Accelerator Neutrino Facility From Past, Present and Future

Physics motivations and Neutrino facilities

Koichiro Nishikawa (KEK)

EPAC@Genova

June 23, 2008

1. First muon neutrino beam with accelerator

- There are electron and muon
  - ν_e from β decay $\neq \nu_\mu$ from $\pi\rightarrow\mu+\nu$ decay ?
  - In 1960, Lee and Yang are realized that if a reaction like $\mu- \rightarrow e- + \gamma$ is not observed,

    this is because two types of neutrinos exist ν_μ and ν_e
- Make ν_μ beam and show they does not make electron when they interact
- How to produce weakly interacting particles in a large quantity

Pontecorvo(1959) and Schwarz (1960)

- p-beam $p+A \rightarrow \pi$ + anything   (Strong interaction)
- π decay $\pi \rightarrow \mu$ + neutrino   (Weak interaction)
- $\pi \rightarrow e$ + neutrino suppressed (10^{-4})

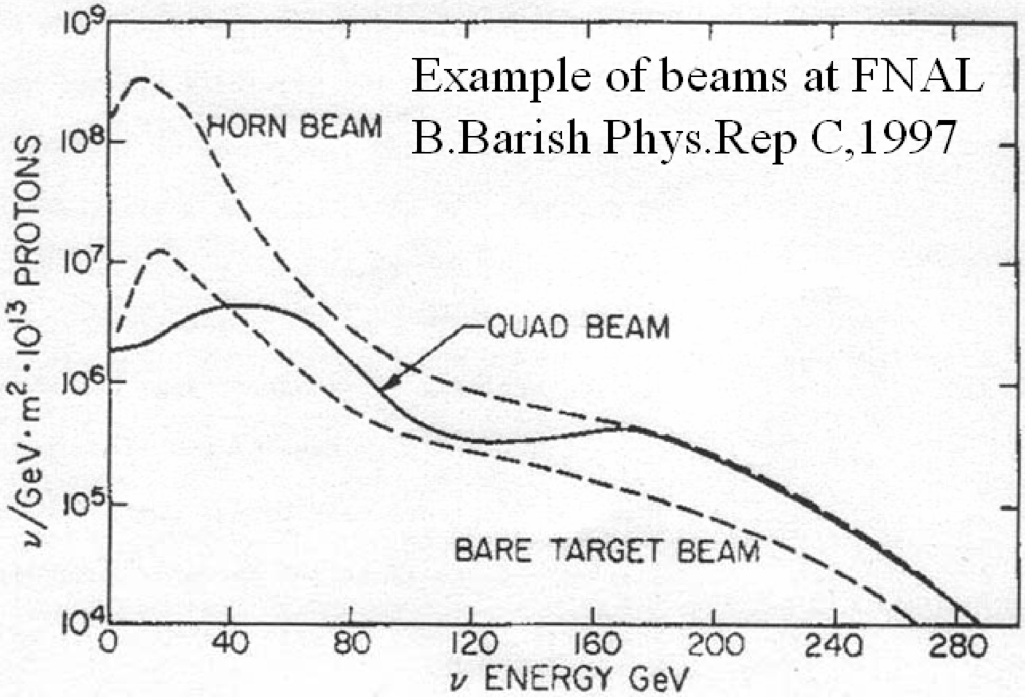
AGS internal target

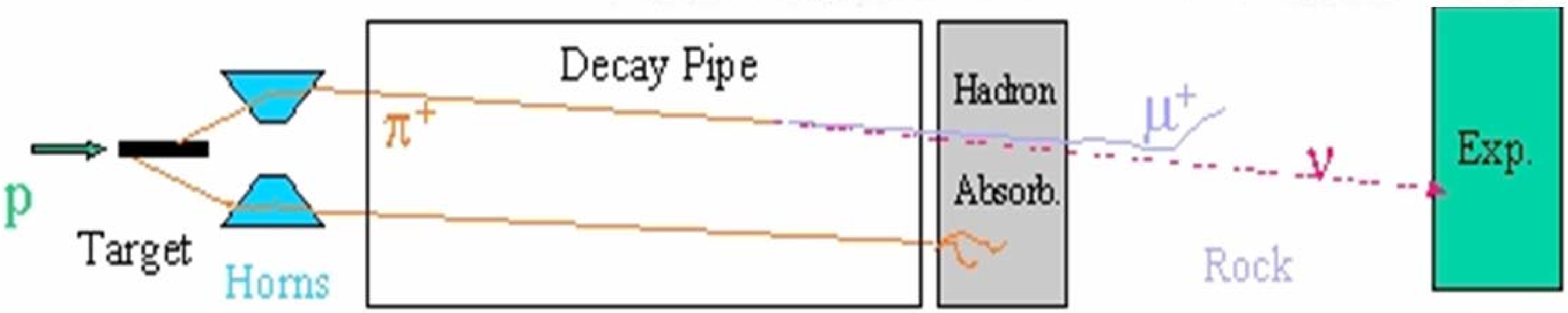
2. Weak interaction, structure of matter and number of neutrino species

- Electromagnetic interaction and weak unification
  - Required a neutral current weak interaction to exist in Weinberg-Salam model
  - neutrinos are the best testing probe to search NC, since they do not have other interactions
- Deep inelastic scatterings show the existence of hard core inside nucleons- partons
  - Is parton quark?
  - comparison with electro-magnetic probe, consistent with fractional charges

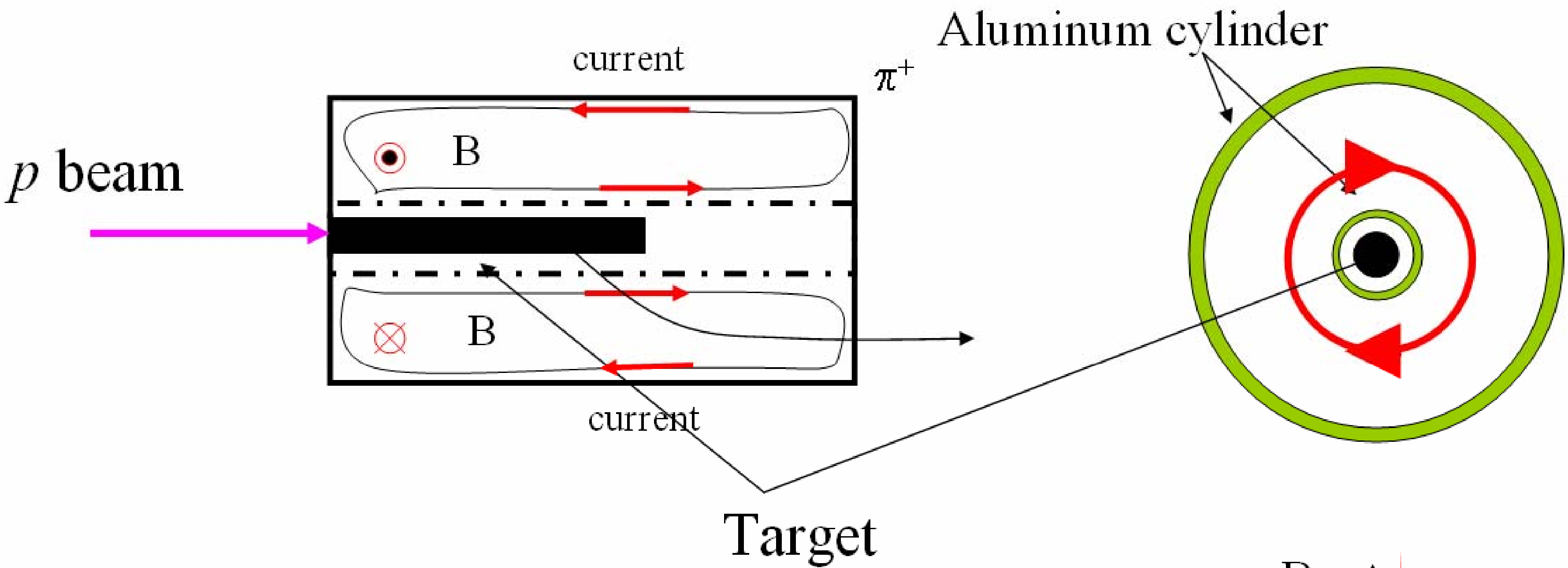
High intensity beam – Horn beam

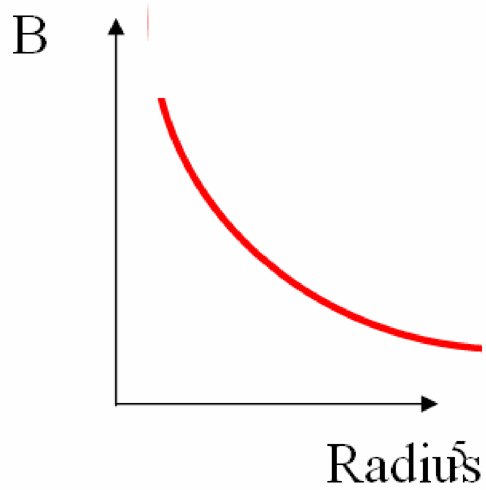
- Focus of π,K by horn
  (S. van der Meer)
- Highest total intensity
  - Simultaneous focus in vertical and horizontal
  - Shortest focal length
  - Pulsed magnet
  - Fast extraction to get short spill width





Magnetic horn





$$\text{Toroidal magnetic filed} \quad B\,[T] = \frac{I\,[A]}{5r\,[m]} \times 10^{-6}$$

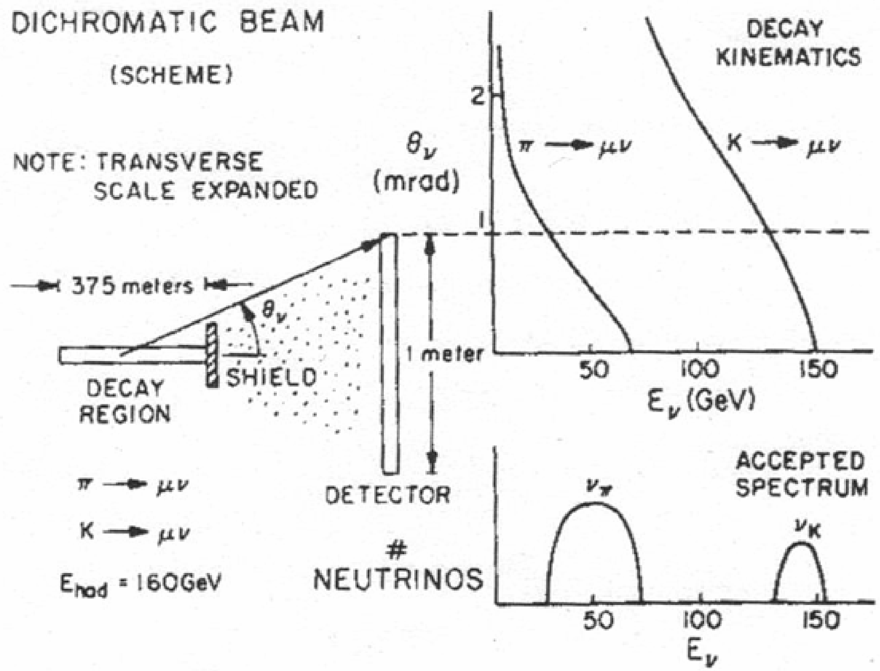
$$100\text{kA},\ r = 1\text{cm} \Rightarrow B = 2\text{T}$$

Narrow Band Beam to study high energy neutrino interactions

- Momentum of π, K are selected by B-Q magnet beam channel
- Well defined two neutrino energies from π, K decay
  - Especially useful for NC measurements
- Acceptance of the beam line limits neutrino intensity

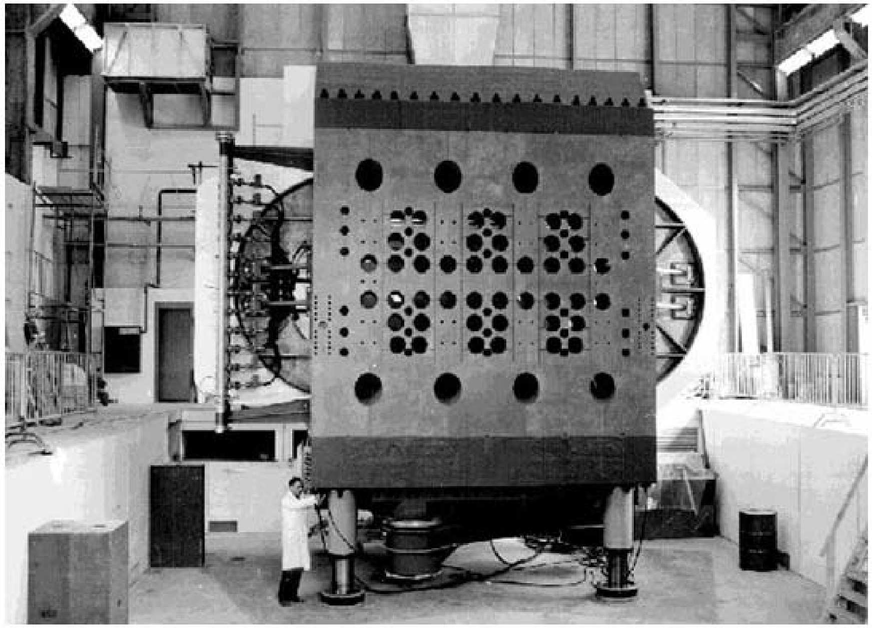
$$E_\nu(\pi - \text{decay}) = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2(1+\gamma^2\theta^2)} E_\pi \approx \frac{0.49 E_\pi}{(1+\gamma^2\theta^2)}$$

$$E_\nu(K - \text{decay}) = \frac{m_K^2 - m_\mu^2}{m_K^2(1+\gamma^2\theta^2)} E_\pi \approx \frac{0.96 E_\pi}{(1+\gamma^2\theta^2)}$$

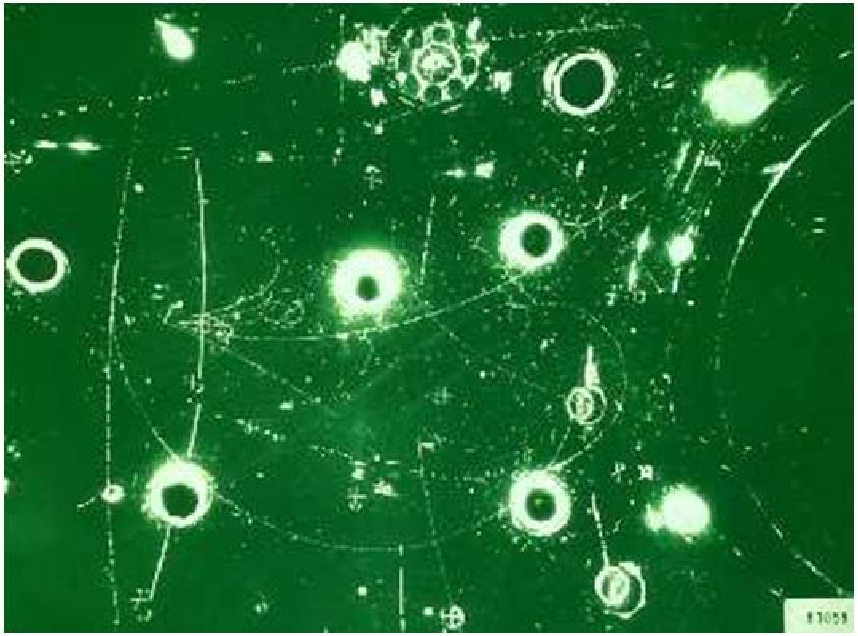


Neutrinos

the weak neutral current



Gargamelle Bubble Chamber
CERN



First evidence for weak neutral current

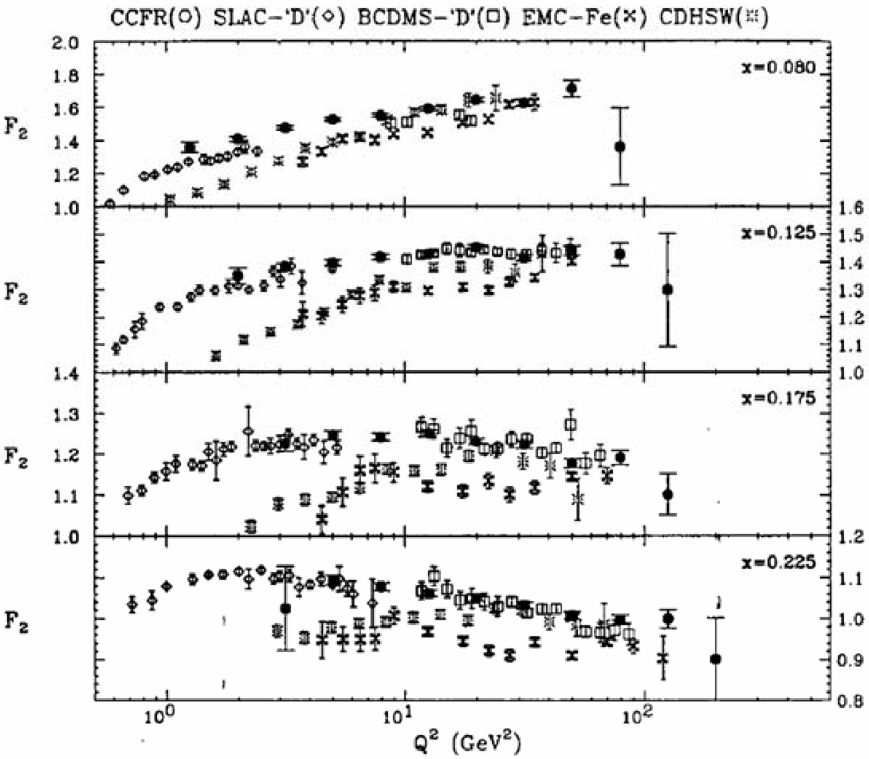
$\nu_\mu + e \rightarrow \nu_\mu + e$

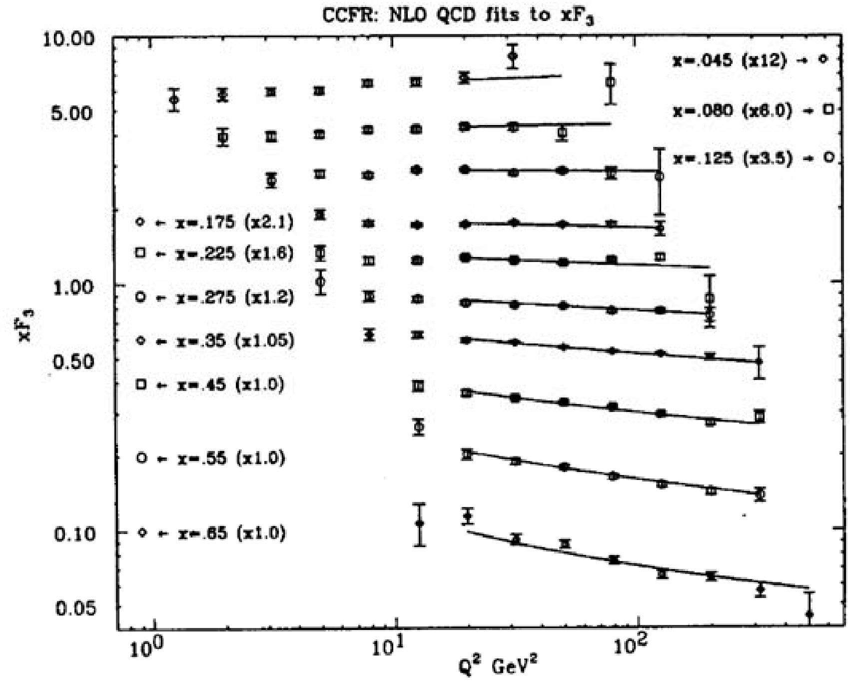
A direct evidence of electro-weak unification by SU(2)xU(1)

Neutrinos

neutrino scattering

CCFR – CDHSW



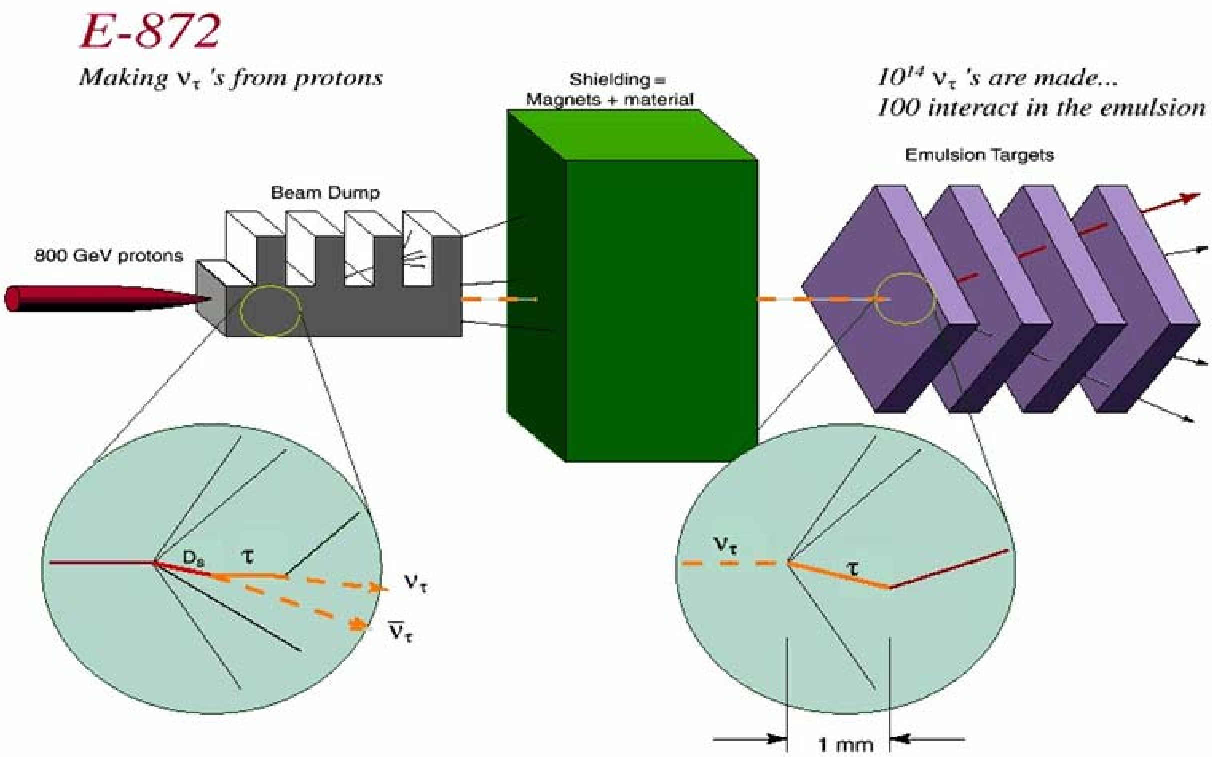


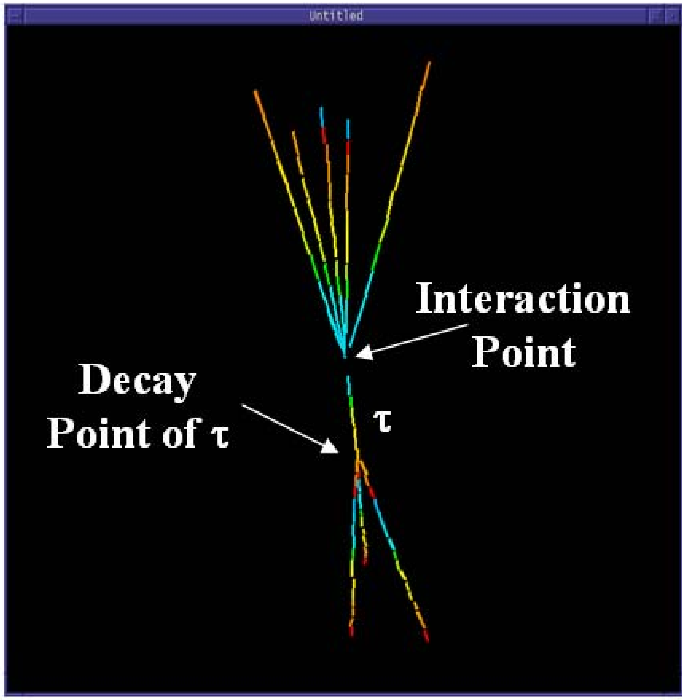
- Parton Structure at large q^2
- Charge of Parton - quark as parton
- QCD

The third neutrino - ν_τ

Beam dump neutrino source : suppress π, K decay by absorption before decay

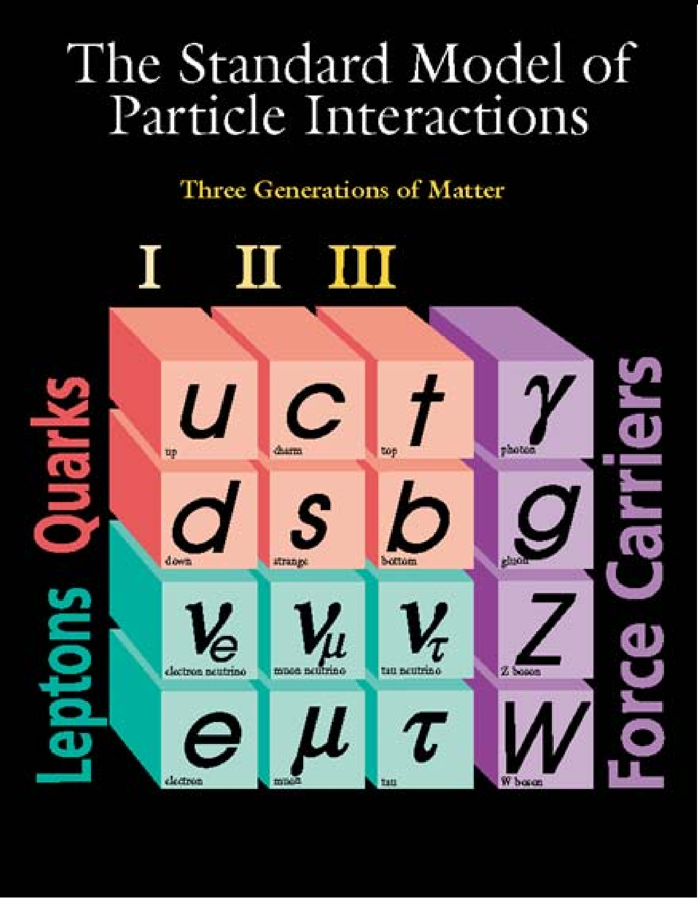
Enhance prompt decay ν source : charm meson





Neutrino interaction and decay of short lived particles

ν_τ exist
produce τ–lepton when it interact with matter

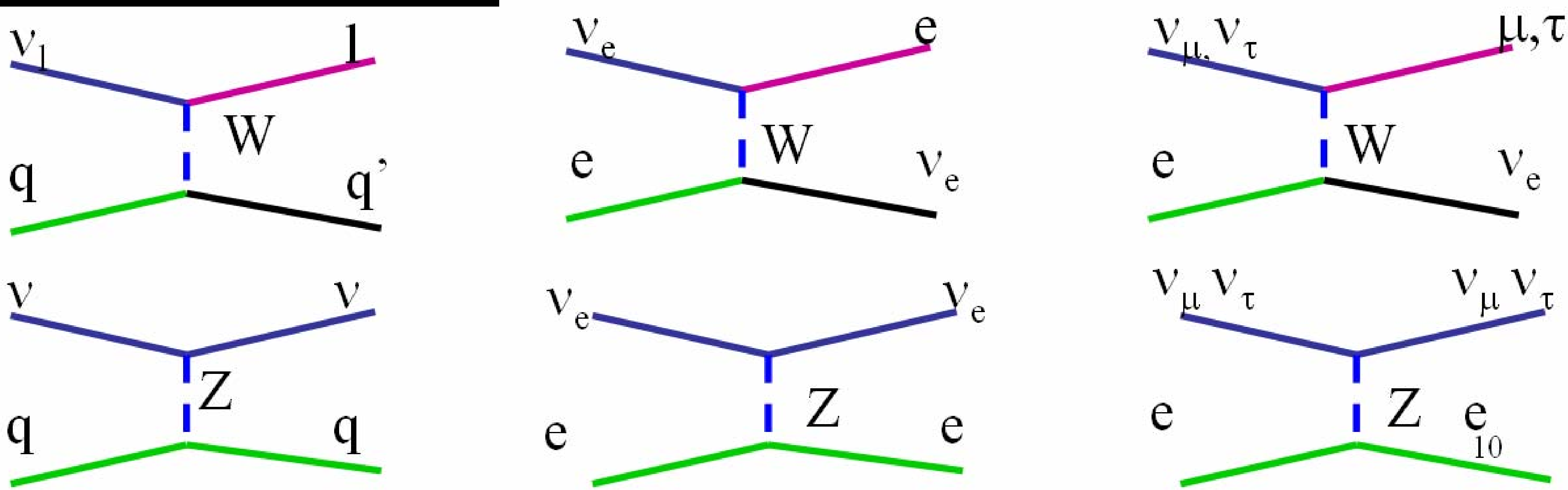


The Standard Model of Particle Interactions

- LEP results on number of ν

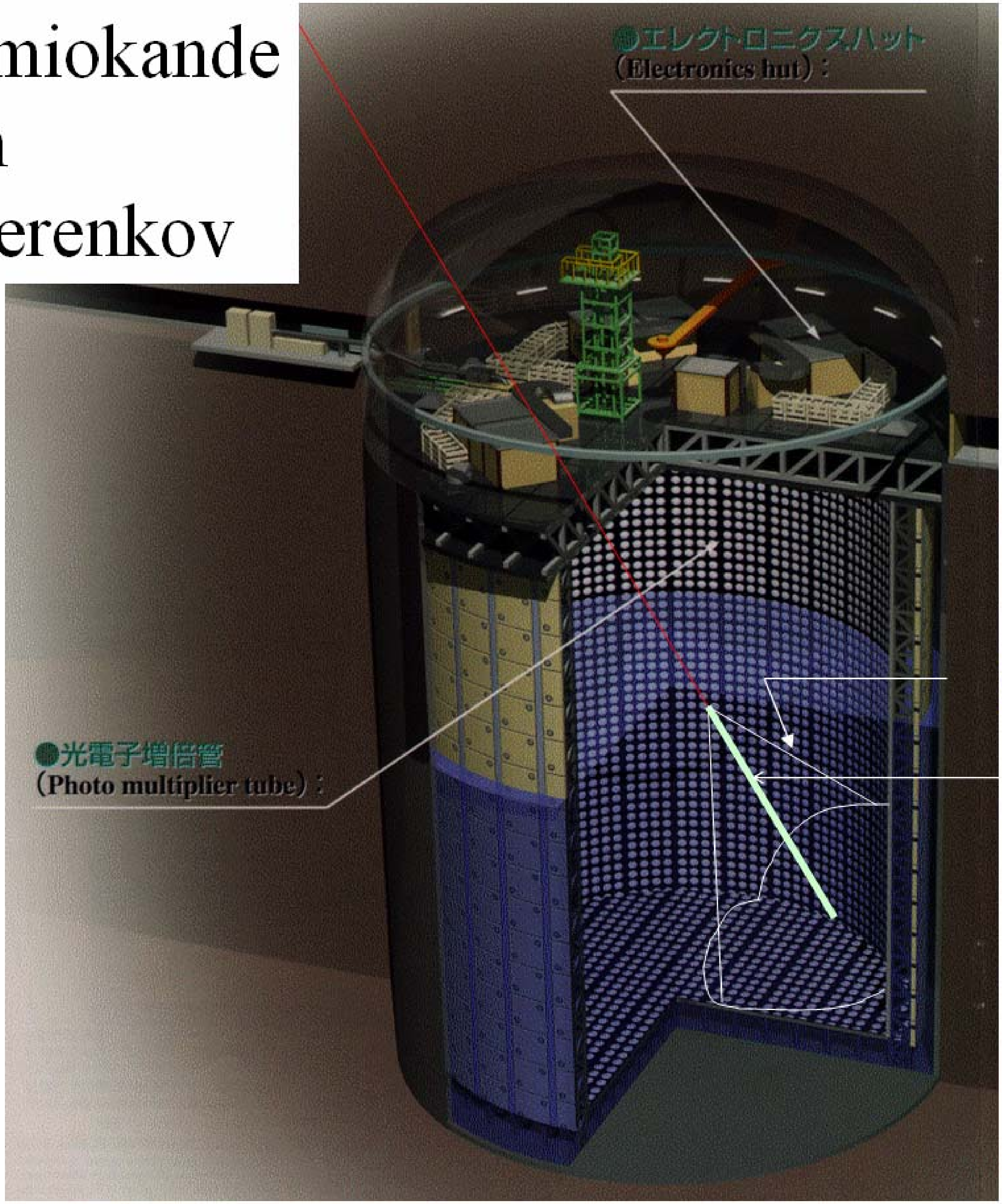
$N_\nu = 2.984 \pm 0.008$

- Three generation of quark and lepton
- (Higgs to be discovered)



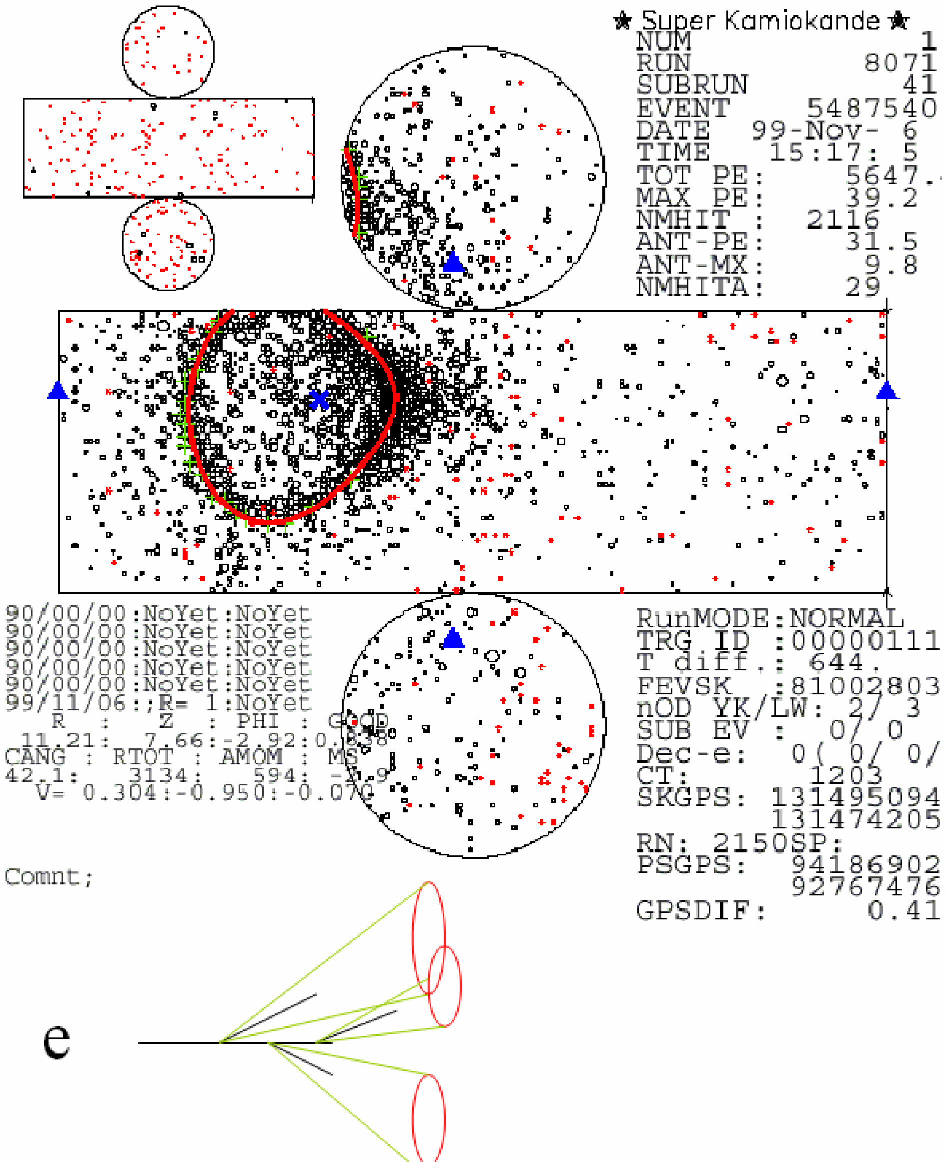
Neutrino oscillation

Super Kamiokande
50,000ton
Water Cherenkov

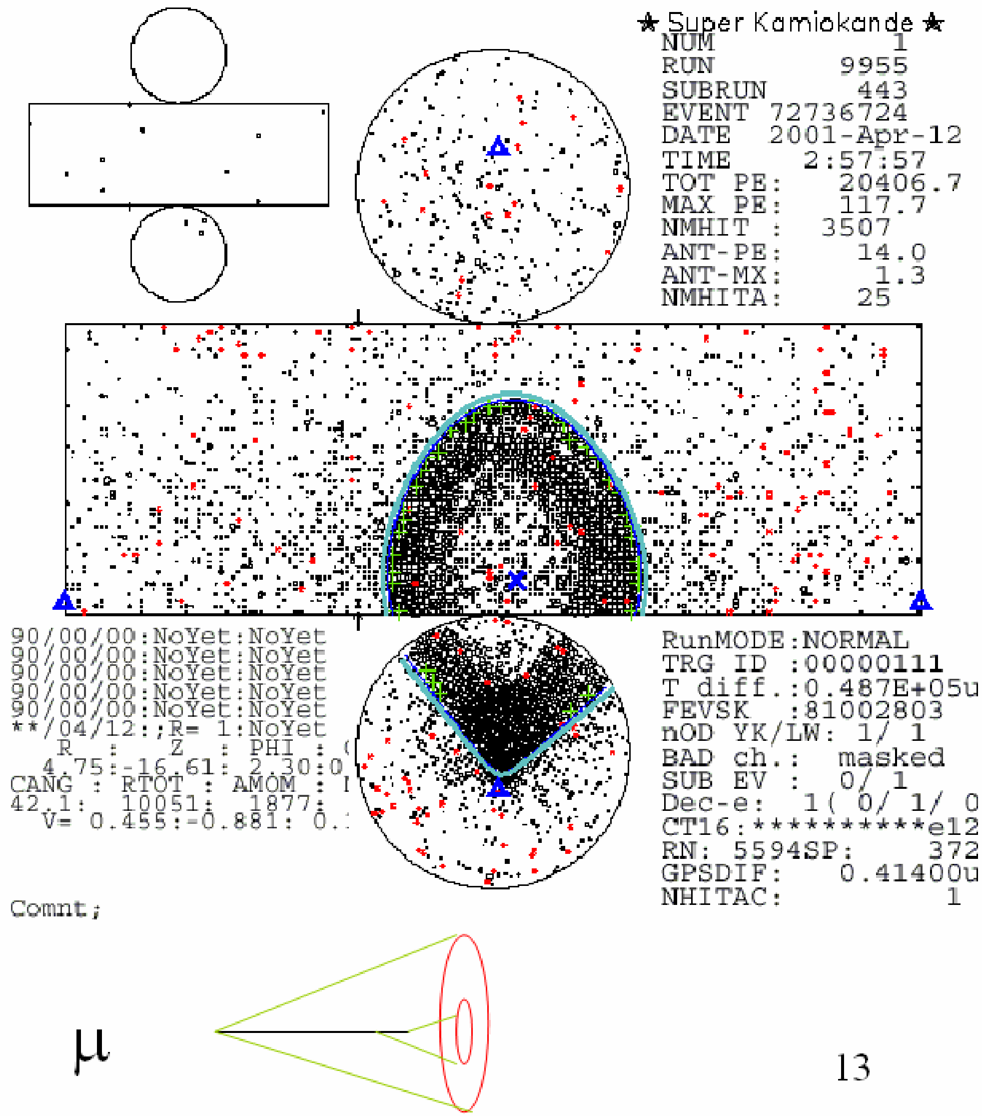


Electron-like and muon-like events

e-like

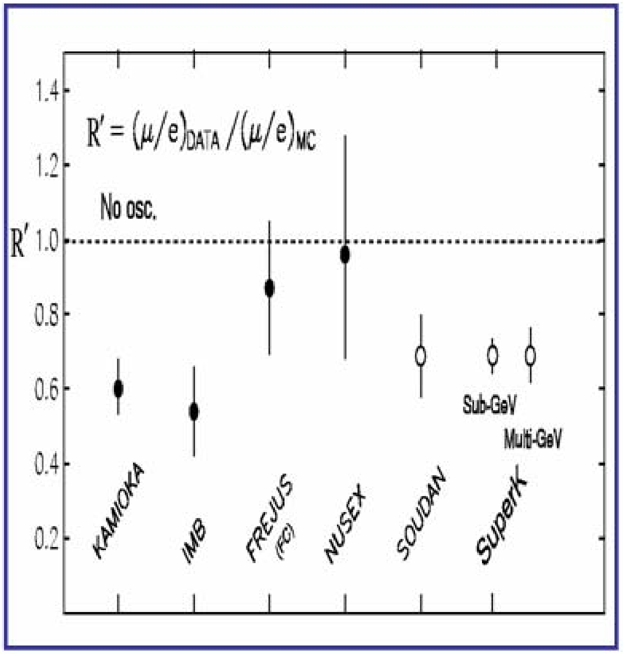


μ-like



Atmospheric neutrino deficiency

1986



1994

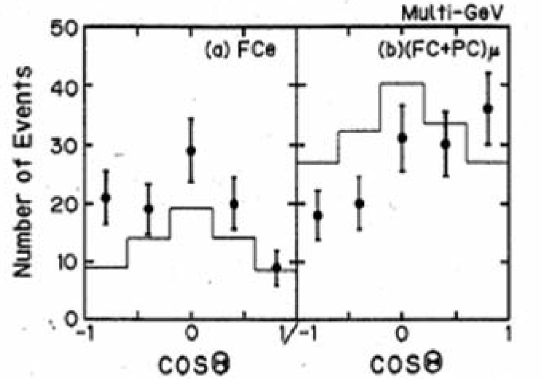


Fig. 3. Zenith-angle distributions for (a) the e-like events and (
μ-like events (the fully-contained and partially-contained even
are combined). The circles with error bars show the data and t
histogram the MC (without neutrino oscillations). The downwa
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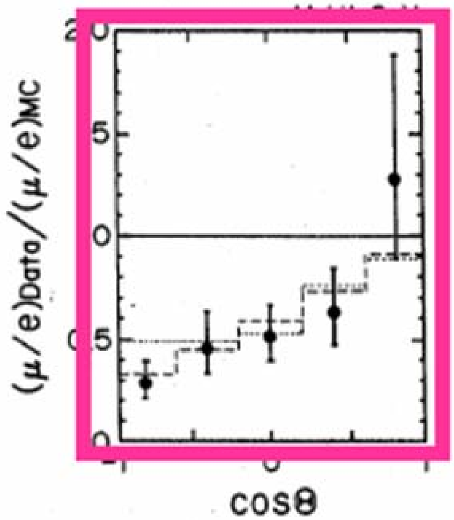
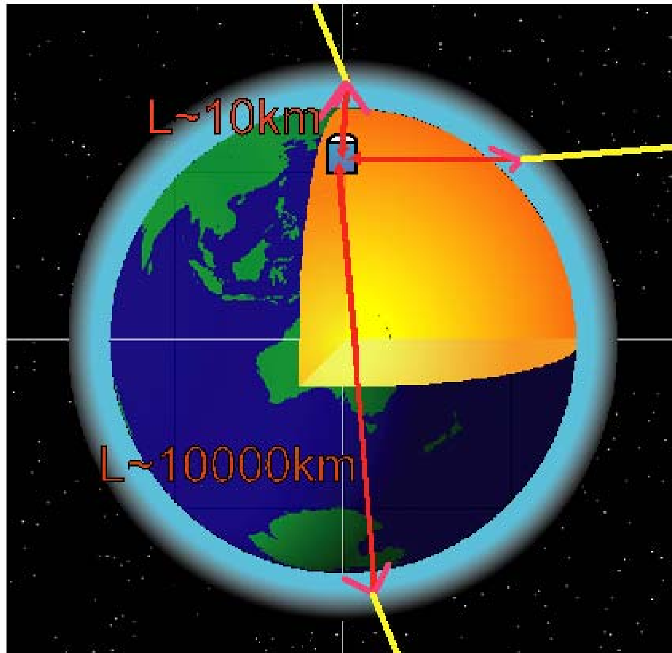
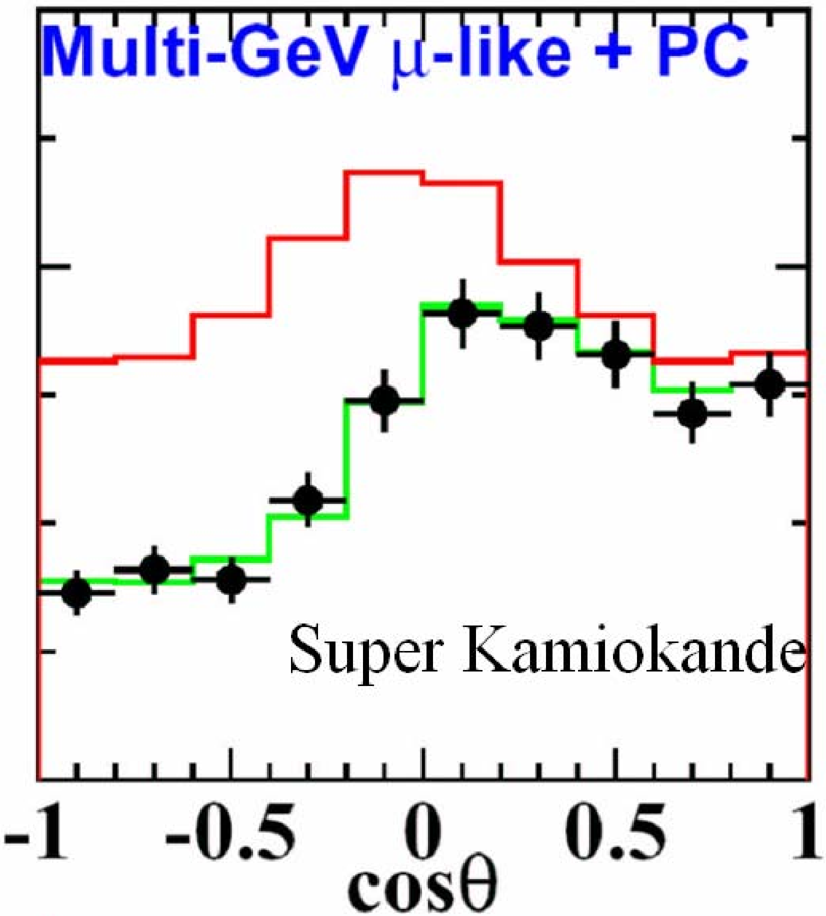
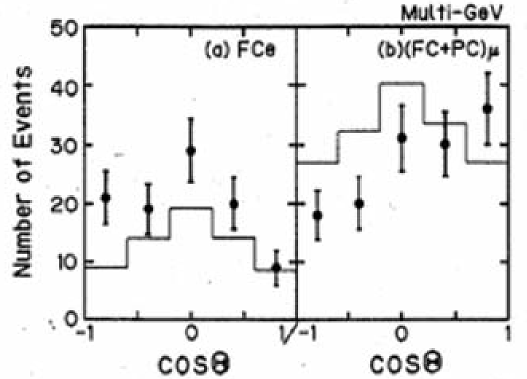




Atmospheric neutrino deficiency



1994



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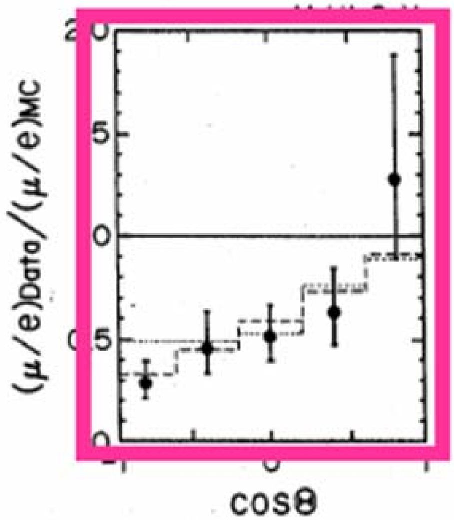
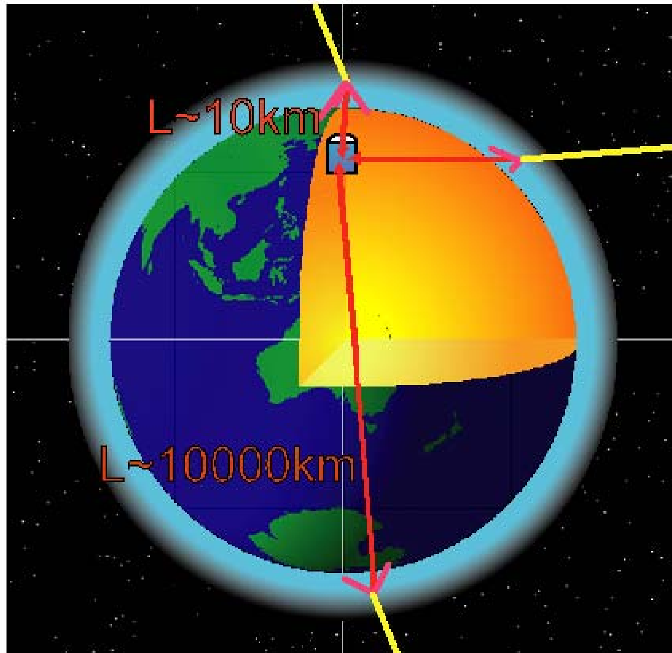




Muon type neutrinos transform to
other type (not electron type)
in a few 100km travel

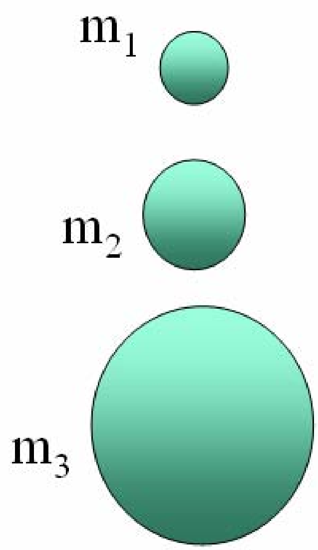
If neutrinos have non-zero mass,
Two kinds of classifications are possible

- when they interact with matter which lepton it produce
- masses

Weak eigenstates

mass eigenstates

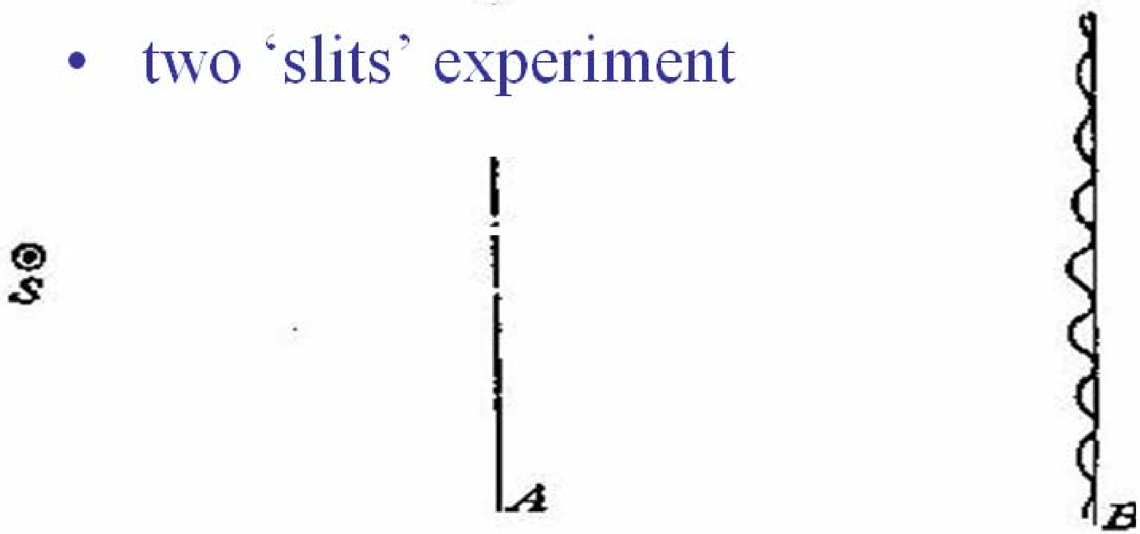
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- $\nu_e\ \nu_\mu\ \nu_\tau$ are, in general, superposition of mass eigenstates $\nu_1\ \nu_2\ \nu_3$
$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$, etc.

Neutrino oscillation

- two 'slits' experiment



Neutrino oscillation

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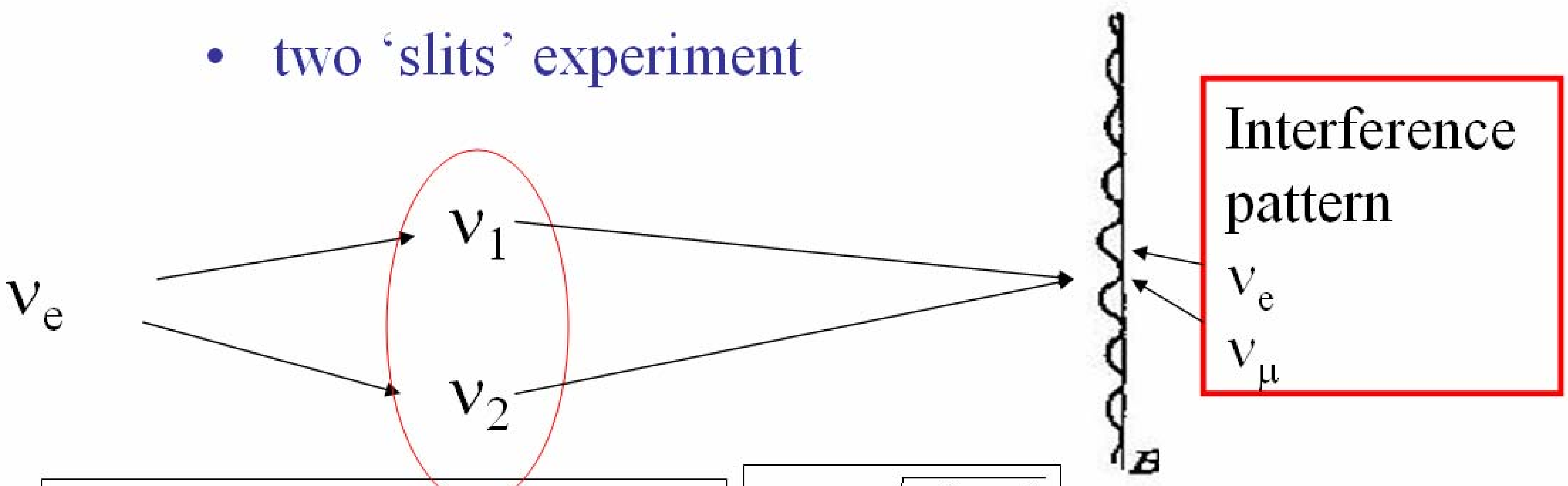


$\nu_1(\cos\theta\cdot\nu_e - \sin\theta\cdot\nu_\mu)(\text{mass}=m_1)$
$\nu_2(\sin\theta\cdot\nu_e + \cos\theta\cdot\nu_\mu)(\text{mass}=m_2)$

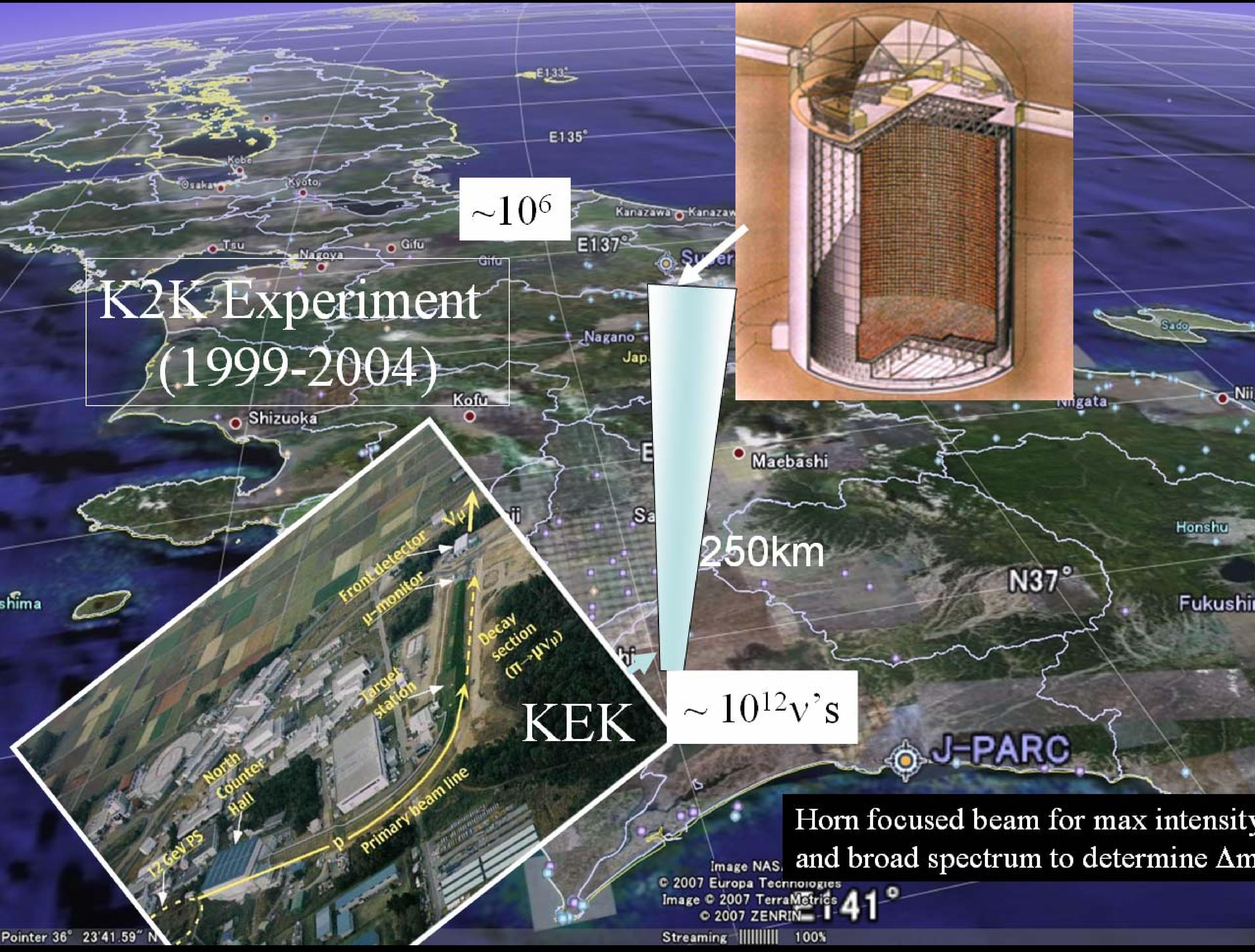
path1 : $\sqrt{m_1^2+p^2}$
path2: $\sqrt{m_2^2+p^2}$

Energy dependence

oscillation prbabilities

$$P(disappearance) = \left|\langle \nu_e, t \mid \nu_e \rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{\mathrm{E}}\right)$$

$$P(appearance) = \left|\langle \nu_\mu, t \mid \nu_e \rangle\right|^2 = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{\mathrm{E}}\right)$$


K2K Experiment
(1999-2004)
~10^6
250km
~ 10^12 ν's
KEK
Horn focused beam for max intensity
and broad spectrum to determine Δm
Front detector
μ-monitor
Decay section (π→μν_μ)
Target station
North Counter Hall
Primary beam line
12 GeV PS
J-PARC
Kanazawa
Nagoya
Gifu
Tsu
Kyoto
Osaka
Kobe
Nagano
Kofu
Shizuoka
Maebashi
Niigata
Sado
Honshu
Fukushi
N37°
E133°
E135°
E137°
E141°
Image NASA
© 2007 Europa Technologies
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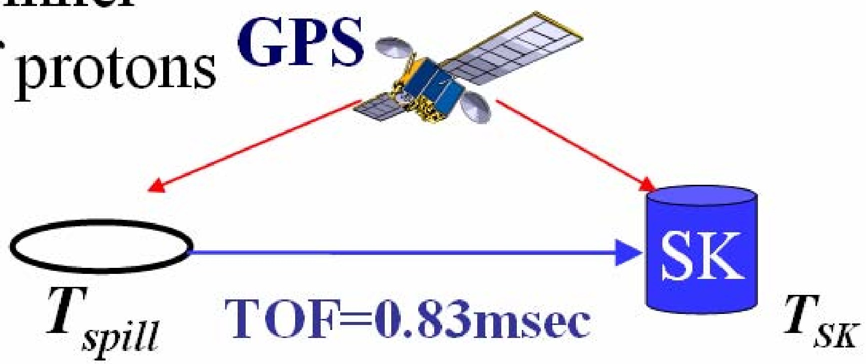
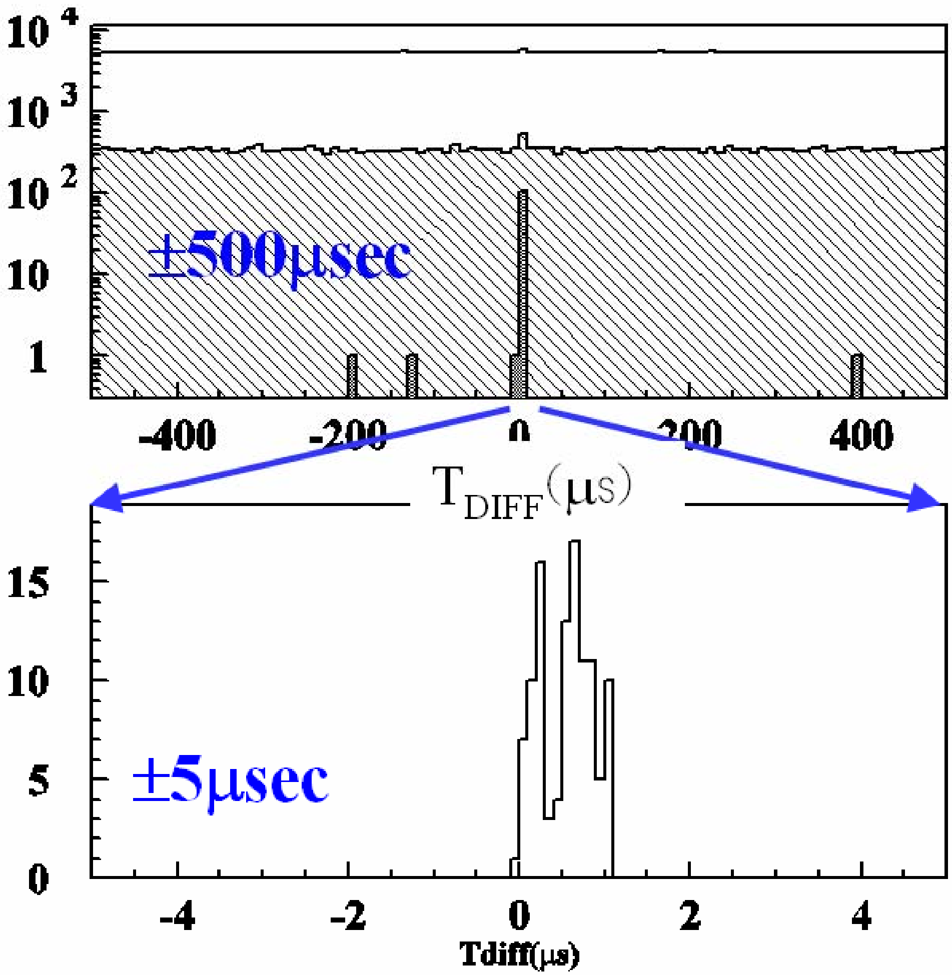
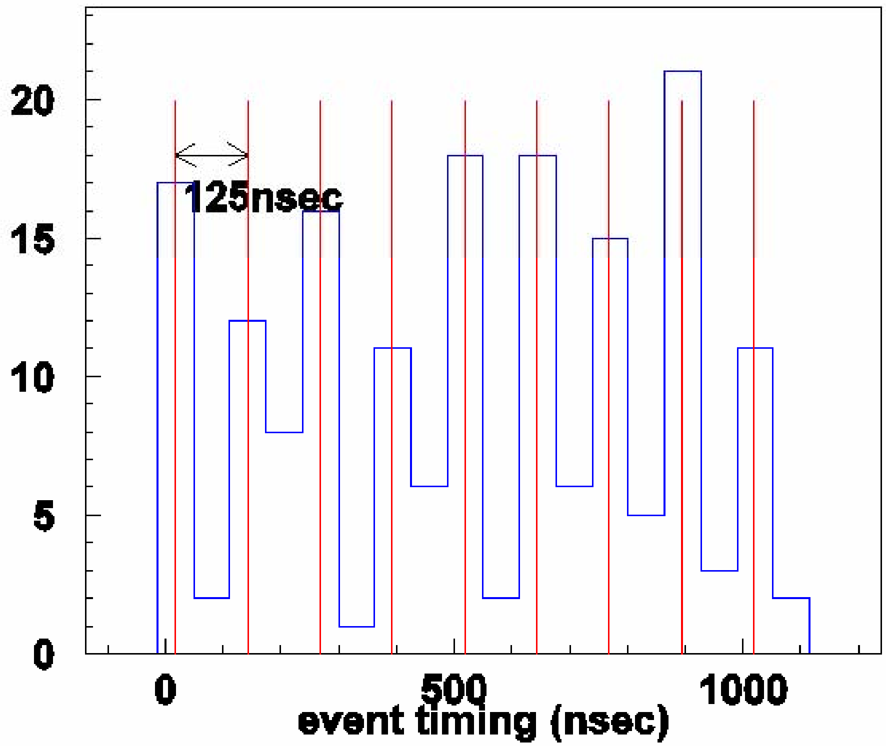
Pointer 36° 23'41.59" N
Streaming 100%

Timing of SK neutrino (contained in inner detector) events relative to extraction of protons



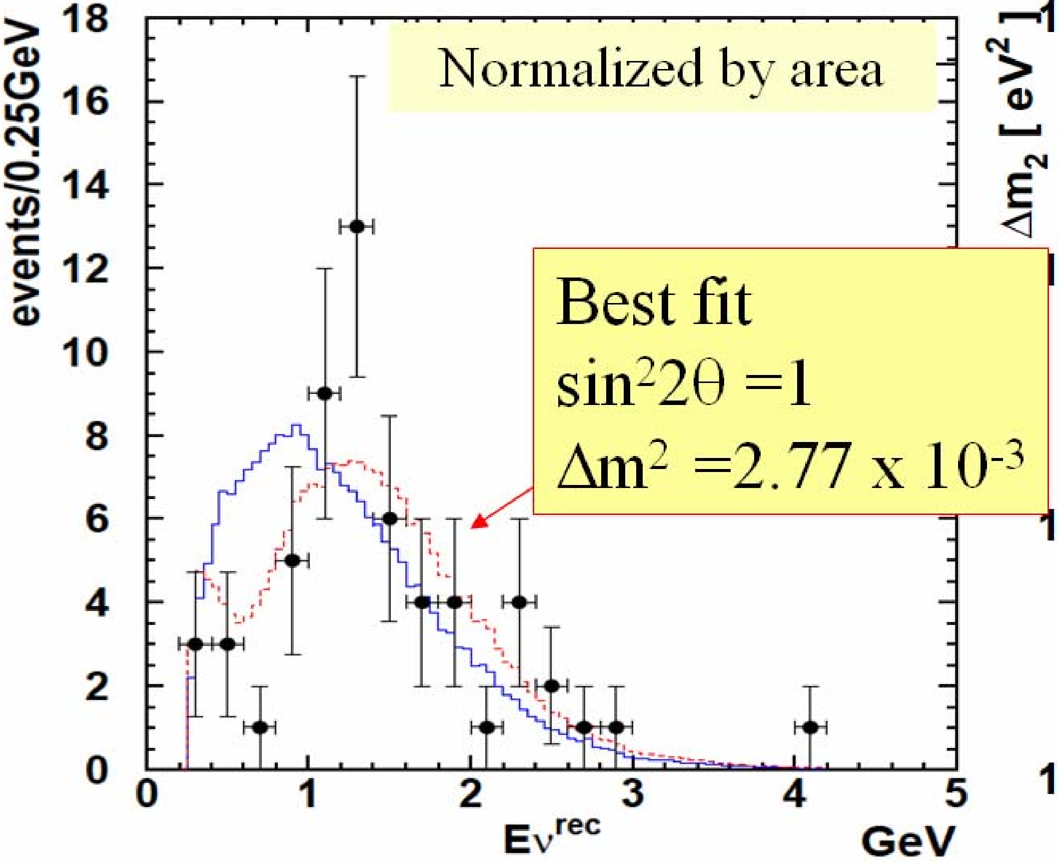




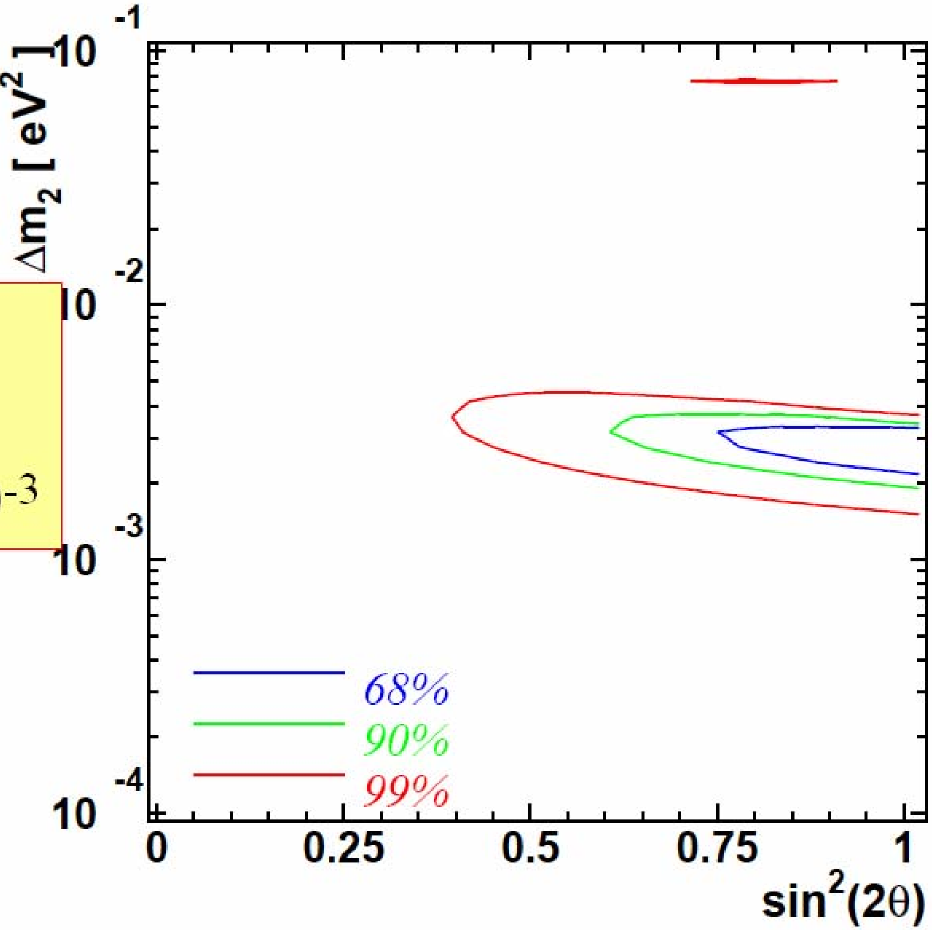
- Single turn extraction from 300m circumference accelerator
- Observation of accelerator RF structure at 250km away
- Clean identification of accelerator originated neutrinos

Final results Phys.Rev.D74:072003, 2006

Dependence on E_ν



Allowed region

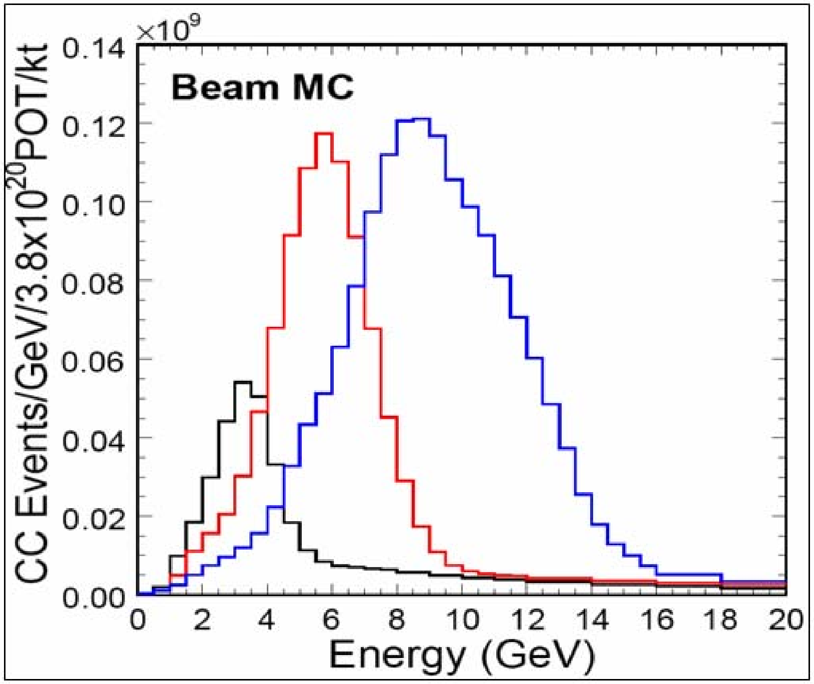


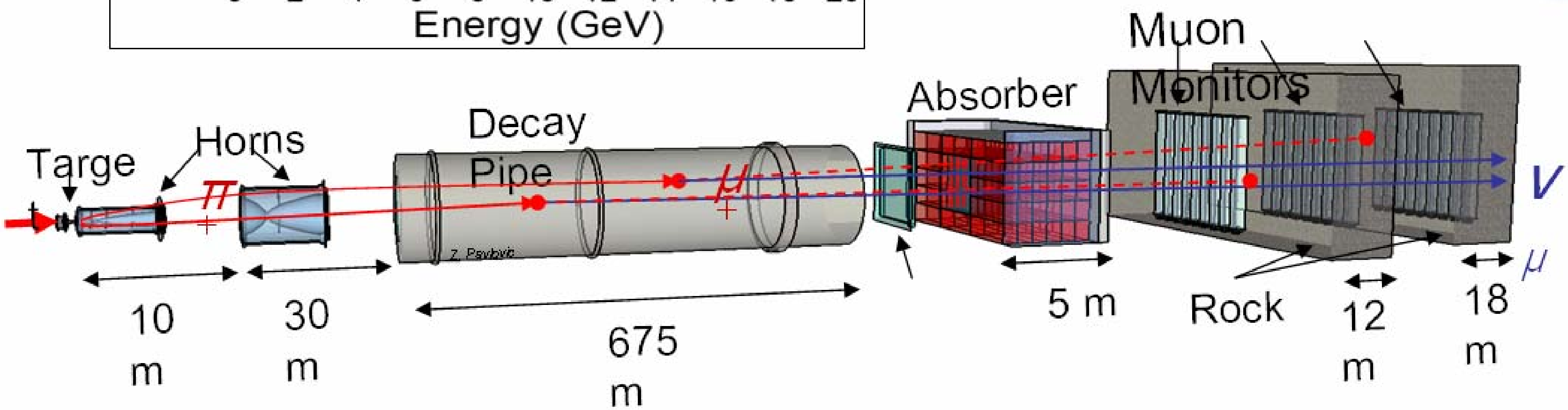
Rate **N_{obs}=112**

N_{exp}=158.4 $^{+9.4}_{-8.7}$

Null oscillation hypothesis excluded at 4.4σ

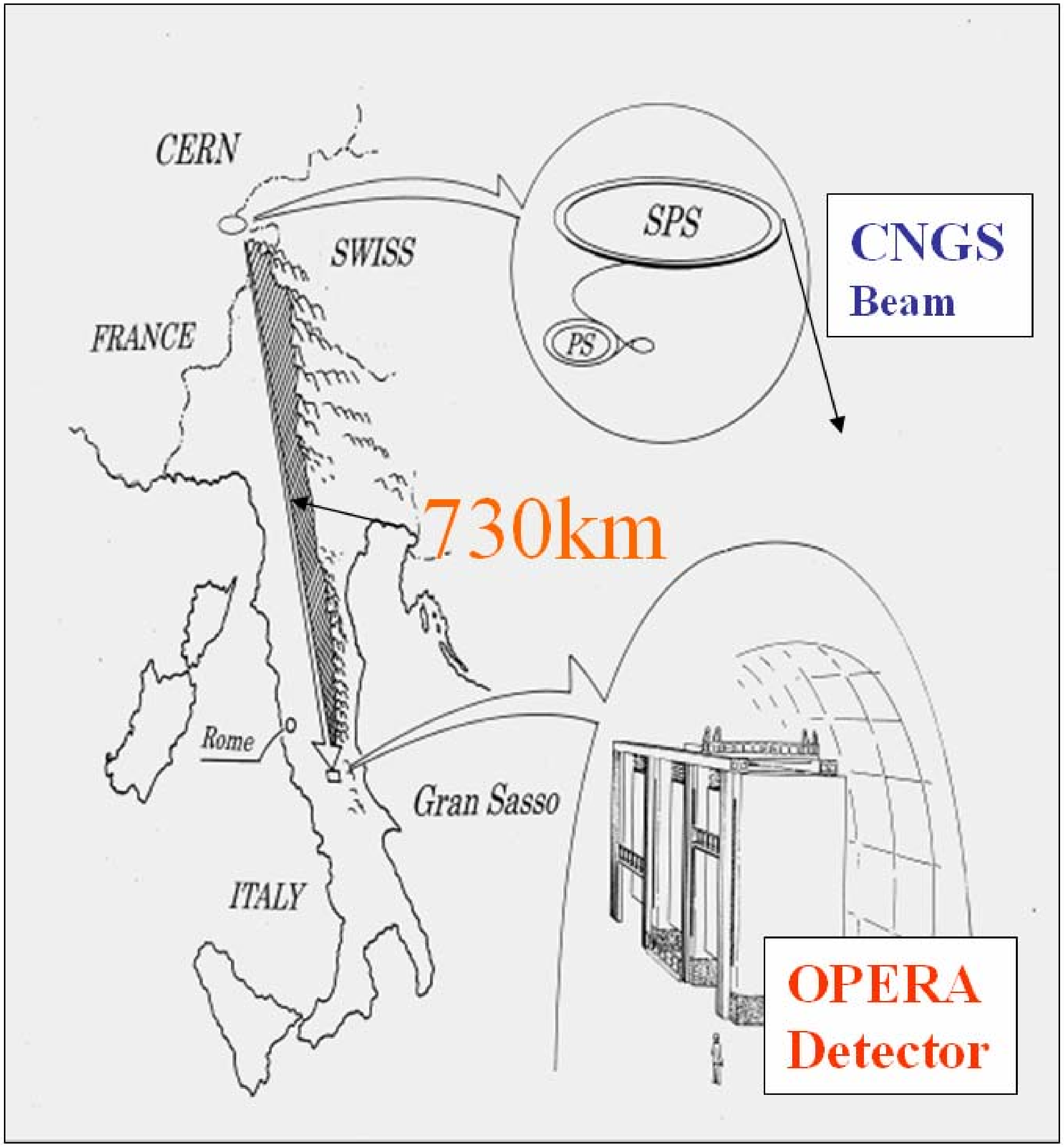
NuMI-MINOS experiment





- Fermilab's NuMI beamline

OPERA



CNGS
Beam

OPERA
Detector

An Emulsion-Counter Hybrid experiment for Tau neutrino Appearance Detection.

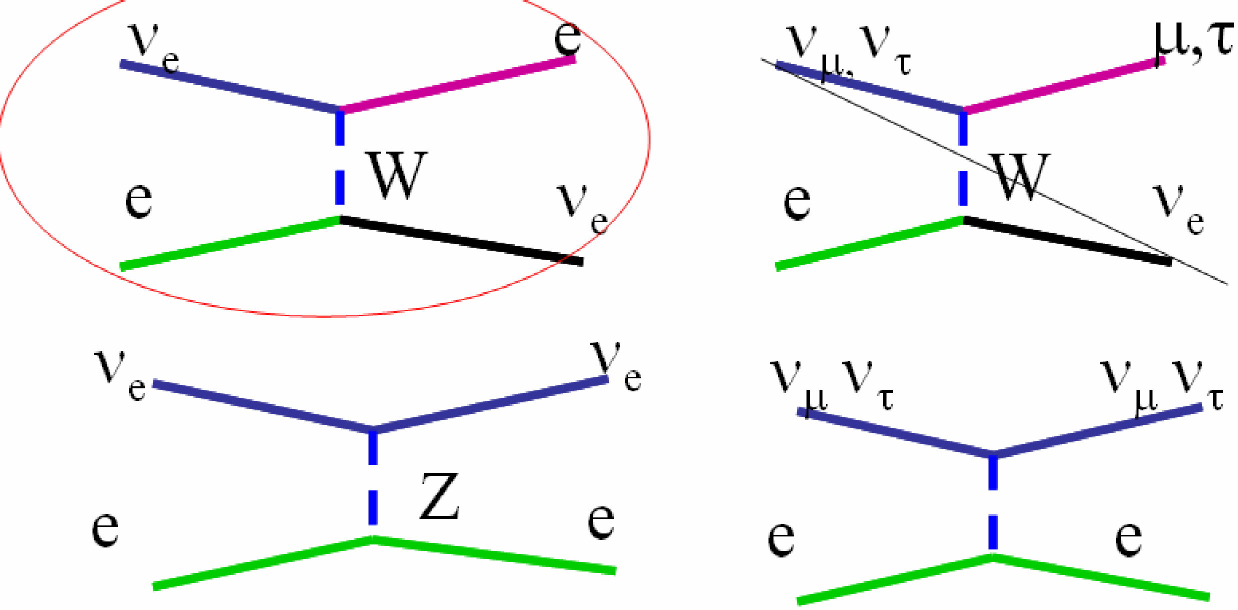
Collaboration :

13countries 37 Institutes

CNGS First Neutrino to Gran Sasso at 2006 August

Matter effect

- light absorbed and re-emitted forward direction results as index of refraction n>1 – change of the light velocity in medium - effective mass
- neutrino propagate in vacuum as $\nu 1, \nu 2, \nu 3$
- interact with matter as ν_e, ν_μ, ν_τ and ν_e has larger forward scattering amplitude than ν_μ, ν_τ
- mass eigenstates $\nu 1, \nu 2, \nu 3$ get effective masses, which are depend on the fractional content of ν_e in each mass eigenstate



effective mass can be calculated for given matter density

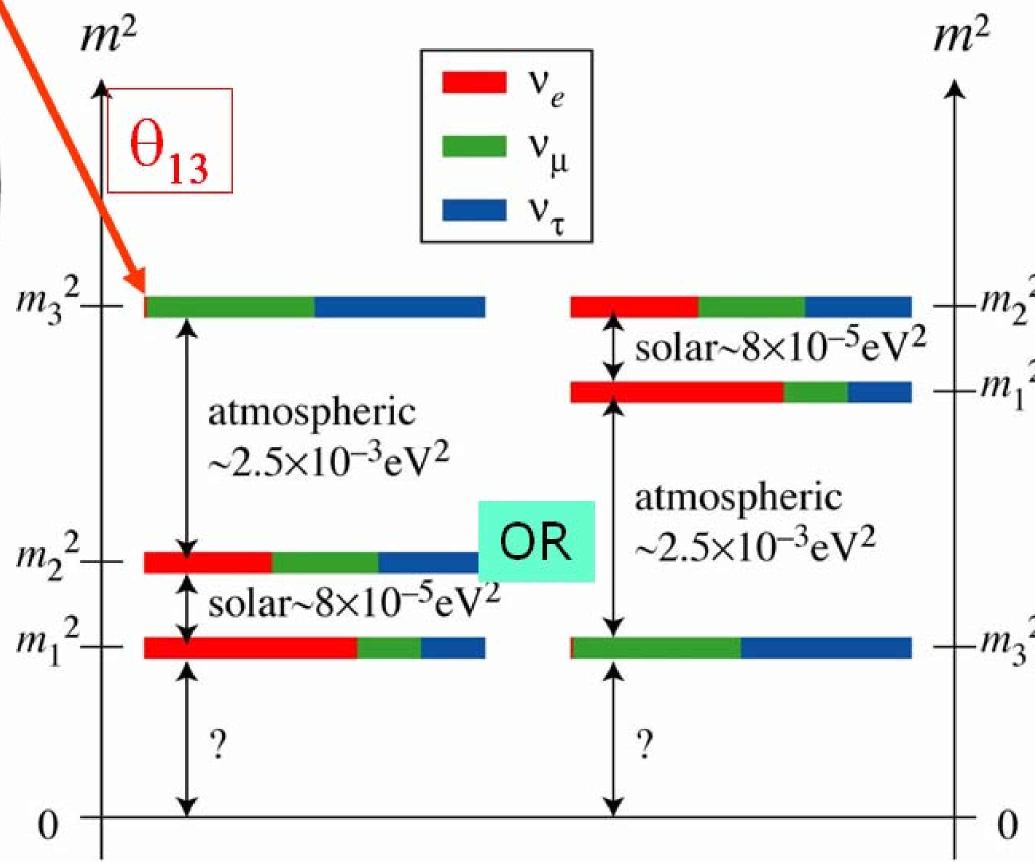
Summary of the results of Atmospheric, Solar, Reactor, Accelerator Neutrino exp'ts

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

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



Final physics goal of oscillation studies

Necessary ingredients to create matter dominated universe from **B = 0** universe

A. Sakharov

1. Baryon number violation
2. Particle and anti-particle non equivalence (CP-violation)
3. Non-thermal equilibrium

(CPV in CKM quarks sector is small to explain the Universe)

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

$$V_M^{CP} = \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\theta_{12}, \theta_{23}, \theta_{13}$

$+ \delta$ (+2 Majorana phase) CPViolation

$\Delta m_{12}^2, \quad \Delta m_{23}^2, \quad \Delta m_{13}^2$

Importance of $\nu_\mu \rightarrow \nu_e$ Appearance as next main issue

δ : CP Violation in Lepton Sector

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \frac{(m_j^2 - m_i^2)L}{4E_\nu}$$

$$\mp 2\sum_{j>i} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \frac{(m_j^2 - m_i^2)L}{2E_\nu}$$

CPV $\propto \sin\theta_{12}\ \sin\theta_{23}\ \sin\theta_{13}\ \Delta m^2_{12}\ (L/E)\ \sin\delta$

ν disappearance $1 - P_{ee}$: $\alpha=\beta$ $|U_{\alpha i}|^2$ Real

Need appearance measurement

Interference of two oscillations, which are comparable in size

Oscillation with $\Delta m^2 \sim 2.5\times10^{-3}$ eV^2 : Suppressed by smallness of θ_{13}

Oscillation with $\Delta m^2 \sim 8\times10^{-5}$ eV^2 : Suppressed by smallness of Δm_{13}

First milestone :
Search for ν_e appearance signal

Searches for non-zero θ_{13}

θ_{13} with reactor experiments

- $\langle E_\nu \rangle \sim$ a few MeV ➔ Disappearance
- $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27 \Delta m^2_{31} L/E) + O(\Delta m^2_{21}/\Delta m^2_{31})$

➔ Almost **pure** measurement of θ_{13} with negligible matter effect.

θ_{13} with accelerator experiments

- $\langle E_\nu \rangle \sim O(\text{GeV})$ ➔ appearance experiments
- $P(\nu_\mu \rightarrow \nu_e) = 1 - \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2(1.27 \Delta m^2_{31} L/E)$ + many terms

Three contributions

1. Term which is same for neutrinos and anti-neutrinos
2. CP violating term (constant in E)
3. Matter effect (proportional to L or E at constant L/E)

- Search/measurements of sub-leading effects
  - High Intensity
- Initial or final states involve ν_e
  - matter effect (distance)
- Background contaminations to the measurements
  - NC π^0 production backgrounds to electron appearance signal
- E_ν determination
  - Precision measurement of oscillation dip in ν_μ diappearance

- Depends on beam energy range and on detector
  - For Japanese project - Super-Kamiokande water Cherenkov detector
  - Low energy and small high energy tail BEAM
  - Matter effect is small (relatively small L (small E))

New idea of off-axis beam small energy tail

1994 TRIUMF KAON factory workshop

Paper presented at the 9th Lake Louise Winter Institute, Lake Louise, Feb. 20-26

TRI-PP-94-34
June 1994

A NEW LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT AT BROOKHAVEN

R. L. HELMER

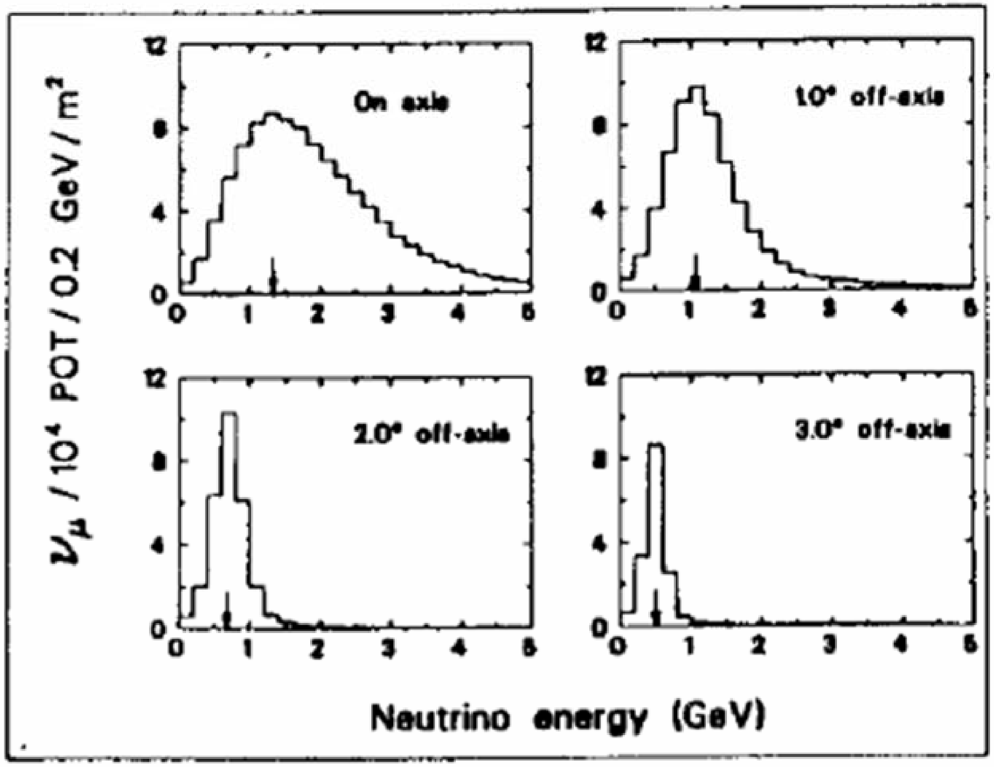
TRIUMF, 4004 Wesbrook Mall
Vancouver, B.C., Canada V6T 2A3

Abstract

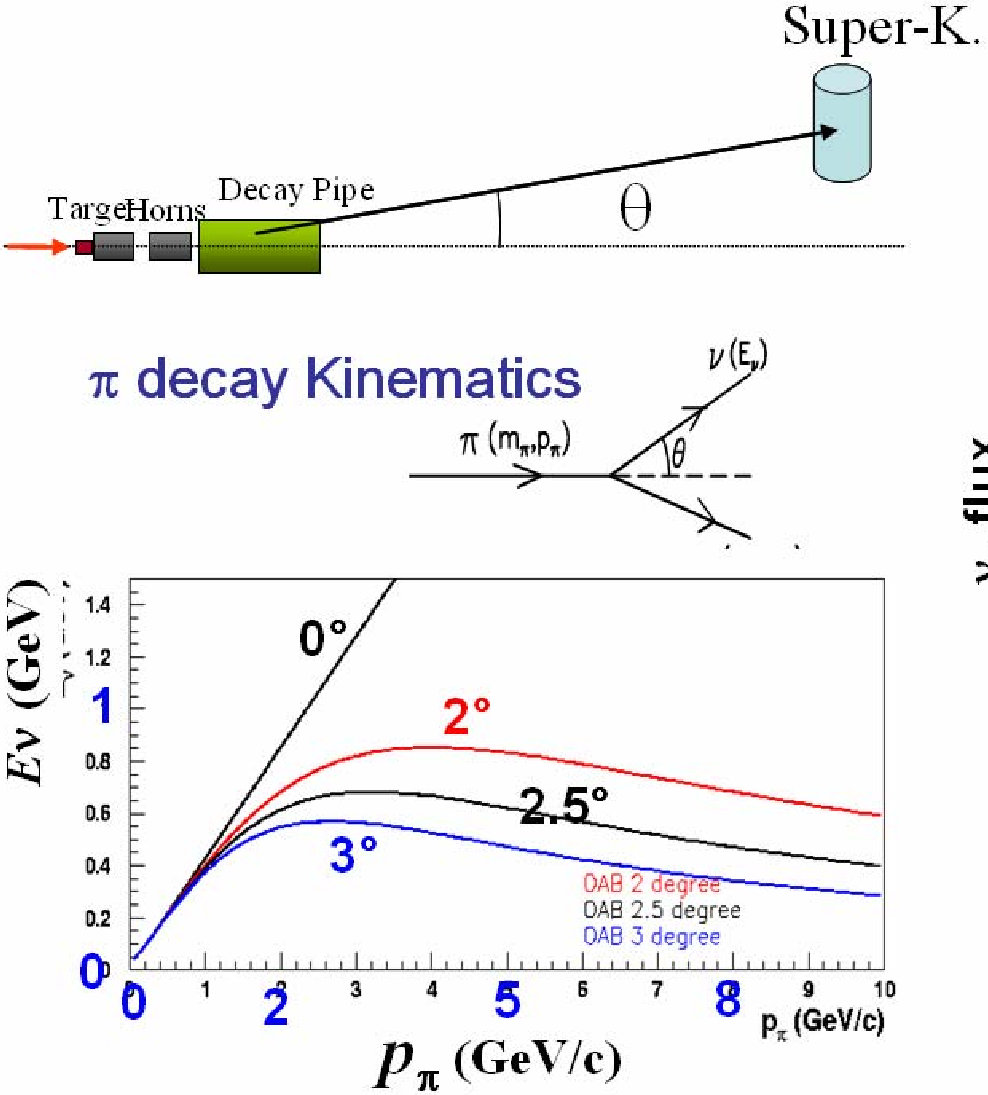
J. Anderson	G. Azuelos	M. Barnes
J. Beveridge	G. Chadwick	B. Dall
P. Depommier	F. Farzanpay	D. Frekers
P. Fuchs	P. Gumplinger	S. Hayward
R. Helmer	R. Henderson	G. Jonkmans
H. Laman	B. Larson	R. Meier-Drees
J.-M. Poutissou	M. Sevior	A. Trudel
B. Vander Ende	M. Vetterli	G. Wait
W. Wall	C. Waltham	N. Weiss
D. Wright	S. Yen	

Table 1: Members of the TRIUMF Neutrino Working Group.

seen, there will be no ambiguities in its interpretation.

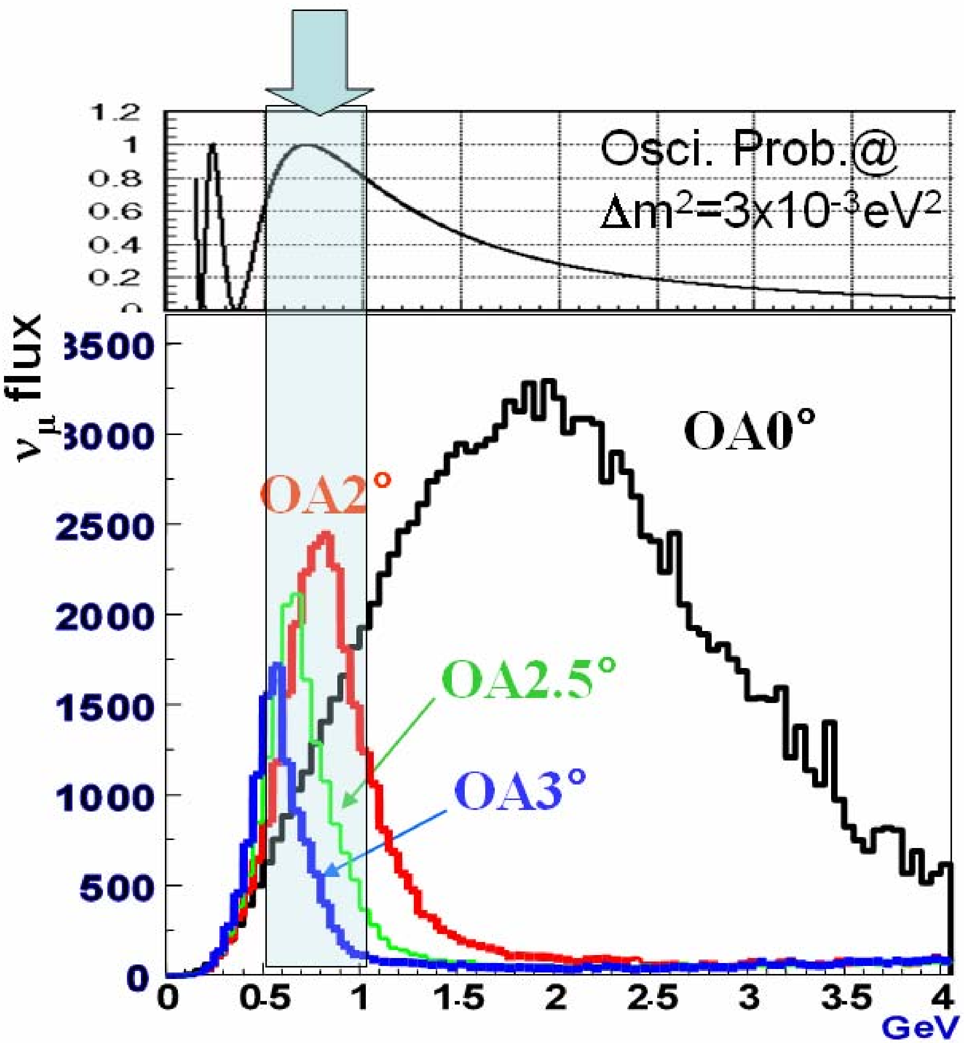


Narrow intense beam: Off-axis beam in T2K



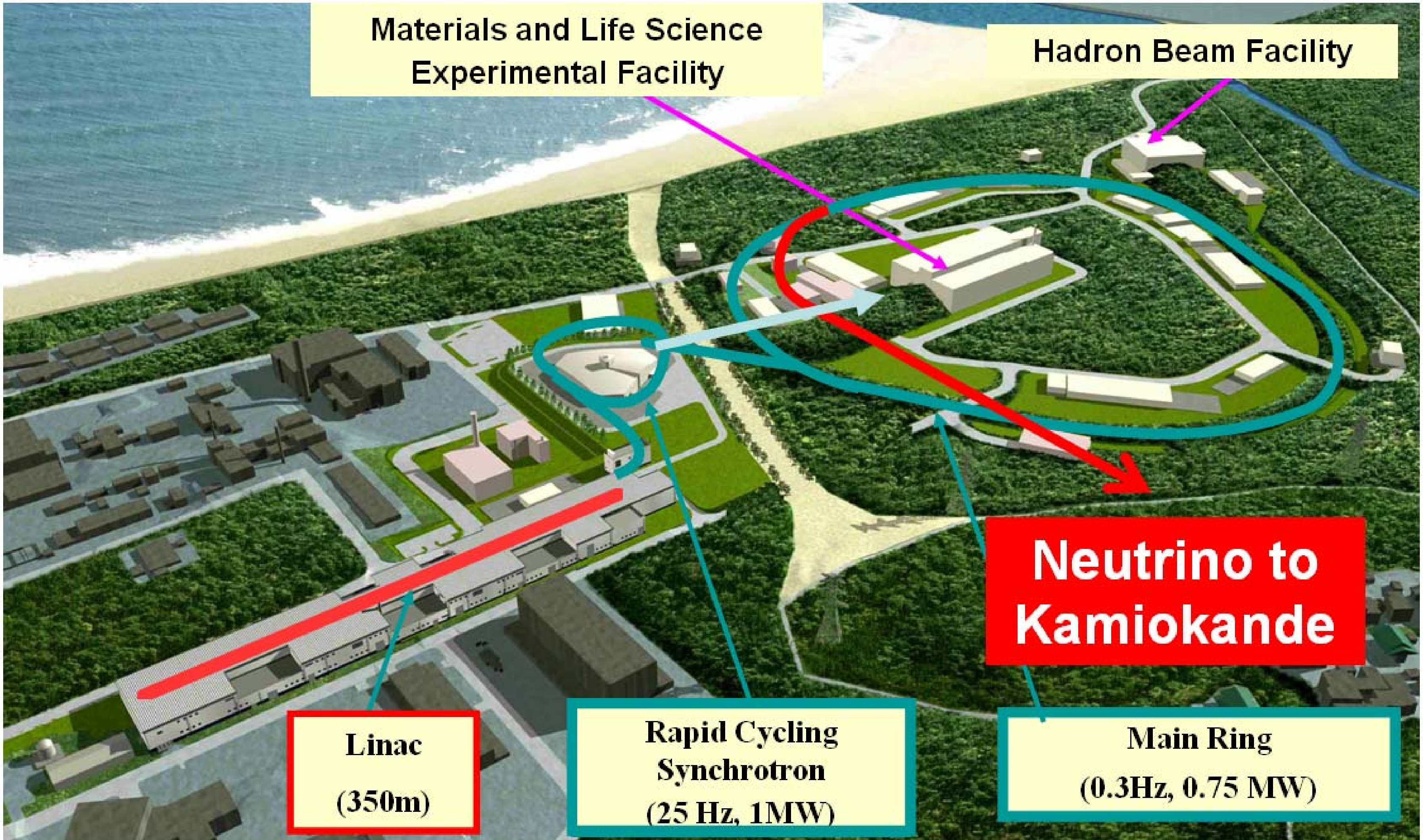
Oscillate most

: large number of oscillated ν



Pions with different energies give neutrinos with similar energy

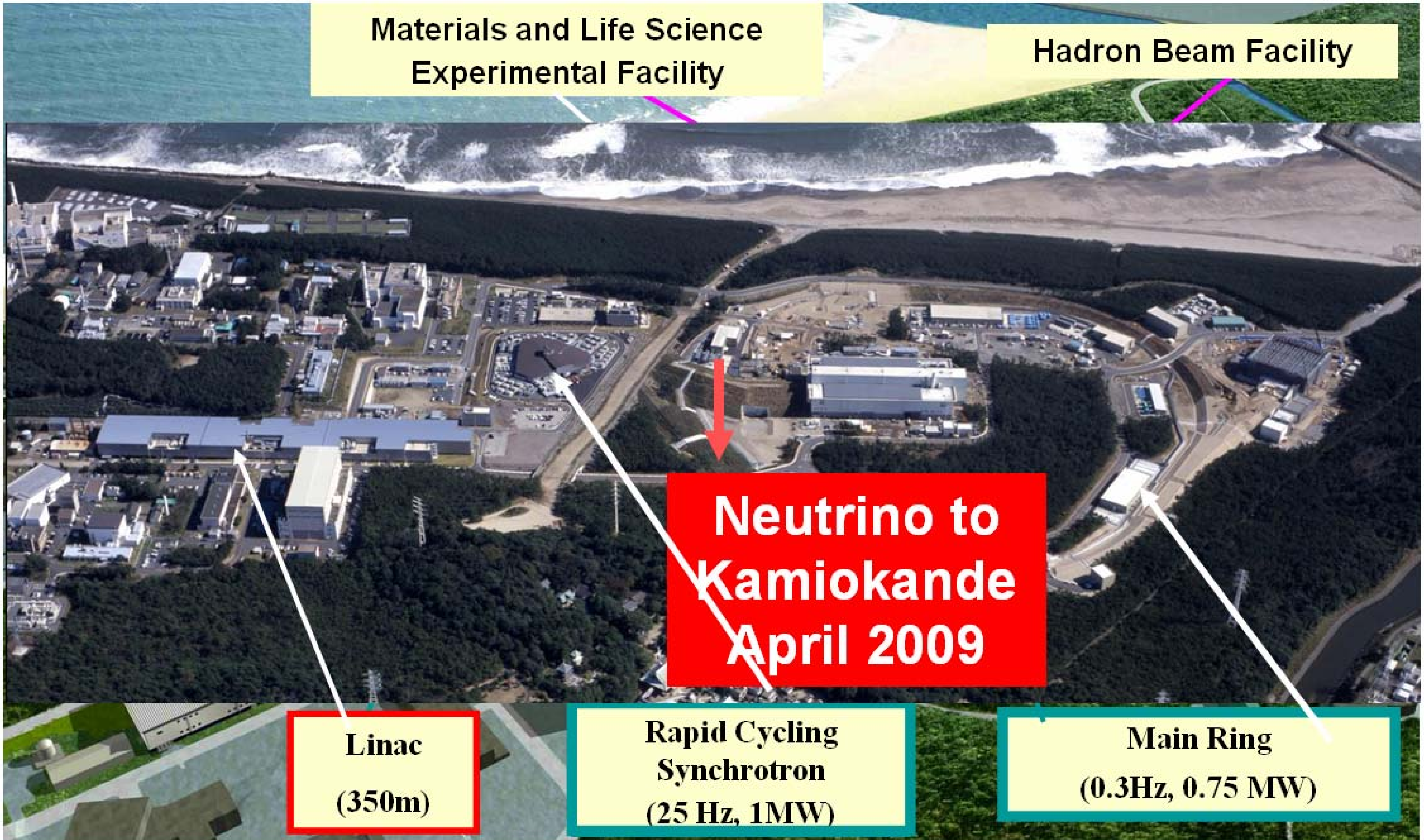
J-PARC (Accelerator being commissioned)



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

J-PARC (Accelerator being commissioned)



J-PARC = Japan Proton Accelerator Research Complex

Joint Project between KEK and JAEA

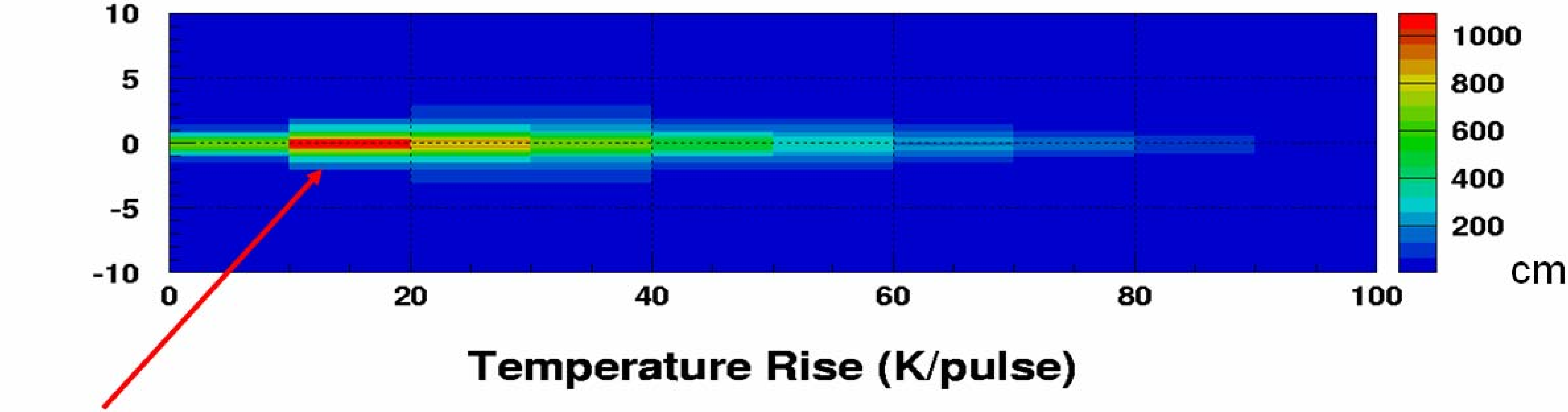
First high enrgy MW fast-ext'ed beam !

3.3E14 ppp w/ 5μs pulse

Residual radiation

> 1000Sv/h

When this beam hits an iron block,



1100°

(cf. melting point 1536°)

Material heavier than iron would melt.

Thermal shock stress $\approx E\alpha\Delta T \approx 3GPa$

(max stress ~300 MPa)

Material heavier than Ti might be destroyed.

Neutrino beam line with MW protons

- Shock wave
  - Graphite for target and dump core
- Heat generation
  - Various sources including dE/dX
  - magnets and their power water cooling
  - Target Horn TS-DV-BD wall /BD core water cooling
- Radioactive water and air

  Production cross section of Tritium in He is 1/10 of air

  radioactive water

  radioactive He

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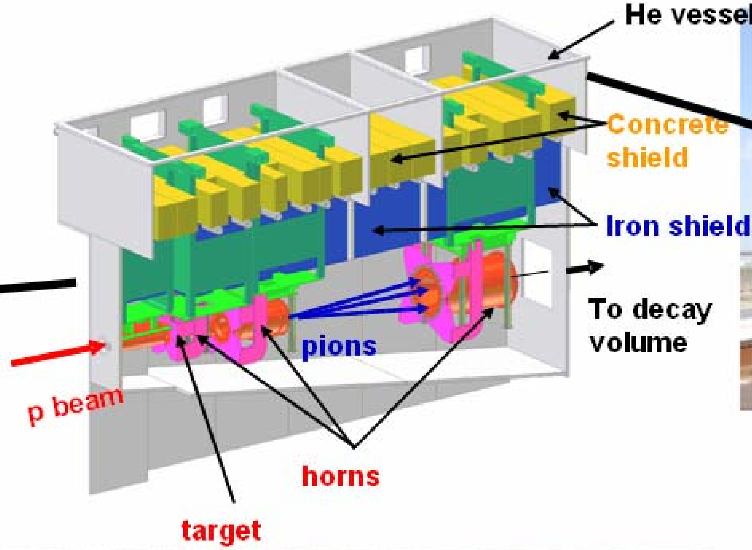
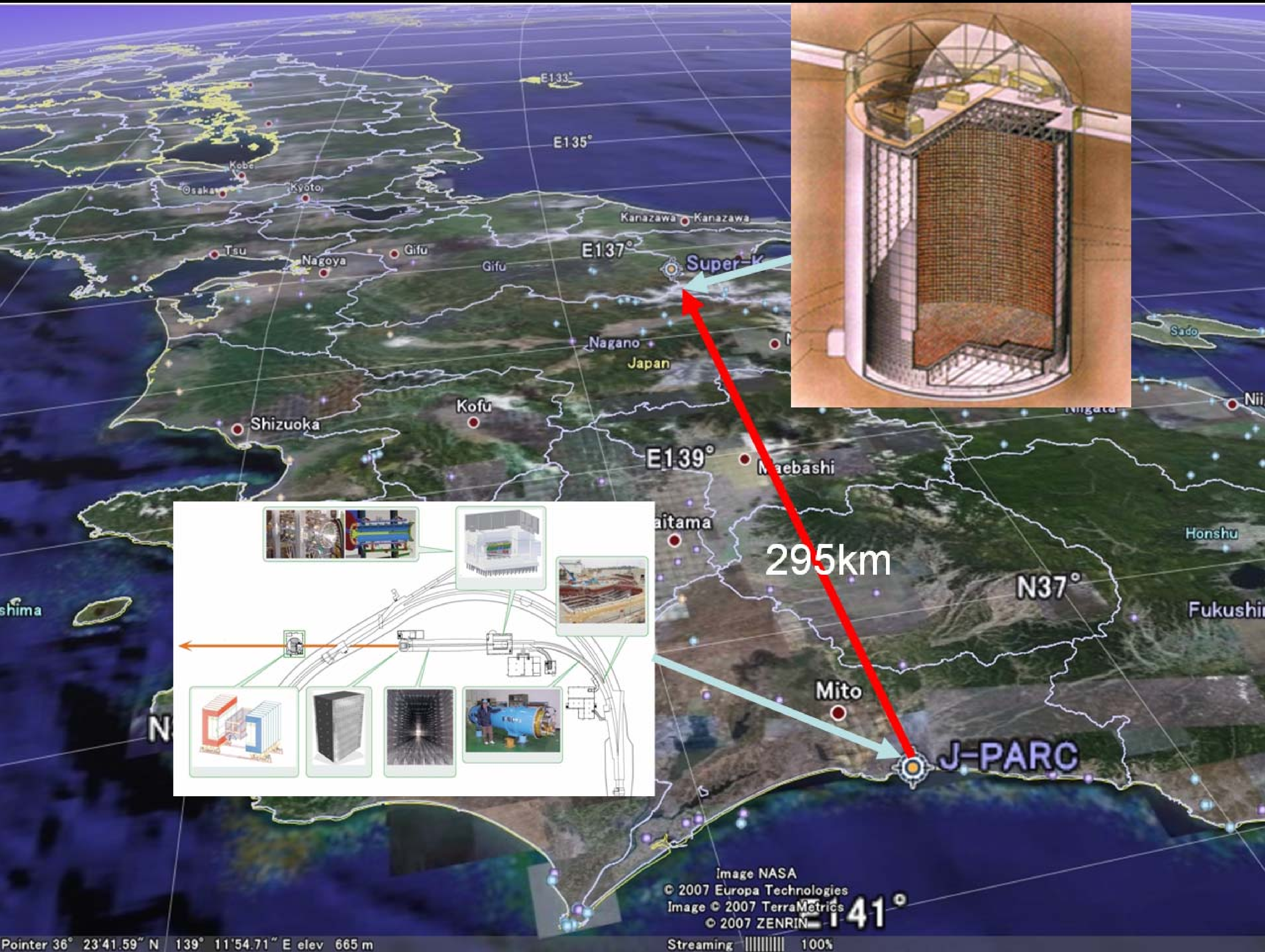
Target Station



- Installation of the helium vessel(~470ton, 1000m^3) finished, passed vacuum test in Nov. 2007 as scheduled

35


E133°
E135°
Kobe
Osaka
Kyoto
Kanazawa
E137°
Tsu
Nagoya
Gifu
Super-K
Nagano
Japan
Sado
Kofu
Shizuoka
E139°
Maebashi
Saitama
295km
Honshu
N37°
Fukushi
Mito
J-PARC
Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN
E141°
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

Summary of T2K neutrino project

In one year

- J-PARC accelerator complex is being commissioned
- Construction of T2K beam line is on time and will be commissioned in April 2009
- Aiming for first results in 2010

In several years

- Plan for 1.66MW in 5 years
- T2K data taking which will provide vital information on θ_{13}, needed to define next step,

After ν_e appearance discovery CPV and mass hierarchy

δ : CP Violation in Lepton Sector

Two approaches

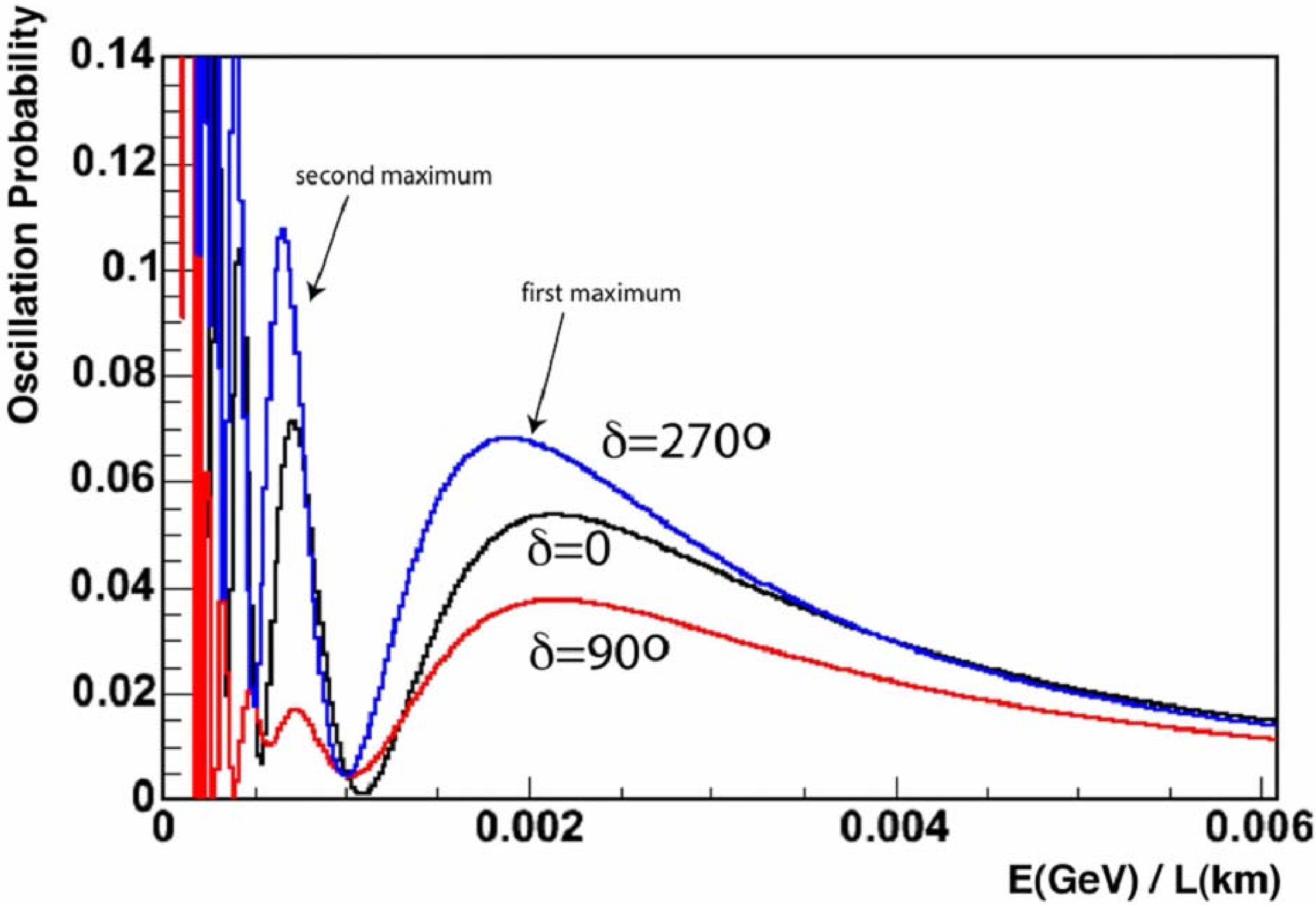
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \frac{(m_j^2 - m_i^2)L}{4E_\nu}$$

$$\mp 2\sum_{j>i} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin \frac{(m_j^2 - m_i^2)L}{2E_\nu}$$

Second Max.

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})} \approx \frac{\Delta m^2_{12}}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta$$

First / Second Maximum and δ



One of the most dangerous bias:

ν Energy mis-reconstruction to lower value than real value

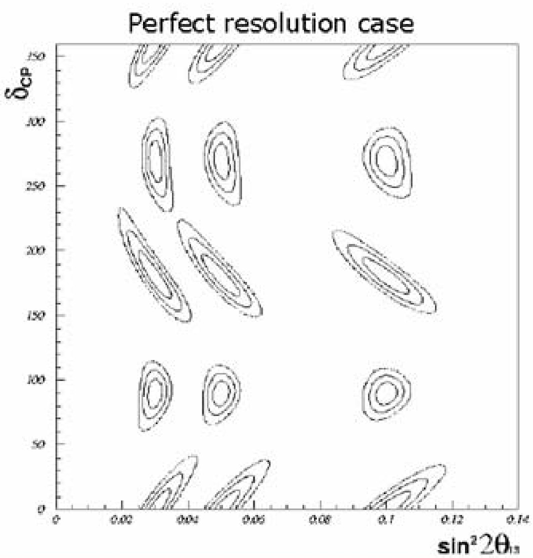
CPV in neutrino oscillation

- Depend on the size of θ_{13} different effects from various systematics
  - Neutrino-Anti-Neutrino asymmetry
    - Cross section, Detection efficiencies
    - Ratios ν_e/ν_μ differences
    - Contamination of wrong sign ν
  - First vs. Second Maximum
    - Wide band beam (small off-axis beam)
    - E (L) at the second maximum should be sufficiently large to have reasonable cross section (E≈0.5 GeV → L≈500km)
    - E_ν measurement over large range of energy (efficiency for low energy particles)

Some physics potential studies (personal view)

100kt Liq Ar TPC @ 660km/0.8deg, 5yr numu

Allowed regions



- This is perfect energy spectrum case
- Cases at δ_{cp}=0,90,180,270 and $\sin^2 2\theta_{13}$=0.1,0.05,0.03 are overlaid.
- Each point has 67,95,99.7% C.L contours

No syst, perfect energy reso.

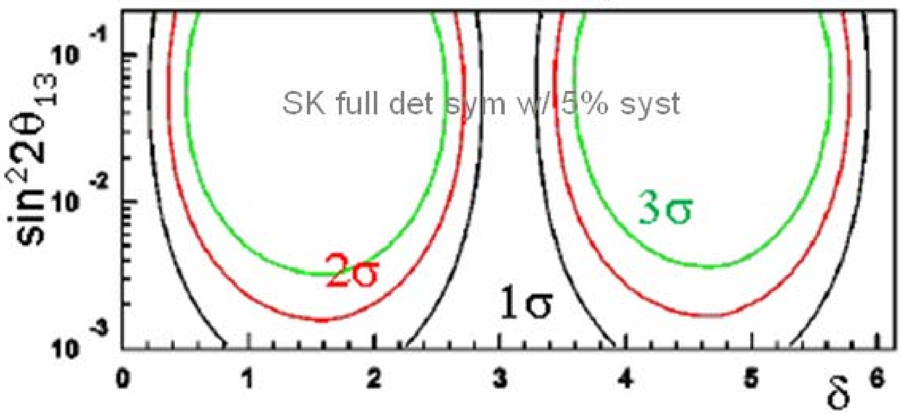
A.Bueno et al   NP08 (@Mito) on Mar-6-2008   32

Presented by T.Maruyama @ NP08

0.54Mt W.C.@295km/2.5deg

1.66MW ν_μ 1.1yr+ν_μ 3.9yr

CP sensitivity



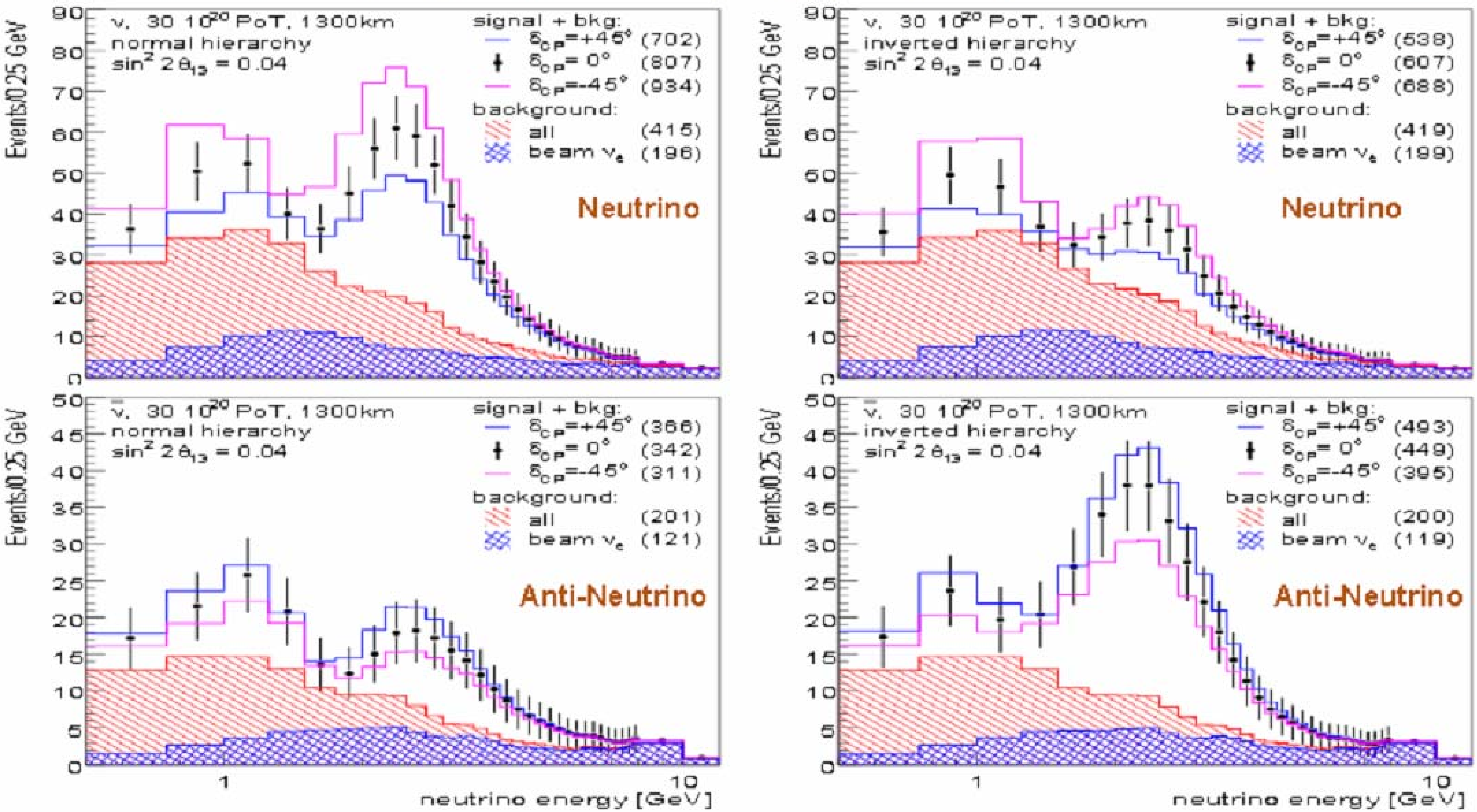
Presented by K.Kaneyuki @ NP08

The U.S. Long Baseline Neutrino Experiment Study

GLoBeS ν_e Appearance Spectra

$\sin^2 2\theta_{13} = 0.04$, **300kT WCe.**, WBLE 120 GeV, 1300km, 30E20 POT.

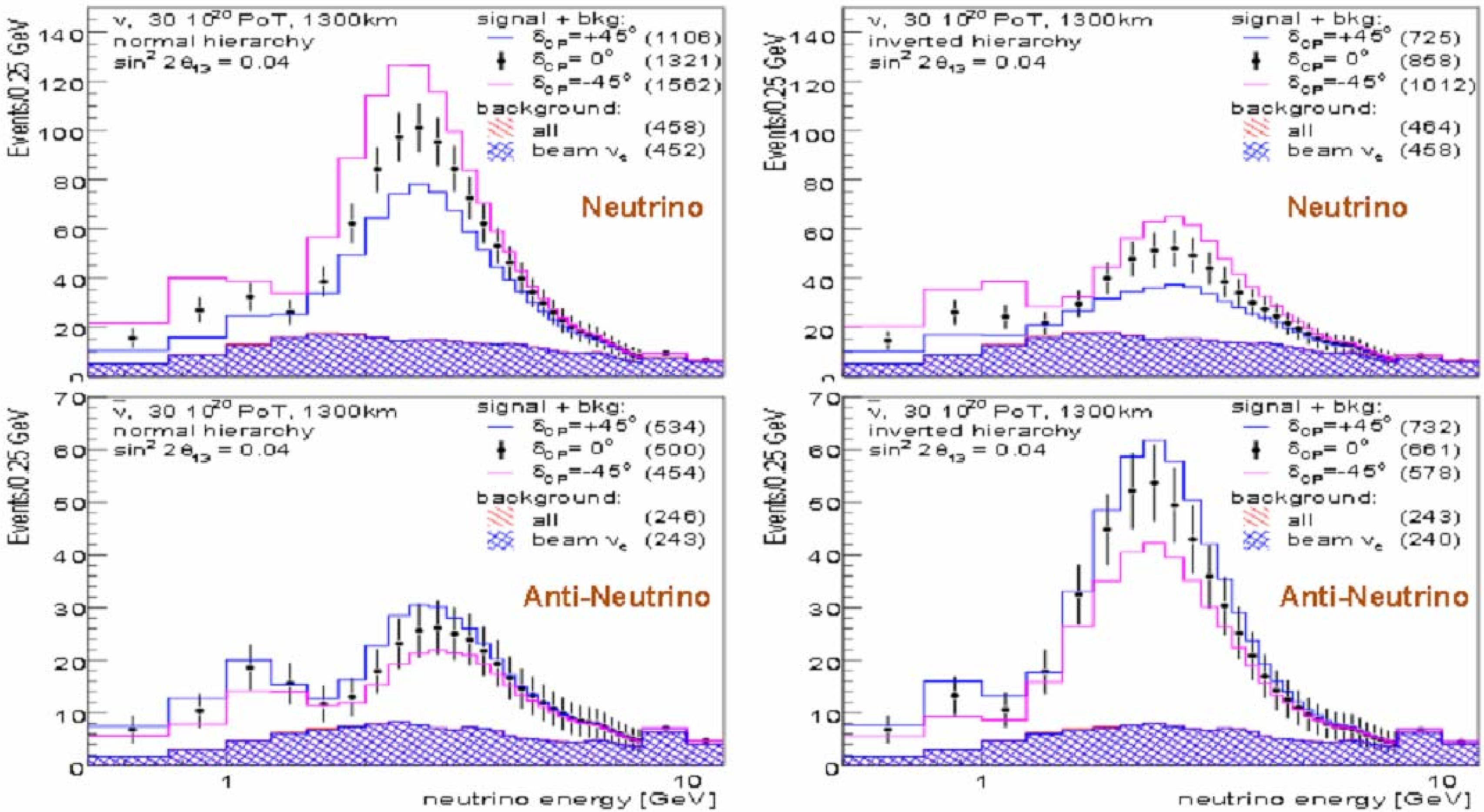
Normal hierarchy $(-\delta_{cp} = -45°, -\delta_{cp} = +45°)$ Reversed hierarchy



GLoBeS ν_e Appearance Spectra

$\sin^2 2\theta_{13} = 0.04$, 100kT LAr. , WBLE 120 GeV, 1300km, 30E20 POT.

Normal hierarchy ($- \delta_{cp} = -45°$, $- \delta_{cp} = +45°$) Reversed hierarchy

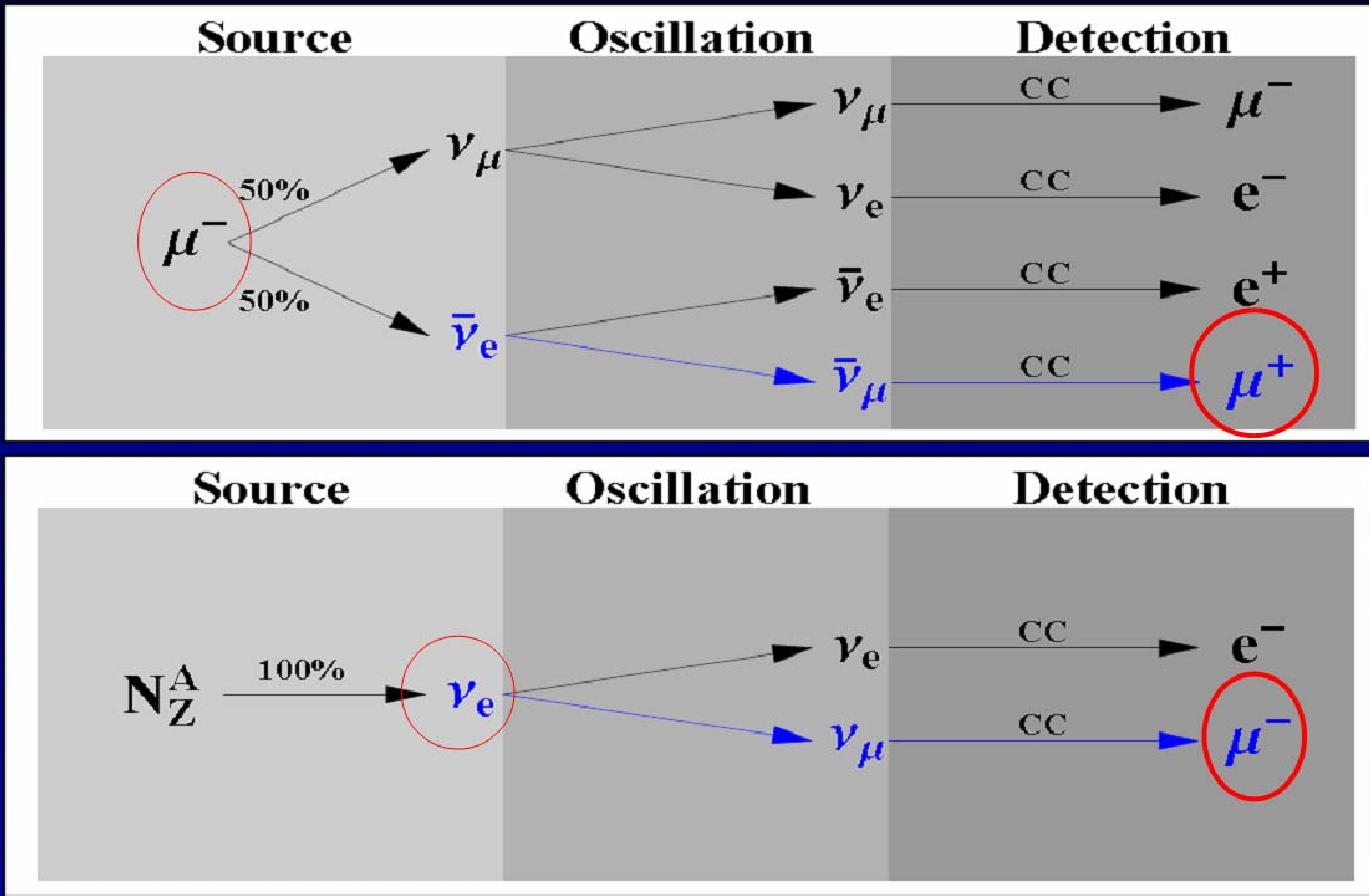


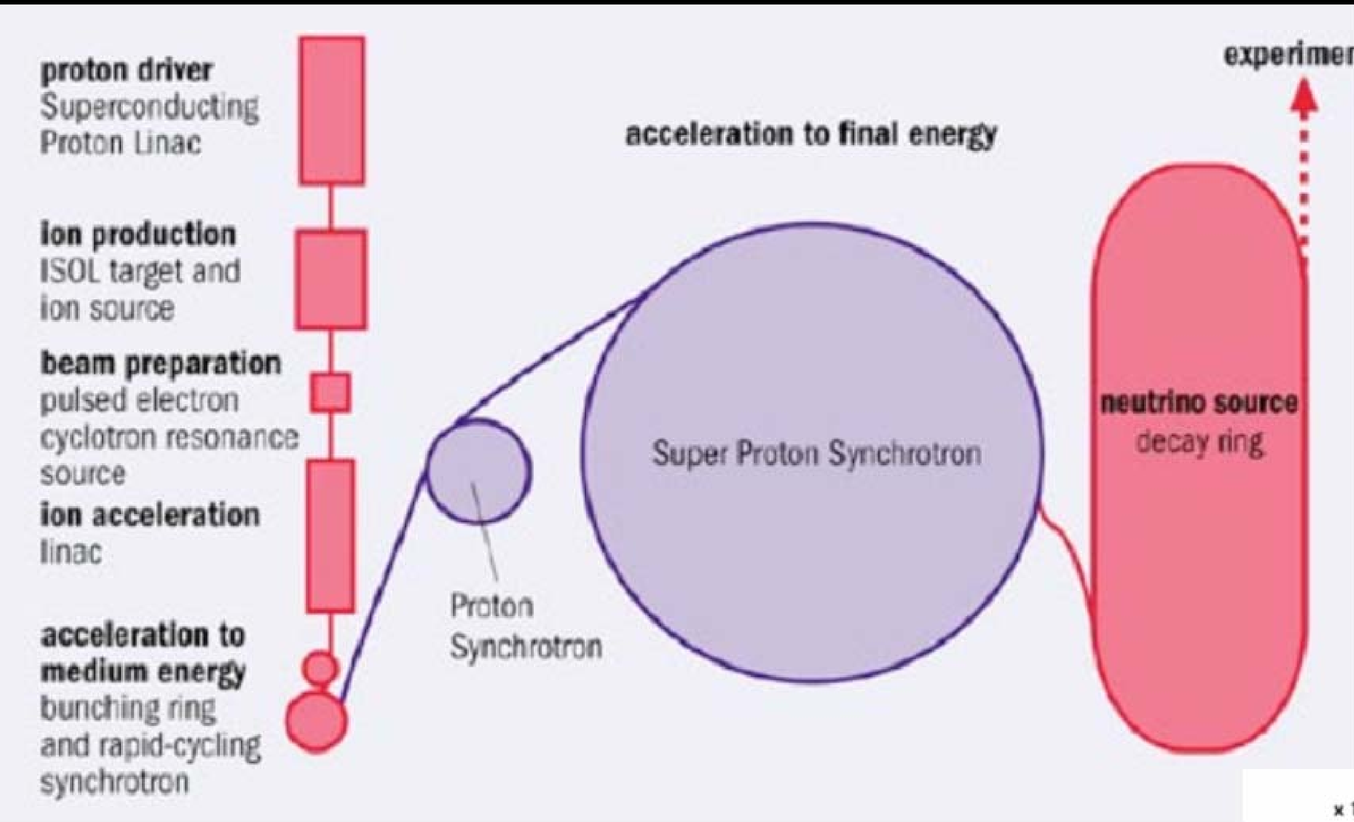
Neutrino factory and β beams

- Need more pure flavor neutrino beam
  - contamination in conventional beam
  - $\tau_\pi \sim 2.6\text{x}10^{-8}$ sec, $\tau_\mu \sim 2.2\text{x}10^{-6}$ sec $(\mu \to e + \nu_\mu + \nu_e)$ 100:1
  - $\tau_{K+} \sim 1.2\text{x}10^{-8}$ sec BR$(K^+ \to \pi + e + \nu_e)$
- a few % ν_e contamination is unavoidable

- New methods of producing neutrino beam
- from talks at NNN07, Oct. 2–5, 2007
- at Nufact07, Aug. 6-11,2007
- at NEUT08

Neutrino factories & β-beams





β beam

J.J.Gomez Cadenaz
NEUT08

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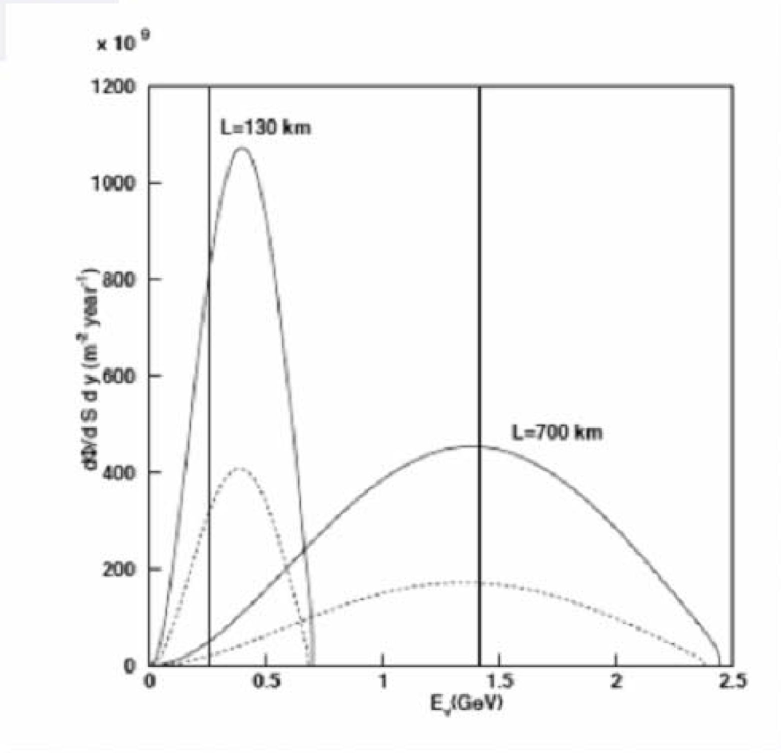


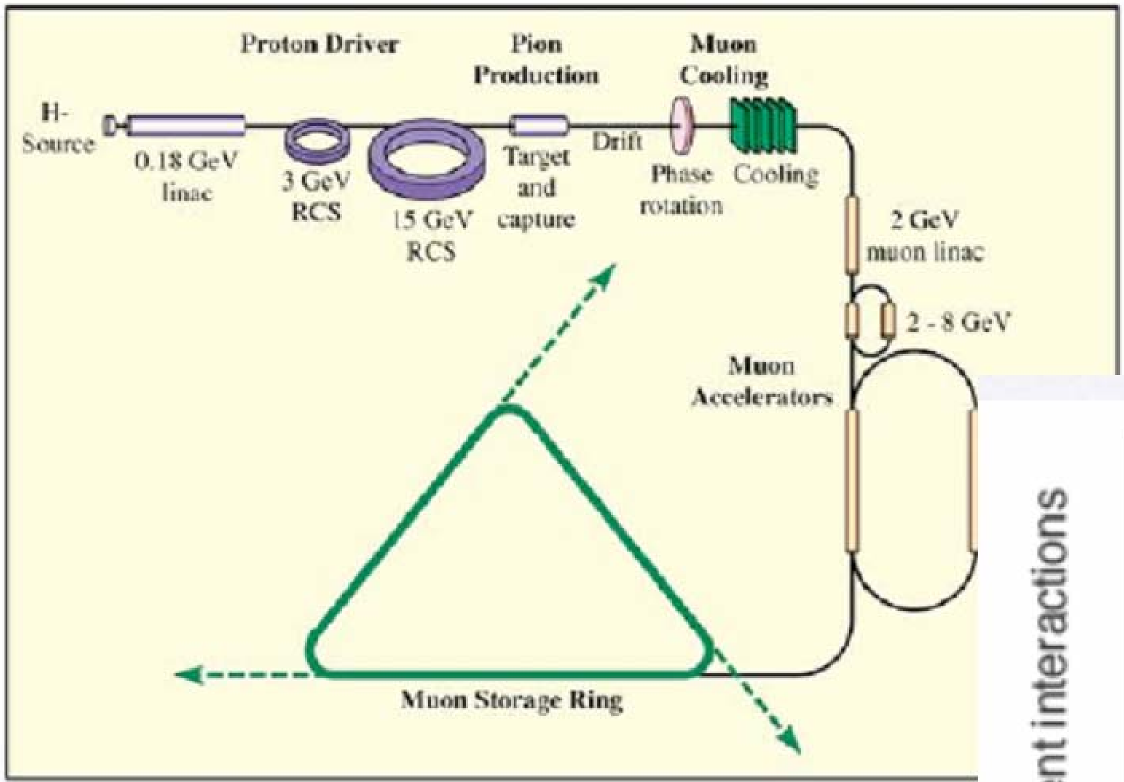
β beam

- Pure beam with one flavor (ν_e or anti-ν_e) by isotope
- E_ν , beam divergence : end point energy of β-decay and Lorentz boost by γ
- Main technical challenges
  - preliminary measurements at Louvain-La-Neuve indicate that direct production of ^{18}Ne by ^{3}He on a ^{16}O target could reach the required rate
  - decay ring
  - rf and collimation systems
    - Radioactive beam (activation of equipments)
    - High ion densities in storage ring
- Need several 100 GeV proton accelerator ring to produce neutrinos above muon threshold

Huber NNN07

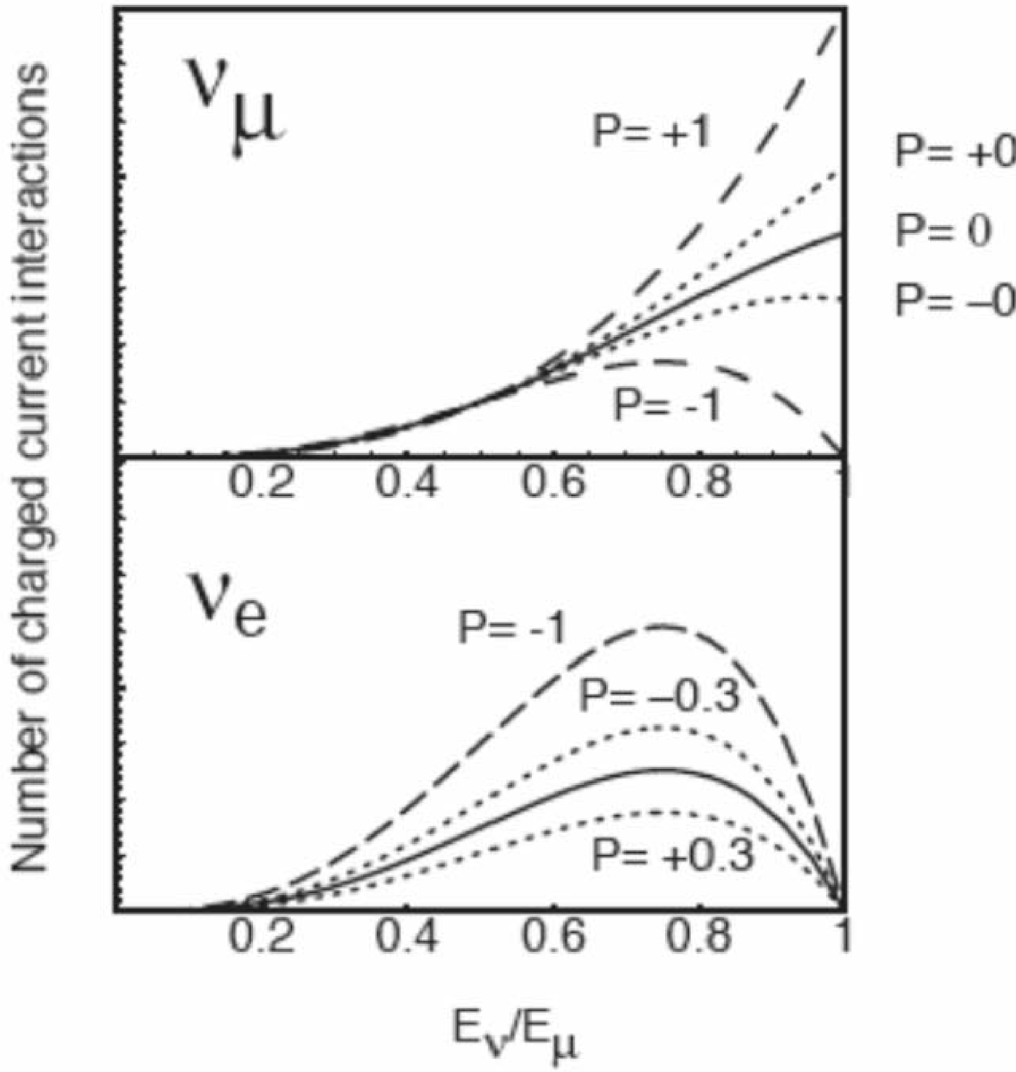
Neutrino Factory

J.J.Gomez Cadenaz
NEUT08



Neutrino Factory at RAL

- E_ν, beam divergence : $\pi-\mu$ decay and Lorentz boost by E_μ
  - Pion collection
  - Muon cooling
  - Rapid acceleration of muon
- Need magnetic analysis to measure oscillation



Proton Decay with massive detector
Ultimate GUTs phenomena

$\tau/B(p\to e^{+}\pi^{0}) > 5.4\times10^{33}$years (90%CL)

$\tau/B(p\to \nu K^{+}) > 2.2\times10^{33}$years (90%CL)

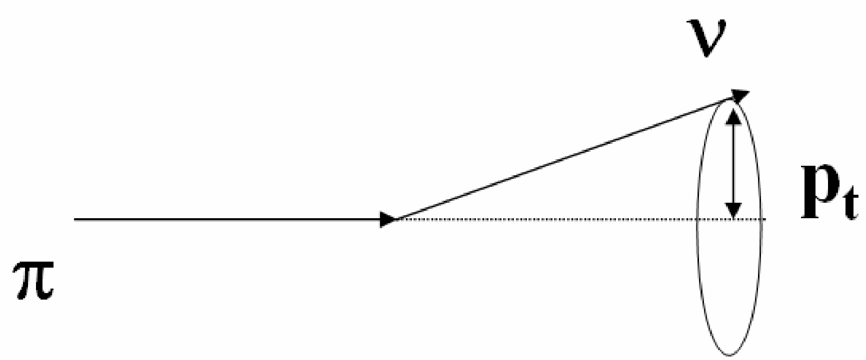
$2.9\text{x}10^{30}$ yr ('minimal' SUSY SU(5))

Future

- High power conventional beam
  - Reliability of the facility and operating resources
  - Detector technology
    - Neutrino anti-neutrino asymmetry and first/second maximum
- Neutrino factory and $\beta-$beam
  - R&D
  - Magnetic detector requirement and very massive detector
- Other important physics, especially proton decay

- Important physics results come from close cooperation of accelerator, beam and detector physicists and engineers

Decay Kinematics



To get max neutrino intensity、focus π beam to 0 degree

$$\gamma = \frac{E_\pi}{m_\pi},\ p_{cm} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} \sim 35\text{MeV}$$

$$p_T = p_{cm}\sin\theta_{cm},\quad p_L = p_{cm}\gamma(\beta + \cos\theta_{cm})$$

$$E_\nu(\theta) = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2(1+\gamma^2\theta^2)}E_\pi \approx \frac{0.5E_\pi}{(1+\gamma^2\theta^2)}$$

Present Knowledge

ν_1 to be the larger component in ν_e $\theta_{12} < \pi/4$

$\sin^2 2\theta_{12} = 0.84 \pm 0.07$ $\delta m^2_{12} \approx 8.3 \times 10^{-5} eV^2 (\delta m^2_{12} > 0)$

solar neutrino (SK,SNO), reactor (KamLAND)
Matter effect fix the sign of $\delta m^2{}_{12}$

$\sin^2 2\theta_{23} = 0.96 - 1.00$
$(\theta_{23} = 45^\circ \pm 5^\circ)$

$|\delta m^2_{23}| \approx 2.5 \times 10^{-3} eV^2 (\pm \text{unkown})$

atm. neutrino (SK), long-baseline (K2K,MINOS)
Oscillation probability sqaured is measured

ν_1 to be the larger component in ν_e $\theta_{13} < \pi/4$

$\sin^2 2\theta_{13} < 0.16 (\text{upper limit})$ $|\delta m^2_{13}| \approx 2.5 \times 10^{-3} eV^2 (\pm \text{unkown})$

reactor neutrino exp.(CHOOZ), K2K, MINOS