UCL

PHASM/G442 Particle Physics

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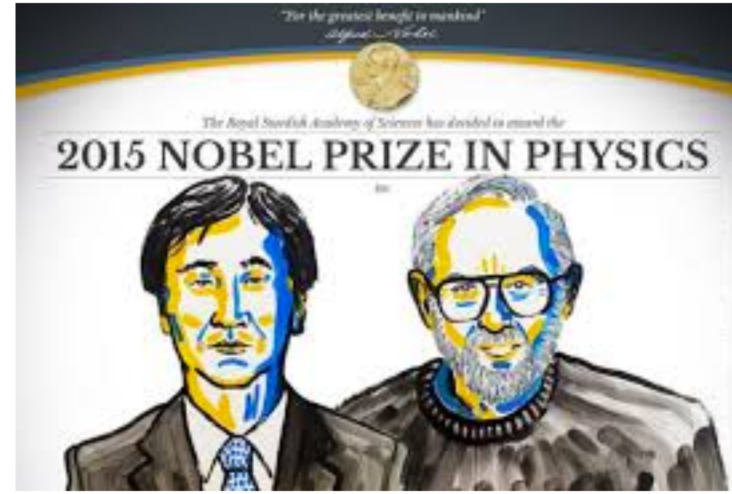
Module IX

Neutrino Mass and Physics Beyond the Standard Model



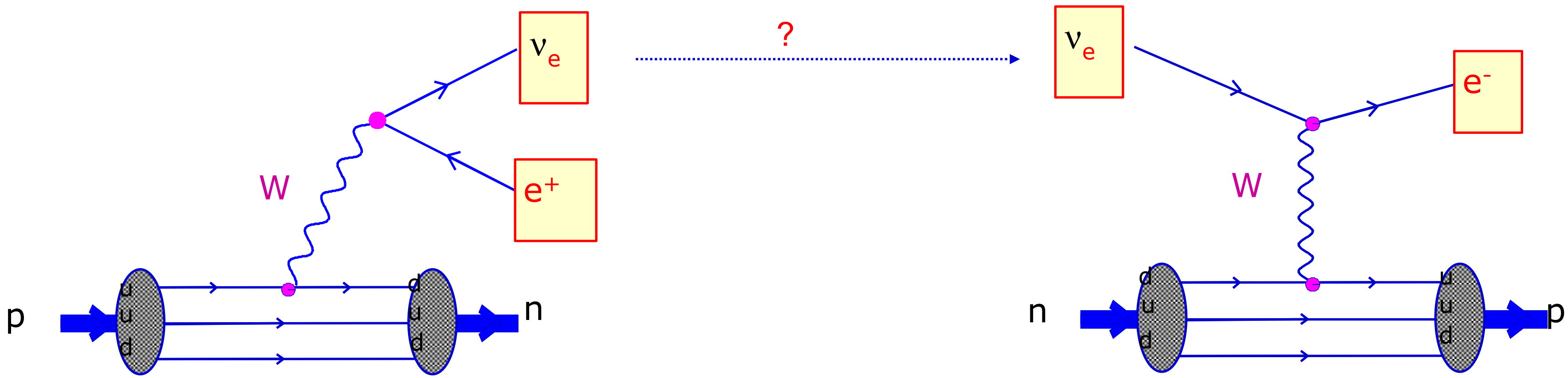
http://moodle.ucl.ac.uk/course/view.php?id=2589

Neutrino Flavours

- Never **directly** detect **neutrinos** - only by their **weak** interactions

- E.g. ν_e is produced along with electron

$\boxed{\nu_e, \nu_\mu, \nu_\tau \quad \text{= weak eigenstates}}$

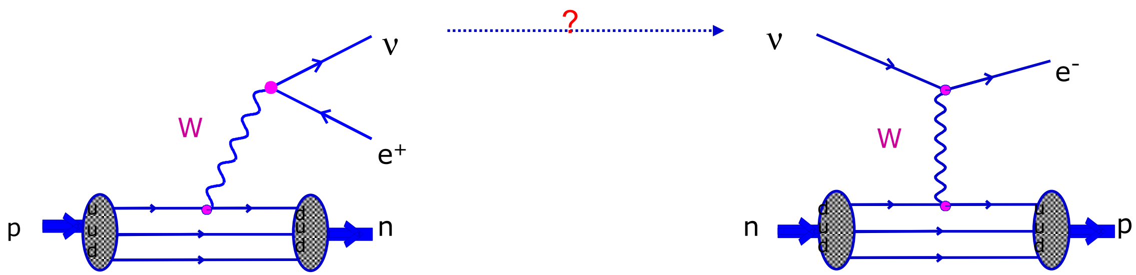


- In **SM** ν_e, ν_μ, ν_τ are **massless** particles

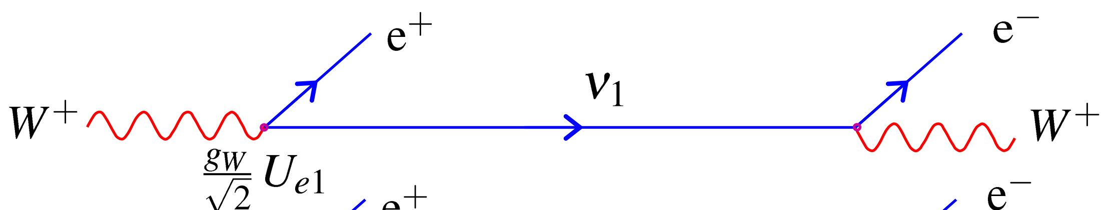
Neutrino mass eigenstates and weak eigenstates

- **If** neutrinos have **non-zero mass**, their **mass eigenstates** may **not** be the **same** as **weak eigenstates**

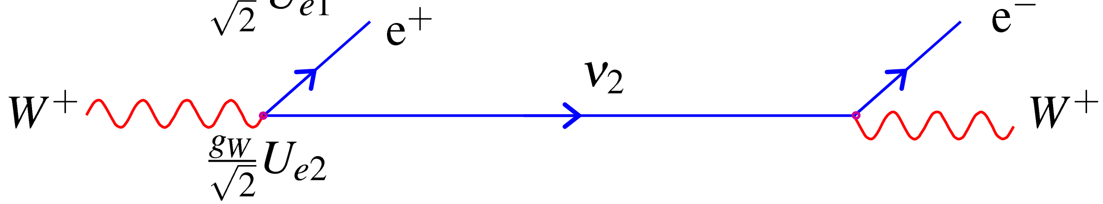
- Suppose there are two mass eigenstates ν_1 and ν_2



i.e.



and



- Cannot know which mass eigenstates is involved

- In QM treat it as a **coherent** state $\psi = \nu_e = U_{e1}\nu_1 + U_{e2}\nu_2$

weak eigenstate

Neutrino Oscillations for Two Flavours

Бруно Понтекорво

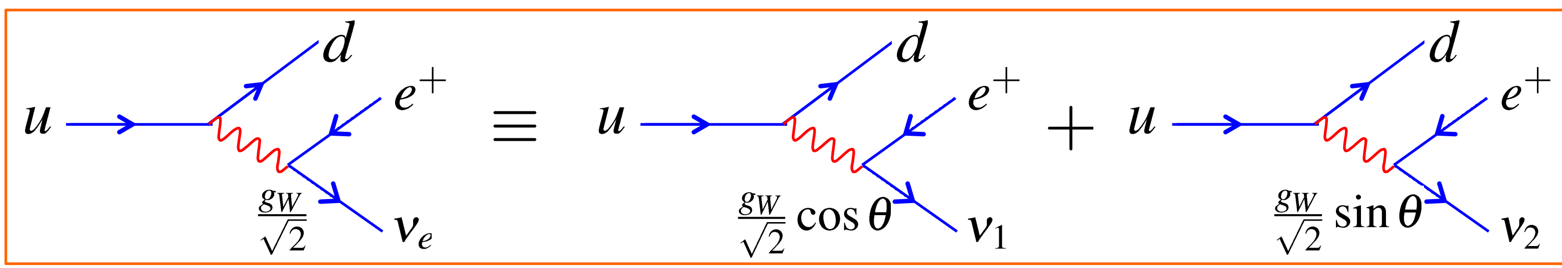
- If neutrino has non-zero mass a neutrino oscillation phenomenon may occur, Bruno Pontecorvo, 1957. (Recall neutral kaon oscillations).

- The mass eigenstates are the free particle solutions of the wave equation

$$|\nu_1(t)\rangle = |\nu_1\rangle e^{i\vec{p}_1.\vec{x}-iE_1 t} \qquad |\nu_2(t)\rangle = |\nu_2\rangle e^{i\vec{p}_2.\vec{x}-iE_2 t}$$

- The weak and mass eigenstates are related by **unitary** 2x2 matrix (recall Cabibbo)

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



- Or inverting it

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

- Suppose a neutrino is produced as a pure ν_e state, e.g $u \rightarrow de^+\nu_e$

$$|\psi(0)\rangle = |\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

- The wave function evolves according to time evolution of **mass eigenstates**. Assuming z-axis is along neutrino direction

$$|\psi(t)\rangle = \cos\theta|\nu_1\rangle e^{-ip_1.x} + \sin\theta|\nu_2\rangle e^{-ip_2.x}$$

where $p_i.x = E_it - \vec{p}_i.\vec{x} = E_it - |\vec{p}_i|z$

- Suppose neutrino interacts in a detector at a distance **L** and time **T**

$$\phi_i = p_i.x = E_iT - |\vec{p}_i|L \qquad \boxed{|\psi(L,T)\rangle = \cos\theta|\nu_1\rangle e^{-i\phi_1} + \sin\theta|\nu_2\rangle e^{-i\phi_2}}$$

- Expressing $|\nu_1\rangle, |\nu_2\rangle$ in terms of weak eigenstates

$$|\psi(L,T)\rangle = \cos\theta(\cos\theta|\nu_e\rangle - \sin\theta|\nu_\mu\rangle)e^{-i\phi_1} + \sin\theta(\sin\theta|\nu_e\rangle + \cos\theta|\nu_\mu\rangle)e^{-i\phi_2}$$

$$\boxed{|\psi(L,T)\rangle = |\nu_e\rangle(\cos^2\theta e^{-i\phi_1} + \sin^2\theta e^{-i\phi_2}) + |\nu_\mu\rangle\sin\theta\cos\theta(-e^{-i\phi_1} + e^{-i\phi_2})}$$

- If the **masses** of ν_1 and ν_2 are the **same**, the mass eigenstates **remain in phase**

$\phi_1 = \phi_2$ and linear combination corresponds to pure $|\nu_e\rangle$

- If the **masses** of ν_1 and ν_2 are **different**, the wave-function is **no longer pure** $|\nu_e\rangle$

$$\begin{aligned}
P(\nu_e \to \nu_\mu) &= |\langle \nu_\mu | \psi(L,T) \rangle|^2 \\
&= \cos^2\theta \sin^2\theta (-e^{-i\phi_1} + e^{-i\phi_2})(-e^{+i\phi_1} + e^{+i\phi_2}) \\
&= \frac{1}{4}\sin^2 2\theta (2 - 2\cos(\phi_1 - \phi_2)) \\
&= \sin^2 2\theta \sin^2\left(\frac{\phi_1 - \phi_2}{2}\right)
\end{aligned}$$

- Define $\Delta\phi_{12} = \phi_1 - \phi_2 = (E_1 - E_2)T - (|p_1| - |p_2|)L$

- Assuming $|p_1| = |p_2| = \mathrm{p}$

$$\Delta\phi_{12} = (E_1 - E_2)T = \left[(\mathrm{p}^2 + m_1^2)^{1/2} - (\mathrm{p}^2 + m_2^2)^{1/2}\right] L \qquad L \approx (c)T$$

$$\Delta\phi_{12} = \mathrm{p}\left[\left(1 + \frac{m_1^2}{\mathrm{p}^2}\right)^{1/2} - \left(1 + \frac{m_2^2}{\mathrm{p}^2}\right)^{1/2}\right] L \approx \frac{m_1^2 - m_2^2}{2\mathrm{p}} L$$

$$\boxed{\Delta\phi_{12} = \frac{m_1^2 - m_2^2}{2\mathrm{p}} L = \frac{\Delta m^2}{2E} L}$$

Summing it up…

- The two-flavour oscillation probability is

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

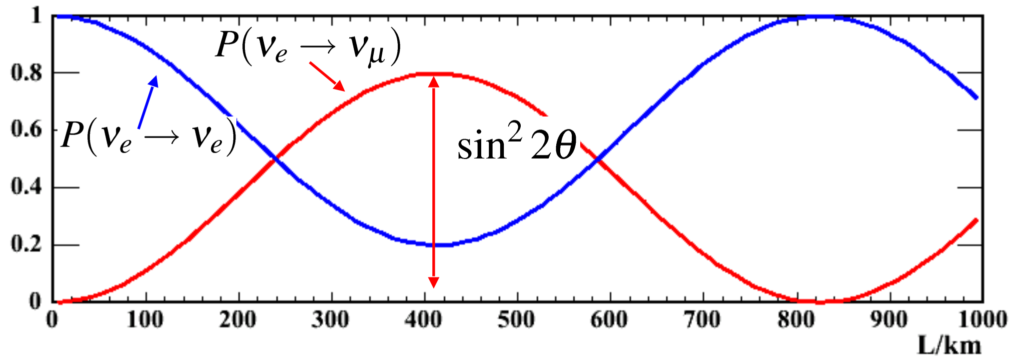
with

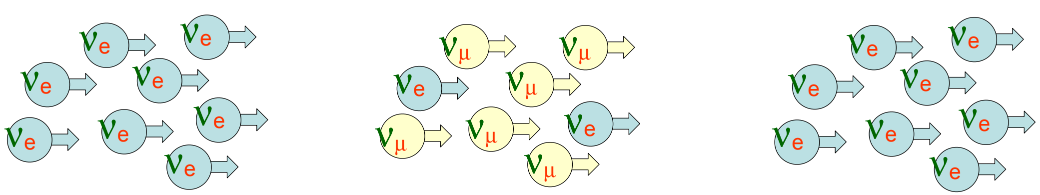
$$\boxed{\Delta m_{21}^2 = m_2^2 - m_1^2}$$

- The corresponding two-flavour survival probability is

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

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





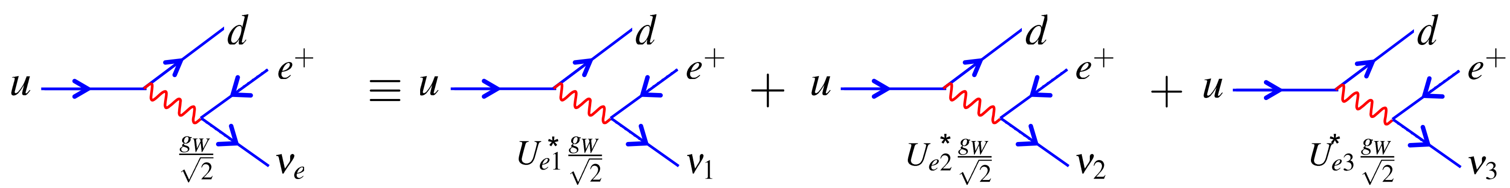
wavelength

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

Neutrino Oscillations For Three Flavours

- It can be extended to three observed generations (flavours) of neutrinos. Recall CKM Matrix

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



- ***U*** is a 3x3 **unitary** matrix known as **Pontecorvo-Maki-Nakagawa-Sakata** (**PMNS**)

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

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{\mu 1} & U^*_{\tau 1} \\ U^*_{e2} & U^*_{\mu 2} & U^*_{\tau 2} \\ U^*_{e3} & U^*_{\mu 3} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

- 3 generations makes the oscillation/survival probability calculations much more tedious but the principle is exactly the same

E.g.
$$\begin{aligned} P(\nu_e \to \nu_\mu) &= |\langle \nu_\mu | \psi(L) \rangle|^2 \\ &= |U_{e1}U^*_{\mu 1}e^{-i\phi_1} + U_{e2}U^*_{\mu 2}e^{-i\phi_2} + U_{e3}U^*_{\mu 3}e^{-i\phi_3}|^2 \end{aligned}$$

$$\begin{aligned} P(\nu_e \to \nu_e) &= |\langle \nu_e | \psi(L) \rangle|^2 \\ &= |U_{e1}U^*_{e1}e^{-i\phi_1} + U_{e2}U^*_{e2}e^{-i\phi_2} + U_{e3}U^*_{e3}e^{-i\phi_3}|^2 \end{aligned}$$

and using unitarity relation, $U_{e1}U^*_{\mu 1} + U_{e2}U^*_{\mu 2} + U_{e3}U^*_{\mu 3} = 0$ and identity:

$$|z_1 + z_2 + z_3|^2 \equiv |z_1|^2 + |z_2|^2 + |z_3|^2 + 2\Re(z_1 z_2^* + z_1 z_3^* + z_2 z_3^*)$$

and doing the full math chain

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

with $\Delta_{21} = \frac{(m_2^2 - m_1^2)L}{4E} = \frac{\Delta m^2_{21} L}{4E}$ and $\boxed{\Delta m^2_{21} = m_2^2 - m_1^2}$ Note: $\Delta_{21} = (\phi_2 - \phi_1)/2$ phase difference

- Only two independent Δm^2_{ij}

$$\boxed{\Delta_{21} = 1.27 \frac{\Delta m^2_{21}(\text{eV}^2) L(\text{km})}{E(\text{GeV})}} \quad \text{and} \quad \boxed{\lambda_{\text{osc}}(\text{km}) = 2.47 \frac{E(\text{GeV})}{\Delta m^2(\text{eV}^2)}}$$

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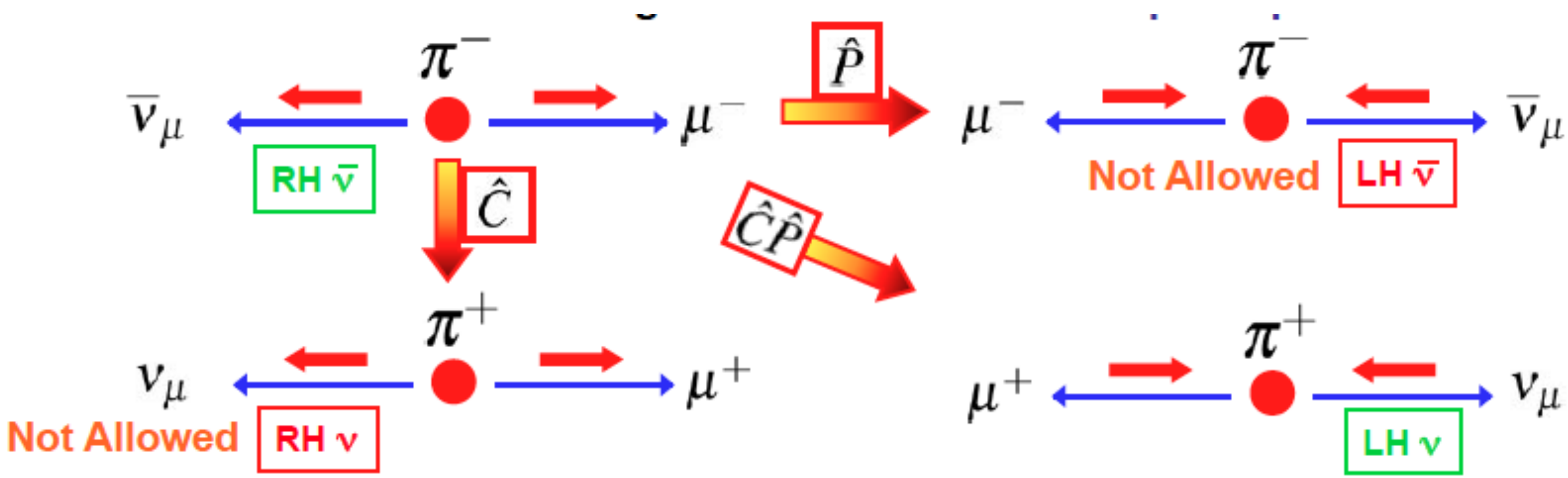
CP and CPT in Weak Interaction

Parity	$\hat{P}$:	$\vec{r} \rightarrow -\vec{r}$
Time Reversal	$\hat{T}$:	$t \rightarrow -t$
Charge Conjugation	$\hat{C}$:	Particle ⟷ Anti-particle

- Weak Interaction violates **Parity**, and so is **C**



- Weak interaction **violates** both **P** and **C** but *appears* to be *invariant* under **CP** (from above example)

CP and CPT in Weak Interaction

- All **Lorentz invariant** Quantum Field Theories (**QFT**) can be shown to be **invariant** under **CPT** transformation
    - Particles/anti-particles have identical mass, lifetime, magnetic moments etc

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

- Given **CPT** holds
    - If **CP** invariance holds $\longrightarrow$ time reversal symmetry
    - If **CP** is violated $\longrightarrow$ time reversal symmetry violated

- **CP violation** is required to explain **excess** of **matter** over **anti-matter**
- We saw that **CP** is **violated** weak interaction of **quarks** (Kaons, B and D-mesons)
- However it is **not sufficient** to explain matter excess. Can it come from the **neutrino** sector?

- For time time reversal swap $(e) \leftrightarrow (\mu)$ i.e.

$$P(\nu_e \to \nu_\mu) = 2\Re\{U_{e1}U_{\mu1}^*U_{e2}^*U_{\mu2}[e^{-i(\phi_1-\phi_2)}-1]\} + 2\Re\{U_{e1}U_{\mu1}^*U_{e3}^*U_{\mu3}[e^{-i(\phi_1-\phi_3)}-1]\} + 2\Re\{U_{e2}U_{\mu2}^*U_{e3}^*U_{\mu3}[e^{-i(\phi_2-\phi_3)}-1]\}$$

$$P(\nu_\mu \to \nu_e) = 2\Re\{U_{\mu1}U_{e1}^*U_{\mu2}^*U_{e2}[e^{-i(\phi_1-\phi_2)}-1]\} + 2\Re\{U_{\mu1}U_{e1}^*U_{\mu3}^*U_{e3}[e^{-i(\phi_1-\phi_3)}-1]\} + 2\Re\{U_{\mu2}U_{e2}^*U_{\mu3}^*U_{e3}[e^{-i(\phi_2-\phi_3)}-1]\}$$

- Unless the element of PMNS matrix are real $P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$

- Hence, if any of elements of the **PMNS** matrix are **complex** neutrino oscillations are **not invariant** under time reversal

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

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

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

- If **CPT** holds $P(\nu_e \to \nu_\mu) = P(\overline{\nu}_\mu \to \overline{\nu}_e)$ $P(\nu_\mu \to \nu_e) = P(\overline{\nu}_e \to \overline{\nu}_\mu)$

- If PMNS is not purely real $P(\nu_e \to \nu_\mu) \neq P(\nu_\mu \to \nu_e)$ $P(\nu_e \to \nu_\mu) \neq P(\overline{\nu}_e \to \overline{\nu}_\mu)$

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

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

To be studied in future neutrino oscillation experiment — in fact it's their **main objective!**

Summary of oscillation probabilities

- Neglecting CP violation and assuming $|\Delta m^2_{31}| \approx |\Delta m^2_{32}|$

$$P(\nu_e \to \nu_e) \approx 1 - 4U^2_{e1}U^2_{e2}\sin^2\Delta_{21} - 4(1-U^2_{e3})U^2_{e3}\sin^2\Delta_{32}$$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4U^2_{\mu1}U^2_{\mu2}\sin^2\Delta_{21} - 4(1-U^2_{\mu3})U^2_{\mu3}\sin^2\Delta_{32}$$

$$P(\nu_\tau \to \nu_\tau) \approx 1 - 4U^2_{\tau1}U^2_{\tau2}\sin^2\Delta_{21} - 4(1-U^2_{\tau3})U^2_{\tau3}\sin^2\Delta_{32}$$

$$P(\nu_e \to \nu_\mu) = P(\nu_\mu \to \nu_e) \approx -4U_{e1}U_{\mu1}U_{e2}U_{\mu2}\sin^2\Delta_{21} + 4U^2_{e3}U^2_{\mu3}\sin^2\Delta_{32}$$

$$P(\nu_e \to \nu_\tau) = P(\nu_\tau \to \nu_e) \approx -4U_{e1}U_{\tau1}U_{e2}U_{\tau2}\sin^2\Delta_{21} + 4U^2_{e3}U^2_{\tau3}\sin^2\Delta_{32}$$

$$P(\nu_\mu \to \nu_\tau) = P(\nu_\tau \to \nu_\mu) \approx -4U_{\mu1}U_{\tau1}U_{\mu2}U_{\tau2}\sin^2\Delta_{21} + 4U^2_{\mu3}U^2_{\tau3}\sin^2\Delta_{32}$$

- The wavelengths associated with $\sin^2\Delta_{21}$ and $\sin^2\Delta_{32}$ are:

"SOLAR" $\lambda_{21} = \dfrac{4\pi E}{\Delta m^2_{21}}$ **"Long"-Wavelength**

and

$\lambda_{32} = \dfrac{4\pi E}{\Delta m^2_{32}}$ **"ATMOSPHERIC"** **"Short"-Wavelength**

PMNS Matrix

- Usually expressed with 3 rotation angles $\theta_{12}, \theta_{23}, \theta_{13}$ and a complex CP-phase δ using notation $s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{"Atmospheric"}} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{"Solar"}}$$

Dominates: **"Atmospheric"** **"Solar"**

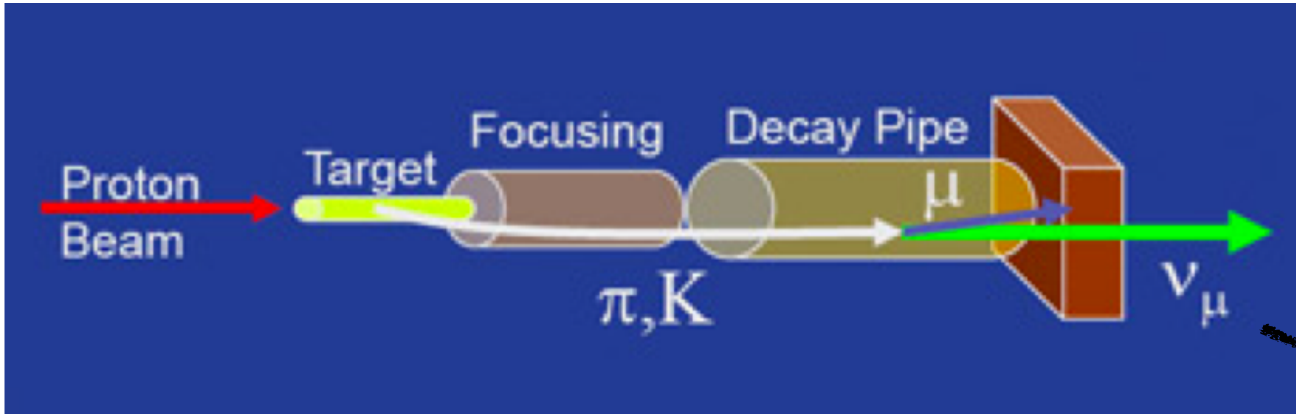
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- There are **six parameters** that can be measured in **neutrino oscillation experiments**

$\|\Delta m_{21}\|^2 = \|m_2^2 - m_1^2\|$	θ_{12}	**Solar and reactor neutrino experiments**
$\|\Delta m_{32}\|^2 = \|m_3^2 - m_2^2\|$	θ_{23}	**Atmospheric and beam neutrino experiments**
	θ_{13}	**Reactor neutrino experiments + future beam**
	δ	**Future beam experiments**

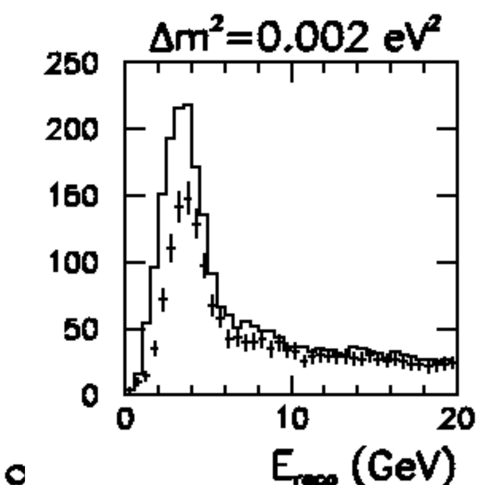
There is also Majorana CP-phase if neutrinos are Majorana particles (see later)

Measuring Neutrino Oscillation Parameters



Neutrino Detector

Mostly ν_μ

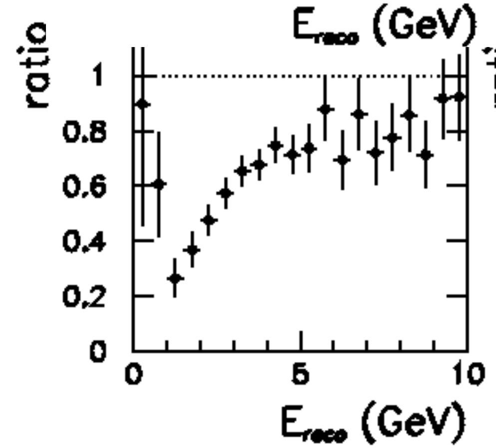


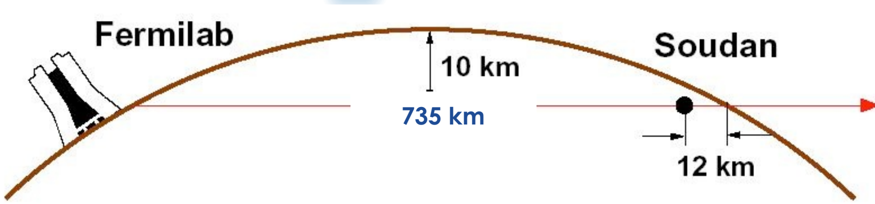
Example: MINOS

- Measure energy spectrum at Near Detector
- Measure energy spectrum at Far Detector
- Compare measurements to study oscillations

Look for disappearance of ν_μ

or look for appearance of $\nu_{e(\tau)}$

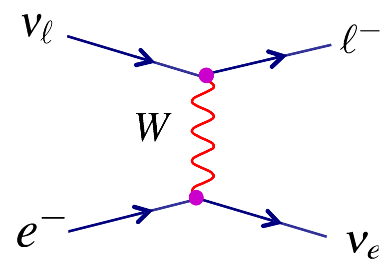


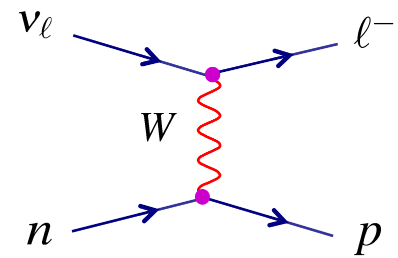


Neutrino detection

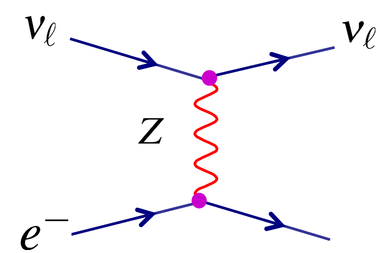
- Two possible “targets”: atomic electrons and nucleons

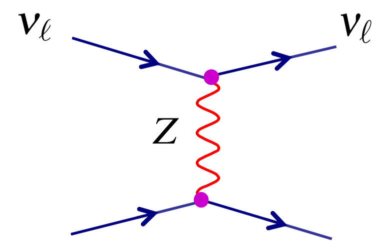
CHARGED CURRENT (CC)



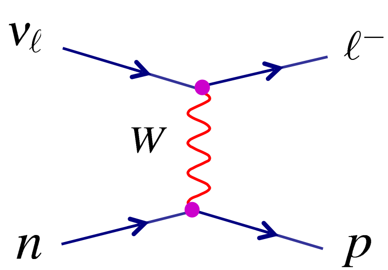


NEUTRAL CURRENT (NC)





- Example: thresholds for interaction with nucleons (CC)



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

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

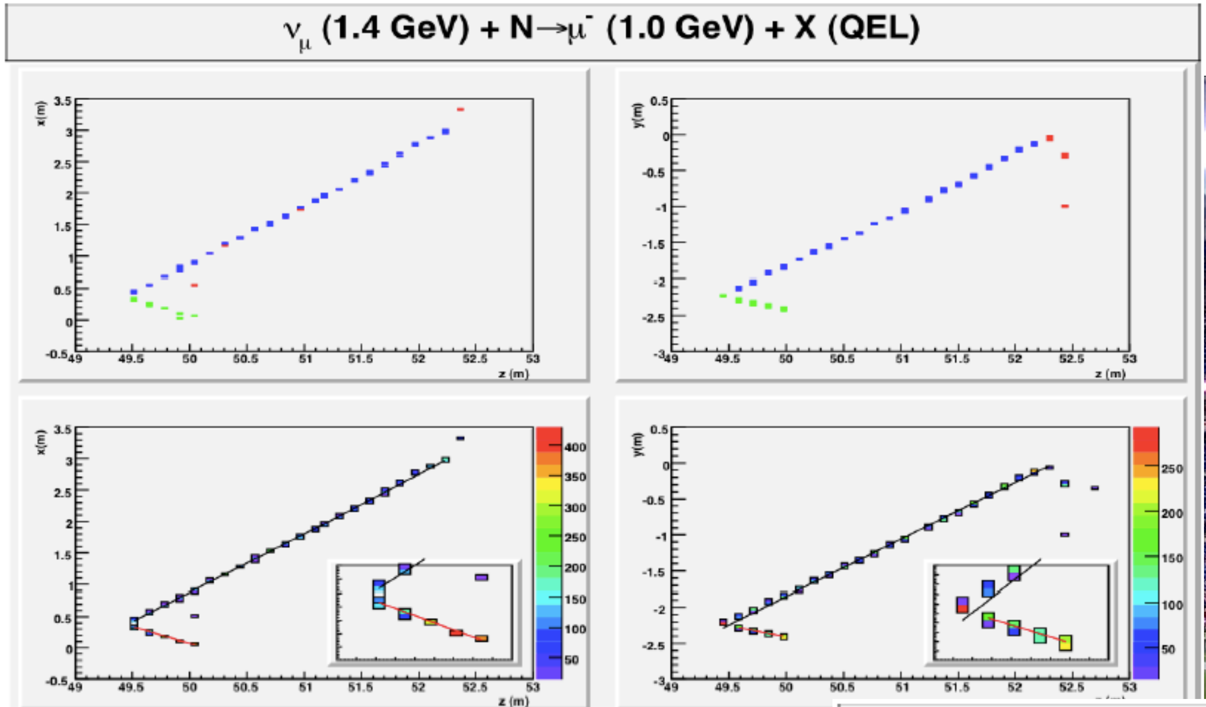
$$\Rightarrow \quad \boxed{E_\nu > \frac{(m_p^2 - m_n^2) + m_\ell^2 + 2m_p m_\ell}{2m_n}}$$

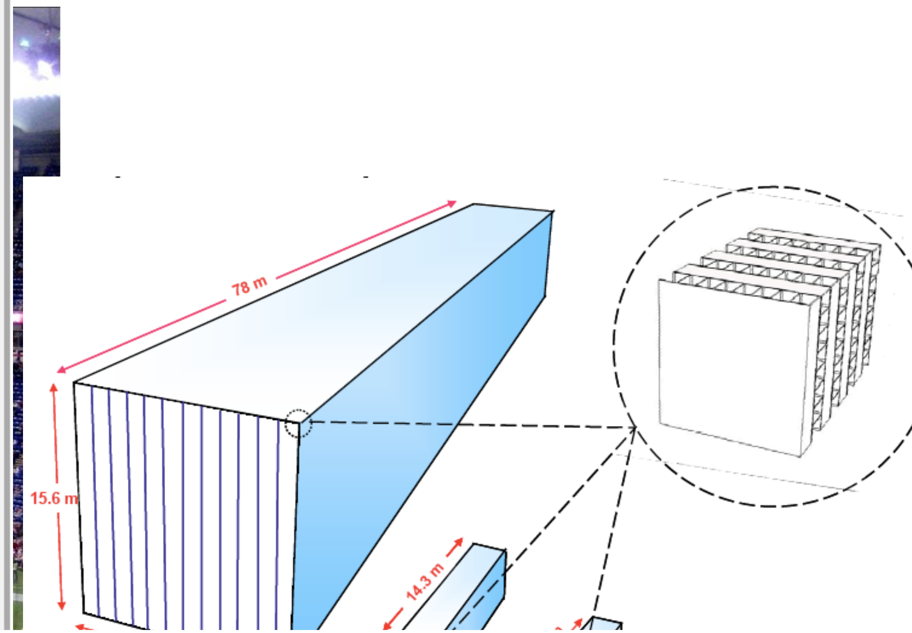
$E_{\nu_e} > 0 \qquad E_{\nu_\mu} > 110\,\mathrm{MeV} \qquad E_{\nu_\tau} > 3.5\,\mathrm{GeV}$

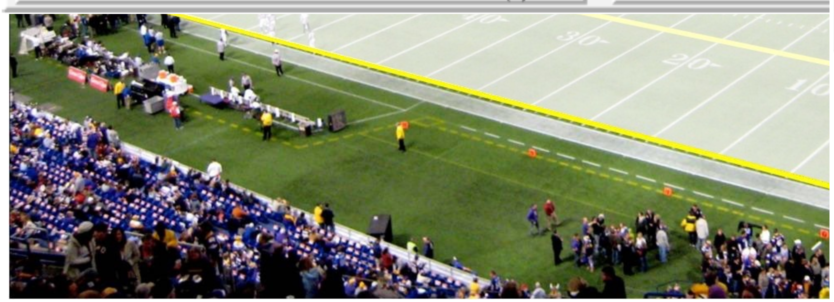
- Experiments often look for “disappearance” of neutrinos

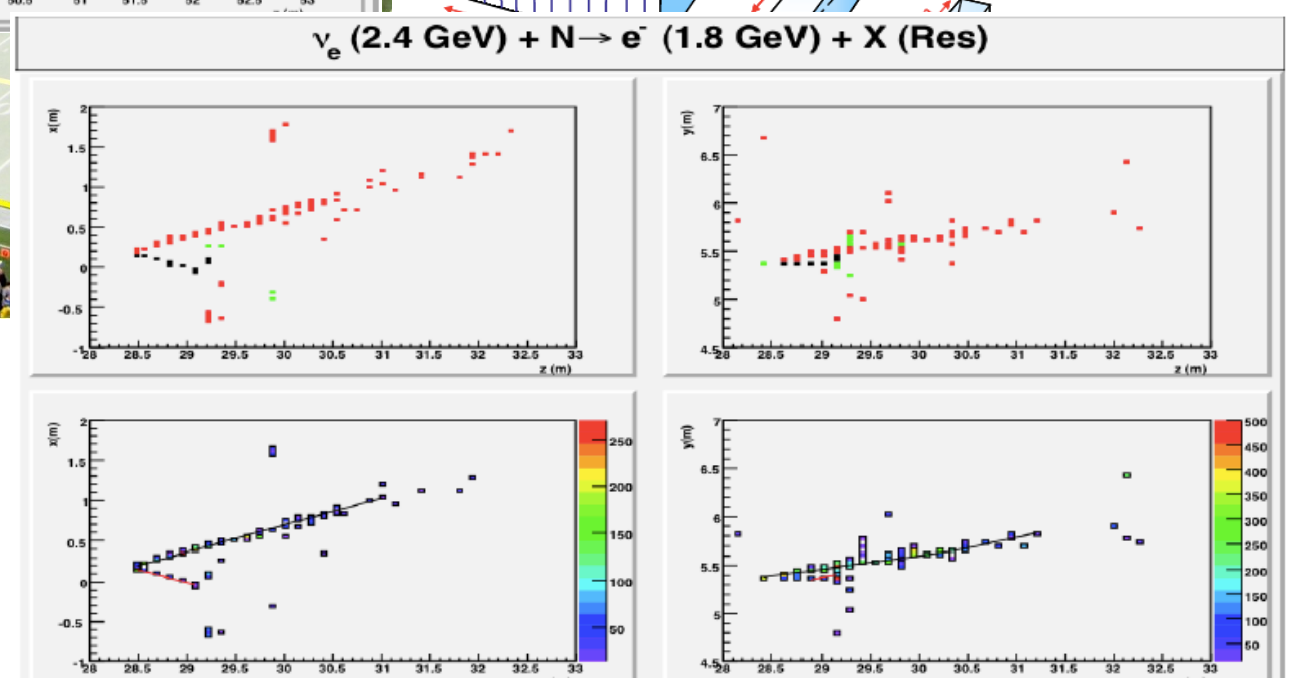
Neutrino Detectors

E.g. NOvA detector — active “cells” filled with liquid scintillator.









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

❶ **Water Čerenkov:** **e.g. Super Kamiokande**

Liquid Argon Detectors (**DUNE**)

❷ **Iron Calorimeters:** **e.g. MINOS, CDHS**

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

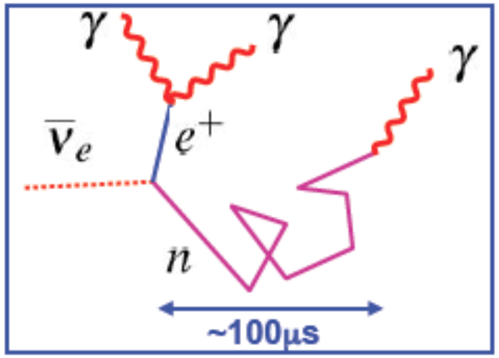
❶ **Water Čerenkov:** **e.g. Super Kamiokande**

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

❷ **Radio-Chemical:** **e.g. Homestake, SAGE, GALLEX**

- **Use inverse beta decay process, e.g.** $\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge}$
- **Chemically extract produced isotope and count decays (only gives a rate)**

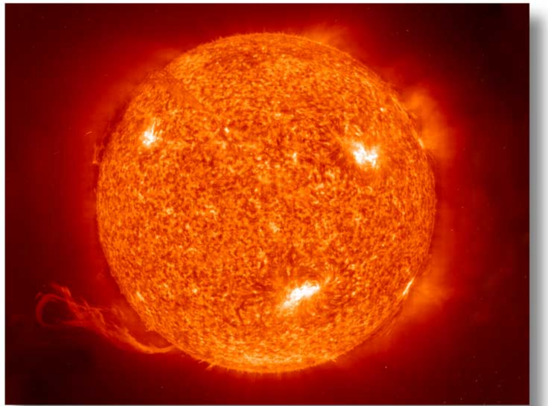
Reactor Neutrinos $\overline{\nu}_e \; : \; E_{\overline{\nu}} < 5\,\mathrm{MeV}$



❶ **Liquid Scintillator:** **e.g. KamLAND**

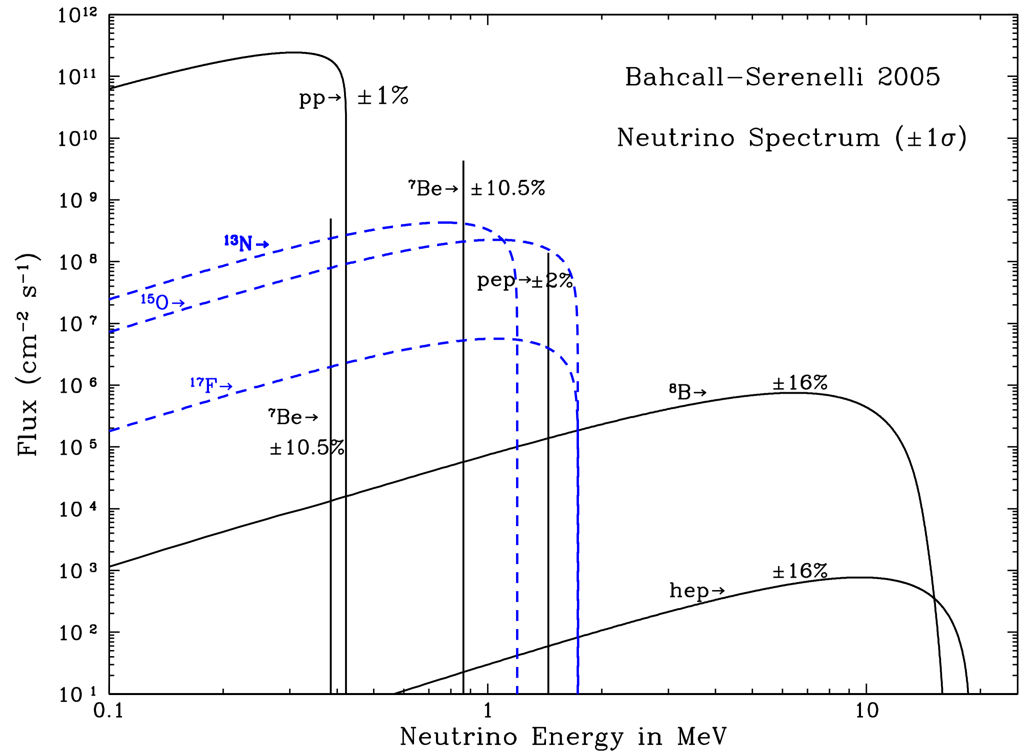
- **Low energies → large radioactive background**
- **Dominant interaction:** $\overline{\nu}_e + p \rightarrow e^+ + n$
- **Prompt positron annihilation signal + delayed signal from *n* (space/time correlation reduces background)**
- **electrons produced by photons excite scintillator which produces light**

Solar neutrinos



Sun produces huge flux of neutrinos

$$\boxed{2 \times 10^{38}\, \nu_e\, s^{-1}}$$



- Neutrinos produced in the sun in several reactions

$$\boxed{p + p \to d + e^+ + \nu_e} \quad E_\nu < 0.5\,\mathrm{MeV}$$

$$\boxed{{}^8B \to {}^8Be^* + e^+ + \nu_e} \quad E_\nu \sim 5\,\mathrm{MeV}$$

$$p + e^- + p \to d + \nu_e$$
$${}^7Be + e^- \to {}^7Li + \nu_e$$
$${}^3He + p \to {}^4He + e^+ + \nu_e$$

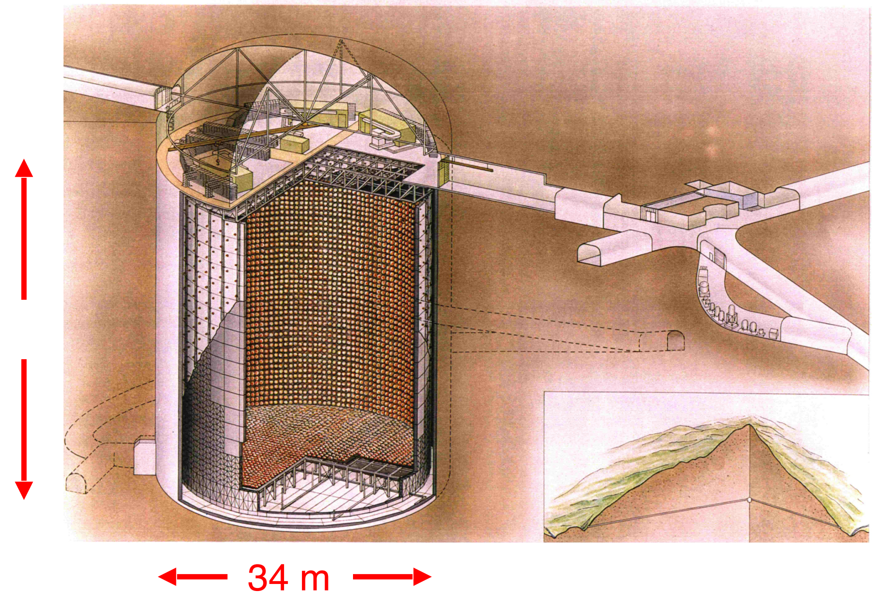
- Observed much fewer neutrinos than predicted by Standard Solar Model
- Eventually explained by neutrino oscillations

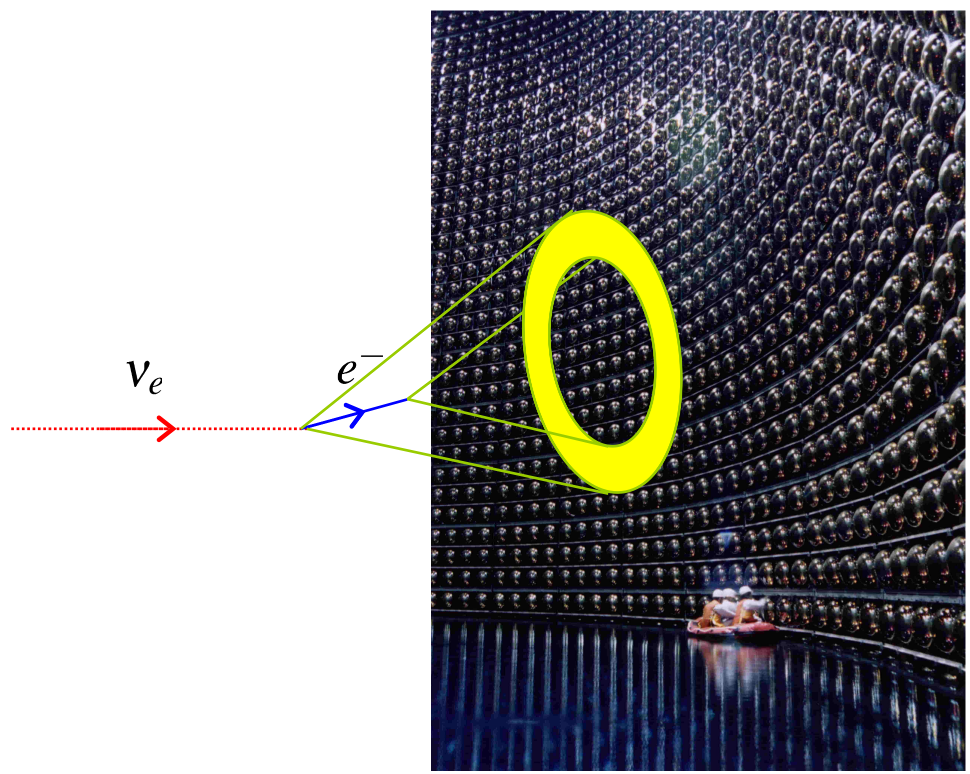
SuperKamiokande

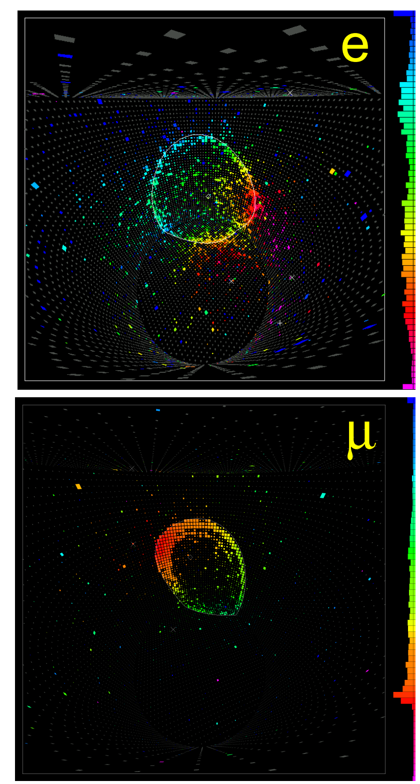
Together with SNO Nobel Prize 2015!

- 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

Used for solar, atmospheric and long baseline neutrino oscillation studies







Neutrino Oscillations
Summary of Current Knowledge

SOLAR Neutrinos/KamLAND

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

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

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

Atmospheric Neutrinos/Long Baseline experiments

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

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

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

- **Recent results from reactor experiments (Daya Bay, Reno)**

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst) \Rightarrow \theta_{13} \approx 9^\circ$$

- **No evidence for CP violation so far. But a relatively large θ_{13} gives hope it is feasible**

Outstanding questions of Neutrino (mass) Physics

UCL

- Neutrino oscillations measure mass squared differences but not the **absolute value of neutrino mass**
  - Only upper limits from **direct kinematic** measurements of neutrino mass

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

e.g. ^{3}H β-decay

Also from cosmological evolution infer the upper limit on the sum

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

- Neutrino mass "hierarchy": $m_1<m_2<m_3$ or $m_3<m_1<m_2$
- **CP violation** in neutrino sector —> possible explanation for observed **matter dominance** in universe — main goal of future long baseline experiments: **DUNE** (LAr), **HyperK** (Water-Cerenkov) **CHIPS** (cheap Water-Cerenkov)

UCL involvement

- Can **neutrino** be its own anti-particle, i.e. **Majorana** particle.

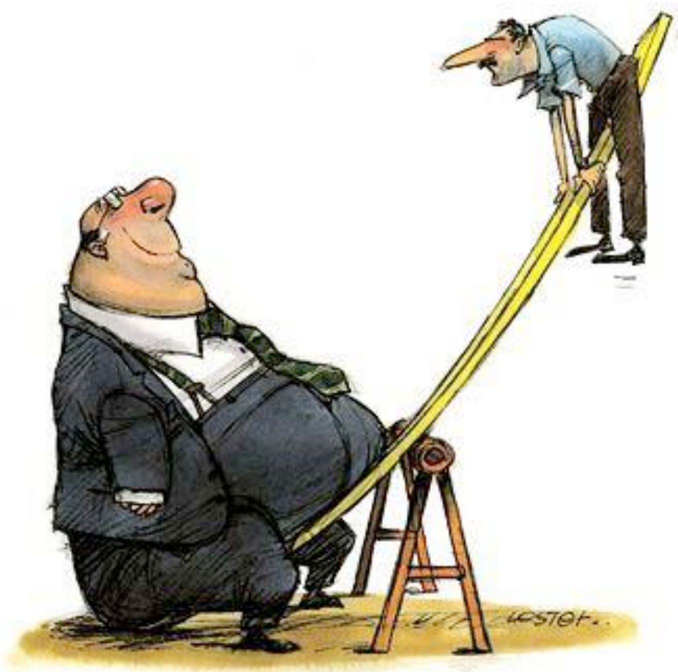
  (In SM all fermions are Dirac particles, i.e. have distinctive anti-particles).

UCL

Nature of Neutrinos: Majorana (ν = anti-ν) or Dirac ($\nu \neq$ anti-ν)?

$\Delta L \neq 0$ $\Delta L = 0$

Directly related to fundamental symmetries of particle interactions



Provides important information on origin of neutrino mass

(probably not simple Higgs mechanism as $m_\nu / m_e \sim 10^{-7}$)

SEE-SAW

$$m_\nu \equiv m_M^L = \frac{m_D^2}{M} << m_D$$

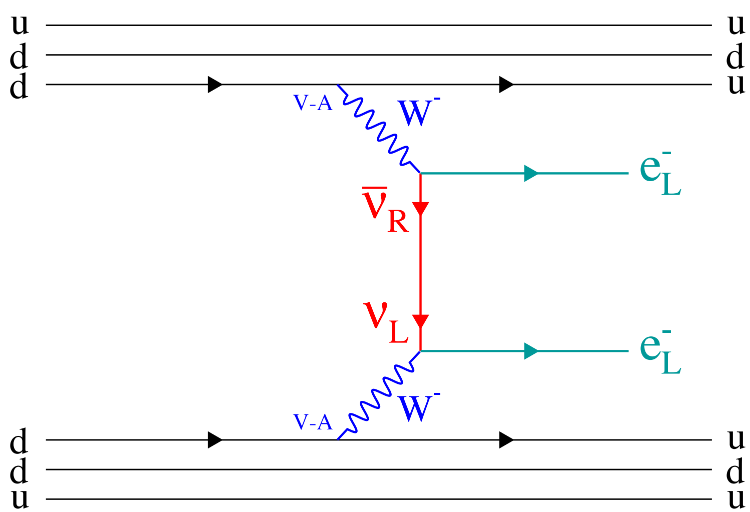
To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

Lepton number violation is one of the key ingredients of **leptogenesis** as the mechanism to generate the baryon asymmetry of the Universe.

More matter than anti-matter!

Neutrinoless Double Beta Decay

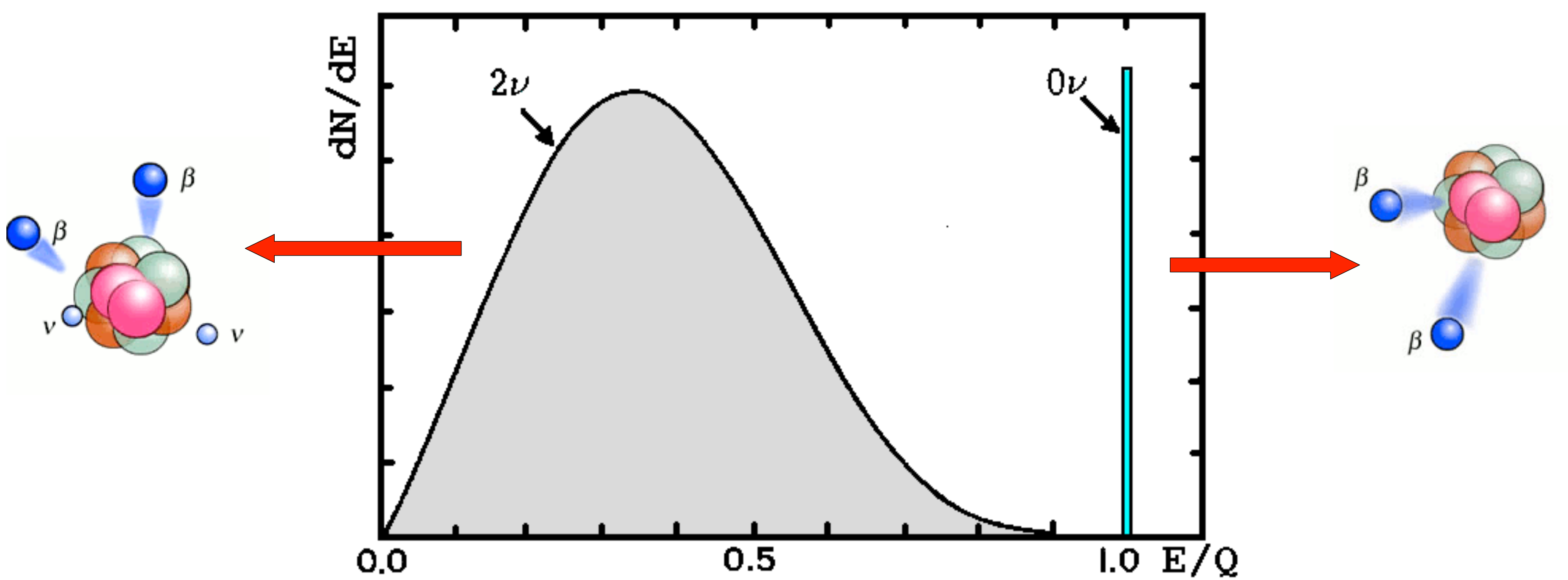
- Can only proceed if **neutrino** is a **Majorana** particle



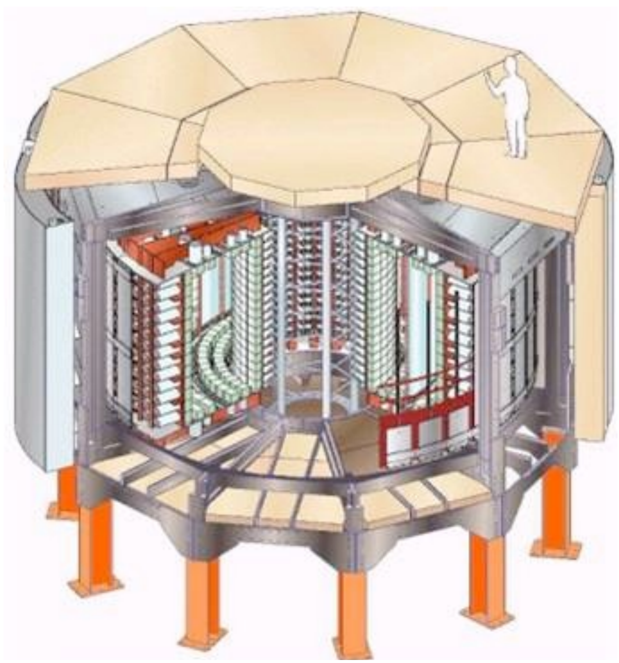
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \langle m_\nu \rangle^2$$

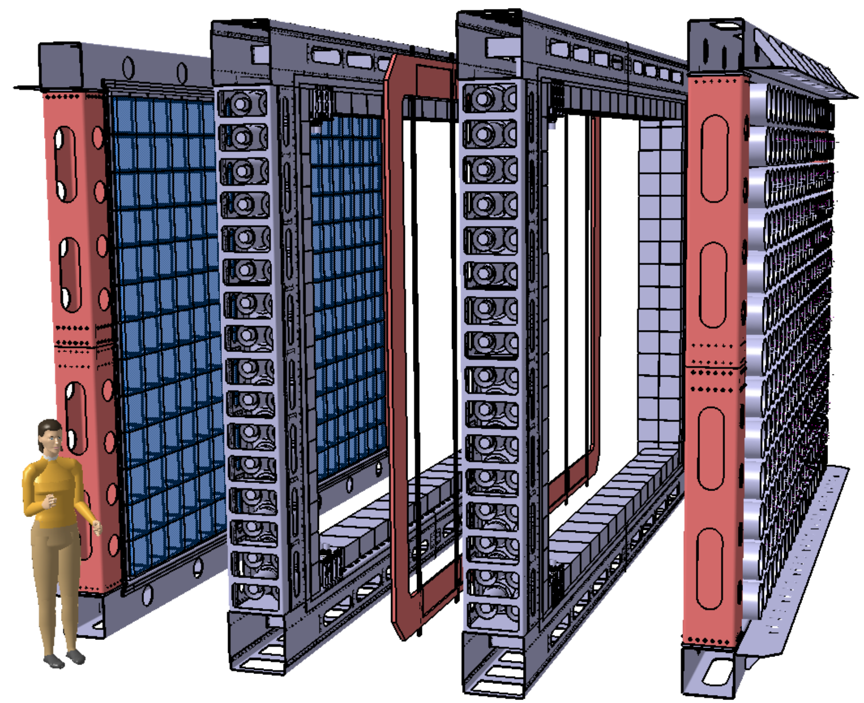
access to absolute neutrino mass

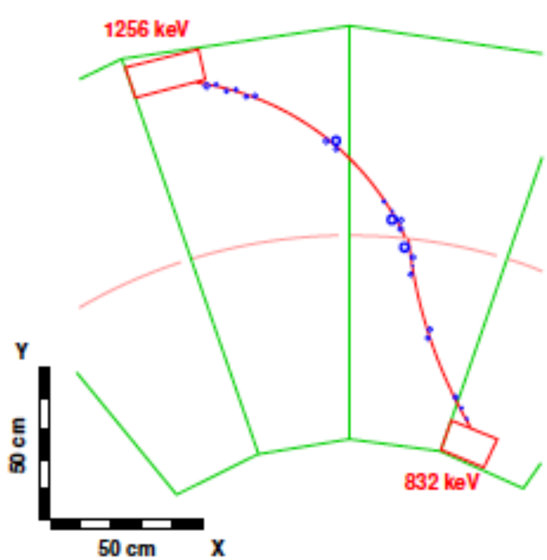
$$\langle m_\nu \rangle = \left|\sum U_{ei}^2 m_i\right| = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}\right|$$



NEMO-3 and SuperNEMO. Search for $0\nu\beta\beta$

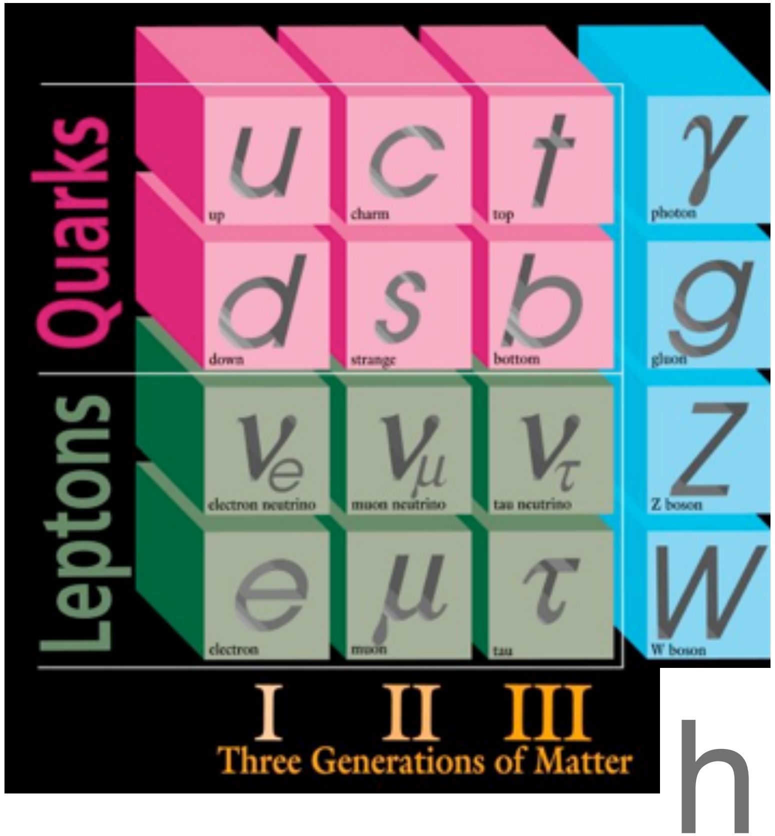


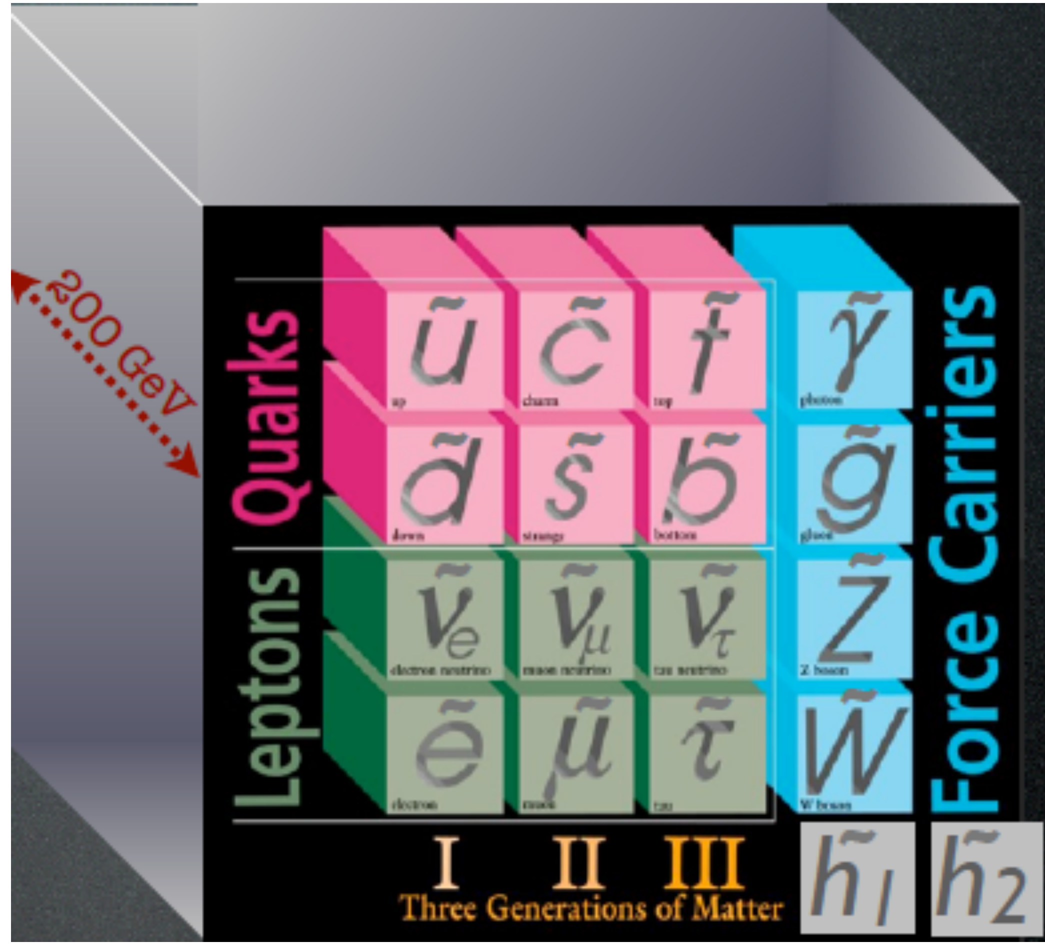




- Reconstruct full topology of final state particles (electrons)
- Measure several isotopes
- Strong UCL involvement

SuperSymmetry (SUSY) in 1 slide

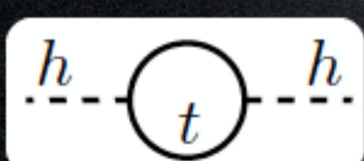




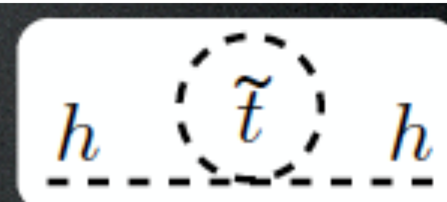
$R = +1$

$R = -1$

$m_{\mathrm{h}} \simeq 125\ \mathrm{GeV}$



$\Delta m_{\mathrm{h}} \propto 10^{19}\ \mathrm{GeV}$



$\Delta m_{\mathrm{h}} \propto -10^{19}\ \mathrm{GeV}$

Dark Matter

- DM exists
- it's a new, unknown particle — *no SM particle can fulfil* — *dilutes as $1/a^3$ with universe expansion*
- makes up 26% of total energy
  82% of total matter — $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ *(notice error!)*
- neutral particle — *'dark'...*
- cold or not too warm — *p/m <<1 at CMB formation*
- very feebly interacting — *-with itself* *-with ordinary matter ('collisionless')*
- stable or very long lived — $\tau_{\rm DM} \gg 10^{17}\,\mathrm{sec}$
- possibly a relic from the EU
- searched for by

Weakly Interacting Massive Particle

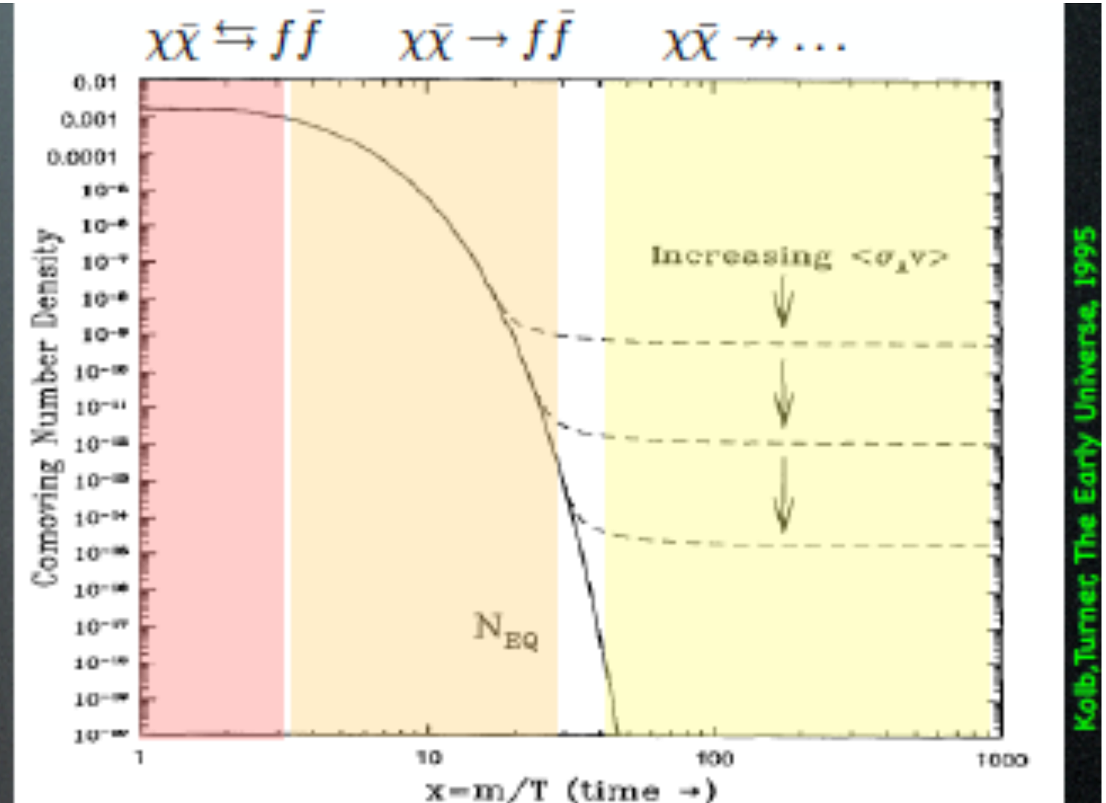
(as dark matter candidate)

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v \rangle}$$

Relic $\Omega_{\mathrm{DM}} \simeq 0.23$ for

$$\langle \sigma_{\mathrm{ann}} v \rangle = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$



Weak cross section:

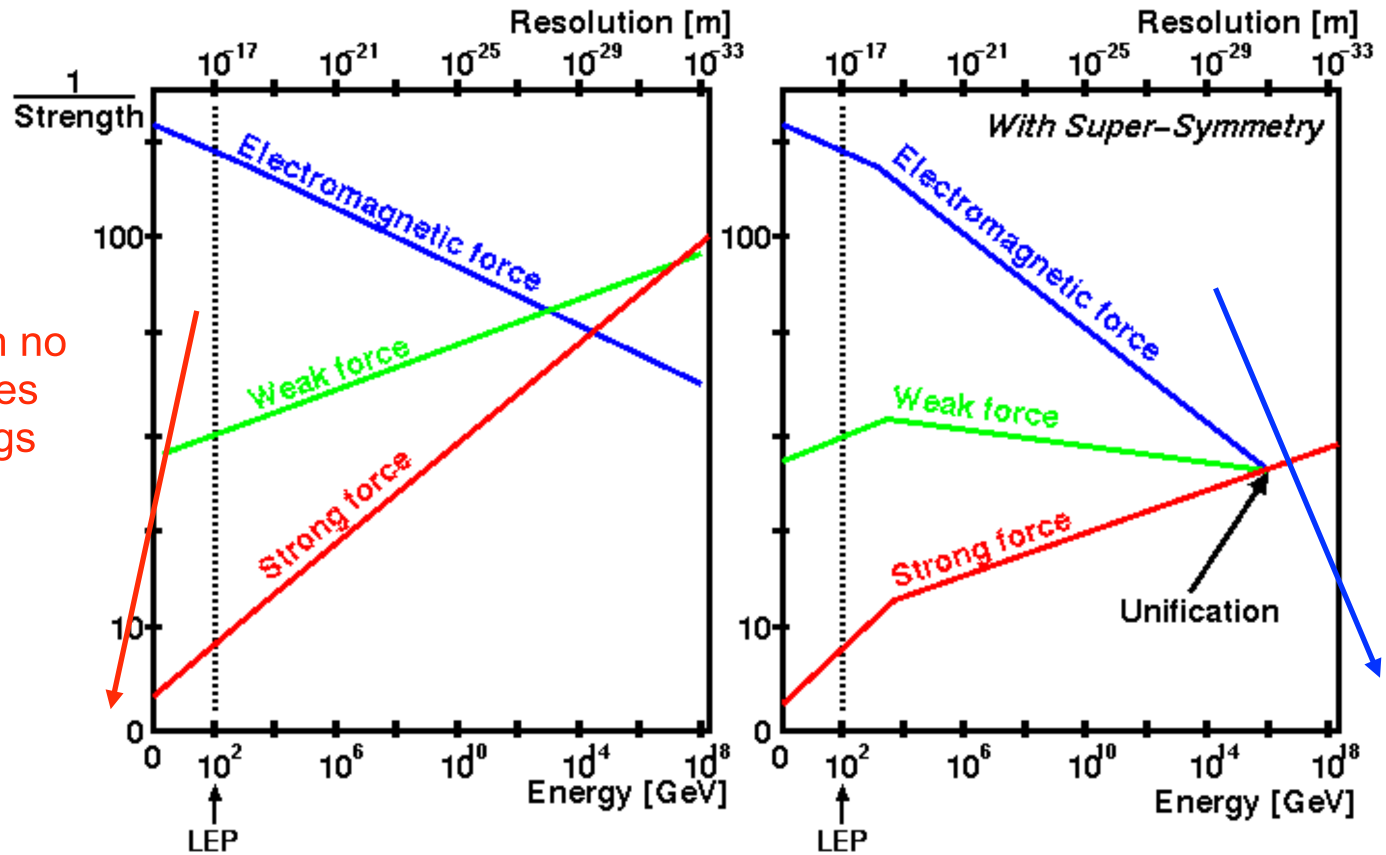
$$\langle \sigma_{\mathrm{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{1\ \mathrm{TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1) \qquad \text{(WIMP)}$$

SUSY' lightest supersymmetric particle, such as neutralino, should be stable (to conserve R-parity) and is often seed as a natural candidate for **WIMP**.

Beyond the Standard Model

- **Standard Model** has worked tremendously well and describes successfully all current data
- Supersymmetry has been a big hope to fix SM “problems” expected at high energies. In particularly **Grand Unification**

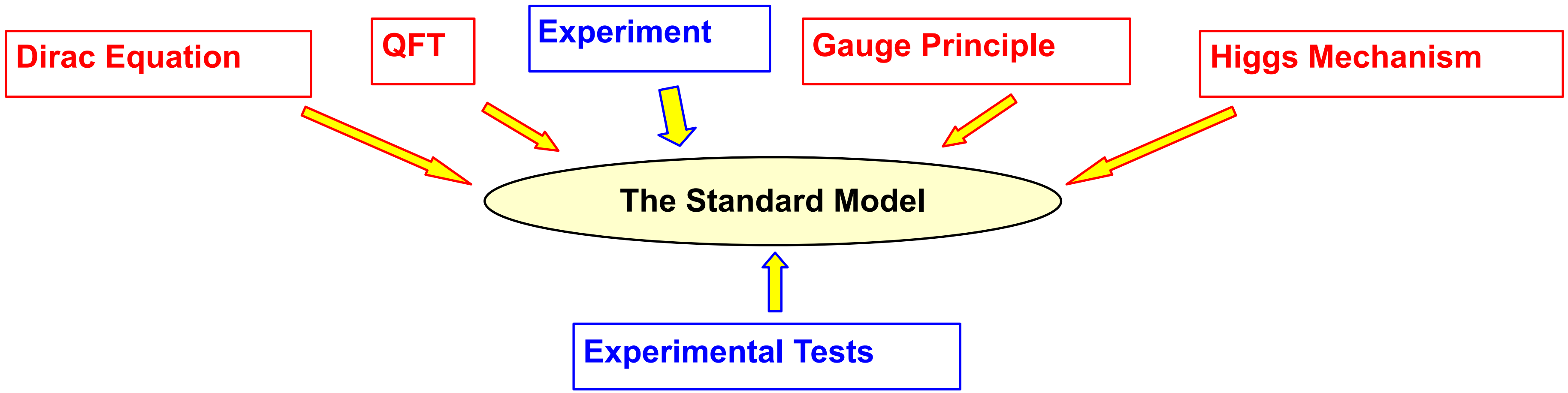
Present “Standard Model” with no new particles except Higgs boson



Model including SuperSymmetric (SUSY) particles

- So far no evidence from **LHC**
- Evidence **beyond** the **Standard Model** so far come only from **neutrinos**

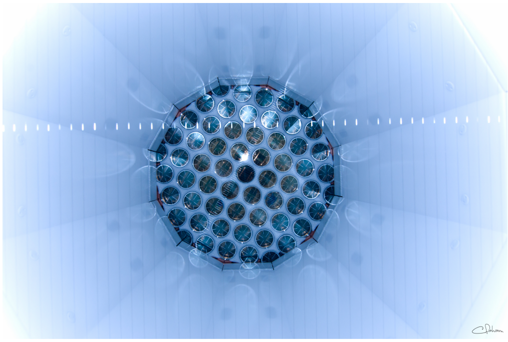
Concluding Remarks

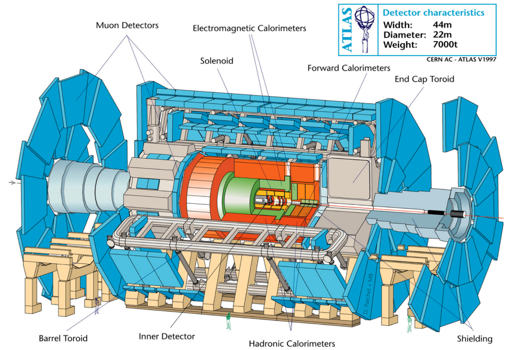


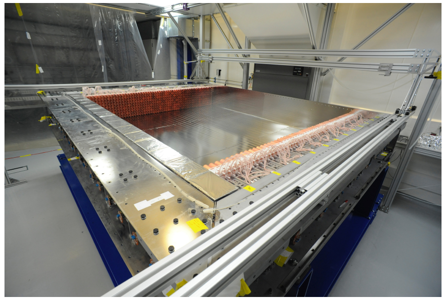
- **Problems/Open questions**
  - SM has too many free parameters: $m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_e, m_\mu, m_\tau, m_d, m_s, m_b, m_u, m_c, m_t$
    $\theta_{12}, \theta_{13}, \theta_{23}, \delta \quad e, G_F, \theta_W, \alpha_S \quad m_H, \theta_{CP}$
  - Why three generation?
  - Why $SU(3)_C \times SU(2)_L \times U(1)$?
  - Unification of Forces
  - Origin of CP violation in early universe
  - Why are neutrinos are so light?
  - What is Dark Matter?
  - Why is the weak interaction V-A?
  - Ultimately need to include gravity

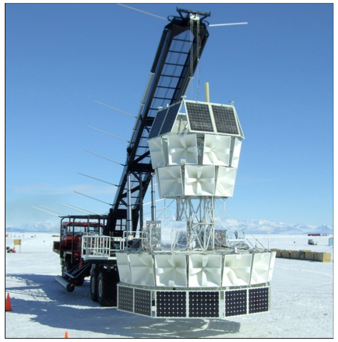
In the next ~10 yrs we will almost certainly have answers to some of these questions…

UCL High Energy Physics Group









http://www.hep.ucl.ac.uk/

Energy Frontier with **ATLAS** at **LHC**

Neutrino Physics with **SuperNEMO**, **NOVA** and new generation neutrino oscillation experiments (**DUNE**, **CHIPS**)

Direct detection of dark matter with **LUX** and **LZ** experiments

Probe physics at energies beyond LHC indirectly with UHE neutrinos at South Pole (**ANITA/ARA**), muon's magnetic moment (**FNAL g-2**), lepton flavour violation (**COMET**)

Theoretical studies of strong interactions, QCD, and physics beyond the standard model

Developing novel instrumentation for future experiments and their applications in **proton cancer therapy** and **muon tomography**

PhD Opportunities! Deadline for applications 31-Jan-2017, see http://www.hep.ucl.ac.uk/postgrad/apply_now.shtml Interviews — 23-24 Feb 2017.