NEUTRINO MASS HIERARCHY MEASUREMENT WITH DUNE

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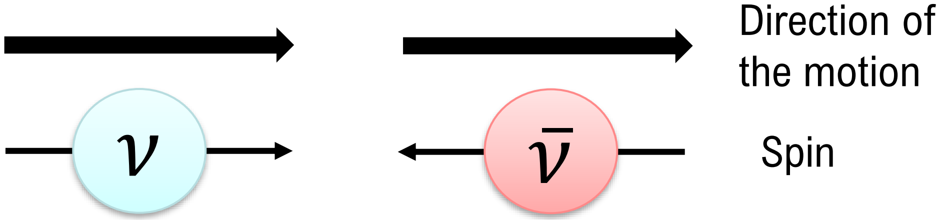
NEUTRINO IN THE STANDARD MODEL

Two notable facts about neutrino

From massless Dirac's equation energy solutions

- Neutrino are emitted with negative helicity
- Antineutrino are emitted with positive helicity



NEUTRINO $\neq$ ANTINEUTRINO

From the V-A structure of the CC processes

$$J^{\mu}_{CC} = \overline{u_1}\gamma^{\mu}\frac{1}{2}\boxed{(1-\gamma^5)}u_2$$

Extract only the *left –handed* component of fermions and *right-handed* component of anti-fermions

ONLY ν_L AND $\overline{\nu_R}$ ENTER IN WEAK INTERACTIONS

DIRAC OR MAJORANA NEUTRINO?

In SM particles can de described either by Dirac or Weyl's equation but massive neutrinos can't:

- Weyl's equation describes massless fermion
- Dirac's equation need 4 states $(f_L,\ f_R, \overline{f_L},\ \overline{f_R})$ to explain mass of any particles →neutrino has only non zero two spinor's components ν_L and $\overline{\nu_R}$

1937 Italian physicist E.Majorana debuted another theory: could Neutrino and Antineutrino be the same particle $\nu_i = \overline{\nu_i}$?

DIRAC FERMIONS

$\nu_i \neq \overline{\nu_i}$

same mass but different lepton number $L(\nu_i) = -L(\overline{\nu_i}) = 1$ and the particles will be described as a quadruplet.

MAJORANA FERMIONS

$\nu_i = \overline{\nu_i}$

No lepton number conservation and distinction between particle and antiparticle. Neutrino is described by only two spin states.

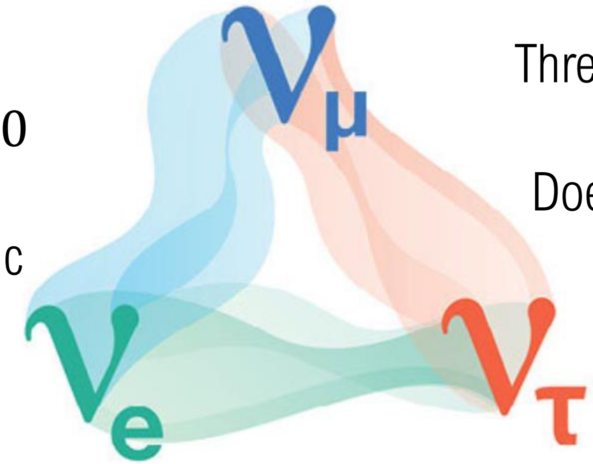
NEUTRINO OSCILLATIONS

STANDARD MODEL

Three flavour eigenstates $\upsilon_e \ \upsilon_\mu \ \upsilon_\tau$

One zero-mass state $m_\upsilon \simeq 0$

Does conserve familiy’s leptonic number $L\alpha$ $(\alpha = e, \mu, \tau)$



OSCILLATION THEORY

Three flavour eigenstates $\upsilon_e \ \upsilon_\mu \ \upsilon_\tau$

Three mass eigenstates $\upsilon_1 \ \upsilon_2 \ \upsilon_3$

Does NOT conserve family leptonic number $L\alpha$ $(\alpha = e, \mu, \tau)$

Experimental observation of flavour changing in propagating neutrino can only be explained by assuming different neutrino mass eigenstates

NEUTRINO OSCILLATIONS

Neutrino with a definite flavour can be expressed as a linear combination of the three mass eigenstate and viceverse

$$|\boldsymbol{v_\alpha}>=\textstyle\sum_i U^*_{\alpha,i}\,|\boldsymbol{v_i}> \qquad \alpha = e,\mu,\tau \quad \text{FLAVOUR}$$

$$|\boldsymbol{v_i}>=\textstyle\sum_\alpha U_{\alpha,i}|\boldsymbol{v_\alpha}> \qquad i = 1,2,3 \quad \text{MASS}$$

$U_{\alpha,i}$ PMNS mixing matrix

Unitary matrix that assumes 3x3 form for three neutrino families → 9 degrees of freedom

DIRAC NEUTRINOS

θ_{12} θ_{12} θ_{23} three mixing angles

δ_{CP} one phase related to the CP symmetry violation

MAJORANA NEUTRINOS

θ_{12} θ_{12} θ_{23} three mixing angles

δ_α δ_β δ_γ three phases related to the CP symmetry violation

NEUTRINO OSCILLATIONS

Using Dirac parametrization for the PMNS matrix

- θ_{12} θ_{12} θ_{23} three mixing angles θ_{12} θ_{12} $\theta_{23} \in [0,\pi]$
- δ_{CP} one phase related to the CP symmetry violation $\in [0,2\pi]$

(observation of oscillation does not distinguish between Majorana and Dirac neutrino!)

$$U_{\alpha,i} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\substack{\textbf{Atmospheric} \\ \upsilon_\mu \to \upsilon_\tau}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix}}_{\substack{\textbf{Accelerated} \\ \upsilon_\mu \to \upsilon_e}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\substack{\textbf{Solar} \\ \upsilon_e \to \upsilon_\alpha}}$$

With $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, $ij = 12, 13, 23$

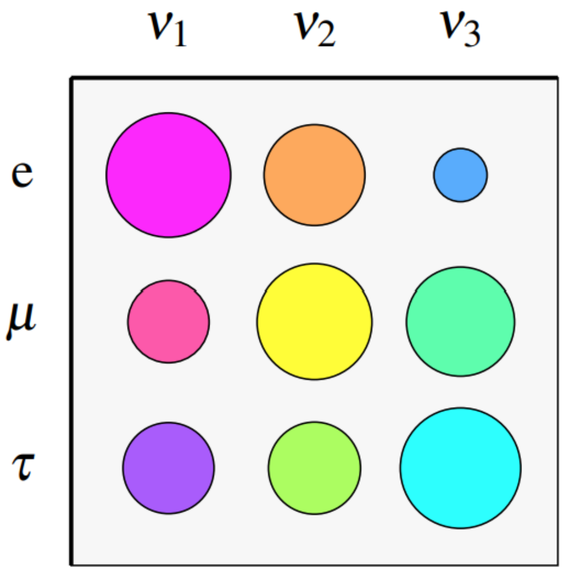
NEUTRINO OSCILLATIONS

Parameter	Normal ordering	Inverted ordering
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$33.45^{+0.78}_{-0.75}$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$49.0^{+0.9}_{-1.3}$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.61^{+0.14}_{-0.12}$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	278^{+22}_{-30}

Respect to CKM matrix parameters the mixing is enhanced

The octant for θ_{23} it has not been determined yet

Currently values for δ_{CP} are in favor of the CP symmetry violation



NEUTRINO OSCILLATIONS

Neutrino oscillation occur with a non zero probability that a neutrino with initial flavour α could be detected after a distance L with a different flavour β ≠ α.

- Each neutrino propagates as a plane wave with different phases for each mass state $\lambda = h/p_i$
- Ultra relativistic particle approssimation $|p_i| \simeq E - \frac{m_i^2}{2E} \simeq E$

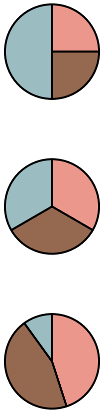
PROBABILITY OF OSCILLATION

$$P_{\alpha\to\beta} = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2 + 2Re \sum_{i>j} U^*_{\alpha,i} U_{\beta,i} U_{\alpha,j} U^*_{\beta,j} e^{\boxed{-i\frac{\Delta m^2_{ij} L}{2E}}} \qquad \Delta m^2_{ij} = m_i^2 - m_j^2$$

Observation of a flavour's transition implies the existance of different non zero mass states

MASS HIERACHY

- $P_{\alpha\to\beta} \propto \Delta m^2_{ij}$ does not give any information about the absolute mass values!
- Any massive state has different probabilities to interact as a neutrino with a given flavour



$\upsilon_1 \longrightarrow 66\%\,\upsilon_e \;\; 17\%\,\upsilon_\mu \;\; 17\%\,\upsilon_\tau$

$\upsilon_2 \longrightarrow 33\%\,\upsilon_e \;\; 33\%\,\upsilon_\mu \;\; 33\%\,\upsilon_\tau$

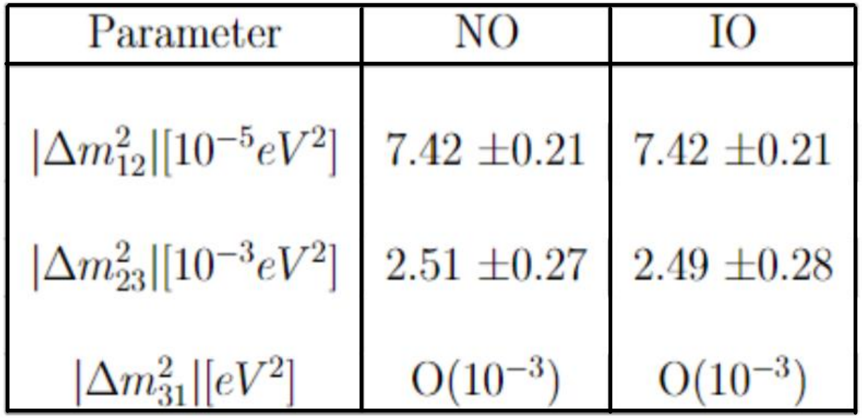
$\upsilon_3 \longrightarrow 10\%\,\upsilon_e \;\; 45\%\,\upsilon_\mu \;\; 45\%\,\upsilon_\tau$

- The measureable quantity is Δm^2_{ij} → studies on solar and atmospheric neutrinos first measured

SOLAR (Δm^2_{12}) $\upsilon_e \to \upsilon_\mu \;\; \upsilon_\tau$ Homestake, Kamiokande, SAGE, SNO, GALLEX, Borexino

ATMOSPHERIC (Δm^2_{23}) $\upsilon_\mu \to \upsilon_\tau$ Super-Kamiokande, K2K, MINOS, OPERa, IceCube

MASS HIERACHY



Parameter	NO	IO
$\lvert\Delta m^2_{12}\rvert[10^{-5}eV^2]$	7.42 ± 0.21	7.42 ± 0.21
$\lvert\Delta m^2_{23}\rvert[10^{-3}eV^2]$	2.51 ± 0.27	2.49 ± 0.28
$\lvert\Delta m^2_{31}\rvert[eV^2]$	$O(10^{-3})$	$O(10^{-3})$

Eigenvalues m_1^2 and m_2^2 are similar while m_3^2 is more separated from the others

$$|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$$

What is the sing of Δm^2_{31} ?

Possible configurations that arise from the sing of Δm^2_{31} are known as *hierarchies* (or ordering)

NORMAL $m_1 < m_2 < m_3$ $\quad \mathrm{sgn}(\Delta m^2_{31}) = +1$

INVERTED $m_3 < m_1 < m_2$ $\quad \mathrm{sgn}(\Delta m^2_{31}) = -1$

MSW EFFECT

- Neutrino interaction with matter can modifies the probability of oscillation
- Propagation is alterated due to the elastic scatterin event with the medium's particles

$$H \rightarrow H_{effecctive} = H + \boxed{V_{MSW}}$$

$\Delta m^2 \rightarrow \Delta m_M^2$

Increase for υ_e

Decrease for $\overline{\upsilon_e}$

NEUTRAL CURRENT WEAK INTERACTION (CN)

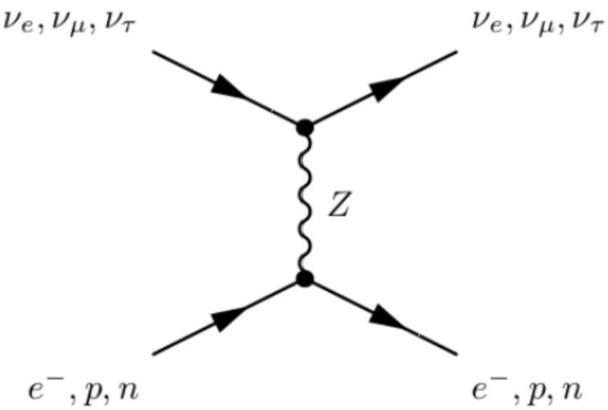
Cross section is independent from the leptonic family, all the three flavour can exchange

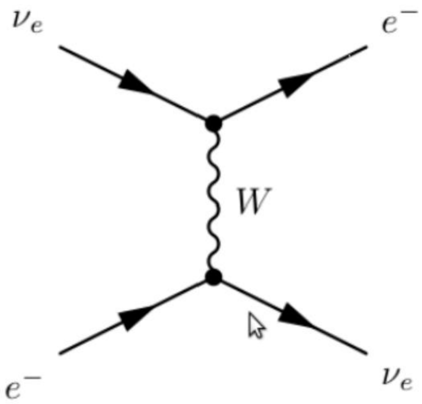
$Z^0 \rightarrow V = 0$

CHARGED CURRENT WEAK INTERACTION (CN)

Only electron neutrino are involved in this processes inducing an additional phase in the Hamiltonian

$W^{\pm} \rightarrow V_{MSW} = \pm\sqrt{2}\, G_F N_e$





MSW EFFECT

- Matter effect modifies the probability of oscillation

$$\mathcal{P}_{\alpha\to\beta}(L,E) = |\Psi_{e,\beta}|^2 = \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$

$$\Delta m_M^2 = \Delta m^2\sqrt{(\cos 2\theta - A)^2 + (\sin 2\theta)^2}$$

$$\tan 2\theta_M = \frac{\sin 2\theta}{\cos 2\theta - A}$$

where $A = \pm\frac{2\sqrt{2}\,G_F N_e E}{\Delta m^2}$

depends on neutrino (+) or antineutrino (-) so it is sensible to $\mathrm{sgn}\left(\Delta m_{ij}^2\right)$ →allows to discriminate the mass hierarchy !

- Becomes more important increasing the ratio

  between *E* and *L* ⟶ *Long-Baseline* $\frac{L}{E} \simeq 10^{-3}\,\frac{Km}{GeV}$

- At fixed parameters <u>results for neutrino and antineutrino are opposite</u>

$$\frac{P_{\upsilon_\alpha\to\upsilon_\beta}}{P_{\overline{\upsilon_\alpha}\to\overline{\upsilon_\beta}}}\begin{cases} > 1 & \textbf{NORMAL (NH)} \\ < 1 & \textbf{INVERTED (IH)}\end{cases}$$

MSW EFFECT

How to measure $\mathbf{sgn}(\Delta m^2_{13})$

- Particular values of N_e allows resonant transition between neutrino with different flavour → the effect is maximized for the condition:

$$N_e^{Resonance} = \Delta m_i^2 \frac{\cos 2\theta_{ij}}{2\sqrt{2}\, G_F E_\nu} \rightarrow \theta_M = \frac{\pi}{4}$$

MAXIMAL MIXING

- Using different effects between neutrino and neutrino due to the presence of matter is an efficient tool for the ordering discrimination

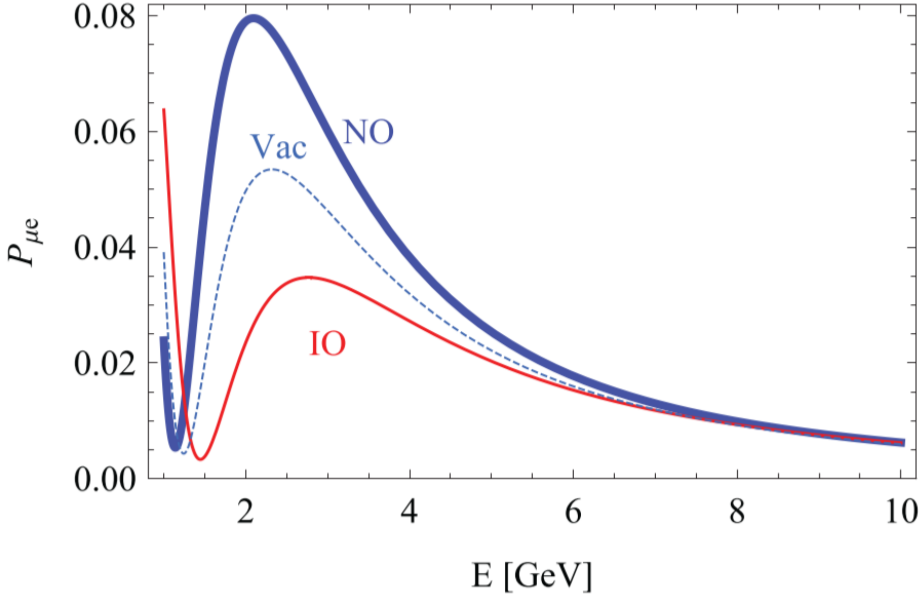
$$\frac{P_{\upsilon_\alpha \rightarrow \upsilon_\beta}}{P_{\overline{\upsilon_\alpha} \rightarrow \overline{\upsilon_\beta}}} \begin{cases} > 1 \\ < 1 \end{cases}$$

NORMAL (NH)

INVERTED (IH)

MSW EFFECT

Example: appereance events for transition $\upsilon_\mu \rightarrow \upsilon_e$ and $\overline{\upsilon_\mu} \rightarrow \overline{\upsilon_e}$ (with neutrino beam)



One of the best ways to use the MSW effect in Earth matter such as in a long baseline neutrino experiment

Observation by MINOS an electrons electron produced by a muon neutrino beam allows the determination of θ_{13}

$$P_{\nu_\mu \longrightarrow \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E_\nu}$$

$$P_{\upsilon_\mu \rightarrow \upsilon_e} <$$

Amplified for NH

Suppressed for IH

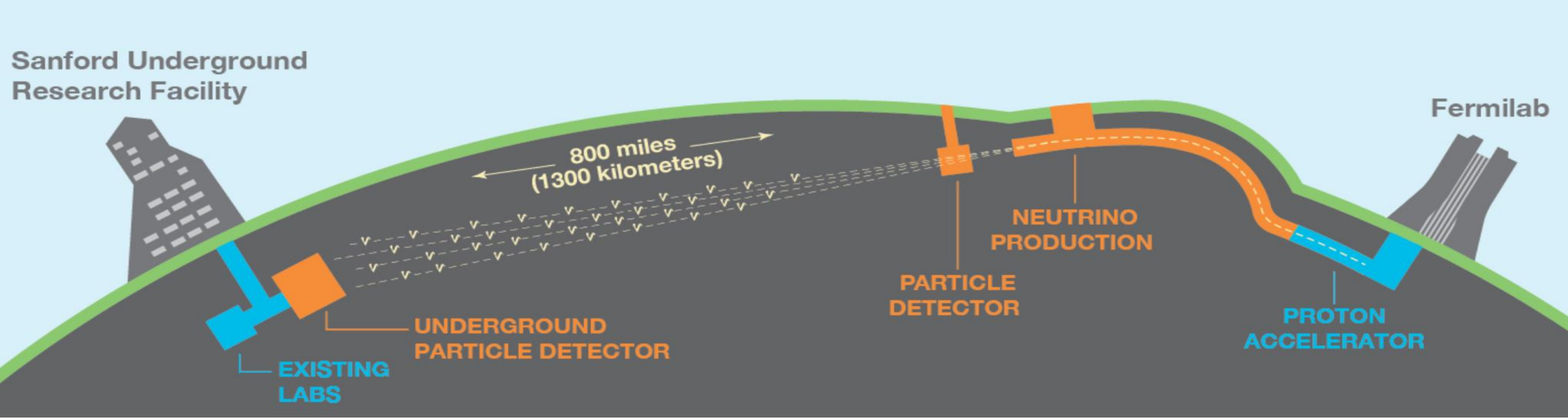
$$P_{\overline{\upsilon_\mu} \rightarrow \overline{\upsilon_e}} <$$

Amplified for IH

Suppressed for NH

DUNE

Deep Underground Neutrino Experiment



- Determine the correct mass hierarchy (confidence >5σ)
- Measuing δ_{CP} to verify CP violation
- Even more precise measurements of the other parameters
- Atmospheric neutrino
- Nuclear decays
- Supernovae neutrinos

PRIMARY GOALS

SECONDARY GOALS

DUNE

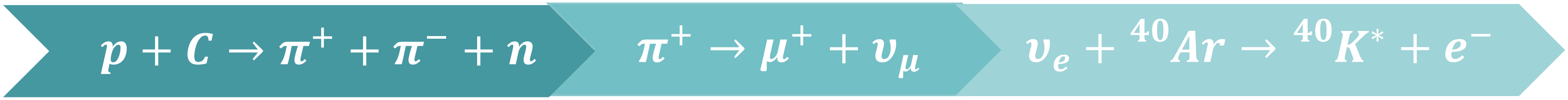
Deep Underground Neutrino Experiment

ACCELERATOR An effective way to access neutrino oscillation is by making intense neutrino beams using particle accelerators

Disappereance channels ⟶ $\left|\Delta m^2_{31}\right|$ and $\sin^2(2\theta_{23})$

Appereance channels ⟶ $\Delta m^2_{31}\quad \theta_{23}\quad \theta_{13}\quad \delta_{CP}$

$$\mathcal{P}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(1.27\Delta m^2_{23}\frac{L}{E}\right)$$



$p + C \rightarrow \pi^+ + \pi^- + n$

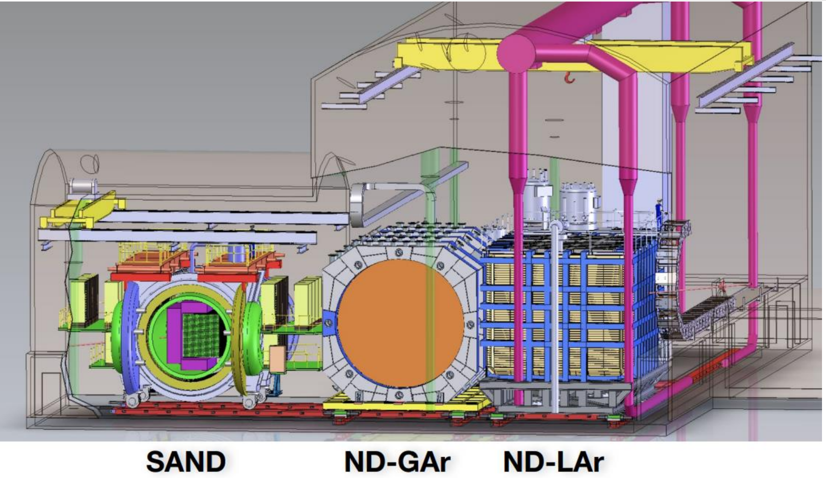
$\pi^+ \rightarrow \mu^+ + \upsilon_\mu$

$\upsilon_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

Forward Horn Current (FHC) mode produces a predominantly υ_μ beam

Reverse Horn Current” (RHC) mode produces predominantly $\overline{\upsilon_\mu}$

DUNE
The Near Detector



3 SUBSYSTEM

SAND	tracker surrounded by ECAL and magnet On-axis monitor of beam spectrum
ND-Gar	high-pressure GArTPC surrounded by ECAL and magnet muon spectrometer Constraint nuclear Interaction model
ND-Lar	modular pixelated LarTPC, primary target similar to FR

- Higher number of interactions with pure neutrino beam
- Information about the intial beam composition
- Smaller sistematic errors on the final measures

- 600 m away from the Fermilab base
- ArgonCube Liquid Argon detector.
- Array of 5x7 ArgonCube modules (5 along and 7 transverse to the beam direction) sharing a common cryostat
- Minimal amount of inactive material

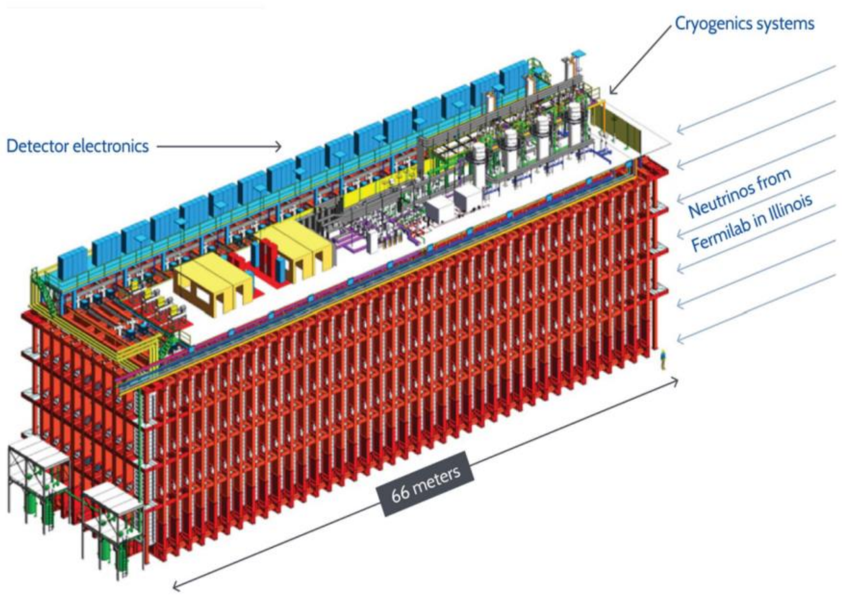
con l'esperimento DUNE

DUNE

Far Detector

- More chances to interact with matter
- Enhancement of oscillation probability
- $\frac{L}{E} \simeq 10^{-3} \frac{Km}{GeV}$

- 1300 km far from Fermilab
- 1.5 km underground
- 4 modules, filled with liquid Argon at -184 each with a total (fiducial) mass of 17 kt (10 kt)



$$\upsilon_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

$$\upsilon_\mu + {}^{40}Ar \rightarrow {}^{40}K^* + \mu^-$$

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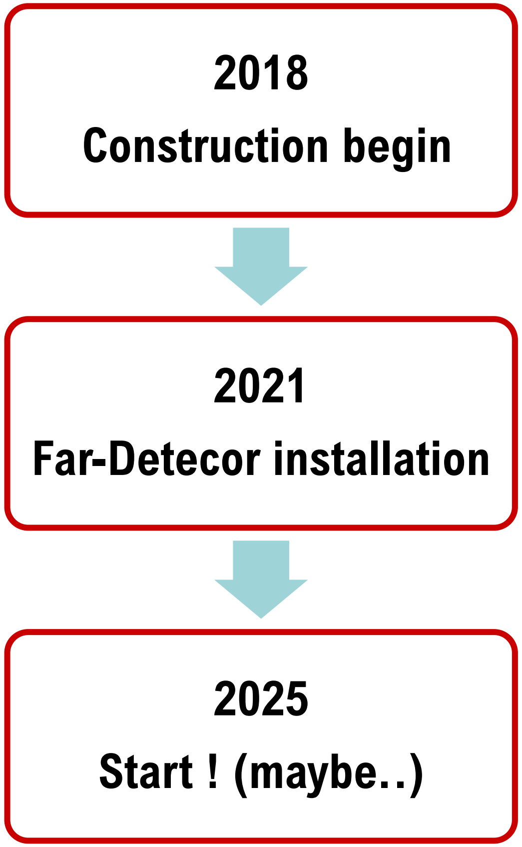
DUNE

Deep Underground Neutrino Experiment



2018

Construction begin

2021

Far-Detecor installation

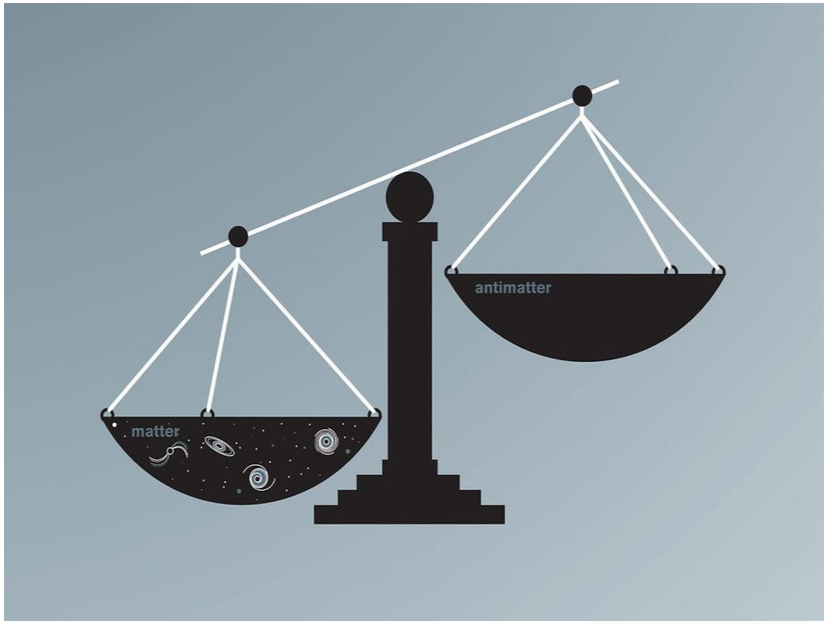
2025

Start ! (maybe..)

CONCLUSION

Still a lot of questions!

- What is the right mechanism through wich neutrino acquire their mass?
- Are neutrino Majorana or Dirac fermions?
- Do they violate CP symmetry?



- Could be the explanation of the discrepancies between matter and antimatter in our universe?
- Are new beyond Standard Model thories necessary? (YES!)

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Ajó

THANKS FOR YOUR ATTENTION!

Giulia Lupi