The Standard Model of Particle Physics. Neutrino Oscillations.

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1. The Standard Model
2. Electroweak fits
3. LHC
4. Neutrinos. Neutrino oscillations
5. Atmospheric neutrinos
6. Long base line ν experiments
7. Conclusions. Outlook

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

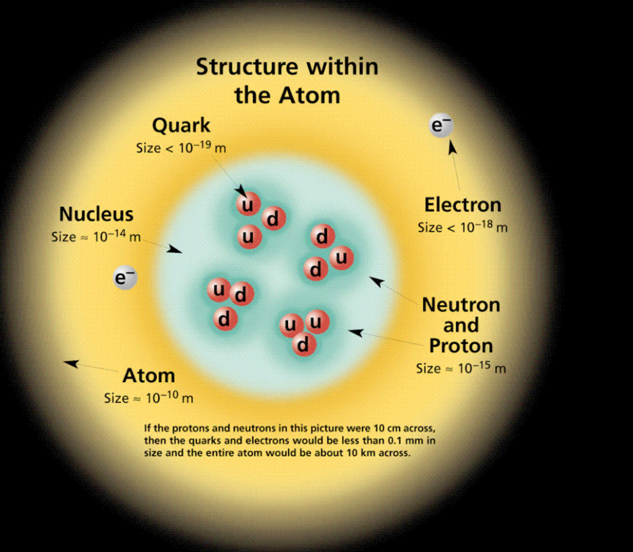
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

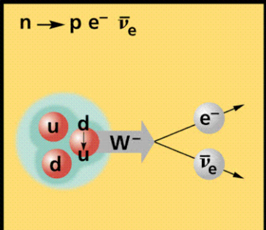
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

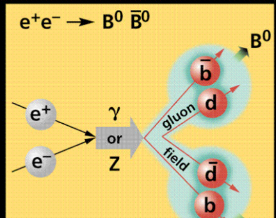
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

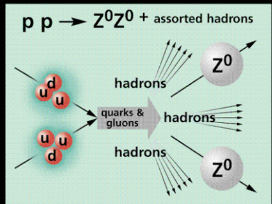
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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American Physical Society, Division of Particles and Fields
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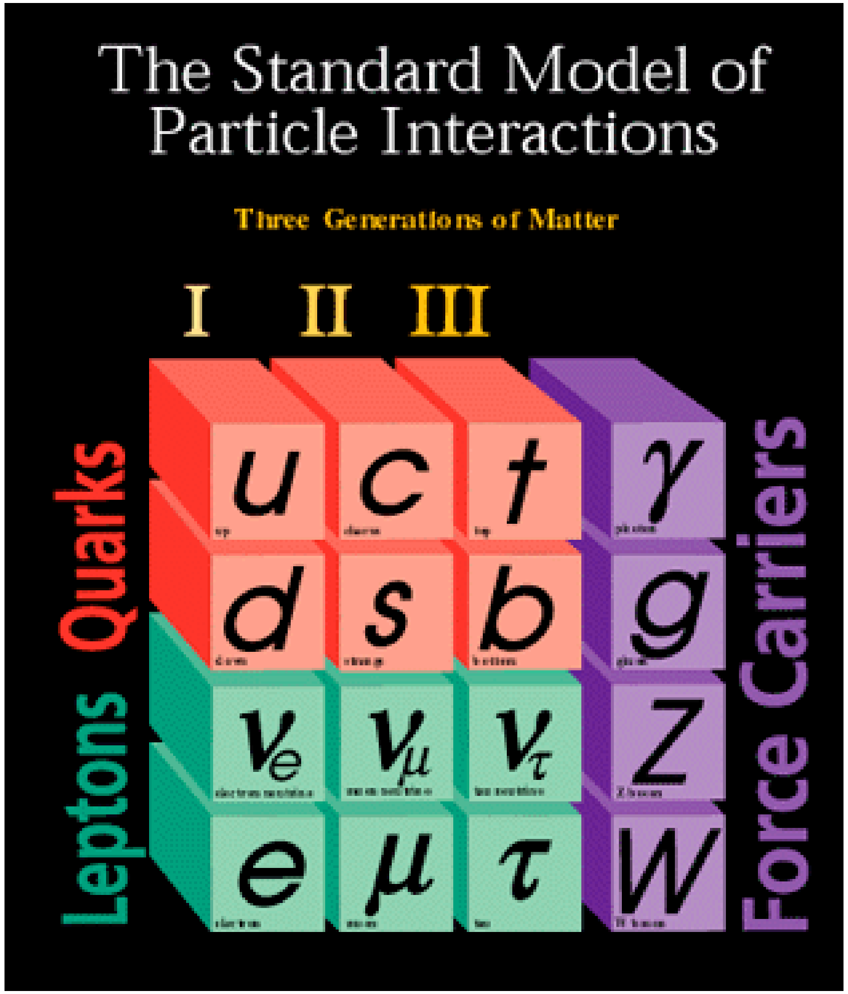
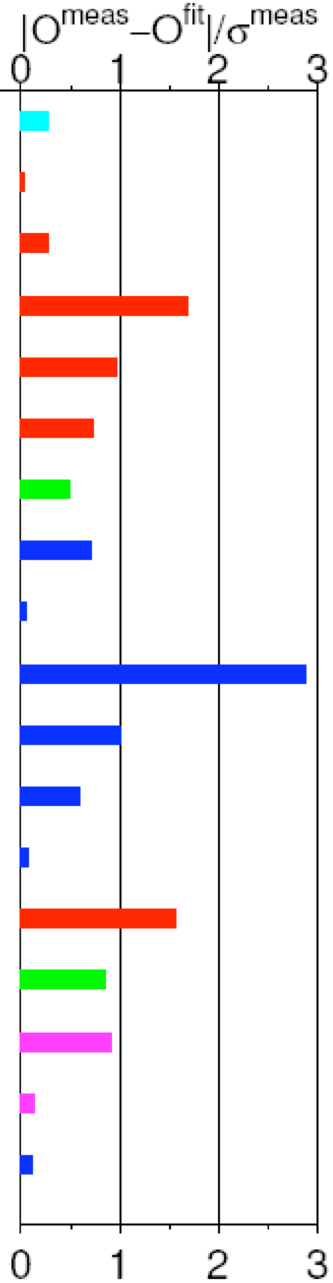
Standard Model of Electroweak and Strong Interactions



2. Electroweak fits

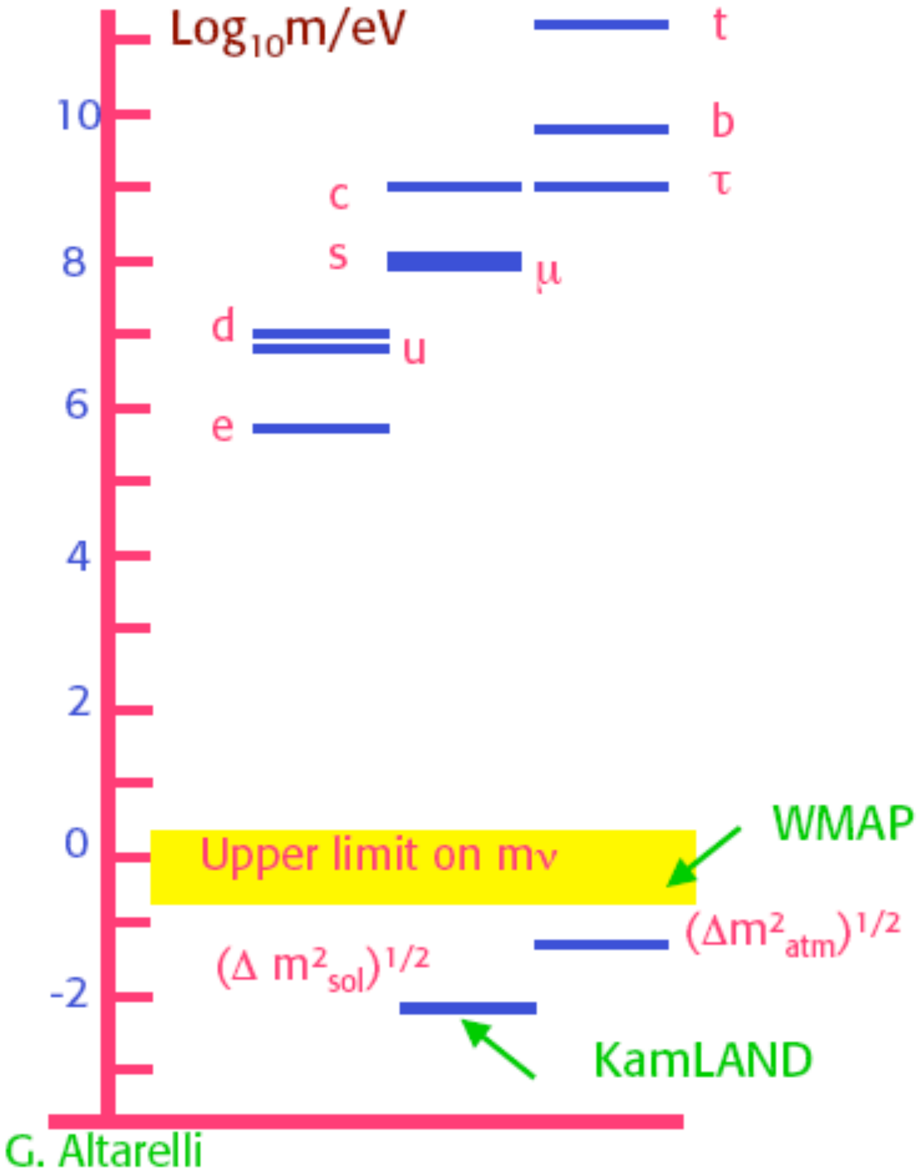
(Verzocchi ICHEP08)

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4958
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01644
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21582
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.376
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	172.4 ± 1.2	172.5



m_H< 154 GeV

July 2008



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

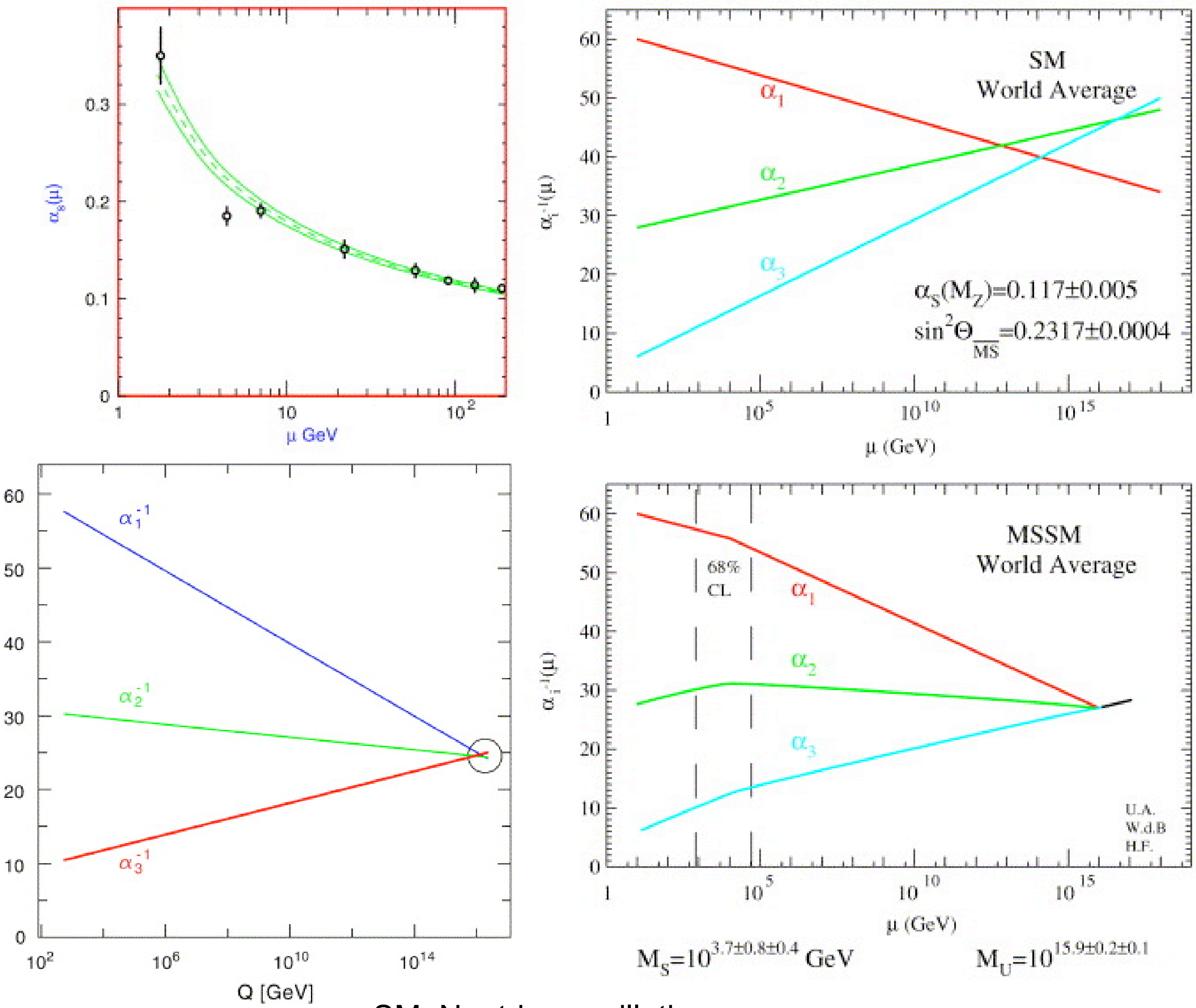
Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

Running of the coupling constants



The Standard Model (Electroweak+QCD)

Precision EW measurements + Tests of SM at LEP, FNAL, SLAC, HERA failed to find discrepancies : **the SM is well off**.

QCD is the established theory of Strong Interactions.

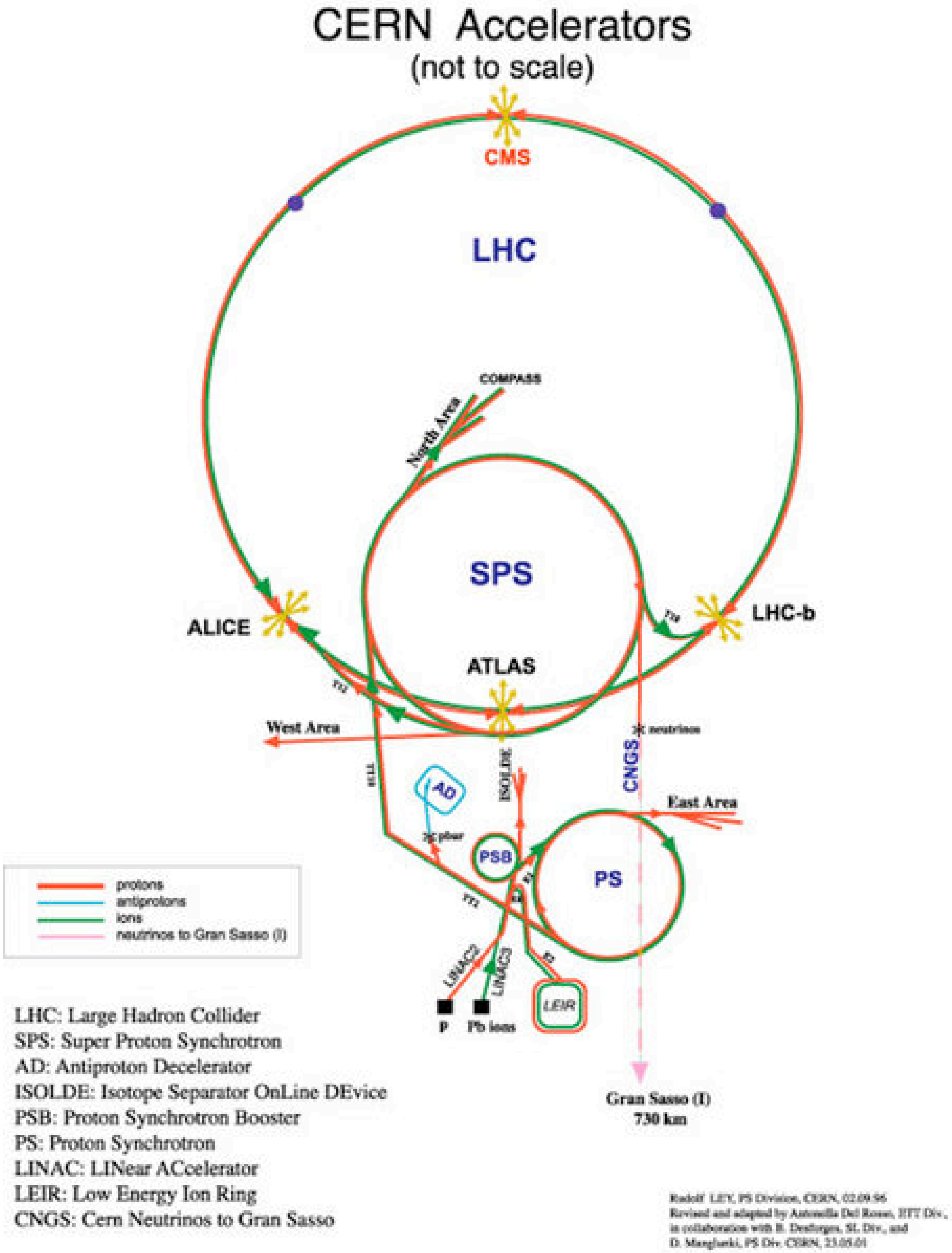
The only missing basic ingredient in the SM is **the Higgs**.
LHC may answer the following questions:
Is there a Higgs? What is its mass?
Is the Higgs a weak doublet? Is it elementary or composite?

Physics beyond the SM

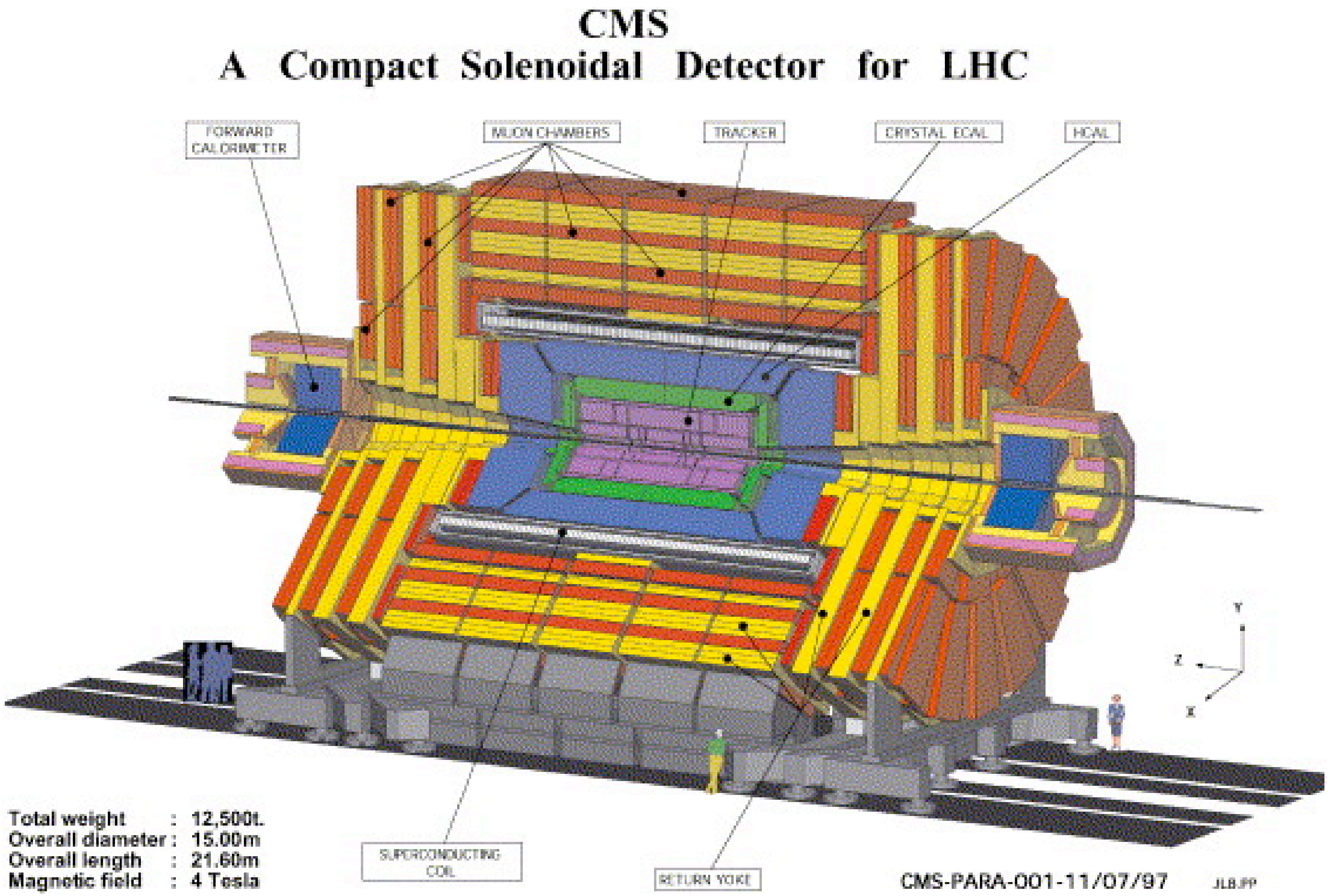
-There are many th reasons to search for physics beyond the SM (Infinities, SUSY, Dark Matter, Extra Dimensions, ...)

-Are ν oscillations hints of new physics?

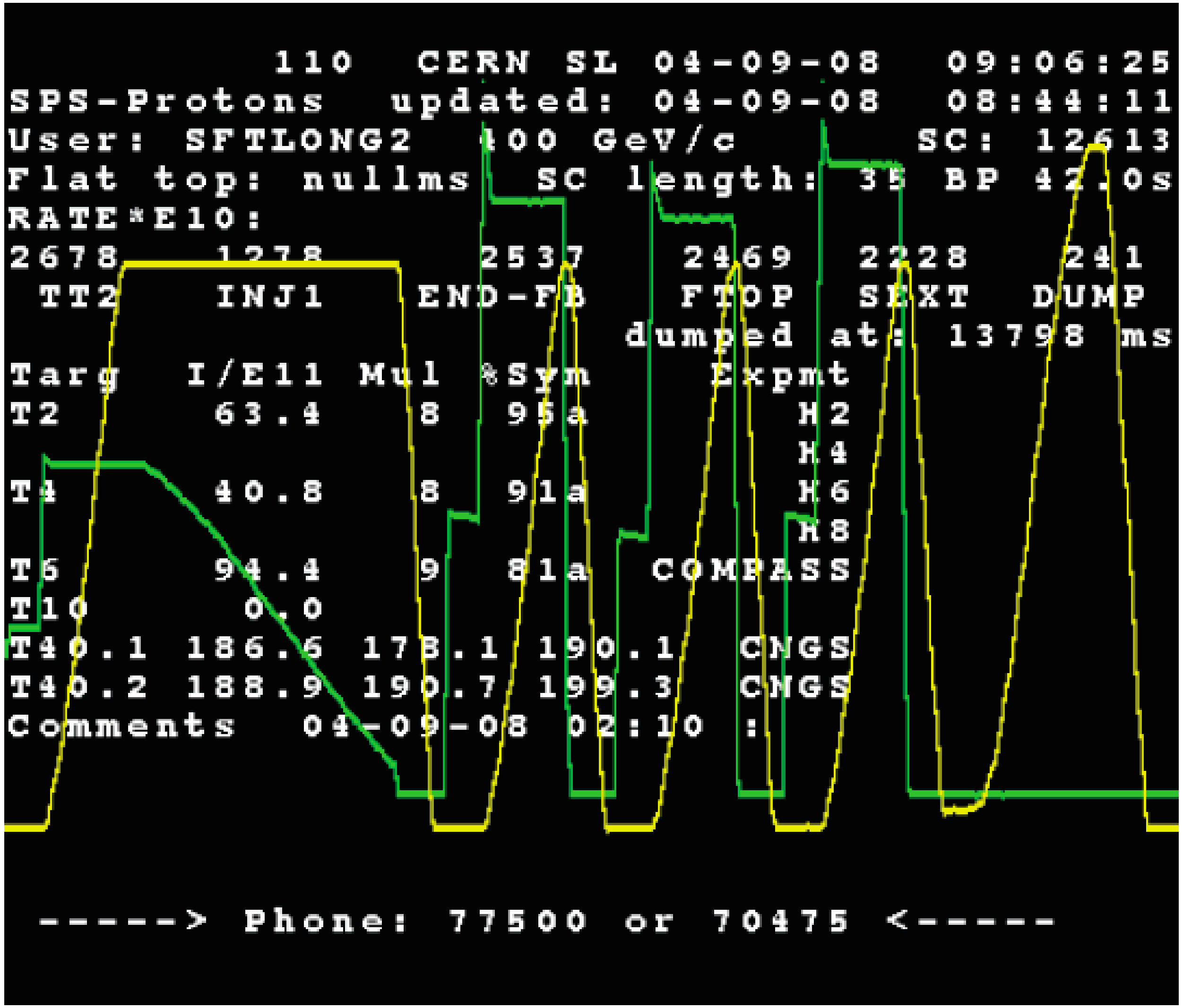
3. LHC
+CERN accelerators



The CMS detector at the LHC

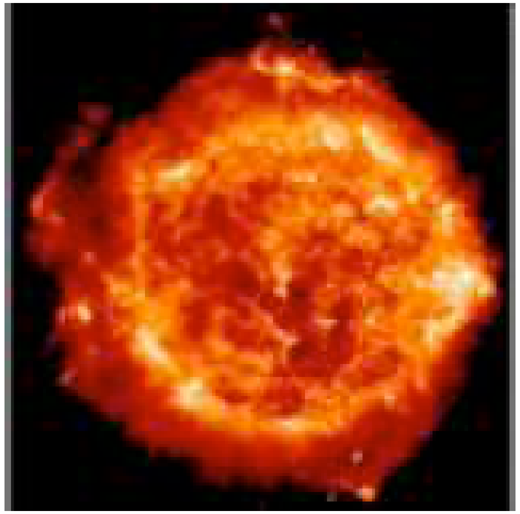


SPS Page 1

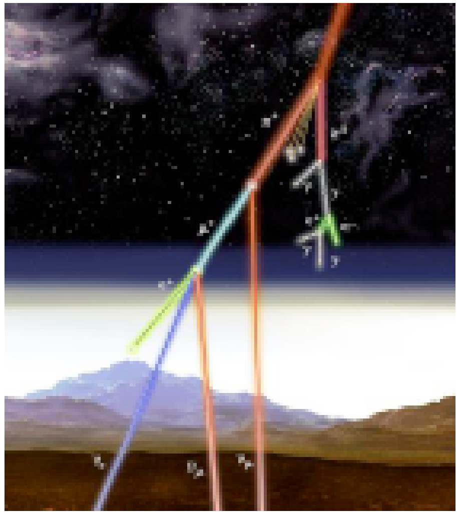

110 CERN SL 04-09-08 09:06:25
SPS-Protons updated: 04-09-08 08:44:11
User: SFTLONG2 400 GeV/c SC: 12613
Flat top: nullms SC length: 35 BP 42.0s
RATE*E10:
2678 1278 2537 2469 2228 241
TT2 INJ1 END-FB FTOP SEXT DUMP
dumped at: 13798 ms
Targ I/E11 Mul %Sym Expmt
T2 63.4 8 95a H2
H4
T4 40.8 8 91a H6
H8
T6 94.4 9 81a COMPASS
T10 0.0
T40.1 186.6 178.1 190.1 CNGS
T40.2 188.9 190.7 199.3 CNGS
Comments 04-09-08 02:10 :
-----> Phone: 77500 or 70475 <-----

4. Neutrinos. Neutrino sources

+ geo-antineutrinos



Solar ν



Atmospheric ν

Reactor ν

Accelerator ν

ν Oscillations (in vacuum)

Weak flavor eigenstates ν_e, ν_μ, ν_τ

Mass eigenstates ν_1, ν_2, ν_3

Decays, Interactions $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\nu_\mu n \rightarrow \mu^- p$

Propagation $\nu_1(t) = \nu_1(0)\, e^{-Et}$

Mixing $\nu_f = \Sigma^3_{m=1} U_{fm}\, \nu_m$

Flavor ν propagate as a superposition of mass eigenstates

If only 2 flavors (ν_μ, ν_τ) , (ν_2, ν_3) :

Oscillation probability (appearance) over a distance L:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \sin^2 (1.27\, \Delta m^2_{23}\, L/E_\nu)$$

Disappearance over a distance L:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau)$$

Simple formulae modified by : Additional flavor oscillations
Matter effects

In case of oscillations: $m_\nu \neq 0$, $\Delta m_\nu < 0.1$ eV
L_e, L_μ, L_τ violation , $L = L_e + L_\mu + L_\tau$ conserved?
Neutrino decays ? Lorentz invariance ?

3 neutrino mixing

(RZK-ν08)

ν_e, ν_μ, ν_τ *(flavor eigenstates)* $\neq$ ν_1, ν_2, ν_3 (mass eigenstates)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = V \, \mathrm{diag}(1, e^{i\alpha_2/2}, e^{i(\alpha_3+2\delta)/2})$$

Majorana CP violating Phases

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

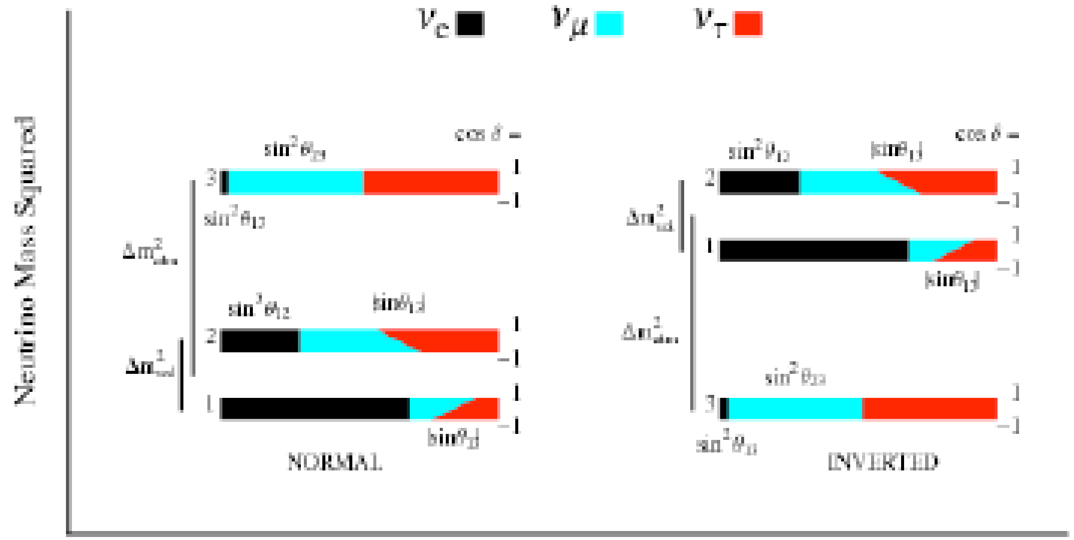
$c_{ij} \equiv \cos\theta_{ij}$ $\quad s_{ij} \equiv \sin\theta_{ij}$ $\quad \theta_{ij} \in [0, \pi/2]$ $\quad \delta \in [0, 2\pi]$ $\quad \alpha_i \in [0, 2\pi]$

Mass scales and hierarchies

Current experimental results imply:

$$\Delta m^2_{12} = \Delta m^2_{\odot} << \Delta m^2_{\rm atm} = |\Delta m^2_{32}| \approx |\Delta m^2_{31}|$$

Two possible hierarchies:



NORMAL

$$m_1 = m_0$$

$$m_2 = \sqrt{m_0^2 + \Delta m^2_{\odot}}$$

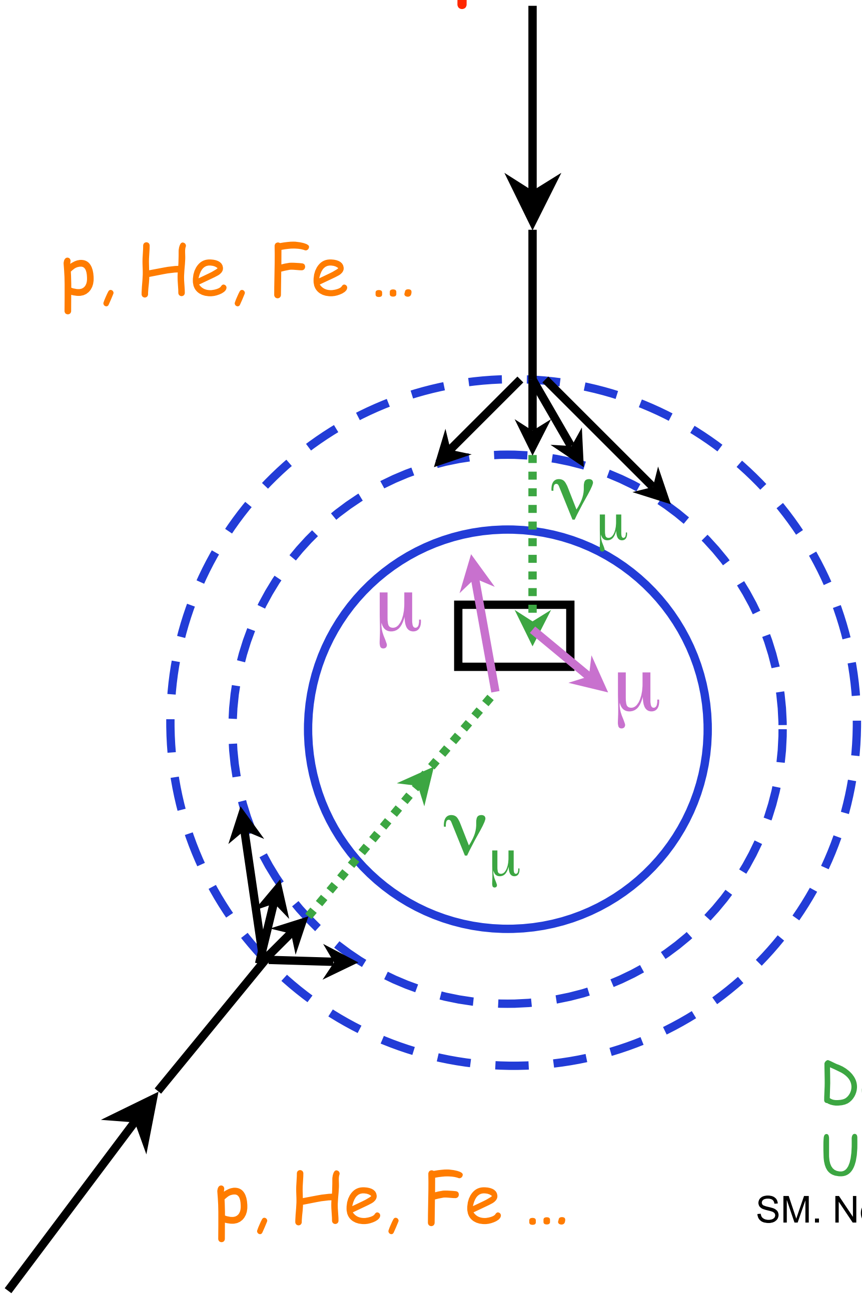
$$m_3 = \sqrt{m_0^2 + \Delta m^2_{\odot} + \Delta m^2_{\rm atm}}$$

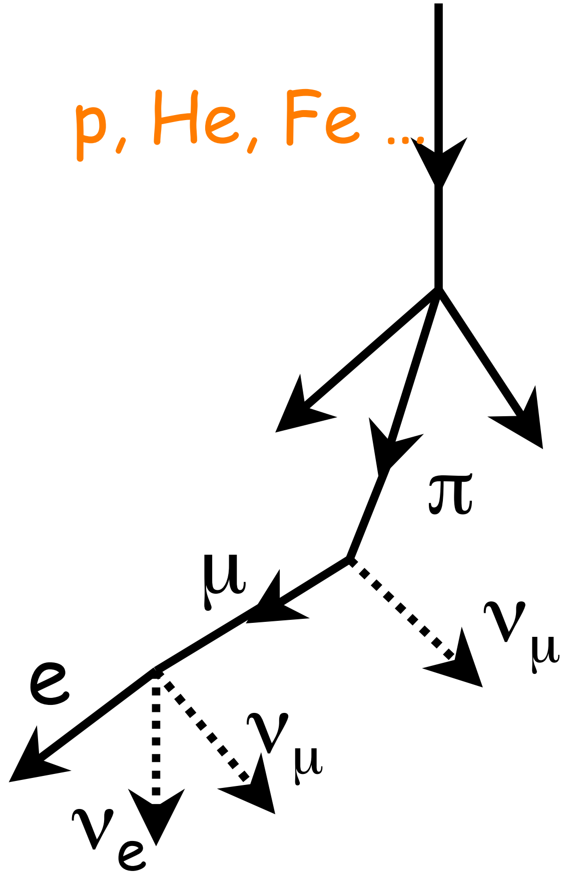
Mixing matrix

Do a more sofisticated evaluation [Gonzalez-Garcia and Maltoni, Phys. Rep. 460, 1 (2008)]

$$|V|_{3\sigma} = \begin{pmatrix} 0.77 - 0.86 & 0.50 - 0.63 & 0.00 - 0.22 \\ 0.22 - 0.56 & 0.44 - 0.73 & 0.57 - 0.80 \\ 0.21 - 0.55 & 0.40 - 0.71 & 0.59 - 0.82 \end{pmatrix}$$

5. Atmospheric neutrinos



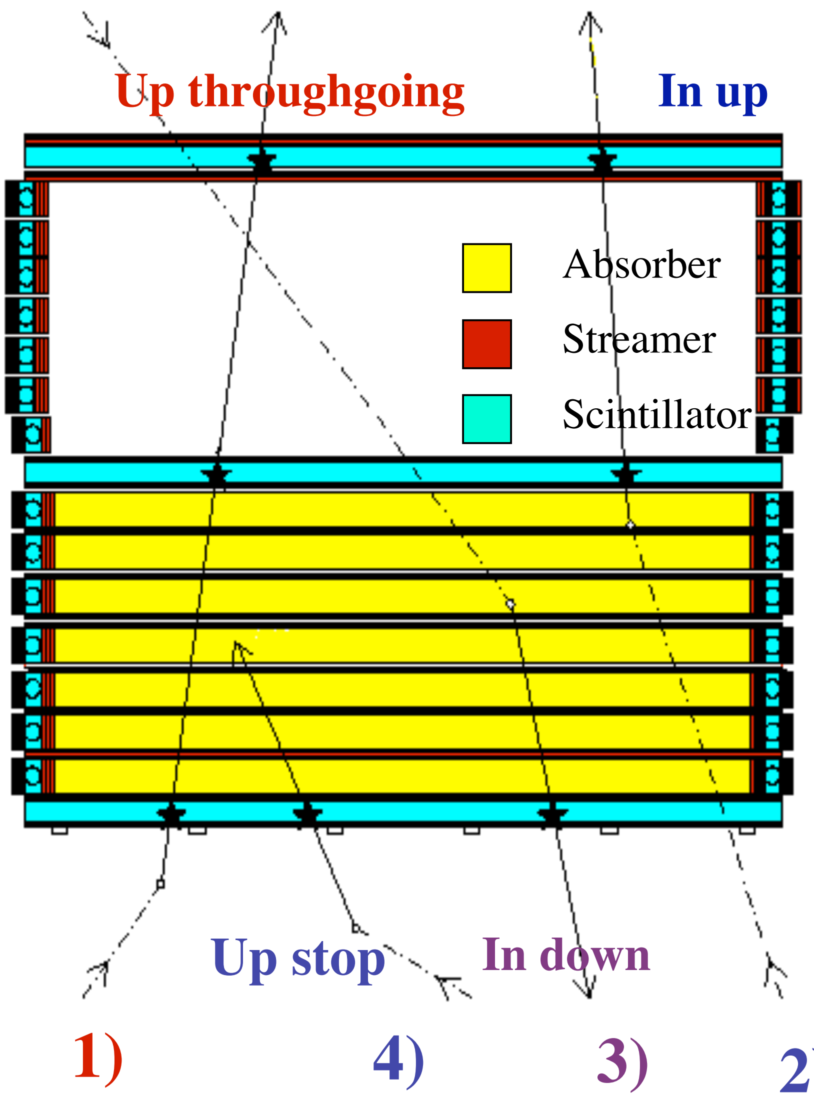


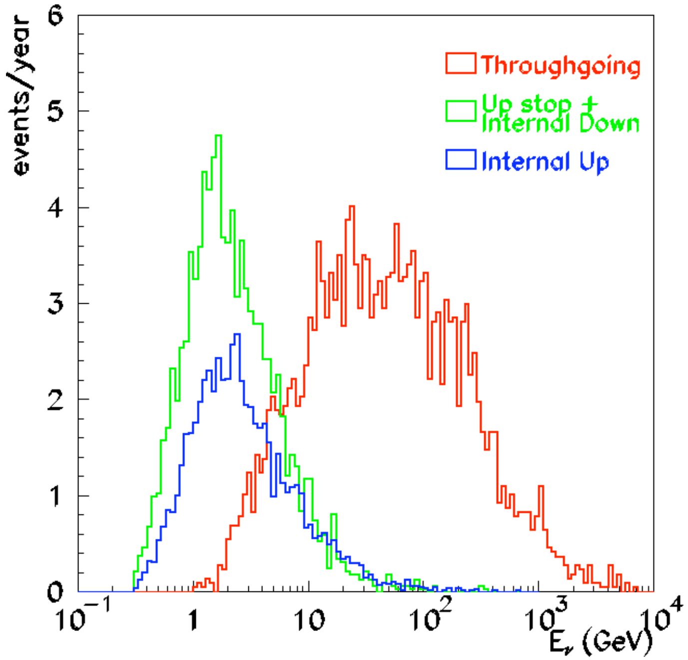
E_ν: 0.1 GeV → 100 GeV
L: 20 km → 13000 km
L/E_ν: 1 km/GeV → 10^5 km/GeV

Downgoing ν_μ: "near" neutrino source
Upgoing ν_μ: "far" neutrino source

MACRO (12mx9mx76m)

Detector mass ~ 5.3 kton





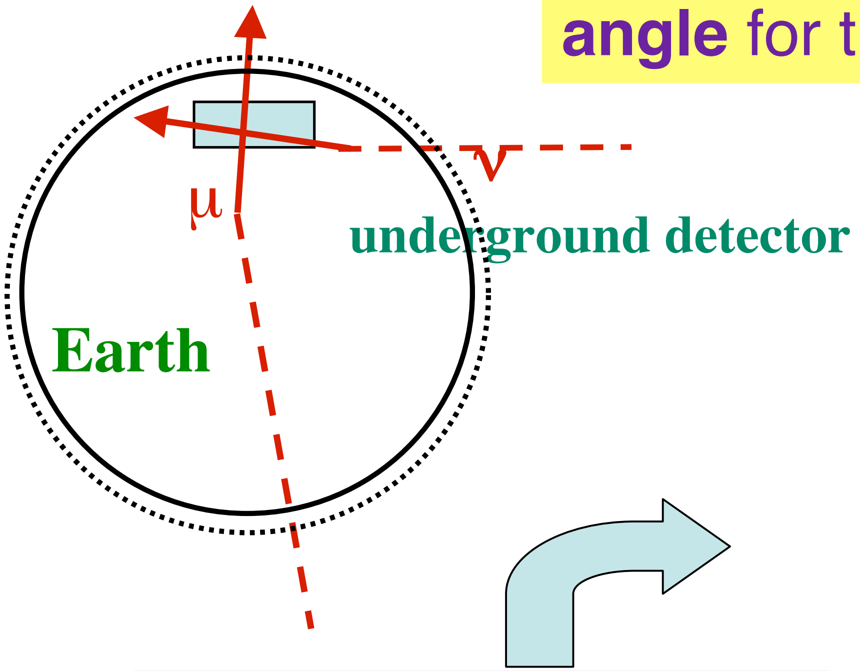
DATA SAMPLES (measured)
Bartol96 expected

Up through(1)	857
	1169
Internal UP(2)	157
	285
In DOWN(3)+Stop(4)	262
	375

MC

Effects of ν_μ oscillations on upthroughgoing events

Flux reduction depending on **zenith angle** for the high energy events

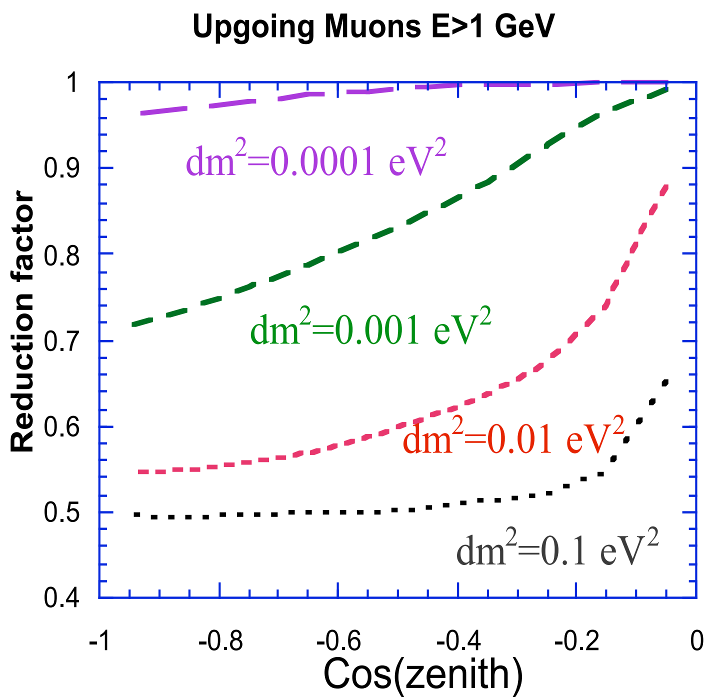


$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2\left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu}\right]$$

From MC: distortion of the angular distribution

$E_\nu \sim 50$ GeV

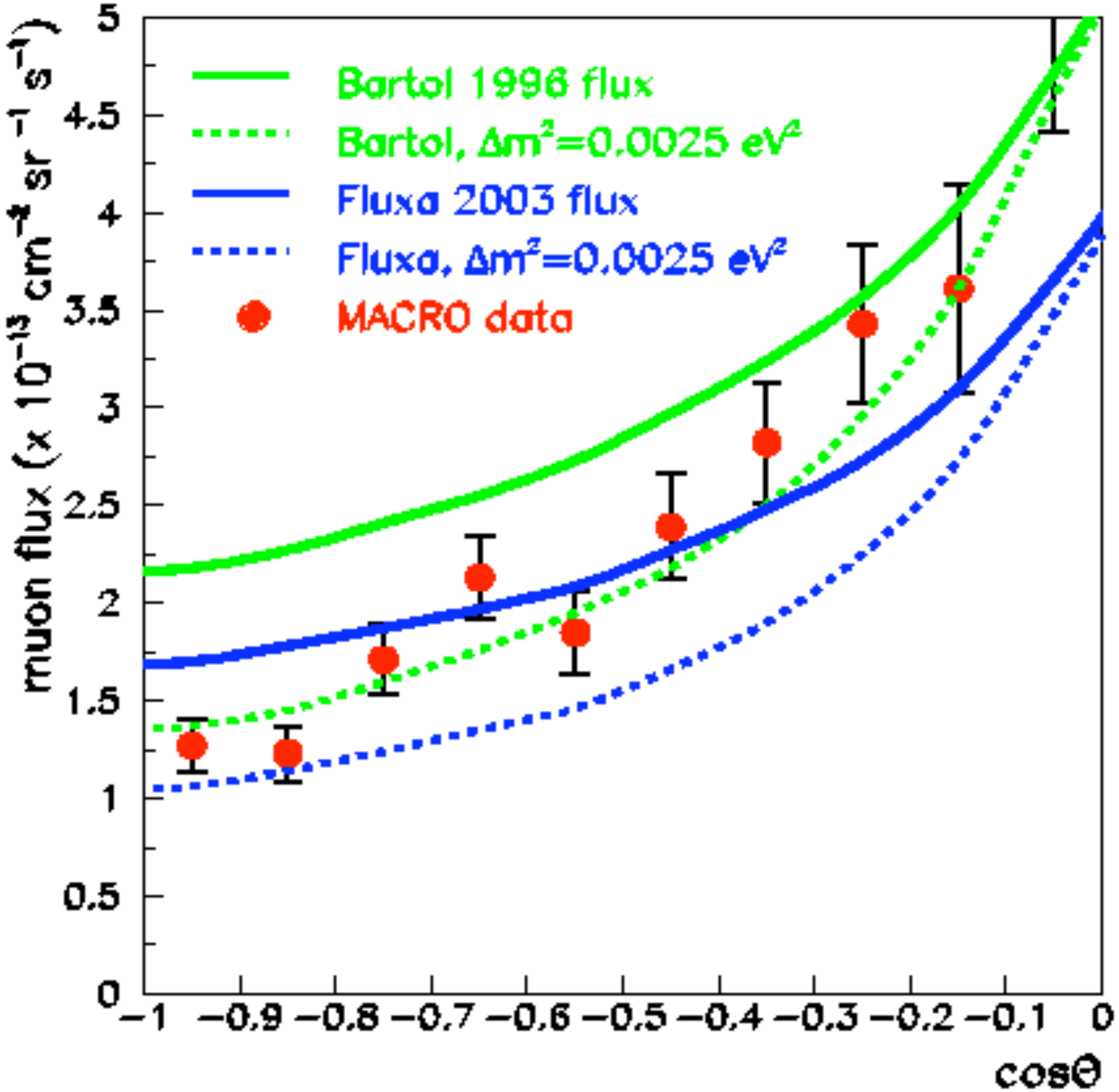
$L_\nu \sim 10 - 10^4$ km



$$P_{\nu_\mu \nu_\mu} = 1 - \sin^2 2\theta \cdot \sin^2 \left[1.27 \frac{\Delta m^2 \cdot L}{E_\nu} \right]$$

*Through the measurement of **the shape** of the muon zenith angle distribution.*

L(cosΘ=-1)~13000 km
L(cosΘ=0)~500 km



MonteCarlos

MACRO : Final Combined Analysis

H.E.
- Zenith distribution — $R_1 = N(\cos\Theta < -0.7)/N(\cos\Theta > -0.4)$
- E_ν estimate — $R_2 = N(\text{low } E_\nu) / N(\text{high } E_\nu)$

L.E. IU, ID and UGS μ — $R_3 = N(ID+UGS) / N(IU)$

NO OSCILLATION HYPOTHESIS RULED OUT BY ~ 5 σ

Best fit parameters for $\nu_\mu \rightarrow \nu_\tau$
$\Delta m_{23}^2 = 2.3\ 10^{-3}\ eV^2$; $\sin^2 2\theta_{23} = 1$

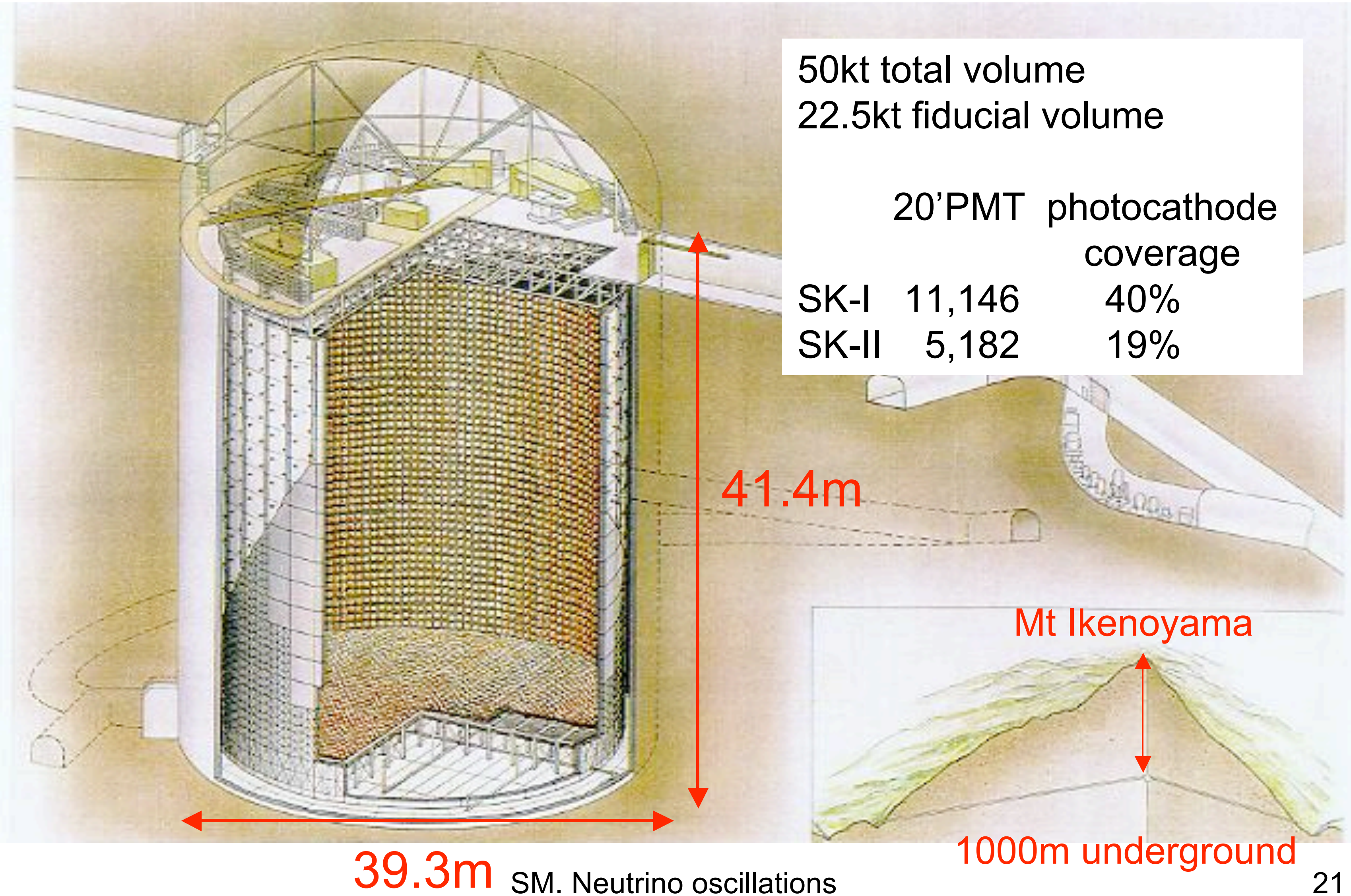
Predictions of the new FLUKA and Honda Monte Carlos
H.E. 25% low ; L.E. 12% low

Bartol96 may give additional evidence for oscillations:
Absolute values referred to Bartol96 MC:

$$R_4 = (Data/MC)_{H.E.} \quad ; \quad R_5 = (Data/MC)_{L.E.}$$

With these informations, the no oscillation hypothesis ruled out by ~6 σ

Super-Kamiokande

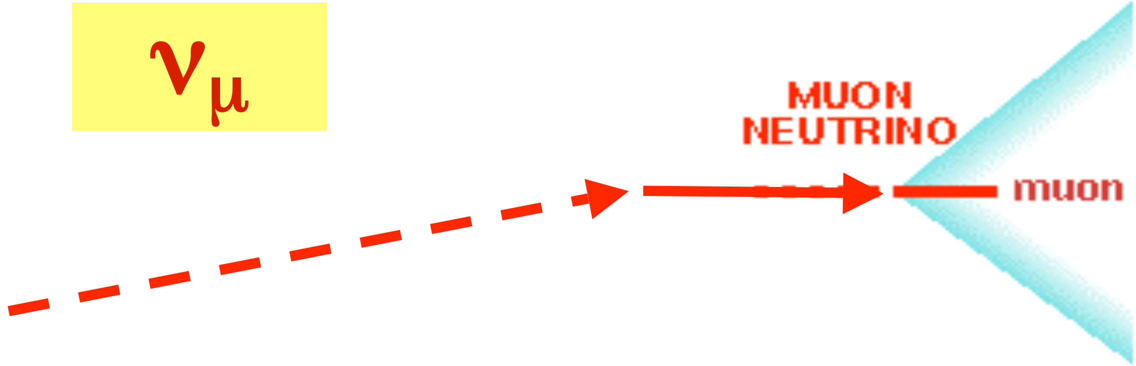


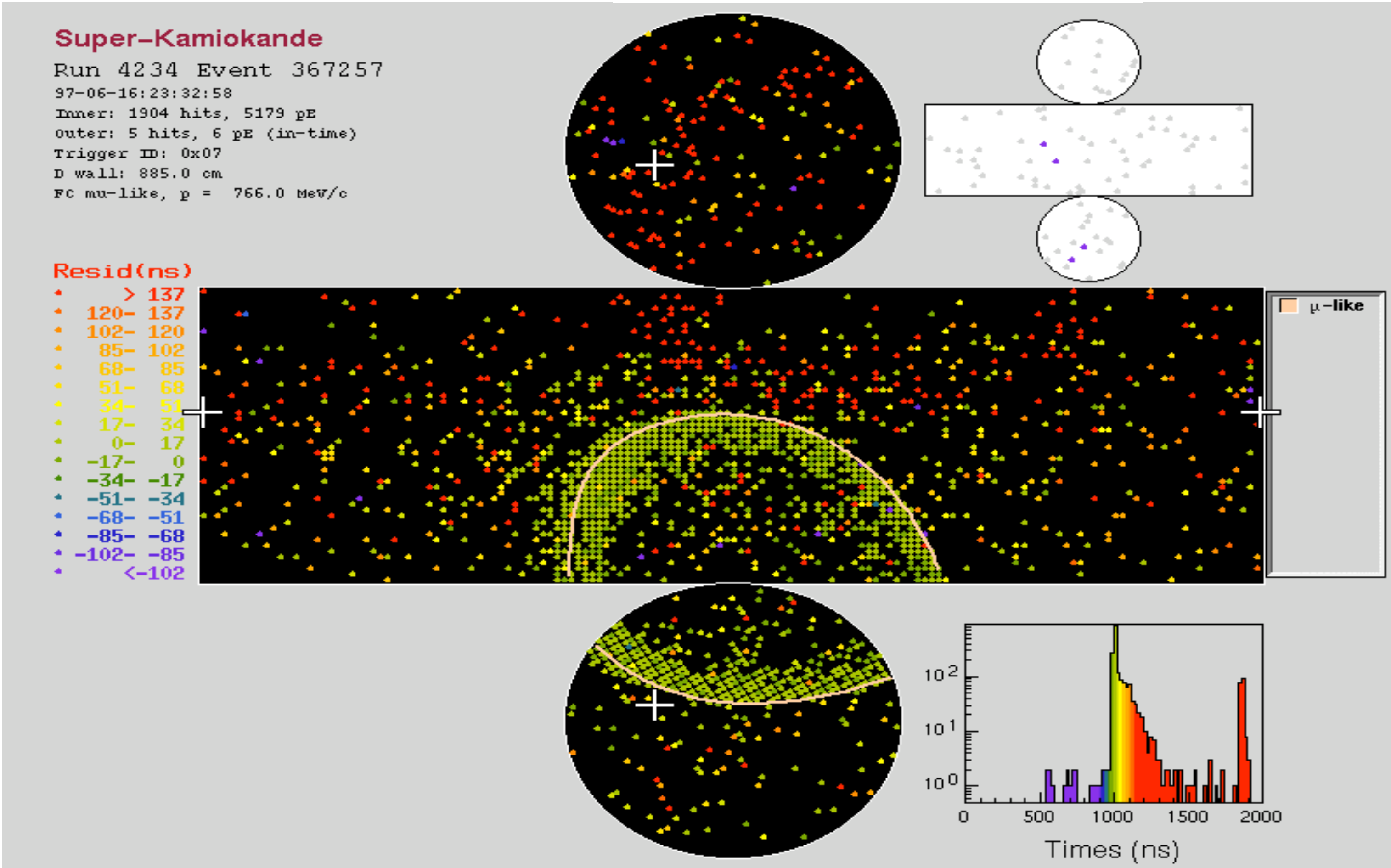
50kt total volume
22.5kt fiducial volume

	20'PMT	photocathode coverage
SK-I	11,146	40%
SK-II	5,182	19%

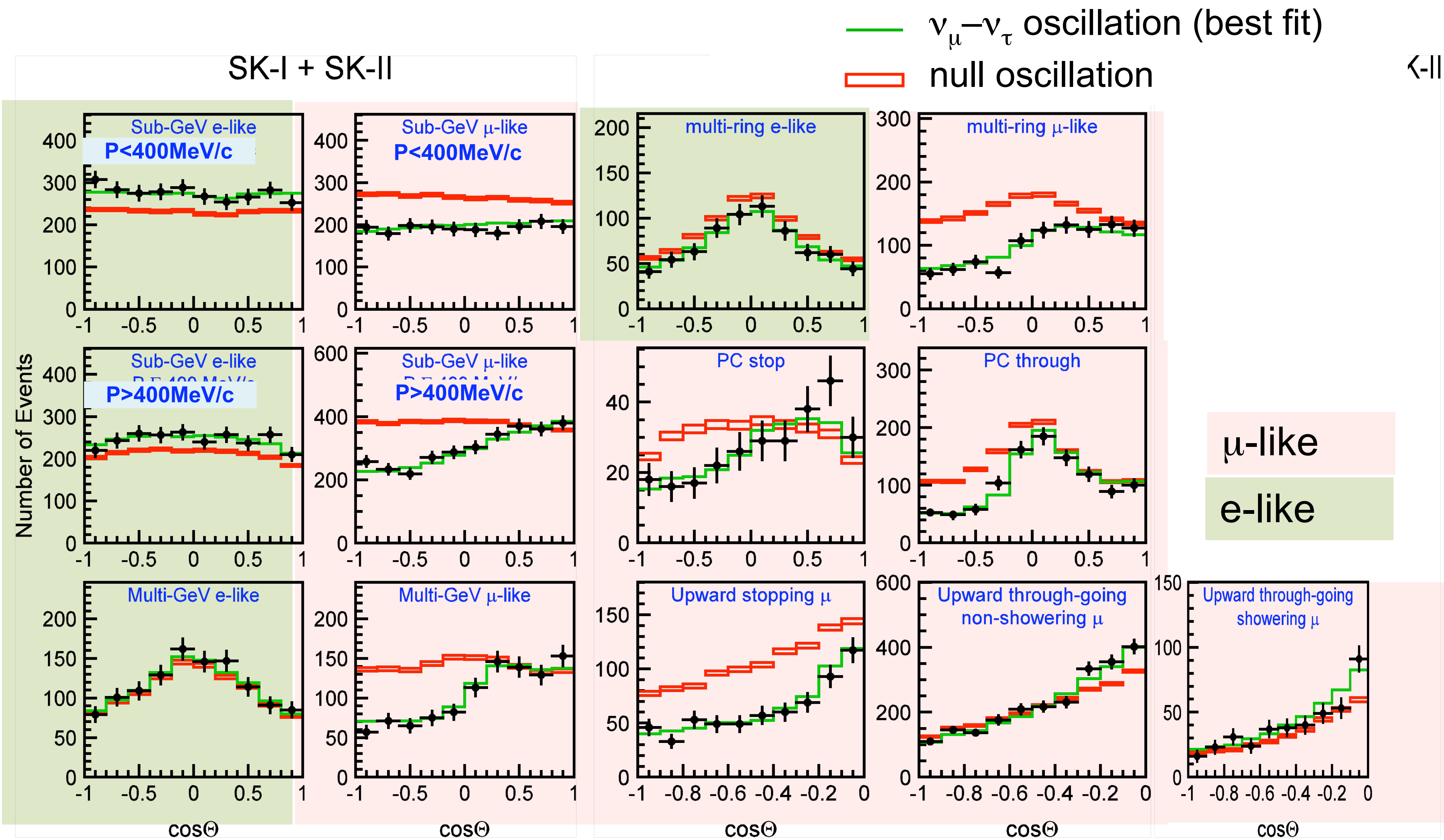
SK

ν_μ


MUON
NEUTRINO
muon


Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 885.0 cm
FC mu-like, p = 766.0 MeV/c
Resid(ns)
> 137
120- 137
102- 120
85- 102
68- 85
51- 68
34- 51
17- 34
0- 17
-17- 0
-34- -17
-51- -34
-68- -51
-85- -68
-102- -85
<-102
μ-like
10^2
10^1
10^0
0
500
1000
1500
2000
Times (ns)

Zenith Angle Distributions (SK-I + SK-II)



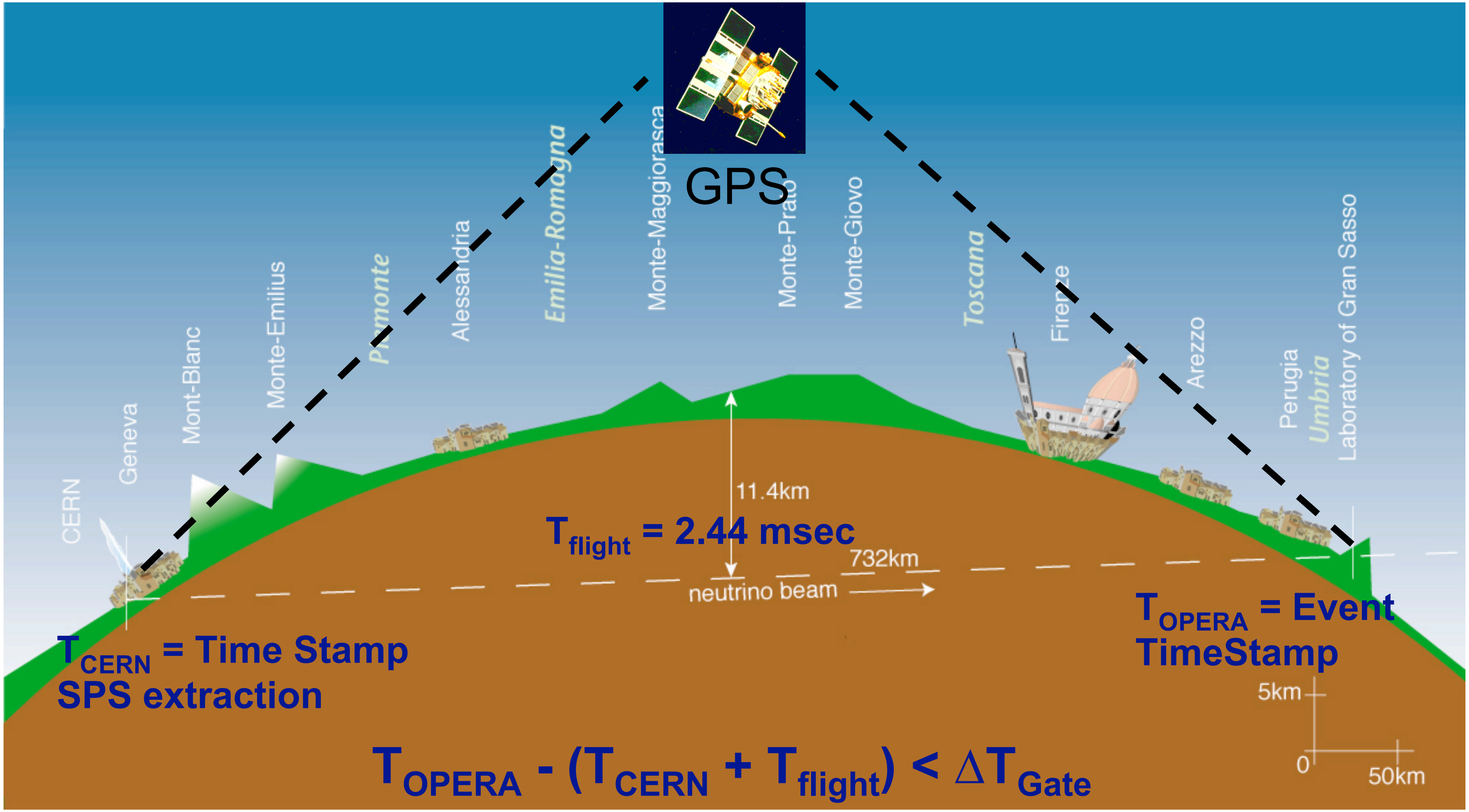
6. Long base line experiments

- **K2K** (KEK to Kamioka) (250 km)
  Near Detector and Far Detector (SuperK)
  Ratio=measured/expected <1 → Δm_{23}^2=2.7 10^{-3} eV^2

- **NuMI** from Fermilab to Soudan mine (735 km)
  Experiment Minos
  Near Detector (1000 t) , Far Detector (5500 t)
  Ratio=measured/expected < 1 → Δm_{23}^2=2.41 10^{-3} eV^2
  Peanut test experiment

- **CNGS** beam from CERN to Gran Sasso (732 km)
  Experiments: Opera: Appearance ν_μ--> ν_τ experiment
  LVD monitor, **Borexino, Icarus**
  Neutrino Beam size at GS : σ about 1 km

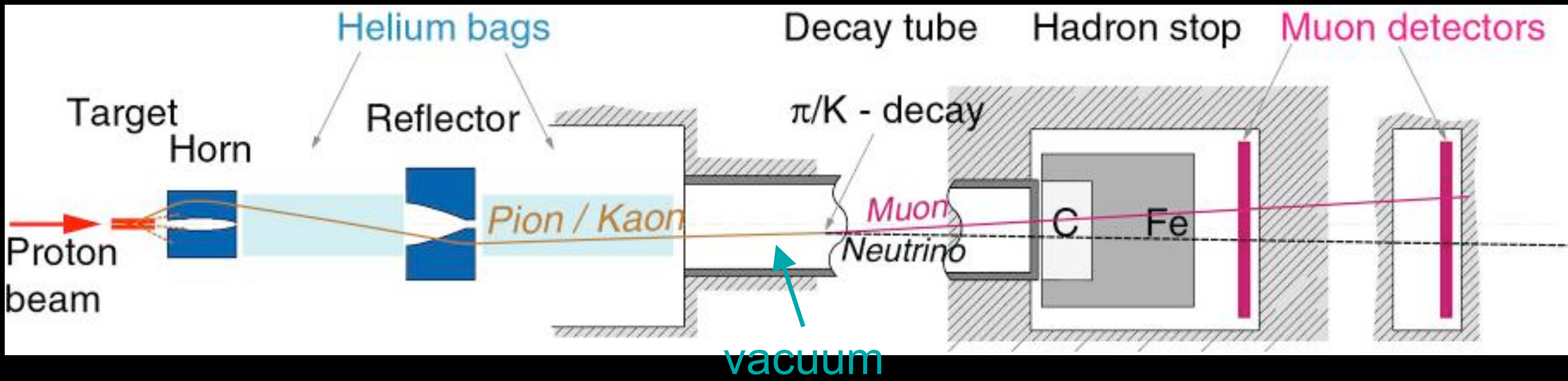
Time Selection of Beam Events



GPS Time Stamp resolution ~ 100 ns

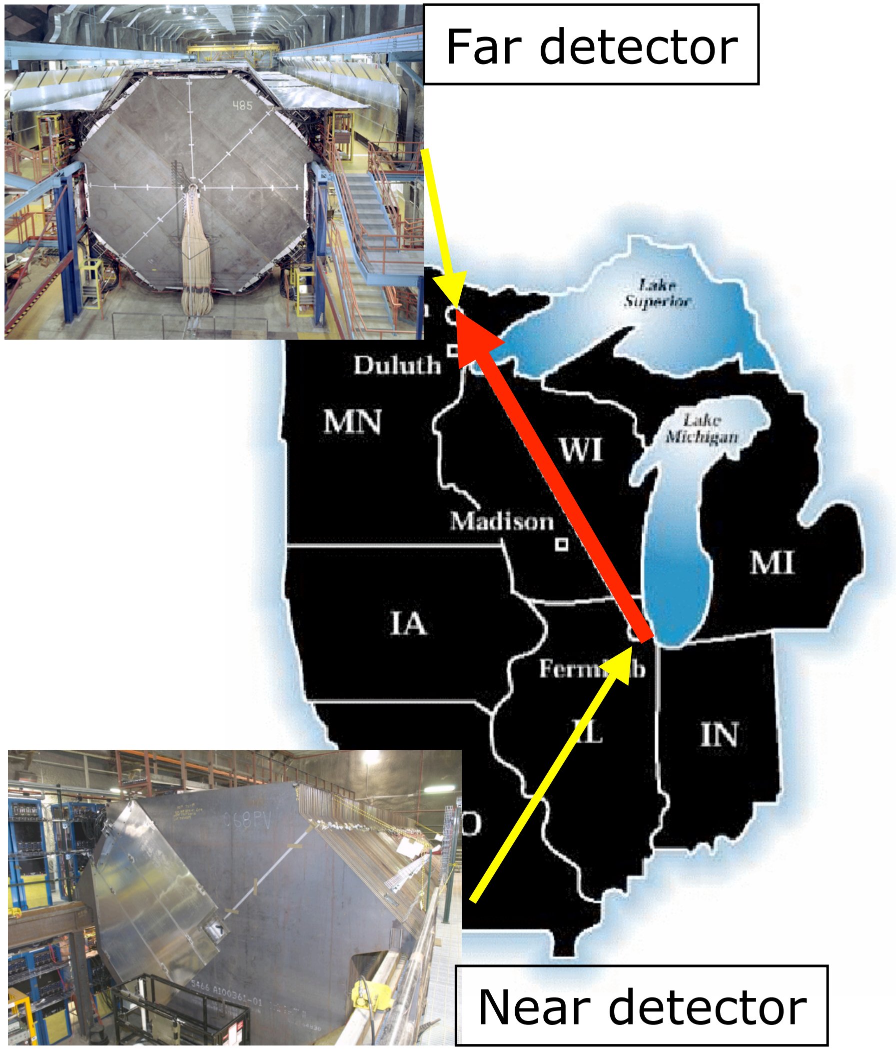
CNGS: the main components

700 m 100 m 1000m 67 m



p + C → interactions → π^+, K^+, (μ^+) → decay in flight → $\mu^+ + \nu_\mu$

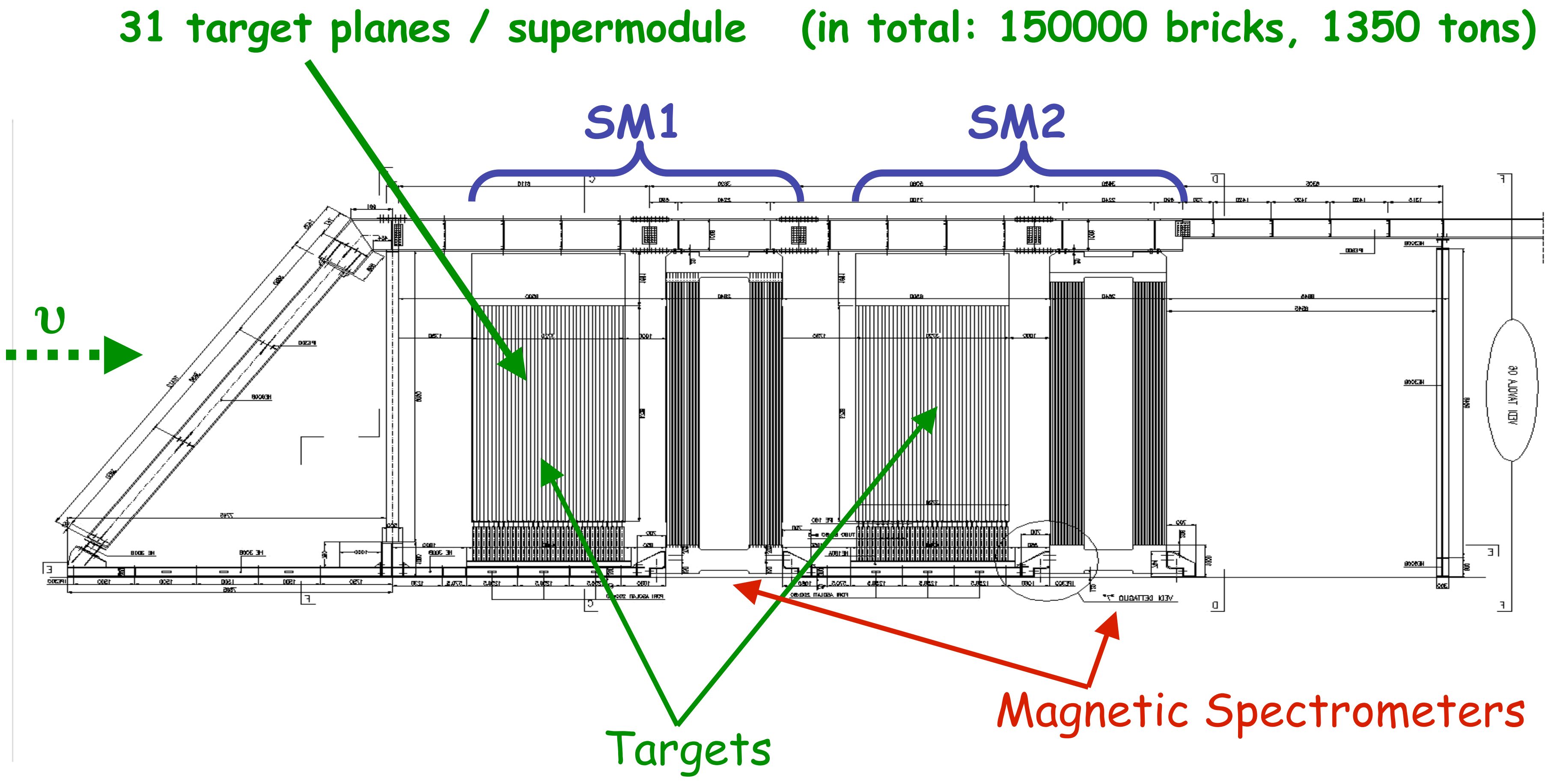
NuMI - MINOS



Far Detector:
Soudan, Minnesota, 735 km from target
5.4 kton mass
484 steel/scintillator planes, 8x8x30 m^3

Near Detector:
Fermilab, 1km from target
1 kton mass
282 steel planes
153 scintillator planes, 3.8x4.8x15 m^3

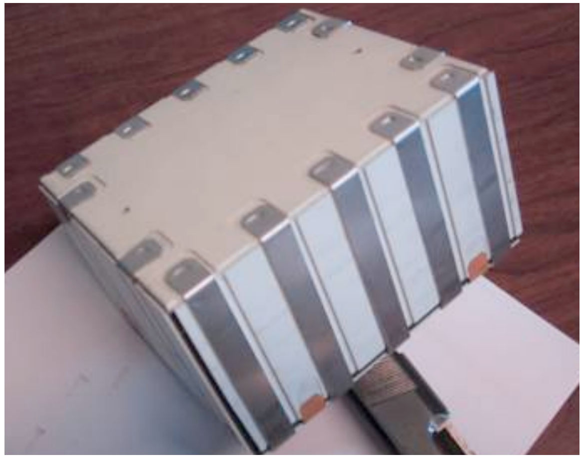
Structure of the OPERA Experiment



OPERA Hybrid concept

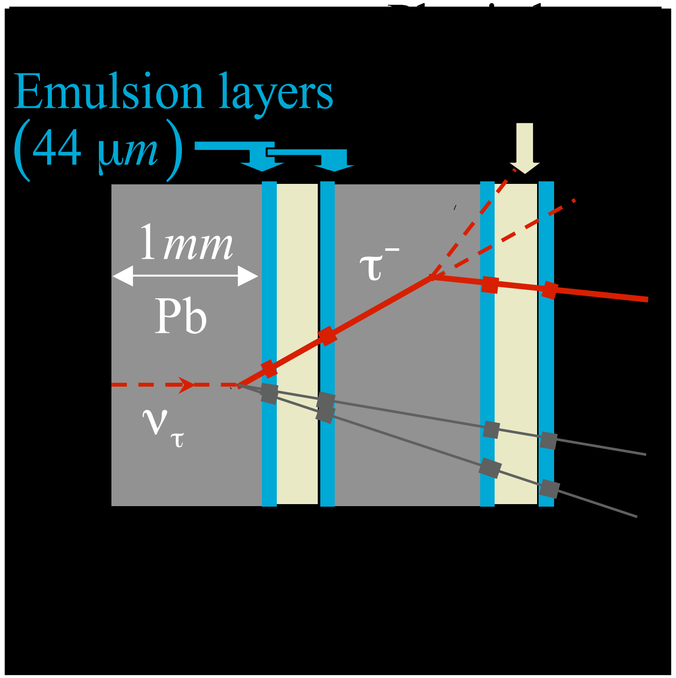
Target is an assemblage of autonomous cells ("bricks")

- based on "Emulsion Cloud Chamber" technique
- provides large mass and micron and mrad precisions
- quasi on-line analysis: bricks in which events have occurred are removed and analysed on daily base.



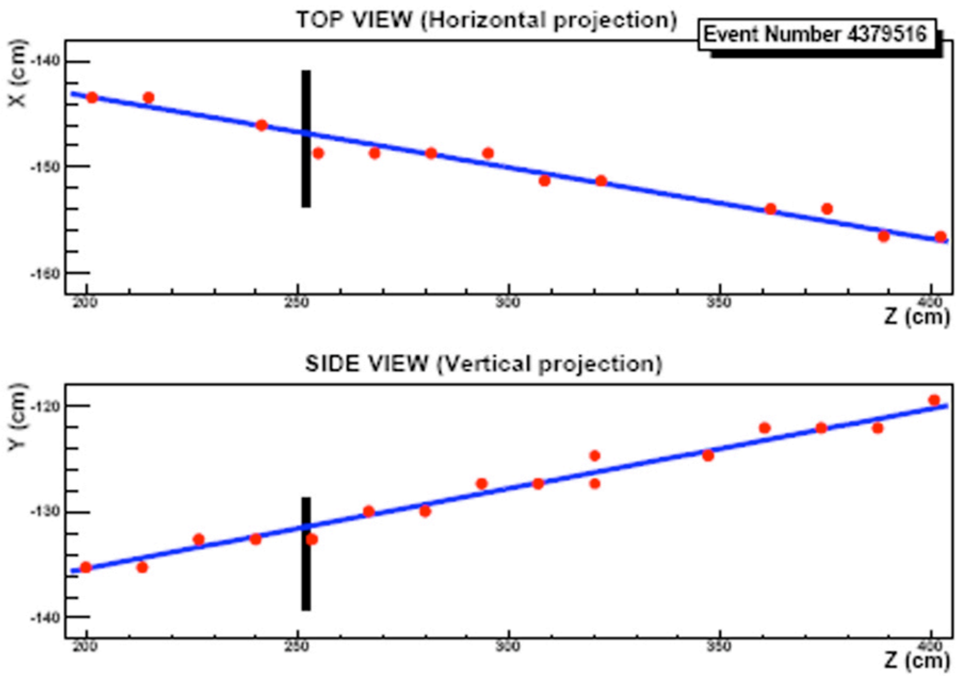
Brick

- **56 lead plates interleaved with 57 sheets of nuclear emulsion**
- ***4″×5″×7.5 cm*, 8.3 *kg*.**
- **10 X_0**

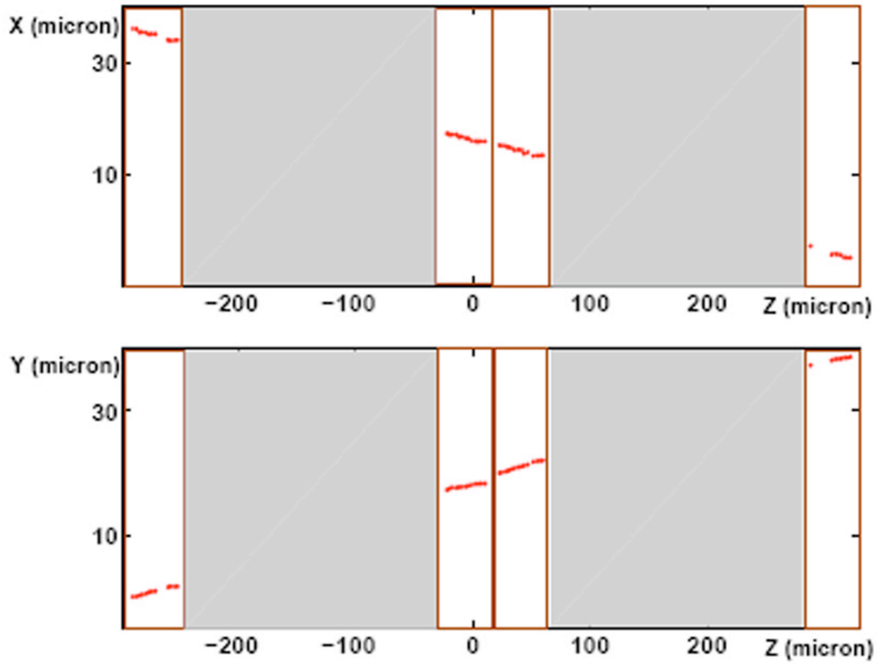


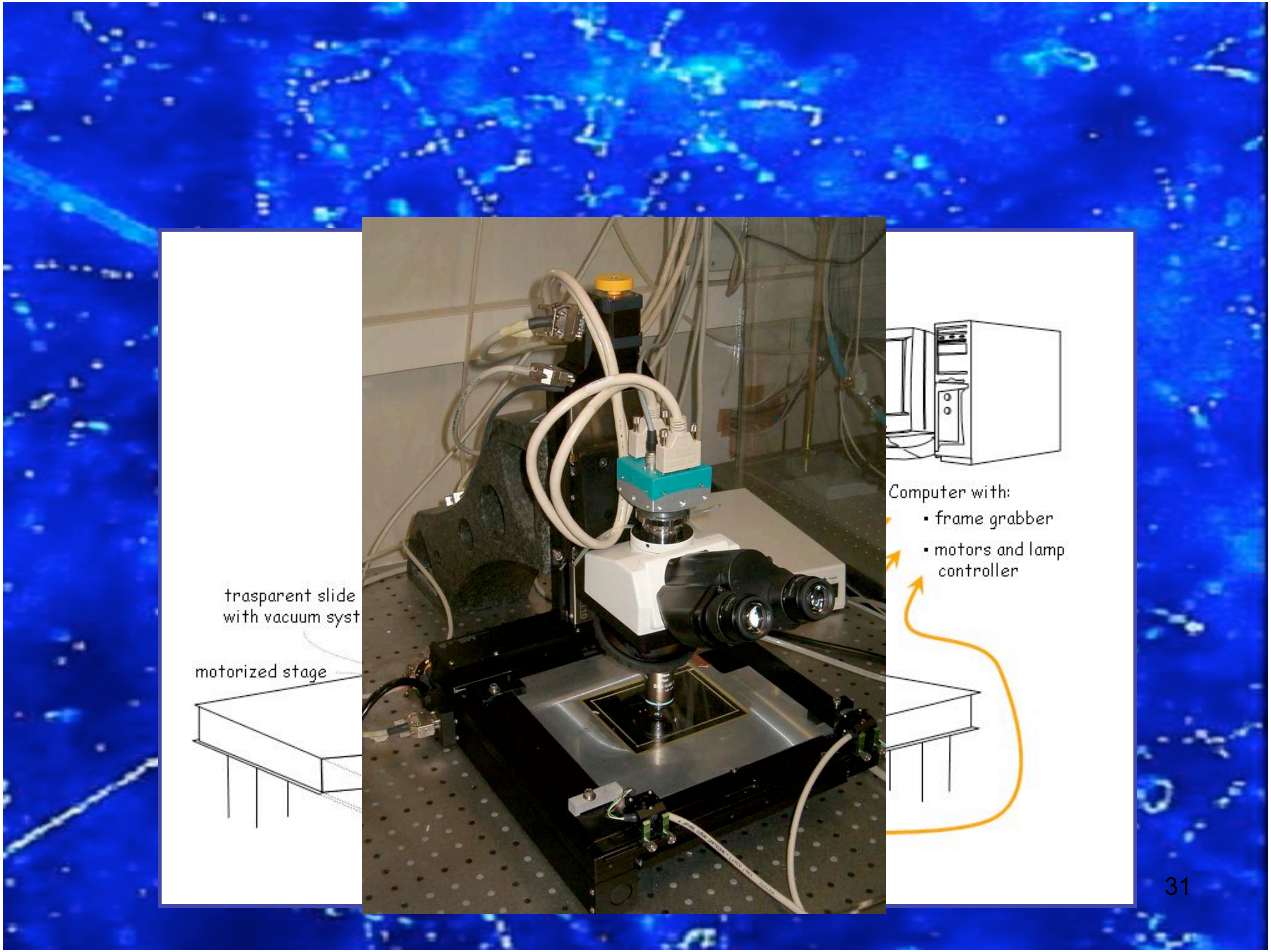
Tracks : series of aligned segments in emulsion layers

A muon in the electronic detectors

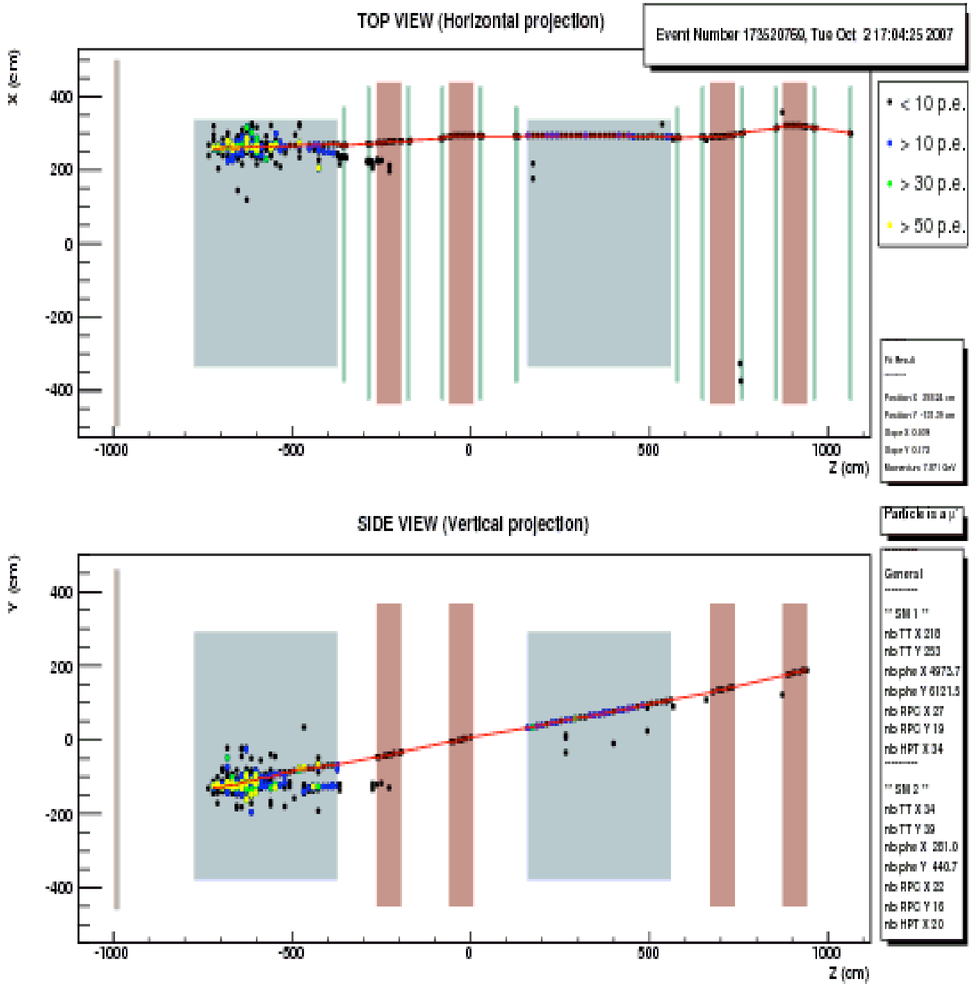


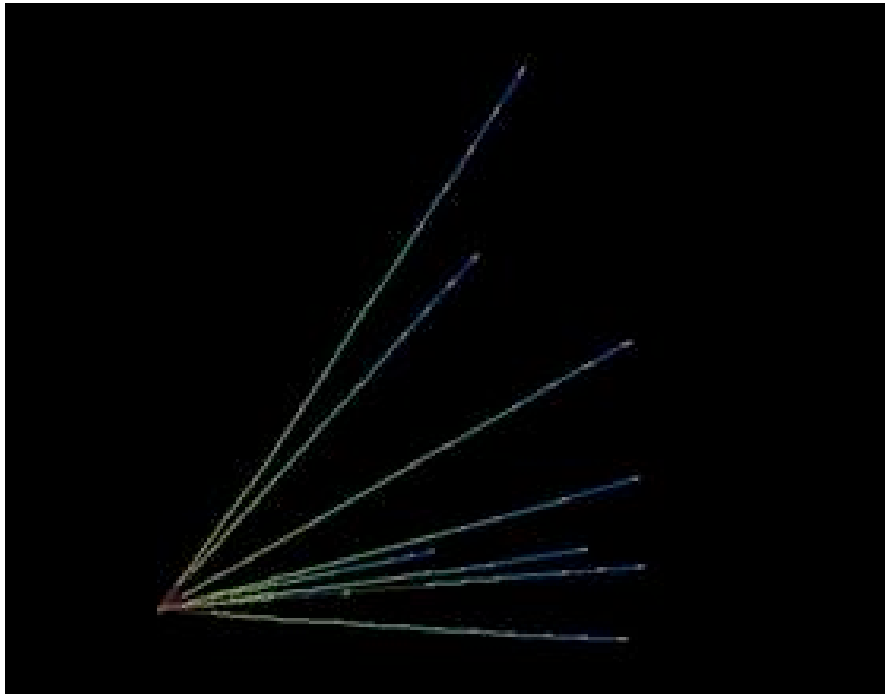
The same muon in emulsions




Computer with:
• frame grabber
• motors and lamp controller
trasparent slide with vacuum syst
motorized stage

One event seen in 2007





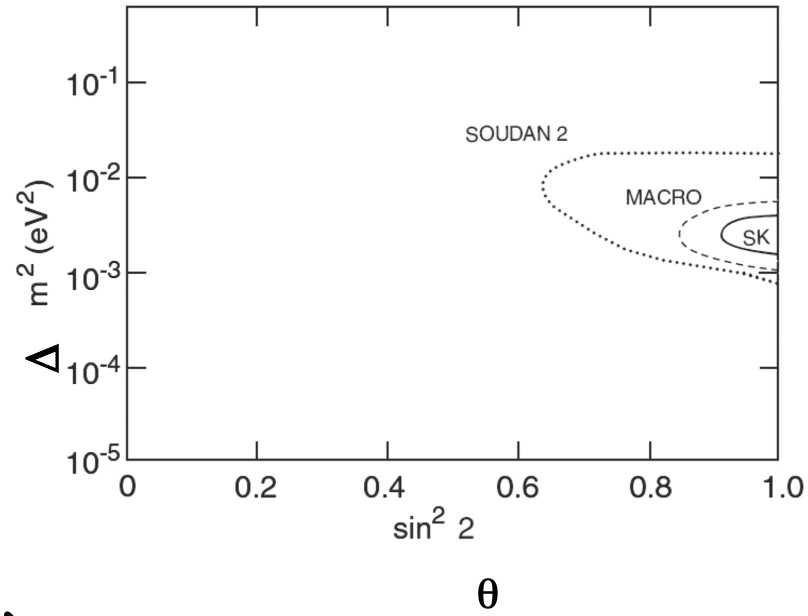
7. Conclusions. Outlook

Atmospheric neutrino and long baseline favor 2-flavor oscillations

Maximal mixing

$\Delta m_{23}^2 =$

Soudan2	5.2 10^{-3} eV^2	
MACRO	2.3	"
SK	2.5	"
K2K	2.7	"
Minos	2.43	"



No $\nu_\mu \rightarrow \nu_\sigma$ oscillations (MACRO, SK)

Oscillation pattern in L/E_ν (SK,MINOS)

More exotic scenarios:

- Lorentz invariance violation : mixing between flavor and velocity eigenstates (MACRO, SK,...)
- neutrino radiative decay, others

Appearance experiments $\nu_\mu \rightarrow \nu_\tau$ (OPERA, SK, ICARUS,...)

Solar neutrinos

Experiments : Homestake, Kamiokande, Sage, Gallex,

Superkamiokande, SNO, Kamland, Borexino

$\Delta m_{12}^2 = 7.5\ 10^{-5}\ eV^2$

$tg^2\theta_{12} = 0.47$

… and next

- T2K and Noνa
  - "Off-Axis" Trick