# Theoretical aspects of neutrino physics

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# Outline

- Status quo
- Origin of neutrino mass
- Key measurements
- Neutrino oscillation
- Outlook

# Status quo

A common framework for all the neutrino data is oscillation.

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \lesssim 0.15$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$$

but we currently do not know which neutrino is the heaviest.

# Status quo

Quarks

$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

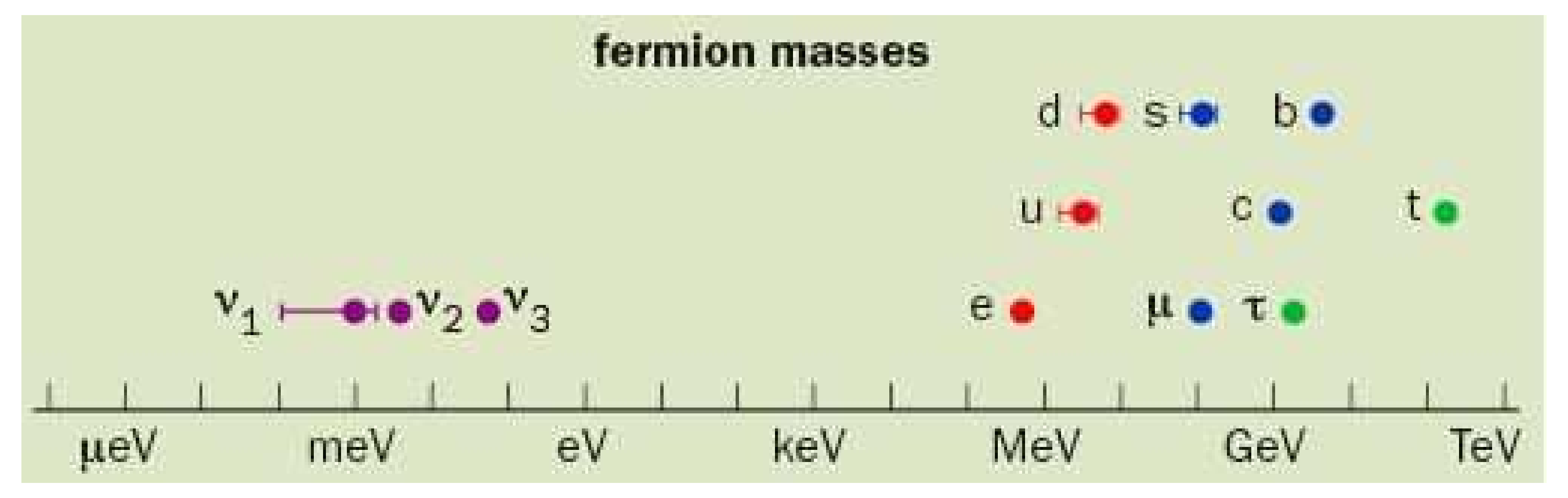
Neutrinos

$$U_\nu = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Why are neutrino mixings so large?

# Status quo

Mass hierarchy in the SM



What makes neutrinos so much lighter?

# Origin of neutrino mass

Neutrinos in the Standard Model (SM) are strictly massless, *ie.* there is no way to write a mass term for neutrinos with only SM fields which is gauge invariant and renormalizable.

Neutrinos are massive in reality – thus neutrino mass requires physics beyond the standard model.

# Origin of neutrino mass

The SM is an effective field theory, *ie.* at some high scale $\Lambda$ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Thus studying neutrino masses is the most sensitive probe for new physics at high scales

# Origin of neutrino mass

One example is the seesaw mechanism

$$\mathcal{L}_\nu = m_D \overline{\nu_L} N_R + \frac{1}{2} m_R \overline{N_L^c} N_R + h.c$$

$N_R$ is a heavy right handed neutrino, *ie*. a singlet under the SM gauge group.

The light neutrino mass is the given by

$$m_\nu \simeq \frac{m_D^2}{m_R}$$

Identifying $m_D \sim 100\,\mathrm{GeV}$ and $m_R \sim m_{GUT} \sim 10^{15}\,\mathrm{GeV}$ yields $m_\nu \simeq 10^{-2}\,\mathrm{eV}$

# Origin of baryons

At the same time $N_R$ can provide a mechanism for creating the observed tiny surplus of matter over anti-matter.

Leptogenesis requires the temperature of the Universe to be high enough that there is a thermal population of $N_R$. Their subsequent out-of-equilibrium decays are a new source of CP violation and lepton number

$$\Gamma(N_R \to LH) - \Gamma(N_R \to \overline{L}H^*) \neq 0$$

which later on is converted to baryon number by non-perturbative processes.

# Key measurements

In the context of GUT scale right handed neutrinos it is very difficult to establish a one-to-one correspondence between high and low-energy observables.

A given model, however, usually has generic predictions for low energy observables. Therefore studying neutrinos allows to gain considerable insight into phenomena which otherwise would be inaccessible.

Colliders can not probe this kind of physics, since any effects in scattering amplitudes are suppressed by $m_{GUT}$, at LHC this would be effects of $\mathcal{O}(10^{-10})$!

# Key measurements

The most sensitive low energy observables are

- Majorana vs Dirac mass – $0\nu\beta\beta$
- Absolute $m_\nu$ – $\beta$-decay endpoint, Cosmology
- How large is $\theta_{13}$? – Oscillation
- Which one is the heaviest neutrino? –$0\nu\beta\beta$, Karmen, Oscillation
- Is $\theta_{23}$ maximal? – Oscillation
- Is there leptonic CP violation? – Oscillation
- Are there only 3 light neutrinos? – Oscillation

# Neutrino oscillations

The mass eigenstates are related to flavor eigenstates by $U_\nu$, thus a neutrino which is produced as flavor eigenstate is a superposition of mass eigenstates. These mass eigenstates propagate with different velocity and a phase difference is generated. This phase difference gives rise to a finite transition probability

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{ij} U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i} e^{-i \frac{\Delta m^2_{ij} L}{2E}}$$

Neutrino oscillation is a quantum mechanical interference phenomenon and therefore it is uniquely sensitive to extremely tiny effects.

# Neutrino oscillations

Like in the quark sector mixing can cause CP violation

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$

The size of this effect is proportional to

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta$$

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$.

# Neutrino oscillation

The charged current interaction of $\nu_e$ with the electrons creates a potential for $\nu_e$

$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$

where $+$ is for $\nu$ and $-$ for $\bar{\nu}$.
This potential gives rise to an additional phase for $\nu_e$ and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \longrightarrow \nu_\beta) - P(\bar{\nu}_\alpha \longrightarrow \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.

# Neutrino oscillation

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

$$\Delta m^2 \simeq A$$

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

| | $\nu$ | $\bar{\nu}$ |
|---|---|---|
| $\Delta m^2 > 0$ | MSW | - |
| $\Delta m^2 < 0$ | - | MSW |

# Outlook

- Neutrinos have mass
- New Physics
- Many candidates
- Oscillation can provide many of the key measurements
- Complimentary to the energy frontier

# Some personal remarks

- Can neutrinos shed light on the flavor problem?
- What if LSND is true?
- Is there a connection between neutrinos and supersymmetry?
- Can neutrinos test large extra dimensions?

All the places where we have looked for new physics we haven’t found anything, but with neutrinos the first searches already were successful – it just took us a long time to believe it. Still, neutrinos are the least known of all fundamental Fermions and therefore even the most exotic things could be just around the corner.