Status of OPERA: Observation of a first candidate for ν_τ-appearance

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Overview

Neutrino Oscillations

The OPERA Experiment

Detector Performance

Special Events: Charm, ν_e

ν_τ Candidate

Outlook

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Neutrino Mass and Mixing

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

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

θ_{atm} θ_{13}, δ θ_{sol}

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

$\theta_{23} \approx 45°$	$\theta_{13} < 13°$, δ ?	$\theta_{12} \approx 33°$
SuperKamiokande, MINOS	Double-Chooz	Solar ν experiments, Kamland

Neutrino Mass and Mixing

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$\theta_{23} \approx 45^o$

$\theta_{13} < 13°$, δ ?

$\theta_{12} \approx 33°$

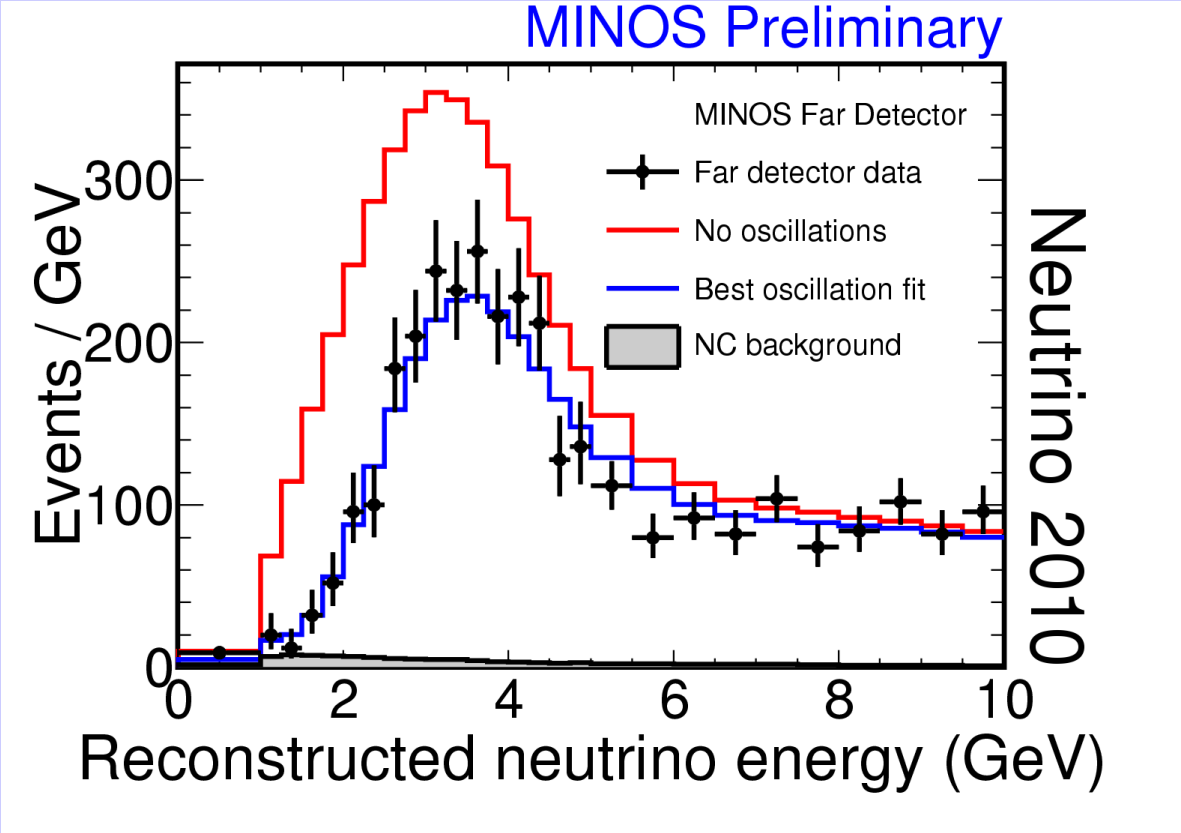
OPERA

SuperKamiokande, MINOS

Double-Chooz

Solar ν experiments, Kamland

MINOS Results: Fit to Oscillation Hypothesis



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

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

(best fit)

(for 7.2·10²⁰pot)

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ν_τ Candidate

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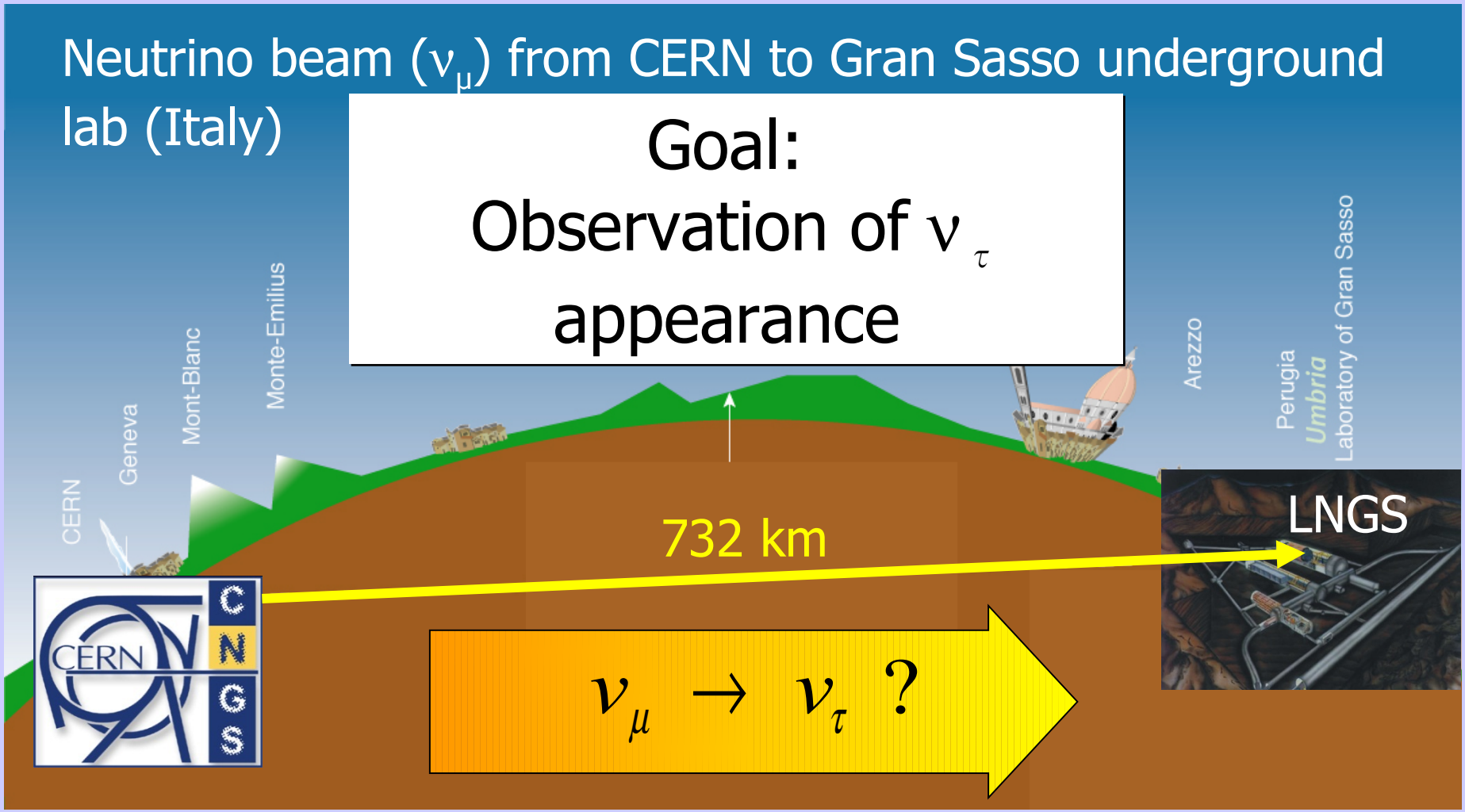
OPERA:
Oscillation Project with Emulsion tRacking Apparatus

Neutrino beam (ν_μ) from CERN to Gran Sasso underground lab (Italy)

Goal:
Observation of ν_τ appearance



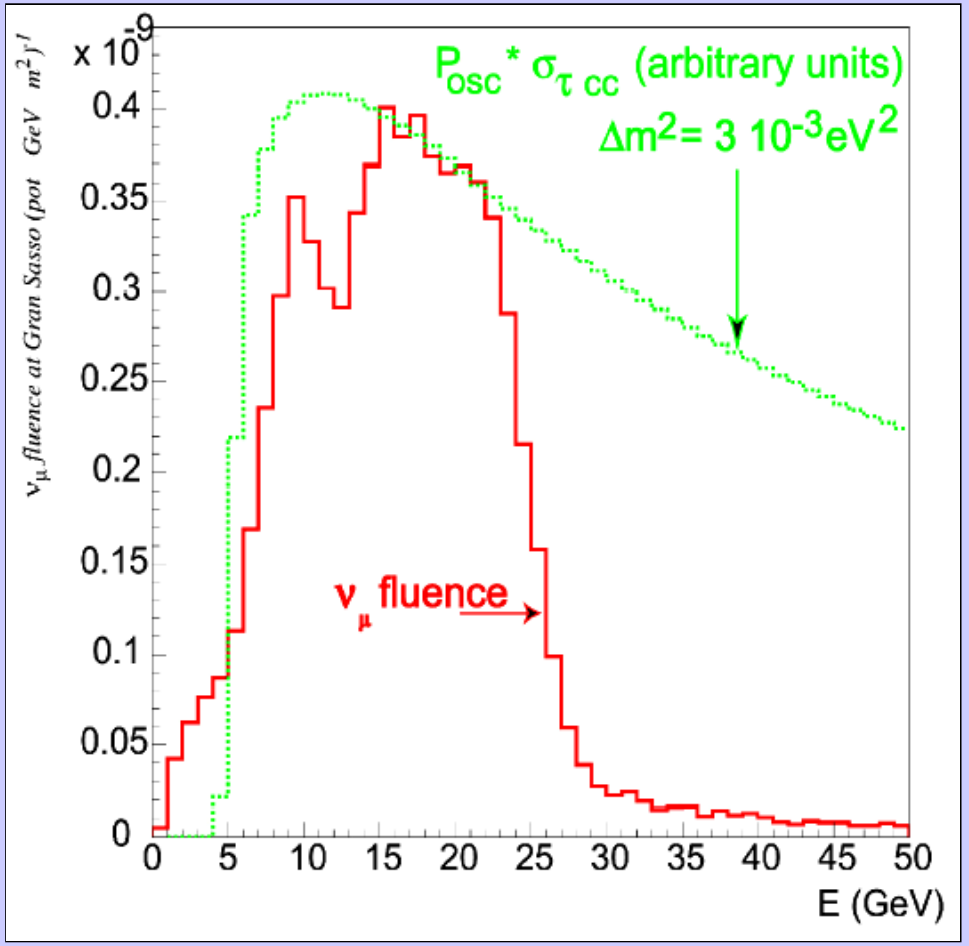
Physics runs: 2008 and 2009 completed, 2010 ongoing

CERN Neutrinos to Gran Sasso Beam

Beam Characteristics:

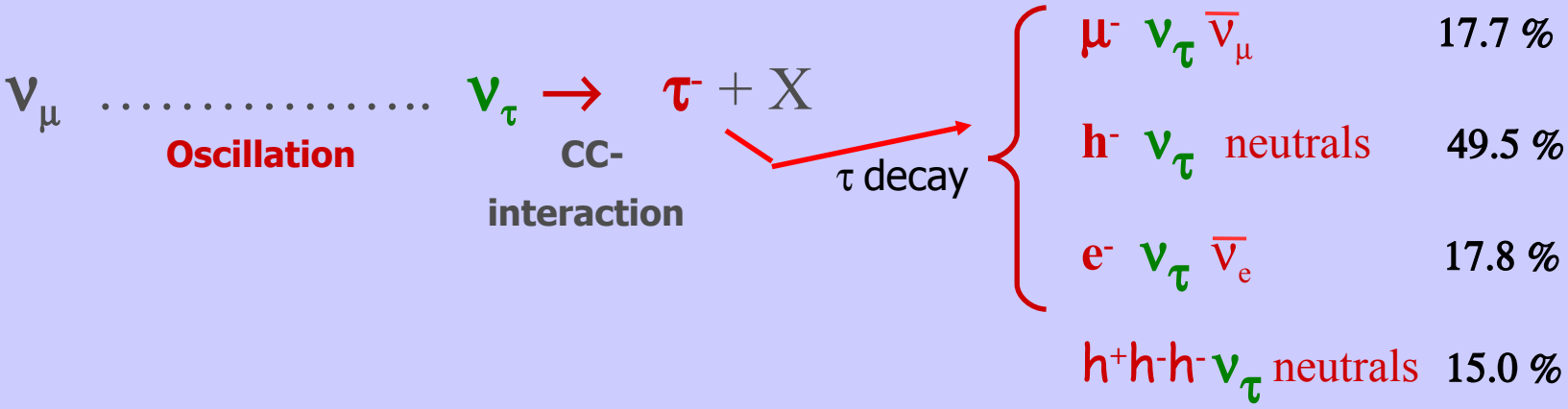
p.o.t./year	$4.5\ 10^{19}$
$<E_\nu>$	17 GeV
L	732 km
$(\nu_e+\nu_e)/\nu_\mu$	0.87%
ν_μ/ν_μ	2.1%
ν_τ/ν_μ	negligible ($\sim 10^{-7}$)

Total exposure expected:
$22.5 \cdot 10^{19}$ p.o.t.

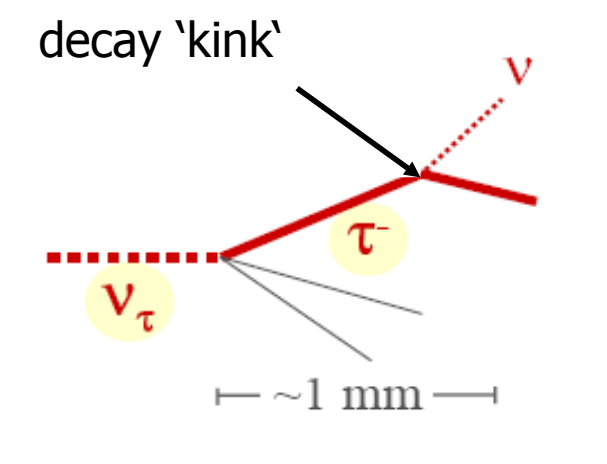


Detector Concept

- Goal: Direct observation of ν_τ in ν_μ beam



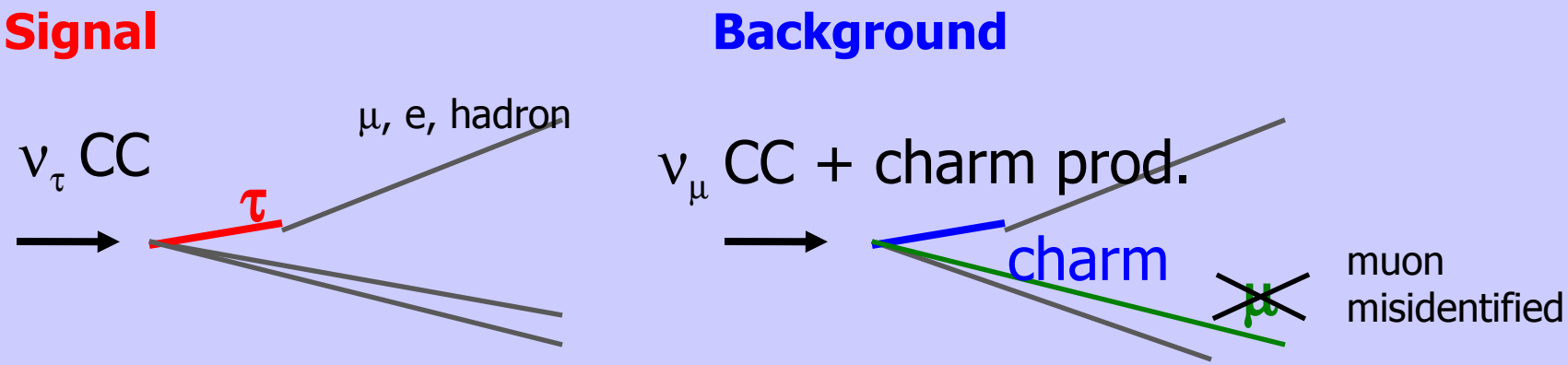
- OPERA has to look for this special topology



Background Processes

Most important background processes:

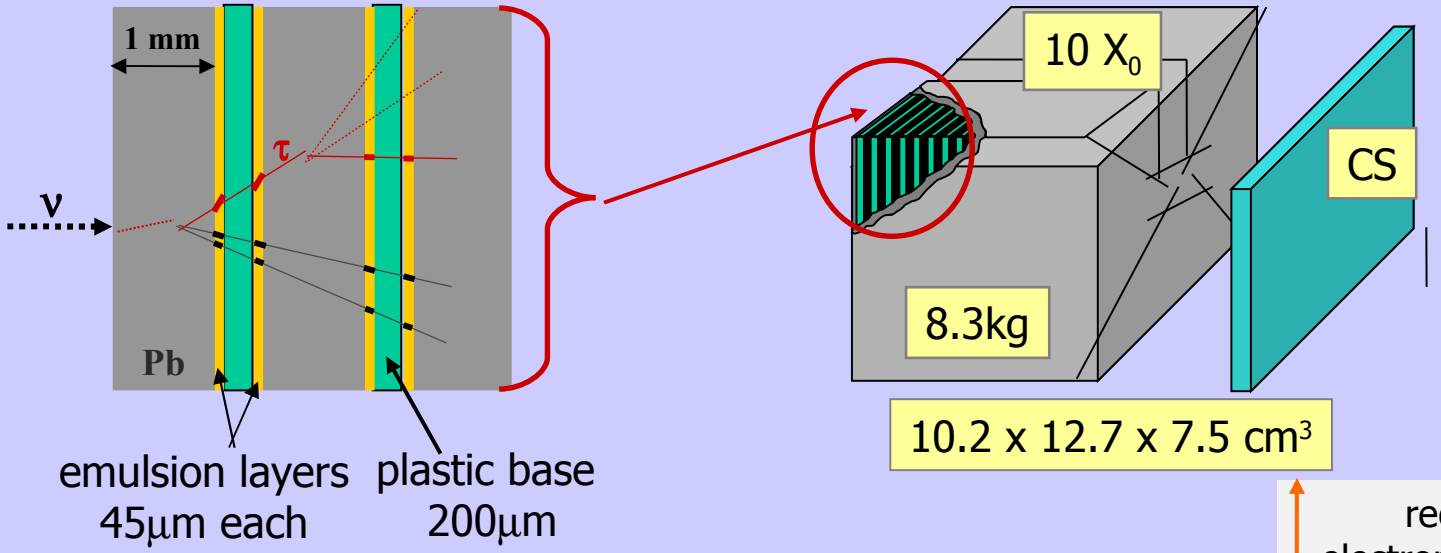
- Charm production and decay
- Hadron re-interactions in lead
- Large-angle muon scattering in lead

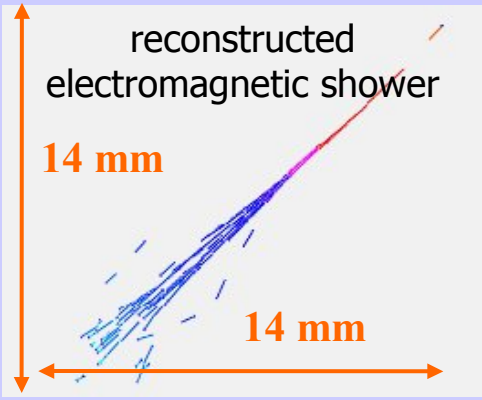


Use Emulsion Cloud Chambers (ECC) to achieve a high enough spatial resolution and density.

The OPERA Brick

- Sandwich of 56 Pb sheets 1mm + emulsions
- High spatial resolution (track: $\sigma_x \approx 0.05\mu m$, $\sigma_\theta \approx 2mrad$, vertex: $\sigma_x \approx 1\mu m$)
- Changeable Sheets (CS) with emulsion doublet for first checks

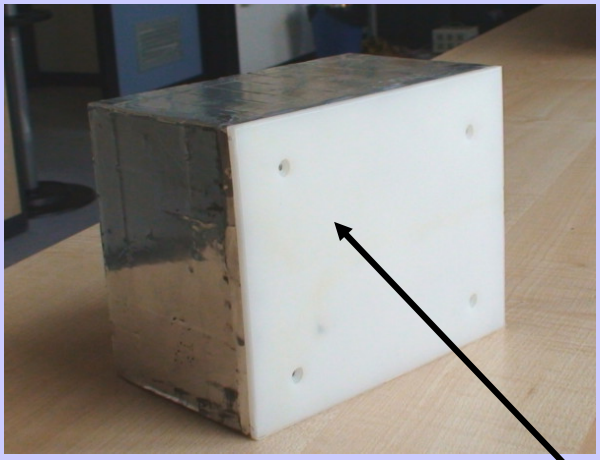


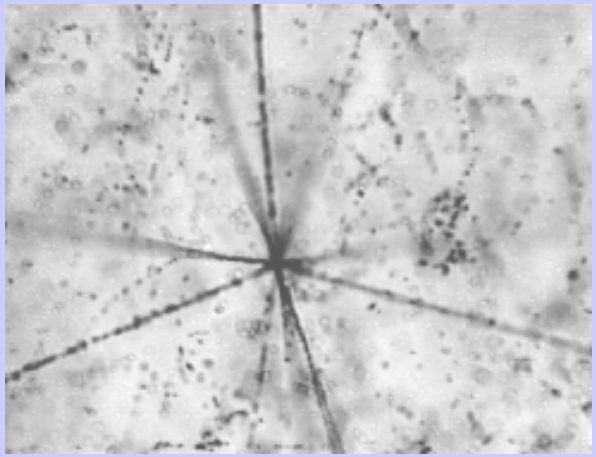


ECC = Stand-alone Detector:

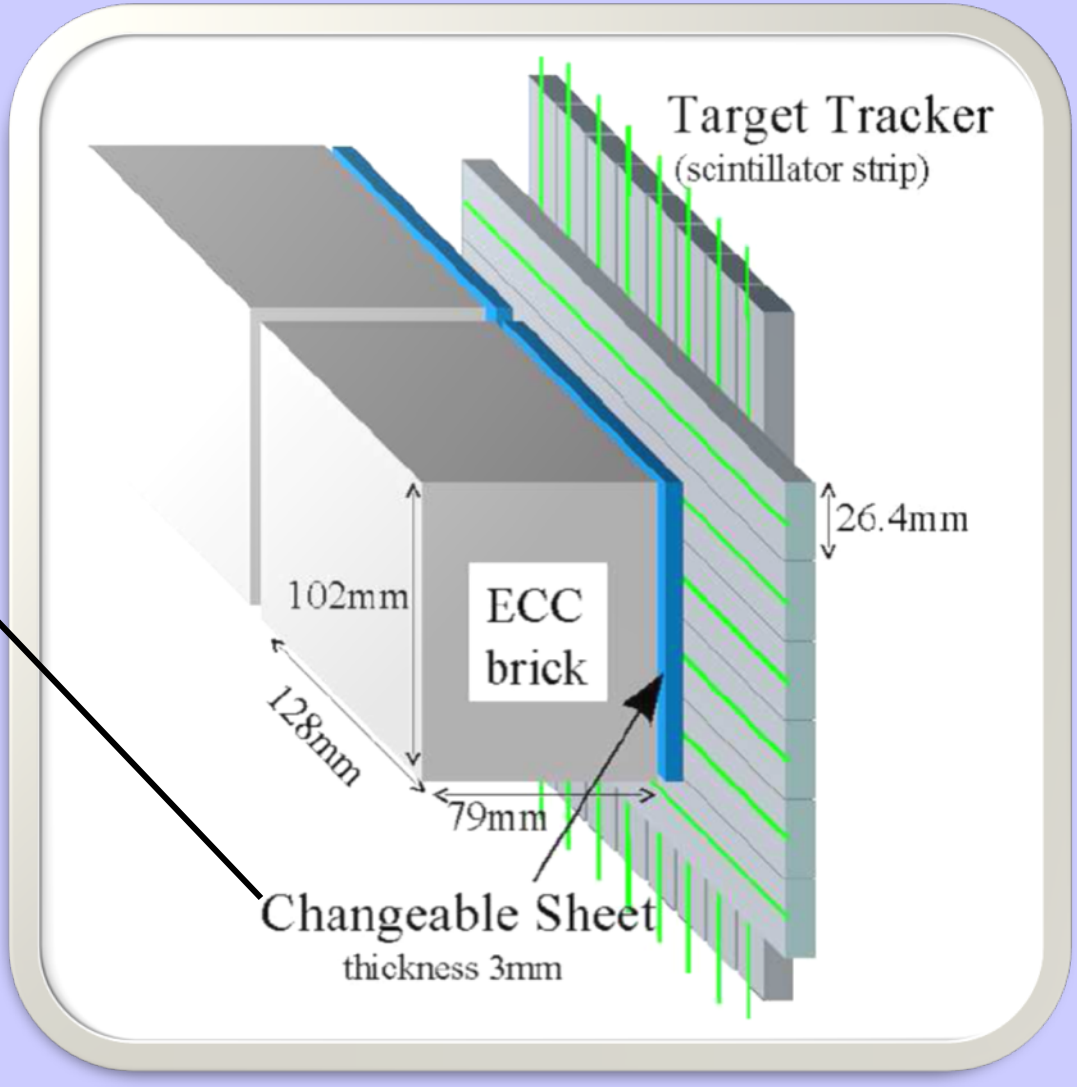
- Momentum measurements for hadrons (multiple scattering)
- Pion/Muon separation at low energy (dE/dx)
- Electron identification and energy measurements for e,γ

Hybrid Detector

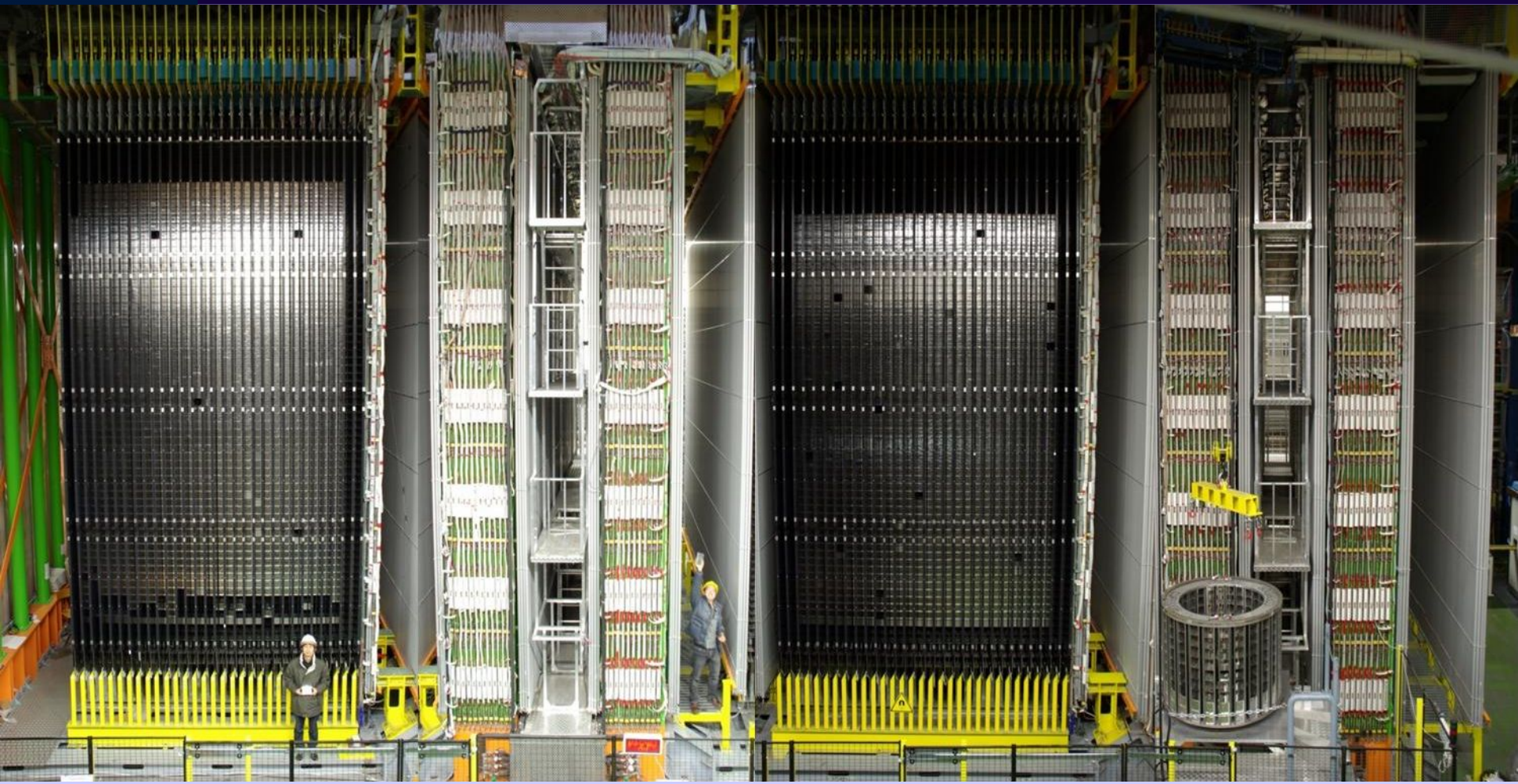




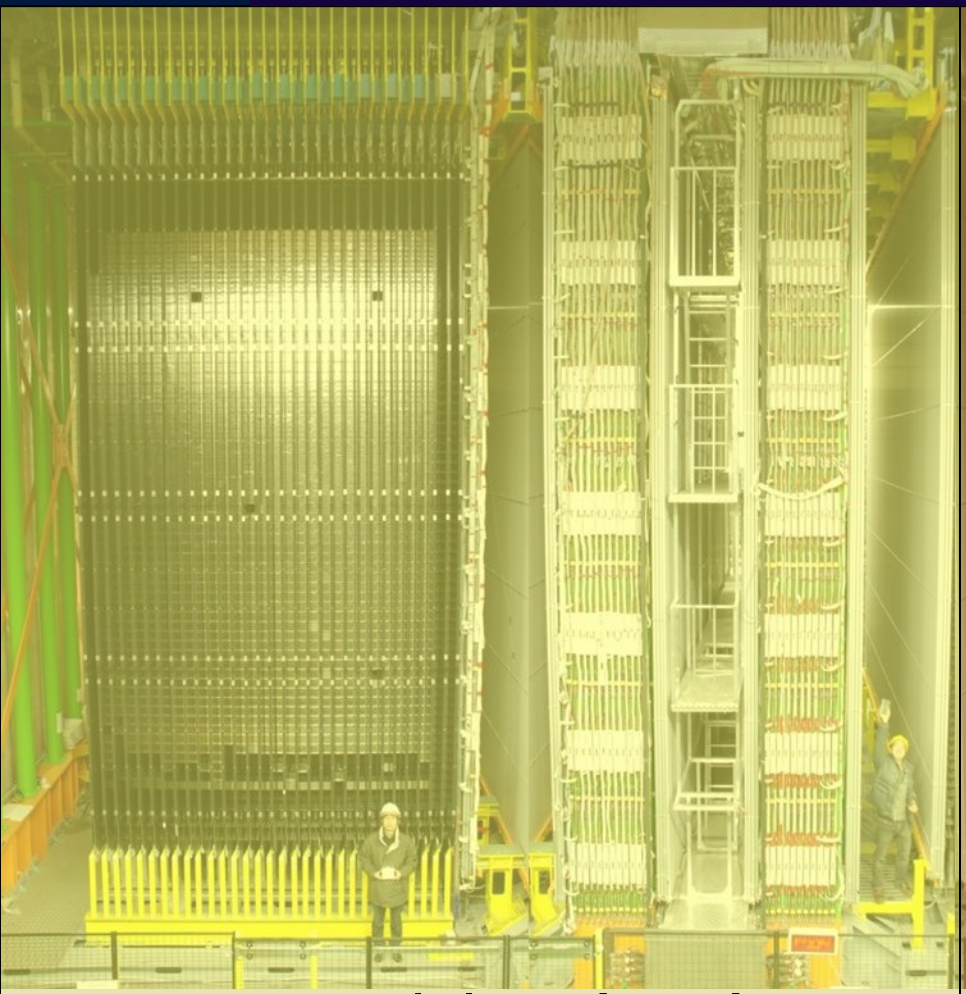
Emulsion Cloud Chambers



The OPERA Detector



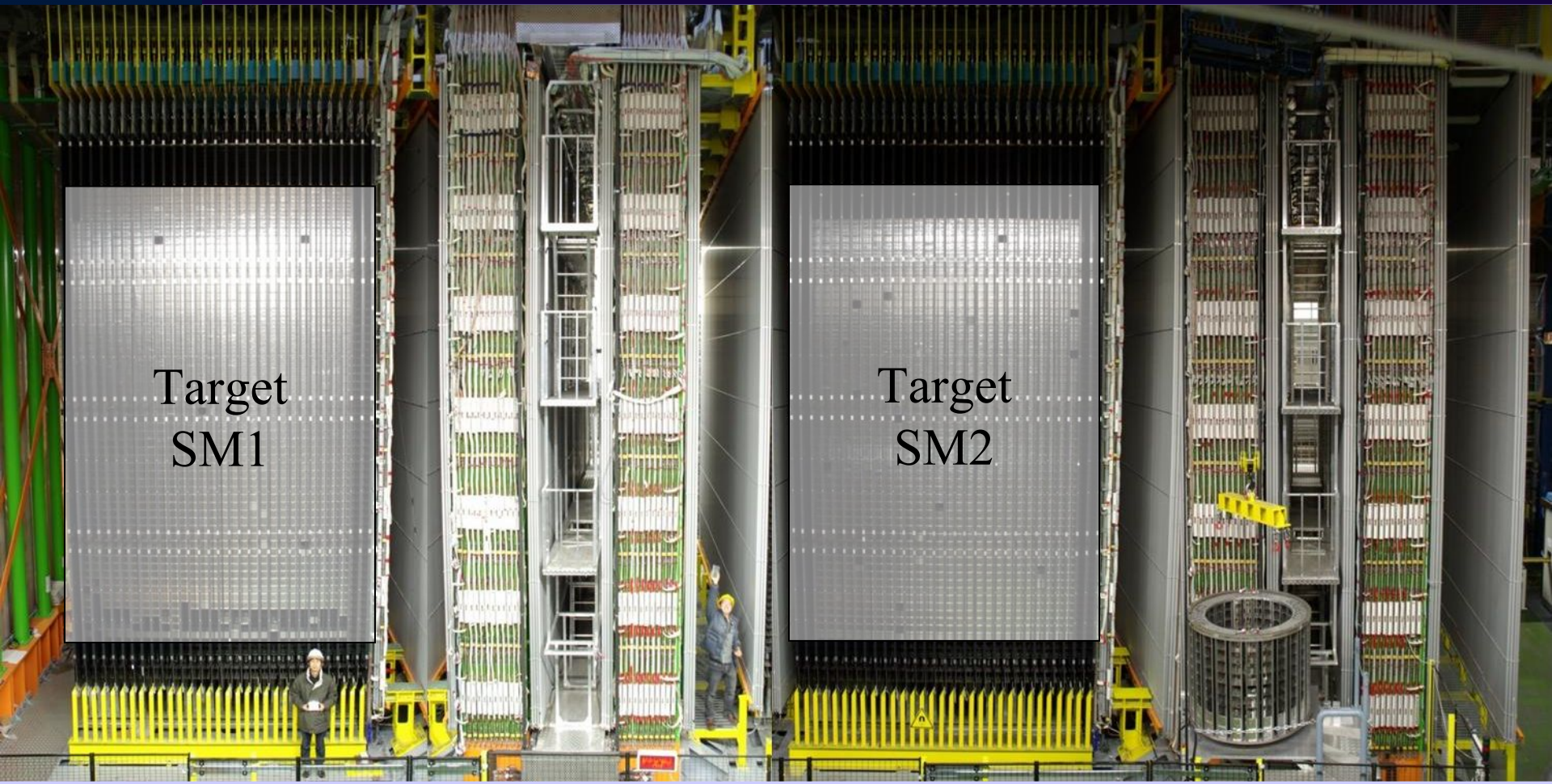
The OPERA Detector



Super Module 1 (SM1)

Super Module 2 (SM2)

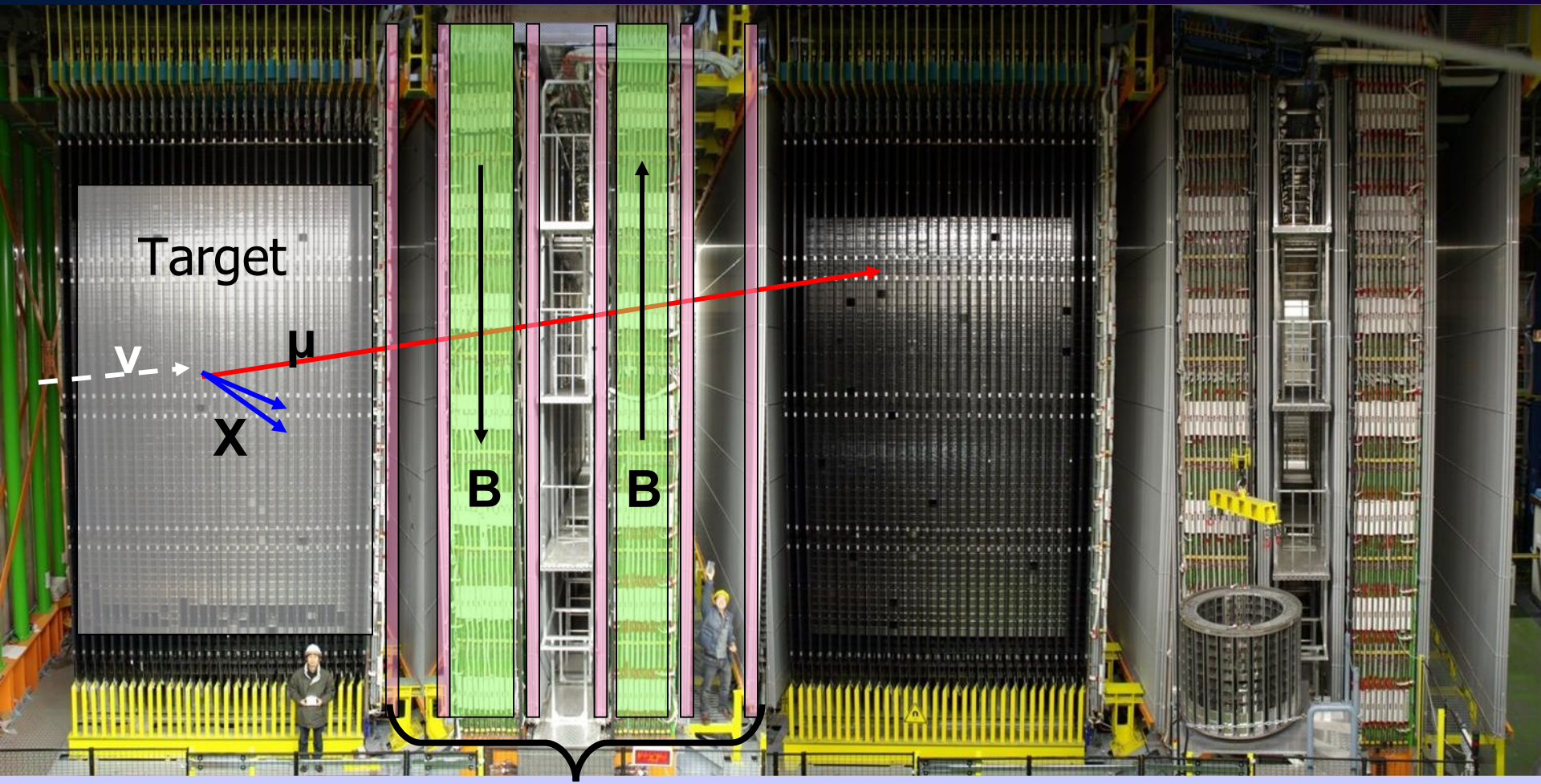
The OPERA Detector



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

→ Target mass: ~1.35 kton

The OPERA Detector



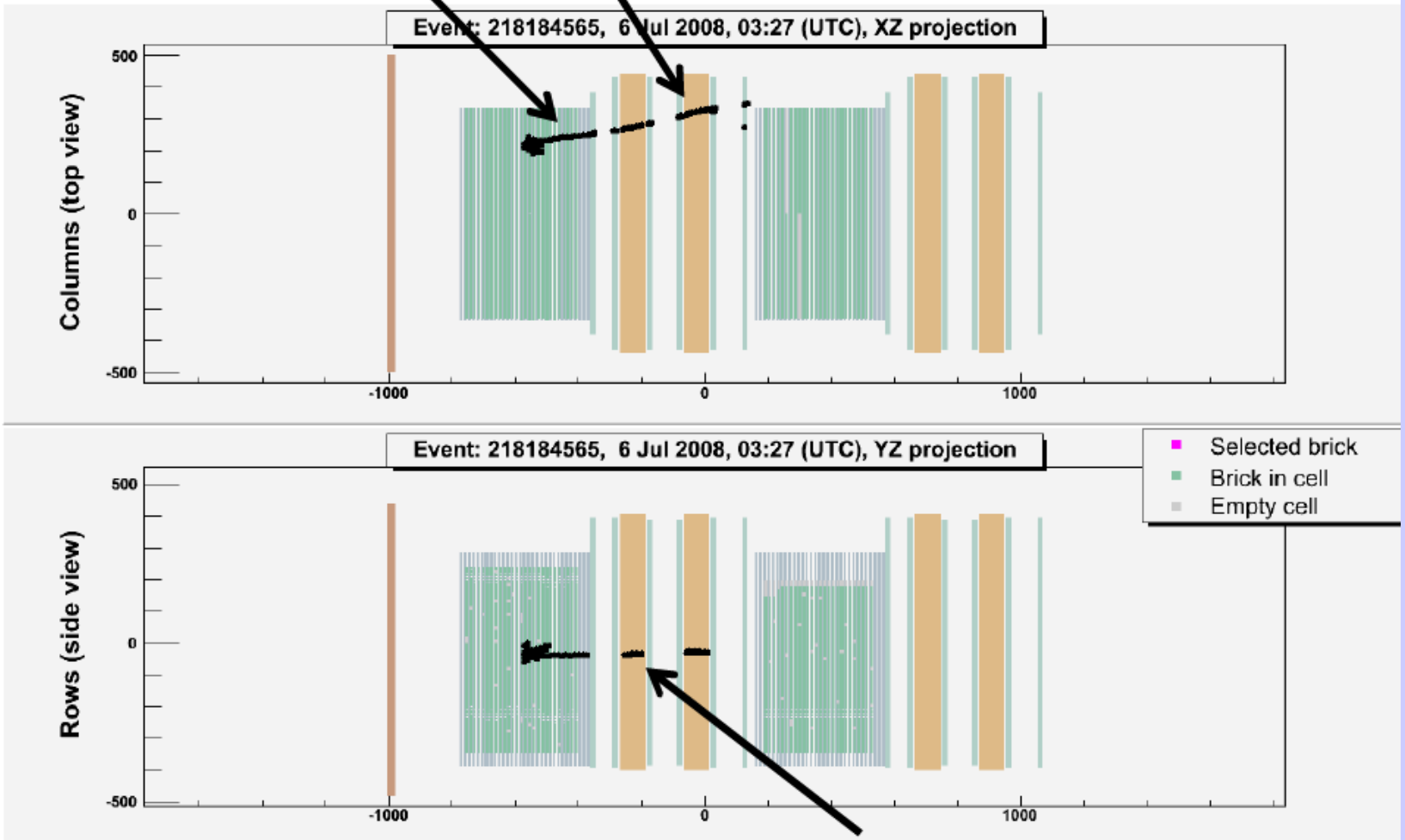
Magnetic Spectrometer:

Magnet Region:
Iron & RPCs

Precision Tracker:
6 planes of drift tubes

Reconstruction (I): Magnetic Spectrometer

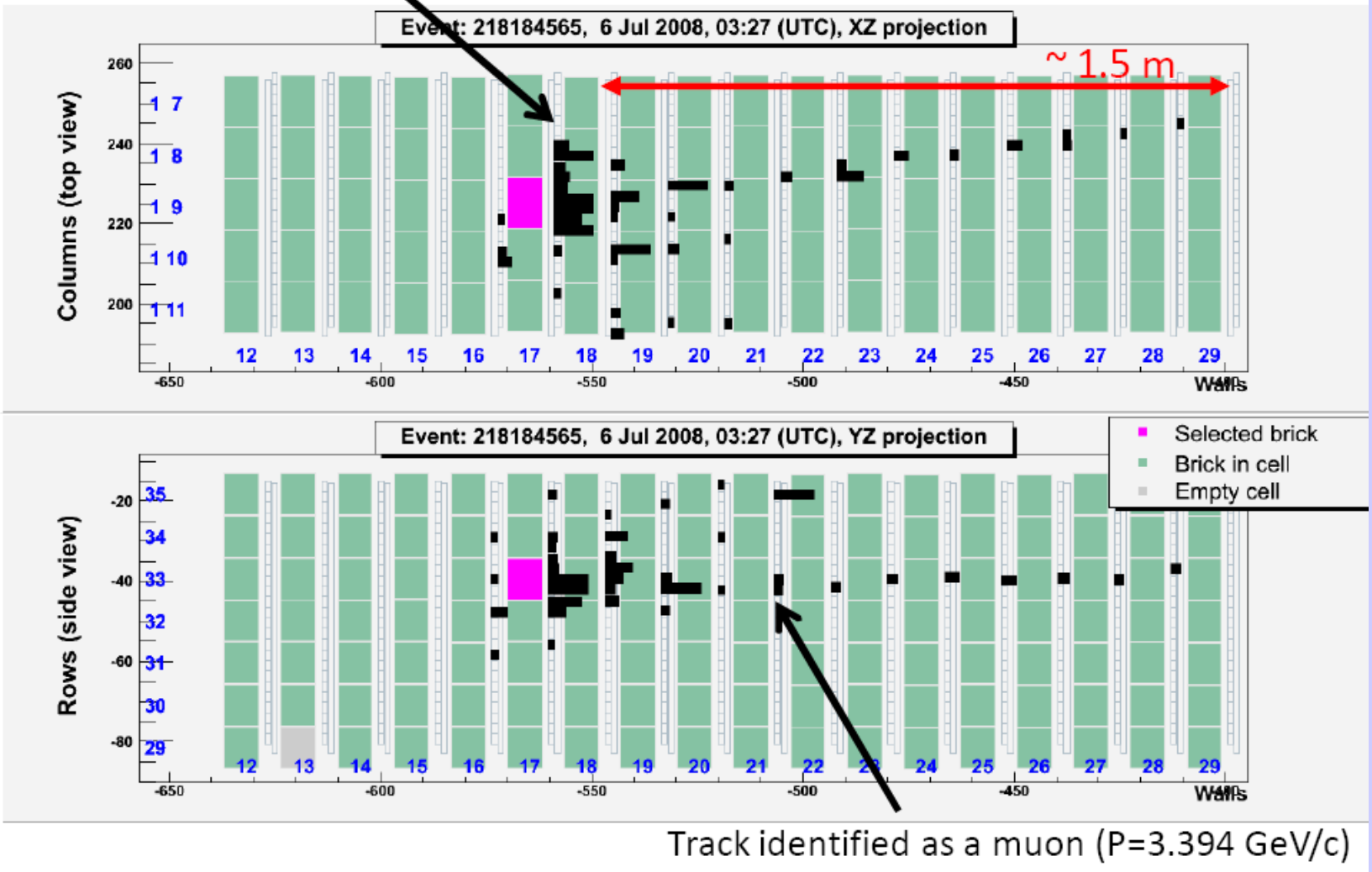
Electronic data (Target Tracker & Muon spectrometer)



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

Reconstruction (II): Brick Finding

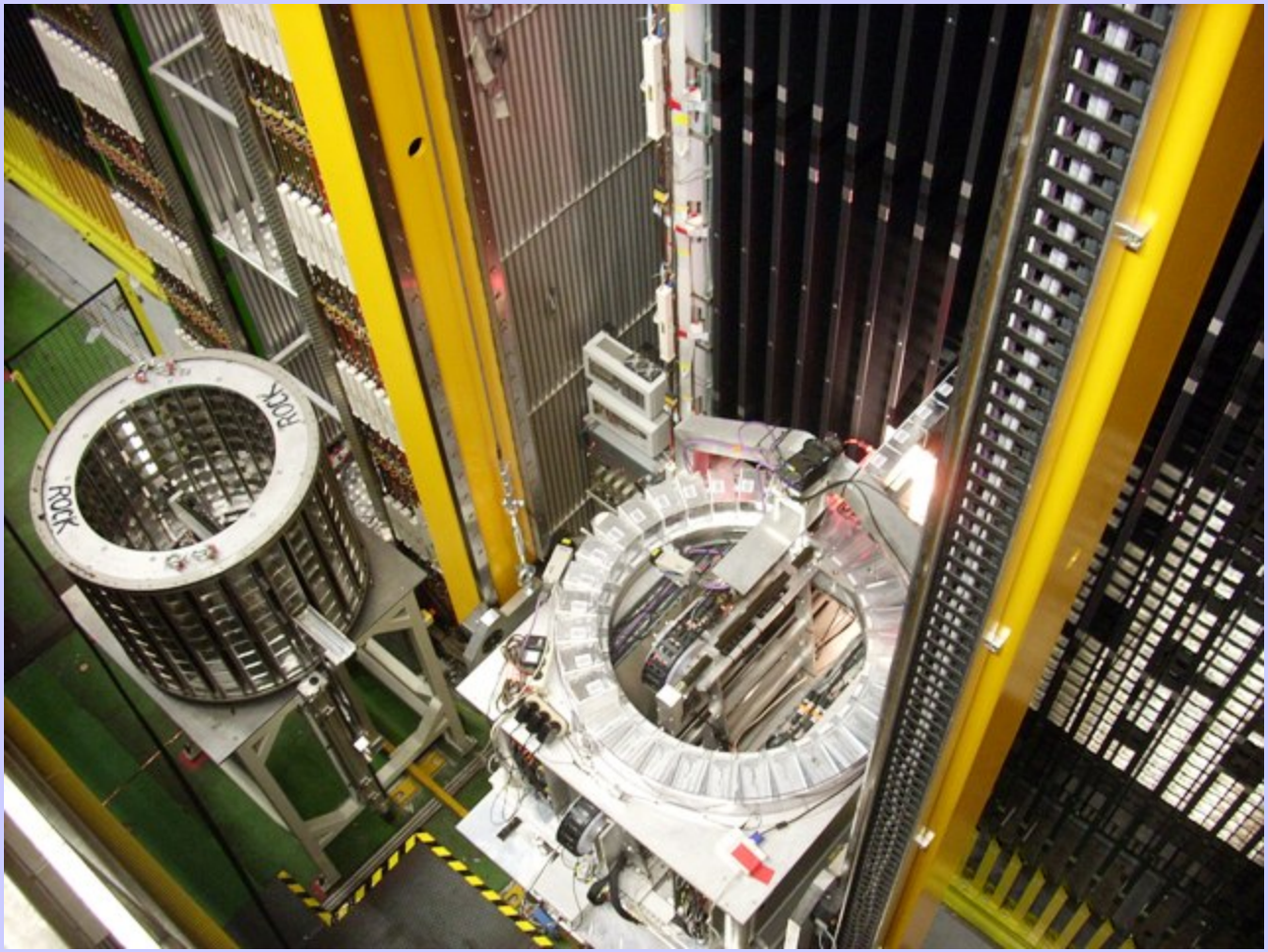
Electronic data (Target Tracker & Muon spectrometer)



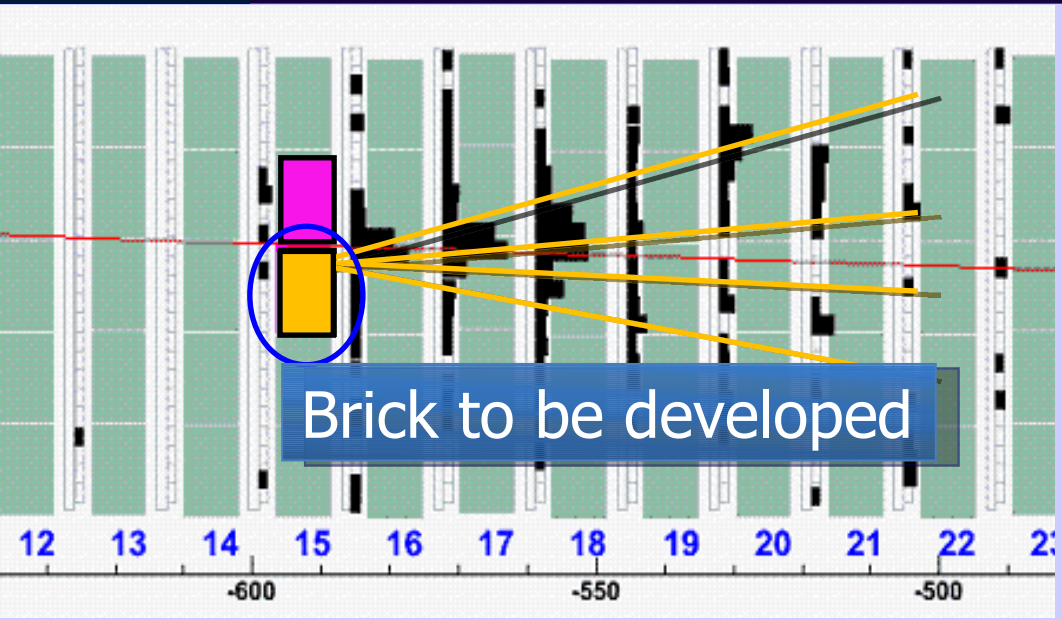
Track identified as a muon (P=3.394 GeV/c)

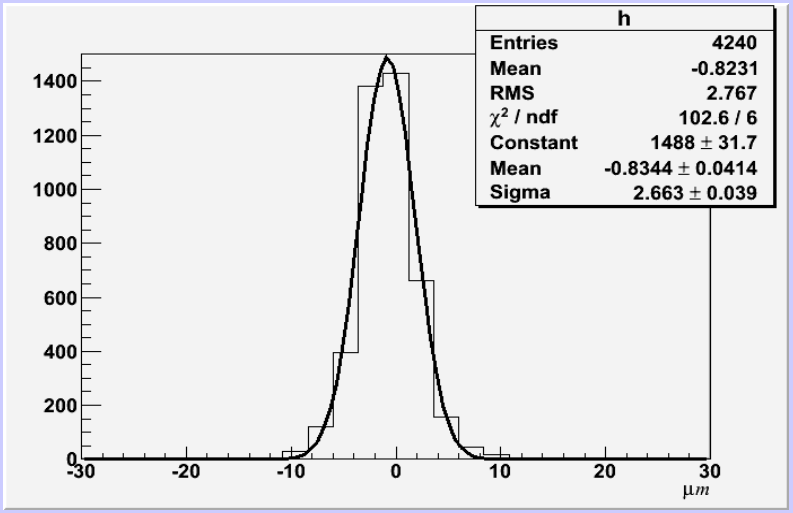
Brick Manipulation System

- Bricks are automatically extracted
- Position of brick at given time is saved



Brick Validation with Changeable Sheet (CS)





CS doublet alignment by Compton electrons: 2.5 microns

Scanning Effort/Event:

CHORUS 1x1 mm²

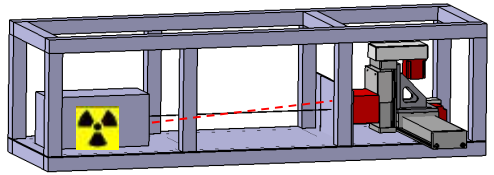
DONUT 5x5 mm²

OPERA 100x100 mm²

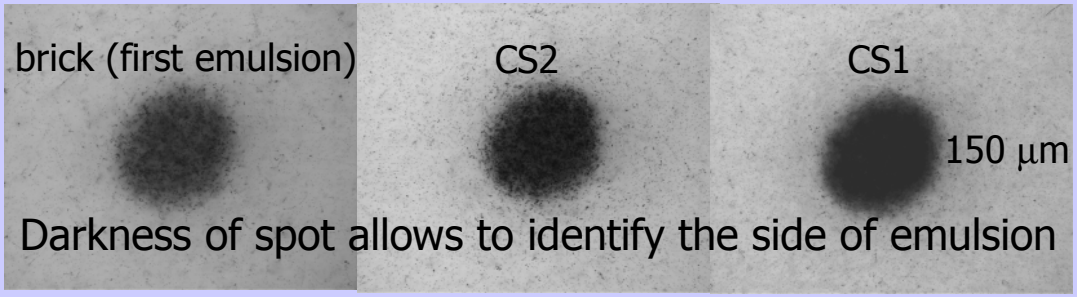
So far, 640.000 cm² of CS surface have been scanned in OPERA

Brick Preparation for Scanning

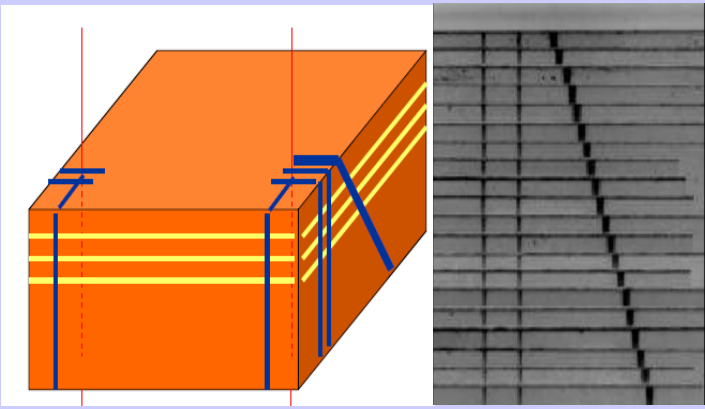
- CS-Analysis
  - X-ray markings for alignment → ~ 10 μm
  - Connection of CS doublets and brick
  - Search area is scanned for track with matching angle



x-ray machine

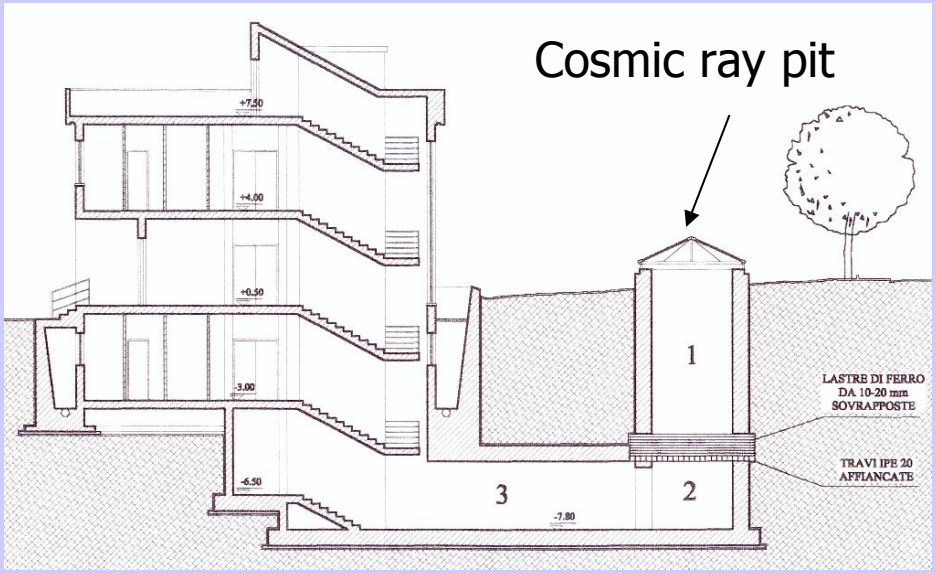


- Brick Alignment
  - X-ray markings → ~ 40 μm
  - First film-to-film connection
  - Film number identifier



Brick Development at GS

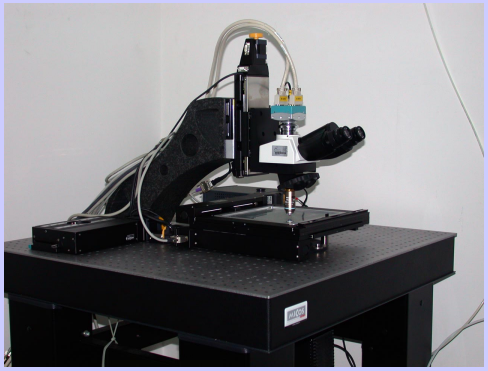
- Bricks are put into cosmic ray pit
- Cosmic rays used for local alignment
- 6 automatic development chains ready
- 150 bricks/week

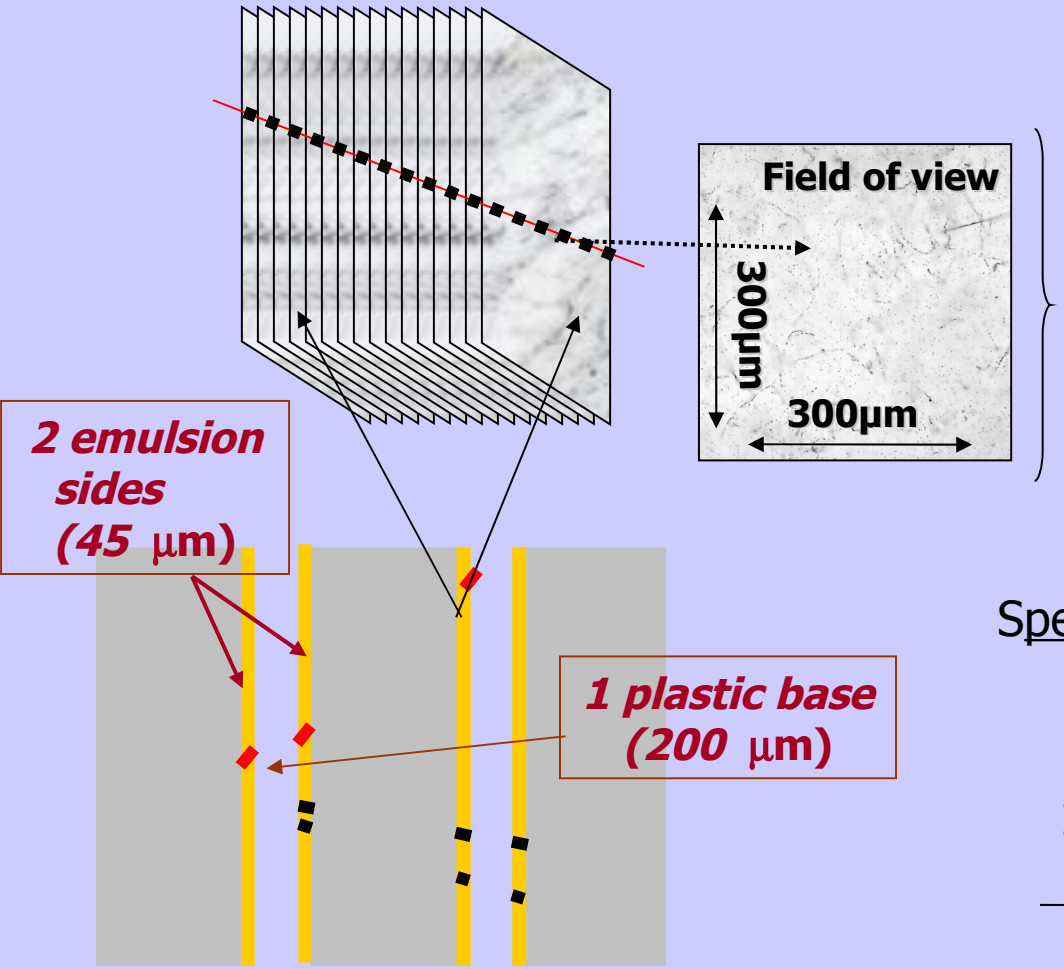


Developing facility

Emulsion Scanning

- 12 scanning laboratories in Europe and Japan





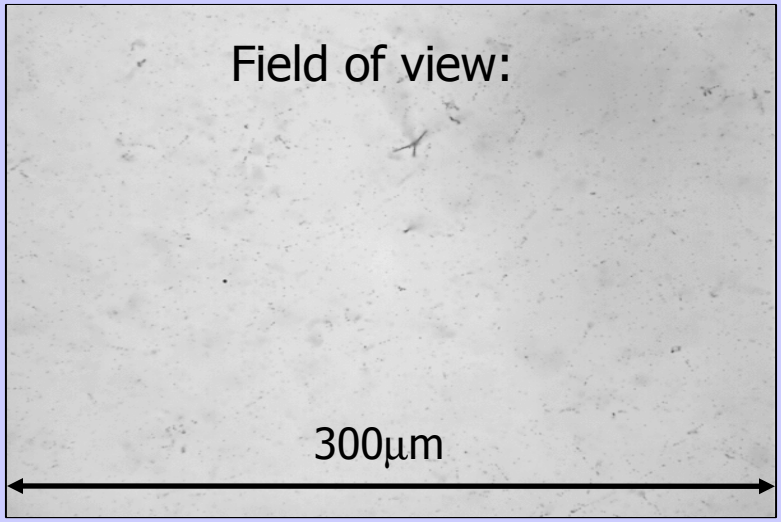
Speed : 20cm²/hour/emulsion side

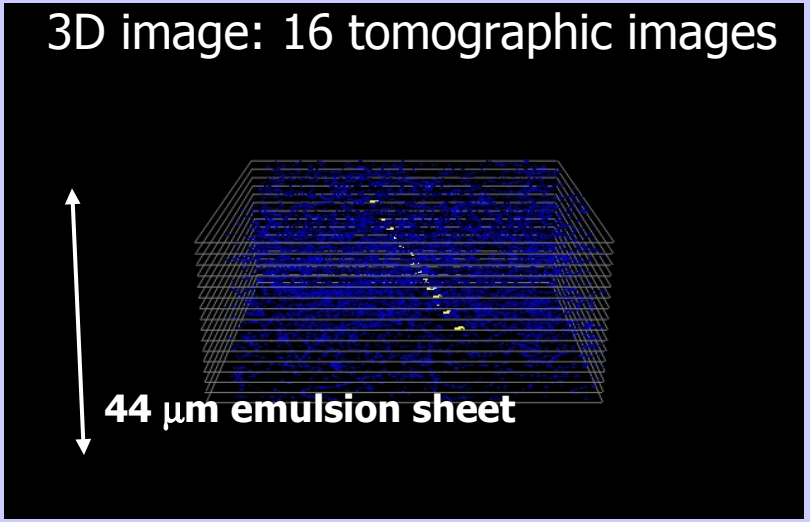
(in Japan >60cm²/hour)

1 emulsion sheet (2 sides)

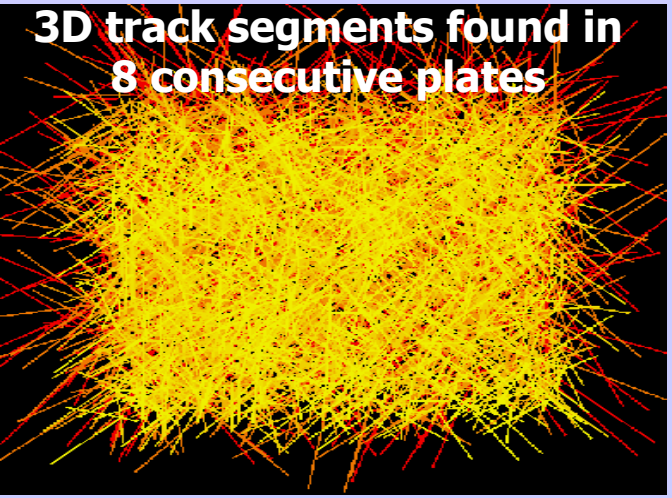
⟶ 12h scanning ~5GB

Emulsion Scanning

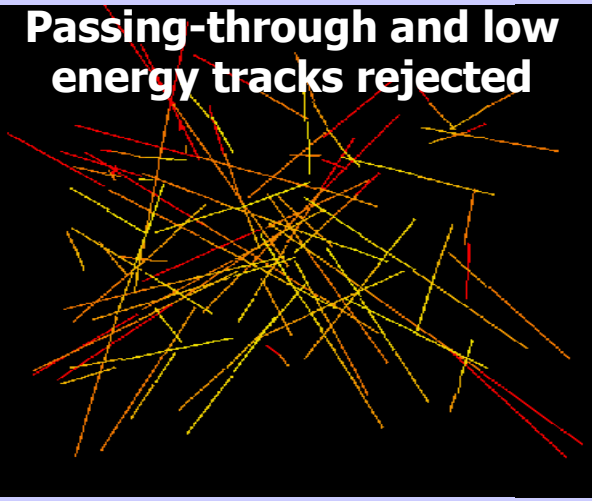




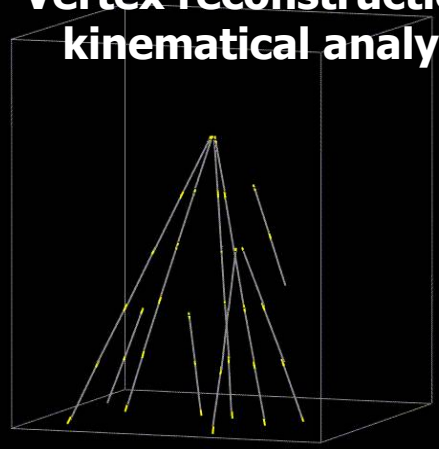
3D track segments found in 8 consecutive plates



Passing-through and low energy tracks rejected



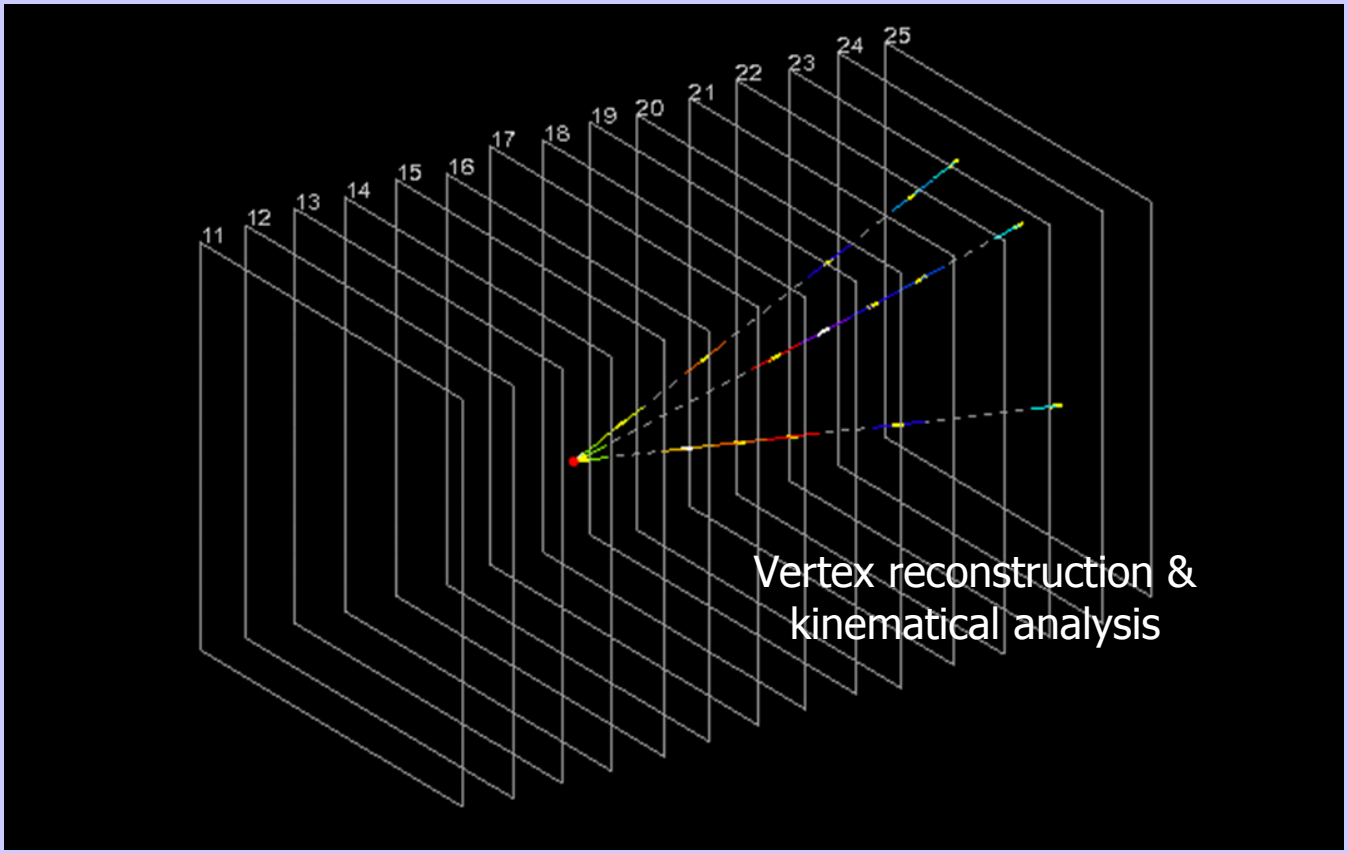
Vertex reconstruction & kinematical analysis



Emulsion Scanning

The frames correspond to the scanning area:

- Yellow short lines: Measured tracks
- Other colored lines: Interpolation or extrapolation



Expected Performance (Proposal)

Assumptions: Maximal mixing, 22.5×10^{19} p.o.t. (5years @ 4.5×10^{19} p.o.t./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

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ν_τ Candidate

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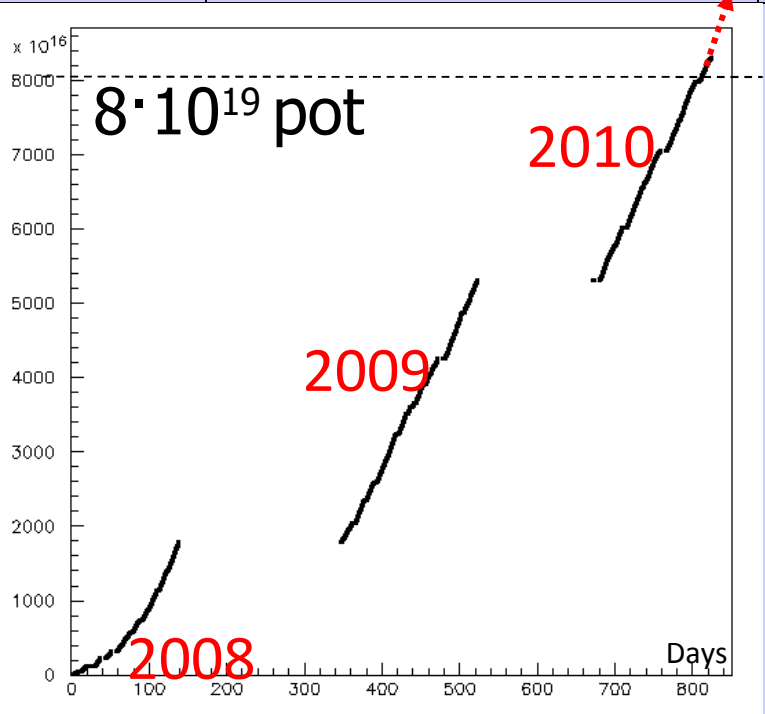
CNGS Beam Performance & Statistics

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

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



Event Statistics (June 2010)

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

- 1813 events found in the target (scan input)

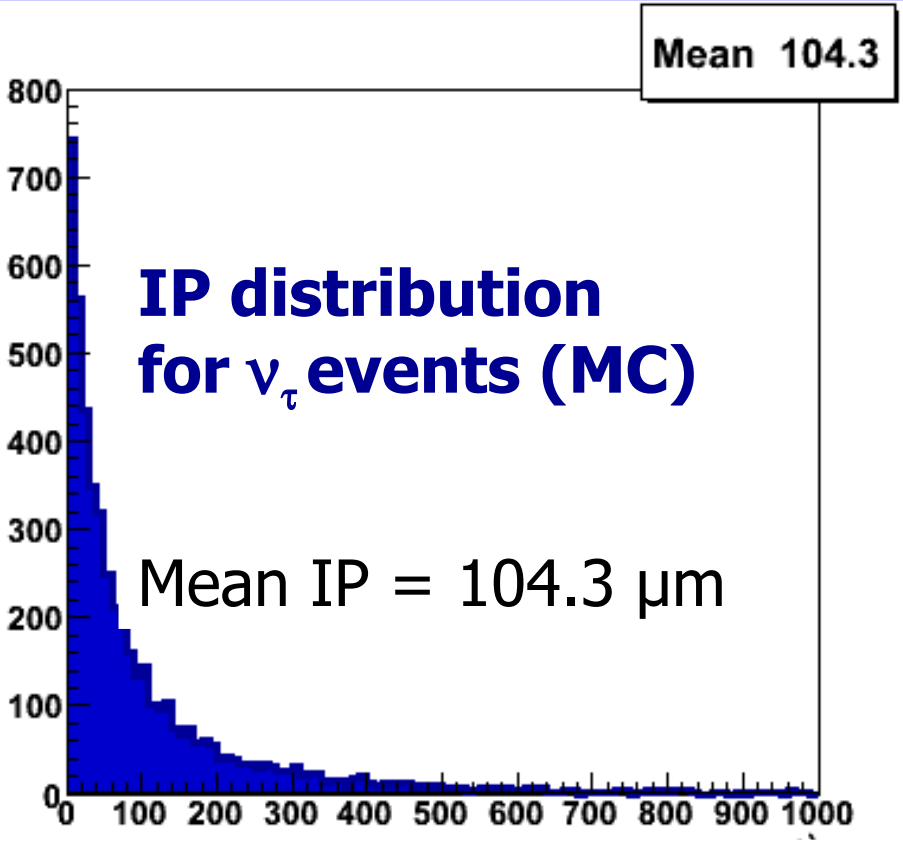
- Events with neutrino vertices located by scanning: 1617
(Brick tagging efficiency) x (vertex location efficiency) ≈ 60%

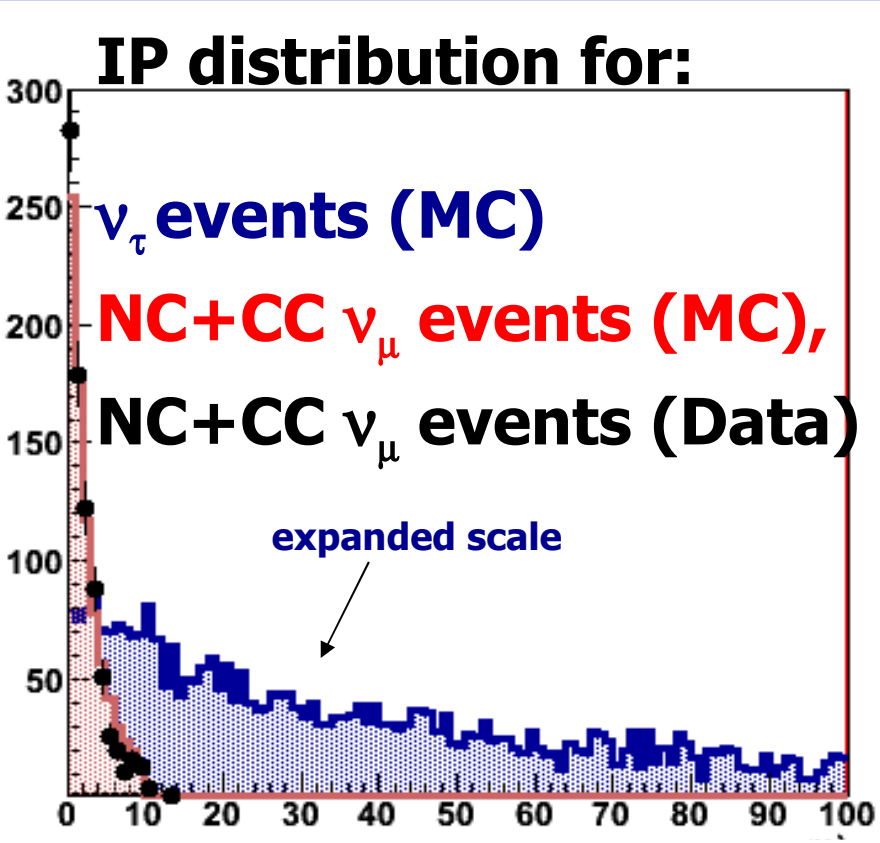
- Events for which "decay search" was completed: 1088
(187NC, 901CC)

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

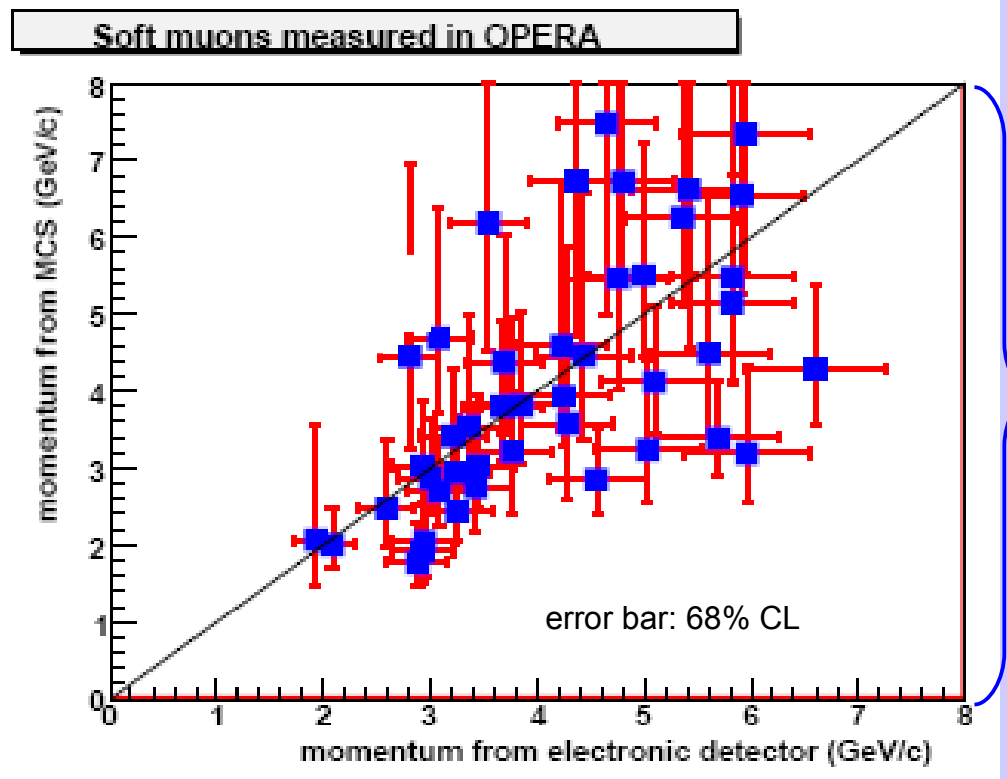
~ 0.5 ν_τ events

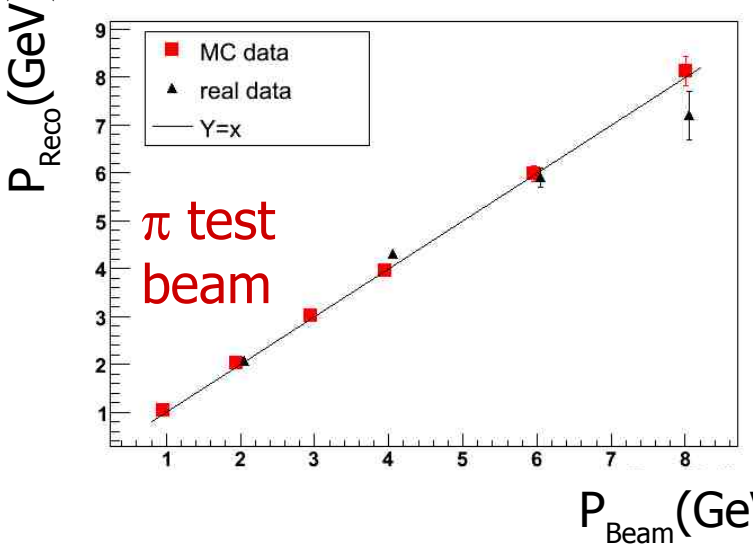
Impact Parameter Measurement

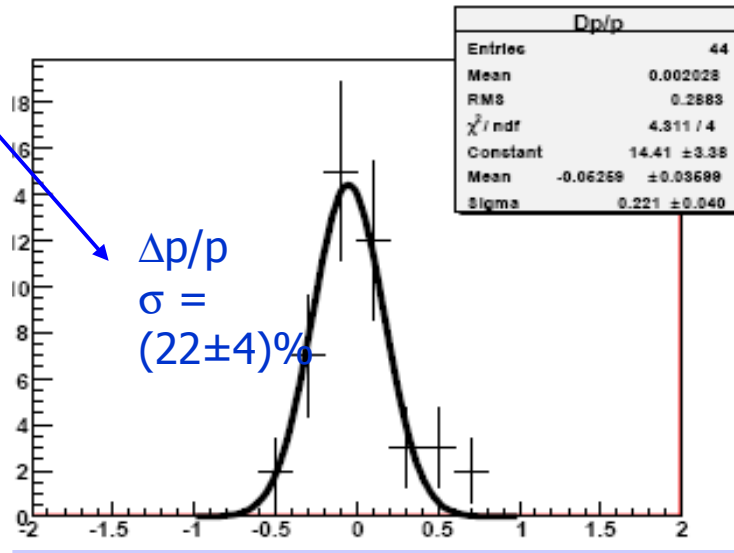




Momentum Measurement (ECC and Electronic Detector)

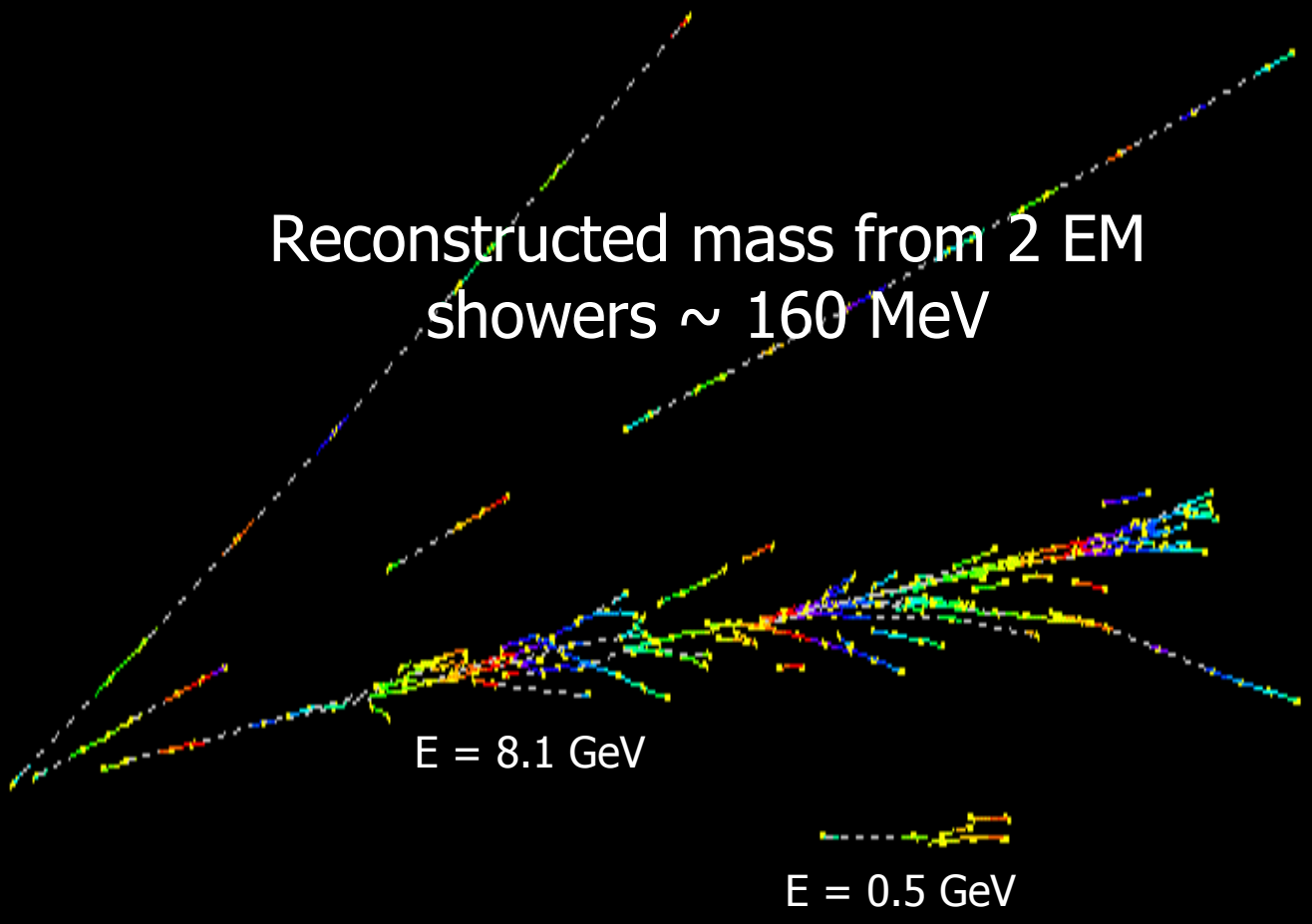




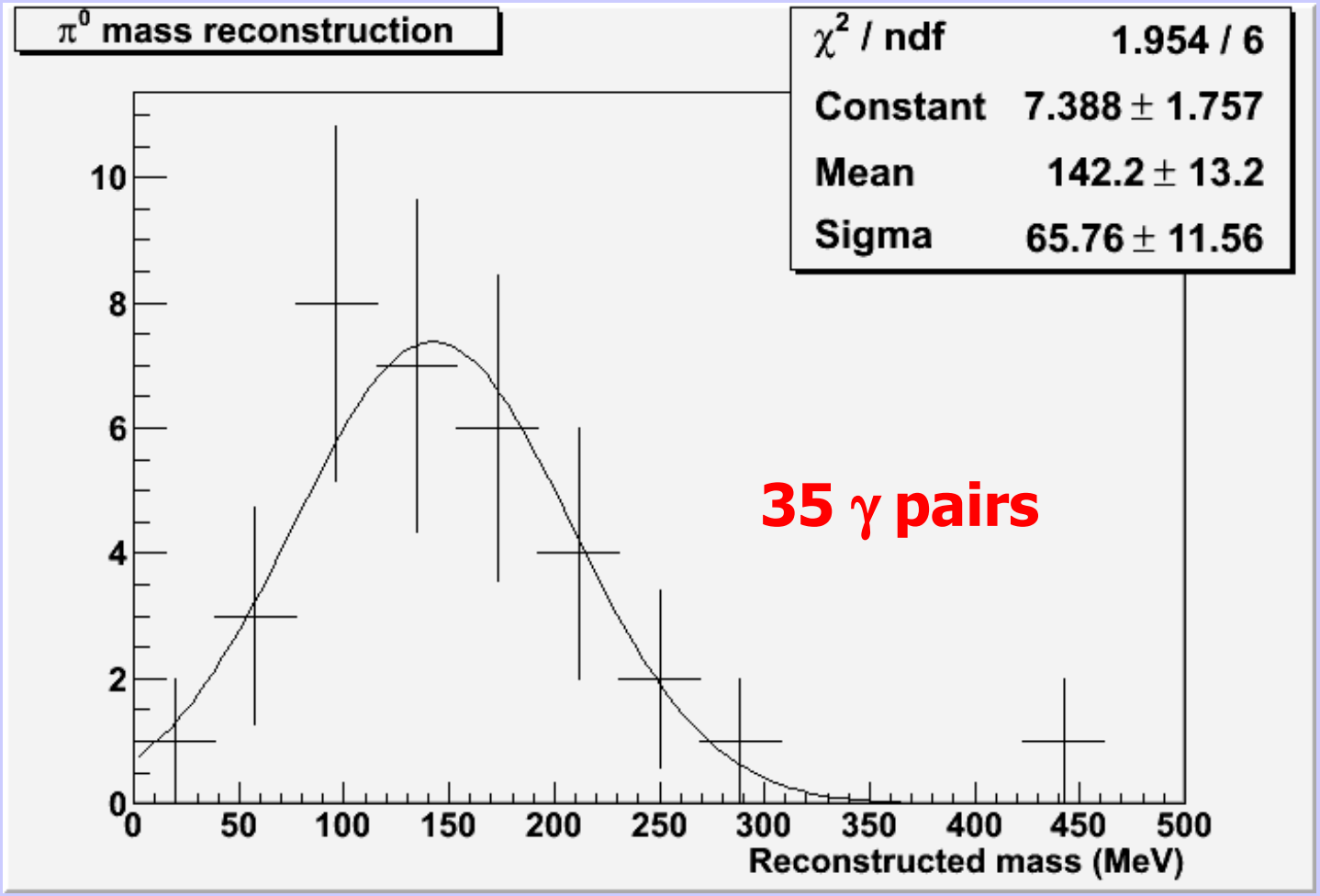


γ-Detection and Reconstruction of π^0 Mass

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



π^0 Mass Resolution (Real Data)



1 σ mass resolution: ~ 66 MeV

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ν_τ Candidate

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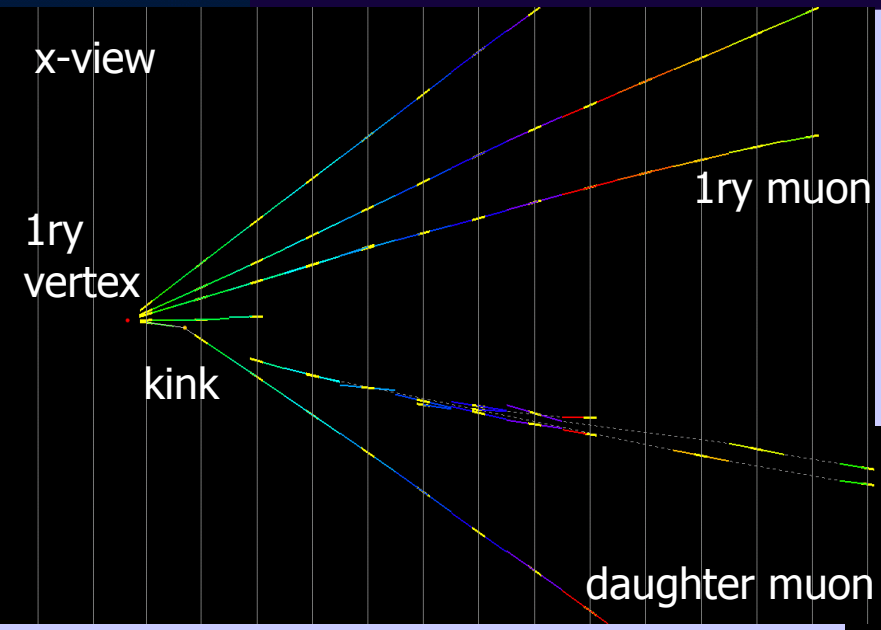
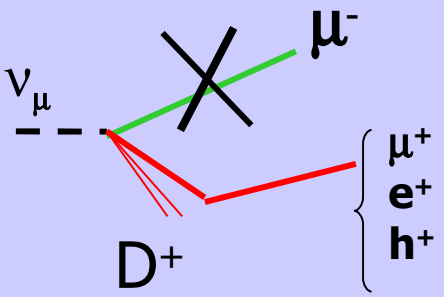
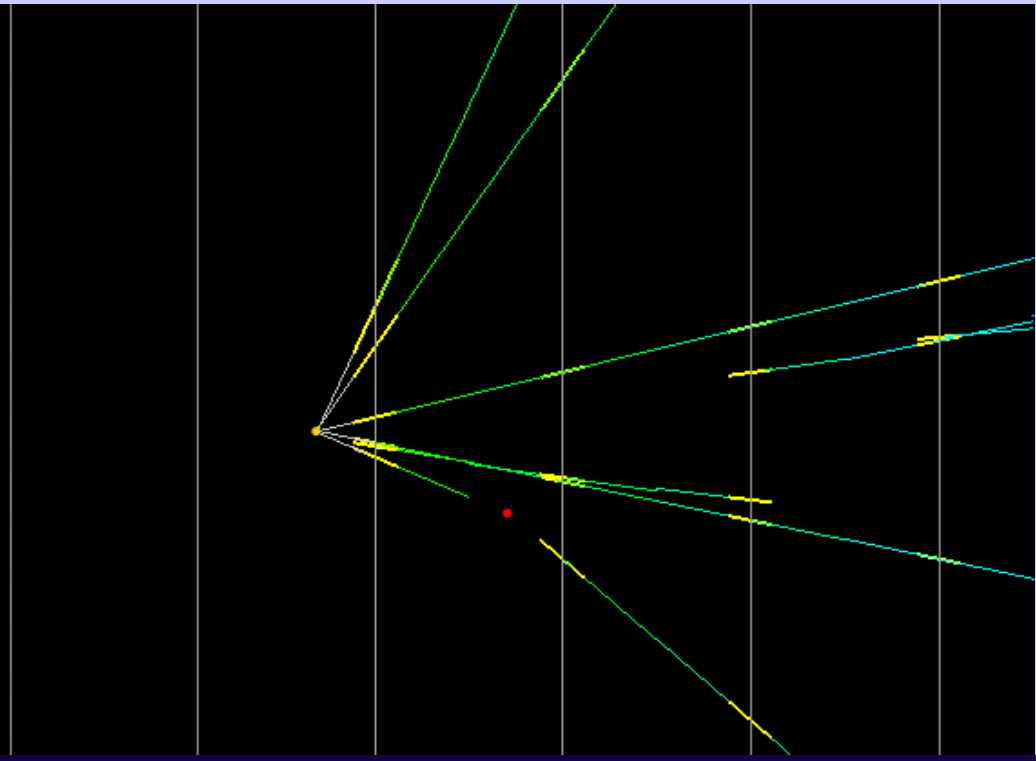
Charm Candidate Event (Dimuon)



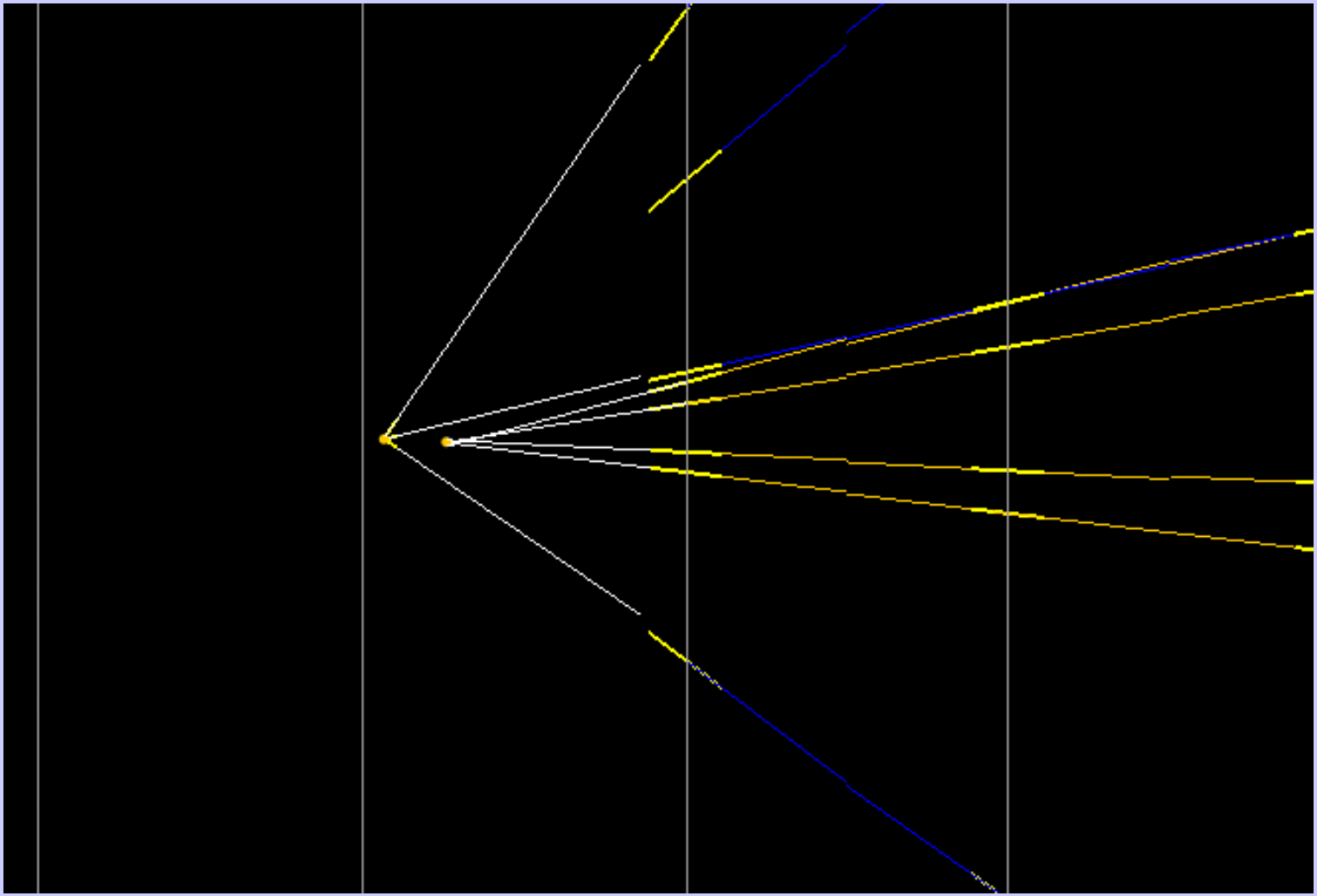
- Flight length: 1330 microns
- Kink angle: 209 mrad
- IP of daughter: 262 microns
- Daughter muon: 2.2 GeV/c
- Decay P_t: 0.46 GeV/c

Background, if primary muon not identified:





Charm Candidate Event (4-prong)



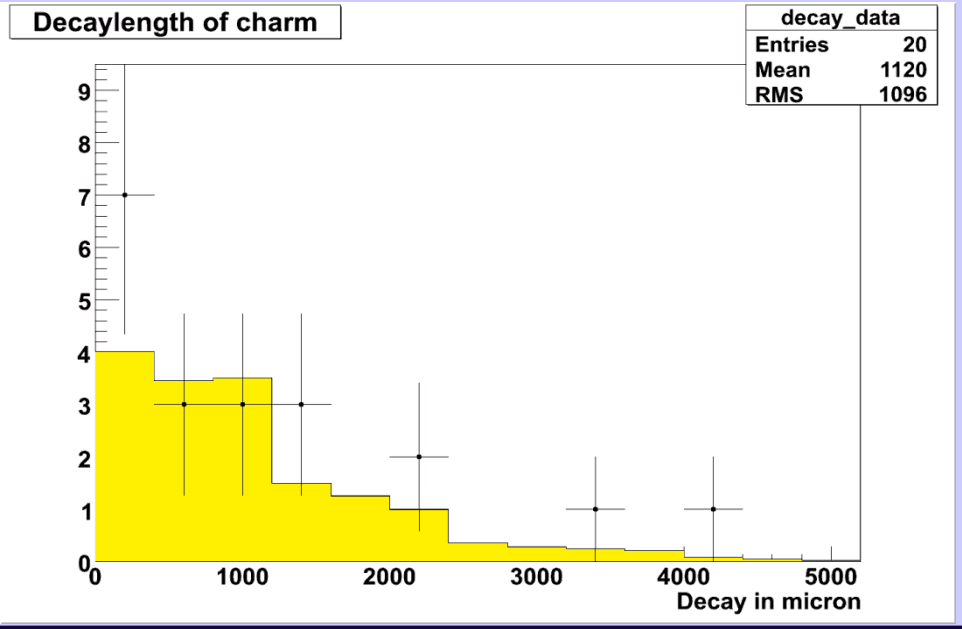
D_0 hypothesis: F.L.= 313.1μm, φ = 173.2^0, invariant mass = 1.7 GeV

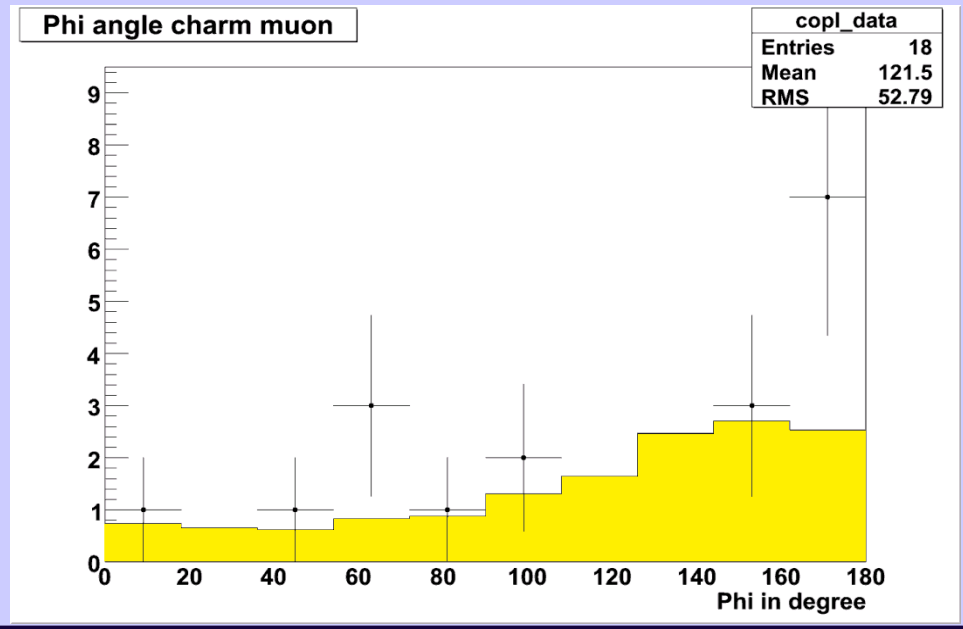
Charm Events Statistics

- P(daughter): >2.5 GeV/c
- P_t(kink): > 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

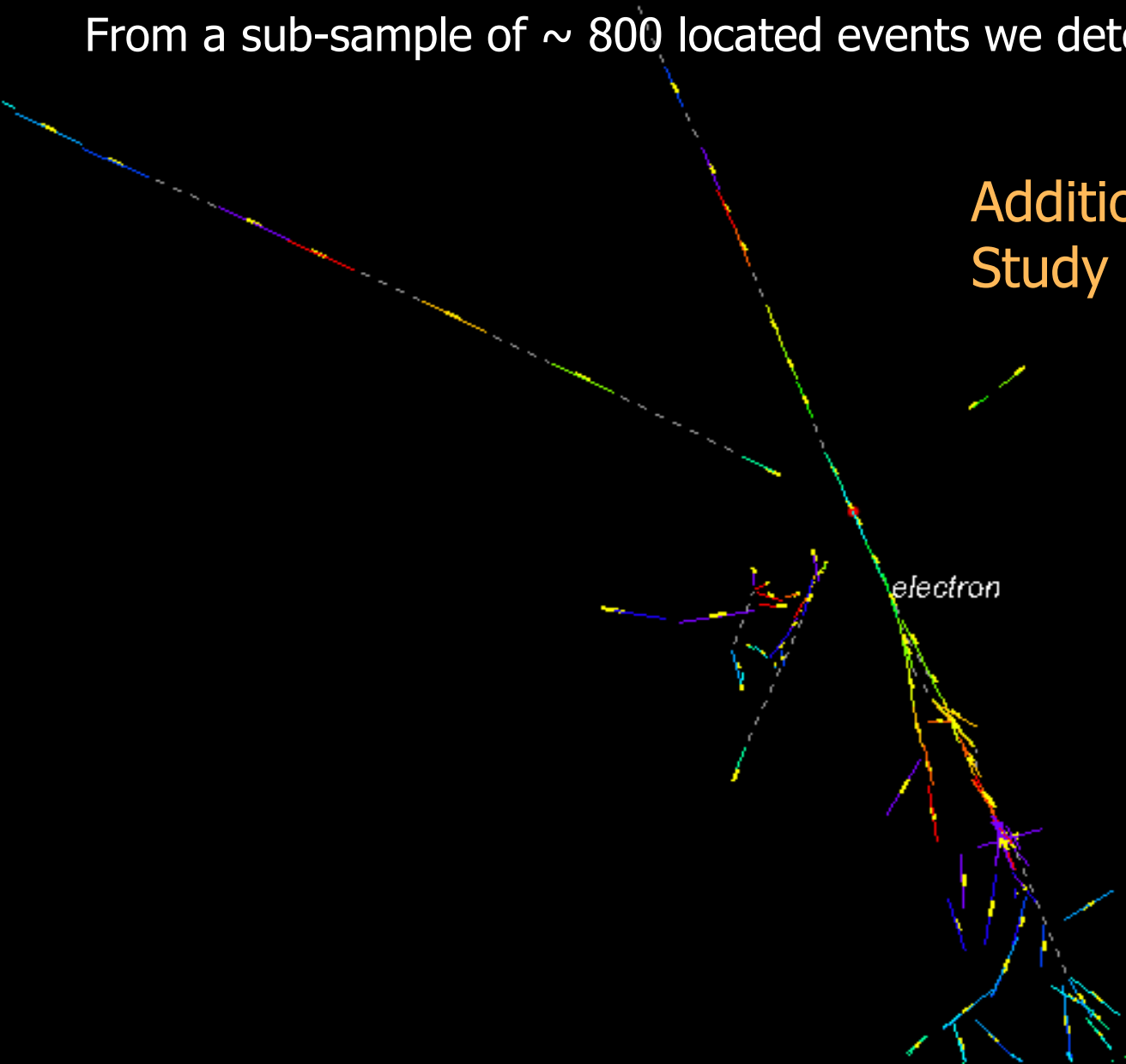
Examples of distributions:





ν_e Candidate Event

From a sub-sample of ~ 800 located events we detected 6 ν_e candidates



Additional physics subject:
Study of $\nu_\mu \rightarrow \nu_e$ oscillations

Overview

Neutrino Oscillations

The OPERA Experiment

Detector Performance

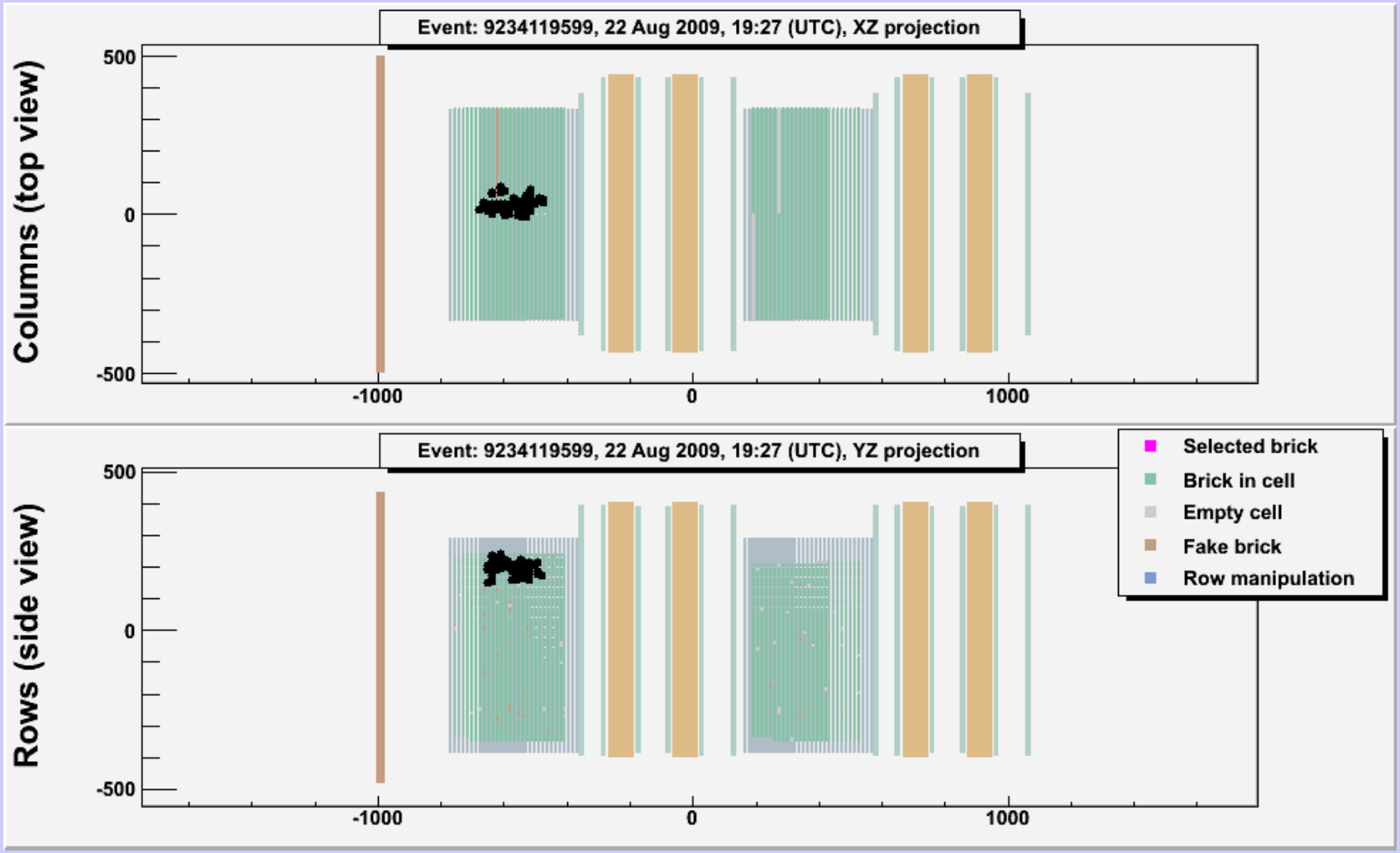
Special Events: Charm, ν_e

ν_τ Candidate

Outlook

Muonless Event 9234119599

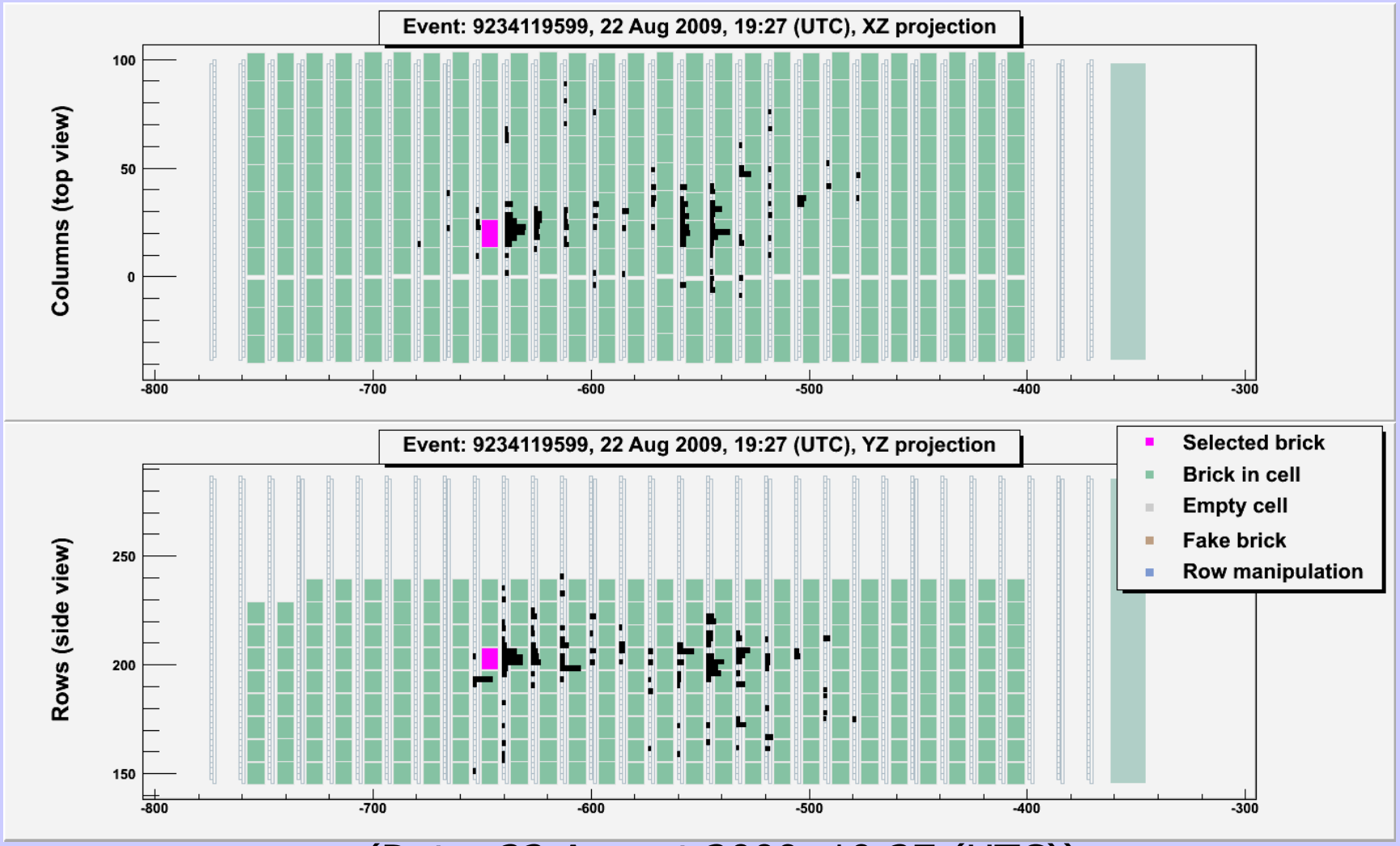
Electronic Detector View:



(Date: 22 August 2009, 19:27 (UTC))

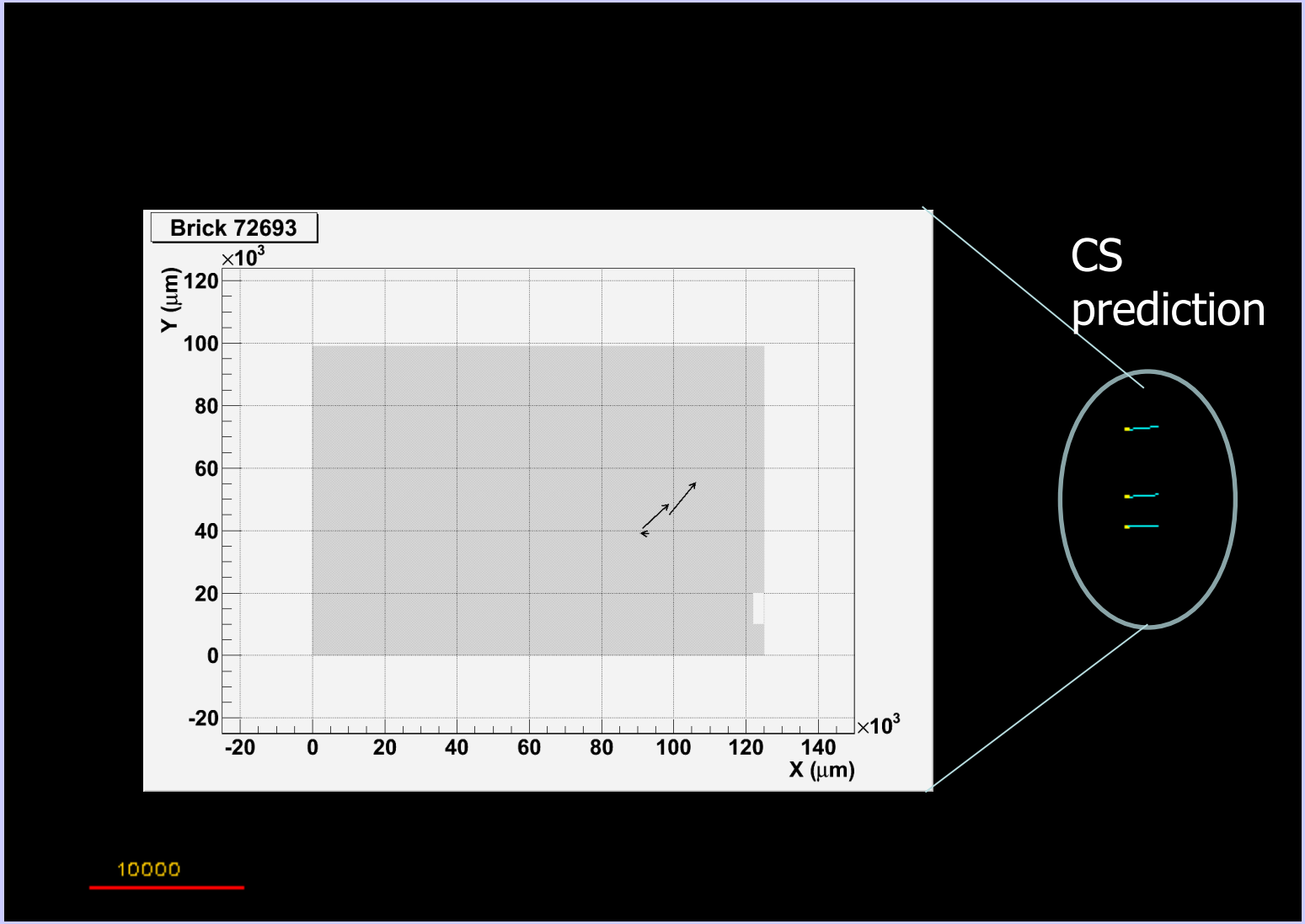
Muonless Event 9234119599

Electronic Detector View:

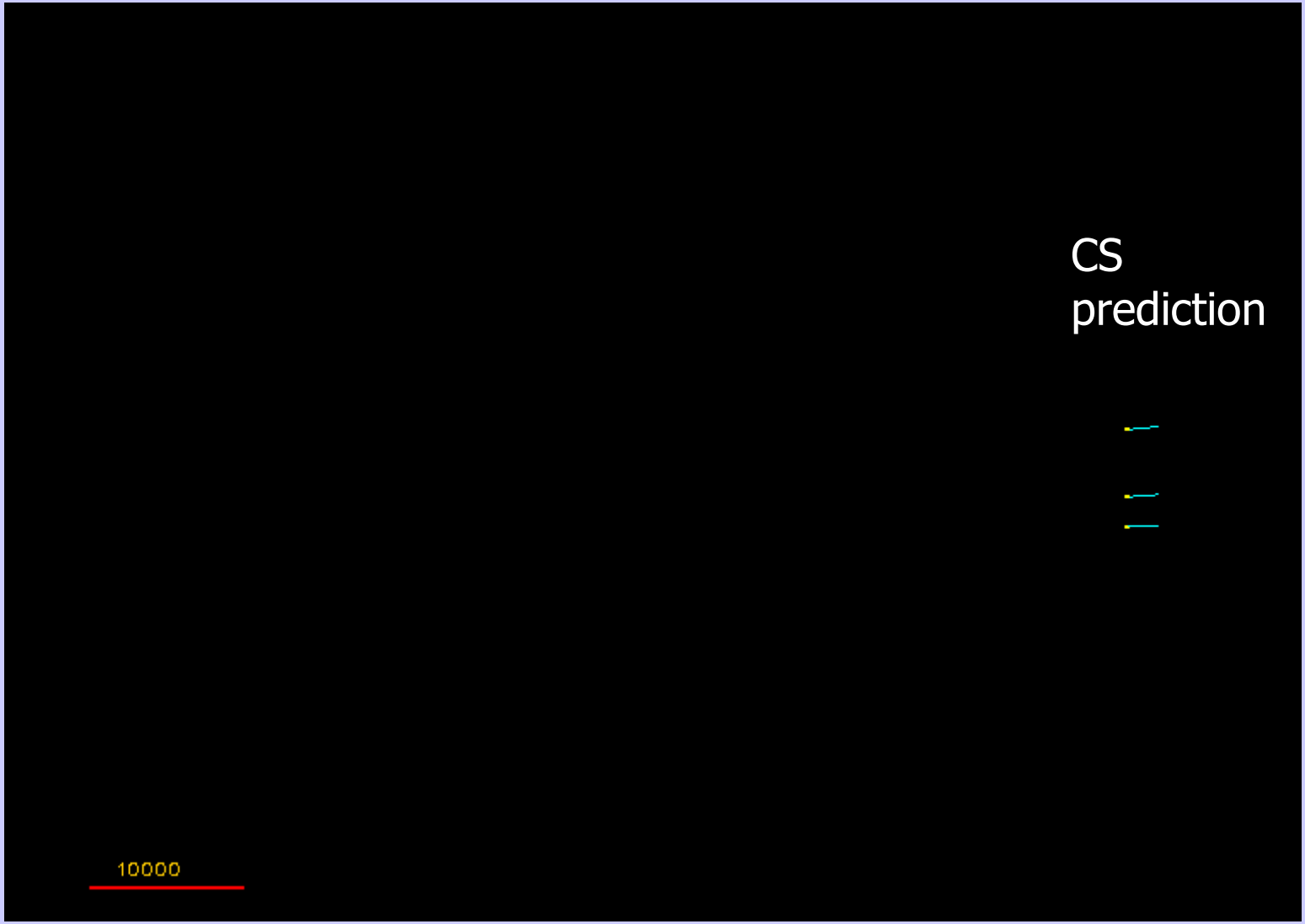


(Date: 22 August 2009, 19:27 (UTC))

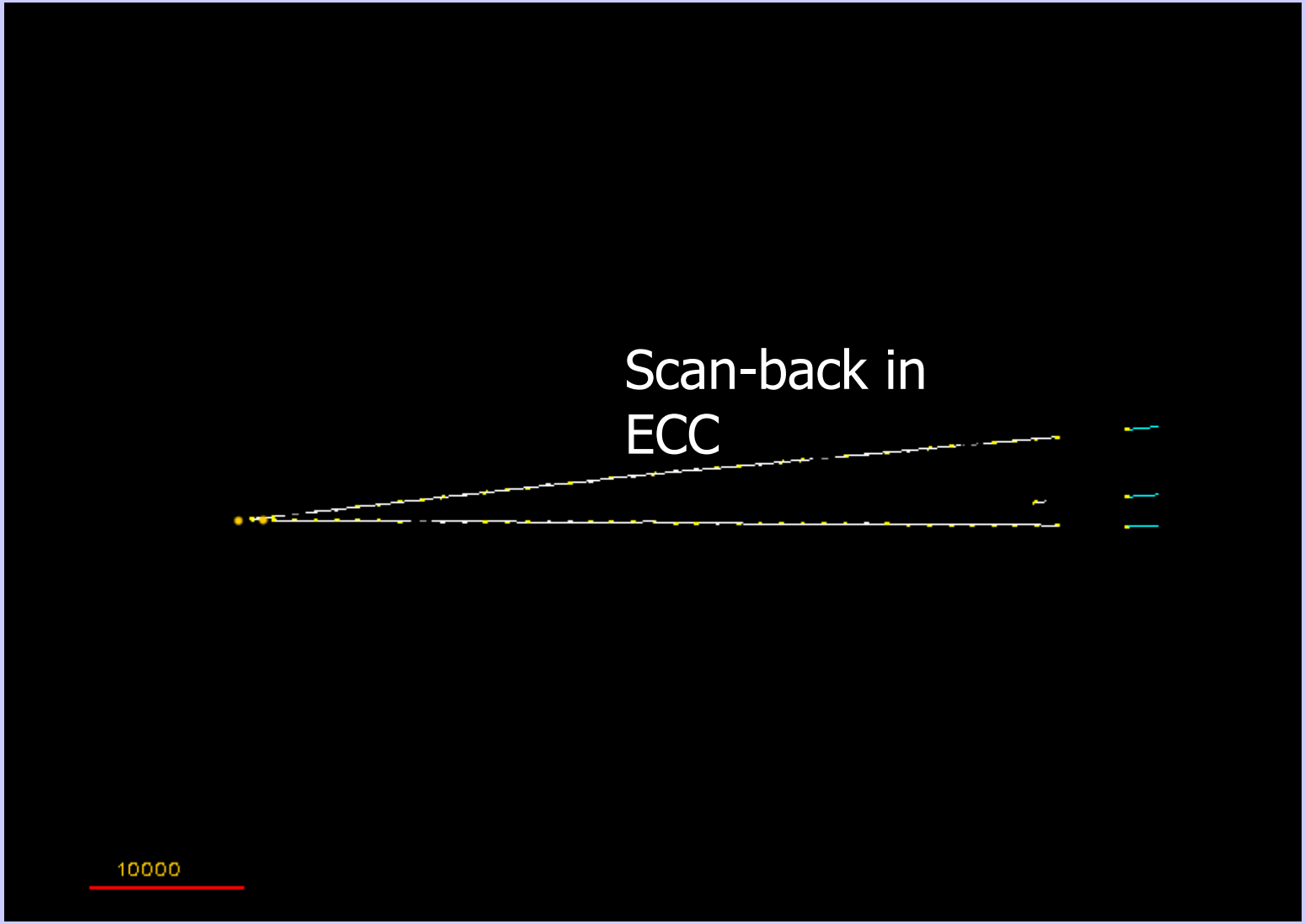
From CS to Vertex Localisation



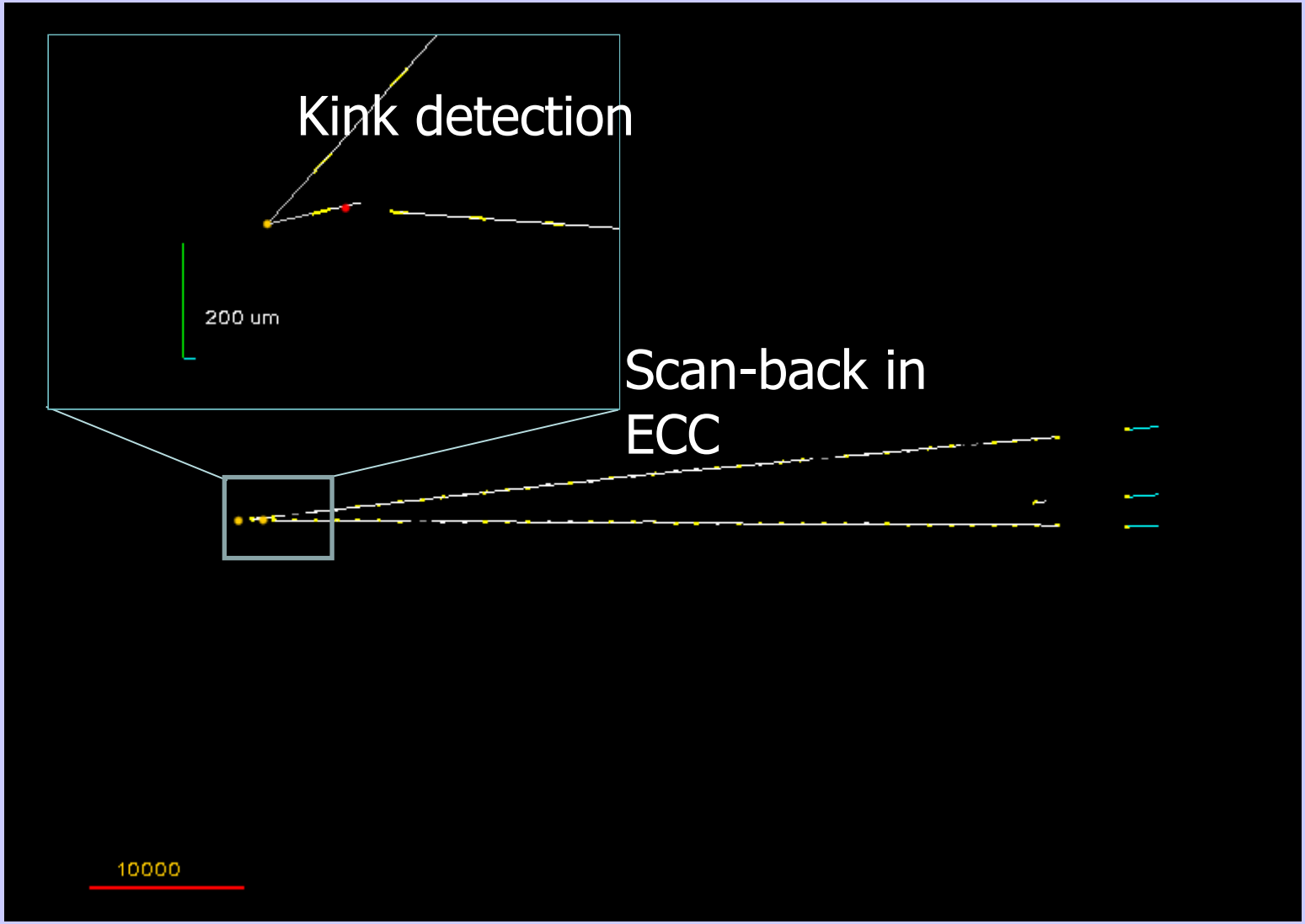
From CS to Vertex Localisation



From CS to Vertex Localisation

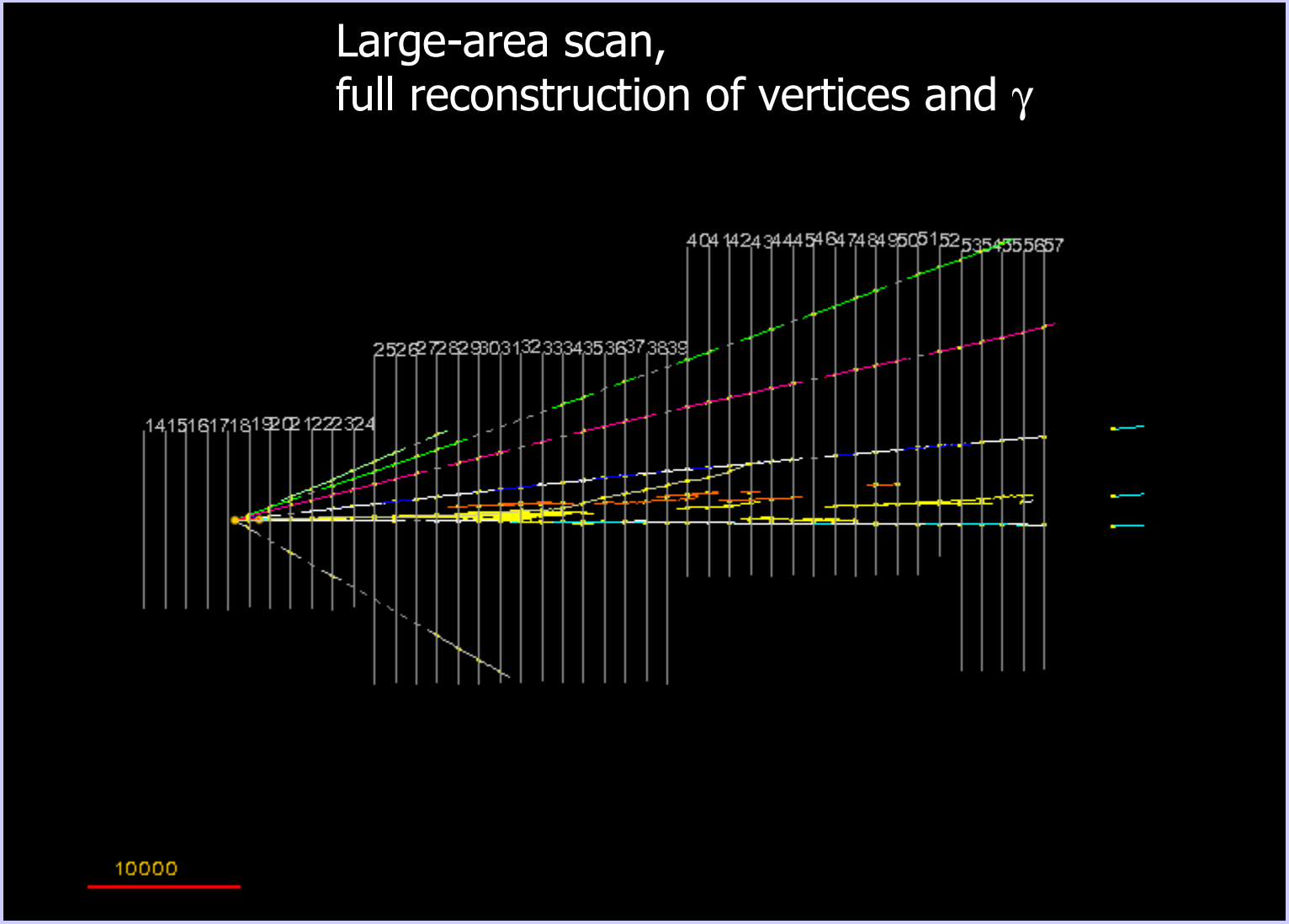


From CS to Vertex Localisation

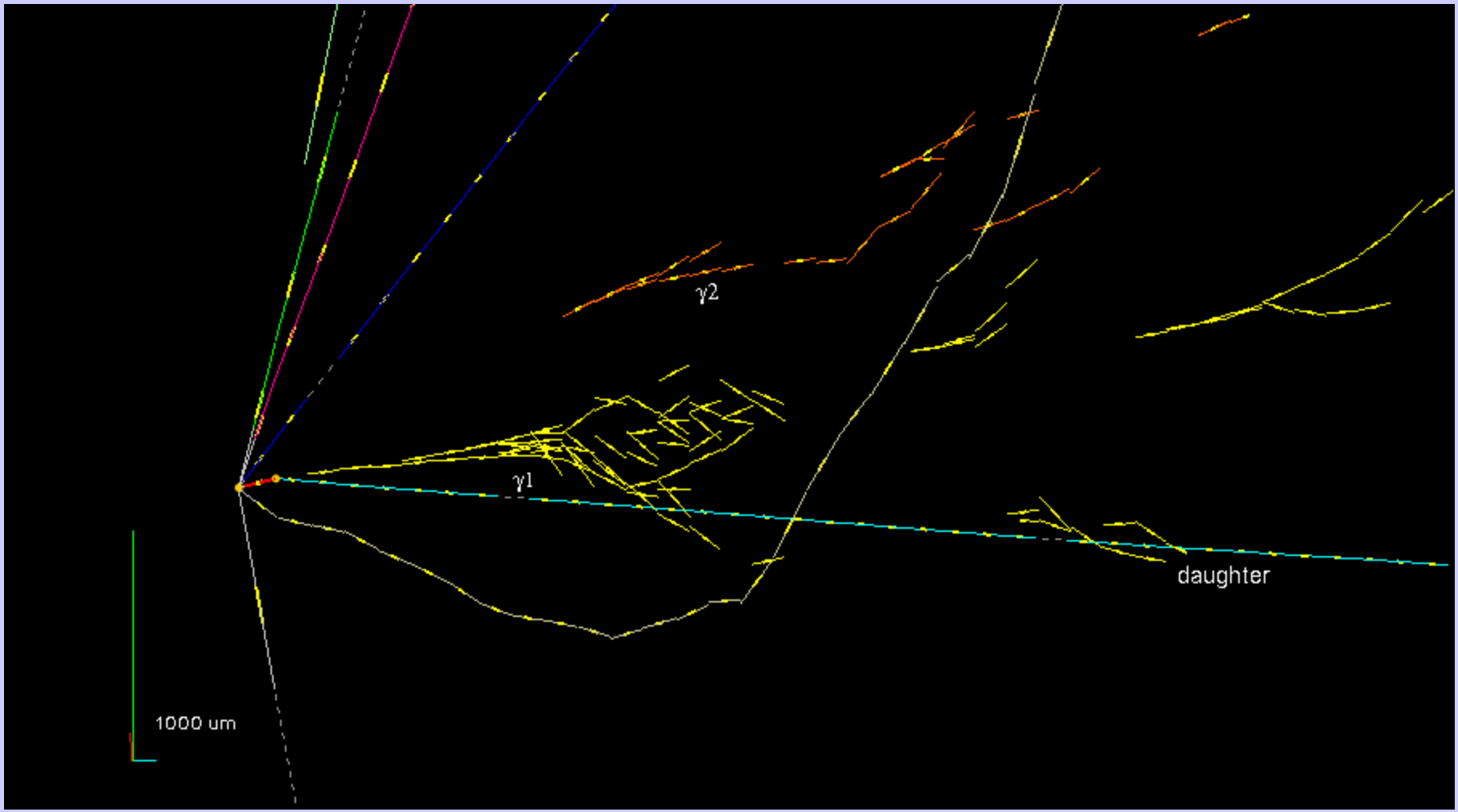


From CS to Vertex Localisation

Large-area scan,
full reconstruction of vertices and γ

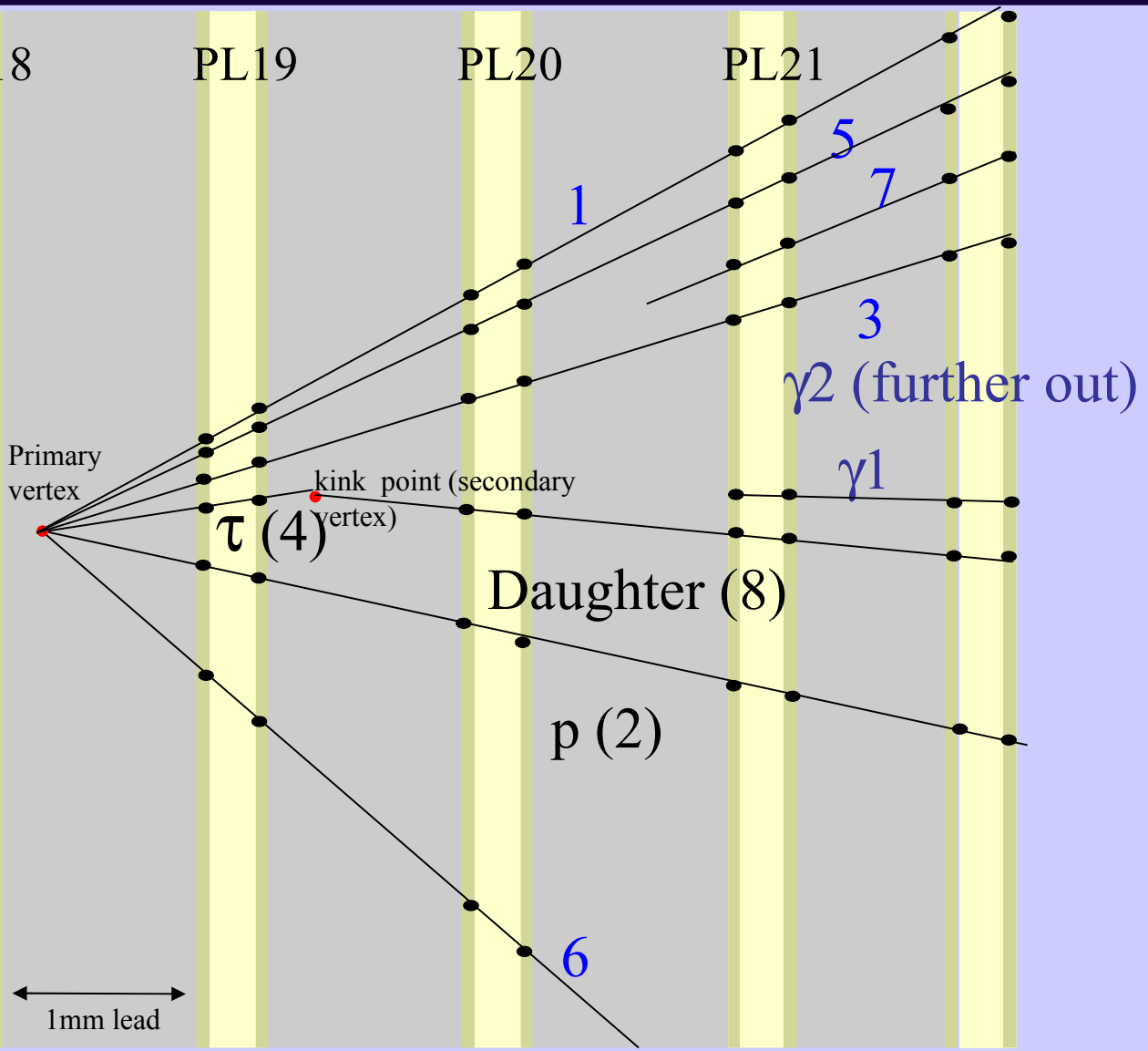


Reconstructed ν_τ Canditate



Reconstructed ν_τ Candidate

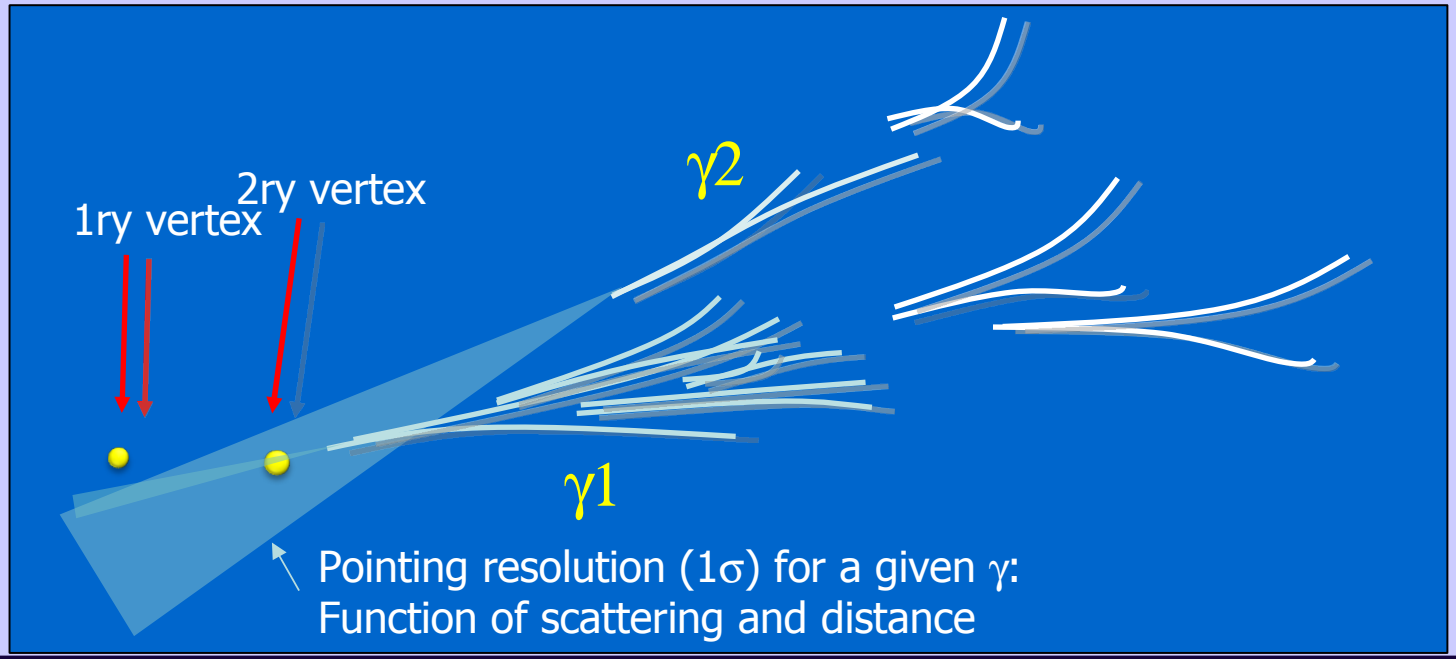
Variable	Value
kink (mrad)	41 ± 2
decay length (μm)	1335 ± 35
P (daughter) (GeV/c)	12^{+6}_{-3}
Pt (daughter) (MeV/c)	470^{+230}_{-120}
missing Pt (MeV/c)	570^{+320}_{-170}
ϕ (deg)	173 ± 2



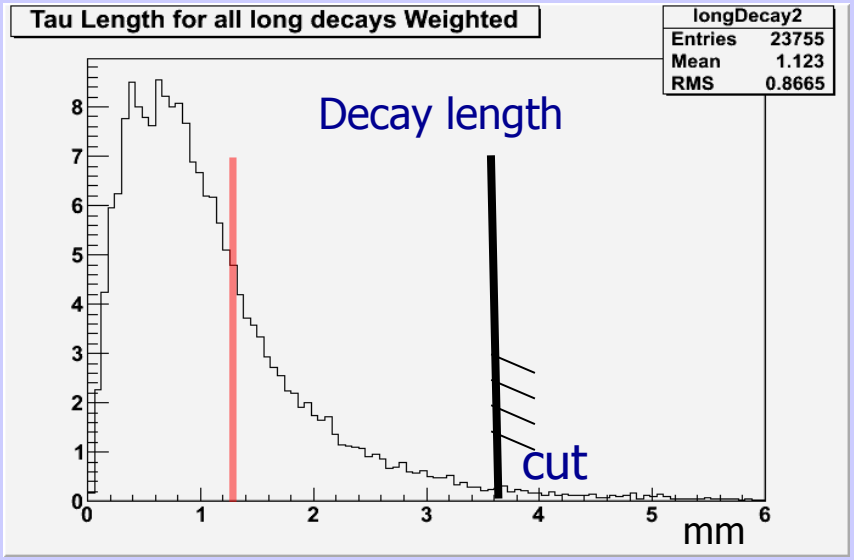
γ-Attachment to Vertices

	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)

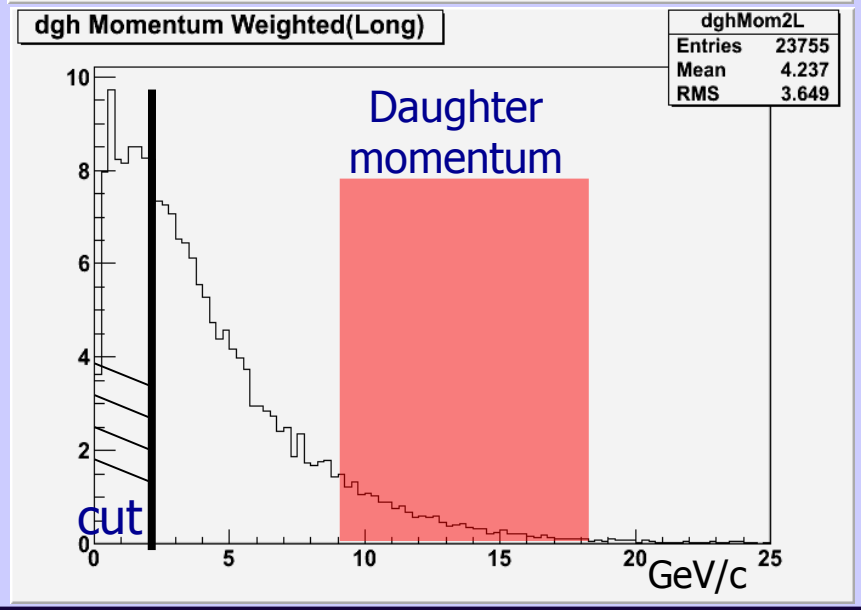
* Probability to find an IP larger than the observed one

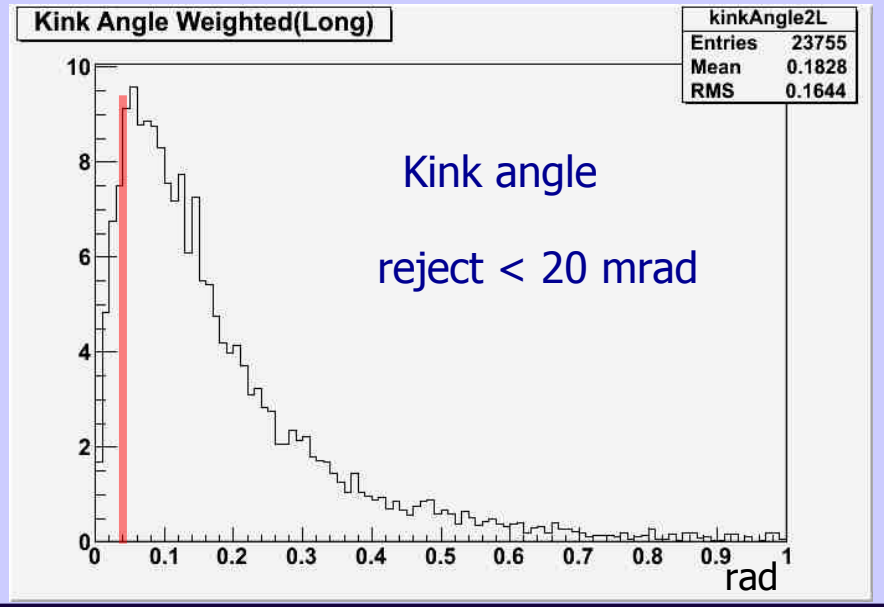


Decay Topology Characteristics



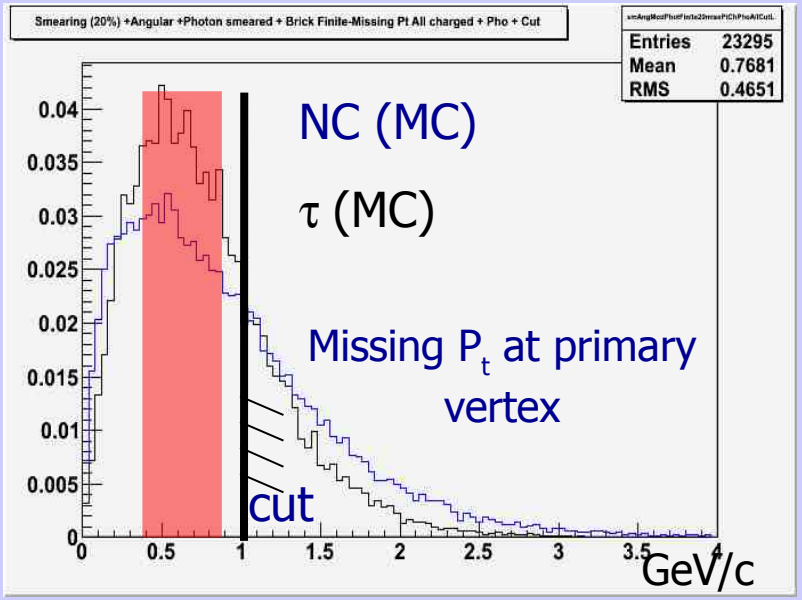
Red regions:
Measured values for ν_τ candidate



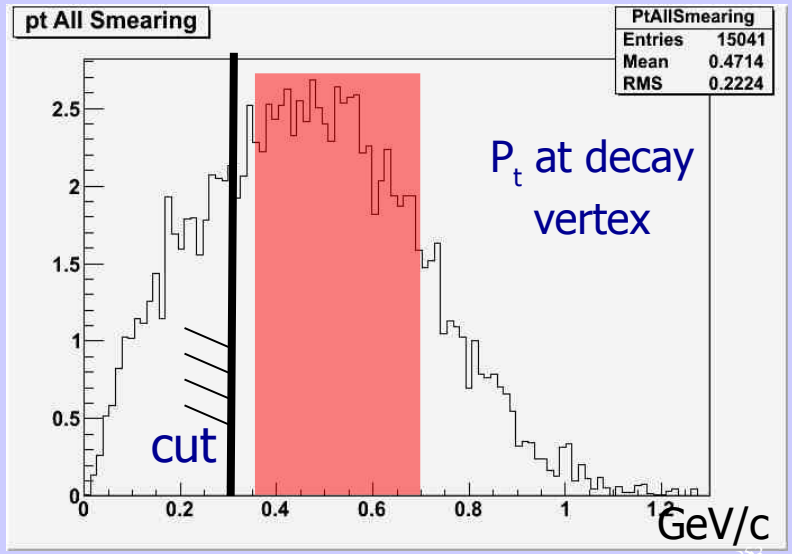


Kinematical Cuts to be Passed

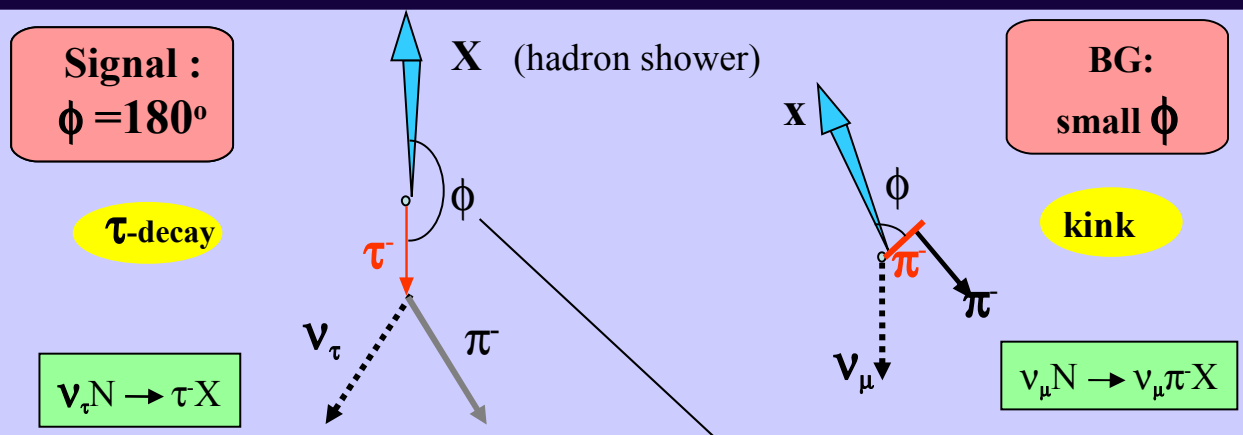
Reject NC events with larger missing P_t (neutrino)

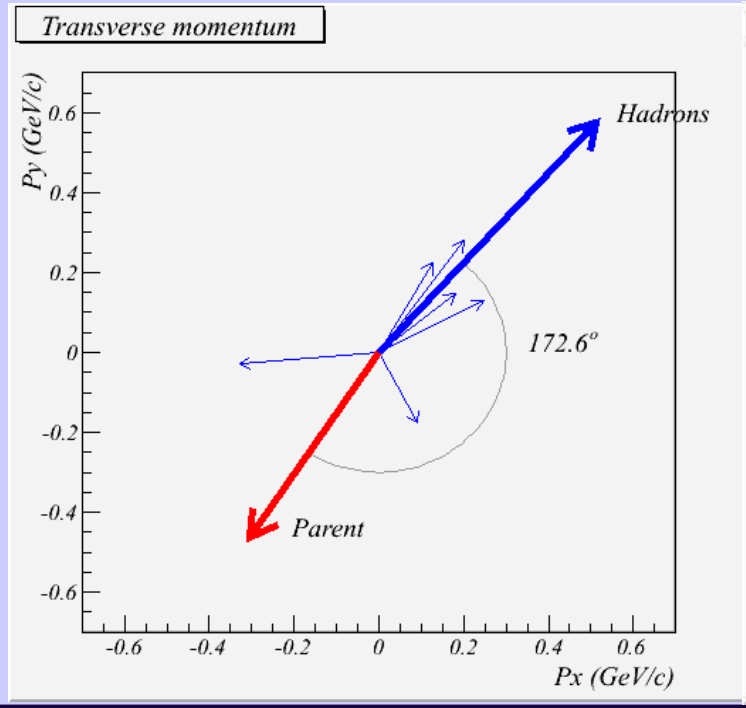


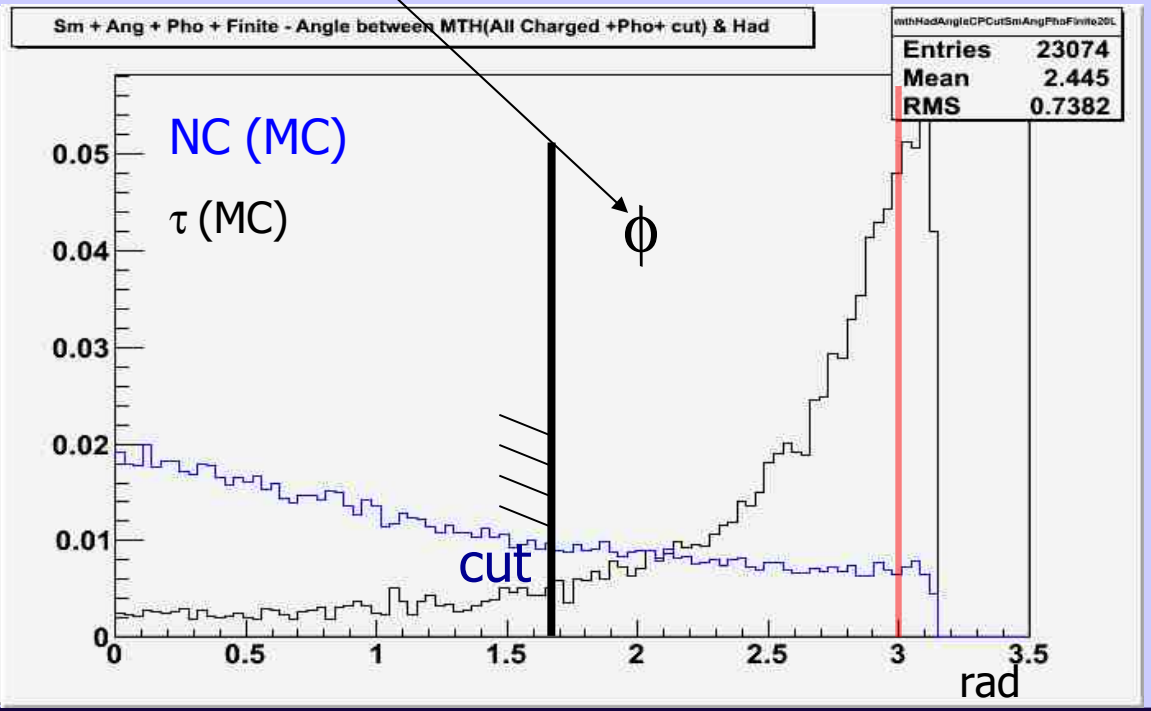
Reject hadron interactions



P_t Characteristics







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
$120 \pm 20 \pm 35$ MeV	$640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

- ρ is created 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 hadronic τ decay channel

- background expectation for 1 prong hadron decay:

  0.011 events (hadronic re-interactions)
  + 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

Overview

Neutrino Oscillations

The OPERA Experiment

Detector Performance

Special Events: Charm, ν_e

ν_τ Candidate

Outlook

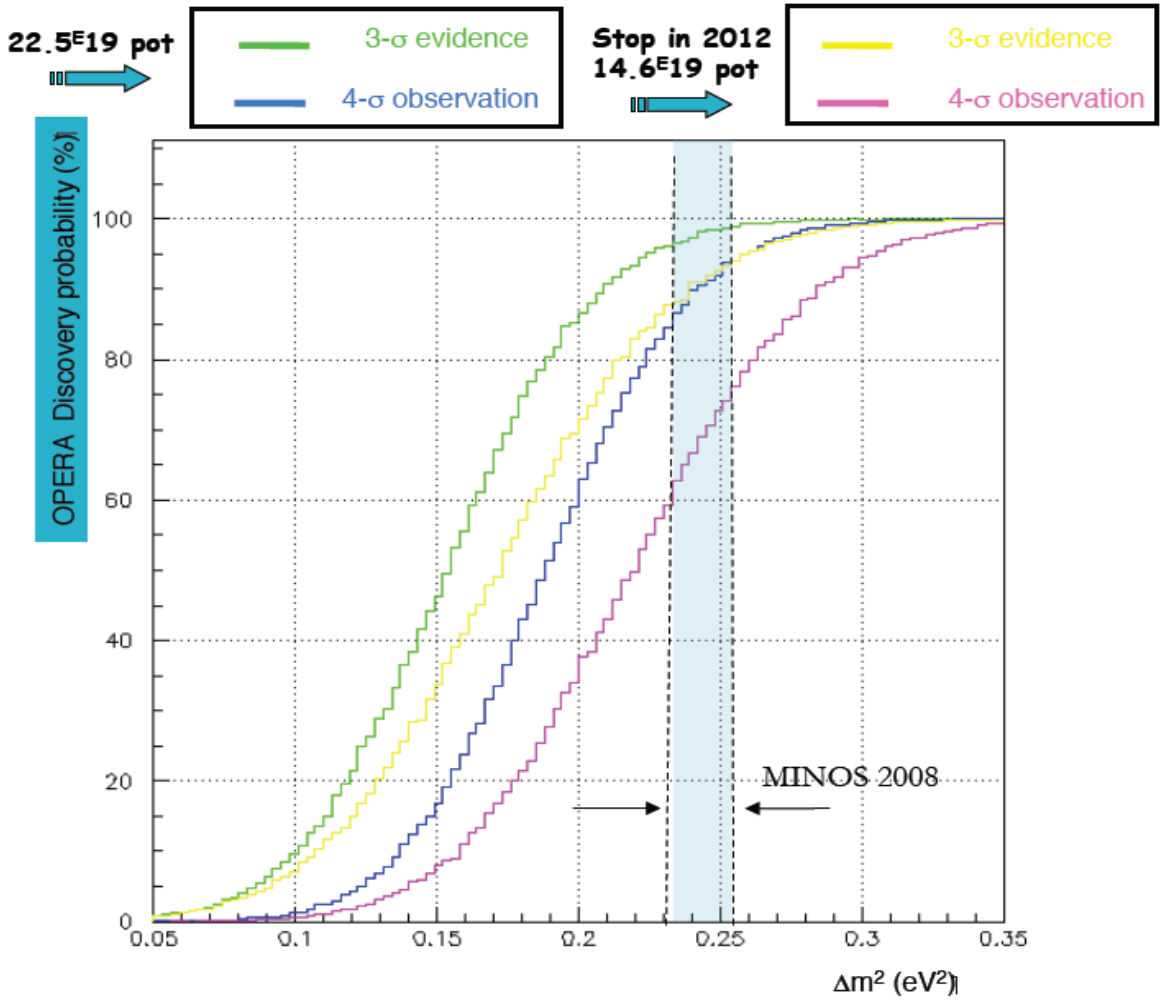
Outlook

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

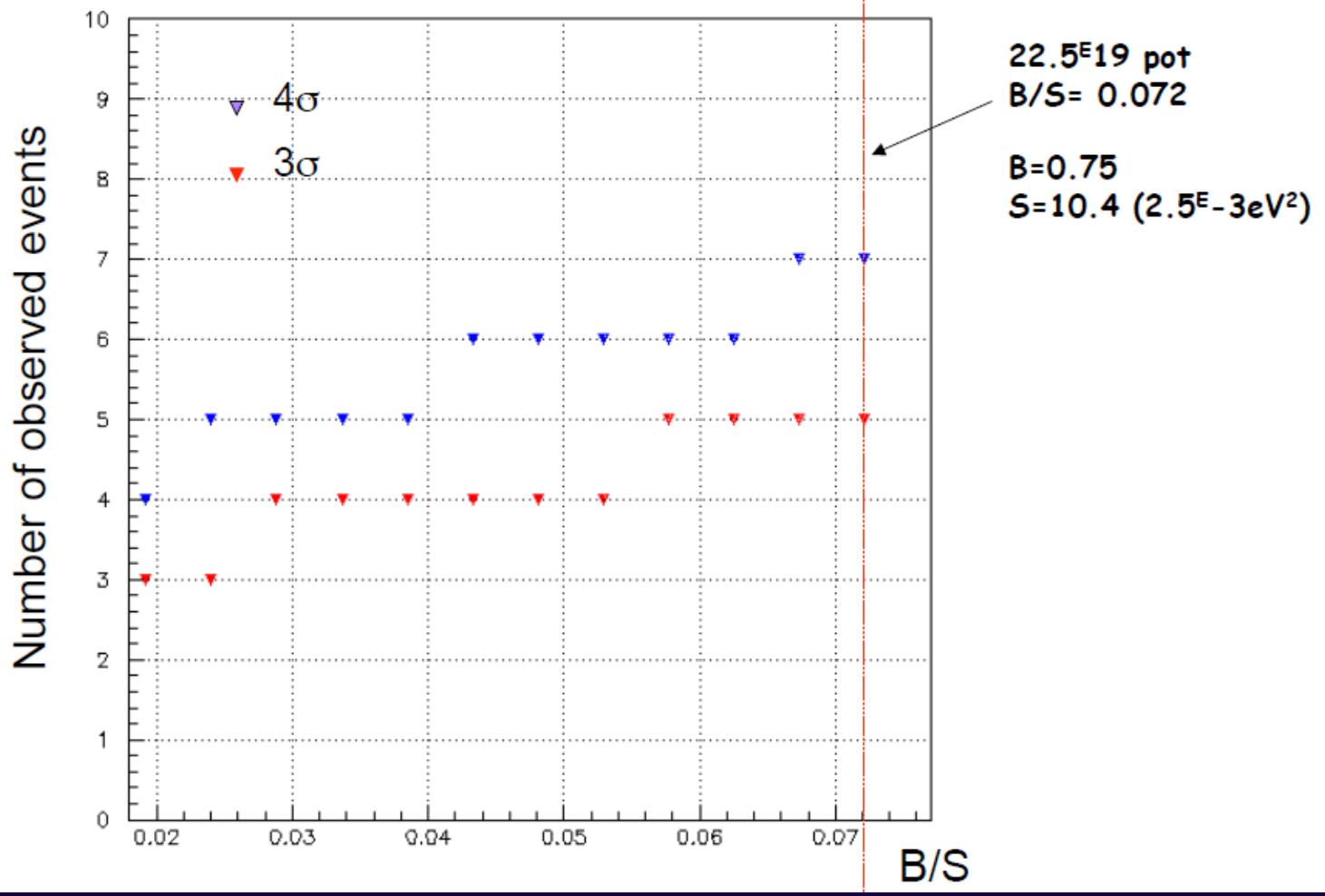
Waiting for more ν_τ candidates…

Backup Slides:

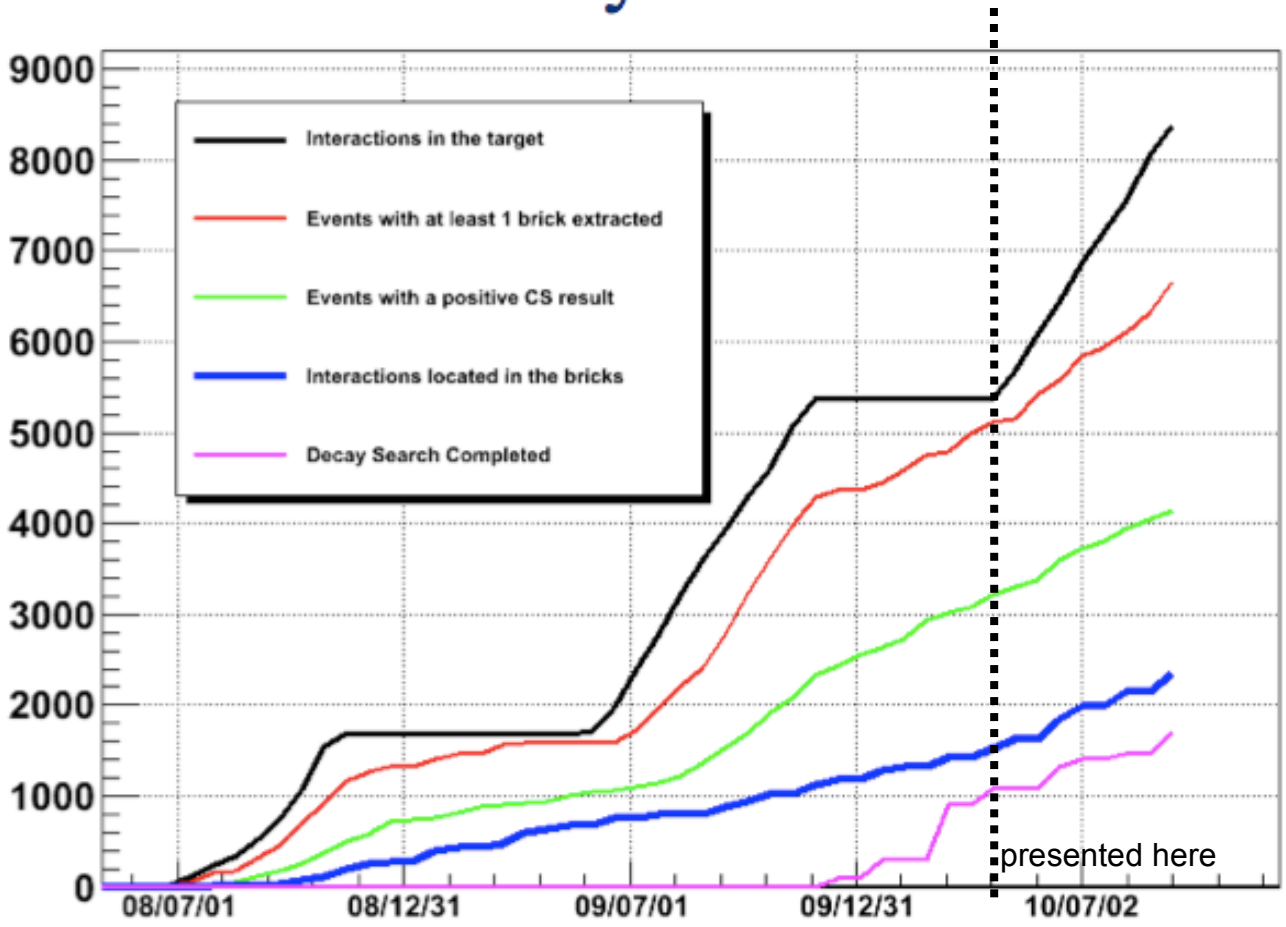
Expected performance of OPERA vs running time



Minimal number of events to be observed to claim a 4σ or 3σ signal in OPERA as a function of the background (B/S ratio)



Analysis status (September 2010)



2367 interactions located, 78% of the 2008-09 expected yield

1718 decay search completed

Status brick handling

CNGS Brick candidate extraction status September 22nd 2010 :

Run 2008: 2609 bricks extracted (for 1700 events). => 1.53 brick/event

+

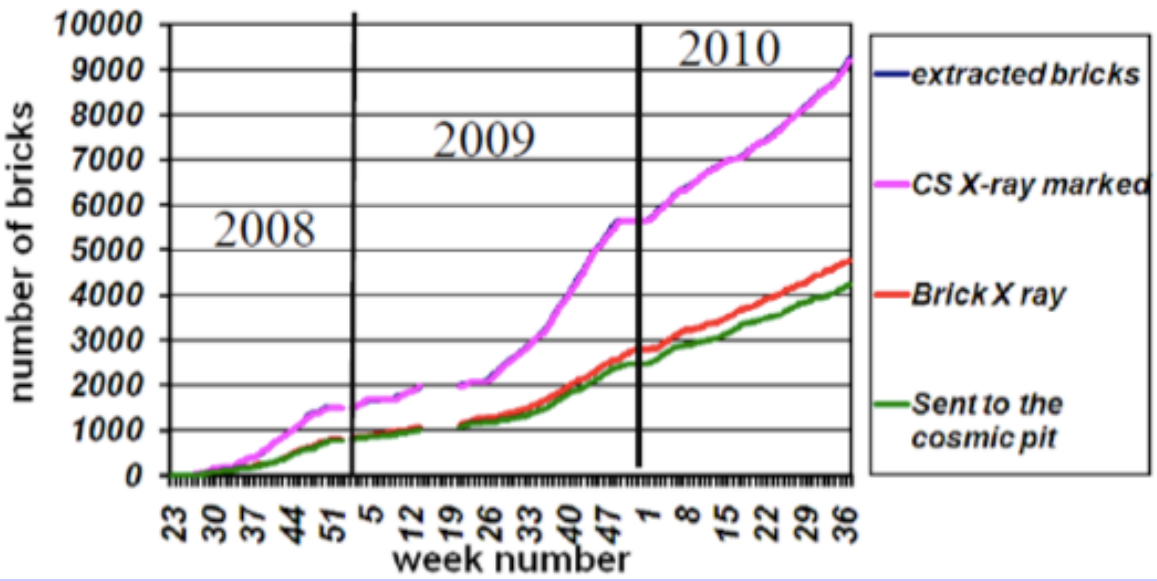
Run 2009: 4943 bricks extracted for 3560 evts => 1.39 brick/event

+

Run 2010: 1758 bricks extracted

Total: 9310 bricks

OPERA brick handling in 2008, 2009 and 2010

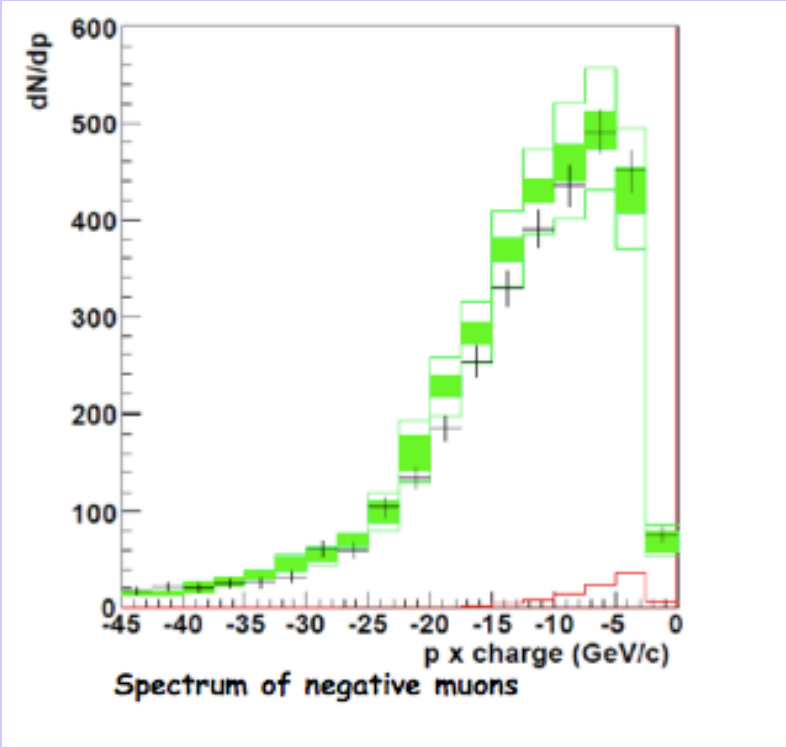


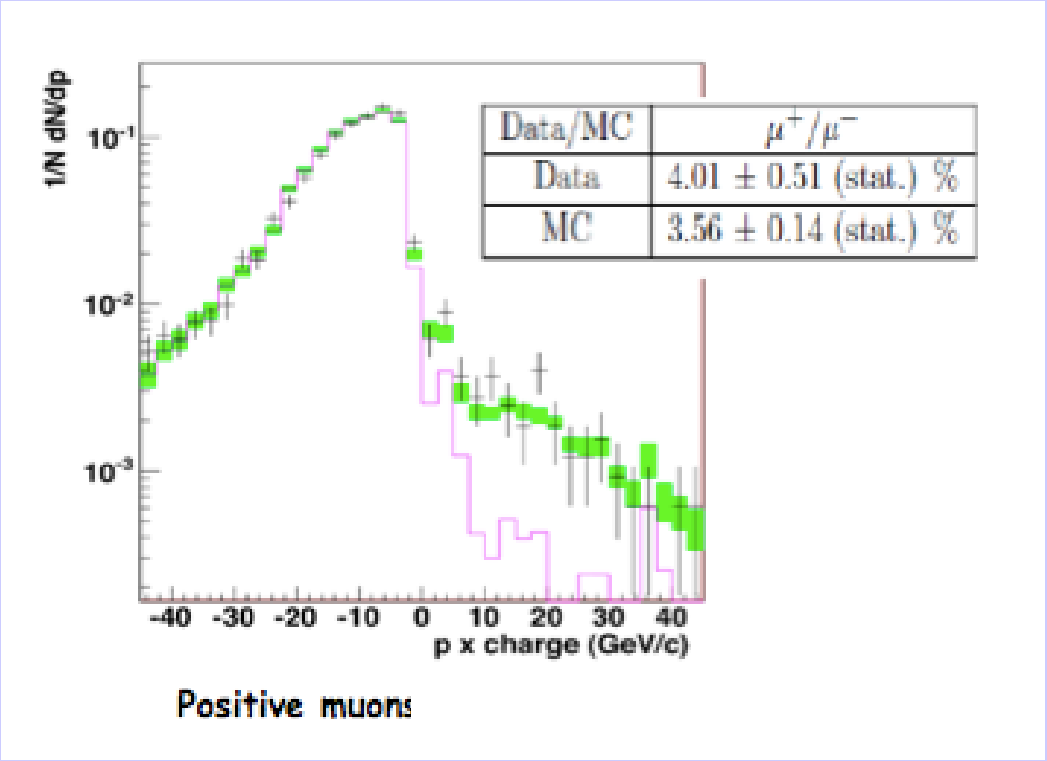
Peculiar topologies

Lab	Events Located	Decay search (CC)	Charm Candidates	ν_e	ν_τ candidates
Total	**2367**	**1406**	**36**	**9**	**1**

Electronic Detectors

Preliminary (paper in preparation)

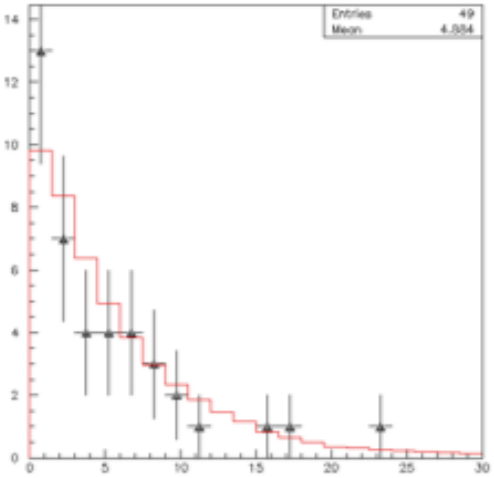




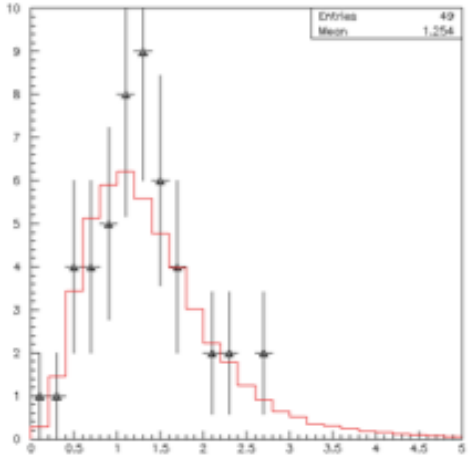
Minimum bias kinematical sample:

A sample of numu CC events with the momenta of all hadronic tracks measured in the ECC by MCS with the scanforth

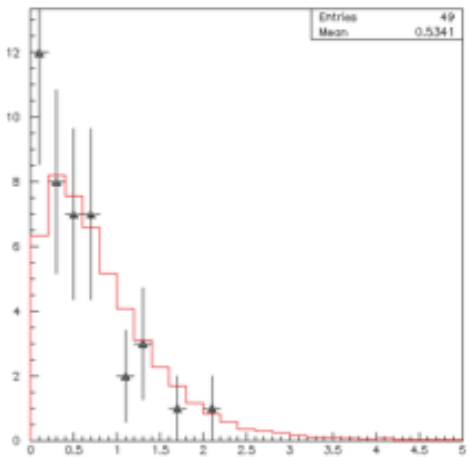
Some preliminary comparisons Data/MC



Total energy of charged hadrons at primary vertex (masses neglected)



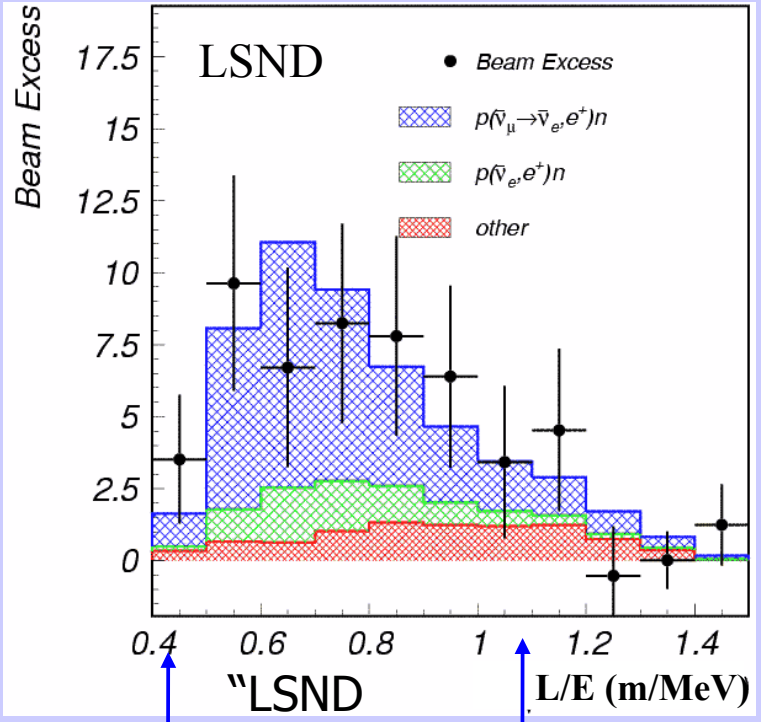
Muon Pt



Total Pt of charged hadrons

Short baseline $\bar{\nu}_e$-appearance ?

LSND



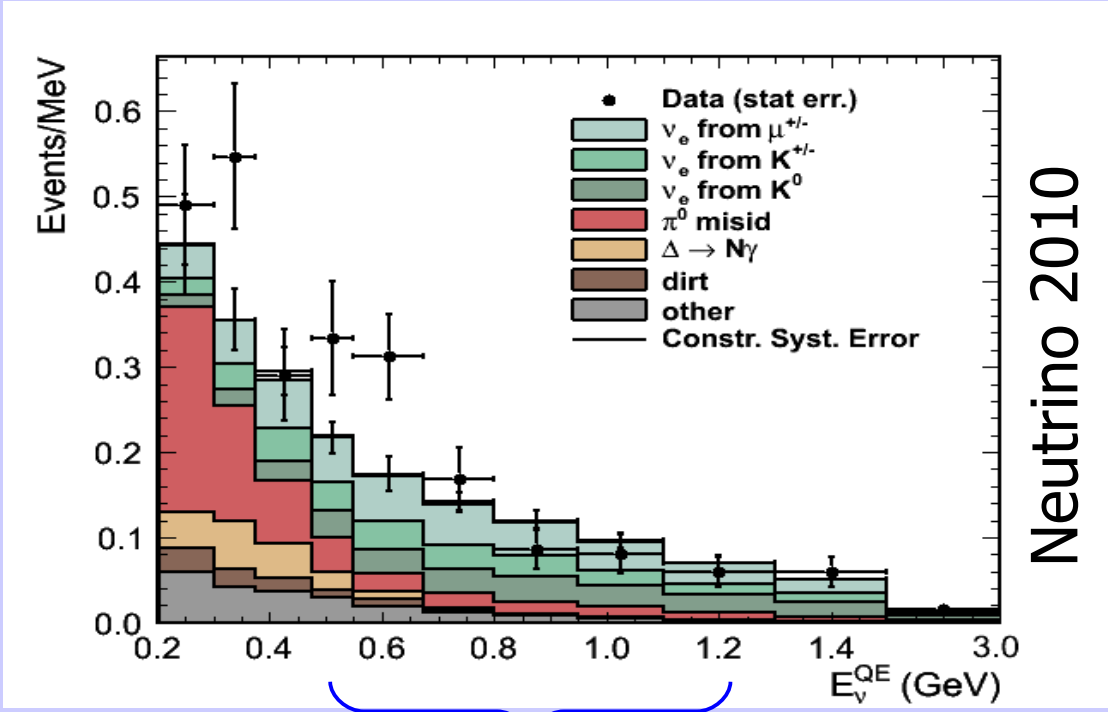
"LSND sweet spot"

1250

475

Energy in MiniBooNE [MeV]

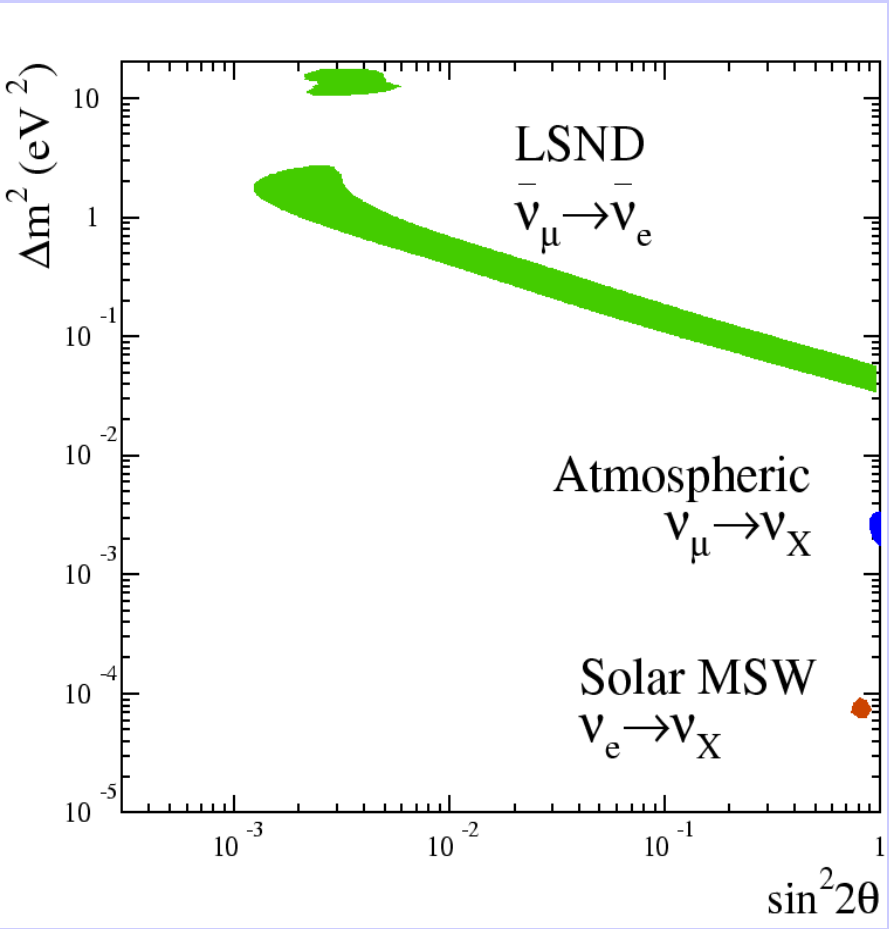
MiniBooNE

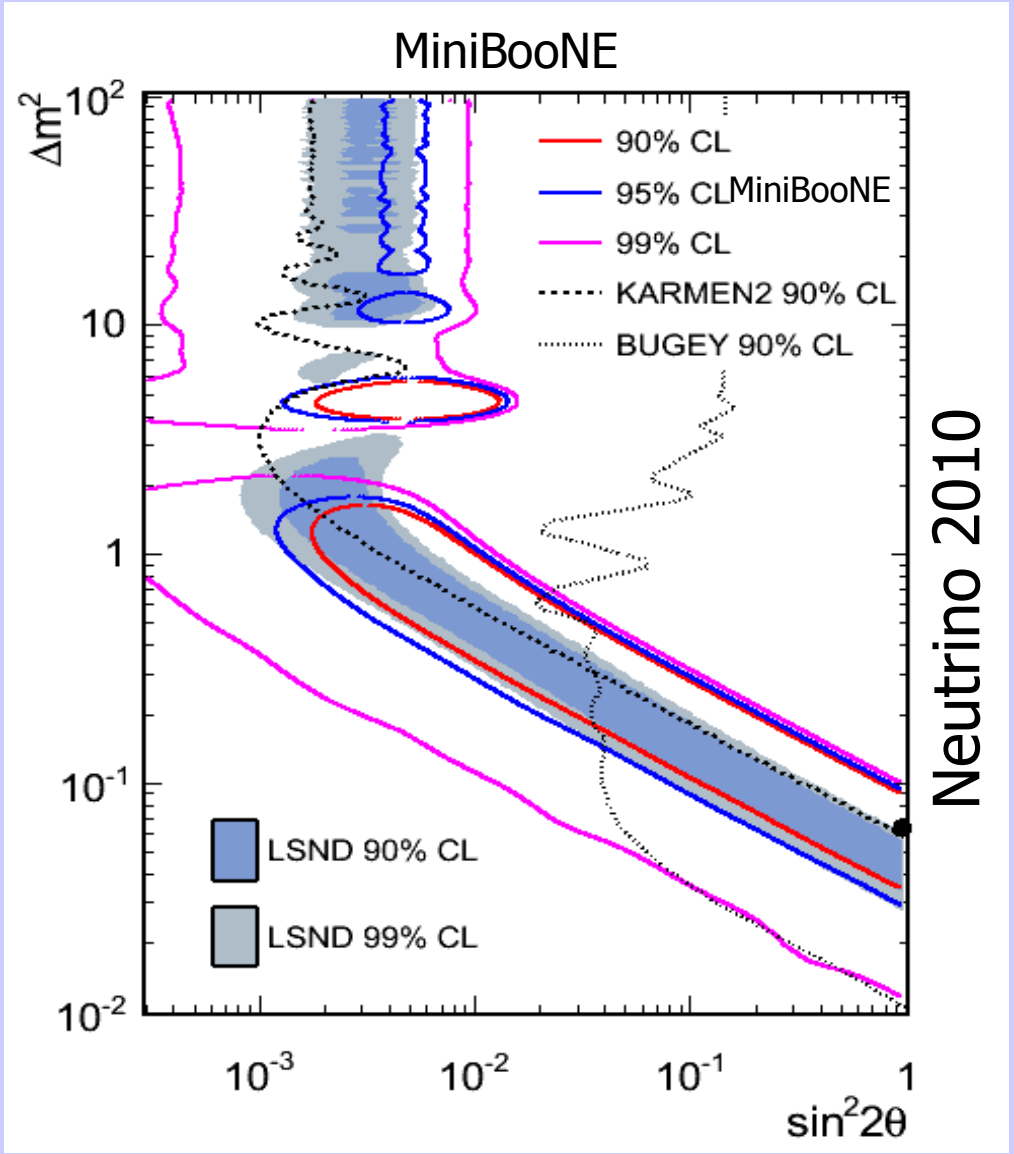


"LSND sweet spot"

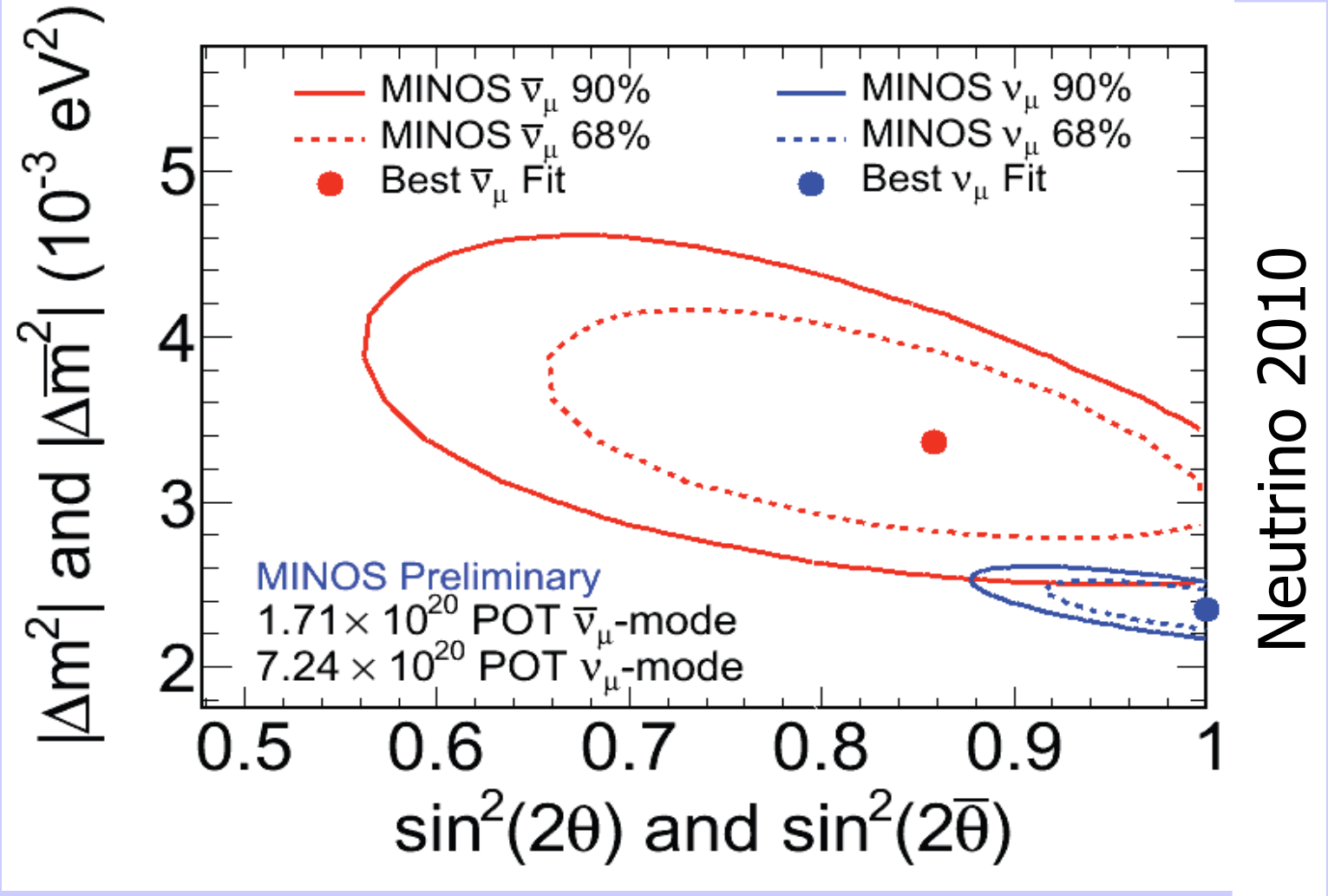
Neutrino 2010

Compatibility of $\overline{\nu}_e$-Data





MINOS $\bar{\nu}_\mu$-data



Overall Status

- Scheme of 3 flavour ν-oscillation is well established.
- We already started to get precise data on the oscillation parameters.
- There seems to be some tension with $\bar{\nu}$-data sets.

→ Suprises are still possible!

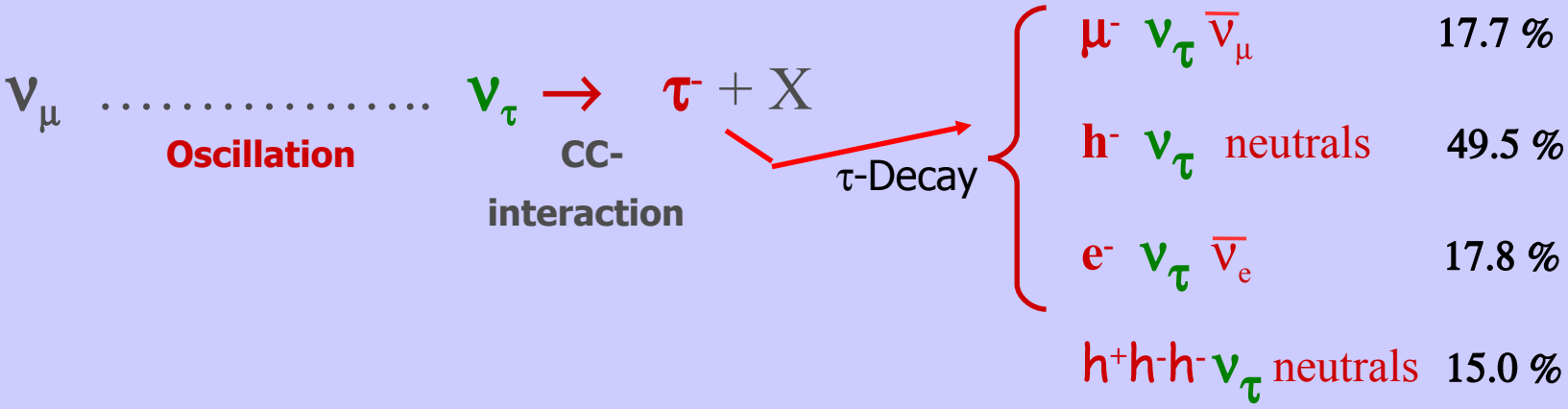
→ We need as many unambiguous answers as possible!


OPERA

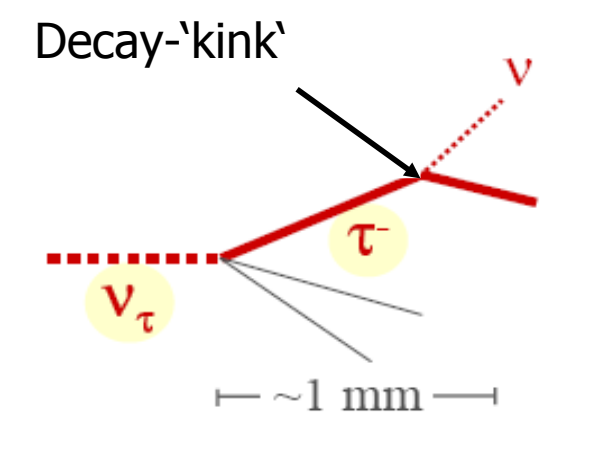

OPERA

Detector Concept

- Goal: direct observation of ν_τ in ν_μ beam



- OPERA has to look for special topology



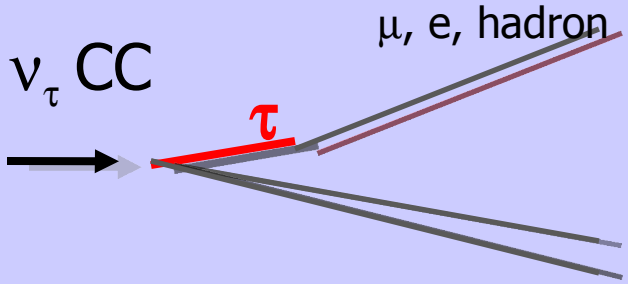
Use Emulsion Cloud Chambers (ECC) to achieve high enough spatial resolution and density.

Background Processes

Most important background processes:

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

Signal



Background