Recent results from the OPERA experiment

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OPERA
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The Collaboration

~140 physicists, 28 institutions, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

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

Switzerland
Bern

Turkey
METU Ankara

Overview

The OPERA Experiment

ν_τ Candidates

ν_e Analysis

Outlook

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The OPERA Experiment

ν_τ Candidates

ν_e Analysis

Outlook

OPERA:
Oscillation Project with Emulsion tRacking Apparatus

Long baseline neutrino oscillation experiment

Very pure ν_μ beam from CERN to LNGS

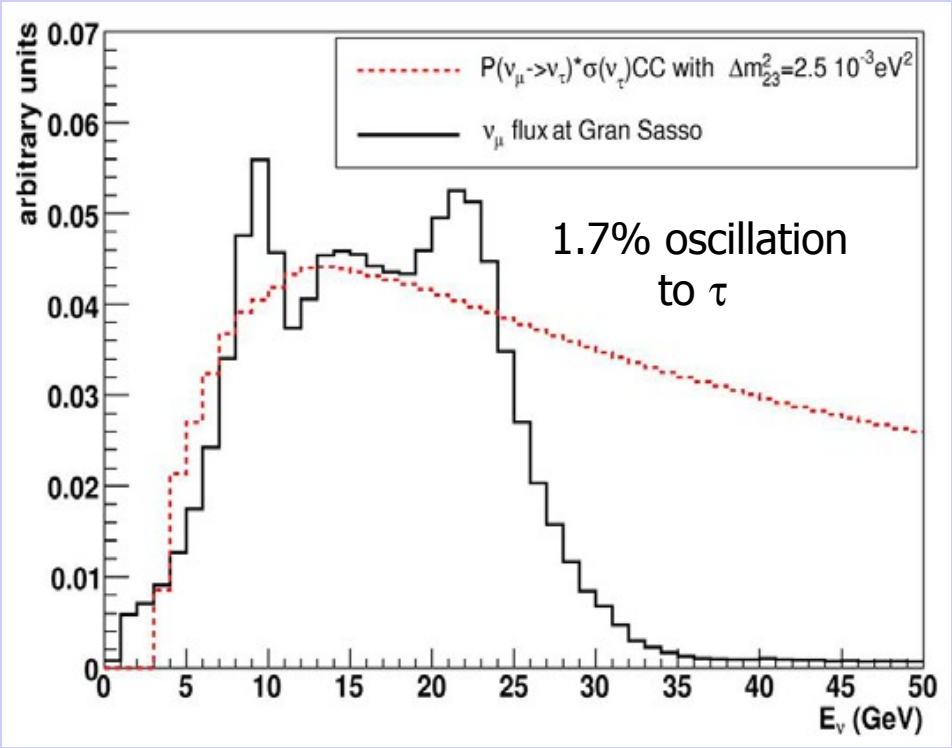
Goal:

Observation of ν_τ appearance

CERN Neutrinos to Gran Sasso Beam

Beam Characteristics:

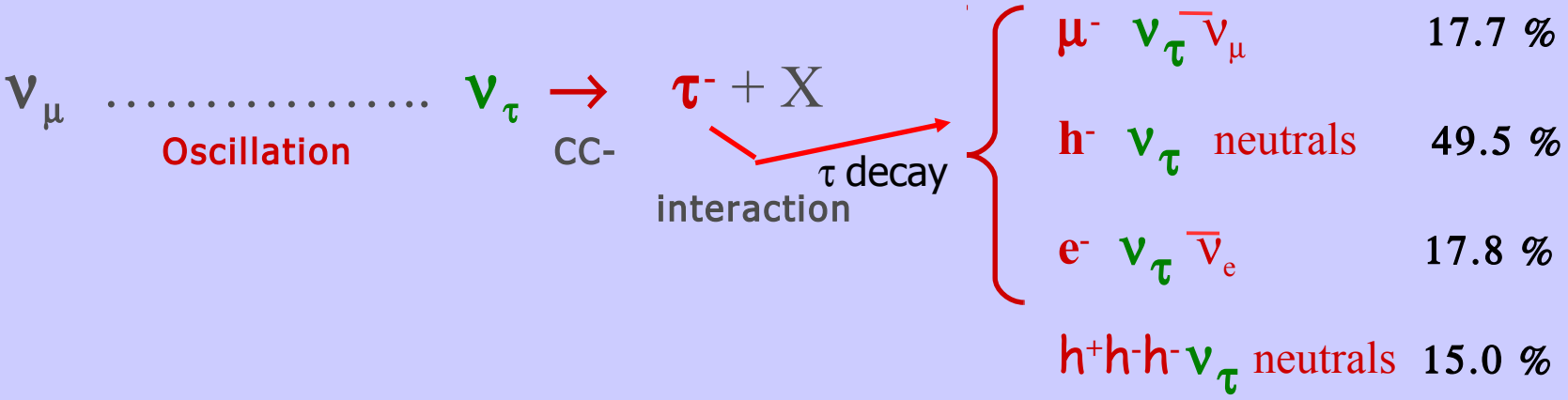
p.o.t./year	$4.5\ 10^{19}$
$\langle E_\nu \rangle$	17 GeV
L	730 km
$(\nu_e+\bar{\nu}_e)/\nu_\mu$	0.87% *
$\bar{\nu}_\mu/\nu_\mu$	2.0% *
ν_τ/ν_μ	negligible ($\sim 10^{-7}$)



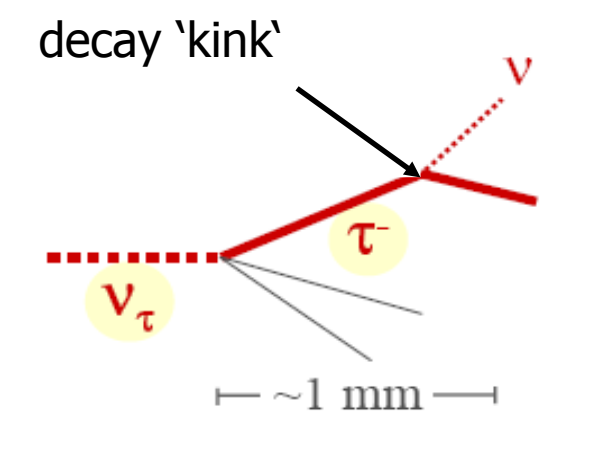
*Interaction rates at LNGS

Detector Concept

- Goal: Direct observation of ν_τ in ν_μ beam



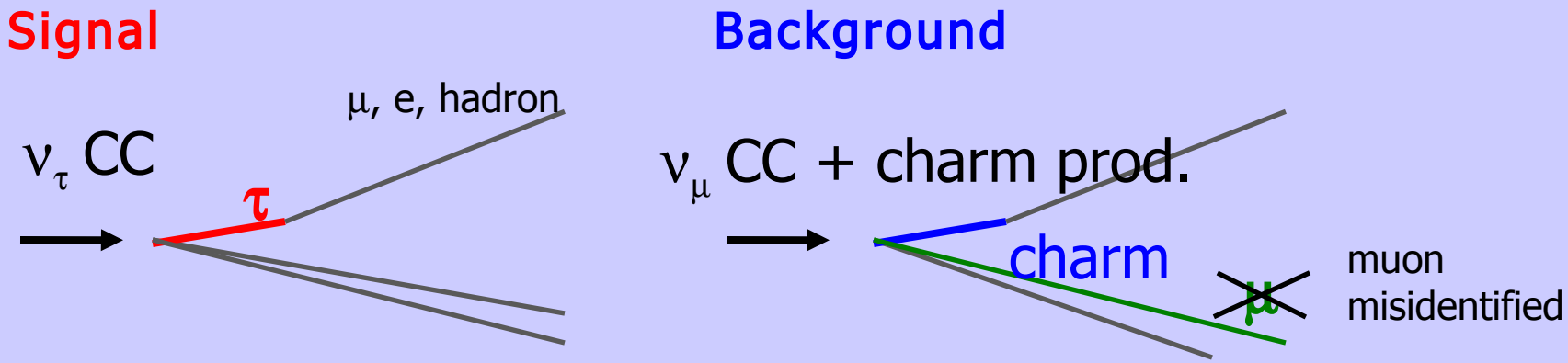
- OPERA has to look for this special topology



Background Processes

Most important background processes:

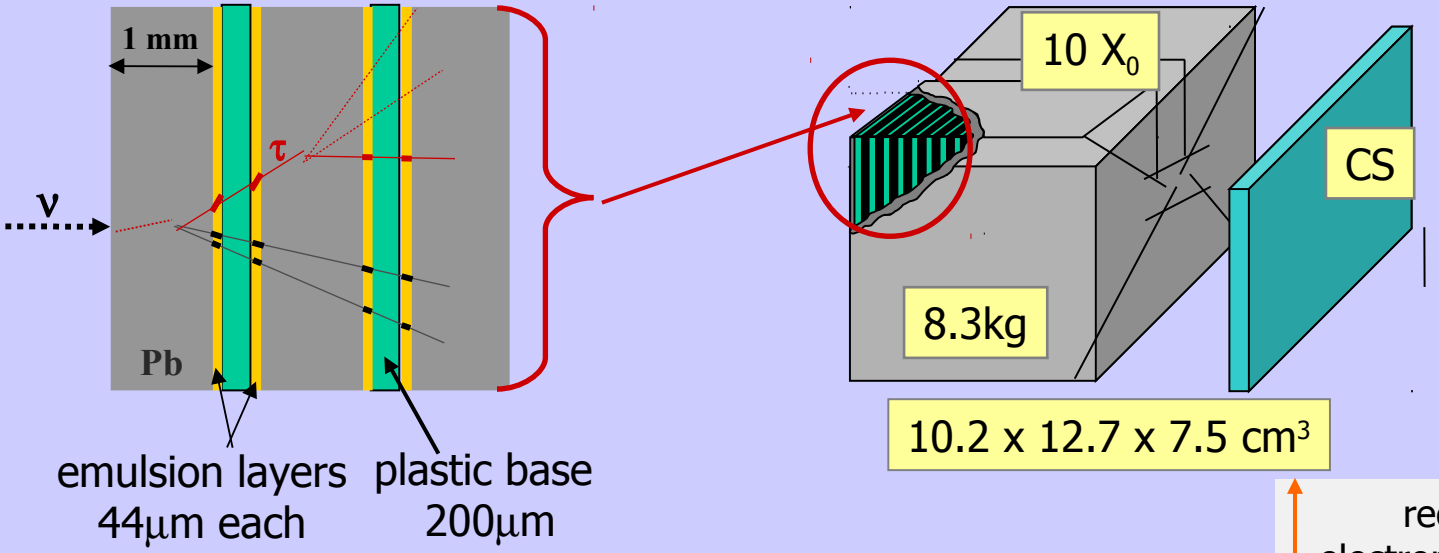
- Charm production and decay
- Hadron re-interactions in lead
- **L**arge-**a**ngle muon **s**cattering in lead (LAS)

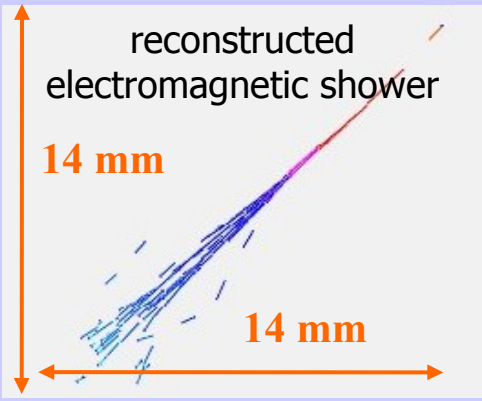


Use Emulsion Cloud Chambers (ECC) to achieve a high enough spatial resolution and density.

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

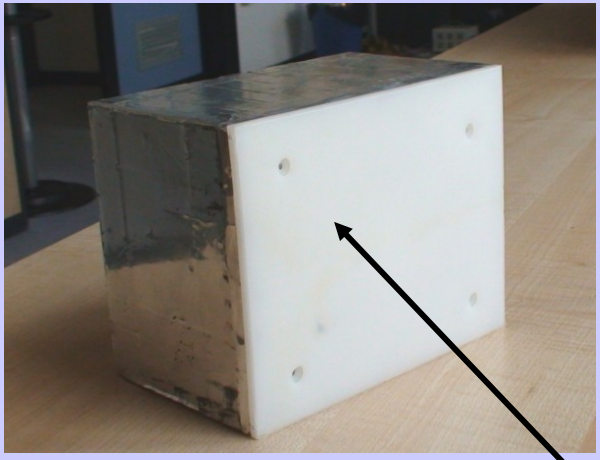


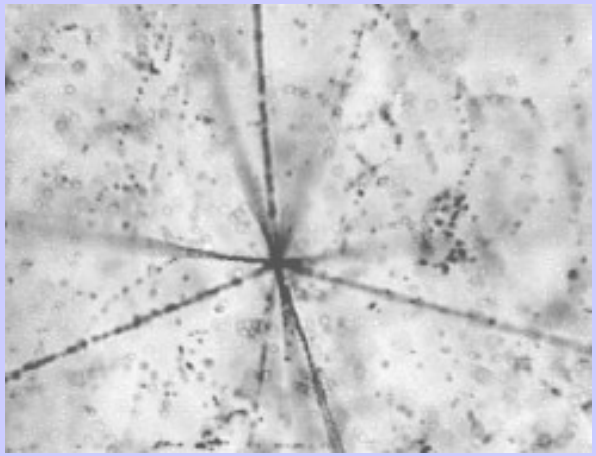


ECC = Stand-alone Detector:

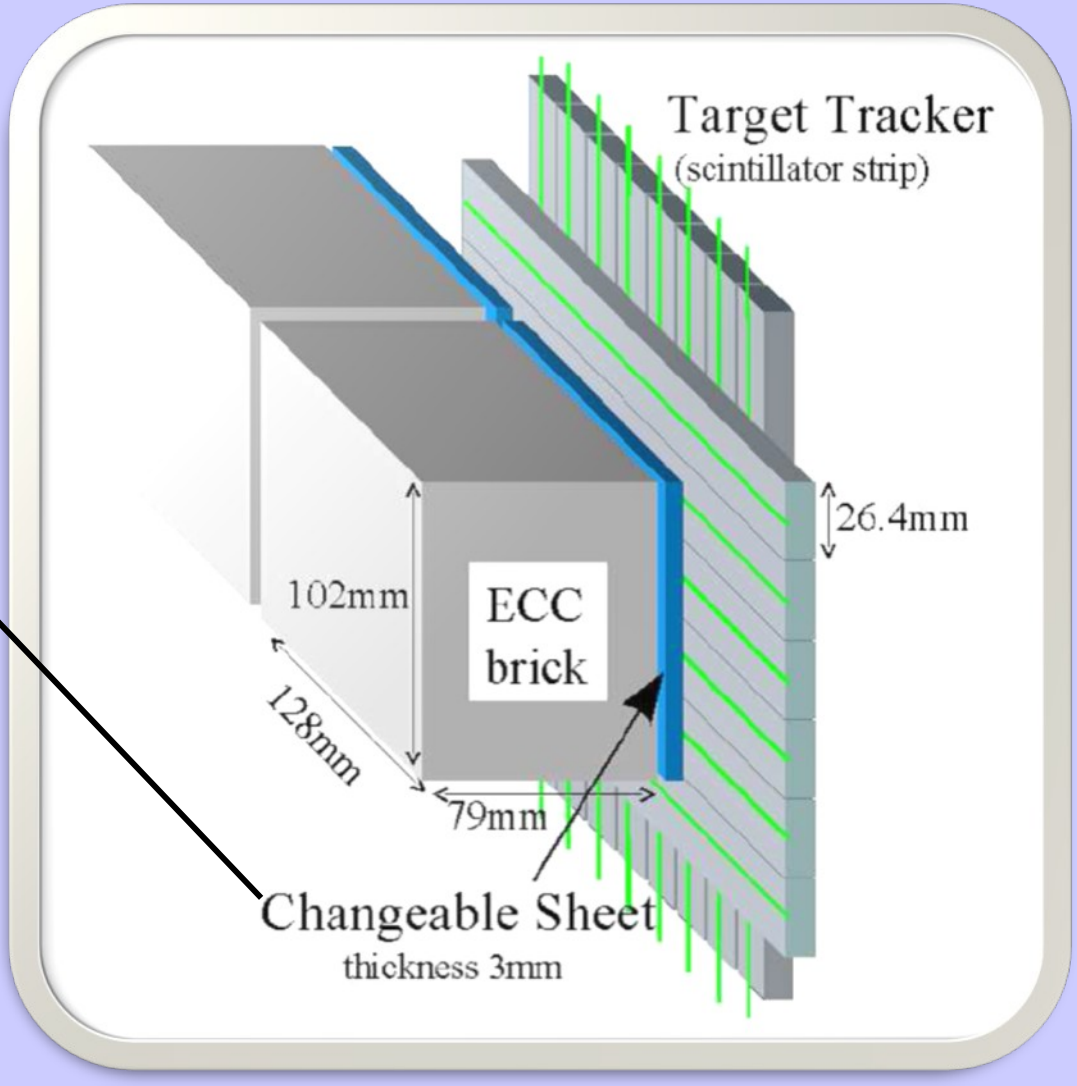
- Momentum measurements for hadrons (multiple scattering)
- Pion/Muon separation at low energy (dE/dx)
- Electron identification and energy measurements for e,γ

Hybrid Detector

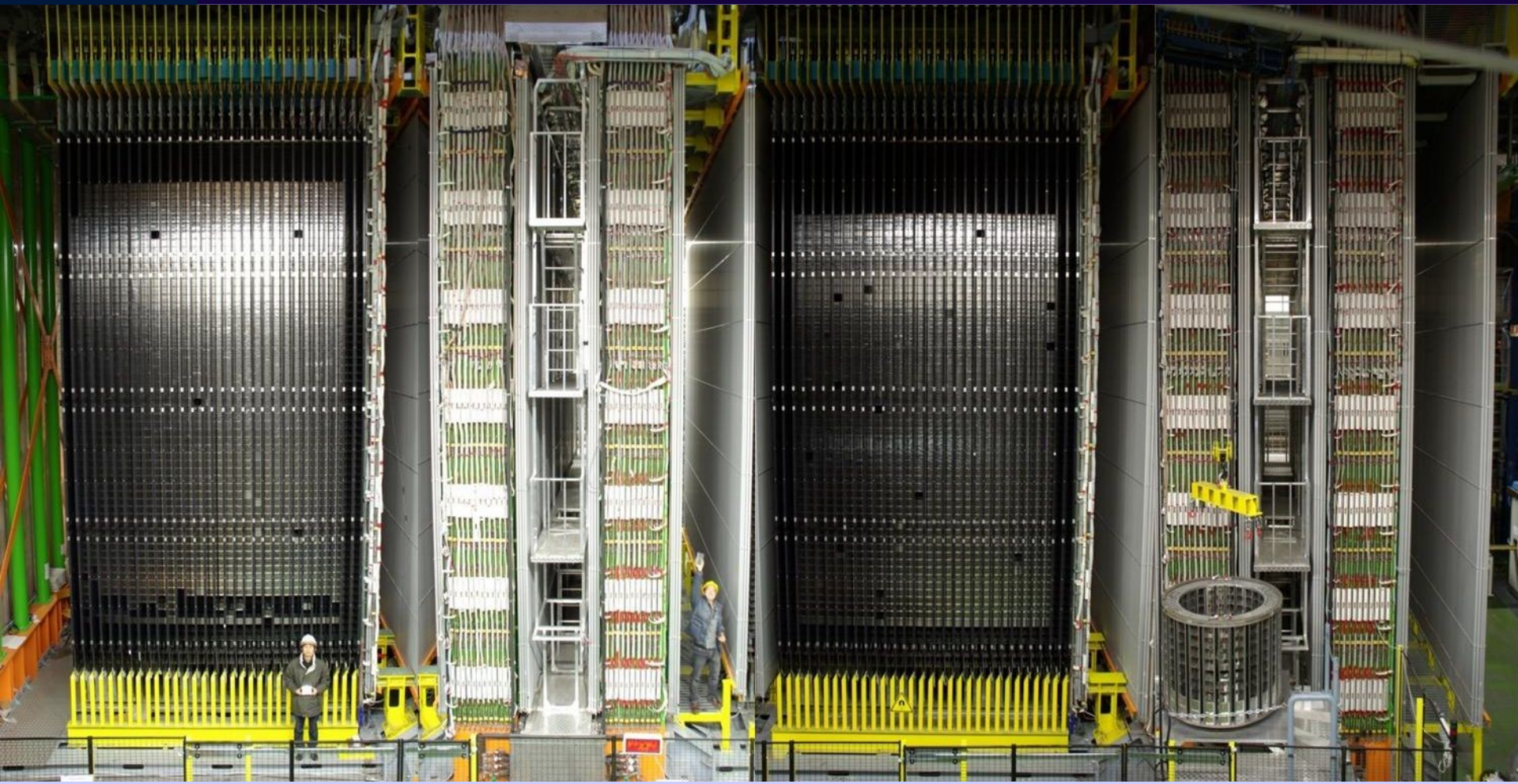




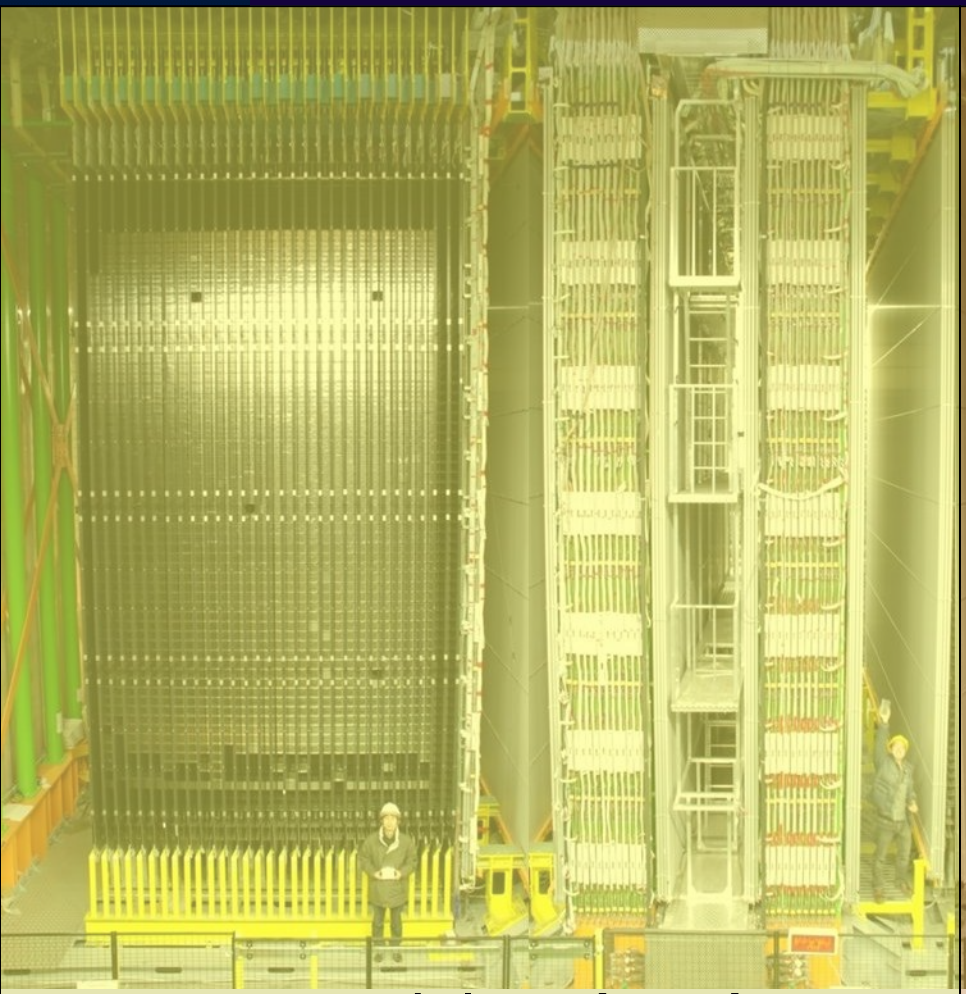
Emulsion Cloud Chambers



The OPERA Detector



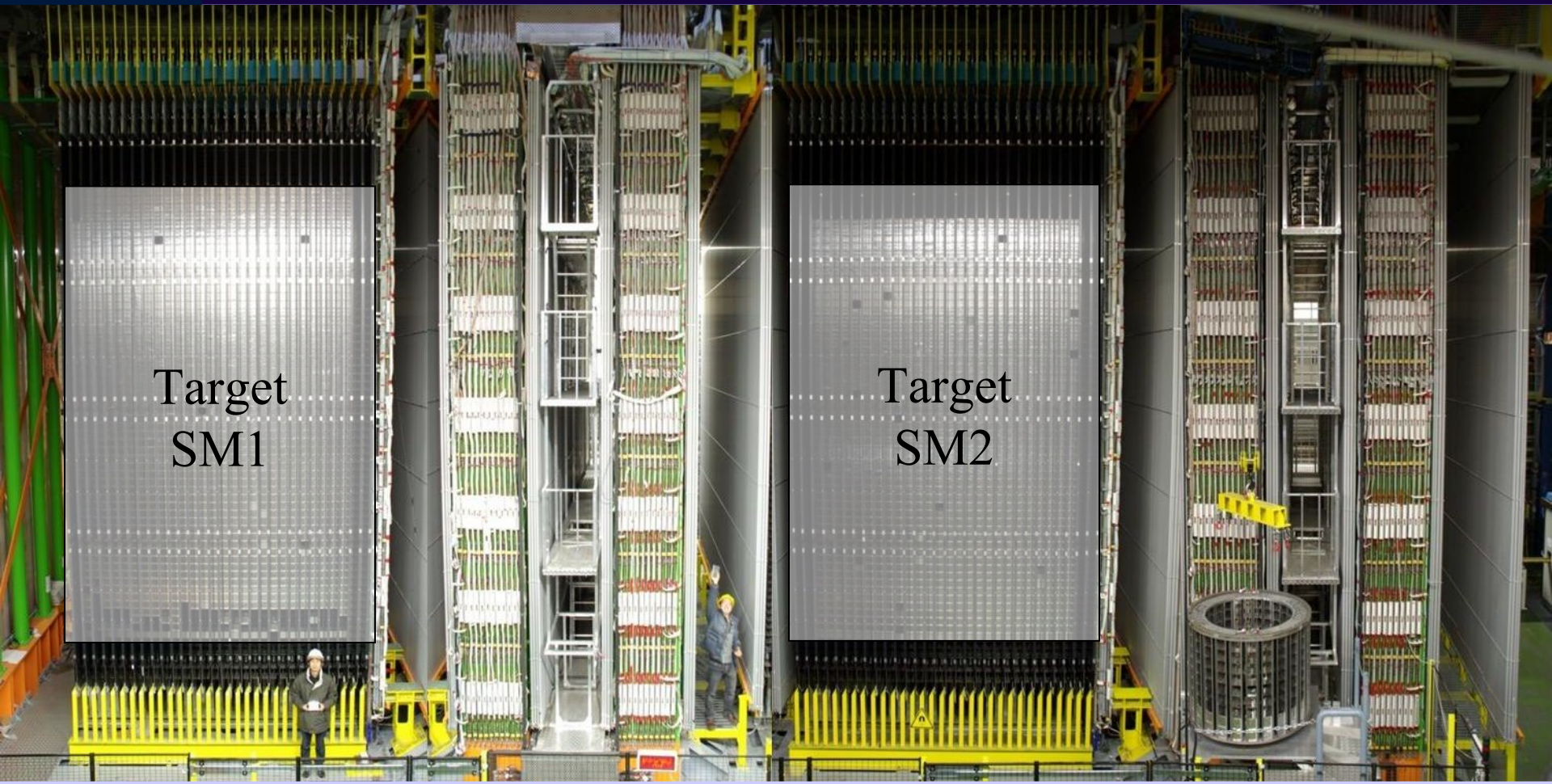
The OPERA Detector



Super Module 1 (SM1)

Super Module 2 (SM2)

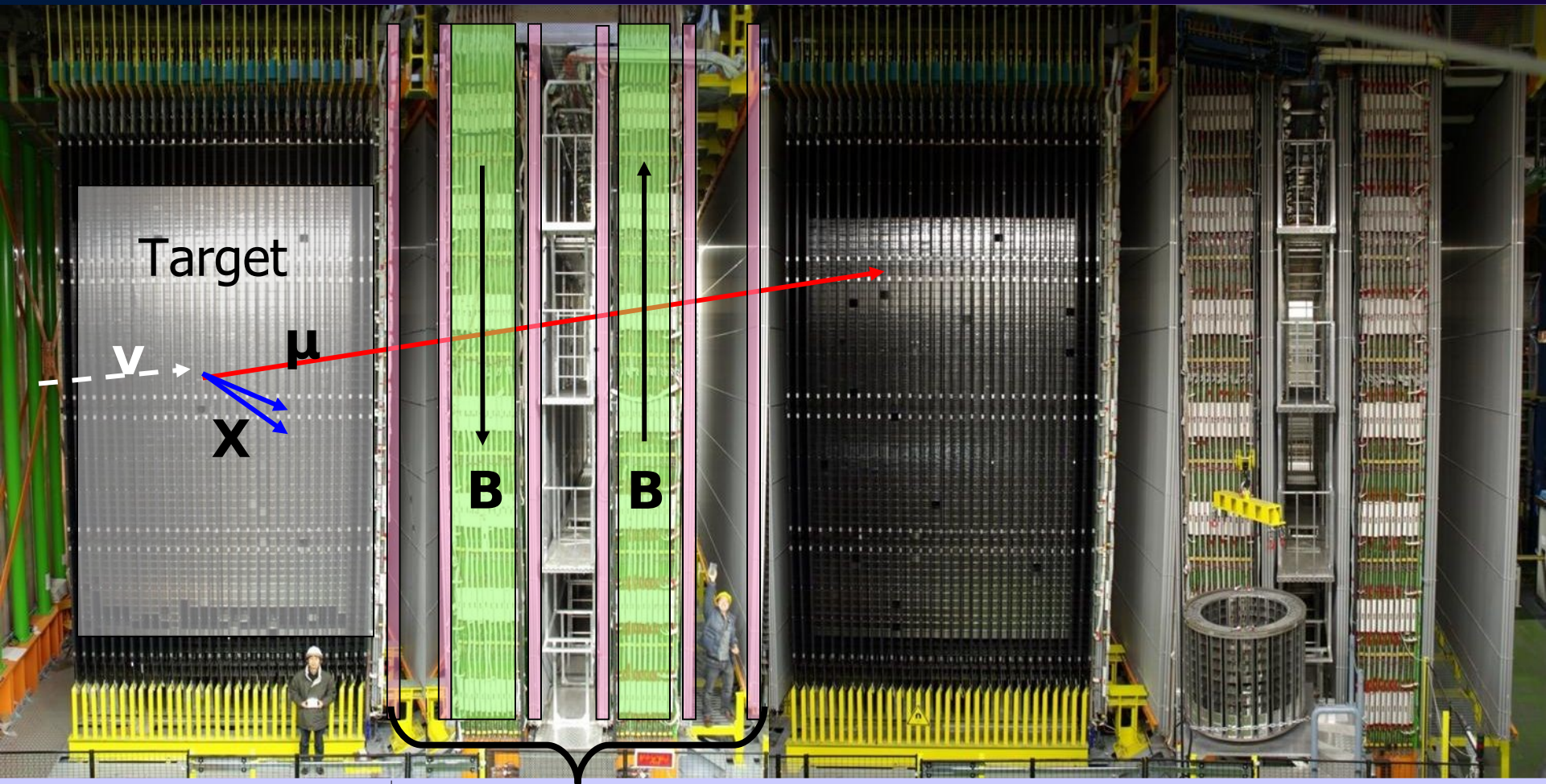
The OPERA Detector



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

→ Target mass: ~1.25 kton

The OPERA Detector



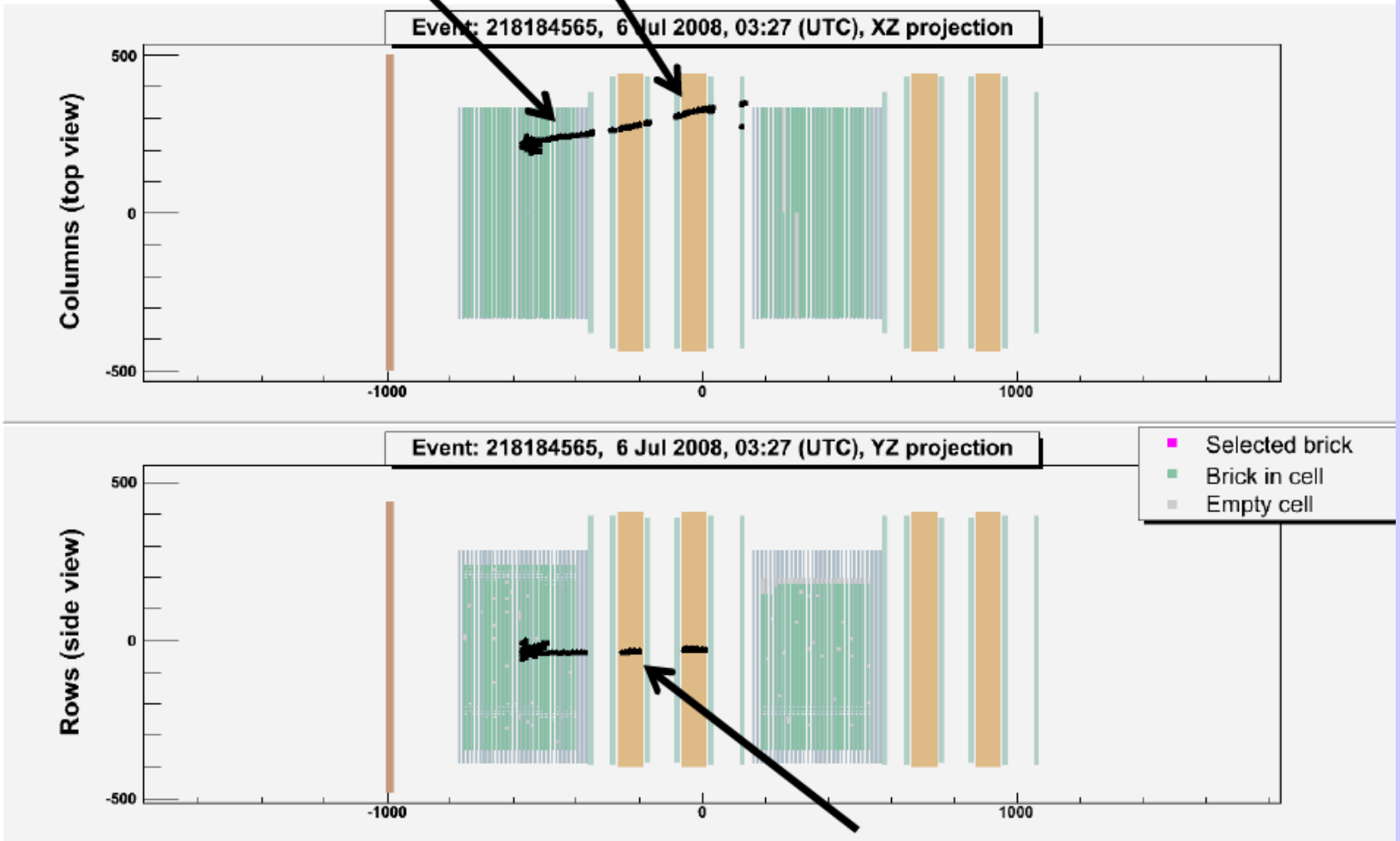
Magnetic Spectrometer:

Magnet Region:
Iron & RPCs

Precision Tracker:
6 planes of drift tubes

Reconstruction (I): Magnetic Spectrometer

Electronic data (Target Tracker & Muon spectrometer)

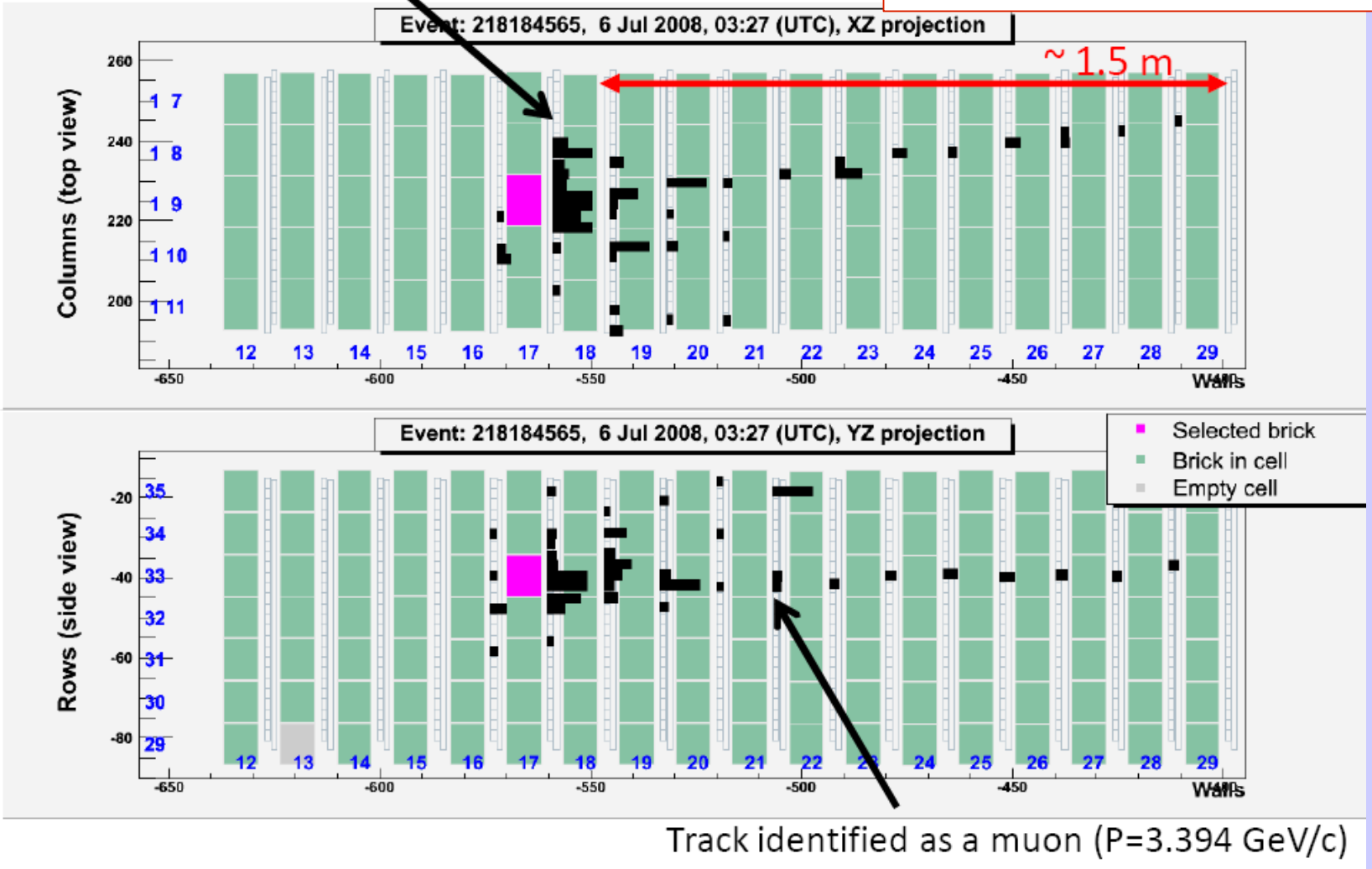


Track identified as a muon (P=3.394 GeV/c)

Reconstruction (II): Brick Finding

Electronic data (Target Tracker)

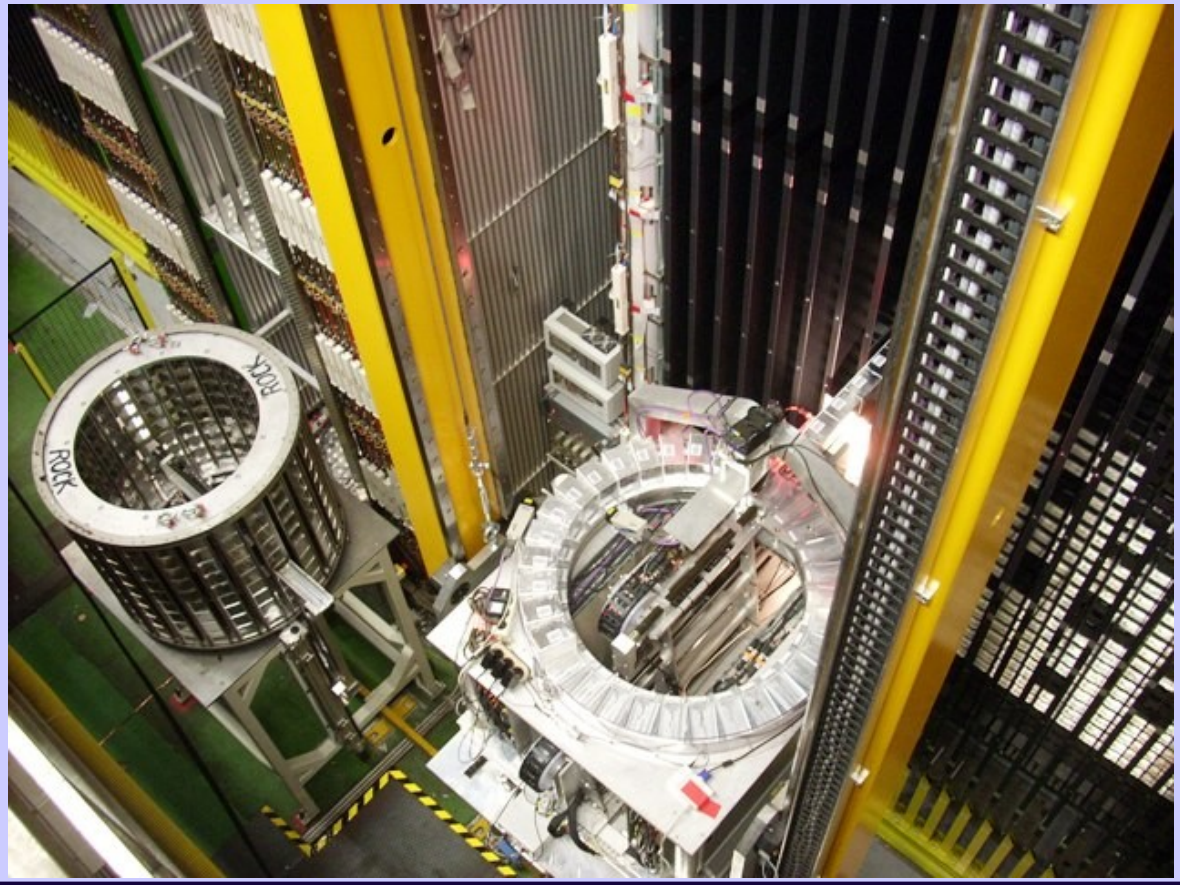
Iterative process: on average 1.6 bricks involved



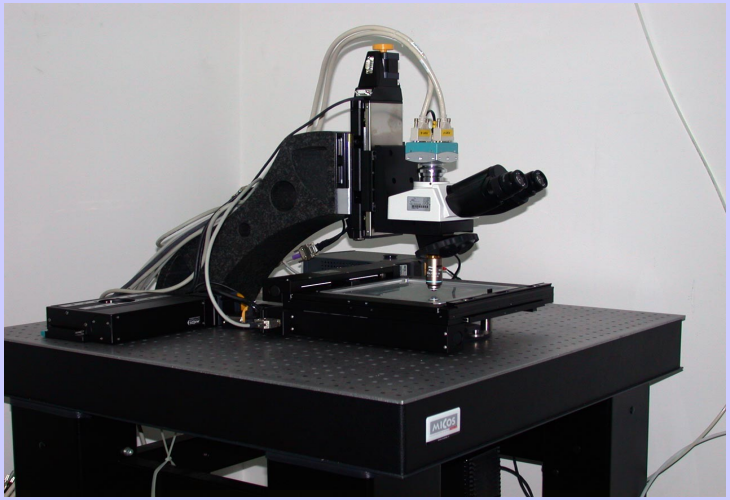
Brick Manipulation System

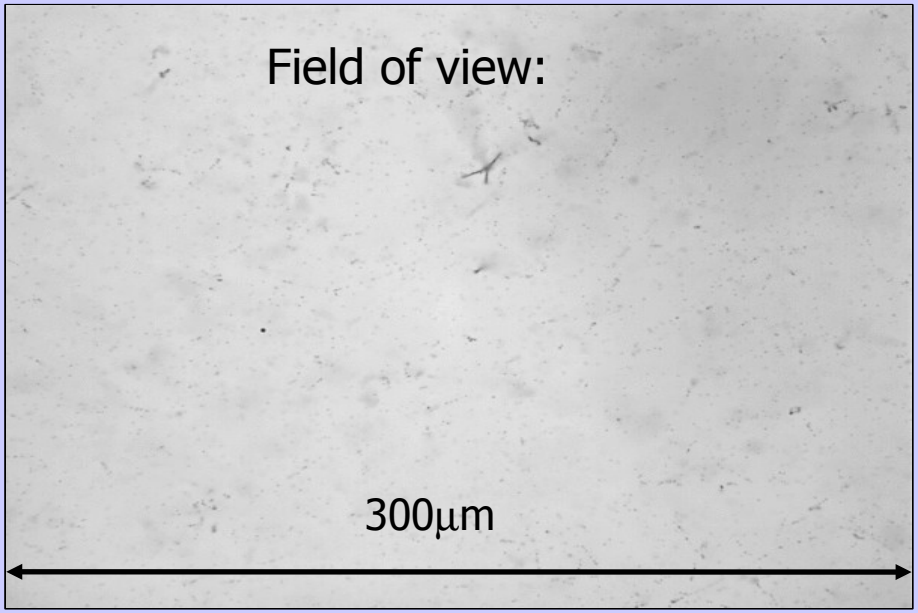
- Bricks are automatically extracted

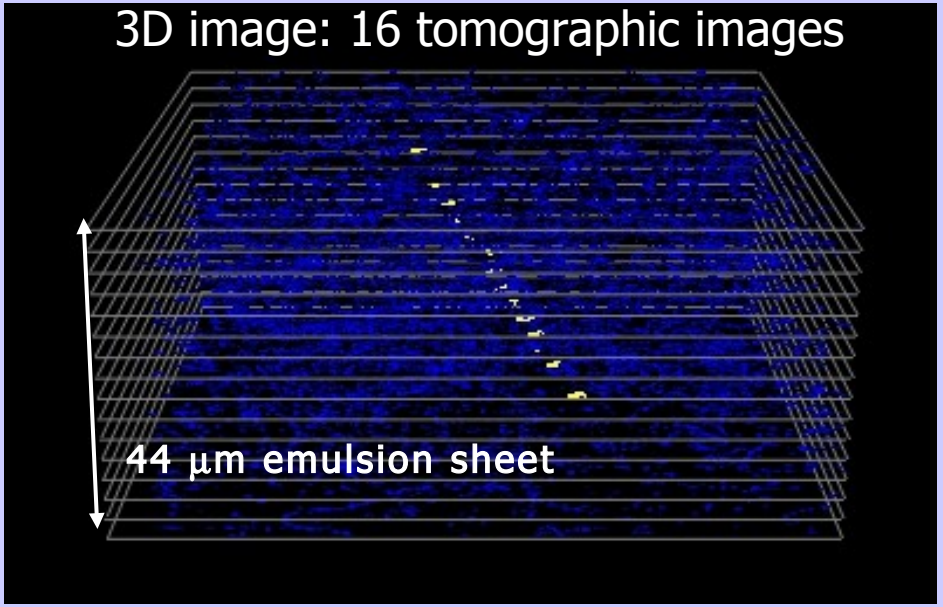
- Position of brick at given time is recorded in database



Emulsion Scanning

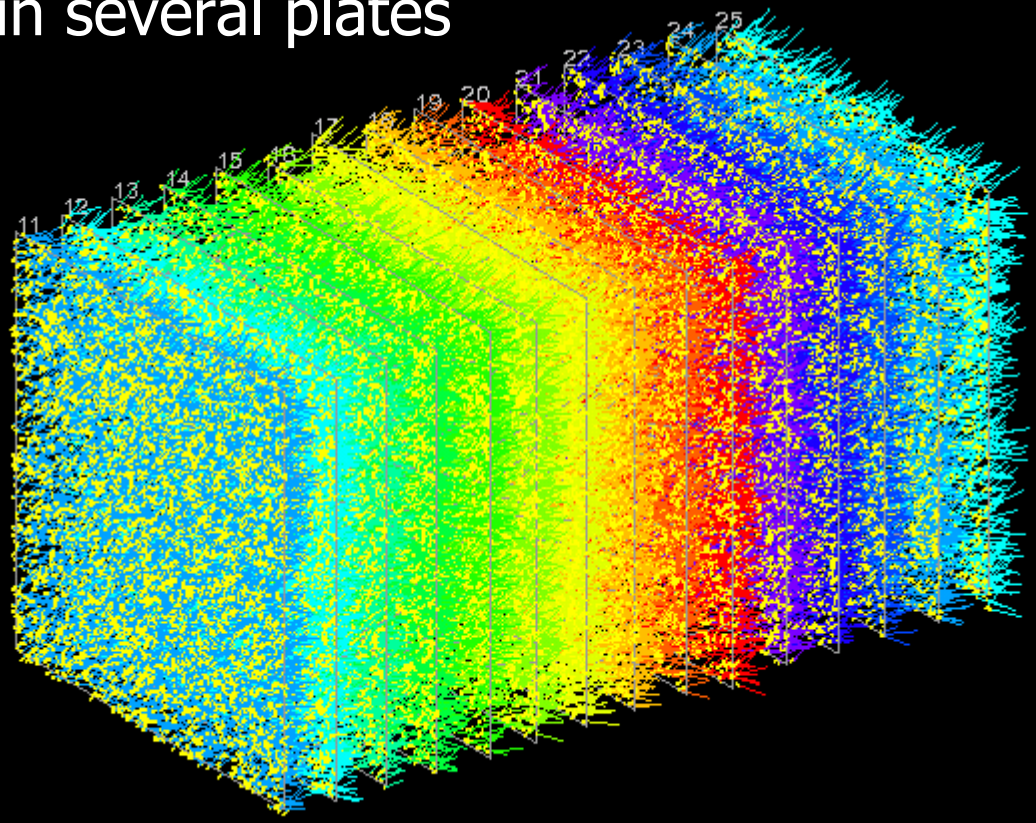






Emulsion Scanning

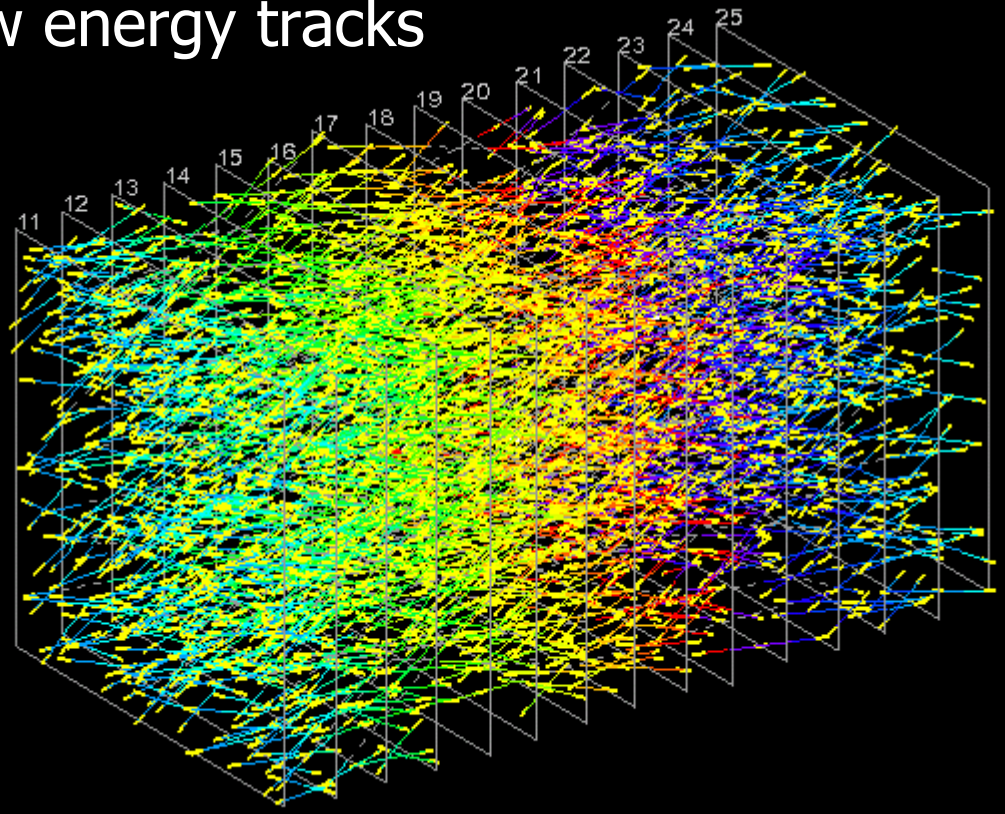
Scan Volume around stopping point for tracks reconstructed in several plates



Volume around interaction point ~2cm^3

Emulsion Scanning

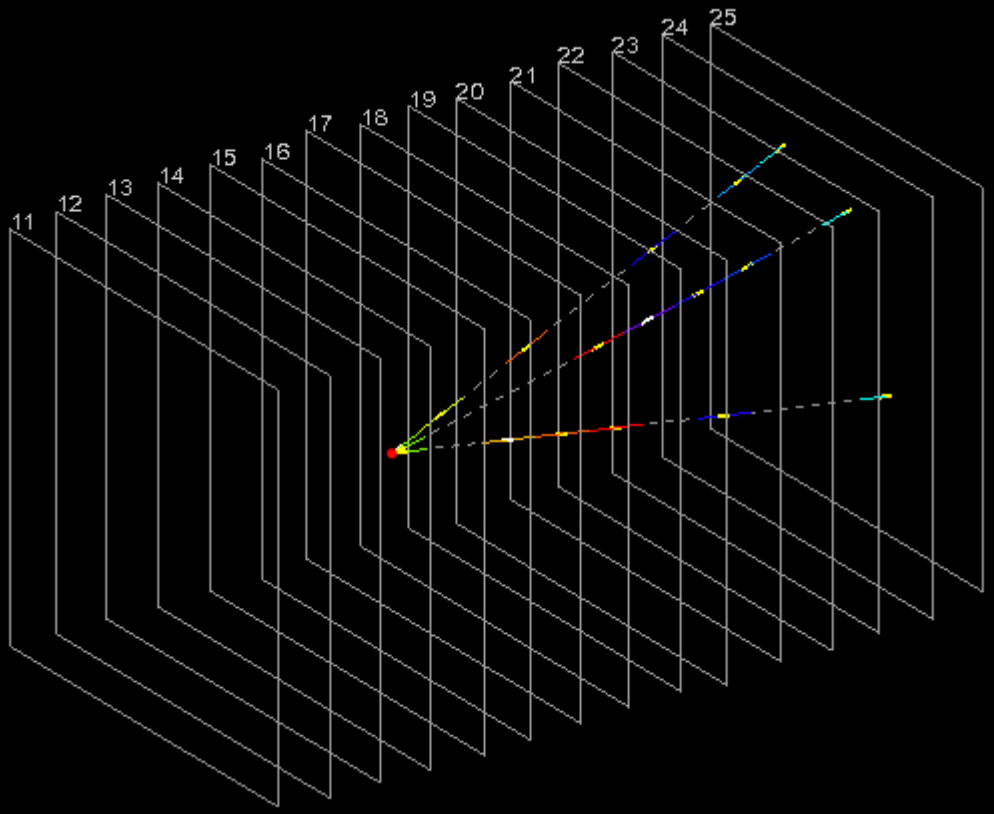
Reject passing through and low energy tracks



Volume around interaction point ~2cm^3

Emulsion Scanning

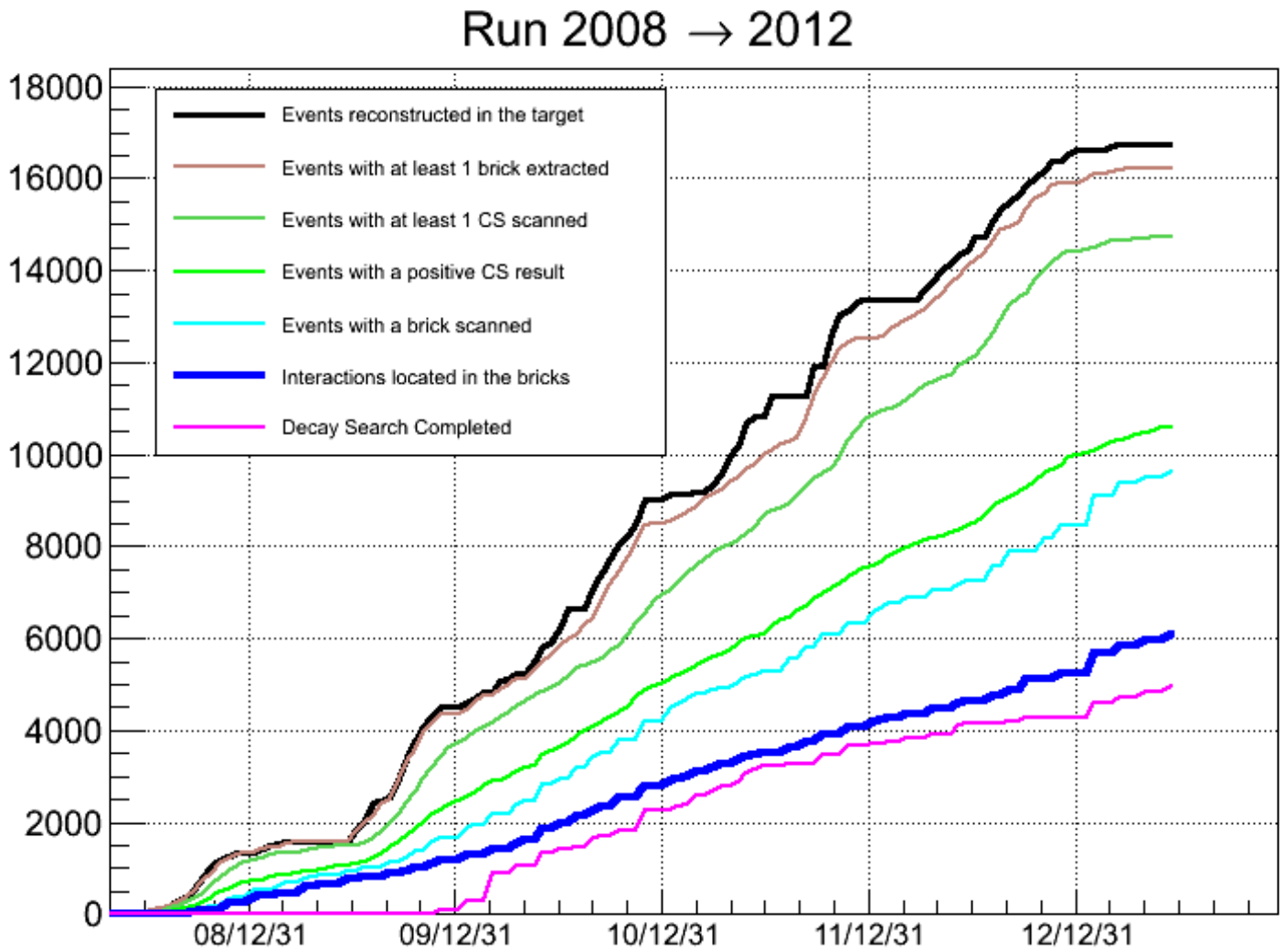
Search tracks pointing to common interaction point



Volume around
interaction point ~2cm^3

Oscillation Analysis

Status of the Data Analysis



Status of the Data Analysis

In total $18 \cdot 10^{19}$ pot → 20% less than in proposal

→ 19505 neutrino interaction within target

<u>At the point of this analysis:</u>

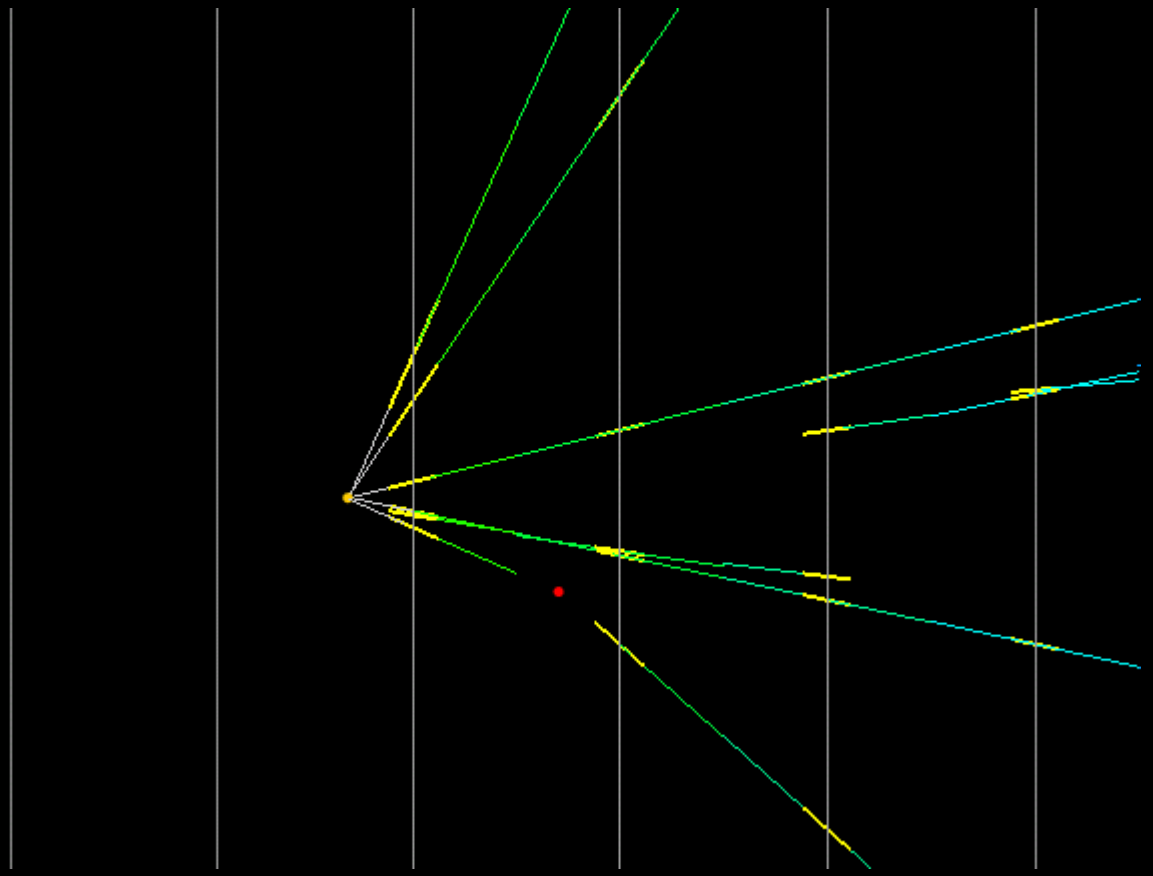
6067 located interaction points

4969 completed decay searches

Years	p.o.t. (x10^{19})	Status	Selected Data sample	# of Decay Searched events
2008-2009	5.27	Completed	mutli-bricks + all P_μ	2783
2010-2011-2012	12.7	In progress	1 brick + P_μ < 15 GeV	2186
Total	18.0		~64%	4969

Charm Hadron Production

Topology similar to τ-decay (decay modes and lifetime)
but with μ at primary vertex → good control sample



Charm Hadron Production

2008-2010 data analysis:

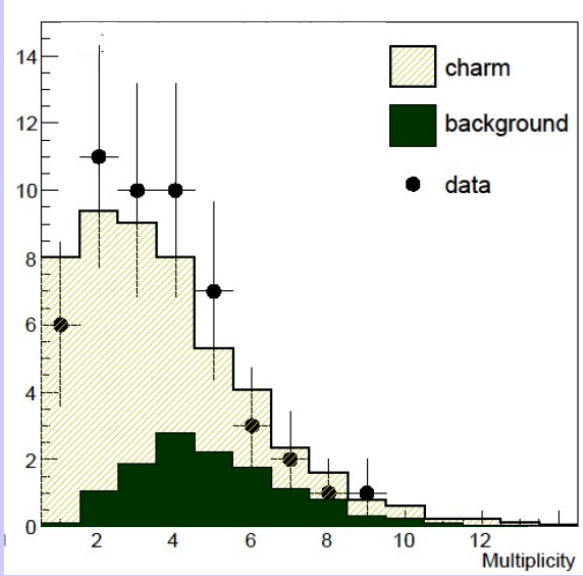
	charm	background	expected	data
1 prong	20 ± 3	9 ± 3	29 ± 4	19
2 prong	15 ± 2	3.8 ± 1.1	19 ± 2	22
3 prong	5 ± 1	1.0 ± 0.3	6 ± 1	5
4 prong	0.8 ± 0.2	-	0.8 ± 0.2	4
All	**41±4**	**14±3**	**55±5**	**50**

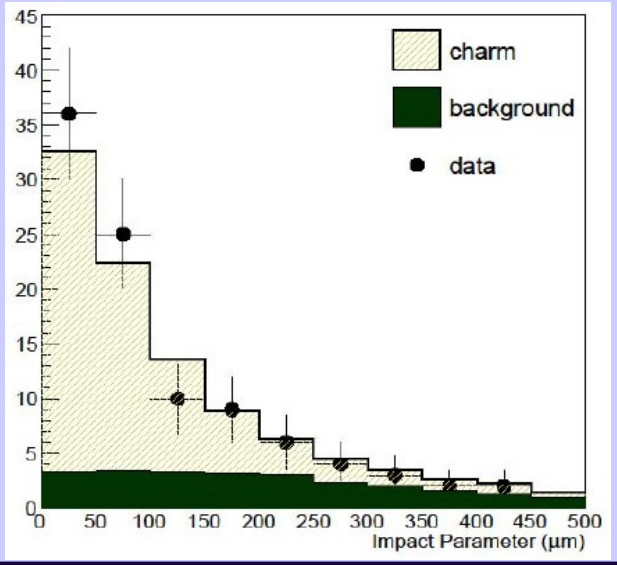
Background mainly from hadronic interaction

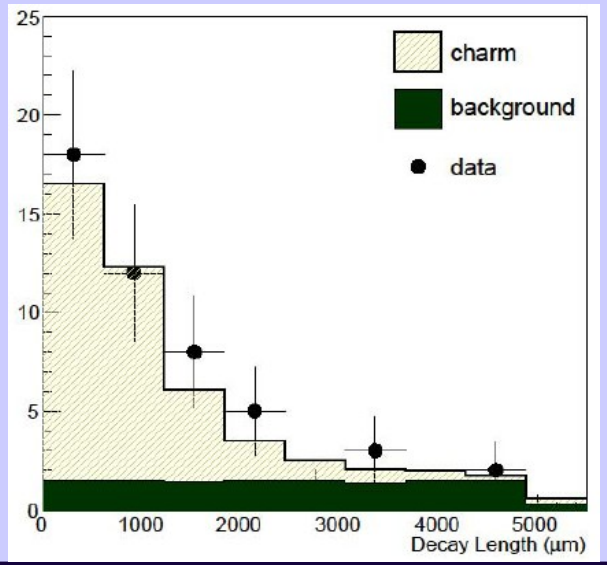
Charm Hadron Production

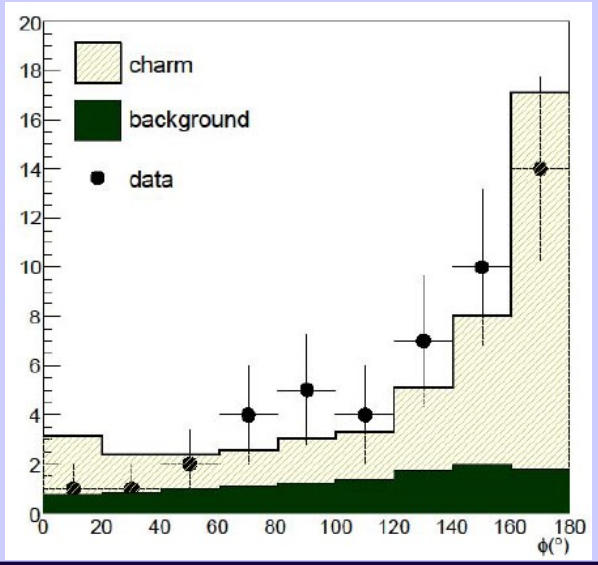
2008-2010 data analysis:

Kolmogorov test > 0.99 for all plots









Overview

The OPERA Experiment

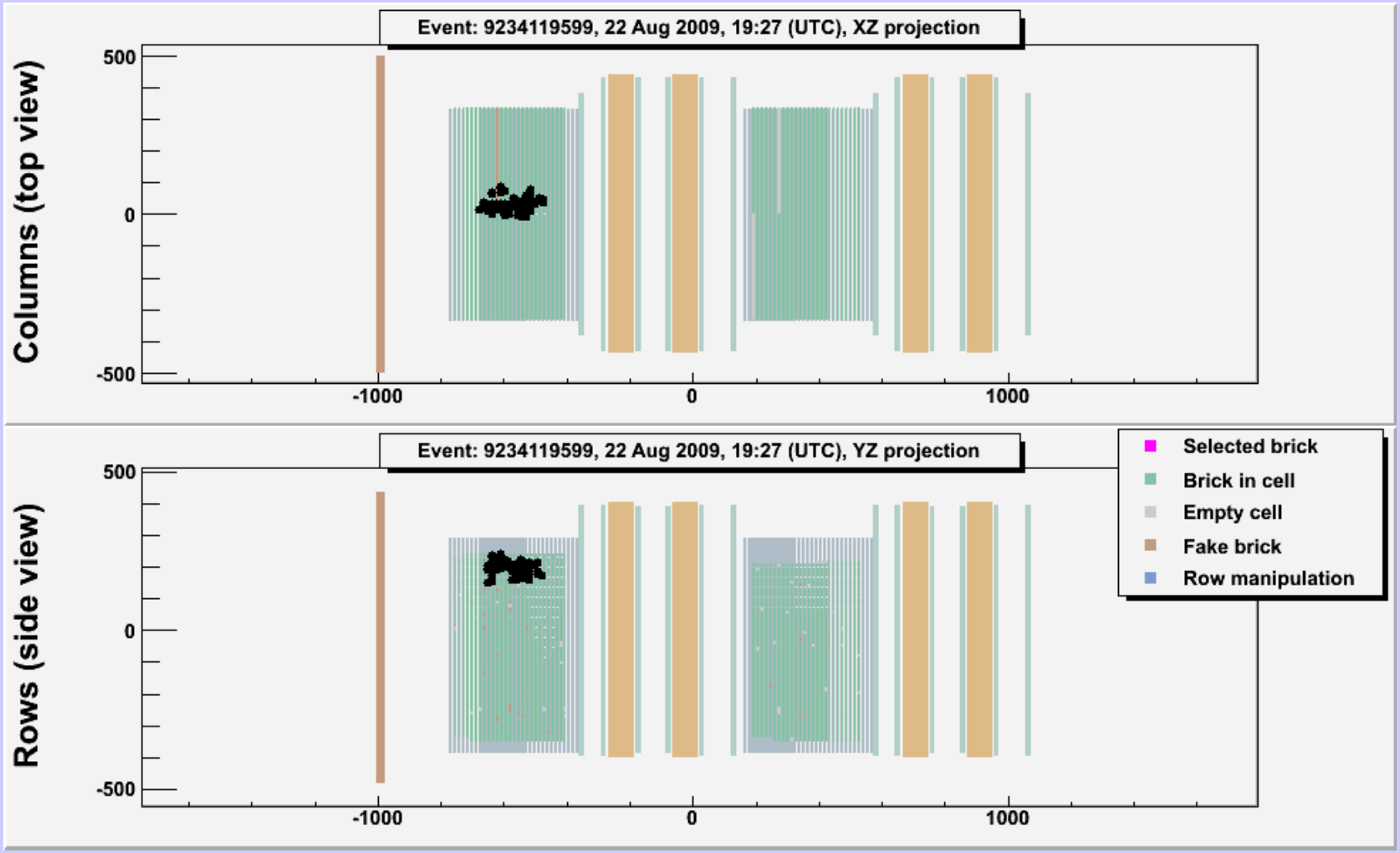
ν_τ Candidates

ν_e Analysis

Summary/Outlook

Muonless Event 9234119599

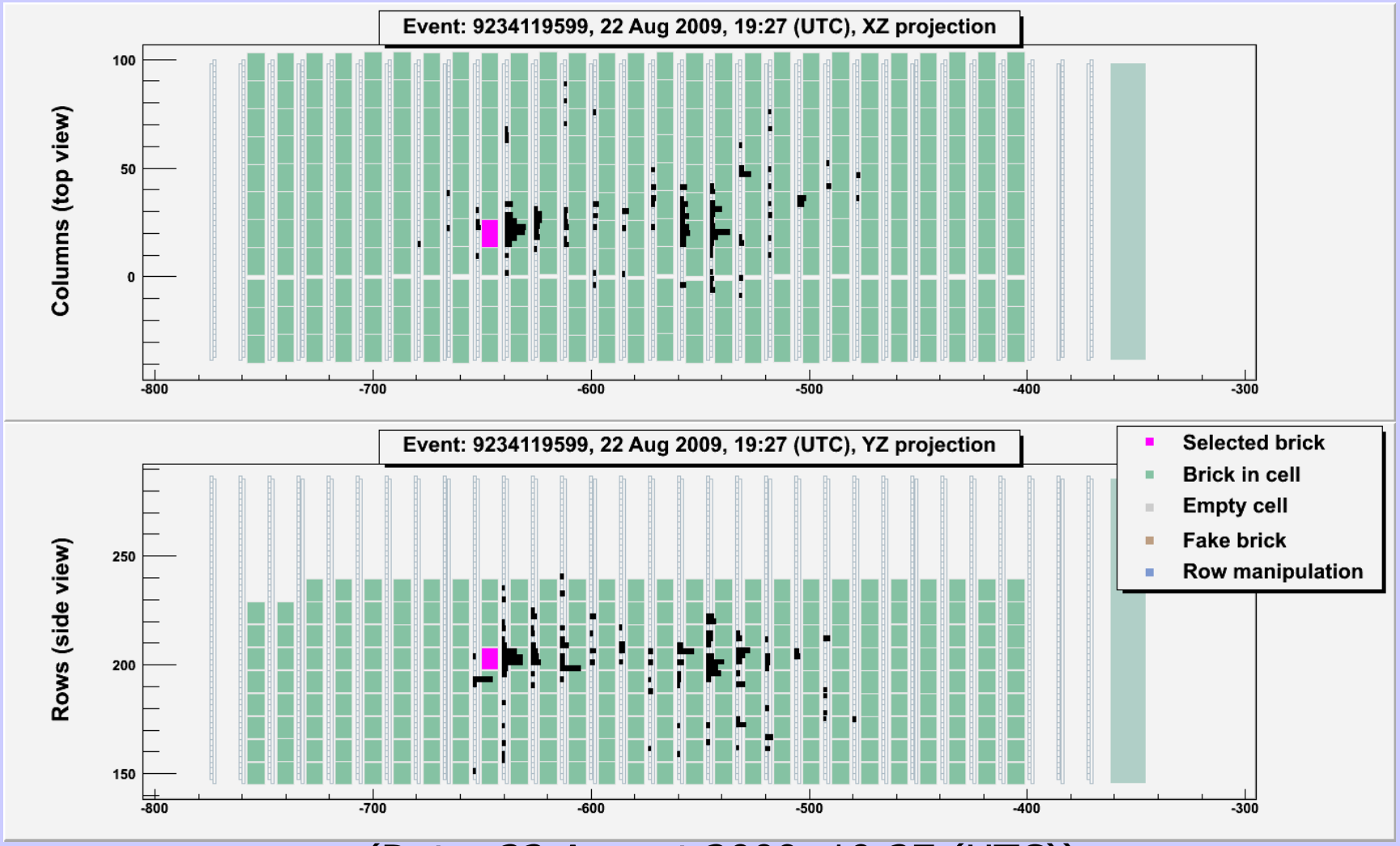
Electronic Detector View:



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

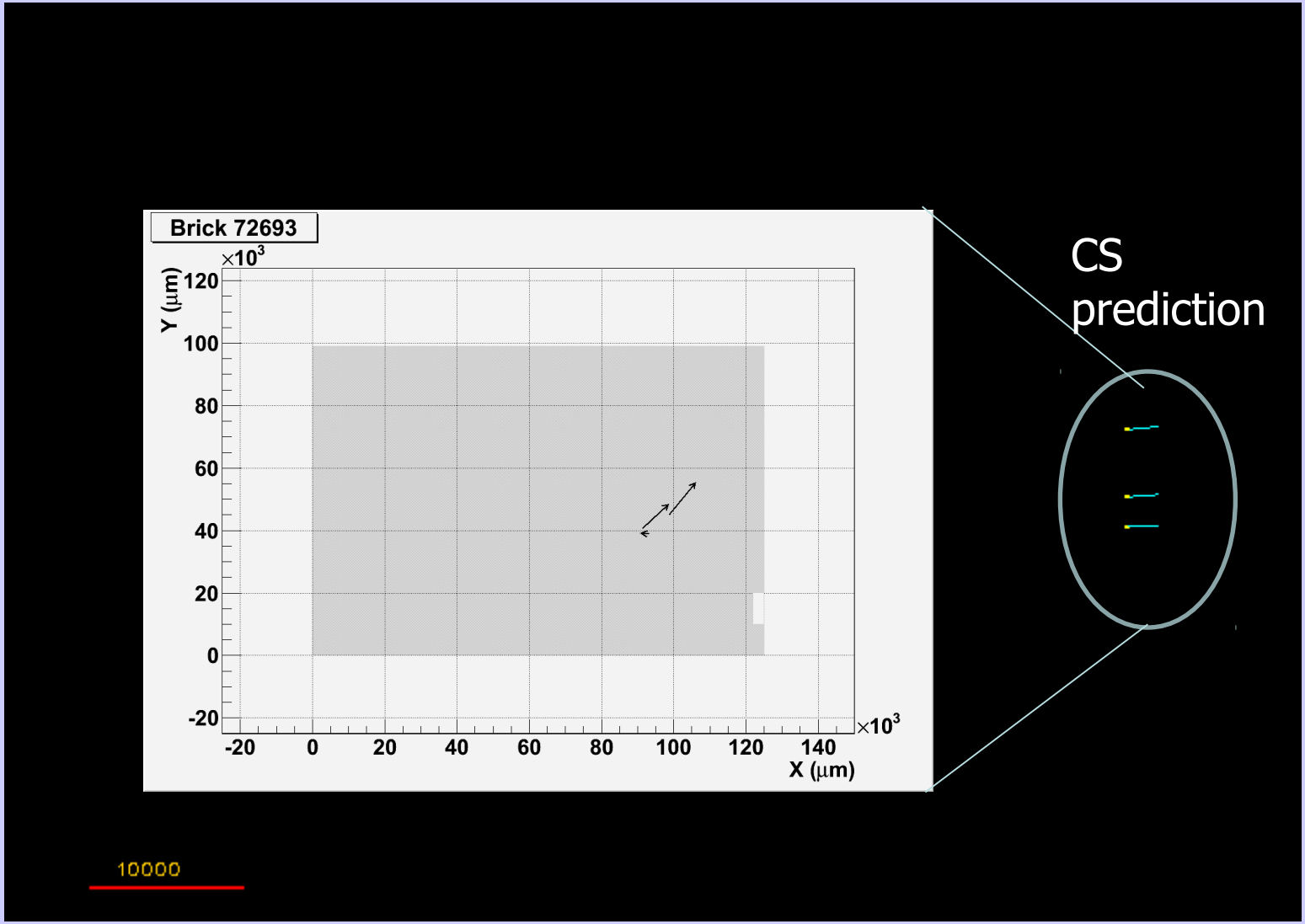
Muonless Event 9234119599

Electronic Detector View:

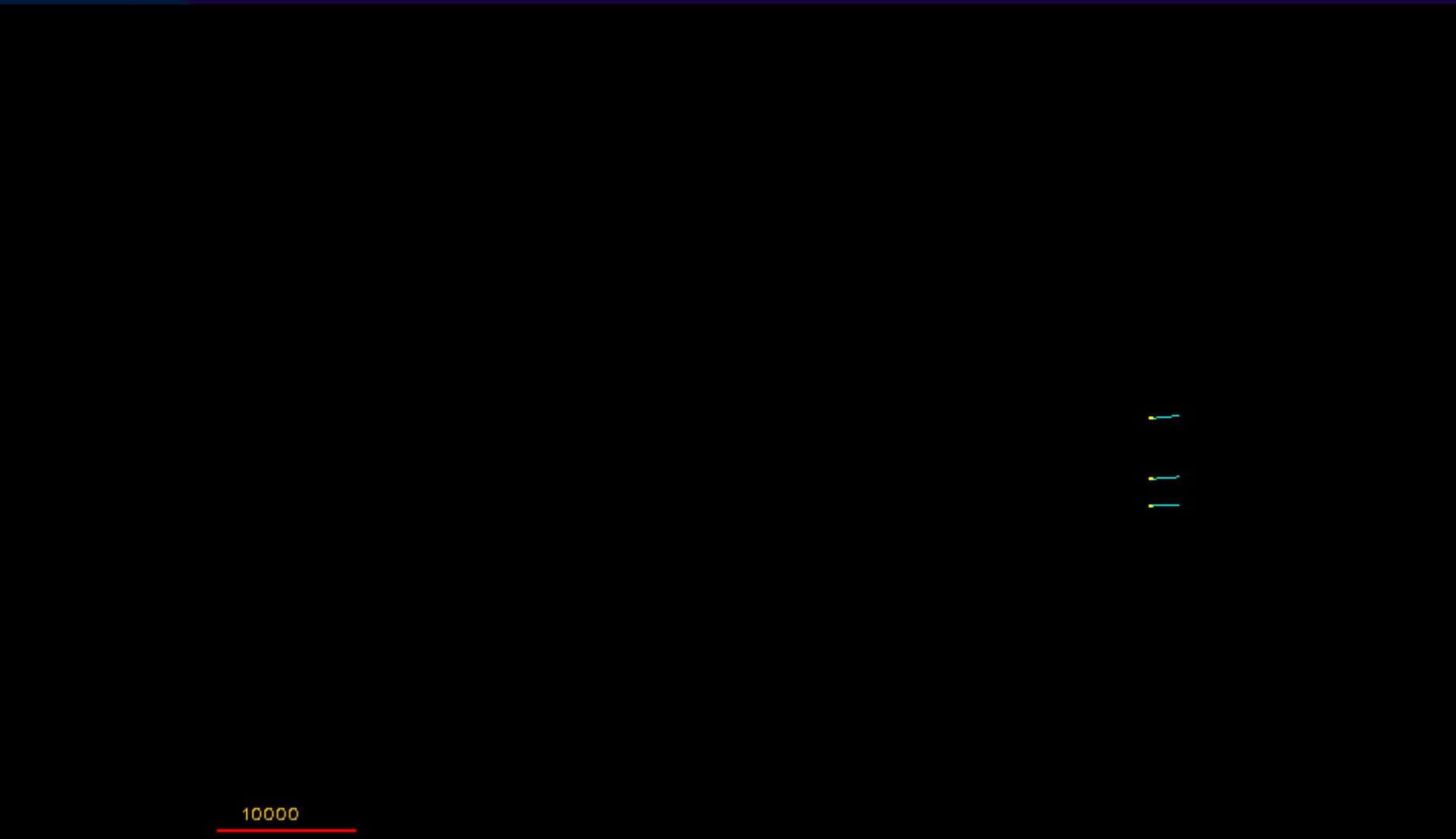


(Date: 22 August 2009, 19:27 (UTC))

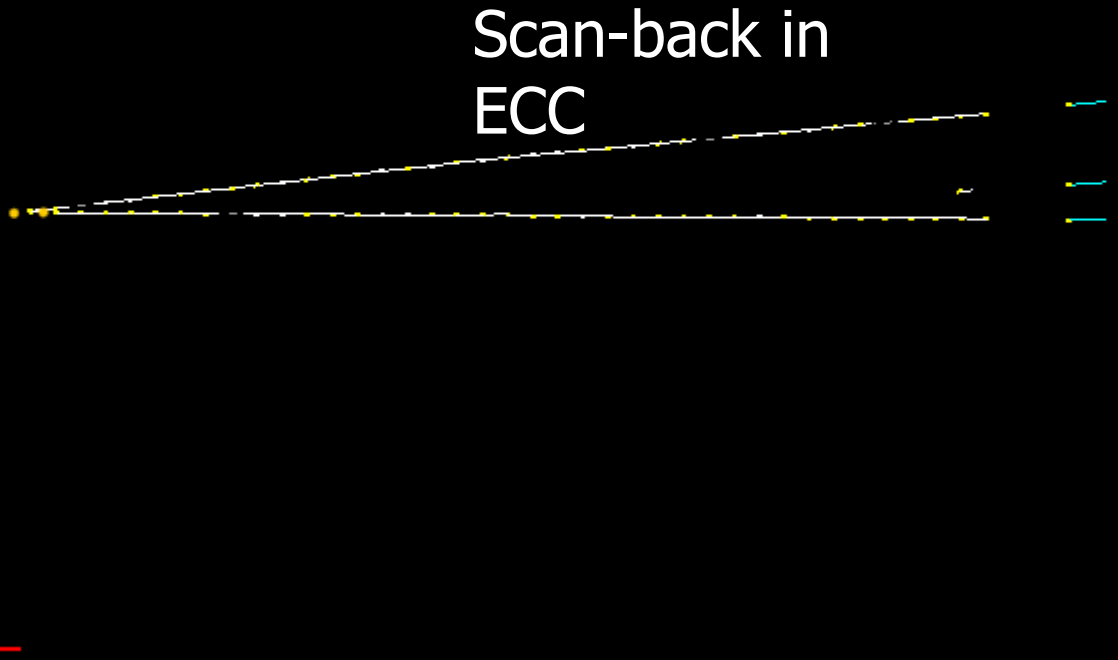
From CS to Vertex Localisation



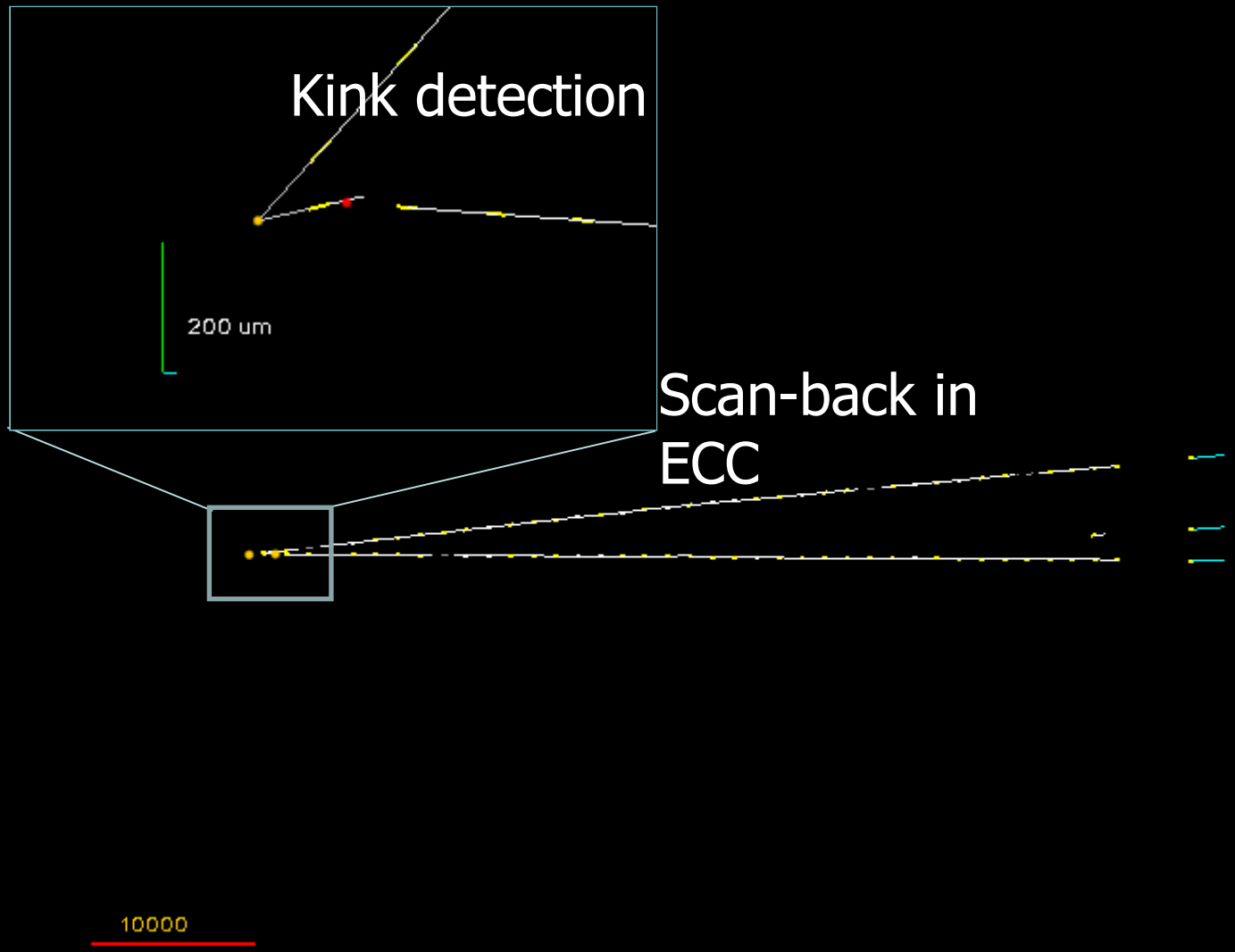
From CS to Vertex Localisation



From CS to Vertex Localisation

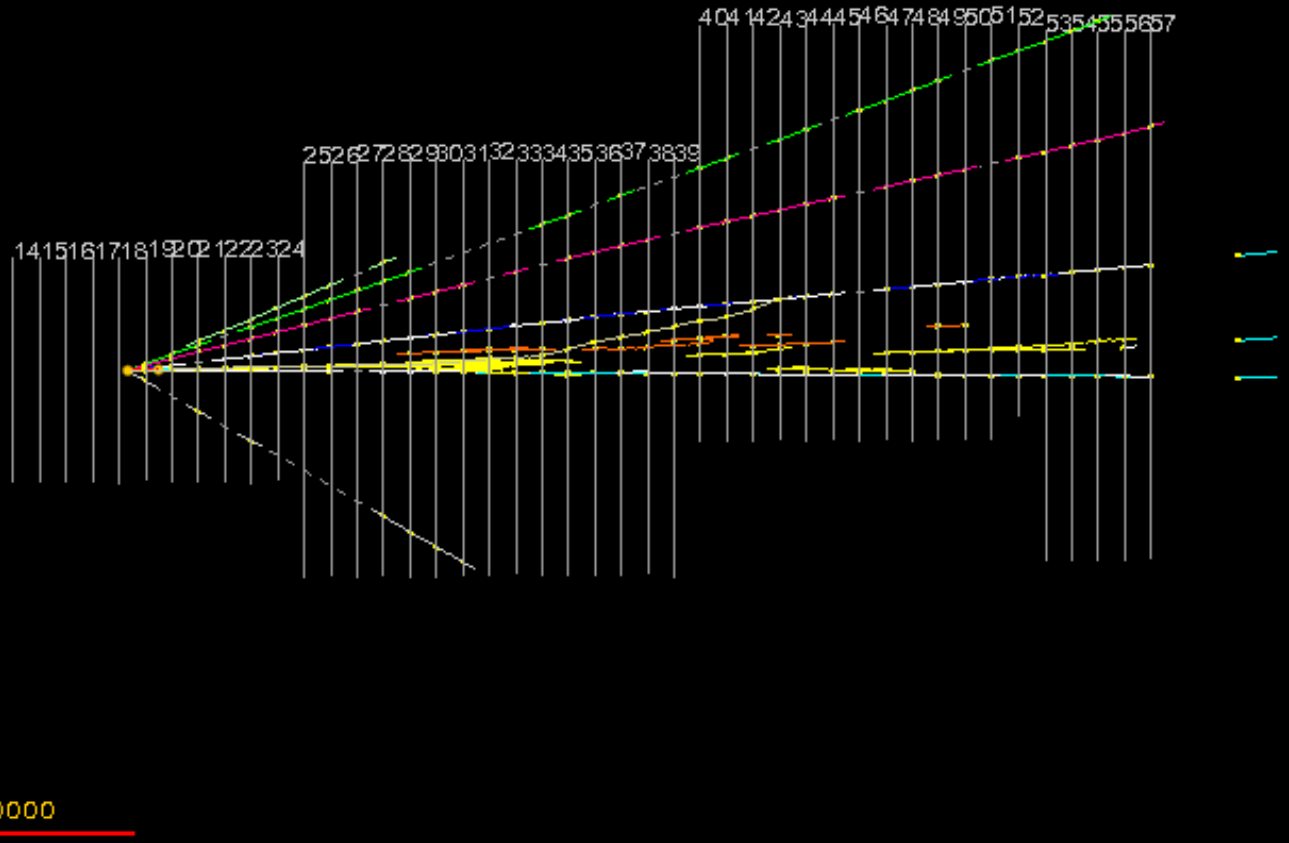


From CS to Vertex Localisation

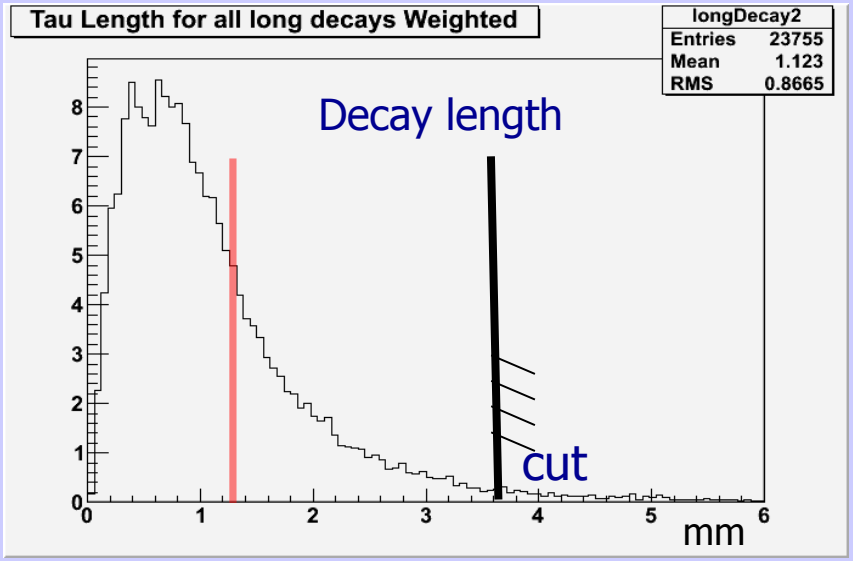


From CS to Vertex Localisation

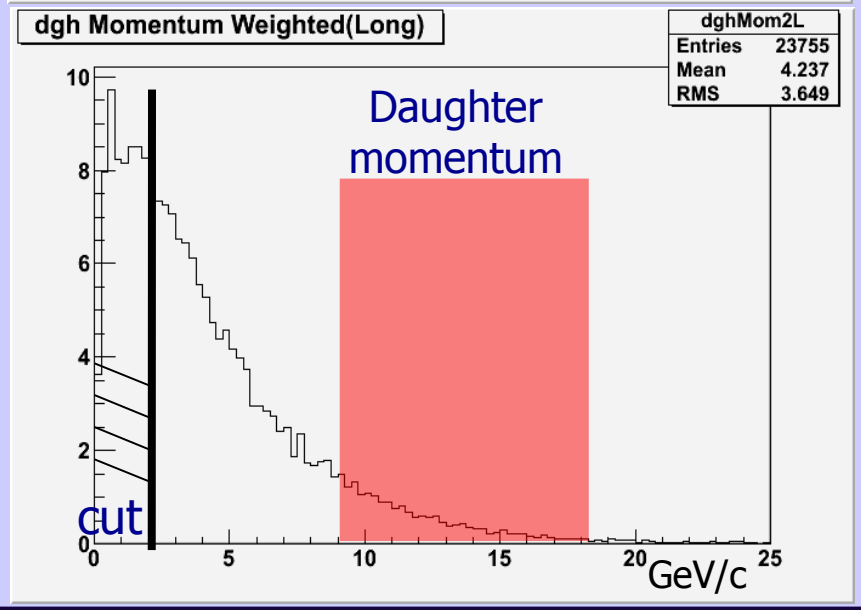
Large-area scan,
full reconstruction of vertices and γ

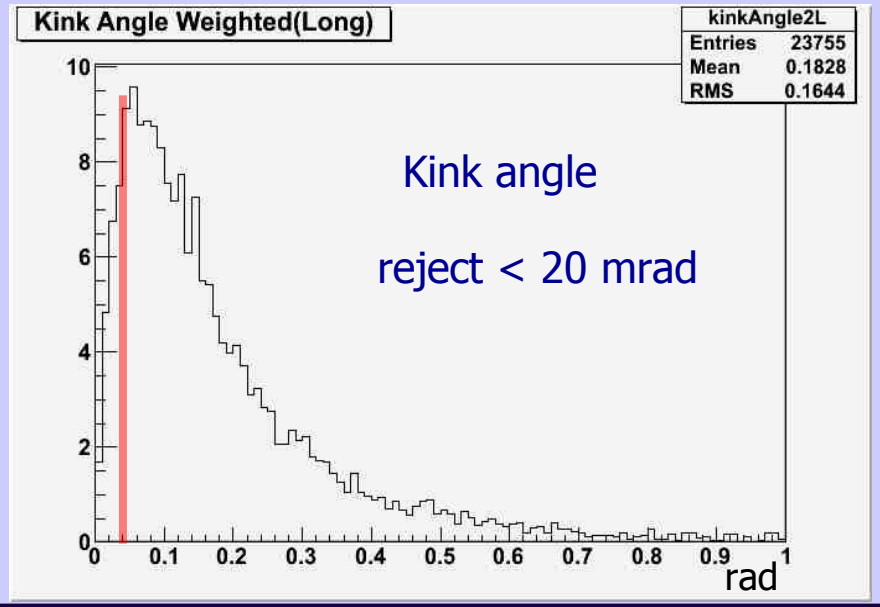


Characteristics of Decay Topology



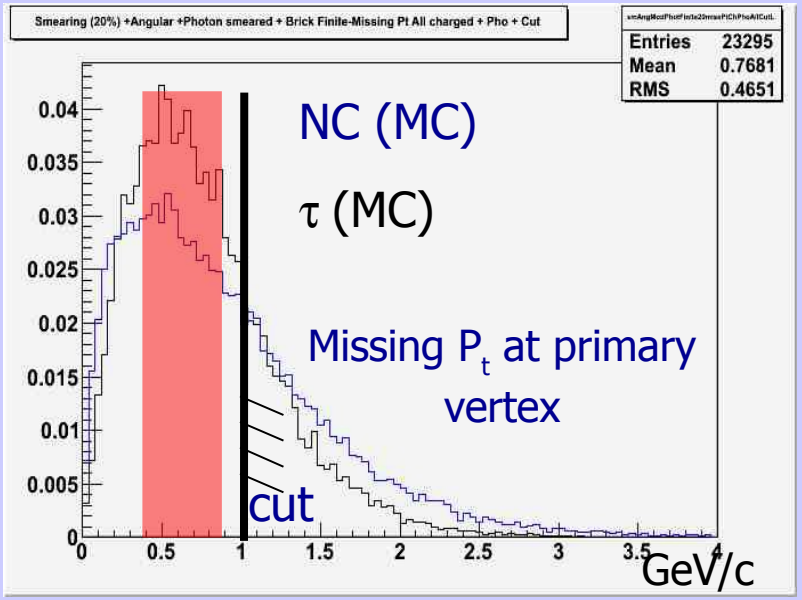
Red regions:
Measured values for ν_τ candidate



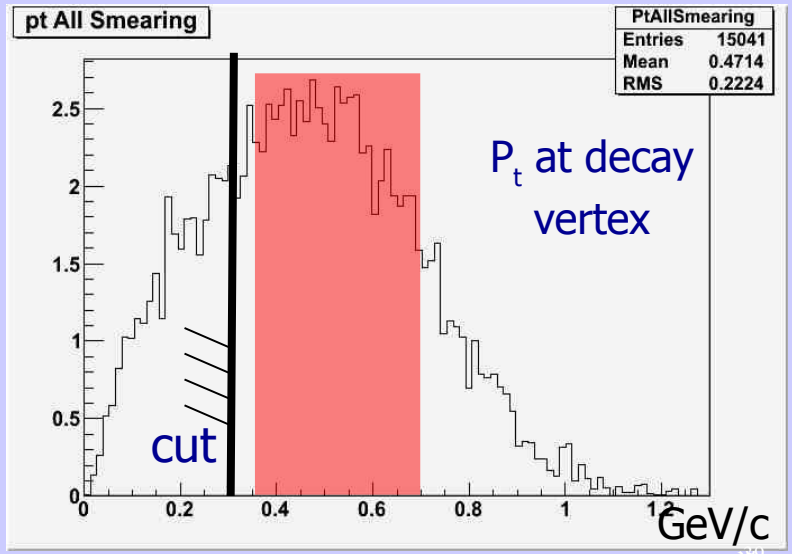


Kinematical Cuts to be Passed

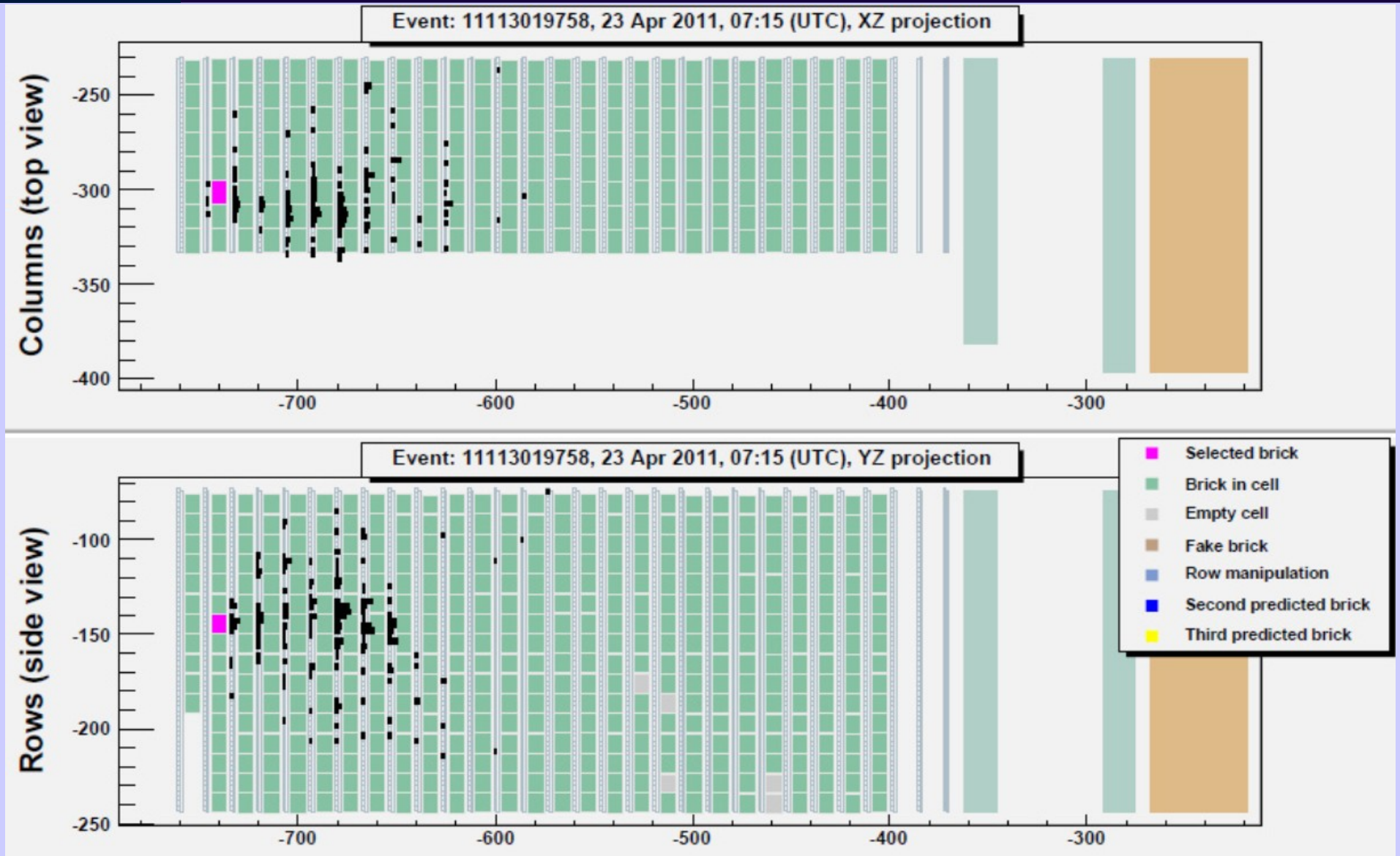
Reject NC events with larger missing P_t (neutrino)



Reject hadron re-interactions

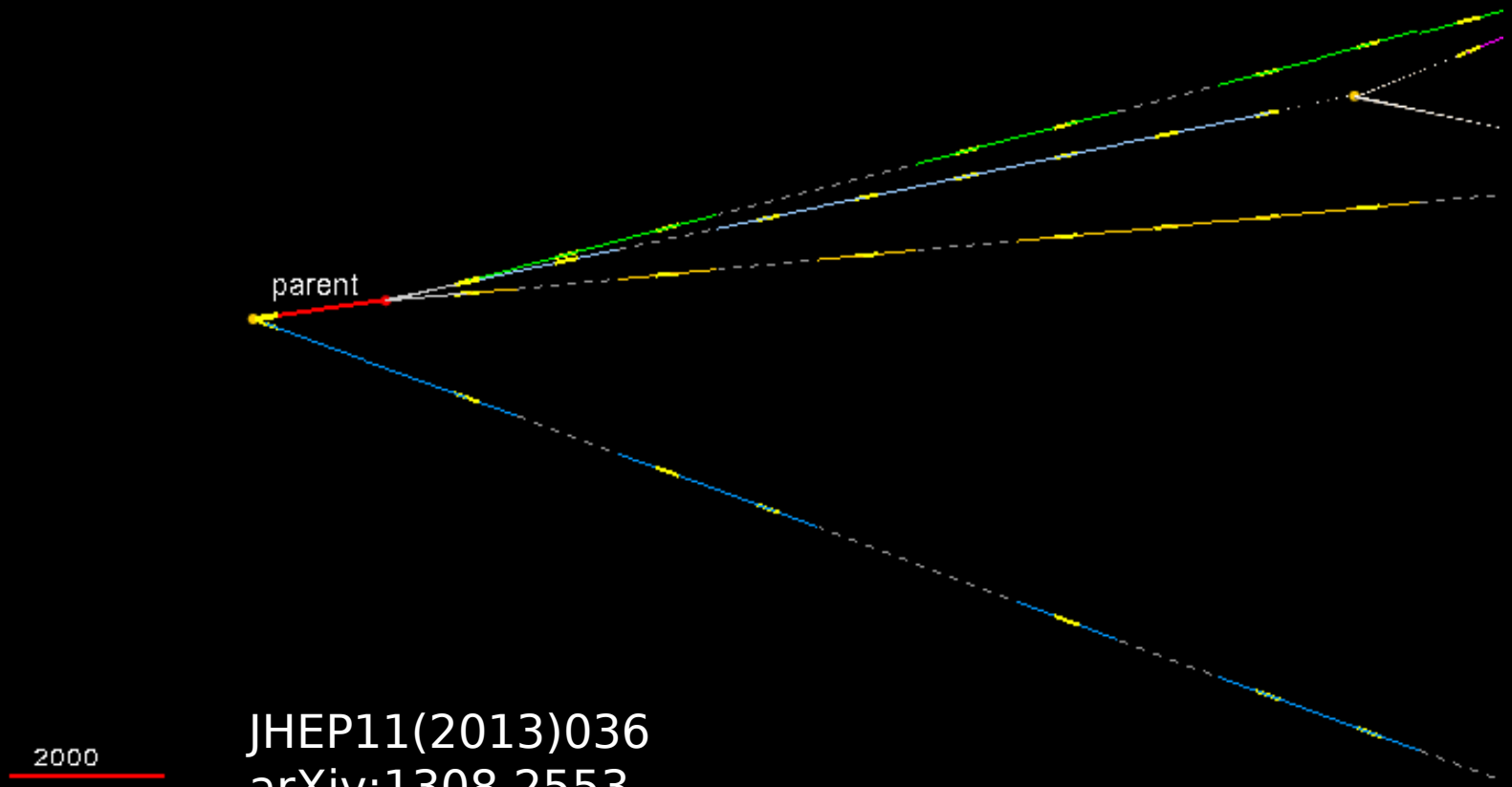


2nd ν_τ Candidate



2nd ν_τ Candidate

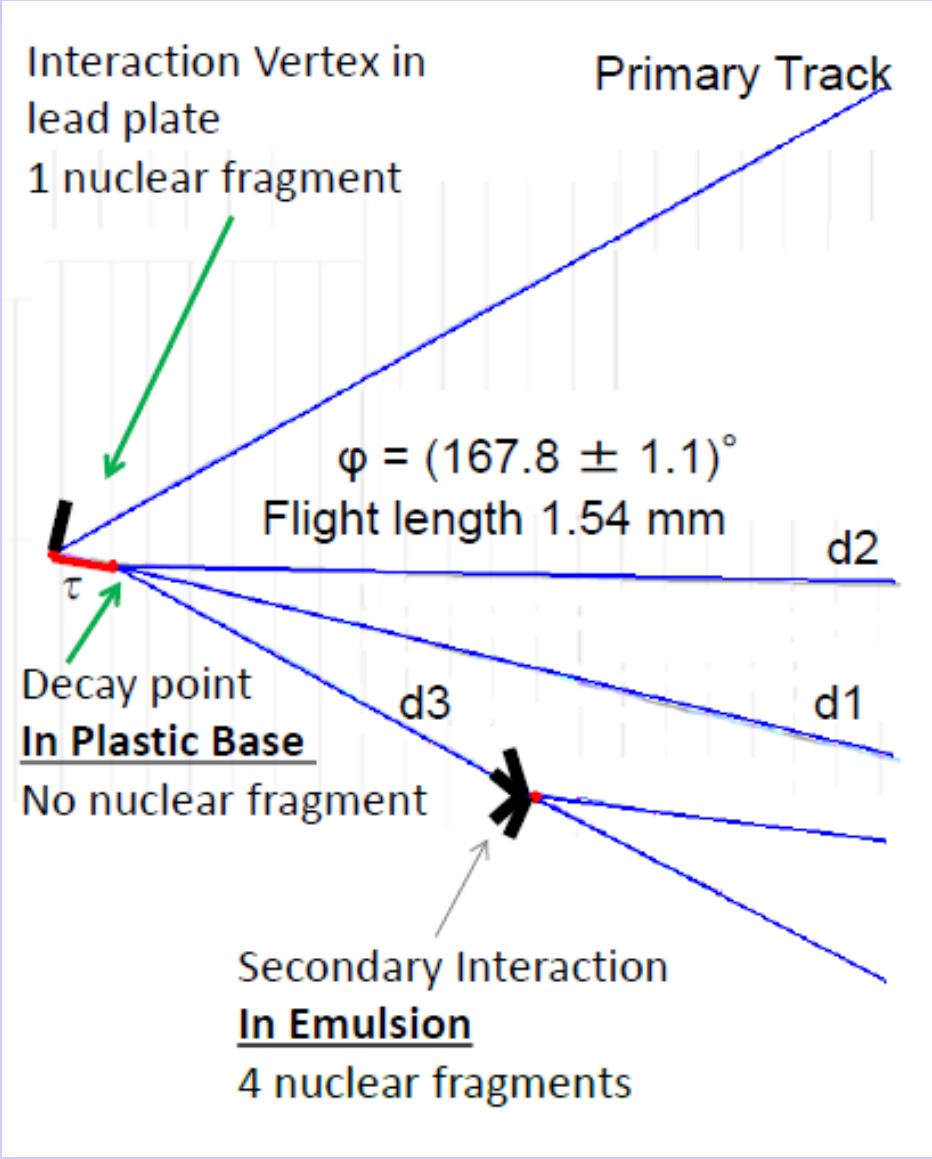
$\tau \rightarrow 3h\ \nu_\tau$



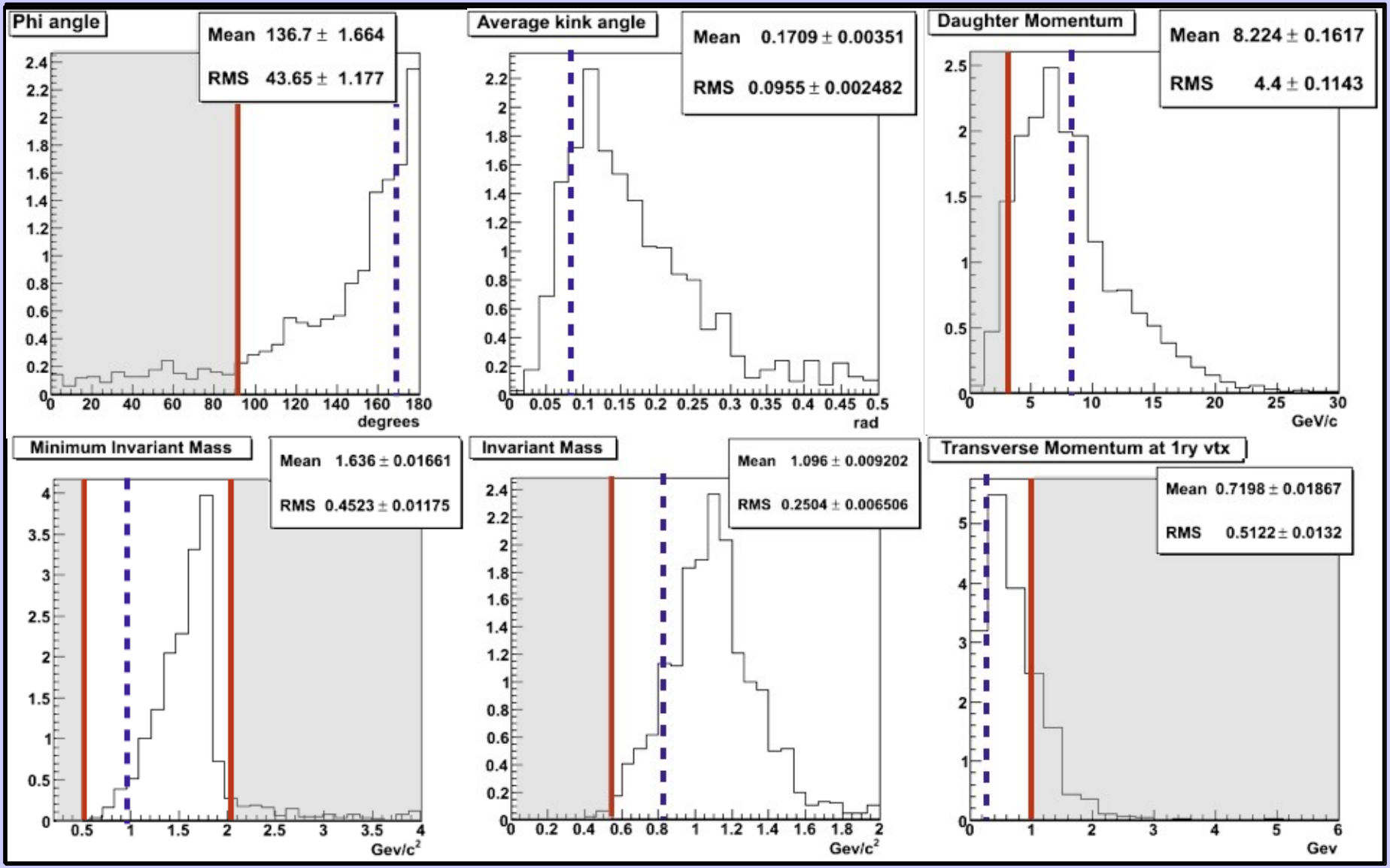
JHEP11(2013)036
arXiv:1308.2553

2nd ν_τ Candidate

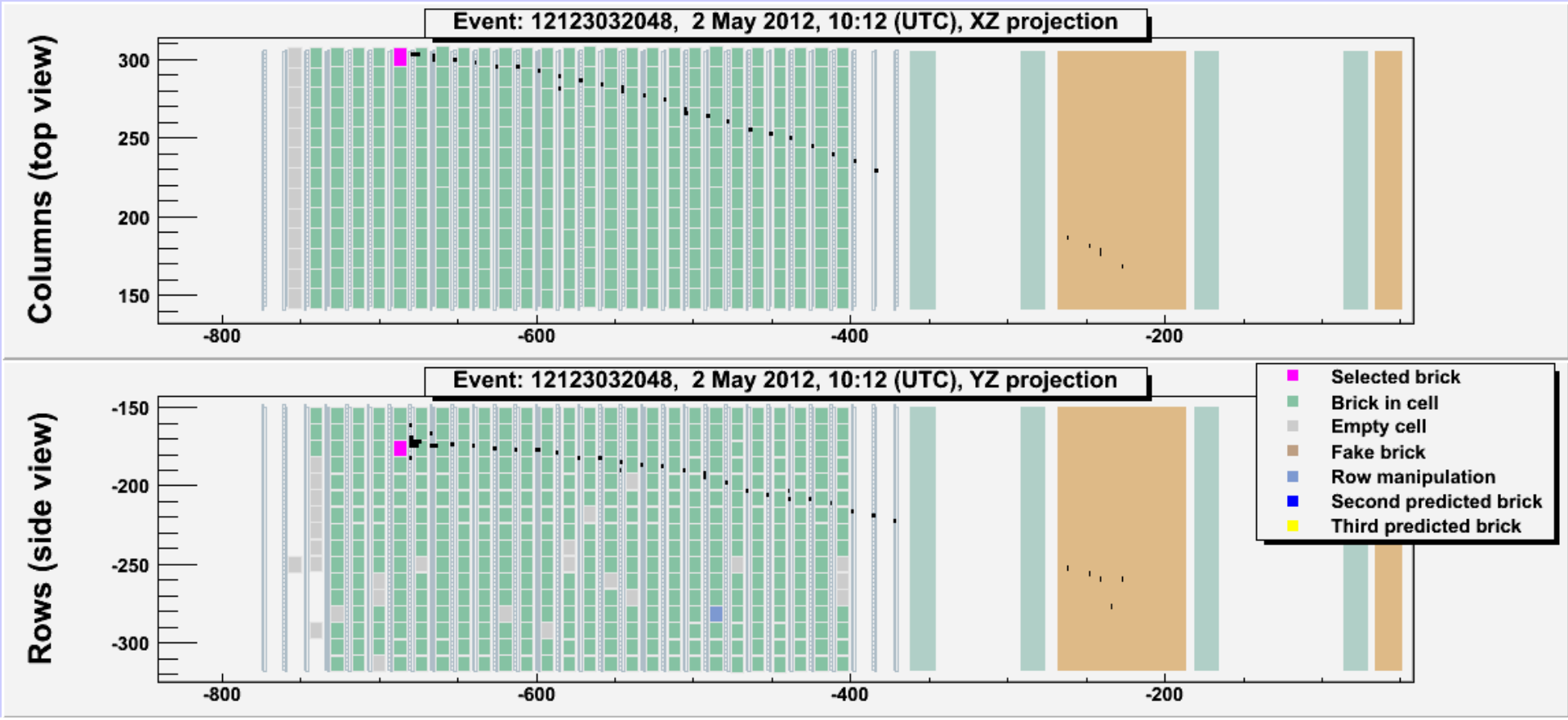
- Nuclear fragments visible as short highly ionizing tracks
- Give additional information for background reduction



2nd ν_τ Candidate



3rd ν_τ Candidate

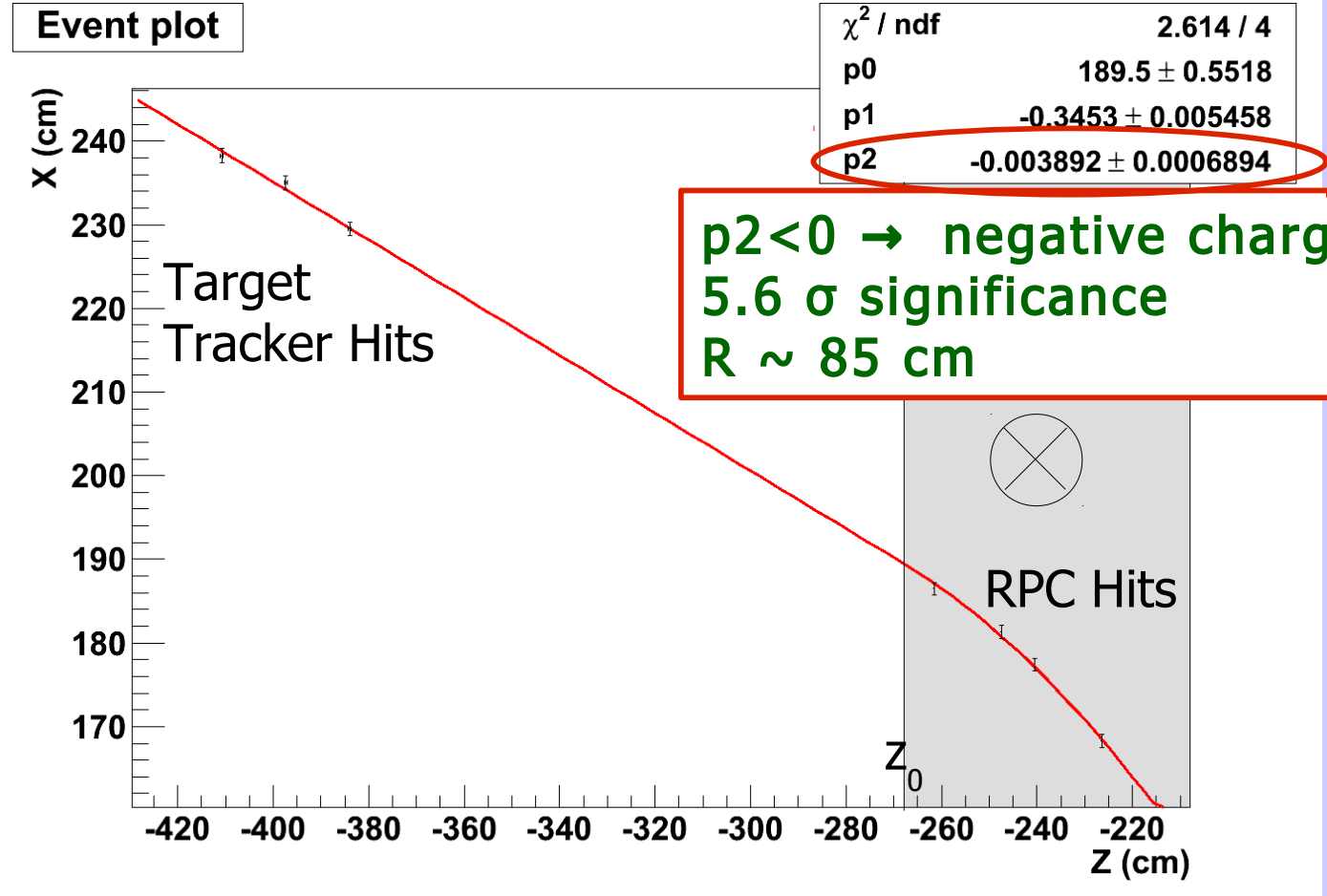


Muon momentum: 2.8±0.2 GeV/c from range
Consistent with MCS in bricks 3.1 [2.6,4.0] GeV/c

Charge Determination of μ

Parabolic fit of RPC hits: $X(z)=p0+p1\cdot x\cdot(z-z_0)+p2\cdot x\cdot(z-z_0)^2$

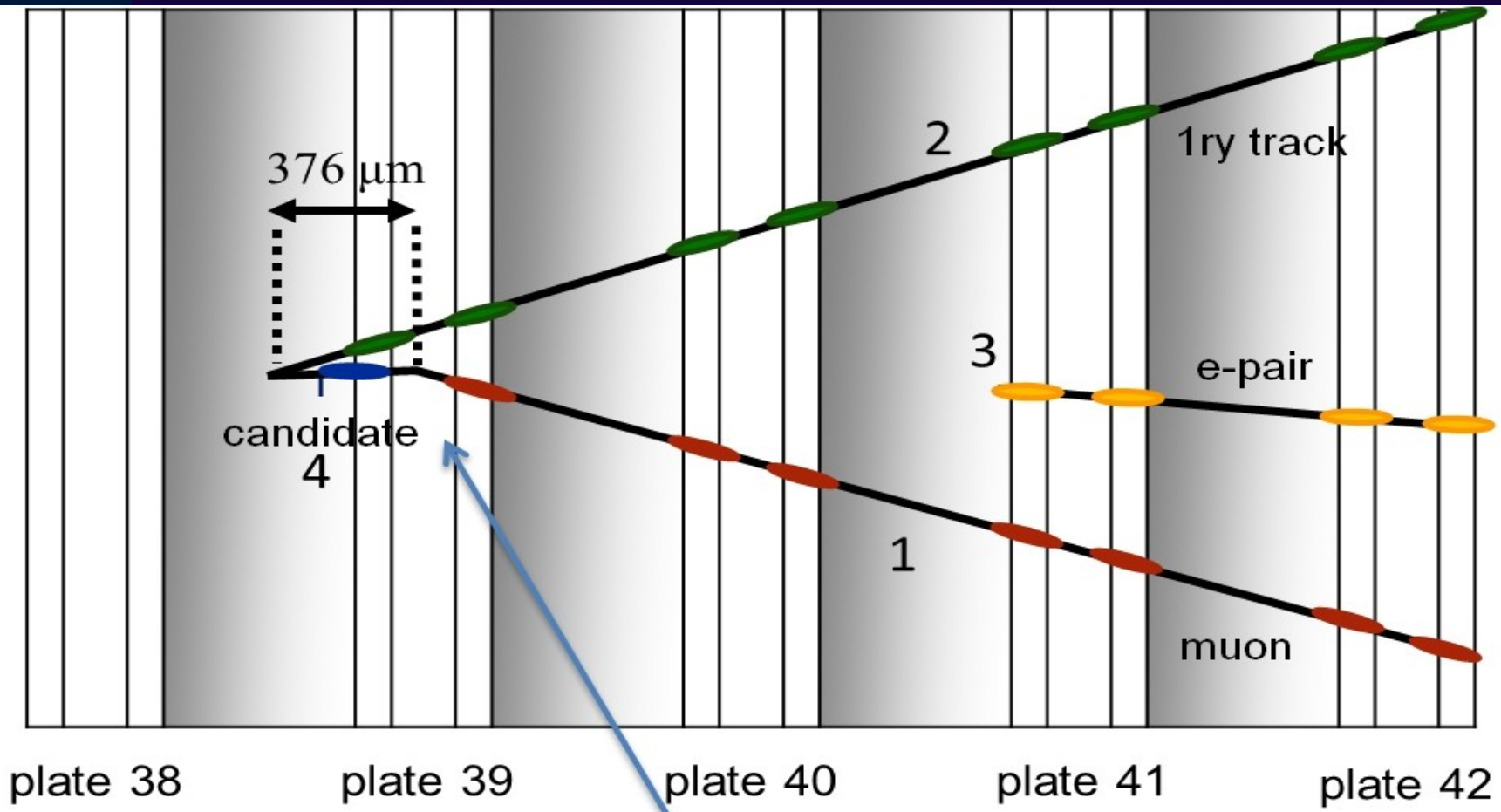
Together with linear fit of TT hits : $X(z)=p0+p1\cdot x\cdot(z-z_0)$



3rd ν_τ Candidate

$\tau \rightarrow \mu$ decay

3rd ν_τ Candidate



Nature of Track 2

- Stops in downstream brick without visible charged particles
- Range vs. momentum inconsistent with muon hypothesis

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

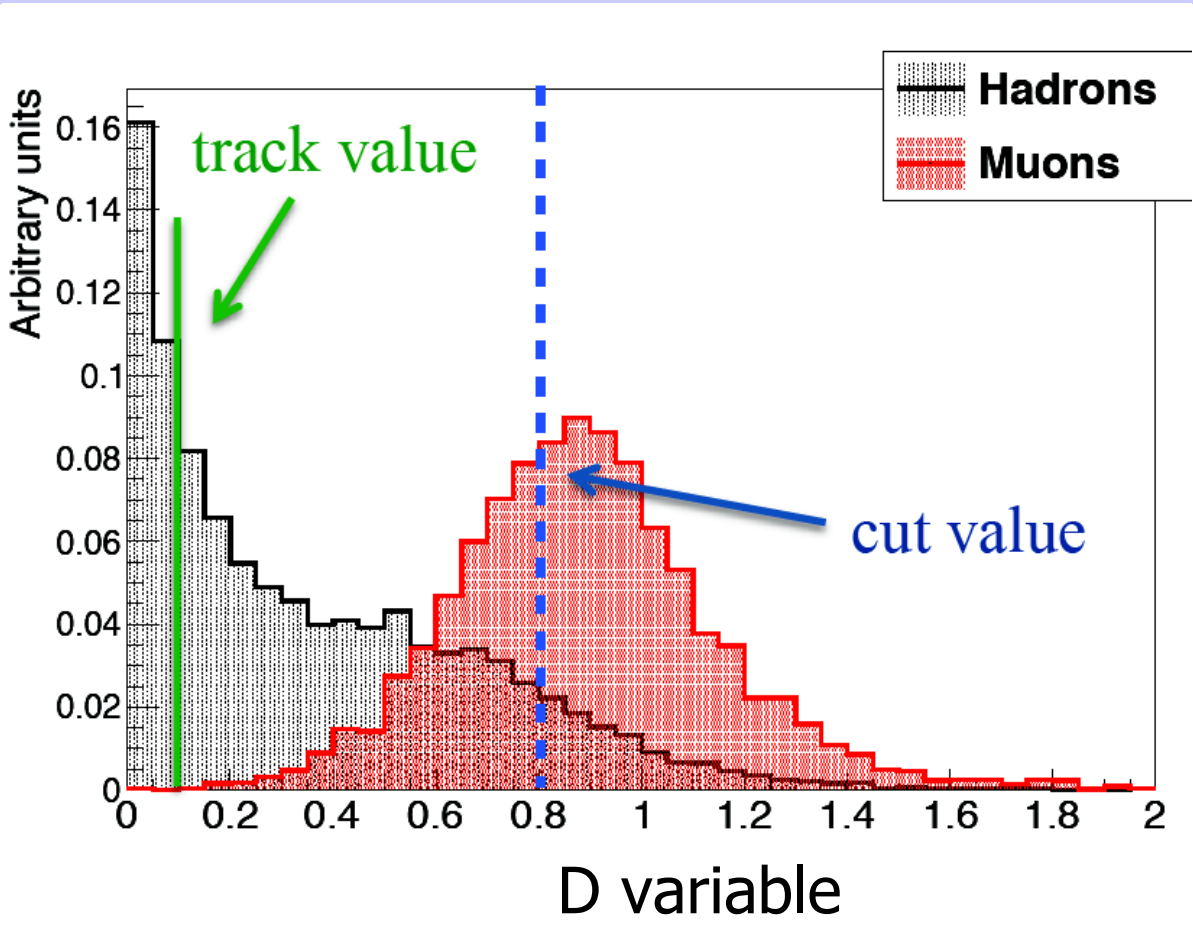
L = track length

R_{lead} = μ range

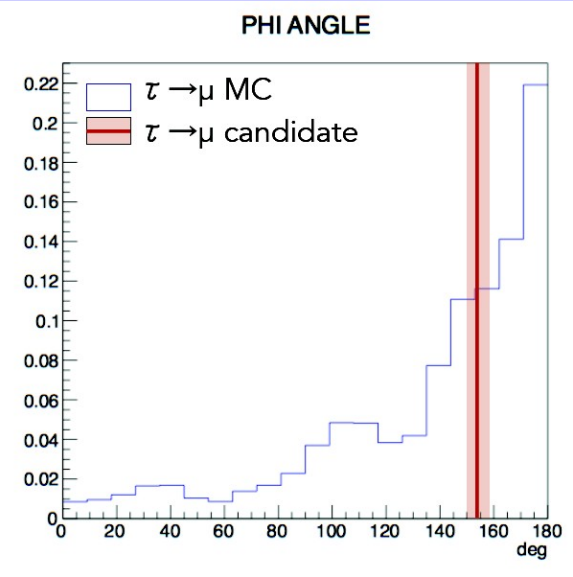
$\rho_{average}$ = average density

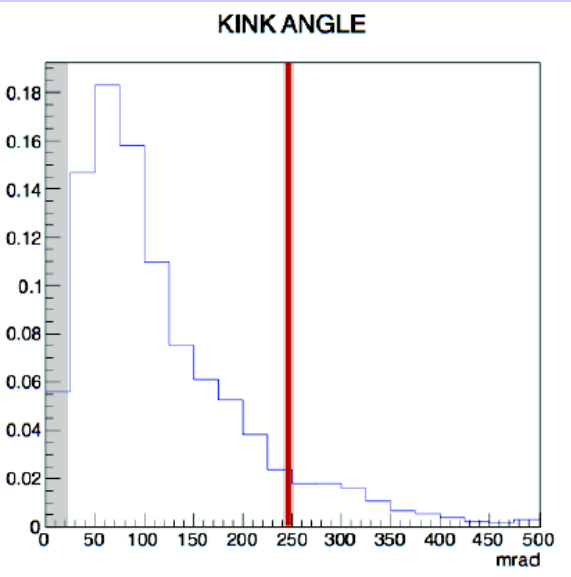
ρ_{lead} = lead density

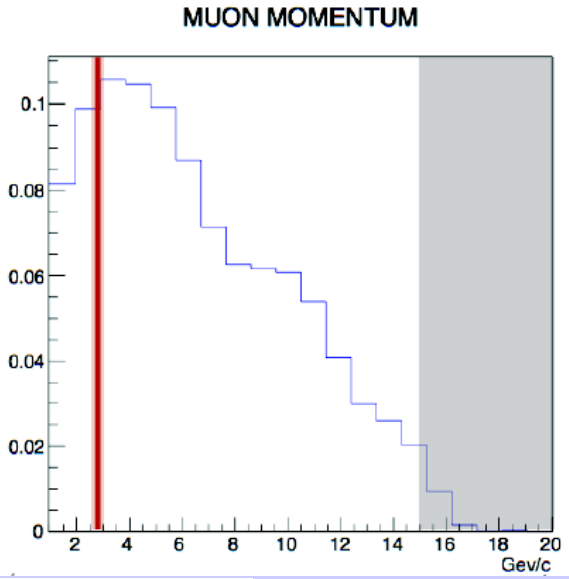
p = momentum in emulsion

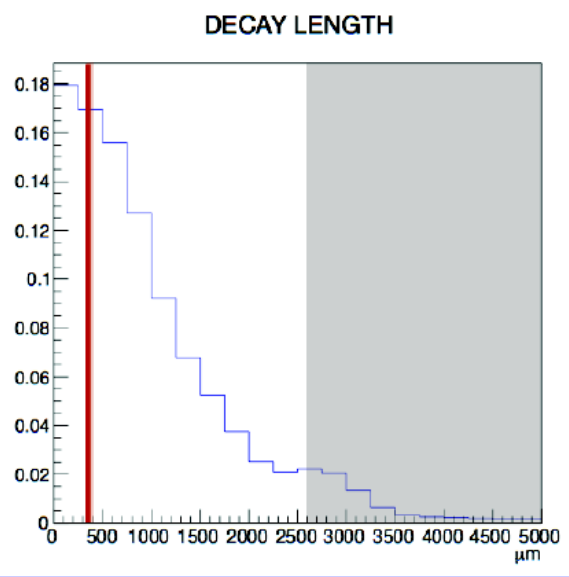


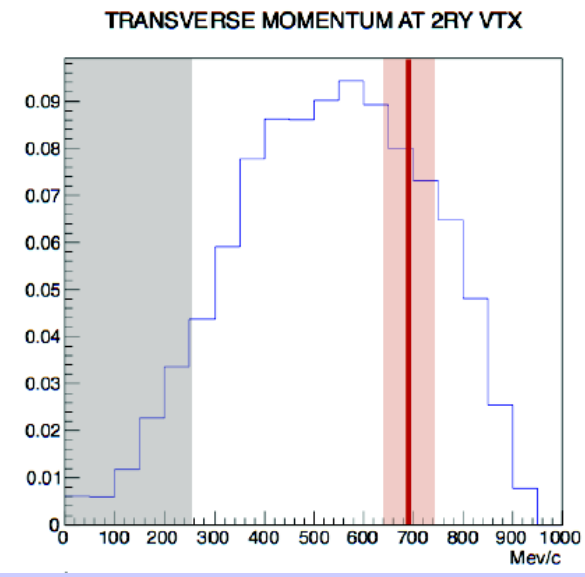
3rd ν_τ Candidate











$\nu_\mu \rightarrow \nu_\tau$ Analysis Overview

Subsample corresponding to 61% of total expectation:
(2008-2009 & selected 2010-2012 sample)

→ 3 events observed vs. 0.22 events bkg.
→ p-value for bgk-fluctuation: $7.3 \cdot 10^{-4}$

→ **No-oscillation hypothesis excluded at 3.2 σ**

Decay channel	expected signal events $\Delta m^2 = 2.32 \times 10^{-3}\ eV^2$		PRELIMINARY	
	Full sample 18×10^{19} p.o.t.	Analysed sample	background analysed sample	Observed events
$\tau \rightarrow \mu$	0.90	0.56	0.026	1
$\tau \rightarrow e$	1.06	0.49	0.065	
$\tau \rightarrow h$	0.70	0.66	0.045	1
$\tau \rightarrow 3h$	0.99	0.51	0.090	1
Total	3.65	2.22	0.216	3

Overview

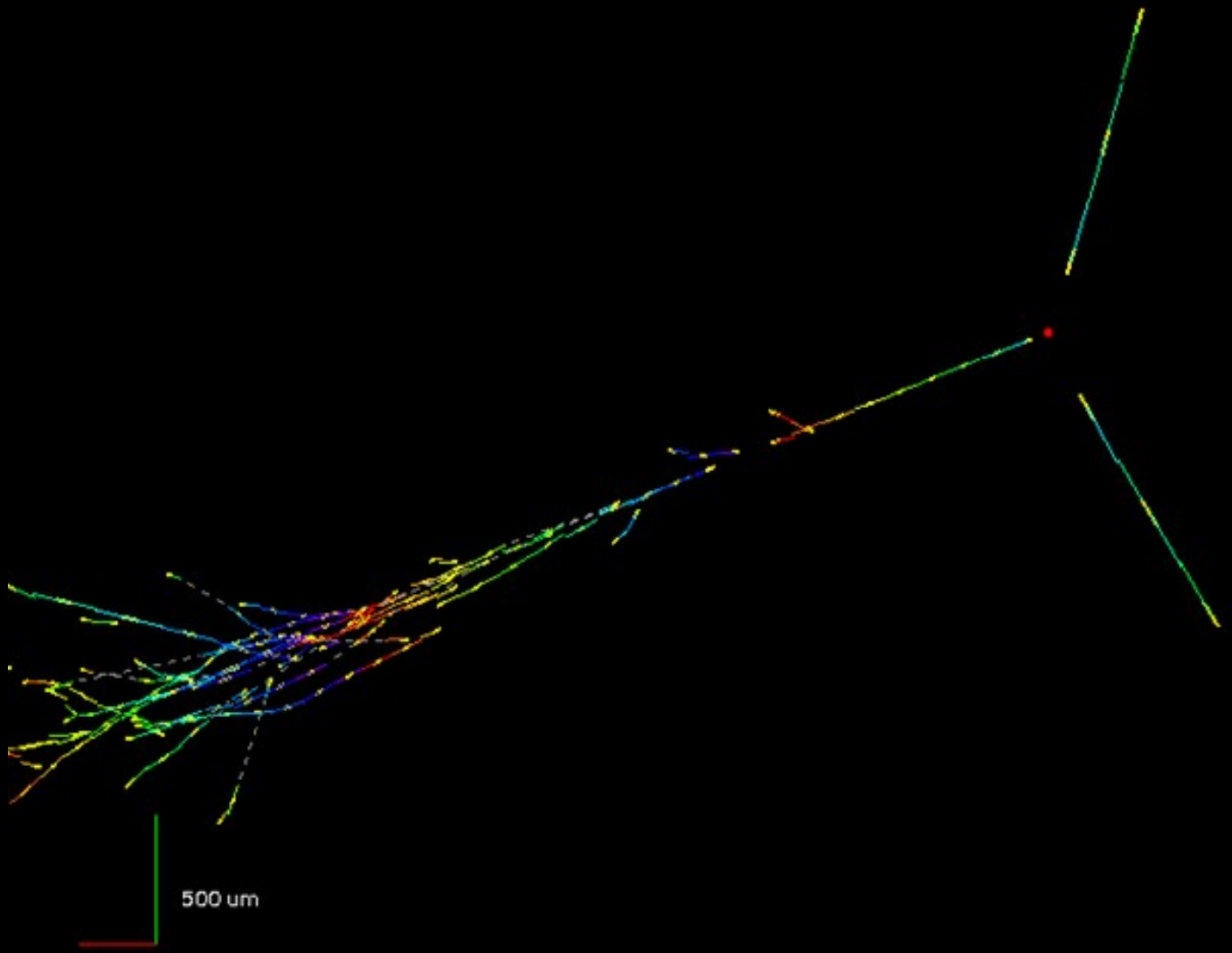
The OPERA Experiment

ν_τ Candidates

ν_e Analysis

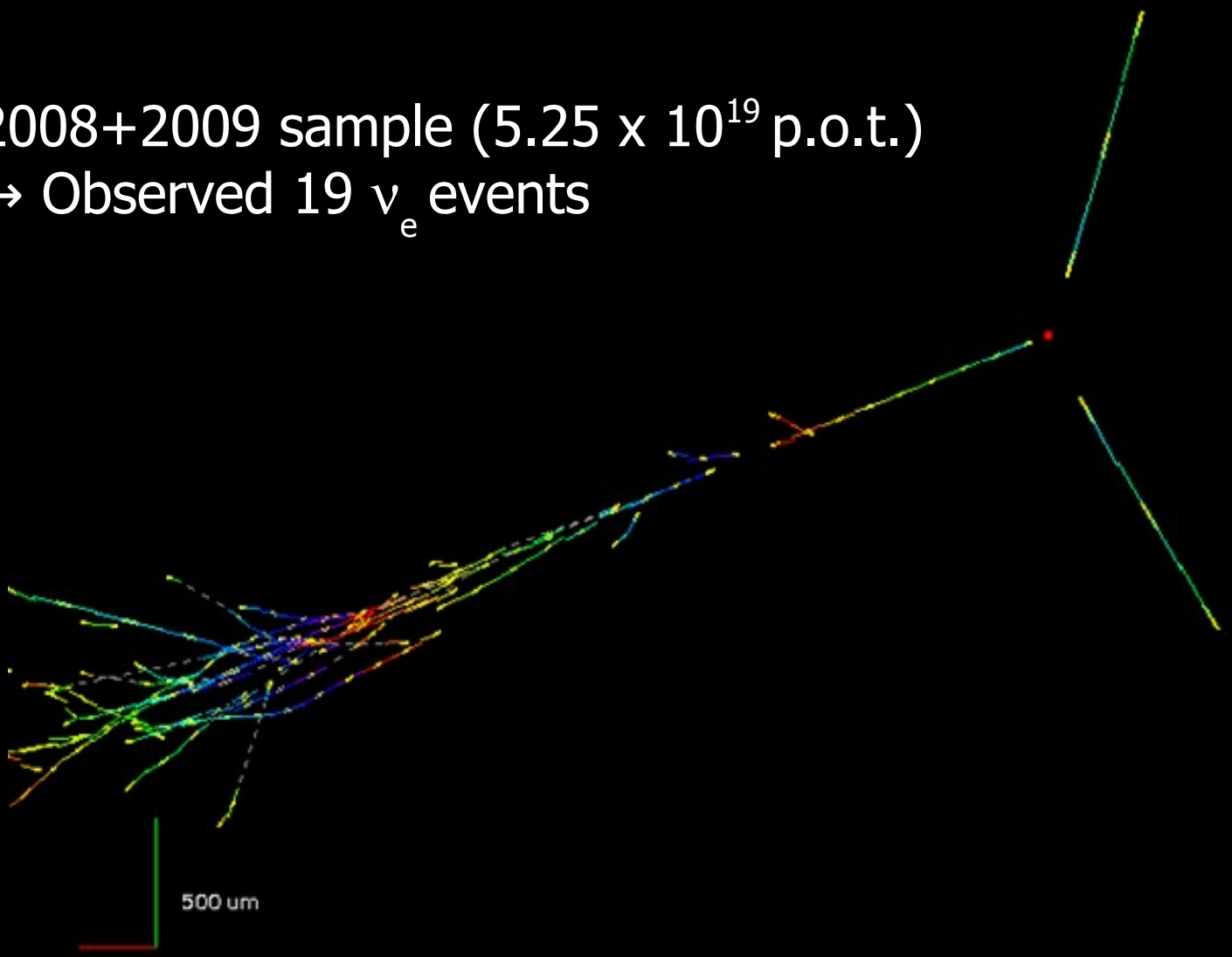
Summary/Outlook

ν_e Appearance Analysis



ν_e Appearance Analysis

2008+2009 sample (5.25 x 10^{19} p.o.t.)
→ Observed 19 ν_e events



ν_e Appearance Analysis

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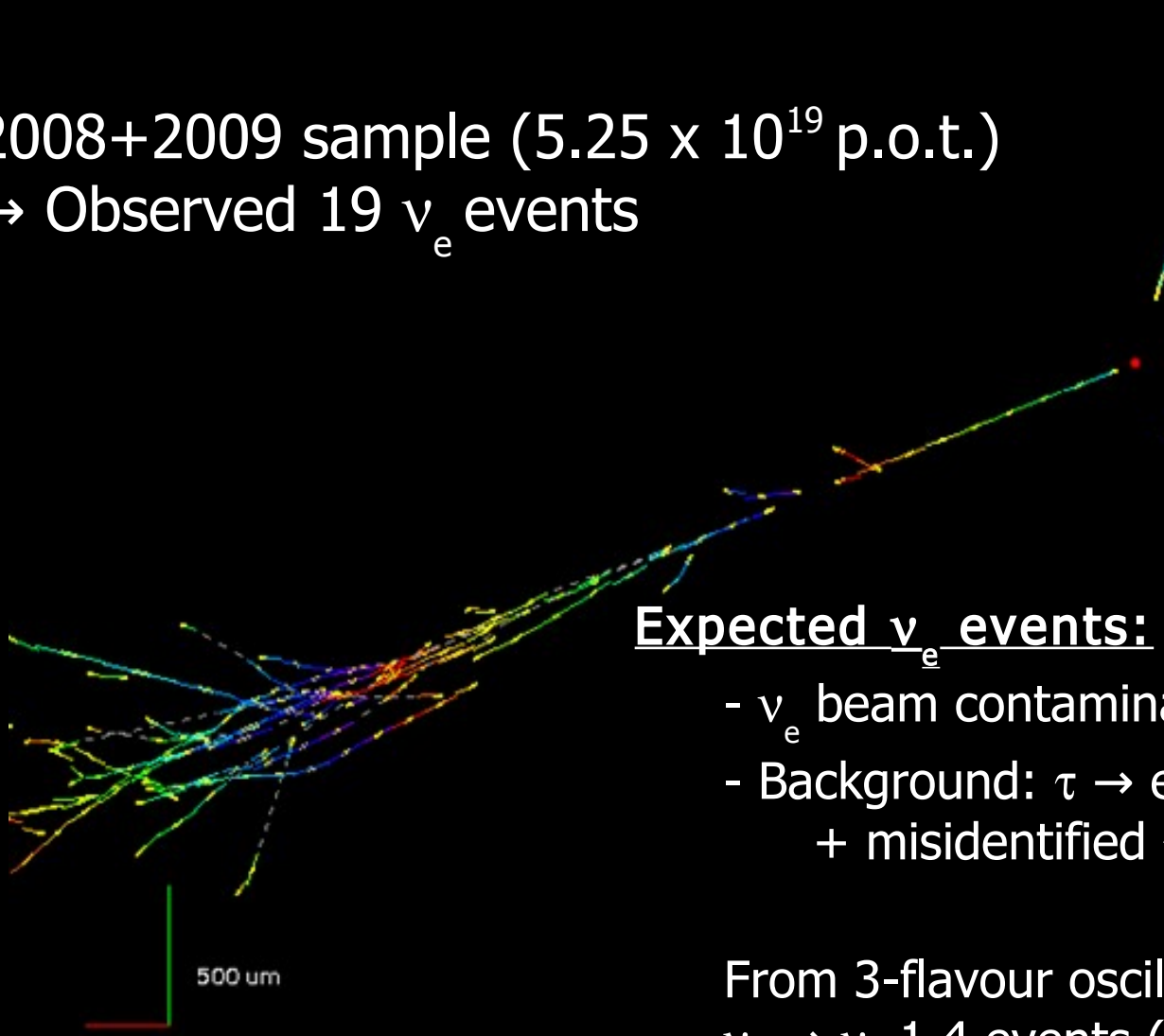


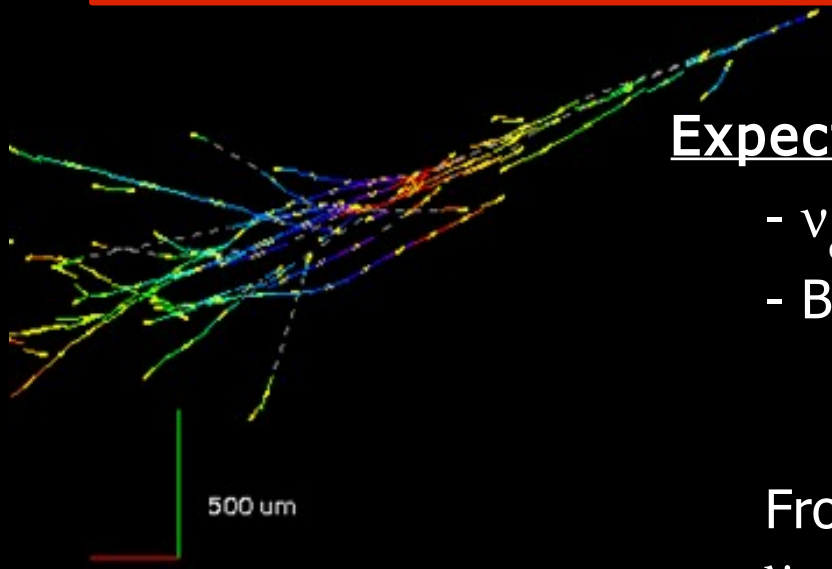
Expected ν_e events:

- ν_e beam contamination 19.3 ± 2.8
- Background: $\tau \rightarrow e$
  + misidentified π_0 0.5 ± 0.2

From 3-flavour oscillation:
$\nu_\mu \rightarrow \nu_e$ 1.4 events ($\sin^2(2\theta_{13}) = 0.098$)

ν_e Appearance Analysis

2008+2009 sample (5.25 x 10^{19} p.o.t.)
→ Observed 19 ν_e events



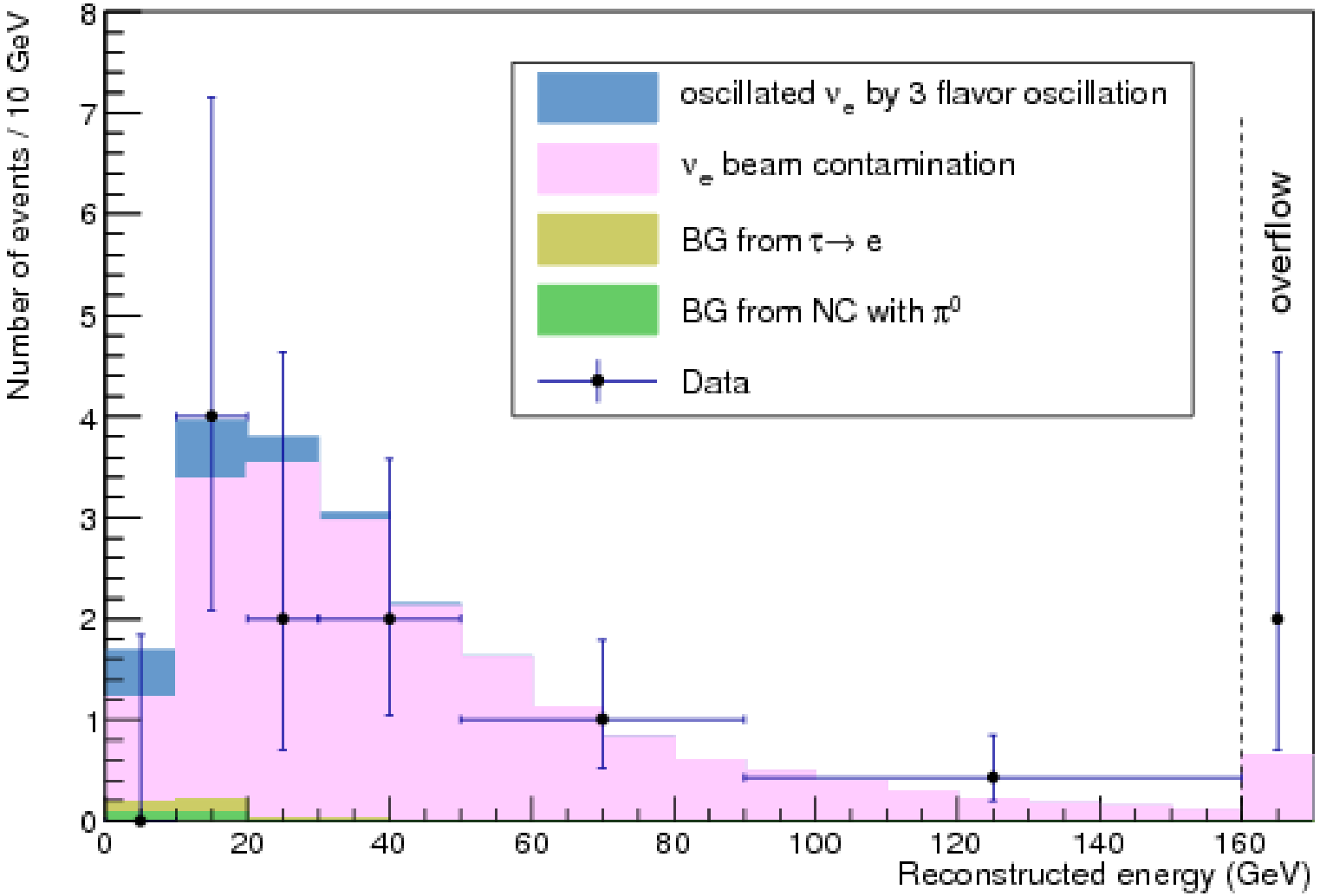
→ compatible with non-oscillation hypothesis

Expected ν_e events:

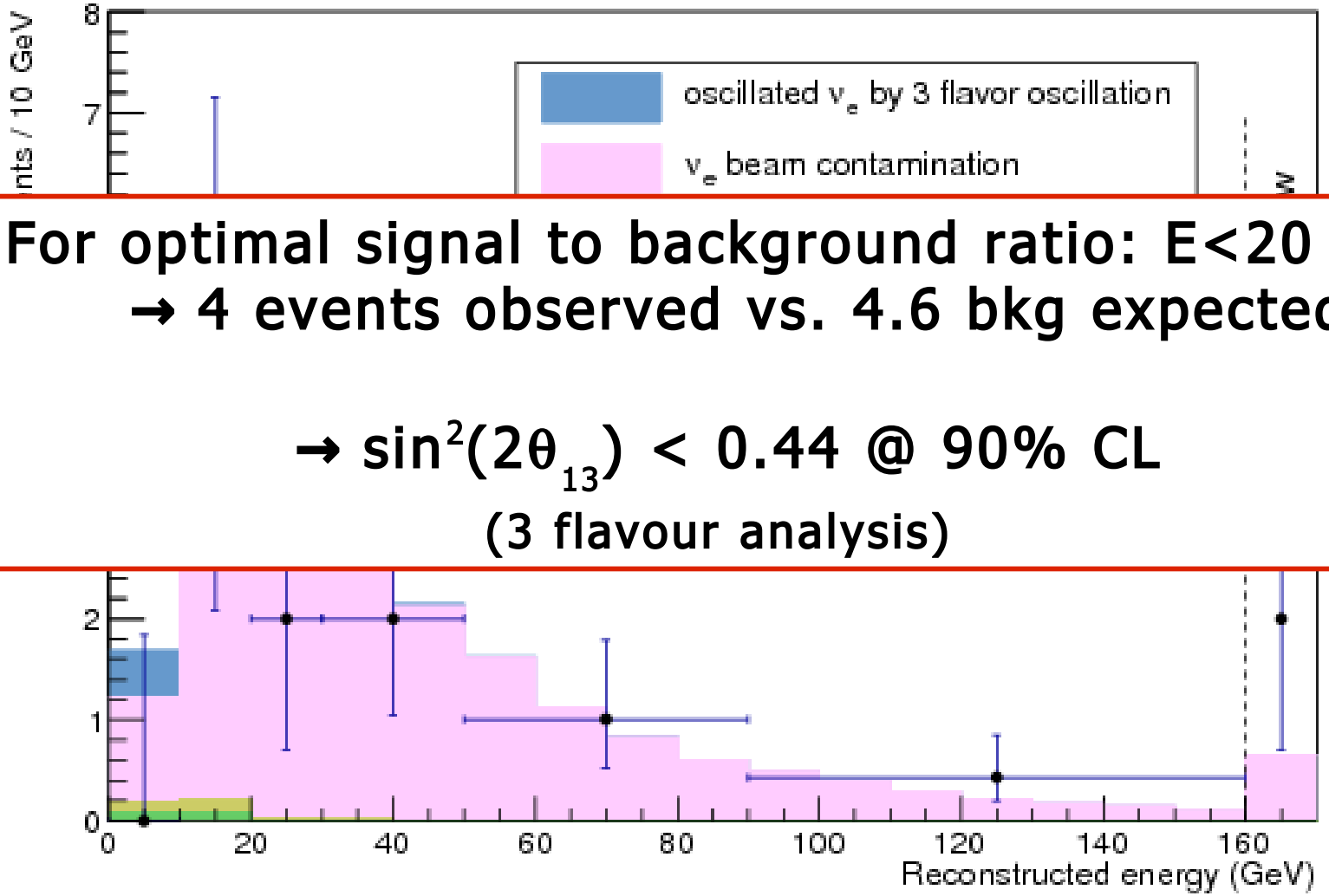
- ν_e beam contamination 19.3 ± 2.8
- Background: $\tau \rightarrow e$
  + misidentified π_0 0.5 ± 0.2

From 3-flavour oscillation:
$\nu_\mu \rightarrow \nu_e$ 1.4 events ($\sin^2(2\theta_{13}) = 0.098$)

ν_e Appearance Analysis



ν_e Appearance Analysis



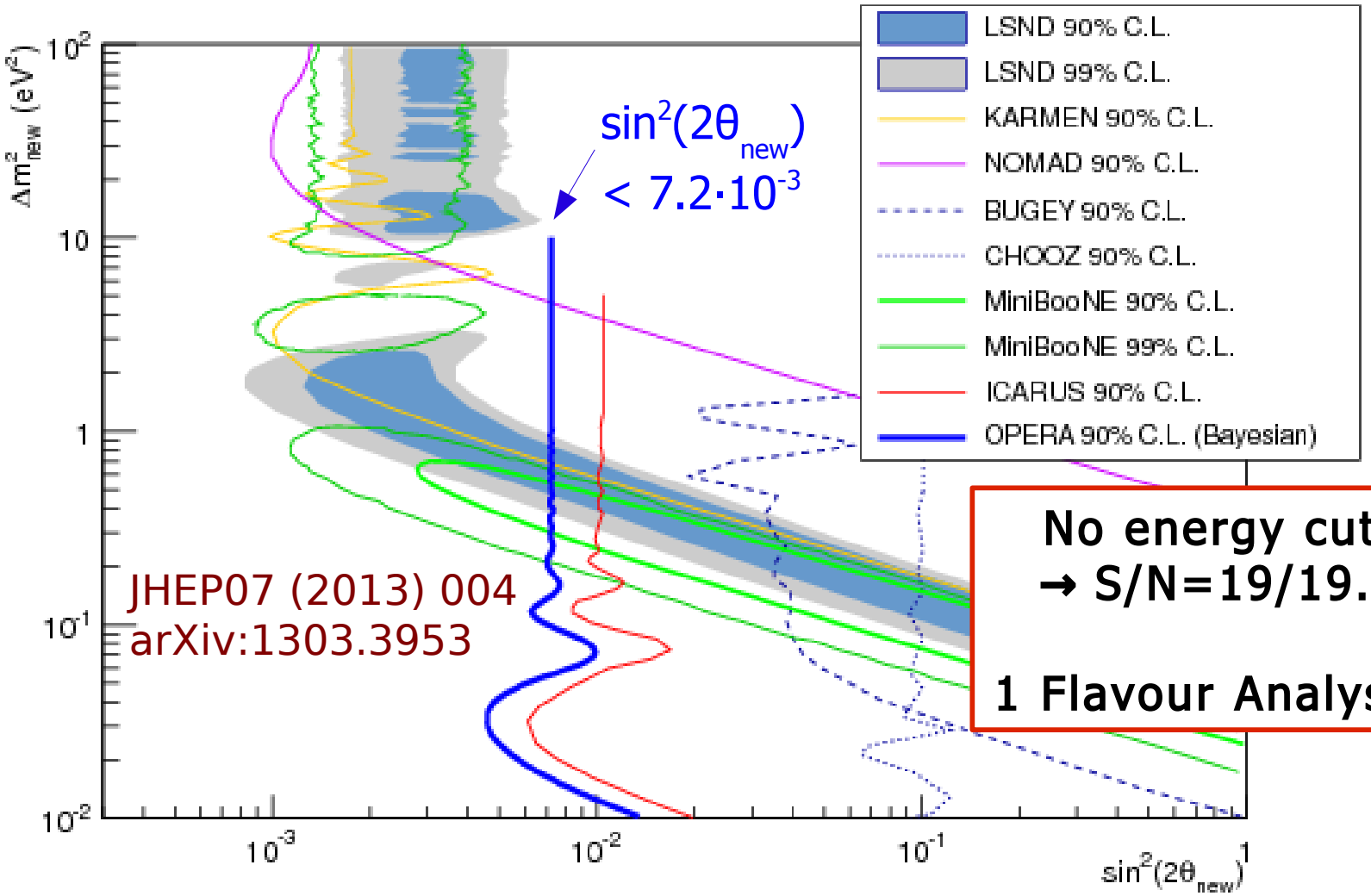
For optimal signal to background ratio: E<20 GeV
→ 4 events observed vs. 4.6 bkg expected

→ $\sin^2(2\theta_{13}) < 0.44$ @ 90% CL

(3 flavour analysis)

ν_e Appearance Analysis

Search for non-standard oscillations with larger Δm^2



No energy cut
→ S/N=19/19.8

1 Flavour Analysis

Overview

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Summary/Outlook

ν_τ-appearance:

- 3 events observed
- Conservative background estimation
  → non-oscillation excluded with 3.2 σ
- Likelihood analysis improves this slightly
- Improved background studies under way
  → 4 σ in reach

ν_e-appearance:

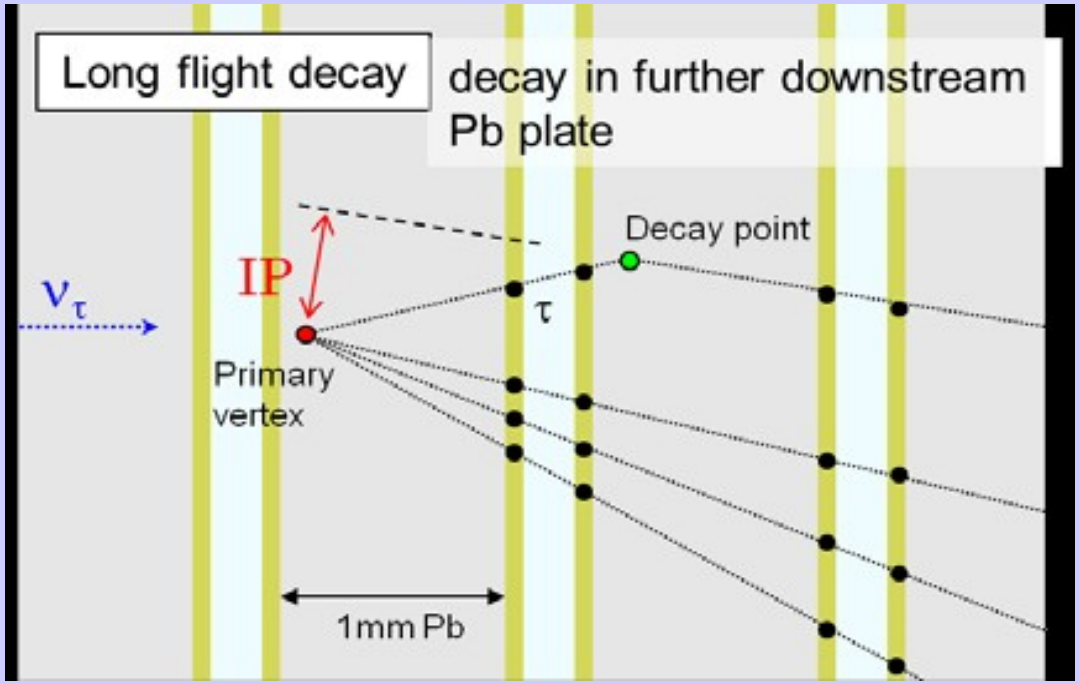
- No oscillation observed
  → can exclude significant parameter space for large Δm^2

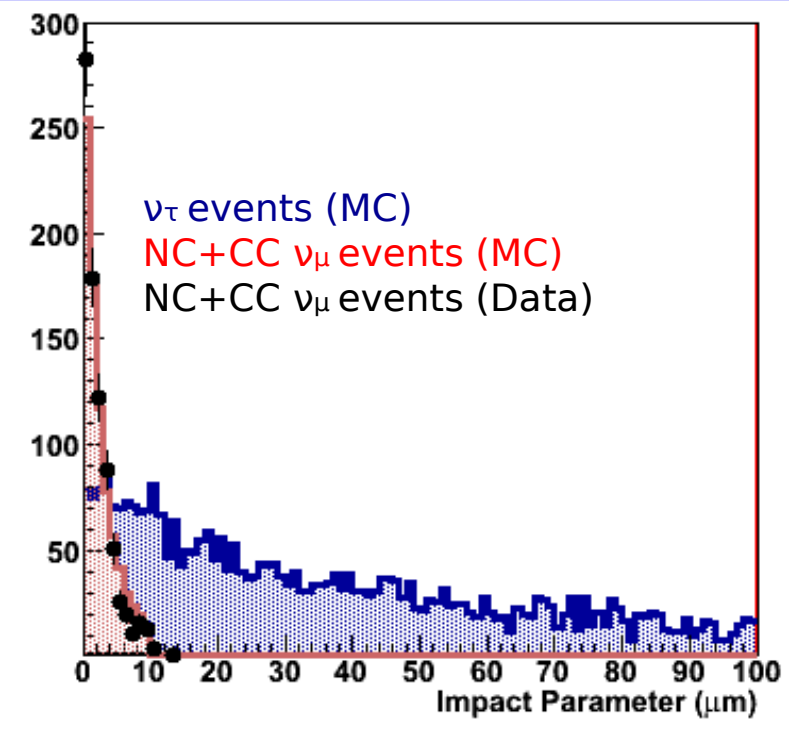
Analysis ongoing, some interesting events under investigation

Thank you for your attention!

Backup slides

Impact Parameter





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	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

~ 520 $\bar{\nu}_\mu$ interactions

~ 205 $\nu_e + \bar{\nu}_e$ interactions

~ 115 ν_τ CC interactions

For full mixing and $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 (scales with $(\Delta m^2)^2$).