Z-Boson Decays Into (Heavy) Neutrinos: Majorana or Dirac?

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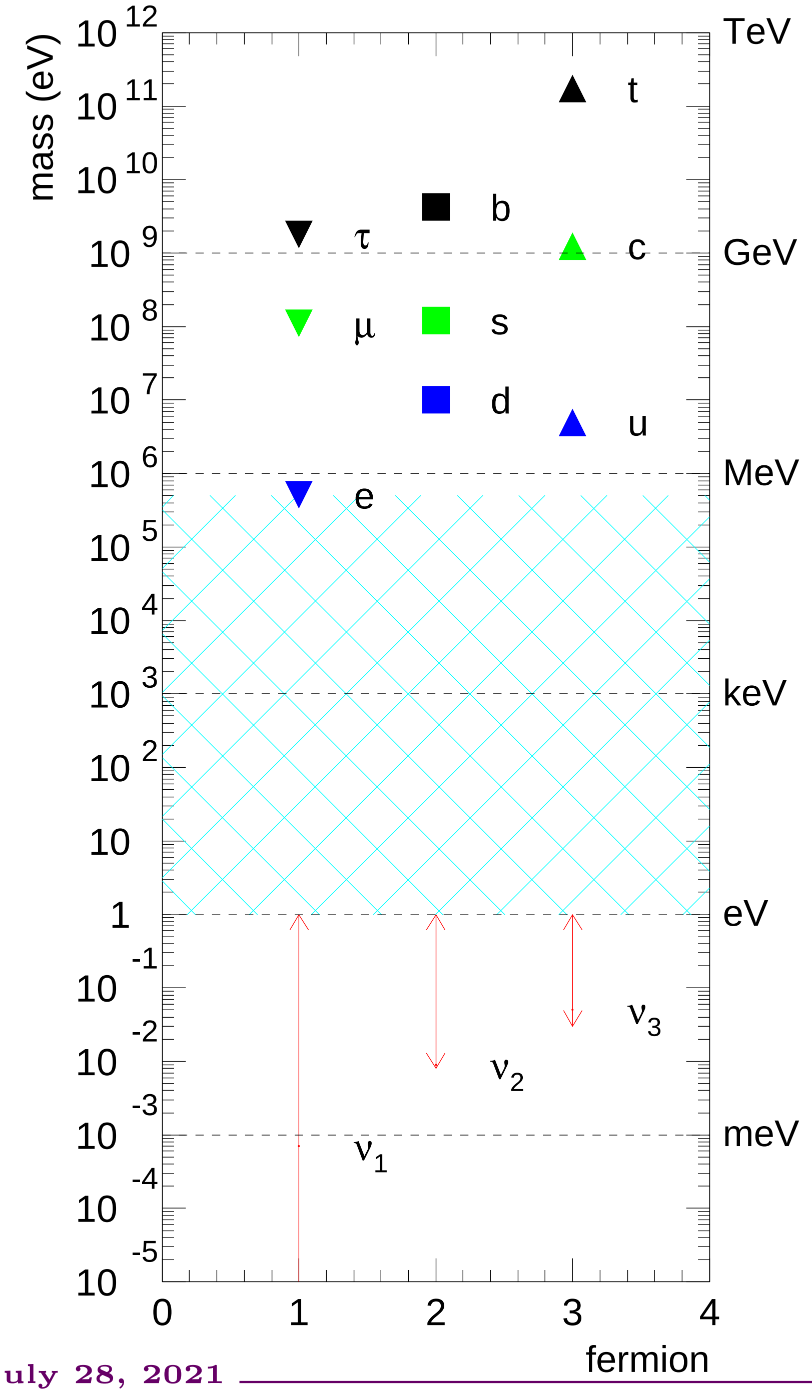
EPS-HEP Conference 2021

July 26–30, 2021

[Based on A. Blodel, AdG, B. Kayser, 2105.06576 [hep-ph]]



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

⇓

NEW PHYSICS

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts, including ...

- **understanding the fate of lepton-number**. Neutrinoless double beta decay.
- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies of charged-lepton properties ($g-2$, edm), and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- **collider experiments**. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- searches for baryon-number violating processes.

Heavy Neutrinos

- Nonzero neutrino masses imply the existence of new degrees of freedom. We don't know what those are and what are their properties – mass, spin, etc.

- These new degrees of freedom could show up a collider experiments as long as they are not too heavy. They may be very weakly coupled. Quintessential example: Heavy Neutrinos ν_4 (aka HNL)

- Definition: heavy neutrinos couple to the W and the Z through their mixing with the SM leptons:

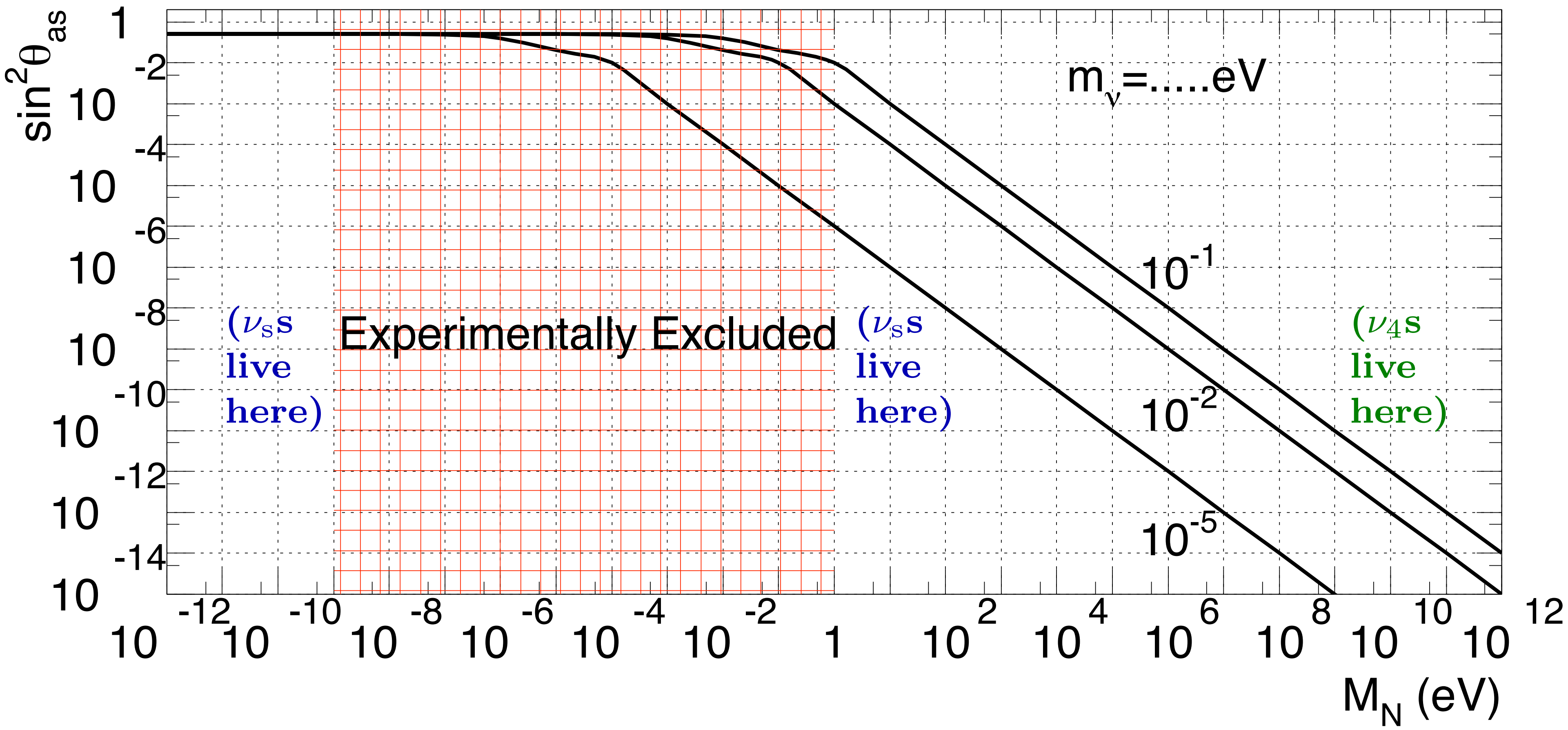
$$\mathcal{L}_{\rm int} \propto (U_{\alpha 4}) W^{\mu} \bar{\nu}_4 \gamma_{\mu} P_L \ell_{\alpha},$$

$$\mathcal{L}_{\rm int} \propto (U_{\alpha 4} U^*_{\alpha i}) Z^{\mu} \bar{\nu}_4 \gamma_{\mu} P_L \nu_i.$$

- If we ever discover one of these, after much rejoicing, we will want to know: do they have anything to do with generating the neutrino masses?

Constraining the Seesaw Lagrangian

[AdG, Huang, Jenkins, arXiv:0906.1611]



Theoretical upper bound: $M_N < 7.6 \times 10^{24}$ eV $\times \left(\frac{0.1\text{ eV}}{m_\nu}\right) \Rightarrow\Rightarrow\Rightarrow$

Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

Neutrinoless Double-Beta Decay! What else? ν_4 Can Help!

ν_4 and Lepton-Number Violation at Hadron Colliders

Heavy neutrinos, when produced at a collider experiment, may also mediate lepton-number violation if they are Majorana fermions. For example,

$$XW^{+(*)} \to X\ell^+\nu_4(\to \ell^- + q\bar{q}').$$

versus

$$XW^{+(*)} \to X\ell^+\nu_4(\to \ell^+ + q\bar{q}').$$

Smoking-gun if the lepton-number of X is known (e.g., zero).

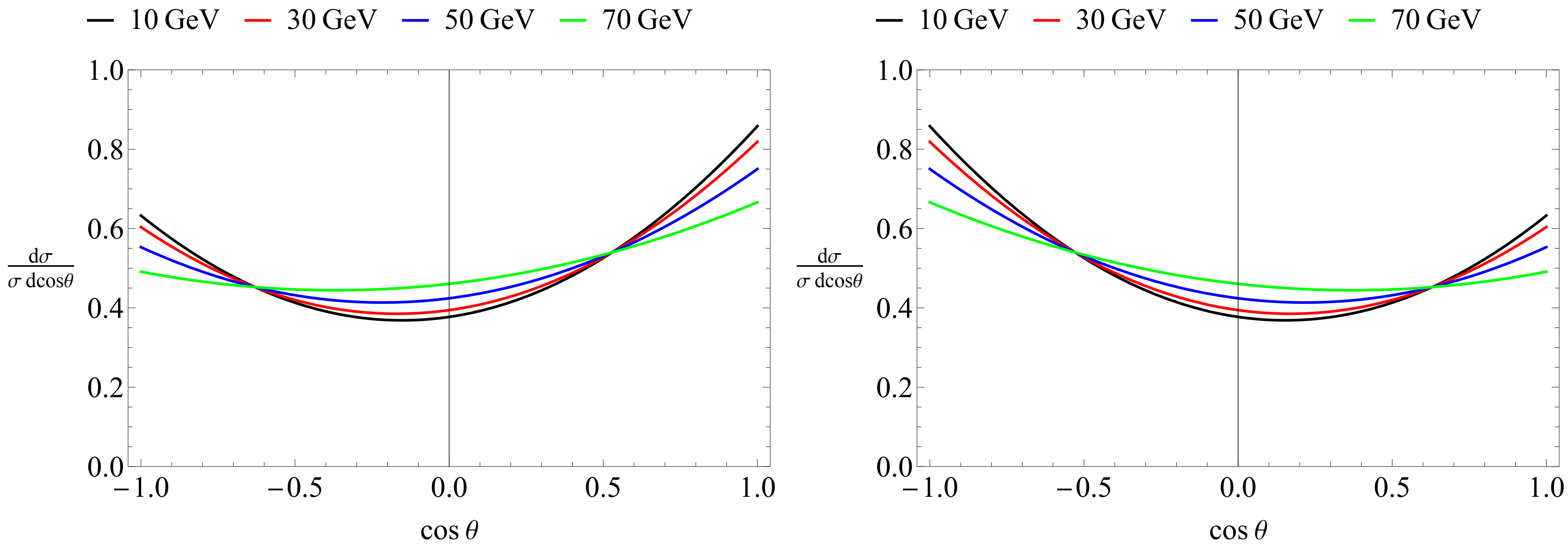
ν_4 at the Z-pole

For $m_4 < M_Z$, heavy neutrinos can be produced in the decay of Z-bosons. For example,

$$e^+e^- \to Z \to \bar{\nu}_{\rm light}\nu_4 \ (\text{or } \nu_{\rm light}\bar{\nu}_4)$$

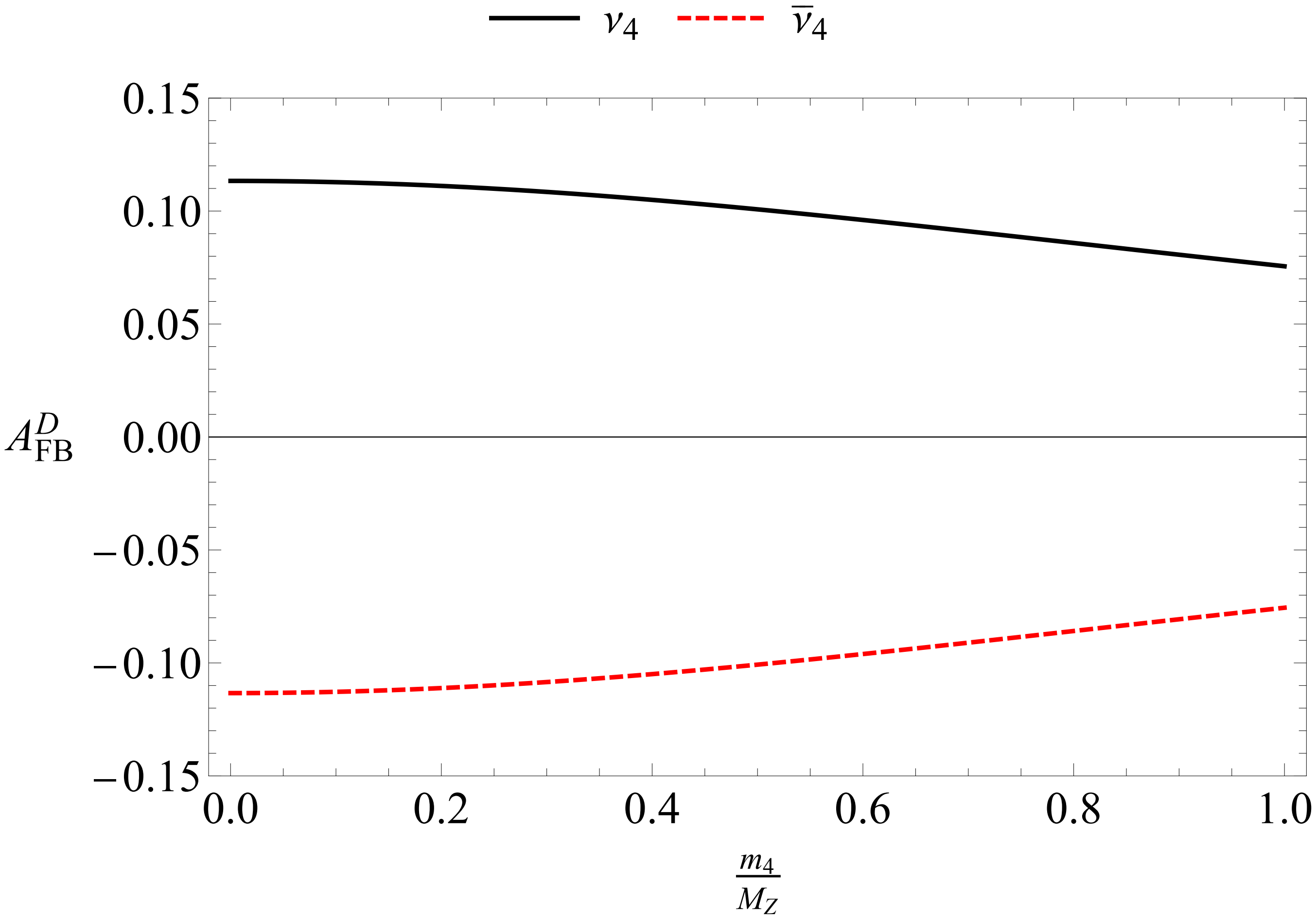
followed by ν_4 decay.

- Why do we care about this? Best constraints on m_4 around 10s of GeV from LEP! A Tera-Z-like experimental setup would be sensitive to seesaw-related heavy neutrinos. Unique opportunity.
- Challenge: Heavy neutrinos produced with light ones. We can't tell whether lepton-number is violated (at least in an event-by-event basis) since we don't get to the detect the light neutrinos.
- Main Message: If m_4 is large enough, Majorana and Dirac ν_4 are produced differently and decay differently!

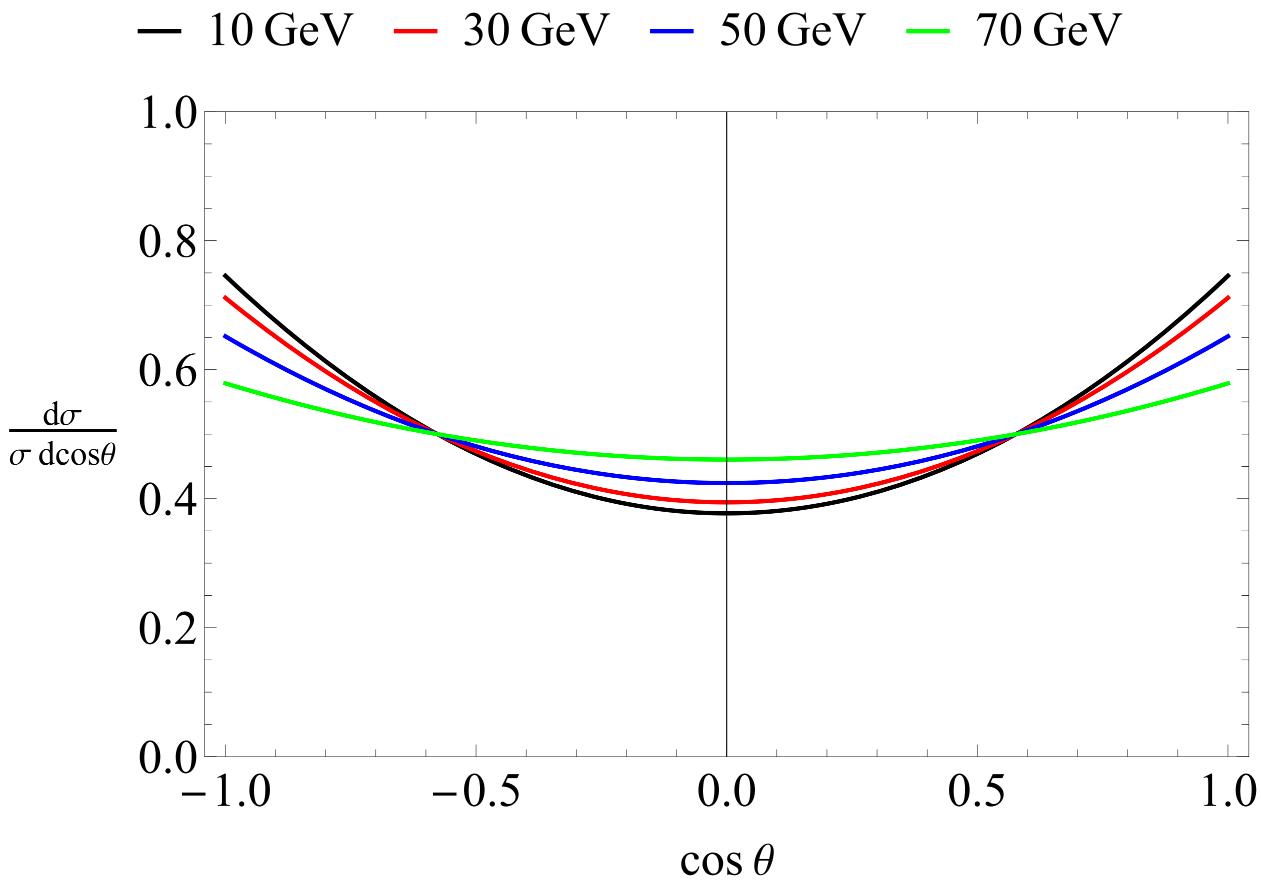


Normalized differential cross-section for $e^+e^- \to Z \to \nu_4\bar{\nu}_{\rm light}$ (left) and $e^+e^- \to Z \to \bar{\nu}_4\nu_{\rm light}$ (right) as a function of the direction of the heavy (anti)neutrino $\cos\theta$, for different values of the heavy neutrino mass m_4. The neutrinos are assumed to be Dirac fermions.

[θ is defined relative to the direction of the e^--beam.]



The Forward-Backward Asymmetry A^D_{FB} of heavy neutrino or antineutrino production in $e^+e^- \to Z \to \nu_4\bar{\nu}_{\rm light}$ or $e^+e^- \to Z \to \bar{\nu}_4\nu_{\rm light}$ as a function of the heavy neutrino mass. The neutrinos are assumed to be Dirac fermions.



Normalized differential cross-section for $e^+e^- \to Z \to \nu_4\nu_{\rm light}$ as a function of the direction of the heavy neutrino, $\cos\theta$, for different values of the heavy neutrino mass m_4. The neutrinos are assumed to be Majorana fermions.

The Forward-Backward Asymmetry A_{FB}^{M} vanishes exactly if ν_4 are Majorana fermions.

When the ν_4 decays via charged-current interactions, Dirac ν_4's decay like this:

$$\nu_4 \to \ell^- + X \quad \text{and} \quad \bar{\nu}_4 \to \ell^+ + X^*$$

so the ℓ^- inherits the angular distribution of the ν_4 while ℓ^+ inherits the angular distribution of the $\bar{\nu}_4$.

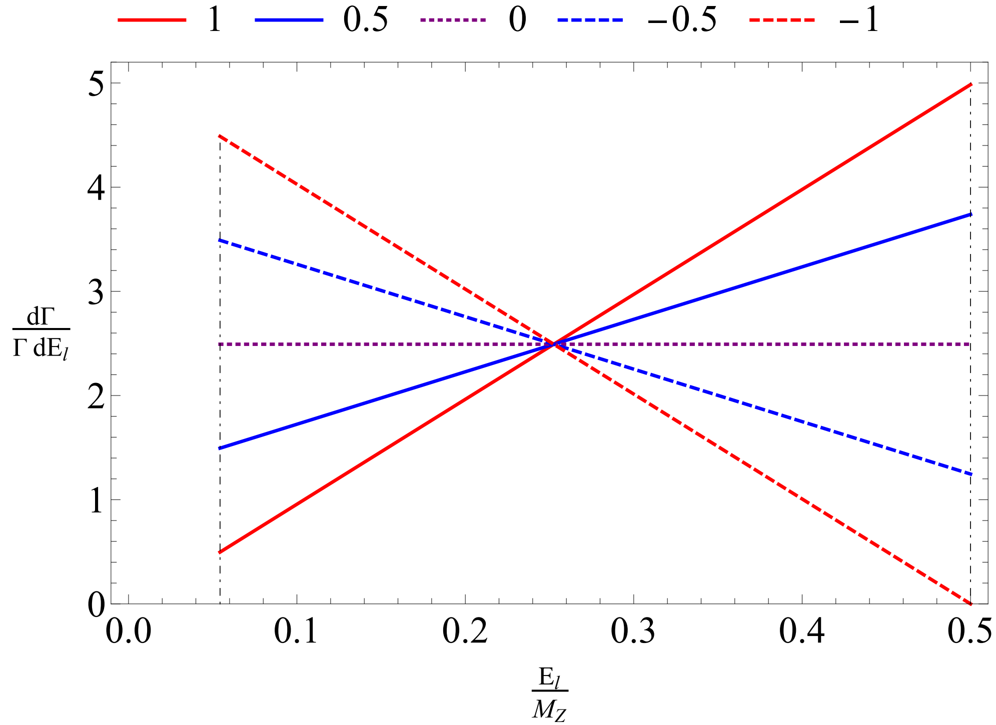
Meanwhile, Majorana ν_4's decay like this:

$$\nu_4 \to \ell^- + X \quad \text{or} \quad \nu_4 \to \ell^+ + X^*$$

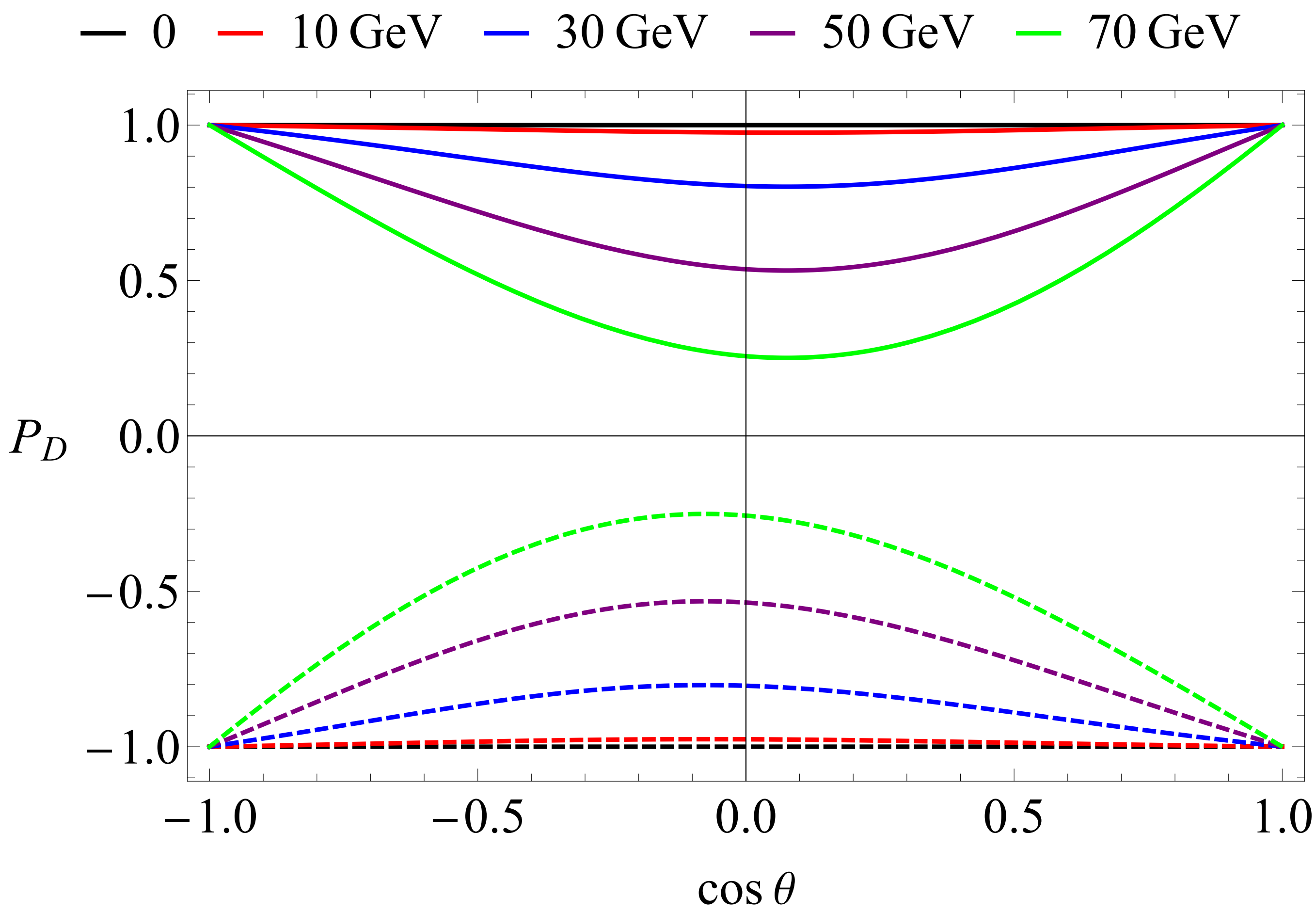
with equal probability. Both the ℓ^+ and the ℓ^- have the same angular distribution and no forward-backward asymmetry.

And there is more...

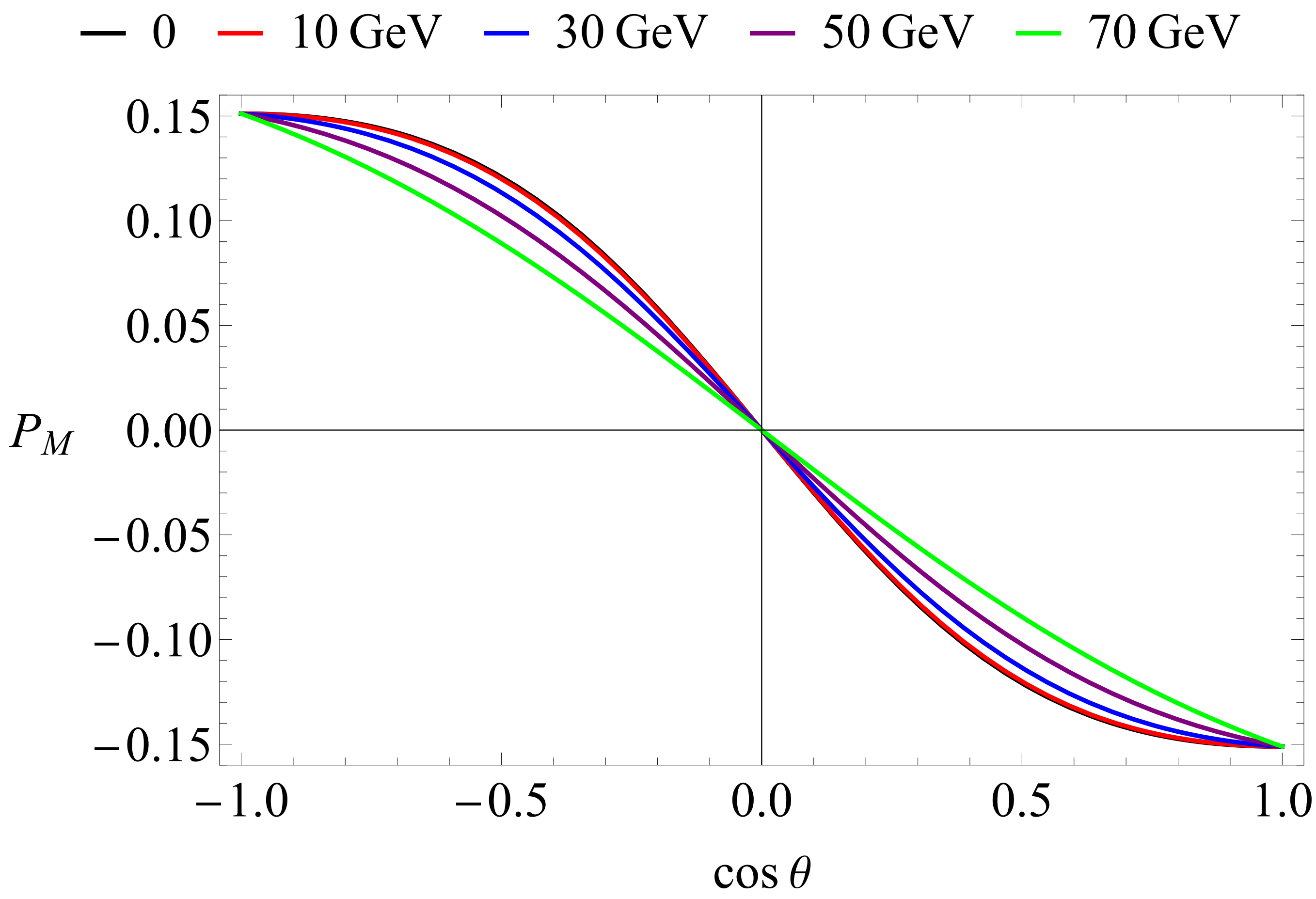
...the energy distribution of the daugther-charged-leptons depends on the polarization of the parent ν_4 (and $\bar{\nu}_4$ if ν_4 is a Dirac fermion). For example,



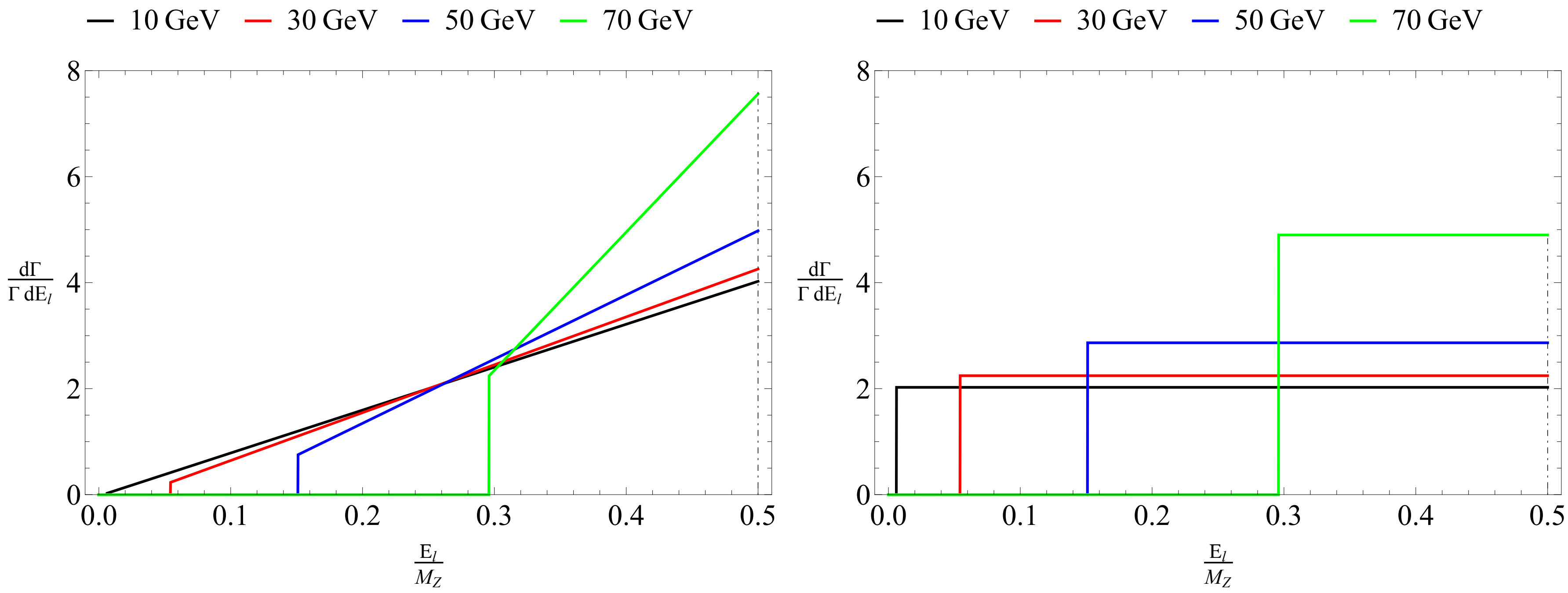
Normalized differential decay widths of $\nu_4 \to \ell^{\pm}\pi^{\mp}$ as a function of the energy of the charged-lepton, for ν_4 produced in Z-decay-at-rest. The different curves correspond to different values of $\alpha_{\pm}P \in [-1, 1]$ and $m_4 = 30$ GeV. $\alpha_{\pm}$ is the decay-asymmetry parameter and is a property of the physics responsible for the decay. For the SM, $\alpha_+ = +1 = -\alpha_-$



The polarizarion P_D of heavy neutrinos (dashed lines) or antineutrinos (solid lines) produced in $e^+e^- \to Z \to \nu_4\bar{\nu}_{\rm light}$ or $e^+e^- \to Z \to \bar{\nu}_4\nu_{\rm light}$ as a function of the direction of the heavy (anti)neutrino $\cos\theta$, for different values of the heavy neutrino mass m_4. The neutrinos are assumed to be Dirac fermions.



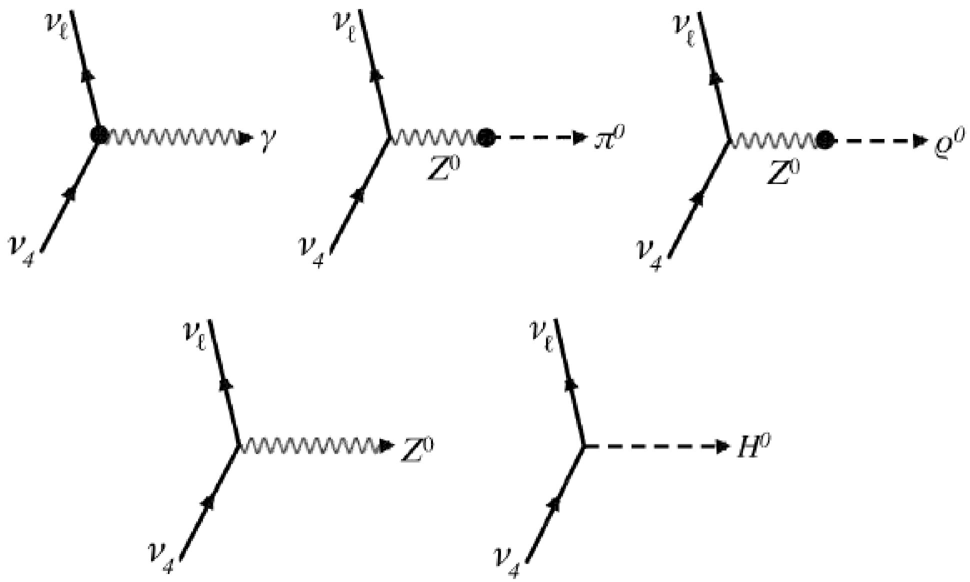
The polarizarion P_M of heavy neutrinos produced in $e^+e^- \to Z \to \nu_4\nu_{\rm light}$ as a function of the direction of the heavy neutrino $\cos\theta$, for different values of the heavy neutrino mass m_4. The neutrinos are assumed to be Majorana fermions. [Range of P_M values much smaller than range of P_D values (previous slide).]



Normalized differential decay widths of $\nu_4 \to \ell^- \pi^+$ as a function of the energy of the charged-lepton, averaged over the heavy-neutrino production angle, for ν_4 produced in Z-decay-at-rest assuming the heavy neutrinos are Dirac (left) and Majorana (right) fermions. The different curves correspond to different values of m_4. The same curves apply, both in the left-hand and in the right-hand panels, to the $\ell^+ \pi^-$ final-states.

Heavy Neutral Leptons – Other Two-Body Decay Modes

[B. Balantekin, AdG, B. Kayser, 1808.10518 [hep-ph]]



All of these decays are isotropic for a Majorana parent. For Dirac parents. . . ↓ (SM)

Boson	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$	1	$\frac{m_4^2-2m_\rho^2}{m_4^2+2m_\rho^2}$	$\frac{m_4^2-2m_Z^2}{m_4^2+2m_Z^2}$	1

Quick Summary

- The existence of Heavy Neutrinos is a potential side-effect of the new physics responsible for nonzero neutrino masses. However, if we ever found a heavy neutrino, how would we know it has anything to do with nonzero neutrino masses?
- Good start: are Heavy Neutrinos Dirac or Majorana fermions?
- Majorana and Dirac Heavy Neutrinos are produced differently in $e^+e^- \to$ heavy plus light (anti)neutrino. Furthermore, the ν_4 decays differently even if one compares the Majorana ν_4 to the "sum" of the Dirac ν_4 and $\bar{\nu}_4$.
- While the lepton number cannot be "tagged," the angular and energy distribution of the events are different enough that the two hypothesis may be distinguishable.
- Some left-over questions: other decay modes? in a realistic setting (e.g. FCC-ee, CEPC, ...), how many events do we need? More new physics in the ν_4 decay?