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

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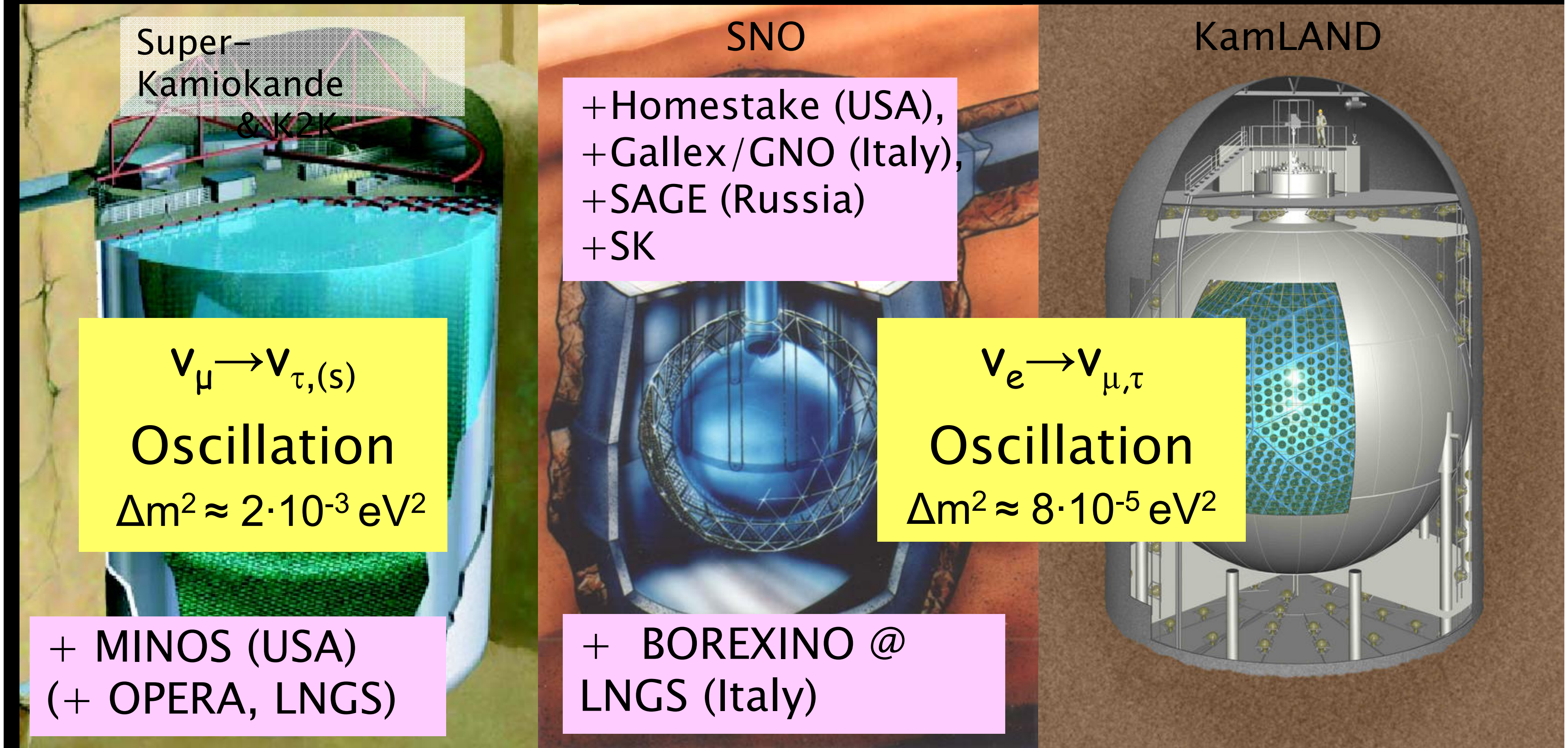
- Introduction: neutrino mass and mixing
- Neutrino Oscillation (I): mu – tau mixing
  - atmospheric neutrinos
  - present neutrino beam experiments:
    - MINOS (NuMi beam: Fermilab – Soudan Mine)
    - OPERA (CNGS beam: Cern – LNGS)
- Neutrino Oscillation (II): e – mu mixing
  - solar neutrino experiments
    - short review on past experiments (SNO)
    - Borexino
    - reactor experiment: KamLand
- Neutrino Oscillation (III): Future prospects (theta13 and CPV)
  - reactor experiments: Double Chooz and Daya Bay
  - off-axis (super)beams: T2K and NovA
  - (neutrinofactory 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 | CANADA | JAPAN



atmospheric neutrinos
accelerator neutrinos

solar neutrinos

reactor neutrinos

Quark-Mixing

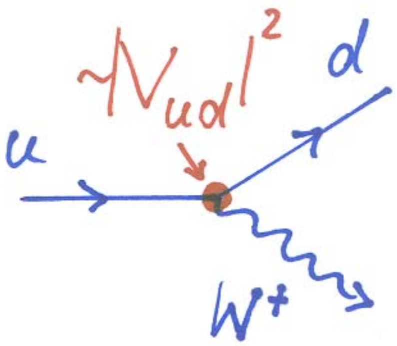
$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$

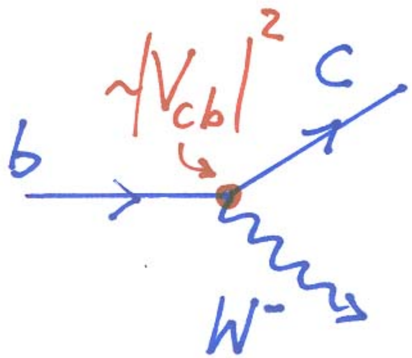
Cabbibo-Kobayashi-Maskawa (CKM) Matrix

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

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

BELLE,
BABAR,
CLEO,…
(BELLE2)





in precision measurement phase

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

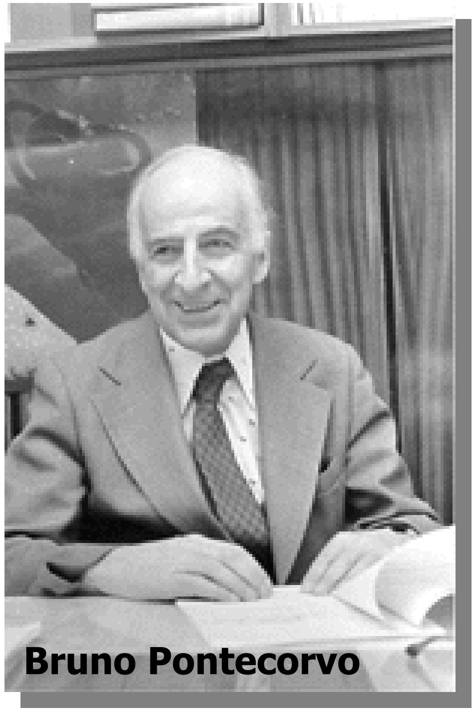
neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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 $\nu \leftrightarrow$ anti-ν)
  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).

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

- 1 Dirac-phase (CP violating): δ

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

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

Parametrisation of Neutrino Mixing (II)

But:
If neutrinos are Majorana particles two additional phases exist:
• 2 Majorana-Phases (CPV): α_1, α_2

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

Leptons vs Quarks

Neutrinos

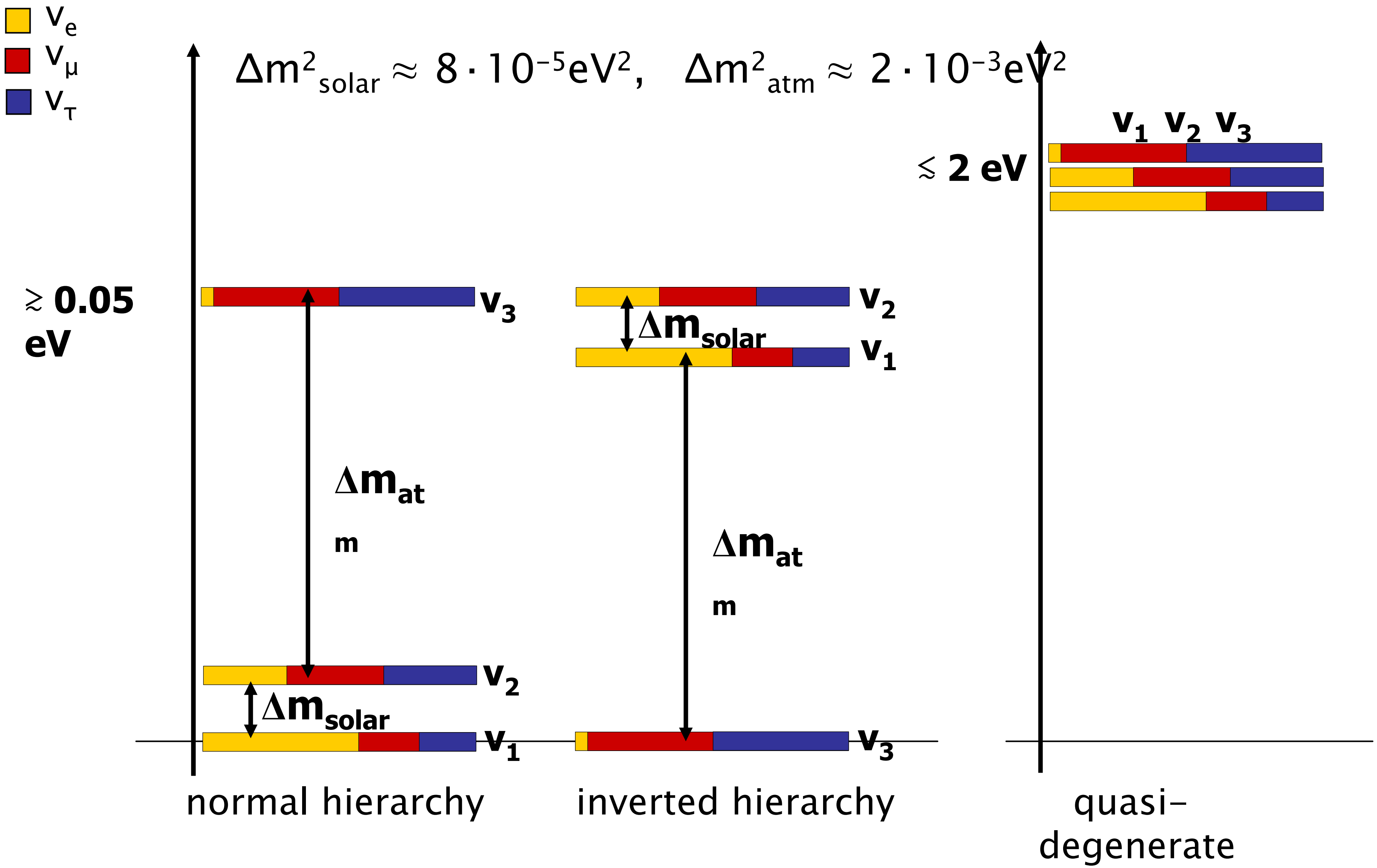
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

What do we know about neutrino masses?

$\Delta m^2_{solar} \approx 8 \cdot 10^{-5} eV^2, \quad \Delta m^2_{atm} \approx 2 \cdot 10^{-3} eV^2$



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

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

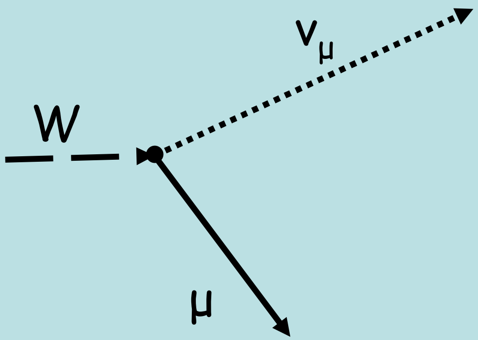
Neutrino Oscillations

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

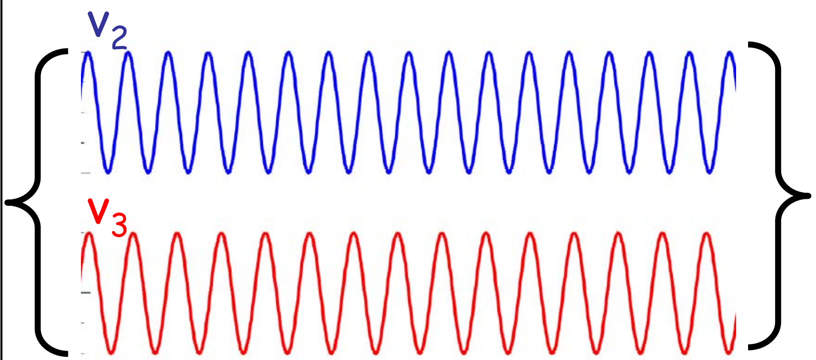
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2, ν_3
with m_2, m_3

source creates
flavor-eigenstates



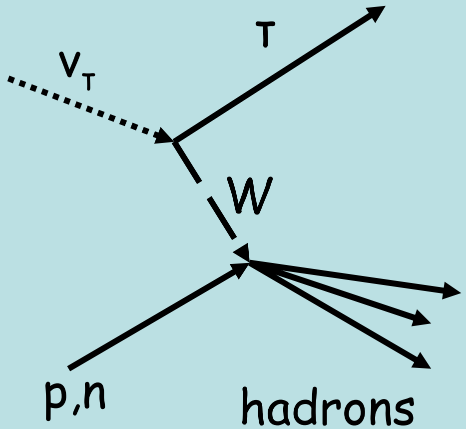
propagation determined by
mass-eigenstates



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

slightly different frequencies
→ phase difference changes

detector sees
flavor-eigenstates



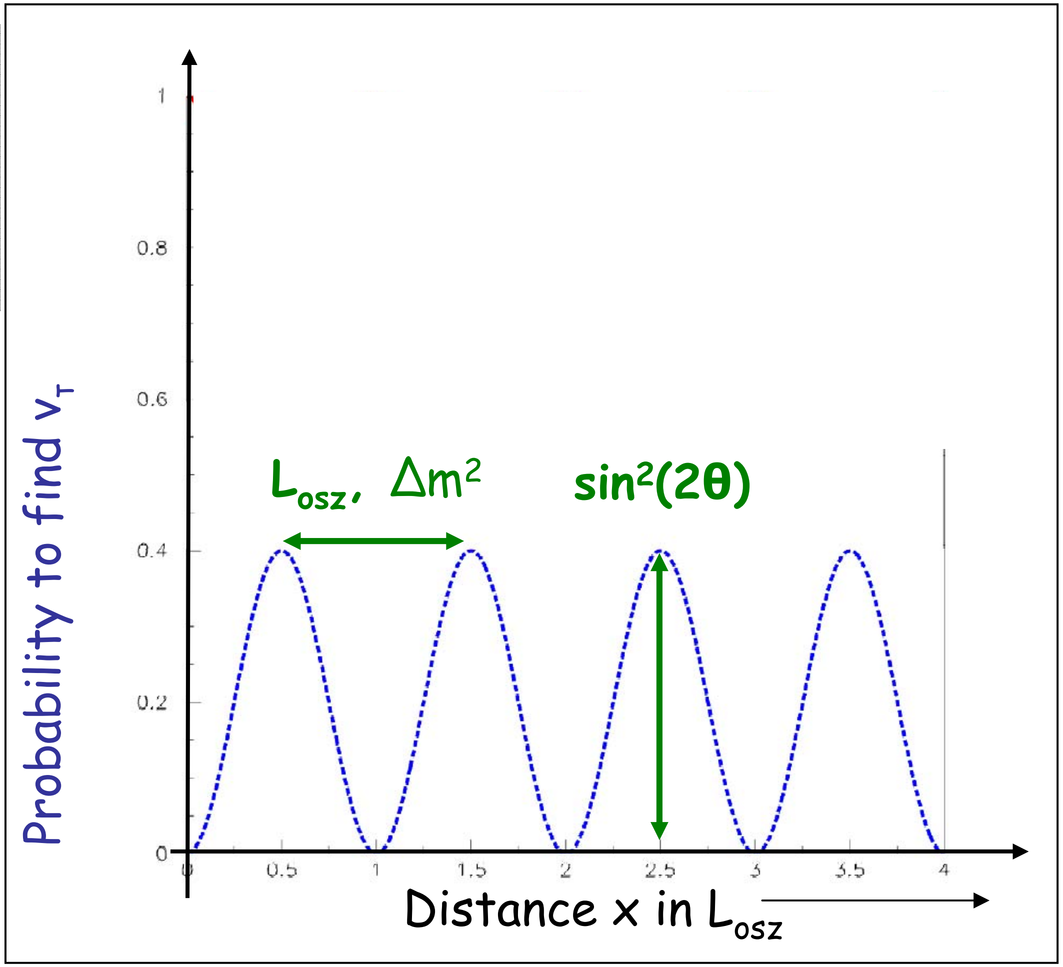
2 Flavor Neutrino Oscillations

<u>Oscillation probability</u>

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

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

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



General oscillation formula:

$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(1.27 \Delta m^2_{ij} \frac{L}{E}\right)$$

$$+ 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(2.54 \Delta m^2_{ij} \frac{L}{E}\right)$$

$\Delta m^2_{ij} \equiv m^2_i - m^2_j$ in eV^2

L in km

E in GeV

Neutrino Oscillations (23)

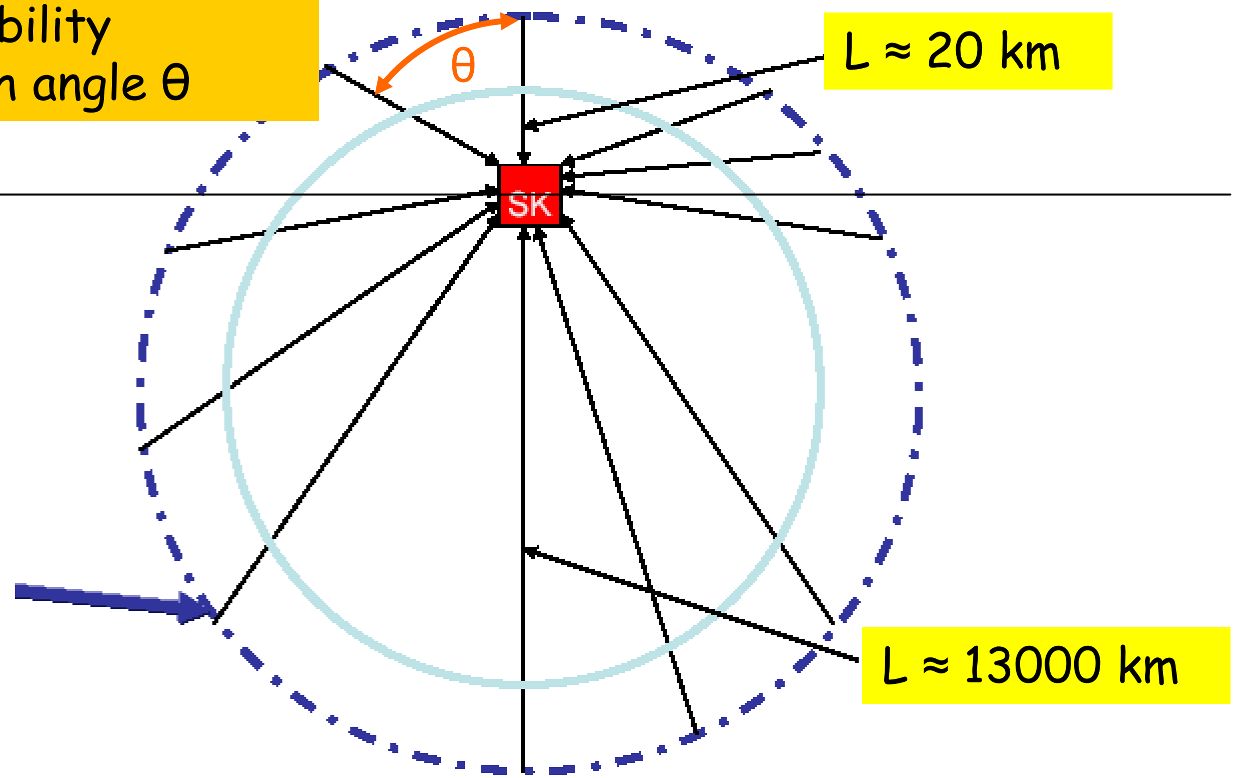
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}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

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

Atmospheric neutrinos & accelerator neutrinos

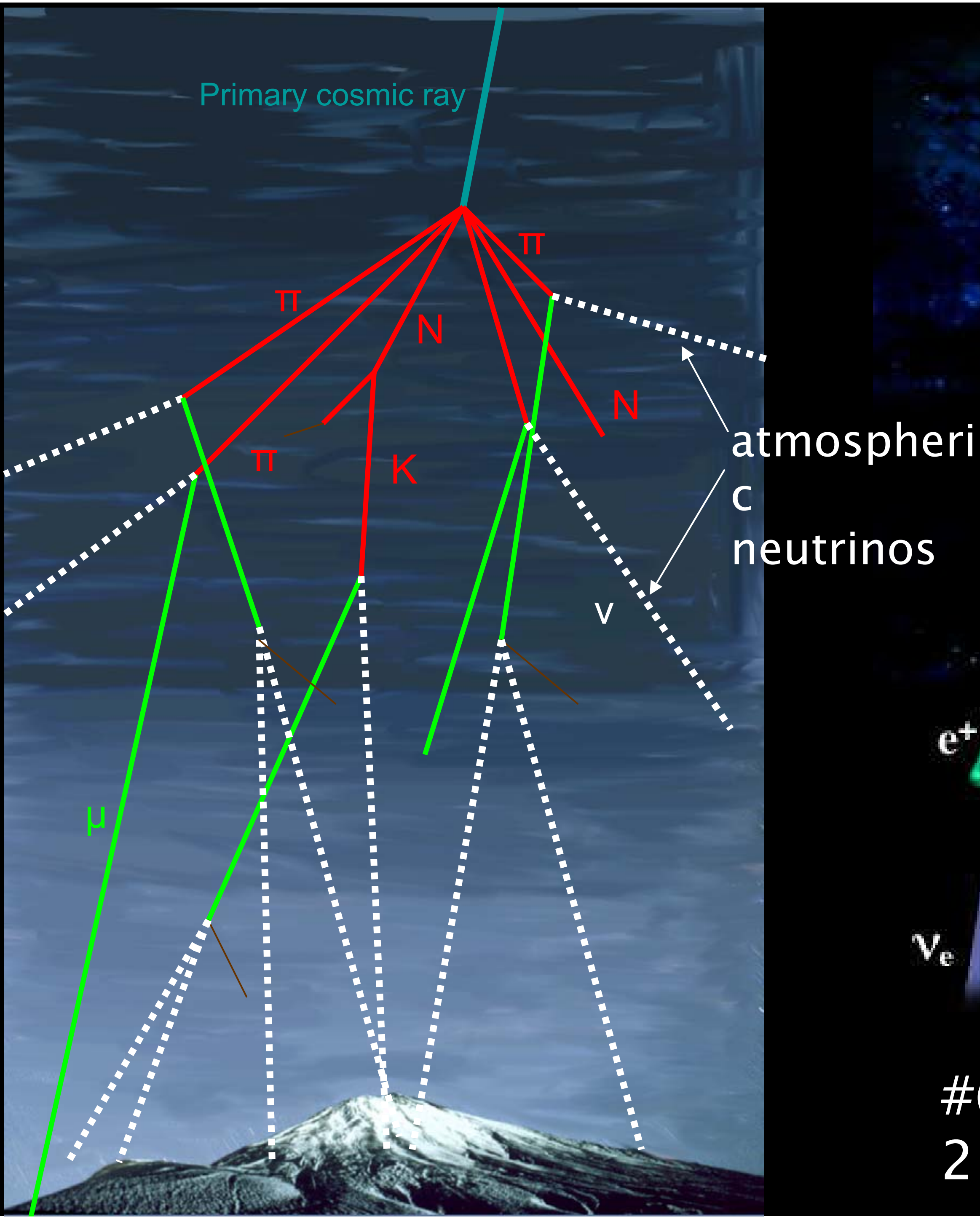
Oscillation of atmospheric neutrinos

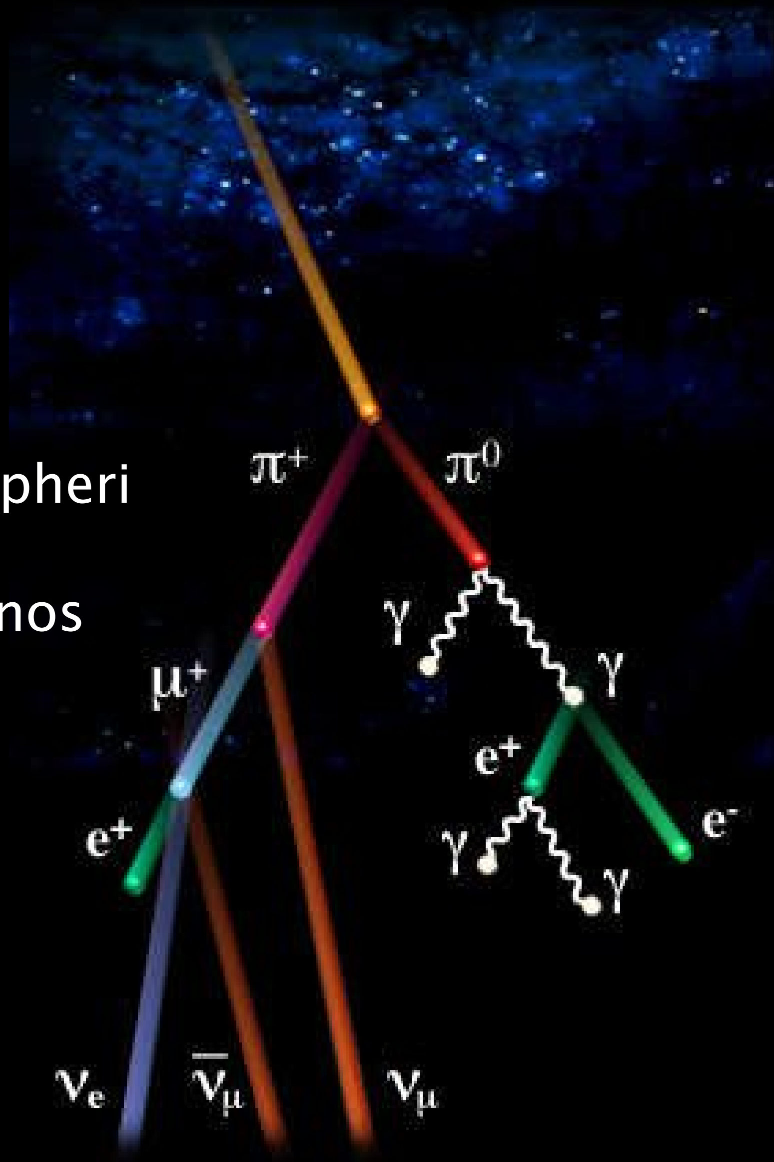
Oscillation probability varies with zenith angle θ



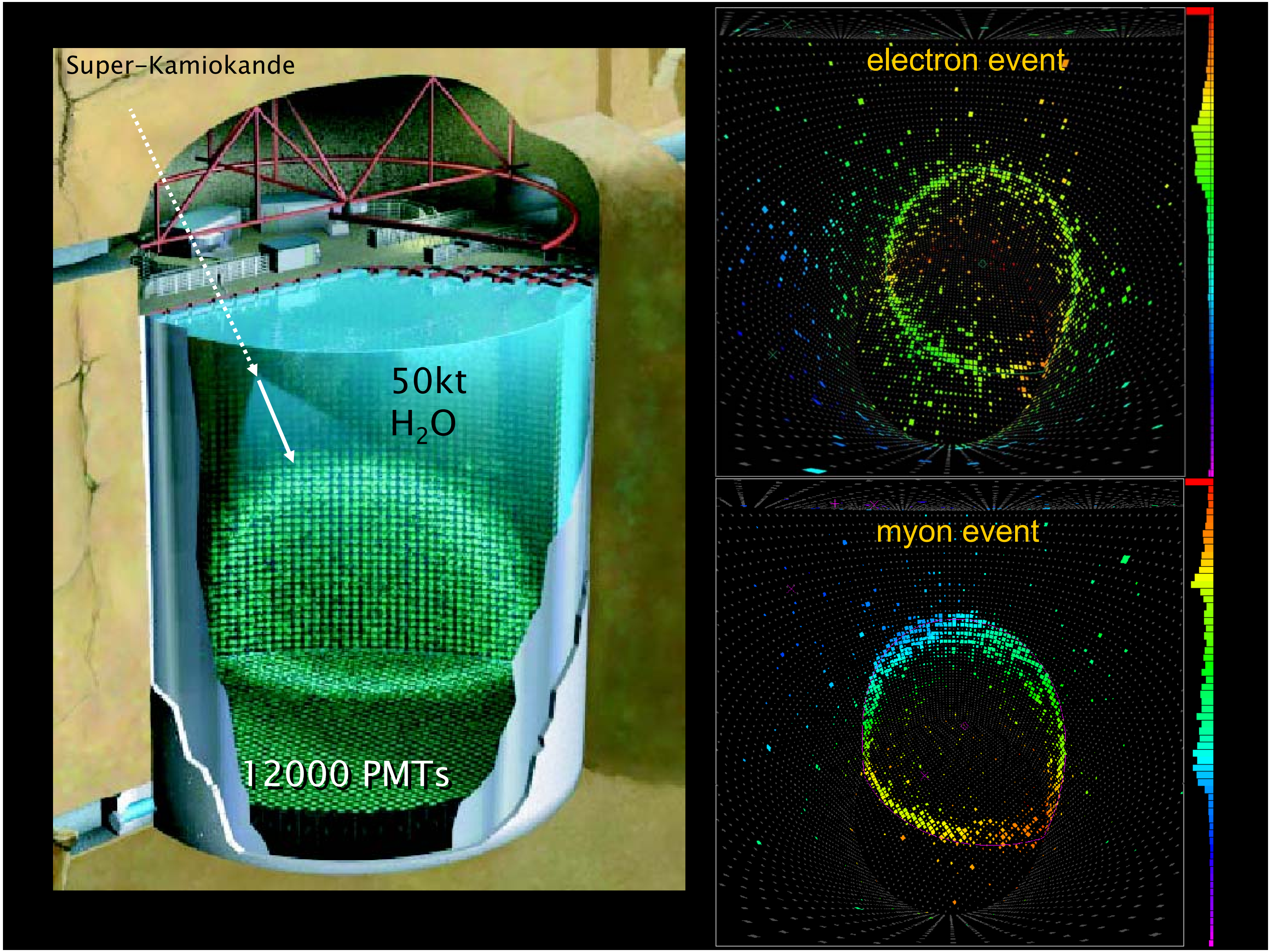
atmospheric neutrinos: E_ν in GeV range

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



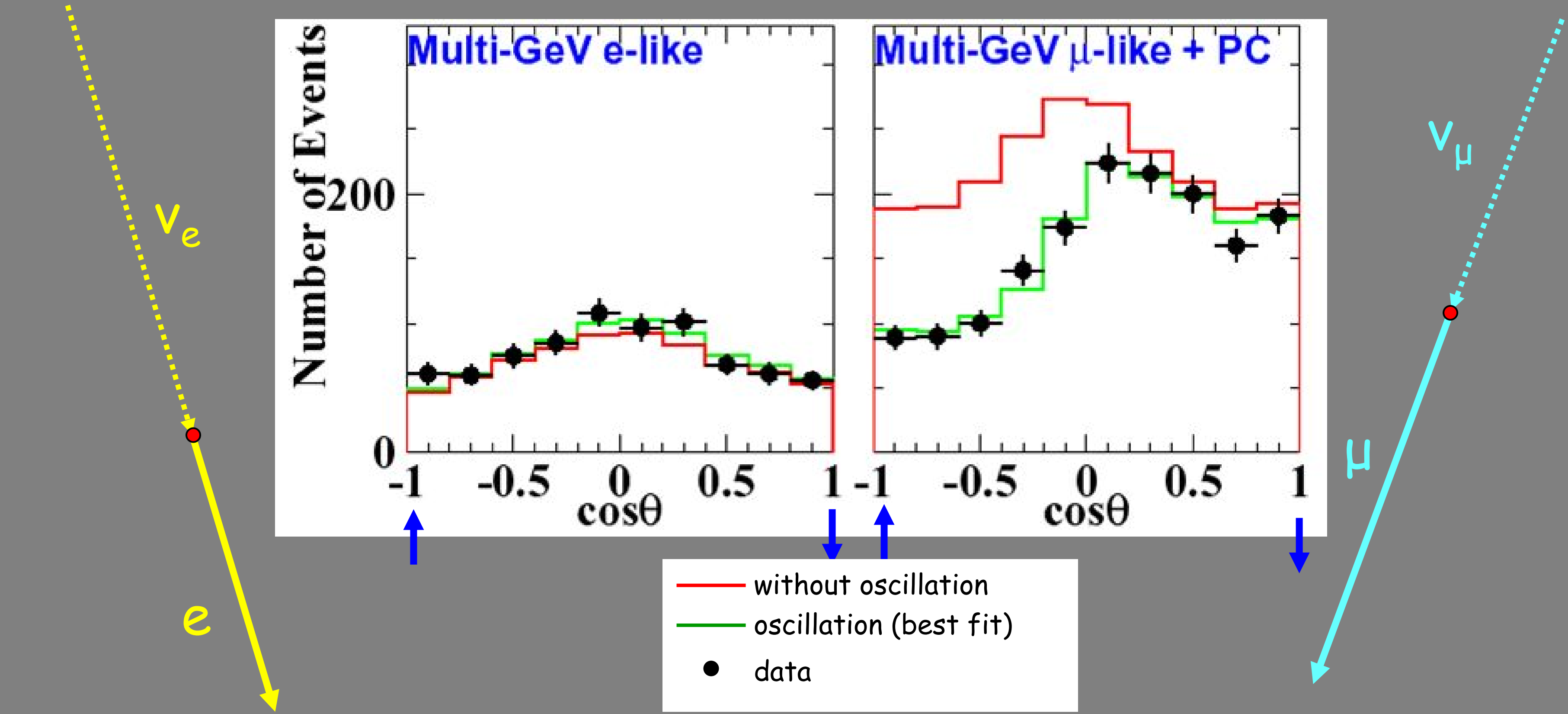


$\#(\nu_\mu) / \#(\nu_e) \approx 2$


Super-Kamiokande
50kt
H_2O
12000 PMTs
electron event
myon event

SuperK – atmospheric neutrinos

e-like events	μ-like events

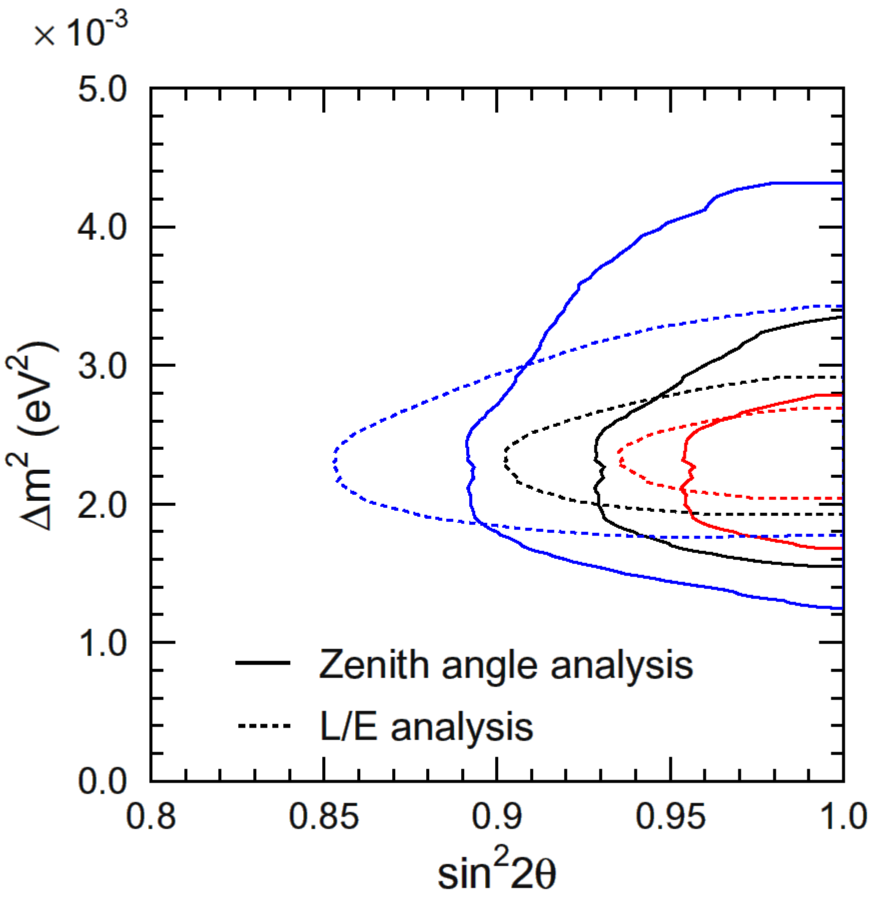


Full SK-I data set, 90% CL (PRD71 (2005) 112005):

$\sin^2 2\theta > 0.92$

$\mathbf{1.5 \cdot 10^{-3}\ eV^2 < \Delta m^2 < 3.4 \cdot 10^{-3}\ eV^2}$

Atmospheric Neutrino Results



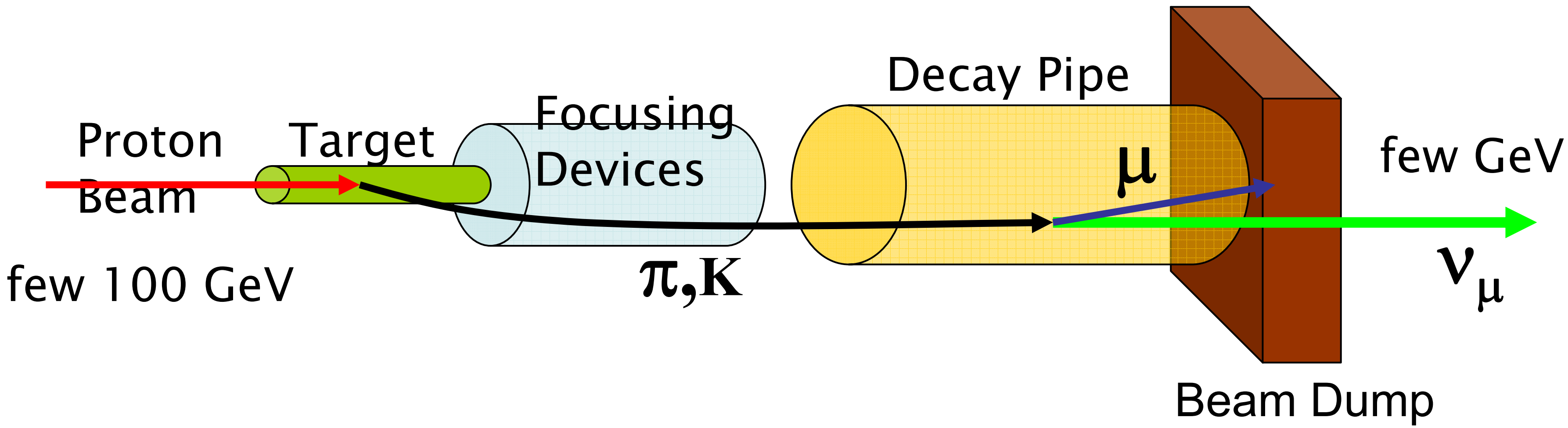
L/E Analysis
(PRL93 (2004) 101801),
Best Fit:
$\sin^2 2\theta = 1.02$
$|\Delta m^2| = 2.4\times10^{-3}\ eV^2$

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

$\sin^2 2\theta > 0.92$

$1.5\cdot10^{-3}\ eV^2 < \Delta m^2 < 3.4\cdot10^{-3}\ eV^2$

Neutrino beams: Principle

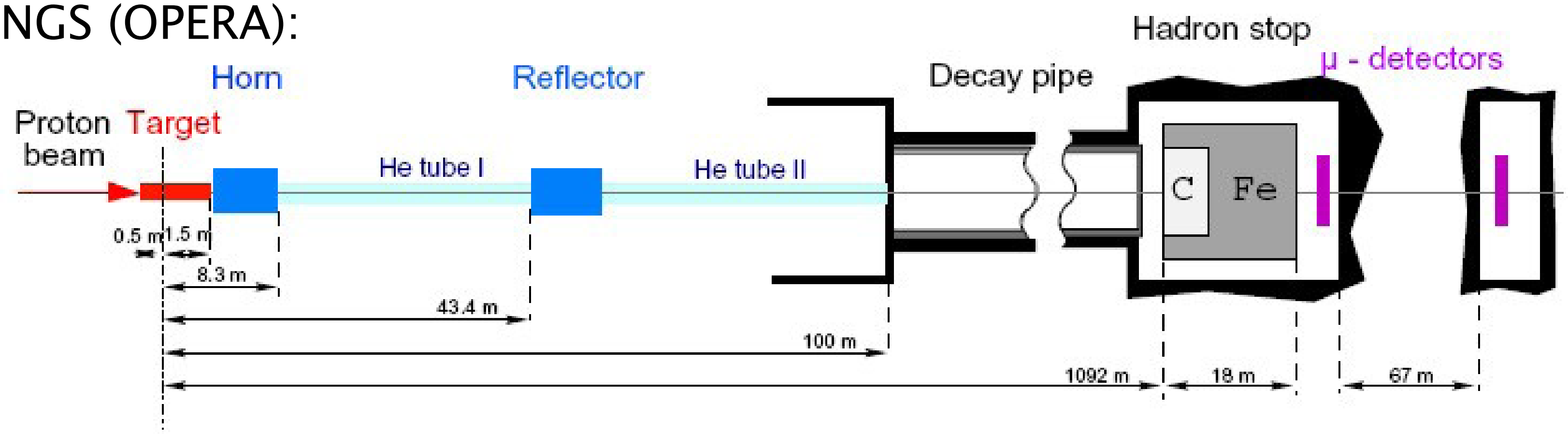


Beam composition (typical example):

- 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 Neutrinobeams

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, NoνA	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

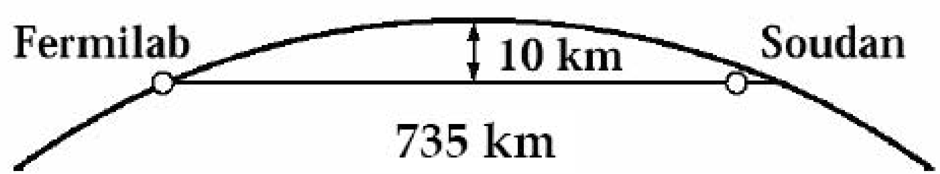
The MINOS Experiment

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



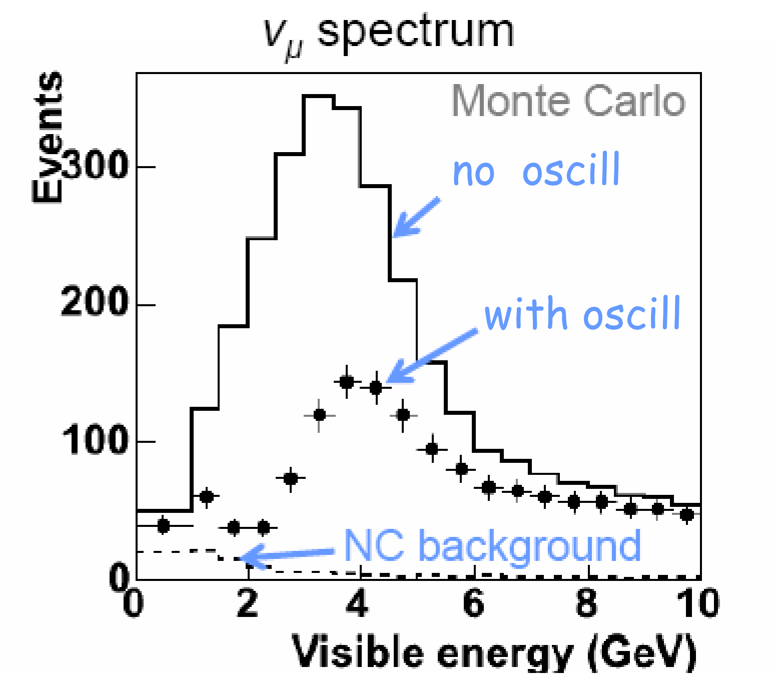
Example of a disappearance measurement

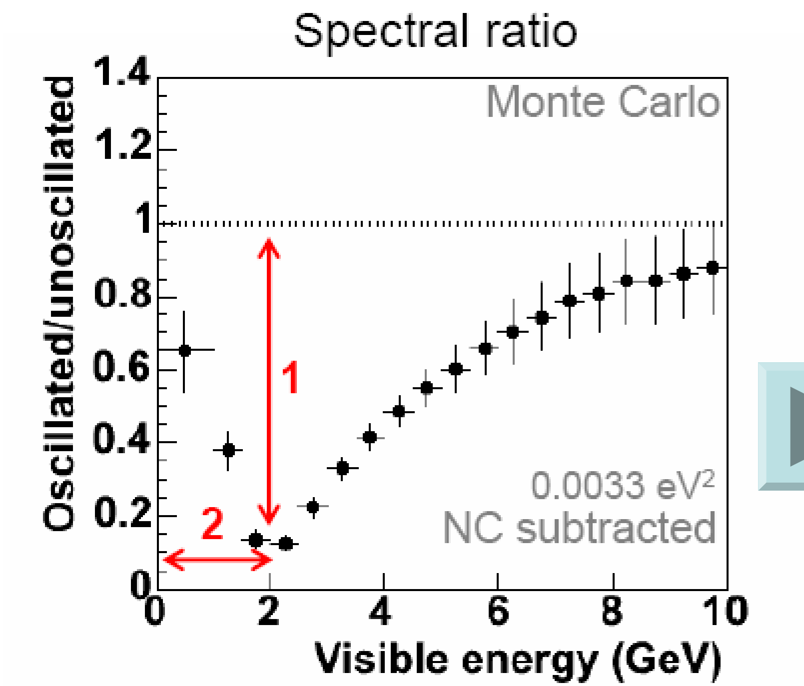
Look for a deficit of ν_μ events at a distance…

$$P(\nu_\mu \to \nu_\mu) = 1 - \boxed{\sin^2 2\theta}\,\sin^2(1.267\,\boxed{\Delta m^2}\,L/E)$$

statistics! 1

2 energy resolution!



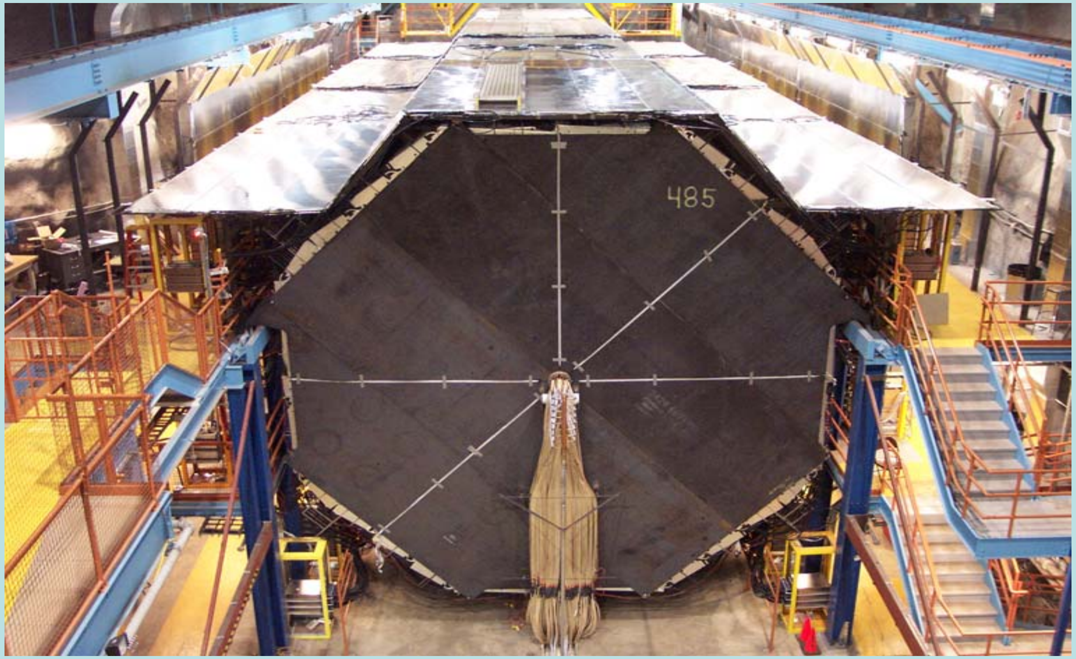


MINOS Detectors

Near Detector (Fermilab): 1km

1 kton, 4×5×15m
282 steel,
153 scintillator planes

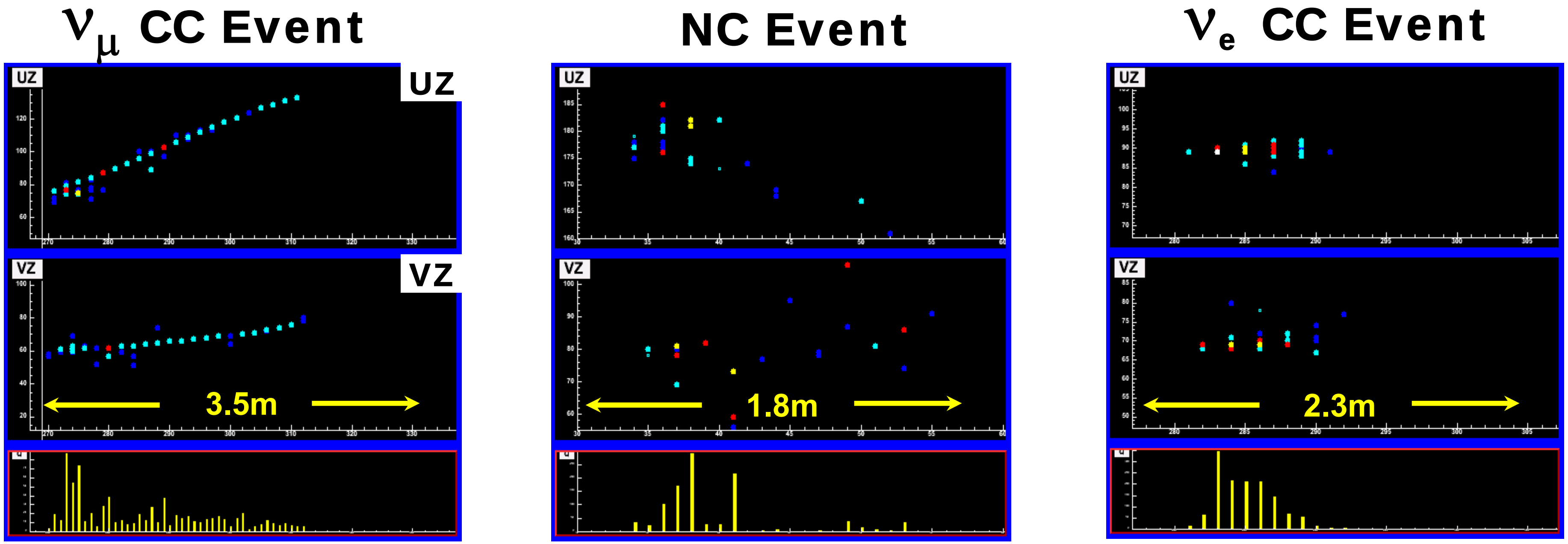
Far Detector (Soudan Mine): 735km



5.4 ktons, 8×8×30m
484 steel/scintillator planes

Event Topologies

Monte Carlo

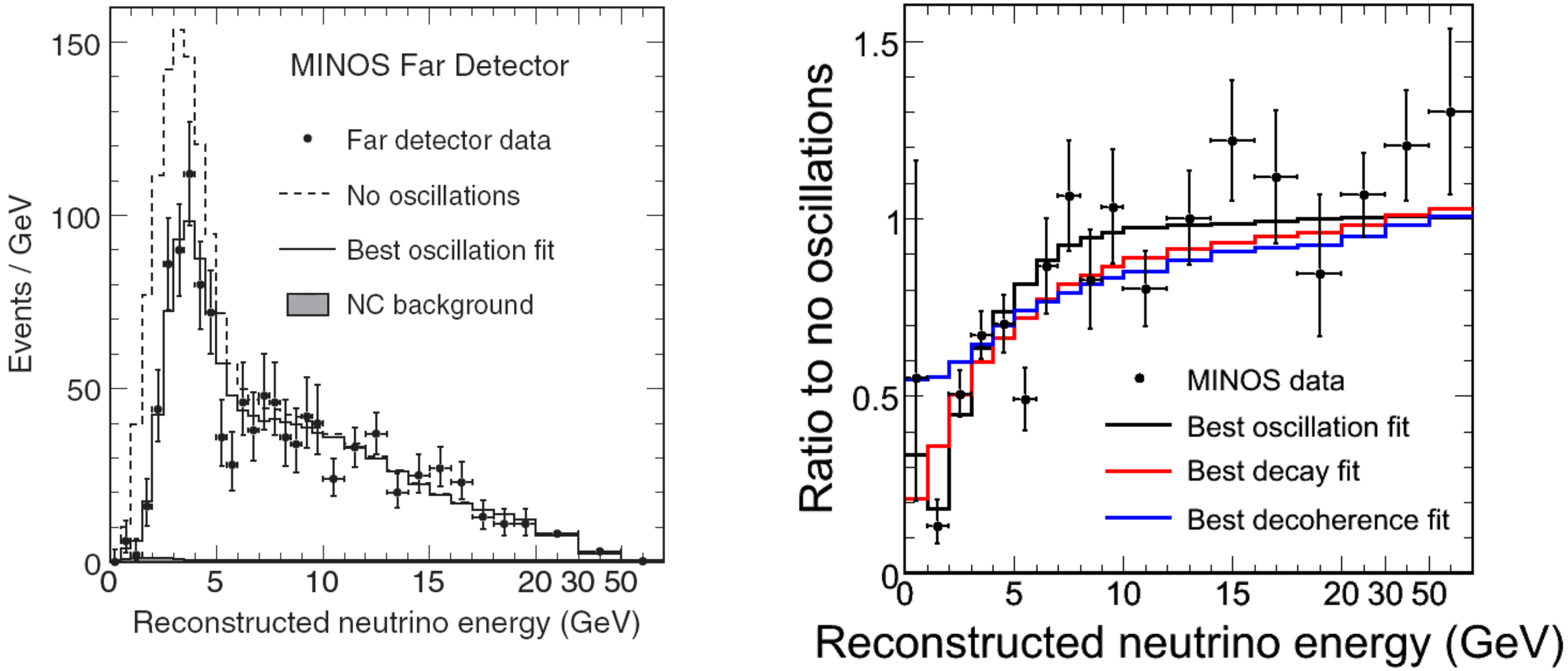


long μ track +
hadronic activity

short event,
often diffuse

short event,
typical EM shower
profile

MINOS Results: Fit to Oscillation Hypothesis



$$\left|\Delta m^2_{32}\right| = (2.43 \pm 0.13) \times 10^{-3}\,\mathrm{eV}^2 \quad (68\%\mathrm{CL})$$

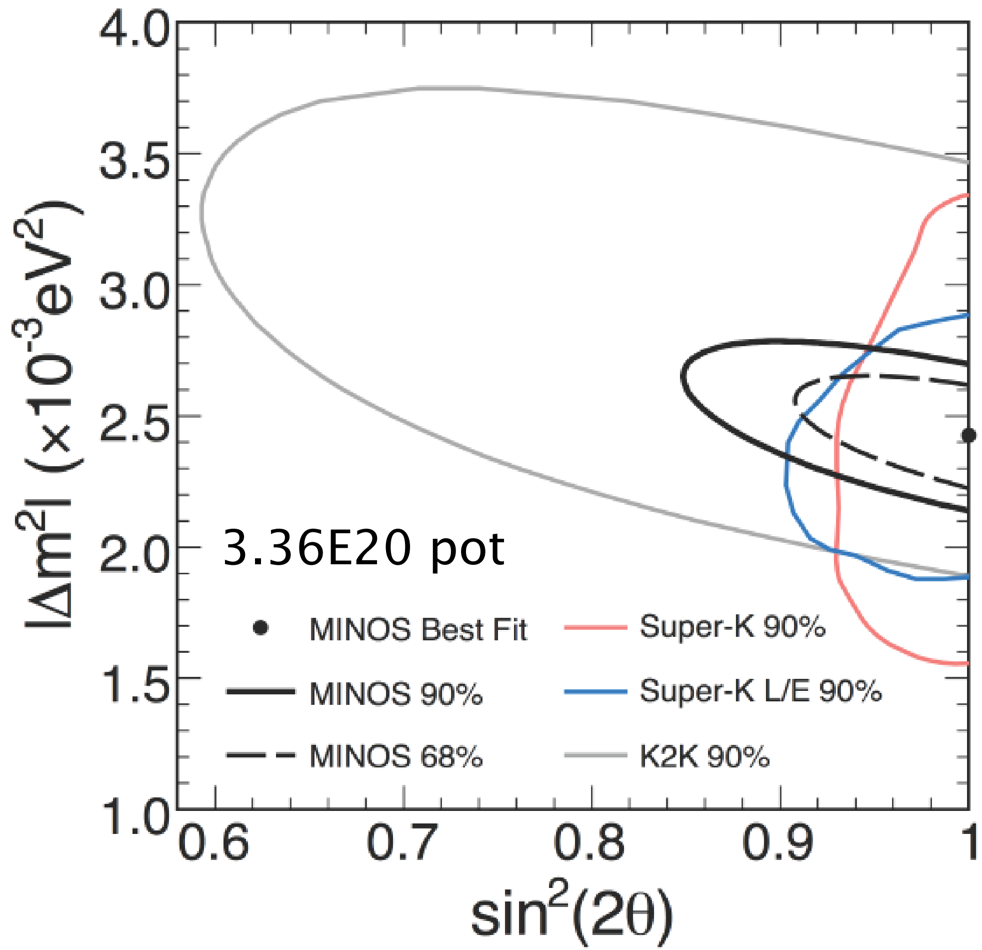
$$\sin^2 2\theta_{23} > 0.90 \quad (90\%\mathrm{CL})$$

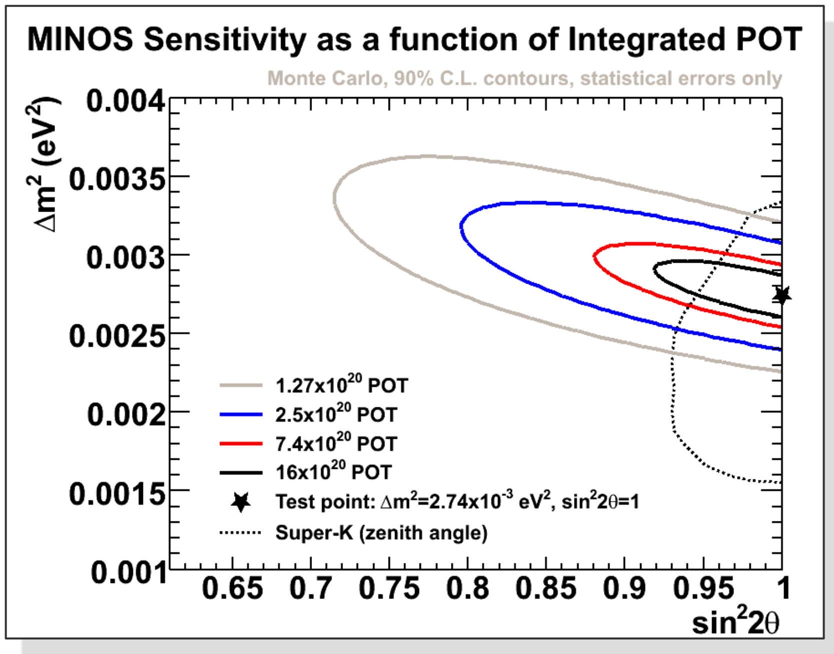
(best fit)

(for $3.36 \cdot 10^{20}$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: 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:

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

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

matter dependent quantities :

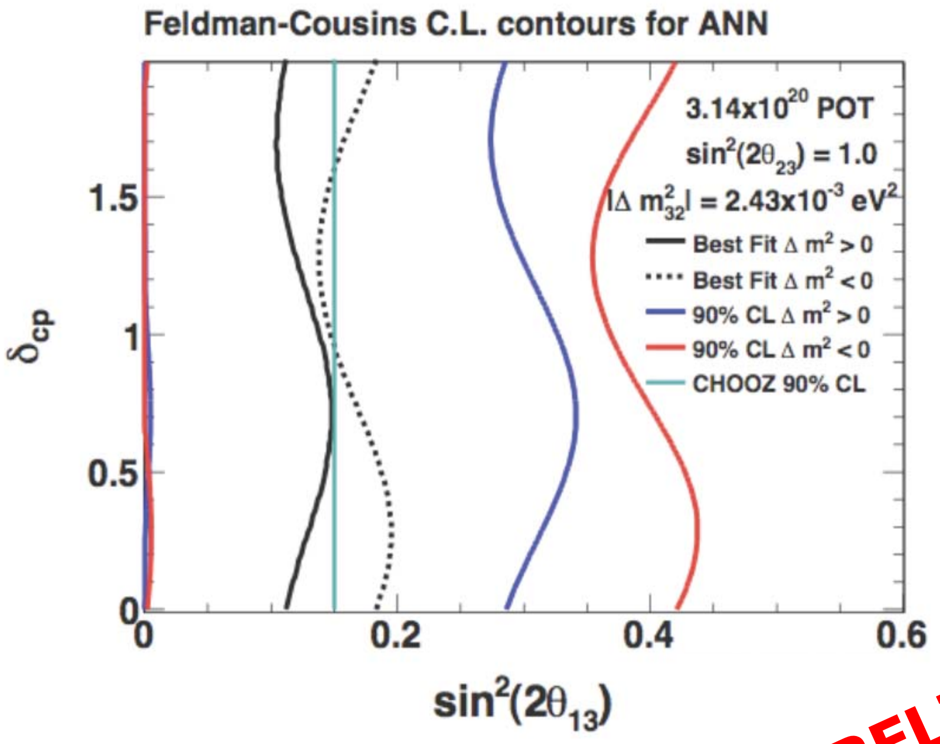
$\hat{A} = 2VE / \Delta m_{31}^2$

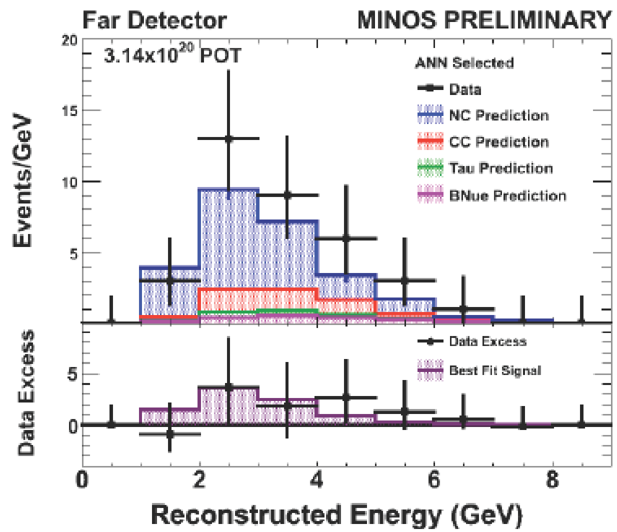
$V = \sqrt{2} G_F n_e$, with electron density n_e (assumed constant)

NEW! MINOS: ν_e appearance

35 events found in signal region, expected background: 27 ± 5(stat) ± 2(sys

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

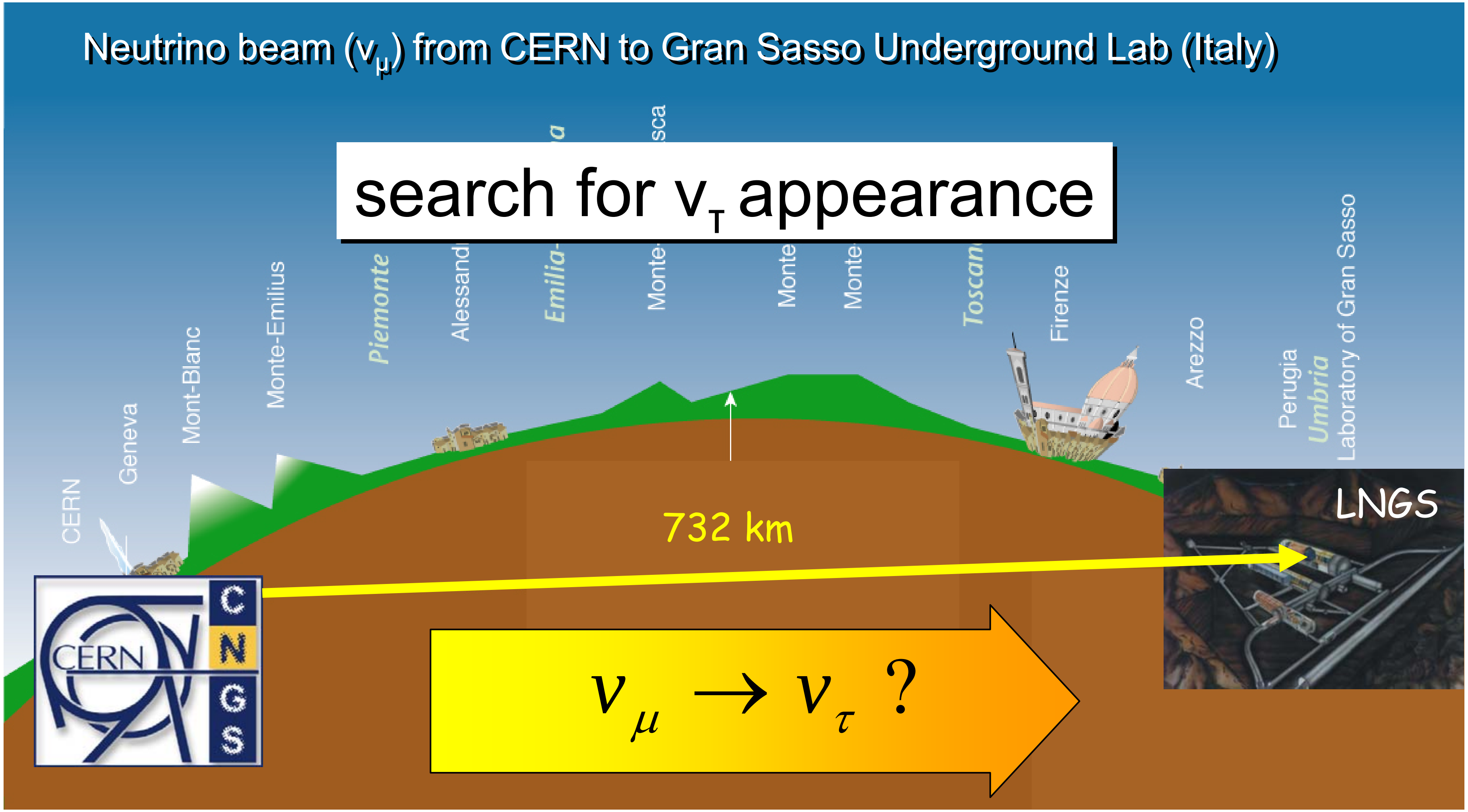




PRELIMINARY

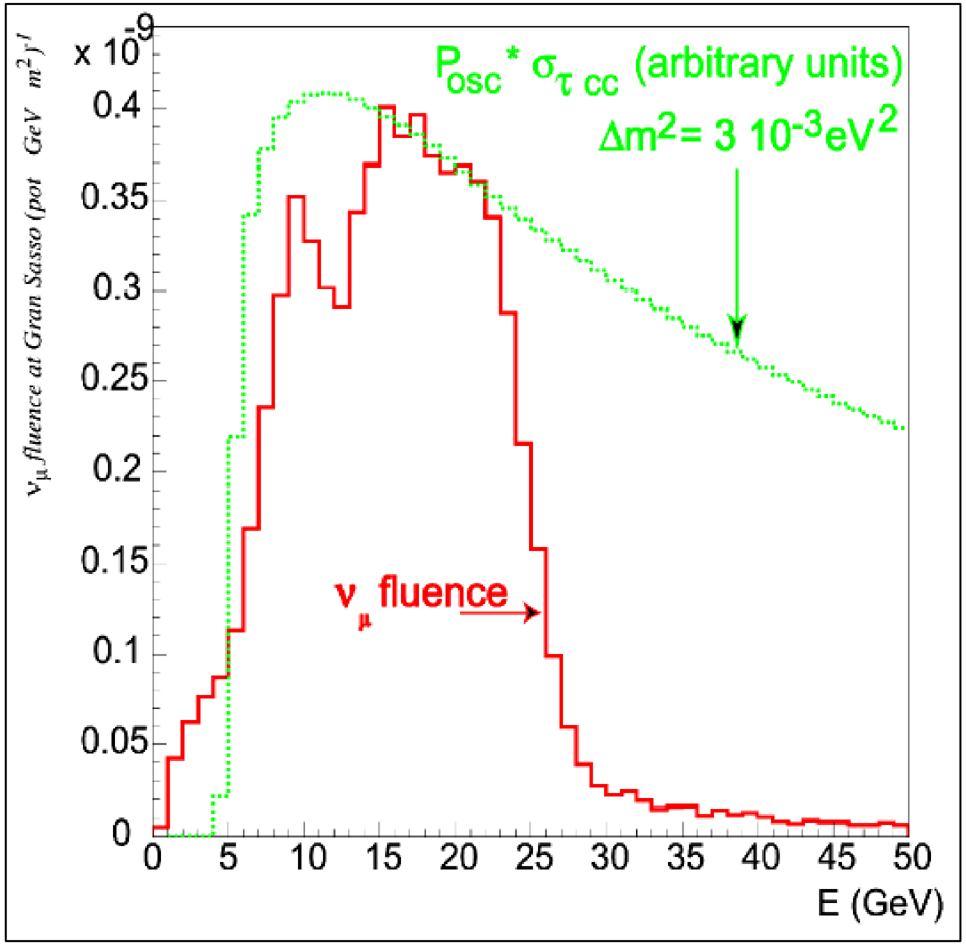
From „Recent Results from the MINOS experiment", M. Diwan @ Neutrino Telescopes Venice March 2009, arXiv:0904.3706

OPERA:
Oscillation Project with Emulsion tRacking Apparatus



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

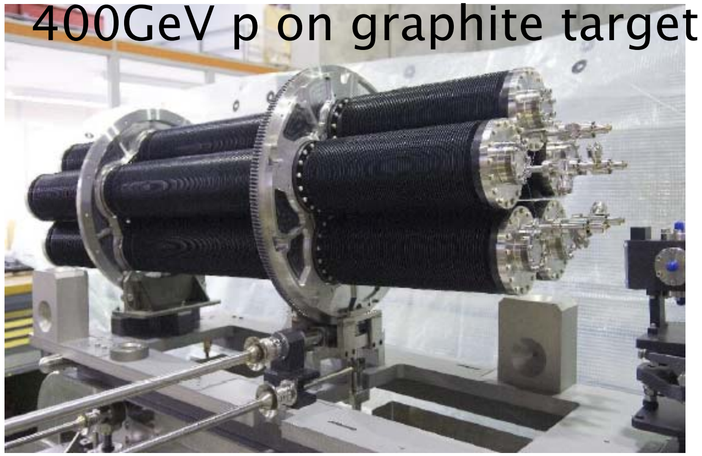
CNGS beam ("pure" ν_μ)



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

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

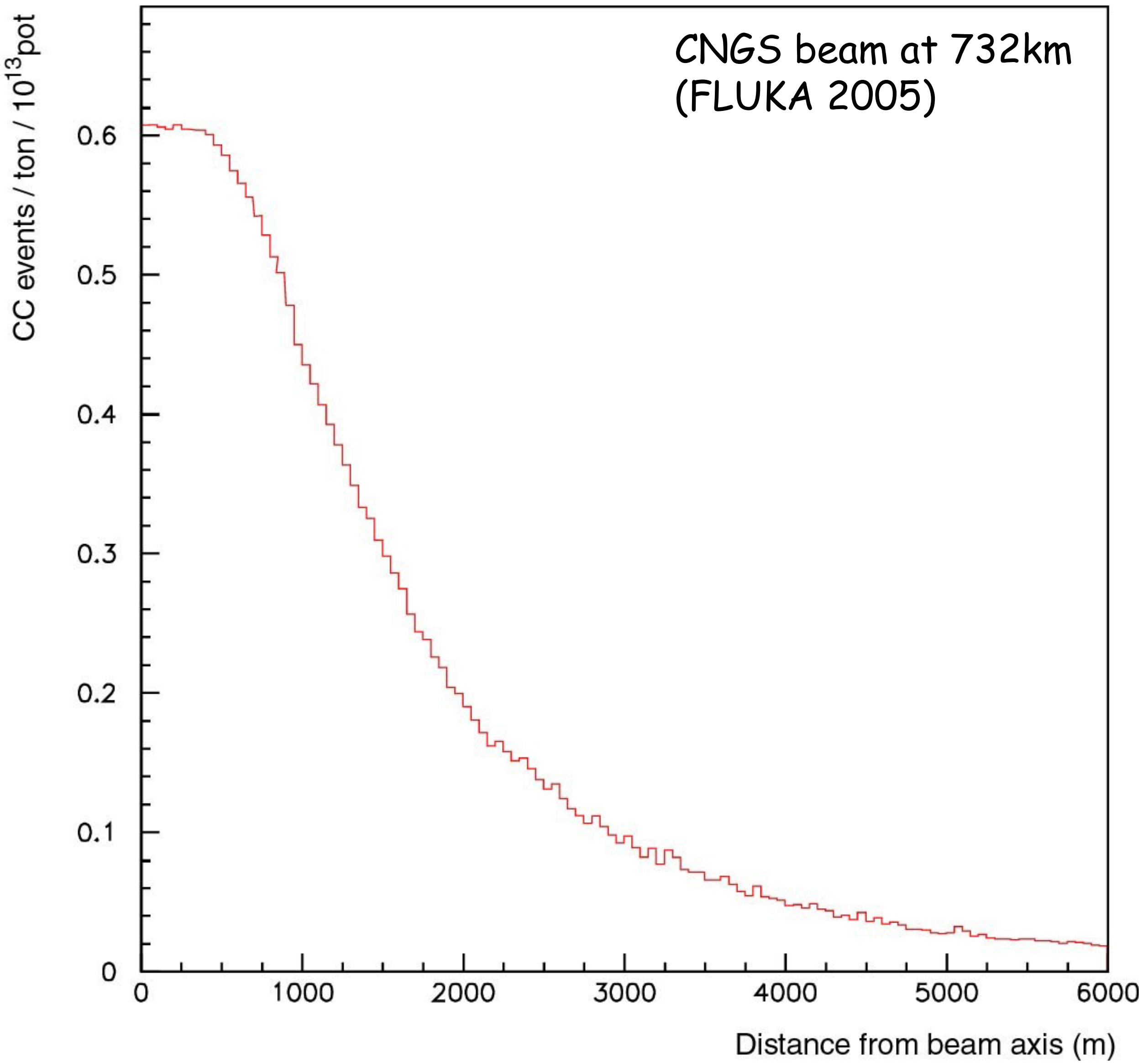
$$(\bar{\nu}_e + \nu_e)/\nu_\mu = 0.87\%$$



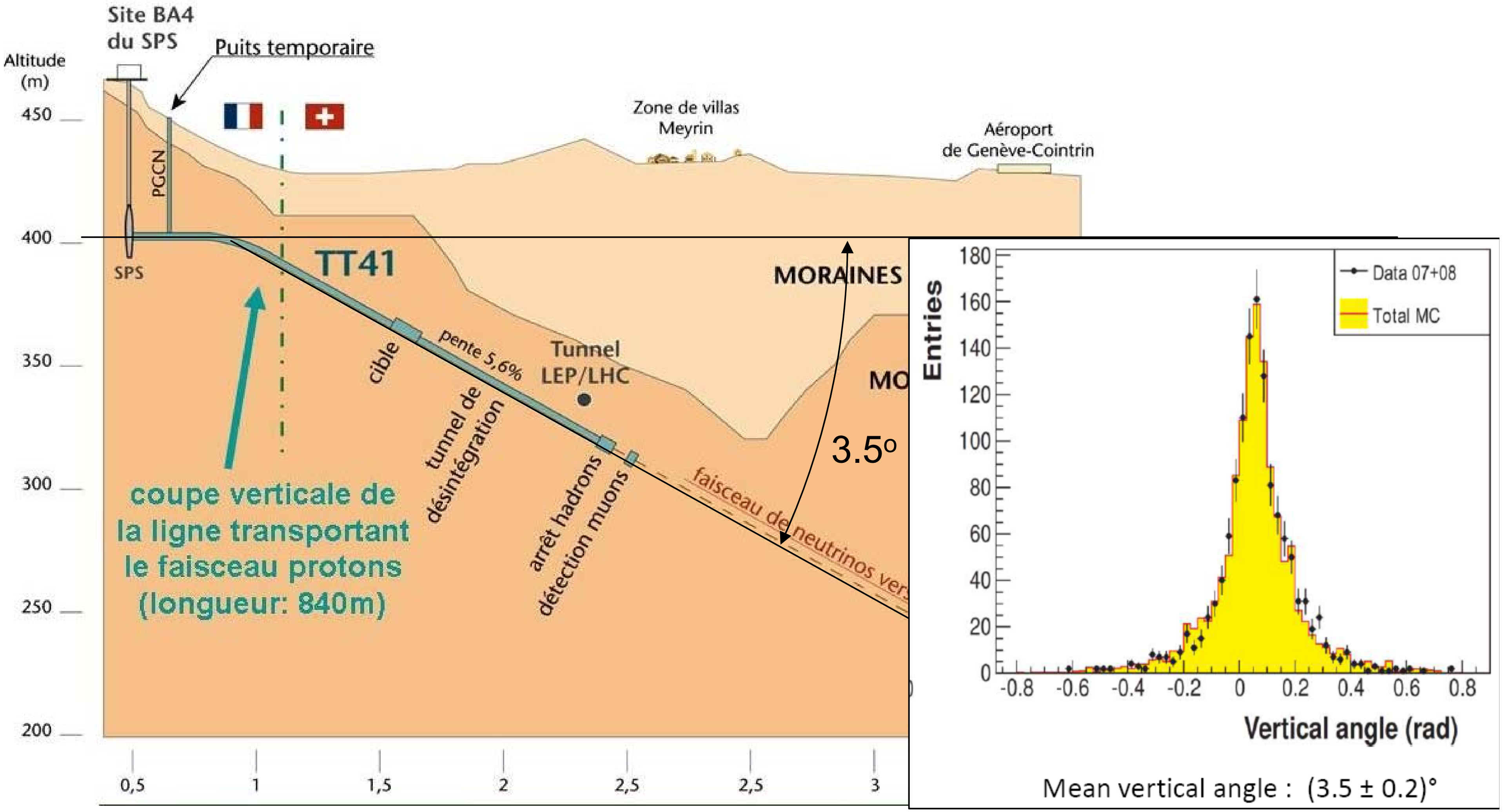
Total exposure expected: 22.5E19 pot

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

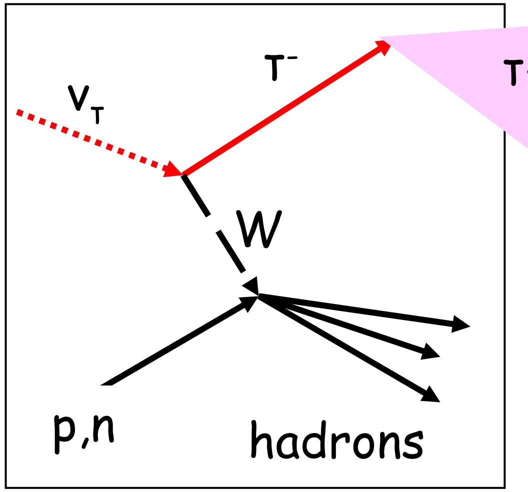
Profile of neutrino beam @ LNGS



Direction of CNGS neutrino beam



OPERA: ν_τ detection



τ-decay:

$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \quad 17.4\%$$

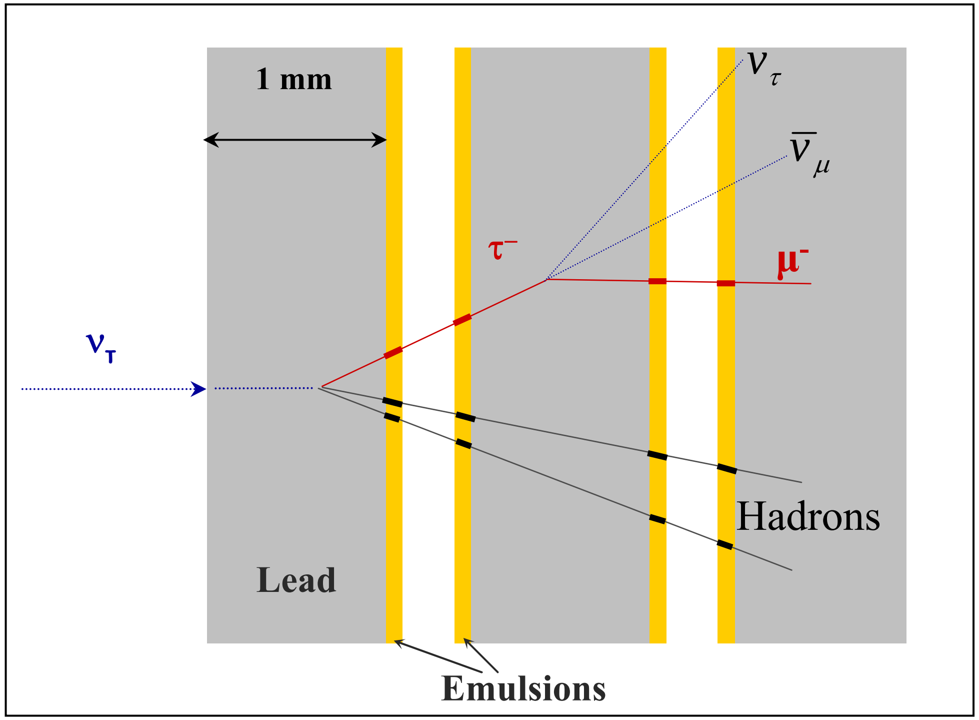
$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau \quad 17.8\%$$

(kink)

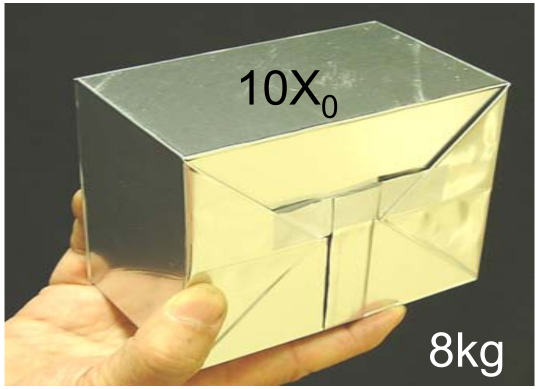
$$\tau^- \to \text{hadron} + \nu_\tau \quad 49.5\%$$

$$\tau^- \to \pi^- \pi^- \pi^+ (n\pi^0) + \nu_\tau \quad 15.2\% \quad \text{trident}$$

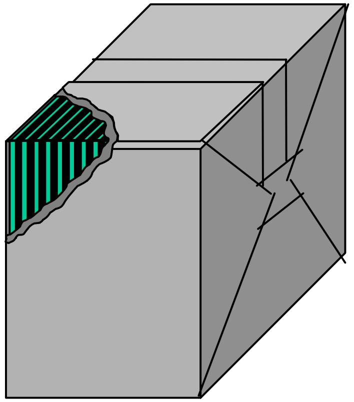
Typical topology of τ–decay:
"Kink" within 1mm from vertex

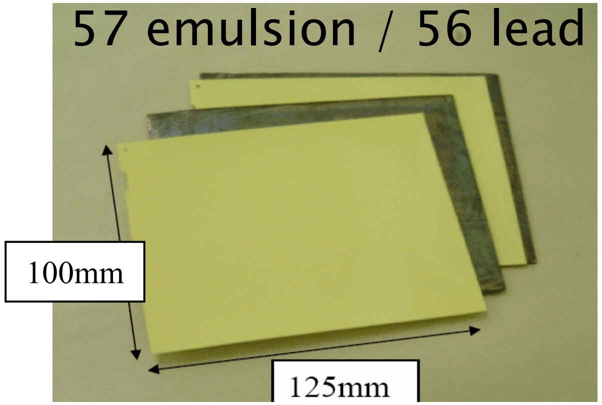


OPERA target: lead-emulsion-bricks

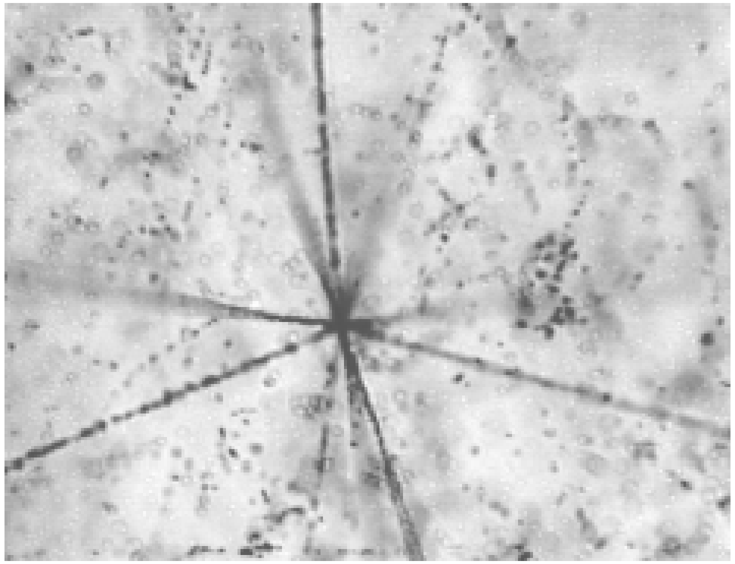


lead-emulsion-brick
(total ≈ 150000)

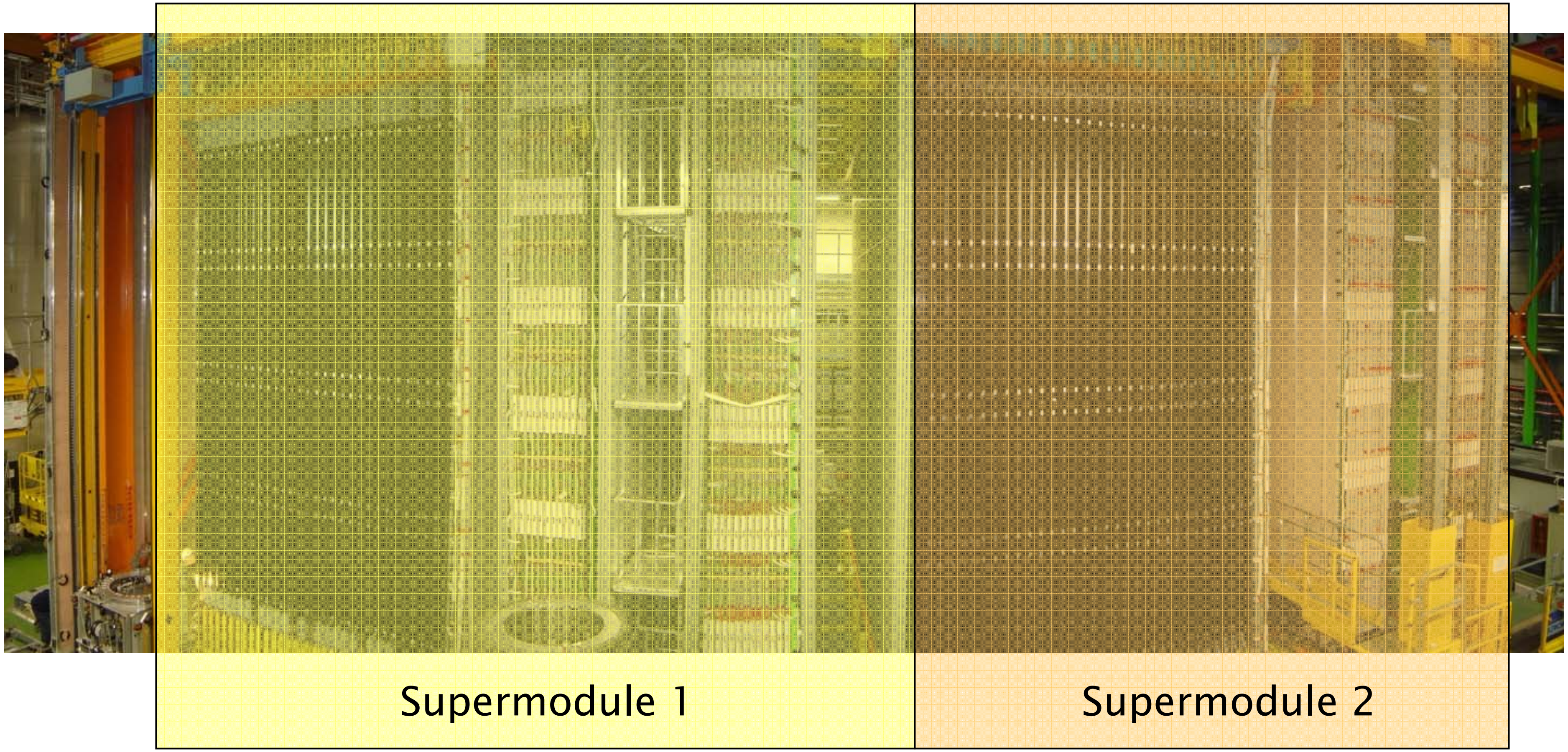




target mass:
≈1.2 kton



OPERA – Detector

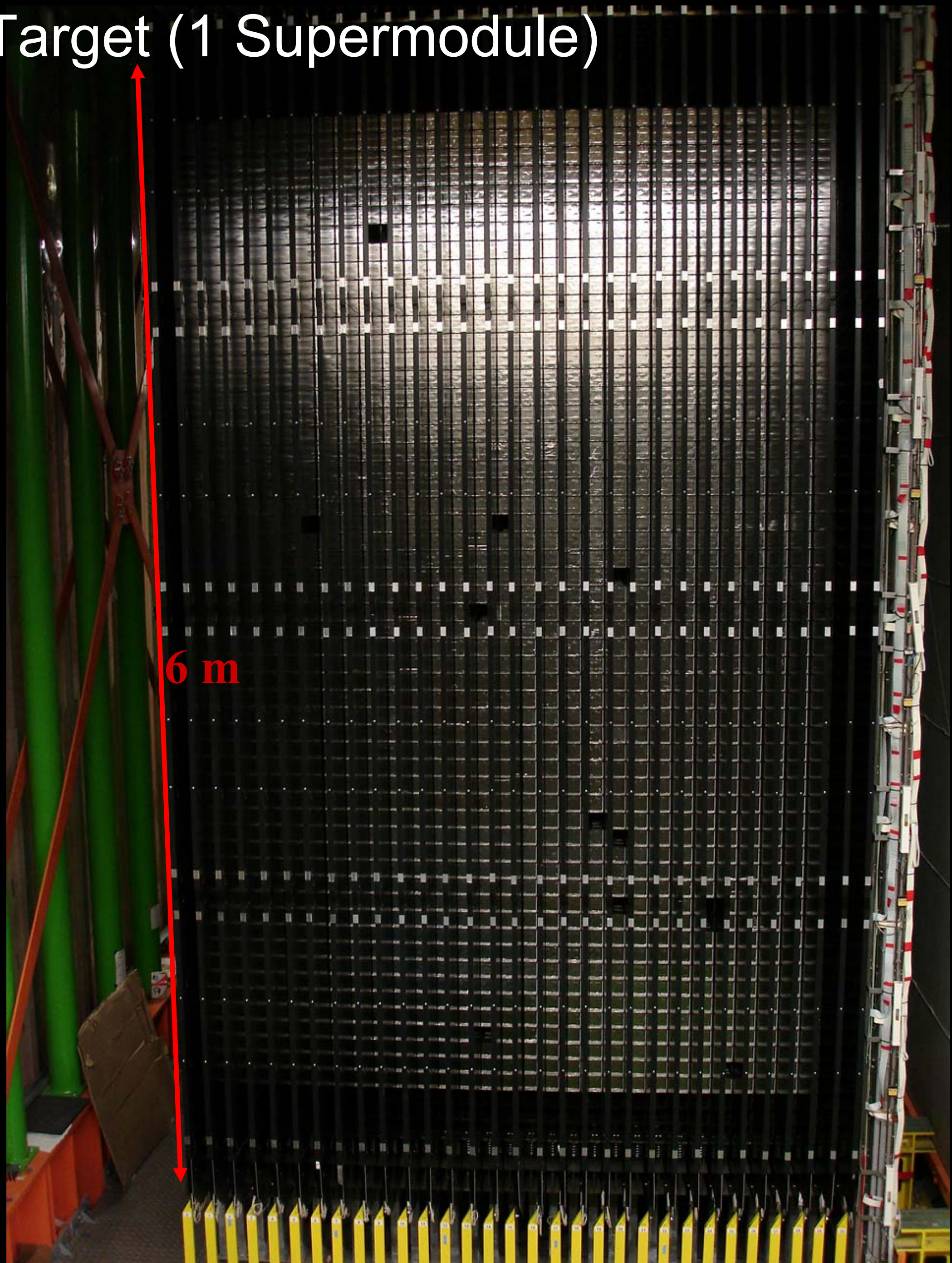


OPERA – Detector

Supermodule 1

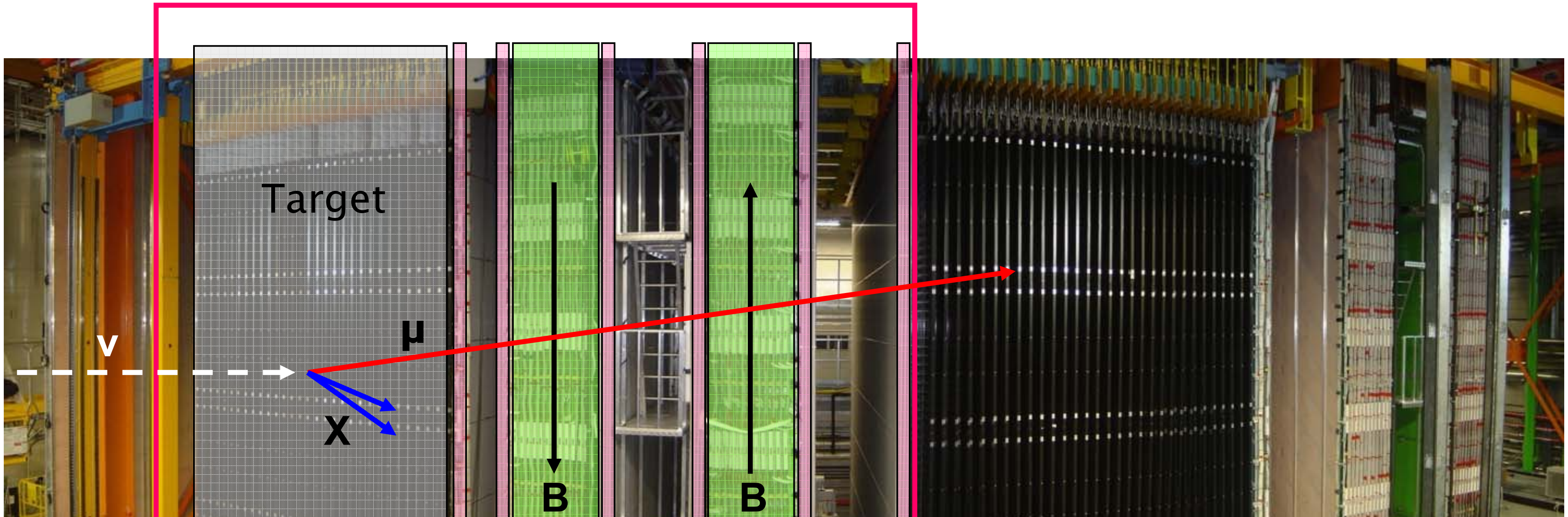
Target Region:
- Target Tracker (Scintillator)
- Lead/Emulsion Bricks (75.000 per Supermodule)

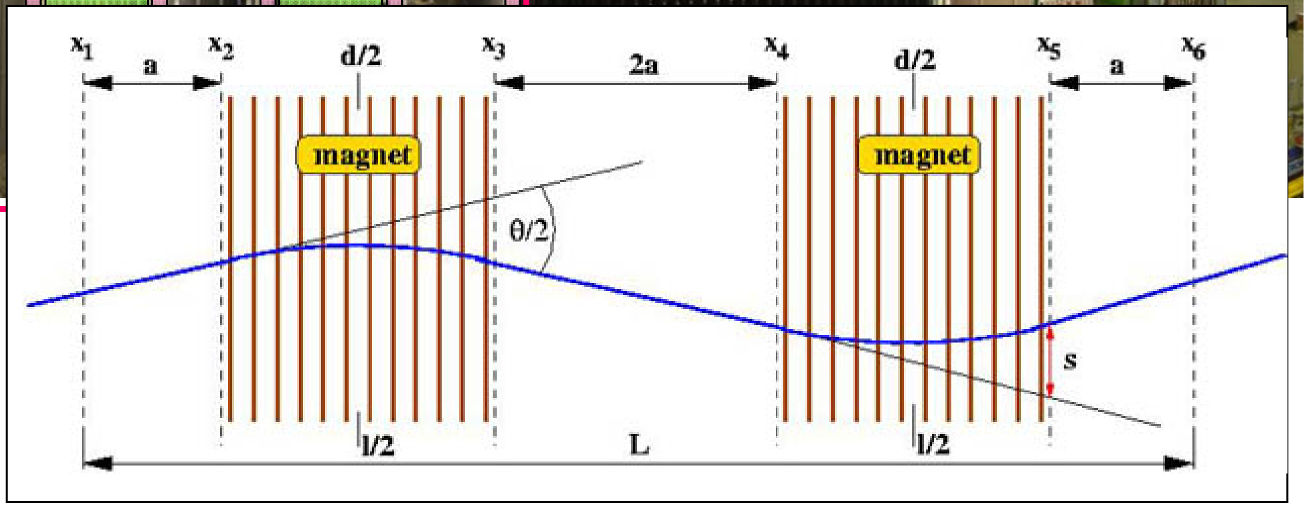
The OPERA Target (1 Supermodule)



OPERA – Detector

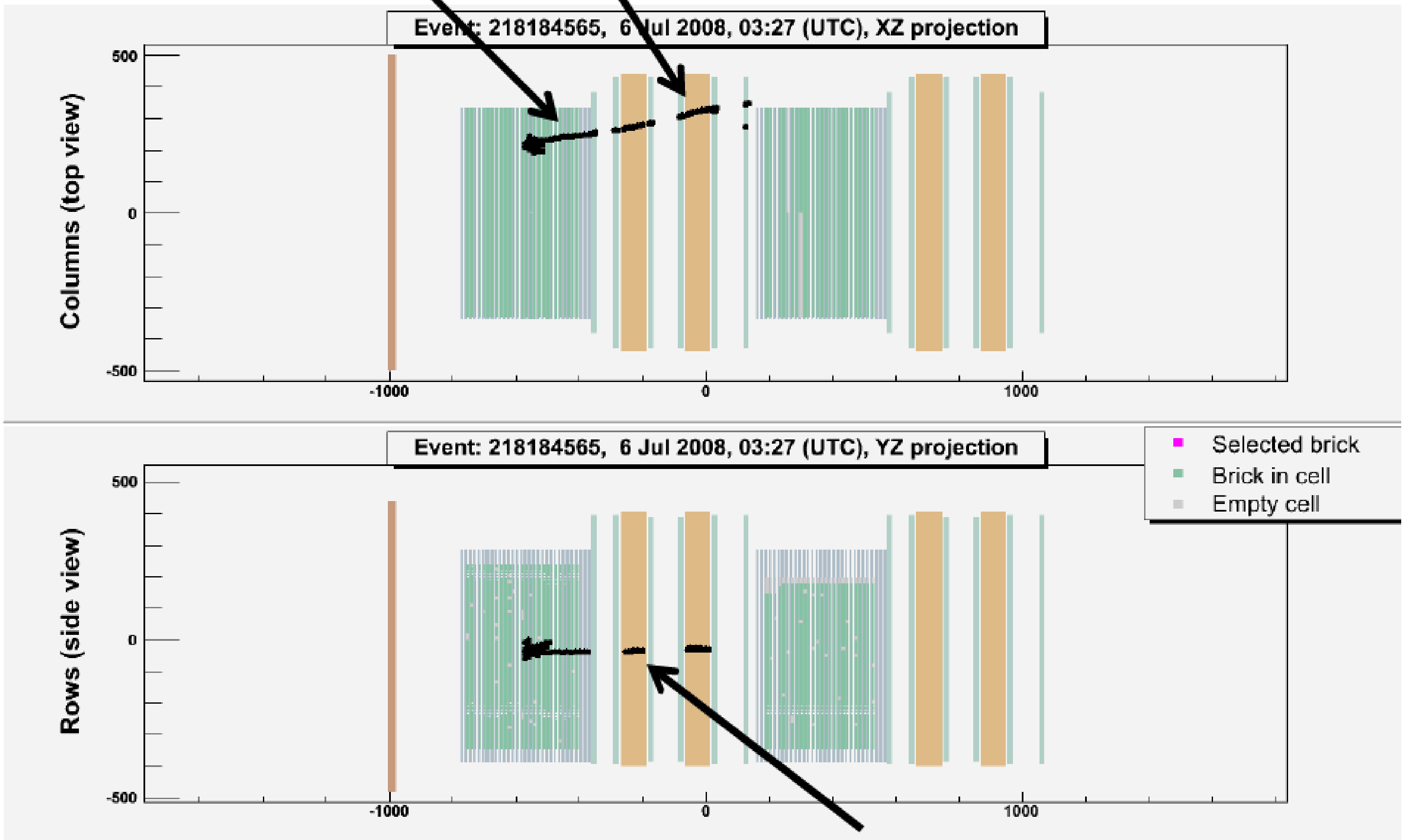
Supermodule 1





Reconstruction (I): Myon-Spectrometer

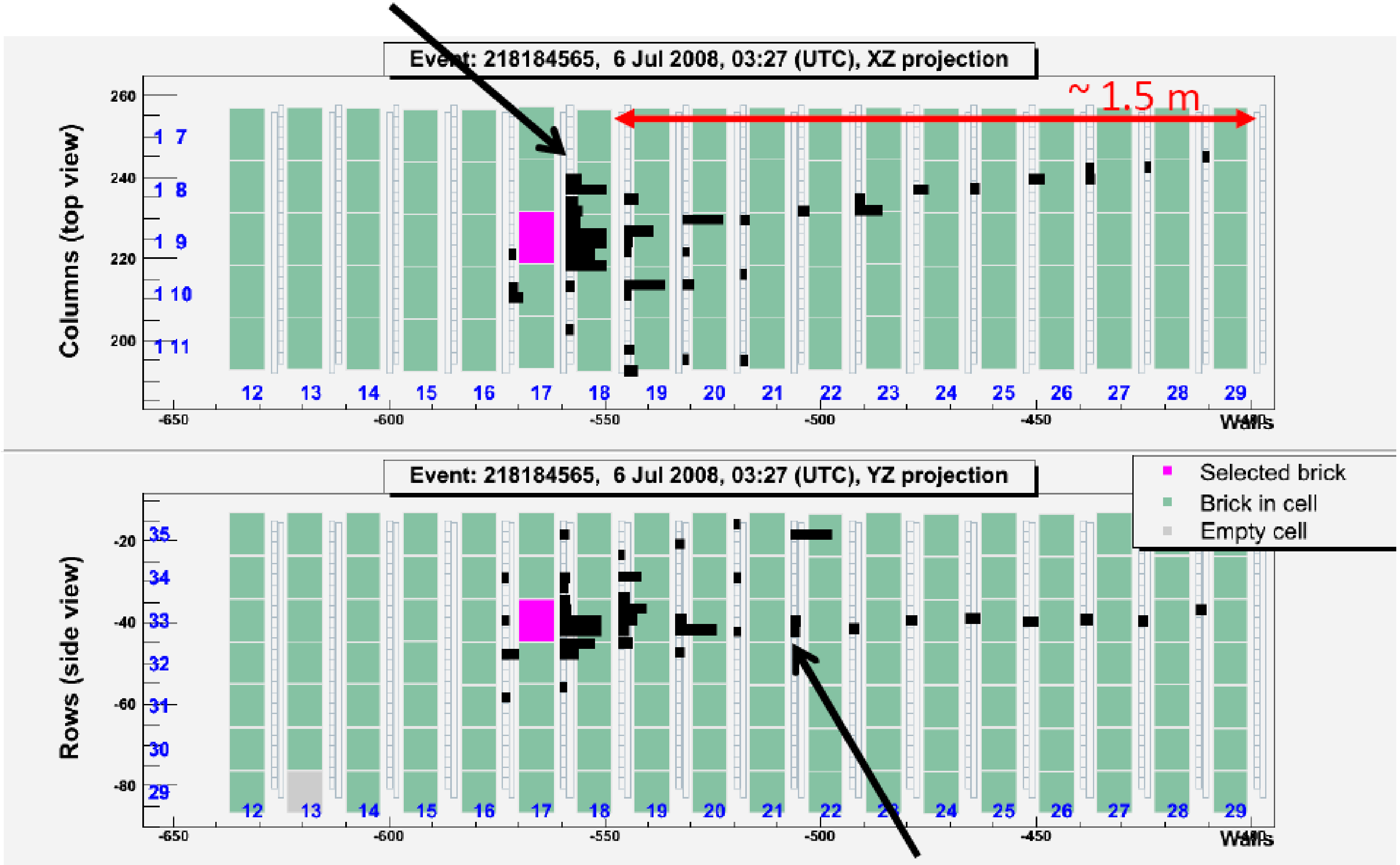
Electronic data (Target Tracker & Muon spectrometer)



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

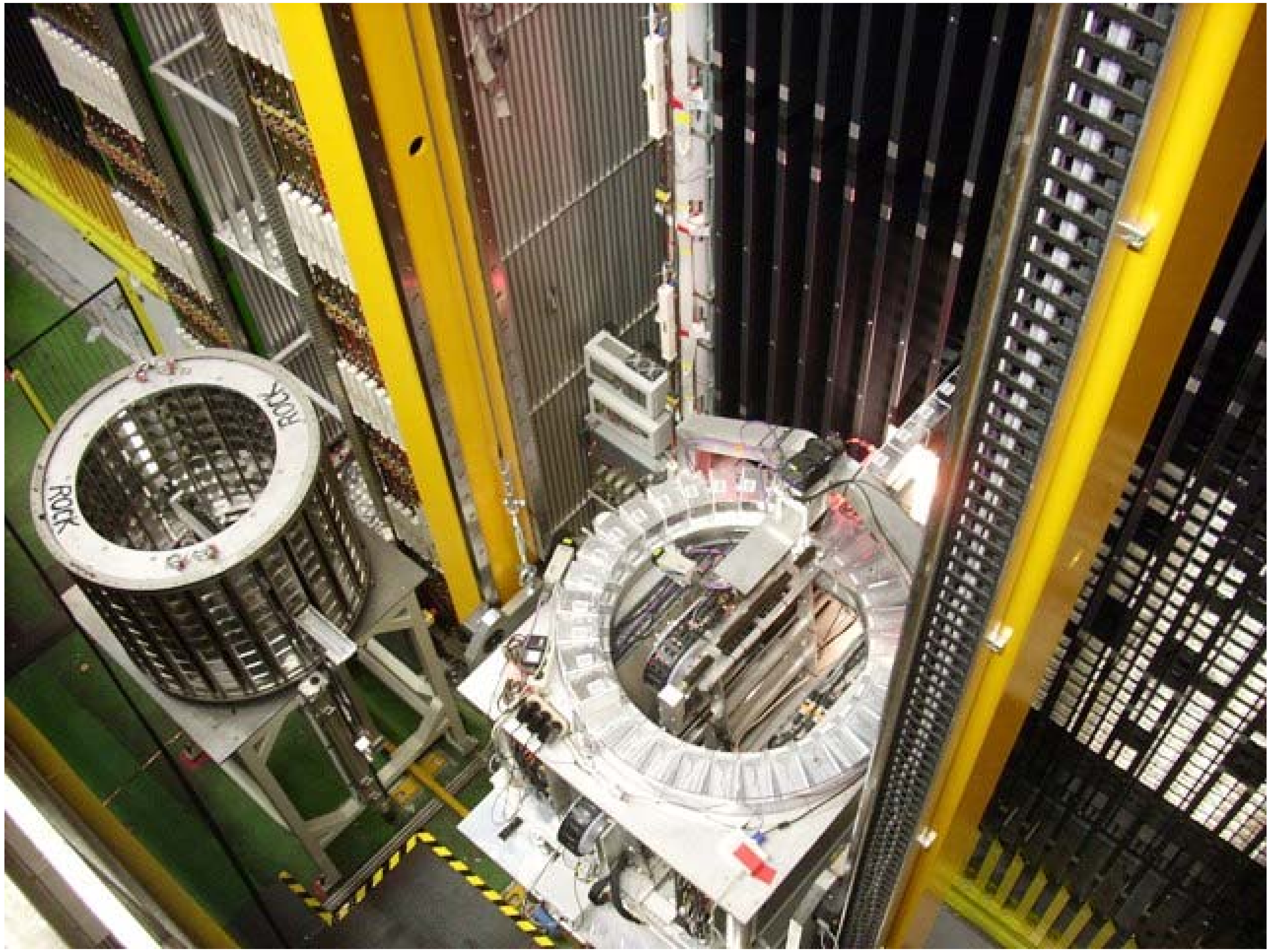
Rekonstruktion (II): Brick Finding

Electronic data (Target Tracker & Muon spectrometer)



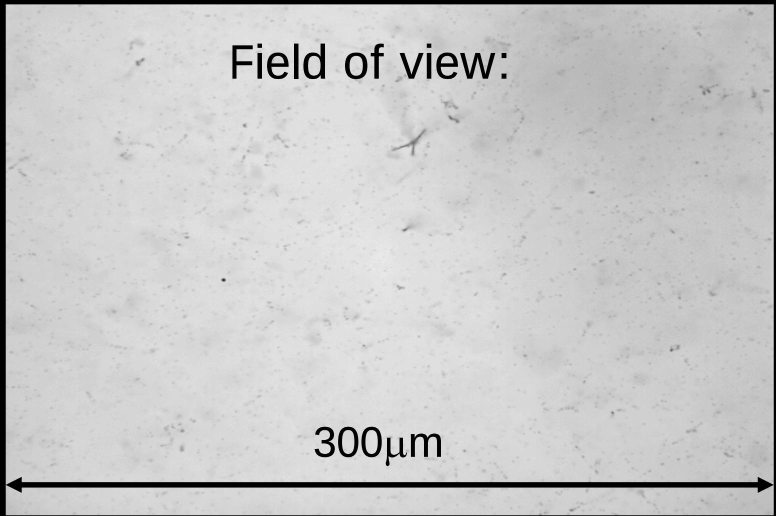
Track identified as a muon (P=3.394 GeV/c)

OPERA – Brick Manipulating System

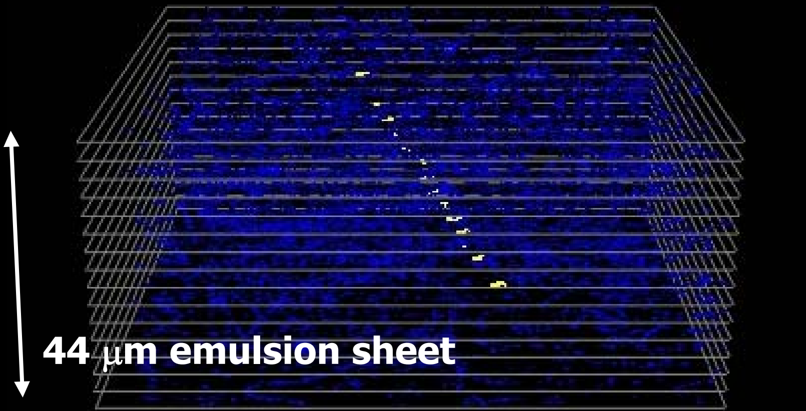


≈30 bricks/day are extracted

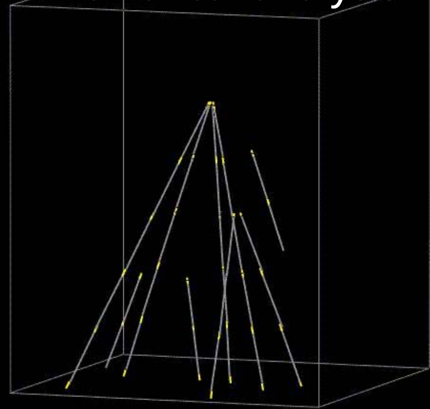
Scanning



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 Δm^2_{23}=2.5 eV^2	Signal Δm^2_{23}=3.0 eV^2	Back-ground
Total	11.06	10.4	14.9	0.75

for OPERA with 1.35kt (75% of proposal)

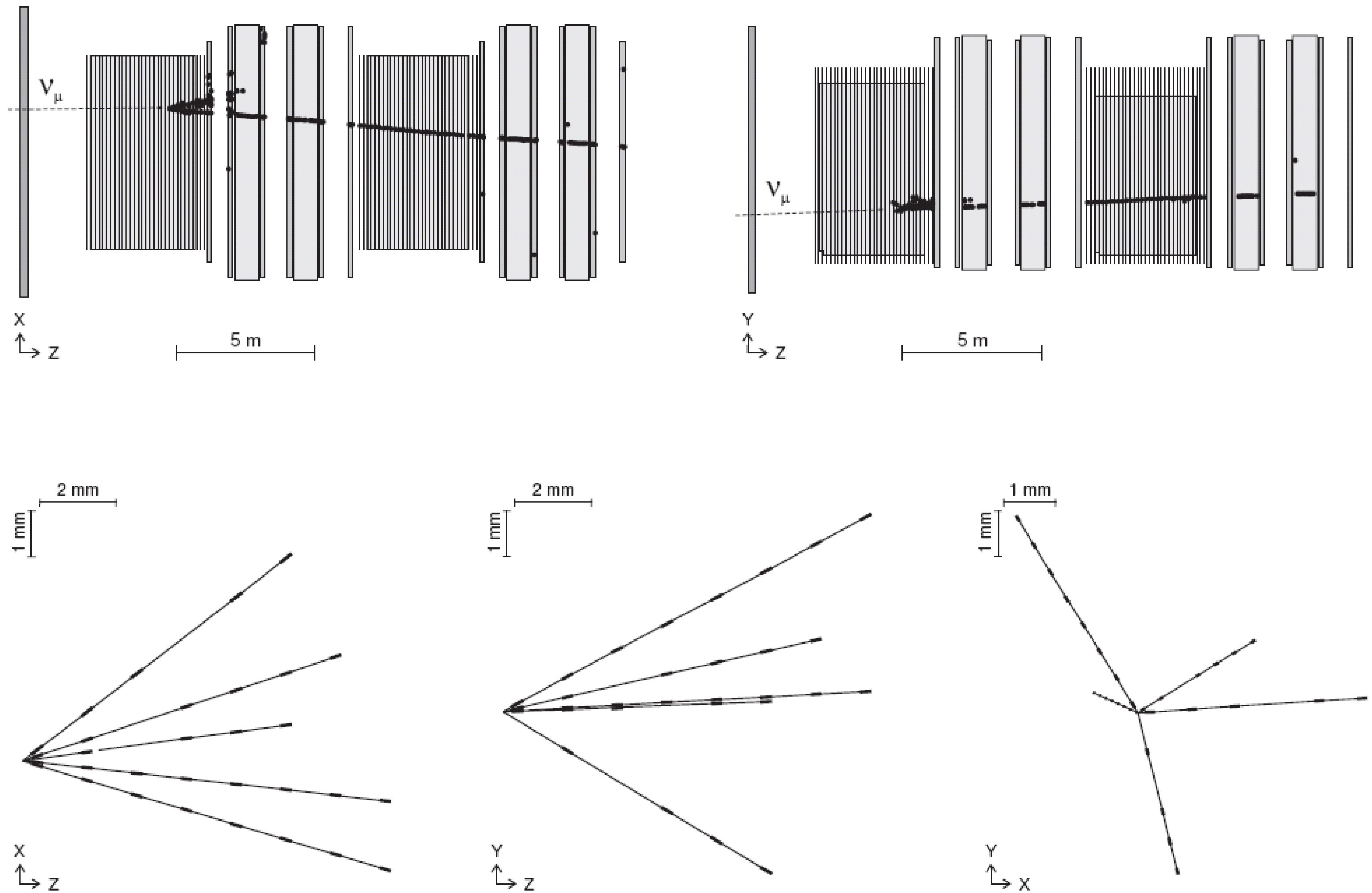
Most important background processes:

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

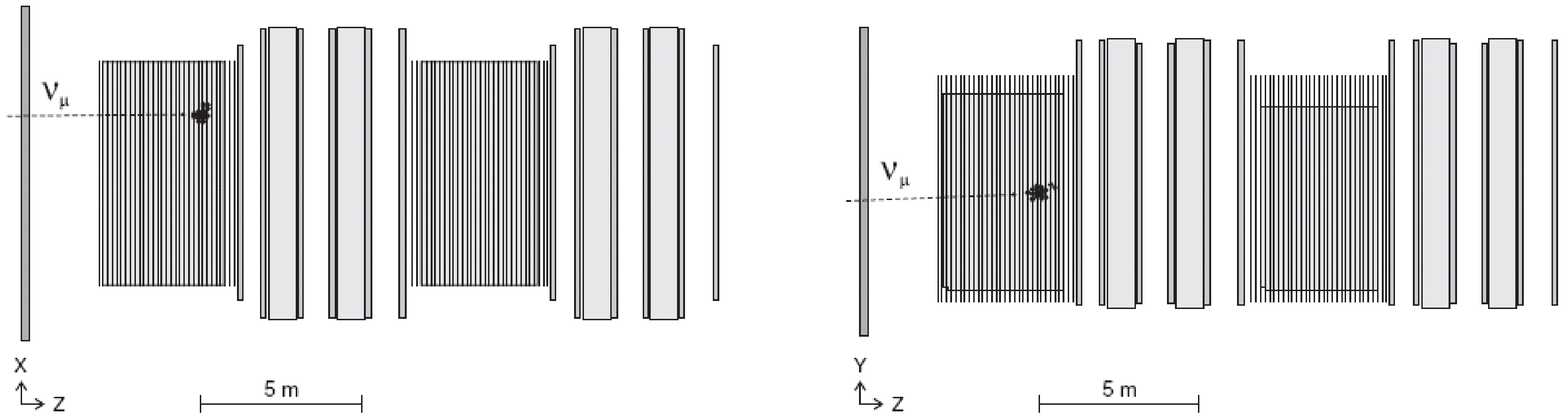
Overview expected events:

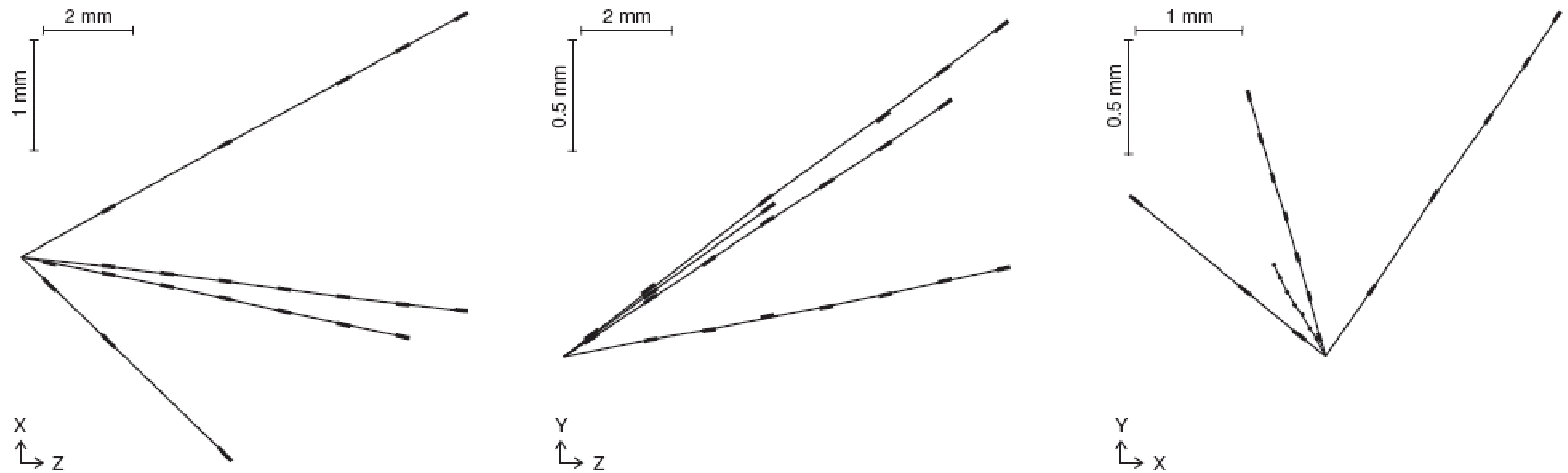
25000	ν interactions
120	ν_τ interactions
~10	identified ν_τ
<1	background

Example of real CC event:

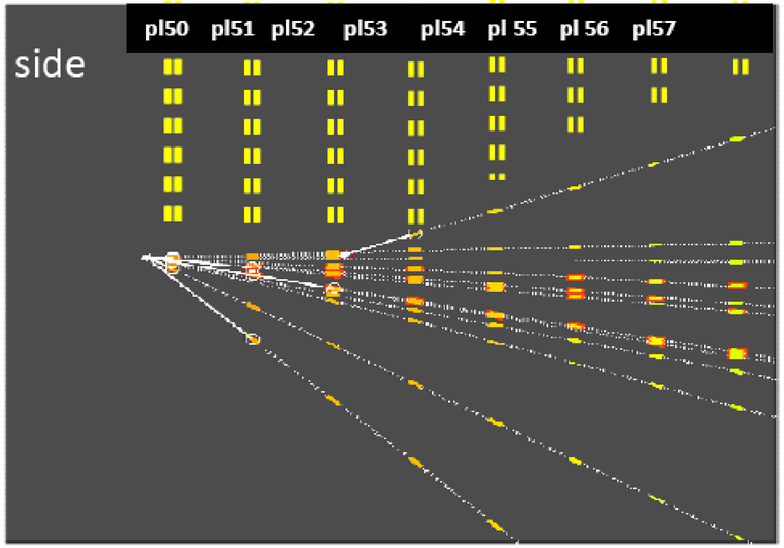


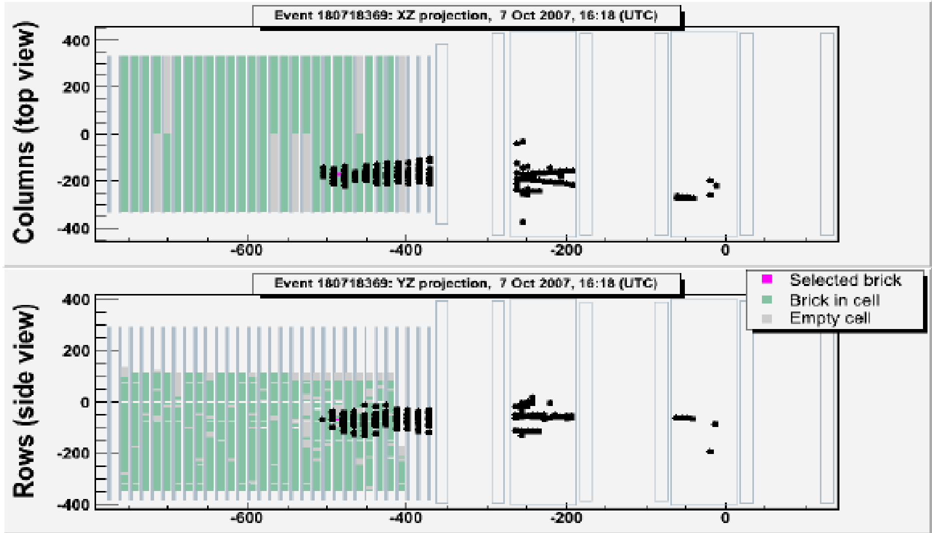
Example of real NC event:

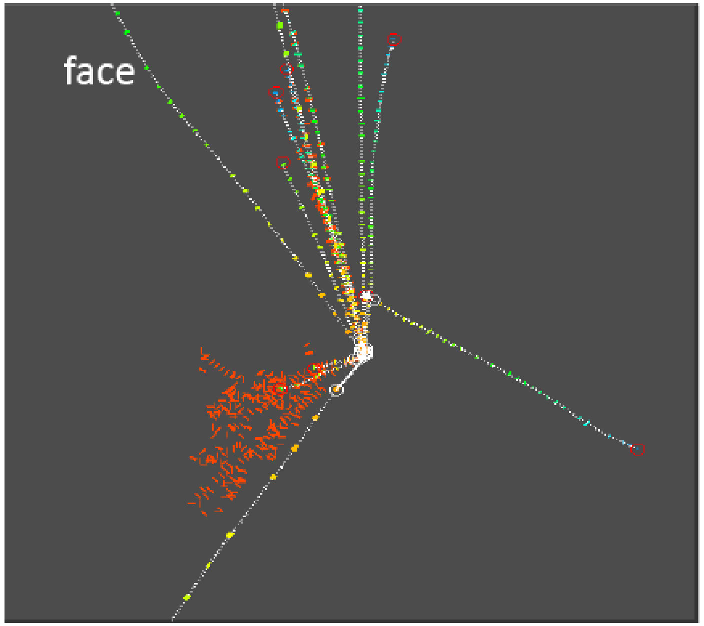




A Charm–Candidate







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 $P_T > 600$ MeV 7

OPERA summary:

- Detector (target) has been completed by July 2008

- First OPERA beam period june – november 2008:
  exposure: 1.8E19 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:
  2.2E19 pot collected up to now in 2009.
  outlook: 3.5E19 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