NEUTRINO REVIEW

Neutrino masses, inferred from oscillation experiments, is the only lab-based evidence of physics beyond the standard model.

What do we know about neutrinos?

1. Z-boson measurements (line shape) implies only 3 neutrinos with weak interactions and $m_\nu < M_Z/2$

2. Oscillation Physics for 3 neutrinos can be parametrized by 3 mixing angles, 2 mass splittings and 1 complex phase.
   - ↳ $\theta_{12}, \theta_{13}, \theta_{23}$
   - ↳ $\Delta m^2_{21}, \Delta m^2_{31}$
   - ↳ δ_{CP}

In general oscillations go like

$$P(\nu_\mu \to \nu_\tau) = \underbrace{\sin^2(2\theta_{23})}_{\text{Oscillation amplitude}} \underbrace{\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)}_{\text{Oscillatory pattern}}$$

(L: Distance traveled)

(and similar for other modes)

This oscillatory pattern has been observed in several experiments:

- KamLAND, Solar → $\Delta m^2_{21}, \theta_{12}$
- Atmospheric, accelerator → $|\Delta m^2_{31}|, \theta_{23}, \delta_{CP}$ → just hint! (2σ-ish)
- Reactors → $|\Delta m^2_{31}|, \theta_{13}$

→ Last unknowns: mass ordering and δ_{CP}

Scanned by CamScanner

3. Neutrino interactions

These have been measured in several energies and on several targets

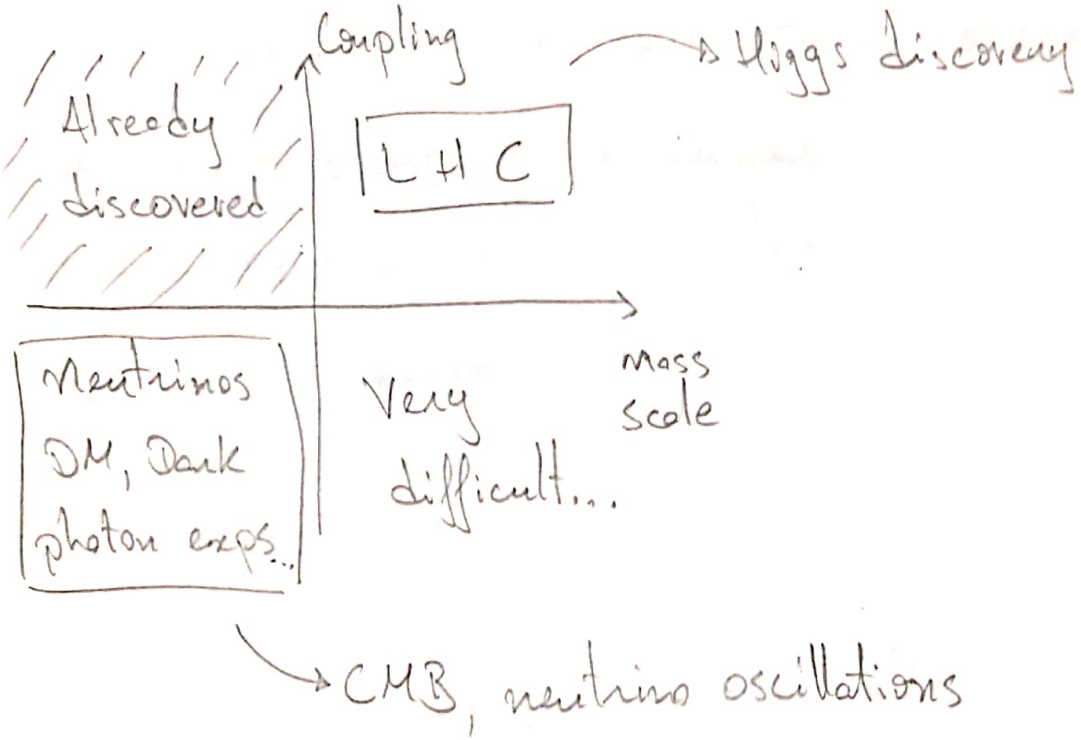
ν-e scattering: few hundred KeV $\longrightarrow$ tens of GeV

ν-N scattering: coherent, inverse beta decay, quasi-elastic, meson exchange, deep inelastic, ...

this is our focus!

also interesting for us!

How to look for new physics



Scanned by CamScanner

ν-N coherent scattering

When the neutrino interaction is very soft, it cannot distinguish the constituents of a nucleus. The scattering is <u>coherent</u>.

- Lorentz invariance: coherence is parametrized by q^2 where

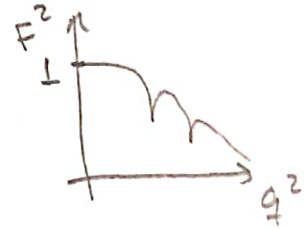
$$q \equiv p_\nu^{in} - p_\nu^{out}$$

Dimension analysis

Weak interaction $\Rightarrow G_F^2 \Longrightarrow \frac{d\sigma}{dQ^2} \sim G_F^2$ $\quad Q^2 = 2E_r m_N$

$\Rightarrow \frac{d\sigma}{dE_r} \sim G_F^2 m_N$

$$\boxed{\frac{d\sigma}{dE_r} \simeq \frac{G_F^2}{4\pi} m_N F^2(q^2) Q_W^2 \left(1 - \frac{m_N E_r}{2E_\nu^2}\right)}$$



$F^2(q^2)$: form factor that parametrizes coherence

Q_W: Weak charge of the nucleus

E_r: Energy recoil of the nucleus

E_ν: Neutrino energy

m_N: mass of the nucleus

Features of CEνNS

1. Neutral current interaction → no flavor information (no standard oscillation)

Scanned by CamScanner

2. Recoil energy needs to be very low for coherent scattering

size of nucleus ~ fm

$Q^2 \sim fm^{-2} \sim \left(\frac{200\,MeV\,fm}{fm}\right)^2 \Rightarrow Q \lesssim 200\,MeV$ to maintain coherence

$\hbar c = 200\,MeV\,fm$

$Q^2 = 2E_r m_N$ for Si $\Rightarrow Q^2 = 2E_r \times 28\,GeV \lesssim (200\,MeV)^2$

$\Rightarrow \boxed{E_r \lesssim \text{hundreds keV}}$

Very challenging!

3. Form factor involves some nuclear physics

4. Nuclear weak charge → similar to electric charge

Due to coherence it is squared in the cross section

$$Q_W^2 = \left[(A-Z) + Z(4\sin^2\theta_W - 1)\right]^2$$

(θ_W: weak mixing angle)

For Si: $A-Z=14$, $\sin^2\theta_W \sim 0.23 \Rightarrow 4\sin^2\theta_W - 1 \sim 0$

$\Rightarrow Q_W^2\big|_{Si} \simeq 200$ → Large enhancement of the cross section!

5. Quenching... more on other talks...

Scanned by CamScanner

What can we do with CEvNS detectors?

Low threshold detectors
Low background
Relatively small

} Light, weakly coupled physics
Standard physics

Standard Physics

1. Nuclear Physics → measurements of form factor

2. Weak mixing angle → measurement of Q_W with precision

BSM

1. Sterile neutrino oscillations.
   no oscillations should be seen in CEvNS. Observing any oscillation features would imply sterile neutrinos (neutrinos without weak interactions).

2. Light mass physics
   Like the photon, light NP interactions would be enhanced for low momentum transfer Q^2.

Scanned by CamScanner

3. Electromagnetic properties of neutrinos

Neutrino magnetic moment or electric millicharge would only show up in low Q^2 processes

4. New neutrino interactions with matter

these are typically parametrized by effective interactions like

$$2\sqrt{2} G_F \varepsilon_{\alpha\beta} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{q} \gamma^\mu q)$$

↳ Non-standard interactions (NSI)

5. Depending on source, dark photons can also be probed

BONUS: ν-e scattering at low energies

Although ν-e scattering is ~5 orders of magnitude below the CEνNS cross section, it is sensitive to much low Q^2:

$$Q^2\Big|_{\nu e} = 2E_r m_e \quad \text{vs.} \quad Q^2\Big|_{\nu N} = 2E_r m_N$$

For the same recoil (electron vs. nucleus) the ratio of Q^2 is given by

$$\frac{Q^2_{\nu e}}{Q^2_{\nu N}} = \frac{m_e}{m_N} \simeq \frac{5\times 10^{-4}\ \text{GeV}}{A \cdot \text{GeV}} \sim 10^{-5}$$

Scanned by CamScanner