Kern- und Teilchenphysik II
Lecture 4: Neutrino Oscillations

(adapted from the Handout of Prof. Mark Thomson)

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http://www.physik.uzh.ch/de/lehre/PHY213/FS2017.html

★ **The textbook neutrino states, ν_e, ν_μ, ν_τ, are not the fundamental particles; these are ν_1, ν_2, ν_3**

★ **Concepts like "electron number" conservation are now known not to hold.**

★ **So what are ν_e, ν_μ, ν_τ ?**

★ **Never directly observe neutrinos – can only detect them by their weak interactions. Hence by definition ν_e is the neutrino state produced along with an electron. Similarly, charged current weak interactions of the state ν_e produce an electron**

➡ ν_e, ν_μ, ν_τ **= weak eigenstates**

ν_e **?** ν_e **e⁻**

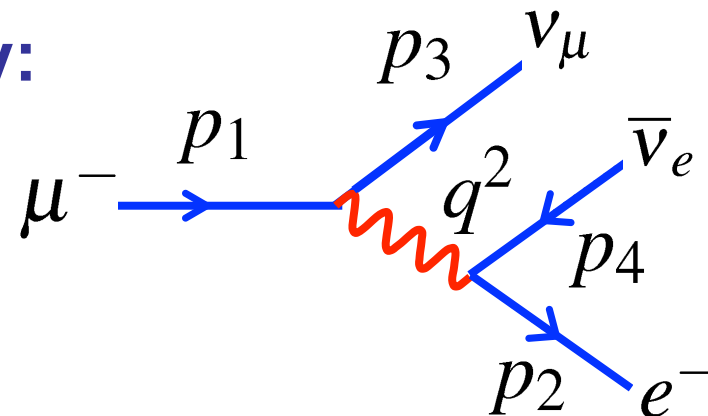**W**   **e⁺**   **W**

p   **n**   **n**   **p**
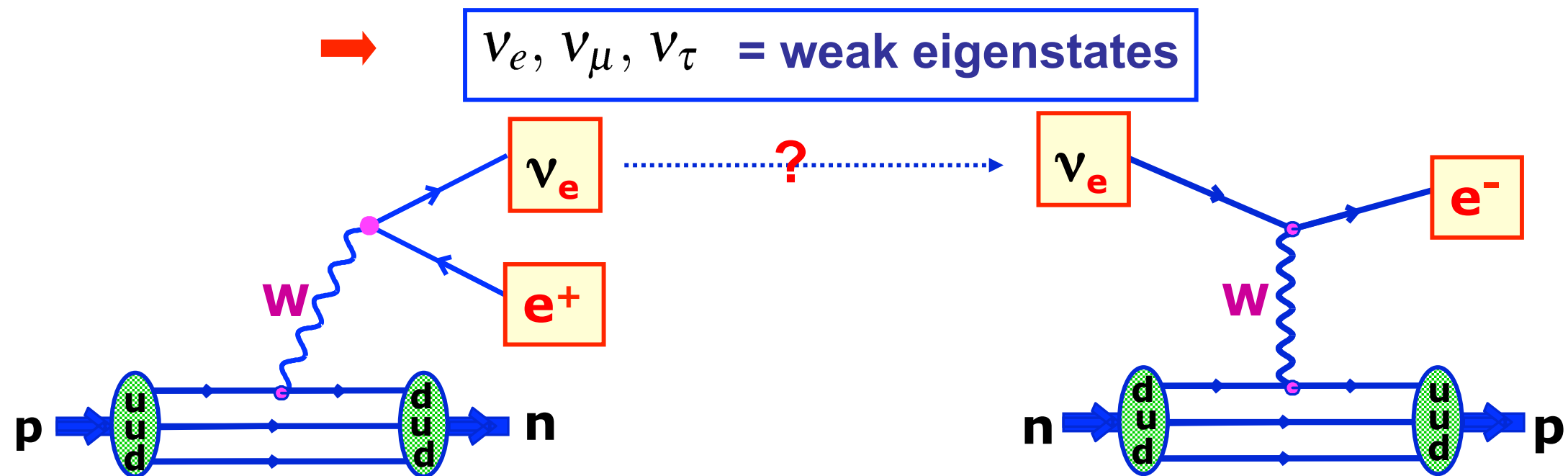
★ **Unless dealing with <u>very large</u> distances: the neutrino produced with a positron will interact to produce an electron. For the discussion of the weak interaction continue to use ν_e, ν_μ, ν_τ as if they were the fundamental particle states.**

Lepton Universality

★**The leptonic charged current (W$^{\pm}$) interaction vertices are:**
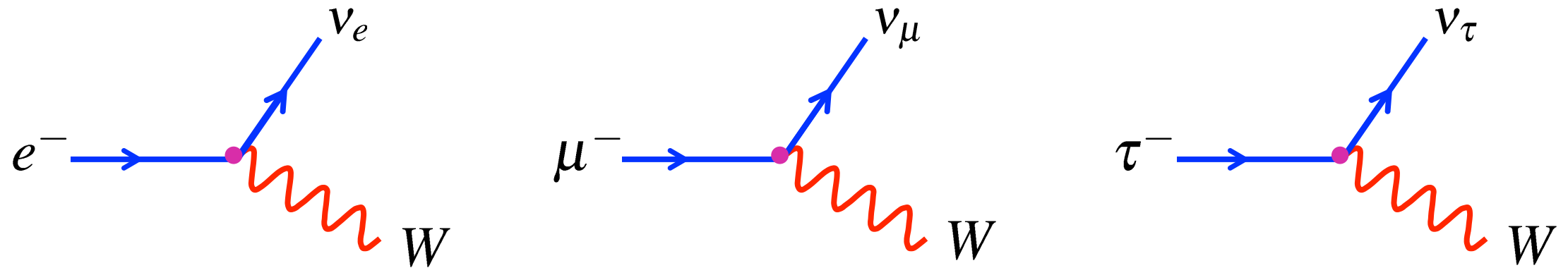
★**Consider muon decay:**

•**It is straight-forward to write down the matrix element**

$$M_{fi} = \frac{g_W^{(e)} g_W^{(\mu)}}{8m_W^2} [\bar{u}(p_3)\gamma^\mu(1-\gamma^5)u(p_1)]g_{\mu\nu}[\bar{u}(p_2)\gamma^\nu(1-\gamma^5)v(p_4)]$$

Note: **for lepton decay** $q^2 \ll m_W^2$ **so propagator is a constant** $1/m_W^2$
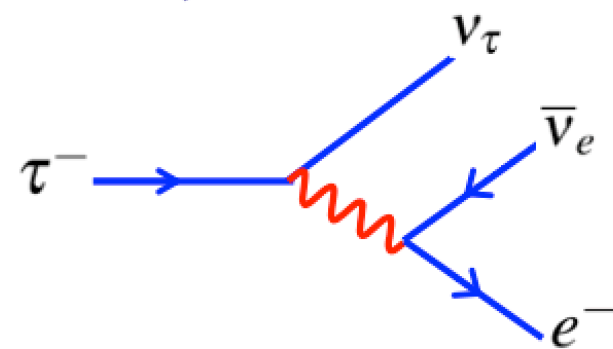**i.e. in limit of Fermi theory**

•**Its evaluation and subsequent treatment of a three-body decay is rather tricky (and not particularly interesting). Here will simply quote the result**
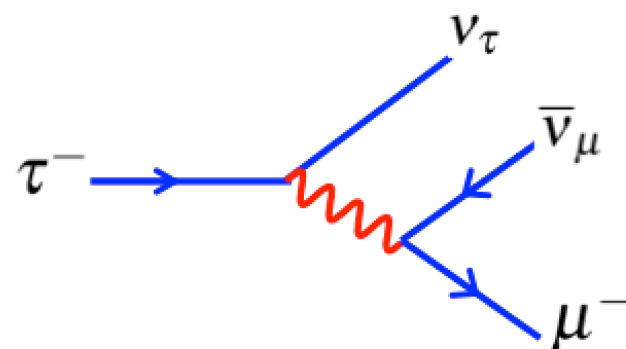
Lepton Universality

- **The muon to electron rate**

$$\Gamma(\mu \to e\nu\nu) = \frac{G_F^e G_F^\mu m_\mu^5}{192\pi^3} = \frac{1}{\tau_\mu} \quad \text{with} \quad G_F = \frac{g_W^2}{4\sqrt{2}m_W^2}$$

- **Similarly for tau to electron**

$$\Gamma(\tau \to e\nu\nu) = \frac{G_F^e G_F^\tau m_\tau^5}{192\pi^3}$$

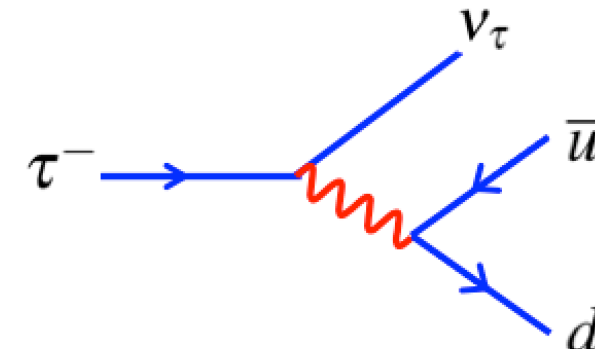- **However, the tau can decay to a number of final states:**

$$Br(\tau \to e\nu\nu) = 0.1784(5) \qquad Br(\tau \to \mu\nu\nu) = 0.1736(5)$$

- **Recall total width (total transition rate) is the sum of the partial widths**

$$\Gamma = \sum_i \Gamma_i = \frac{1}{\tau}$$

- **Can relate partial decay width to total decay width and therefore lifetime:**

$$\Gamma(\tau \to e\nu\nu) = \Gamma_\tau Br(\tau \to e\nu\nu) = Br(\tau \to e\nu\nu)/\tau_\tau$$

- **Therefore predict**

$$\tau_\mu = \frac{192\pi^3}{G_F^e G_F^\mu m_\mu^5} \qquad \tau_\tau = \frac{192\pi^3}{G_F^e G_F^\tau m_\tau^5} Br(\tau \to e\nu\nu)$$

Lepton Universality

- **All these quantities are precisely measured:**

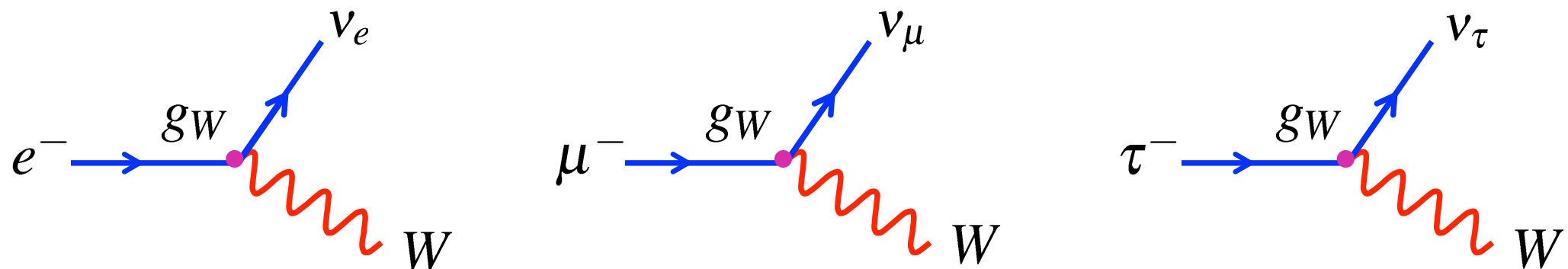$$m_\mu = 0.1056583692(94)\,\text{GeV} \qquad \tau_\mu = 2.19703(4) \times 10^{-6}\,\text{s}$$

$$m_\tau = 1.77699(28)\,\text{GeV} \qquad \tau_\tau = 0.2906(10) \times 10^{-12}\,\text{s}$$

$$Br(\tau \to e\nu\nu) = 0.1784(5)$$

$$\boxed{\frac{G_F^\tau}{G_F^\mu} = \frac{m_\mu^5 \tau_\mu}{m_\tau^5 \tau_\tau} Br(\tau \to e\nu\nu) = 1.0024 \pm 0.0033}$$

- **Similarly by comparing** $Br(\tau \to e\nu\nu)$ **and** $Br(\tau \to \mu\nu\nu)$

$$\boxed{\frac{G_F^e}{G_F^\mu} = 1.000 \pm 0.004}$$

★ **Demonstrates the weak charged current is the same for all leptonic vertices**


Charged Current Lepton Universality

Neutrino Deep Inelastic Scattering

- **Let's consider the weak interaction equivalent:** **Neutrino Deep Inelastic Scattering** **where a virtual W-boson probes the structure of nucleons**

  ➡ **additional information about parton structure functions**

 **+ provides a good example of calculations of weak interaction cross sections.**

★ **Neutrino Beams:**

- **Smash high energy protons into a fixed target** ➡ **hadrons**
- **Focus positive pions/kaons**
- **Allow them to decay** $\pi^+ \rightarrow \mu^+ \nu_\mu$ **+** $K^+ \rightarrow \mu^+ \nu_\mu \; (BR \approx 64\%)$
- **Gives a beam of "collimated"** ν_μ
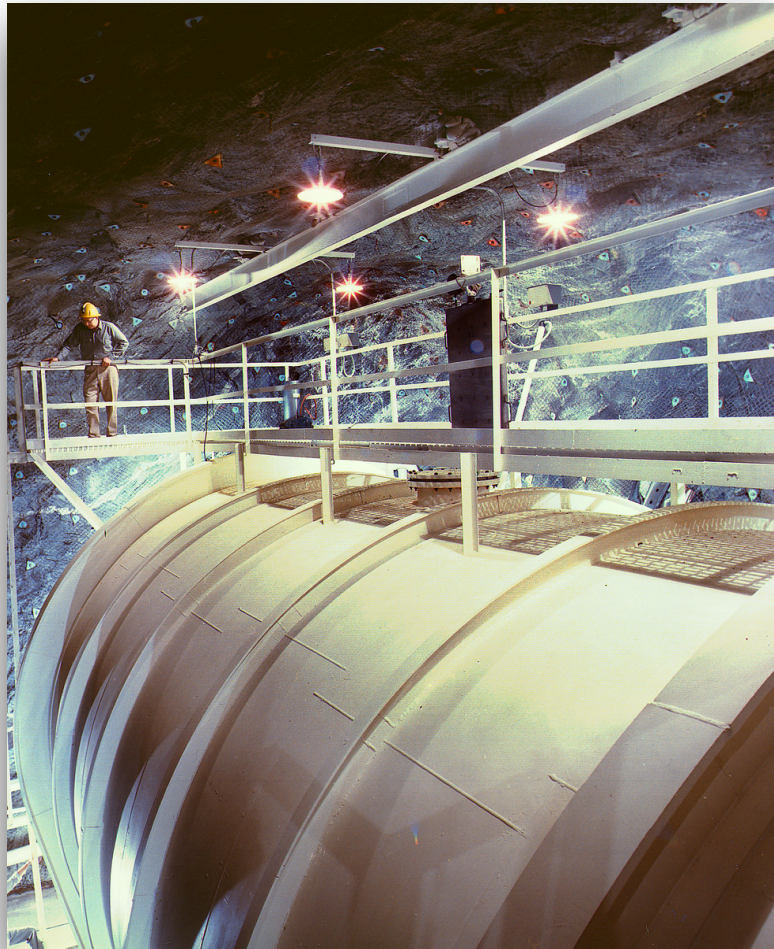- **Focus negative pions/kaons to give beam of** $\overline{\nu}_\mu$
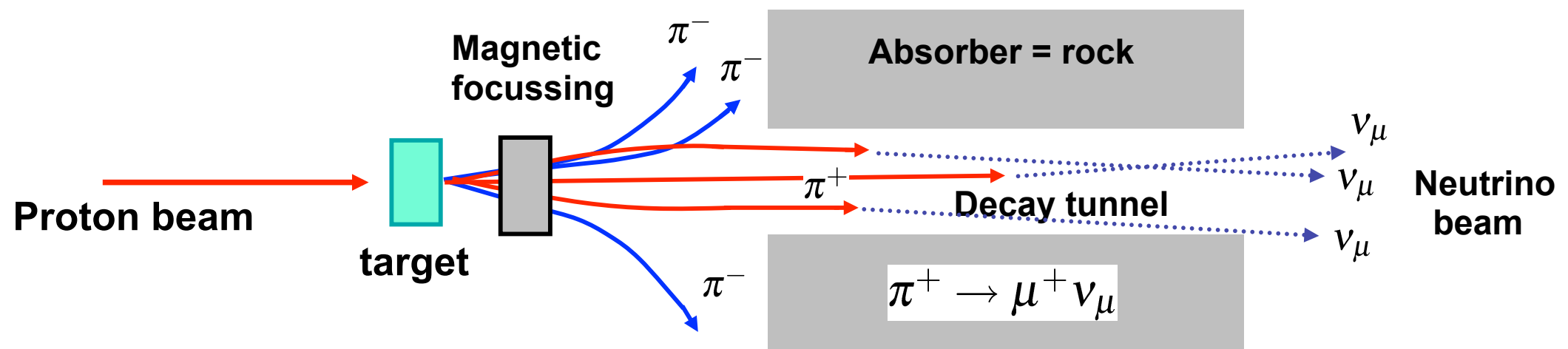
Neutrino Flavour

- There are three neutrino flavours

- We can distinguish them because neutrinos that are produced associated with muons only produce anti-muons in charged currents interactions (same thing for electrons and taus)

- This is another aspect of Lepton Flavour Conservation

$$\pi^- \rightarrow \mu^- \overline{\nu}_\mu$$

μ^-

μ^+

$\overline{\nu}_\mu$

W^-

p

n
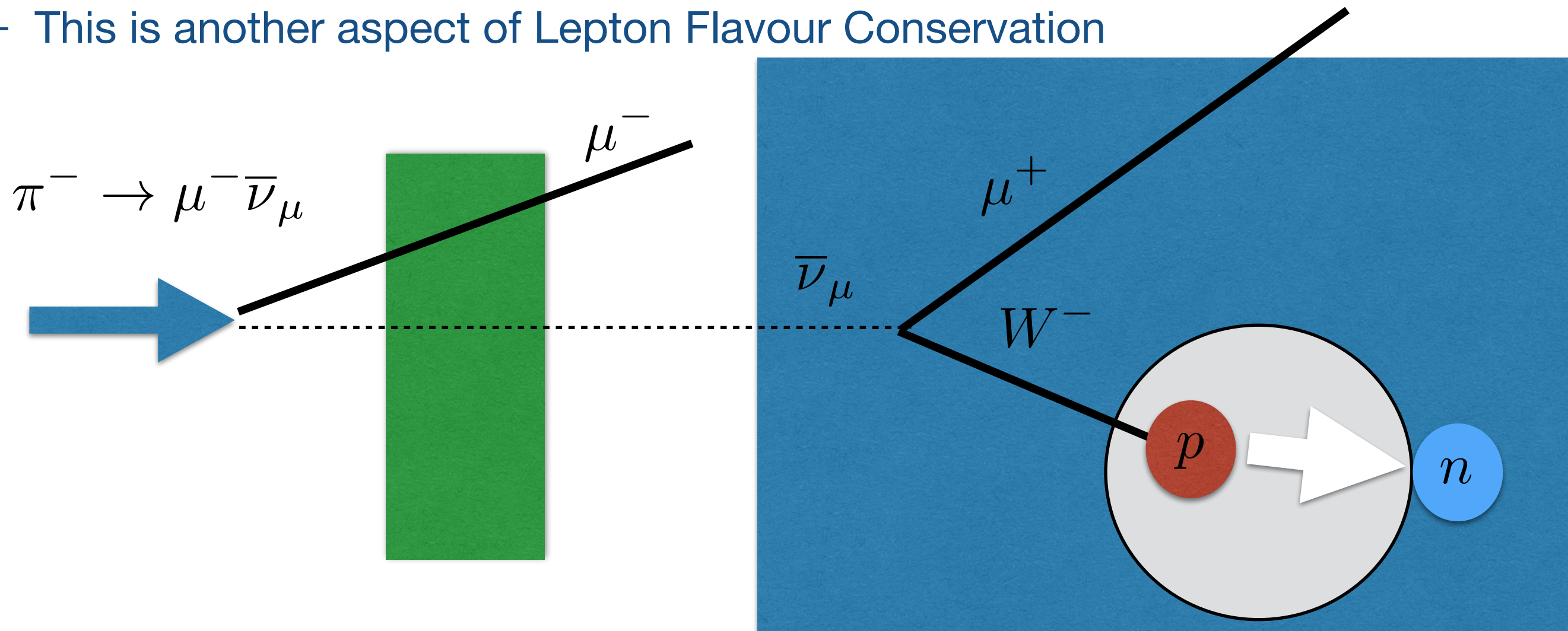
Solar Neutrino Problem

1970s Homestake experiment:
Solar neutrino problem

Reaction	Abbr.	Flux (cm^{-2} s^{-1})
$pp \to d\,e^+\,\nu$	pp	$5.97(1 \pm 0.006) \times 10^{10}$
$pe^-p \to d\,\nu$	pep	$1.41(1 \pm 0.011) \times 10^{8}$
$^3\mathrm{He}\,p \to {}^4\mathrm{He}\,e^+\nu$	hep	$7.90(1 \pm 0.15) \times 10^{3}$
$^7\mathrm{Be}\,e^- \to {}^7\mathrm{Li}\,\nu + (\gamma)$	$^7\mathrm{Be}$	$5.07(1 \pm 0.06) \times 10^{9}$
$^8\mathrm{B} \to {}^8\mathrm{Be}^*\,e^+\nu$	$^8\mathrm{B}$	$5.94(1 \pm 0.11) \times 10^{6}$
$^{13}\mathrm{N} \to {}^{13}\mathrm{C}\,e^+\nu$	$^{13}\mathrm{N}$	$2.88(1 \pm 0.15) \times 10^{8}$
$^{15}\mathrm{O} \to {}^{15}\mathrm{N}\,e^+\nu$	$^{15}\mathrm{O}$	$2.15(1^{+0.17}_{-0.16}) \times 10^{8}$
$^{17}\mathrm{F} \to {}^{17}\mathrm{O}\,e^+\nu$	$^{17}\mathrm{F}$	$5.82(1^{+0.19}_{-0.17}) \times 10^{6}$

Measured neutrino flux

Detector based on the reaction

$$\nu_e + {}^{37}\mathrm{Cl} \mapsto {}^{37}\mathrm{Ar} + e^-$$

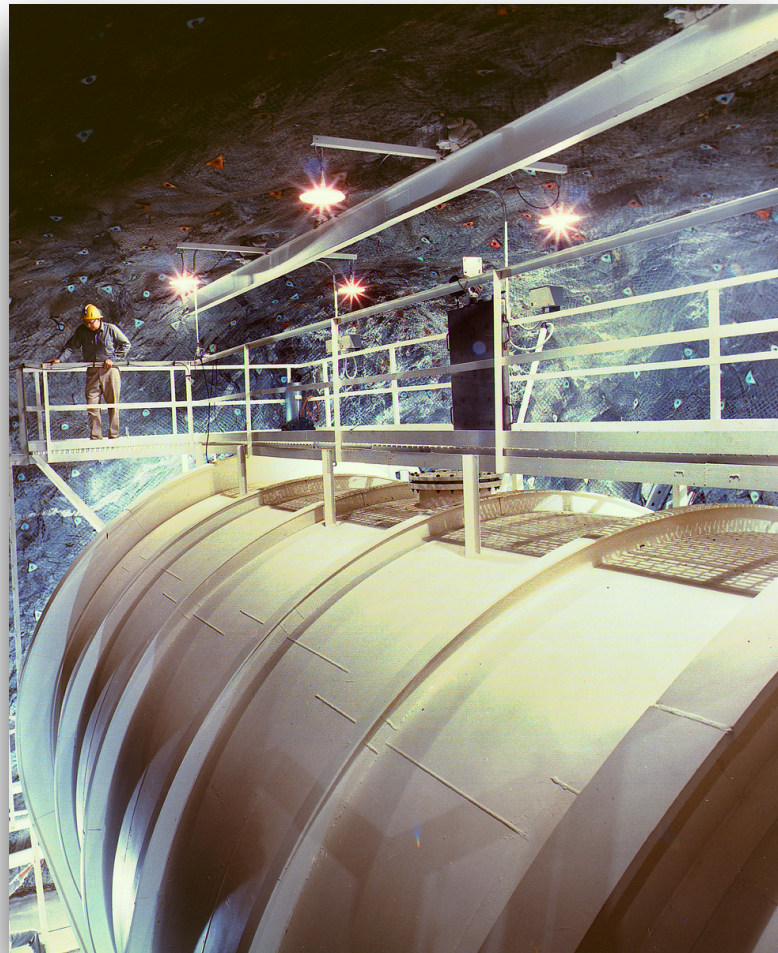| measured flux	ratio exp/BP98
2.56 ± 0.16 ± 0.16	0.33 ± 0.03 ± 0.05

Experiment sensitive to electron neutrinos!

Solar Neutrino Problem

1970s Homestake experiment:
Solar neutrino problem

Measured neutrino flux

measured flux	ratio exp/BP98
2.56 ± 0.16 ± 0.16	0.33 ± 0.03 ± 0.05

Hypothesis:
- Neutrinos have a mass and oscillate (like neutral mesons)
- Since the experiment sensitive to electron neutrinos, the missing neutrinos have oscillated to another specie

$$\nu_e \rightarrow \nu_\mu \qquad \nu_e \rightarrow \nu_\tau$$

Solar Neutrino Problem

This observation was confirmed by several experiments

Experiment	measured flux	ratio exp/BP98	threshold energy	Years of running
Homestake	$2.56 \pm 0.16 \pm 0.16$	$0.33 \pm 0.03 \pm 0.05$	0.814 MeV	1970-1995
Kamiokande	$2.80 \pm 0.19 \pm 0.33$	$0.54 \pm 0.08\ ^{+0.10}_{-0.07}$	7.5 MeV	1986-1995
SAGE	$75 \pm 7 \pm 3$	$0.58 \pm 0.06 \pm 0.03$	0.233 MeV	1990-2006
Gallex	$78 \pm 6 \pm 5$	$0.60 \pm 0.06 \pm 0.04$	0.233 MeV	1991-1996
Super-Kamiokande	$2.35 \pm 0.02 \pm 0.08$	$0.465 \pm 0.005\ ^{+0.016}_{-0.015}$ (BP00)	5.5 (6.5) MeV	1996-
GNO	$66 \pm 10 \pm 3$	$0.51 \pm 0.08 \pm 0.03$	0.233 MeV	1998-
SNO	$1.68 \pm 0.06 \pm\ ^{+0.08}_{-0.09}$ (CC) $2.35 \pm 0.22 \pm 0.15$ (ES) $4.94 \pm 0.21\ ^{+0.38}_{-0.34}$ (NC)		6.75 MeV	1999-

In addition to solar neutrino problem, neutrino disappearance has been observed in atmospheric neutrinos and nuclear reactors

Solar Neutrino Problem

- **Neutrinos have a mass and, like in the quark sector, eigenstate of flavour are not eigenstate of mass**

- **Therefore neutrinos oscillate from one flavour to the other**

- **This is now confirmed and therefore we know the SM with massless neutrinos is not correct**

- **There are various ways to add neutrino masses (not part of the program)**

Mass and Flavour Eigenstates

$|\nu_\alpha\rangle$
    Flavour Eigenstate
$|\nu_1\rangle$
    Mass Eigenstate
$|\nu_\beta\rangle$
$|\nu_2\rangle$

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Rotation (Unitary Matrix) that relates Flavour to mass eigenstates

$$\begin{pmatrix} \nu_1 \\ \nu_1 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix}$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Let's start from the flavour $|\nu_\alpha\rangle$ at time t=0, after a time t we have

$$
\begin{aligned}
|\nu(t)\rangle &= \cos\theta e^{-iE_1 t}|\nu_1\rangle - \sin\theta e^{-iE_2 t}|\nu_2\rangle \\
&= \cos\theta e^{-iE_1 t}\left(\cos\theta|\nu_\alpha\rangle - \sin\theta|\nu_\beta\rangle\right) + \sin\theta e^{-iE_2 t}\left(\sin\theta|\nu_\alpha\rangle + \cos\theta|\nu_\beta\rangle\right) \\
&= \left(\cos^2\theta e^{-iE_1 t} + \sin^2\theta e^{-iE_2 t}\right)|\nu_\alpha\rangle + \sin\theta\cos\theta\left(e^{-iE_2 t} - e^{-iE_1 t}\right)|\nu_\beta\rangle
\end{aligned}
$$

If $m_1 = m_2$, for the free particle means $E_1 = E_2$ we have $|\nu(t)\rangle = |\nu_\alpha\rangle$

If $m_1 \neq m_2$ we have $\quad \langle\nu_\beta|\nu(t)\rangle = \sin\theta\cos\theta\left(e^{-iE_2 t} - e^{-iE_1 t}\right)$

$$
\left(e^{-iE_2 t} - e^{-iE_1 t}\right) = e^{-iE_0 t}\left(e^{-i\frac{\Delta E}{2}t} - e^{i\frac{\Delta E}{2}t}\right)
$$

for $E_{1,2} \gg m_{1,2}$ we have $E_1 = \sqrt{p^2 + m_1^2} \simeq p + \frac{m_1^2}{2p}$

Remember that these are not eigenstate of mass, so not eigenstates of energy, but eigenstates of momentum (free particle)

and $E_2 - E_1 \simeq \frac{m_2^2 - m_1^2}{2p} \simeq \frac{\Delta m^2}{2E}$

Since neutrinos are almost massless, they go almost at the speed of light, i.e. $L \simeq ct$

$$\langle \nu_\beta | \nu(t) \rangle \simeq 2 e^{-iE_0 t} \sin\theta \cos\theta \left(\sin\left(\frac{\Delta m^2}{4E} L \right) \right)$$

We can compute the transition probability from flavour $|\nu_\alpha\rangle$ to flavour $|\nu_\beta\rangle$

$$\mathcal{P}(\alpha \to \beta; t) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L \right)$$

Mass and Flavour Eigenstates

★ **Hence the two-flavour oscillation probability is:**

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

with $\Delta m_{21}^2 = m_2^2 - m_1^2$

★ **The corresponding two-flavour survival probability is:**

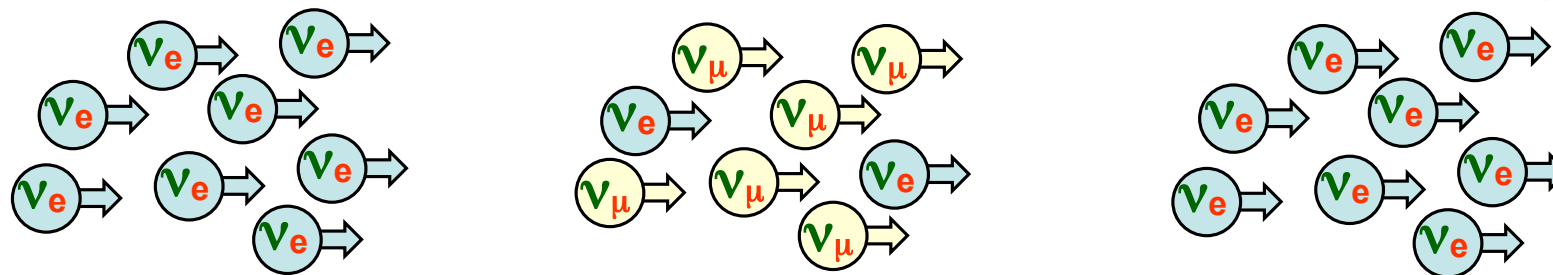$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

•**e.g.** $\quad \Delta m^2 = 0.003\,\mathrm{eV}^2, \qquad \sin^2 2\theta = 0.8, \qquad E_\nu = 1\,\mathrm{GeV}$
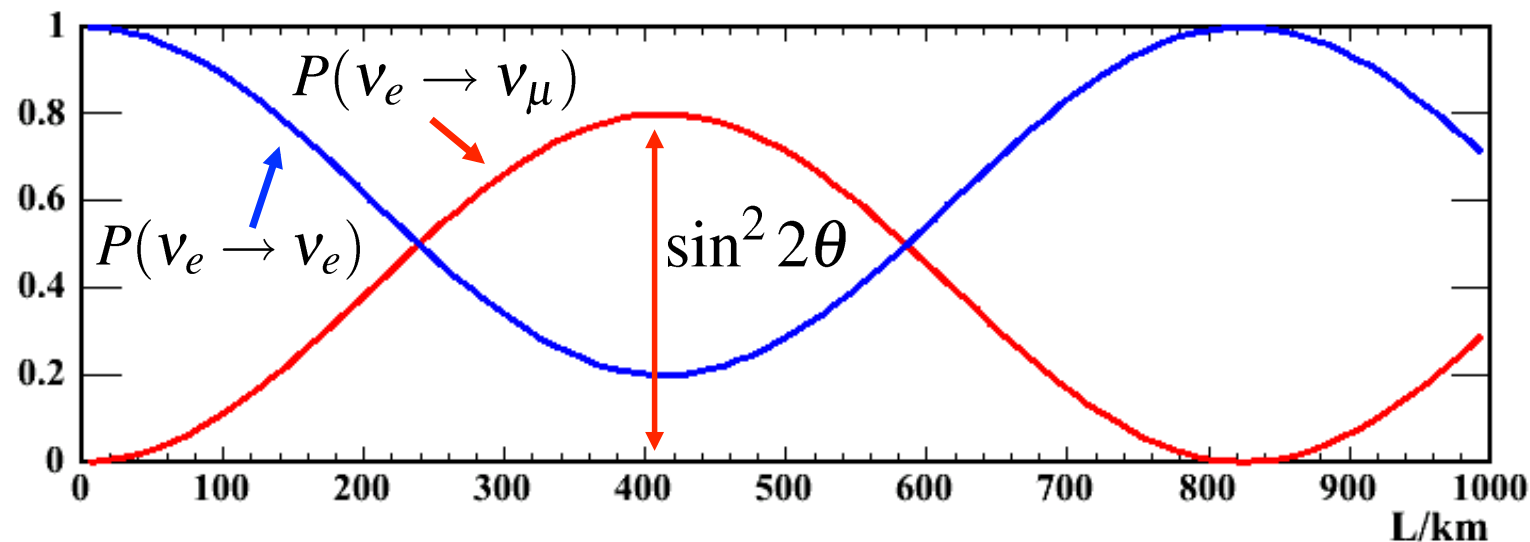
•**wavelength**

$$\lambda_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2}$$

Mass and Flavour Eigenstates

★ **It is simple to extend this treatment to three generations of neutrinos.**
★ **In this case we have:**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$
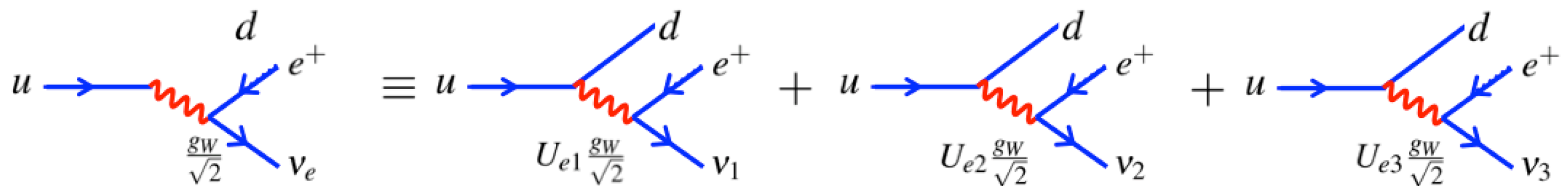
★ **The 3x3 Unitary matrix** U **is known as the Pontecorvo-Maki-Nakagawa-Sakata matrix, usually abbreviated PMNS**

★ **Note : has to be unitary to conserve probability**

•**Using** $\qquad U^\dagger U = I \qquad \Rightarrow \qquad U^{-1} = U^\dagger = (U^*)^T$

gives $\qquad \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{\mu1}^* & U_{\tau1}^* \\ U_{e2}^* & U_{\mu2}^* & U_{\tau2}^* \\ U_{e3}^* & U_{\mu3}^* & U_{\tau3}^* \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$

Mass and Flavour Eigenstates

- **Before we had**

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right)$$

with $\boxed{\Delta m_{21}^2 = m_2^2 - m_1^2}$

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right)$$

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

- **This can be written as**

$$P(\nu_e \rightarrow \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2 \Delta_{21}$$

$$\Delta_{21} = \frac{(m_2^2 - m_1^2)L}{4E} = \frac{\Delta m_{21}^2 L}{4E}$$

- **This can be generalized to the 3 flavours as**

$$P(\nu_e \rightarrow \nu_e) = 1 - 4|U_{e1}|^2|U_{e2}|^2 \sin^2 \Delta_{21} - 4|U_{e1}|^2|U_{e3}|^2 \sin^2 \Delta_{31} - 4|U_{e2}|^2|U_{e3}|^2 \sin^2 \Delta_{32}$$

★ **Note that since we only have three neutrino generations there are only two independent mass-squared differences, i.e.**

$$m_3^2 - m_1^2 = (m_3^2 - m_2^2) + (m_2^2 - m_1^2)$$

Mass and Flavour Eigenstates

- **The representation of neutrino oscillation is the following**

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) &= |\langle \nu_\mu | \psi(L) \rangle|^2 \\
&= |U_{e1}U_{\mu1}^* e^{-i\phi_1} + U_{e2}U_{\mu2}^* e^{-i\phi_2} + U_{e3}U_{\mu3}^* e^{-i\phi_3}|^2
\end{aligned}
$$
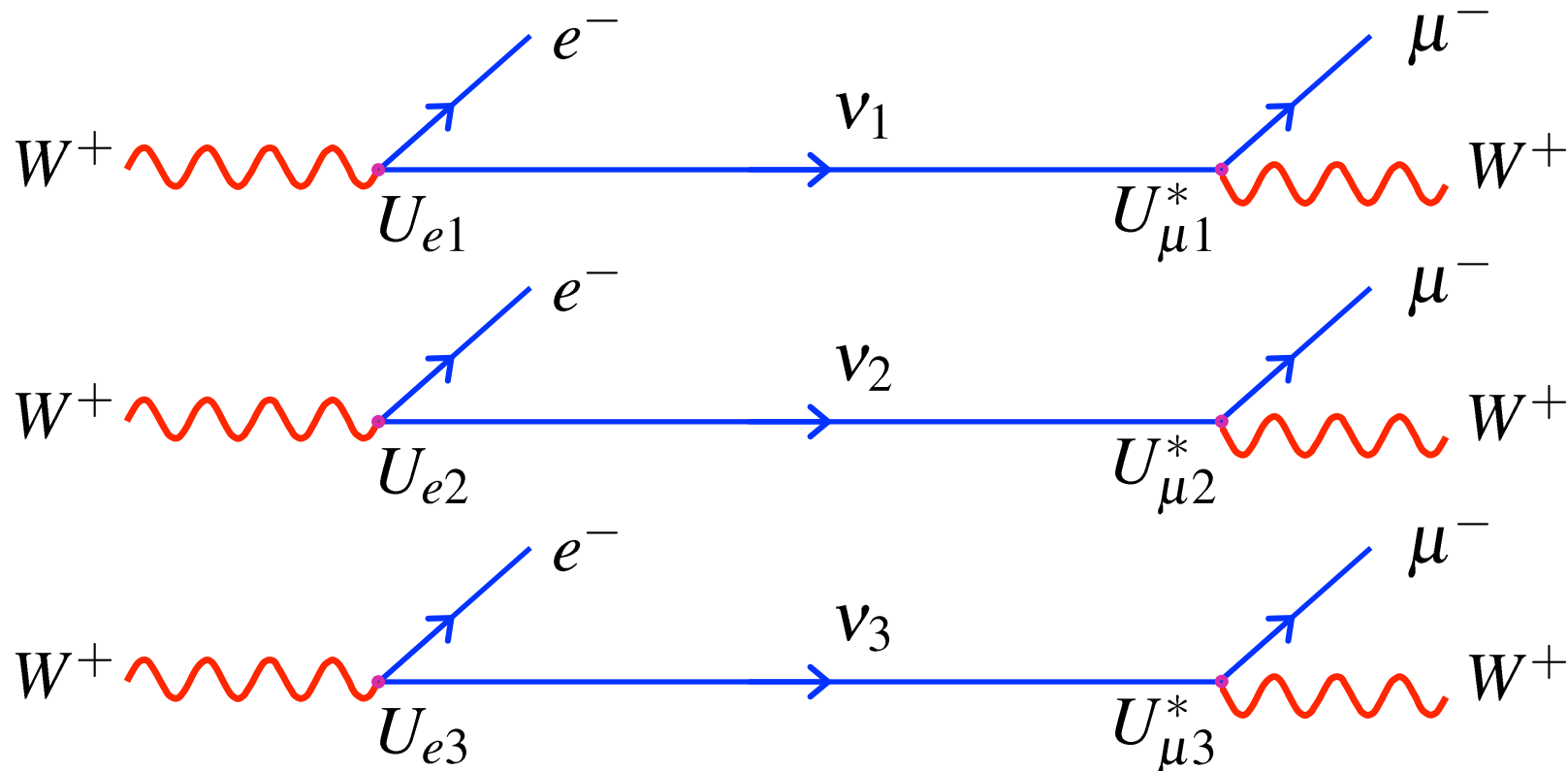
★**As before the oscillation depend on the difference in mass of the eigenstates**

★**All expressions are in Natural Units, conversion to more useful units here gives:**

$$
\Delta_{21} = 1.27 \frac{\Delta m_{21}^2 (\text{eV}^2) L(\text{km})}{E(\text{GeV})}
$$

and

$$
\lambda_{\text{osc}}(\text{km}) = 2.47 \frac{E(\text{GeV})}{\Delta m^2(\text{eV}^2)}
$$

Mass and Flavour Eigenstates

★ **The Unitarity of the PMNS matrix gives several useful relations:** $UU^{\dagger} = I$

The number of free parameters are three real angles and a complex phase

• **It can be shown that the oscillation probability for $\nu_e \to \nu_\mu$ is**

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \quad = \quad & 2\Re\{U_{e1}U_{\mu 1}^* U_{e2}^* U_{\mu 2}[e^{-i(\phi_1 - \phi_2)} - 1]\} \\
+ \quad & 2\Re\{U_{e1}U_{\mu 1}^* U_{e3}^* U_{\mu 3}[e^{-i(\phi_1 - \phi_3)} - 1]\} \\
+ \quad & 2\Re\{U_{e2}U_{\mu 2}^* U_{e3}^* U_{\mu 3}[e^{-i(\phi_2 - \phi_3)} - 1]\}
\end{aligned}
$$

• **The oscillation probability for $\nu_\mu \to \nu_e$ can be obtained in the same manner or by simply exchanging the labels $(e) \leftrightarrow (\mu)$**

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad = \quad & 2\Re\{U_{\mu 1}U_{e1}^* U_{\mu 2}^* U_{e2}[e^{-i(\phi_1 - \phi_2)} - 1]\} \\
+ \quad & 2\Re\{U_{\mu 1}U_{e1}^* U_{\mu 3}^* U_{e3}[e^{-i(\phi_1 - \phi_3)} - 1]\} \\
+ \quad & 2\Re\{U_{\mu 2}U_{e2}^* U_{\mu 3}^* U_{e3}[e^{-i(\phi_2 - \phi_3)} - 1]\}
\end{aligned}
$$

★ **Unless the elements of the PMNS matrix are real**

$$P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$$

• **If any of the elements of the PMNS matrix are <u>complex</u>, neutrino oscillations are not invariant under time reversal $t \to -t$**

CP and CPT in the Weak Interaction

★ In addition to parity there are two other important discrete symmetries:

Parity $\hat{P}:$ $\vec{r} \rightarrow -\vec{r}$

Time Reversal $\hat{T}:$ $t \rightarrow -t$

Charge Conjugation $\hat{C}:$ Particle $\longleftrightarrow$ Anti-particle

★ The weak interaction violates parity conservation, but what about C ? Consider pion decay remembering that the neutrino is ultra-relativistic and only left-handed neutrinos and right-handed anti-neutrinos participate in WI

π^-

$\overline{\nu}_\mu$ μ^-

RH $\overline{\nu}$

$\hat{P}$

μ^- π^- $\overline{\nu}_\mu$

Not Allowed   LH $\overline{\nu}$

$\hat{C}$

$\hat{C}\hat{P}$

π^+

ν_μ μ^+

Not Allowed   RH ν

π^+

μ^+ ν_μ

LH ν
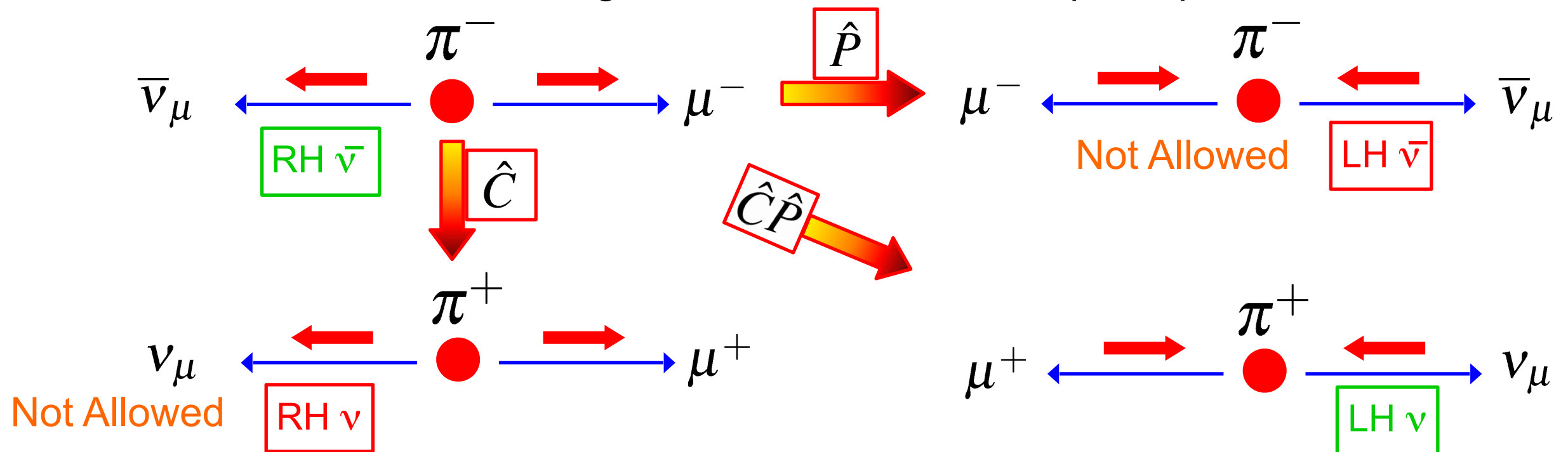
★ Hence weak interaction also violates charge conjugation symmetry but appears to be invariant under combined effect of C and P

CP transforms:

RH Particles ⟸⟹ LH Anti-particles

LH Particles ⟸⟹ RH Anti-particles

★ If the weak interaction were invariant under CP expect

$$\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu) = \Gamma(\pi^- \rightarrow \mu^- \overline{\nu}_\mu)$$

★ All Lorentz invariant Quantum Field Theories can be shown to be invariant under CPT (charge conjugation + parity + time reversal)

➡ Particles/anti-particles have identical mass, lifetime, magnetic moments,…

Best current experimental test: $m_{K^0} - m_{\overline{K}^0} < 6 \times 10^{-19} m_{K^0}$

★ Believe CPT has to hold:

     if CP invariance holds ➡ time reversal symmetry

     if CP is violated ➡ time reversal symmetry violated

★ To account for the small excess of matter over anti-matter that must have existed early in the universe require CP violation in particle physics !

★ CP violation can arise in the weak interaction

CP and T Violation in Neutrino Oscillations

- Previously derived the oscillation probability for $\nu_e \to \nu_\mu$

$$P(\nu_e \to \nu_\mu) = 2\Re\{U_{e1}U_{\mu1}^*U_{e2}^*U_{\mu2}[e^{-i(\phi_1-\phi_2)} - 1]\}$$

$$+ 2\Re\{U_{e1}U_{\mu1}^*U_{e3}^*U_{\mu3}[e^{-i(\phi_1-\phi_3)} - 1]\}$$

$$+ 2\Re\{U_{e2}U_{\mu2}^*U_{e3}^*U_{\mu3}[e^{-i(\phi_2-\phi_3)} - 1]\}$$

- The oscillation probability for $\nu_\mu \to \nu_e$ can be obtained in the same manner or by simply exchanging the labels $(e) \leftrightarrow (\mu)$

$$P(\nu_\mu \to \nu_e) = 2\Re\{U_{\mu1}U_{e1}^*U_{\mu2}^*U_{e2}[e^{-i(\phi_1-\phi_2)} - 1]\}$$

$$+ 2\Re\{U_{\mu1}U_{e1}^*U_{\mu3}^*U_{e3}[e^{-i(\phi_1-\phi_3)} - 1]\}$$

$$+ 2\Re\{U_{\mu2}U_{e2}^*U_{\mu3}^*U_{e3}[e^{-i(\phi_2-\phi_3)} - 1]\}$$

(8)

★ Unless the elements of the PMNS matrix are real (see note below)

$$P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$$

(9)

- If any of the elements of the PMNS matrix are complex, neutrino oscillations are not invariant under time reversal $t \to -t$

NOTE: can multiply entire PMNS matrix by a complex phase without changing the oscillation prob. T is violated if one of the elements has a different complex phase than the others

- Consider the effects of T, CP and CPT on neutrino oscillations

$\boxed{\text{T}}$ $\qquad \nu_e \to \nu_\mu \qquad \xrightarrow{\hat{T}} \qquad \nu_\mu \to \nu_e$

$\boxed{\text{CP}}$ $\qquad \nu_e \to \nu_\mu \qquad \xrightarrow{\hat{C}\hat{P}} \qquad \overline{\nu}_e \to \overline{\nu}_\mu$

$\boxed{\text{CPT}}$ $\qquad \nu_e \to \nu_\mu \qquad \xrightarrow{\hat{C}\hat{P}\hat{T}} \qquad \overline{\nu}_\mu \to \overline{\nu}_e$

Note C alone is not sufficient as it transforms LH neutrinos into LH anti-neutrinos (not involved in Weak Interaction)

- If the weak interactions is invariant under CPT

$$P(\nu_e \to \nu_\mu) = P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

and similarly $$P(\nu_\mu \to \nu_e) = P(\overline{\nu}_e \to \overline{\nu}_\mu) \qquad (10)$$

- If the PMNS matrix is not purely real, then (9)

$$P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$$

and from (10) $$\boxed{P(\nu_e \to \nu_\mu) \neq P(\overline{\nu}_e \to \overline{\nu}_\mu)}$$

★Hence unless the PMNS matrix is real, CP is violated in neutrino oscillations!

Future experiments, e.g. "a neutrino factory", are being considered as a way to investigate CP violation in neutrino oscillations. However, CP violating effects are well below the current experimental sensitivity. In the following discussion we will take the PMNS matrix to be real.

Mass and Flavour Eigenstates

★ **To date, results on neutrino oscillations only determine**

$$|\Delta m_{ji}^2| = |m_j^2 - m_i^2|$$

★ **Two distinct and very different mass scales:**

- **Atmospheric neutrino oscillations :** $\qquad |\Delta m^2|_{\text{atmos}} \sim 2.5 \times 10^{-3}\,\text{eV}^2$
- **Solar neutrino oscillations:** $\qquad |\Delta m^2|_{\text{solar}} \sim 8 \times 10^{-5}\,\text{eV}^2$

•**Two possible assignments of mass hierarchy:**
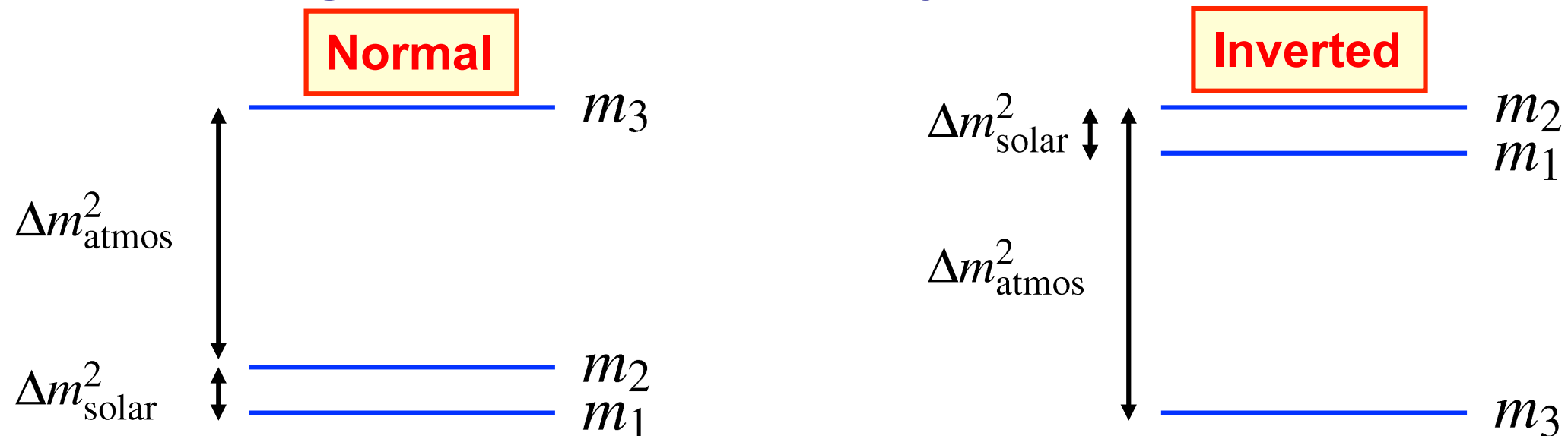
•**In both cases:** $\quad \Delta m_{21}^2 \sim 8 \times 10^{-5}\,\text{eV}^2 \qquad$ **(solar)**

$$|\Delta m_{31}^2| \approx |\Delta m_{32}^2| \sim 2.5 \times 10^{-3}\,\text{eV}^2 \qquad \textbf{(atmospheric)}$$

•**Hence we can approximate** $\quad \Delta m_{31}^2 \approx \Delta m_{32}^2$

★ **As for the quark matrix, the PMNS matrix has in principle one imaginary phase (not yet measured)**

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \approx \begin{pmatrix} 0.85 & 0.53 & 0.1e^{i\delta}? \\ -0.37 & 0.60 & 0.71 \\ 0.37 & -0.60 & 0.71 \end{pmatrix}$$

★ **Have approximate expressions for mass eigenstates in terms of weak eigenstates:**

$$|\nu_3\rangle \approx \frac{1}{\sqrt{2}}(|\nu_\mu\rangle + |\nu_\tau\rangle)$$

$$|\nu_2\rangle \approx 0.53|\nu_e\rangle + 0.60(|\nu_\mu\rangle - |\nu_\tau\rangle)$$

$$|\nu_1\rangle \approx 0.85|\nu_e\rangle - 0.37(|\nu_\mu\rangle - |\nu_\tau\rangle)$$

$$|\Delta m_{32}^2| \approx 2.5 \times 10^{-3}\,\text{eV}^2$$

$$|\Delta m_{21}^2| \approx 8 \times 10^{-5}\,\text{eV}^2$$
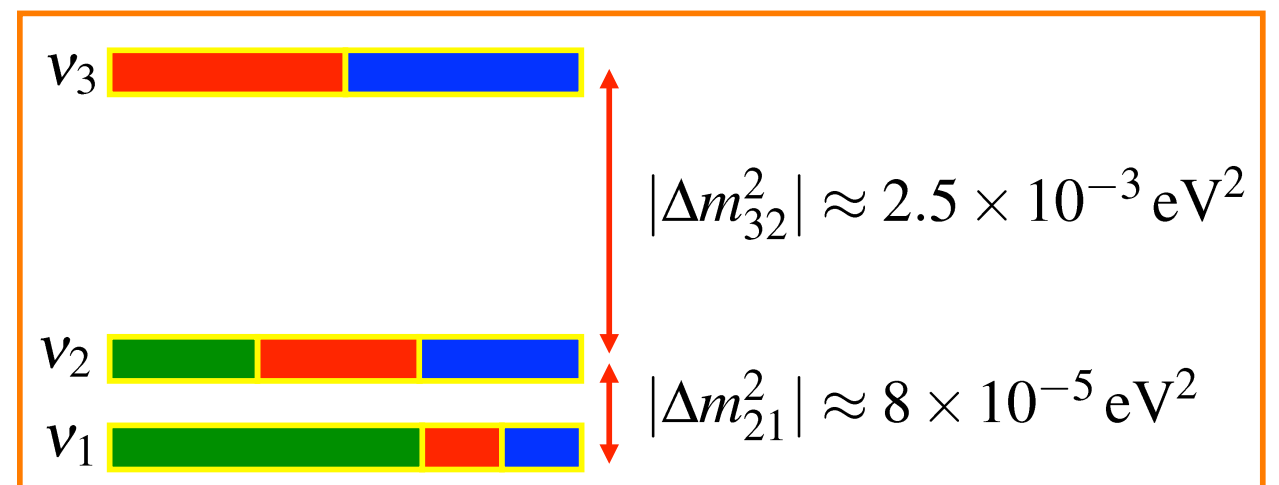
Mass and Flavour Eigenstates

- **Neutrino oscillations require non-zero neutrino masses (for at least 2 neutrinos)**
- **But only determine mass-squared differences – not the masses themselves**
- **No direct measure of neutrino mass – only mass limits:**

$$m_\nu(e) < 2\,\mathrm{eV}; \quad m_\nu(\mu) < 0.17\,\mathrm{MeV}; \quad m_\nu(\tau) < 18.2\,\mathrm{MeV}$$

Note the e, μ, τ **refer to charged lepton flavour in the experiment, e.g.**
$m_\nu(e) < 2\,\mathrm{eV}$ **refers to the limit from tritium beta-decay**

- **Also from cosmological evolution infer that the sum**

$$\sum_i m_{\nu_i} < \text{few eV}$$

★ **10 years ago – assumed massless neutrinos + hints that neutrinos might oscillate !**

★ **Now, know a great deal about massive neutrinos**

Mass and Flavour Eigenstates
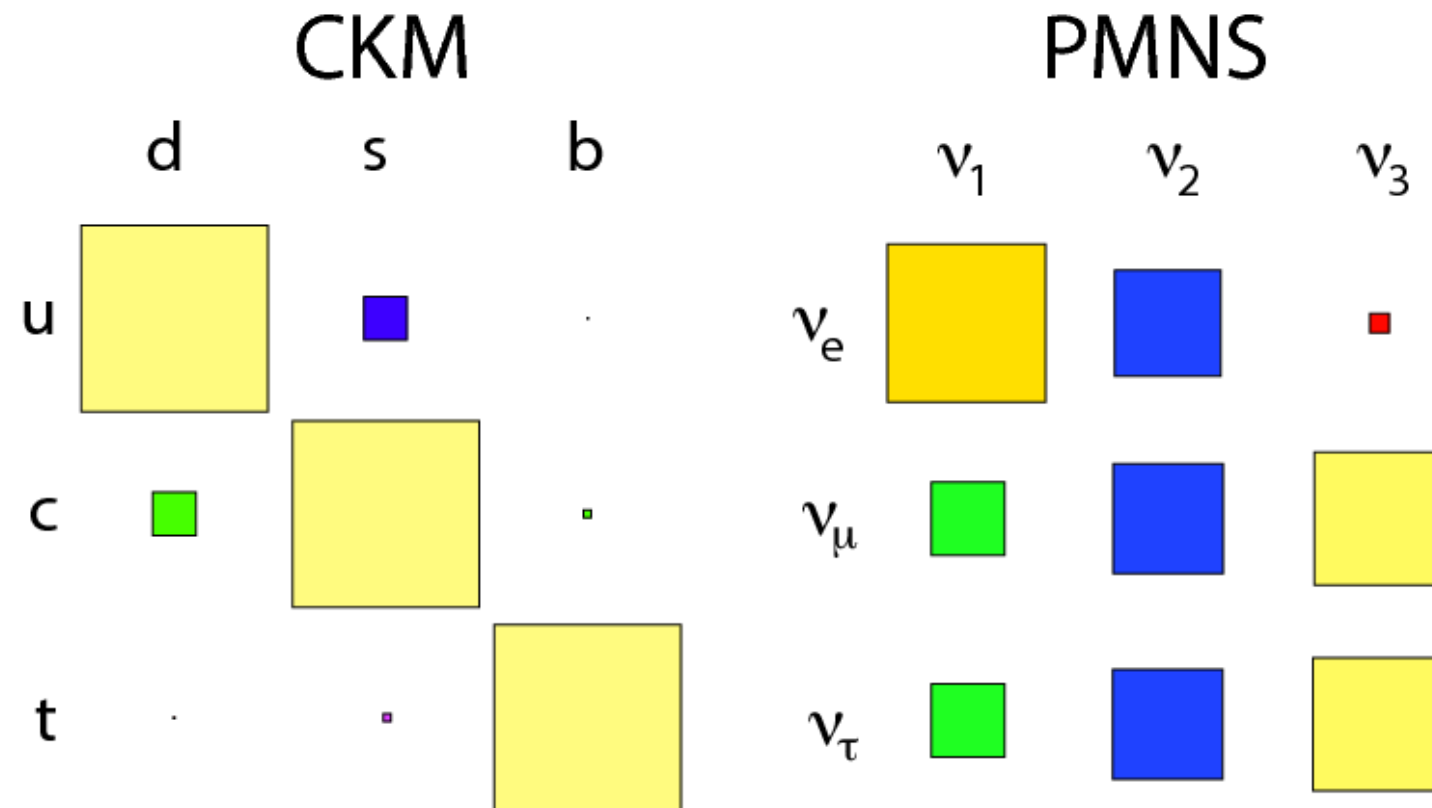
★ **The elements of these two matrixes are free parameters in the SM**
★ **The CKM is almost diagonal, while the PMNS is completely different, we do not know why**

Neutrino Experiments
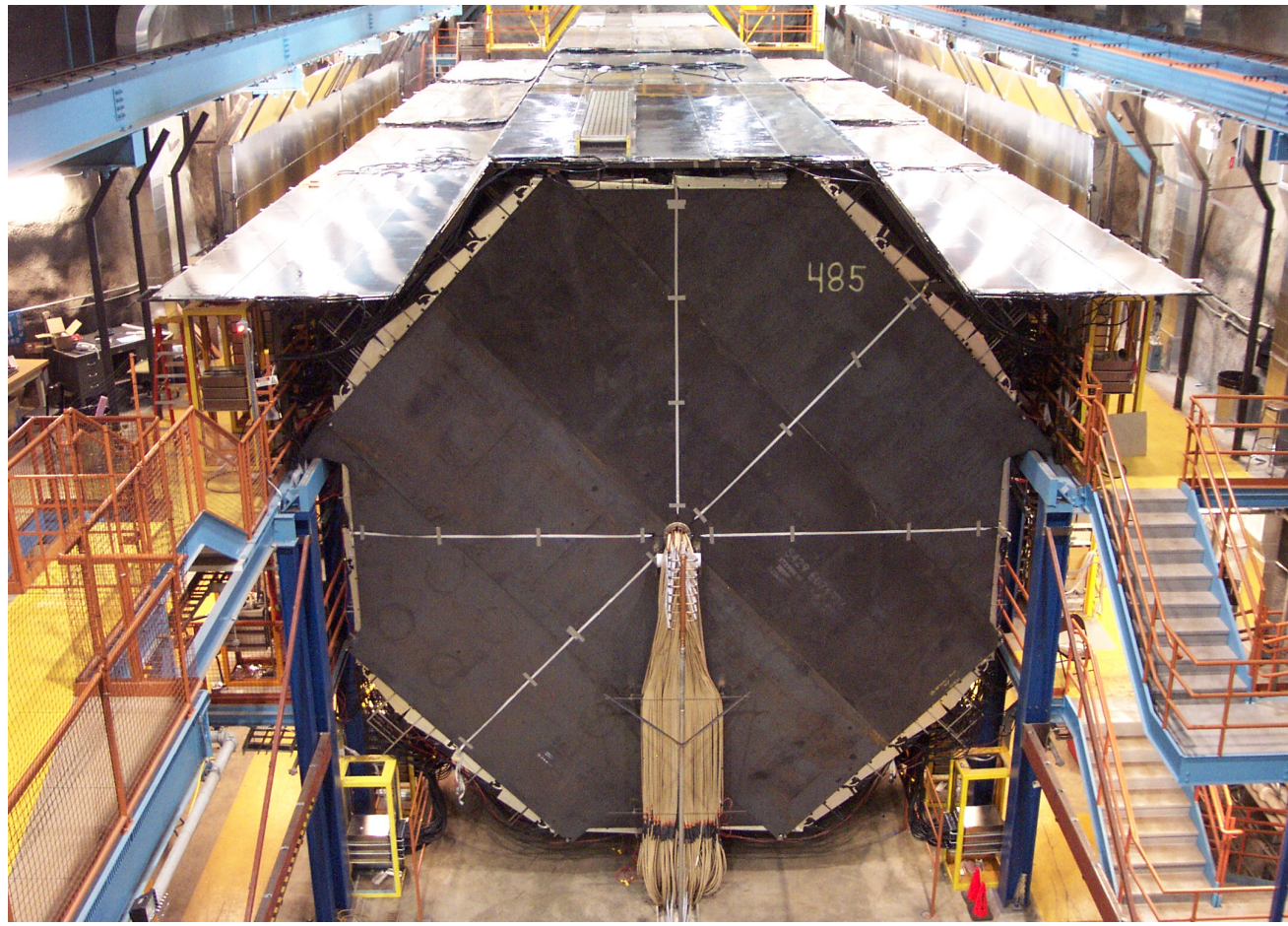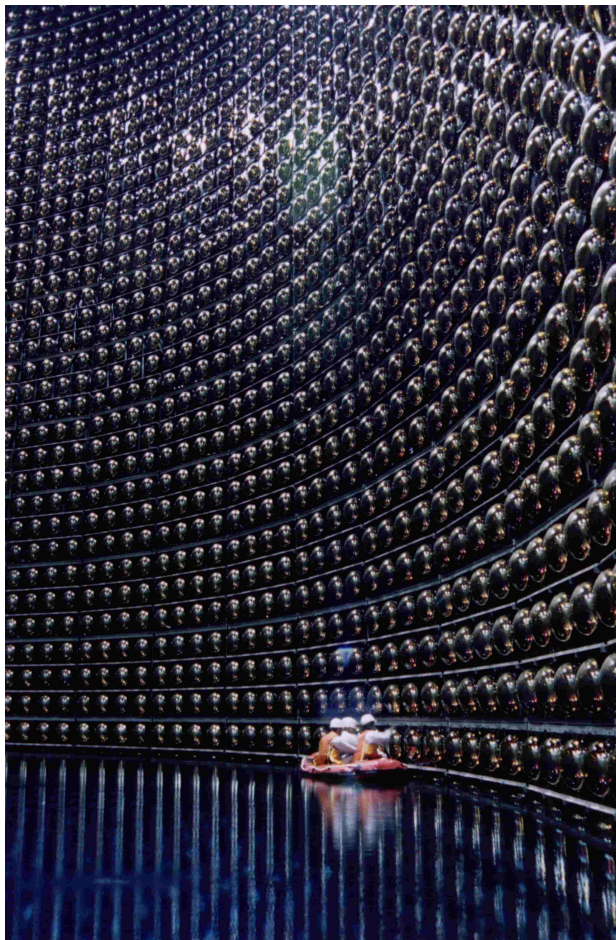
Neutrino Experiments

- Before discussing current experimental data, need to consider how neutrinos interact in matter (i.e. our detectors)

  <u>Two processes:</u>
  - Charged current (CC) interactions (via a W-boson) ⇒ charged lepton
  - Neutral current (NC) interactions (via a Z-boson)

  <u>Two possible "targets":</u> can have neutrino interactions with
  - atomic electrons
  - nucleons within the nucleus

CHARGED CURRENT
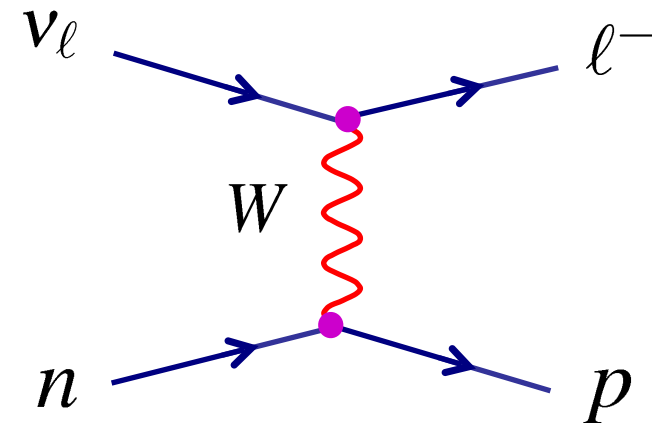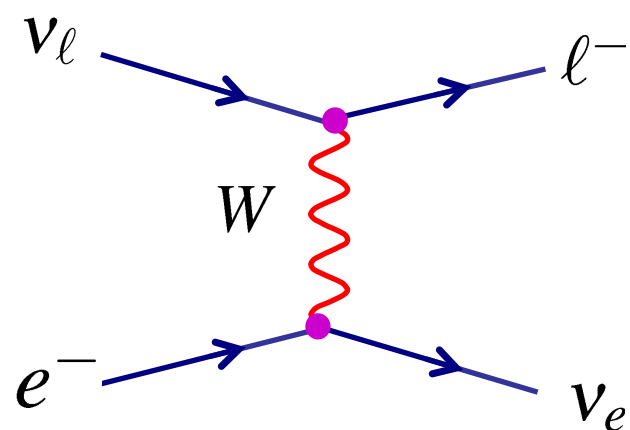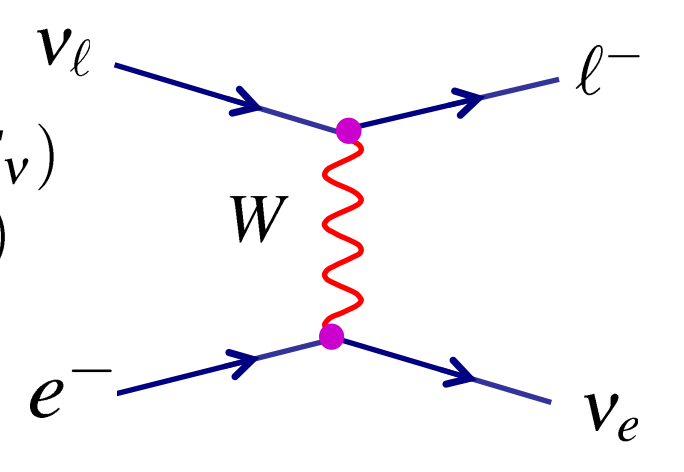
NEUTRAL CURRENT
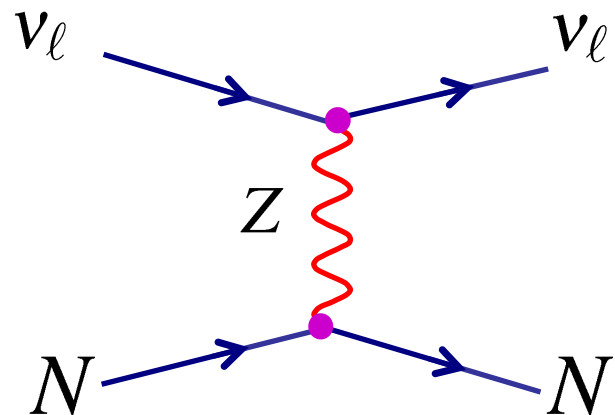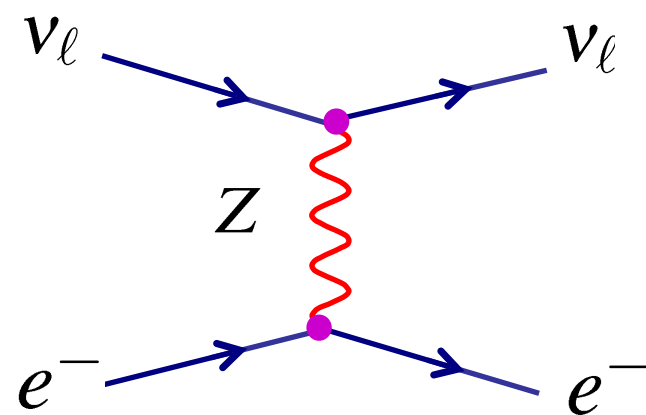
Neutrino Interaction Thresholds

★ Neutrino detection method depends on the neutrino energy and (weak) flavour

• Neutrinos from the sun and nuclear reactions have $E_\nu \sim 1\,\mathrm{MeV}$

• Atmospheric neutrinos have $E_\nu \sim 1\,\mathrm{GeV}$

★ These energies are relatively low and not all interactions are kinematically allowed, i.e. there is a threshold energy before an interaction can occur. Require sufficient energy in the centre-of-mass frame to produce the final state particles

❶ Charged current interactions on atomic electrons (in laboratory frame)

$p_\nu = (E_\nu, 0, 0, E_\nu)$
$p_e = (m_e, 0, 0, 0)$

$s = (p_\nu + p_e)^2 = (E_\nu + m_e)^2 - E_\nu^2$

Require: $s > m_\ell^2$

$$\Rightarrow \quad E_\nu > \left[\left(\frac{m_\ell}{m_e} \right)^2 - 1 \right] \frac{m_e}{2}$$

• Putting in the numbers, for CC interactions with atomic electrons require

$$E_{\nu_e} > 0 \qquad E_{\nu_\mu} > 11\,\mathrm{GeV} \qquad E_{\nu_\tau} > 3090\,\mathrm{GeV}$$

High energy thresholds compared to typical energies considered here

❷ charged current interactions on nucleons (in lab. frame)

$$s = (p_\nu + p_n)^2 = (E_\nu + m_n)^2 - E_\nu^2$$

Require: $s > (m_\ell + m_p)^2$

$$\Rightarrow \quad \boxed{E_\nu > \frac{(m_p^2 - m_n^2) + m_\ell^2 + 2m_p m_\ell}{2m_n}}$$
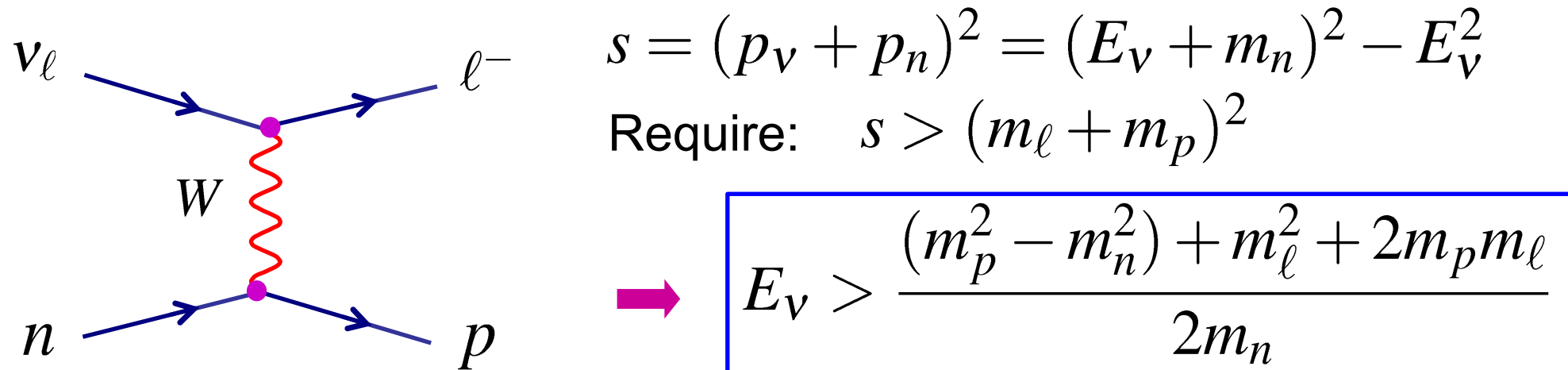
- For CC interactions from neutrons require

$$E_{\nu_e} > 0 \qquad E_{\nu_\mu} > 110\,\mathrm{MeV} \qquad E_{\nu_\tau} > 3.5\,\mathrm{GeV}$$

★ Electron neutrinos from the sun and nuclear reactors $E_\nu \sim 1\,\mathrm{MeV}$ which oscillate into muon or tau neutrinos cannot interact via charged current interactions – "they effectively disappear"

★ Atmospheric muon neutrinos $E_\nu \sim 1\,\mathrm{GeV}$ which oscillate into tau neutrinos cannot interact via charged current interactions – "disappear"

- To date, most experimental signatures for neutrino oscillation are a deficit of neutrino interactions (with the exception of SNO) because below threshold for produce lepton of different flavour from original neutrino

• For high energy muon neutrinos can directly use the results from page 316 (book)
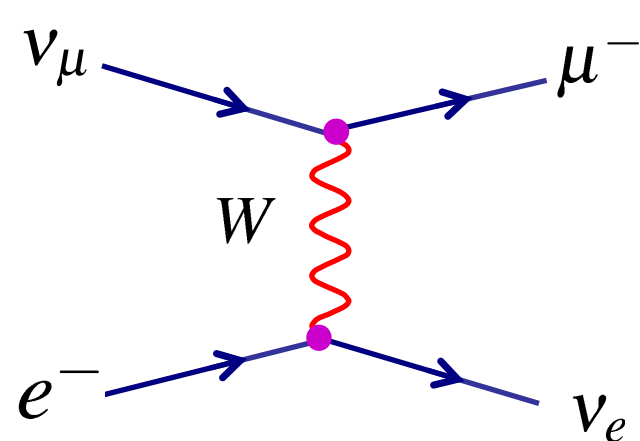
$$\sigma_{\nu_\mu e^-} = \frac{G_F^2 s}{\pi}$$

with $\quad s = (E_\nu + m_e)^2 - E_\nu^2 \approx 2m_e E_\nu$

$$\sigma_{\nu_\mu e^-} = \frac{2m_e G_F^2 E_\nu}{\pi}$$

Cross section increases linearly with lab. frame neutrino energy

• For electron neutrinos there is another lowest order diagram with the same final state
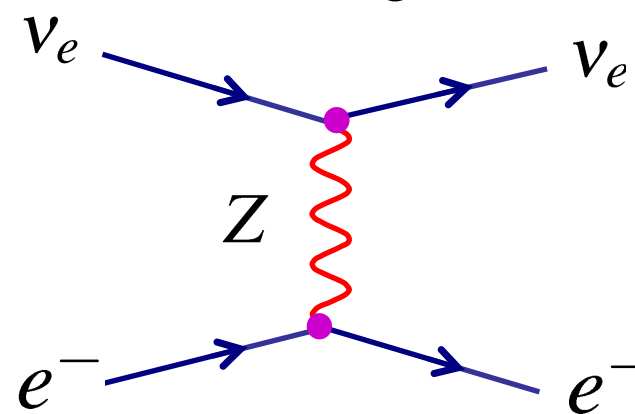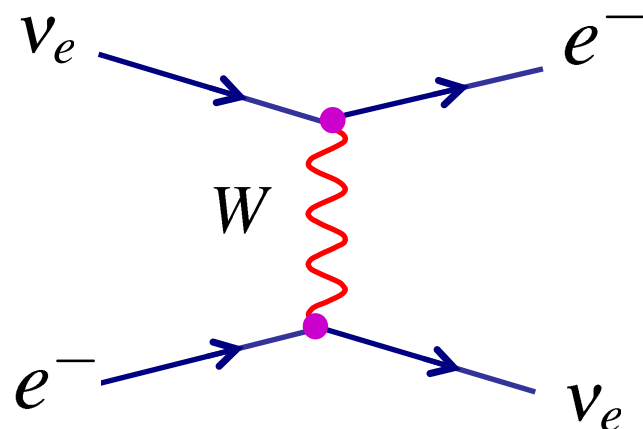
It turns out that the cross section is lower than the pure CC cross section due to negative interference when summing matrix elements $\quad |M_{CC} + M_{NC}|^2 < |M_{CC}|^2$

$$\sigma_{\nu_e e} \approx 0.6 \sigma_{\nu_e e}^{CC}$$

• In the high energy limit the CC neutrino-nucleon cross sections are larger due to the higher centre-of-mass energy: $\quad s = (E_\nu + m_n)^2 - E_\nu^2 \approx 2m_n E_\nu$

Neutrino Detection

★ The detector technology/interaction process depends on type of neutrino and energy
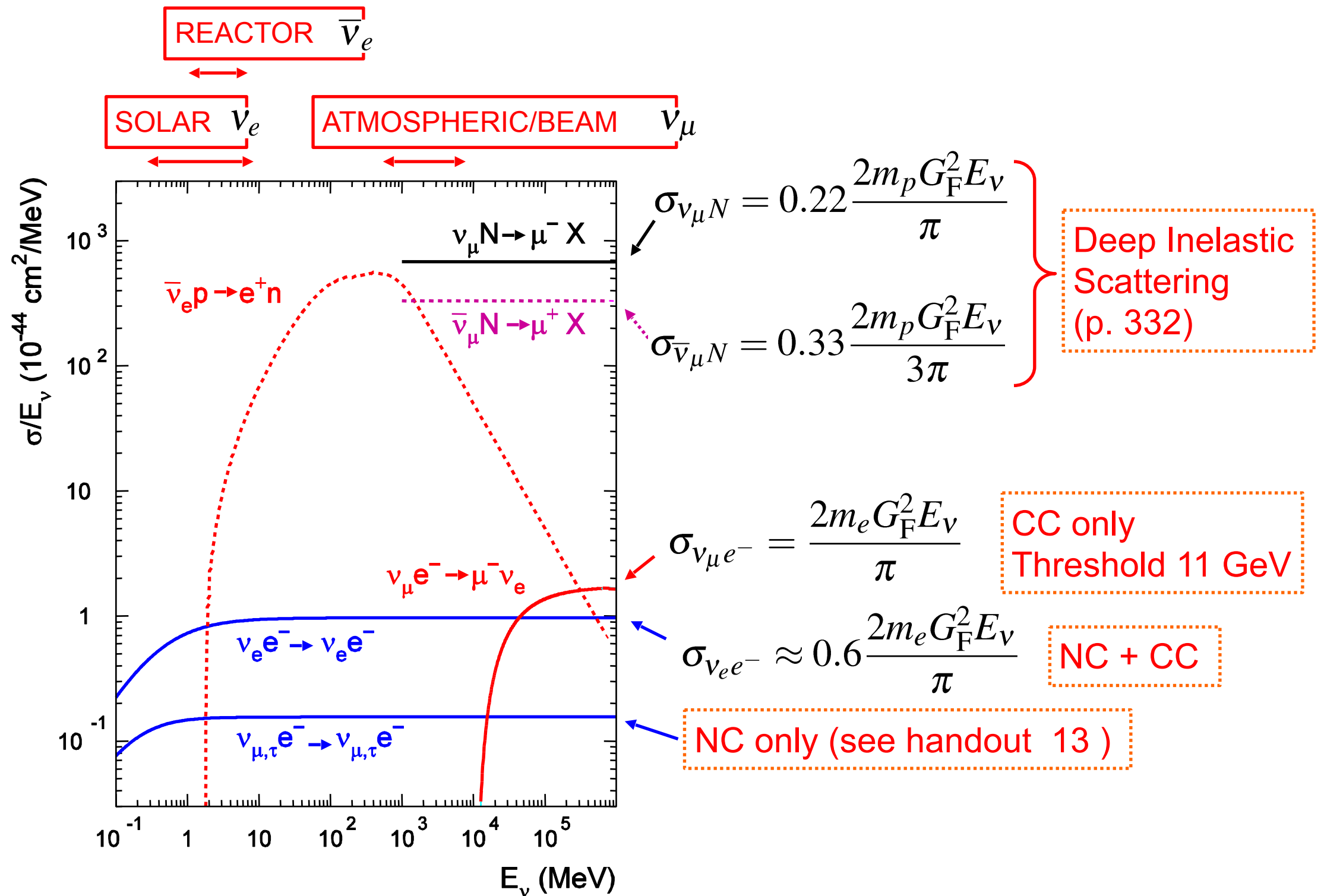
REACTOR $\overline{\nu}_e$

SOLAR ν_e

ATMOSPHERIC/BEAM ν_μ

σ/E_ν (10^{-44} cm^2/MeV)

$\nu_\mu N \rightarrow \mu^- X$

$\overline{\nu}_e p \rightarrow e^+ n$

$\overline{\nu}_\mu N \rightarrow \mu^+ X$

$\nu_\mu e^- \rightarrow \mu^- \nu_e$

$\nu_e e^- \rightarrow \nu_e e^-$

$\nu_{\mu,\tau} e^- \rightarrow \nu_{\mu,\tau} e^-$

E_ν (MeV)

$$\sigma_{\nu_\mu N} = 0.22 \frac{2 m_p G_F^2 E_\nu}{\pi}$$

$$\sigma_{\overline{\nu}_\mu N} = 0.33 \frac{2 m_p G_F^2 E_\nu}{3\pi}$$

Deep Inelastic Scattering (p. 332)

$$\sigma_{\nu_\mu e^-} = \frac{2 m_e G_F^2 E_\nu}{\pi}$$

CC only Threshold 11 GeV

$$\sigma_{\nu_e e^-} \approx 0.6 \frac{2 m_e G_F^2 E_\nu}{\pi}$$

NC + CC

NC only (see handout 13)

$$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu : E_\nu > 1\,\mathrm{GeV}$$

❶ Water Čerenkov: e.g. Super Kamiokande
❷ Iron Calorimeters: e.g. MINOS, CDHS

• Produce high energy charged lepton – relatively easy to detect

Solar Neutrinos

$$\nu_e \; : \; E_\nu < 20\,\mathrm{MeV}$$

❶ Water Čerenkov: e.g. Super Kamiokande

• Detect Čerenkov light from electron produced in $\quad \nu_e + e^- \rightarrow \nu_e + e^-$
• Because of background from natural radioactivity limited to $\quad E_\nu > 5\,\mathrm{MeV}$
• Because Oxygen is a doubly magic nucleus don't get $\quad \nu_e + n \rightarrow e^- + p$

❷ Radio-Chemical: e.g. Homestake, SAGE, GALLEX
• Use inverse beta decay process, e.g. $\quad \nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$
• Chemically extract produced isotope and count decays (only gives a rate)

Reactor Neutrinos

$$\overline{\nu}_e \; : \; E_{\overline{\nu}} < 5\,\mathrm{MeV}$$

❶ Liquid Scintillator: e.g. KamLAND
• Low energies ➡ large radioactive background
• Dominant interaction: $\quad \overline{\nu}_e + p \rightarrow e^+ + n$
• Prompt positron annihilation signal + delayed signal
  from n (space/time correlation reduces background)
• electrons produced by photons excite scintillator which produces light
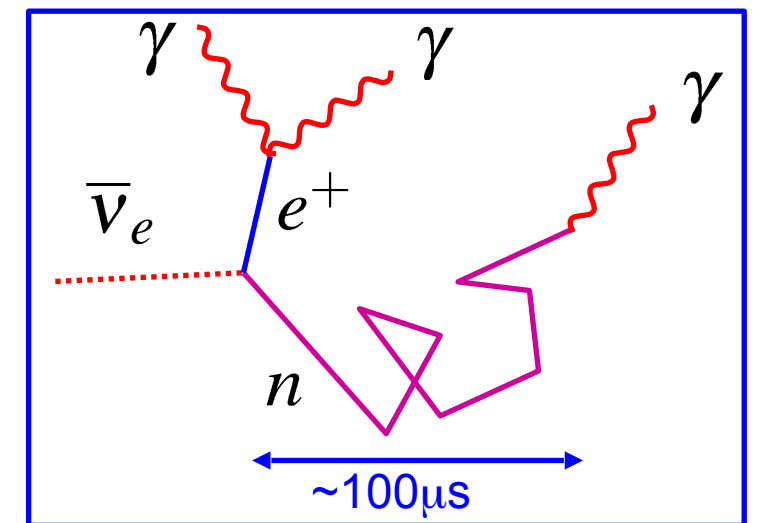
1) Long Baseline Neutrino Experiments

- Initial studies of neutrino oscillations from atmospheric and solar neutrinos
  - atmospheric neutrinos discussed in examinable appendix
- Emphasis of neutrino research now on neutrino beam experiments
- Allows the physicist to take control – design experiment with specific goals
- In the last few years, long baseline neutrino oscillation experiments have started taking data: K2K, MINOS, CNGS, T2K

Basic Idea:

★ Intense neutrino beam

★ Two detectors: one close to beam the other hundreds of km away

★ Measure ratio of the neutrino energy spectrum in far detector (oscillated) to that in the near detector (unoscillated)

★ Partial cancellation of systematic biases

Near Detector (unoscillated)

Far Detector (oscillated)

Depth of minimum ➡ $\sin 2\theta^2$

Position of min. ➡ Δm^2

$\Delta m^2 = 0.002$ eV^2
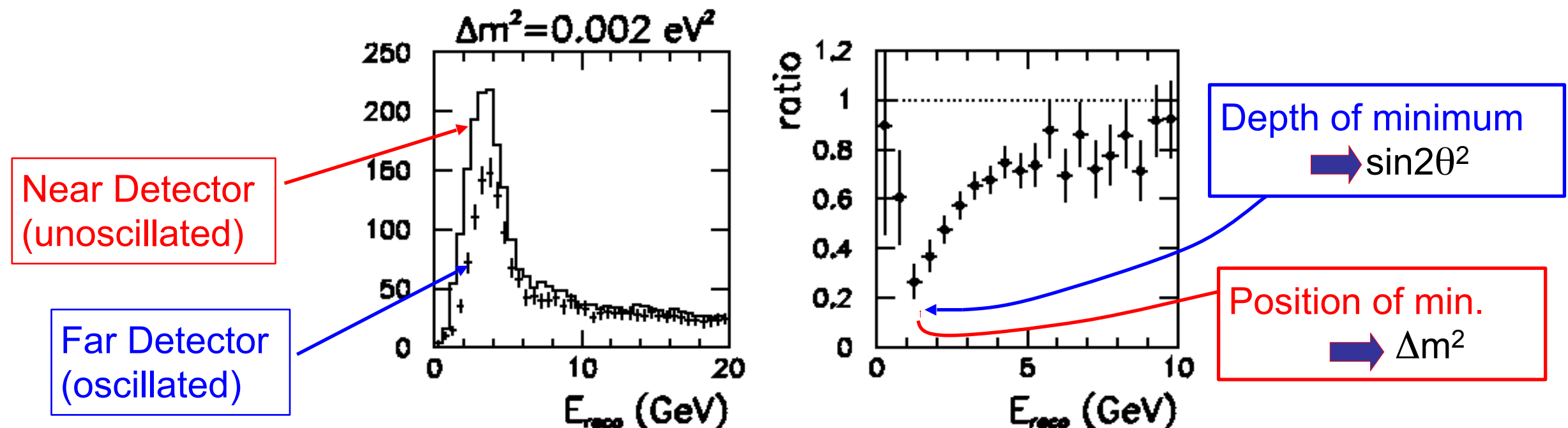
MINOS

- •120 GeV protons extracted from the MAIN INJECTOR at Fermilab
- • 2.5×10^{13} protons per pulse hit target ➡ very intense beam - 0.3 MW on target

Soudan Mine, Minnesota
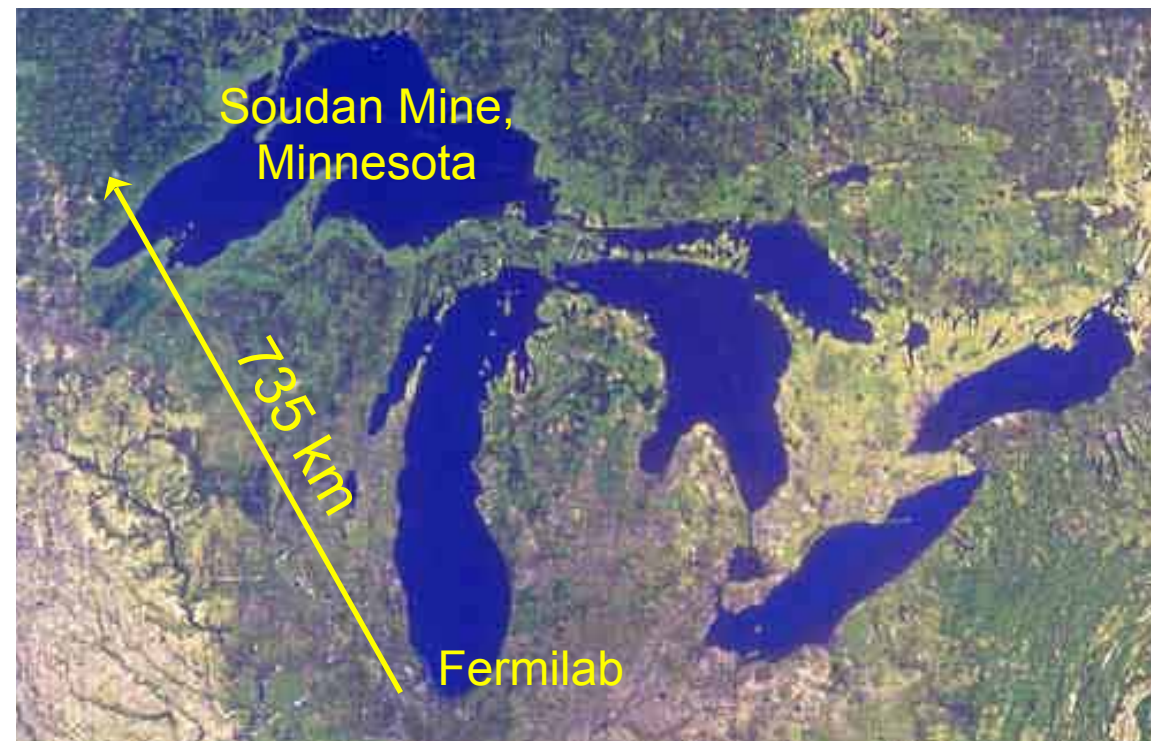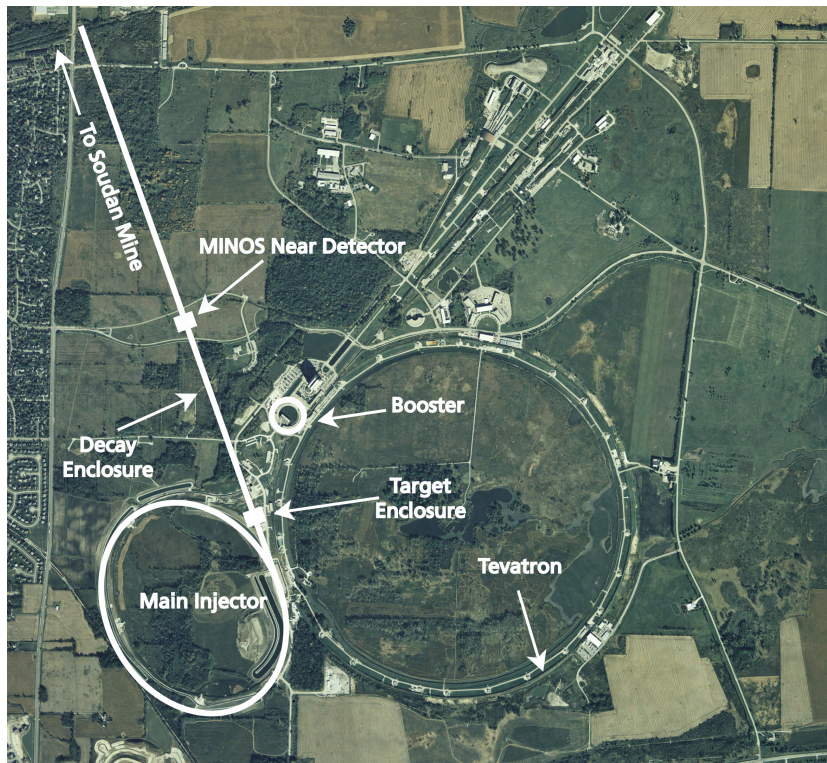
735 km

Fermilab
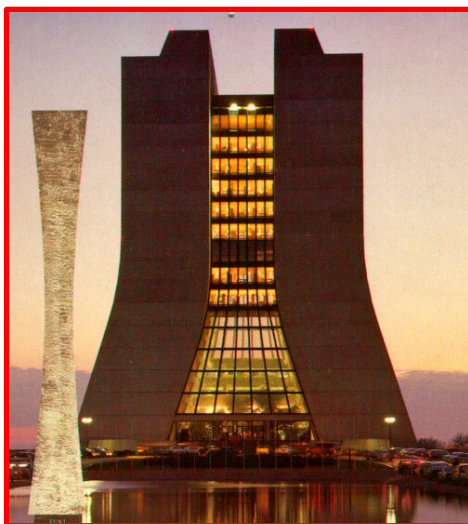
Two detectors:

★ 1000 ton, NEAR Detector at Fermilab : 1 km from beam

★ 5400 ton FAR Detector, 720m underground in Soudan mine, N. Minnesota: 735 km from beam

Mark Thomson/Nico Serra

Nuclear and Particle Physics II
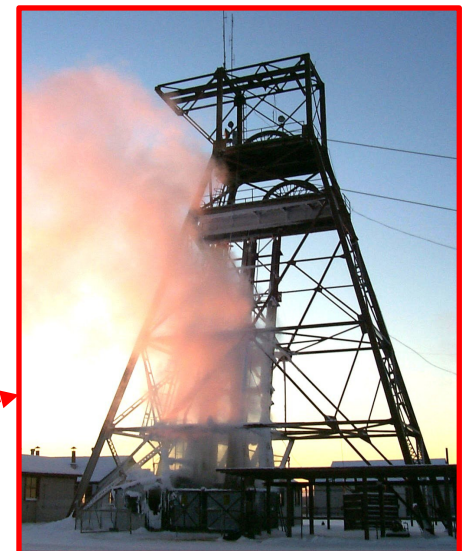
The MINOS Detectors:

- Dealing with high energy neutrinos $\quad E_\nu > 1\,\text{GeV}$
- The muons produced by ν_μ interactions travel several metres
- Steel-Scintillator sampling calorimeter
- Each plane: 2.54 cm steel +1 cm scintillator
- A charged particle crossing the scintillator produces light – detect with PMTs

Steel

Plastic scintillator

Alternate layers have strips in x/y directions

FAR

NEAR
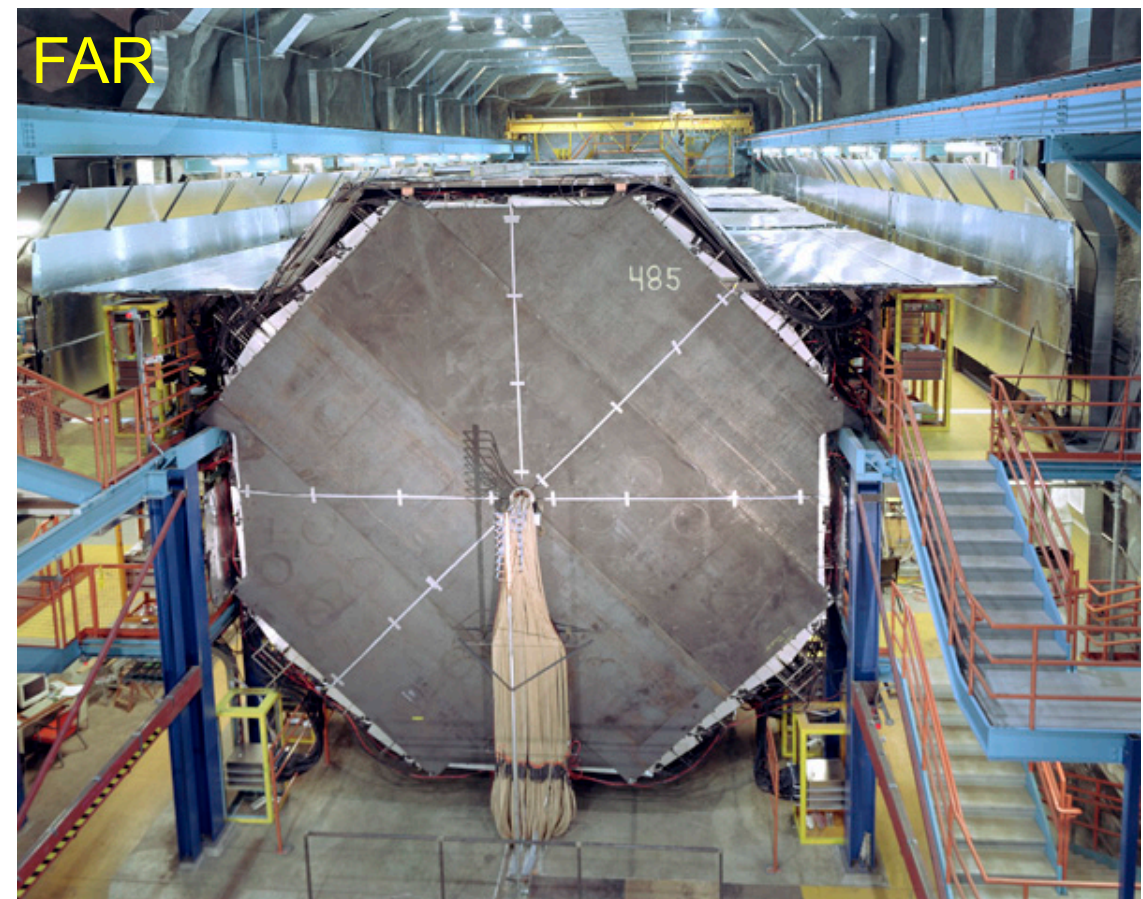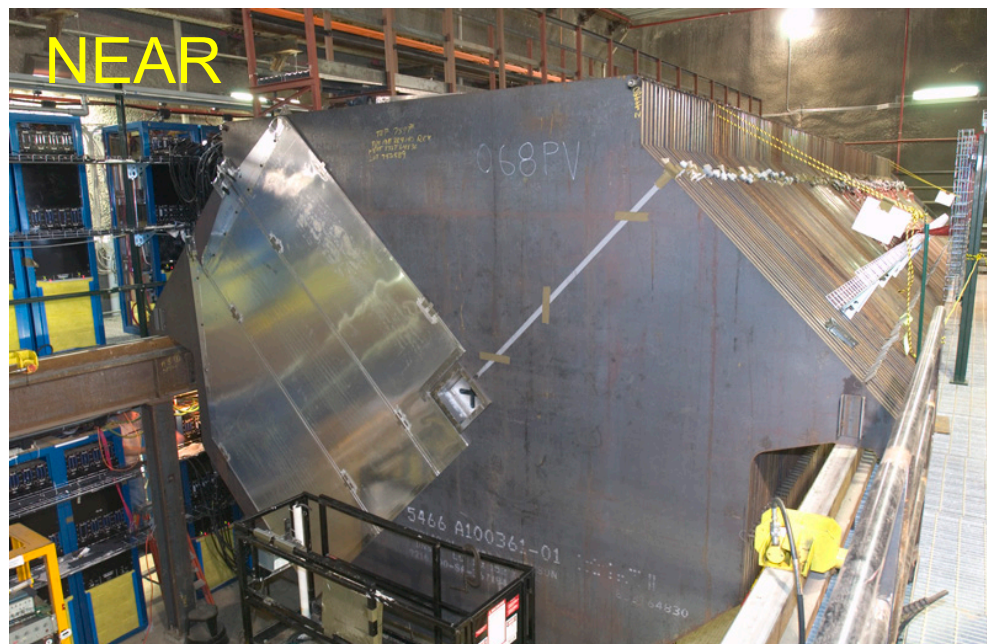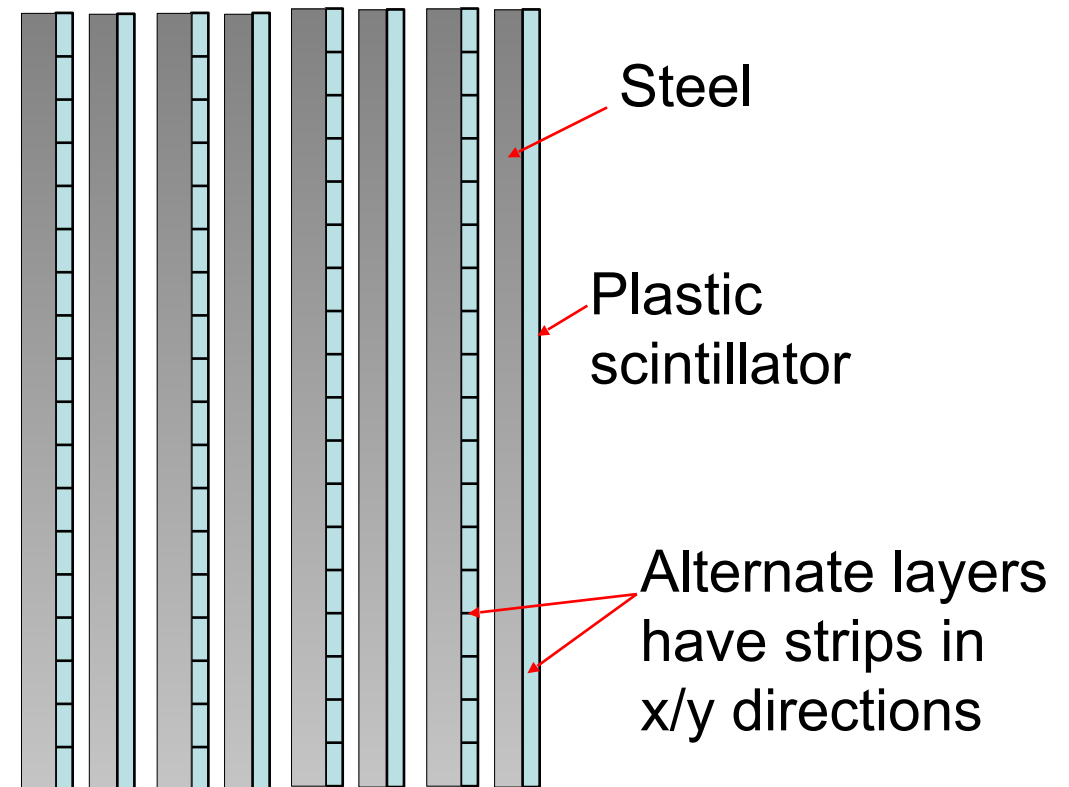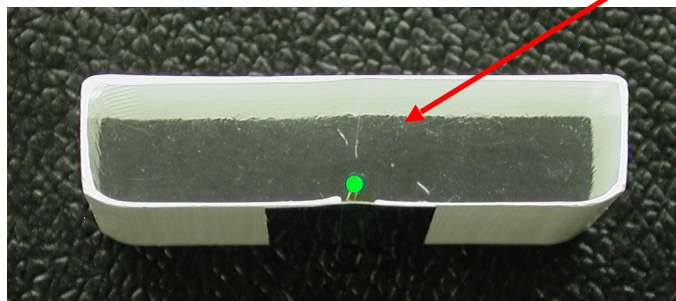
- Neutrino detection via CC interactions on nucleon

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

$$\nu_\mu \qquad X$$

$$\mu^-$$

Example event:

Signal from hadronic shower
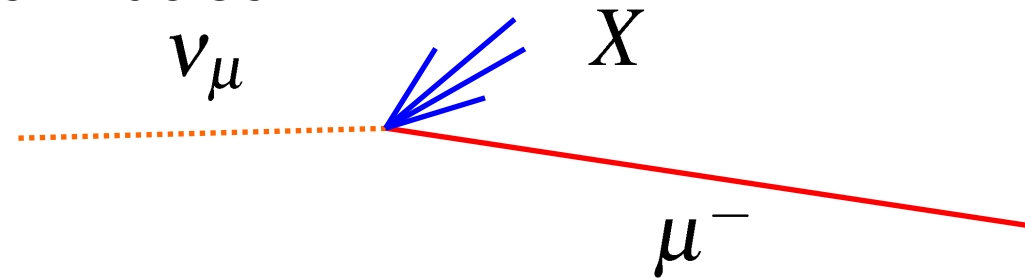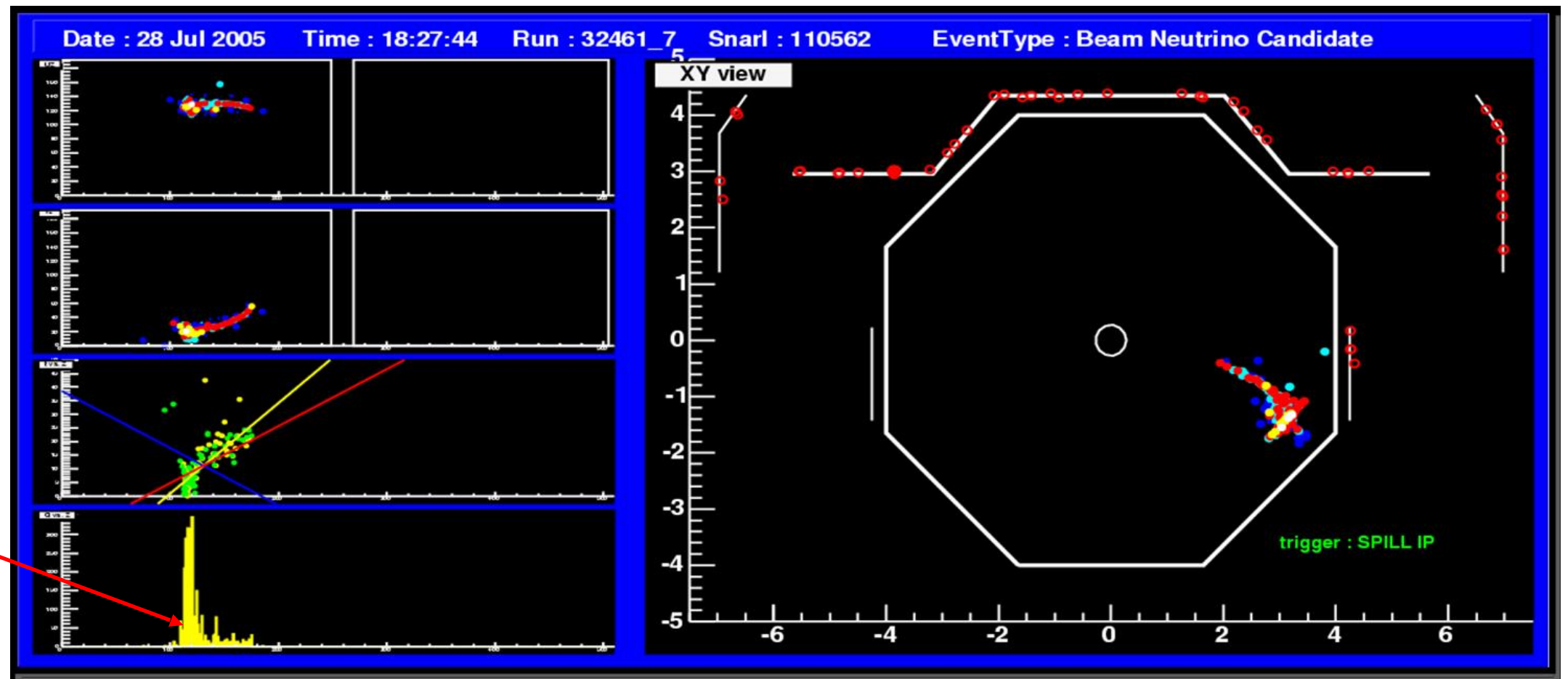
- The main feature of the MINOS detector is the very good neutrino energy resolution

$$E_\nu = E_\mu + E_X$$

- Muon energy from range/curvature in B-field
- Hadronic energy from amount of light observed

MINOS Results

- For the MINOS experiment L is fixed and observe oscillations as function of E_ν
- For $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2$ first oscillation minimum at $E_\nu = 1.5\,\mathrm{GeV}$
- To a very good approximation can use two flavour formula as oscillations corresponding to $|\Delta m^2_{21}| \sim 8 \times 10^{-5}\,\mathrm{eV}^2$ occur at $E_\nu = 50\,\mathrm{MeV}$ beam contains very few neutrinos at this energy + well below detection threshold

MINOS Collaboration, Phys. Rev. Lett. 101, 131802, 2008
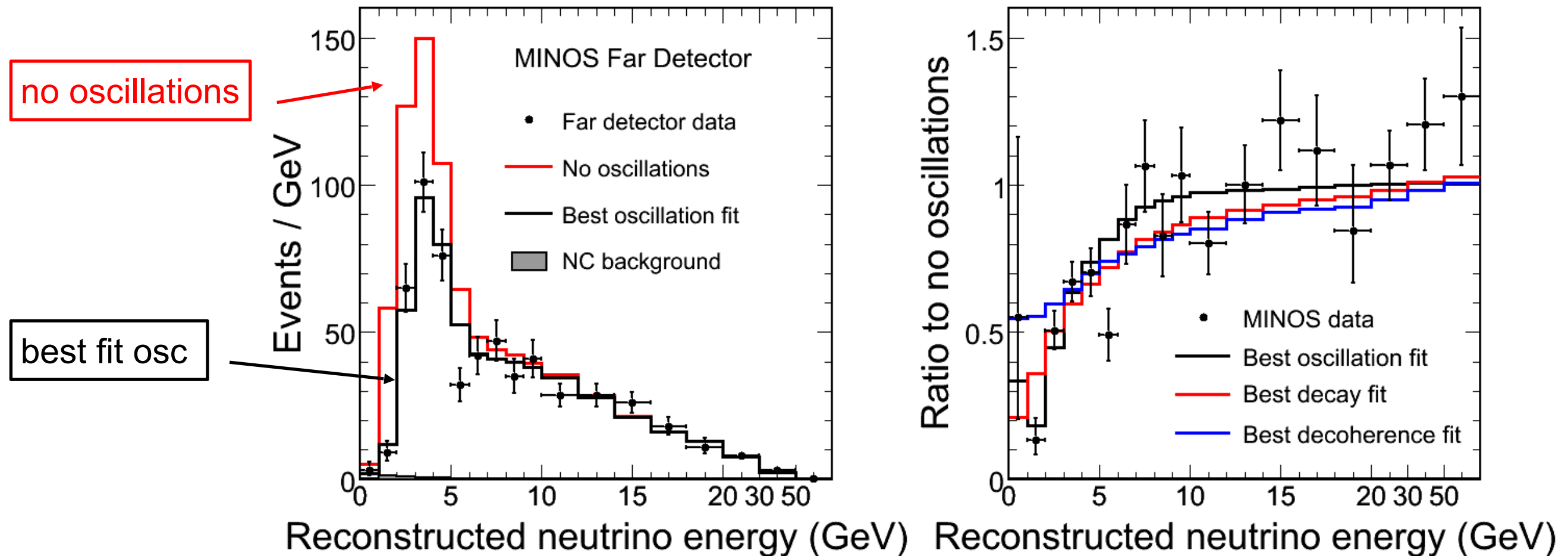
$$|\Delta m^2_{32}| = (2.43 \pm 0.12) \times 10^{-3}\,\mathrm{eV}^2$$

2) Solar Neutrinos
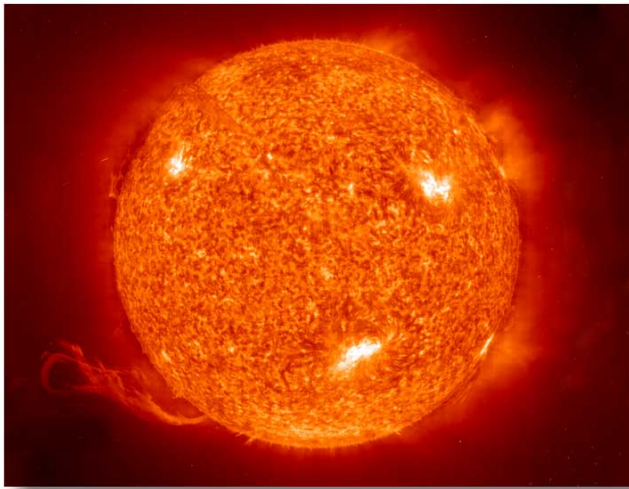
- The Sun is powered by the weak interaction – producing a very large flux of electron neutrinos

$$2 \times 10^{38} \, \nu_e \, \text{s}^{-1}$$
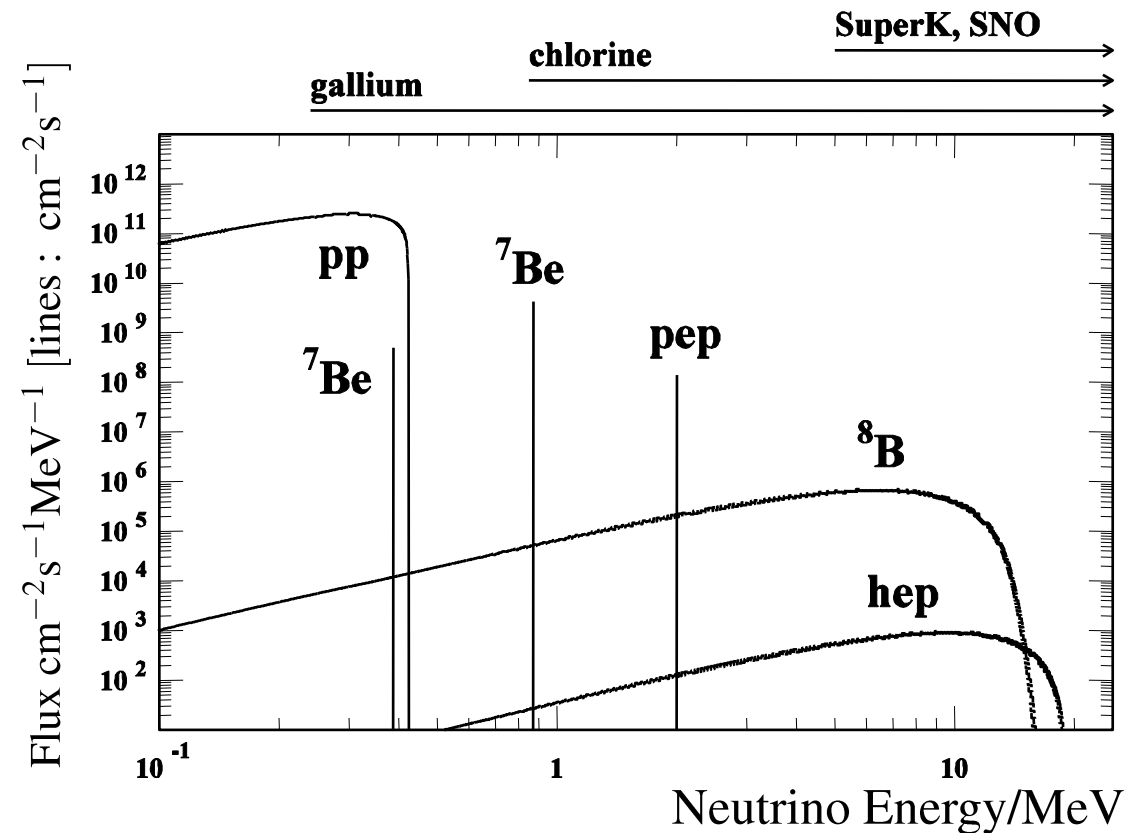
- Several different nuclear reactions in the sun $\Rightarrow$ complex neutrino energy spectrum

$$p + p \rightarrow d + e^+ + \nu_e \quad E_\nu < 0.5 \, \text{MeV}$$

$$^8B \rightarrow ^8Be^* + e^+ + \nu_e \quad E_\nu \sim 5 \, \text{MeV}$$

$$p + e^- + p \rightarrow d + \nu_e$$

$$^7Be + e^- \rightarrow ^7Li + \nu_e$$

$$^3He + p \rightarrow ^4He + e^+ + \nu_e$$
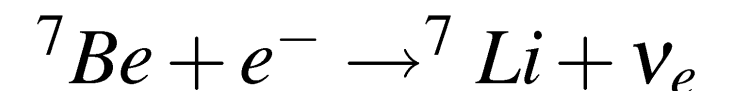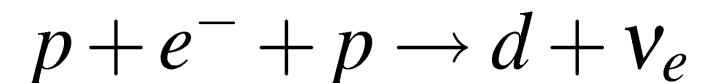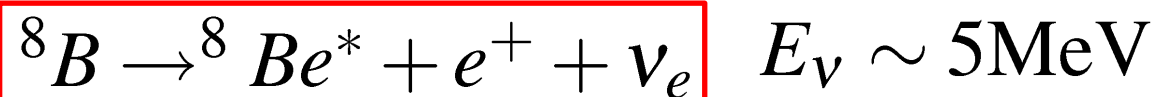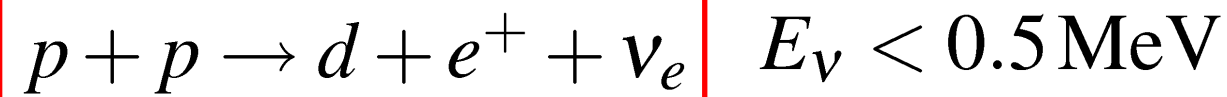
- All experiments saw a deficit of electron neutrinos compared to experimental prediction – the SOLAR NEUTRINO PROBLEM

- e.g. Super Kamiokande

Solar Neutrinos I: Super Kamiokande

- 50000 ton water Čerenkov detector
- Water viewed by 11146 Photo-multiplier tubes
- Deep underground to filter out cosmic rays otherwise difficult to detect rare neutrino interactions

Mt. Ikenoyama, Japan

36 m

34 m
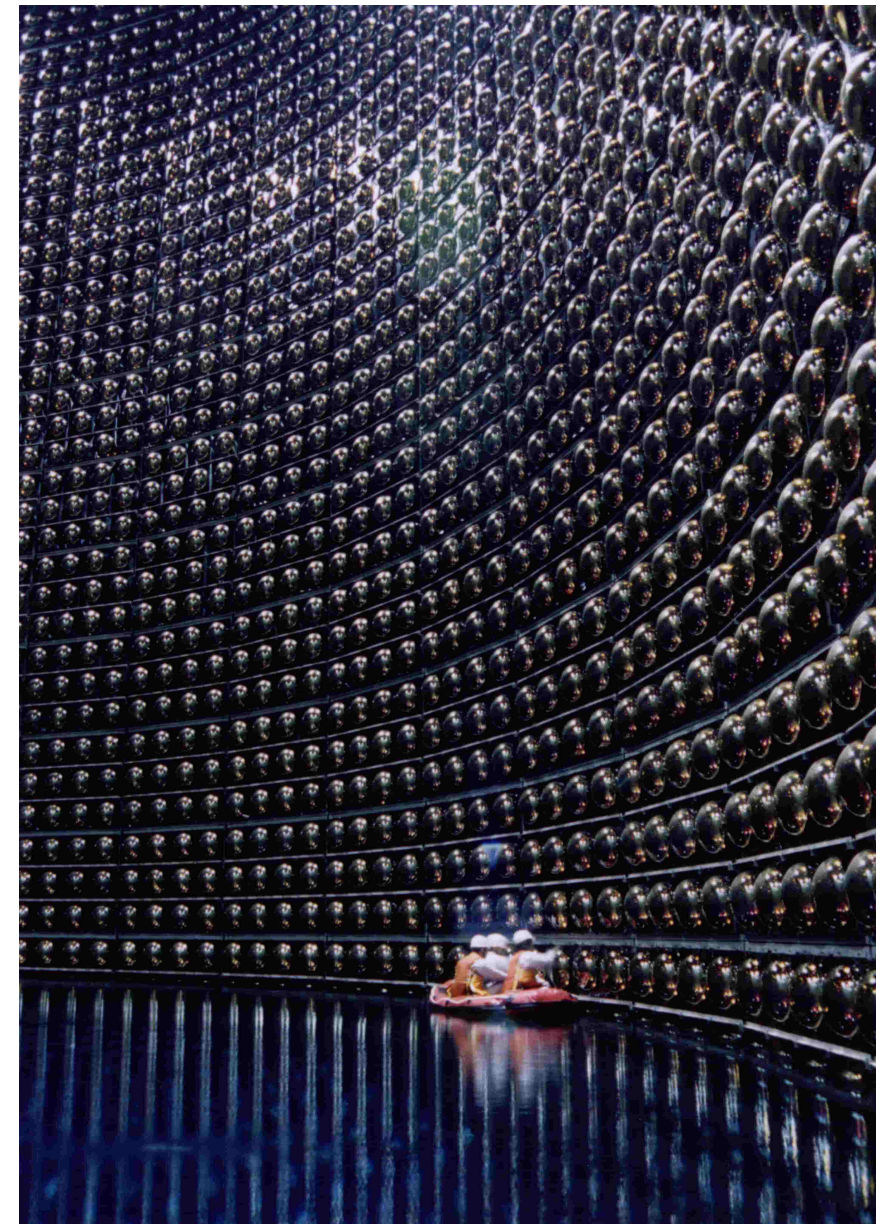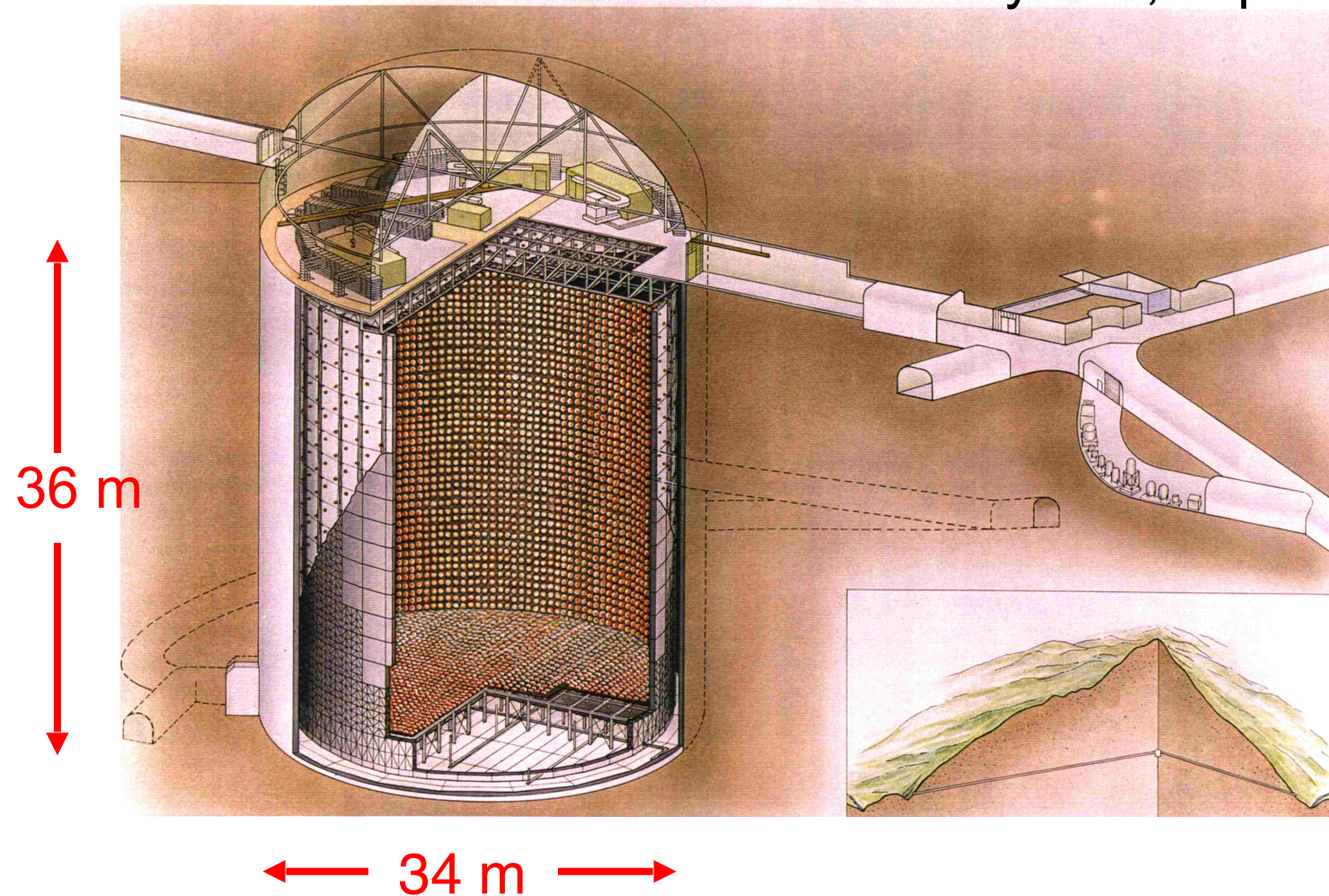
- Detect neutrinos by observing Čerenkov radiation from charged particles which travel faster than speed of light in water *c/n*

ν_e

e^-
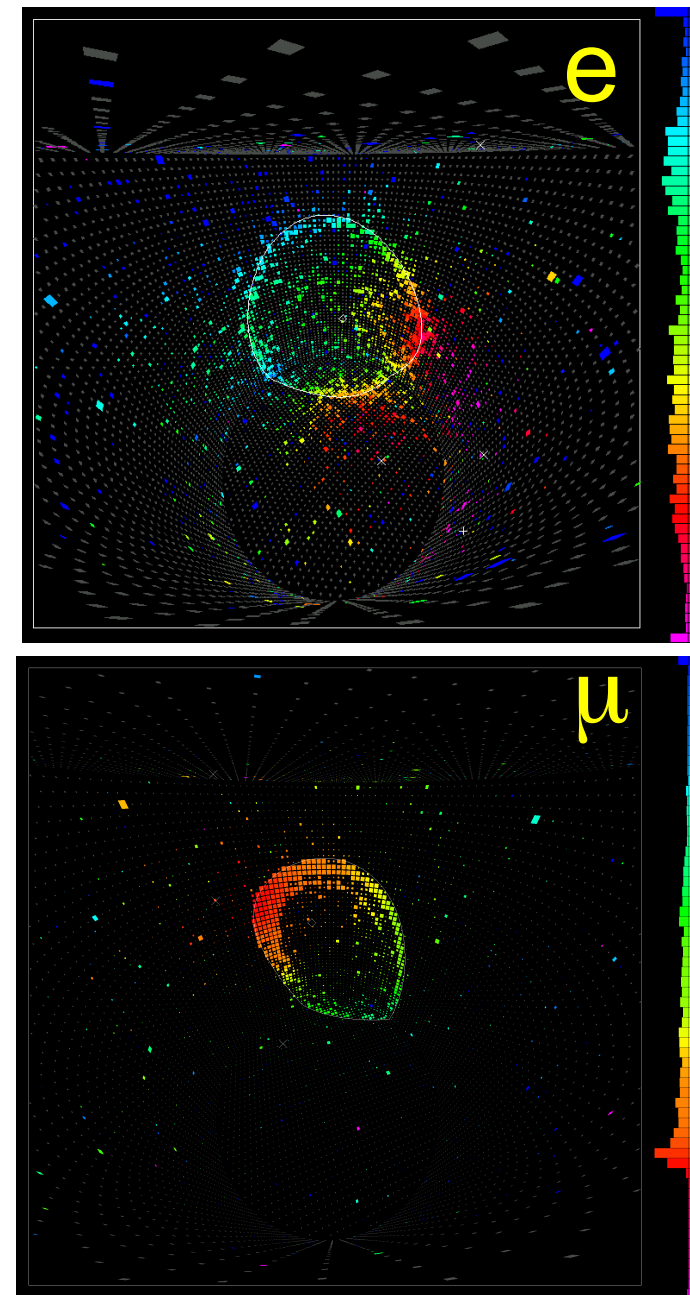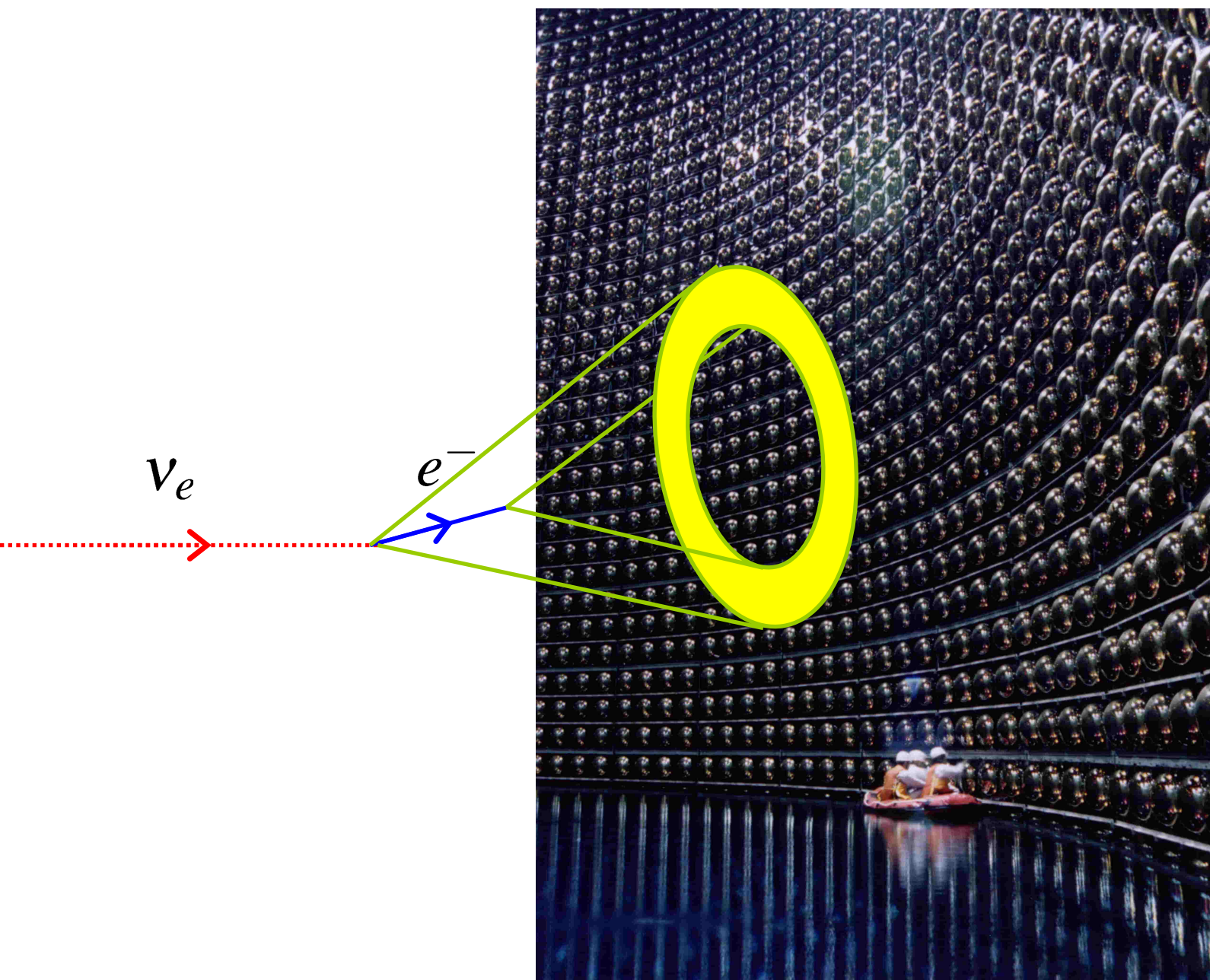
- Can distinguish electrons from muons from pattern of light – muons produce clean rings whereas electrons produce more diffuse "fuzzy" rings

- Sensitive to solar neutrinos with $E_\nu > 5\,\mathrm{MeV}$
- For lower energies too much background from natural radioactivity (β-decays)
- Hence detect mostly neutrinos from $^8B \rightarrow\, ^8Be^* + e^+ + \nu_e$

- Detect electron Čerenkov rings from

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- In LAB frame the electron is produced preferentially along the ν_e direction

background due to natural radioactivity (β-decay)

ν_e from the sun

$5 < E_\nu < 20\,\mathrm{MeV}$
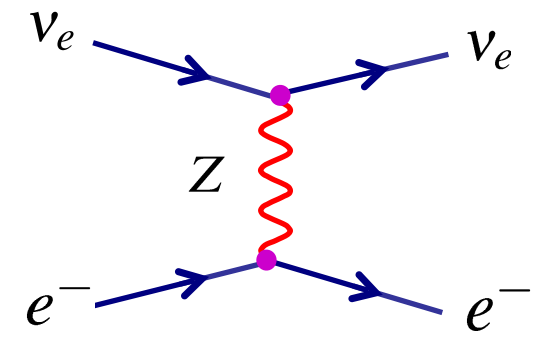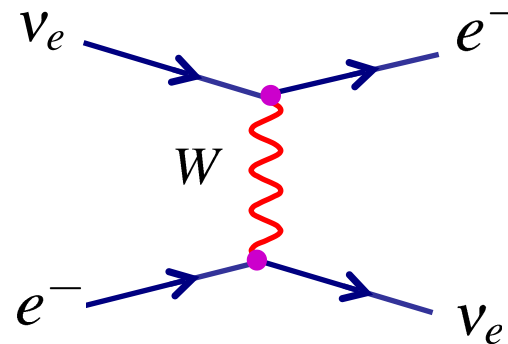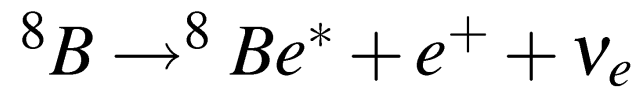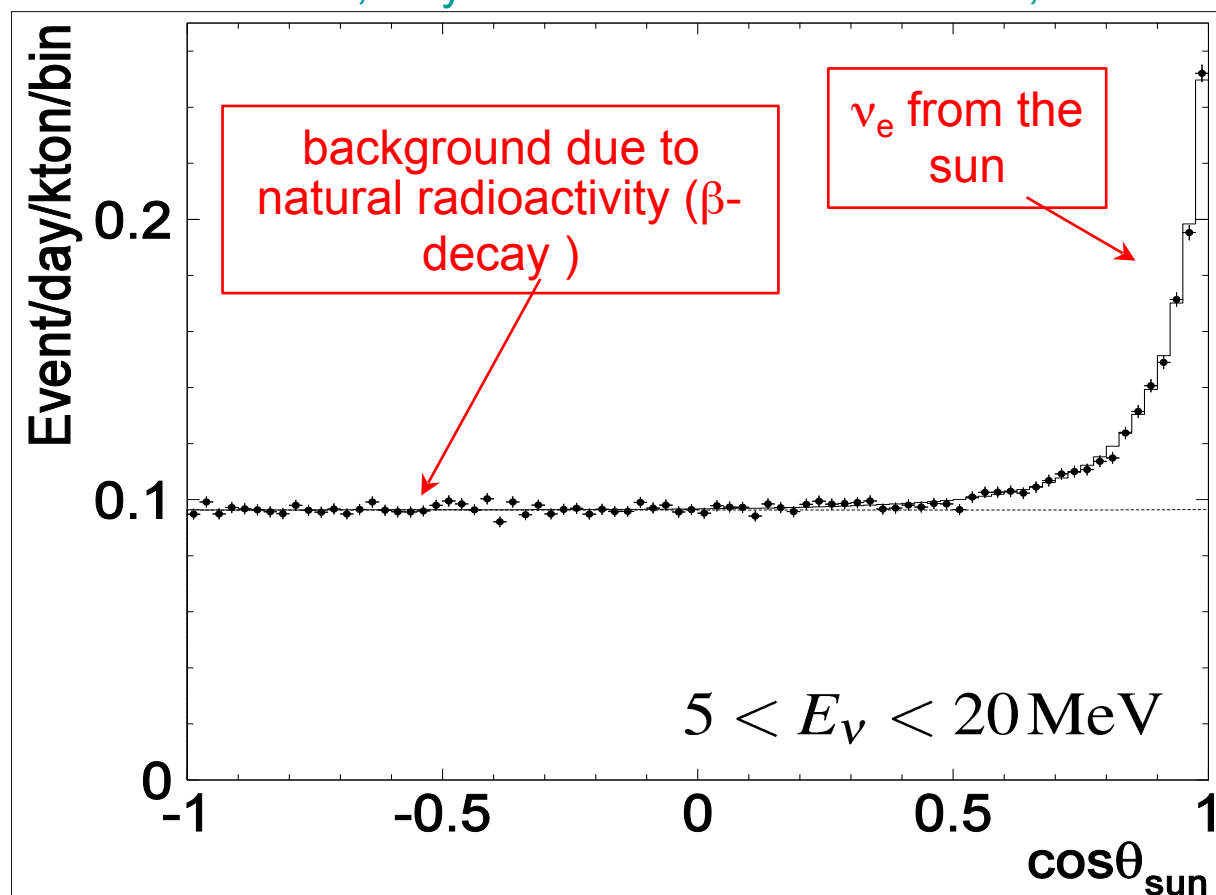
Results:
- Clear signal of neutrinos from the sun
- However too few neutrinos

DATA/SSM = 0.45±0.02

SSM = "Standard Solar Model" Prediction

The Solar Neutrino "Problem"

Solar Neutrinos II: SNO

• <u>S</u>udbury <u>N</u>eutrino <u>O</u>bservatory located in a deep mine in Ontario, Canada
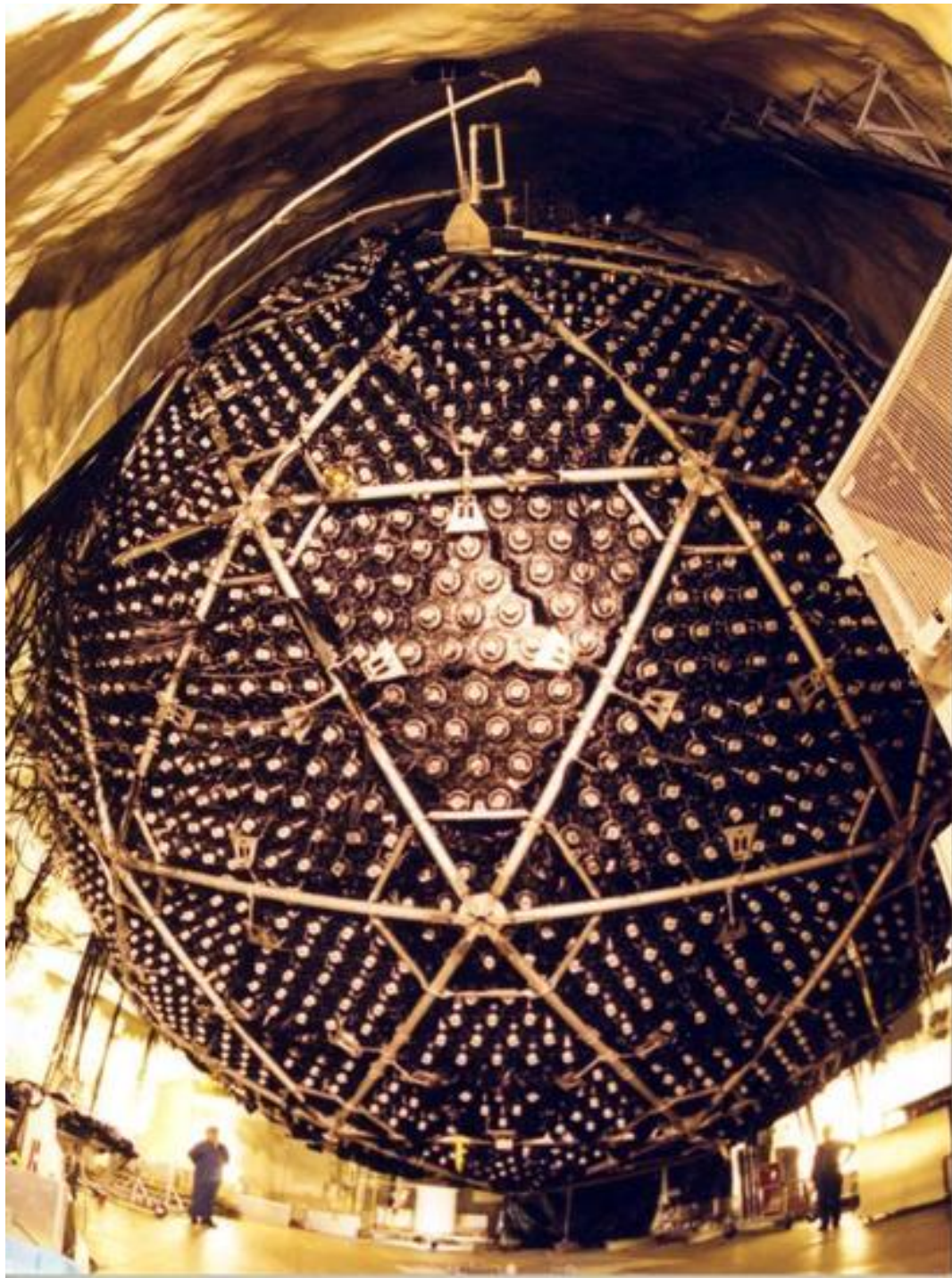
- 1000 ton heavy water (D_2O) Čerenkov detector
- D_2O inside a 12m diameter acrylic vessel
- Surrounded by 3000 tons of normal water
- Main experimental challenge is the need for very low background from radioactivity
- Ultra-pure H_2O and D_2O
- Surrounded by 9546 PMTs

Transparent acrylic vessel

H_2O

D_2O

PMTs

Ultra-pure H_2O and D_2O
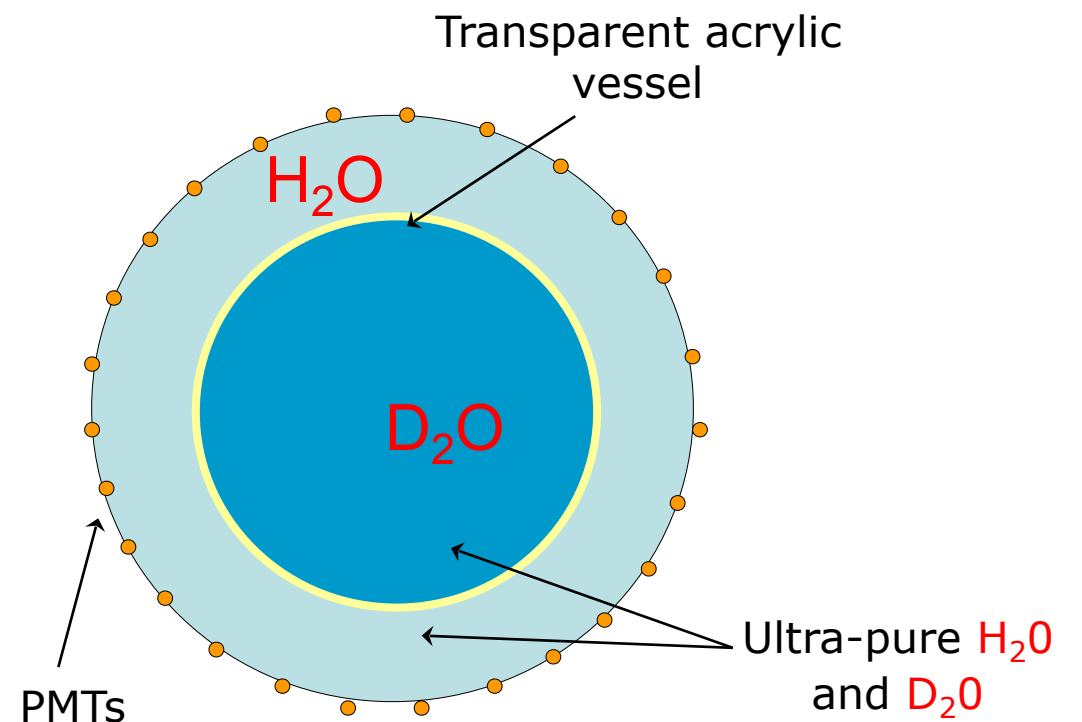
★ Detect Čerenkov light from three different reactions:

CHARGE CURRENT

- Detect Čerenkov light from electron
- Only sensitive to ν_e (thresholds)
- Gives a measure of ν_e flux

$$\text{CC Rate} \propto \phi(\nu_e)$$

ν_e → e^-

W

$d(np)$ → p
p
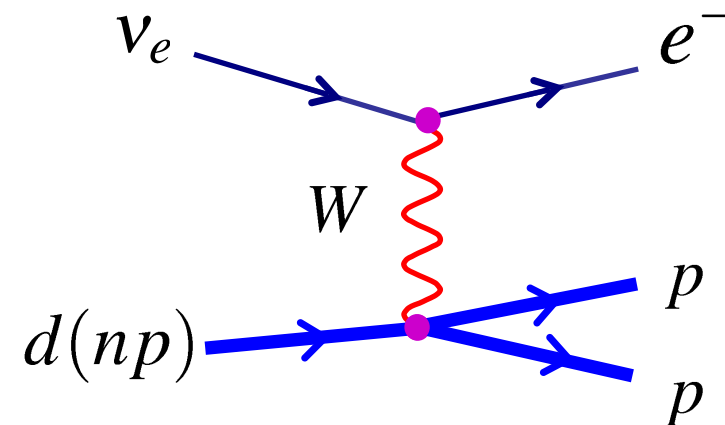
NEUTRAL CURRENT

- Neutron capture on a deuteron gives 6.25 MeV
- Detect Čerenkov light from electrons scattered by γ
- Measures total neutrino flux

$$\text{NC Rate} \propto \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)$$

ν_x → ν_x

Z

$d(np)$ → n
p
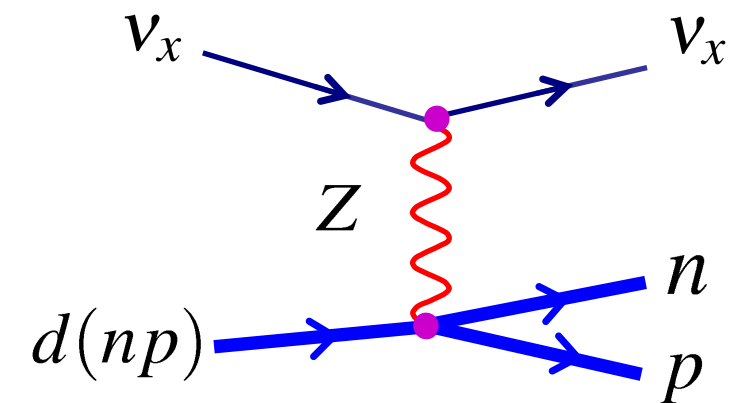
ELASTIC SCATTERING

- Detect Čerenkov light from electron
- Sensitive to all neutrinos (NC part) – but larger cross section for ν_e

$$\text{ES Rate} \propto \phi(\nu_e) + 0.154(\phi(\nu_\mu) + \phi(\nu_\tau))$$

ν_e → e^-

W

e^- → ν_e

ν_x → ν_x

Z

e^- → e^-
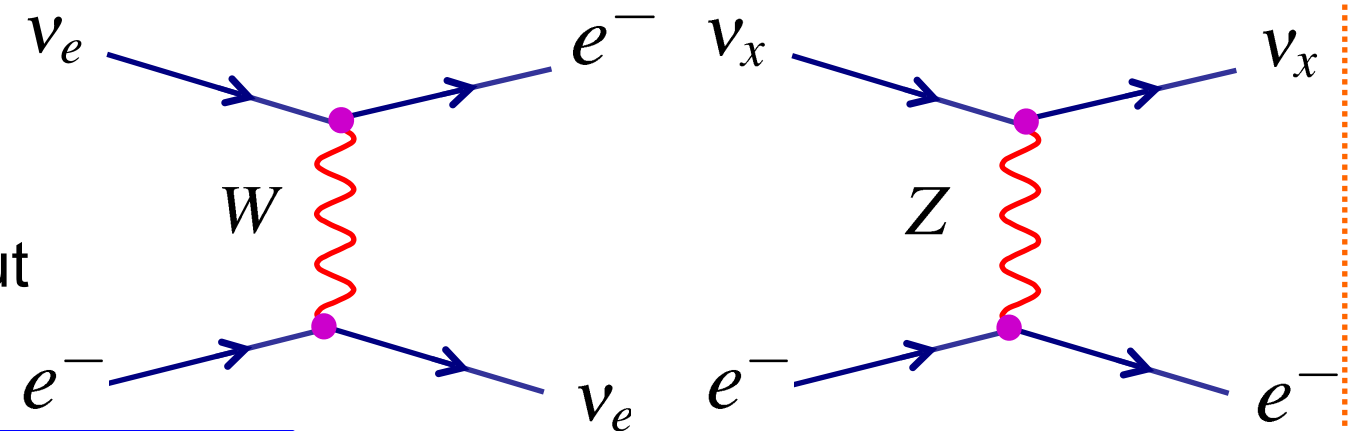
★ Experimentally can determine rates for different interactions from:
  • angle with respect to sun: electrons from ES point back to sun
  • energy: NC events have lower energy – 6.25 MeV photon from neutron capture
  • radius from centre of detector: gives a measure of background from neutrons

SNO Collaboration, Q.R. Ahmad et al., Phys. Rev. Lett. 89:011301, 2002

★ Using different distributions
  obtain a measure of numbers
  of events of each type:

CC : 1968 ± 61 $\propto \phi(\nu_e)$

ES :   264 ± 26 $\propto \phi(\nu_e) + 0.154[\phi(\nu_\mu) + \phi(\nu_\tau)]$

NC :   576 ± 50 $\propto \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)$

➡ Measure of electron neutrino flux + total flux !

★ Using known cross sections can convert observed numbers of events into fluxes

★ The different processes impose different constraints

★ Where constraints meet gives separate measurements of ν_e and $\nu_\mu + \nu_\tau$ fluxes

SNO Results:

$$\phi(\nu_e) = (1.8 \pm 0.1) \times 10^{-6}\, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$$

$$\phi(\nu_\mu) + \phi(\nu_\tau) = (3.4 \pm 0.6) \times 10^{-6}\, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$$

SSM Prediction:

$$\phi(\nu_e) = 5.1 \times 10^{-6}\, \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$$

- Clear evidence for a flux of ν_μ and/or ν_τ from the sun
- Total neutrino flux is consistent with expectation from SSM
- Clear evidence of $\nu_e \rightarrow \nu_\mu$ and/or $\nu_e \rightarrow \nu_\tau$ neutrino transitions

Interpretation of Solar Neutrino Data

★ The interpretation of the solar neutrino data is complicated by MATTER EFFECTS
  - The quantitative treatment is non-trivial and is not given here
  - Basic idea is that as a neutrino leaves the sun it crosses a region of high electron density
  - The coherent forward scattering process ($\nu_e \to \nu_e$ for an electron neutrino

$$\boxed{CC} \quad + \quad \boxed{NC}$$
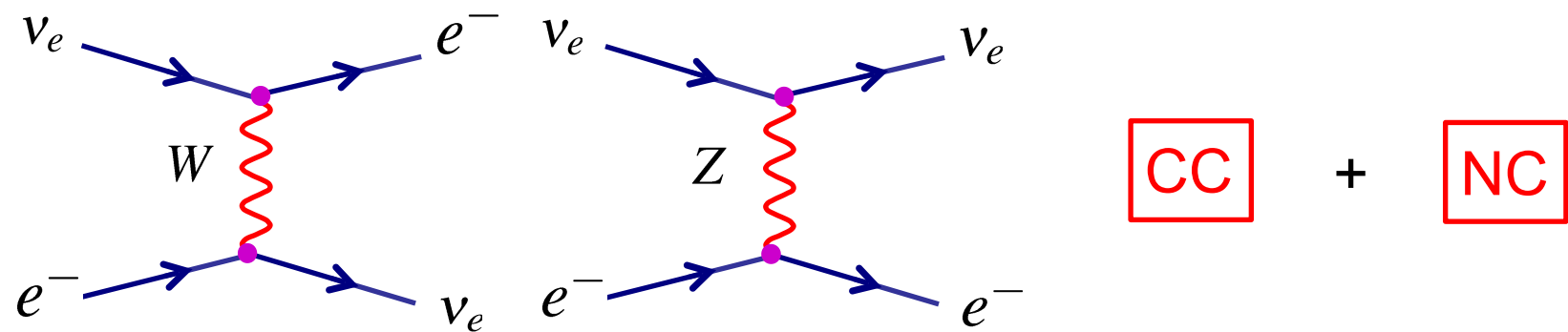
  is different to that for a muon or tau neutrino

$$\boxed{NC}$$
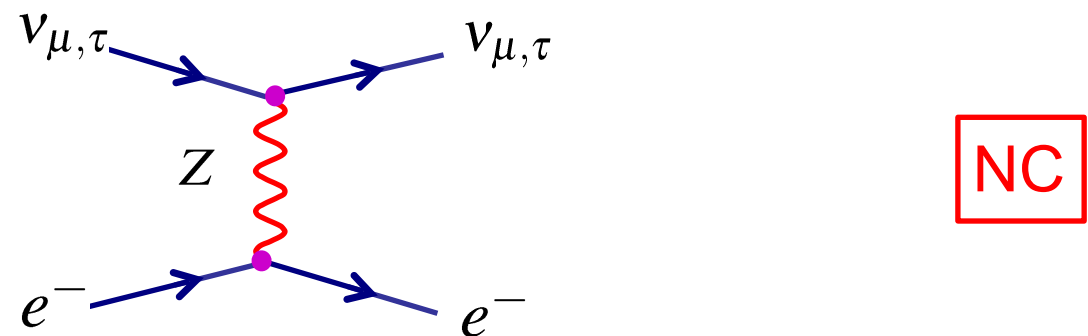
  - Can enhance oscillations – "MSW effect"

★ A combined analysis of all solar neutrino data gives:

$$\Delta m^2_{\text{solar}} \approx 8 \times 10^{-5}\,\text{eV}^2, \ \sin^2 2\theta_{\text{solar}} \approx 0.85$$

3) Reactor Experiments

- To explain reactor neutrino experiments we need the full three neutrino expression for the electron neutrino survival probability (11) which depends on U_{e1}, U_{e2}, U_{e3}
- Substituting these PMNS matrix elements in Equation (11):

$$
\begin{aligned}
P(\nu_e \to \nu_e) &\approx 1 - 4U_{e1}^2 U_{e2}^2 \sin^2 \Delta_{21} - 4(1 - U_{e3}^2)U_{e3}^2 \sin^2 \Delta_{32} \\
&= 1 - 4(c_{12}c_{13})^2(s_{12}c_{13})^2 \sin^2 \Delta_{21} - 4(1 - s_{13}^2)s_{13}^2 \sin^2 \Delta_{32} \\
&= 1 - c_{13}^4(2s_{12}c_{12})^2 \sin^2 \Delta_{21} - (2c_{13}s_{13})^2 \sin^2 \Delta_{32} \\
&= 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{32}
\end{aligned}
$$

- Contributions with short wavelength (atmospheric) and long wavelength (solar)
- For a 1 MeV neutrino

$$
\lambda_{\mathrm{osc}}(\mathrm{km}) = 2.47 \frac{E(\mathrm{GeV})}{\Delta m^2 (\mathrm{eV}^2)}
$$

$$\Rightarrow \quad \lambda_{21} = 30.0\,\mathrm{km}$$

$$\lambda_{32} = 0.8\,\mathrm{km}$$

- Amplitude of short wavelength oscillations given by

$$\sin^2 2\theta_{13}$$
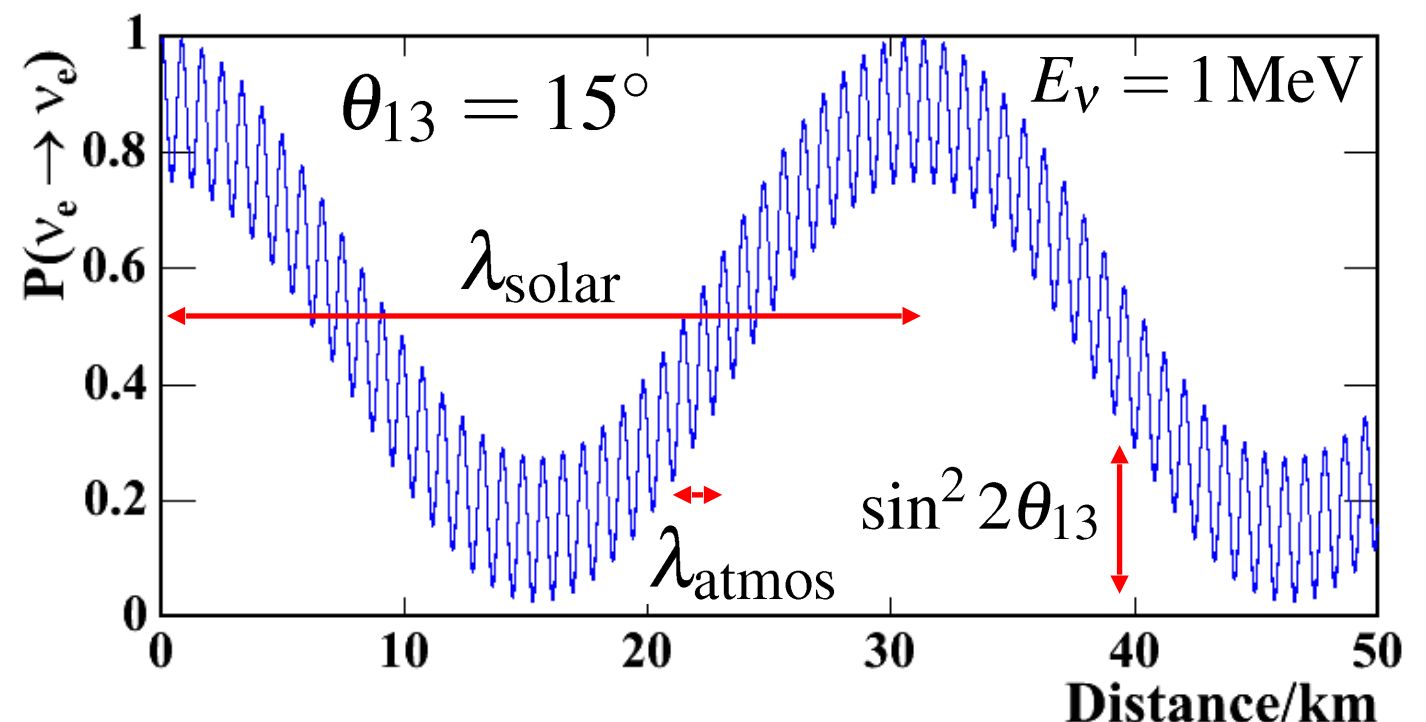
Reactor Experiments I : CHOOZ

- Two nuclear reactors, each producing 4.2 GW
- Place detector 1km from reactor cores
- Reactors produce intense flux of $\overline{\nu}_e$

France
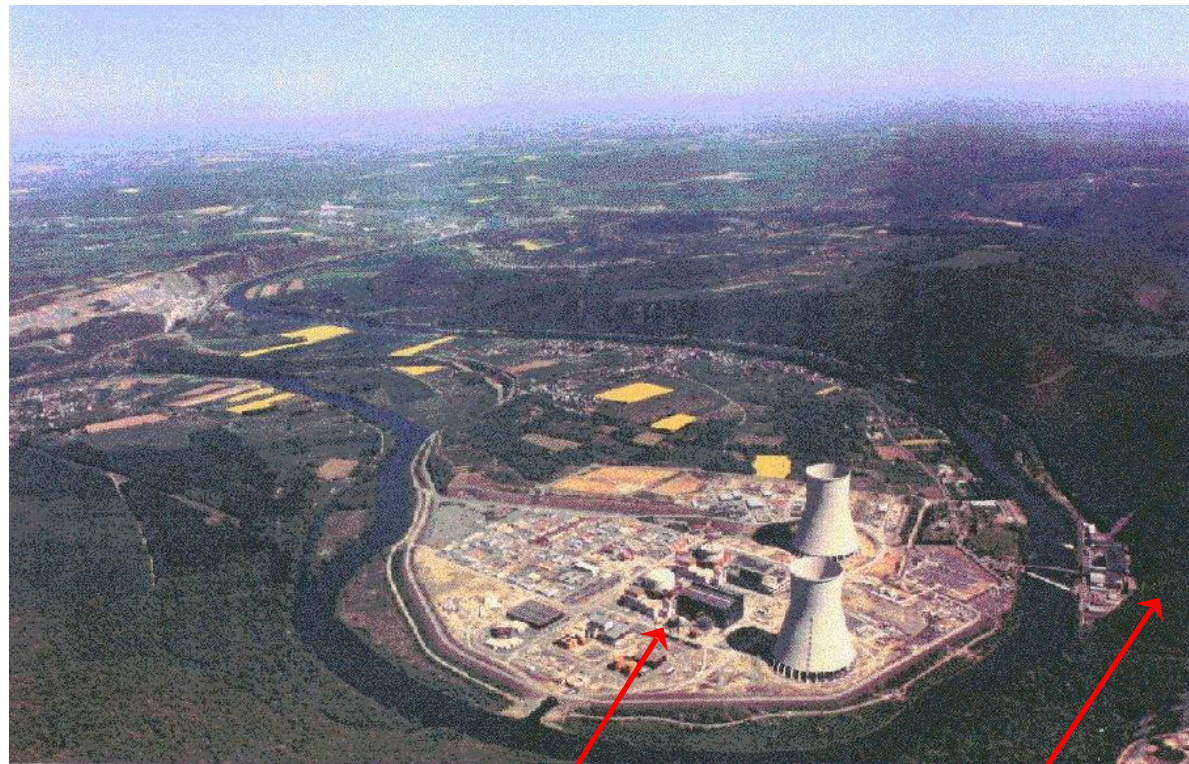
reactors

Detector
150m underground

Detector

- Anti-neutrinos interact via inverse beta decay $\quad \overline{\nu}_e + p \rightarrow e^+ + n$
- Detector is liquid scintillator loaded with Gadolinium (large n capture cross section)
- Detect photons from positron annihilation and a delayed signal from photons
  from neutron capture on Gadolinium
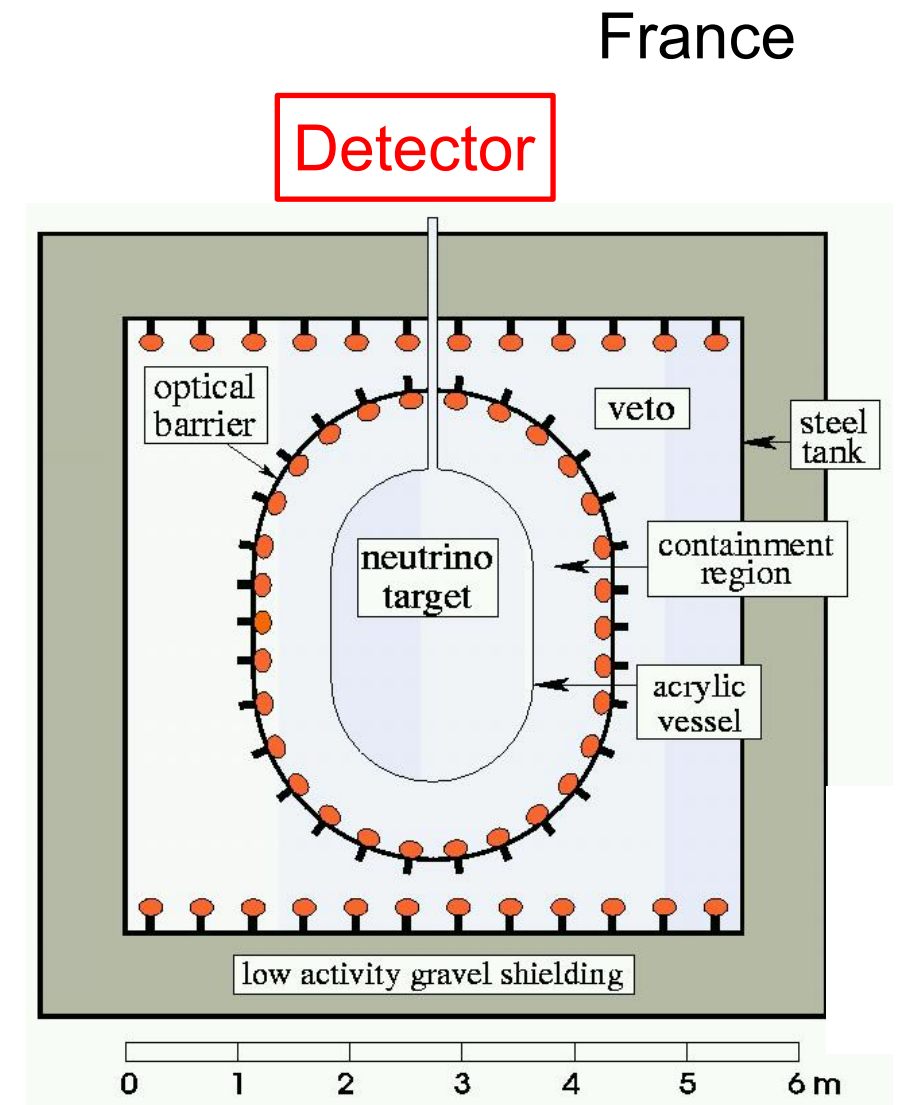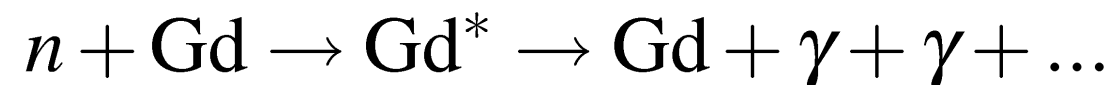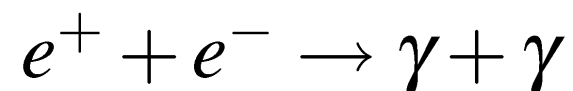
$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$n + \mathrm{Gd} \rightarrow \mathrm{Gd}^* \rightarrow \mathrm{Gd} + \gamma + \gamma + \ldots$$

- At 1km and energies > 1 MeV, only the short wavelength component matters

$$P(\nu_e \rightarrow \nu_e) \quad = \quad 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32} \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

CHOOZ Raw Data

Background subtracted

Compare to effect of oscillations

$\sin^2 2\theta_{13}$

$\theta_{13} = 15°$
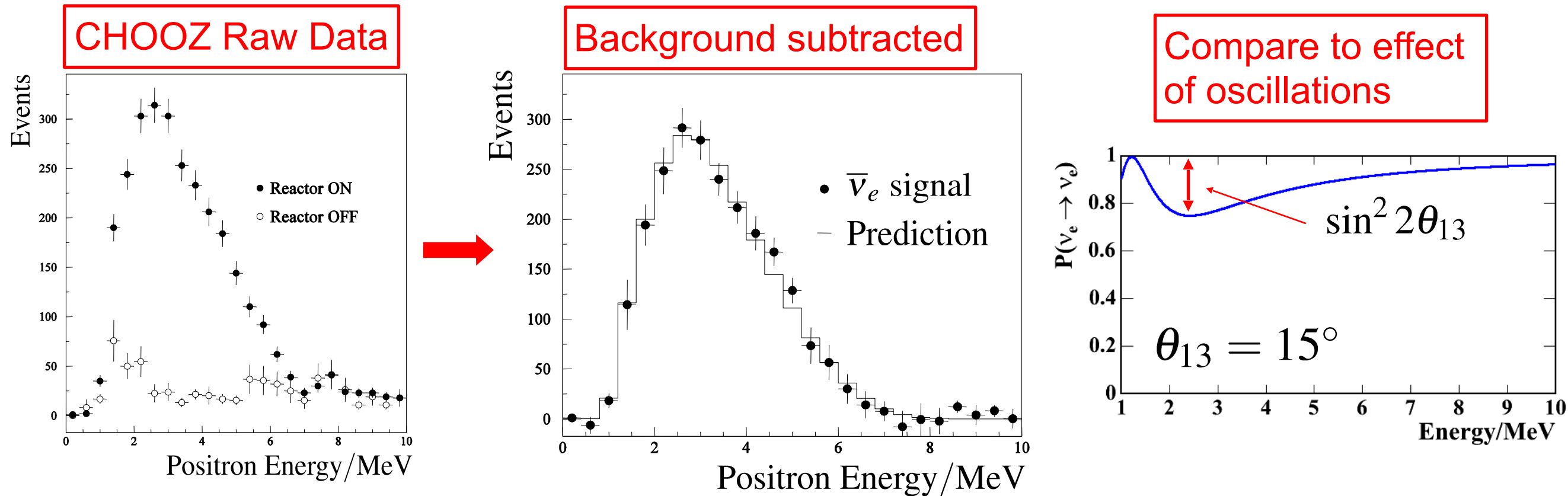
★ Data agree with unoscillated prediction both in terms of rate and energy spectrum

$$N_{\text{data}}/N_{\text{expect}} = 1.01 \pm 0.04$$

CHOOZ Collaboration,
M.Apollonio et al.,
Phys. Lett. B420, 397-404, 1998

★ Hence $\sin^2 2\theta_{13}$ must be small !

$$\sin^2 2\theta_{13} < 0.12 - 0.2$$

Exact limit depends on $|\Delta m^2_{32}|$

★ From atmospheric neutrinos (see appendix) can exclude $\theta_{13} \sim \frac{\pi}{2}$

- Hence the CHOOZ limit: $\sin^2 2\theta_{13} < 0.2$ can be interpreted as $\sin^2\theta_{13} < 0.05$

Reactor Experiments II : KamLAND
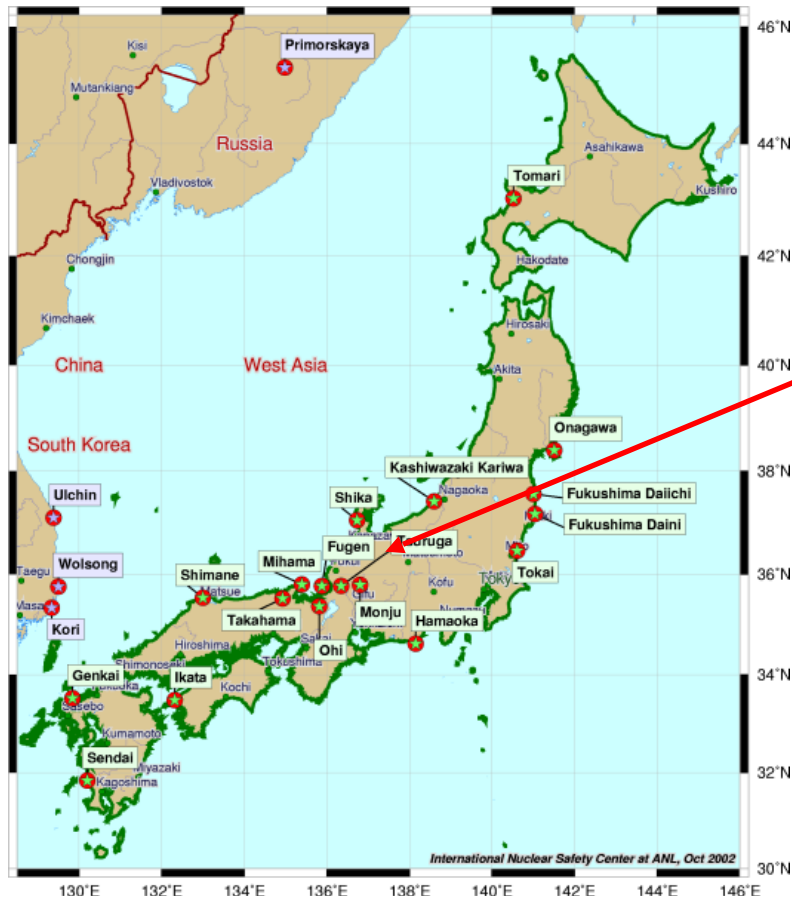
•Detector located in same mine as Super Kamiokande

18m
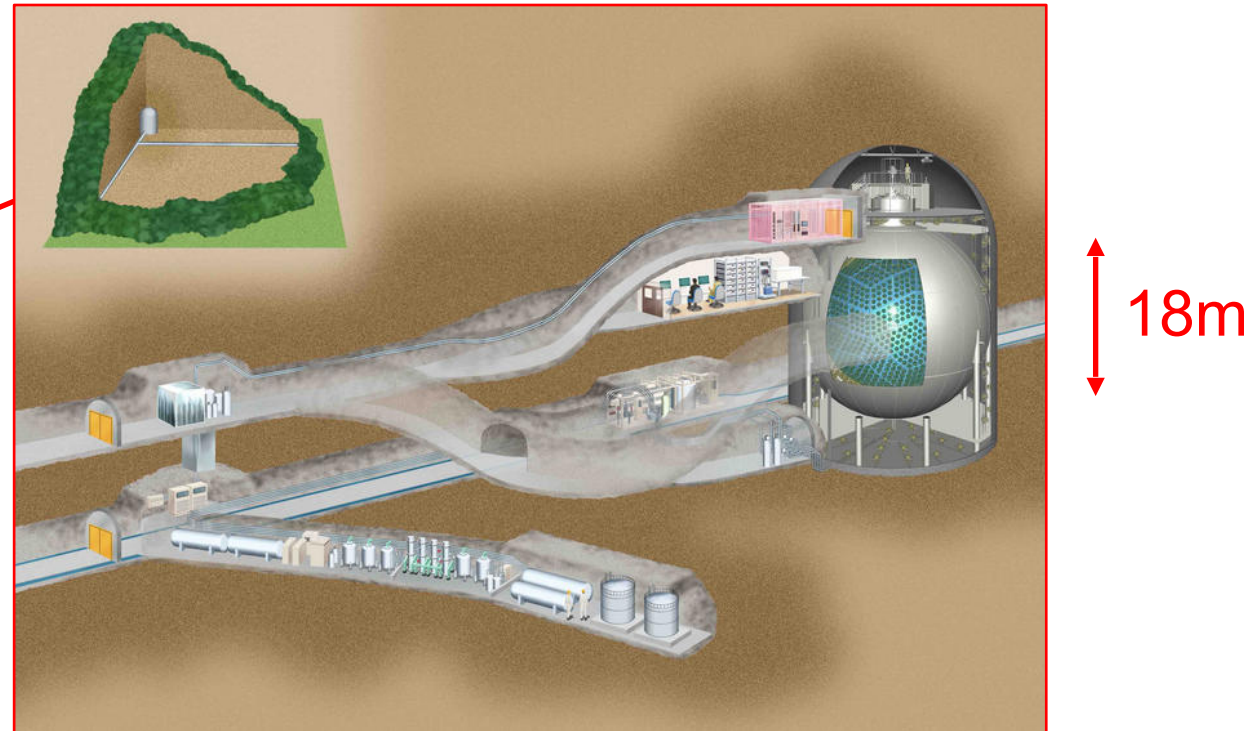
- 70 GW from nuclear power (7% of World total) from reactors within 130-240 km
- Liquid scintillator detector, 1789 PMTs
- Detection via inverse beta decay: $\quad \nu_e + p \rightarrow e^+ + n$

  Followed by $\qquad e^+ + e^- \rightarrow \gamma + \gamma \qquad$ prompt

  $\qquad\qquad\quad n + p \rightarrow d + \gamma(2.2\,\text{MeV}) \qquad$ delayed

- For MeV neutrinos at a distance of 130-240 km oscillations due to Δm_{32}^2 are very rapid

- Experimentally, only see average effect

$$\langle \sin^2 \Delta_{32} \rangle = 0.5$$

$$\sin^2 2\theta_{13} = 0.15 \qquad E_\nu = 2\,\text{MeV}$$

★ Here:

$$
\begin{aligned}
P(\nu_e \to \nu_e) \;&=\; 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 \Delta_{32} \\
&\approx\; 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \frac{1}{2}\sin^2 2\theta_{13} \\
&=\; \cos^4 \theta_{13} + \sin^4 \theta_{13} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \\
&\approx\; \cos^4 \theta_{13}(1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}) \qquad \text{neglect } \sin^4 \theta_{13}
\end{aligned}
$$

Averaging over rapid oscillations

- Obtain two-flavour oscillation formula multiplied by $\cos^4 \theta_{13}$
- From CHOOZ $\quad \cos^4 \theta_{13} > 0.9$
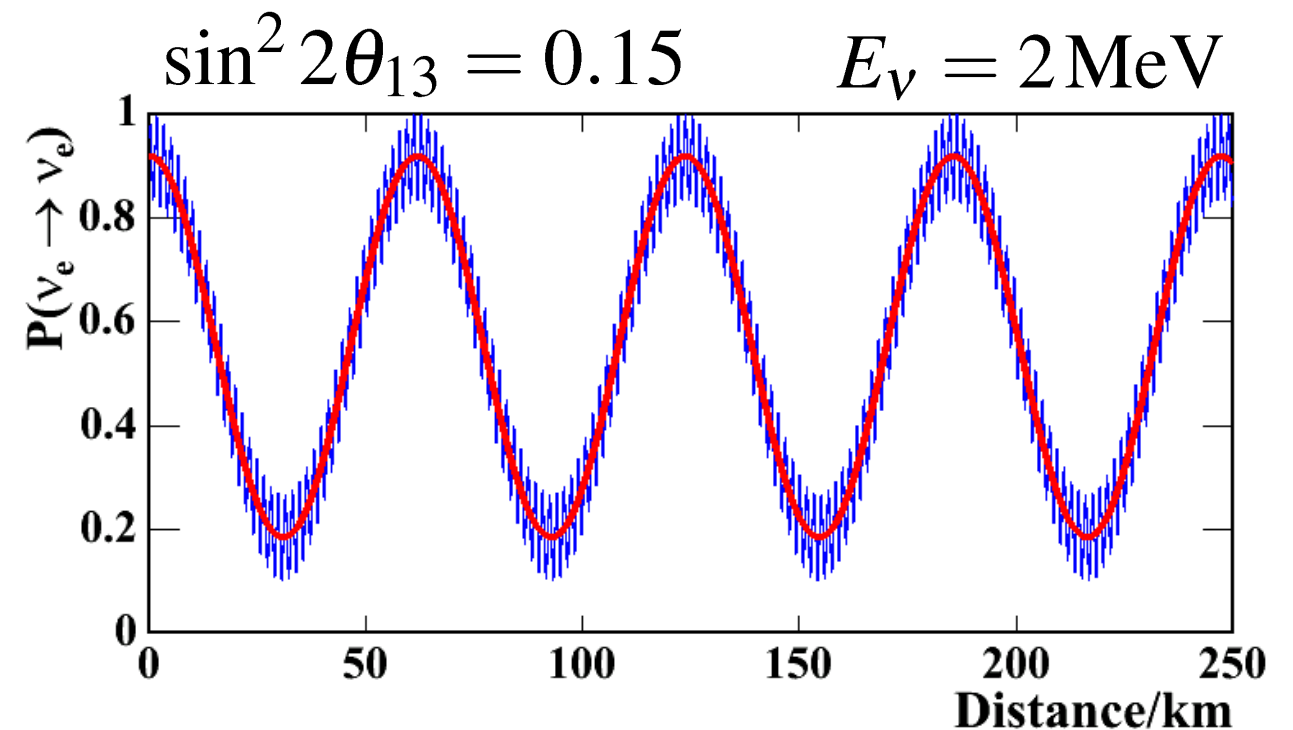
KamLAND RESULTS:

Observe: 1609 events
Expect: 2179±89 events (if no oscillations)

KamLAND Collaboration, Phys. Rev. Lett., 221803, 2008
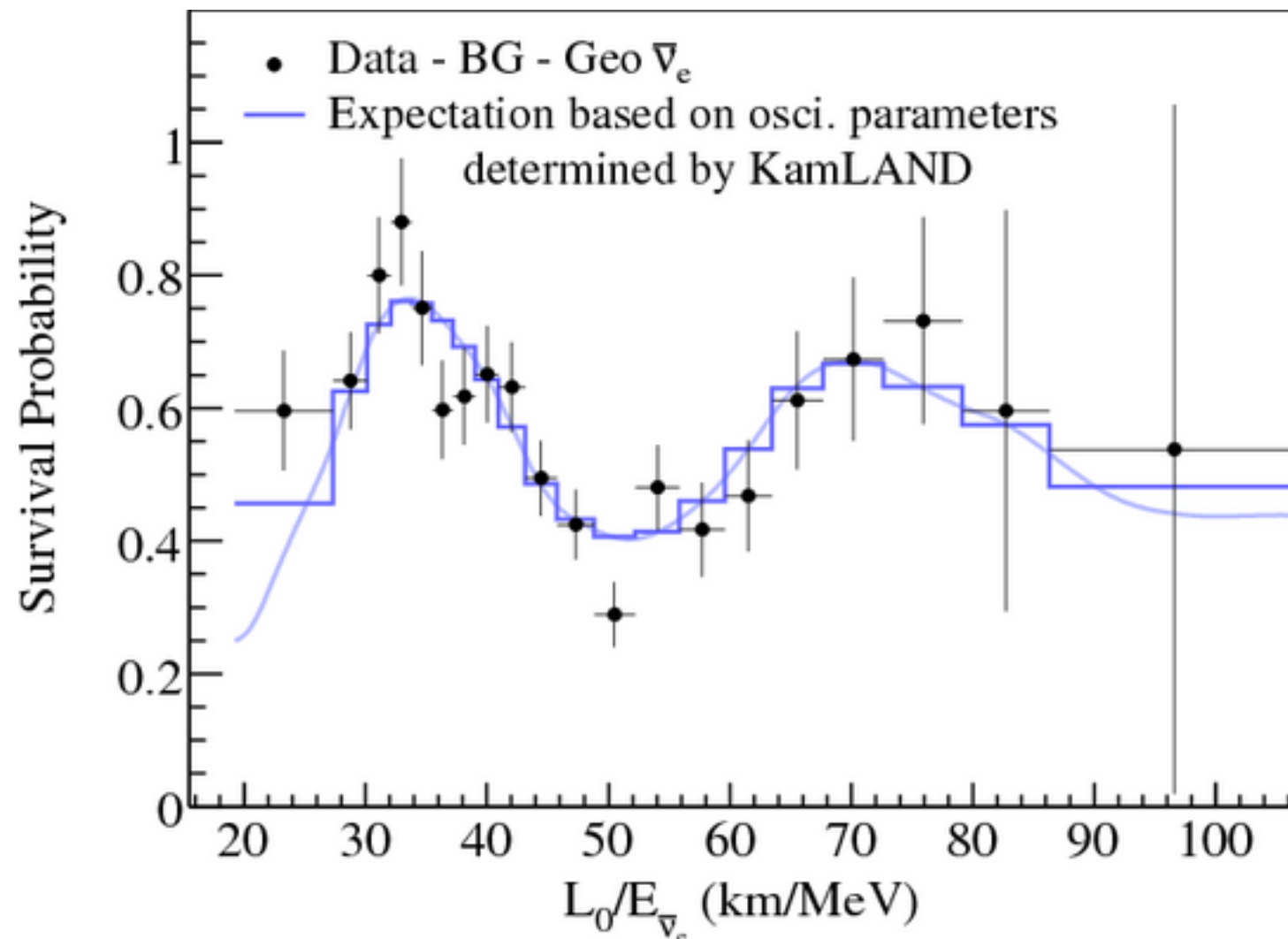
★Clear evidence of electron anti-neutrino oscillations consistent with the results from solar neutrinos

★Oscillatory structure clearly visible

★Compare data with expectations for different osc. parameters and perform χ^2 fit to extract measurment

Combined Solar Neutrino and KamLAND Results

★ KamLAND data provides strong constraints on $|\Delta m_{21}^2|$

★ Solar neutrino data (especially SNO) provides a strong constraint on θ_{12}
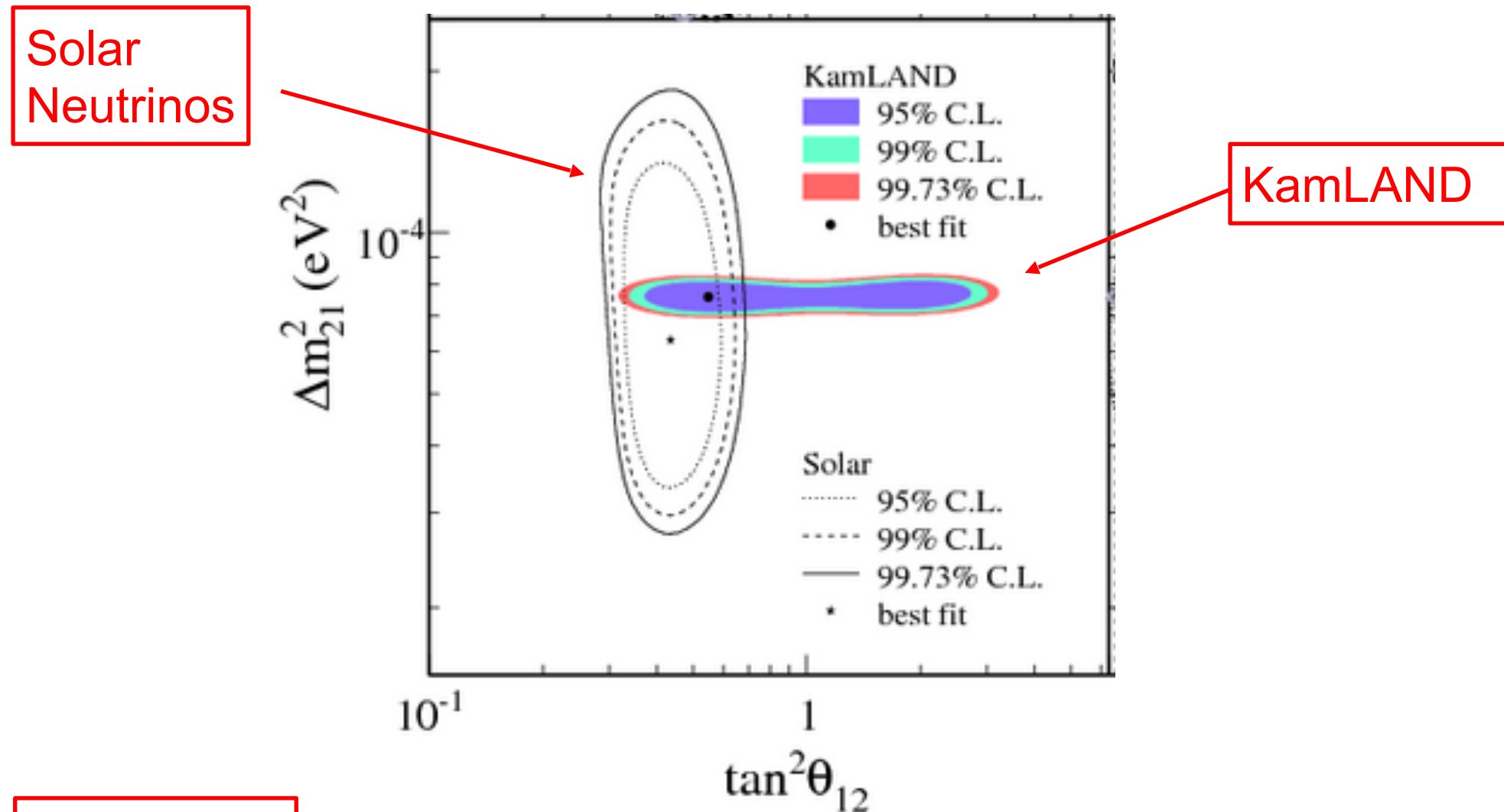
$$|\Delta m_{21}^2| = (7.59 \pm 0.21) \times 10^{-5}\,\mathrm{eV}^2 \qquad \tan^2 \theta_{12} = 0.47^{+0.06}_{-0.05}$$

Atmospheric Neutrinos

- **High energy cosmic rays** (up to 10^{20} eV) interact in the upper part of the Earth's atmosphere
- The cosmic rays (~86% protons, 11% He Nuclei, ~1% heavier nuclei, 2% electrons) mostly interact hadronically giving showers of mesons (mainly pions)

- Neutrinos produced by:

$$\pi^+ \to \mu^+ \nu_\mu \qquad \pi^- \to \mu^- \overline{\nu}_\mu$$
$$\hookrightarrow e^+ \nu_e \overline{\nu}_\mu \qquad \hookrightarrow e^- \overline{\nu}_e \nu_\mu$$
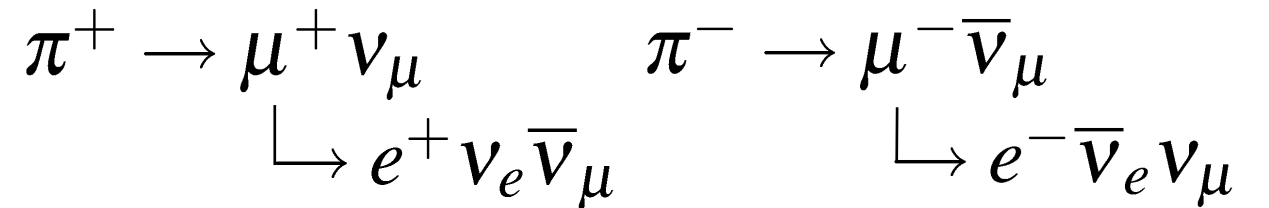
- Flux $\quad \sim 1\,\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$
- Typical energy : $\quad E_\nu \sim 1\,\mathrm{GeV}$
- Expect $\quad \dfrac{N(\nu_\mu + \overline{\nu}_\mu)}{N(\nu_e + \overline{\nu}_e)} \approx 2$
- Observe a lower ratio with deficit of $\nu_\mu / \overline{\nu}_\mu$ coming from below the horizon, i.e. large distance from production point on other side of the Earth
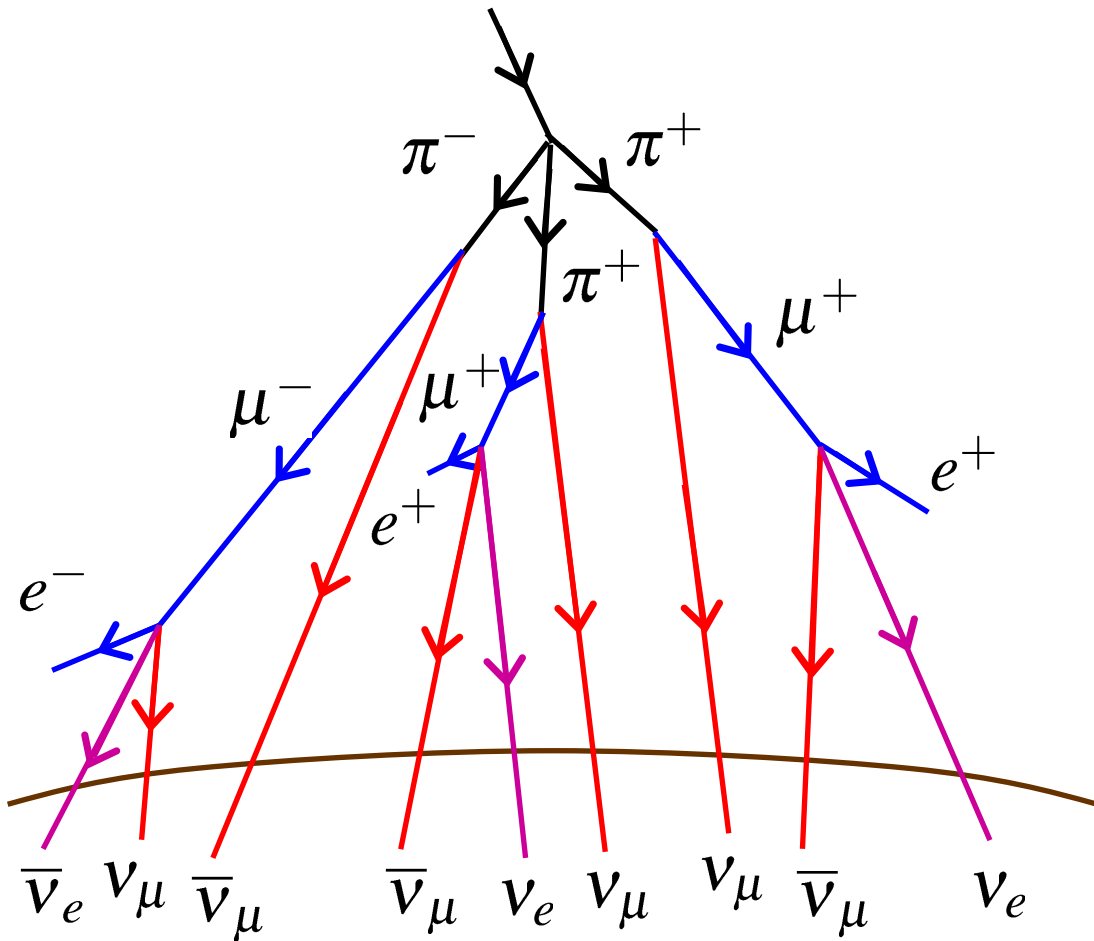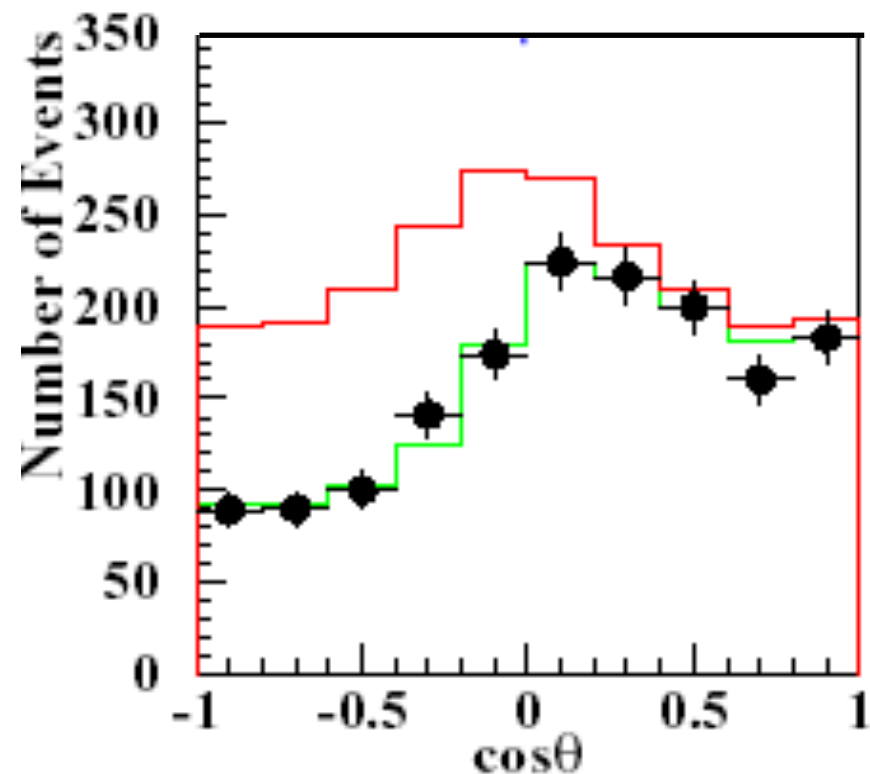
Super Kamiokande Atmospheric Results

- Typical energy: $E_\nu \sim 1\,\mathrm{GeV}$ (much greater than solar neutrinos – no confusion)
- Identify ν_e and ν_μ interactions from nature of Čerenkov rings
- Measure rate as a function of angle with respect to local vertical
- Neutrinos coming from above travel ~20 km
- Neutrinos coming from below (i.e. other side of the Earth) travel ~12800 km
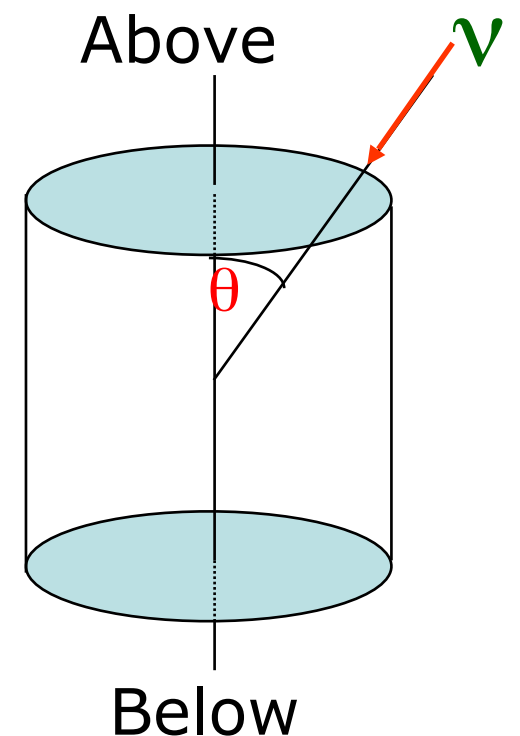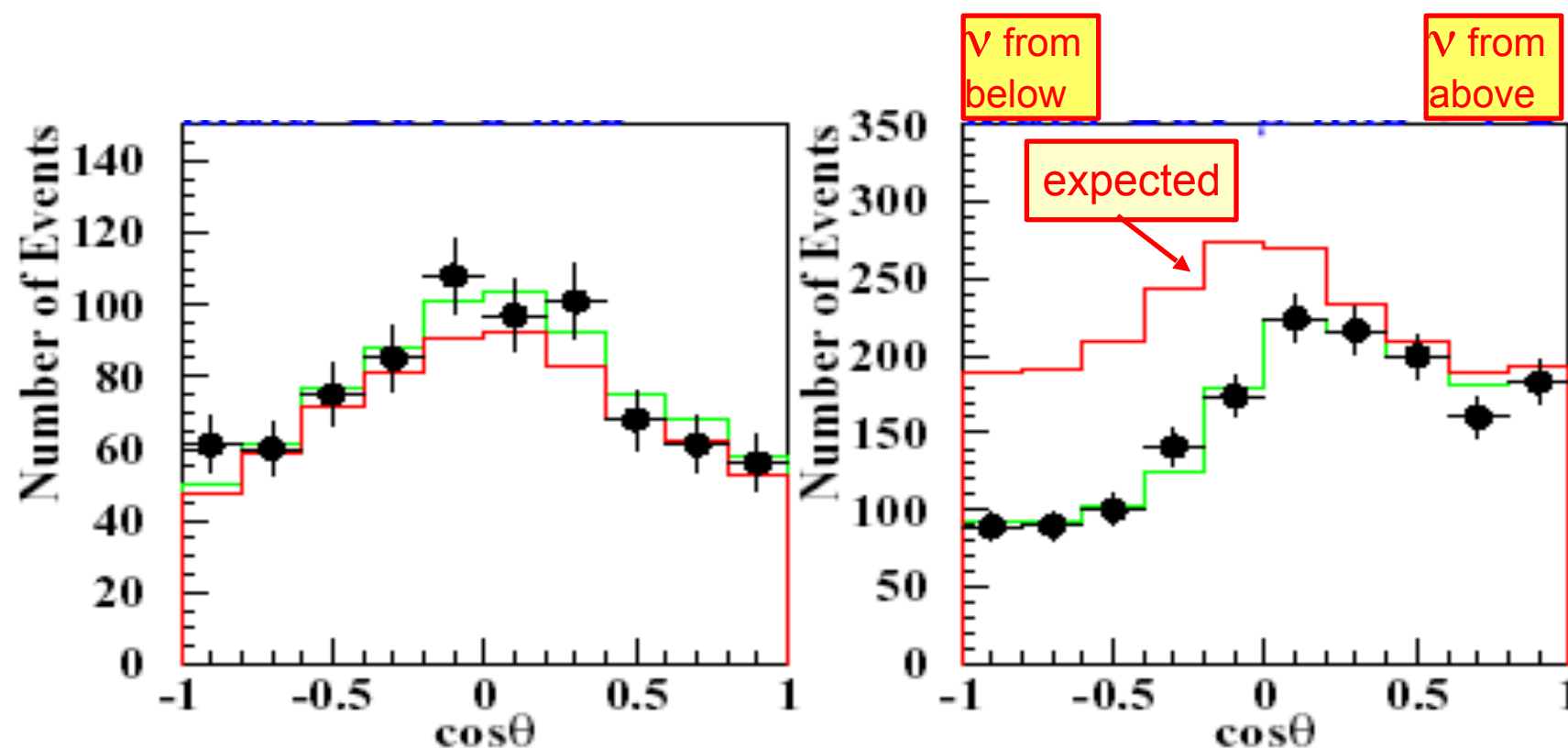
★ Prediction for ν_e rate agrees with data
★ Strong evidence for disappearance of ν_μ for large distances
★ Consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations
★ Don't detect the oscillated ν_τ as typically below interaction threshold of 3.5 GeV

Interpretation of Atmospheric Neutrino Data

- Measure muon direction and energy not neutrino direction/energy
- Don't have E/θ resolution to see oscillations
- Oscillations "smeared" out in data
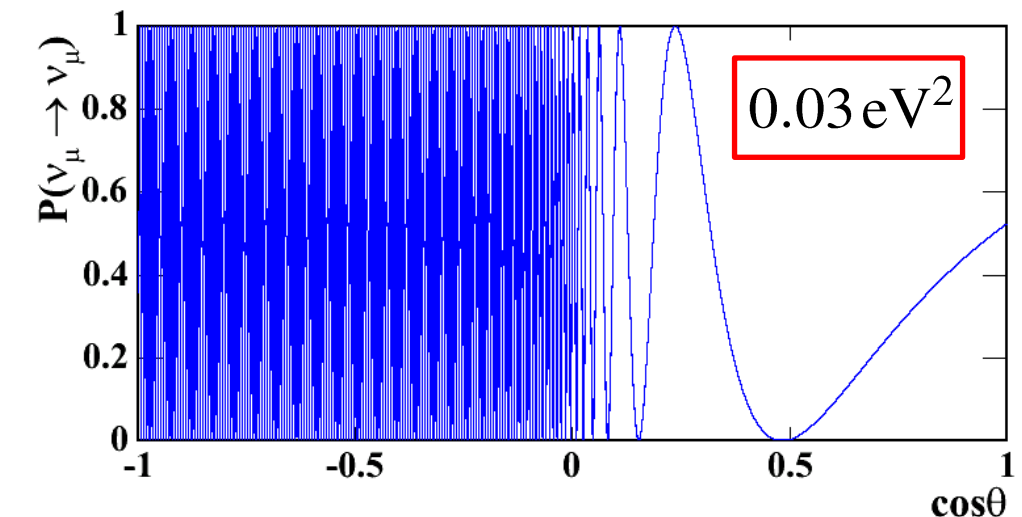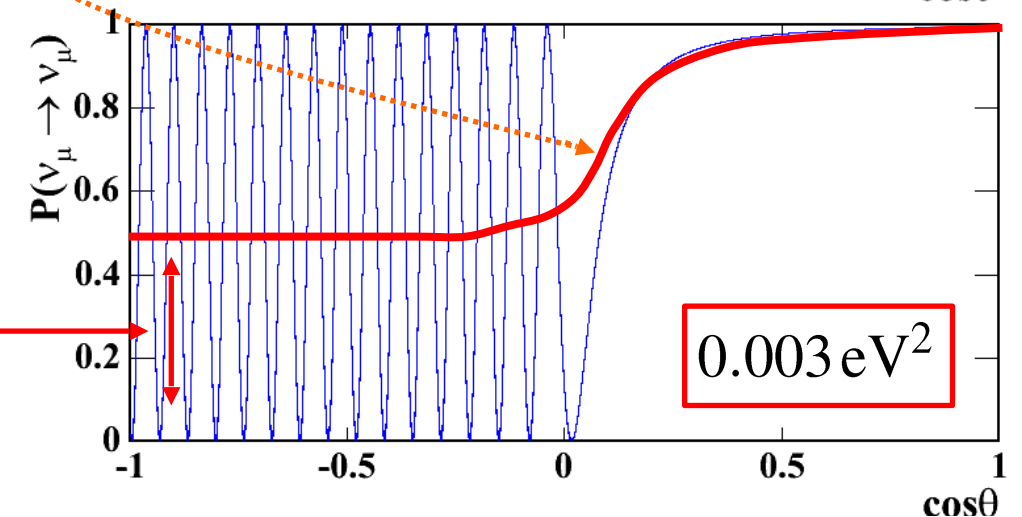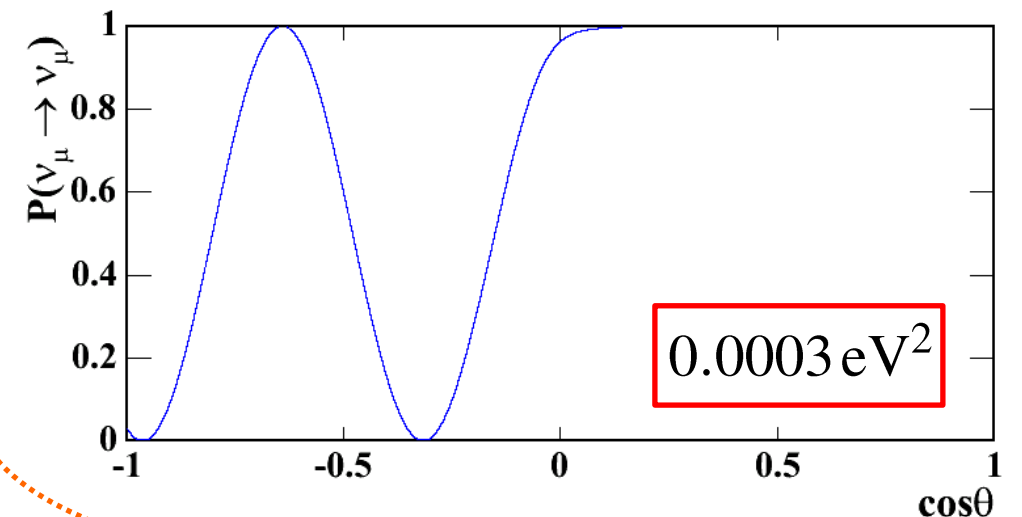- Compare data to predictions for $|\Delta m^2|$

$$1 - \tfrac{1}{2}\sin^2 2\theta$$

★ Data consistent with:

$$|\Delta m^2_{\text{atmos}}| \approx 0.0025\,\text{eV}^2$$
$$\sin^2 2\theta_{\text{atmos}} \approx 1$$

Summary of Current Knowledge

SOLAR Neutrinos/KamLAND

KamLAND + Solar: $\qquad |\Delta m_{21}^2| \approx (7.6 \pm 0.2) \times 10^{-5}\,\mathrm{eV}^2$

SNO + KamLAND + Solar: $\quad \tan^2 \theta_{12} \approx 0.47 \pm 0.05$

➡ $\quad \sin \theta_{12} \approx 0.56; \qquad \cos \theta_{12} \approx 0.82$

Atmospheric Neutrinos/Long Baseline experiments

MINOS: $\qquad |\Delta m_{32}^2| \approx (2.4 \pm 0.1) \times 10^{-3}\,\mathrm{eV}^2$

Super Kamiokande: $\quad \sin^2 2\theta_{23} > 0.92$

$$\cos \theta_{23} \approx \sin \theta_{23} \approx \frac{1}{\sqrt{2}}$$

CHOOZ + (atmospheric) $\qquad\qquad$ 2011 hints

$$\sin^2 2\theta_{13} < 0.15 \qquad\qquad \sin^2 2\theta_{13} \approx 0.04 - 0.08\,?$$

★Currently no knowledge about CP violating phase $\quad \delta$

- Regardless of uncertainty in θ_{13}

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \approx \begin{pmatrix} c_{12} & s_{12} & ? \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23} \\ s_{12}s_{23} & -c_{12}s_{23} & c_{23} \end{pmatrix}$$

- For the approximate values of the mixing angles on the previous page obtain:
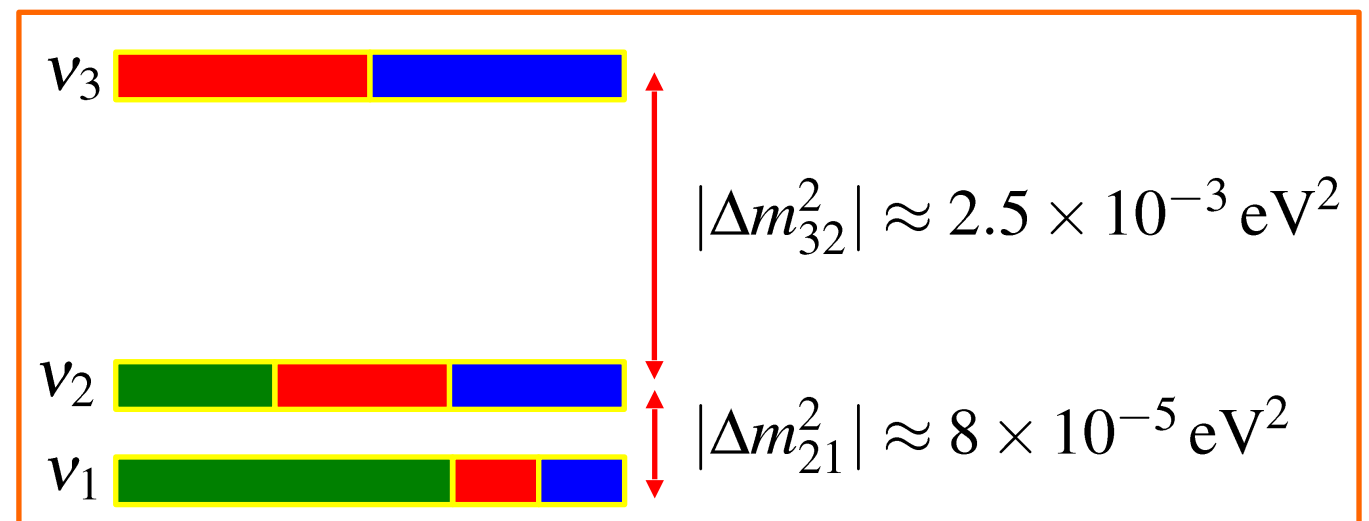
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \approx \begin{pmatrix} 0.85 & 0.53 & 0.1e^{i\delta}? \\ -0.37 & 0.60 & 0.71 \\ 0.37 & -0.60 & 0.71 \end{pmatrix}$$

★Have approximate expressions for mass eigenstates in terms of weak eigenstates:

$$|\nu_3\rangle \approx \frac{1}{\sqrt{2}}(|\nu_\mu\rangle + |\nu_\tau\rangle)$$

$$|\nu_2\rangle \approx 0.53|\nu_e\rangle + 0.60(|\nu_\mu\rangle - |\nu_\tau\rangle)$$

$$|\nu_1\rangle \approx 0.85|\nu_e\rangle - 0.37(|\nu_\mu\rangle - |\nu_\tau\rangle)$$

$$|\Delta m_{32}^2| \approx 2.5 \times 10^{-3}\,\text{eV}^2$$

$$|\Delta m_{21}^2| \approx 8 \times 10^{-5}\,\text{eV}^2$$
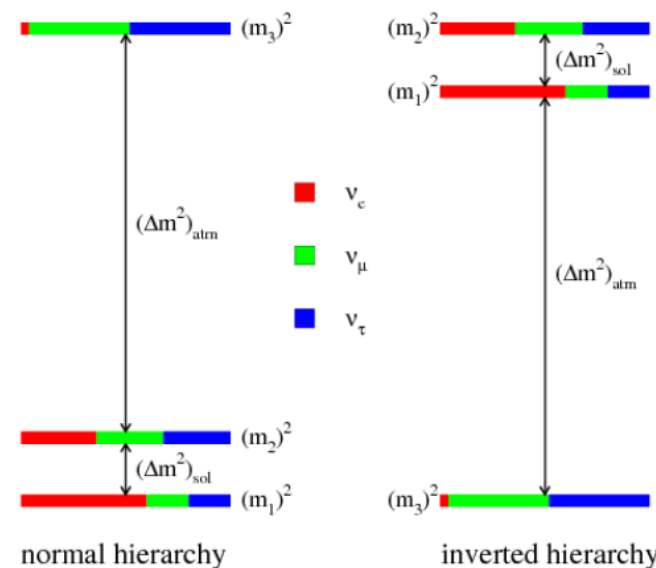
News from T2K (Summer 2016)

H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF)
ON BEHALF OF THE T2K COLLABORATION

- **$\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$**

  - enhance/suppress both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- **CP violating parameter δ_{CP}**   *up to ±30% effect at T2K*

  - $\delta_{CP}=0,\pi$: no CP violation: vacuum oscillation probabilities equal

  - $\delta_{CP} \sim -\pi/2$: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

  - $\delta_{CP} \sim +\pi/2$: suppress $\nu_\mu \rightarrow \nu_e$, enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

"normal" hierarchy (NH):

- enhance $\nu_\mu \rightarrow \nu_e$

- suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

±10% effect at T2K

"inverted" hierarchy: (IH)

- suppress $\nu_\mu \rightarrow \nu_e$

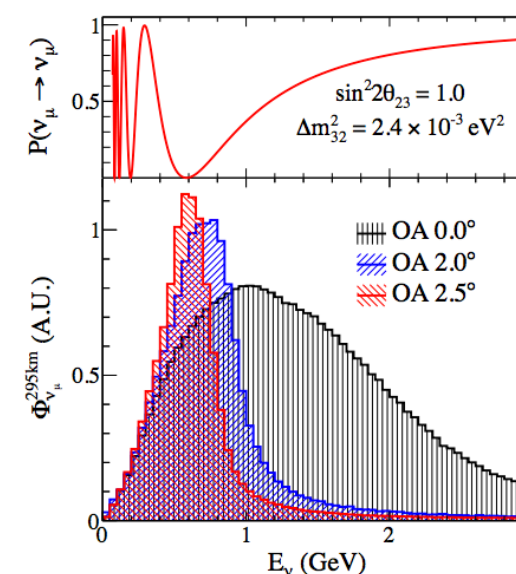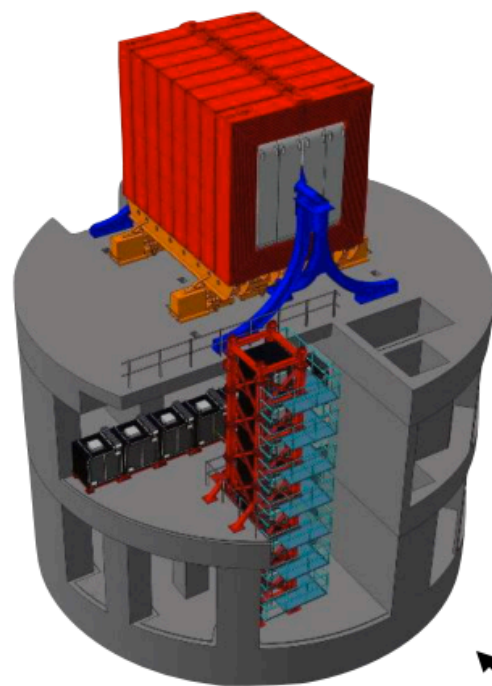- enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

News from T2K (Summer 2016)

H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF)
ON BEHALF OF THE T2K COLLABORATION

PRODUCING THE BEAM
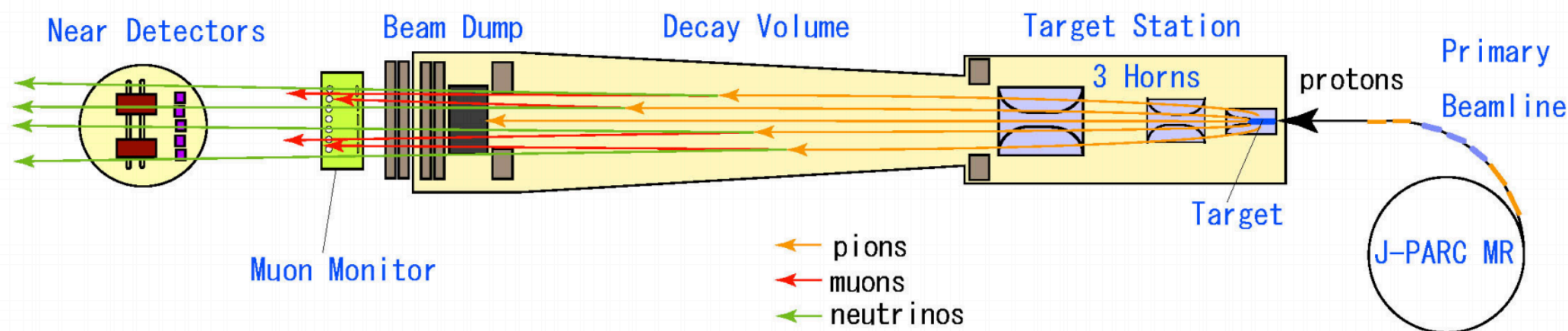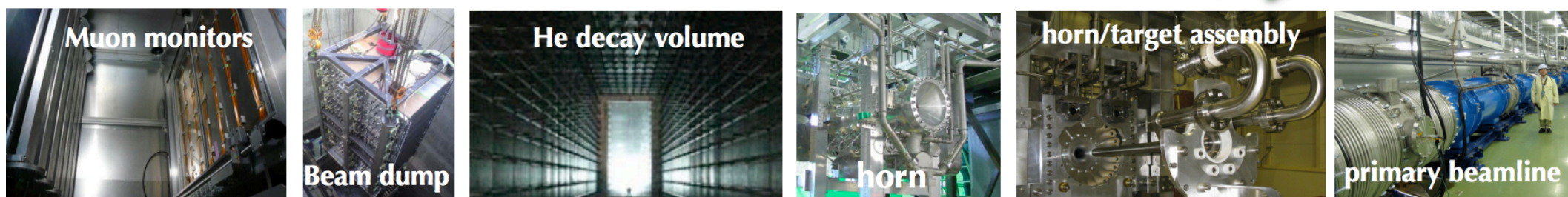
- 30 GeV protons extracted from J-PARC MR to carbon target

  - secondary π^+ focussed by three magnetic "horns"

  - primarily ν_μ beam from $\pi^+ \to \mu^+ + \nu_\mu$

    - reverse polarity for antineutrino beam: $\pi^- \to \mu^- + \bar{\nu}_\mu$

  - spectrum peaked at 600 MeV 2.5° "off axis" towards SK

    - expected oscillation "maximum" for L=295 km

8

News from T2K (Summer 2016)

H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF)
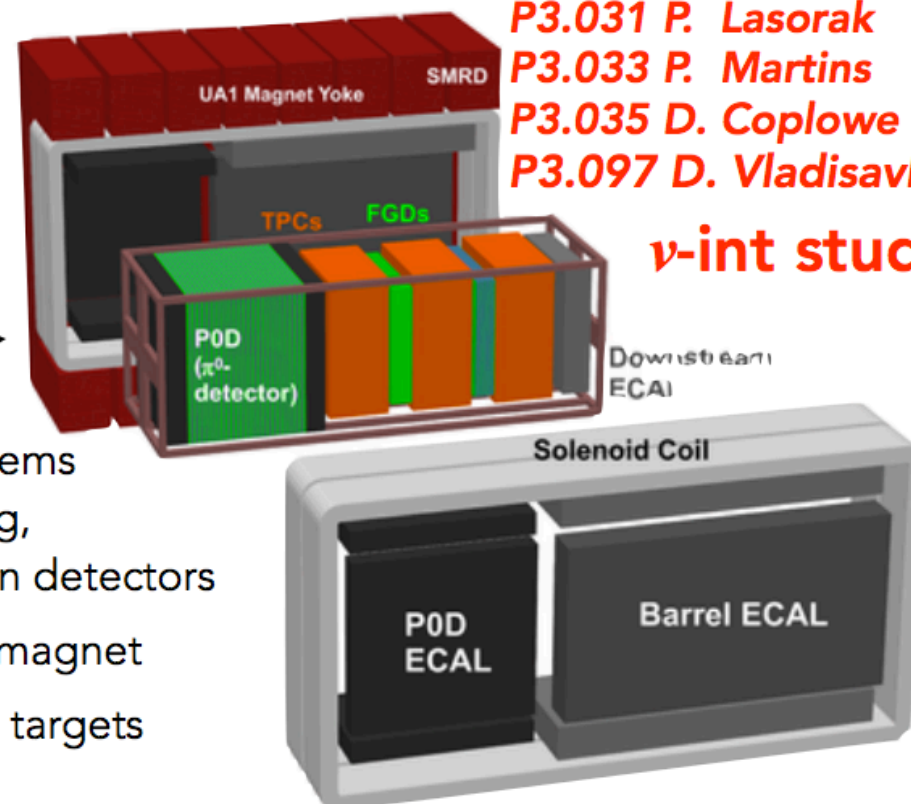ON BEHALF OF THE T2K COLLABORATION

P1.042 D. Shaw
P3.031 P. Lasorak
P3.033 P. Martins
P3.035 D. Coplowe
P3.097 D. Vladisavljevic

NEAR DETECTORS

ν-int studies

ν

ND280:

- off-axis detector systems comprised of tracking, calorimetry and muon detectors
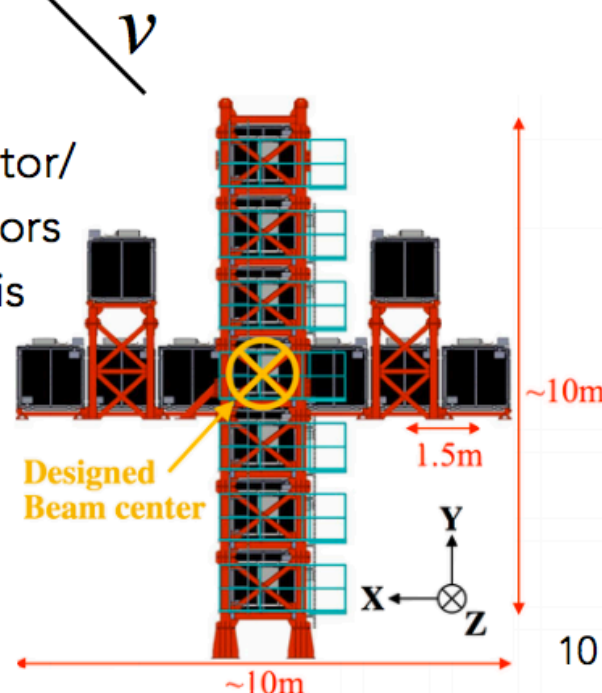- 0.2 T field from UA1 magnet
- scintillator and water targets

ν

INGRID

- 7x7 grid of scintillator/Fe neutrino detectors spanning beam axis
- monitor beam direction and rate

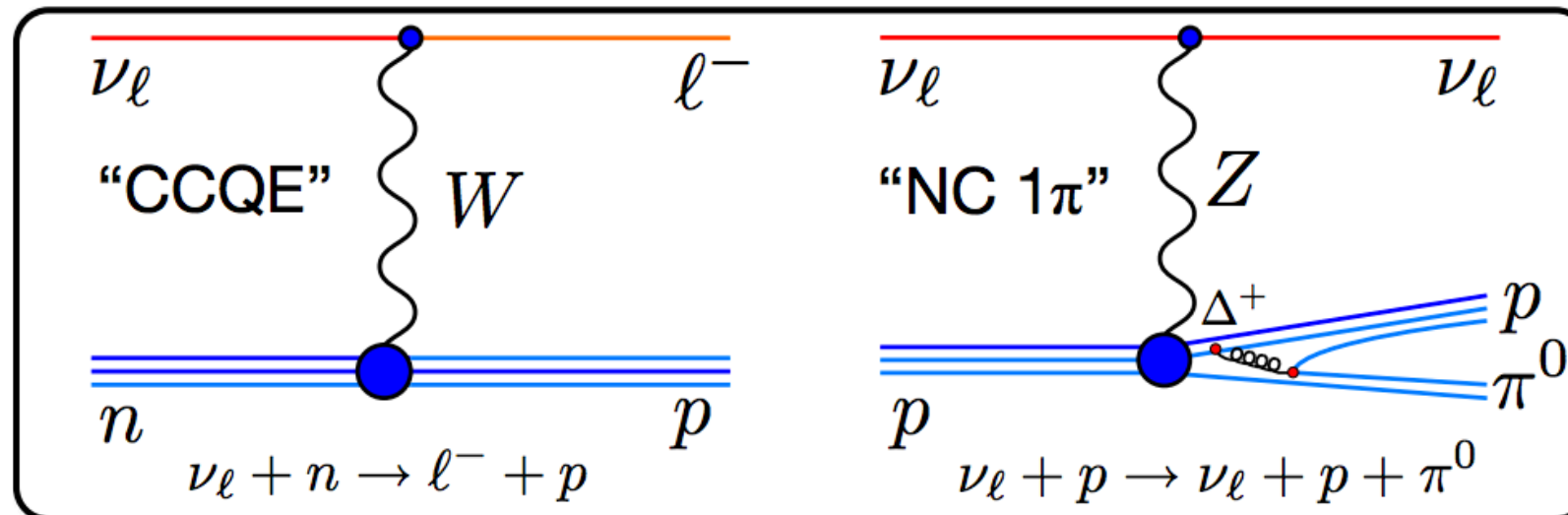**P1.036 T. Hayashino**

Exotics   **P3.074 S. Bordoni P4.014 A. Izmaylov**
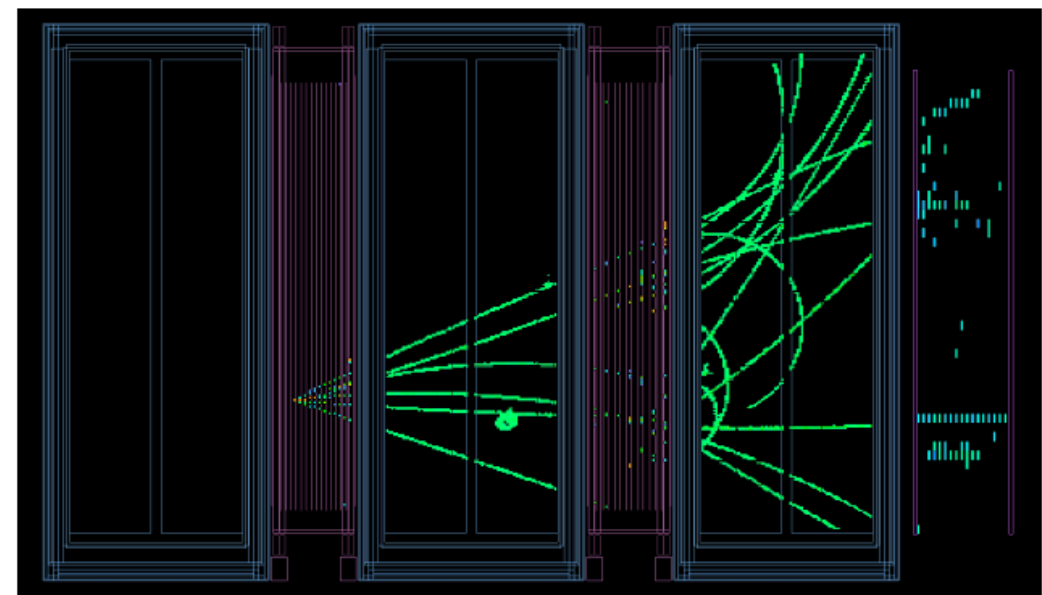
Reconstruction   **P3.029 L. Koch**
P3.034 J. Zalipska

H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF) ON BEHALF OF THE T2K COLLABORATION

NEUTRINOS AT T2K-SK

"CCQE" W

$\nu_\ell + n \to \ell^- + p$

"NC 1π" Z

Δ^+

$\nu_\ell + p \to \nu_\ell + p + \pi^0$

Signal

$\nu_\ell + n \to \ell^- + p \qquad \bar{\nu} + p \to \ell^+ + n$

- Single μ/e-like ring
- E_{rec} by energy/direction of lepton, 2-body kinematics

Backgrounds

$\nu_\ell + (n/p) \to \nu_\ell + (n/p) + \pi^0$
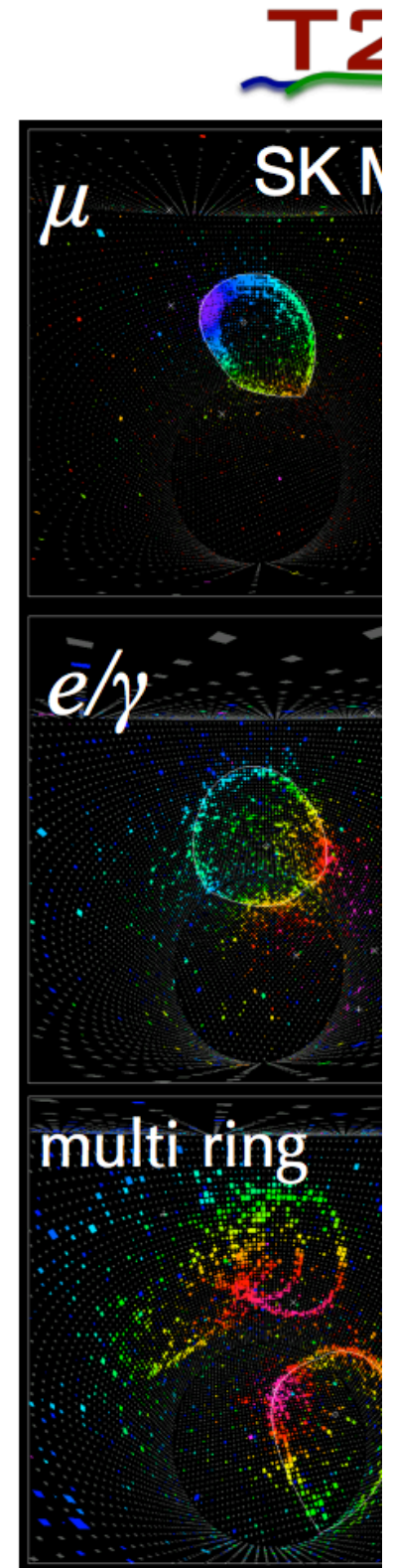$\nu_\ell + (n/p) \to \ell^- + (n/p) + \pi$

- $\pi^0 \to \gamma + \gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
  - powerful rejection capabilities reduce this by $O(10^2)$
- Ring counting, decay electron cut to reject nCCQE

- Pure ν_e samples (S/B~10 at peak) obtained with high efficiency
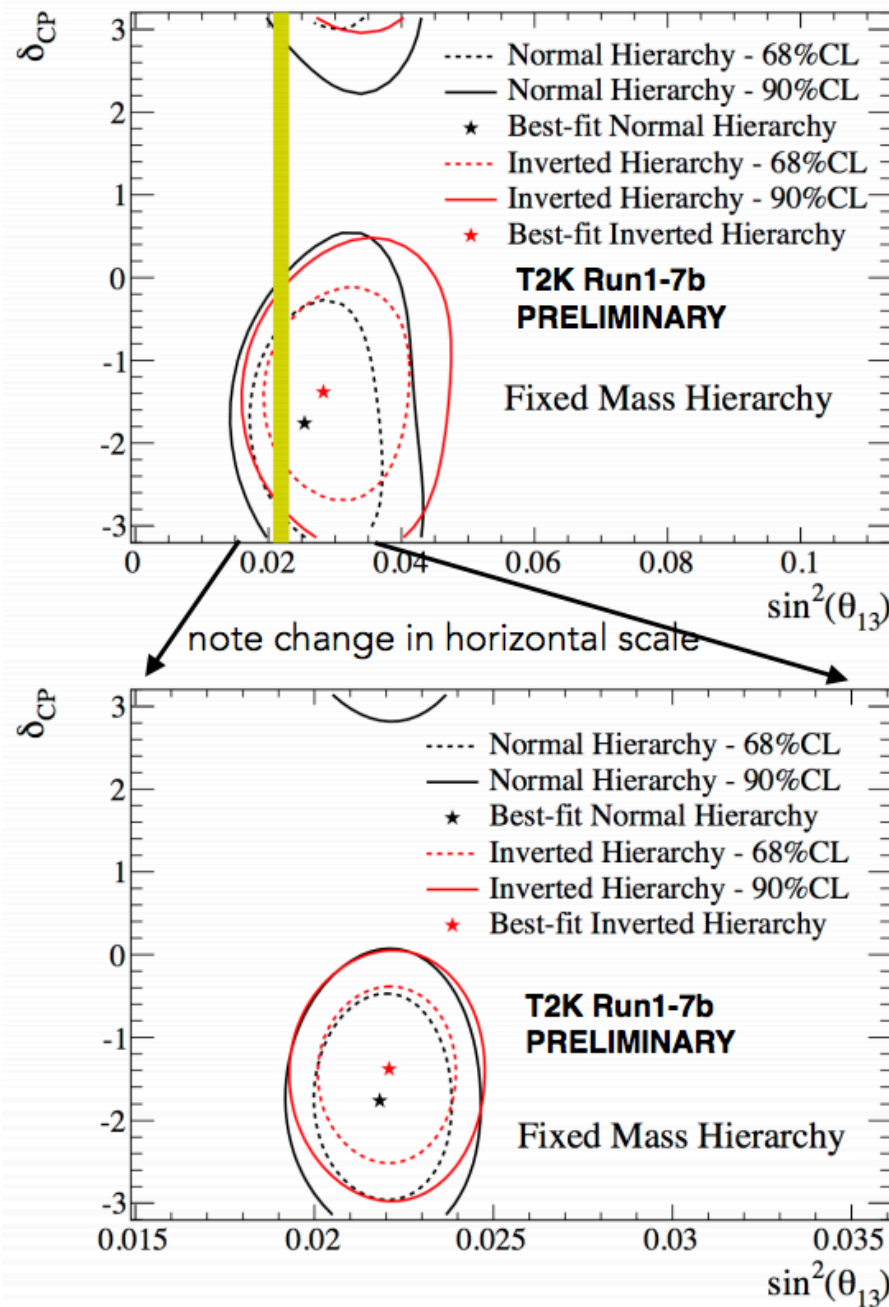
P1.040 A. Missert 11

SK

μ

e/γ

multi ring

H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF) ON BEHALF OF THE T2K COLLABORATION

δ_{CP} VS. θ_{13}

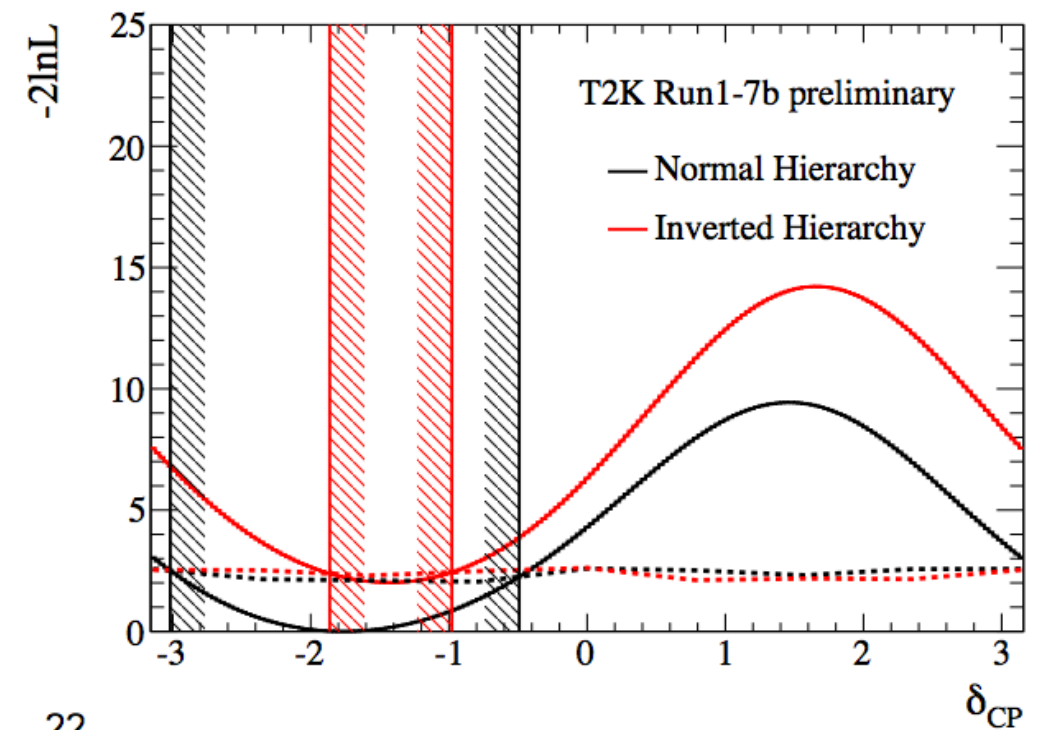Left: δ_{CP} vs. θ_{13} (fixed $\Delta\chi^2$, fixed hierarchy)

- T2K-only

- T2K with reactor $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

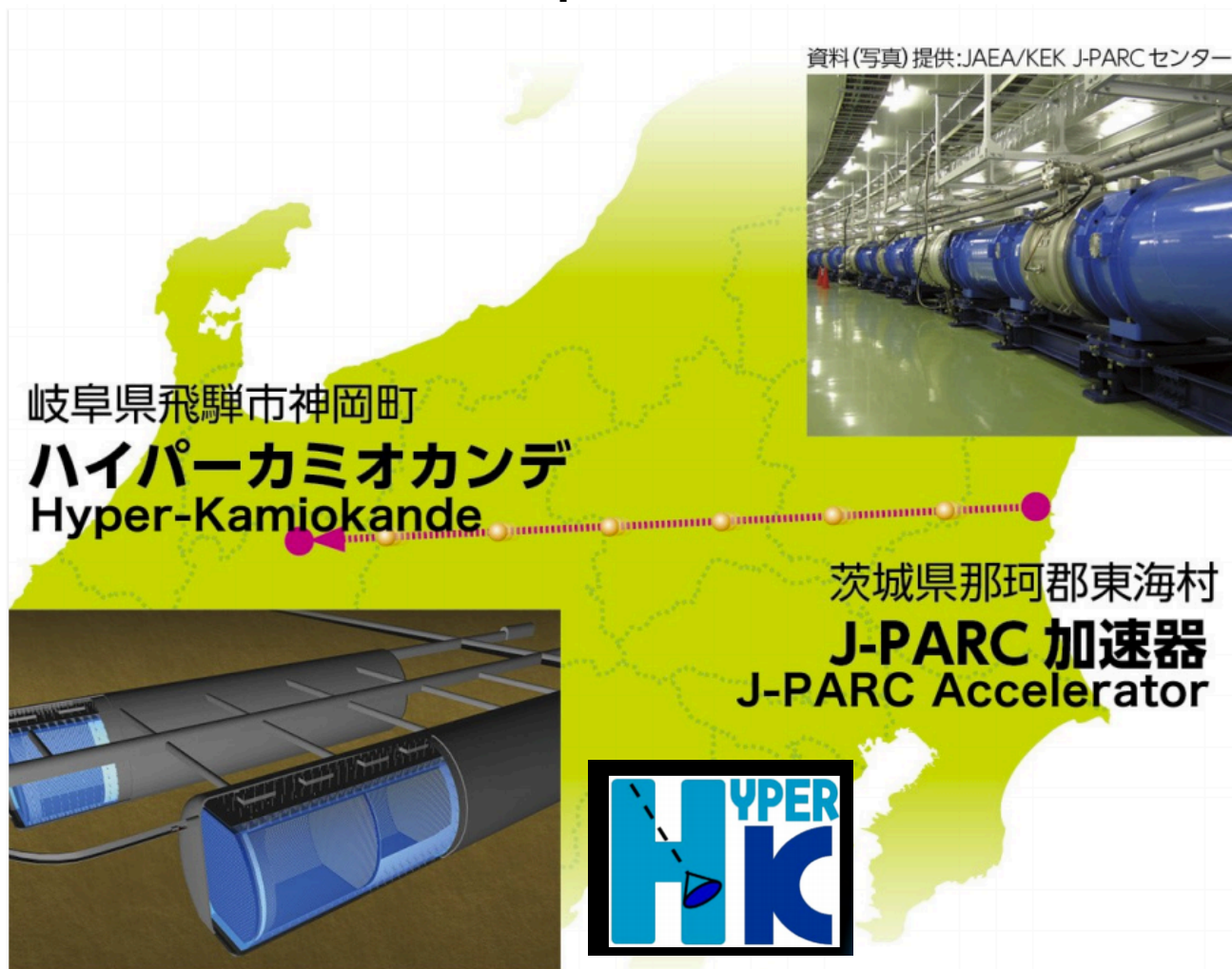Below: δ_{CP} with Feldman-Cousins critical values and reactor θ_{13}

$\delta_{CP} = [-3.02, -0.49]$ (NH), $[-1.87, -0.98]$ (IH) @90% CL

22

Future facilities

Japan

US
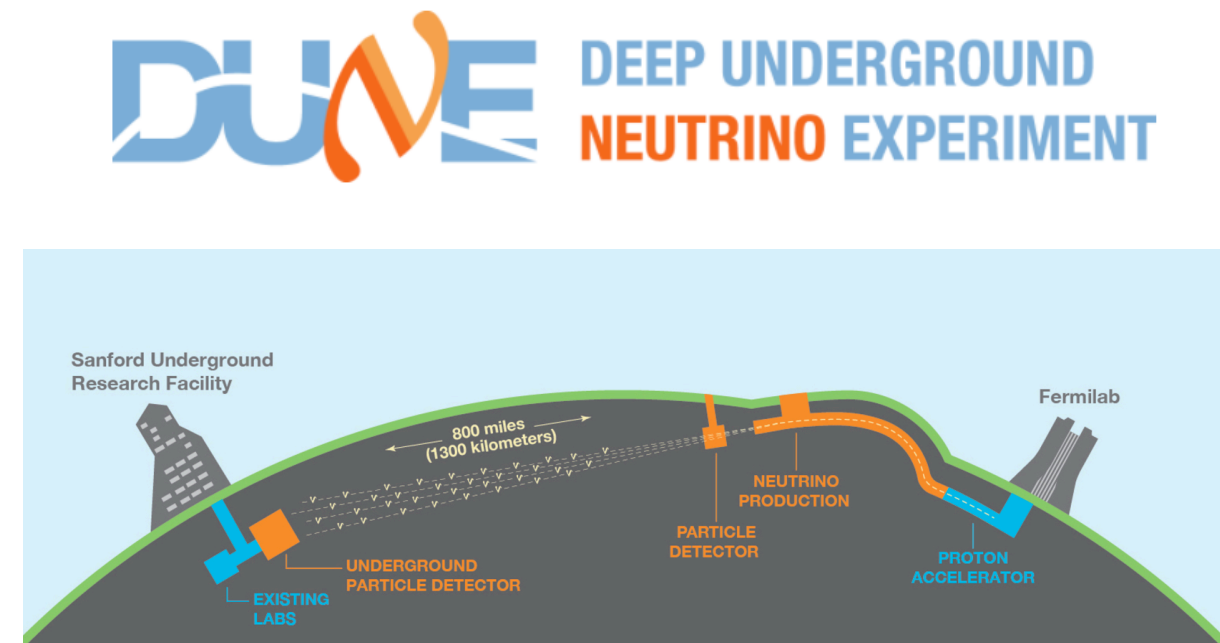

Two major experiment in the future will be able to measure precisle CP violation in the neutrino sector