Neutrino Oscillations

4th IDPASC School
Braga, January 2014

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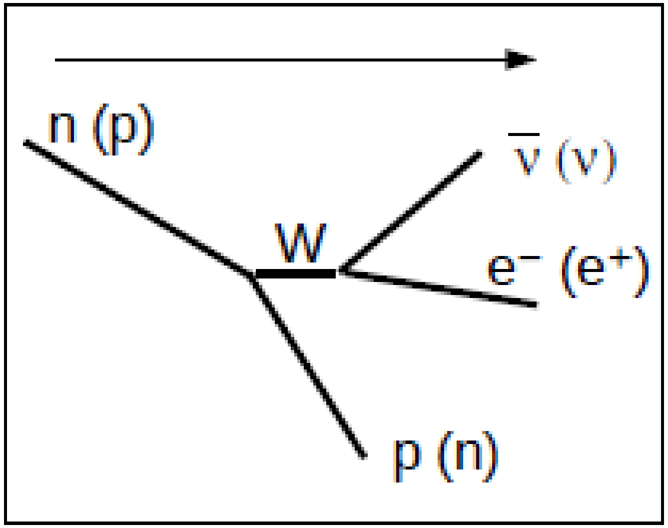
3 neutrino types: ν_e, ν_μ, ν_τ



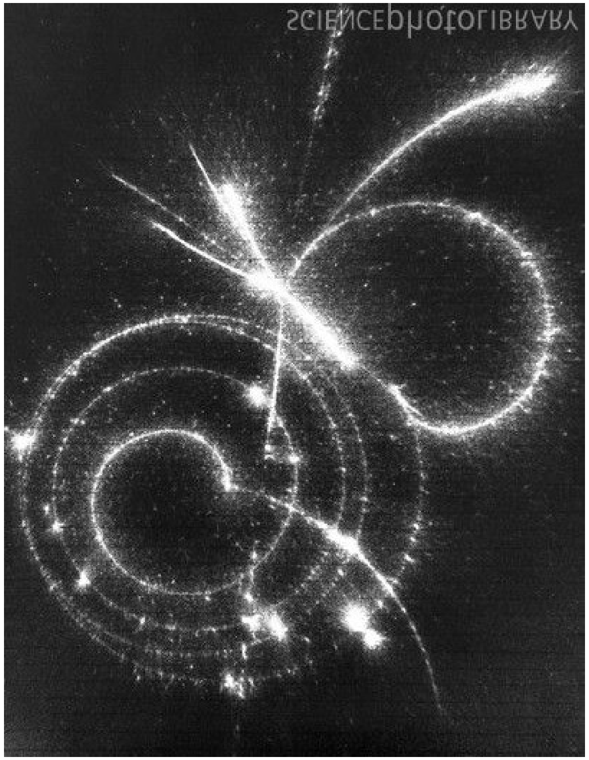
Beta decay and nuclear fission
(enough energy for electron mass = 511 keV)

"undetectable" ν, only weak force (1930)
needed for energy conservation, Ee < $M_1 - M_2$

1st observation by Reines & Cowen (1956)
$\nu + p \rightarrow e^+ + n$, seen as delayed coincidence
Annihilation (2 gammas)
Neutron Capture (N gammas)

Nuclear fusion and Solar Neutrinos:
"the solar neutrino problem": 4 p -> 4He + 2(e^+, ν) + Energy
Real time monitoring of the Sun fusion (compare with luminosity)
Electron-neutrino deficit in all experiments for more than 30 yrs

3 neutrino types: ν_e, ν_μ, ν_τ



$\pi \rightarrow \mu\ \nu$ decay for accelerator neutrino beams
(decay to electrons suppressed by helicity)
(E > 100 MeV; muon mass)

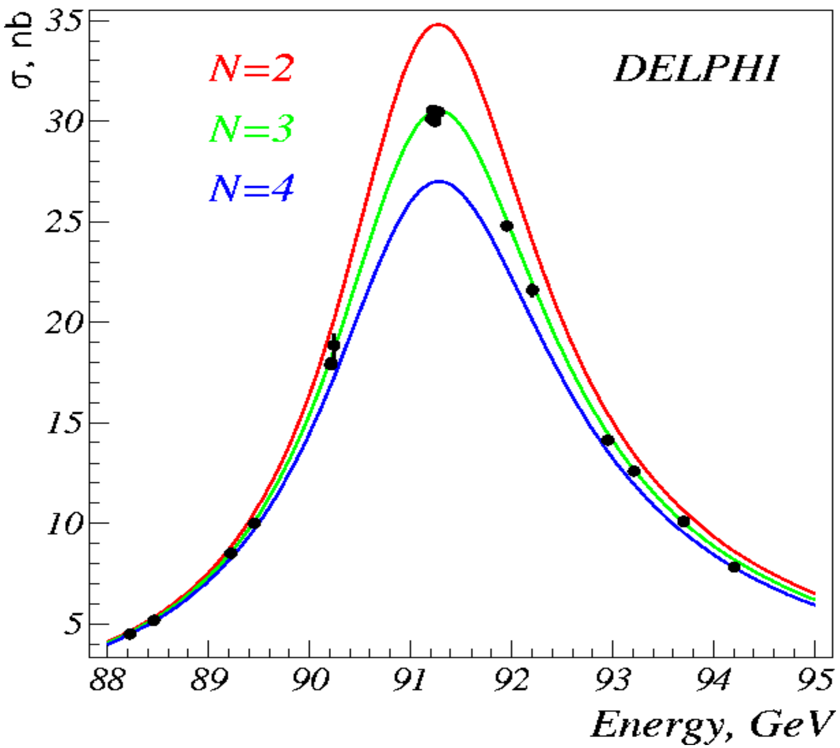
Discovery in 1962:

original muons deviated with magnetic field
neutrinos produce (only) muons in detector

neutrino / anti-neutrino from pion charge

Atmospheric Neutrinos:
continuous energy spectrum from cosmic ray showers
(equal for neutrinos and anti-neutrinos)
ratio of 2 ν_μ / ν_e in all directions, after muon decay
broken by neutrino oscillations (seen as disappearance of ν_μ)

3 neutrino types: νe, $\nu\mu$, $\nu\tau$



High energy Z -> νν / W -> τν
needed for tau mass (~GeV);

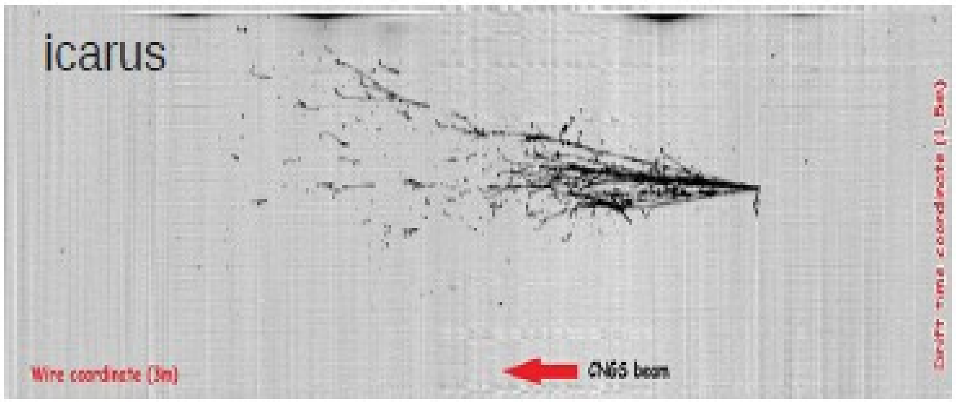
Tau neutrinos also in tau decays

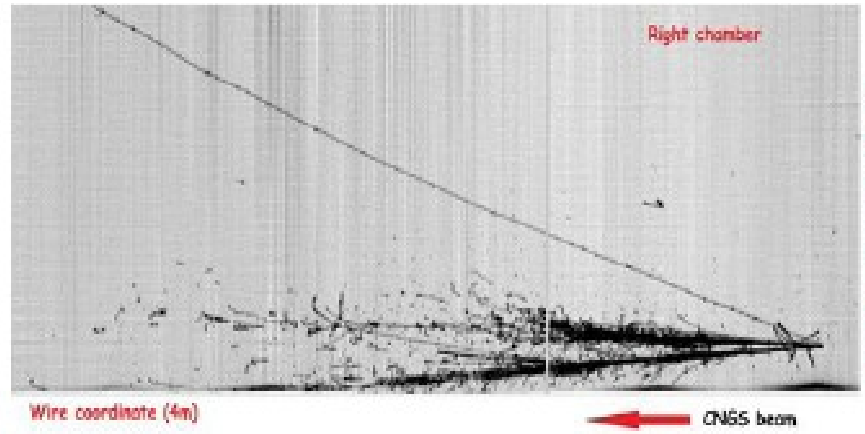
Direct observation in 1998/2000

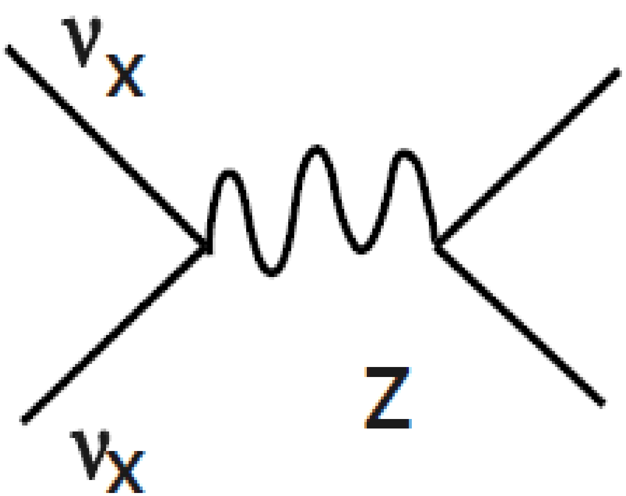
Measurement of 3 families in 1990s & 2000s:
three neutrinos with same Neutral Current
and lepton universality in Charged Current

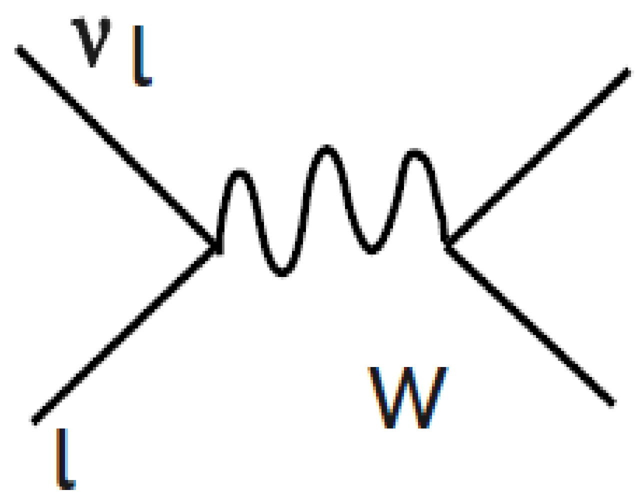
In all three types neutrino =/= anti-neutrino
All direct mass measurements ~ 0
(different experimental limits for e/μ/τ**)**

Neutrinos and Weak Interaction



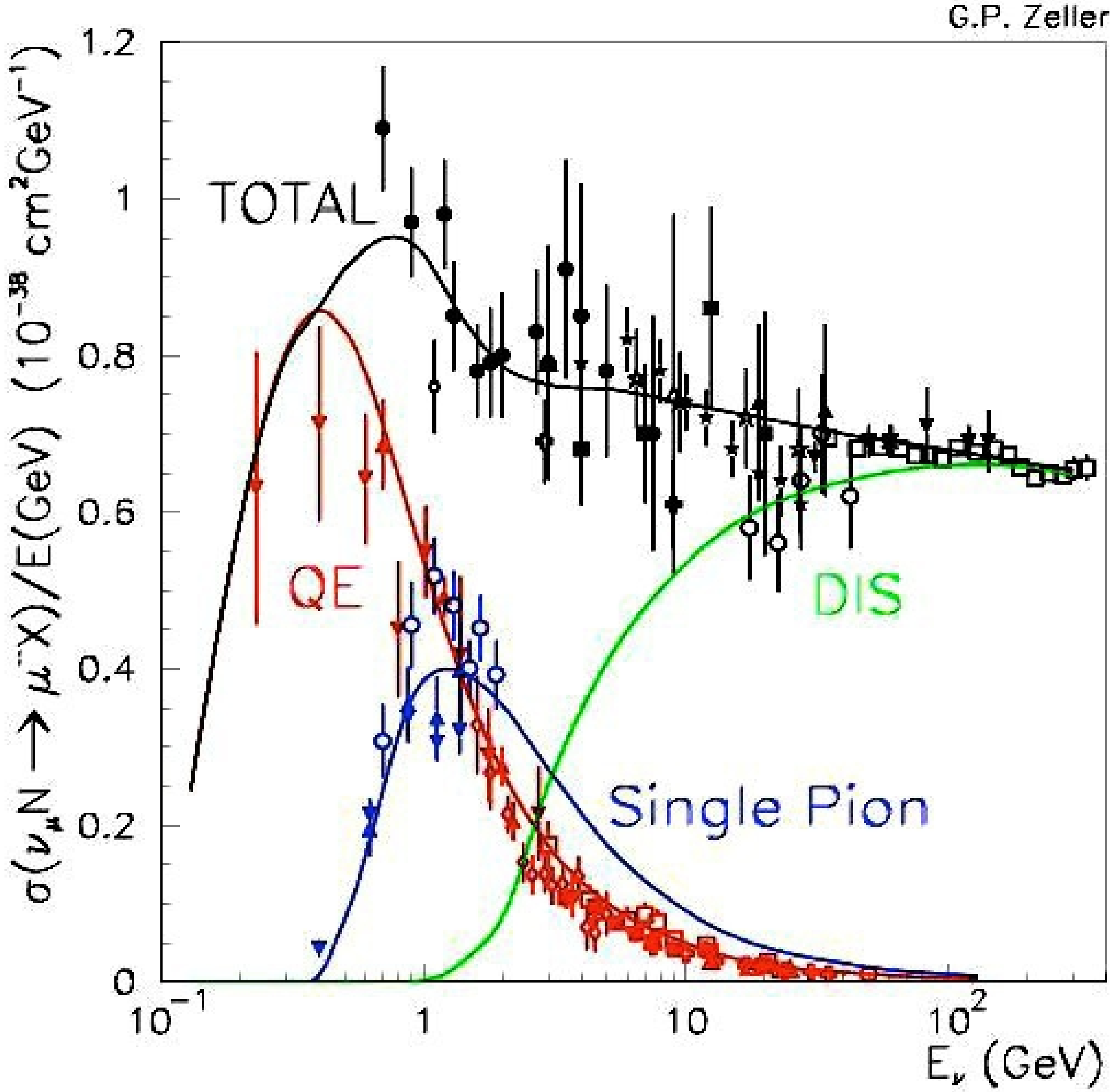


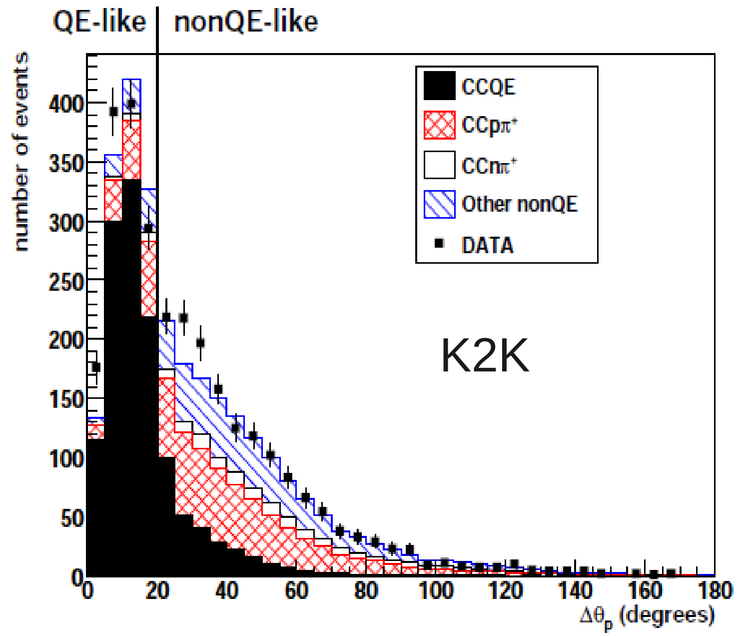


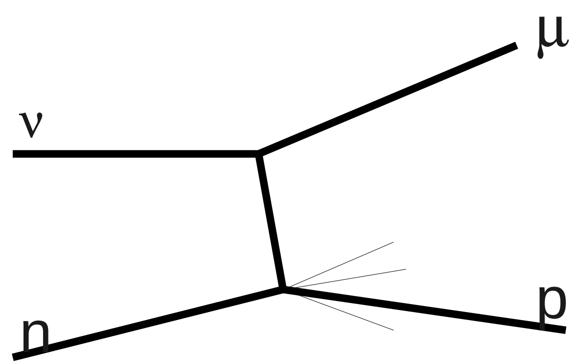


Same NC interaction for all neutrino; CC needs E > lepton mass (also more interactions for νe with electrons in dense matter)

Neutrinos and Weak Interaction



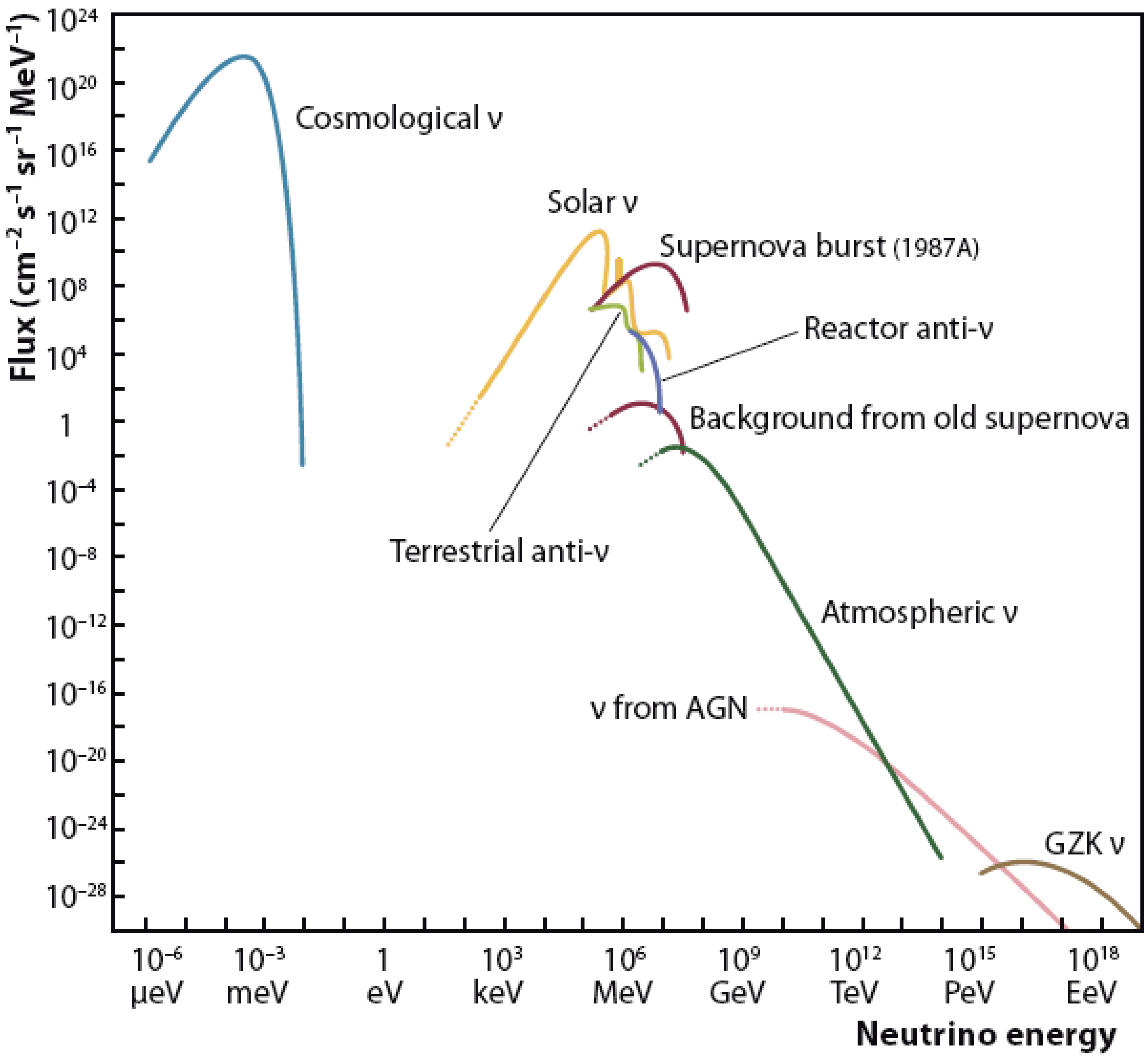


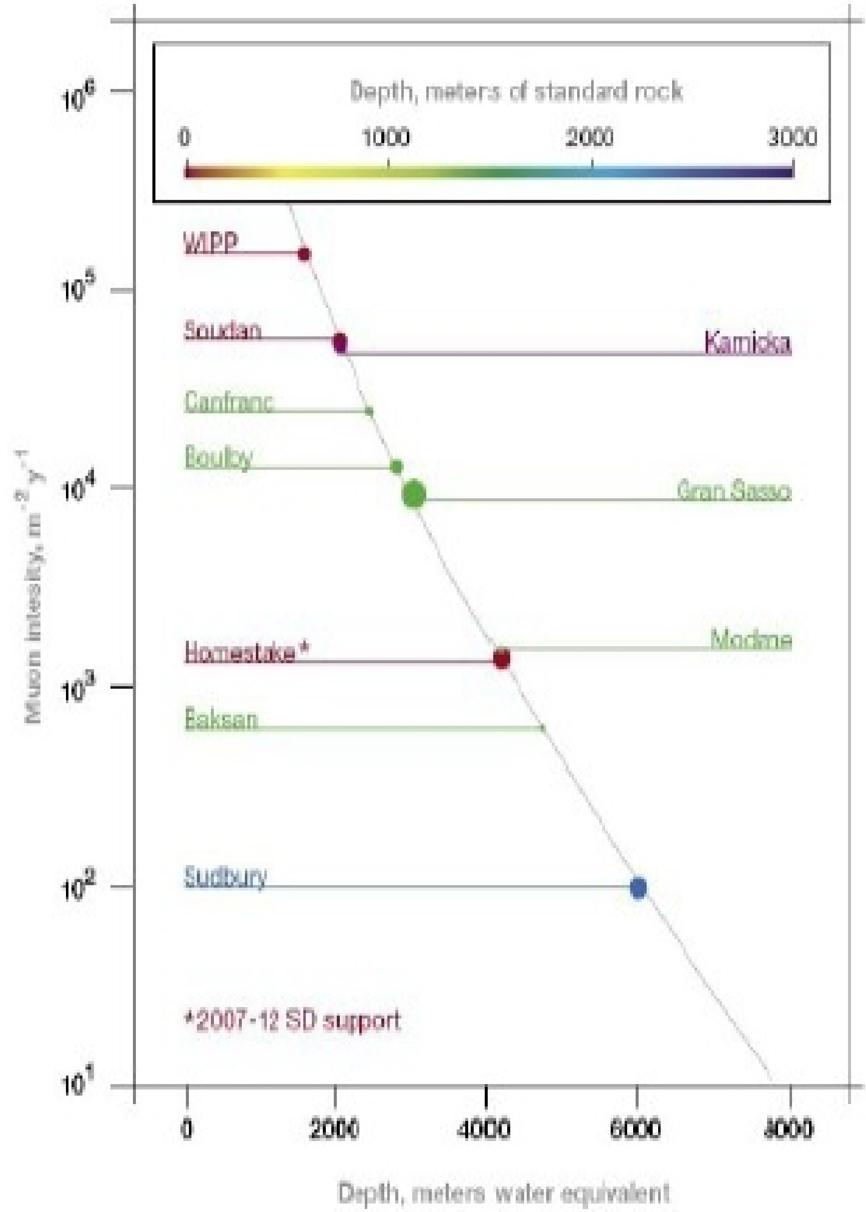


NC processes with cross-section of the same order.

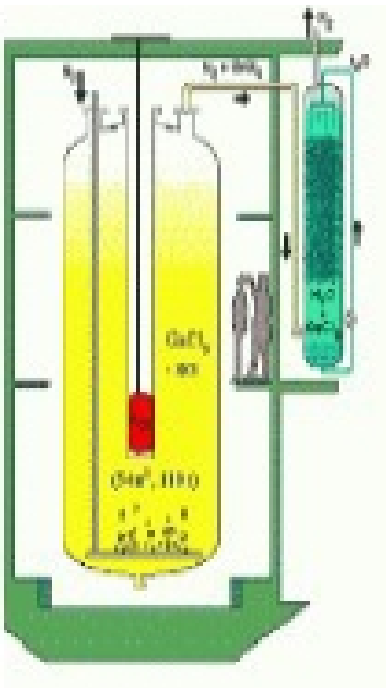
Interaction probability crossing all Earth is negligible!

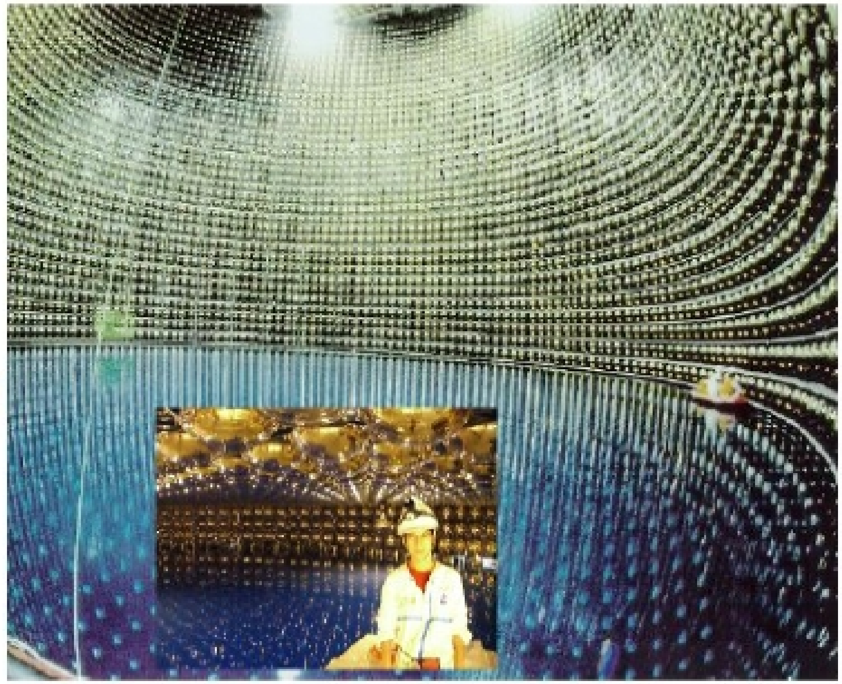
Neutrino Sources and Detectors

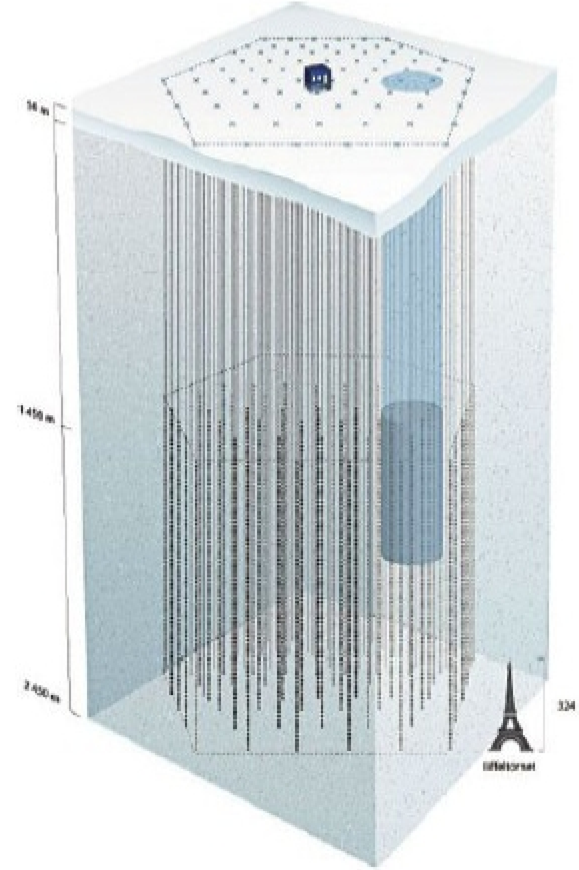


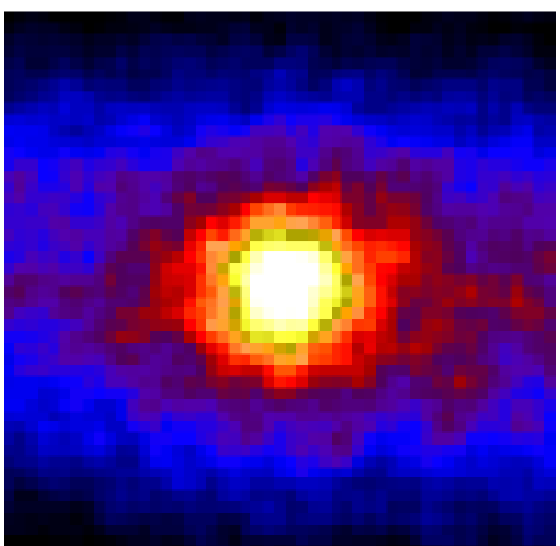


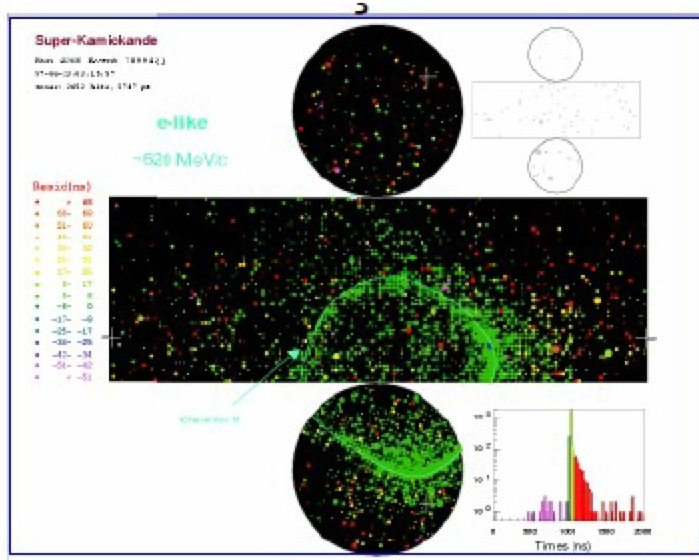
Neutrino Sources and Detectors

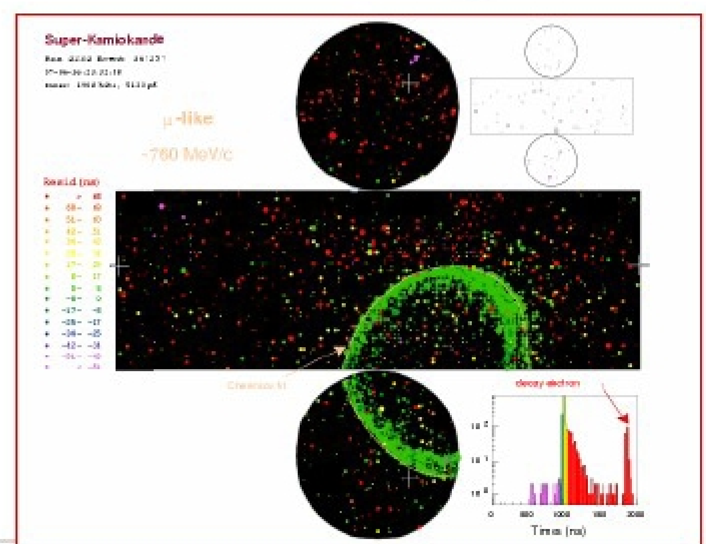




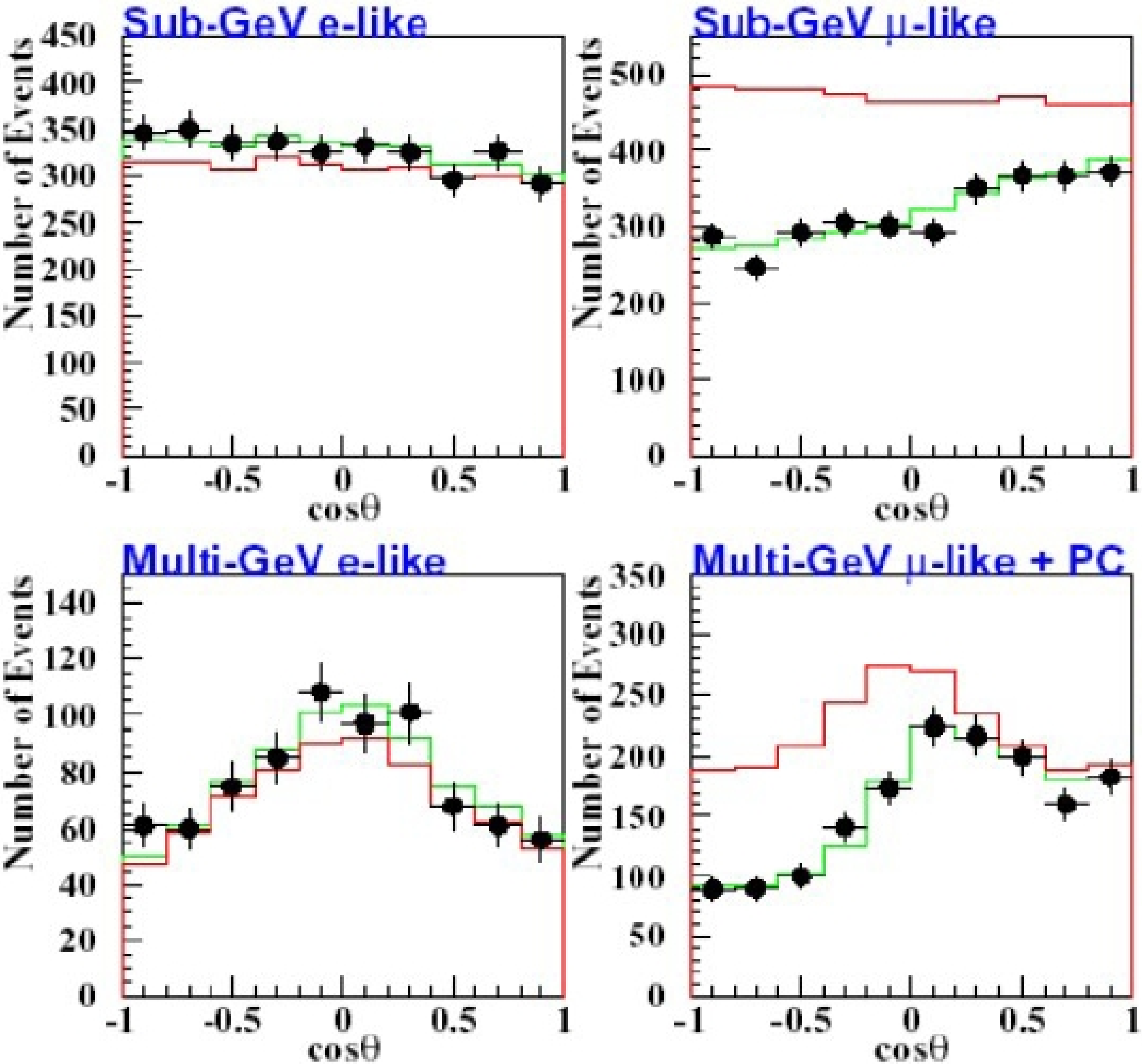


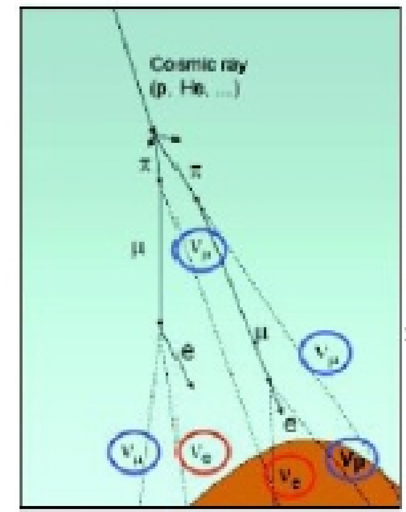


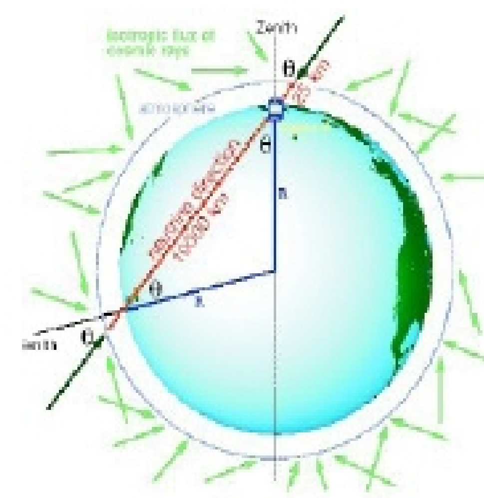




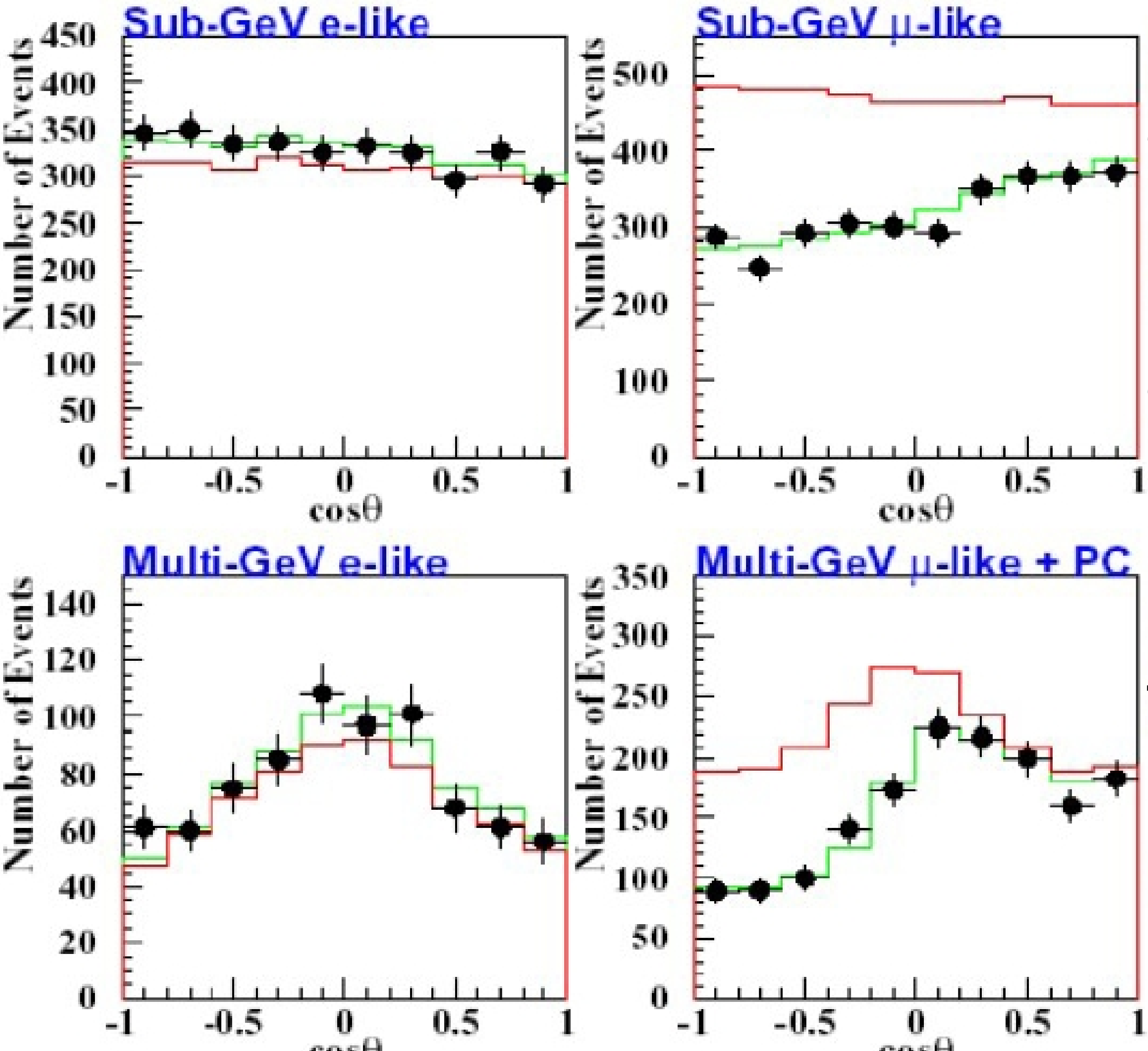
Atmospheric Neutrinos: Results and Interpretation







Atmospheric Neutrinos: Results and Interpretation

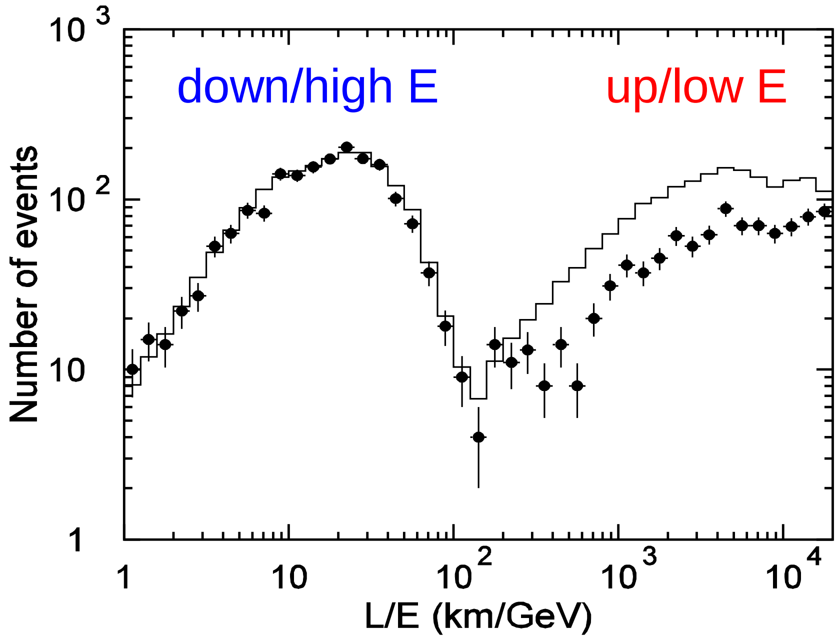


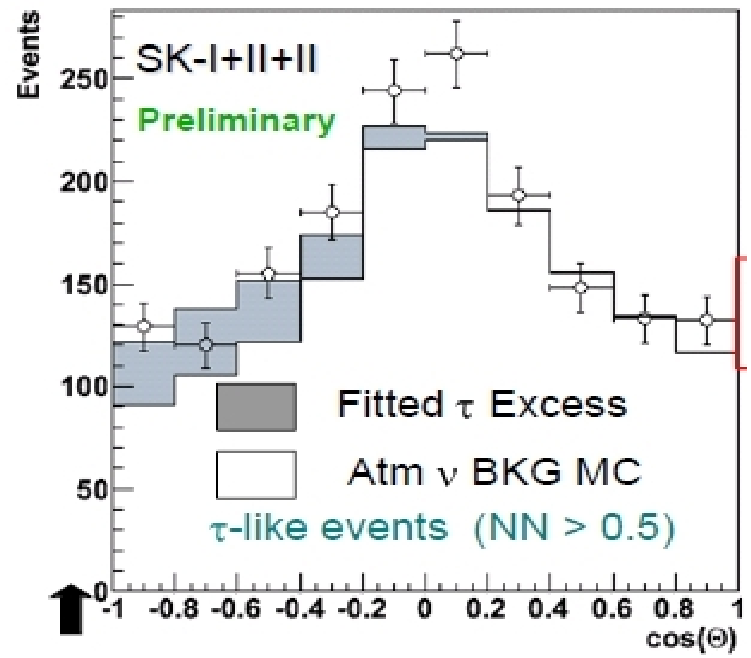
Muon neutrino disappearance (no change in electron)

Up to 50% effect, depends on energy and distance

The results fit a $1 - A \, . \, \sin^2(B \;\; L/E)$ expectation

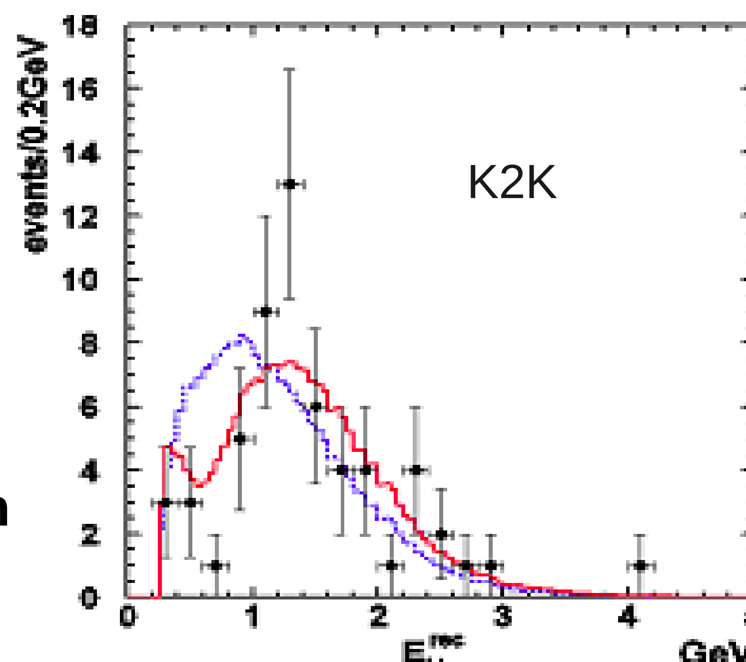
Atmospheric Neutrinos: Results and Interpretation





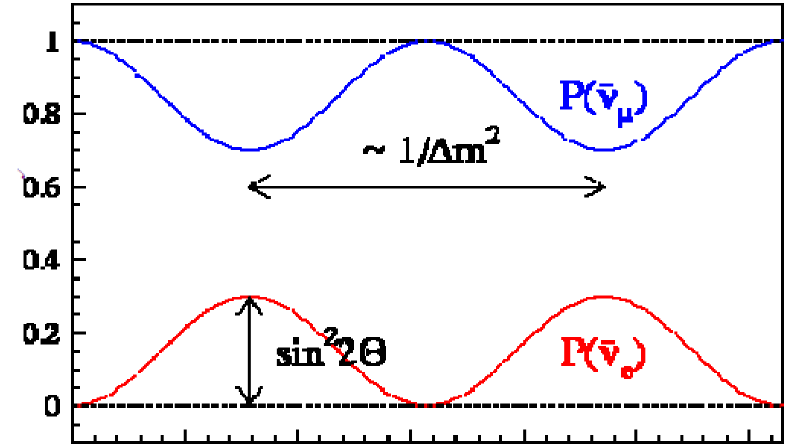
Confirmations at SuperKamiokande
included dedicated L/E analysis,
NC and tau neutrino searches and

K2K: a dedicated muon neutrino beam
with similar E spectrum from L=250 km



Oscillations from mass mixing

Flavour states (α) determine neutrino production and detection BUT mass states (j) determine neutrino propagation in vacuum.



$$\begin{bmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{bmatrix} = \begin{bmatrix} c & s \\ -s & c \end{bmatrix} \begin{bmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{bmatrix}$$

$$|\nu(t=0)\rangle = |\nu_e\rangle = c|\nu_1\rangle + s|\nu_2\rangle.$$

$$|\nu(t)\rangle = c\, e^{-iE_1 t}|\nu_1\rangle + s\, e^{-iE_2 t}|\nu_2\rangle$$

$$E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E}$$

$$\begin{aligned} P(\nu_e \to \nu_\mu; t) &= |\langle \nu_\mu | \nu(t) \rangle|^2 \\ &= |\{-s\,\langle \nu_1| + c\,\langle \nu_2|\}|\nu(t)\rangle|^2 \\ &= c^2\, s^2\, \left| e^{-iE_2 t} - e^{-iE_1 t} \right|^2 \\ &= 2\, c^2\, s^2\, \{1 - \cos[(E_2 - E_1)t]\} \\ &= \sin^2 2\theta\, \sin^2 \left[\frac{\Delta m^2}{4E} t \right], \end{aligned}$$

Neutrinos have different masses. Different from zero!

$$P(\nu_e \to \nu_\mu; L) = \sin^2 2\theta\, \sin^2 \left[1.27\, \Delta m^2 \frac{L}{E} \right]$$

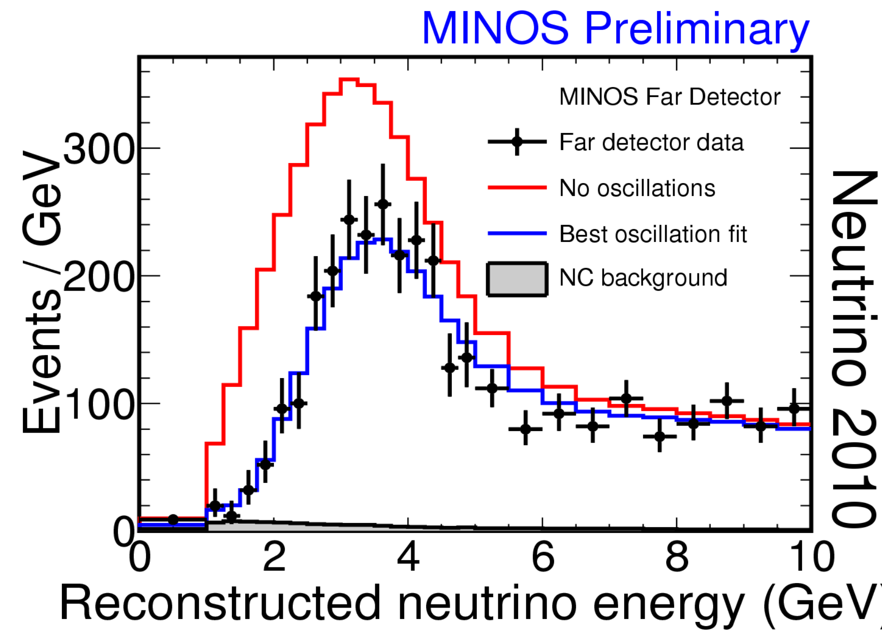
In natural units [eV²][km]/[GeV]

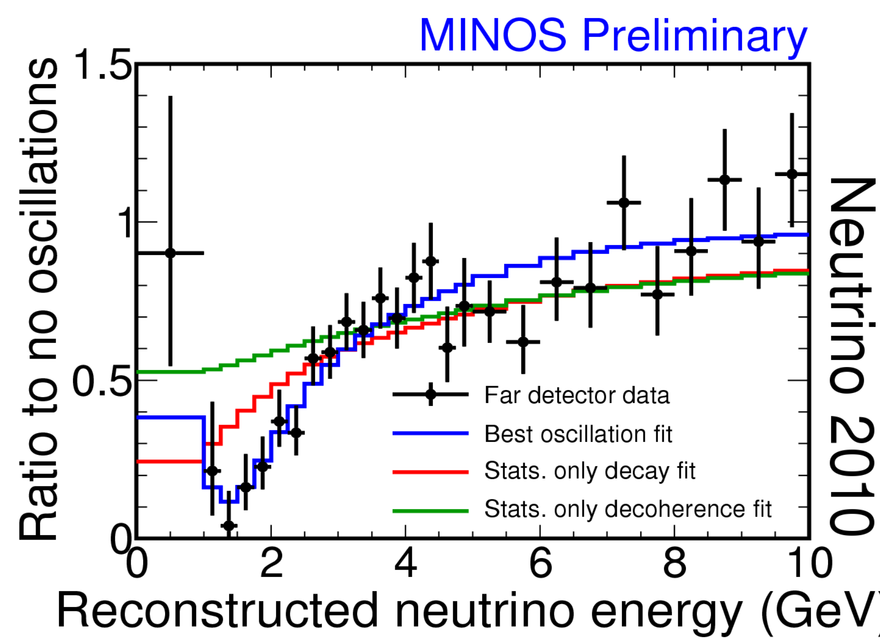
Neutrino Oscillations in Accelerator Beams – MINOS

K2K: 235 km, “atmospheric” spectra, @SK

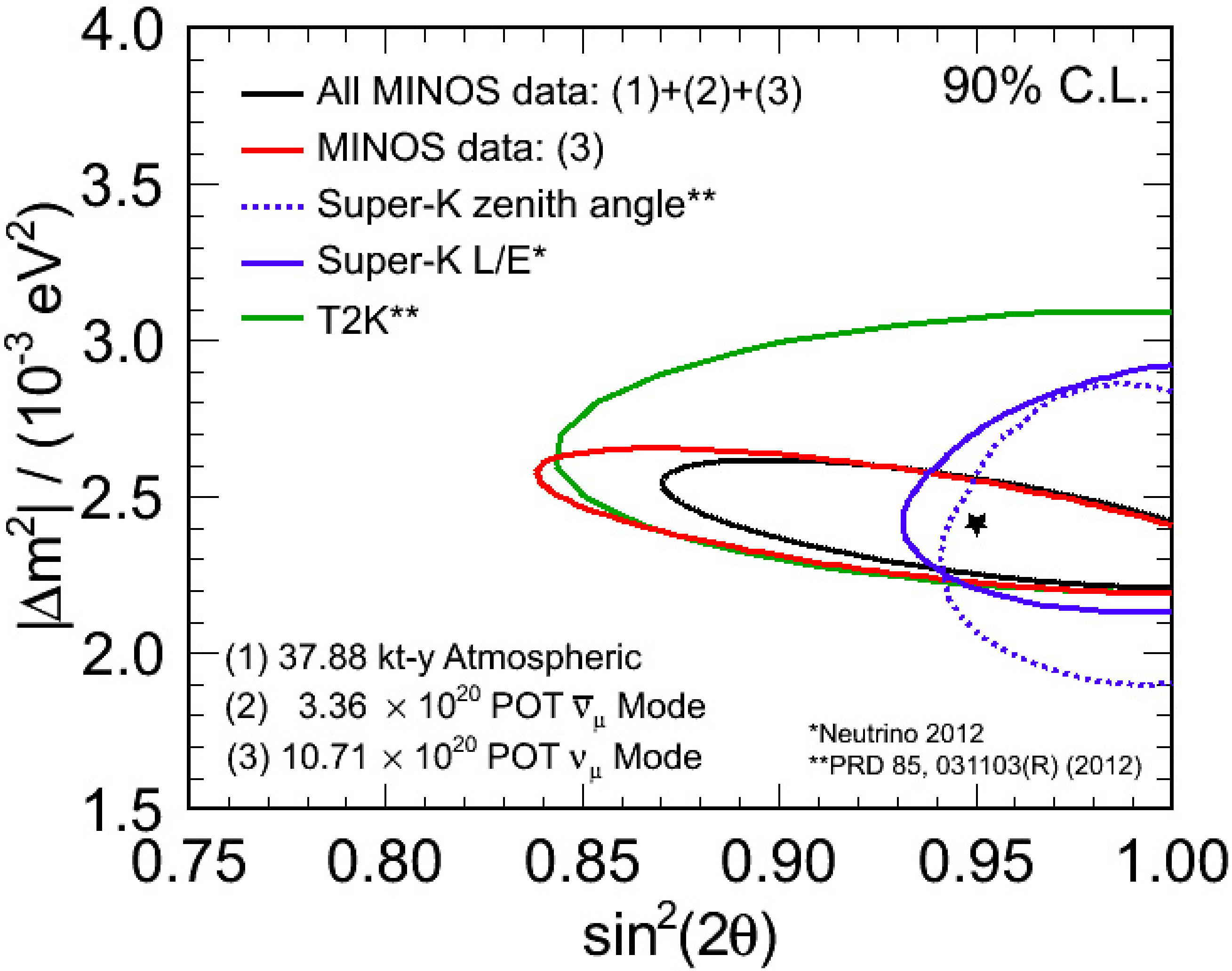
MINOS: 732 km, spectra peaks at 3GeV,

a large tracker with magnetic field





Neutrino Oscillations in Accelerator & Atmospherics



Complementarity:

Natural sources give very high fluxes ($\sin^2(2\theta)$ resolution)

Artificial sources with fixed L, known E ($|\Delta m^2|$ resolution)

Oscillations $\nu_\mu \rightarrow \nu_\tau$ (equal for neutrino/anti-neutrino)

Almost maximal mixing (>> than in quark sector)

and Δm^2 ~ 0.001 eV^2 (<< than normal masses)

3 neutrinos : ν_e, ν_μ, ν_τ : ν_1, ν_2, ν_3

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

PMNS (Pontecorvo, Maki, Nakagawa, Sakata)

PMNS Matrix, same as CKM for quarks (but very different values)
Can be factorized in three rotations (needed for CP violation),
which are experimentally selected by resonant (Δm^2) ~ L / E,

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

Historically:

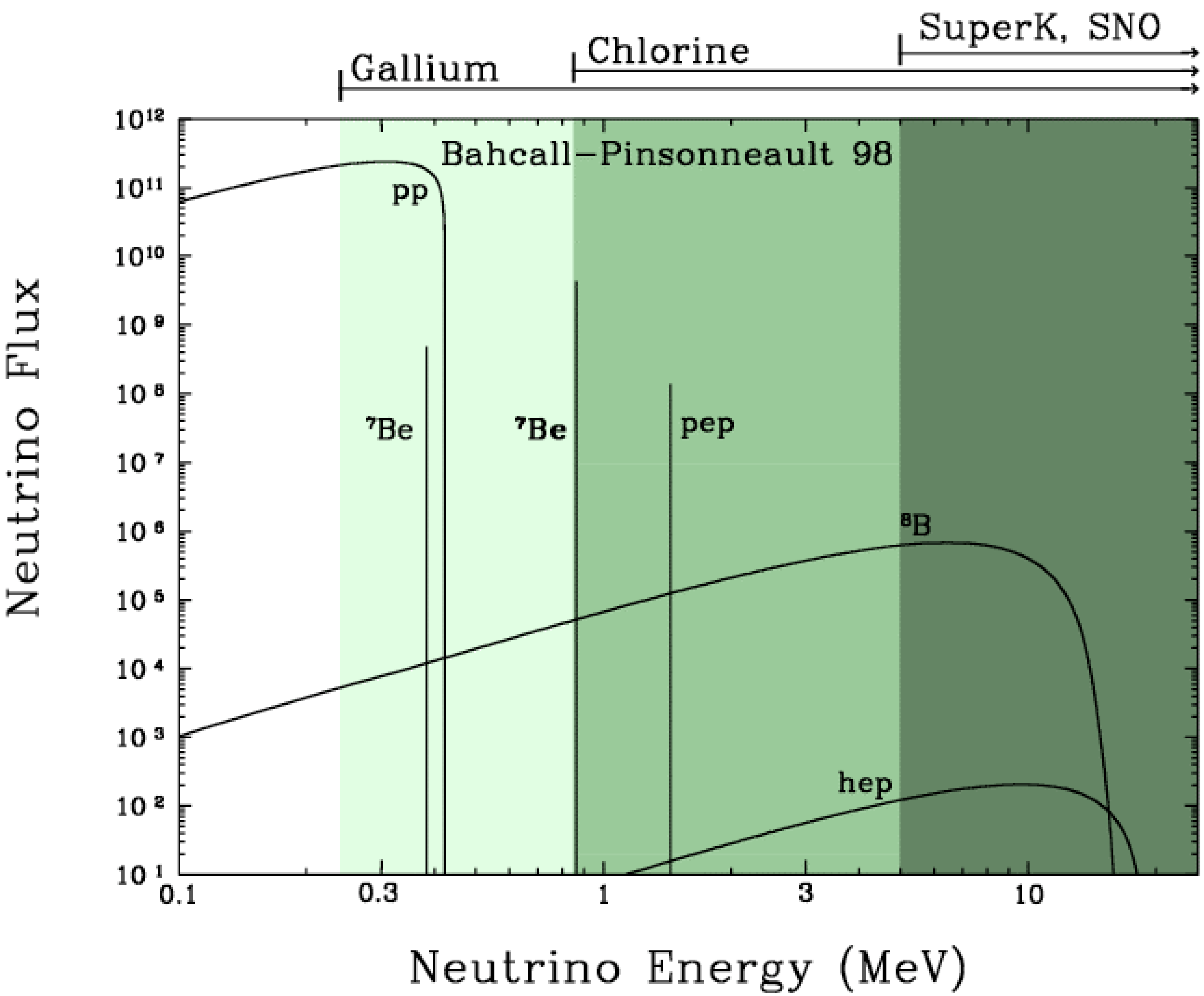
Solar (small) Atmospheric (extra)

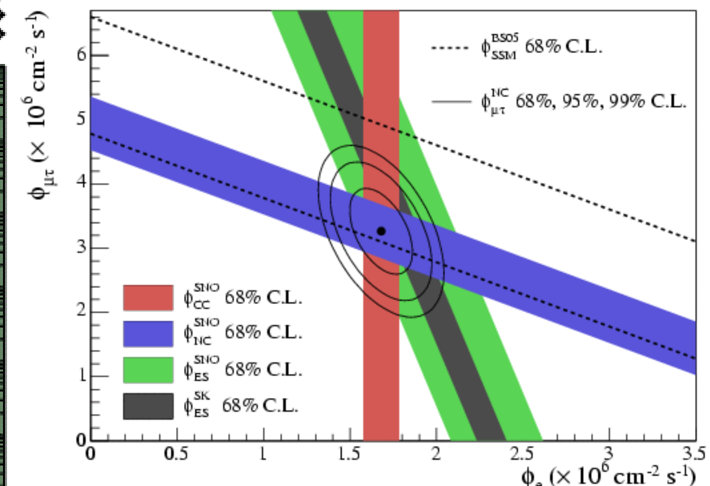
Solar Neutrino Oscillations (30 years of measurements)

~50% of expected flux in Galium experiments

~30% of expected flux in Chlorine experiments

~40% of expected flux in Water Cherenkov experiments ($\nu_e \to \nu_e$)



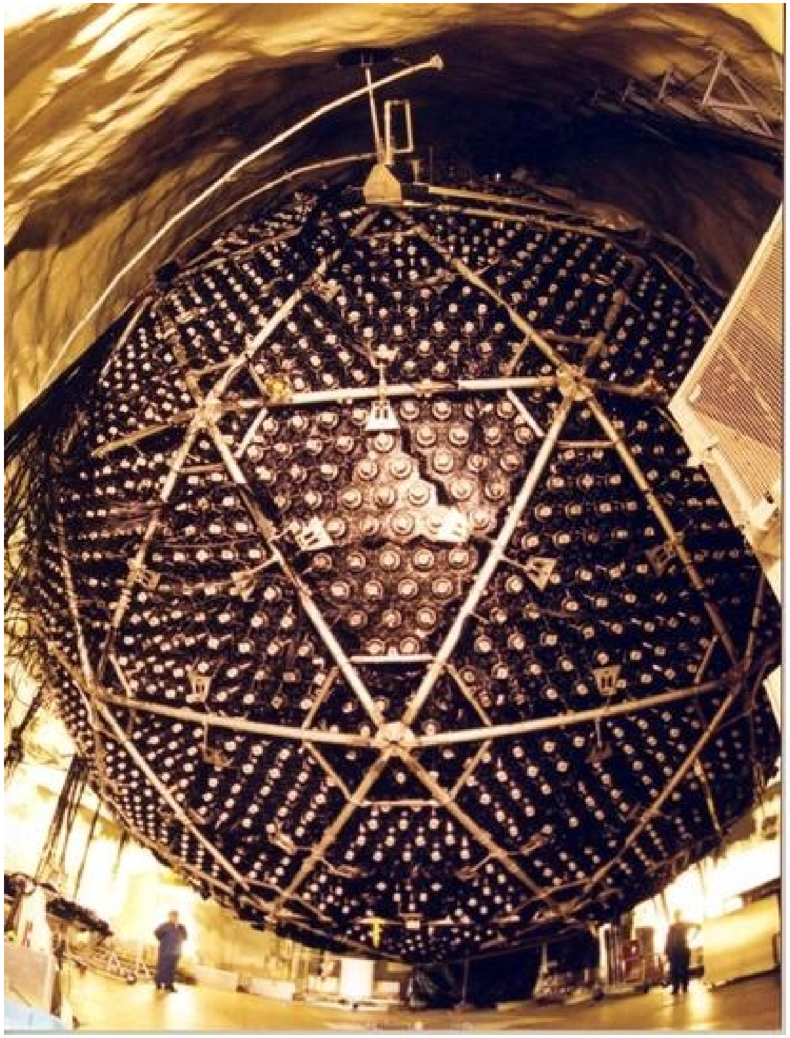


Solar Neutrino Problem solved by SNO with NC measurements of

($\nu_e \to \nu_x$)

Confirming total flux

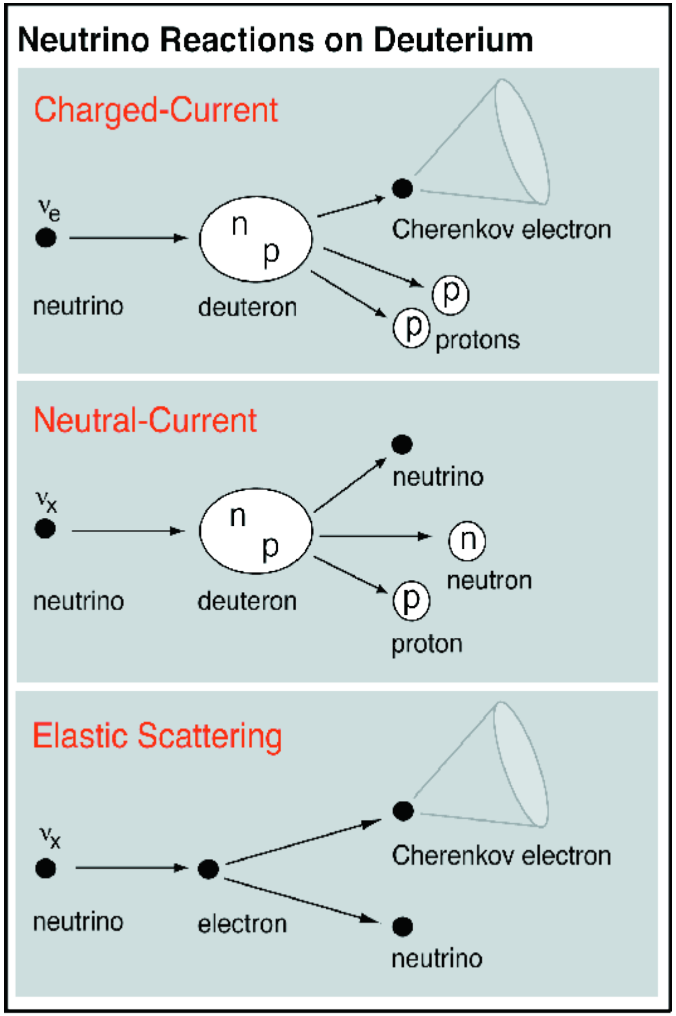
Solar Neutrino Observatory



ν + D --> p + p + l
(electron neutrinos)
Energy sensitivity

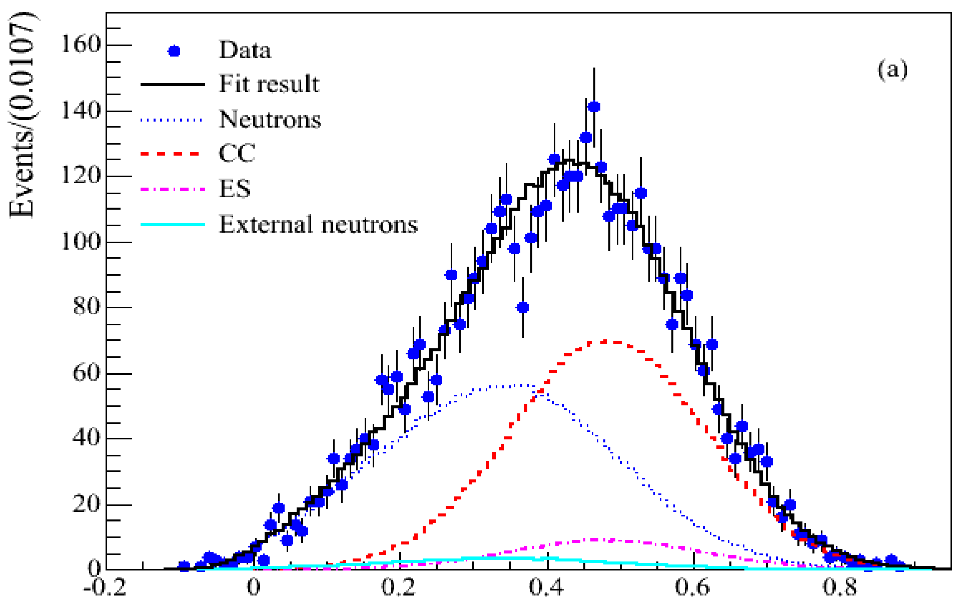
ν + D --> p + n + ν
(equally all neutrinos)
N + Cl ---> Cl + $\gamma\gamma$

ν + e --> ν + e
(5x more for electron)
Direction sensitivity



Sudbury Neutrino Observatory is a (Salted) Heavy Water Detector:
CC measure electron neutrinos; NC measure all neutrino types

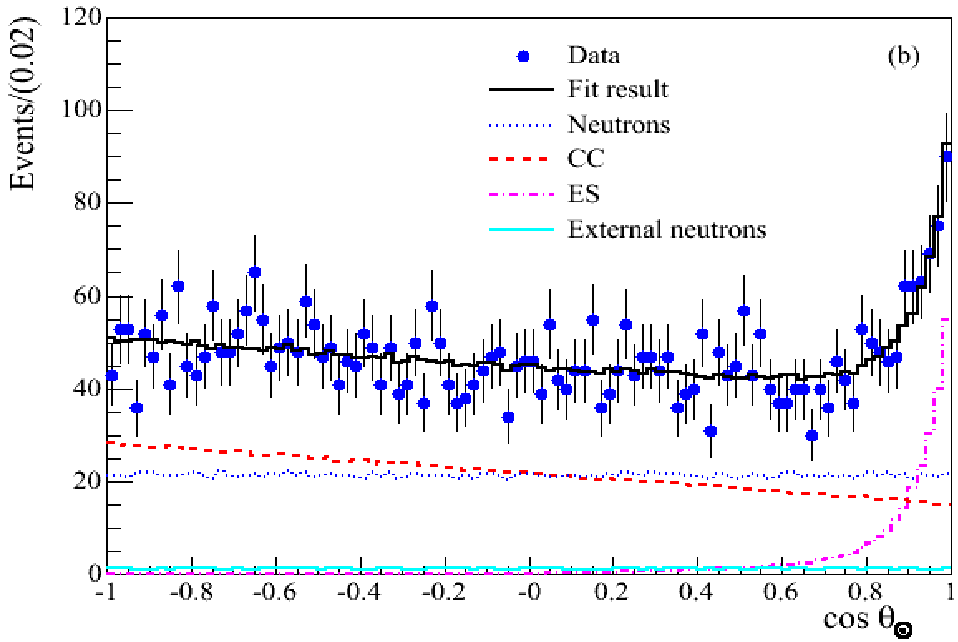
Solar Neutrino Observatory

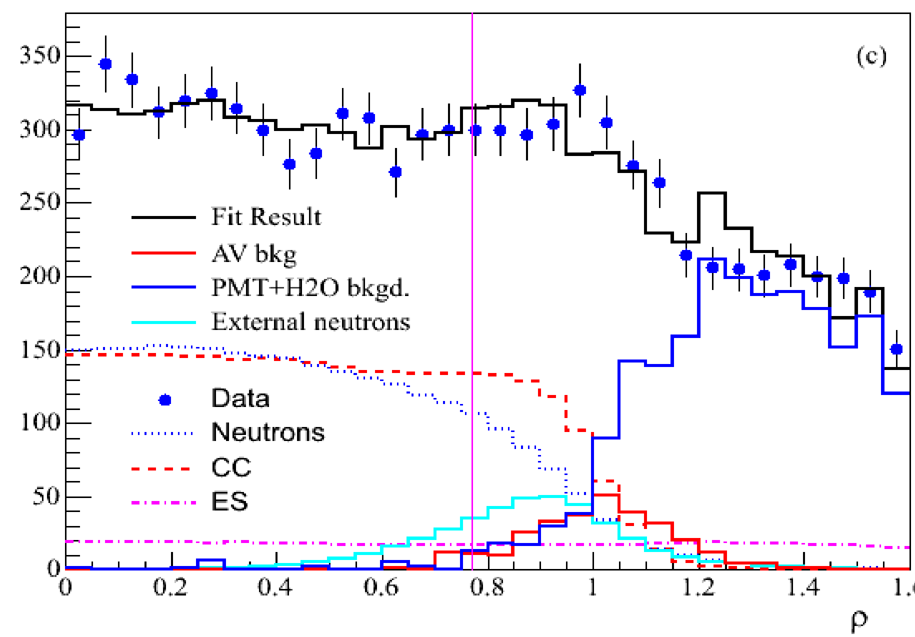


CC / NC / ES / backgrounds

CC / NC = 0.35 !
NC/Solar Model = 1.00 !
--> electron neutrinos oscillate and arrive as other neutrino types

1st "neutrino appearance"!

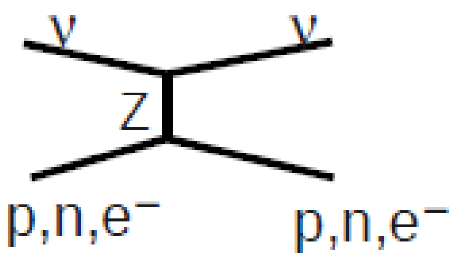


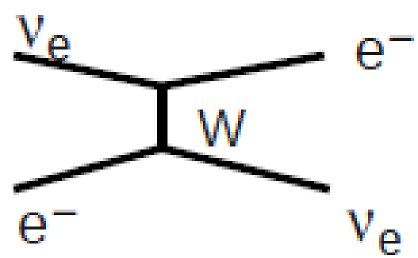


Oscillations in Matter

MSW (Mikheyev-Smirnov-Wolfstein) effect

$$\begin{bmatrix} e \\ x \end{bmatrix} = \left(Z\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} + W\begin{bmatrix}1 & 0\\ 0 & 0\end{bmatrix} + H\begin{bmatrix}-c & s\\ s & c\end{bmatrix}\right)\begin{bmatrix} e \\ x \end{bmatrix}$$





electron neutrinos share mass states with other ν types

no net effect

depends on E_ν and N_e

depends on basic neutrino properties

$$\begin{bmatrix} e \\ x \end{bmatrix} = \frac{\Delta m_*^2}{4E}\begin{pmatrix}-\cos 2\theta_* & \sin 2\theta_*\\ \sin 2\theta_* & \cos 2\theta_*\end{pmatrix}\begin{bmatrix} e \\ x \end{bmatrix}$$

Neutrino optics altered by solar density profile

$\Delta m_*^2 = \Delta m^2 \,.\, X$ $\quad$ $\sin 2\theta_* = \sin 2\theta \,/\, X$

$X^2 = \sin^2 2\theta + (\cos 2\theta + 2\sqrt{2}G_F N_e E/\Delta m^2)^2$

Oscillations in Matter – adiabatic / non-adiabatic cases

$$\begin{bmatrix} e \\ x \end{bmatrix} = \frac{\Delta m_*^2}{4E} \begin{pmatrix} -\cos 2\theta_* & \sin 2\theta_* \\ \sin 2\theta_* & \cos 2\theta_* \end{pmatrix} \begin{bmatrix} e \\ x \end{bmatrix}$$

$\Delta m_*^2 = \Delta m^2 \,.\, X$ $\quad$ $\sin 2\theta_* = \sin 2\theta \,/\, X$

$X^2 = \sin^2 2\theta + (\cos 2\theta + 2\sqrt{2} G_F N_e E / \Delta m^2)^2$

Resonant sin $2\theta_* = 1$

for a given Ne . E /Δm^2

-> νe == $\nu 2_*$; νx==-$\nu 1_*$

Ne >> Nres: suppress e/x oscillation [in Sun center & high Energy]

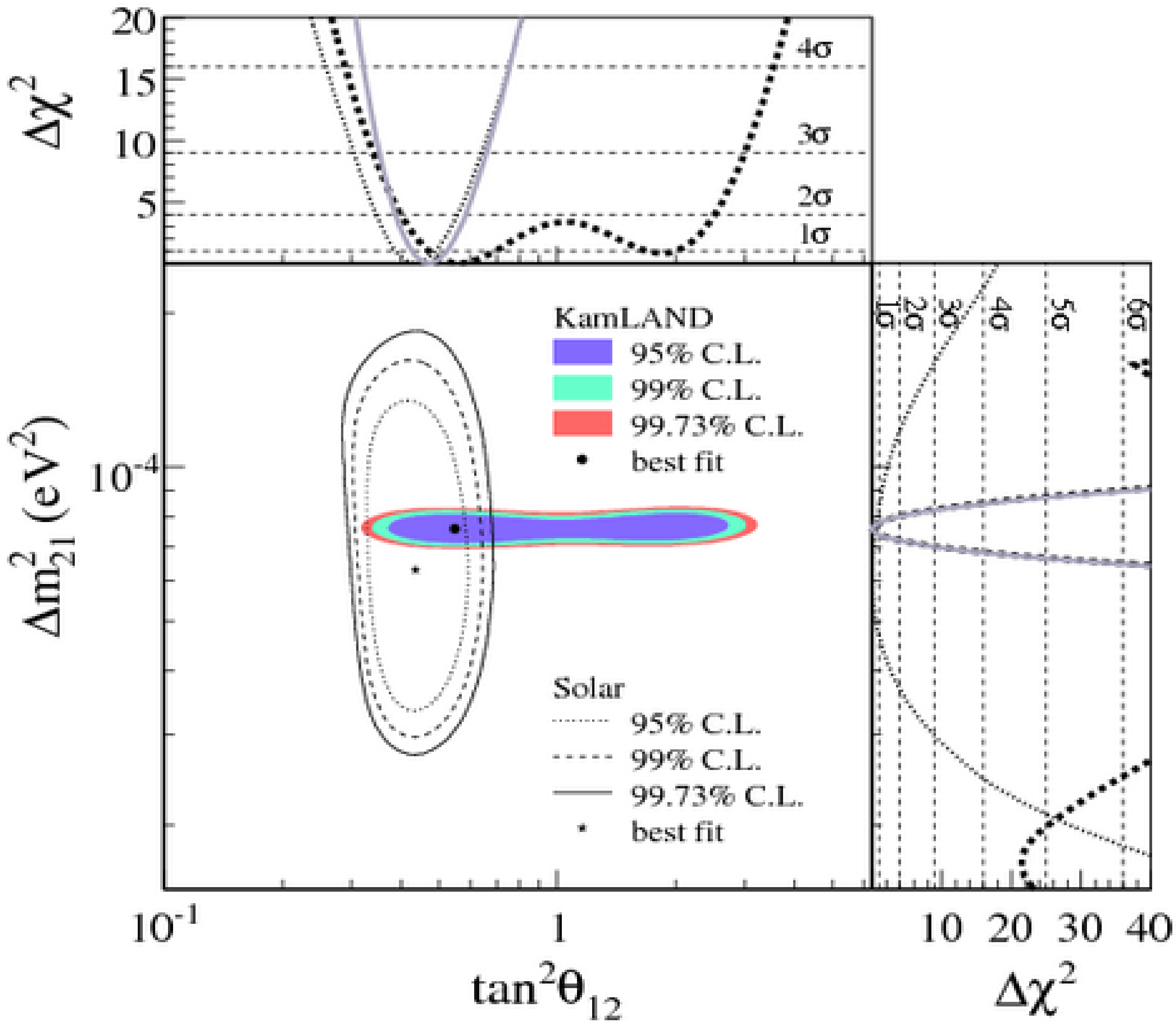
Solar density changes exponentially from 100 N_A/cm^3 to zero,
the two definite energy levels, E1 and E2, are kept adiabatically,
all neutrinos will be ν2 at Sun surface, (then detectable as νe/νx)
** measures sin2θ but depends on signal of cos2θ !

Ne << Nres: vaccuum oscillation [at Sun surface & low Energy]

is much much smaller, and only important for very low energy lines,
** measurement goal for next-generation solar ν experiments

$\nu\mu \rightarrow \nu\tau$ unchanged in matter;
anti νe -> νx w/ opposite sign

Solar and Reactor Neutrino Oscillations



Complementarity:

Natural sources give very high fluxes ($\sin^2(2\theta)$ resolution)

Matter effects break degeneracy in angle

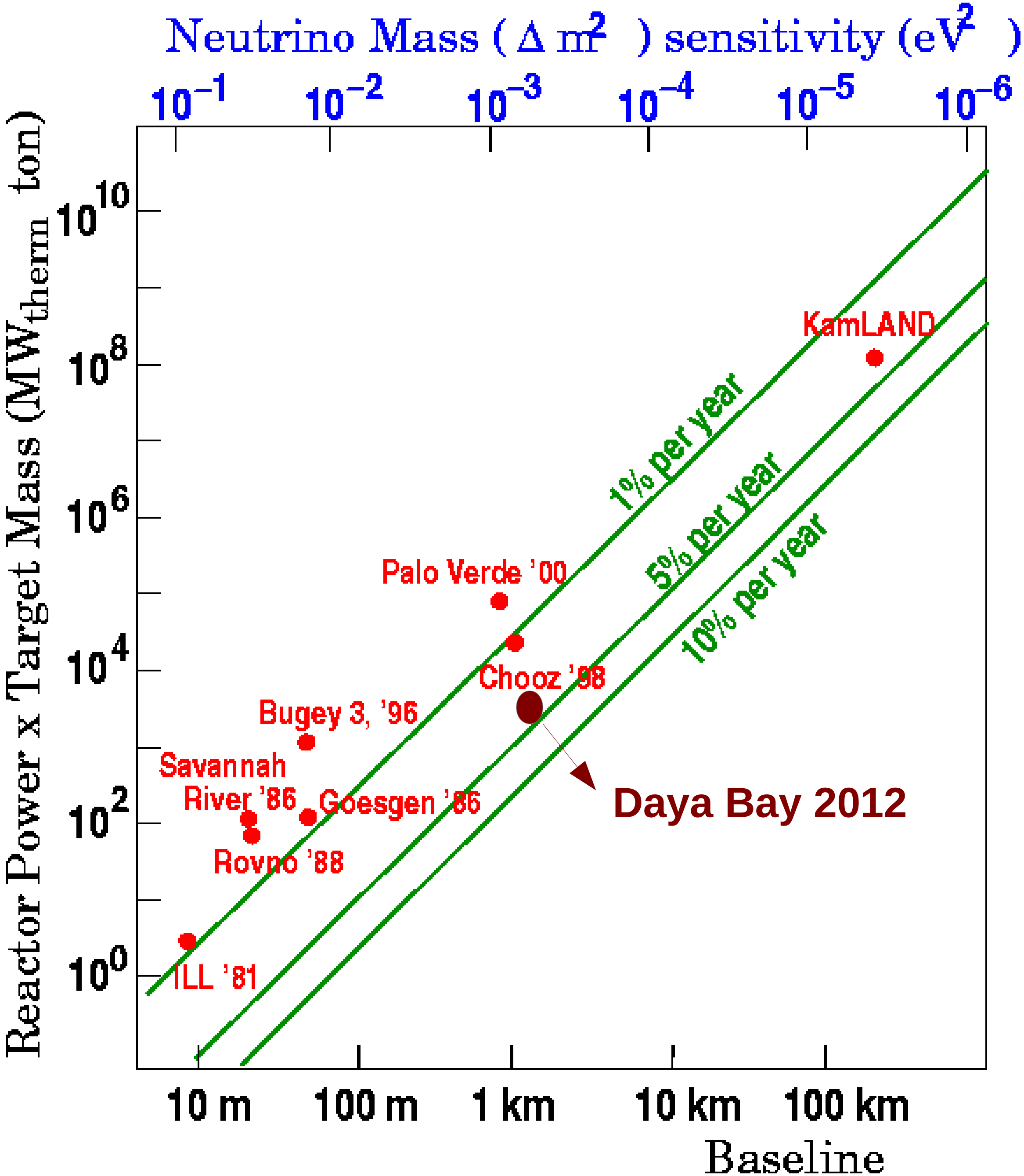
Artificial sources with fixed L, known E ($|\Delta m^2|$ resolution)

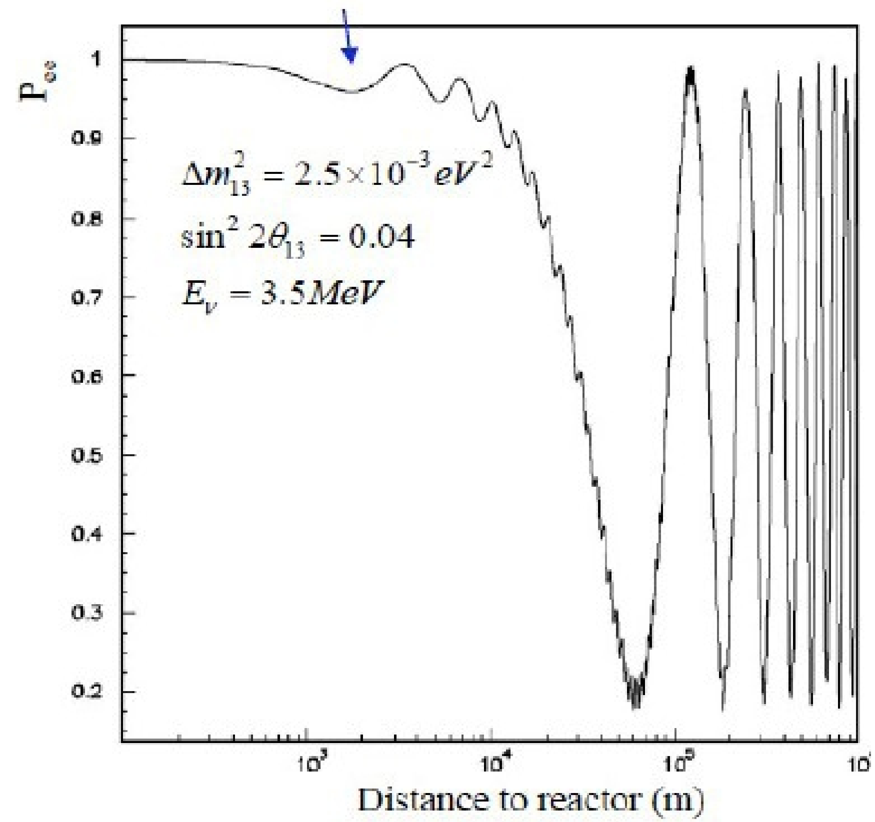
Oscillations $\nu_e \rightarrow \nu_\mu + \nu_\tau$ (equal for neutrino/anti-neutrino?)

Non-maximal mixing (still >> than in quark sector)

and δm^2 ~ 0.0006 eV^2 (<< than other squared mass difference)

More Reactor Neutrino Oscillations

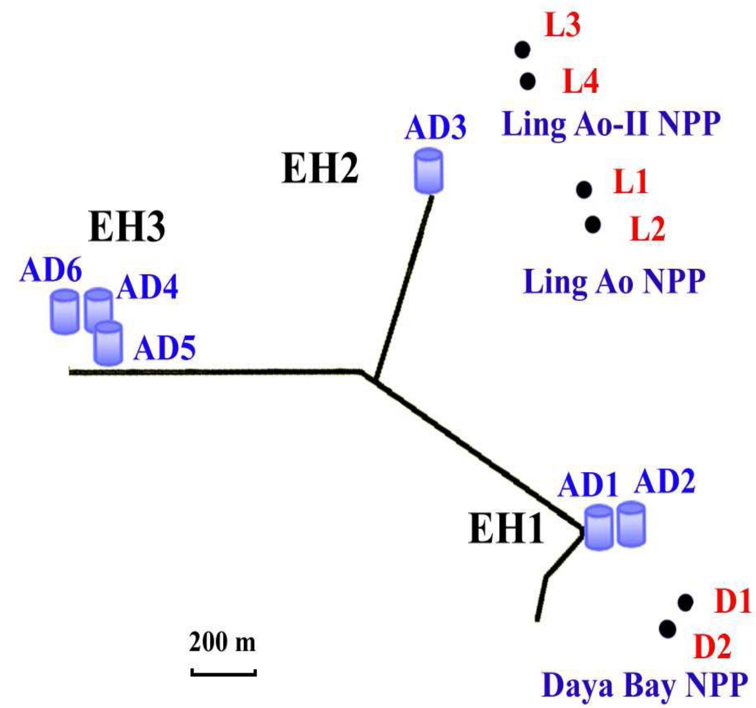


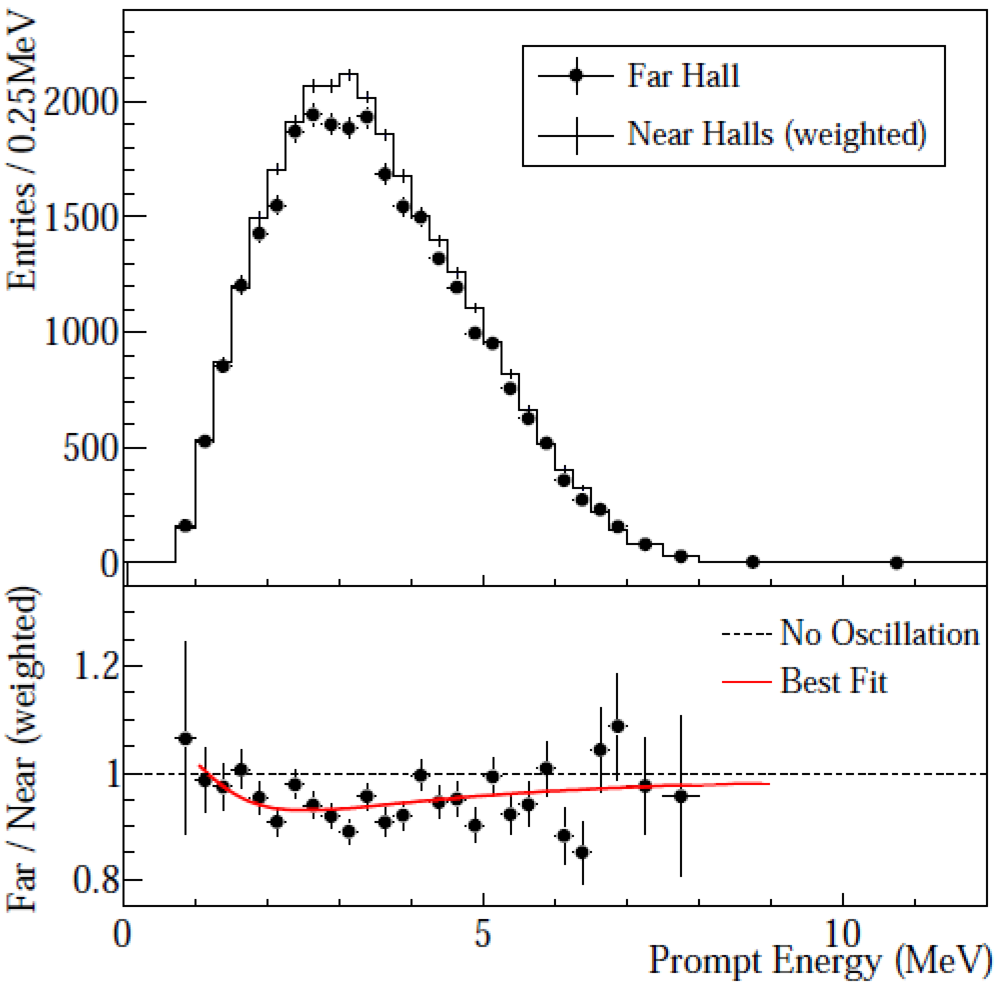


More Reactor Neutrino Oscillations

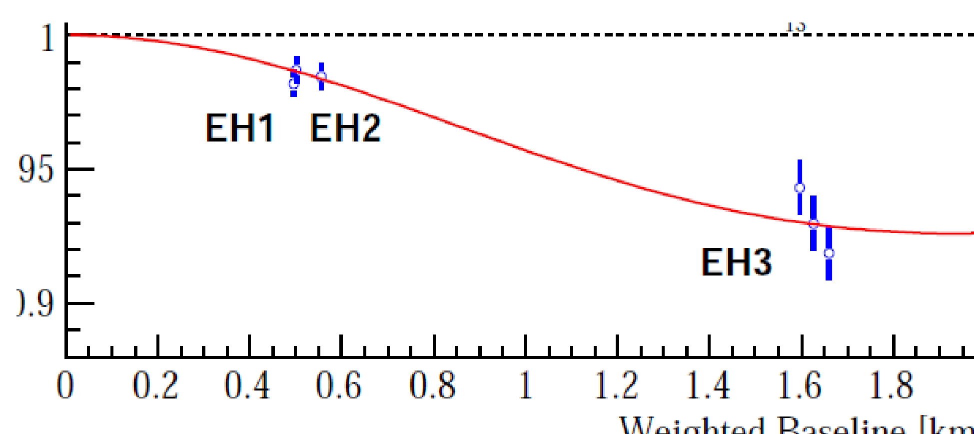
$\Delta m^2_{31} = \Delta m^2_{atm}$ [$\delta\ m^2_{sol} \sim 0$]

$\sin^2(2\theta_{13}) = 0.089$
$+ 0.010$ (stat) $+ 0.005$ (syst)





Pee = 1 – $\sin^2(2\theta_{13}) \sin^2(1.267\Delta m^2_{31}$ L/E)



The Neutrino Mass Matrix is (almost) complete !

$\theta 12 \sim 34^o$ $\Delta m^2 \sim 7x10^{-5}$ eV^2
$\theta 23 \sim 45^o$ $\Delta m^2 \sim 3x10^{-3}$ eV^2
$\theta 13 \sim 5^o$ $\Delta m^2 \sim 3x10^{-3}$ eV^2

Δm^2 with precision of ~3%

$\sin^2\theta$ with precision of 5%-20%

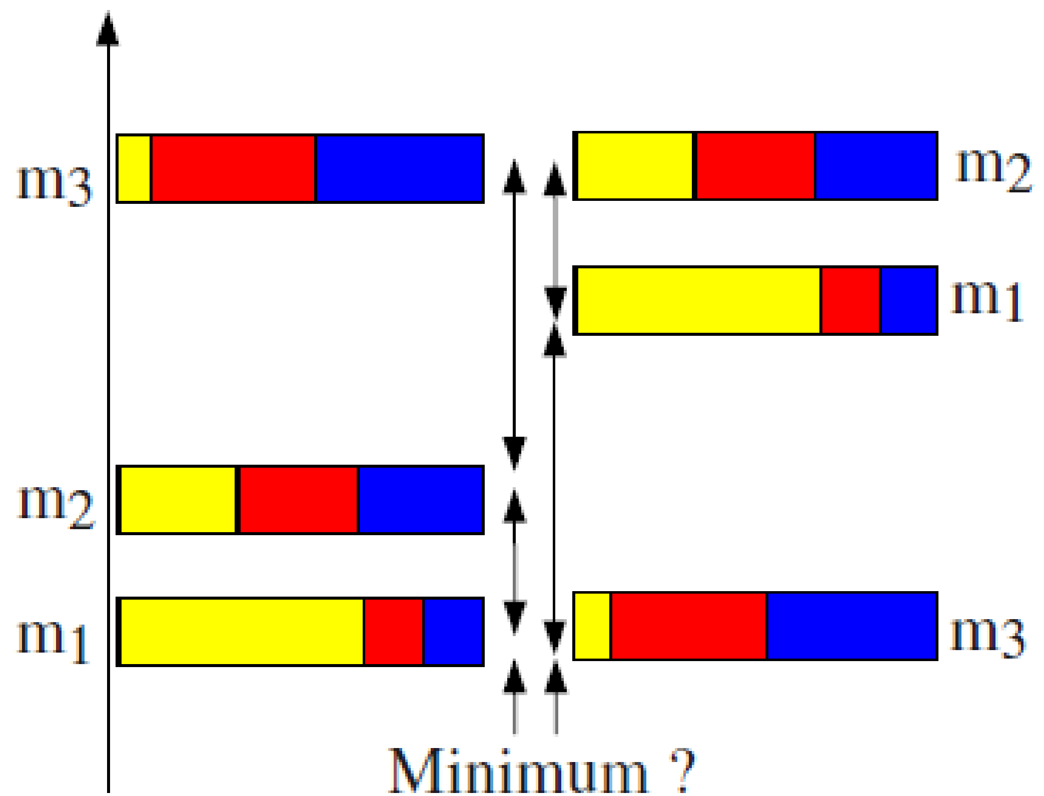
Exact PMNS still has large errors
But very different from CKM

*** delta CP will also enter PMNS**

*** hierarchy not measured yet**

*** Majorana phases can also exist**

$$\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix} = \begin{pmatrix} 0.82 & 0.55 & -0.15 \\ -0.35 & 0.70 & 0.61 \\ 0.44 & -0.45 & 0.77 \end{pmatrix} \begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}$$



Neutrino Missing Matrix very different from quarks'

Pontecorvo–Maki–
–Nakagawa–Sakata

$|U_{e1}|\ |U_{e2}|\ |U_{e3}|$
$|U_{\mu 1}|\ |U_{\mu 2}|\ |U_{\mu 3}|$
$|U_{\tau 1}|\ |U_{\tau 2}|\ |U_{\tau 3}|$

$$\begin{bmatrix} 0.82 & 0.55 & 0.15 \\ 0.35 & 0.70 & 0.61 \\ 0.44 & 0.45 & 0.77 \end{bmatrix}$$

Largest angle is 45º

Cabibbo–Kobayashi–
–Maskawa

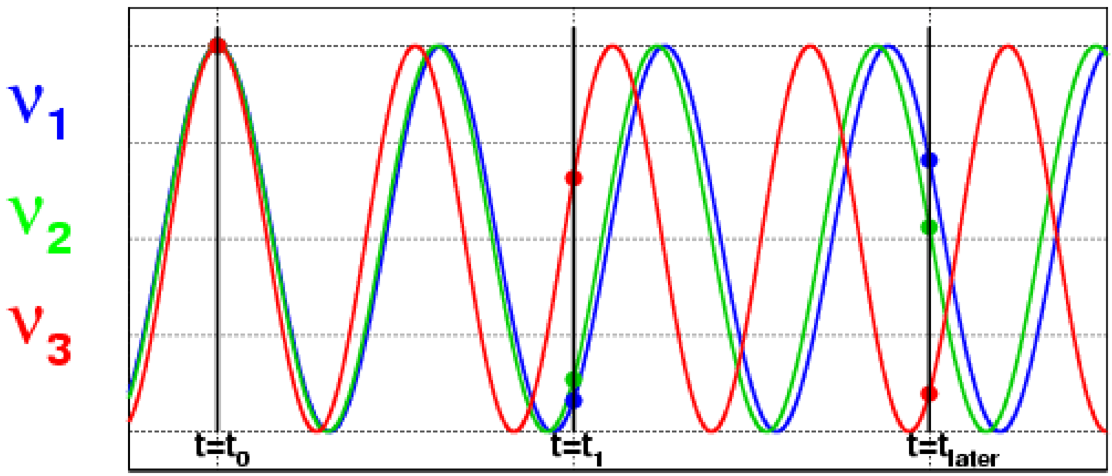
$|V_{ud}|\ |V_{us}|\ |V_{ub}|$
$|V_{cd}|\ |V_{cs}|\ |V_{cb}|$
$|V_{td}|\ |V_{ts}|\ |V_{tb}|$

$$\begin{bmatrix} 0.97 & 0.23 & 0.00 \\ 0.23 & 0.97 & 0.04 \\ 0.01 & 0.04 & 1.00 \end{bmatrix}$$

Largest angle is 13º

Smallest angle > 0 implies the possibility of direct CP violation (one complex phase that can not be absorbed by rotations)

Use three families to measure other parameters



In general, three-fold mixing should occur

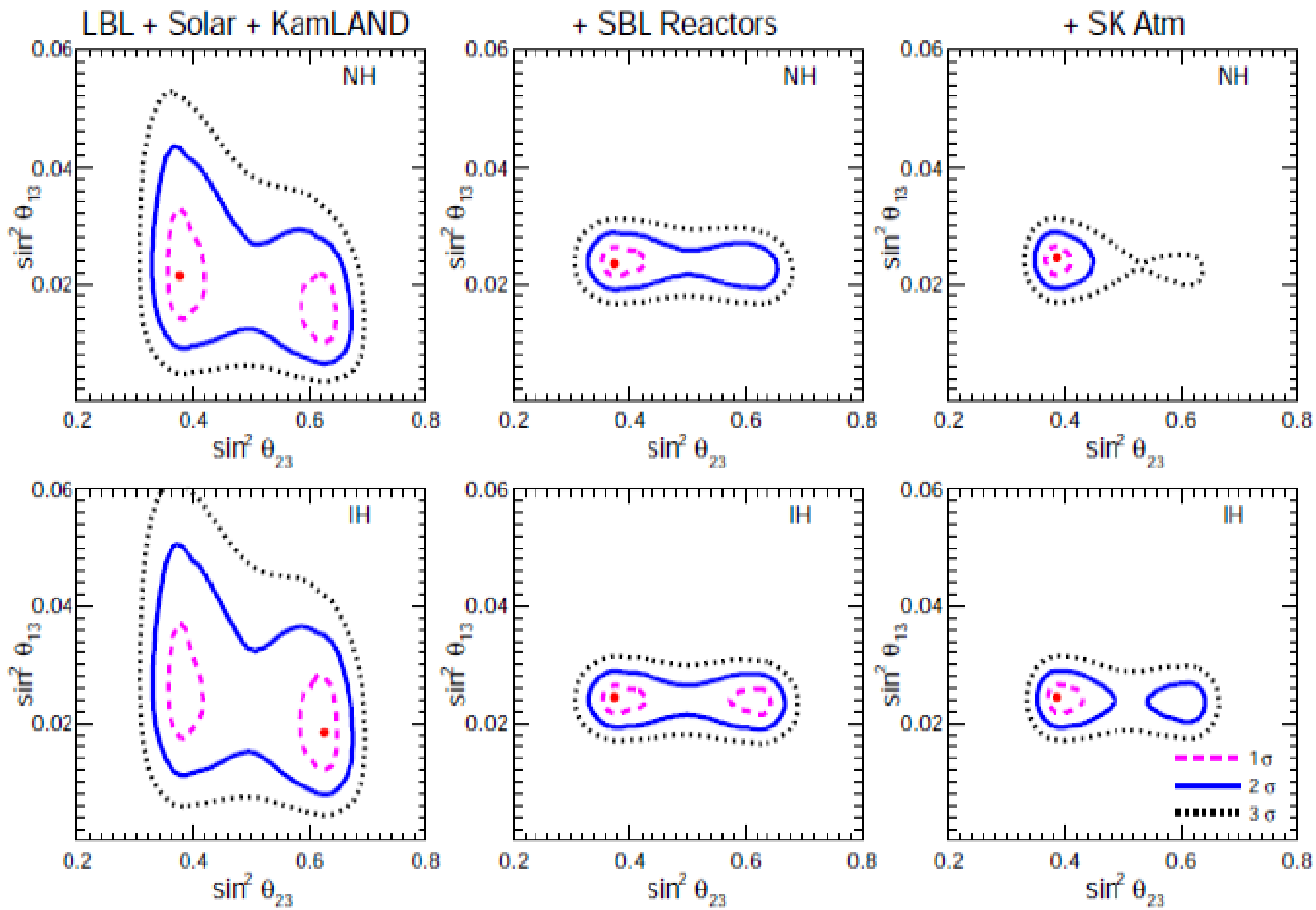
"Solar" and "Atmospheric" Oscillations selected by different $L/E.\Delta m^2$
---> we measure only mass differences: 10^{-5} eV^2 and 10^{-3} eV^2

Solar neutrinos get an effective mass in dense solar matter,
from electron scattering (CC+NC for electron neutrinos; NC for other).
---> distinguish sign of $\sin^2(2\theta).F \sin^2 (1.27\ L/E.\Delta m^2/F)$

$$F=\sin^2(2\theta) + (\cos(2\theta)-2\sqrt{2}\ G_F Ne/\Delta m^2)^2$$

All results seem compatible for neutrinos and anti-neutrinos, CP?

Neutrino Oscillations: 2nd order effects



Neutrino Oscillations: 2nd order effects

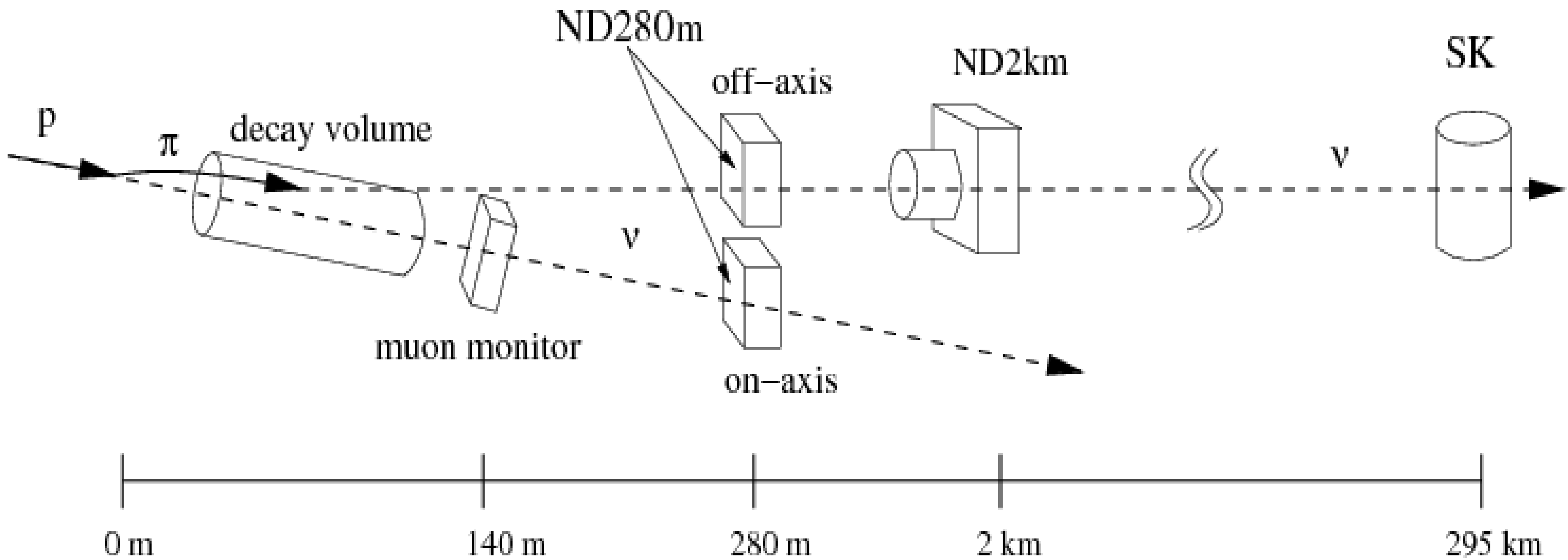
$$
\begin{aligned}
P_{\nu_\mu\to\nu_e} =& \frac{1}{(A-1)^2}\sin^2 2\theta_{13}\,\sin^2\theta_{23}\,\sin^2[(A-1)\Delta] \\
& -(+)\frac{\alpha}{A(1-A)}\cos\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\sin 2\theta_{13}\times \\
& \sin\delta_{CP}\,\sin\Delta\,\sin A\Delta\,\sin[(1-A)\Delta] \\
& +\frac{\alpha}{A(1-A)}\cos\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,\sin 2\theta_{13}\times \\
& \cos\delta_{CP}\,\cos\Delta\,\sin A\Delta\,\sin[(1-A)\Delta] \\
& +\frac{\alpha^2}{A^2}\cos^2\theta_{23}\,\sin^2 2\theta_{12}\,\sin^2 A\Delta
\end{aligned}
$$

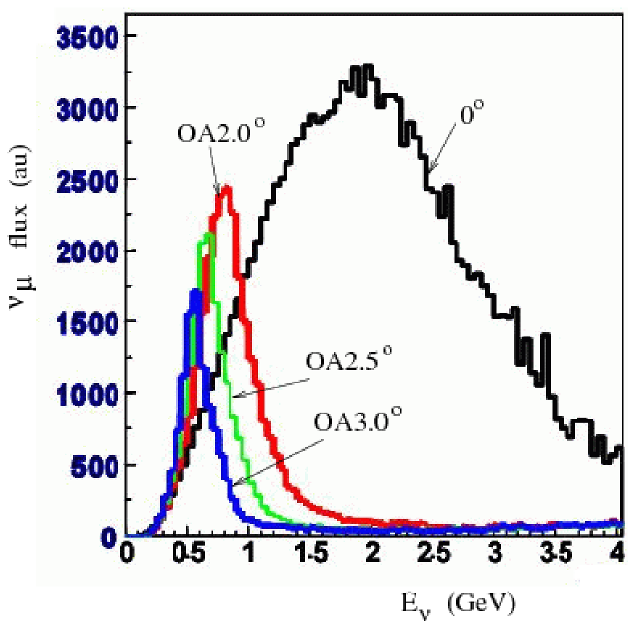
Difference for neutrino / anti-neutrino (proportional to sinδ and all three mixing angles!)

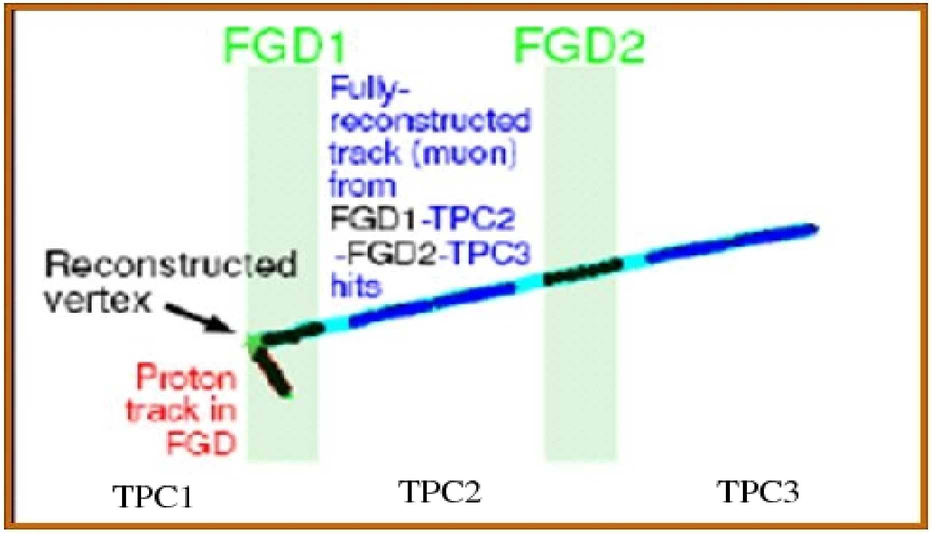
Here $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}} << 1$, $\Delta = \frac{\Delta m^2_{32} L}{4E_\nu}$ and $A = 2\sqrt{2}G_F N_e \frac{E_\nu}{\Delta m^2_{32}}$, where N_e is the electron density of the

But also matter effects are different for electron neutrino/ anti-neutrino

2nd Order Neutrino Oscillation Measurements: T2K







Characterize
ν beam and
ν interactions
In all targets

T2K near detector measurements: studying the beam

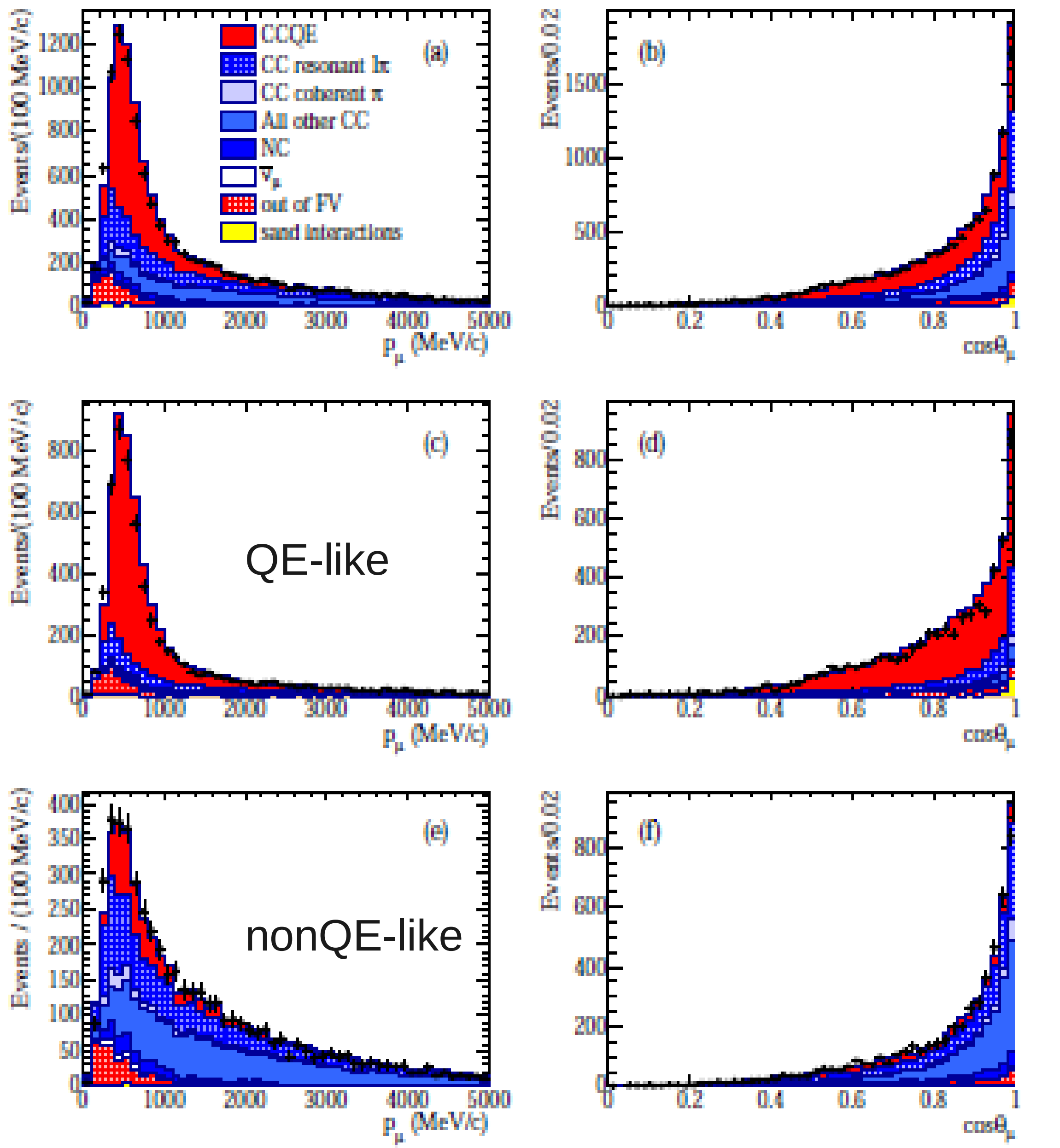


FIG. 15: Muon momentum for the CC-inclusive (a), CCQE-like (c), and CCnonQE-like (e) samples. Cosine of the muon angle for the CC-inclusive (b), CCQE-like (d), and CCnonQE-like (f) samples. The errors on the data points are the statistical errors.

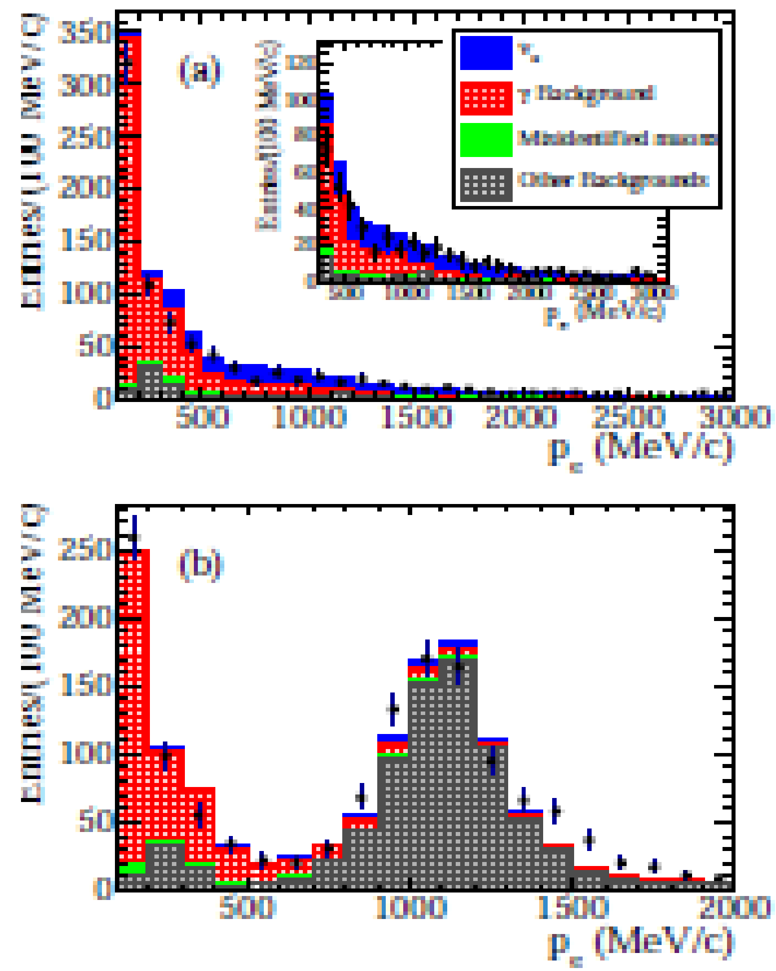
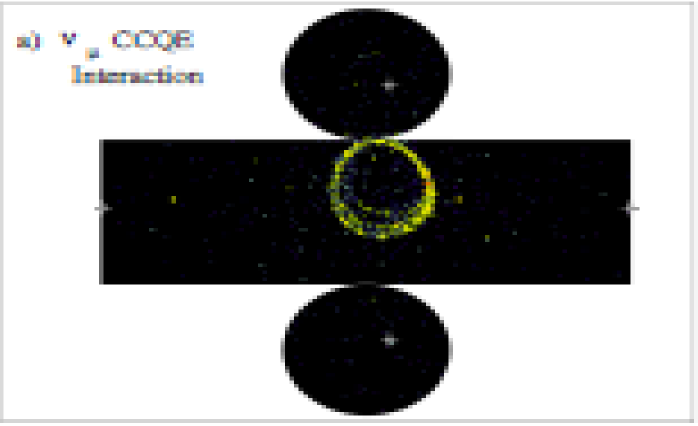
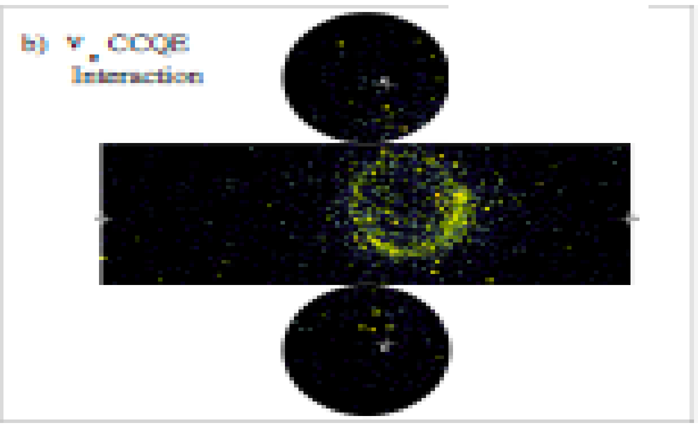
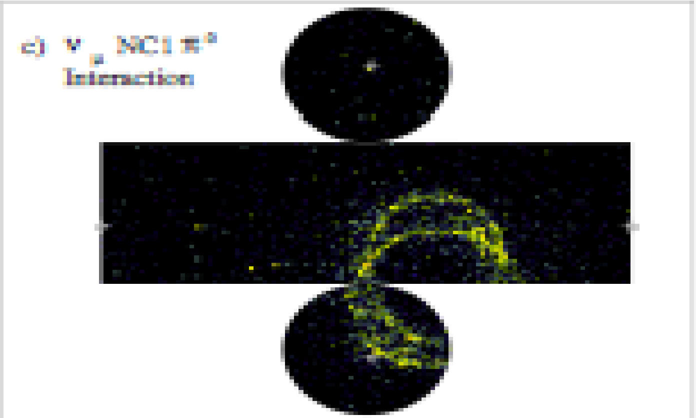


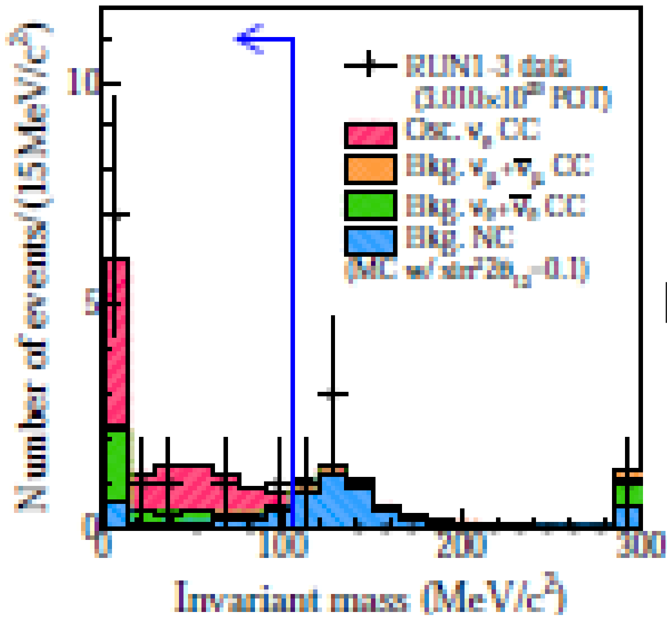
FIG. 17: (a) Momentum distribution of the highest momentum track with negative charge for each event in the electron candidate sample at ND280. The inset shows the region with momentum ≥ 300 MeV/c. (b) Momentum distribution of the highest momentum track with positive charge for each event of the positron candidate control sample. The "Other Backgrounds" component is mainly due to protons and pions from NC and CC ν_μ interactions in the FGD. The energy loss of positrons and protons (pions) is similar at p ≈1000 MeV/c (200 MeV/c), resulting in the presence of these particles in the positron candidate sample.

T2K: electron neutrino appearance at SK

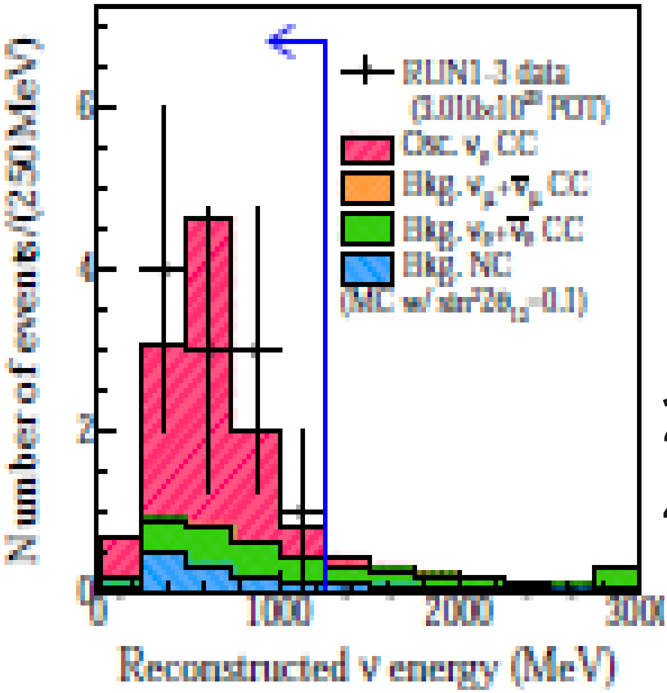








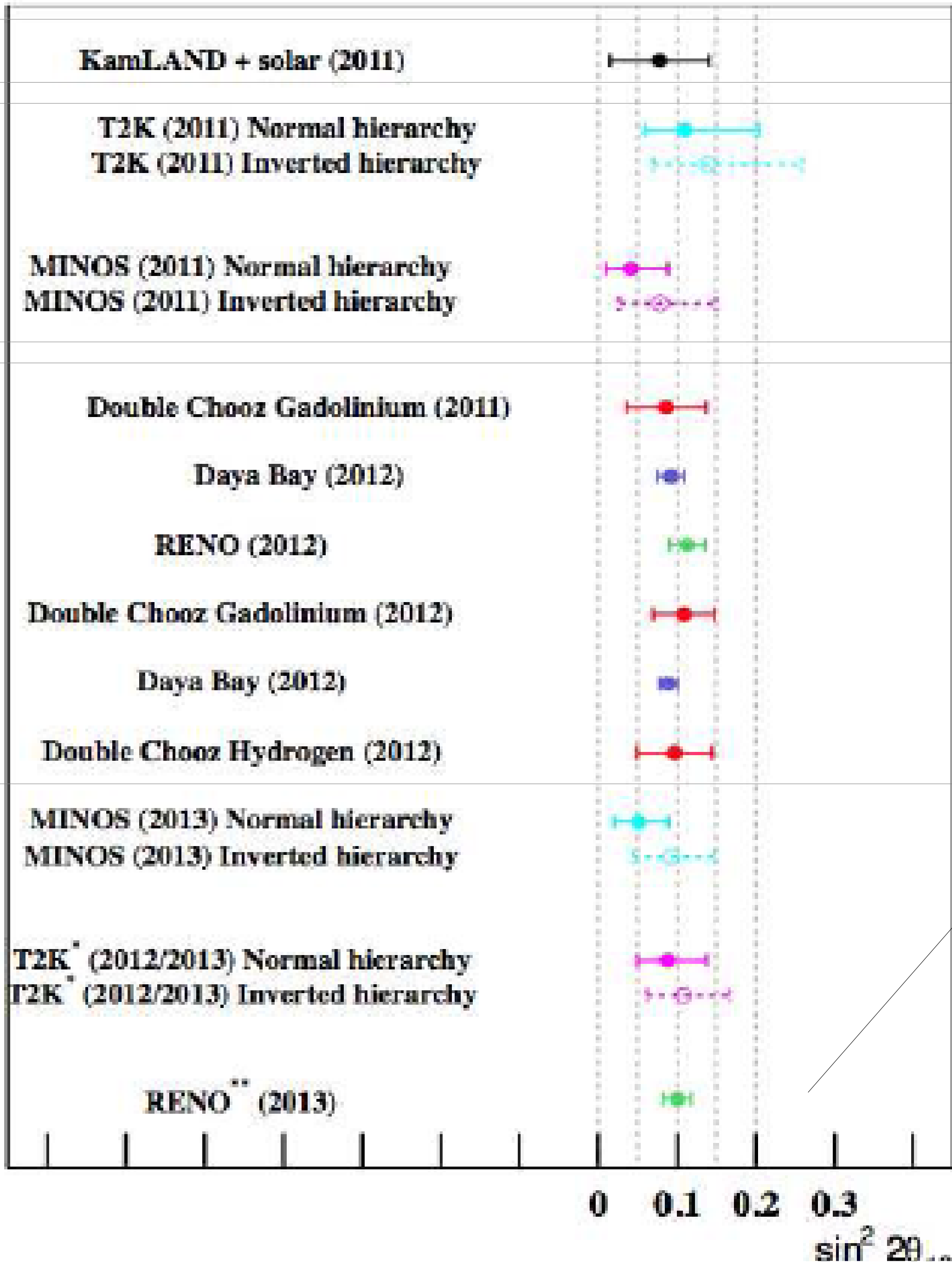
Main backgrounds:
π^0 in NC events



νe in original beam
(from K decays)

28 events seen for
4.92 +– 0.55 in MC

The smallest angle consistency



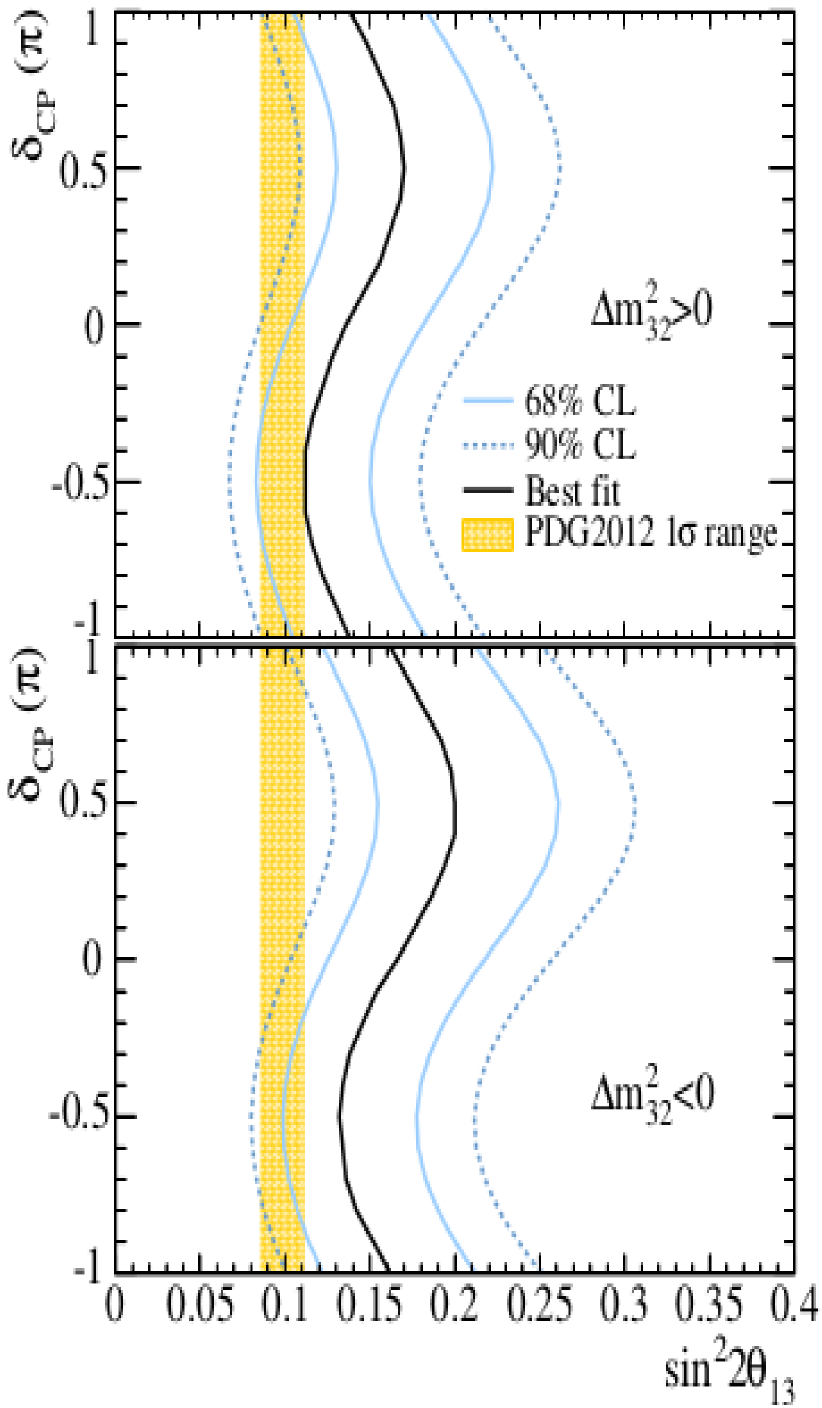
Compatibility

νμ -> νe appearance

Reactor anti-nu-e disappearance

Improve sensitivity to hierarchy (depends also on δCP)

2nd Order Neutrino Oscillation Measurements



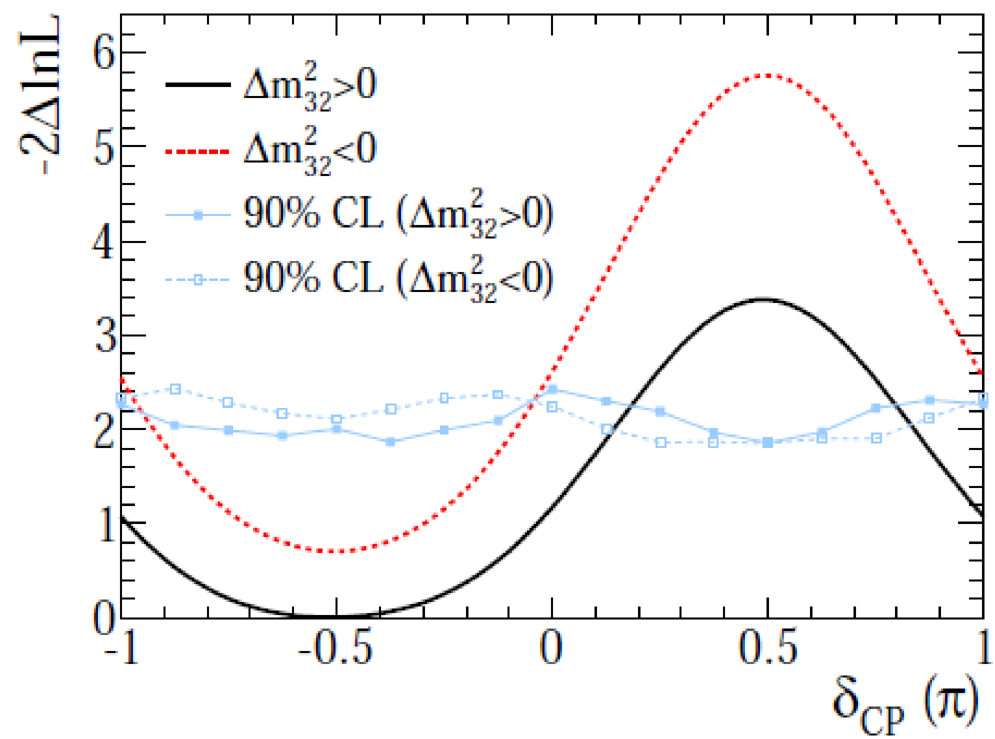
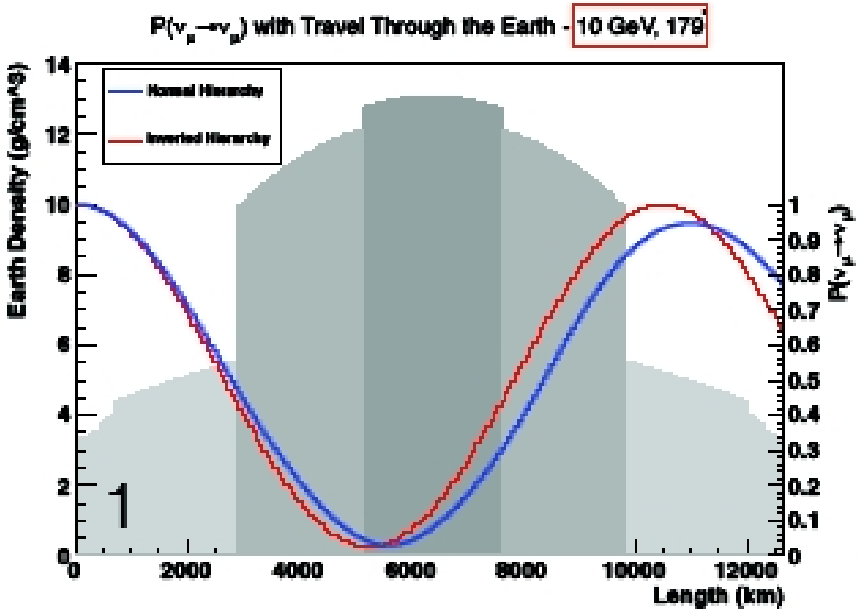
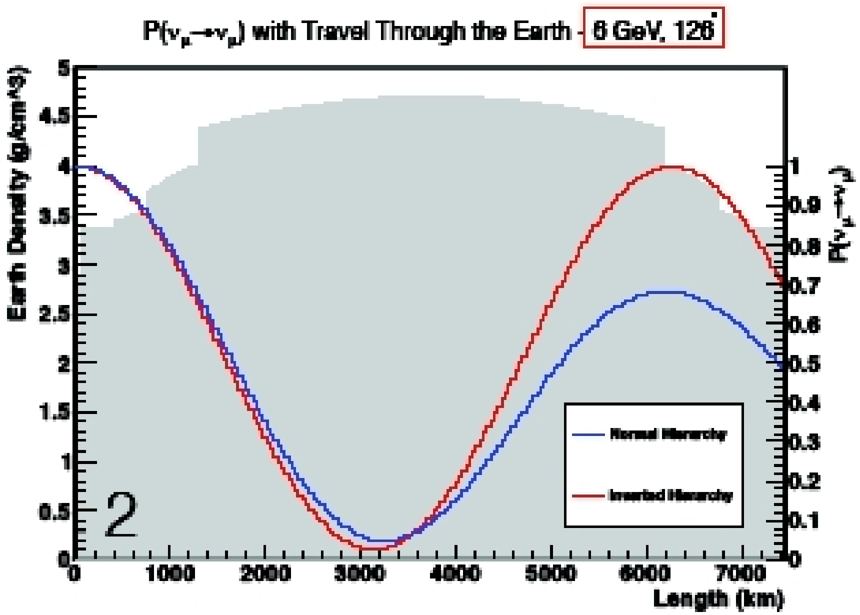
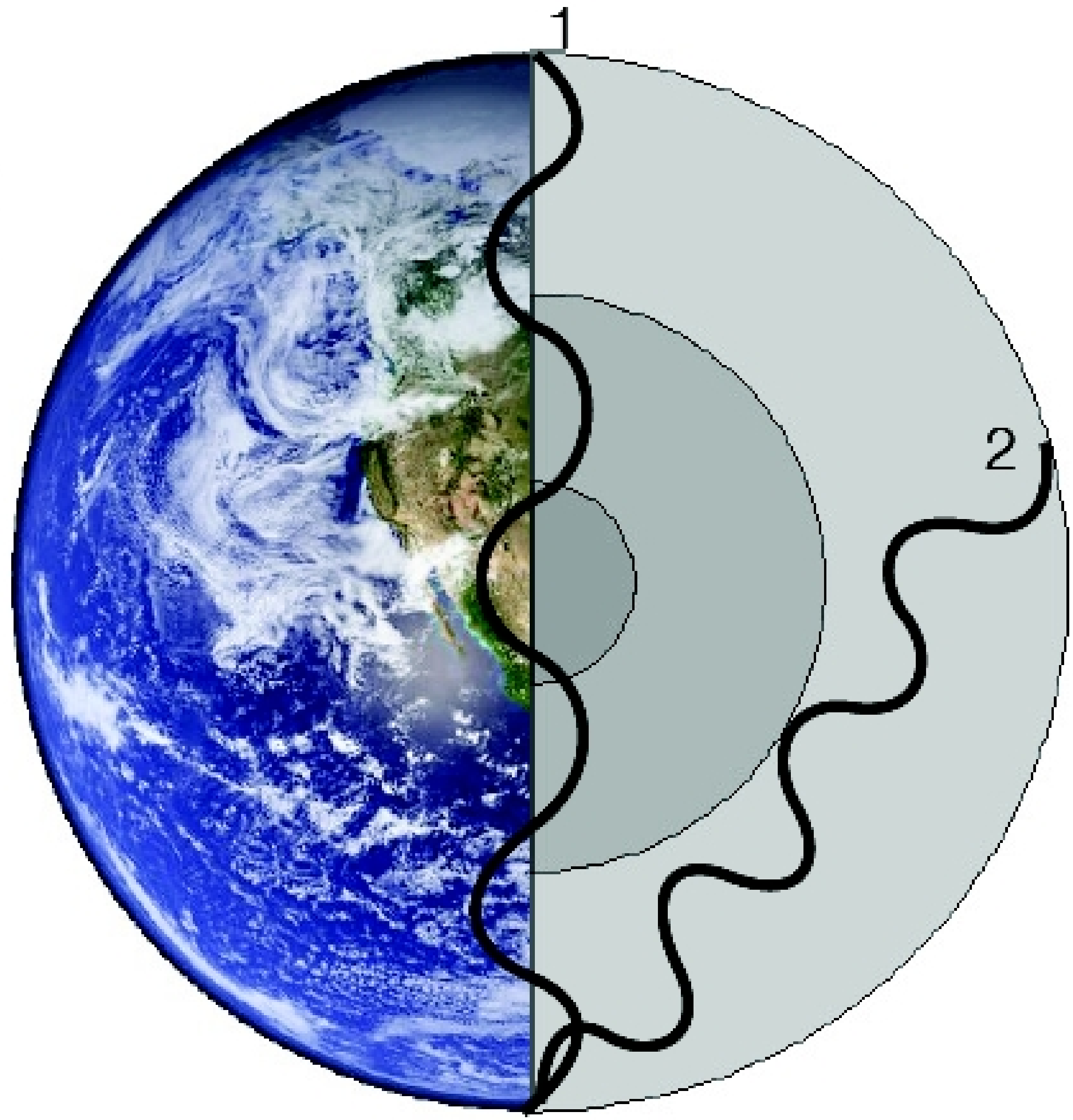


FIG. 6. The $-2\Delta \ln \mathcal{L}$ value as a function of δ_{CP} for normal hierarchy (solid line) and inverted hierarchy (dotted line). The likelihood is marginalized over $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$ and Δm^2_{32}. The solid (dotted) line with markers corresponds to the 90% CL limits for normal (inverted) hierarchy, evaluated by using the Feldman-Cousins method. The δ_{CP} regions with values above the lines are excluded at 90% CL.

Natural sources still useful for neutrino precision?







may need Earth matter effects (>> distance / fluxes) for hierarchy

Neutrino Oscillations: Present Status and Future

Description of neutrinos must be changed from Standard Model

Mass is as fundamental as flavor, mixing seems non trivial

Almost all neutrino oscillation parameters are measured

Can use them to study natural sources (Sun, Earth, SN, etc...)

Need precision in mixing matrix to limit possible mass models

PMNS is strongly non–diagonal, all mixing angles are reasonably large

Need to measure still hierarchy and CP phase (leptogenesis...)

All experiments will contribute to 2^{nd} order oscillation analyses

From now on all analyses must be done using the full matrix