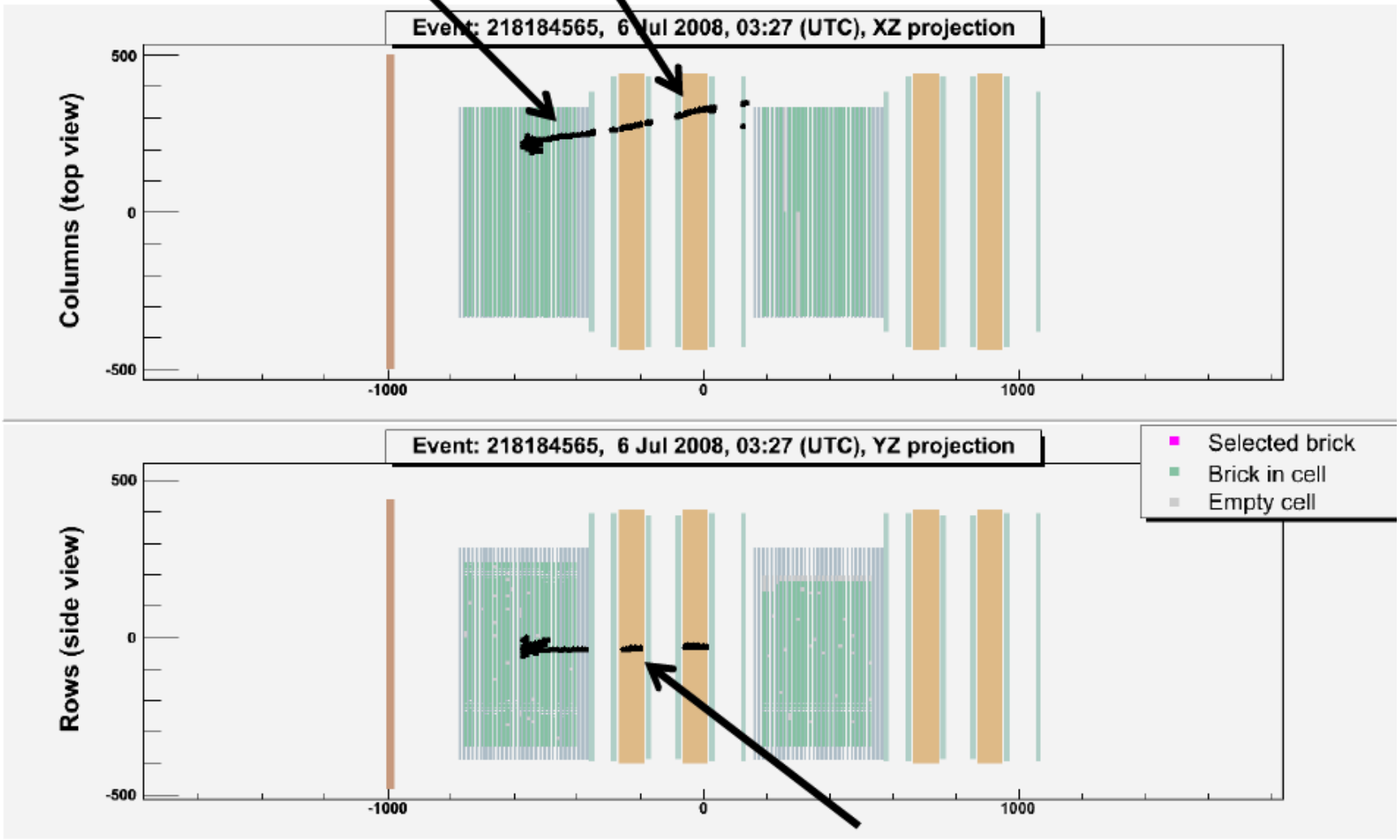






Reconstruction (I): Magnetic Spectrometer

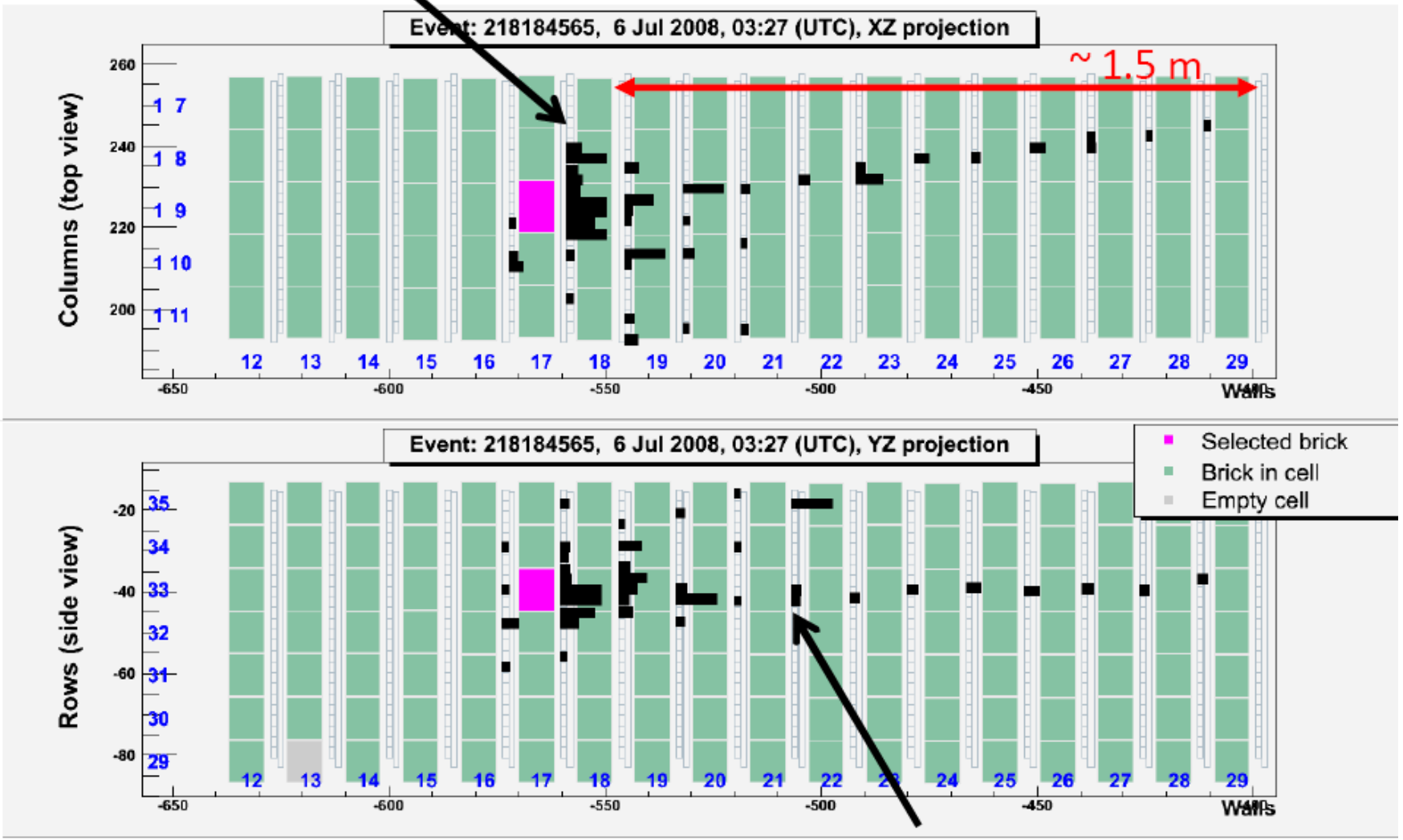
Electronic data (Target Tracker & Muon spectrometer)



Track identified as a muon (P=3.394 GeV/c)

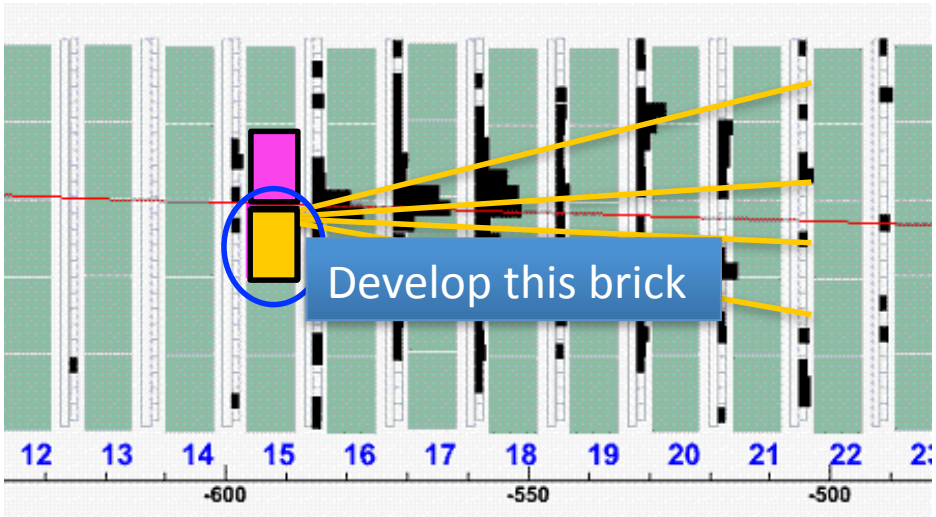
Rekonstruktion (II): Brick Finding

Electronic data (Target Tracker & Muon spectrometer)



Track identified as a muon (P=3.394 GeV/c)

Brick Validation with Changeable Sheet



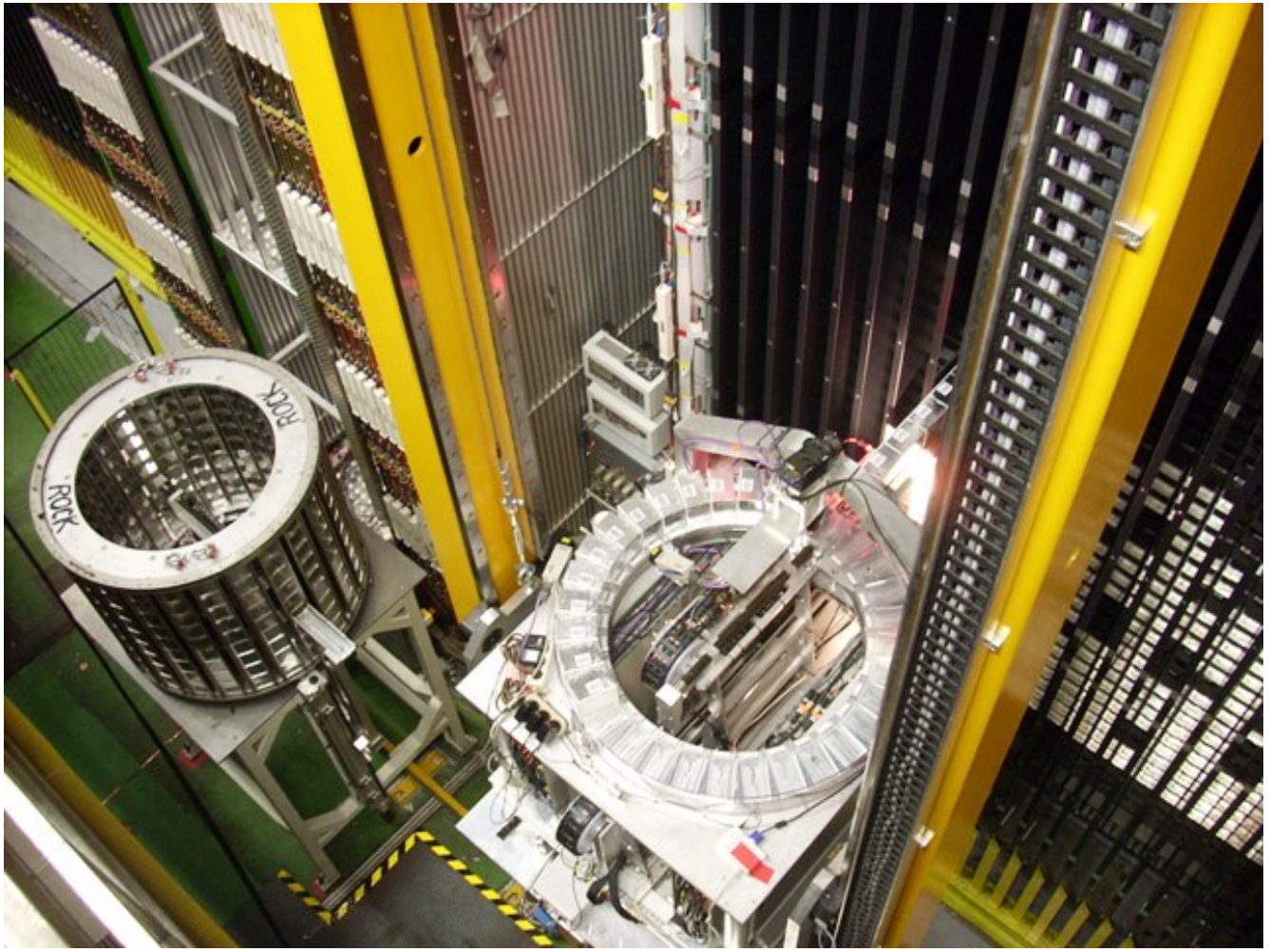
Scanning effort/event: CHORUS 1x1 mm^2

DONUT 5x5 mm^2

OPERA 100x100 mm^2

So far, 640.000 cm^2 of CS surface have been scanned in OPERA

OPERA – Brick Manipulation System



- automatic extraction of 25 bricks / 8 hour shift
- ~90’000 bricks handled until 2009 for the extraction of ~7000 event bricks

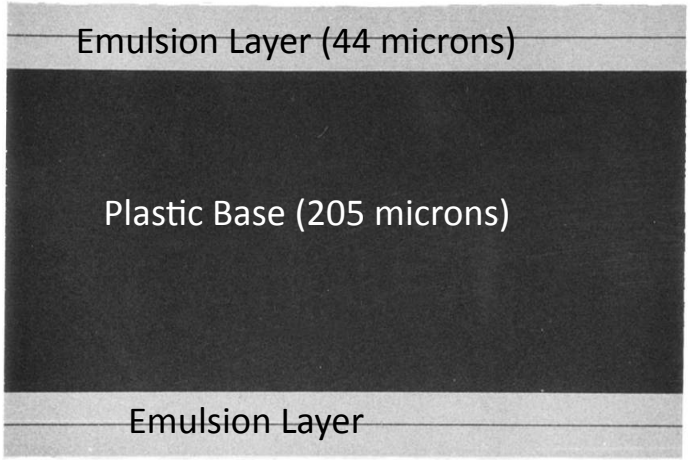
Handling the ECC bricks

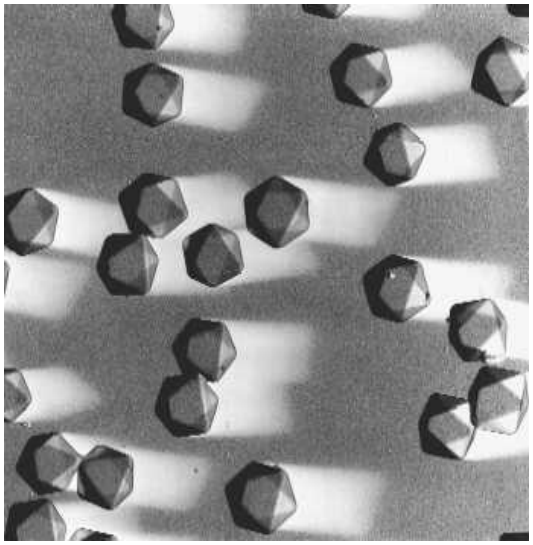
- Inserting and extracting the bricks by Brick Manipulation System (BMS)
- Aligning the films (X-ray and cosmics)
- Developing the films
- Scanning

Brick Analysis

The selected bricks are sent to scanning labs (at present 12)

Performance of Emulsion Film Detector





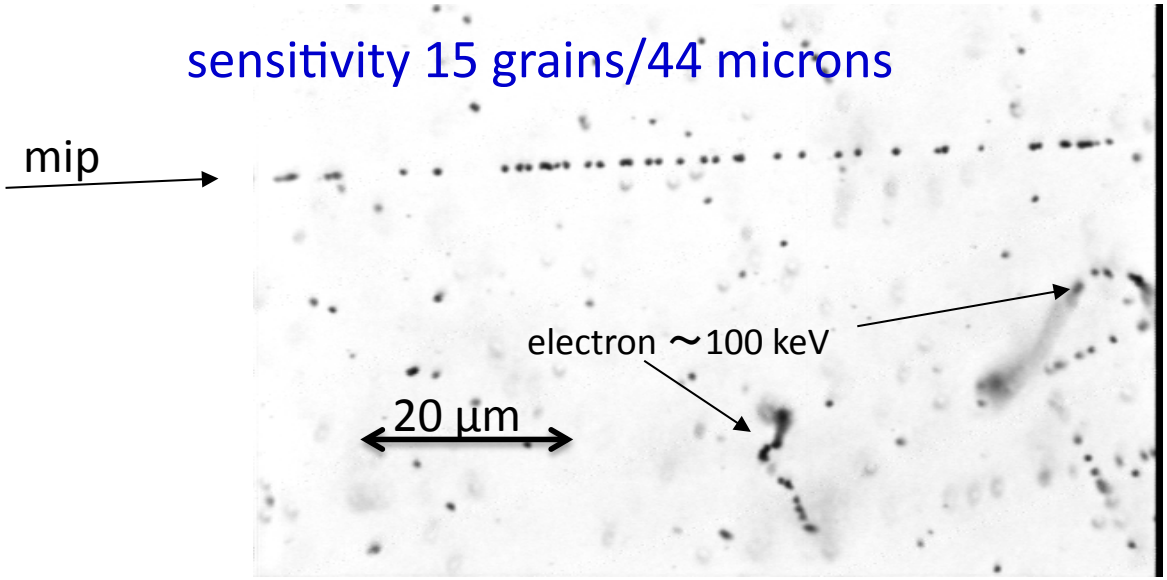
basic detector: AgBr crystal,

size = 0.2 micron

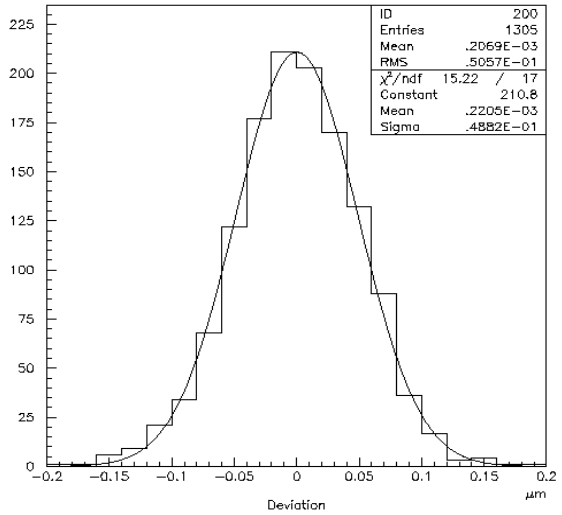
detection eff.= 0.16/crystal

10^{13} "detectors" per film

sensitivity 15 grains/44 microns



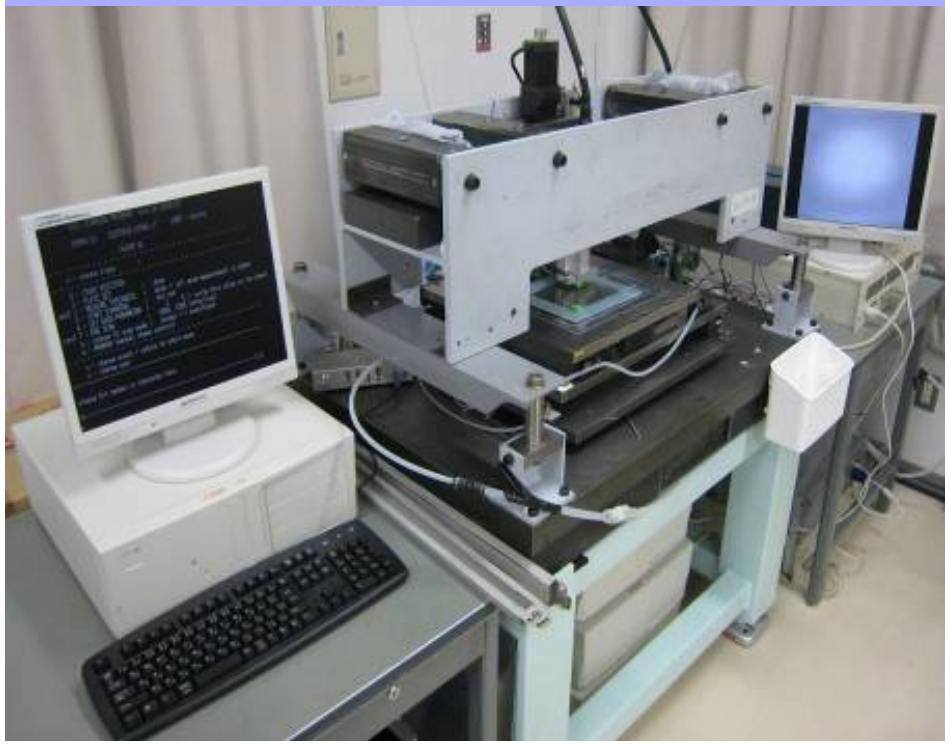
intrinsic resolution: 50 nm



deviation from linear-fit line. (2D)

Scanning of Emulsions

Japanese Scanning System (S-UTS)



4 systems + sub systems

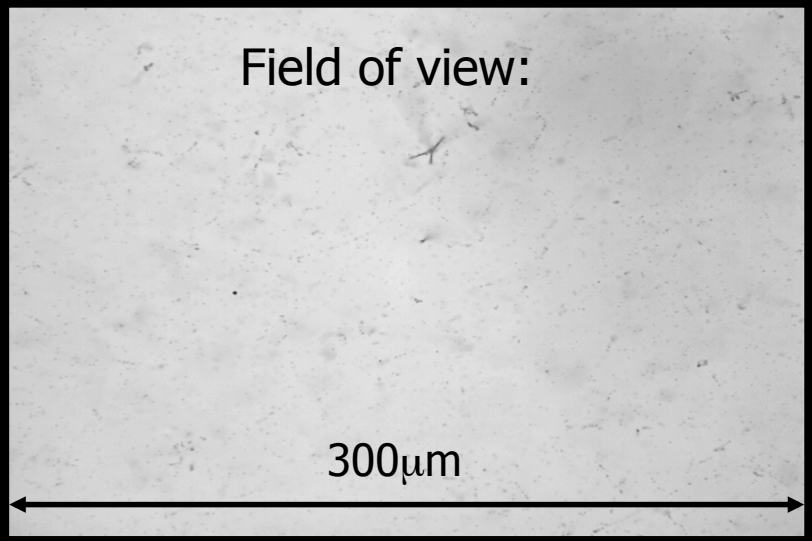
Total scanning power : 325 cm^2/h

European Scanning System (ESS)

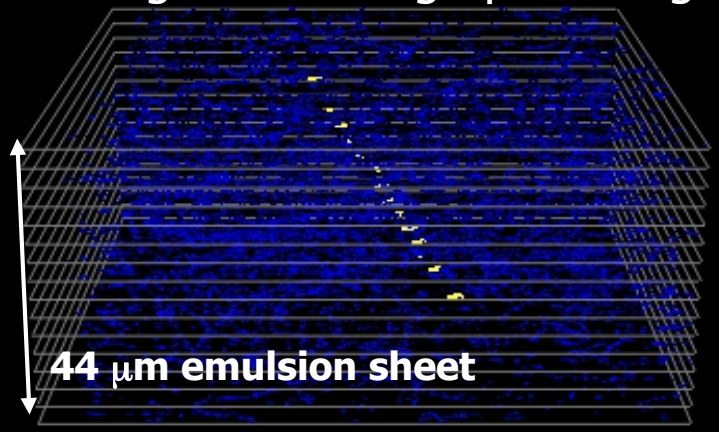
33 systems in Europe

Total scanning power : 660 cm^2/h

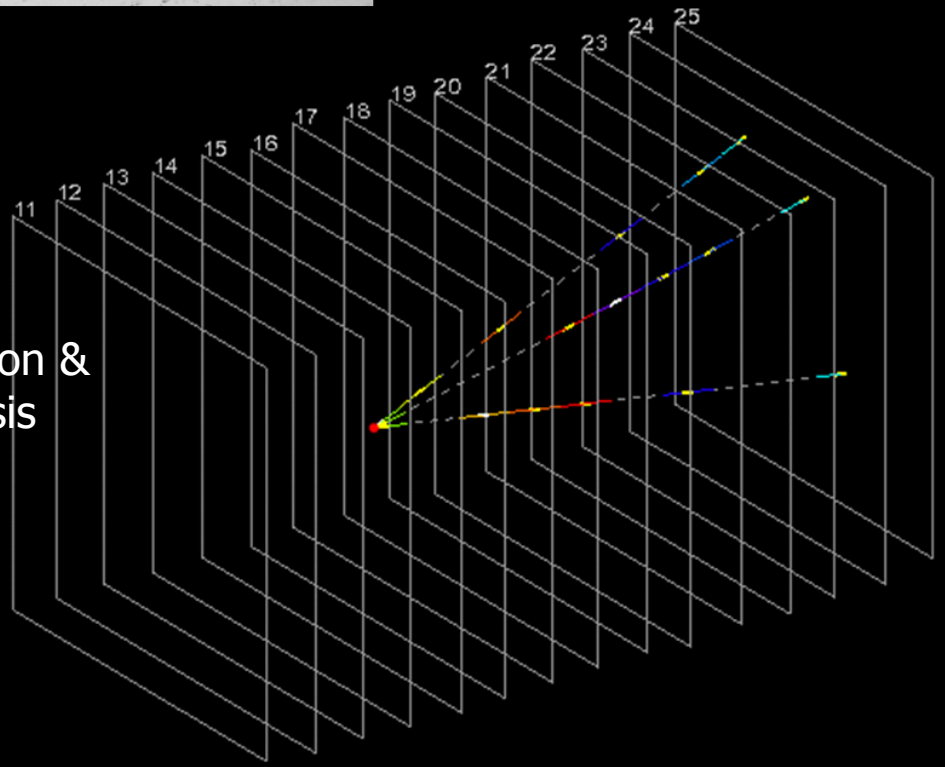
Scanning



2d image: 16 tomographic images



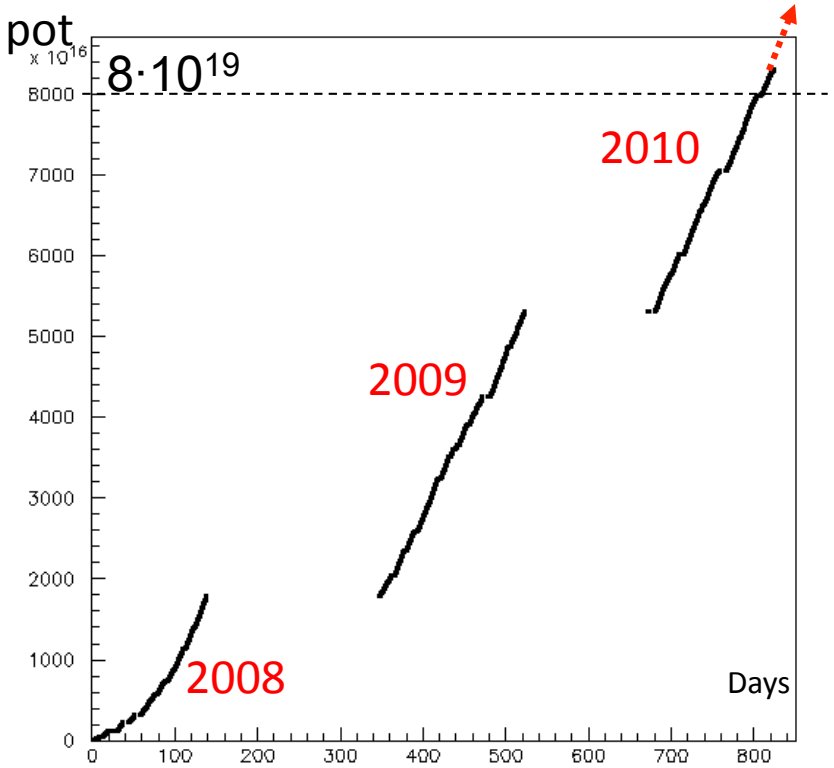
Vertex reconstruction & kinematic analysis



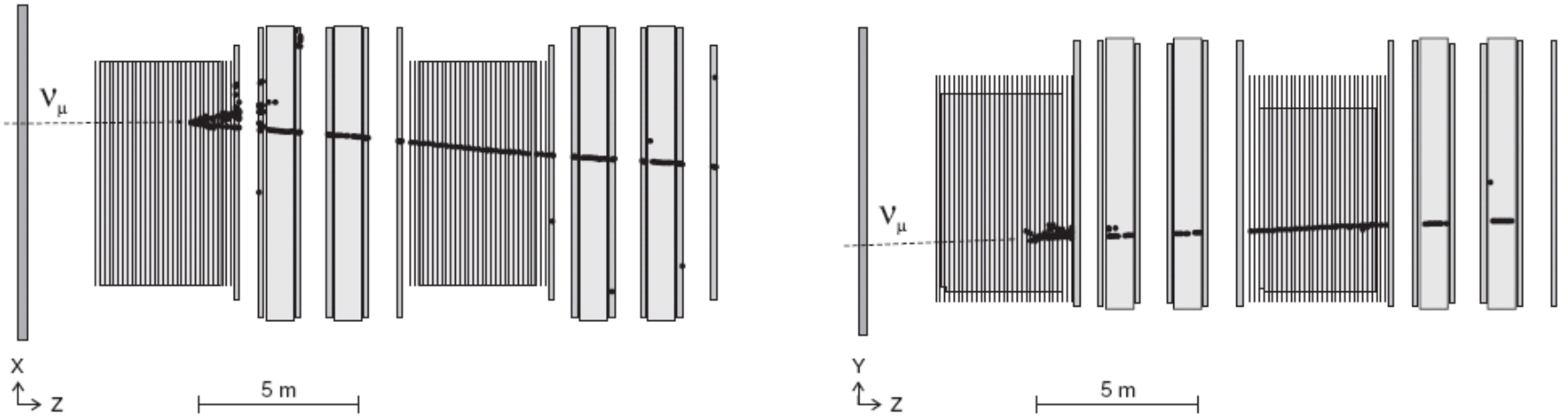
CNGS beam performance & statistics

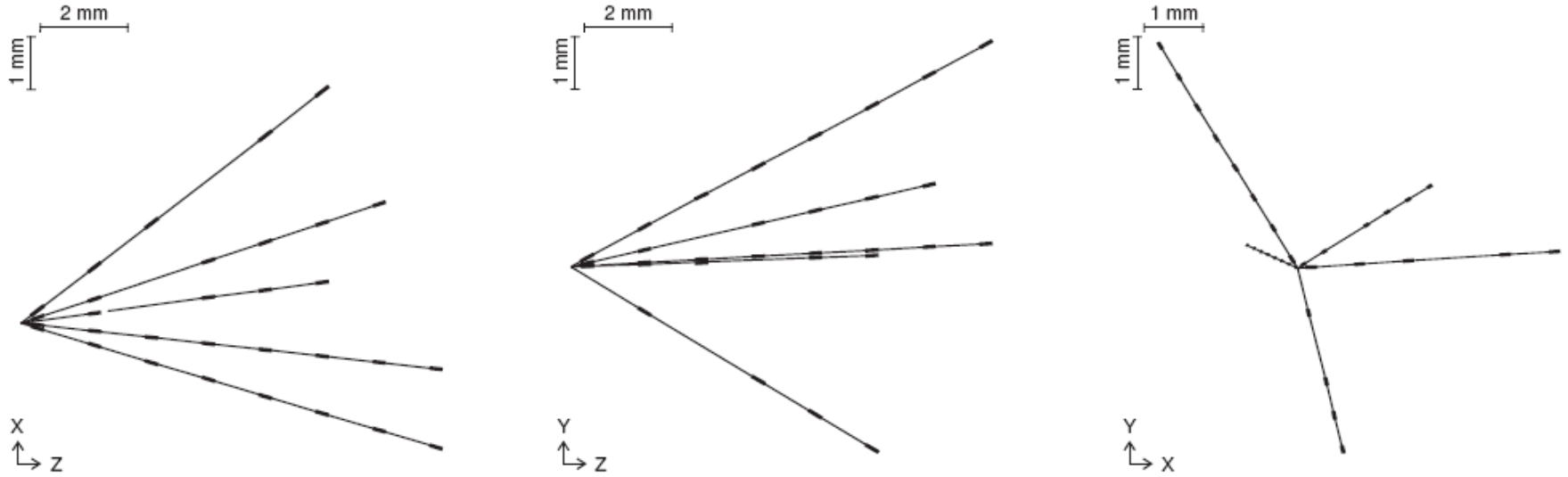
2006	0.076x10^{19} pot	no bricks	Commissioning
2007	0.082x10^{19} pot	38 events	Commissioning
2008	**1.78x10^{19} pot**	**1698 evts(scan input)**	**First physics run**
2009	**3.52x10^{19} pot**	**3693 evts(scan input)**	**Physics run**
2010 (ongoing)	**3.01x10^{19} pot (20.Sept.)**	**3167 evts (20. Sept.)**	**Physics run**

8558 evts (scan input) collected until 20/9/2010

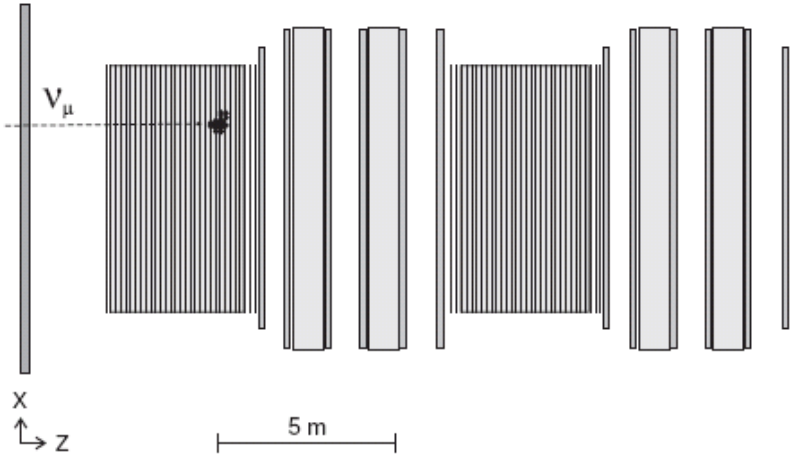


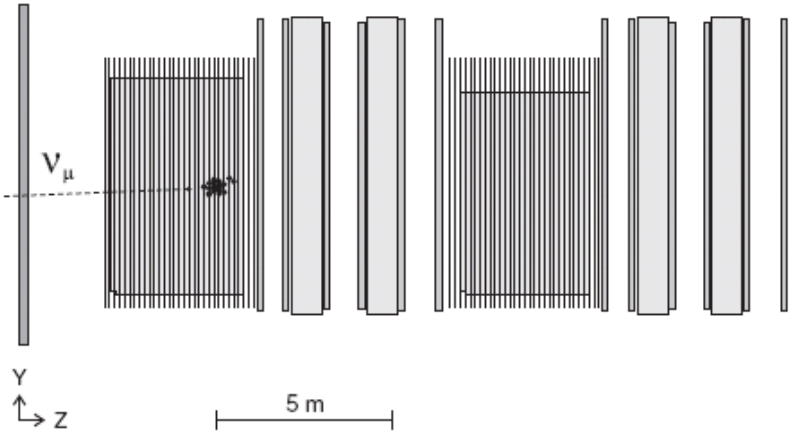
Example of a CC event:

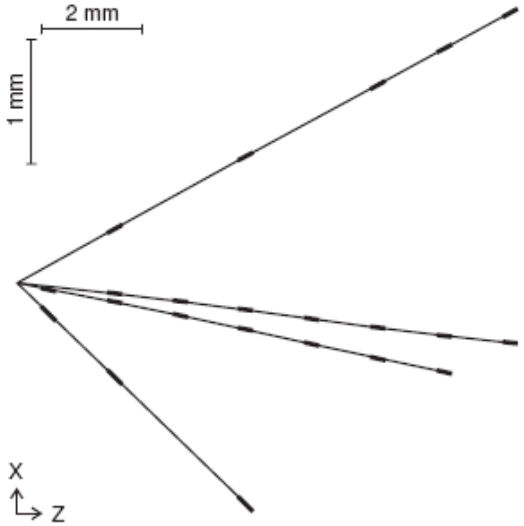


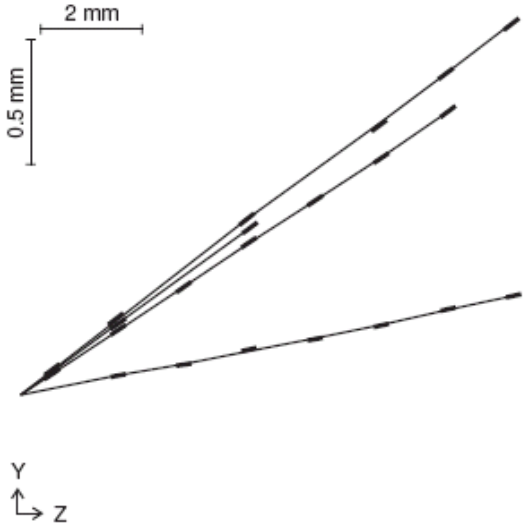


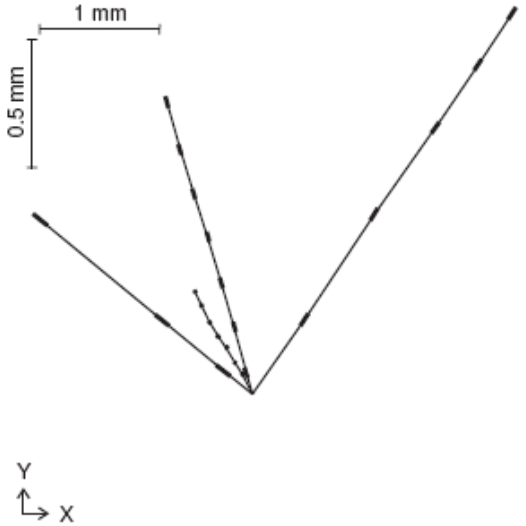
Example of a NC event:











The measured ratio NC/CC is ≈20%, as expected from simulations

Event statistics (June 2010)

This analysis corresponds to ~35% of the 2008-2009 run statistics,
= 1.89 x 10^{19} pot

1813 events found in the target (scan input)

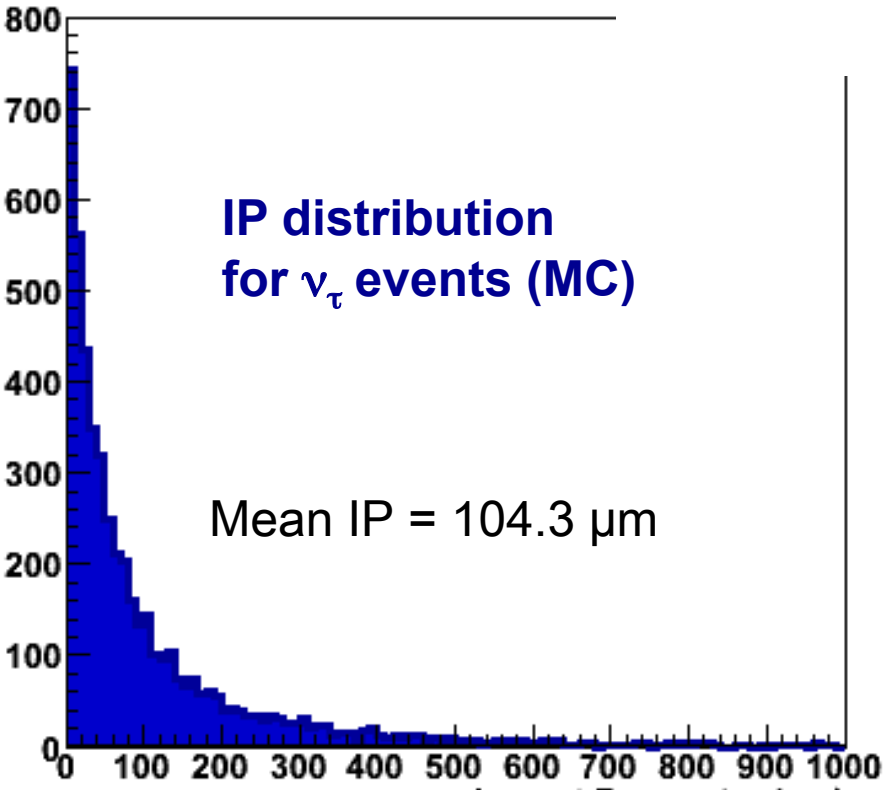
Events with neutrino vertices located by scanning: 1617
(Brick tagging efficiency) x (vertex location efficiency) ≈ 60%

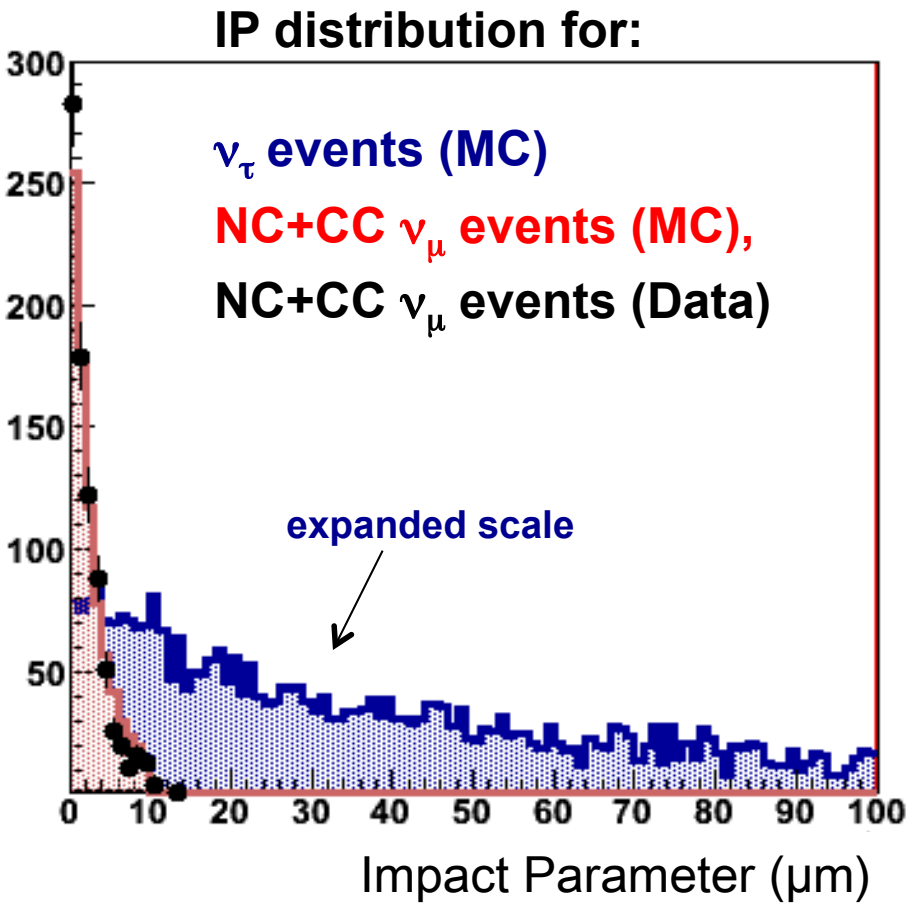
Events for which "decay search" was completed: 1088 (187NC, 901CC)

With the above statistics, and for Δm^2_{23} = 2.5 x10^{-3} eV^2 and full mixing, OPERA expects:

~ 0.5 ν_τ events

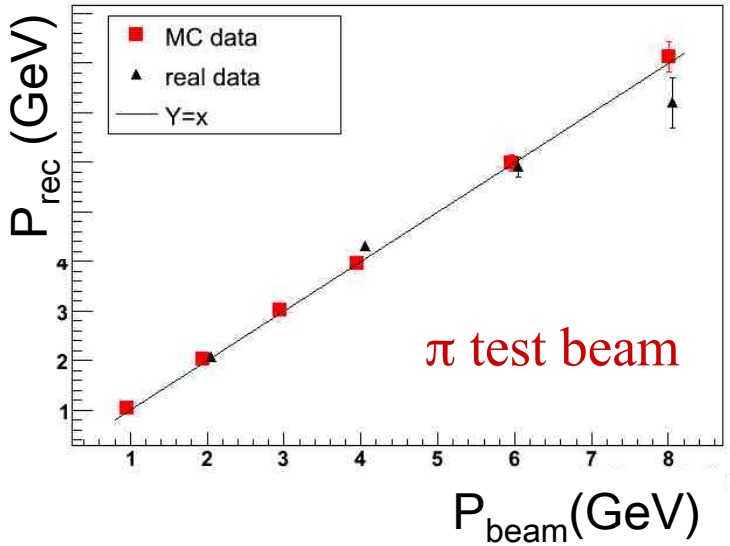
Impact Parameter Measurement

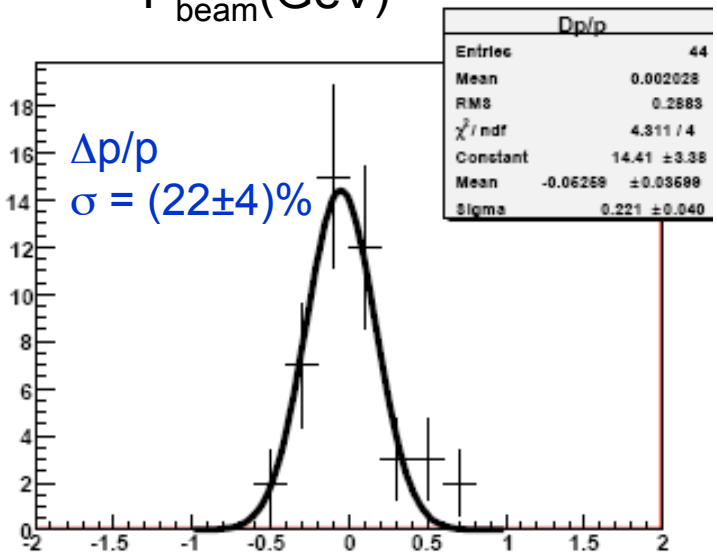




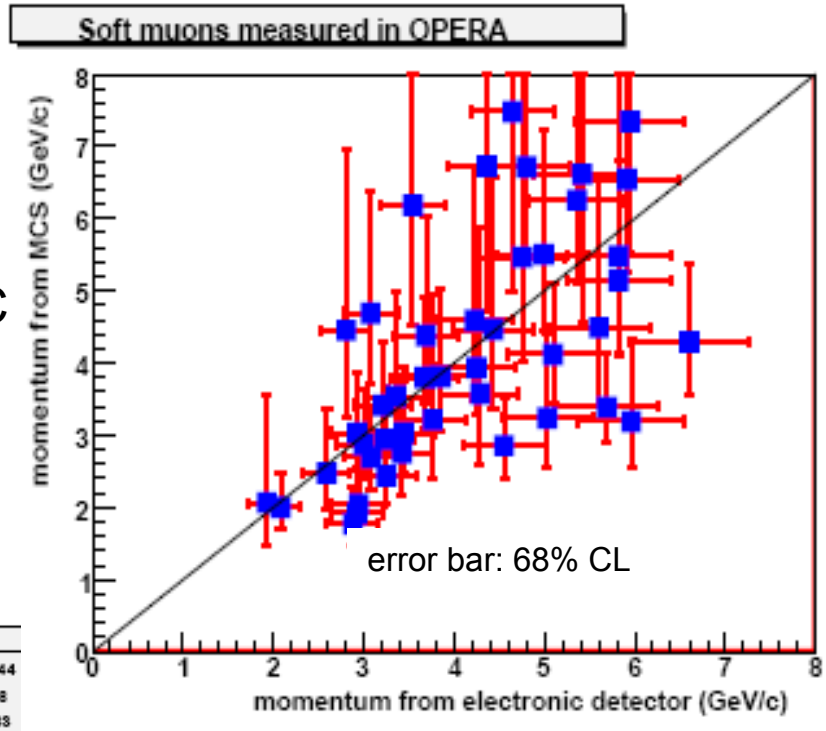
Momentum Measurement with ECC and Electronic Detector

Momentum measured in ECC
(by multiple Coulomb scattering)





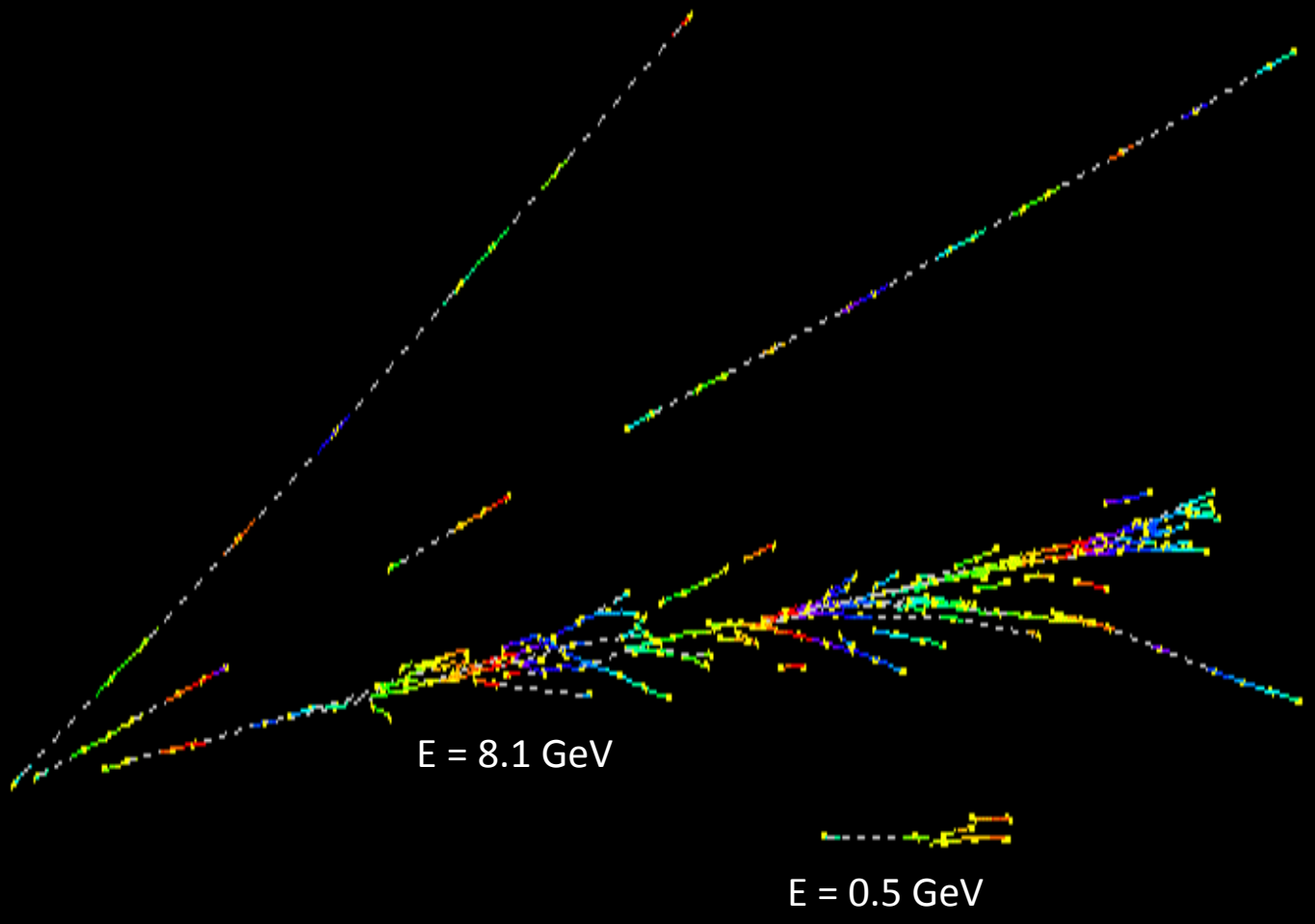
ECC



Electronic Detector

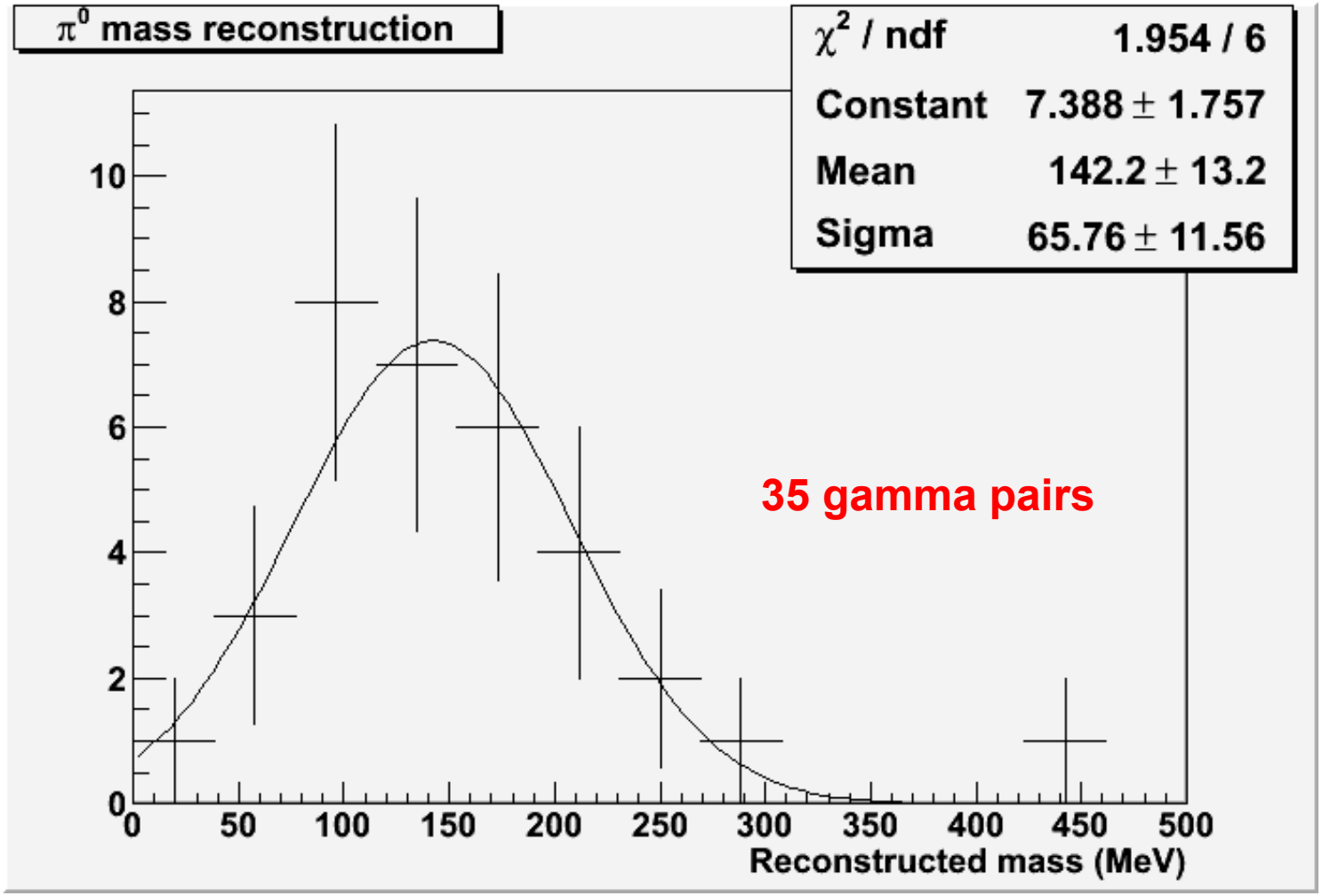
γ – Detection and Reconstruction of π^0 mass

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



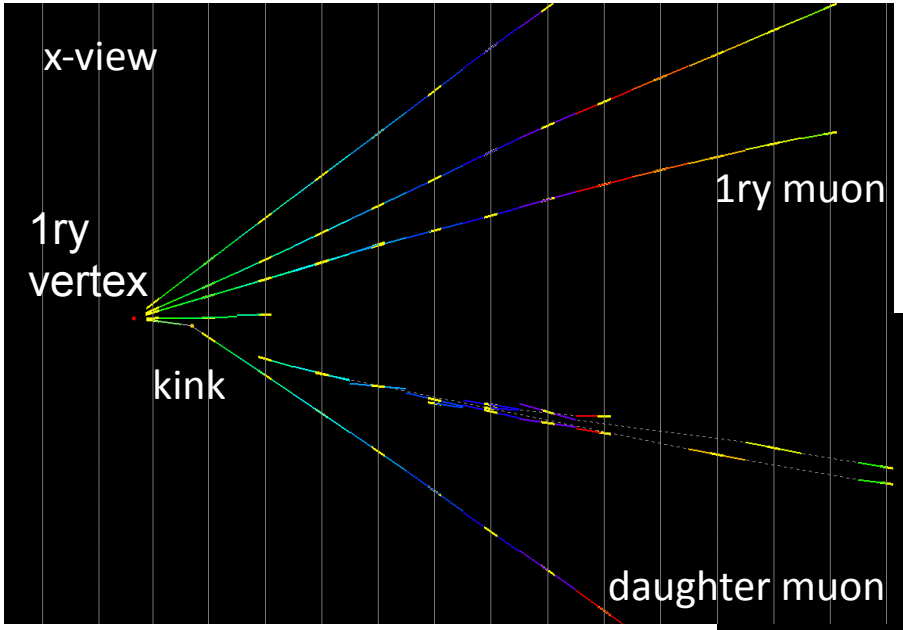
reconstructed mass from 2 EM showers ~ 160 MeV

π^0 mass resolution (real data)

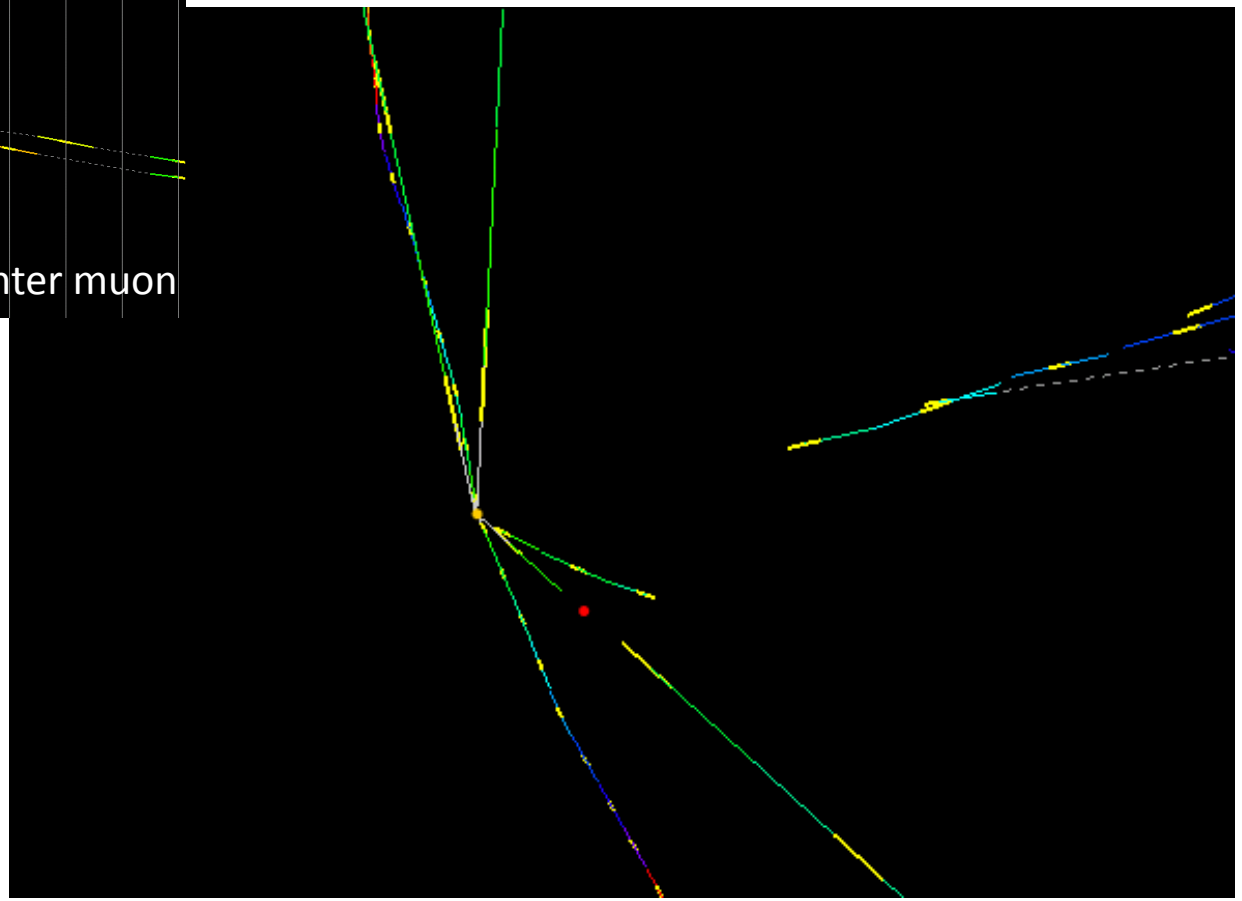


1 σ mass resolution: ~ 66 MeV

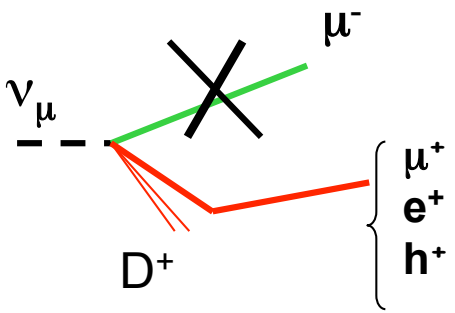
Charm candidate event (dimuon)



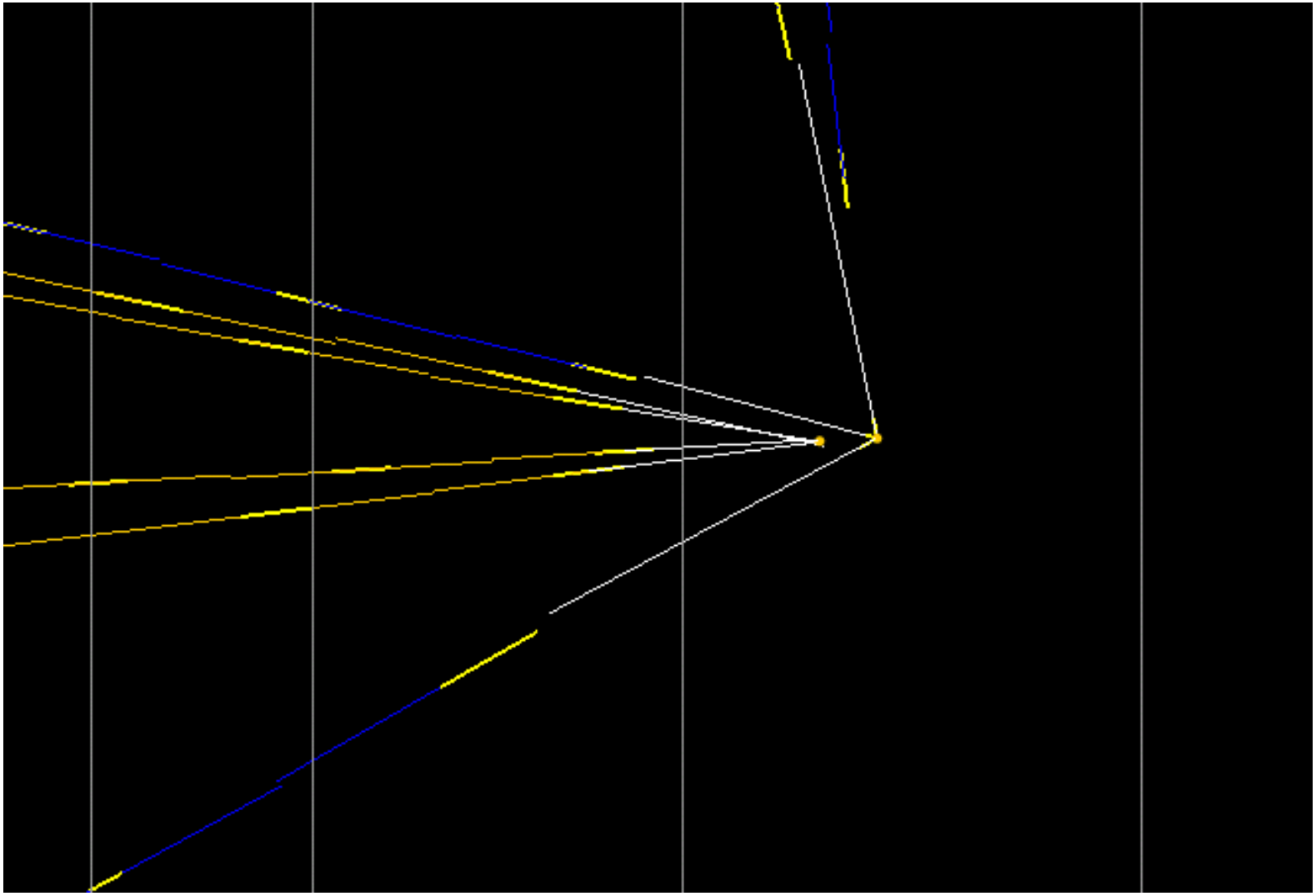
flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay Pt: 0.46 GeV/c



Background, if primary muon not identified



Charm candidate event (4-prong)



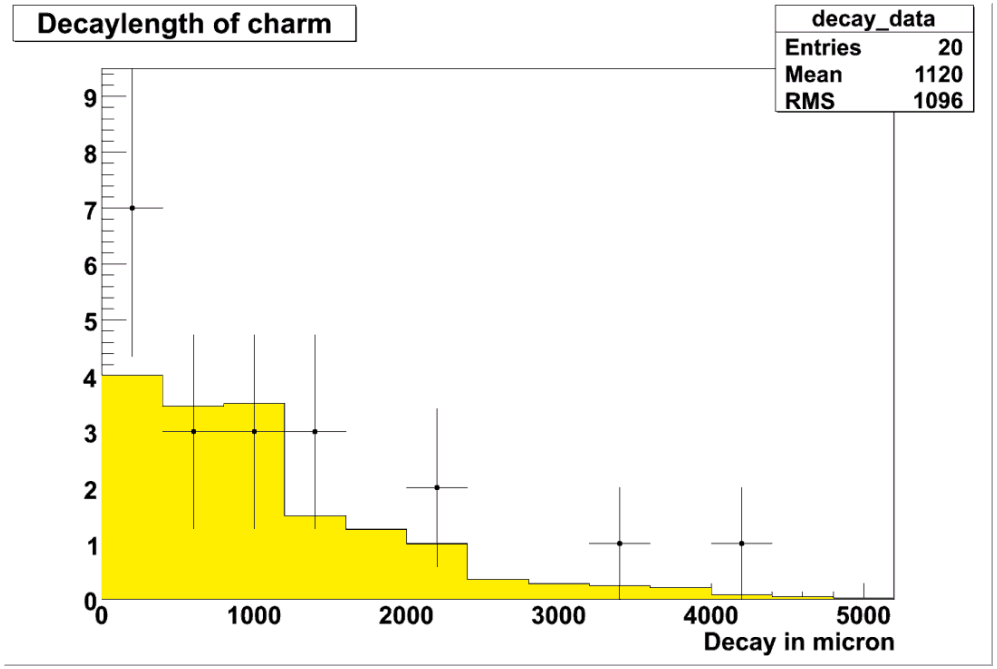
D_0 hypothesis: F.L.= 313.1μm, φ = 173.2^0, invariant mass = 1.7 GeV

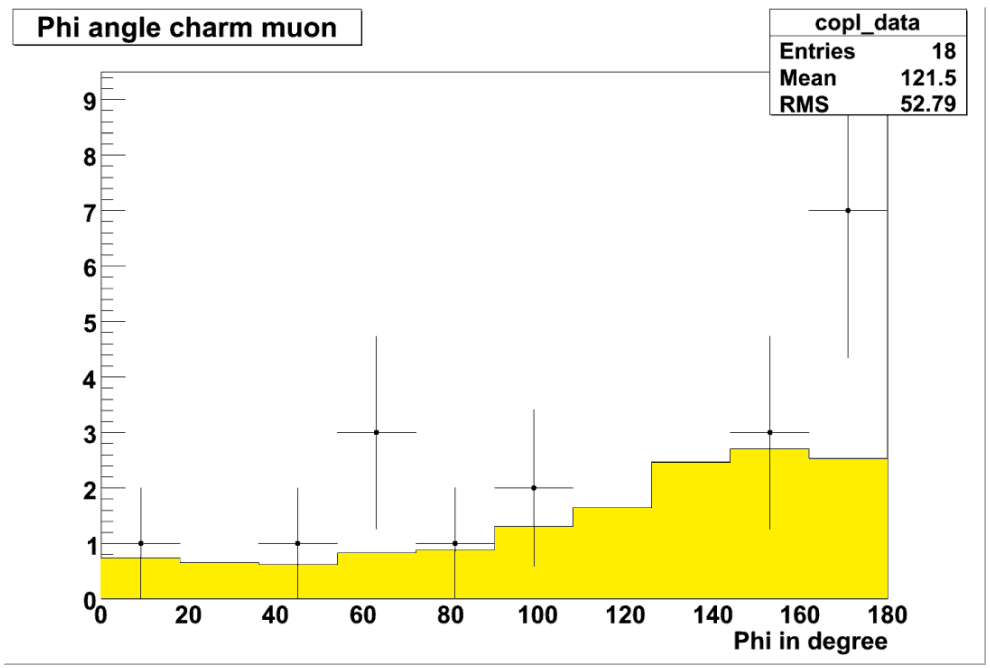
Main Kinematic Cuts for Charm Events

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

20 charm candidate events selected by the kinematic 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

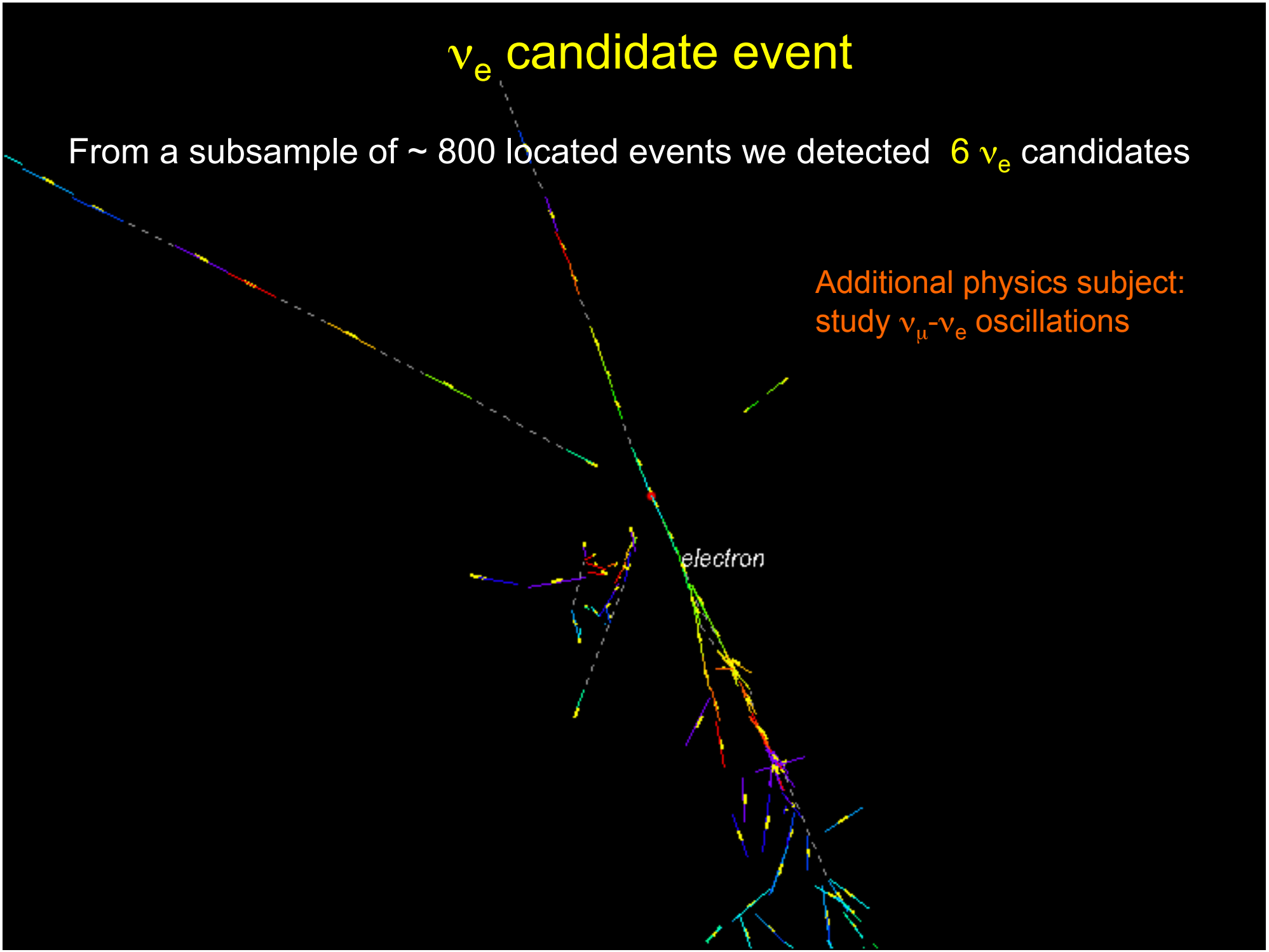
Examples of distributions:





ν_e candidate event

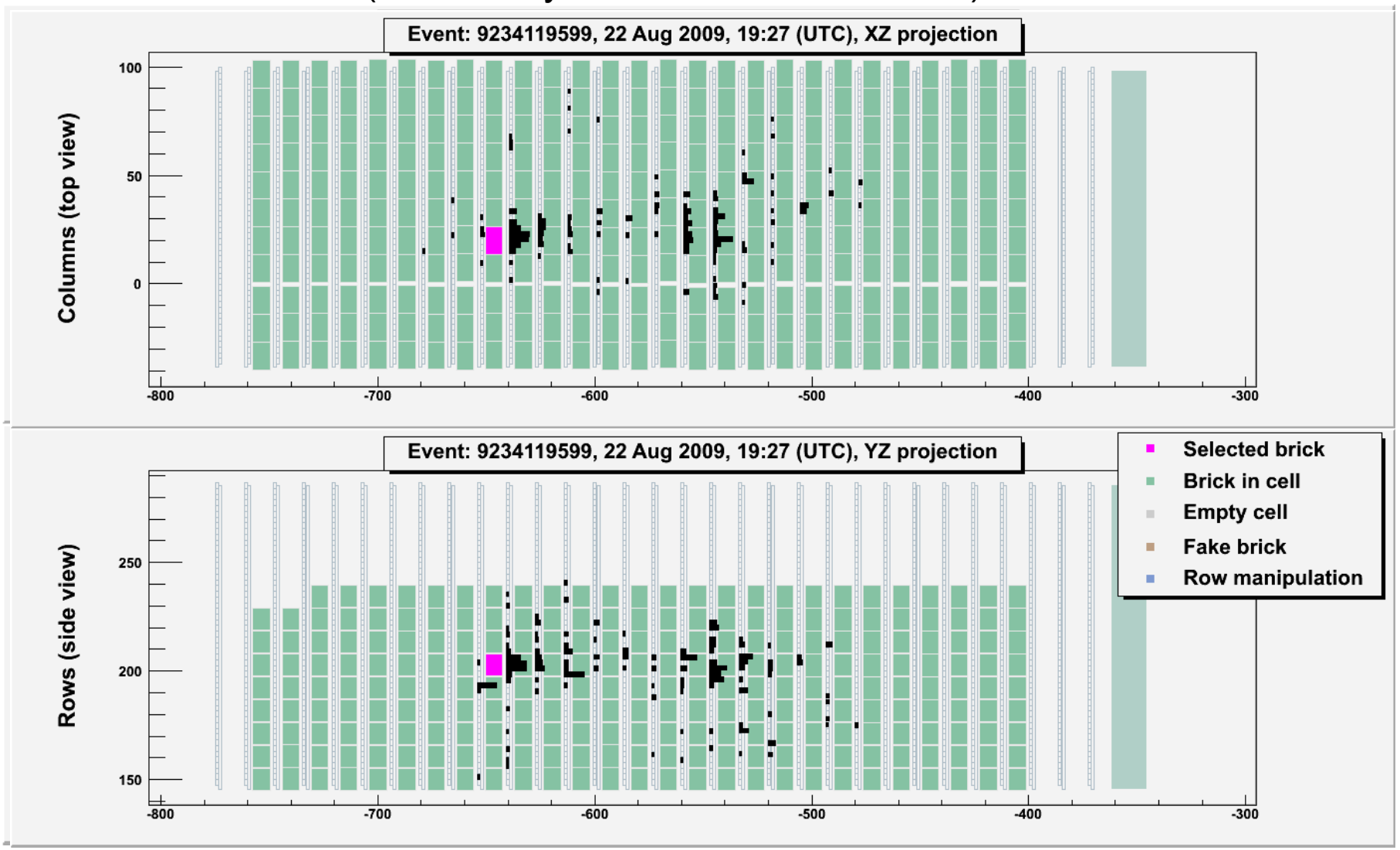
From a subsample of ~ 800 located events we detected 6 ν_e candidates



Additional physics subject:
study ν_μ-ν_e oscillations

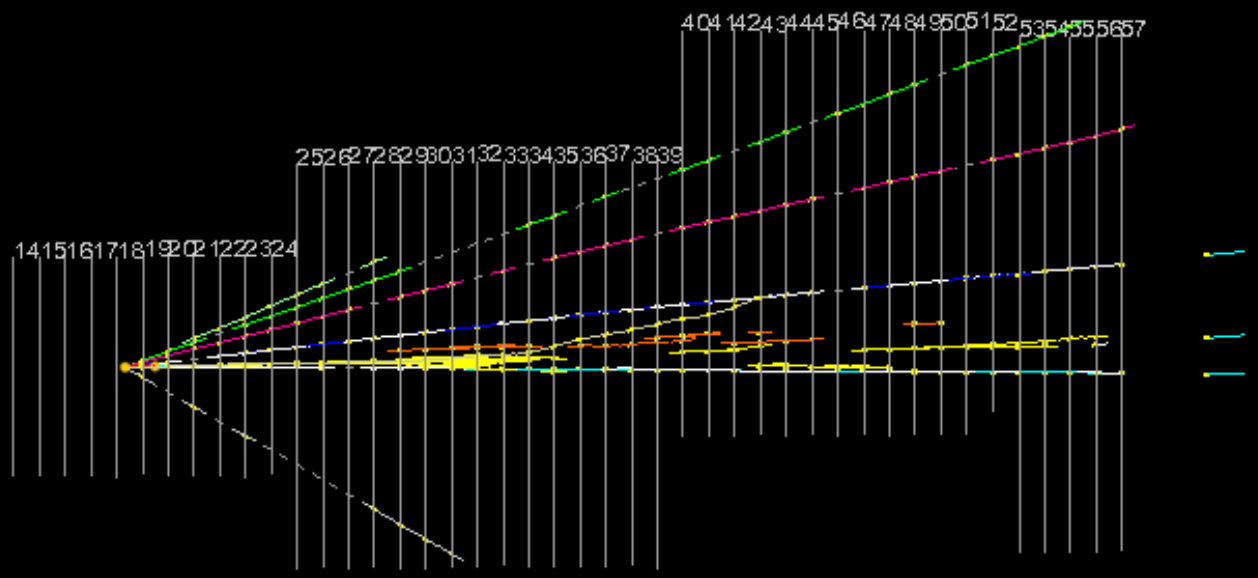
The ν_τ candidate event

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

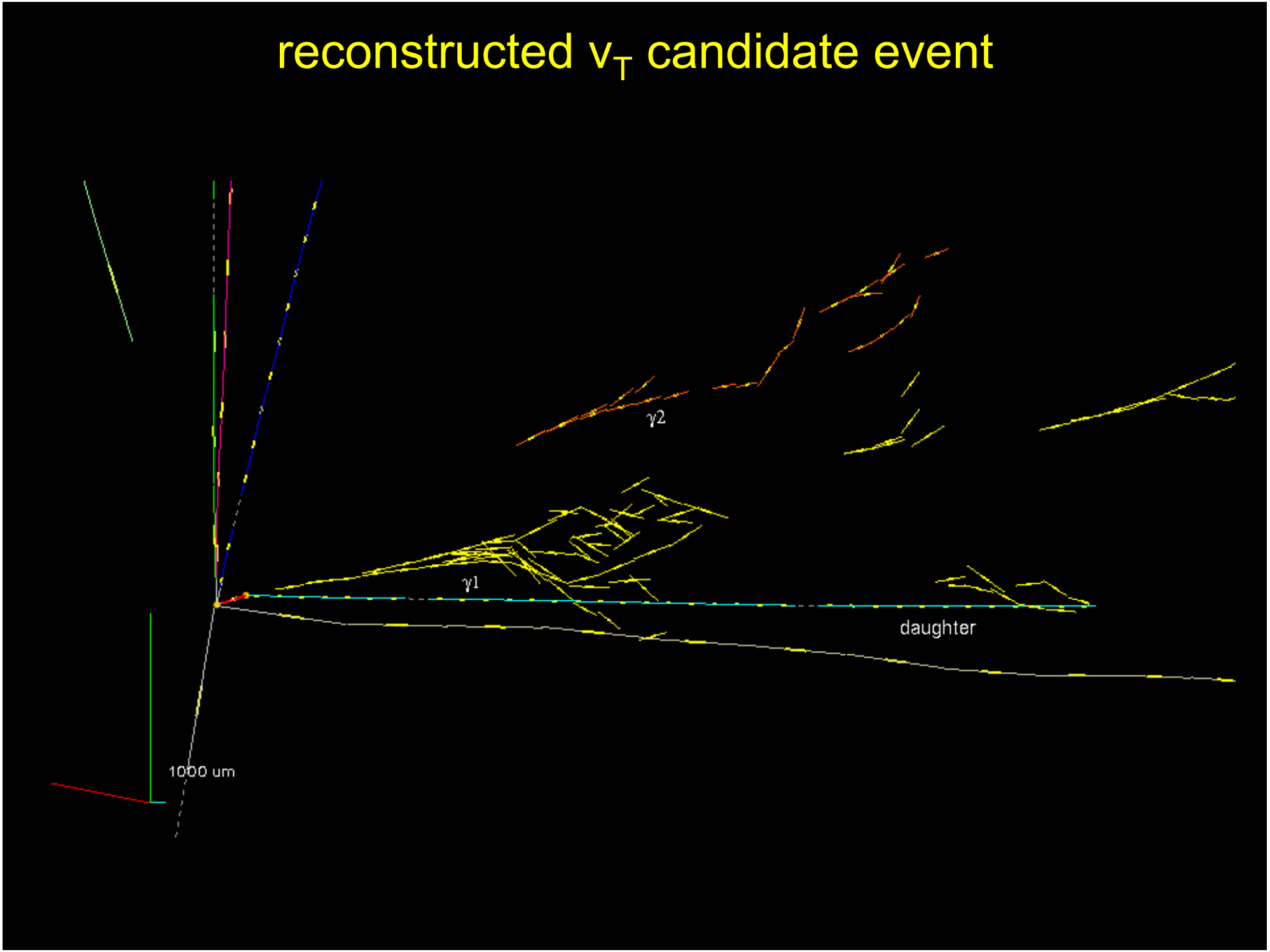


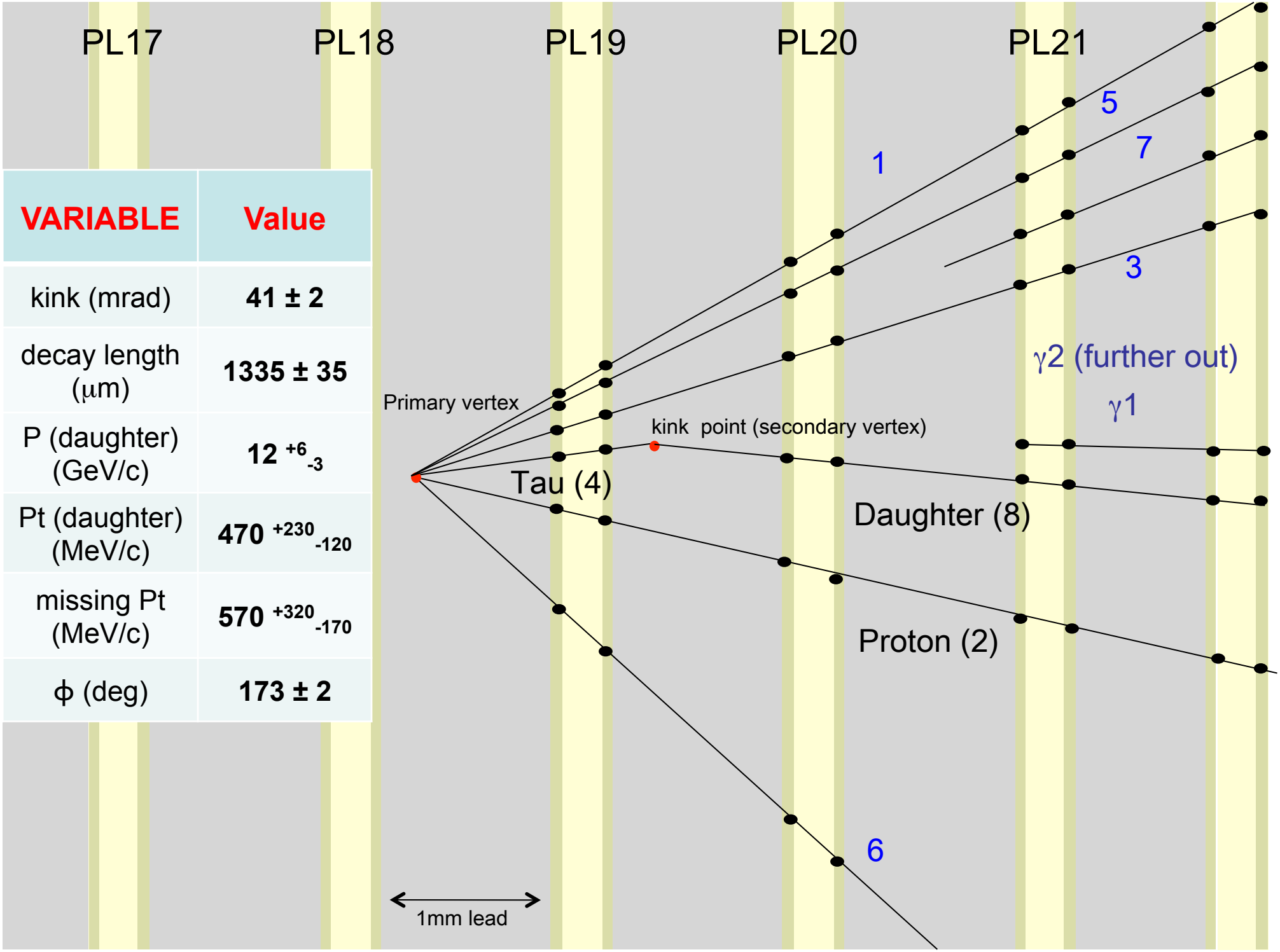
ν_T candidate: from CS to vertex location

Large area scanning
Full reconstruction of vertices and gammas

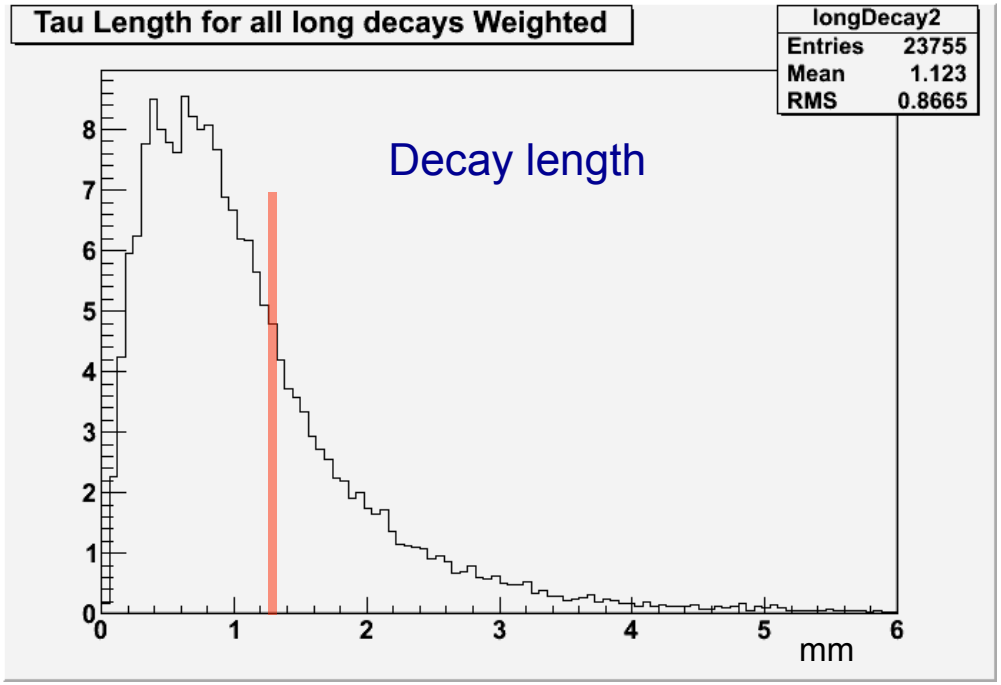


reconstructed ν_T candidate event

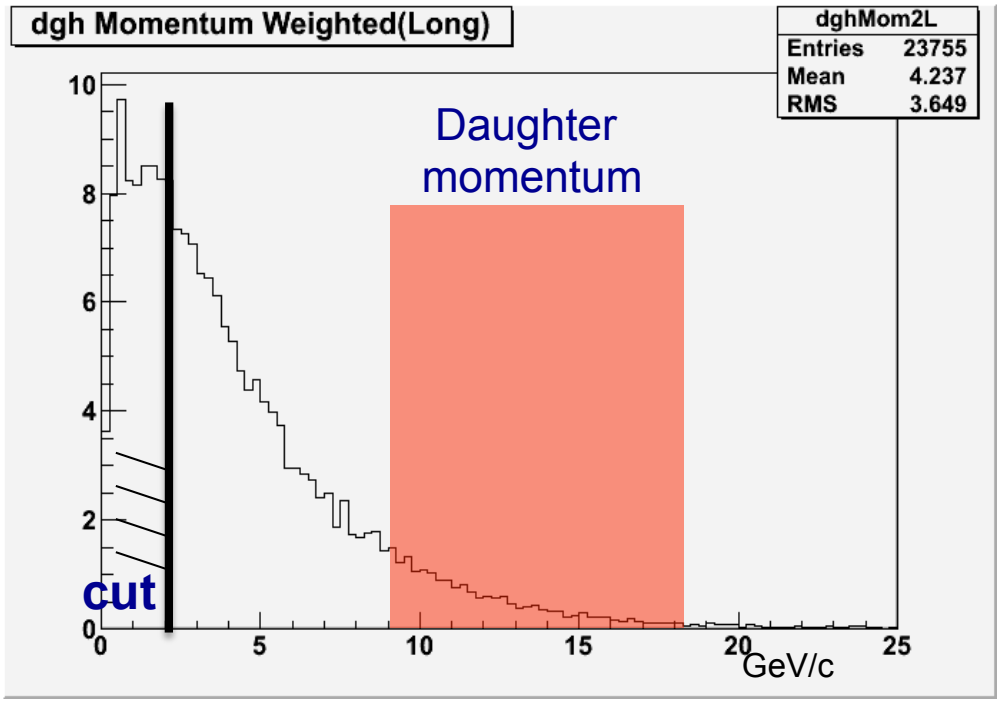


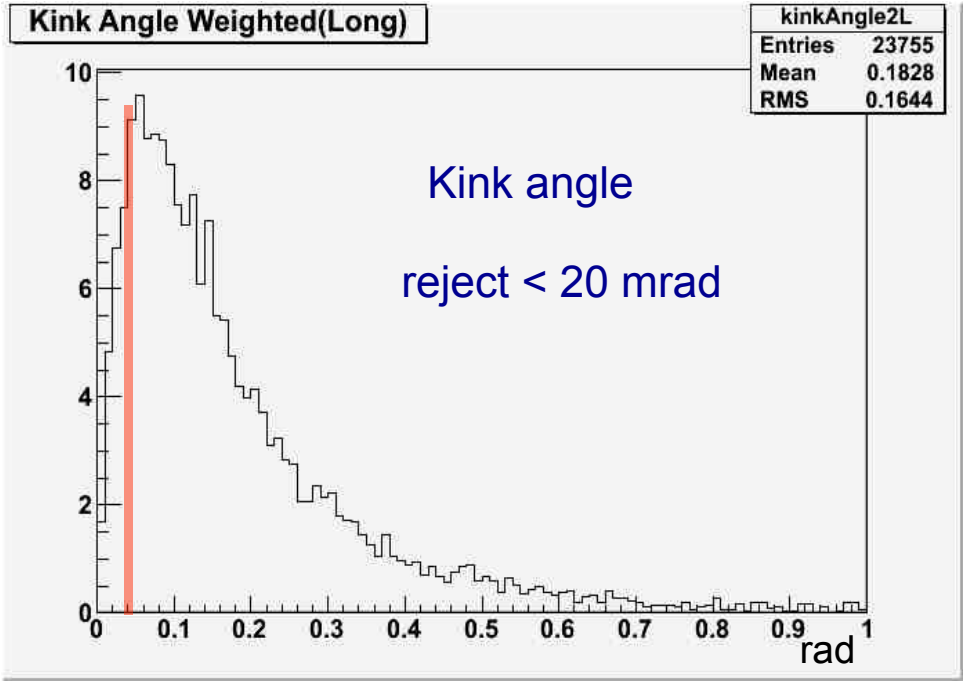


VARIABLE	Value
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P (daughter) (GeV/c)	**12^{+6}_{-3}**
Pt (daughter) (MeV/c)	**470^{+230}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**



Red regions:
measured values for v_T candidate





Interpretation of the event

- Invariant mass of $\gamma\,\gamma$ system compatible with π^0 mass value.
- Invariant mass of the $\pi\,\gamma\,\gamma$ system compatible with ρ (770)

π^o mass	ρ mass
120 ± 20 ± 35 MeV	$640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

- ρ appears in about 25% of the τ decays:

$$\tau \rightarrow \rho\,(\pi\,\pi^0)\,\nu_\tau$$

OPERA collaboration:
„Observation of a first ν_τ candidate event in the OPERA experiment…”,
Phys. Lett. B 691 (2010) 138.

Significance of ν_τ Observation

We observe 1 event in the 1-prong hadron τ decay channel

- background expectation for 1 prong hadron decay :

  0.011 events (reinteractions)
  + 0.007 events (charm)
  = 0.018 ± 0.007 (syst) events 1-prong hadron

  probability that the observed event is due to background: 1.8 %
  significance of ν_τ observation in OPERA: 2.36 σ

- background from all decay modes:

  0.045 ± 0.020 (syst) events total BG

  probability that the observed event is due to background: 4.5 %
  significance of ν_τ observation in OPERA: 2.01 σ

Oscillation Analysis

for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and full mixing, we expect:

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 have observed 1 event.

We can exclude at 90% CL, that

$$|\Delta m^2_{23}| > 7.5 \times 10^{-3} \text{ eV}^2 \quad \text{(for full mixing)}$$

Outlook

- 2010: Getting close to nominal 4.5×10^{19}pot
- 2011: Negotiations with Cern ongoing,
  aim at partial compensation for 2012 break
- 2012 (?): LHC stop → no SPS, no pots
- We need enough pots (22.5×10^{19})
  to obtain a significant (4σ) result with high probability
- All events of 2008 and 2009 scanned by end 2010.

Waiting for more ν_τ candidates…

OPERA Collaboration

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

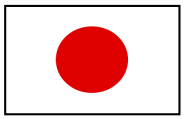
France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg
Münster
Rostock

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya



Korea
Jinju

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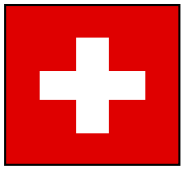
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern
ETH Zurich



Tunisia
CNSTN Tunis

Turkey
METU Ankara