Neutrinos: Majorana or Dirac Particles?

Saiyad Ashanujjaman, Ana Sofia Inácio, Nicholas William Kamp, Varun Mathur

International Neutrino Summer School 2021

Neutrinos: Dirac or Majorana?

Dirac

- ❑ $\nu \neq \overline{\nu}$
- ❑ LNC

Majorana

- ❑ $\nu = \overline{\nu}$
- ❑ LNV

Dirac vs. Majorana: Why should we care?

- ❑ Origin of neutrino masses and mixings
- ❑ If Majorana, possible explanation for the matter-antimatter asymmetry
- ❑ Neutrinos have been full of surprises.

Why determining this is very challenging?

- ❑ When a neutrino is ultra-relativistic, its behavior is insensitive to its nature.

How to address Dirac vs. Majorana question?

- ❑ Find exception to the property that a Majorana neutrino behaves almost like a Dirac one.

  E.g., *kaon/pion decays to heavy neutrino.*

- ❑ Find an effective way of working with non-relativistic neutrinos.

  E.g., *the relic neutrinos from the Big Bang.*

- ❑ Find some process that addresses the question even though it does not involve neutrinos at all.

  E.g., *Neutrinoless double beta decay.*

Neutrinos: Dirac or Majorana?

The most promising approach

- 0νββ: observation of 0νββ would imply Majorana nature of neutrino.

Other approaches

- Capture the relic neutrinos from the Big Bang on tritium

  The total capture rate is two times larger in the Majorana case compared to that in the Dirac one.

- (Heavy) neutrino decays: N → ν + X

  Angular distribution of X in the N's rest frame: *isotropic if Majorana, almost never isotropic if Dirac.*

  Physics Letters B 789 (2019) 488-495

- Many more … *E.g., LNV at LHC and ee collider.*

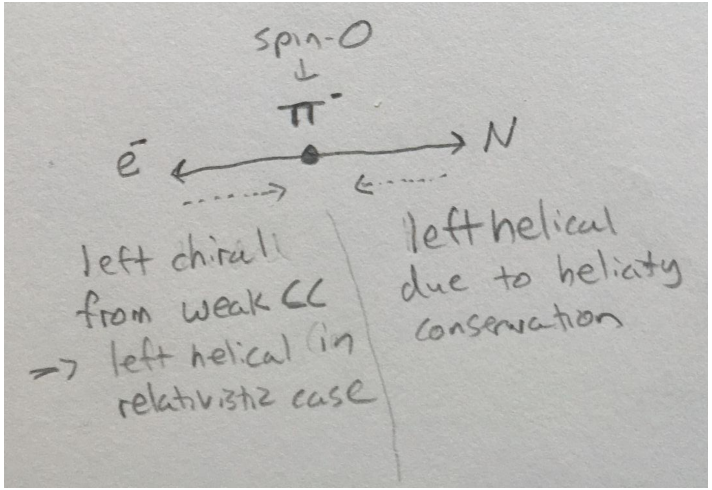
Pion Decay to Heavy Neutrinos

https://arxiv.org/abs/1805.00922

Suppose there is a fourth neutrino mass state which has some coupling to the weak flavor states. Consider

$$\pi^- \to e^- N$$

$$m_e << m_N << m_\pi$$



Dirac *N*:

- Lepton number conservation means interactions of the left-helical heavy antineutrino are suppressed

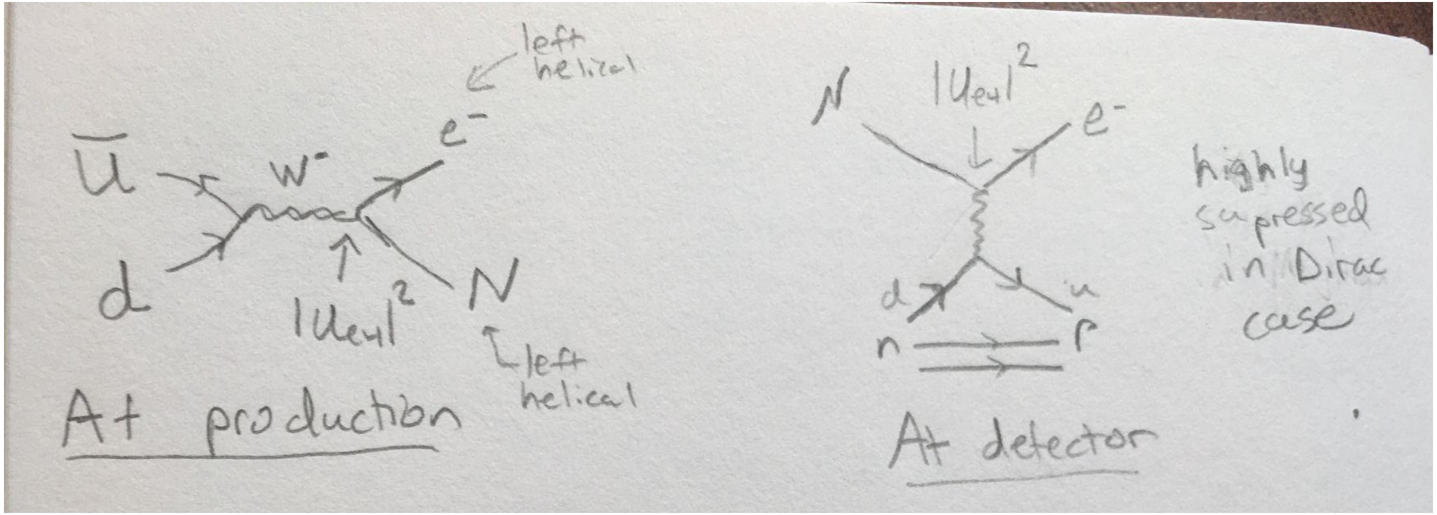
Majorana *N*:

- Lepton number not a good symmetry
- left-helical *N* can interact like a left-handed Dirac neutrino without helicity suppression

Pion decay into heavy Neutrinos

If the *N* is Majorana in nature, we can look for an excess of charged-current quasi-elastic events from these left-handed *N* states in a pi- source

In a LArTPC these events would show up with a 1-lepton-1-proton topology, which cannot be mimicked by an antineutrino from the pi- source



Unfortunately suppressed by the fourth power of the new mixing

Pion decay into heavy Neutrinos

[1] https://arxiv.org/pdf/1905.00284v2.pdf
[2] https://arxiv.org/abs/1905.09694

We can look for an excess of charged-current quasi-elastic events from these left-handed *N* states in an anti-neutrino beam

In a LArTPC these events would show up with a 1-lepton-1-proton topology, which cannot be mimicked by an antineutrino

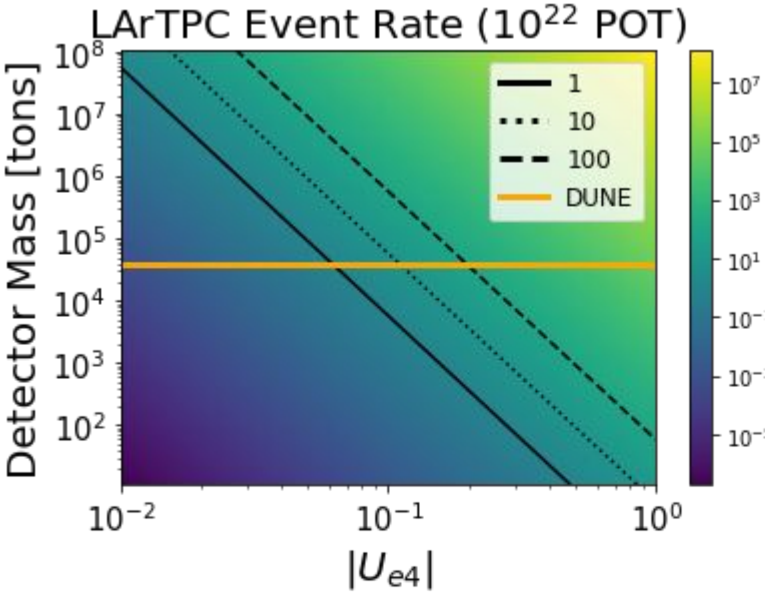
For an example flux, we consider the anti-nue flux at the DUNE far detector [1]

$$\phi_{\bar{\nu}_e} \approx 10^{-12}\ \nu/\mathrm{POT}/\mathrm{cm}^2$$

$$\phi_{\mathcal{N}} = |U_{e4}|^2 \phi_{\bar{\nu}_e}$$

The CCQE cross section on LAr is [2]

$$\sigma_{\nu_e}^{\mathrm{CCQE}} \approx 10^{-38}\mathrm{cm}^2 \quad \sigma_{\mathcal{N}}^{\mathrm{CCQE}} = |U_{e4}|^2 \sigma_{\bar{\nu}_e}^{\mathrm{CCQE}}$$



Neutrino Magnetic Moment

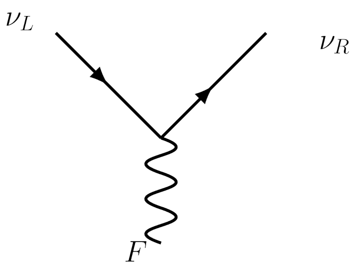
•The Lagrangian describing neutrino magnetic moments is:

$$\mathcal{L} = \mu_\nu^{ij}(\nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + h.c. \quad \text{(Majorana)}, \qquad \text{or} \qquad \mathcal{L} = \mu_\nu^{ij}(\bar{\nu}_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + h.c. \quad \text{(Dirac)},$$

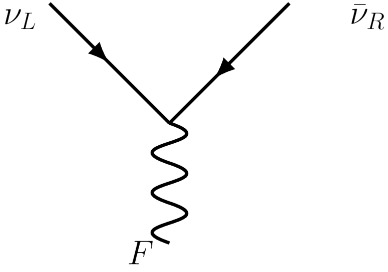
In the case of Majorana neutrinos, μ_ν^{ij} s constrained to be antisymmetric under CPT invariance. Whereas Dirac neutrino magnetic moments can have diagonal or transition moments.

Standard model predicts O[10^{-19}] Bohr Magneton.

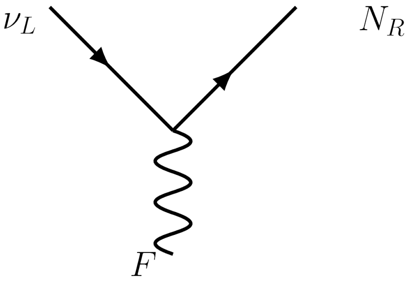
The final state neutrino is sterile in the Dirac case. It is possible to write a lepton number violating transition magnetic moment in the Majorana case. We can in principle detect these transition moments.



Dirac



Majarona



Heavy Sterile Neutrino

Detecting large neutrino magnetic moments.

We can look at regions of high magnetic fields to .

1. Solar neutrinos could undergo spin flavour precesssion. This
   don't see the appropriate antrineutrinos.
2. Supernova neutrino oscillations could be affected

Interestingly, mass of neutrino forces stronger constraints on Dirac
moments.

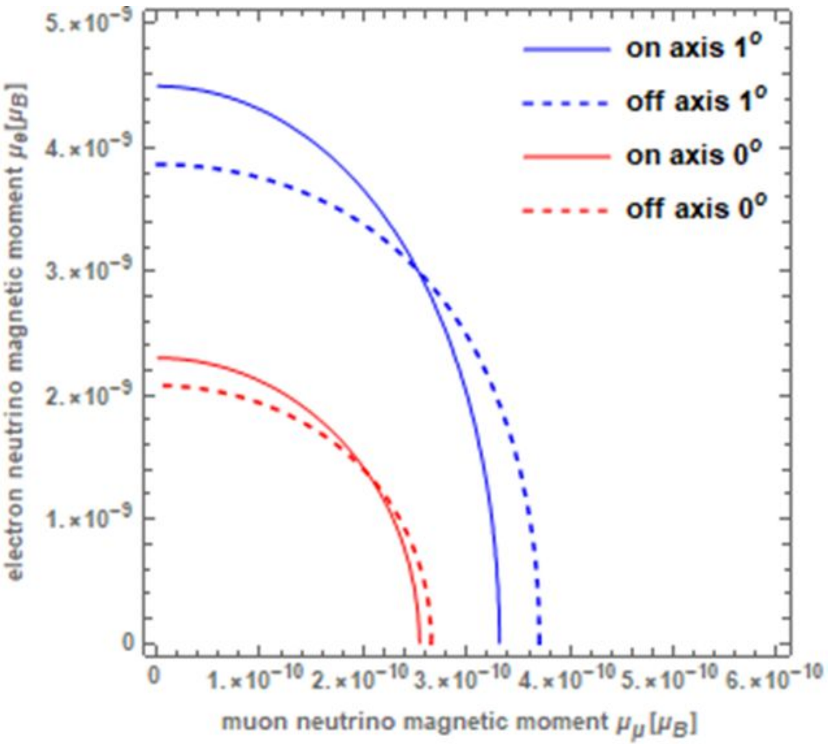
Neutrino electron scattering:

$$\frac{d\sigma}{dT}(\nu_j e \to \nu_i e)_{em} = \mu^2 \frac{\pi\alpha^2}{E_\nu m_e^2}\left(\frac{E_\nu}{T} - 1\right).$$

We can look for low energy recoils at dark matter detectors like Xe

Best terrestrial constraints from solar neutrinos, but they can't cont

We can also place constraints on muon and electron flavor magnet



Neutrino Magnetic Moment

Neutrino masses imply that neutrinos have non-zero electromagnetic dipole moments. The nature of μ_ν will depend on whether the neutrinos are Majorana or Dirac fermions.

$$\mathcal{L} = \mu_\nu^{ij}(\nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + h.c. \quad \text{(Majorana)}$$

anti-symmetric by CPT invariance ν and $\bar{\nu}$ must have magnetic moments of equal magnitude

$$\mathcal{L} = \mu_\nu^{ij}(\bar{\nu}_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + h.c. \quad \text{(Dirac)}$$

Majorana have only transition moments, Dirac have diagonal and transition moments.

Effective neutrino magnetic moment measured by an experiment:

$$\mu_\nu^2(\nu_\alpha, L, E) = \sum_j \sum_{kk'} U_{\alpha k}^* U_{\alpha k'} e^{-i\Delta m_{kk'}^2 L/2E} \mu_{jk} \mu_{jk'}$$

	Dirac	Majorana
μ_{ii}	$\frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left(\frac{m_i}{1\ eV}\right) \mu_B$	0
μ_{ij}, i≠j	$\sim 4 \times 10^{-23} \mu_B$	~2 x μ_{ij}^D

Measuring a magnetic moment different than what predicted for Dirac neutrinos would indicate BSM physics!

But it would be tricky to distinguish between Majorana and Dirac, since it is difficult to distinguish between diagonal and transition moments.

Neutrino Magnetic Moment

Triangle Inequalities for Majorana-Neutrino Magnetic Moments

Example: muon neutrino beam interacting with a target.

$$\nu_\mu e^- \rightarrow \nu_X e^-$$

Final flavour not known

Results in an "effective" magnetic moment that considers the superposition of flavour states for the outgoing neutrino:

$$|\mu_{\nu_\mu}| \equiv \sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}$$

Which comes from the vertex

$$\sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}\left(\overline{\nu_X^c}\sigma_{\alpha\beta}\nu_\mu F^{\alpha\beta}\right),$$

where

$$\overline{\nu_X^c} \equiv \frac{(\mu_{e\mu}\overline{\nu_e^c} + \mu_{\tau\mu}\overline{\nu_\tau^c})}{\sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}}.$$

If $\left|\mu_{\nu_\tau}\right|^2 \leq \left|\mu_{\nu_e}\right|^2 + \left|\mu_{\nu_\mu}\right|^2$, neutrinos are Majorana.

Due to the antisymmetry of μ_{ij} in the Majorana case.

Practically, the most promising approach to checking these inequalities is to improve the limits on μ_{ν_τ}, which is possible at the proposed SHiP experiment at CERN.

Upper limits from accelerator experiments:

$\mu_{\nu_e}^{\text{eff}} < 1.1 \cdot 10^{-9} \mu_B$ LAMPF

$\mu_{\nu_\mu}^{\text{eff}} < 6.8 \cdot 10^{-10} \mu_B$ LSND

$\mu_{\nu_\tau}^{\text{eff}} < 3.9 \cdot 10^{-7} \mu_B$ DONUT

Summary and Outlook

Neutrinoless double beta decay is, currently, the most promising way to probe the nature of neutrinos - Dirac or Majorana.

There are many other ways to probe Majorana vs. Dirac nature such as look for interactions/decays with heavy neutrinos, measure the cosmic neutrino background, measure the (tau-)neutrino magnetic moment, etc.

- Need experiments with impressive energy resolution, better sensitivities, large statistics, etc...