Leptonic Flavor and CP violation

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Introduction

- Neutrino masses and mixings have been found
- Leptons are similar to quarks
- The leptons are a bit behind the quarks

Next: New Physics with leptons

In this talk
SM: Massive neutrinos with mixings
NP: Also new flavor changing interactions

Quarks

We understand the SM flavor sector

- The quark masses
- The CKM mixing angles
- Establish δ_{CKM} as a major source of CPV

We look for new physics

- New sources for flavor mixings
- New CP violating sources

Leptons

We are uncovering the SM lepton flavor sector

- Rough idea about the neutrino masses
- Rough idea about the mixing angles

We would like to fully understand the SM lepton sector

- Solid determinations of masses and mixing angles
- Signals of CPV
- Determine the nature of the masses (Dirac or Majorana)

What Next?

Can we look for new physics in the lepton sector?

- Additional sources of lepton flavor violation
- Other sources of lepton number violation
- CP violation sources beyond the leptonic mixing matrix

Such searches are well motivated and there are many ways to probe possible new leptonic flavor physics

Outline

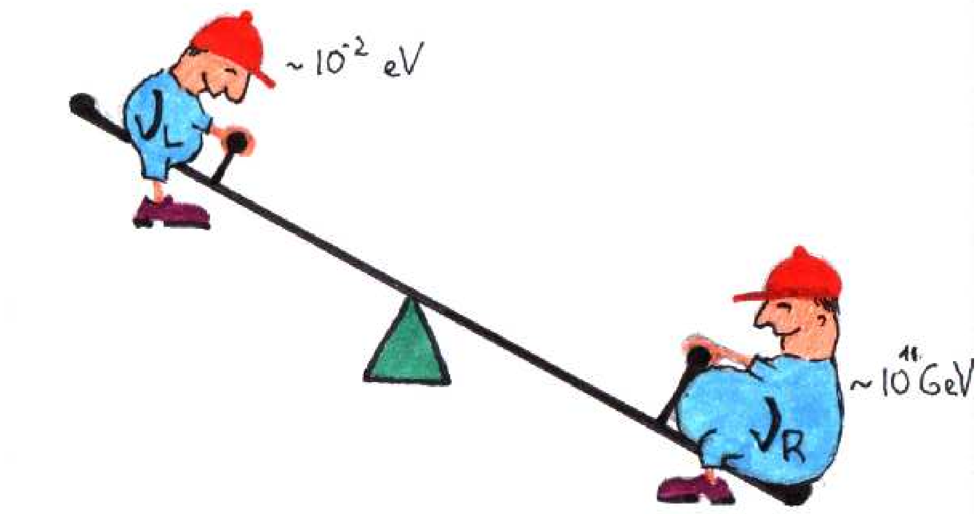
- Neutrino masses and mixing in the SM
- Searching for new physics
  - New flavor physics with charged lepton decays
  - New flavor physics with neutrino oscillation
    (work with Gonzalez-Garcia, Gusso and Nir)
  - Lepton number violation with sneutrino oscillation
    (work with Haber)
- Conclusions

Neutrino masses in the SM

In the “improved” SM we have non-renormalizable terms

$$\frac{\lambda_{ij}}{M} L_i L_j H H \quad \Rightarrow \quad (m_\nu)_{ij} \sim \lambda_{ij} \frac{v^2}{M}$$

Example: seesaw mechanism



Lepton number violation

- In the “improved” SM neutrinos have Majorana masses
  - “Standard” probe of L violation is $0\nu2\beta$ decays
  - Are there other sources of $\Delta L = 2$ interactions?
- In general, $(m_\nu)_{ij} \not\propto (m_\ell)_{ij} \;\Rightarrow$ flavor mixing
  - In the SM, flavor is encoded in the mixing matrix U
  - The way to probe it is via neutrino oscillation
  - Is U the only source of flavor mixing?

Charged leptons decays

Charged leptons decays

- SM: leptonic GIM is very effective

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-54} \times \left(\frac{m_\nu}{10^{-2}\,\mathrm{eV}}\right)^4$$

- SUSY GUT:

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-12}$$

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Observation of $\mu \to e\gamma$

$$\Downarrow$$

New lepton flavor physics

NP with charged leptons

- Many decay modes to look at

$$\mu \to e\gamma \quad \mu \to eee \quad \tau \to \mu\gamma \quad \tau \to \mu\mu e$$

- Other modes probe $\Delta L = 2$ interactions

$$\tau^- \to \mu^+\pi^-\pi^-$$

- Relatively easy experimentally
- Probably the best probe of NP

Neutrino oscillation

NP with neutrino oscillation

Usually,

- Neutrino oscillation: probe of neutrino masses and mixing
- Charged lepton decay: probe new physics

However, neutrino oscillation are sensitive to new physics

$$\ell^+ : \ A_{NP}^2 \qquad \nu : \ A_{NP}$$

Thinking about long baseline experiments, we have observables that are linear in the small NP amplitude

Analog: $D - \bar{D}$ Oscillations

We look for

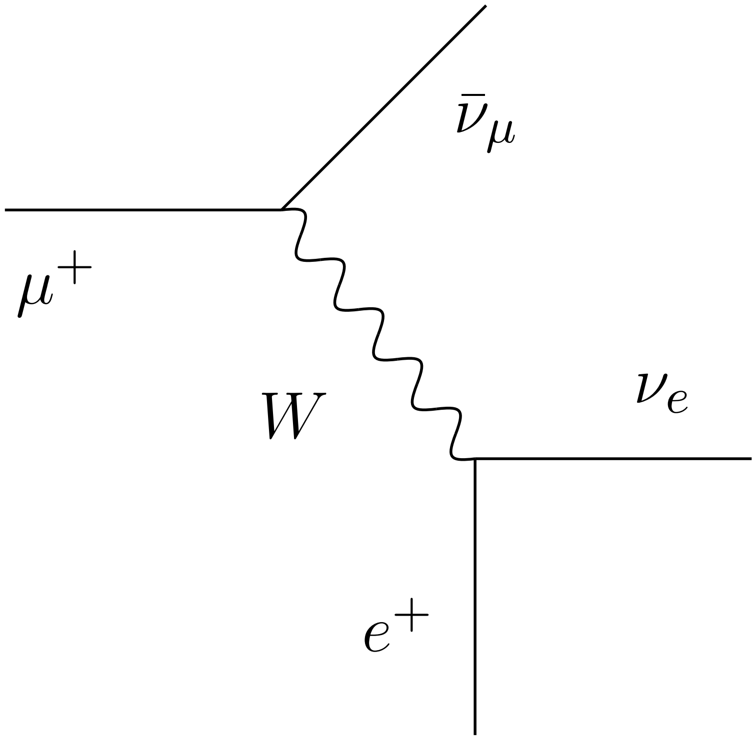
$$\Gamma[D^0(t) \to K^+\pi^-] \propto e^{-\Gamma t}\left[|r|^2 + 2\,\mathcal{I}m(r)\,\Delta M t + (\Delta M t)^2\right]$$

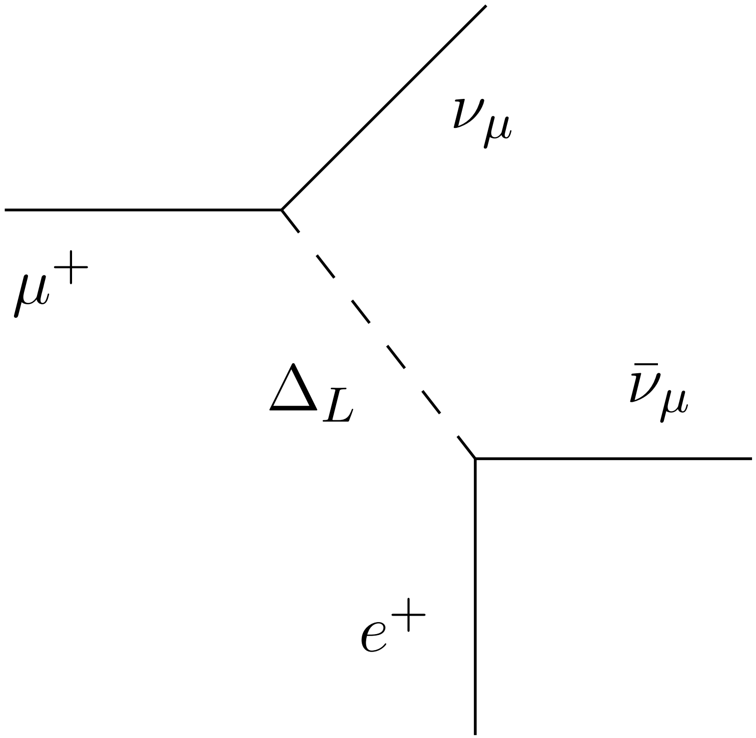
$$x \equiv \frac{\Delta M}{\Gamma} \ll 1 \qquad r \equiv \frac{A(D \to K^+\pi^-)}{A(D \to K^-\pi^+)} \ll 1$$

- 3 terms: DCS decay, mixing and interference
- In general, the interference term enhance the sensitivity
- Since $x \ll r$, CPV enhances the sensitivity to x

Neutrino Oscillations

- In the SM, $P(\nu_e \rightarrow \nu_\mu)[t=0] = 0$
- With new direct decay term $P(\nu_e \rightarrow \nu_\mu)[t=0] \neq 0$
- Example, LRS: $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ and $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_\mu$





Example:LRS

We define a complex small parameter

$$\epsilon \equiv \frac{G_{\rm NP}}{G_F} \sim \frac{f^2}{g^2}\,\frac{m_W^2}{M_\Delta^2}$$

- The produced state: $|\nu_e^s\rangle = |\nu_e\rangle + \epsilon|\nu_\mu\rangle$
- The detected state: $|\nu_\mu^d\rangle = |\nu_\mu\rangle$

Thus

$$\langle\nu_\mu^d|\nu_e^s\rangle = \epsilon \begin{cases} = 0 & \text{SM} \\ \neq 0 & \text{NP} \end{cases}$$

Can we probe ϵ in neutrino oscillation experiments?

Neutrino oscillations

We consider $\nu_e \to \nu_\mu$ oscillations ($i = 1, 2$)

$$P_{e\mu} = \sin^2 x \sin^2 2\theta - \sin 2x \sin 2\theta \, \mathcal{I}m(\epsilon) + |\epsilon|^2 \qquad x = \frac{\Delta m^2 t}{4E}$$

For small x and $\sin 2\theta = 1$

$$P_{e\mu} = |\langle \nu_\mu^d | \nu_e^s(t) \rangle|^2 \sim |\epsilon - ix|^2 = x^2 - 2\,\mathcal{I}m(\epsilon) x + |\epsilon|^2$$

- $O(x^2)$ - SM mixing
- $O(x^0)$ - Direct decay term
- $O(x^1)$ - Interference

When $x > \epsilon$ the interference term enhances the sensitivity to the NP

All together

We can measure $P_\pm = P_{e\mu} \pm P_{\bar{e}\bar{\mu}}$. For $(x \ll 1)$

$$\begin{aligned} P_+ &\approx c_2 x^2 \\ P_- &\approx a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 \end{aligned}$$

where relative to c_2

$$a_1 \sim \mathcal{I}m(\epsilon) \quad a_2 \sim A\,\mathcal{R}e(\epsilon) \quad a_3 \sim (\Delta m^2_{12}/\Delta m^2_{13})\,\delta \quad a_4 \sim A s_{13}$$

and A is the matter effect

- Different x dependence is crucial
- There is sensitivity to both $\mathcal{I}m(\epsilon)$ and $\mathcal{R}e(\epsilon)$

Sensitivity

Optimistically, muon factory with 10^{20} muons

- Sensitivity up to $\epsilon \sim 10^{-5}$
- Roughly, this is similar to $\mathrm{BR} \sim 10^{-10}$ in rare decays

Neutrino oscillation can probe new flavor physics

Sneutrino oscillation

New MSSM

Two candidates to extend the SM

- Massive neutrinos. Found
- Supersymmetry. Almost half found

$$\Downarrow$$

MSSM with massive neutrinos

MSSM with massive neutrinos

Two possible ways

- R-parity conserving supersymmetric extension of the “improved” SM
- R-parity violating supersymmetric extension of the “old” SM

In both cases the effect of the $\Delta L = 2$ interaction is to induce sneutrino “Majorana” mass

$$m^2_{\Delta L=2}\,\tilde{\nu}\,\tilde{\nu}$$

Sneutrino – antisneutrino mixing

We then have

$$\mathcal{L} = m^2_{\tilde{\nu}}\, \tilde{\nu}^* \tilde{\nu} + m^2_{\Delta L=2}\, \tilde{\nu}\, \tilde{\nu}$$

where

- $m_{\tilde{\nu}}$: large ($\sim m_Z$) $\Delta L = 0$ SUSY breaking mass
- $m_{\Delta L=2}$: small ($\sim m_\nu$) $\Delta L = 2$ “Majorana” mass

The sneutrino mass squared matrix is

$$\begin{pmatrix} m^2_{\tilde{\nu}} & m^2_{\Delta L=2} \\ m^2_{\Delta L=2} & m^2_{\tilde{\nu}} \end{pmatrix}$$

This results in $\tilde{\nu} - \tilde{\nu}^*$ mixing and small mass splitting

Analog: $B - \bar{B}$ mixing

In the B system

$$m_{\Delta B=0} \sim 5\,\mathrm{GeV}, \qquad m_{\Delta B=2} \sim 3 \times 10^{-4}\,\mathrm{eV}$$

- $B_{L,H} = (B \pm \bar{B})/\sqrt{2}$ with $\Delta m_B/m_B \sim 6 \times 10^{-14}$
- Oscillations: $P(B \to \bar{B}) = \frac{1}{2}e^{-\Gamma t}(1 - \cos\Delta m t)$
- Same sign dilepton events

No mixing $e^+e^- \to B\bar{B} \to \ell^+\ell^- X$

With mixing $e^+e^- \to B\bar{B} \to BB \to \ell^+\ell^+ X$

- To observe oscillation $\Delta m/\Gamma$ should not be very small

Sneutrino mixing

The sneutrino system is very similar

- The mass eigenstates are

$$\tilde{\nu}_{1,2} = (\tilde{\nu} \pm \tilde{\nu}^*)/\sqrt{2}$$

- Very small mass splitting

$$\Delta m_{\tilde{\nu}}/m_{\tilde{\nu}} \ll 1$$

- Expectation: $\Delta m_{\tilde{\nu}} \sim m_{\nu}$
- The sneutrino exhibits lepton number oscillation

Example: Super see saw mechanism

With one generation we add a singlet $\hat{N}$

$$W = \lambda \hat{H}_u \hat{L} \hat{N} + \tfrac{1}{2} M \hat{N} \hat{N}$$

$$V_{\rm soft} = m^2_{\tilde{L}} \tilde{\nu}^* \tilde{\nu} + m^2_{\tilde{N}} \tilde{N}^* \tilde{N} + (\lambda A_\nu H_u \tilde{\nu} \tilde{N}^* + M B_N \tilde{N} \tilde{N} + {\rm h.c.})$$

Dirac mass: $m_D = \lambda v_u$ Seesaw scale: M

- Neutrino mass $m_\nu = m_D^2/M$
- Sneutrino masses $m^2_{\tilde{\nu}} = m^2_{\tilde{L}} + \frac{1}{2} m_Z^2 \cos 2\beta \pm \Delta m^2_{\tilde{\nu}}$

$$\Delta m_{\tilde{\nu}} = 2\, m_\nu \times \, (A_\nu - \mu \cot \beta - B_N)/m_{\tilde{\nu}}$$

- $\Delta m_{\tilde{\nu}} \sim m_\nu$ when all the mass parameters are $O(m_Z)$,

Experimental signatures

Model dependent

- $\Delta m_{\tilde{\nu}} \gtrsim 1\,\mathrm{GeV}$: Direct reconstruction
- $\Delta\Gamma_{\tilde{\nu}}/\Gamma_{\tilde{\nu}} \gtrsim 1$: Measure $\Delta\Gamma_{\tilde{\nu}}$
- Indirect effect $0\nu 2\beta$ and $e^-e^- \to \chi^-\chi^-$
- Most promising $x_{\tilde{\nu}} \equiv \Delta m_{\tilde{\nu}}/\Gamma_{\tilde{\nu}} \gtrsim 1$: Same sign lepton signal

  $$e^+e^- \to \tilde{\nu}\tilde{\nu}^* \to \tilde{\nu}\tilde{\nu} \to \ell^-\ell^- X$$

  Higher sensitivity when $\Gamma_{\tilde{\nu}}$ is small

Sneutrino mixing: Conclusions

- Sneutrino – antisneutrino mixing is another probe of L violation
- Sneutrino exchange contributes to $0\nu2\beta$
- In practice, it can be observed in part of the parameter space where $\Delta m/\Gamma$ is not too small

Conclusions

Conclusions

- We are currently probing the SM leptonic sector
    - Measuring neutrino masses
    - Measuring mixing angles
    - Thinking about finding CPV
- We also look for new sources of flavor and CPV
    - Charged leptons decay
    - Neutrino oscillation
    - Sneutrino oscillation
    - Other methods