Majorana vs. Dirac and neutrino decays

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Moriond EW

March 15, 2018

Based on —

Baha Balantekin, André de Gouvêa, B.K.

and

Baha Balantekin, B.K.

— to appear in days.

Is each neutrino mass eigenstate ν —

a Dirac fermion $\bar{\nu} \neq \nu$

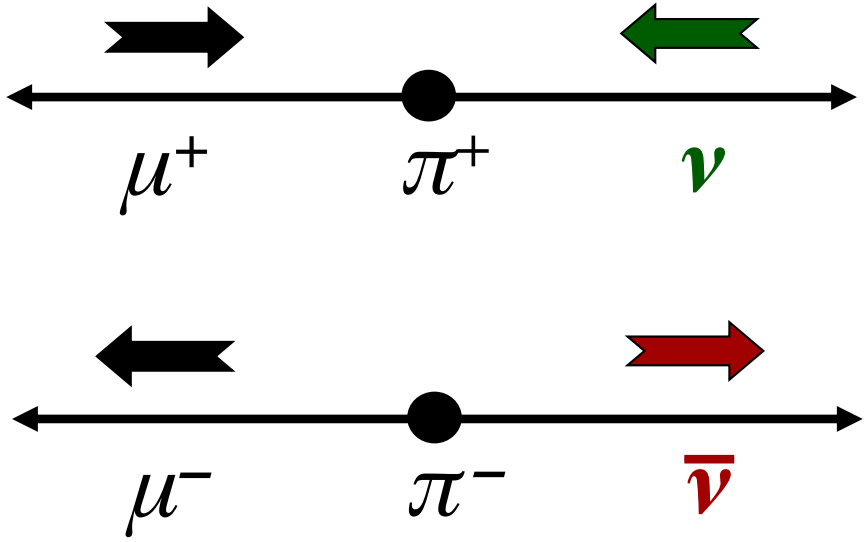
or

a Majorana fermion $\bar{\nu} = \nu$

Why is it so hard for us to find the answer to this question?

All the neutrinos we have been able to study directly so far have been **ultra-relativistic**.

Let us consider the neutrinos from pion decay.

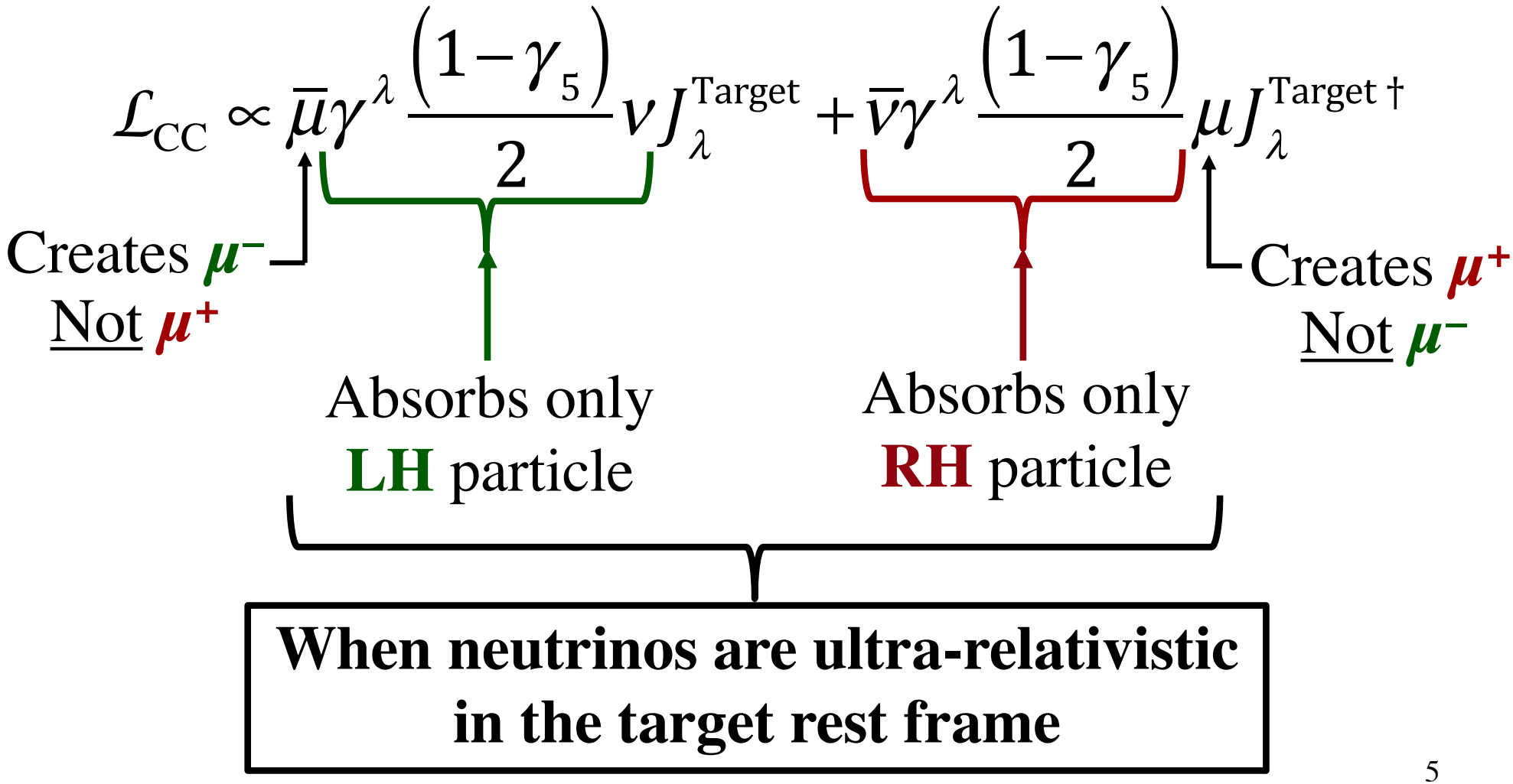


The "ν" : ~ 100 % "Left-Handed" helicity

The "$\bar{\nu}$" : ~ 100 % "Right-Handed" helicity

Suppose the neutral lepton from pion decay has a charged-current interaction with some target.

Majorana case: The neutrinos from π^+ and π^- differ only in helicity.



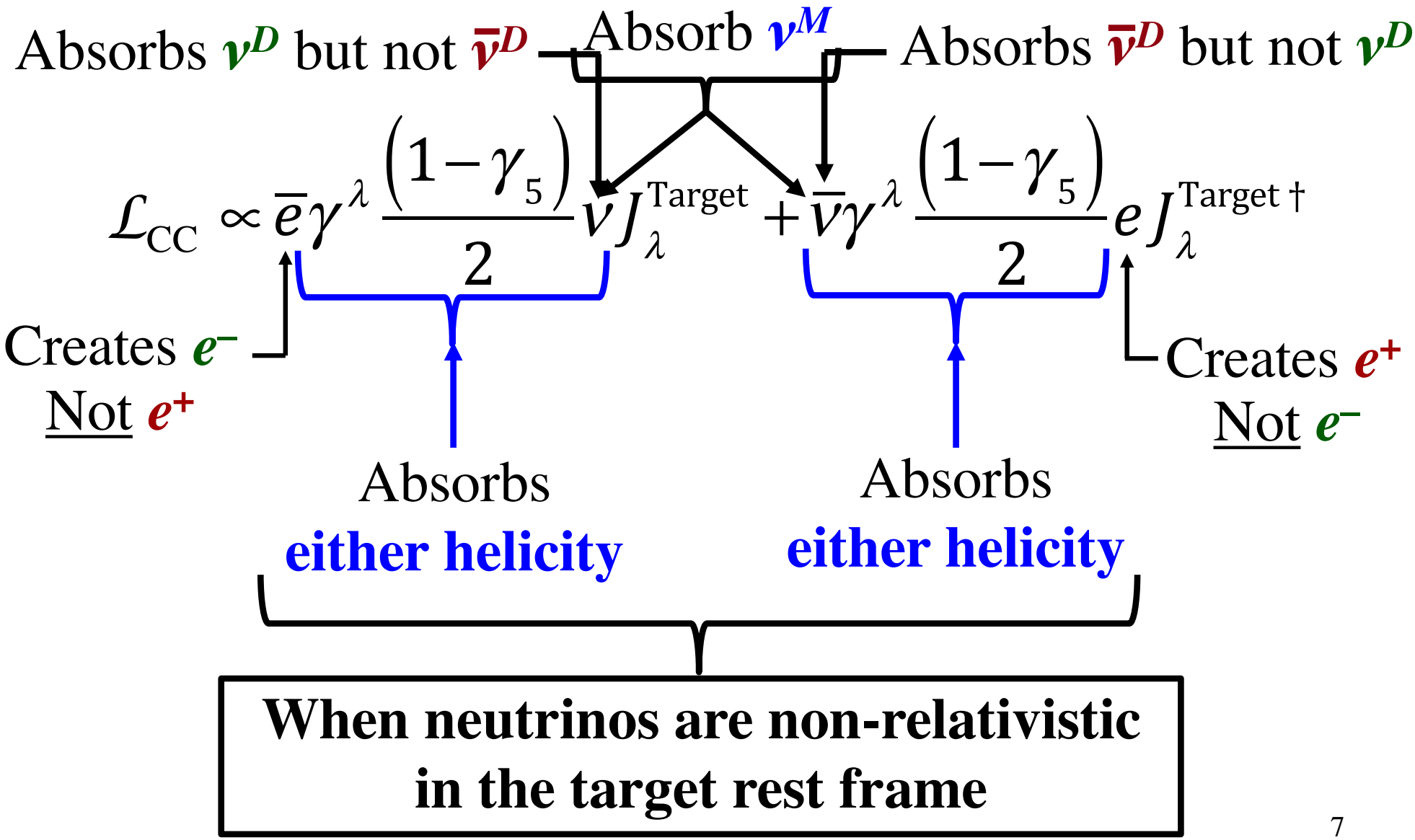
In almost all circumstances —

When neutrinos are ultra-relativistic,
helicity* is a substitute for the *lepton number
that distinguishes antileptons from leptons.

Whether there is a conserved lepton number
or not makes no difference.

Majorana and Dirac neutrinos behave identically.

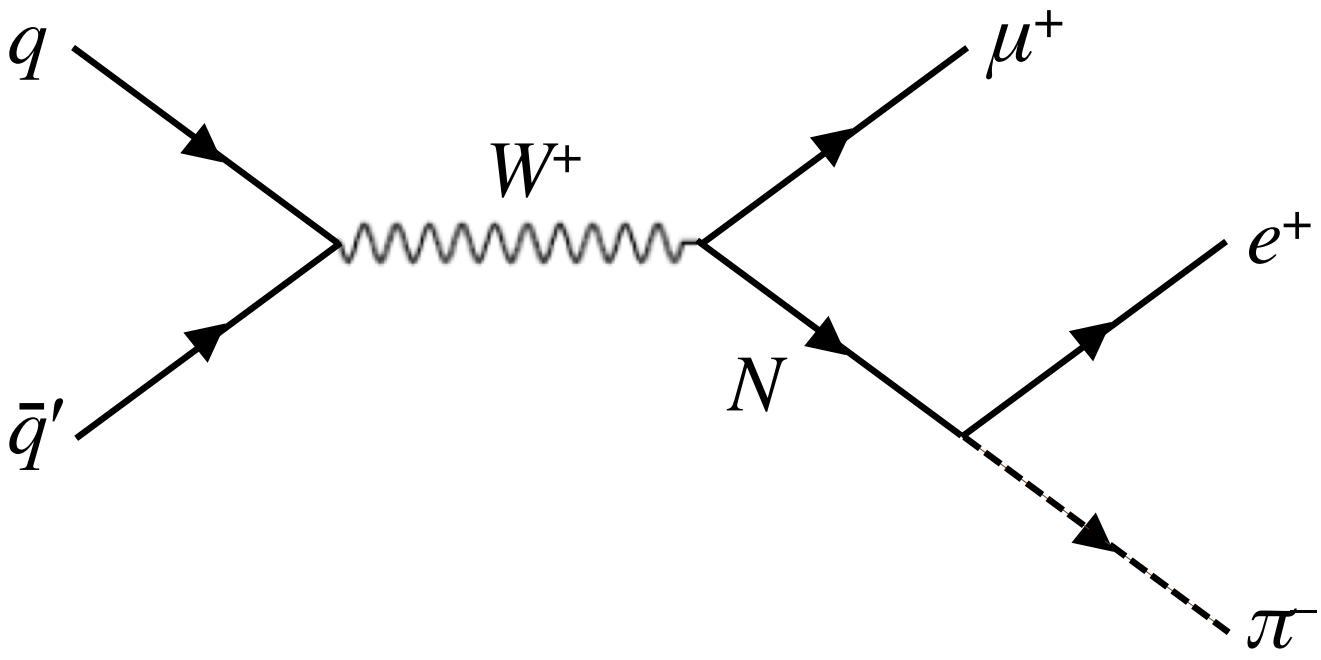
Non-Relativistic $\nu^{\mathrm{D(irac)}}$ and $\nu^{\mathrm{M(ajorana)}}$ Can Behave Quite Differently



Decays of a Heavy Neutrino

Suppose there is a heavy neutral lepton ***N*.**

A chain like —



would violate lepton number conservation,
and signal that *N* is a Majorana neutrino.

Very Neutral *N* Decay Modes

The decays —

$$N \to \nu + X$$

$\nu_1, \nu_2,$ or ν_3 — ν ; $X = \bar{X}$

could reveal whether neutrinos are Dirac or Majorana particles.

Depending on the mass of *N*, we could have —

$$X = \gamma, \pi^0, \rho^0, Z^0, \text{or } H^0.$$

For each of these decay modes,

$$\Gamma\left(N^{M} \to \nu^{M} + X\right) = 2\Gamma\left(N^{D} \to \nu^{D} + X\right)$$

Majorana — N^{M}, ν^{M}

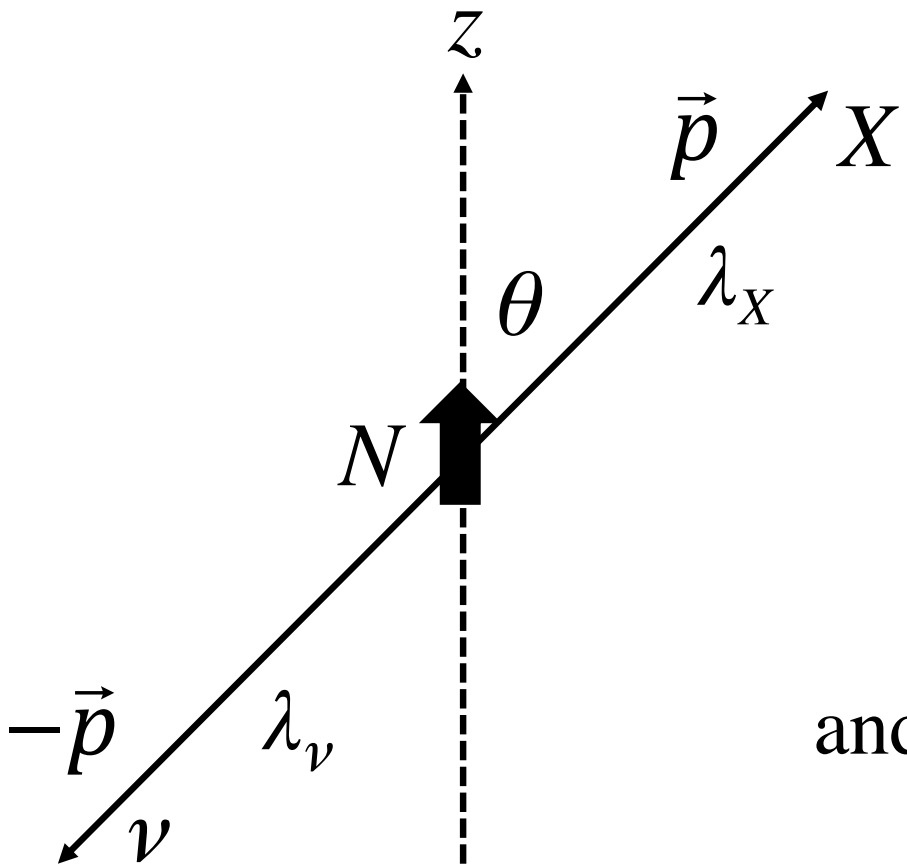
Dirac — N^{D}, ν^{D}

(Gorbunov and Shaposhnikov)

This difference may not be too useful, because the decay rate also depends on unknown mixing angles.

The ***angular distribution*** of the daughter *X* in the *N* rest frame, when *N* has been polarized by the mechanism that produced it, also depends on whether neutrinos are Majorana or Dirac particles.

General analysis: Balantekin, de Gouvêa, B.K.



We assume N is fully polarized.

λ_X, λ_ν are helicities, and $\lambda \equiv \lambda_X - \lambda_\nu = \vec{J}_{\text{final}} \bullet \vec{p}$.

Majorana neutrinos

Rotational invariance:

$$\frac{d\Gamma\left(N^M \to \nu^M + X\right)}{d\left(\cos\theta\right)} = \Gamma_{\lambda=+1/2}\left(1+\cos\theta\right) + \Gamma_{\lambda=-1/2}\left(1-\cos\theta\right)$$

$$= \Gamma_0\left(1+\alpha\cos\theta\right)\ ;\ -1 \le \alpha \le +1$$

CPT invariance:

$$\left|\left\langle X\left(\vec{p},\lambda_X\right)\nu^M\left(-\vec{p},\lambda_\nu\right)\middle|H\middle|N^M\left(\vec{s}\right)\right\rangle\right|^2 = \left|\left\langle X\left(-\vec{p},-\lambda_X\right)\nu^M\left(\vec{p},-\lambda_\nu\right)\middle|H\middle|N^M\left(\vec{s}\right)\right\rangle\right|^2$$

$$\Rightarrow\ \Gamma_{\lambda=+1/2} = \Gamma_{\lambda=-1/2}$$

$$\Rightarrow\ \alpha = 0$$

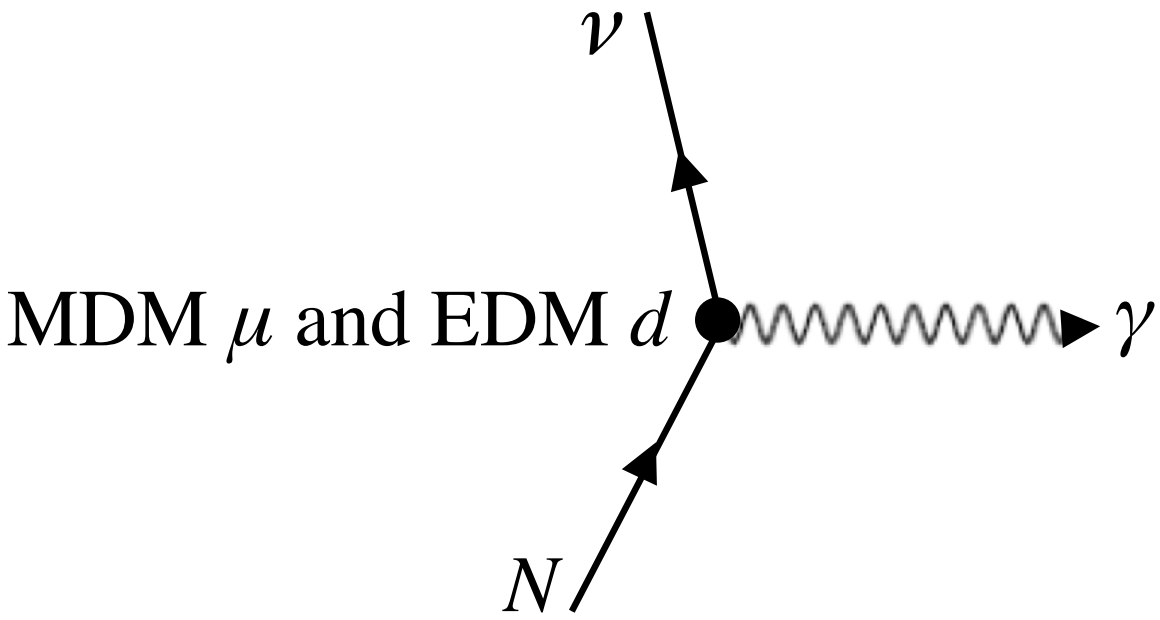
The angular distribution is isotropic.

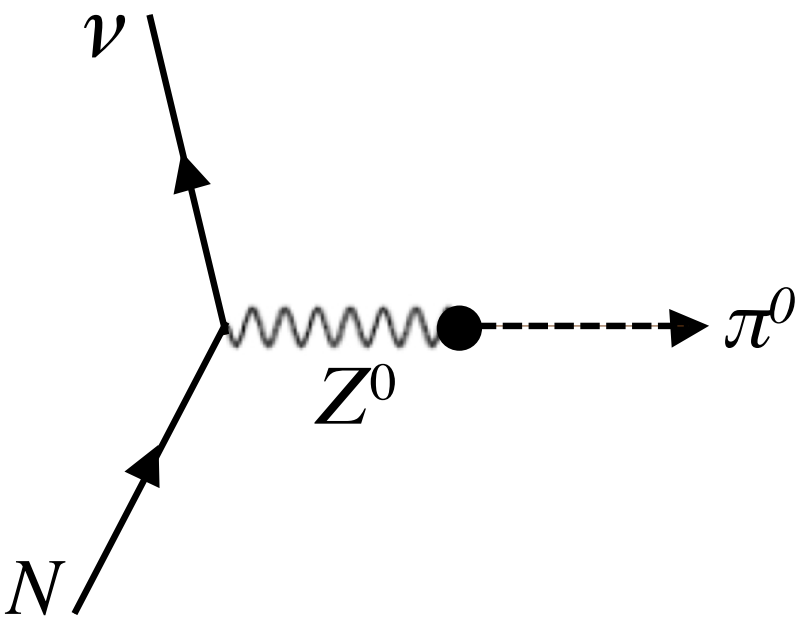
The isotropy in the Majorana case does not depend on the details of the interaction driving the decay.

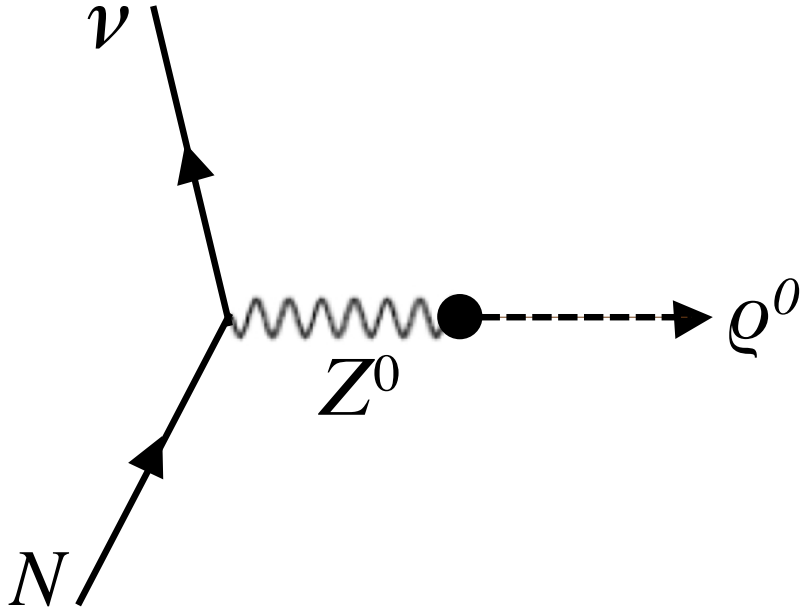
What Is the Angular Distribution in the Dirac Case?

This does depend on the interaction.

What we assume




ν
N
Z0
π0


ν
N
Z0
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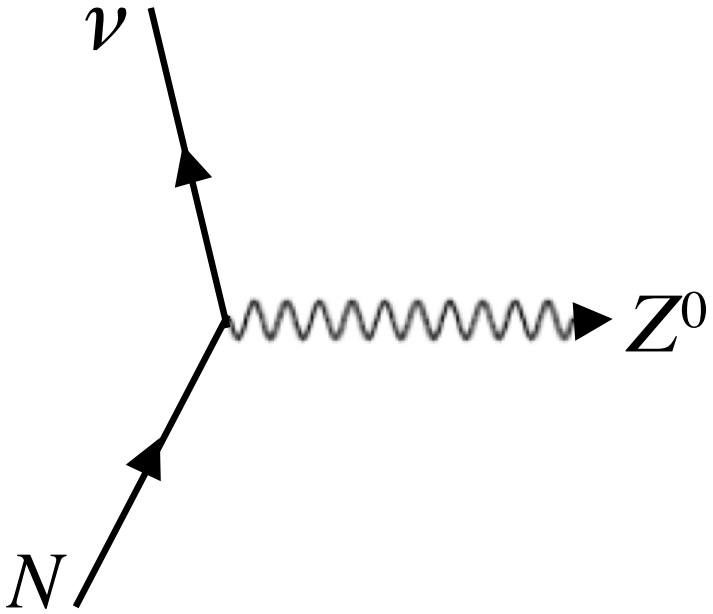
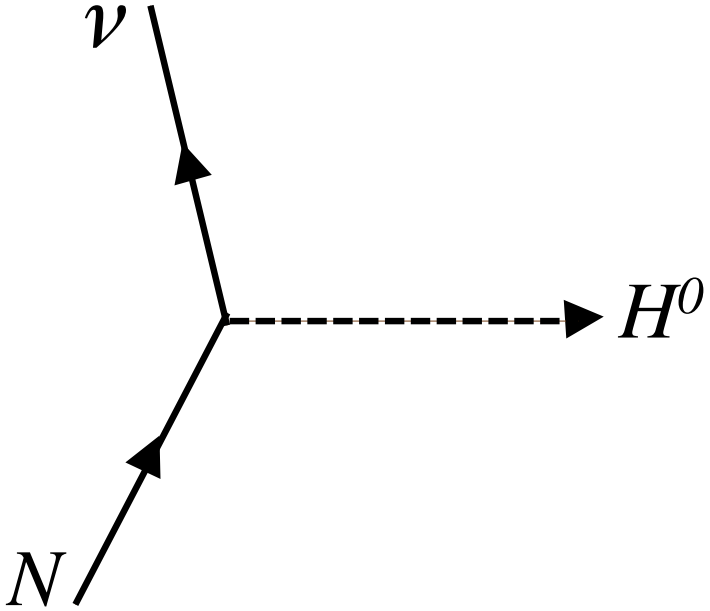

ν
N
Z0


ν
N
H0

An Example: $N^D \rightarrow \nu^D + \pi^0$

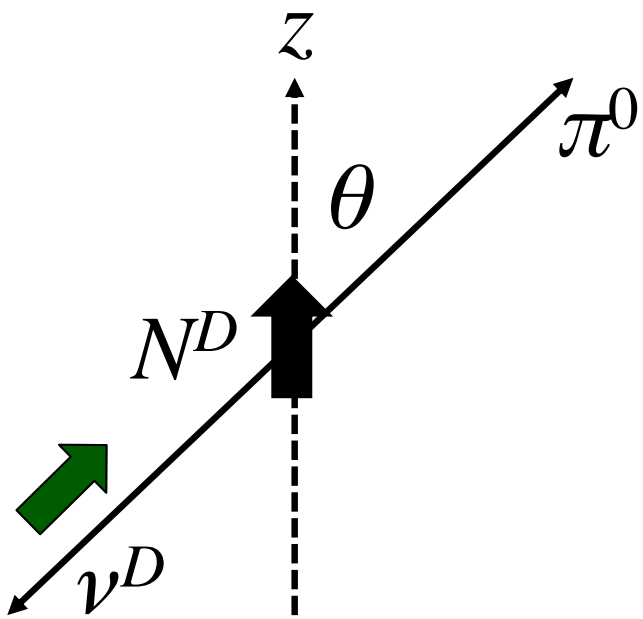
Pion momentum

Mass of N

$$\text{Amplitude}\left(N^D \rightarrow \nu^D + \pi^0\right) \propto \bar{u}_\nu \not{p}_\pi \frac{\left(1-\gamma_5\right)}{2} u_N = m_N \left[\frac{\left(1-\gamma_5\right)}{2} u_\nu\right]^\dagger \gamma^0 u_N$$

Dirac spinors

Allows only LH ν helicity



yields $\dfrac{d\Gamma}{d\left(\cos\theta\right)} \propto \left(1+\cos\theta\right)$

Not isotropic.

The Angular Distributions in the Dirac Case

$$\frac{d\Gamma\left(N^D \to \nu^D + X\right)}{d\left(\cos\theta\right)} = \Gamma_0\left(1+\alpha\cos\theta\right)$$

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

Except in very special circumstances, these angular distributions are not isotropic.

Once m_N is measured, most of them will not depend on any unknown parameters.

CMS is looking for a heavy neutrino.

Some of its physics has been considered by —

Ballett, Pascoli, Ross-Lonergan

and

Hernandez, Kekic, Lopez-Pavon, Racker, Rius, Salvado.

The angular distribution and related photon polarization in radiative neutrino decays has been considered in specific formalisms as a probe of whether neutrinos are Dirac or Majorana particles by —

Li and Wilczek and Shrock.

Conclusion

If a heavy neutrino is discovered, the angular distributions of its decays could tell us whether neutrinos are Dirac or Majorana particles.