TECHNISCHE UNIVERSITÄT DRESDEN

Neutrino physics

K.Zuber, Bad Liebenzell 5-7.10.2011

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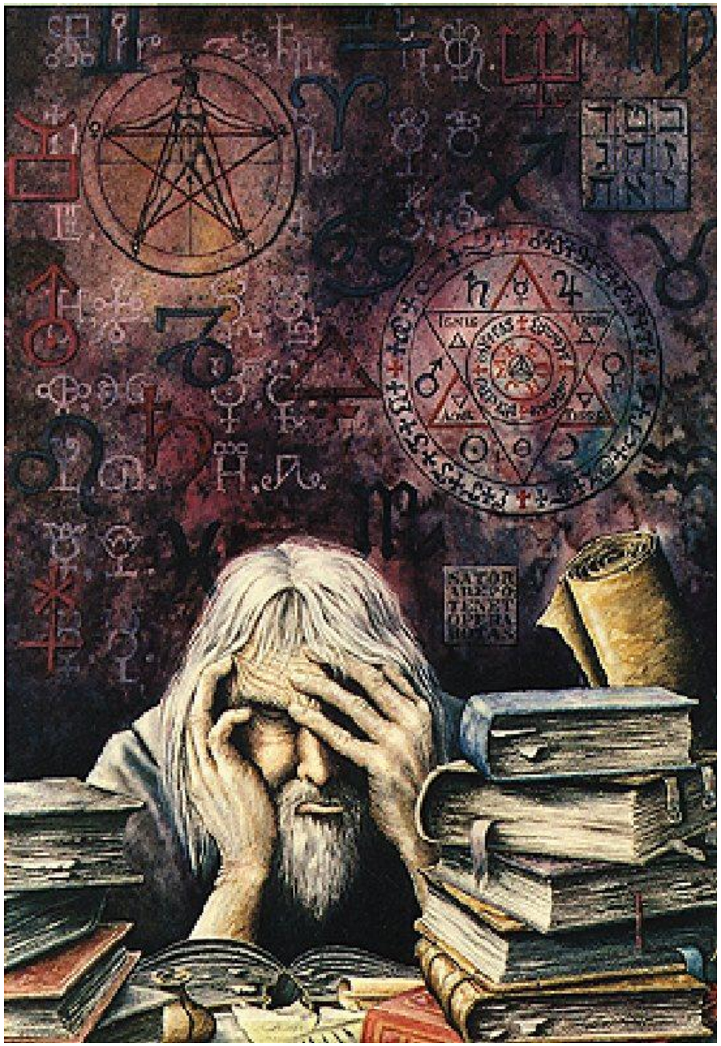
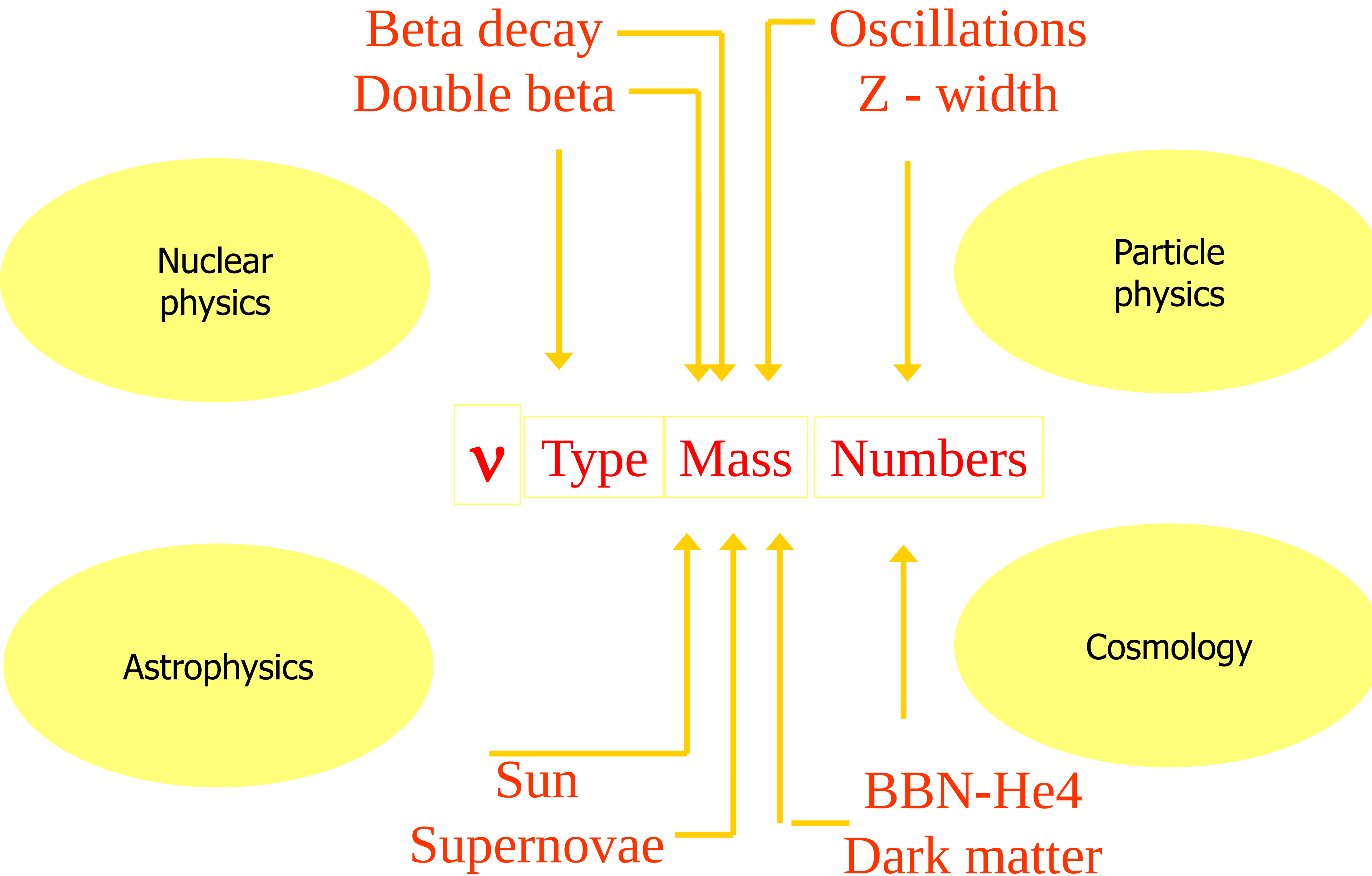
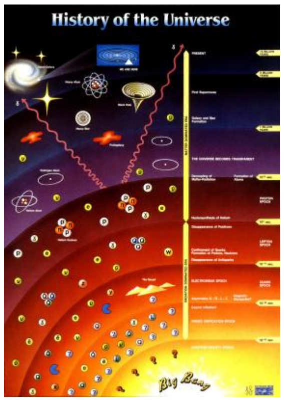


- ★ Lecture 1:
  Neutrinos in the Standard Model
  Evidence for neutrino masses (oscillations)
- ★ Lecture 2:
  Evidence for neutrino masses (c‘td)
  Absolute neutrino mass measurements
  (beta, double beta decay)
- ★ Lecture 3:
  What‘s next? Future activities
  Things to do

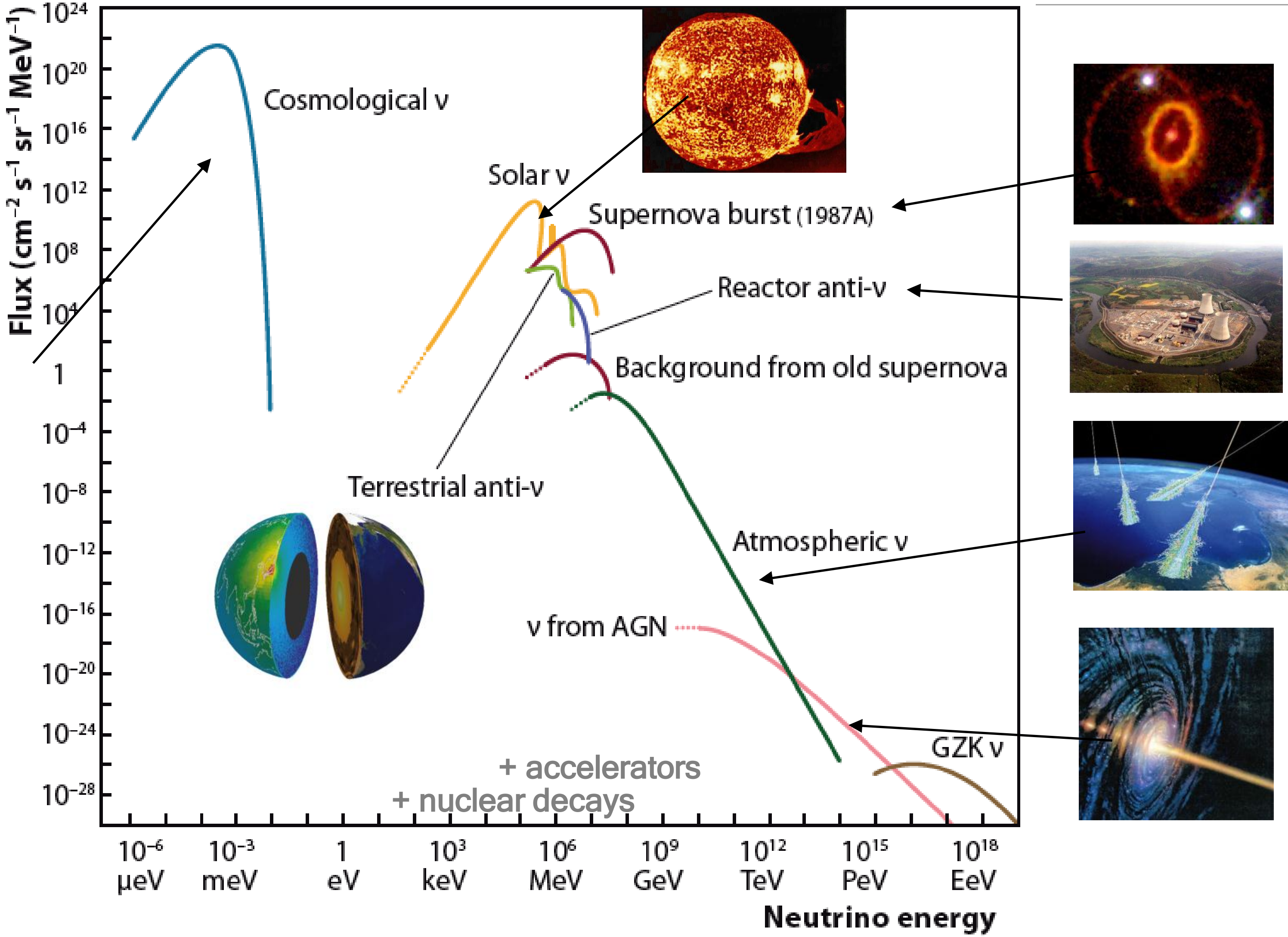
Neutrino Physics



Universal neutrino spectrum



1.95 K neutrino background

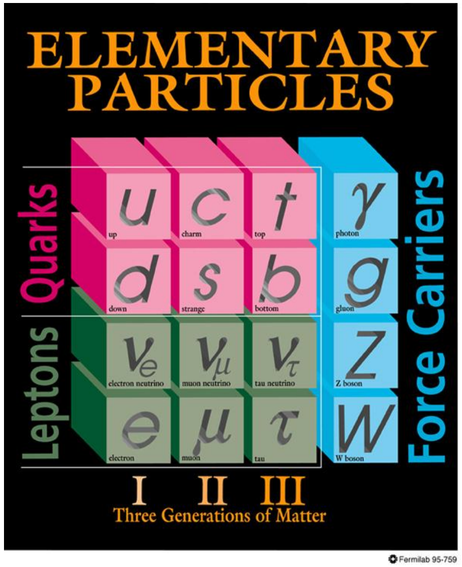


K. Zuber

Standard Model

Group theoretical structure: $SU(3) \otimes SU(2) \otimes U(1)$

QCD — Weak isospin — Hypercharge



$$Q = I_3 + \frac{Y}{2}$$

W-exchange $\updownarrow \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$

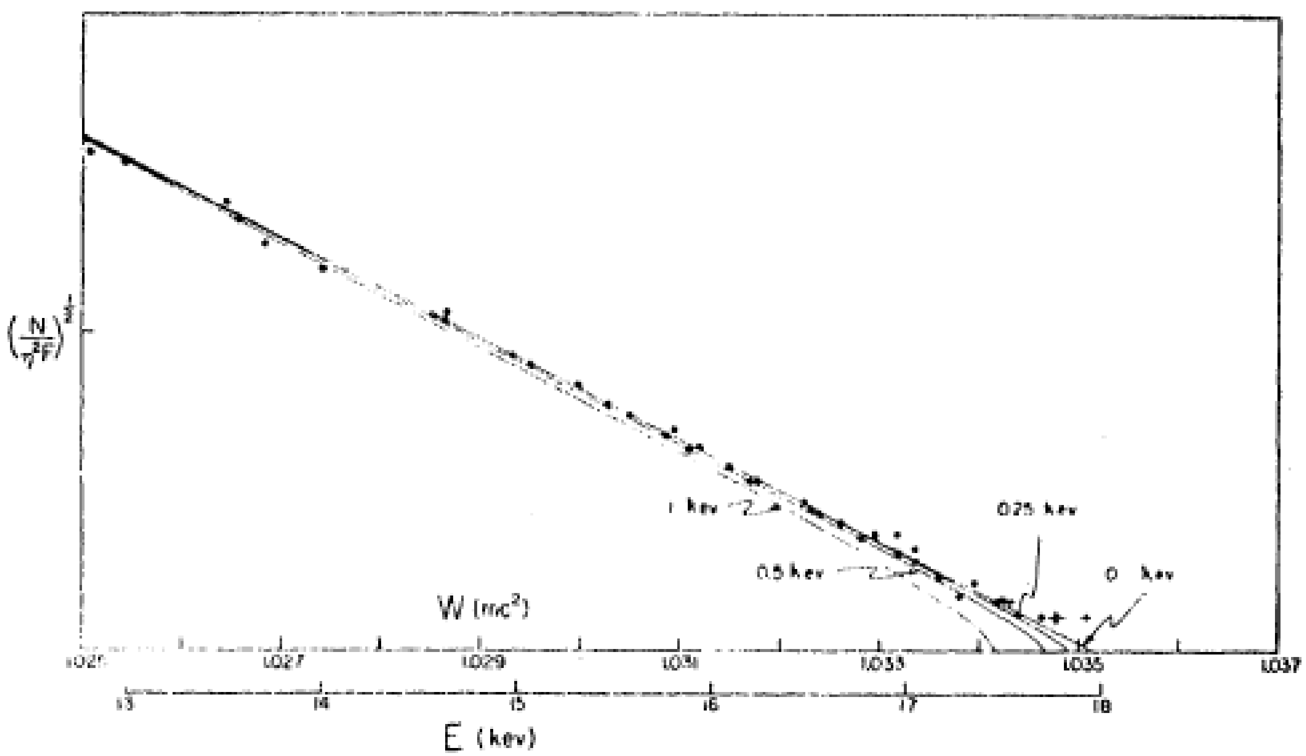
$$u_R \quad d_R \quad s_R \quad c_R \quad b_R \quad t_R \quad e_R \quad \mu_R \quad \tau_R.$$

Singlet states because there are no right handed weak charged currents

All particles are massless

Neutrino masses in SM

1952: Beta decay limit of m<250 eV ➔ Assumption for SM: Massless

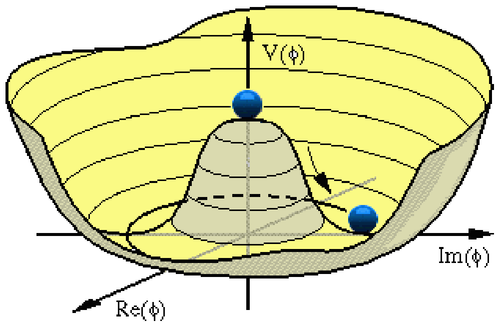


Langer, Moffat, Phys. Rev. 88, 689 (1952)

Why is the neutrino mass so small???

Fermion masses in SM

In general: Masses via spontaneous symmetry breaking – Higgs Mechanism



Doublet of complex scalar fields

$$\phi = \begin{pmatrix} \phi^{\dagger} \\ \phi^{0} \end{pmatrix}$$

Vacuum expectation value (VEV)

$$v = (\sqrt{2} G_F)^{-1/2} \approx 246 \text{ GeV}$$

Particle masses via coupling to Higgs VEV (for fermions = Yukawa- couplings)

$$\mathcal{L}_{\text{Yuk}} = -c_e \bar{e}_R \phi^{\dagger} \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} + h.c.$$

$$= -c_e \frac{v}{\sqrt{2}} \bar{e} e$$

m_e

Neutrino masses in SM

Easiest way: Include right-handed neutrino singlets in SM

$$\mathcal{L}_{\text{Yuk}} = -c_\nu \bar{\nu}_R \phi^\dagger \begin{pmatrix} \nu_{e_L} \\ e_L \end{pmatrix} + h.c.$$
$$= c_\nu \frac{v}{\sqrt{2}} \bar{\nu}\nu$$

Why is neutrino so much lighter?

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$
$$u_R \quad d_R \quad s_R \quad c_R \quad b_R \quad t_R \quad e_R \quad \mu_R \quad \tau_R.$$

$$\nu_{eR};\nu_{\mu R};\nu_{\tau R}$$

More symmetric solution

You have to explain why c_ν is so much smaller than the other couplings

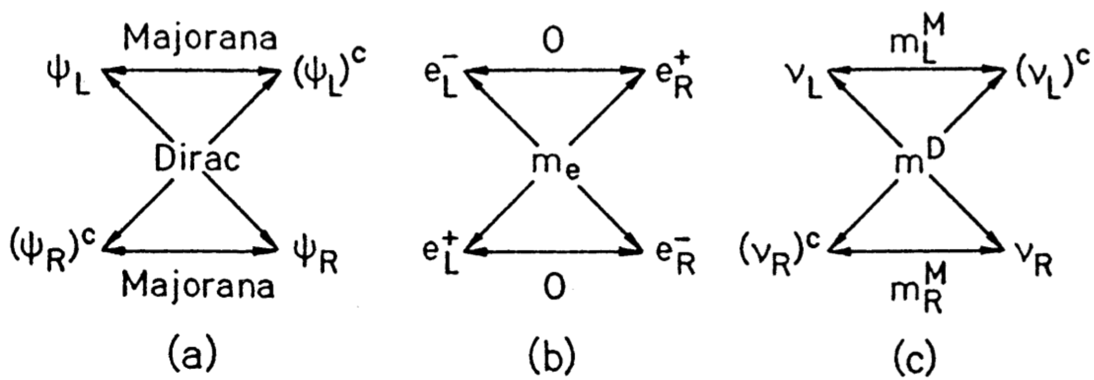
Neutrinos would be Dirac particles (4-state objects like the other fermions)

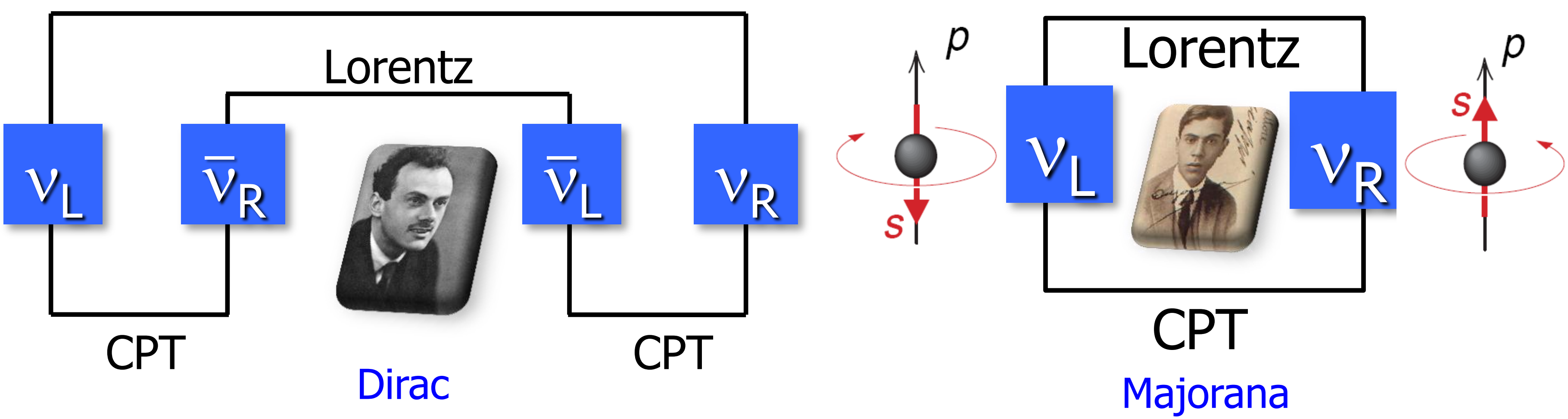
Is there a chance to generate neutrino masses without adding neutrino states?

Neutrino masses

Option: Couple neutrino to its charge conjugate,
consequence lepton number violation – Majorana neutrinos

Lorentz-scalars: $\overline{\Psi}\Psi, \overline{\Psi}^C\Psi^C, \overline{\Psi}^C\Psi, \overline{\Psi}\Psi^C$

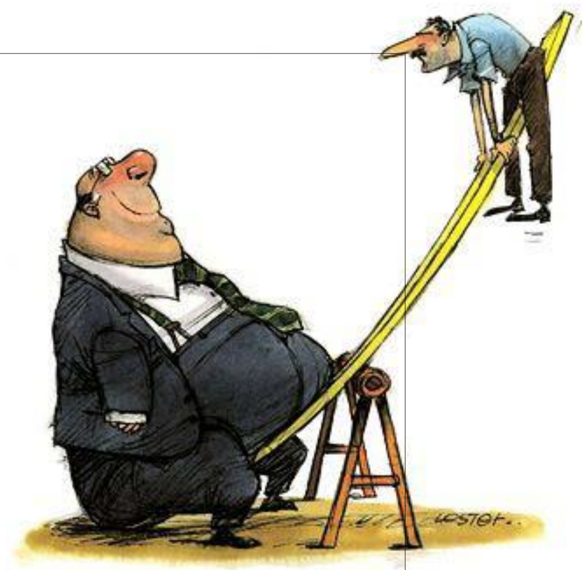




Neutrino masses

Master equation $2 \otimes 2 = 3 \oplus 1$

$\Rightarrow$ (1, 0) or (3, 2) or (3, 0)



Why is neutrino so much lighter?
See-saw mechanism

a) Introduce fermion singlet N_R (type I)
N_R with Majorana mass term

$$m_\nu \approx \frac{m_D^2}{M_R}$$

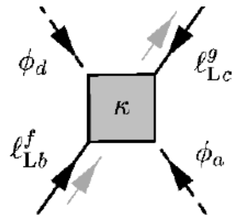
b) Introduce higgs triplet Δ_L (type II) $\begin{pmatrix} \Delta^0 \\ \Delta^- \\ \Delta^{--} \end{pmatrix}$
Vev: $v_T << v$

$$v_T = \frac{\mu v^2}{M_\Delta^2}$$

c) Introduce fermion triplets Σ (type III)
hyperchargeless

$$m_\nu \approx \frac{(m_D^\Sigma)^2}{M_\Sigma}$$

d) Higher dimensional operator



d=5

Weinberg 1979

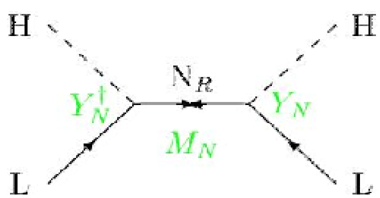
$$\frac{1}{\Lambda} O_5 \rightarrow m_\nu = \frac{cv^2}{2\Lambda} \longrightarrow \Lambda \geq c\left(\frac{0.1eV}{m_\nu}\right) 10^{14} GeV$$

Neutrino masses

The 3 basic seesaw models

i.e. tree level ways to generate the dim 5 operator

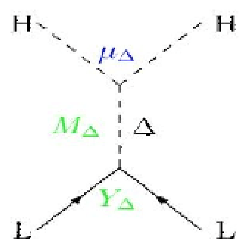
Right-handed singlet:
(type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida; Glashow; Mohapatra, Senjanovic

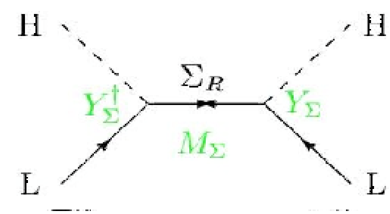
Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Fermion triplet:
(type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; Ma; Ma, Roy; T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

slide by T. Hambye

Neutrino masses

What if neutrinos have a non-vanishing rest mass ?

➔ Physics beyond the Standard Model

•Of course a lot of new things can be explored (absolute mass, magnetic moments, decays ...)

• Weak eigenstates could be different from mass eigenstates like in quark sector – neutrino mixing (PMNS matrix analog to CKM-matrix)

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

c=cos Θ, s=sinΘ

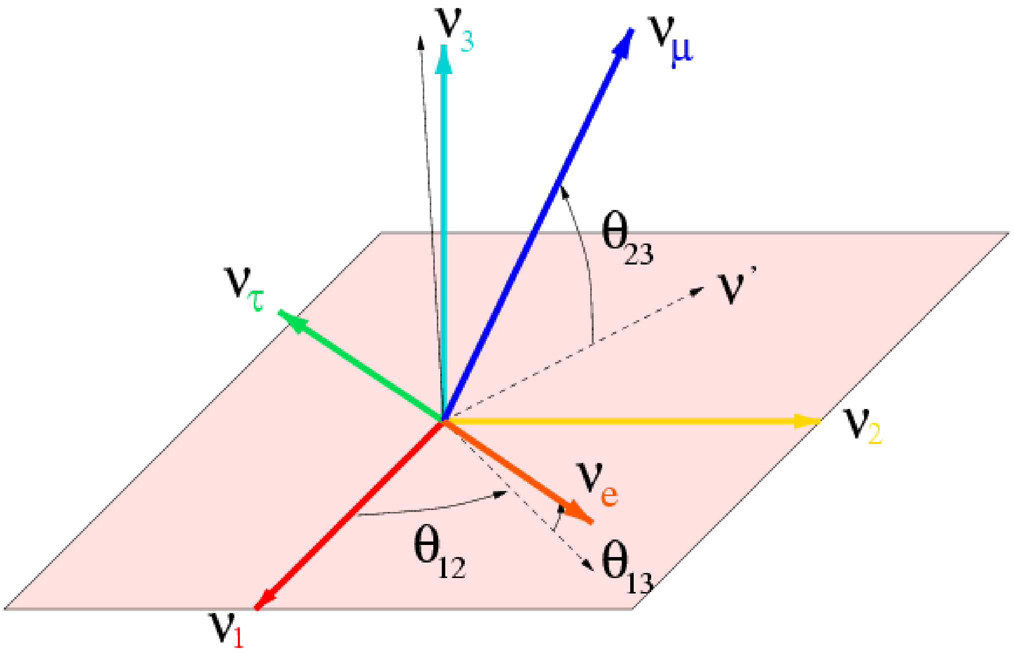
The twofold way....

- ★ Precision determination of mixing matrix elements (PMNS), CP violation in lepton sector
- ★ Absolute neutrino mass measurement

See also lecture 2

Neutrino mixing

Known in the quark - sector for more than 40 years



$$|\nu_i\rangle = \sum U_{\alpha i} |\nu_\alpha\rangle$$

2 Flavour Scenario

$$U = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix}$$

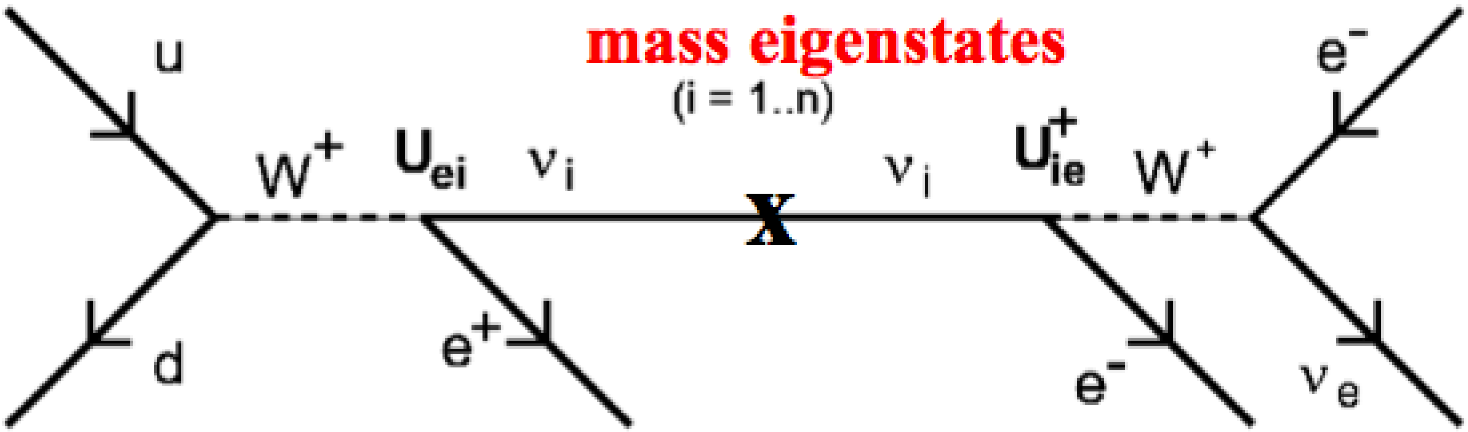
3 Flavour Scenario

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Neutrino mixing

E. Akhmedov, A. Smirnov, arXiv:1008.2077
E. Akhmedov, J. Kopp, arXiv:1001.4815
E. Akhmedov, A. Smirnov, arXiv:0905.1903

Production | Propagation | Detection



$p + p \to d + \nu_e + e^+$
solar fusion process ➔ ν_e

electron scattering
➔ projection on ν_e

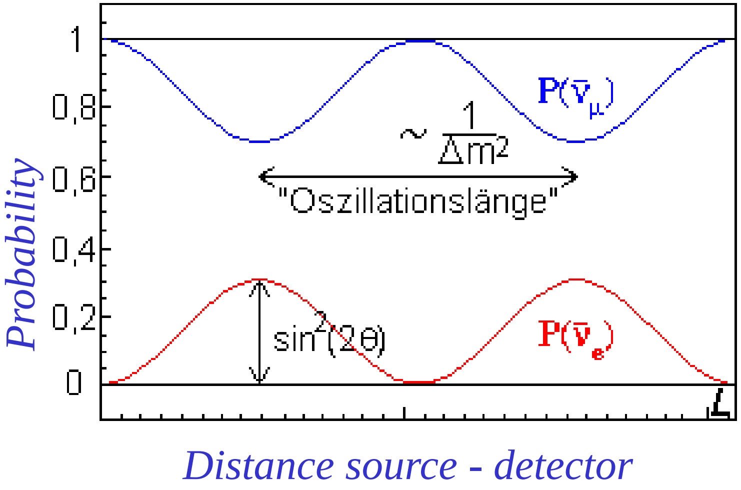
$$A_{ee} = \sum |U_{ei}|^2 e^{ip_i x} = \dots$$

After M. Lindner

Neutrino Mixing

Oscillation probability:

$$P(|\nu_\alpha\rangle \rightarrow |\nu_\beta\rangle) = \sin^2 2\Theta \sin^2(1.27\Delta m^2 \frac{L}{E})$$



with $\Delta m^2 = m_2^2 - m_1^2$

Sensitivity $\Delta m^2 \propto \frac{E}{L}$

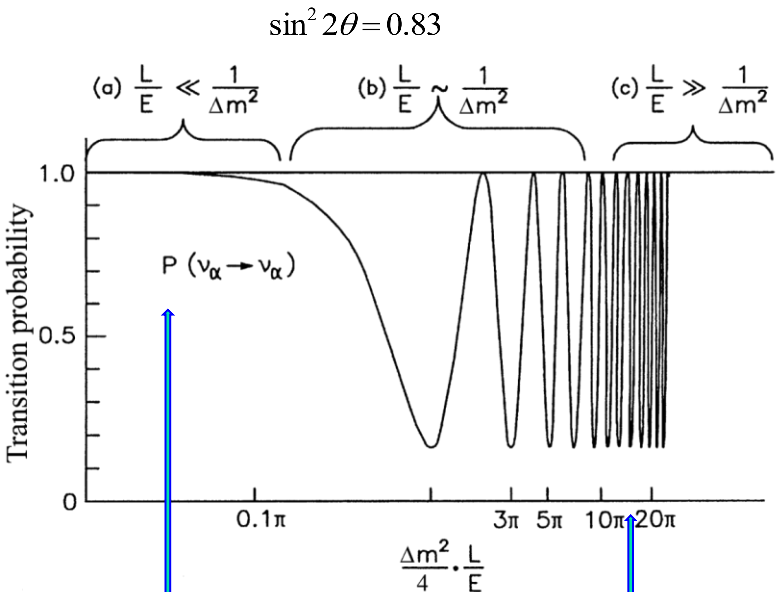
2 unknown Parameters: $\sin^2 2\theta$, Δm^2

No absolute neutrino mass measurement!

Oscillation search

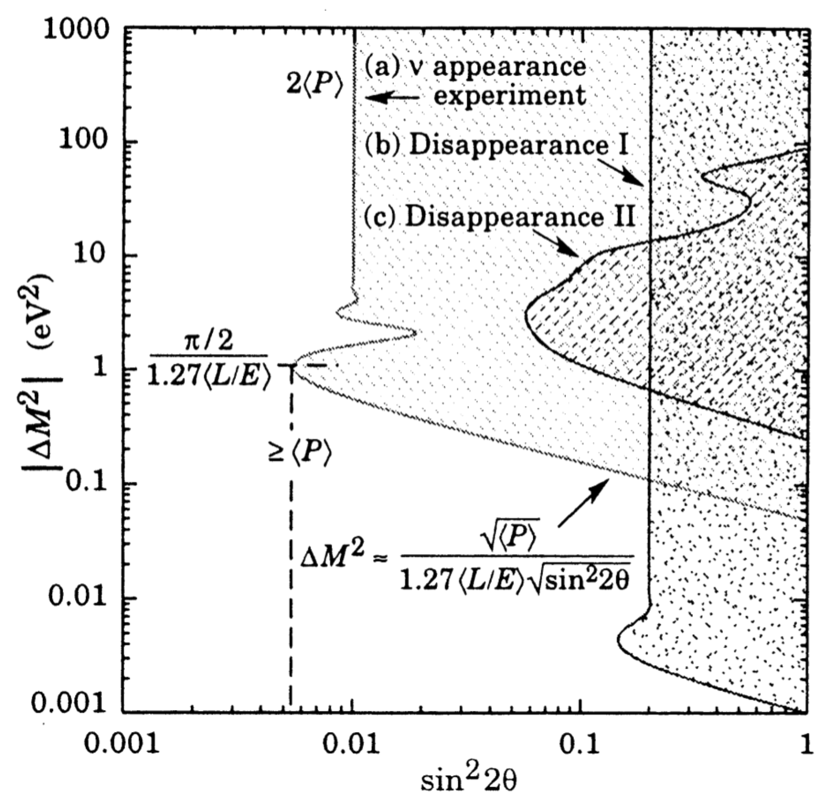
Disappearance: Reduction of original flavour

Appearance: New flavour not present at source

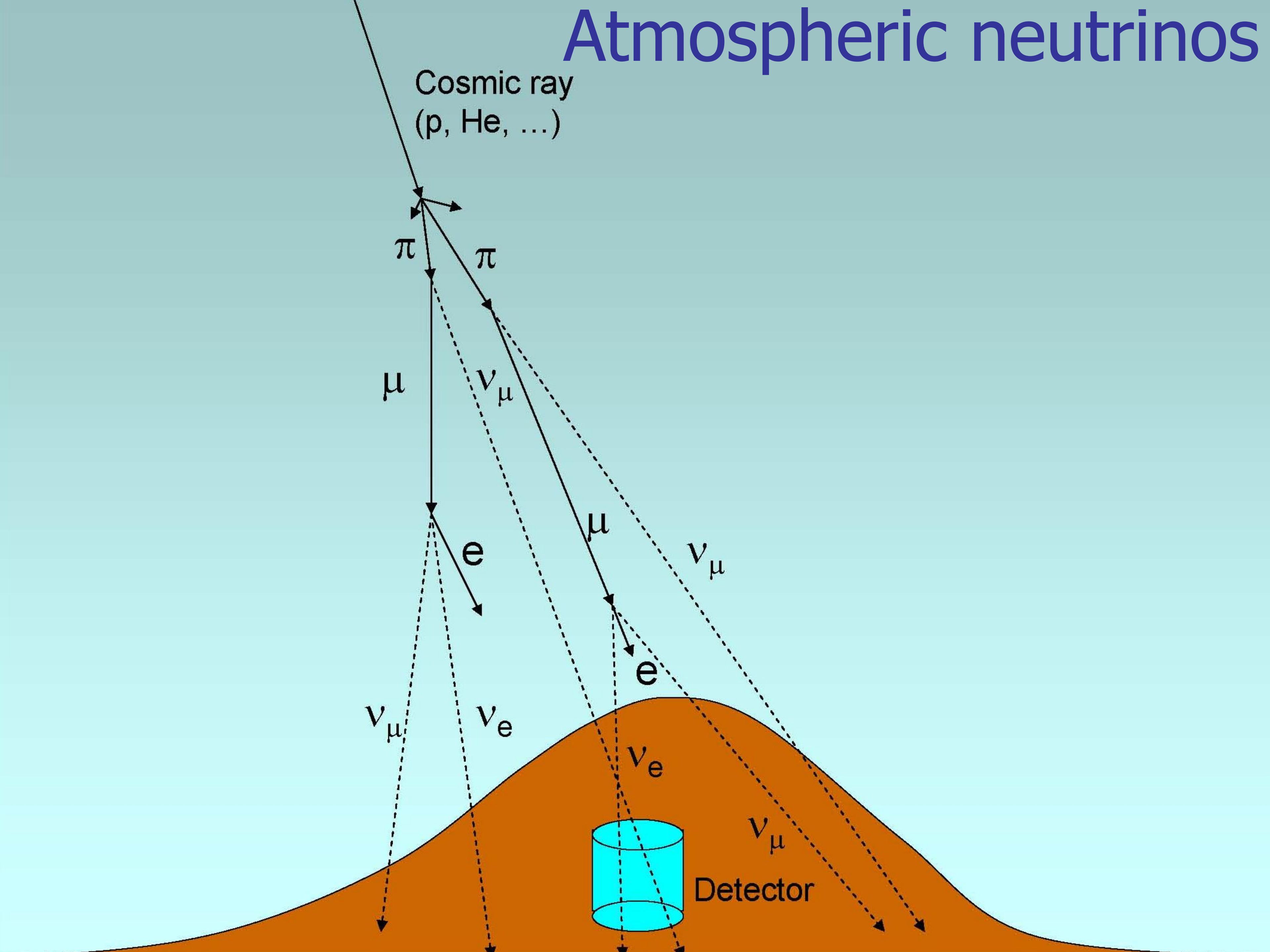


Oscillations haven't started

Average

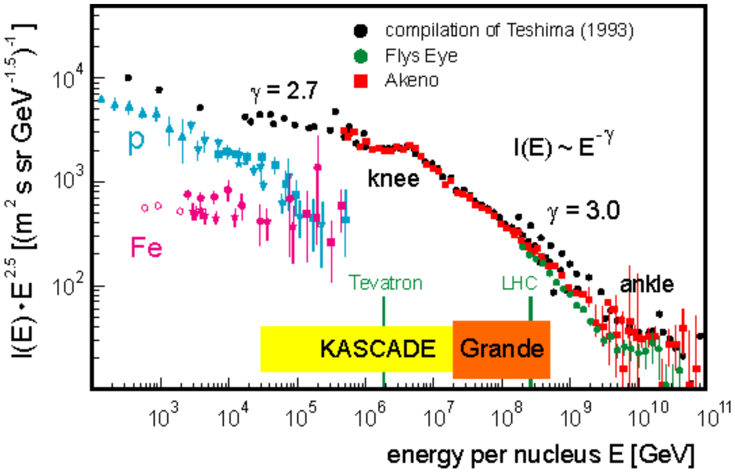


Atmospheric neutrinos

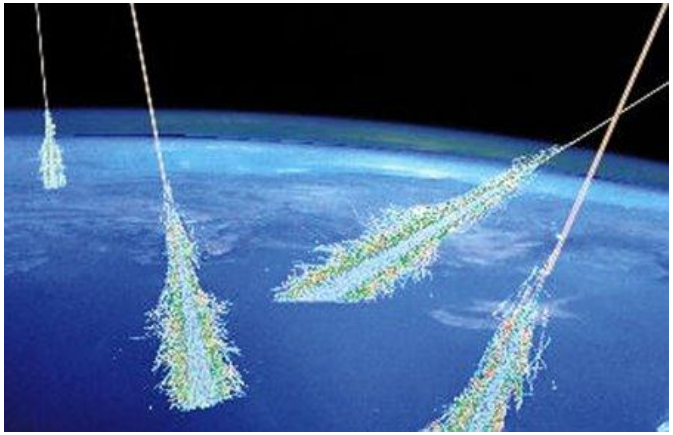


Atmosperic neutrinos

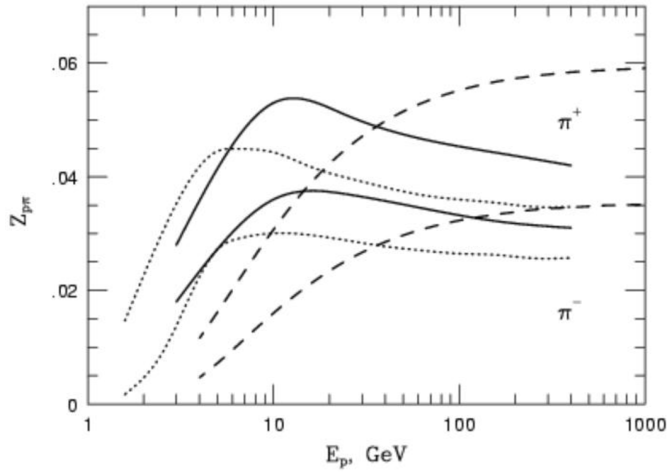
The beam



The target

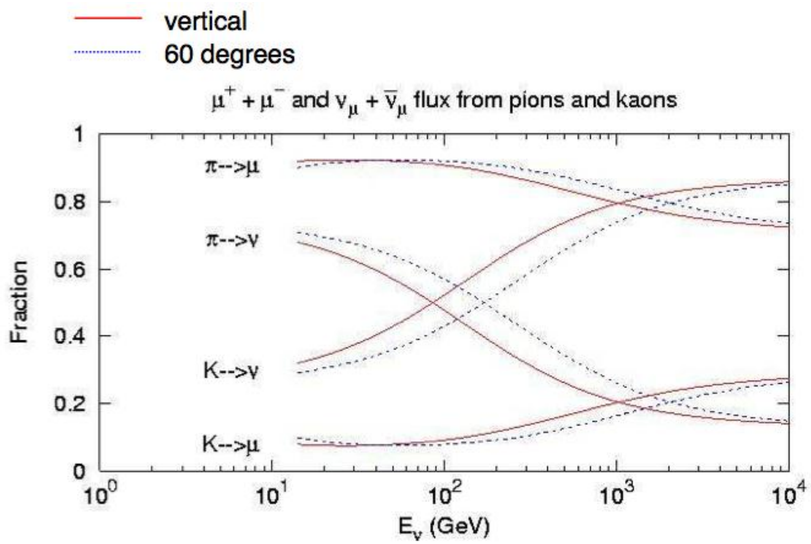


The ingredient

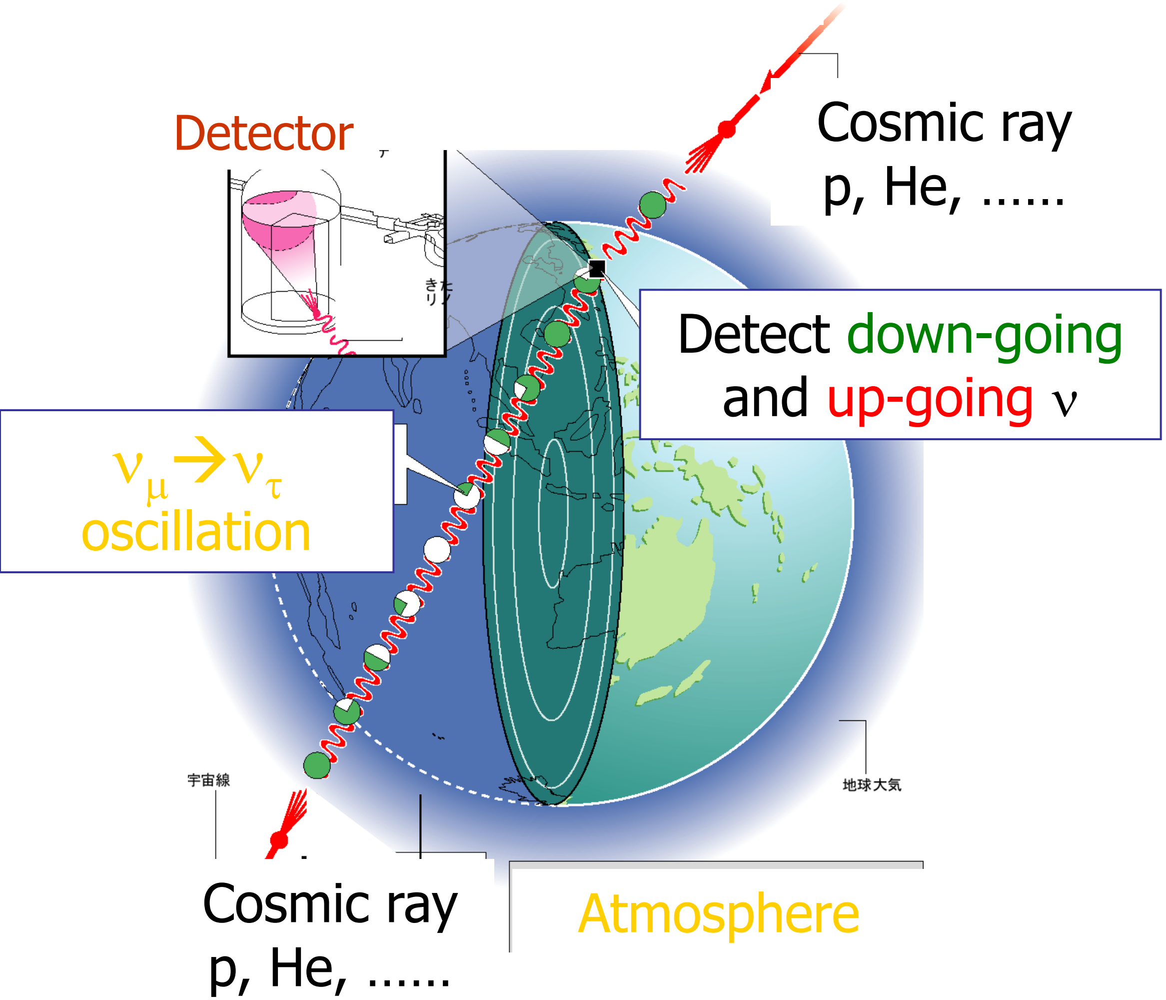


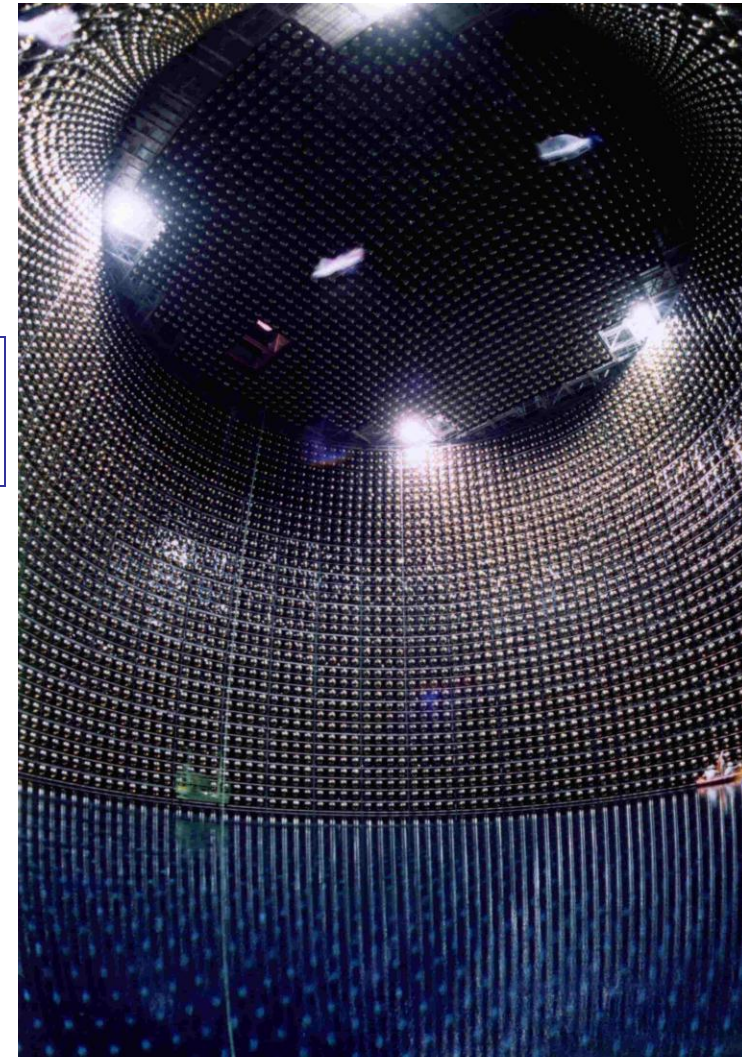
$$Z_{ab} \equiv \int \xi^{(\gamma-1)} F_{ab}(\xi)\, d\xi$$

The result



Super-Kamiokande

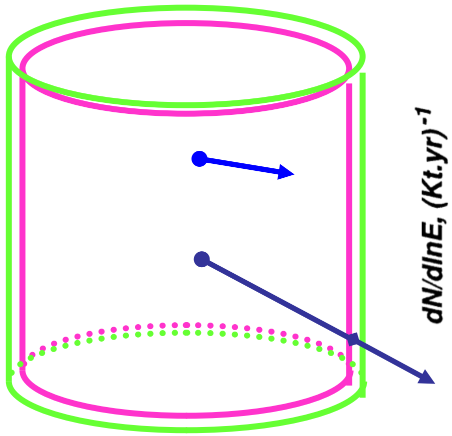


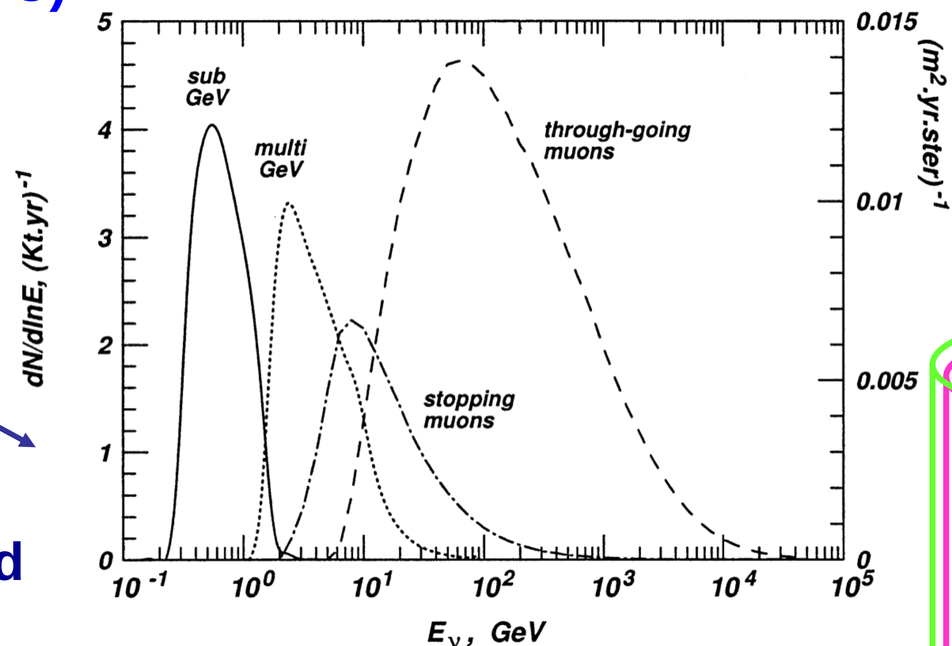


50 kt water Cerenkov detector

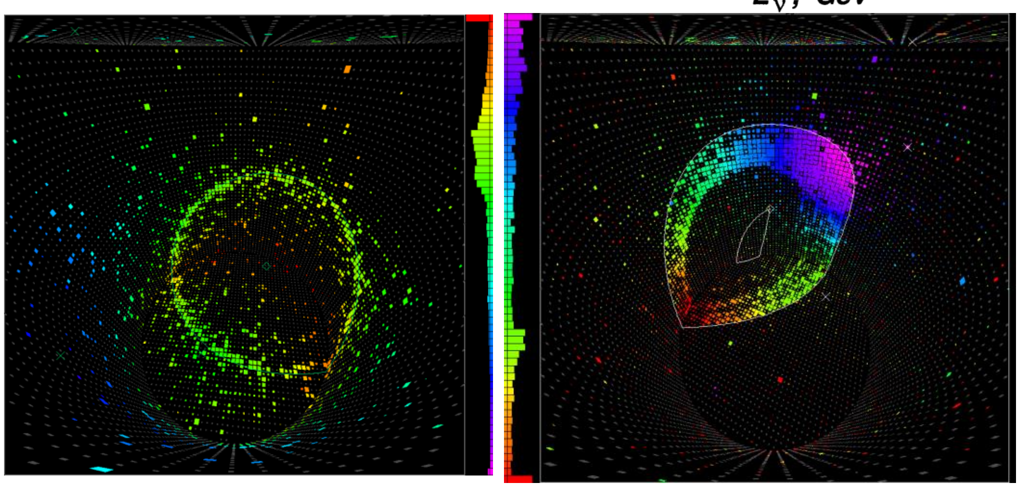
Event classes

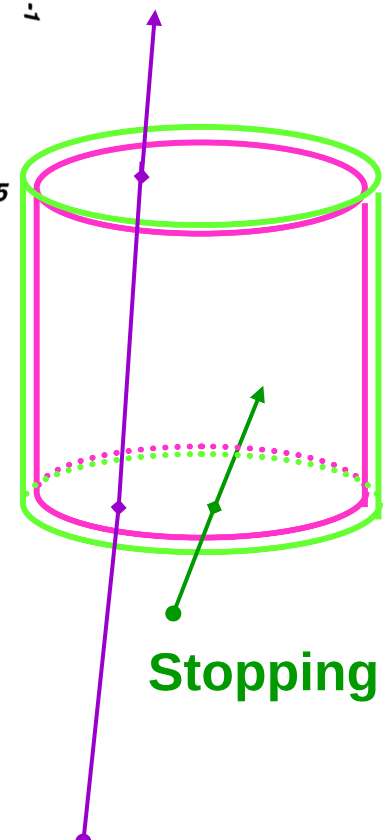
Fully Contained (FC)





Partially Contained (PC)

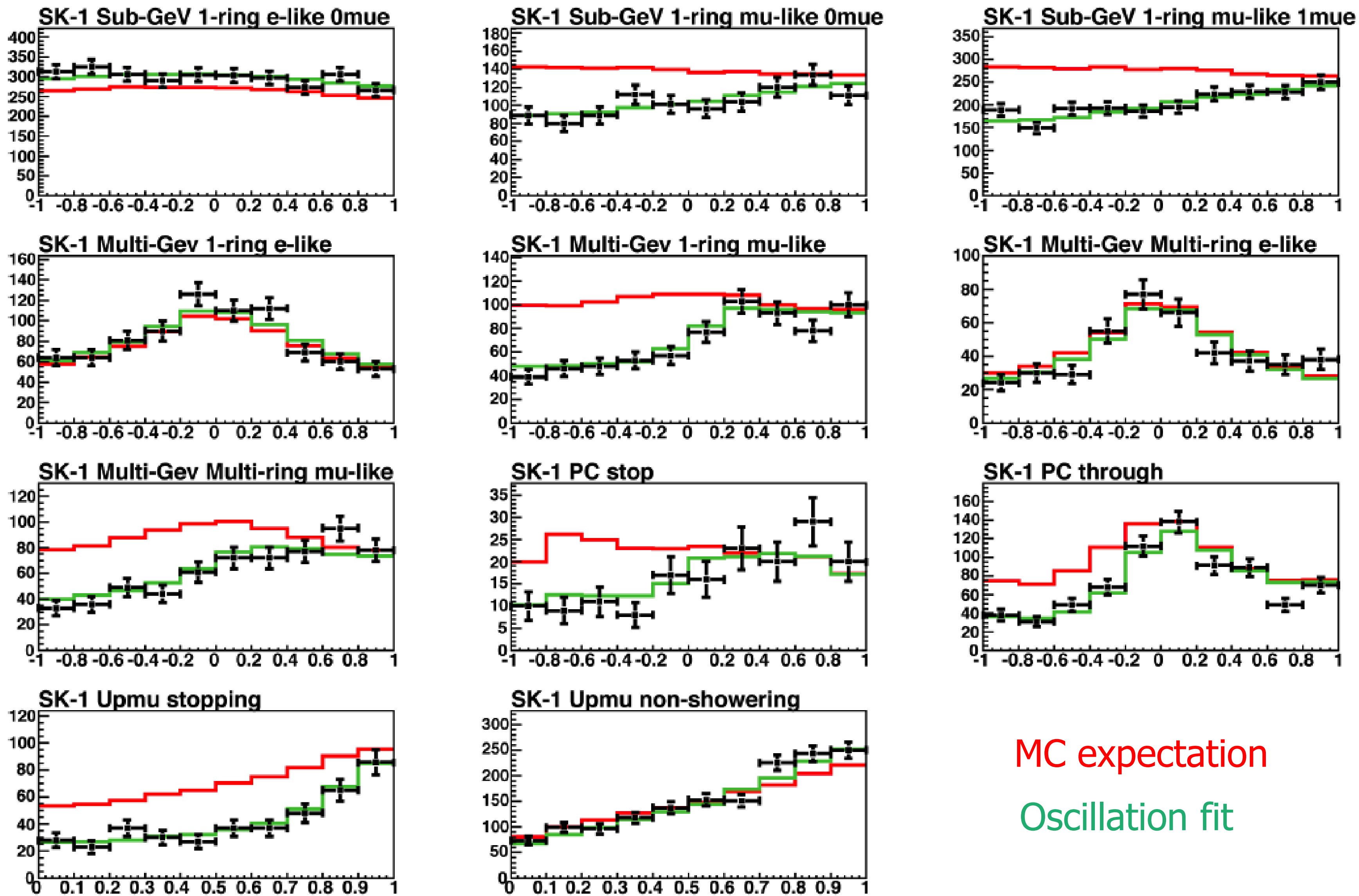




Stopping μ

Through-going μ

Zenith angle distribution

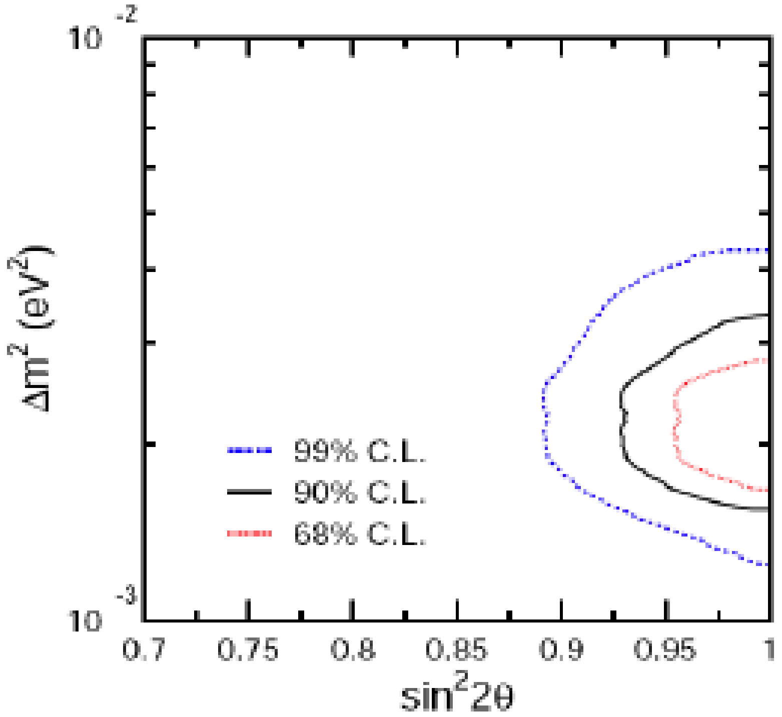


MC expectation

Oscillation fit

Super-K atmospheric

Nowadays linked to Θ_{23} and Δm^2_{23}

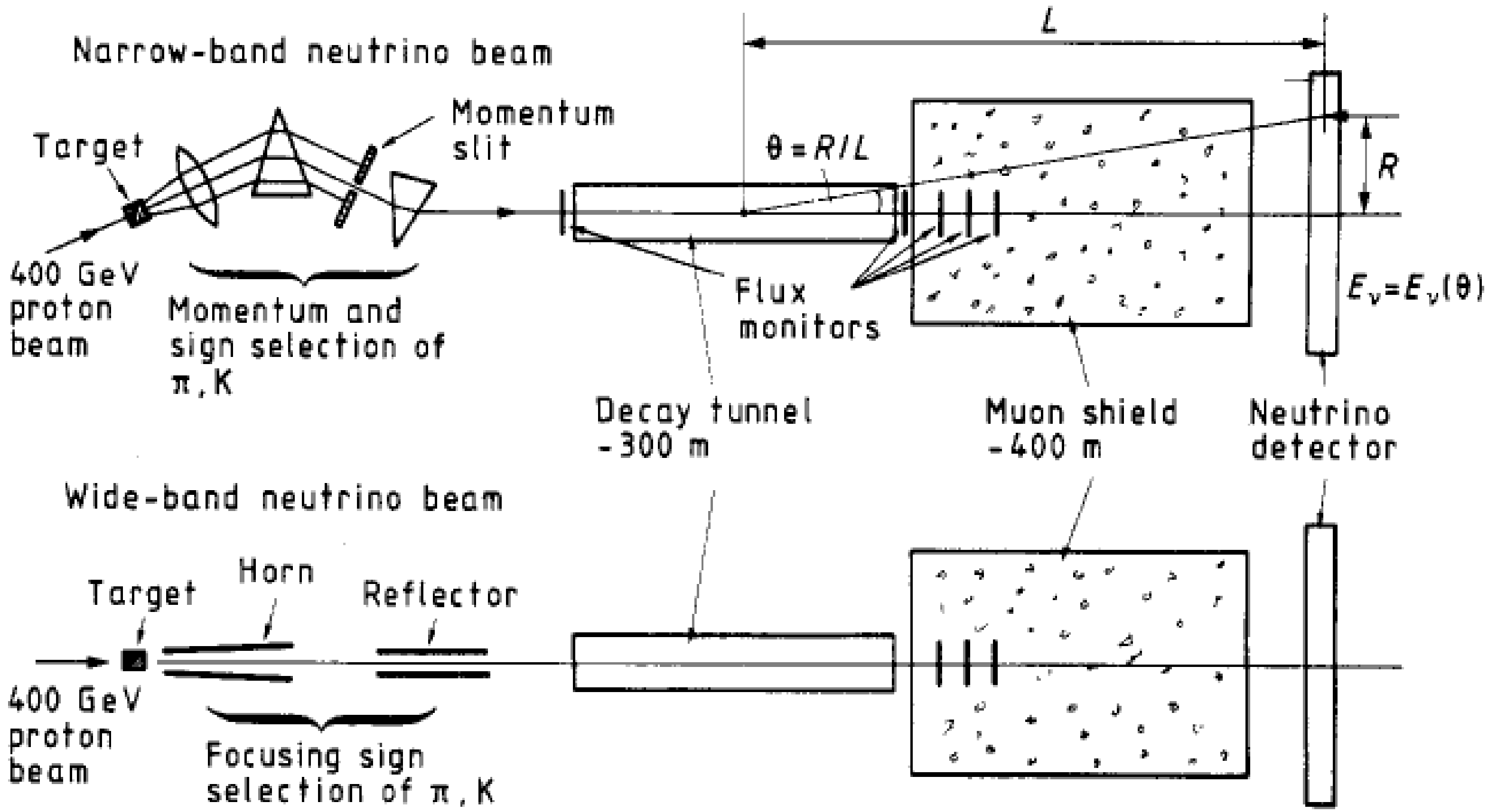


$$\sin^2 2\theta > 0.92 (90\% CL)$$

$$1.5\times10^{-3} < \Delta m^2 < 3.4\times10^{-3} eV^2$$

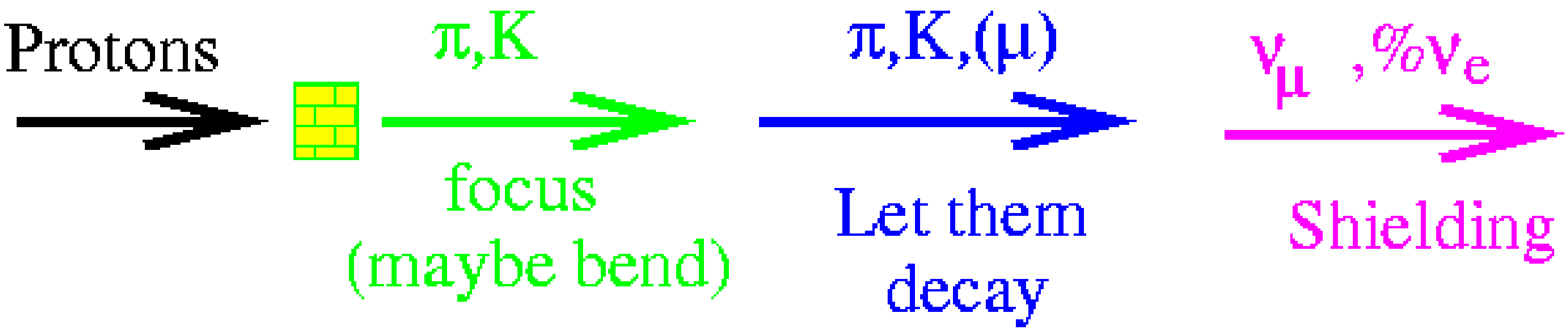
Neutrino beams

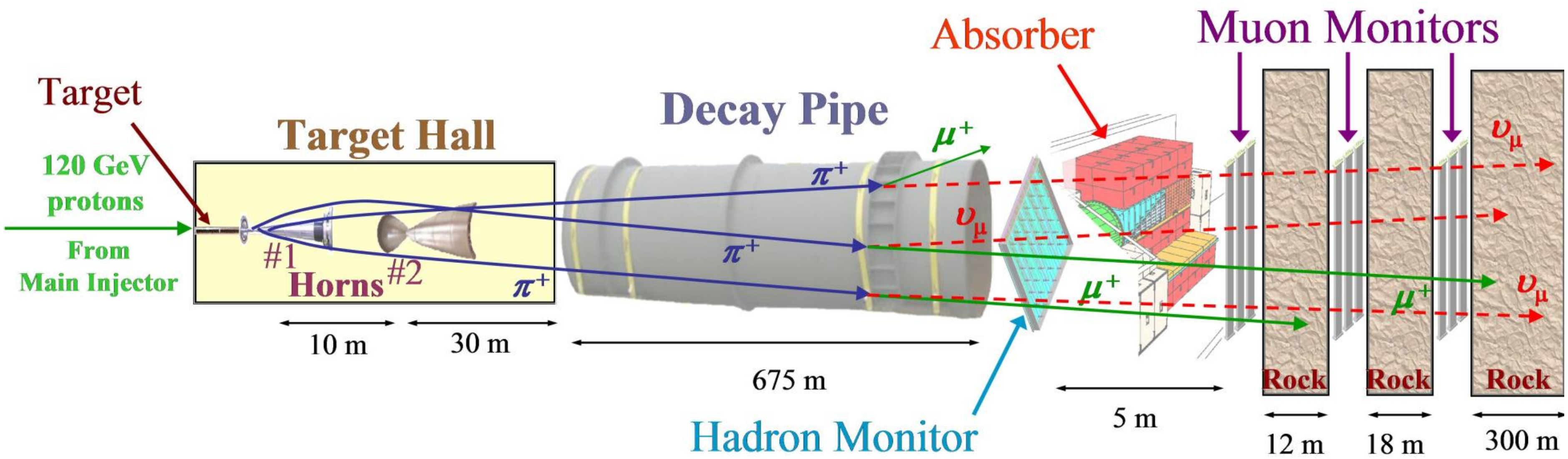
NBB: monochromatic neutrinos, small flux
WB: energy spectrum of neutrinos, high flux



F. Eisele, Rep. Prog. Phys. 49, 233 (1986)

Example beam (MINOS)





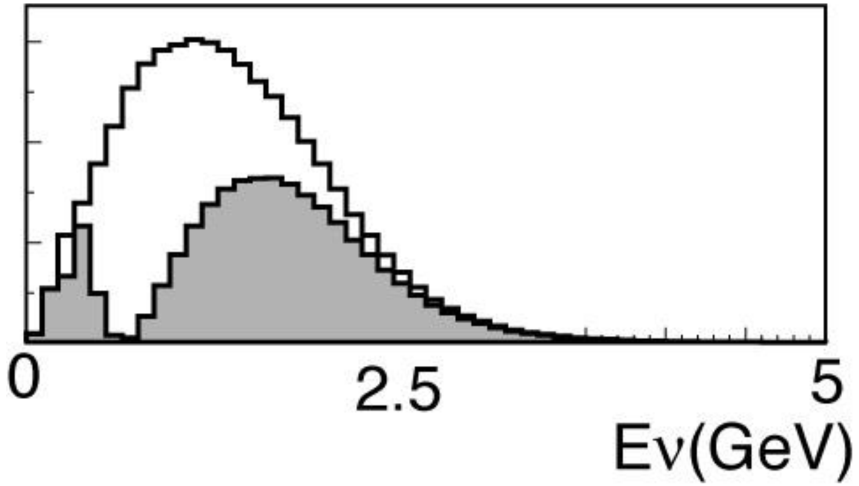
Major problem: Precise knowledge of neutrino energy spectrum at experiment

K2K

mean neutrino energy: 1.4 GeV

ν_μ disappearance experiment

Baseline: 235 km



K2K near neutrino detectors

SciBar detector

Full active scintillator tracker

CH target (9.38t fid. vol.)

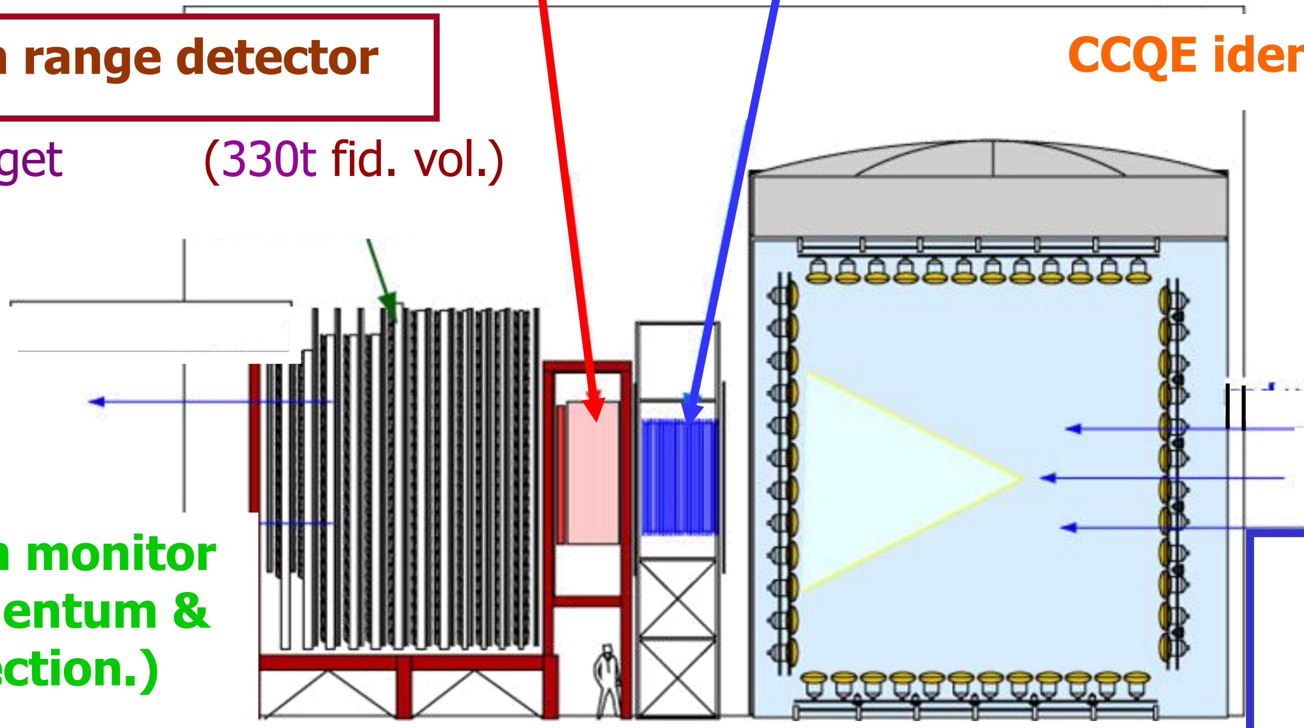
Scintillating fiber tracker

water target (6t fid. vol.)

Muon range detector

Iron target (330t fid. vol.)

CCQE identification



ν beam

νbeam monitor (momentum & direction.)

1kt water Cherenkov detector

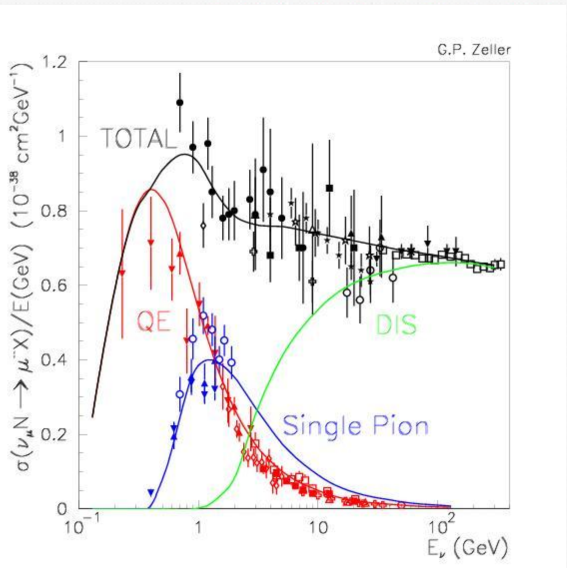
water target

(25t fiducial volume)

Neutrino-Nucleon QEL

- Form factors introduced since proton, neutron not elementary.
- Depend on vector and axial weak charges of the proton and neutron.
- Two hypotheses determine form factors: Conservation of Vector Current (CVC) and Partial Conservation of Axial Current (PCAC)

$$F_V(q^2) = \frac{F_V(0)}{\left(1 - q^2/0.71\right)^2} \qquad F_A(q^2) = \frac{F_A(0)}{\left(1 - q^2/1.065\right)^2}$$



$$F_V(0) = 1$$

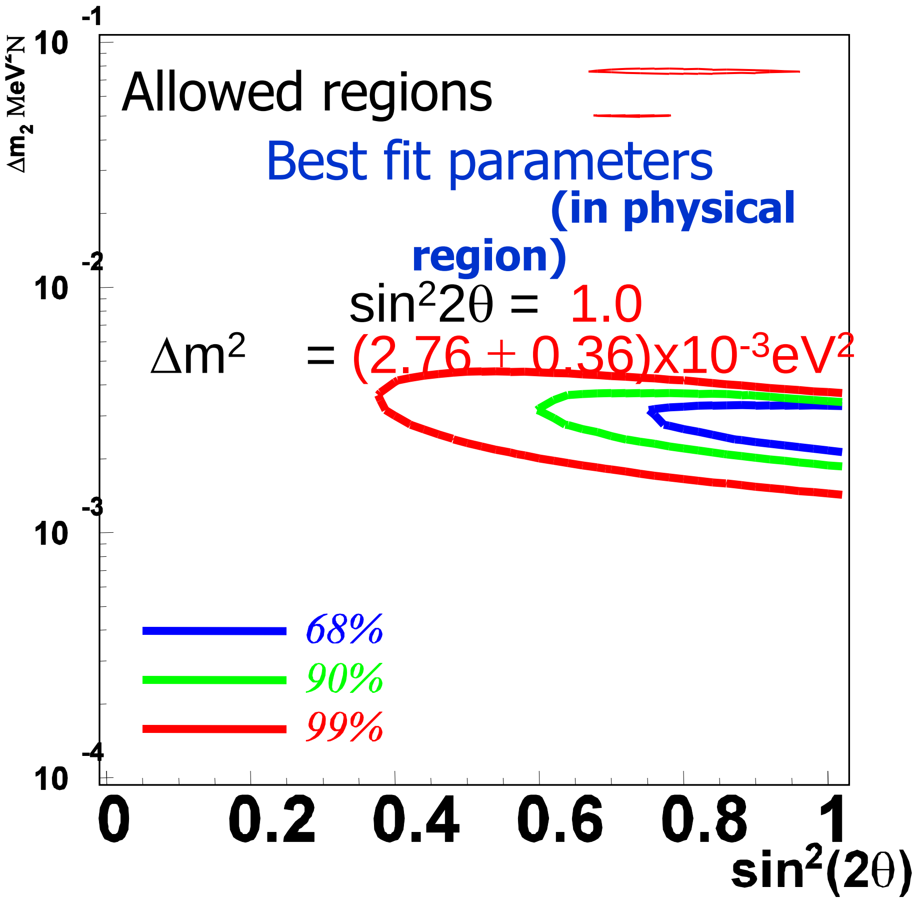
$$F_A(0) = g_A = -1.2573 \pm 0.028$$

- For low energy ν ($E_\nu \ll m_N$):

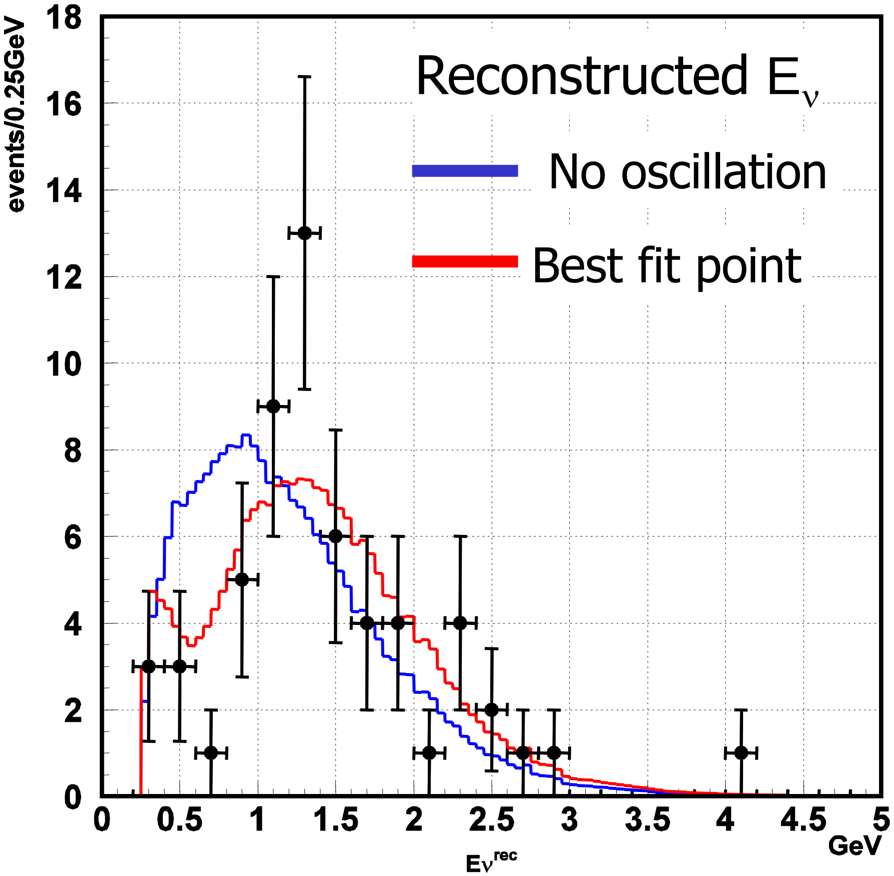
$$\sigma(\nu_e n) = \sigma(\bar{\nu}_e p) = \frac{\left(G_F \cos\theta_C\right)^2 E_\nu^{\,2}}{\pi}\left[F_V(0)^2 + 3F_A(0)^2\right] \approx 9.75\times 10^{-42}\left(\frac{E_\nu}{10\,MeV}\right)^2 cm^2$$

QE scattering crucial for next generation of neutrino oscillation experiments!!

K2K results

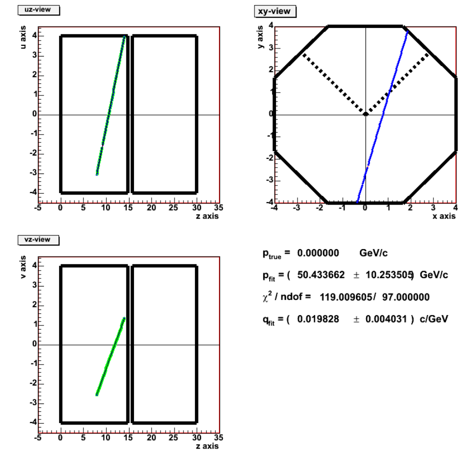


Allowed regions
Best fit parameters
(in physical region)
$\sin^2 2\theta = 1.0$
$\Delta m^2 = (2.76 \pm 0.36) \times 10^{-3} eV^2$
68%
90%
99%
Δm_2 MeV^{2}N
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
$\sin^2(2\theta)$



Reconstructed E_ν
No oscillation
Best fit point
events/0.25GeV
$E\nu^{rec}$
GeV
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
2
4
6
8
10
12
14
16
18

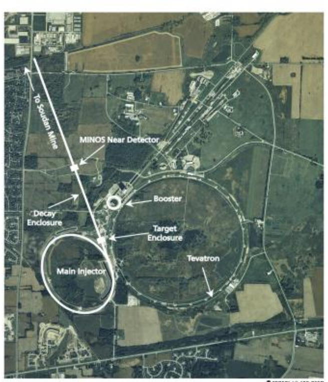
MINOS



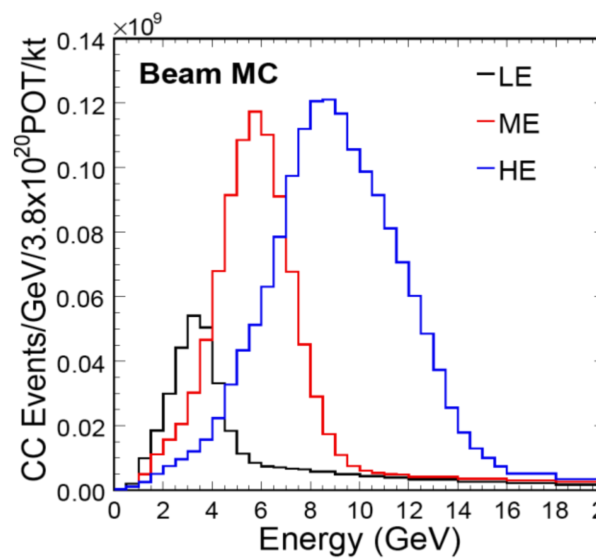
5.4 kt magnetized
iron spectrometer

Disappearance experiment

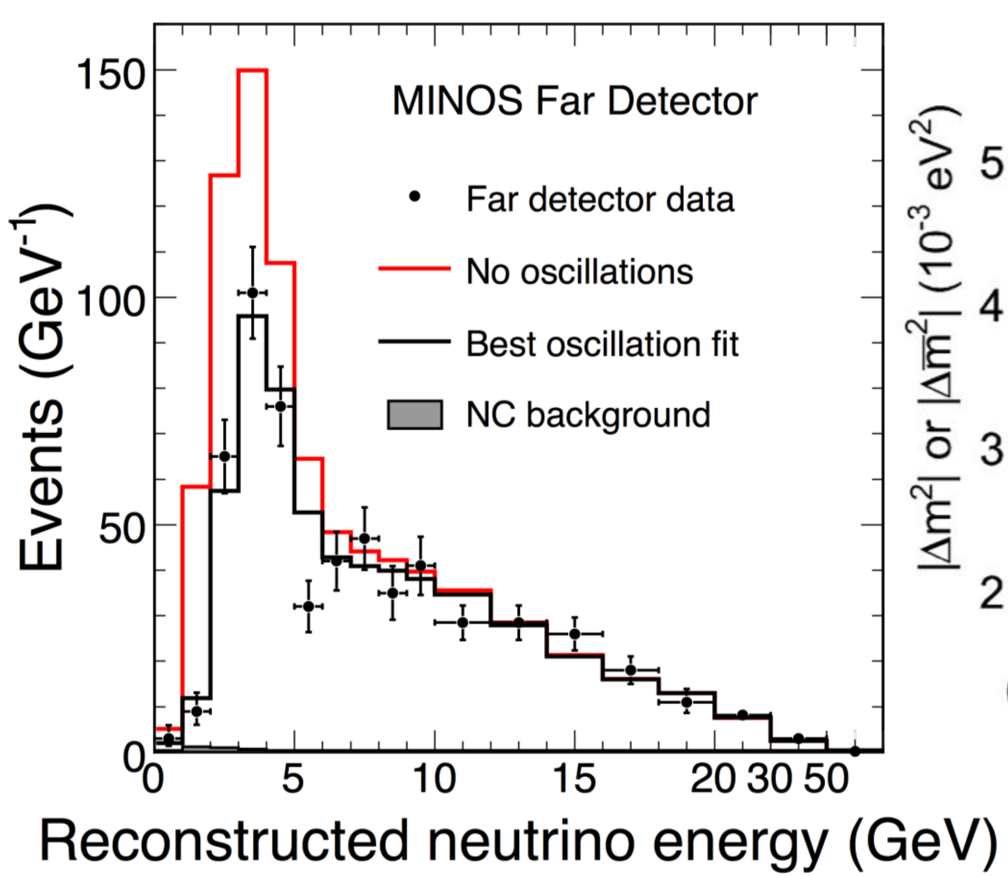
Baseline: 732 km

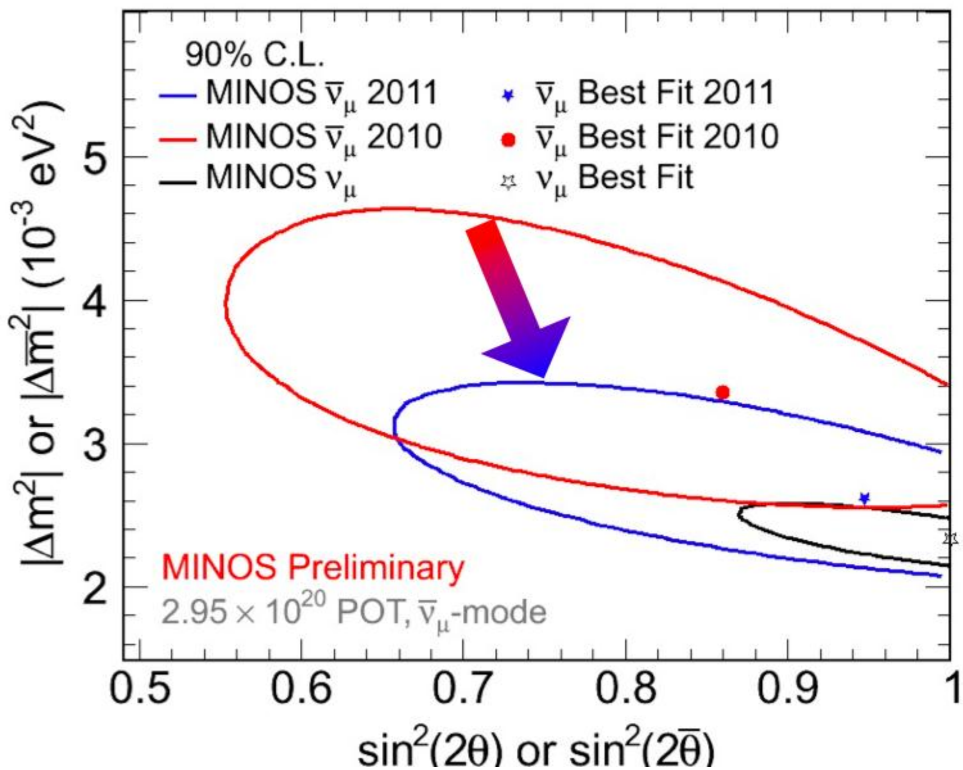


LE option chosen
Neutrino and antineutrino runs



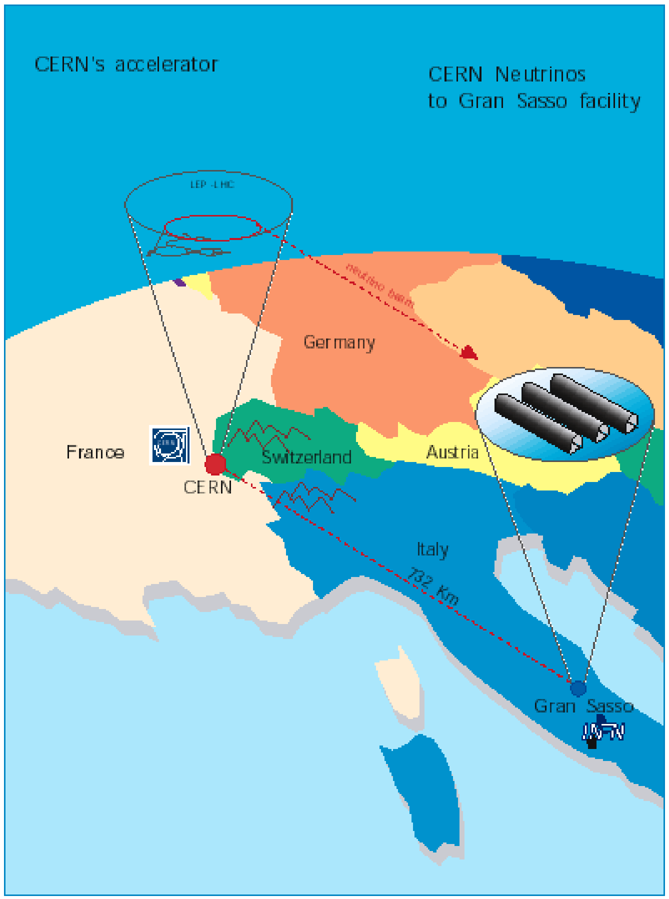
MINOS + SuperK results





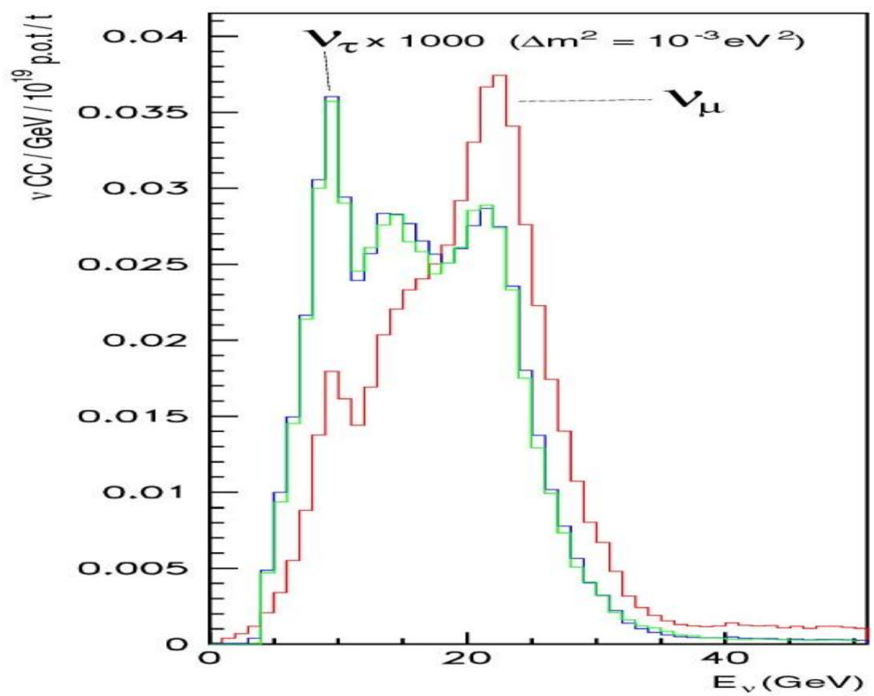
CNGS

Same baseline as Fermilab – Soudan

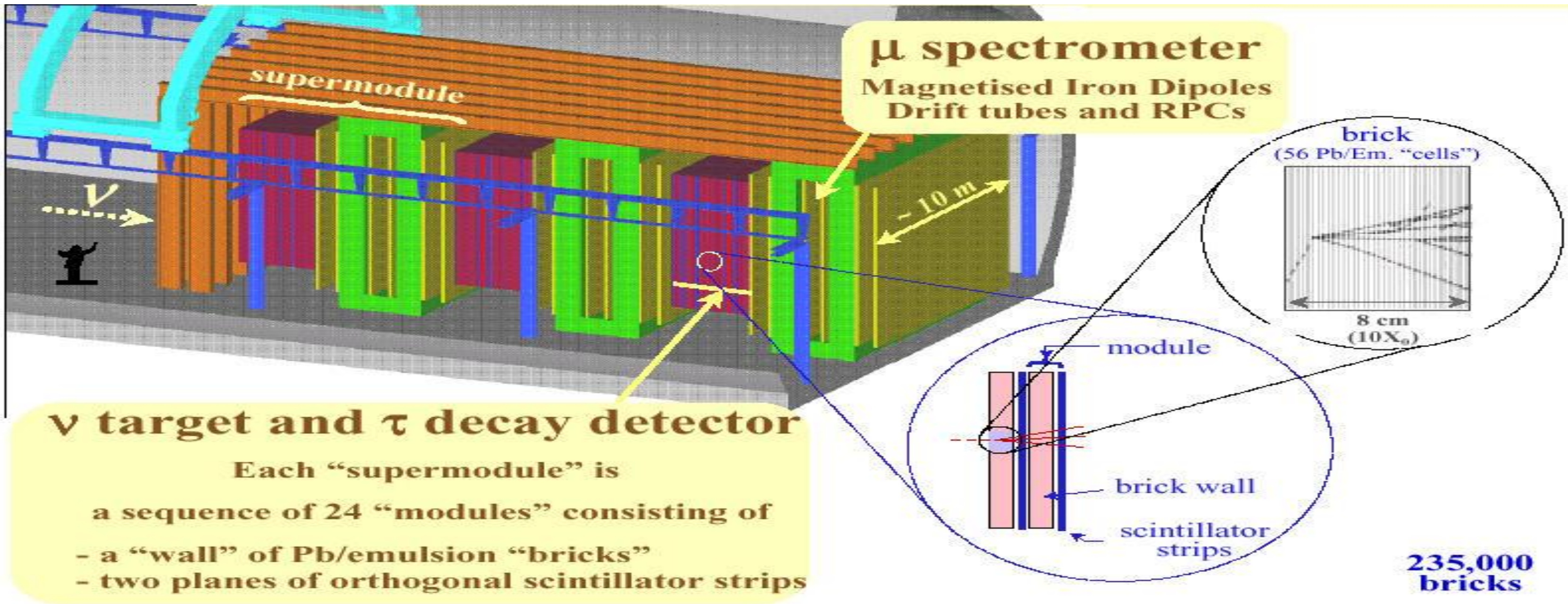


Beam optimised for detection
Appearance experiment

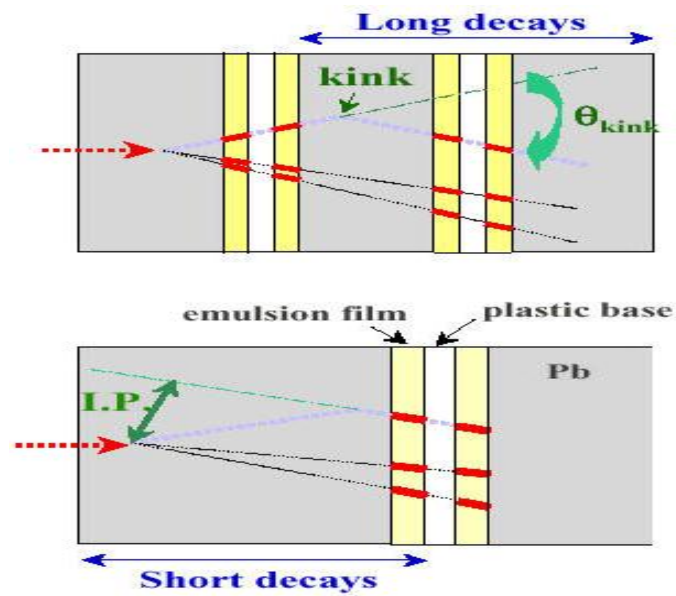
$$\nu_\tau + N \rightarrow \tau^- + X$$



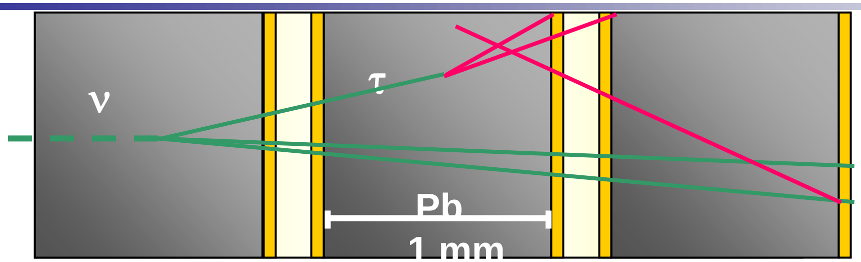
OPERA

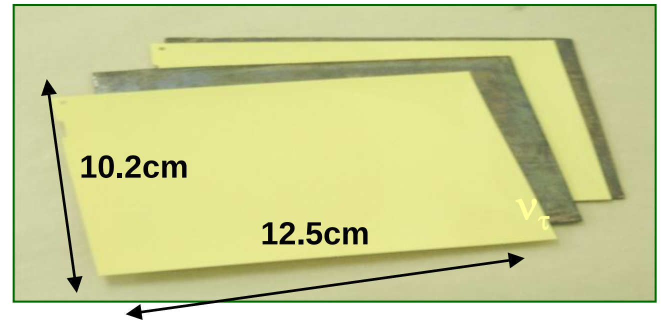


- Challenge: making a Fine-grained and massive detector to see kink when tau decays to something plus ν_τ

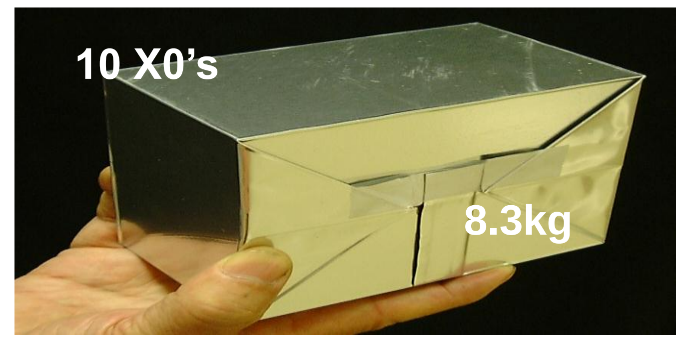


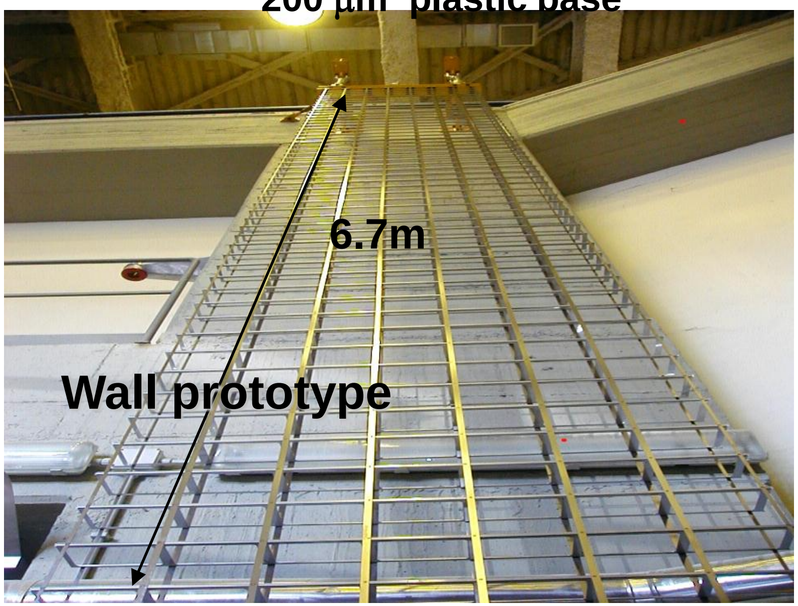
Lead-Emulsion Target





2 emulsion layers
(44 μm thick)
glued onto a
200 μm plastic base





52 x 64 bricks

BRICK: 57 emulsion foils +56 interleaved Pb plates

Emulsion films (Fuji)
production rate ~8,000m^2/month
(206,336 brick ⇔ ~150,000m^2)

Lead plates (Pb + 2.5% Sb)
requirements:
low radioactivity level,emulsion compatibility,
constant and uniform thickness

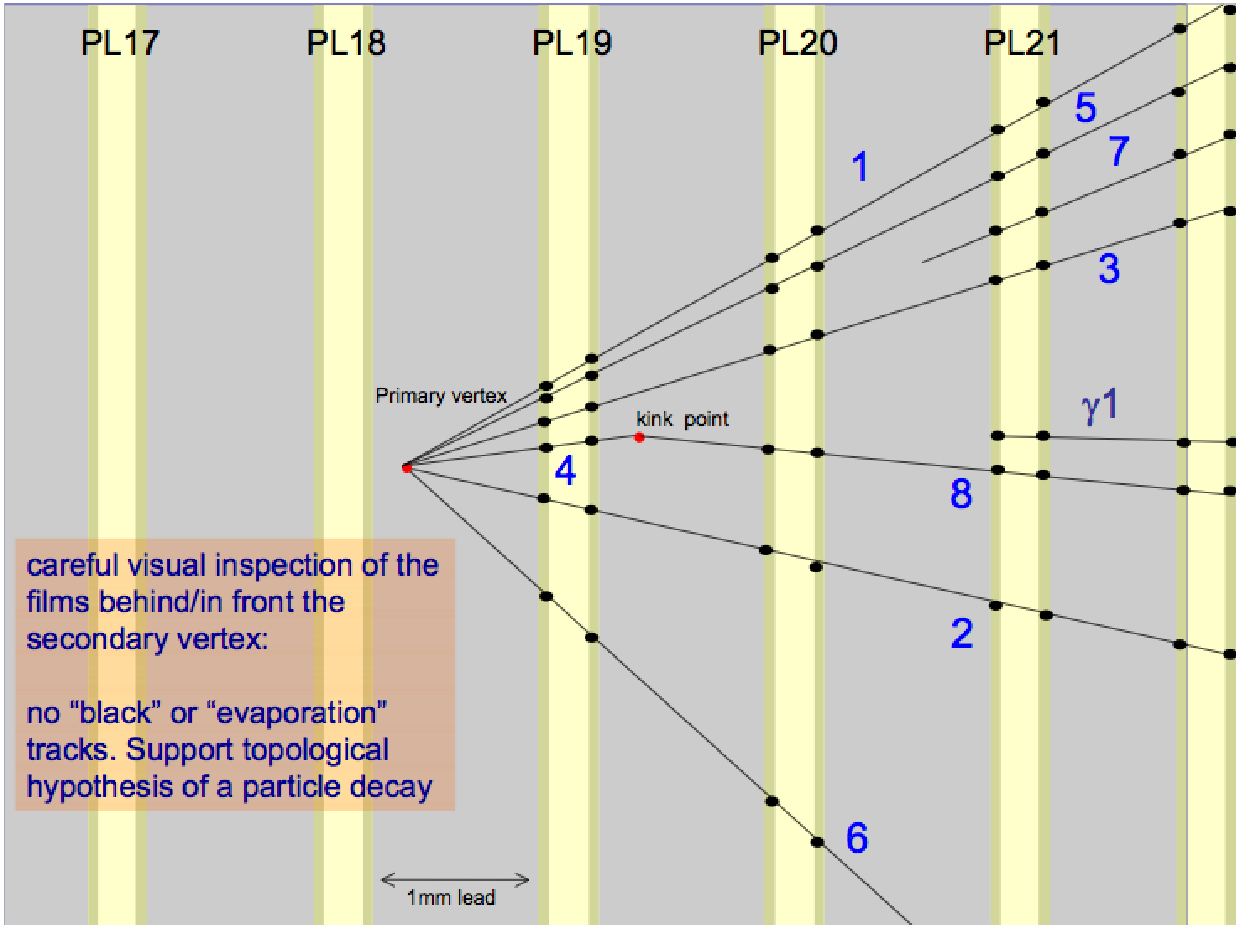
OPERA - Expectation

τ decay channels	Signal		Background
	$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	
$\tau \rightarrow \mu$	2,9	4,2	0,17
$\tau \rightarrow e$	3,5	5,0	0,17
$\tau \rightarrow h$	3,1	4,4	0,24
$\tau \rightarrow 3h$	0,9	1,3	0,17
ALL	10,4	14,9	0,75

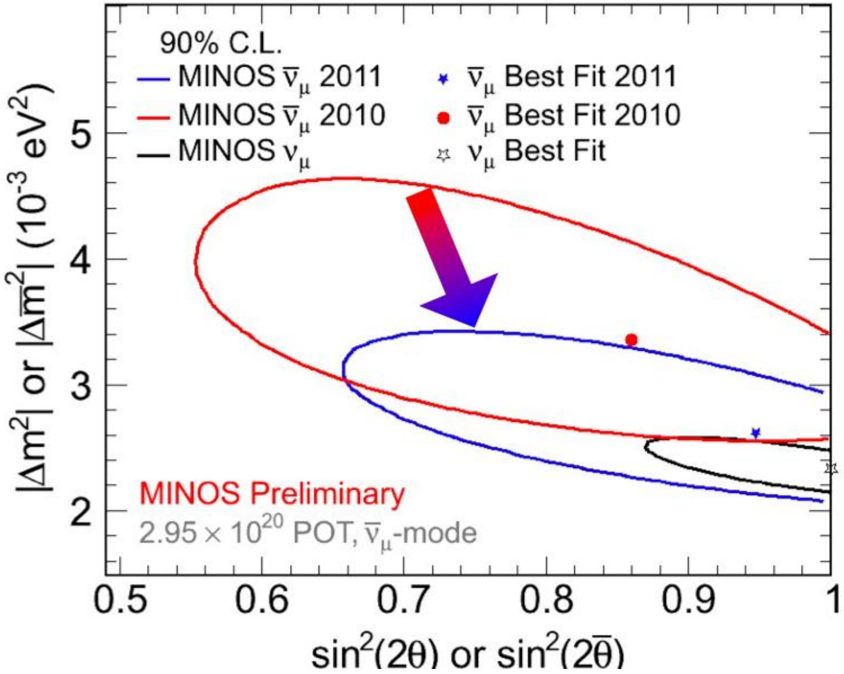
There should be 1 event in the data by now...

OPERA- 1st event

First candidate event observed



Summary so far



- ★ Neutrinos have a non-vanishing rest mass
- ★ Observed in atmospheric neutrinos, confirmed by accelerators
- ★ Best fit is maximal mixing and

$|\Delta m^2|$ =(2.32±0.10) x 10^{-3} eV^2
(90% C.L.)
$\sin^2 2\theta = 1$