Pathways to Dirac Neutrinos

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Outline

1. Are Majorana Neutrinos Natural?
2. Dirac Neutrinos
3. Implications of Dirac Neutrinos
4. Conclusions

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3. Implications of Dirac Neutrinos
4. Conclusions

Mysterious Neutrinos

- Neutrinos: Old and Mysterious
- Even after 80+ years we know very little about them :
    - Nature of neutrinos: Dirac or Majorana?
    - Number of neutrino species: Sterile Neutrinos?
    - Mass Hierarchy: Normal or Inverted?
    - CP violation: $\delta_{CP} \neq 0$?
    - Octant of θ_{23} mixing angle: $\theta_{23} < 45^\circ$ or $\theta_{23} > 45^\circ$?
    - Why lepton and quark mixing parameters are so different?

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Neutrinos: Dirac or Majorana
What Experiments Tell?

- Debate about neutrino nature: As old as neutrinos themselves
- Discerning their nature from experiments: A difficult task
  - V-A nature of Standard Model: All observables sensitive to nature of neutrinos suppressed by powers of m_ν
- Still some potentially feasible processes:
  - Neutrinoless Double Beta Decay ($0\nu 2\beta$)
  - LHC signatures of lepton number violation
  - KATRIN measures m_ν + no $0\nu 2\beta$
- Current Status: No experimental or observational evidence/hint in favor of either Dirac or Majorana neutrinos

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Majorana Neutrinos: The Favorite Child

- No experimental signature $\Rightarrow$ Dirac/Majorana neutrinos equally likely
  - Expectation: Dirac and Majorana neutrinos considered equally in literature
  - Reality: Theorist predominantly consider/believe neutrinos are Majorana in nature
  - Even books and reviews on neutrinos either never discuss or barely consider Dirac neutrinos, often as a passing afterthought
  - With possible exception of "String Theory", no under paradigm has such an universal acceptance without any shred of experimental evidence
- This begs the question: Why Majorana neutrinos are the favorite child of theorists?
- Is there any really compelling theoretical reason for such an overwhelming preference for Majorana neutrinos?

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- Majorana neutrinos more natural: In what sense?
- Current understanding: Under Poincaré group
  - Majorana fermions: Two-component fundamental irreducible spinorial representations
  - Dirac fermions: Four component reducible spinorial representations
  - From Poincaré symmetry point of view: Majorana fermions are more fundamental
  - Dirac fermions: Can be thought of as two Majorana fermions degenerate in mass
  - All fermions should be Majorana and all scalars should be real scalars
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- Electromagnetism $U(1)_{EM}$ and Color $SU(3)_C$ Symmetries seem to be conserved
    - Majorana mass term: Violates both $U(1)_{EM}$ and $SU(3)_C$
    - Conserved Internal Symmetries: Charged leptons and quarks are forced to be Dirac particles
- Dirac/Majorana nature: Take into account all conserved symmetries
    - Accidental Symmetries: Lepton number $U(1)_L$ and Baryon number $U(1)_B$ are accidentally conserved in SM
    - $U(1)_L$ and $U(1)_B$ conservation has important consequences
        - Baryon number conservation: Proton stability
        - Lepton number conservation: Dirac neutrinos
    - In absence of any other hitherto unknown conserved symmetry: Dirac/Majorana nature depends on the $U(1)_L$ breaking pattern

Are Majorana Neutrinos Natural?

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Are Majorana Neutrinos Natural?
Elegance/Unnaturalness

- Majorana neutrinos: Elegant mass generation mechanisms e.g. seesaws, radiative mechanisms
  - Dirac Neutrinos: Tiny Yukawa couplings of $\mathcal{O}(10^{-12})$ or less are needed
  - Not True: See Salvador's talk
- Majorana neutrinos more economical in some sense
  - A given model can be more economical than other
  - Certainly not all Majorana neutrino mass models are more economical than any and all Dirac neutrino mass models
- Majorana neutrinos fit nicely in a bigger picture
  - Very little attempt has been made to develop bigger picture with Dirac neutrinos
- Dirac neutrinos are plain boring
  - I will try to address this issue a bit :)

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  - Certainly not all Majorana neutrino mass models are more economical than any and all Dirac neutrino mass models
- Majorana neutrinos fit nicely in a bigger picture
  - Very little attempt has been made to develop bigger picture with Dirac neutrinos
- Dirac neutrinos are plain boring
  - I will try to address this issue a bit :)

Are Majorana Neutrinos Natural?
Elegance/Unnaturalness

- Majorana neutrinos: Elegant mass generation mechanisms e.g. seesaws, radiative mechanisms
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Outline

1. Are Majorana Neutrinos Natural?
2. Dirac Neutrinos
3. Implications of Dirac Neutrinos
4. Conclusions

Dirac Neutrinos: The Neglected Child

- If $U(1)_L$ is conserved[1]: Neutrinos are Dirac
  - Accidental Symmetry of SM: New physics beyond SM need not conserve it
- If $U(1)_L$ is broken: Symmetry breaking pattern will determine the nature of neutrinos
- $U(1)$ symmetry only admits Z_m subgroups i.e. cyclic groups of m elements
  - If x is a non-identity group element of Z_m, then $x^{m+1} \equiv x$
  - The Z_m groups only admit one-dimensional irreducible representations
  - Conveniently represented by using the n-th roots of unity, $\omega = e^{\frac{2\pi I}{m}}$, where $\omega^m = 1$

[1] While $U(1)_B$ and $U(1)_L$ both are separately anomalous at the quantum level, there are anomaly free combinations, such as $U(1)_{B-L}$. For simplicity here I discuss only $U(1)_L$, though this argument remains valid for $U(1)_{B-L}$

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$$U(1)_L \to Z_m \equiv Z_{2n+1} \text{ where } n \geq 1 \text{ is a positive integer}$$
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- For neutrinos to be Dirac particle:
  - Right handed neutrinos (ν_R) should be added to Standard Model
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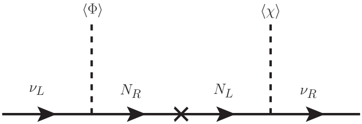

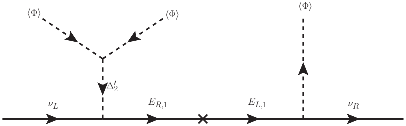

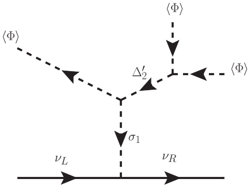

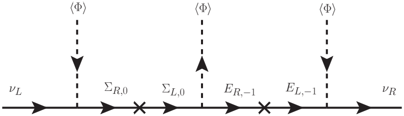

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1 Are Majorana Neutrinos Natural?

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3 Implications of Dirac Neutrinos

4 Conclusions

- Symmetry ensuring Dirac nature of neutrinos: Can provide stability to the dark matter
  - Links Diracness and dark matter stability intimately[4]
- For illustration take Z_4 lepton quarticity symmetry
  - Can arise as a residual subgroup of $U(1)_L$ or $U(1)_{B-L}$
  - Under the quarticity symmetry: Lepton doublets L_i and right handed neutrinos $\nu_{i,R}$ transform as ω; $\omega^4 = 1$
  - Preserved quarticity symmetry: No Z_4 charge carrying scalar should get vev
  - Thus we have:

$$\text{If } \zeta_i \nsim 1 \text{ under } Z_4, \text{ then } \langle \zeta_i \rangle = 0 .$$

$$\text{If } \langle \chi_i \rangle \neq 0, \text{ then } \chi_i \sim 1 \text{ under } Z_4$$

[4] S.C.Chuliá, E.Ma, RS, J.W.F.Valle, Phys.Lett. B 767 (2017) 209-213, arXiv:1606.04543
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- If $U(1)_L$ is completely broken or broken to Z_{2n} with $\nu \sim \omega^n$
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  - Neutrinoless Double Beta Decay[5]
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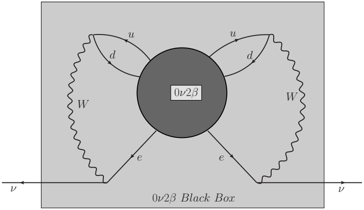

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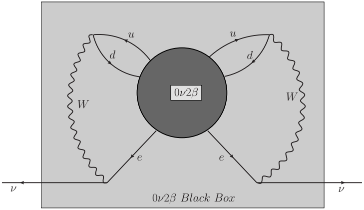

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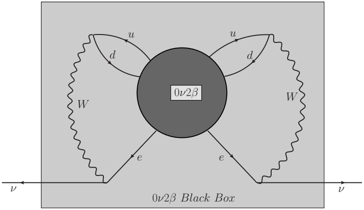

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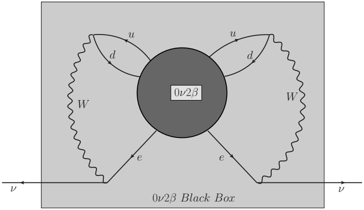

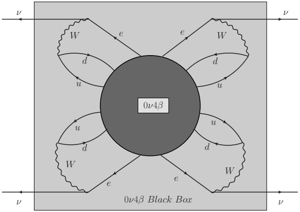

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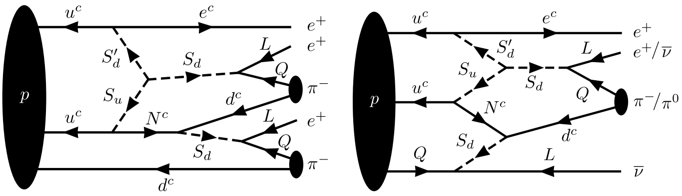

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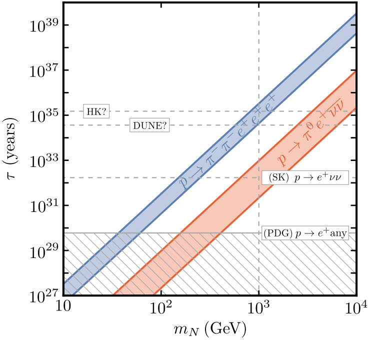

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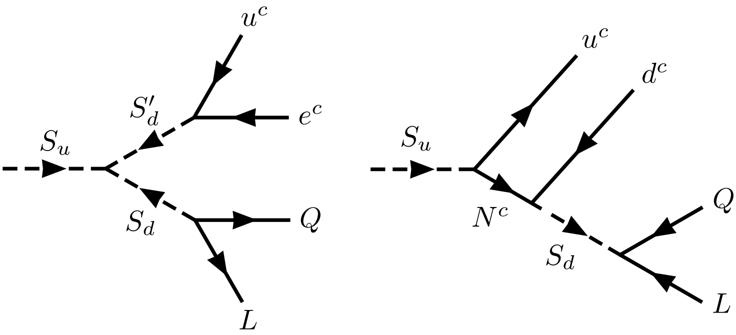

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Outline

1 Are Majorana Neutrinos Natural?

2 Dirac Neutrinos

3 Implications of Dirac Neutrinos

4 Conclusions

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- Perhaps the most important question is nature of neutrinos: Dirac or Majorana
- So far experiments have been unable to infer nature of neutrinos
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