Majorana vs Dirac Heavy Neutral Leptons (at the FCC-ee)

5th FCC Physics workshop

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hello and thank you for the invitation!

why the FCC-ee and why heavy neutrinos?

2020 Update of the European Strategy for Particle Physics

These are our priorities (ESU summary document; ESU deliberation document)

a) An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

The discovery of neutrino oscillations is a compelling sign of new physics, because new particle states or new interactions are required to generate the relevant mass term in the theory. Neutrinos are known to be orders of magnitude lighter than charged leptons. The explanations for this lightness span many orders of magnitude in the scale of new physics. There could be light (sterile neutrinos) or heavier neutral leptons. Neutrinos could be their own antiparticles, in which case lepton number conservation would be violated. Such an extended neutrino sector could potentially be linked to the matter-antimatter asymmetry observed in the universe. Their mixing pattern is also very different from that observed for quarks, with some terms still not fully known. Neutrino physics is an integral part of the flavour quest. It is thus essential to pursue the exploration of the neutrino sector with accelerator, reactor, solar, atmospheric and cosmic neutrino experiments.

Long, rich history of sterile neutrinos at e^+e^- colliders! E.g., Tsai (PRD'71), Petcov (PLB'84)

See extensive review by Han, RR, et al [1711.02180]

the big question:

If N exist, how to check if Dirac or Majorana?[1]

[1] In practice, pseudo-Dirac N tend to be Dirac-like in viable scenarios.

For details, see Pascoli, RR, & Weiland [1812.08750]

a natural answer:

a natural answer: search for lepton number violation

the next slide is the most important slide of this talk[2]

[2] You may decouple after the next slide! ☹

Dirac vs Majorana N

The Blackbox Theorem states: Majorana neutrinos $\Longleftrightarrow$ LNV

Schechter & Valle (PRD'82);

but see also Hirsch, et al [hep-ph/0608207]; Duerr, et al [1105.0901]; Kobach [1604.05726]; Pascoli, et al [1712.07611]

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Majorana neutrinos mediate processes that:

- **violate lepton flavor**
- **conserve lepton number**
- **violate lepton number**

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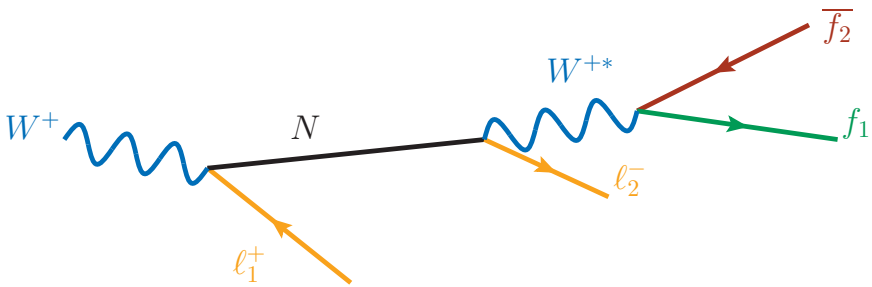
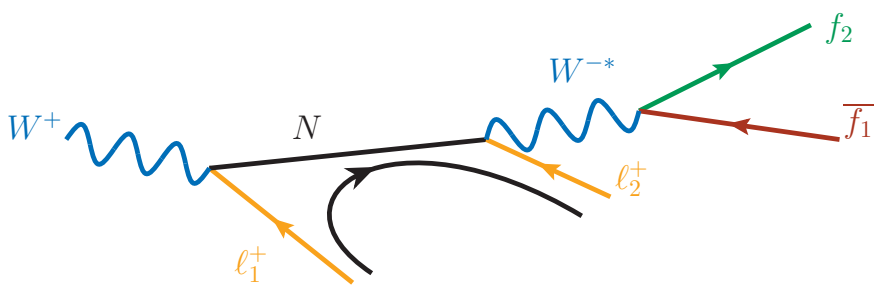
Differences between Dirac and Majorana amount to LNV

Dirac vs Majorana N (in practice)

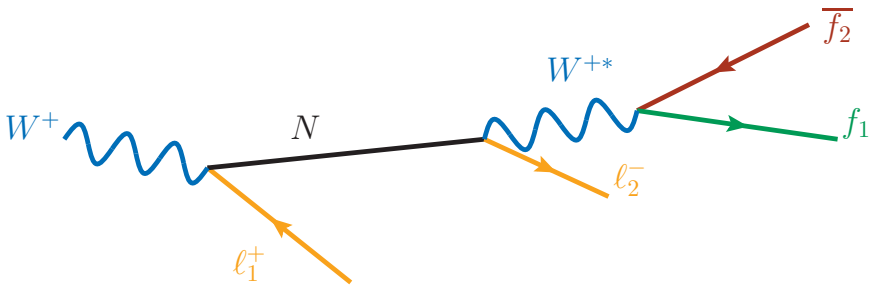
Opening of LNV channels cause differences between D and M N:

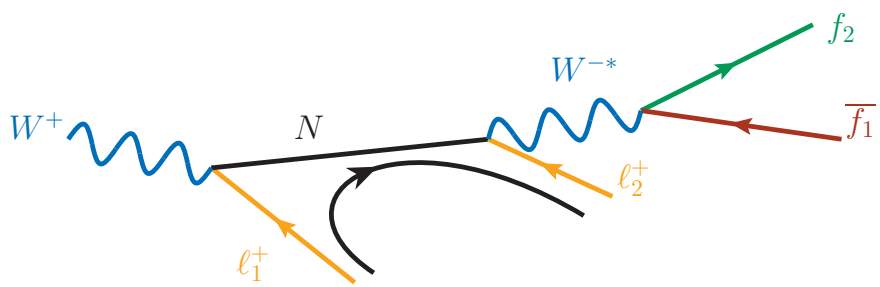
- Widths of Majorana N are **twice** the widths of Dirac N
- Lifetimes of Majorana N are **half** the lifetimes of Dirac N
- Intermediate N experience extra parity inversion in LNV processes



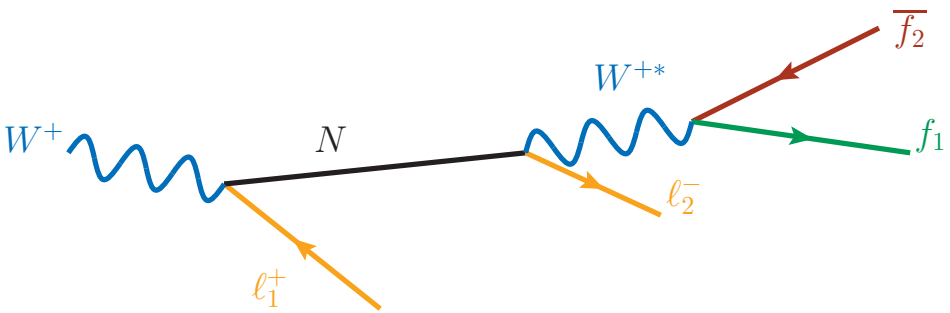


parity inversion in $W \to \ell_i \ell_j f \overline{f'}$ decays





helicity preservation in LNC decays



The helicity amplitude for the LNC process $W^+ \to \ell_1^+ \ell_2^- f \overline{f'}$ is

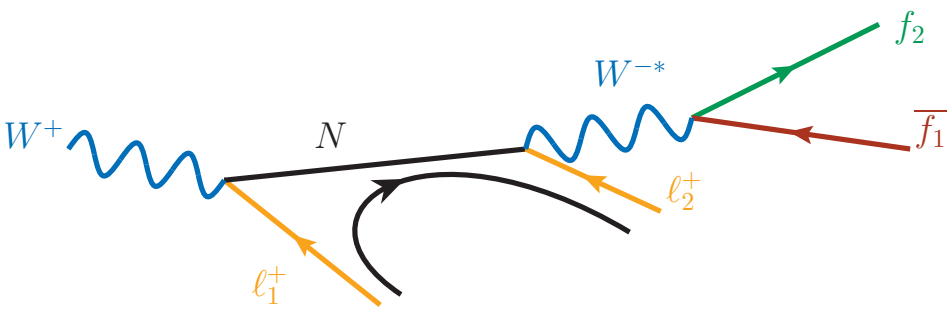
$$\mathcal{M}_{LNC} = \varepsilon_\mu J^\nu_{f_2 f_2'} \Delta^W_{\nu\rho} T^{\rho\mu}_{LNC} \mathcal{D}(p_N)$$

Intuition: successive LH chiral interactions $\Longrightarrow$ LH helicity eigenstate

$$T^{\rho\mu}_{LNC} = \overline{u_L}(p_2)\gamma^\rho P_L \times (\underbrace{\not{p}_N}_{\text{LH helicity state}} + \underbrace{m_N}_{P_L m_N P_R = 0}) \times \gamma^\mu P_L v_R(p_1)$$

$$\Longrightarrow \mathcal{M}_{LNC} \sim \frac{p_N}{(p_N^2 - m_N^2) + i(\Gamma_N m_N)}$$

helicity inversion in LNV decays



The helicity amplitude for the LNV process $W^+ \to \ell_1^+ \ell_2^+ \overline{f} f'$ is

$$\mathcal{M}_{LNV} = \varepsilon_\mu J^\nu_{f_2 f_2'} \Delta^W_{\nu\rho} T^{\rho\mu}_{LNV} \mathcal{D}(p_N)$$

Intuition: CPT Theorem $\Longrightarrow$ C-inversion $=$ PT-inversion

$$T^{\rho\mu}_{LNV} = \overline{u_R}(p_2)\gamma^\rho \underbrace{P_R}_{CPT:\ P_L \to P_R} \times (\underbrace{\not{p}_N}_{P_R \not{p}_N P_R = 0} + \underbrace{m_N}_{\text{RH helicity state}}) \times \gamma^\mu P_L \nu_R(p_j)$$

$$\Longrightarrow \mathcal{M}_{LNV} \sim \frac{m_N}{(p_N^2 - m_N^2) + i(\Gamma_N m_N)}$$

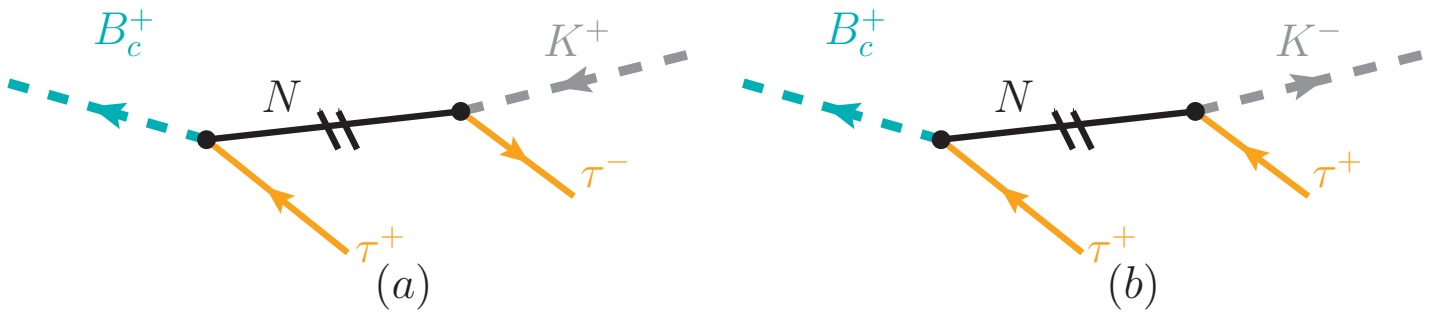
Extra parity inversion on N $\Longrightarrow$ relative helicity inversion of N

Kayser ('82) , Mohapatra & Pal ('98), Denner, et al (NPB'92, PLB'92)

$\Longrightarrow$ shifts in kinematic distributions

Many dedicated works, e.g., Han, RR, et al [1211.6447]; RR [2008.01092]

Shifts can occur at all scales, e.g., meson decays



Extra parity inversion on $N \implies$ relative helicity inversion of N

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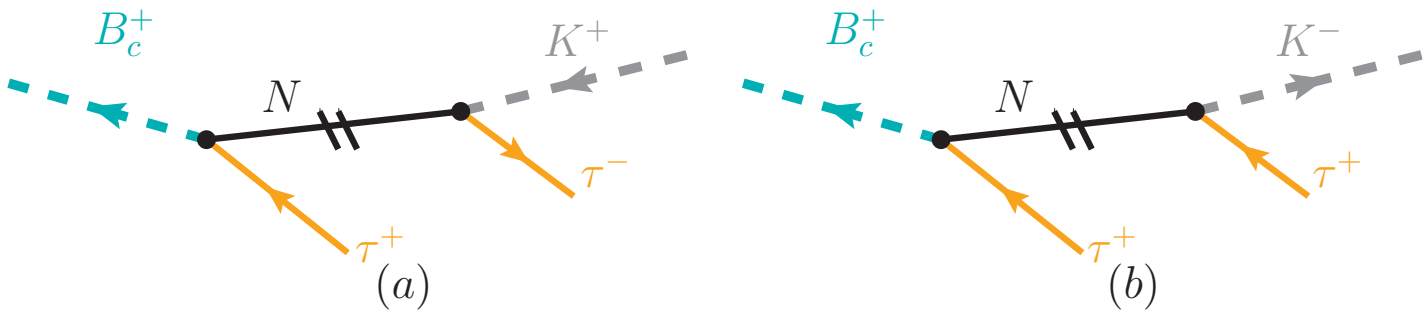
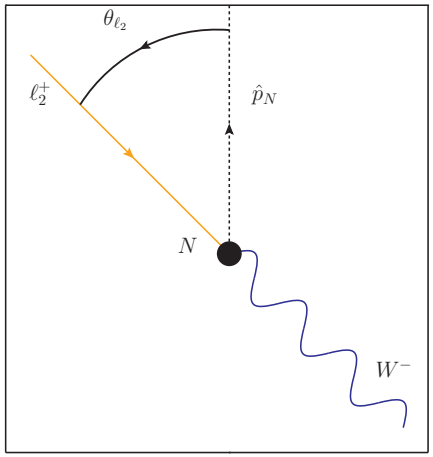
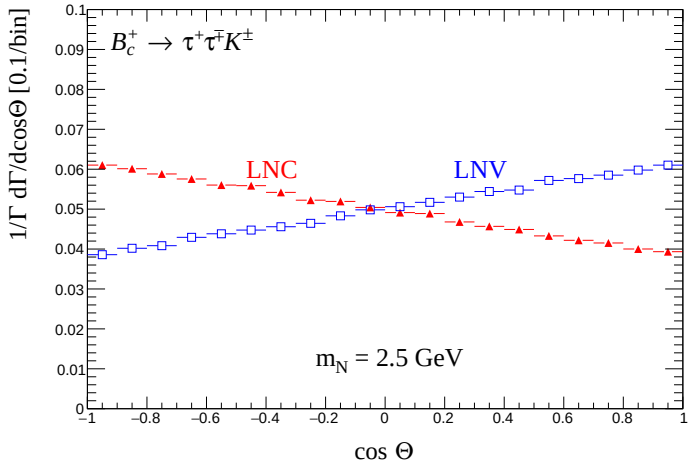


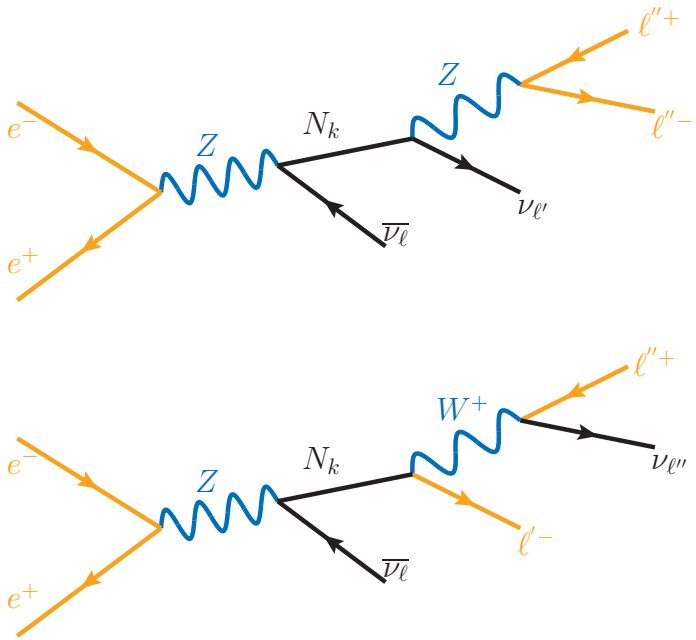


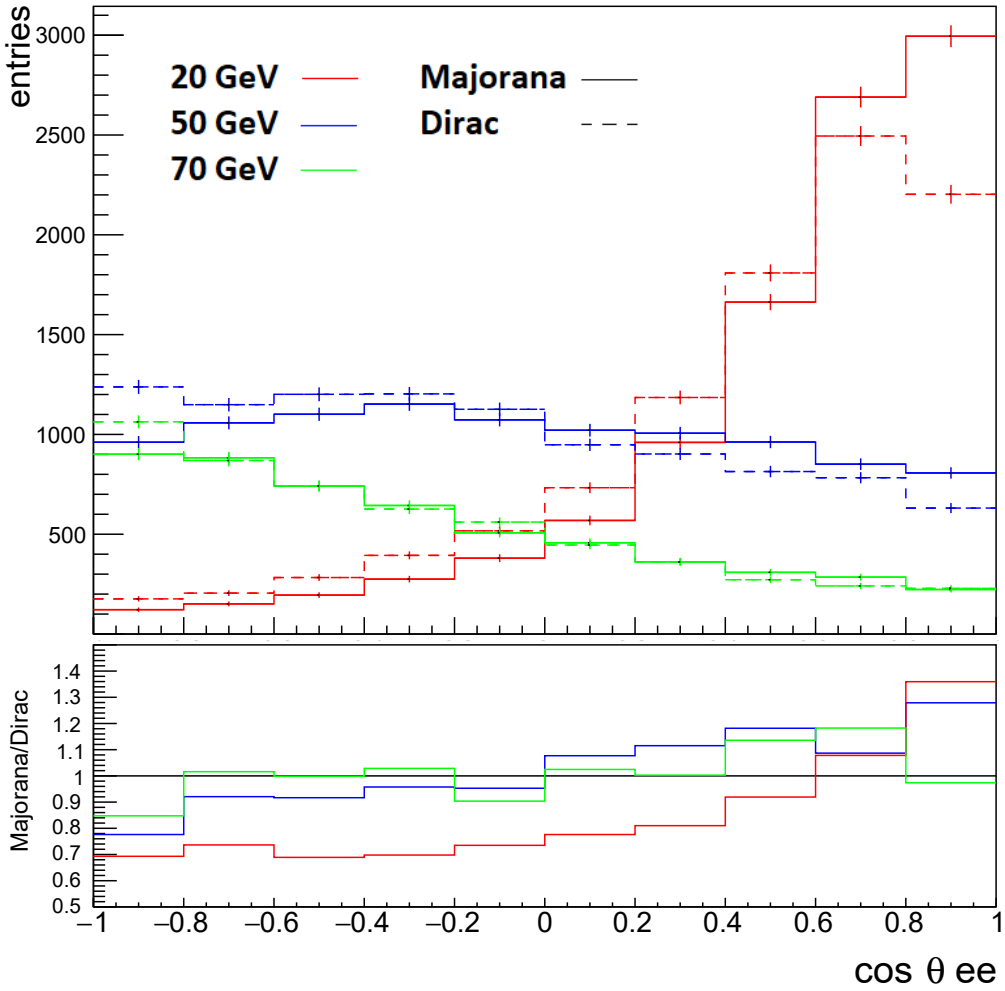


FYI: Events generated with MadGraph5_aMC@NLO [w/ Jeon, Fernandez-Martinez, Kulkarni, et al (*to appear*)]

Shifts in kinematic distributions also appear when event is not fully reconstructable, e.g. $e^+e^- \to Z \to N\nu \to e^+e^-\nu\nu$

lots of recent activity! E.g., de Gouvea, et al [1808.10518, 2104.05719, 2105.06576 (FCC-ee), 2109.10358]





θ_{ee} = opening between final-state e^+e^-

– Dirac = LNC
– Majorana = LNC+LNV

w/ Alimena,Gonzalez Suarez, Sfyrla, Sharma, et al (*In progress*)

final words

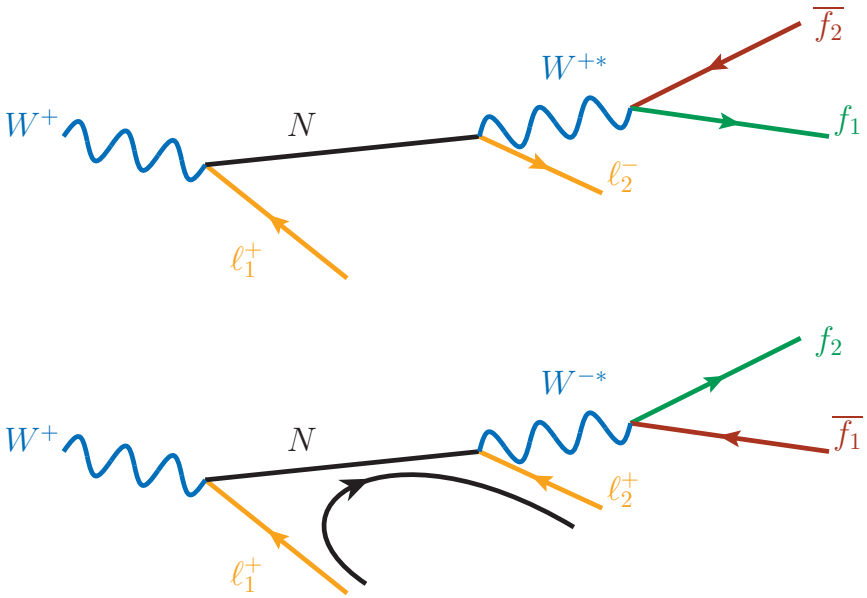
LNC vs LNV

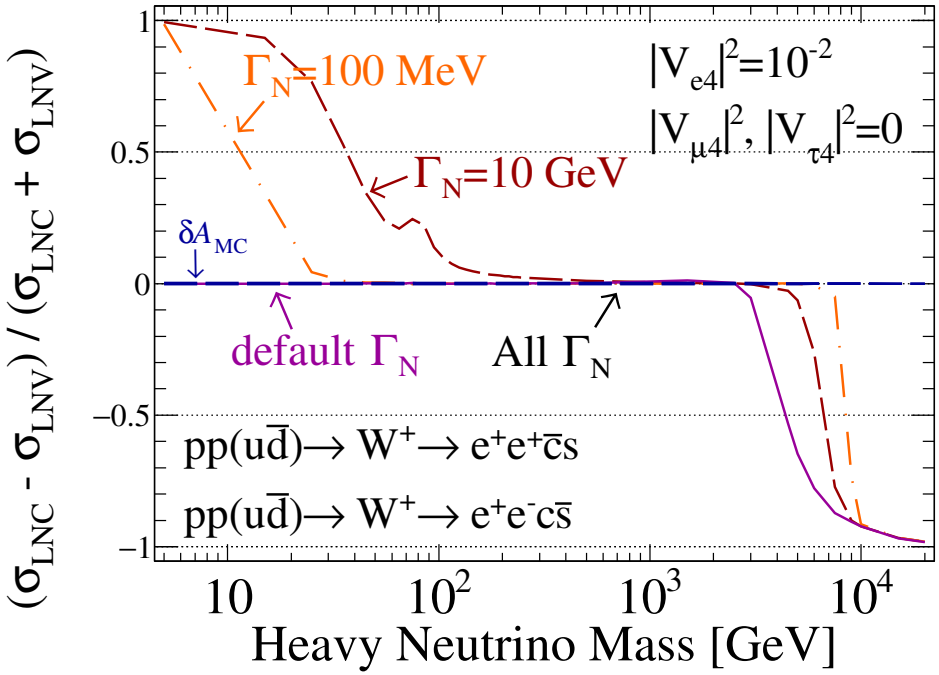
What if N are too heavy for on-shell production

- N can induce LNV decays of W/Z at dimension $d = 7$
- N can induce LNC decays of W/Z at dimension $d = 8$

$\Longrightarrow$ LNC operators decouple faster than LNV operators

Kobach [1604.05726]





RR [2008.01092]

Thank you.