Helicity Inversion and Suppression with Long-Lived Majorana Neutrinos [1]

8th LHC LLP (#LLP8) Workshop - University of Zoom

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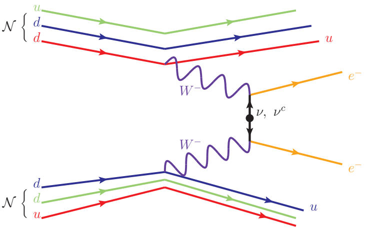
17 November 2020

[1] See RR [2008.01092]; and w/ Fuk, et al [2011.02547, 2012.zooom]

what and why?

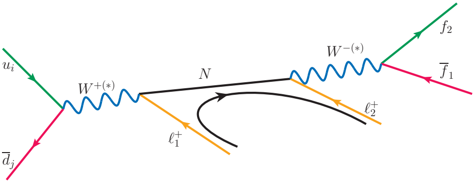
the big picture

in processes that involve Majorana neutrinos and SM particles internal fermions' helicities are often flipped Kayser ('82); Mohapatra & Pal ('98)



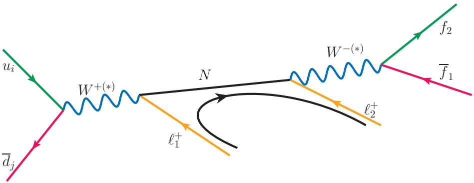
sometimes this "helicity inversion" suppresses transition rates

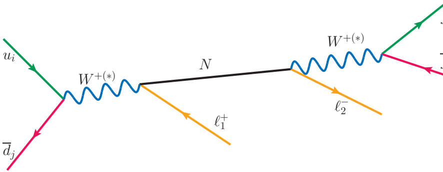
e.g., this is why $0\nu\beta\beta$ is so hard to measure!



Question: Does helicity inversion impact collider searches for Majorana neutrinos?

Question: Do rates for processes that violate lepton number (LNV) differ from rates for analogous processes that conserve lepton number (LNC)?





the answer?

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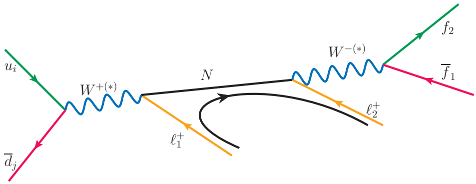

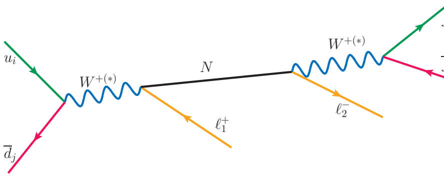

the answer? yes and no

summary

Summary

The role of helicity inversion in *LNV* processes is under fresh investigation:

RR [2008.01092]; and w/ Fuk, et al [2011.02547, 2012.soon]

- In the LNC decays, e.g., $W^{\pm} \to \ell_i^{\pm} \ell_j^{\mp} f \overline{f'}$, helicity is preserved
- In the LNV decays, e.g., $W^{\pm} \to \ell_i^{\pm} \ell_j^{\pm} f \overline{f'}$, helicity is inverted

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Three different outcomes:

1. If N is (nearly) on-shell and $(\Gamma_N/m_N) \ll 1$: LNV rate $\approx$ LNC rate
2. If N can be on-shell but $\Gamma_N \sim m_N$: LNV rate $\ll$ LNC rate
3. If N is too heavy to be on-shell: LNV rate $\gg$ LNC rate

what and how?

but first a few disclaimers

the remainder of this talk...

is not:

1. about the differences between chirality and helicity

   Not important to understand underlying physics but feel free to ask if unsure!

2. a lecture on helicity amplitudes — for math details see [2008.01092, 2011.02547]
3. a lecture on heavy neutrinos in MadGraph — feynrules.irmp.ucl.ac.be/wiki/HeavyN
4. a review on lepton number violation — interested folks should see [1711.02180]

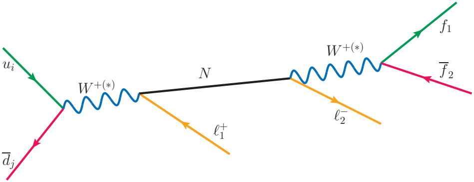
is:

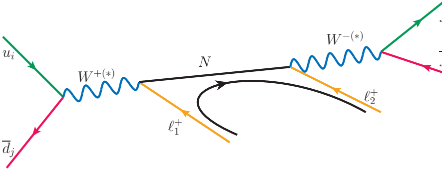
- about a few concrete answers (analytical and numerical) to really interesting questions raised[2] by hep-ex'ers
- a case study in the Type I Seesaw but holds for other neutrino mass models, e.g., Type III and Left-Right Symmetry models

[2] See also Q&A by A. Boyarsky, et al at the "Ghent Helicity Workshop" indico.cern.ch/event/897833/.

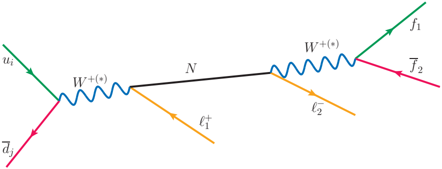
helicity preservation and inversion

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





helicity preservation in LNC decays



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

$$\mathcal{M}_{LNC} = J^{\mu}_{f_1 f_1'} J^{\nu}_{f_2 f_2'} \Delta^{W}_{\mu\rho} \Delta^{W}_{\nu\sigma} T^{\rho\sigma}_{LNC} \mathcal{D}(p_N)$$

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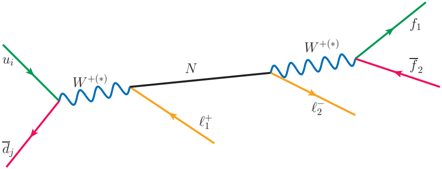

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$$T^{\rho\sigma}_{LNC} = \overline{u_L}(p_2)\gamma^{\rho} P_L \times (\underbrace{\not{p}_N}_{\text{LH helicity state}} + \underbrace{m_N}_{P_L m_N P_R = 0}) \times \gamma^{\sigma} P_L v_R(p_1)$$

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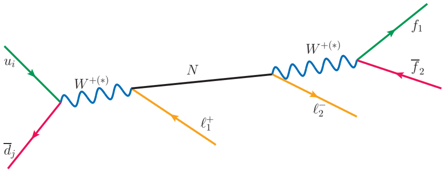

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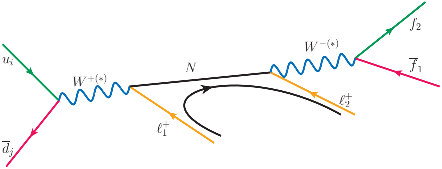
$$\implies \mathcal{M}_{LNC} \sim \frac{p_N}{(p_N^2 - m_N^2) + i(\Gamma_N m_N)}$$

helicity inversion in LNV decays



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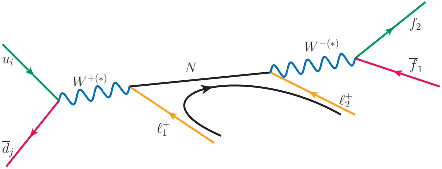

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Intuition: CPT Theorem $\implies$ CT-inversion = P-inversion

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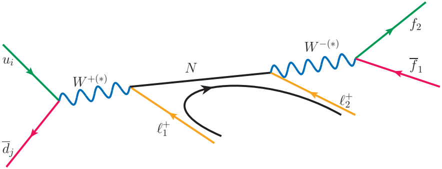

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Amplitudes vs Squared Amplitudes

At the amplitude level, a difference appears:

- The LNC amplitude scales as $\mathcal{M}_{LNC} \sim p_N \sim M_W$ (or $\sim \sqrt{\hat{s}}$)
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This difference is misleading (unphysical). At the squared amplitude level:

- The LNC squared amplitude scales as

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

- The LNV squared amplitude scales as

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

Any LNC vs LNV asymmetry depends on **off-shellness**:

$$\mathcal{A} \sim |\mathcal{M}_{LNC}|^2 - |\mathcal{M}_{LNV}|^2 \sim \frac{p_N^2 - m_N^2}{(p_N^2 - m_N^2)^2 + (\Gamma_N m_N)^2}$$

running the numbers

Question: Helicity suppression possible but is it numerically relevant?

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Monte Carlo Setup:

- `MadGraph5_aMC@NLO v2.7.0(bzr)`
  - fully differential, general purpose, precision event generator
  - builds (massive) helicity amplitude routines using `HELAS` and `ALOHA`

    H. Murayama, I. Watanabe, and K Hagiwara ('92); F. Maltoni, O. Mattelaer, T. Stelzer, et al ('11)
  - phase space integration adaptive Monte Carlo integration
  - helicity formalism tested heavily against LEP
  - MGX tested heavily against Tevatron / LHC

    ($\implies$ ongoing development and support!)

- `HeavyN` UFO libraries
  - Input libraries (Feynman rules) `mg5amc` can model / simulate Phenomenological Type I Seesaw
  - Uses dedicated Feynman Rules for Majorana currents Denner, et al [PLB('92)]
  - helicity formalism $\implies$ readily reproduces hep-ph collider literature

HeavyN: URL feynrules.irmp.ucl.ac.be/wiki/HeavyN

- TypeIISeesaw, EffLRSM, WZPrime,
  also available from feynrules.irmp.ucl.ac.be/wiki/NLOModels!

HeavyN : The Standard Model + Heavy Neutrinos at NLO in QCD

Contact Author

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In collaboration with: Daniel Alva and Tao Han [1]; Celine Degrande, Olivier Mattelear, and Jessica Turner [2]; and Silvia Pascoli and Cedric Weiland [3, 4].

For detailed instructions and examples on using the HeavyN UFO libraries, see C. Degrande, et al, arXiv:1602.06957 and S. Pascoli, et al, arXiv:1812.08750

- For studies of heavy Majorana neutrinos, please consider citing [5] for the Lagrangian and [1, 2] for the Majorana FR/UFO files.
- For studies of heavy Dirac neutrinos, please consider citing [2, 4].

Model Description

Majorana

This effective/simplified model extends the Standard Model (SM) field content by introducing three right-handed (RH) neutrinos, which are singlets under the SM ga
or weak hypercharge charges). Each RH neutrino possesses one RH Majorana mass. After electroweak symmetry breaking, the Lagrangian with three heavy Majora
[5]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_N + \mathcal{L}_{N~\rm Int}. \qquad (1$$

The first term is the Standard Model Lagrangian. In the mass basis, i.e., after mixing with active neutrinos, the heavy Majorana neutrinos' kinetic and mass terms a

$$\mathcal{L}_N = \frac{1}{2}\overline{N_k} i \not\partial N_k - \frac{1}{2} m_{N_k} \overline{N_k} N_k, \quad k = 1, \ldots, 3, \qquad (1$$

and its interactions with the Weak gauge and Higgs bosons are given by

HeavyN: URL feynrules.irmp.ucl.ac.be/wiki/HeavyN

- Polarization matches helicity amplitude computations (literally this talk!)
- HeavyN built for NLO in MadGraph5_aMC@NLO [1602.06957]
- multiple N coupling to all charged leptons possible by default
- HeavyN_Dirac public since '18 [1812.08750]
- other variants, e.g., generation I masses, also available
- happy to make more public, just ask!

LHC LLP WG 2/2

- Potential topics:
  - HNL polarisation issue
  - HNL analyses: do we sure the same tools and use them in the same way in the LHC experiments?
  - Are there other measurements to explore; special decay modes?
  - NLO in Madgraph? Any prospects for that
  - Madgraph simulation for other than just one single Majorana or Dirac Flavor
  - Any other program than Madgraph/PYTHIA MC?
  - Decays at very low mass 2/3 body decays transition at low HNL masses
  - B-decays to be used in ATLAS and CMS & appropriate tools for that (learn from LHCb)

Building Asymmetries

Question: Helicity suppression possible but is it numerically relevant?

1. Partial width asymmetry
   - LNC: $W^+ \to e^+ e^- c\overline{s}$ (1 diagram)
   - LNV: $W^+ \to e^+ e^+ \overline{c}s$ (2 diagrams)

$$\mathcal{A}_\Gamma = \frac{\Gamma_{LNC}-\Gamma_{LNV}}{\Gamma_{LNC}+\Gamma_{LNV}} = \frac{\Gamma\left(W^+\to e^+ e^- c\overline{s}\right)-\Gamma\left(W^+\to e^+ e^+ \overline{c}s\right)}{\Gamma(W^+\to e^+ e^- c\overline{s})+\Gamma(W^+\to e^+ e^+ \overline{c}s)}$$

2. Cross section asymmetry
   - LNC: $u\overline{d} \to W^+ \to e^+ e^- c\overline{s}$ (1 diagram)
   - LNV: $u\overline{d} \to W^+ \to e^+ e^+ \overline{c}s$ (2 diagrams)

$$\mathcal{A}_\sigma = \frac{\sigma_{LNC}-\sigma_{LNV}}{\sigma_{LNC}+\sigma_{LNV}} = \frac{\sigma\left(u\overline{d}\to W^+\to e^+ e^- c\overline{s}\right)-\sigma\left(u\overline{d}\to W^+\to e^+ e^+ \overline{c}s\right)}{\sigma\left(u\overline{d}\to W^+\to e^+ e^- c\overline{s}\right)+\sigma\left(u\overline{d}\to W^+\to e^+ e^+ \overline{c}s\right)}$$

Case I: N is (nearly) on-shell and $(\Gamma_N/m_N) \ll 1$

(the LLP regime!)

Results:

- Compute $\Gamma_N^{\text{Tot.}}$ on-the-fly to ensure unitarity (probability conservation)
- Varied mixing
- Decoupled other mass eigenstates (*tiny* mixing, **large** mass)
- LHC: $\sqrt{s} = 13$ TeV with NNPDF 2.3LO

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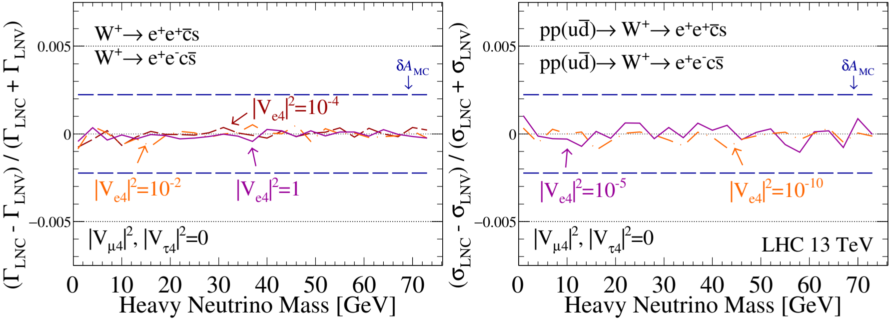

Results: asymmetry is insignificant for resonant N in the LLP regime!

NEW Case II: N is off-shell

(the prompt and EFT regime!)

Results:

- Fixed mixing but varied m_N over much larger range
- Fixed $\Gamma_N^{\rm Tot.} =$ 100 MeV and 10 GeV (add'l new physics)

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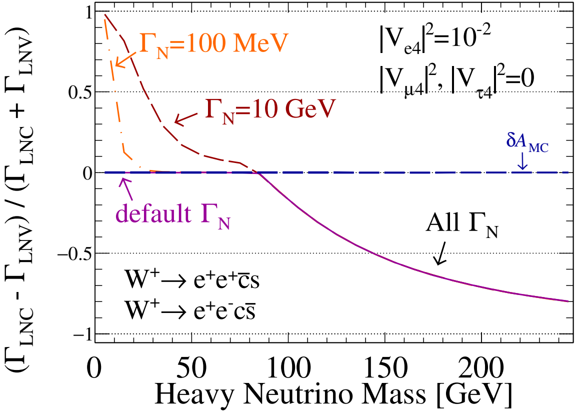

Results: asymmetry can be significant for off-shell processes

- In decoupling (EFT) limit, $d = 6$ operators (LNC) decouple faster than $d = 5$ operators (LNV)

Summary

1. The Standard Model as a gauge theory is pretty interesting
   - chiral structure of EW interactions + massive fermions
     $\implies$ helicity inversion can and does happen
   - helicity inversion inherently occcurs in LNV processes

2. For Majorana fermions, this leads to three different outcomes:

   RR [2008.01092]; and w/ Fuk, et al [2011.02547, 2012.soon]

   - If N is (nearly) on-shell and $(\Gamma_N/m_N) \ll 1$: LNV rate $\approx$ LNC rate
   - If N can be on-shell but $\Gamma_N \sim m_N$: LNV rate $\ll$ LNC rate
   - If N is too heavy to be on-shell: LNV rate $\gg$ LNC rate

3. In LLP searches for N at the LHC (or your favorite experiment)
   - Numerical impact of helicity suppression depends on inputs but simulation software seem fine

   Majorana N, Degrande, Mattelaer, RR, Turner [1602.06957]

   (pseudo)-Dirac N, Pascoli, RR, et al [1812.08750]

Thank you, keep safe,

and may the L-violating forces be with you!