

Neutrino Physics: Aspects on Neutrino (Mass-) and Mixing

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- Introduction: neutrino mass and mixing
- Neutrino Oscillation (I): $\mu - \tau$ mixing
 - atmospheric neutrinos
 - present neutrino beam experiments:
 - MINOS (NuMi beam: Fermilab – Soudan Mine)
 - OPERA (CNGS beam: Cern – LNGS)
- Neutrino Oscillation (II): $e - \mu$ mixing
 - solar neutrino experiments
 - short review on past experiments (SNO)
 - Borexino
 - reactor experiment: KamLand
- Neutrino Oscillation (III): Future prospects (θ_{13} and CPV)
 - reactor experiments: Double Chooz and Daya Bay
 - off-axis (super)beams: T2K and NovA
 - (neutrino)factory and beta beams)
- Nature of neutrino mass: Majorana or Dirac?
 - Double beta decay

Neutrino Oscillations have been observed → Add Neutrino Mass & Mixing to SM

JAPAN

Super-Kamiokande
& K2K

$$\nu_{\mu} \rightarrow \nu_{\tau,(\text{s})}$$

Oscillation

$$\Delta m^2 \approx 2 \cdot 10^{-3} \text{ eV}^2$$

+ MINOS (USA)
(+ OPERA, LNGS)

atmospheric neutrinos
accelerator neutrinos

CANADA

SNO

+ Homestake (USA),
+ Gallex/GNO (Italy),
+ SAGE (Russia)
+ SK

+ BOREXINO @
LNGS (Italy)

solar neutrinos

JAPAN

KamLAND

$$\nu_e \rightarrow \nu_{\mu, \tau}$$

Oscillation

$$\Delta m^2 \approx 8 \cdot 10^{-5} \text{ eV}^2$$

reactor neutrinos

Quark and Lepton Mixing:

Eigenstates of weak interaction $\neq$ Eigenstates of mass

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

$\swarrow$ $\swarrow$ $\swarrow$

$$\sum_{d,s,b} \quad \sum_{d,s,b} \quad \sum_{d,s,b}$$

mass eigenstates

Quark - Mixing

Neutrino - Mixing

mass eigenstates

$$\begin{matrix}
 \sum_{\nu_1, \nu_2, \nu_3} & \sum_{\nu_1, \nu_2, \nu_3} & \sum_{\nu_1, \nu_2, \nu_3} \\
 \nwarrow & \nwarrow & \nearrow \\
 \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} & \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} & \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}
 \end{matrix}$$

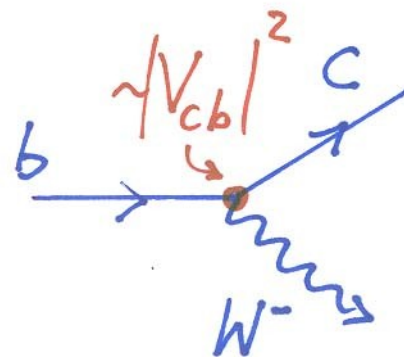
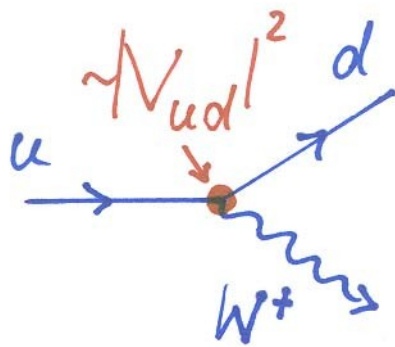
Quark-Mixing

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

Cabbibo-Kobayashi-Maskawa (CKM) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- 3 mixing angles
- 1 phase: $e^{i\delta}$
CP-violation



in precision measurement phase

BELLE,
BABAR,
CLEO,...
(BELLE2)

Neutrino Mass and -Mixing

3 massive neutrinos: ν_1, ν_2, ν_3 with masses: m_1, m_2, m_3

flavor-Eigenstates $\nu_e, \nu_\mu, \nu_\tau \neq$ mass-Eigenstates

neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

example: $|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$

Historical remark

- 1957-58: **B. Pontecorvo** proposed neutrino oscillations (because only ν_e was known, he thought of $\nu \leftrightarrow \text{anti-}\nu$)

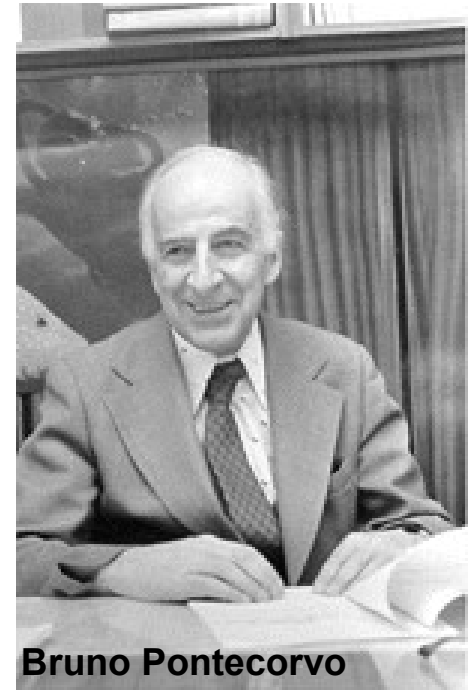
B. Pontecorvo, JETP **6**, 429 (1957); B. Pontecorvo, JETP **7**, 172 (1958).

- 1962 **Maki, Nakagawa, Sakata** described the 2 flavor mixing and discussed neutrino flavour transition.

Z.Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. **28**, 870 (1962).

- 1967 full discussion of 2 flavor mixing, possibility of solar neutrino oscillations, question of sterile neutrinos by B. Pontecorvo.

B. Pontecorvo, Zh. Eksp. Teor. Fiz. **53**, 1717 (1967), and JETP **26**, 984 (1968).



Bruno Pontecorvo

Therefore the neutrino mixing matrix is often called PMNS-Matrix

Parametrisation of Neutrino Mixing(I)

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

- 3 mixing angles: θ_{12} , θ_{23} , θ_{13}
- 1 Dirac-phase (CP violating): δ

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

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

$$\theta_{13} < 13^\circ, \delta ?$$

$$\theta_{12} \approx 33^\circ$$

Parametrisation of Neutrino Mixing (II)

But:

If neutrinos are Majorana particles two additional phases exist:

- 2 Majorana-Phases (CPV): α_1, α_2

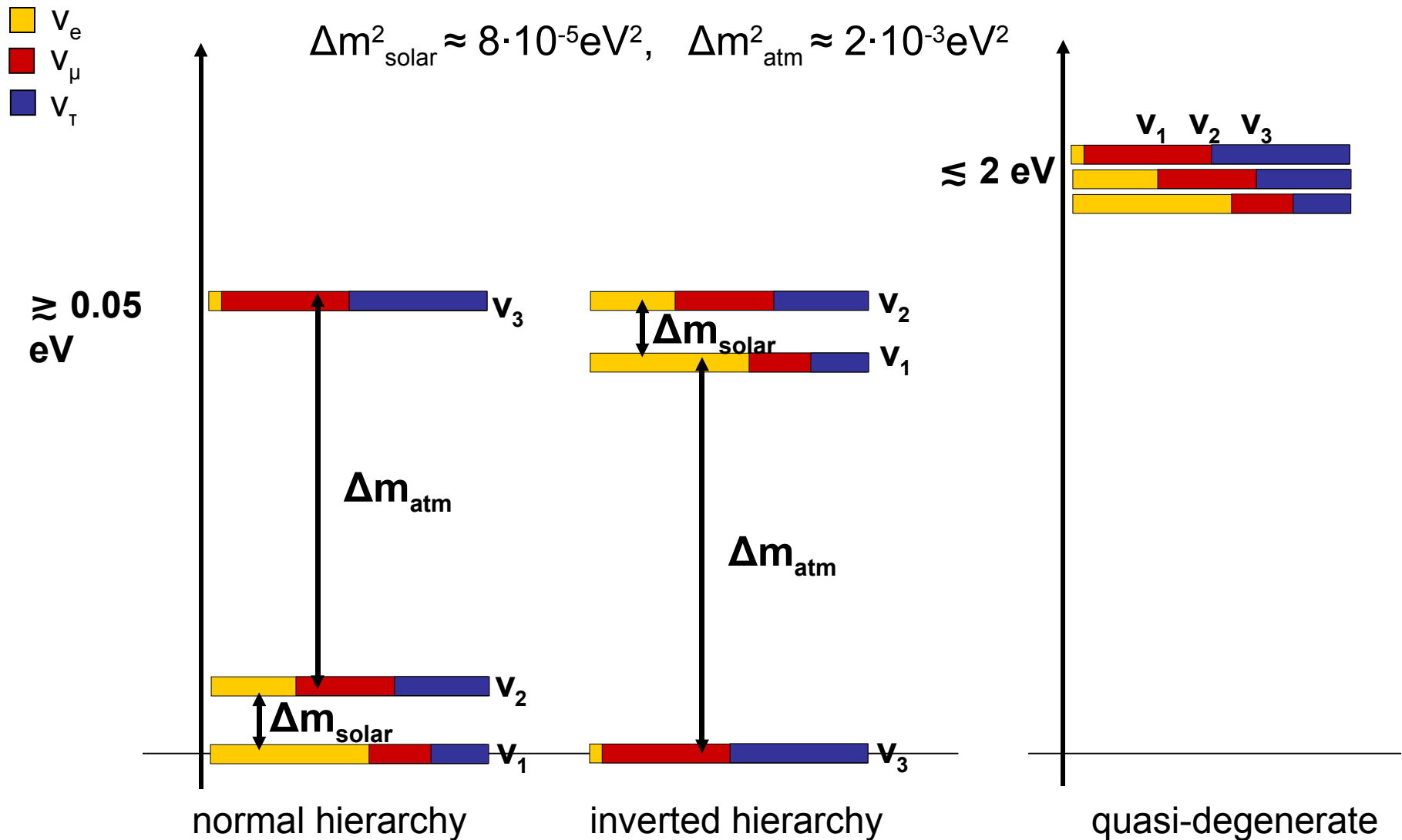
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\alpha_1} & s_{13}e^{-i\delta}e^{i\alpha_2} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & [c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & s_{23}c_{13}e^{i\alpha_2} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & [-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta}]e^{i\alpha_1} & c_{23}c_{13}e^{i\alpha_2} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Leptons vs Quarks

$$\begin{array}{l} \text{Neutrinos} \\ U_{MNSP} \end{array} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$\begin{array}{l} \text{Quarks} \\ V_{CKM} \end{array} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

What do we know about neutrino masses?



Neutrino Mixing for 2 Flavors

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos \theta_{23} & \sin \theta_{23} \\ -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_\mu\rangle = \cos \theta_{23} |\nu_2\rangle + \sin \theta_{23} |\nu_3\rangle$$

We have measured that $\theta_{23} \approx 45^\circ$:

$$|\nu_\mu\rangle = \frac{1}{\sqrt{2}} (|\nu_2\rangle + |\nu_3\rangle) \quad |\nu_\tau\rangle = \frac{1}{\sqrt{2}} (-|\nu_2\rangle + |\nu_3\rangle)$$

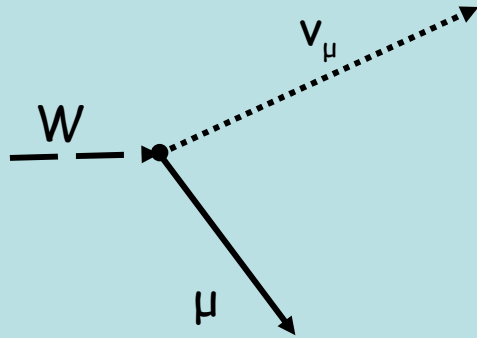
Neutrino Oscillations

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos \theta_{23} & \sin \theta_{23} \\ -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

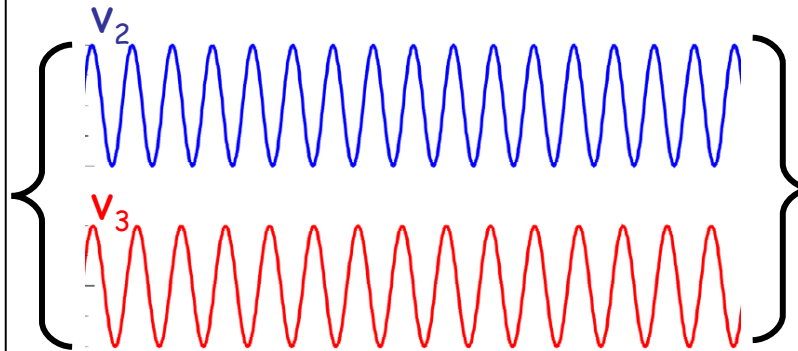
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2, ν_3
with m_2, m_3

source creates
flavor-eigenstates



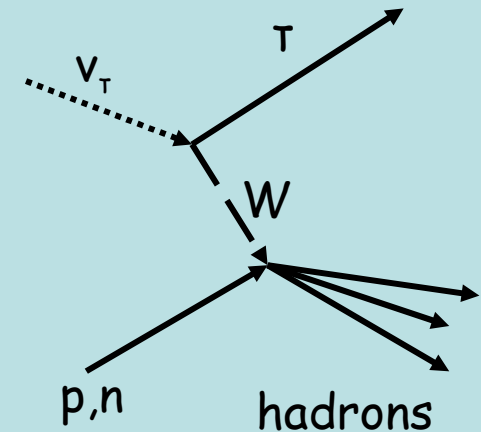
propagation determined by
mass-eigenstates



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

slightly different frequencies
→ phase difference changes

detector sees
flavor-eigenstates



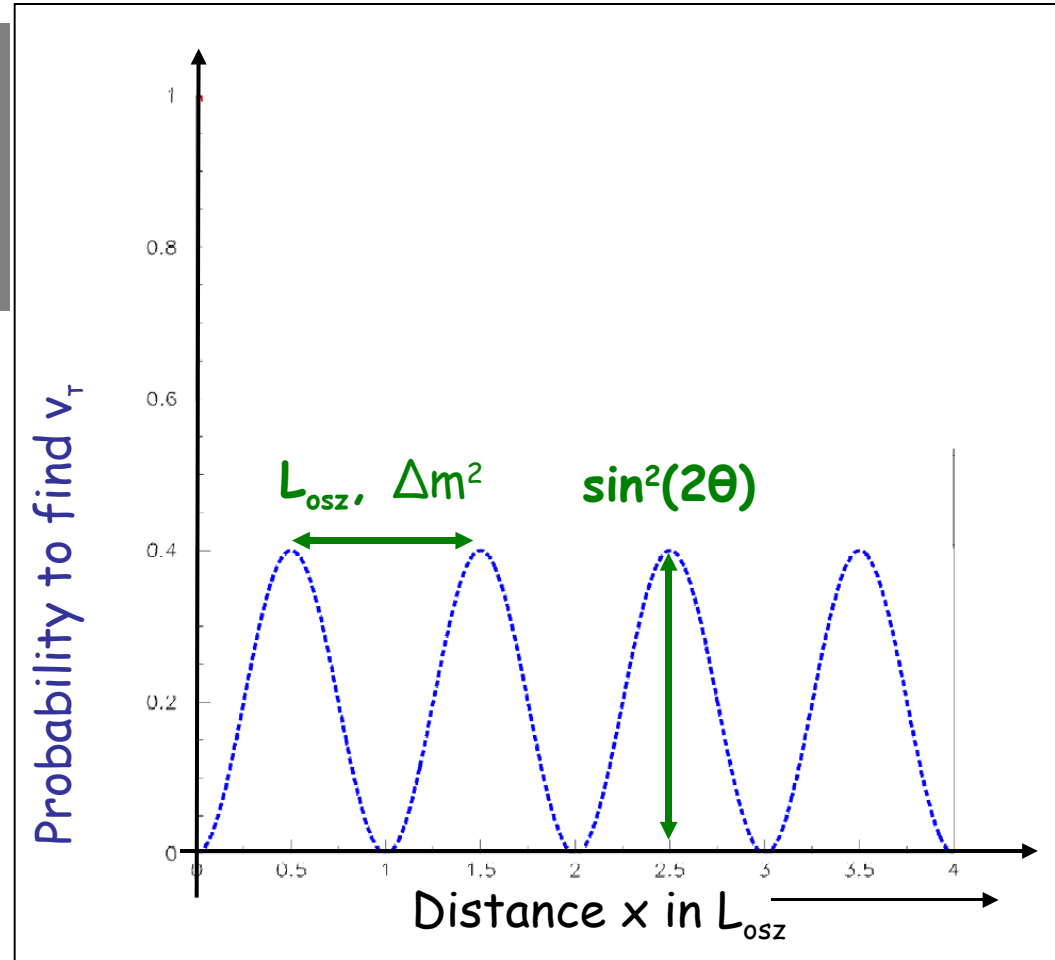
2 Flavor Neutrino Oscillations

Oscillation probability

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

$$L_{osz} \text{ (in km)} = \frac{2.48 \cdot E \text{ (in GeV)}}{\Delta m^2 \text{ (in eV}^2\text{)}}$$

$$\Delta m^2 = m_2^2 - m_3^2$$



General oscillation formula:

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left(1.27 \Delta m_{ij}^2 \frac{L}{E} \right) \\ + 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left(2.54 \Delta m_{ij}^2 \frac{L}{E} \right)$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \text{ in eV}^2$$

L in km

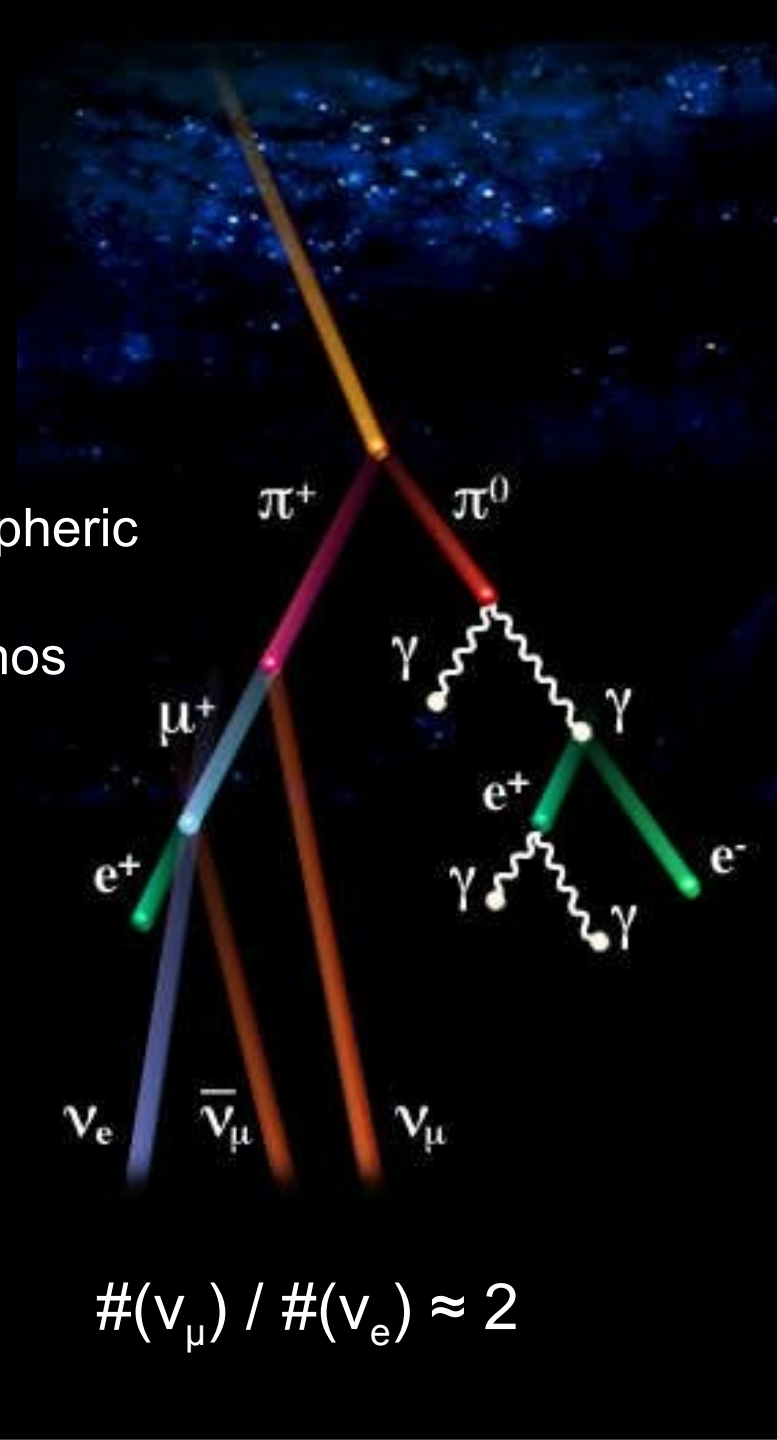
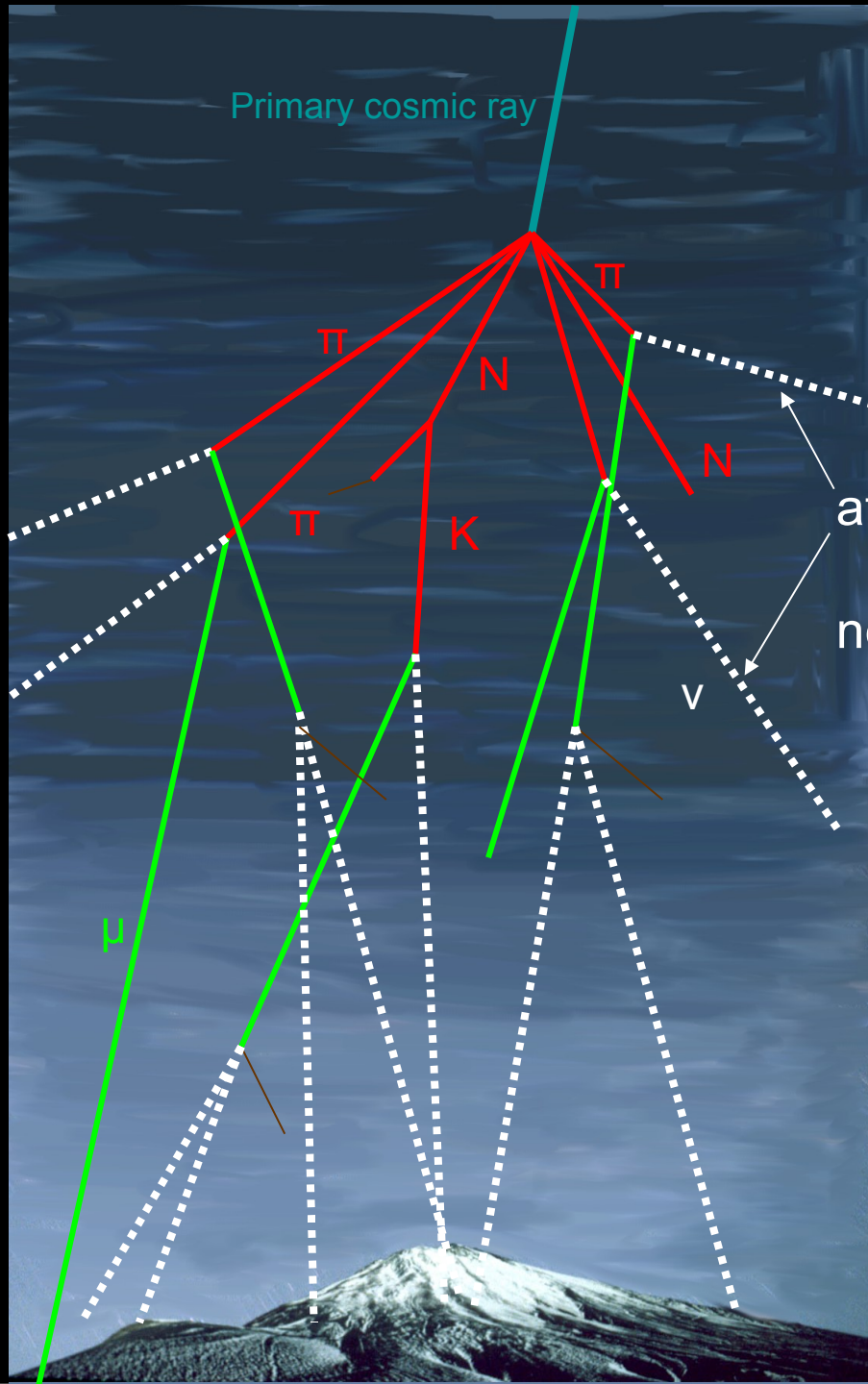
E in GeV

Neutrino Oscillations (23)

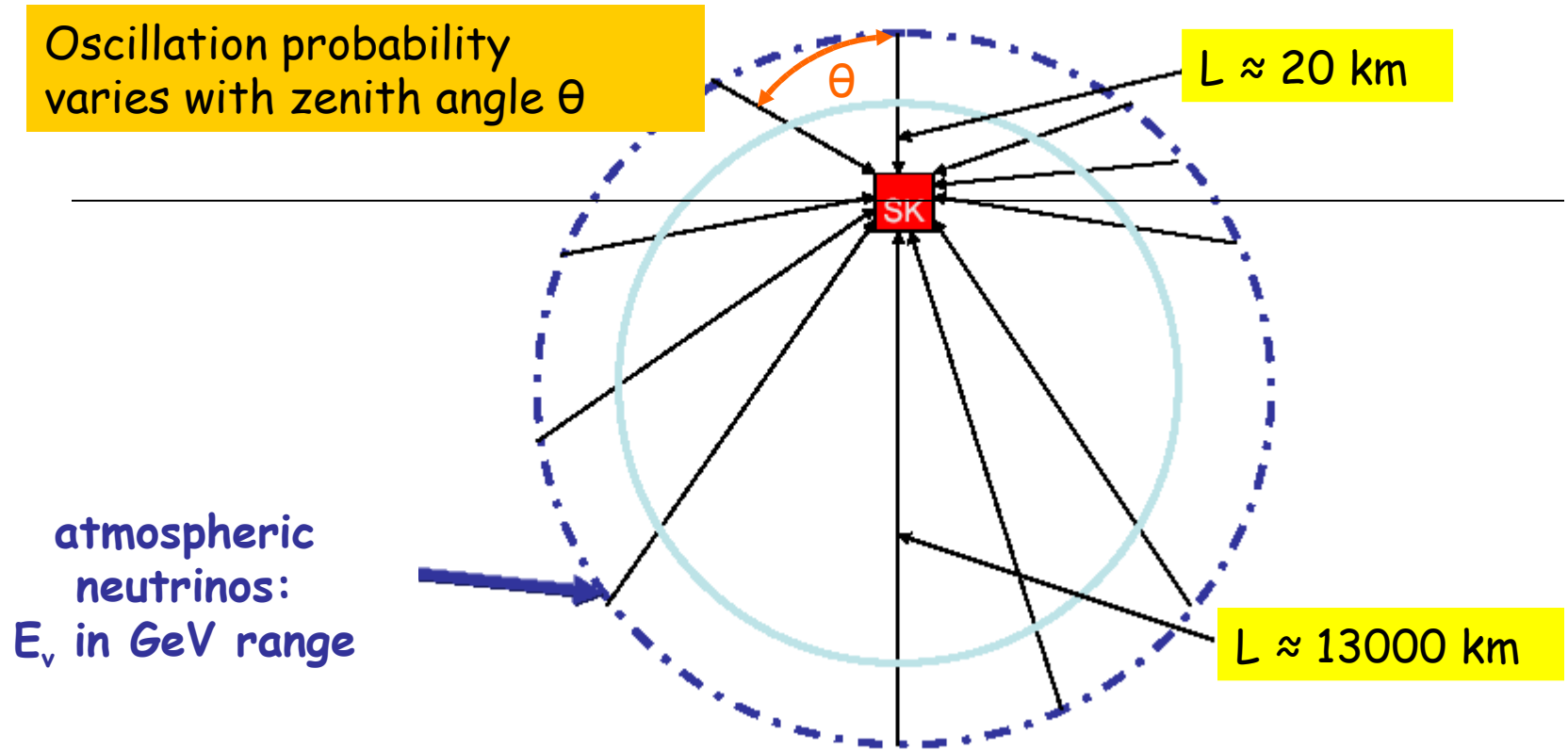
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

$\nu_\mu \rightarrow \nu_\tau$ Oscillations

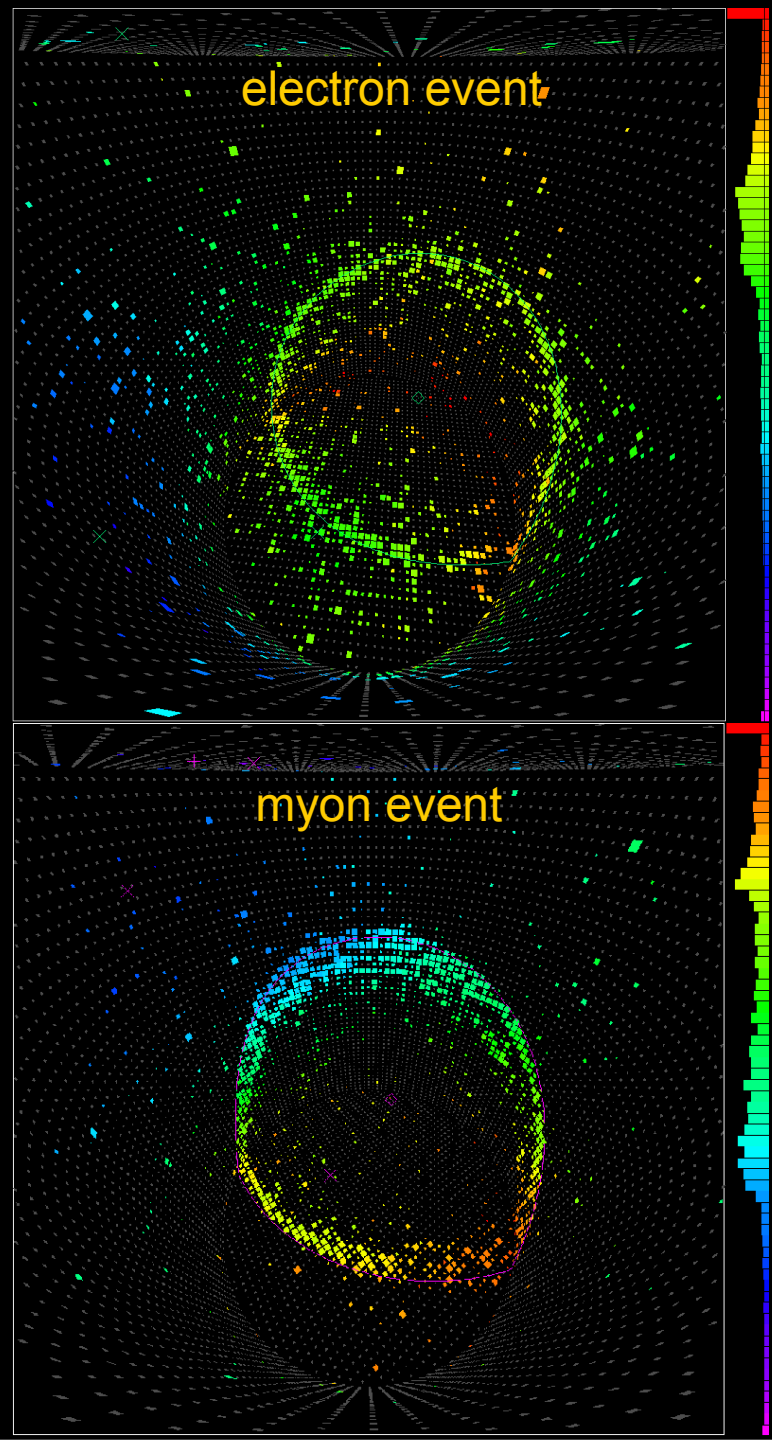
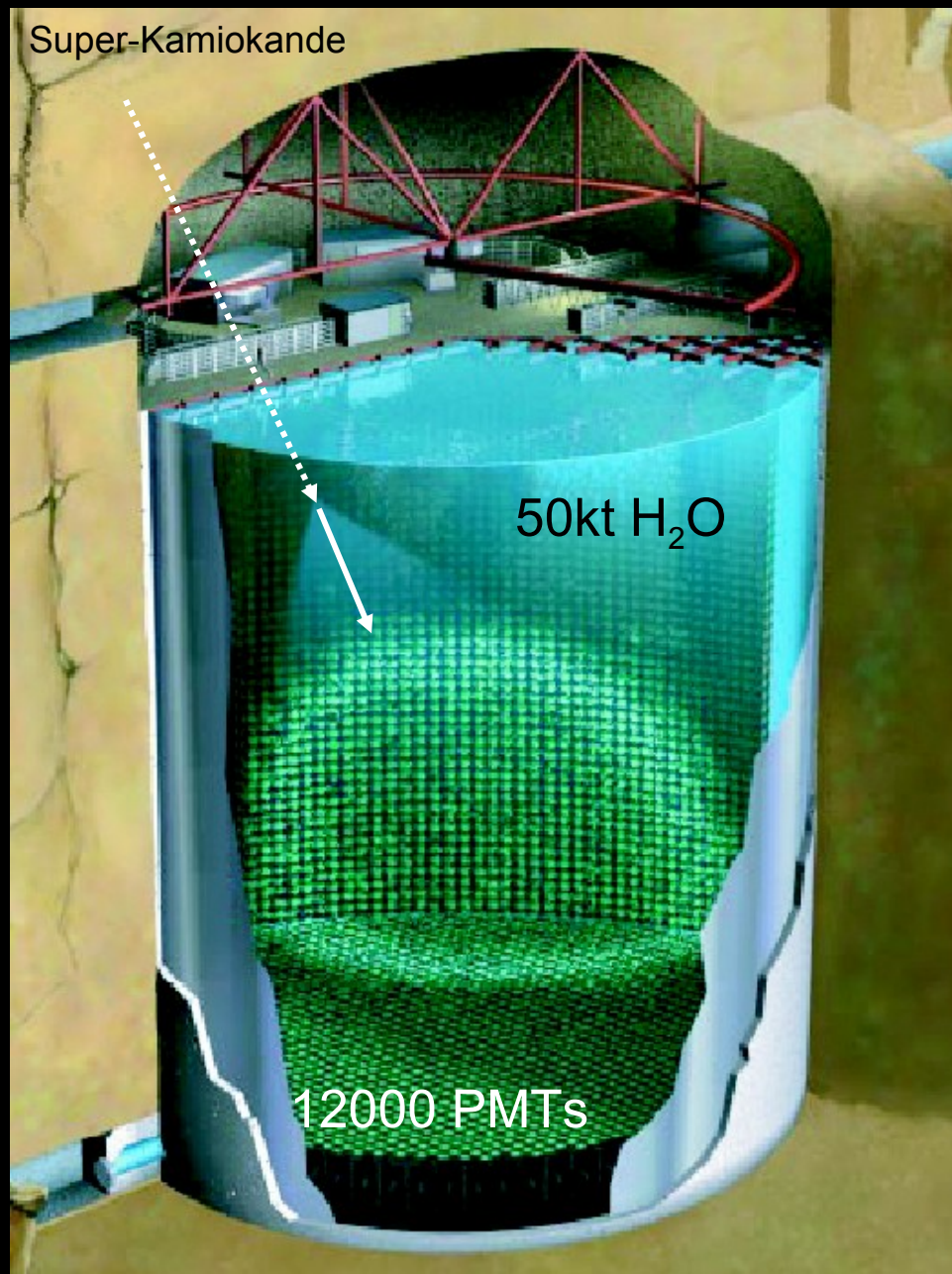
Atmospheric neutrinos & accelerator neutrinos



Oscillation of atmospheric neutrinos



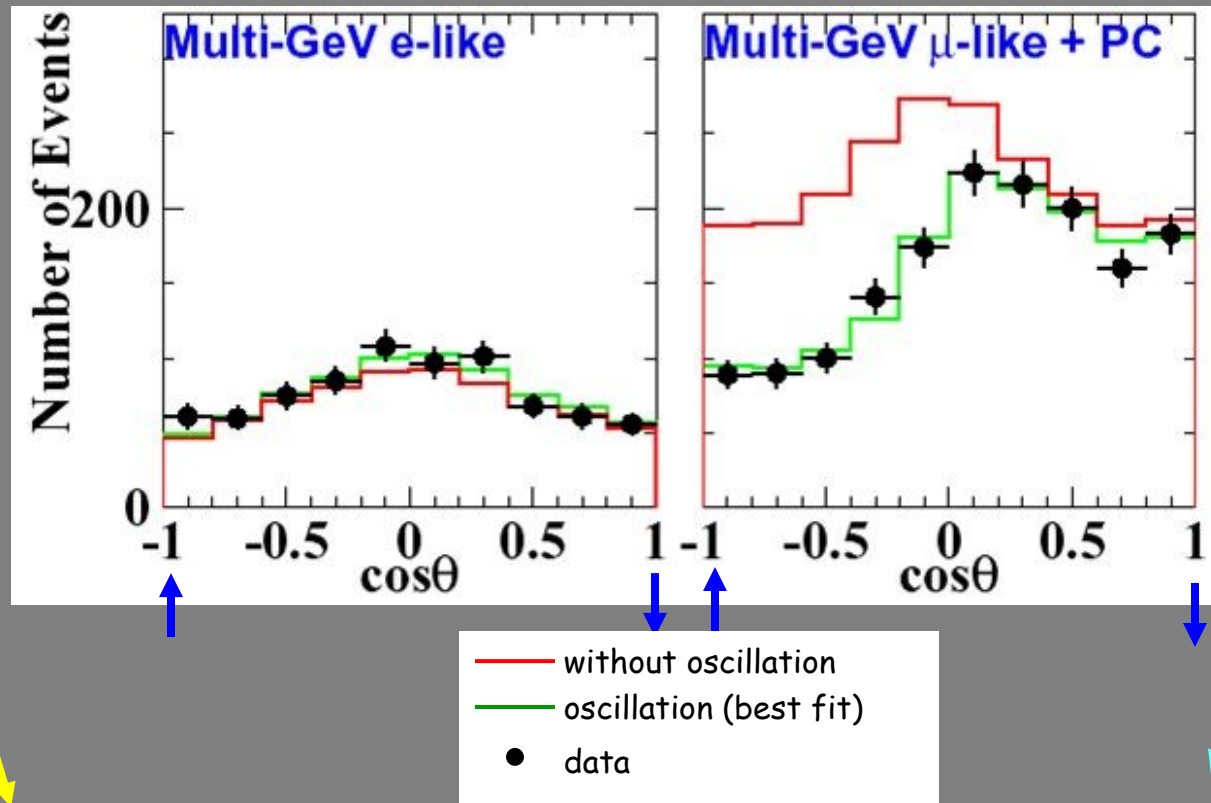
$$P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta_{atm} \sin^2 \left(\frac{1.27 \Delta m_{atm}^2 [\text{eV}^2] L [\text{km}]}{E_\nu [\text{GeV}]} \right)$$



SuperK – atmospheric neutrinos

e-like events

μ -like events

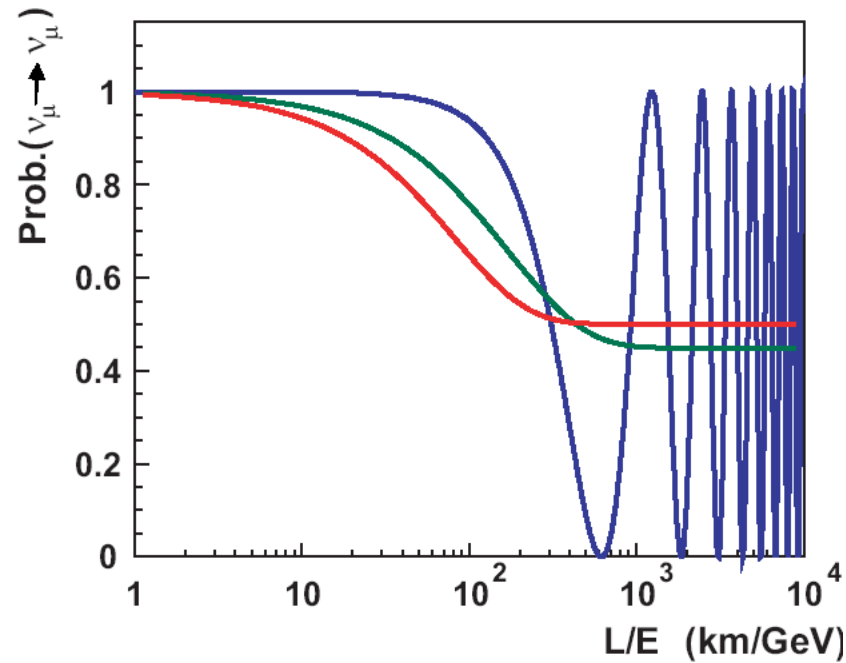


Full SK-I data set, 90% CL (PRD71 (2005) 112005):

$$\sin^2 2\theta > 0.92$$

$$1.5 \sum 10^{-3} \text{ eV}^2 < \Delta m^2 < 3.4 \sum 10^{-3} \text{ eV}^2$$

SK: Analysis of events with high L/E resolution

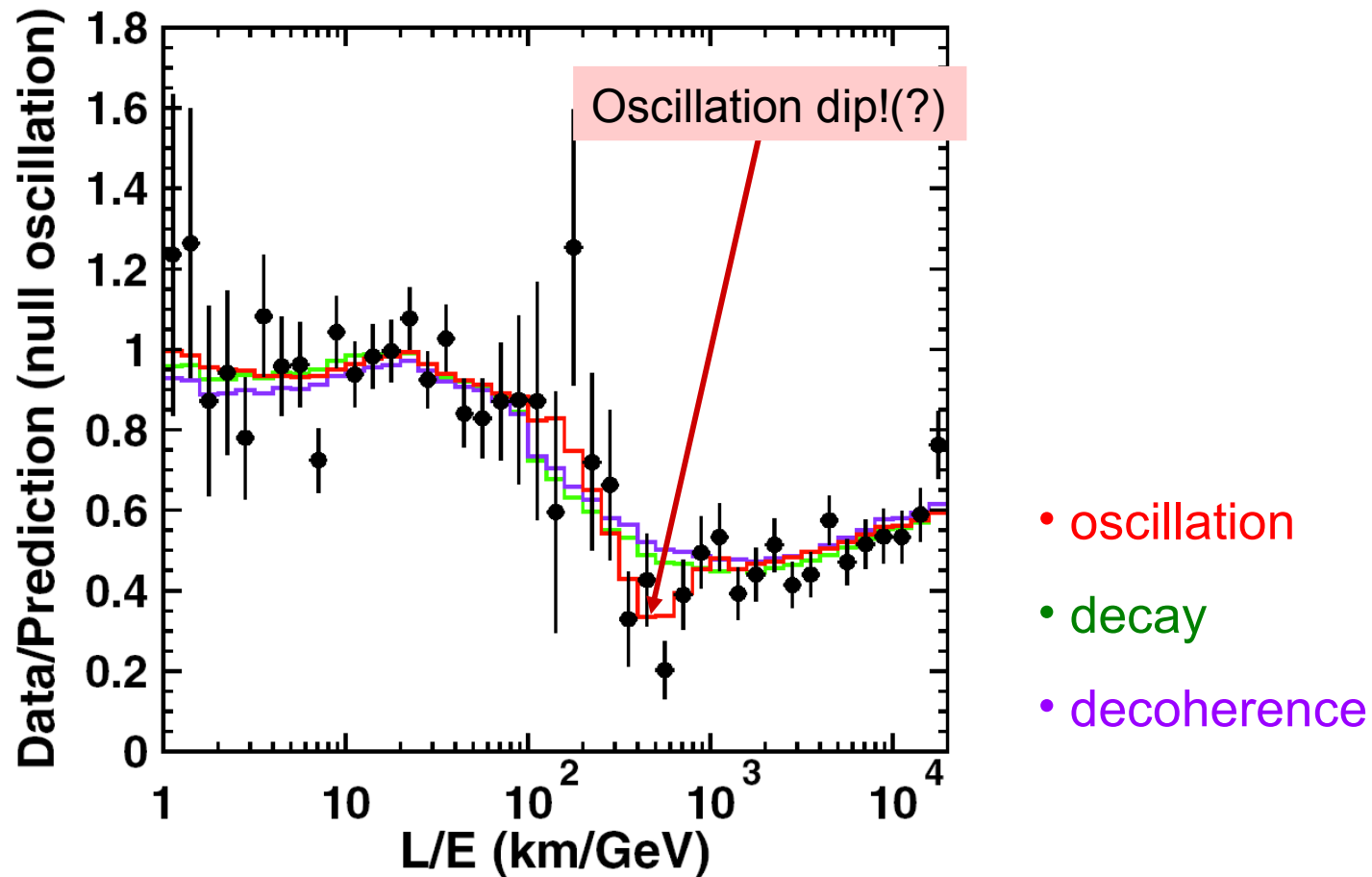


Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$

Neutrino decay : $P_{\mu\mu} = \left(\cos^2 \theta + \sin^2 \theta \times \exp\left(-\frac{m}{2\tau} \frac{L}{E}\right)\right)^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2} \sin^2 2\theta \times \left(1 - \exp\left(-\gamma_0 \frac{L}{E}\right)\right)$

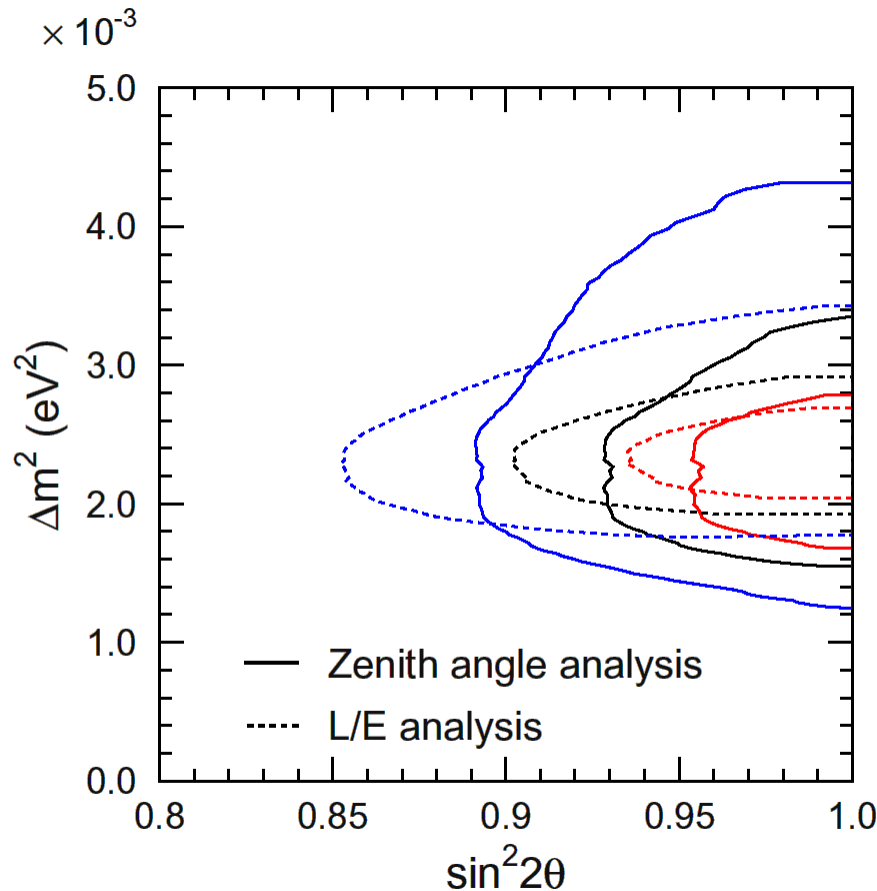
Superkamiokande: atm. Neutrinos L/E



“EVIDENCE FOR AN OSCILLATORY SIGNATURE IN ATMOSPHERIC NEUTRINO OSCILLATION.”

Super-Kamiokande Apr 2004., Submitted to Phys.Rev.Lett., [hep-ex/0404034](#)

Atmospheric Neutrino Results



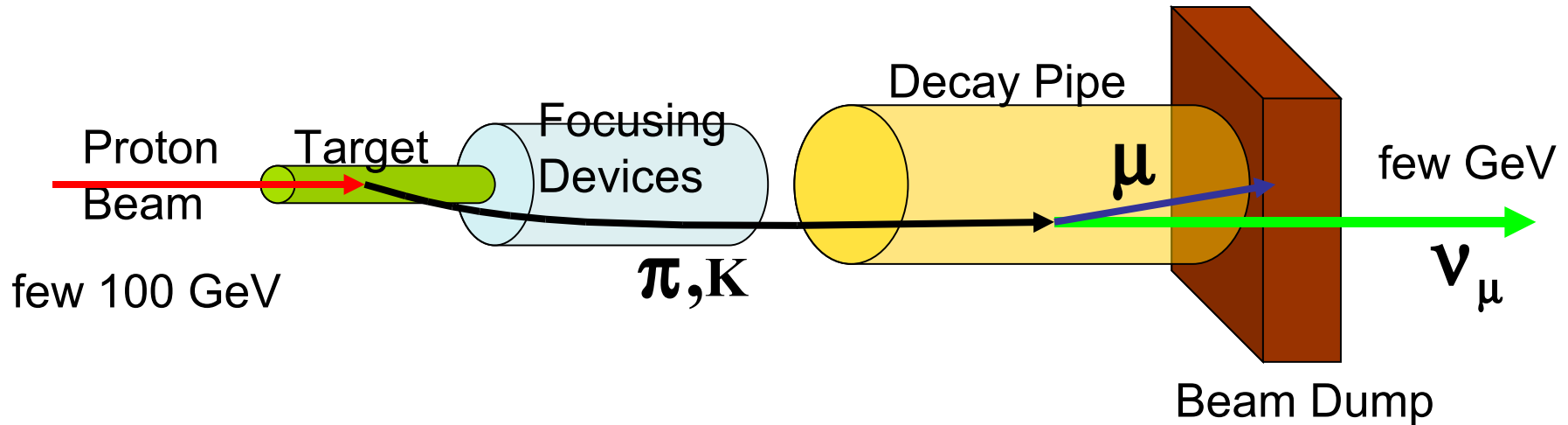
L/E Analysis
(PRL93 (2004) 101801),
Best Fit:
 $\sin^2 2\theta = 1.02$
 $|\Delta m^{2-3} 10 \times 2.4 = 1 \text{ eV}^2$

Full SK-I data set, 90% CL
(PRD71 (2005) 112005):

$\sin^2 2\theta > 0.92$

$1.5 \sum 10^{-3} \text{ eV}^2 < \Delta m^2 < 3.4 \sum 10^{-3} \text{ eV}^2$

Neutrino beams: Principle

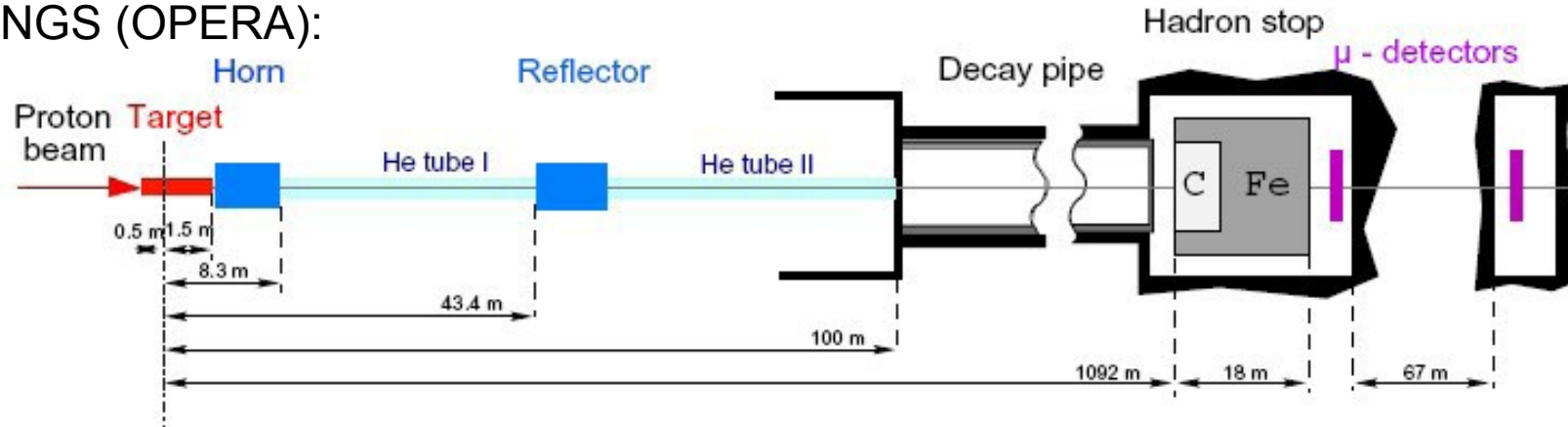


Beam composition (typical example):

- dominantly ν_μ
- contamination from $\bar{\nu}_\mu$ ($\approx 6\%$), ν_e ($\approx 0.7\%$), $\bar{\nu}_e$ ($\approx 0.2\%$)
- $\nu_\tau \lesssim 10^{-6}$

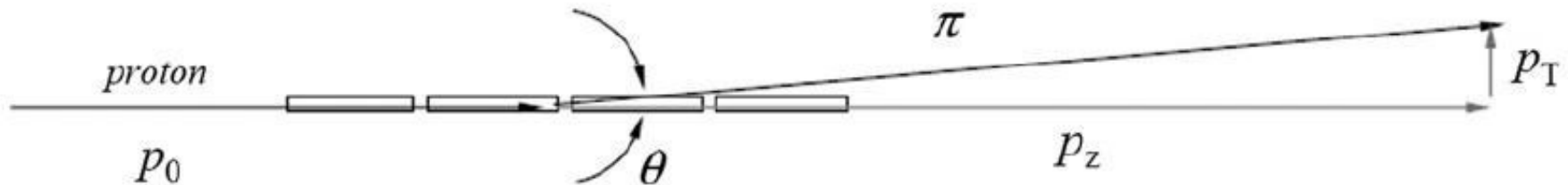
Technical Overview Conventional Neutrino Beams

CNGS (OPERA):



proton source	experiments	E_{proton}	pot/yr.	Power	E_{ν}
SPS	OPERA	400 GeV	$0.45 \cdot 10^{20}$	0.12 MW	25 GeV
FNAL Main Injector	MINOS, NO ν A	120 GeV	$2.5 \cdot 10^{20}$	0.25 MW	3-17 GeV
J-PARC	T2K	40-50 GeV	$11 \cdot 10^{20}$	0.75 MW	0.8 GeV

Neutrino Beam: Target



neutrino beamline	experiments	material	$\varnothing$ [mm]	length [cm]
CNGS (SPS)	OPERA	graphite	4-5	200
NuMI (Fermilab)	MINOS, NoνA	graphite	6.4	90
J-PARC (KEK)	T2K	graphite	12-15	90
BoosterNeutrino	MiniBooNe	Be	10	60

Power can be up to 100GW!



CNGS Target





The MINOS Experiment

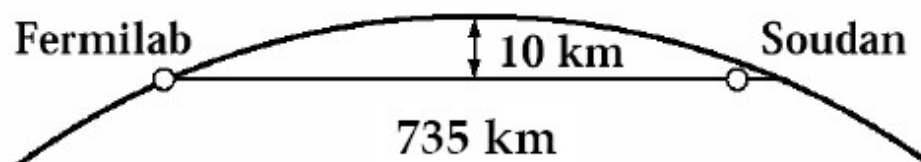


A large detector at Soudan

A smaller detector at Fermilab

Measure the beam and neutrino energy spectrum near the source

> See how it differs far away





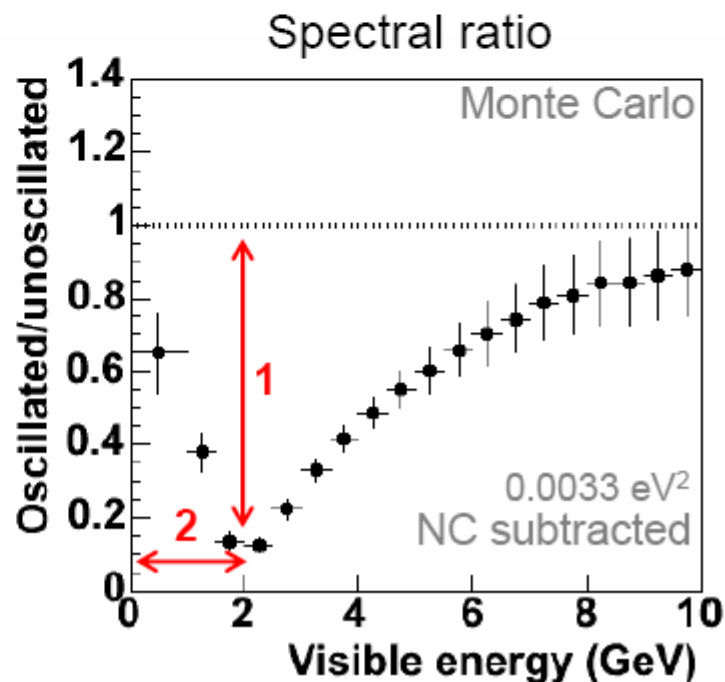
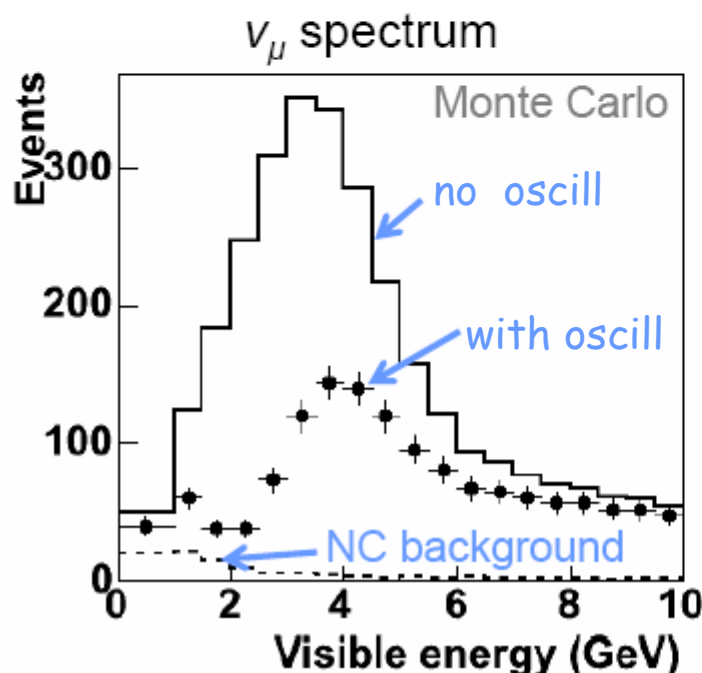
Example of a disappearance measurement

Look for a deficit of ν_μ events at a distance...

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$

statistics! ¹

² energy resolution!





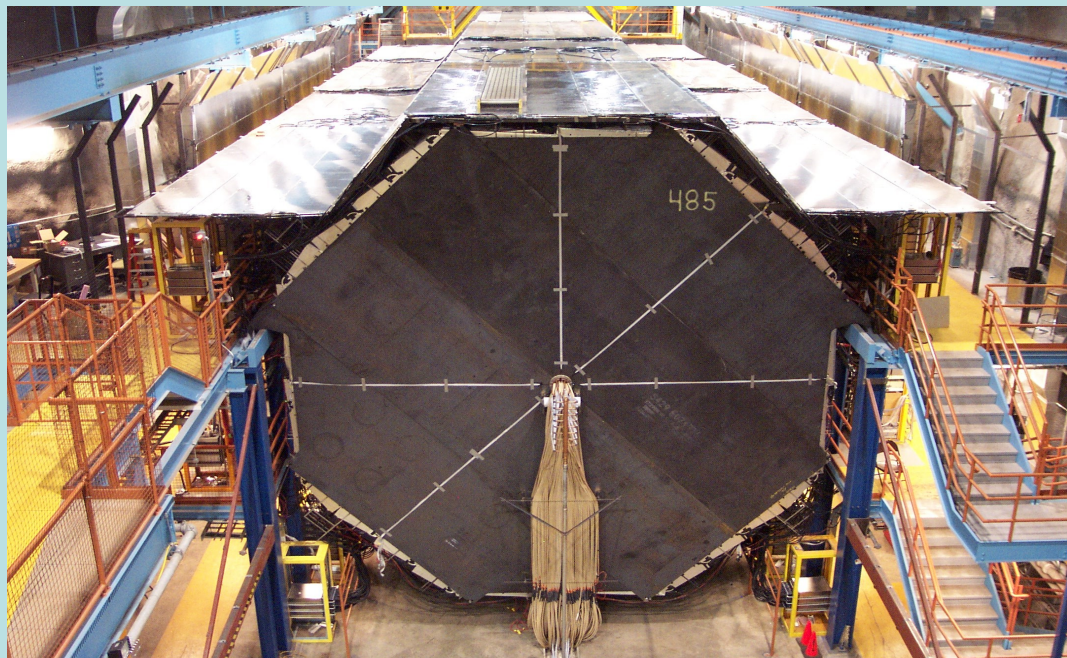
MINOS Detectors

Near Detector (Fermilab): 1km



1 kton, $4 \times 5 \times 15$ m
282 steel,
153 scintillator planes

Far Detector (Soudan Mine): 735km



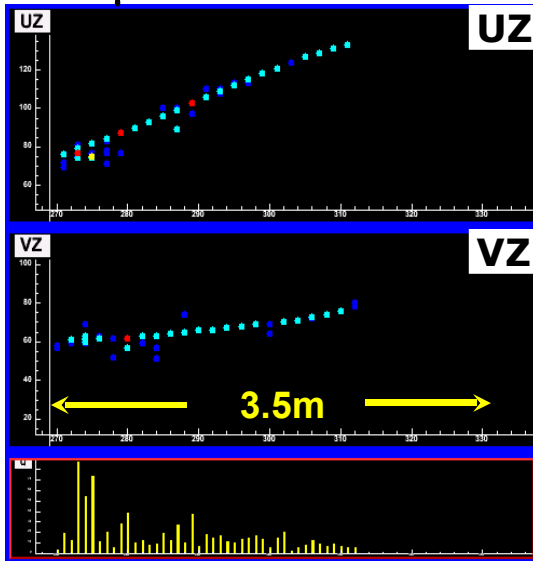
5.4 ktons, $8 \times 8 \times 30$ m
484 steel/scintillator planes



Event Topologies

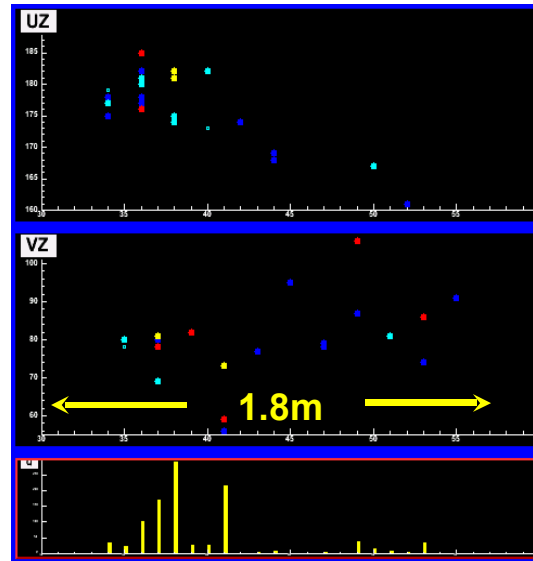
Monte Carlo

ν_μ CC Event



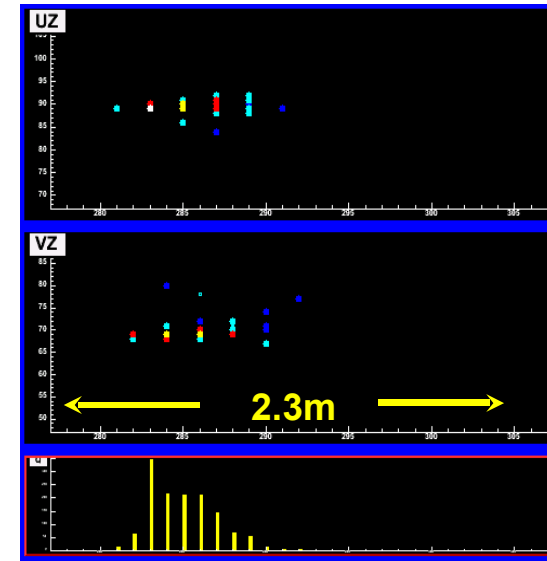
long μ track +
hadronic activity

NC Event



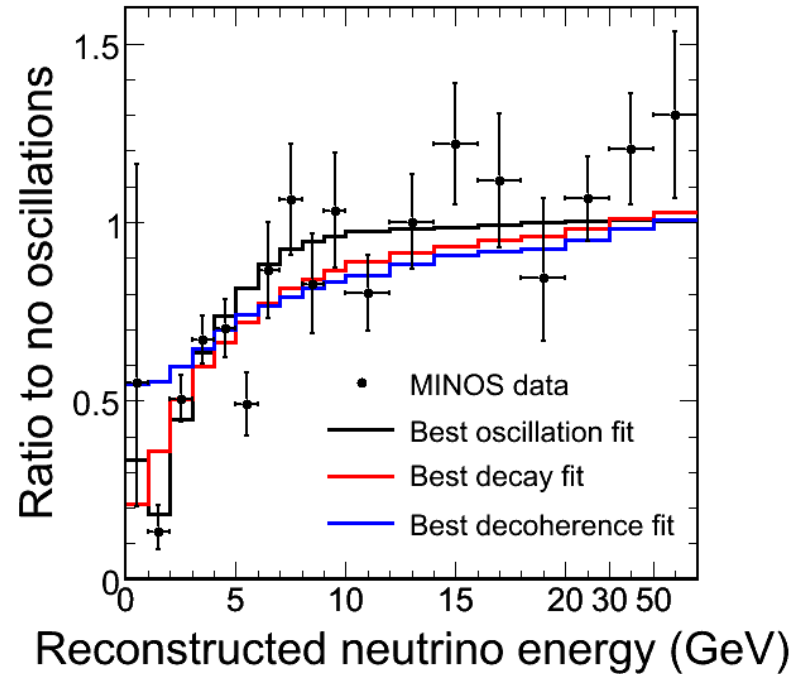
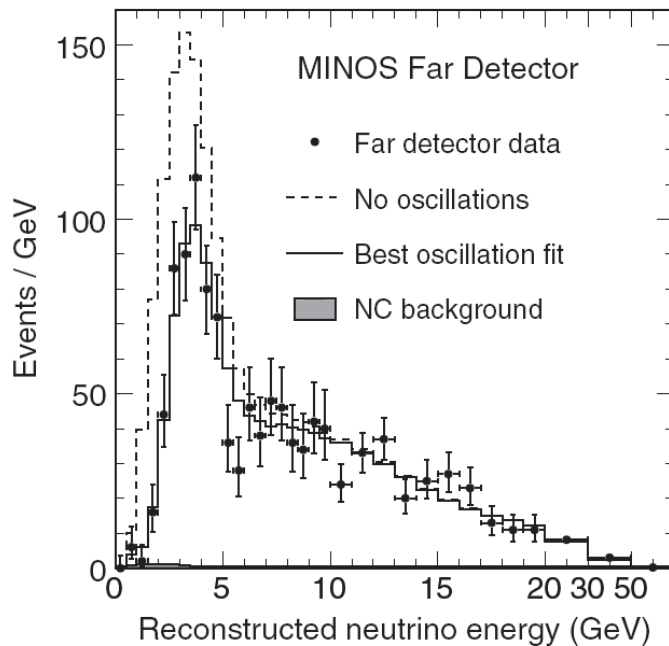
short event,
often diffuse

ν_e CC Event



short event,
typical EM shower
profile

MINOS Results: Fit to Oscillation Hypothesis



$$|\Delta m_{32}^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2 \quad (68\% \text{CL})$$

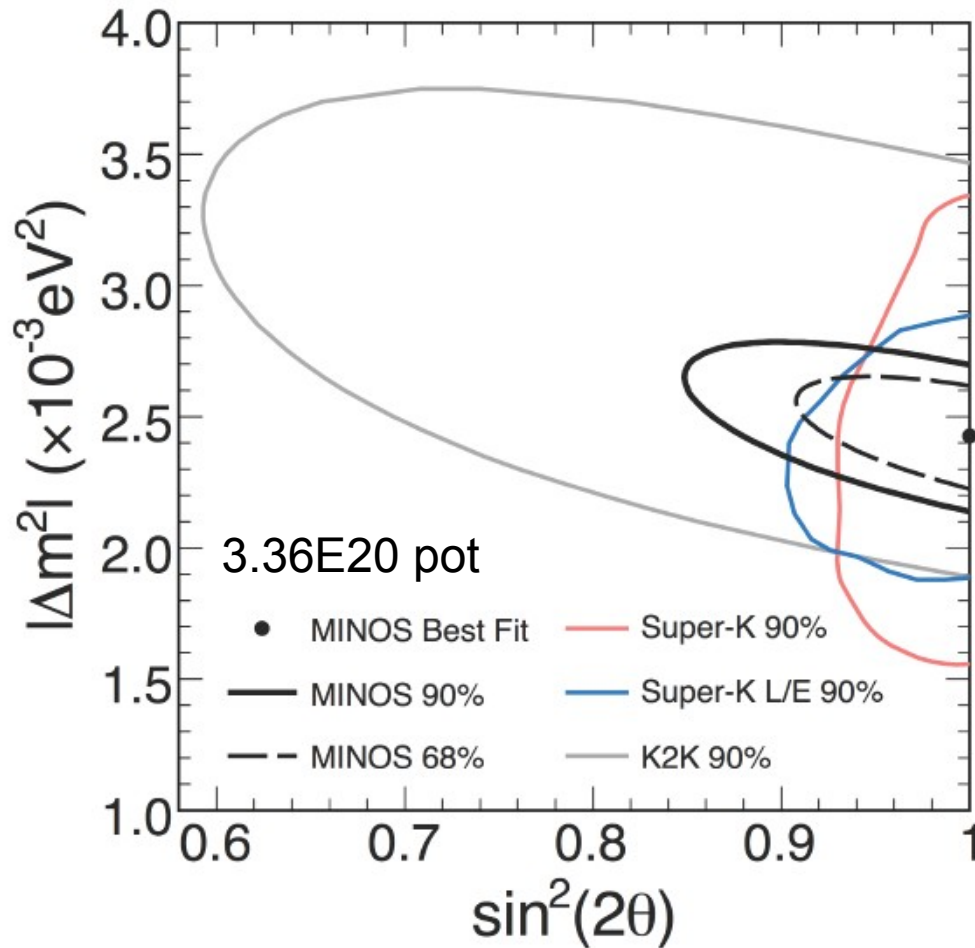
$$\sin^2 2\theta_{23} > 0.90 \quad (90\% \text{CL})$$

(best fit)

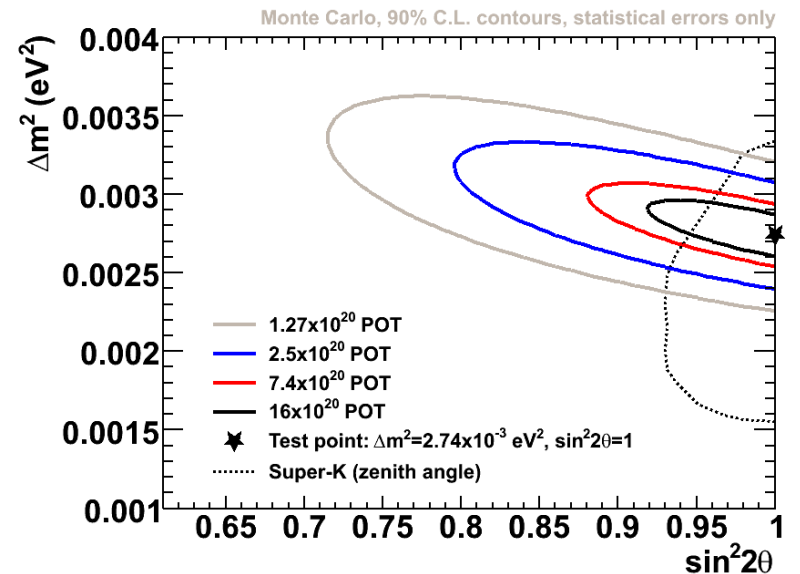
(for $3.36 \sum 10^{20} \text{pot}$)

„Measurement of Neutrino Oscillations with the MINOS Detectors in the NuMI Beam“
 MINOS Coll., Phys. Rev. Lett. 101, 131802 (2008)

MINOS: Allowed Regions (new)



MINOS Sensitivity as a function of Integrated POT





MINOS: search for ν_e appearance

Why? This is one possibility to measure θ_{13} and δ_{CP} :

The Oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ is approximately given by:

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A} - 1)^2} \sin^2((\hat{A} - 1)\Delta) \\
 & + \alpha \frac{\sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) \\
 & + \alpha \frac{\cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}}{\hat{A}(1 - \hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) \\
 & + \alpha^2 \frac{\cos^2 \theta_{23} \sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)
 \end{aligned}$$

with:

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2 \ll 1$$

$$\Delta = \Delta m_{31}^2 L / 4E$$

matter dependent quantities :

$$\hat{A} = 2VE / \Delta m_{31}^2$$

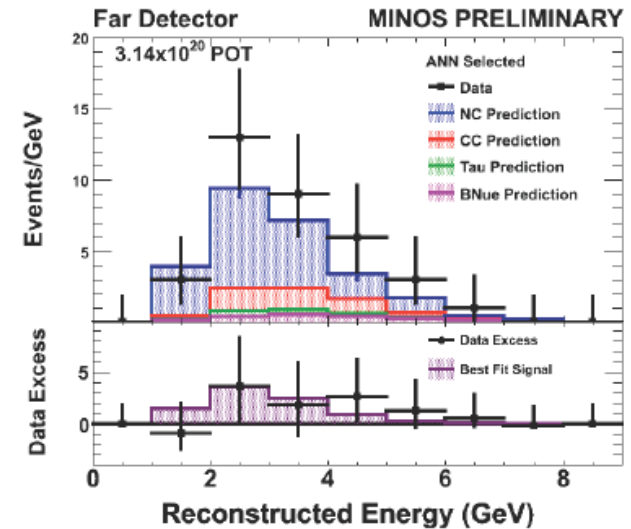
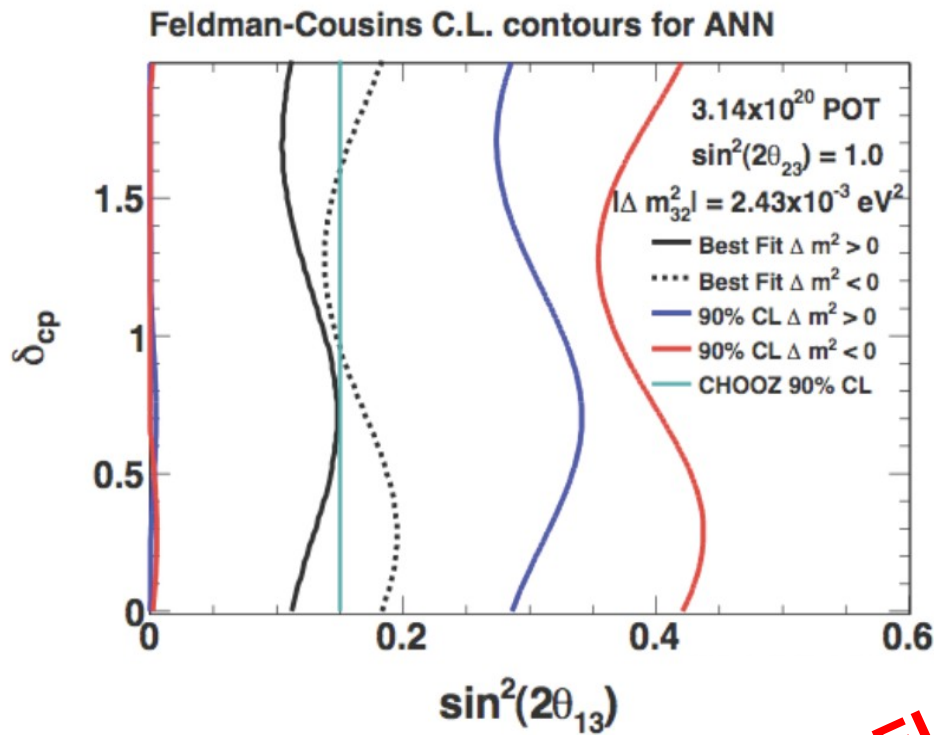
$$V = \sqrt{2}G_F n_e, \text{ with electron density } n_e \text{ (assumed constant)}$$



NEW! MINOS: ν_e appearance

35 events found in signal region, expected background: $27 \pm 5(\text{stat}) \pm 2(\text{syst})$

$\sin^2 2\theta_{13} < 0.29$ (90% CL) for $\delta_{CP} = 0$ and normal hierarchy



PRELIMINARY

From „Recent Results from the MINOS experiment“, M. Diwan @ Neutrino Telescopes Venice March 2009, arXiv:0904.3706

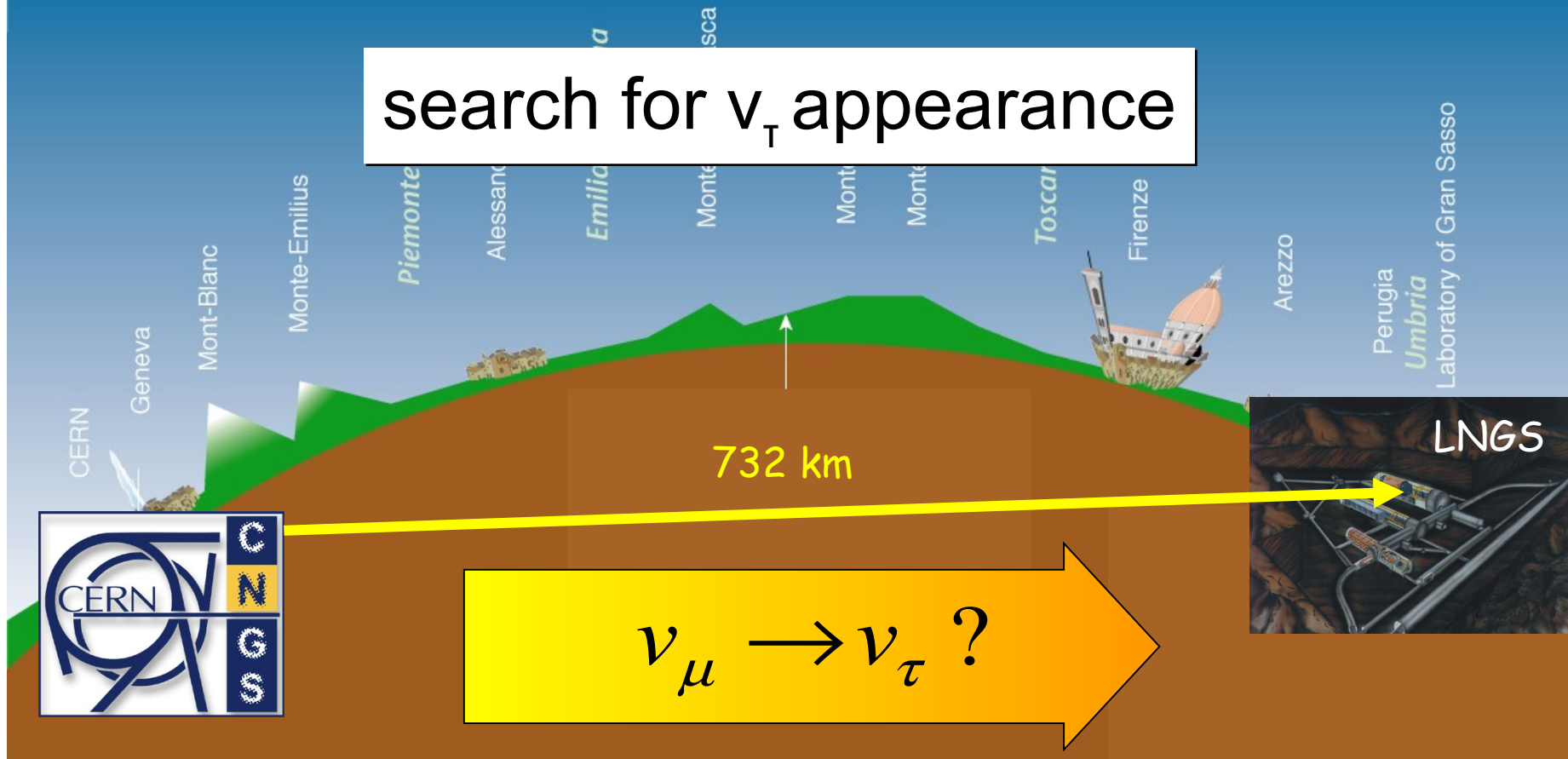


OPERA:

Oscillation Project with Emulsion tRacking Apparatus

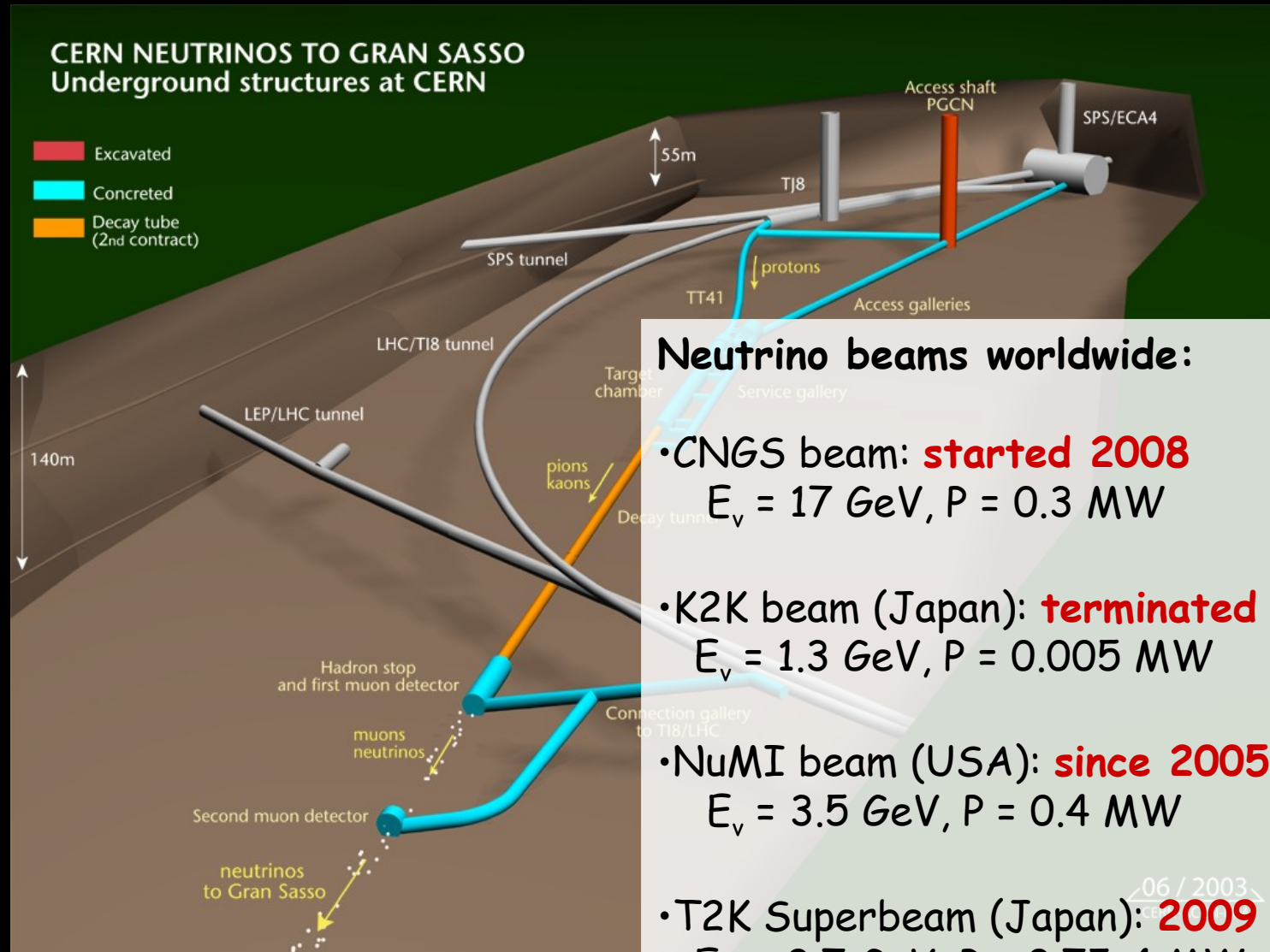
Neutrino beam (ν_μ) from CERN to Gran Sasso Underground Lab (Italy)

search for ν_τ appearance



first physics run: june-november 2008; run 2009: ongoing

CNGS Neutrino Beam



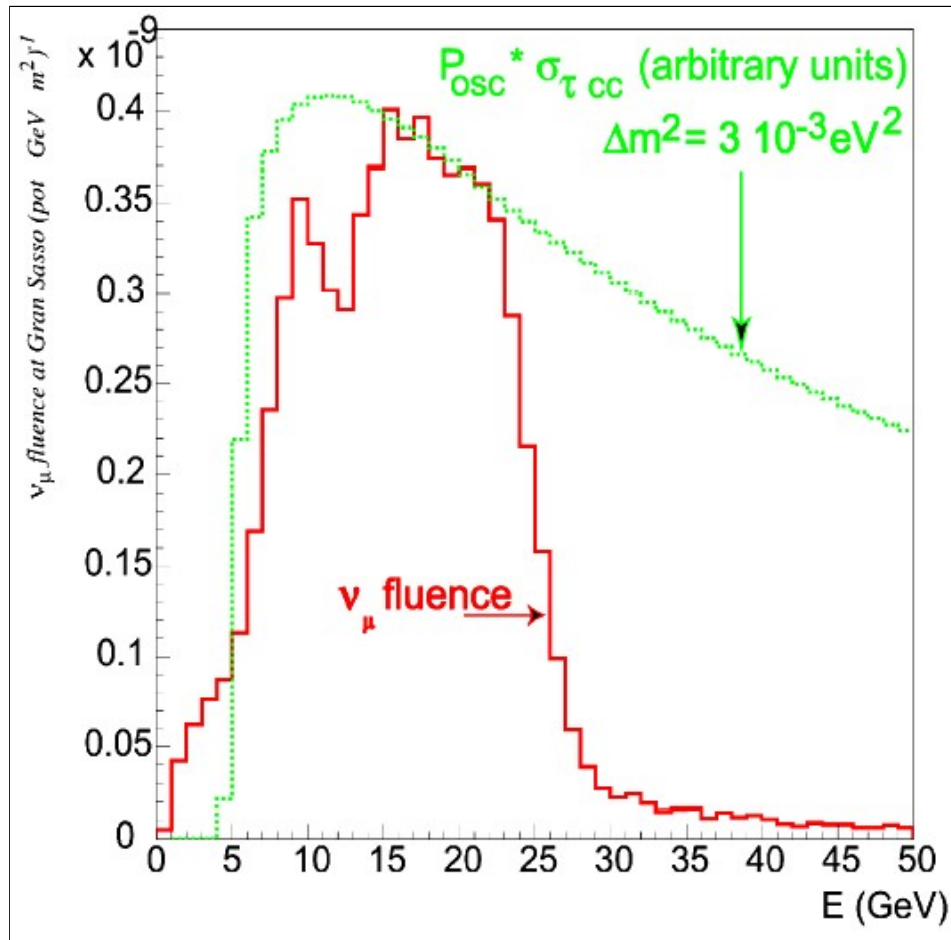
Neutrino beams worldwide:

- CNGS beam: **started 2008**
 $E_\nu = 17 \text{ GeV}$, $P = 0.3 \text{ MW}$
- K2K beam (Japan): **terminated**
 $E_\nu = 1.3 \text{ GeV}$, $P = 0.005 \text{ MW}$
- NuMI beam (USA): **since 2005**
 $E_\nu = 3.5 \text{ GeV}$, $P = 0.4 \text{ MW}$
- T2K Superbeam (Japan): **2009**
 $E_\nu = 0.7 \text{ GeV}$, $P = 0.75\text{-}4 \text{ MW}$

06 / 2003
CERN



CNGS beam ("pure" ν_μ)

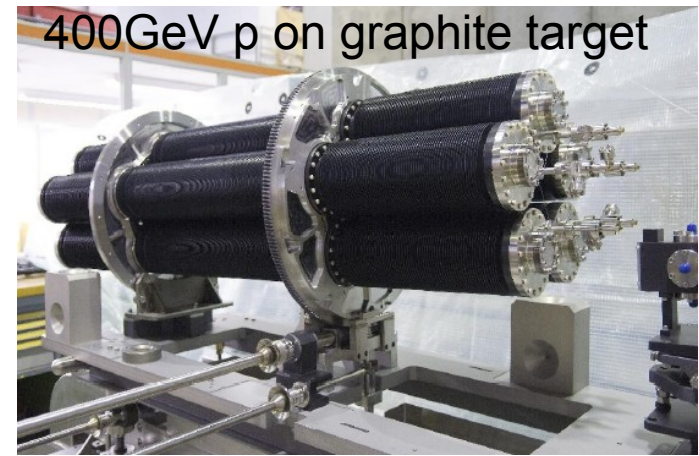


Total exposure expected: $22.5 \cdot 10^{19}$ pot

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

$$\bar{\nu}_\mu / \nu_\mu = 4\%$$

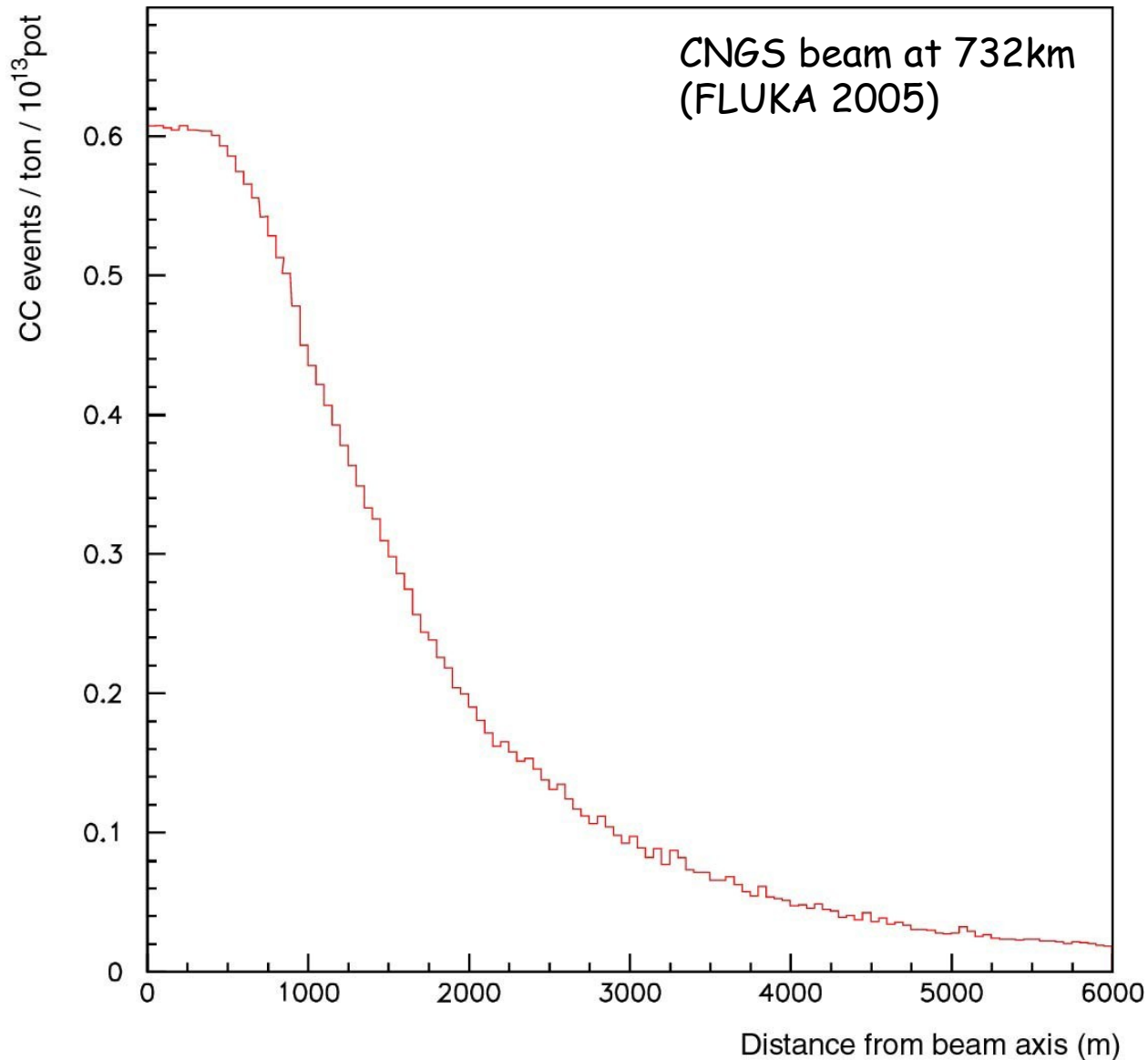
$$(\bar{\nu}_e + \nu_e) / \nu_\mu = 0.87\%$$



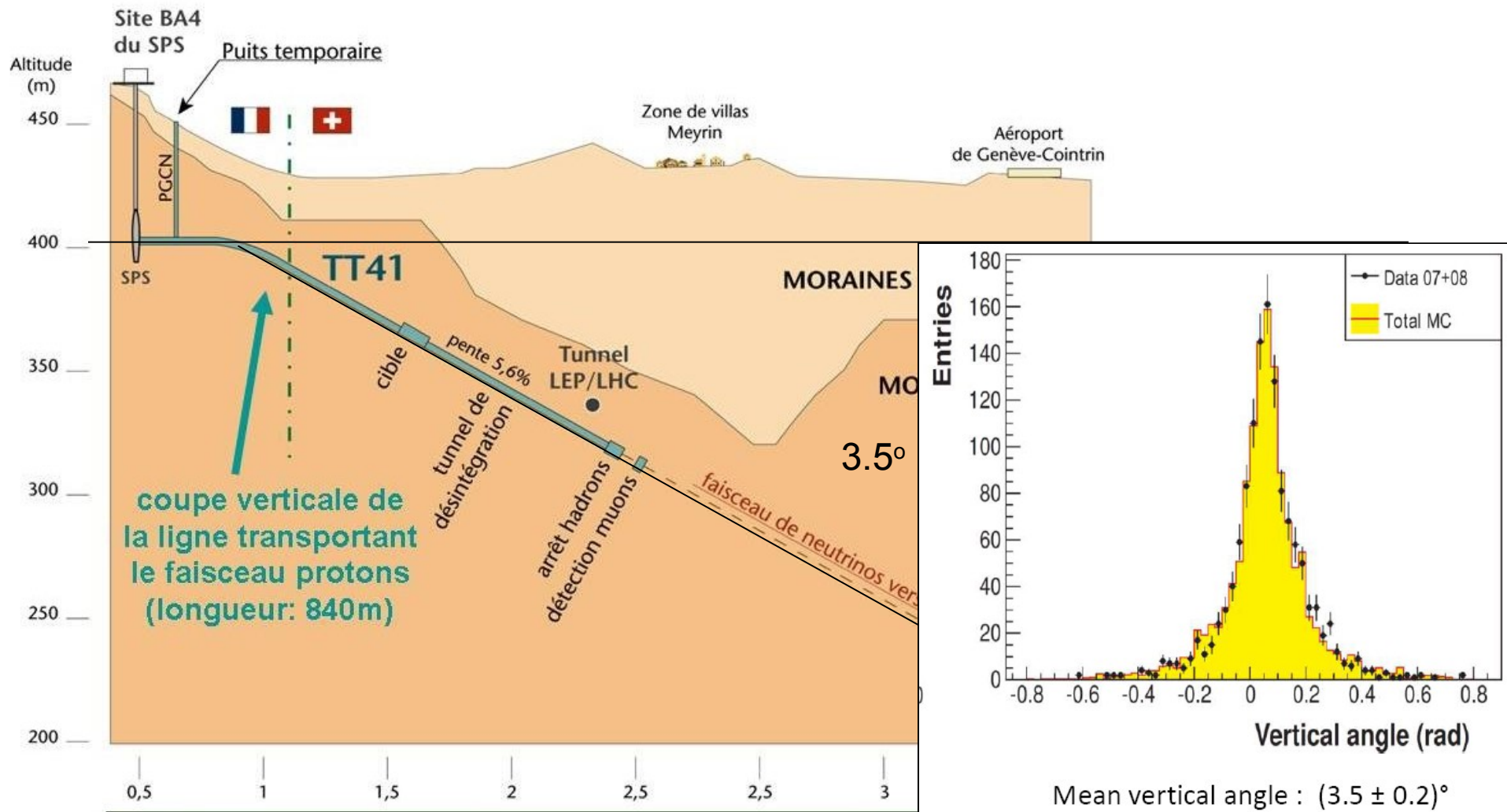
$4.5 \cdot 10^{19}$ pot/year



Profile of neutrino beam @ LNGS

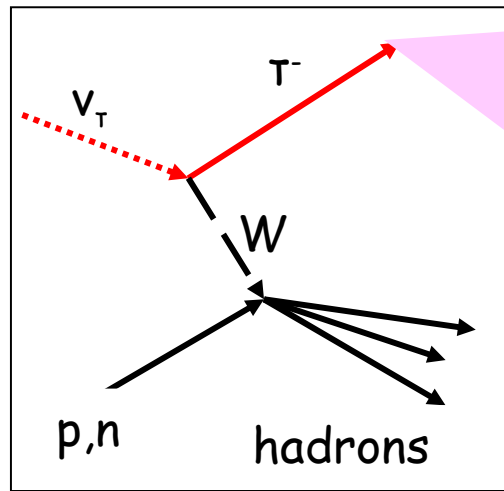


Direction of CNGS neutrino beam





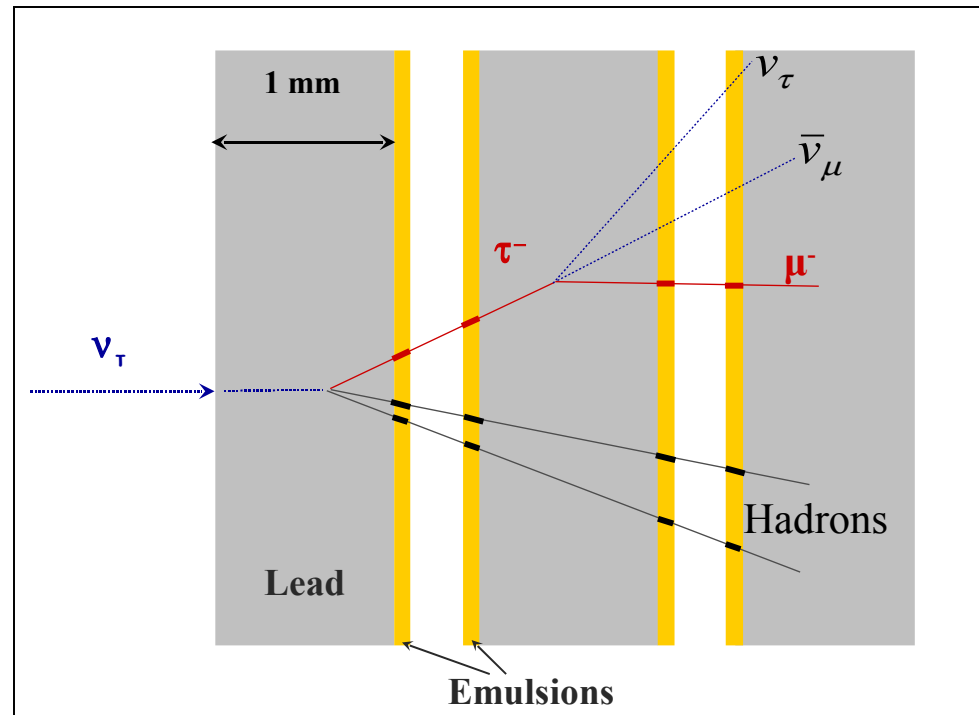
OPERA: ν_τ detection



τ -decay:

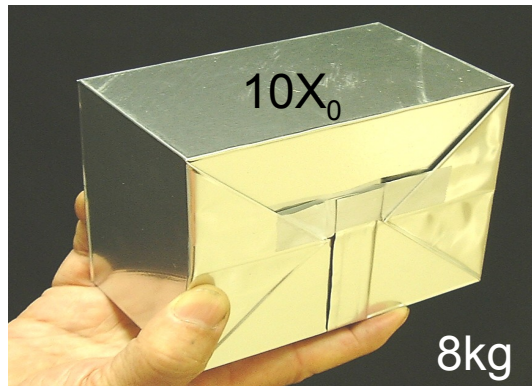
$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$	17.4%	} kink
$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$	17.8%	
$\tau^- \rightarrow \text{hadron} + \nu_\tau$	49.5%	
$\tau^- \rightarrow \pi^- \pi^- \pi^+ (n\pi^0) + \nu_\tau$	15.2%	trident

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



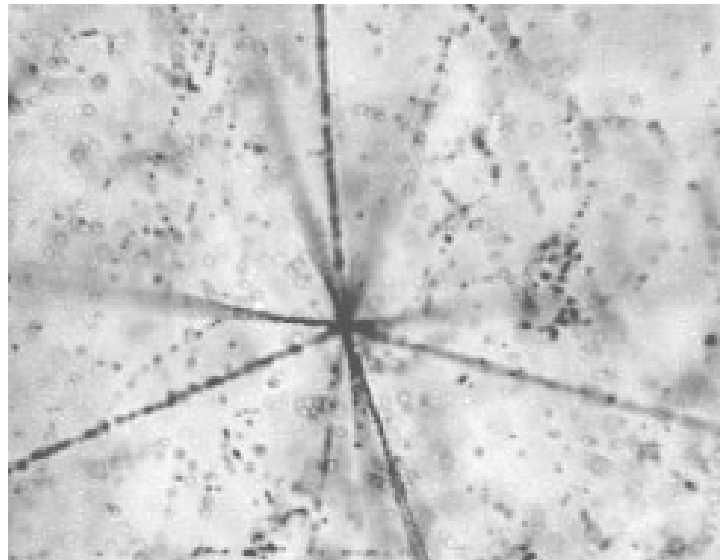
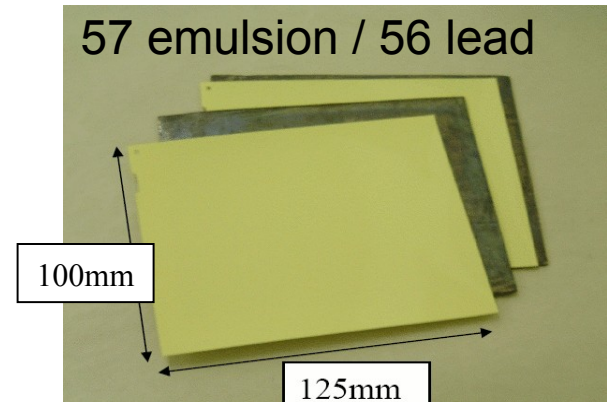
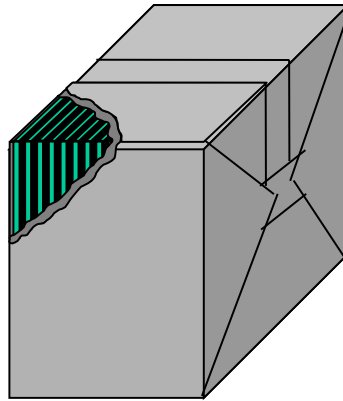


OPERA target: lead-emulsion-bricks



lead-emulsion-brick
(total ≈ 150000)

target mass:
 ≈ 1.2 kton

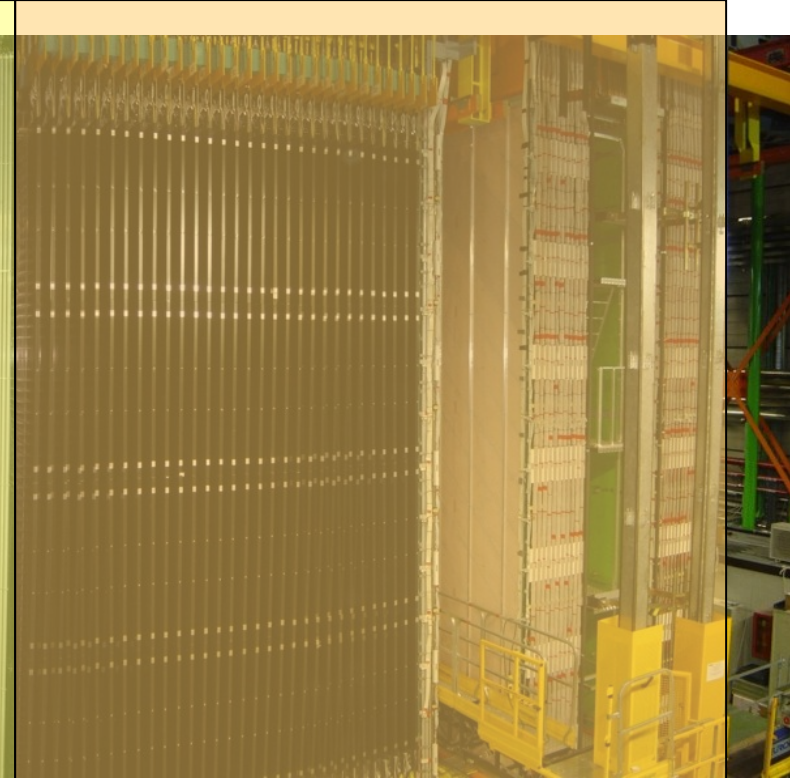




OPERA - Detector



Supermodule 1

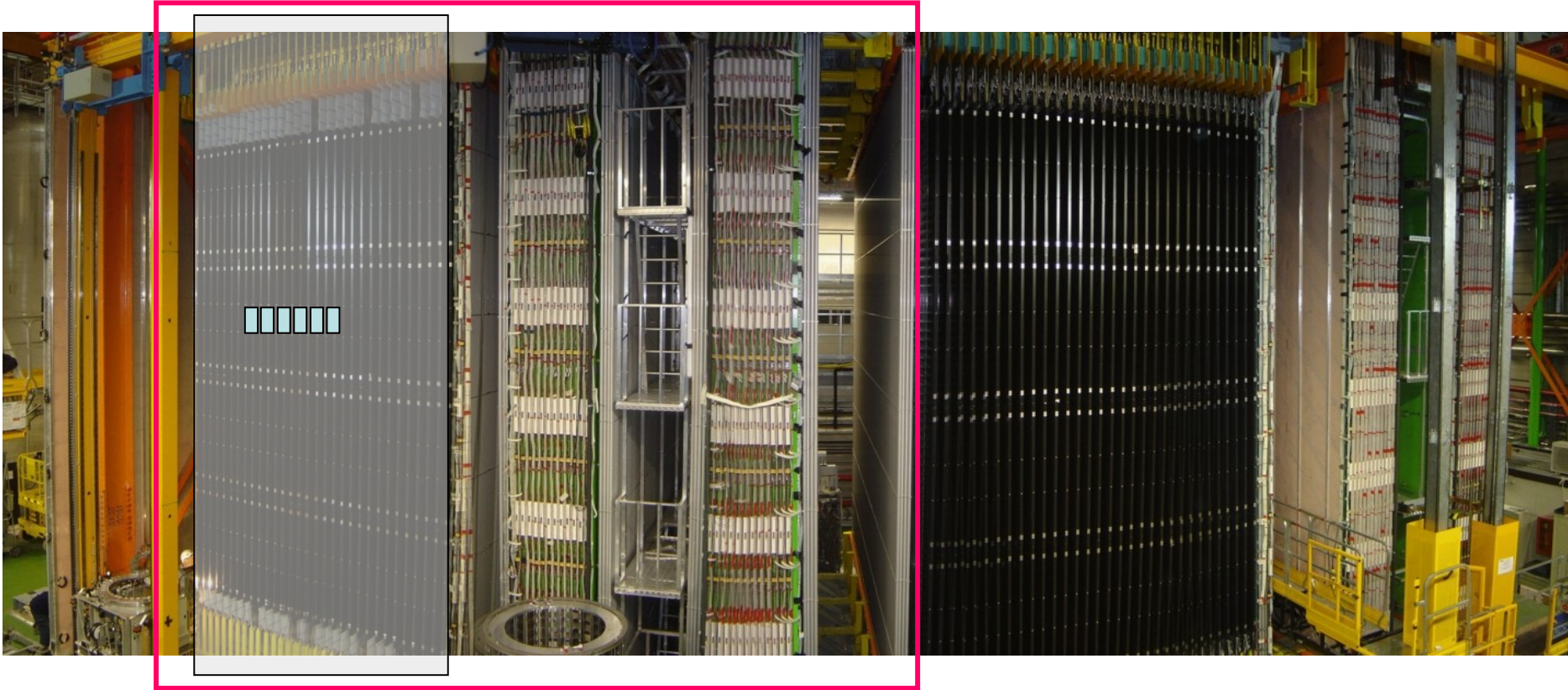


Supermodule 2



OPERA - Detector

Supermodule 1



Target Region:

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

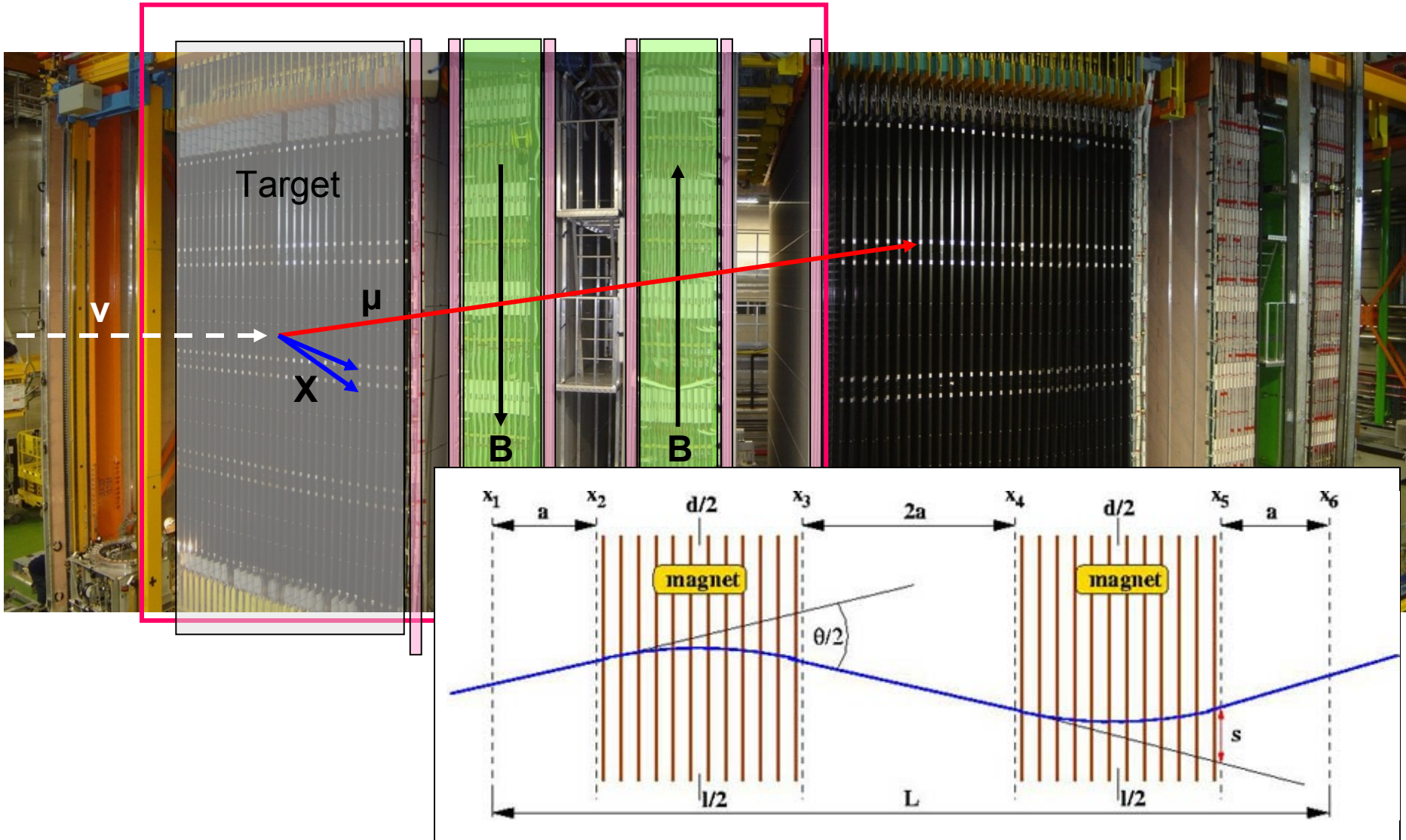
The OPERA Target (1 Supermodule)





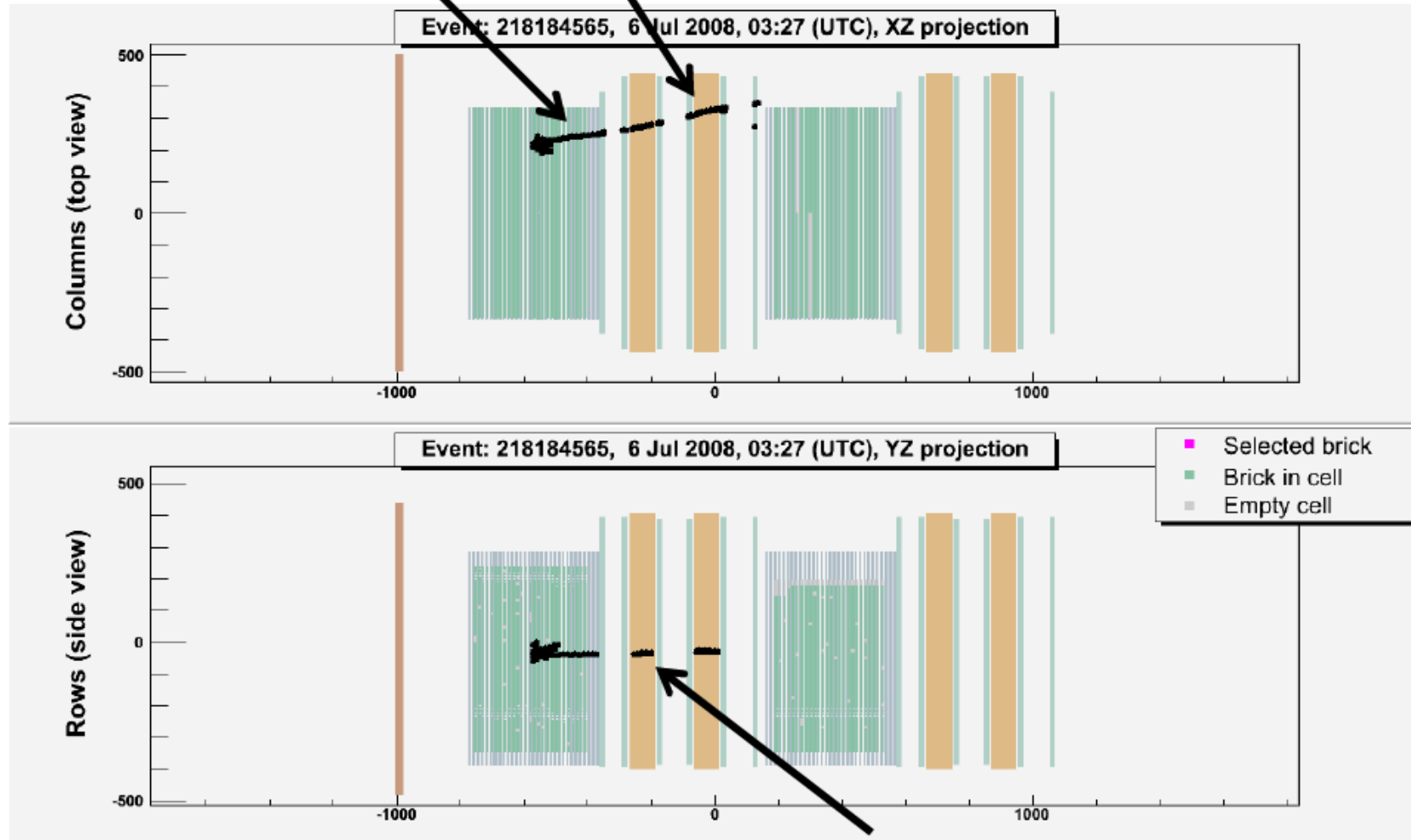
OPERA - Detector

Supermodule 1



Reconstruction (I): Myon-Spectrometer

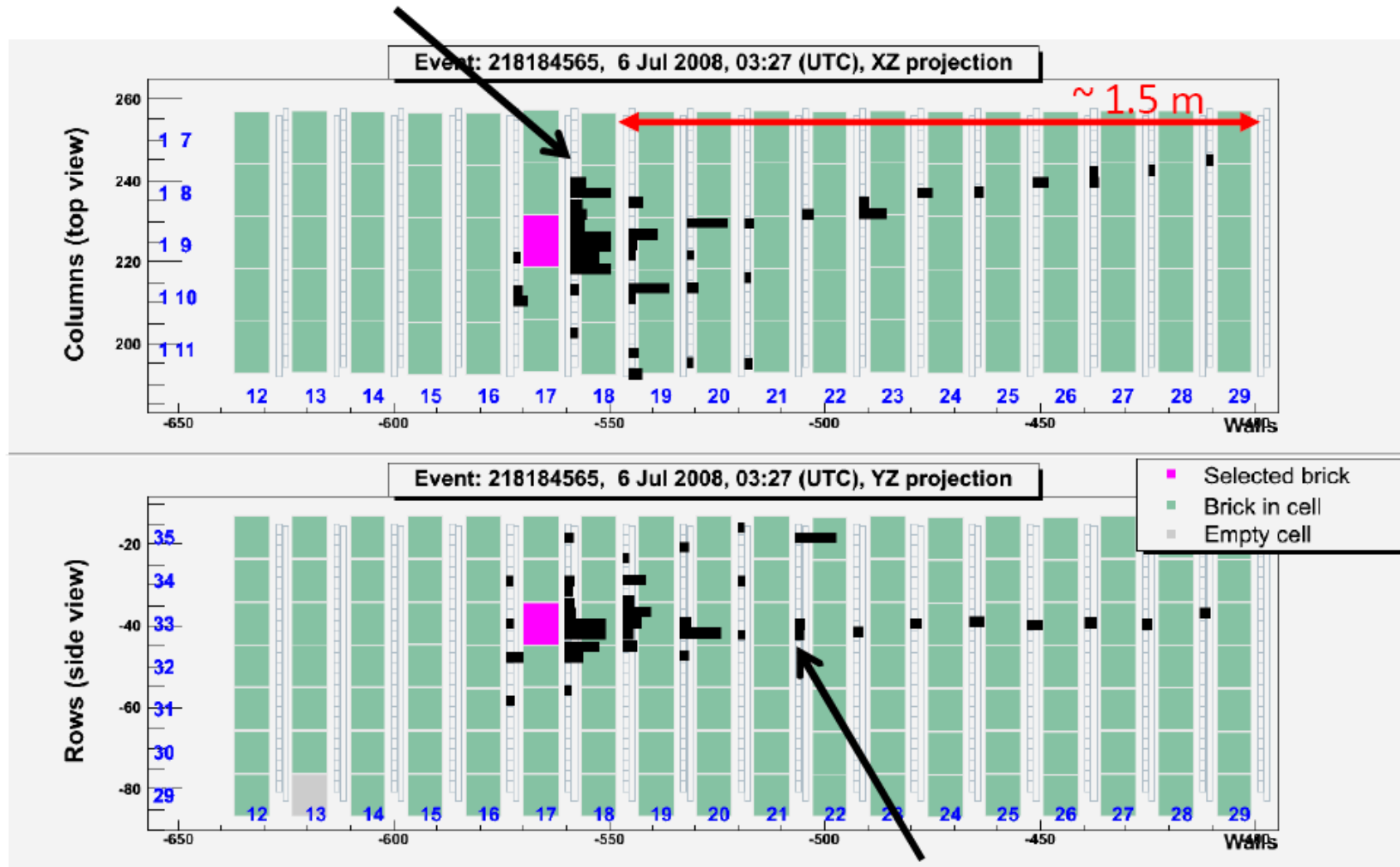
Electronic data (Target Tracker & Muon spectrometer)



Track identified as a muon ($P=3.394 \text{ GeV}/c$)

Rekonstruktion (II): Brick Finding

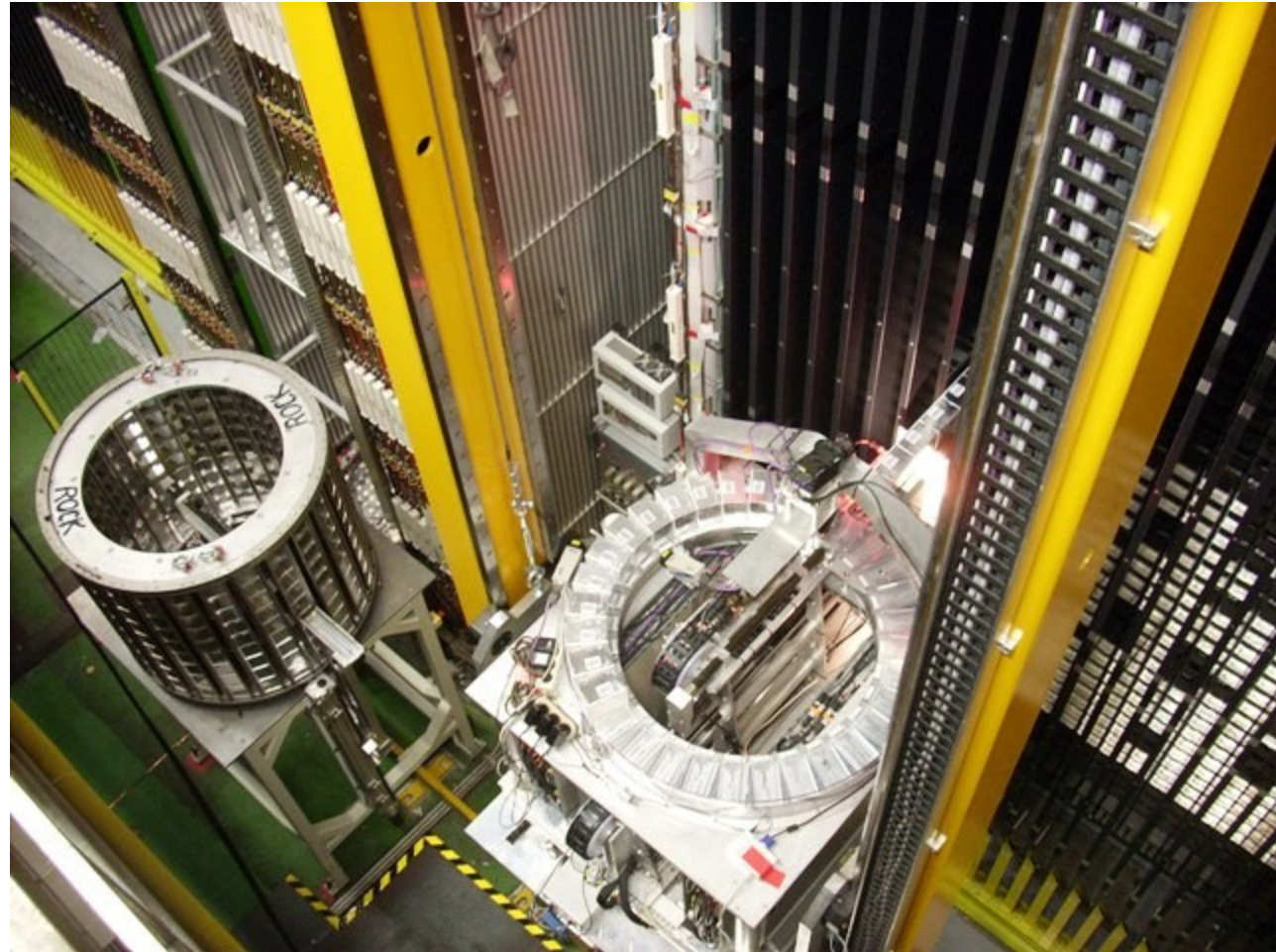
Electronic data (Target Tracker & Muon spectrometer)



Track identified as a muon ($P=3.394 \text{ GeV}/c$)



OPERA – Brick Manipulating System



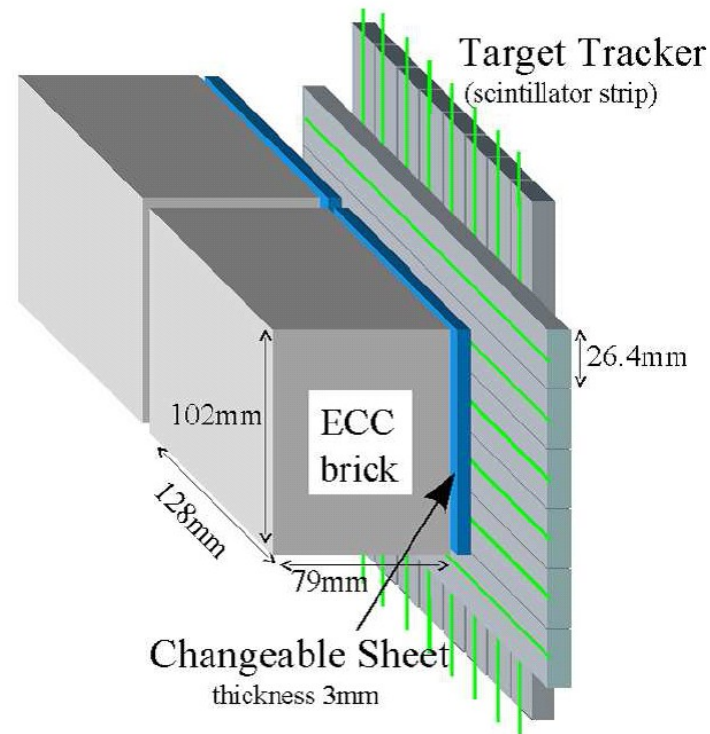
≈30 bricks/day are extracted



OPERA – Changeable Sheet (CS) Method

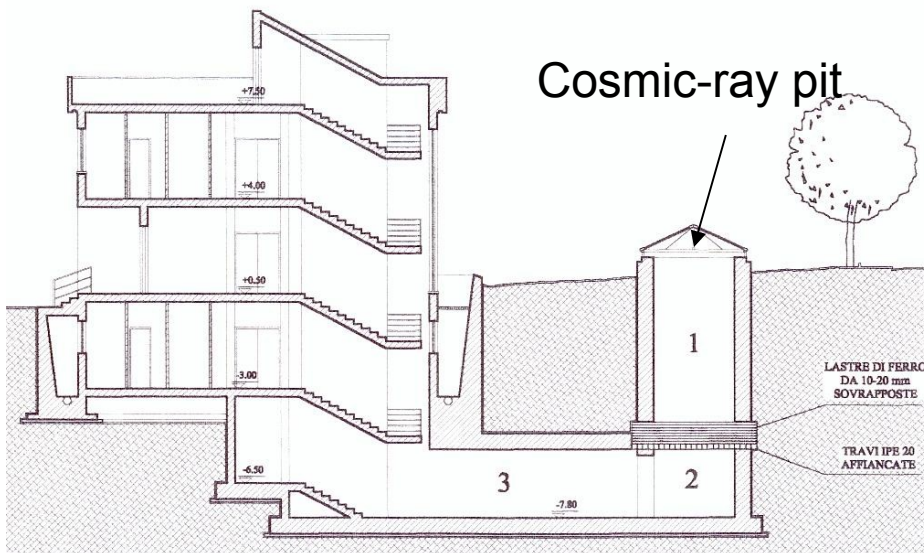
After extraction:

- 1.) First X-ray exposure of brick with CS
- 2.) CS is detached and developed underground
brick is kept in shielding box (5cm iron)
- 3.) If track in CS is compatible with track reconstructed by electronic detectors:
Second X-ray exposure of brick,
brick brought to surface



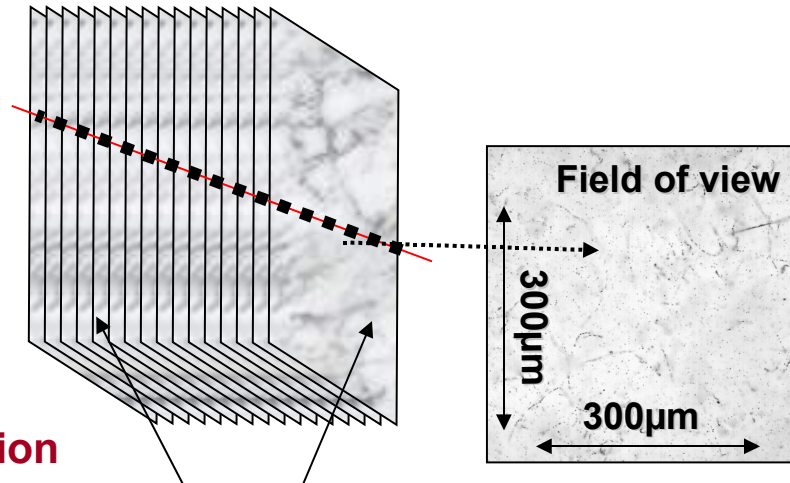
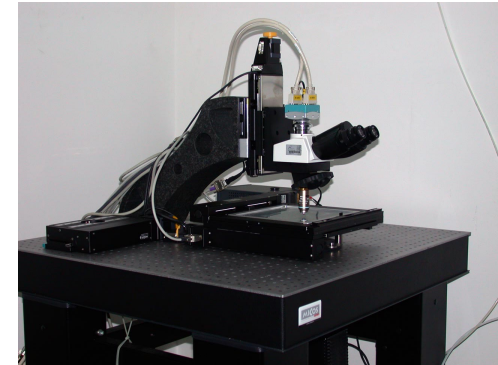
Emulsion Development @ LNGS

- Bricks brought to “cosmic ray pit” (@ surface), exposure 24h.
- Local alignment with cosmic myons (afterwards precision of 1-2 μ m).
- bricks are developed in 5 (6) automatic development lanes.
- 50 bricks/day can be developed (16h).



Scanning

≈40 automatic microscopes
in scanning labs in Europe(ESS) and Japan(S-UTS)



16 tomographic
images

2D image
processing

**3D reconstruction of
particle tracks**

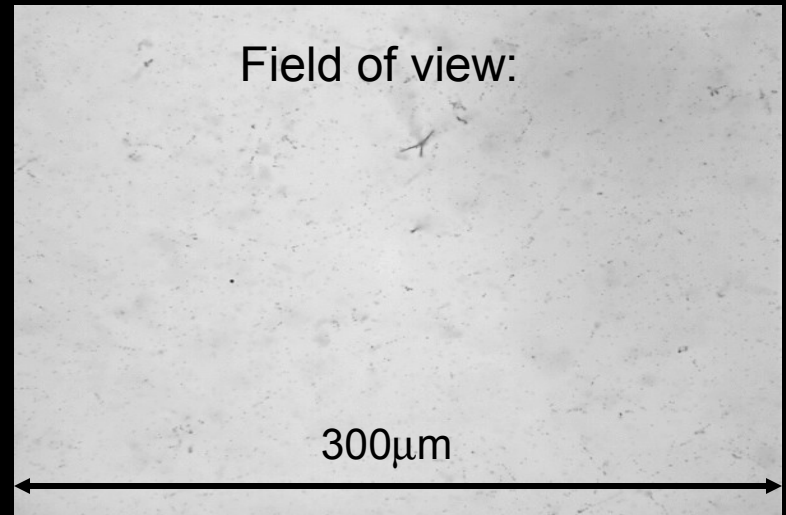
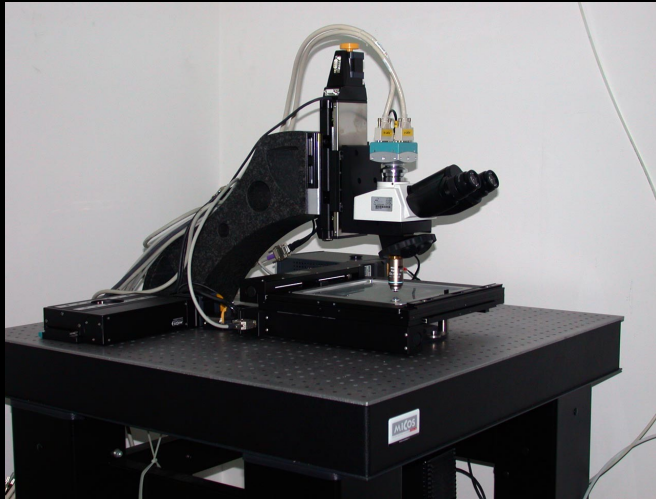
**2 emulsion
sides
(44 µm)**

**1 plastic base
(200 µm)**

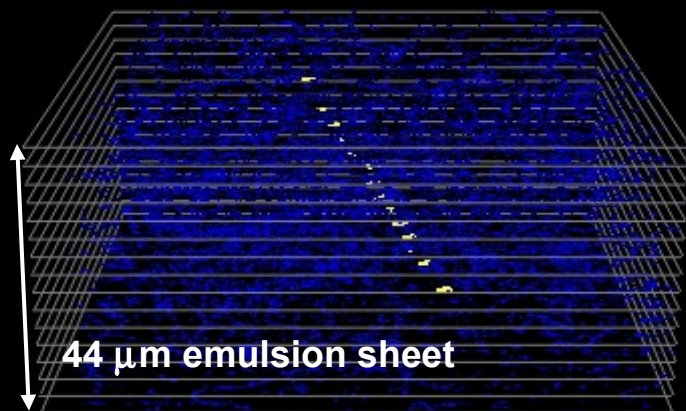
speed : 20cm²/hour/emulsion side

(1 emulsion sheet = 2 sides)

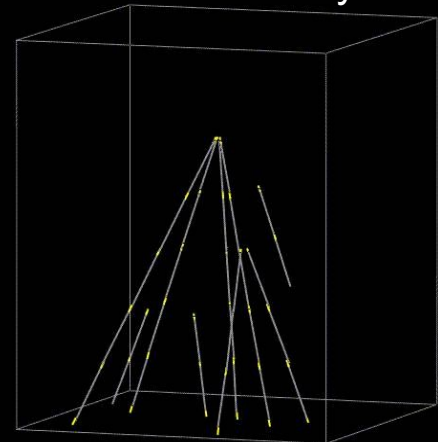
Scanning



2d image: 16 tomographic images



Vertex reconstruction & kinematical analysis



Expected Signal

Maximal mixing, run time of 5 years @ 4.5×10^{19} pot / year

channel	Reconstruction efficiency x BR %	Signal $\Delta m_{23}^2 = 2.5 \text{ eV}^2$	Signal $\Delta m_{23}^2 = 3.0 \text{ eV}^2$	Back- ground
Total	11.06	10.4	14.9	0.75

for OPERA with 1.35kt (75% of proposal)

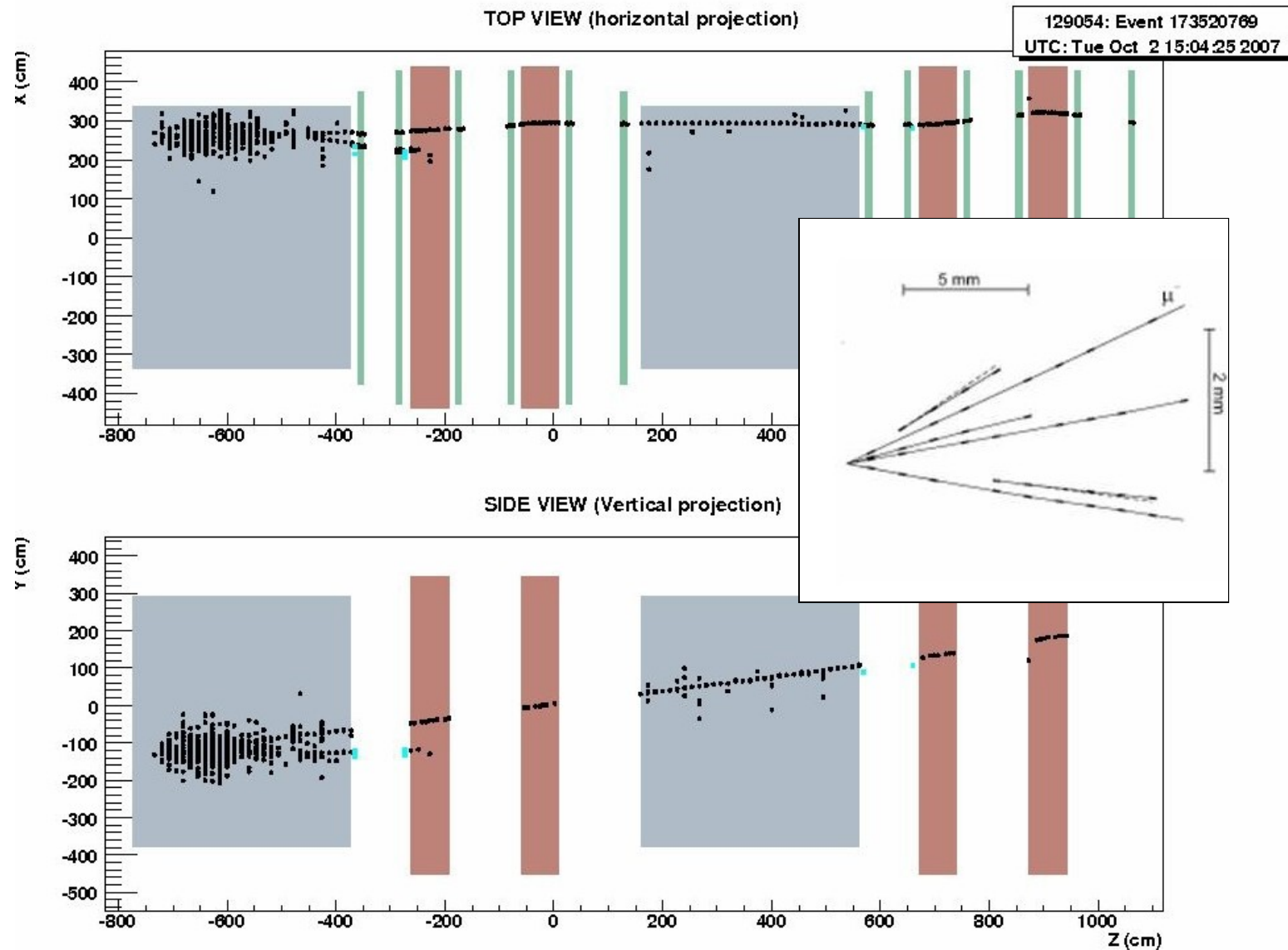
Most important background processes:

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

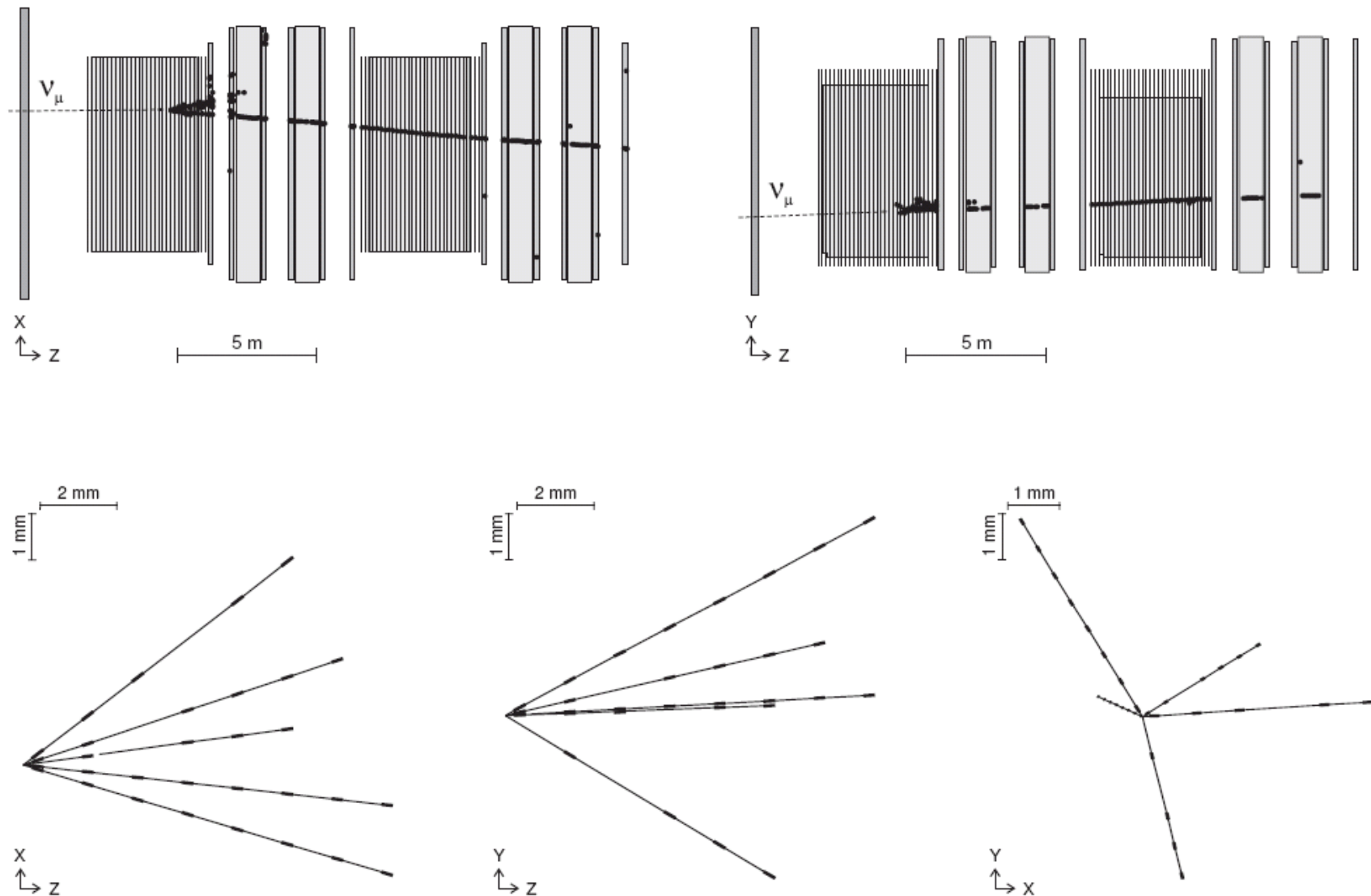
Overview expected events:

25000 ν interactions
120 ν_τ interactions
~10 identified ν_τ
<1 background

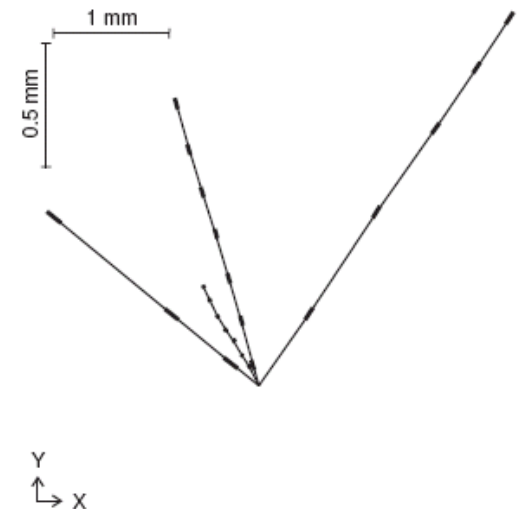
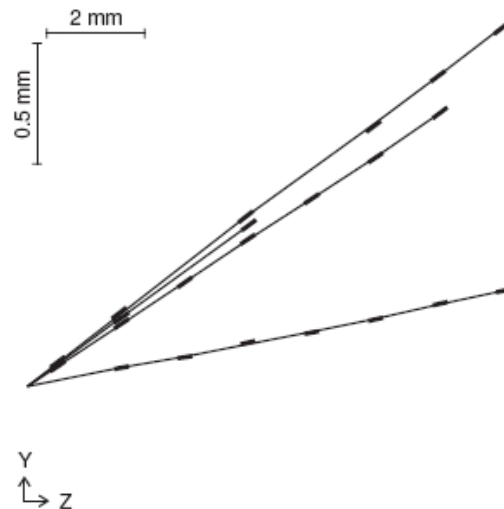
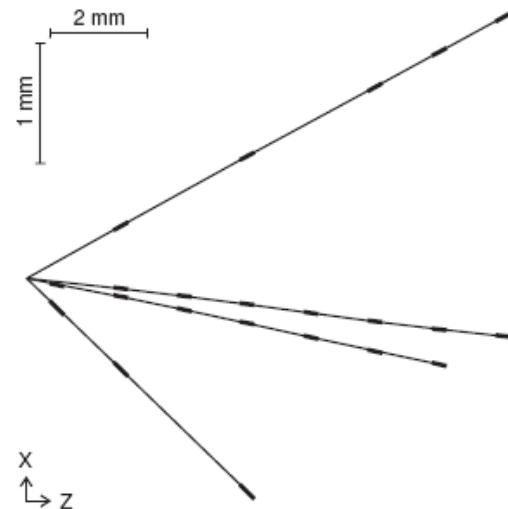
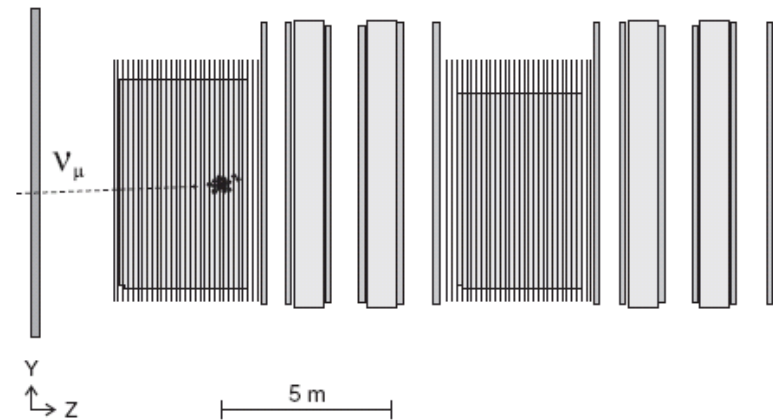
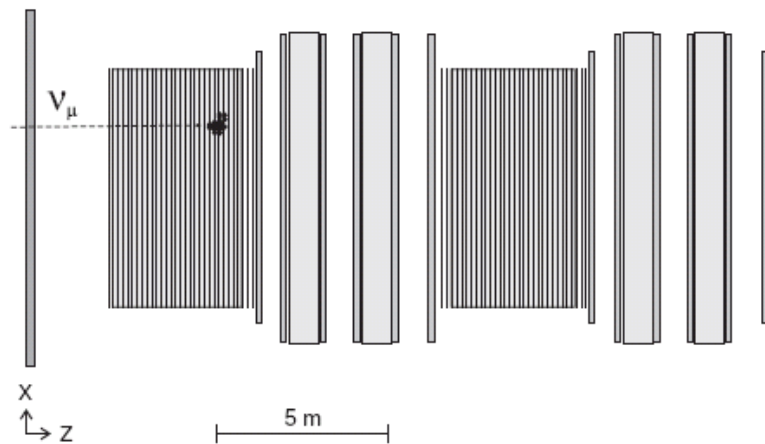
October 2007: first OPERA-event in a brick observed



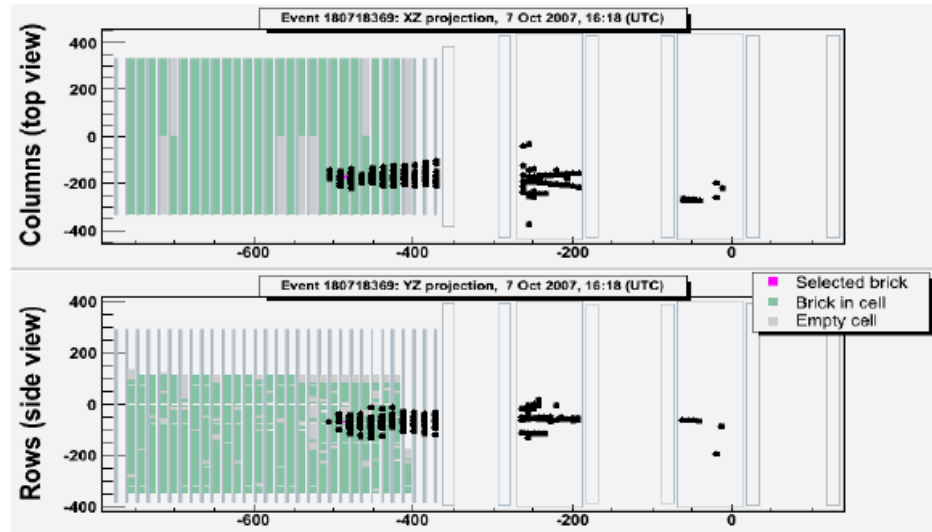
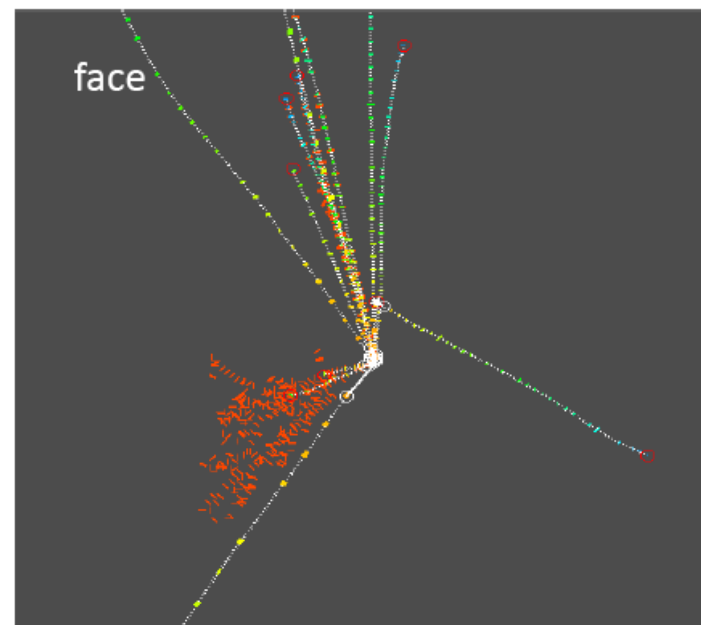
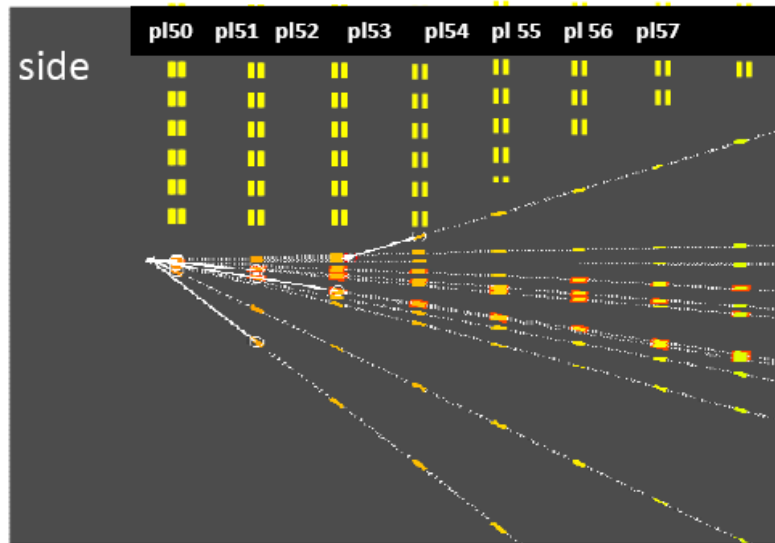
Example of real CC event:



Example of real NC event:



A Charm-Candidate



Clear kink topology

Two EM showers pointing to the vertex

Flight length	3247.2 μm
θ_{kink}	0.204 rad
P_{daughter}	3.9 (+1.7 -0.9) GeV
P_{T}	796 MeV

4×10^{-4} % probability for a hadron re-interaction to have a $P_{\text{T}} > 600$ MeV

7



OPERA summary:

- Detector (target) has been completed by July 2008
- First OPERA beam period june - november 2008:
exposure: 1.8^{E19} pot, 1700 bricks with events extracted.
Brick analysis is ongoing (≈ 450 vertices found by march09).
First candidates for charm have been identified.

OPERA collaboration: arXiv:0903.2973v1, accepted for publication in JINST.
„The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment“.

- Beam period 2009 ongoing since June 2009:
 2.2^{E19} pot collected up to now in 2009.
outlook: 3.5^{E19} pot from CNGS -> 3500 events in bricks expected,
-> we may expect 2 ν_{τ} candidates in 2009...

OPERA is awaiting the first ν_{τ} - candidate