CP Violation in Rare Lepton-Number-Violating W Decays at the LHC

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BSM-2021

Thursday, April 1, 2021

Talk based on work done in collaboration with F. Najafi and J. Kumar [arXiv:2011.03686 [hep-ph]].

Introduction

Baryon asymmetry of universe: requires (i) baryon number violation, (ii) CP violation, (iii) out of equilibrium.

Leptogenesis: create lepton-number asymmetry via CP-violating (CPV) lepton-number-violating (LNV) processes, convert to baryon-number asymmetry via ($B - L$-conserving) sphaleron processes.

Common scenario in leptogenesis models: $\exists$ pair of almost-degenerate heavy sterile neutrinos. Good for CPV (I will show later how this works).

Seesaw mechanism w/ 1 LH and 1 RH (sterile) neutrino:

$$M = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \implies m_\nu = \frac{m_D^2}{m_R} \ , \quad m_N = m_R \ .$$

Standard choice: $m_D \sim m_t$, $m_R \sim 10^{15}$ GeV.
But can also have (e.g.) $m_D \sim m_e$, $m_R \sim 1$ TeV.

With 3 LH and 3 RH neutrinos, have more free parameters. Find: can obtain 3 ultralight neutrinos ν_i and 3 heavy Majorana neutrinos N_i, with N_1 and N_2 nearly degenerate and with masses of $O(\mathrm{GeV})$.

L. Canetti et al., Phys. Rev. D **90**, 125005 (2014)

Also, $\exists$ heavy-light neutrino mixing:

$$\nu_\ell = \sum_{j=1}^{3} B_{\ell j} \nu_j + \sum_{i=1}^{3} B_{\ell N_i} N_i \ .$$

Here the parameters $B_{\ell N_i}$ parametrize the mixing.

Point: with $B_{\ell N_i} \neq 0$ and $M_N < M_W$, can have $W^- \to \ell_1^- N_i$, with $N_i \to \ell_2^- \ell_3^+ \nu_{\ell_3}$, $\ell_2^- (q' \bar{q})^+$ (LNV) or $N_i \to \ell_2^+ \ell_3^- \bar{\nu}_{\ell_3}$ (LNC). Searches for such decays constrain

$$|B_{\ell N}|^2 \leq 10^{-5} \quad (\ell = e, \mu), \quad \text{for 1 GeV} \leq m_N \leq 80 \text{ GeV}.$$

$\Longrightarrow$ can look for CPV LNV processes in decays of mesons and tau leptons. E.g., $B^\pm \to D^0 \ell_1^\pm \ell_2^\pm \pi^\mp$. Occurs via $B^\pm \to D^0 W^{*\pm} (\to \ell_1^\pm N_i)$, with $N_i \to \ell_2^\pm W^{*\mp} (\to \pi^\mp)$. G. Cvetič et al., Eur. Phys. J. C **80**, 1052 (2020)

Key point: can search for similar effects in the decays of *real* Ws at the LHC, in $W^- \to \ell_1^- \ell_2^- (f' \bar{f})^+$.

This decay has been studied extensively as a signal of LNV. Here we push further and study CP violation in this decay.

Note: in $W^- \to \ell_1^- \ell_2^- (f' \bar{f})^+$, in our study we focus on the pure LNV decay $W^- \to \ell_1^- \ell_2^- (q' \bar{q})^+$.

A difference between the rates of $W^- \to \ell_1^- \ell_2^- (q' \bar{q})^+$ and its CP-conjugate decay $W^+ \to \ell_1^+ \ell_2^+ (q' \bar{q})^-$ is a signal of CP violation.

CP Violation – Review

Suppose the decay $W^- \to F$ has two contributing amplitudes, A and B:

$$A_{\rm tot} = A + B = |A| e^{i\phi_A} e^{i\delta_A} + |B| e^{i\phi_B} e^{i\delta_B} ~,$$

where $\phi_{A,B}$ and $\delta_{A,B}$ are CP-odd and CP-even phases, respectively. The CP asymmetry is

$$\begin{aligned} A_{\rm CP} &= \frac{BR(W^- \to F) - BR(W^+ \to \bar{F})}{BR(W^- \to F) + BR(W^+ \to \bar{F})} \\ &= \frac{2|A||B| \sin(\phi_A - \phi_B) \sin(\delta_A - \delta_B)}{|A|^2 + |B|^2 + 2|A||B| \cos(\phi_A - \phi_B) \cos(\delta_A - \delta_B)} ~. \end{aligned}$$

Point: a nonzero $A_{\rm CP}$ requires $\phi_A - \phi_B \neq 0$ *and* $\delta_A - \delta_B \neq 0$. Also, $A_{\rm CP}$ is sizeable only when the two amplitudes are of similar size ($|A| \sim |B|$).

In $W^- \to \ell_1^- \ell_2^- (q' \bar{q})^+$, the two amplitudes are $W^- \to \ell_1^- \bar{N}_{1,2}$, with each of $\bar{N}_{1,2} \to \ell_2^- (q' \bar{q})^+$. Here $\phi_1 = \arg[B_{\ell_1 N_1} B_{\ell_2 N_1}]$ and $\phi_2 = \arg[B_{\ell_1 N_2} B_{\ell_2 N_2}]$, $\phi_1 - \phi_2$ can be nonzero.

$\exists$ two sources of CP-even phases. First, the N_i propagator:

$$\frac{1}{(p_N^2 - M_{N_i}^2) + iM_{N_i}\Gamma_{N_i}} = \frac{1}{\sqrt{(p_N^2 - M_{N_i}^2)^2 + M_{N_i}^2\Gamma_{N_i}^2}}\, e^{i\eta_i} ~,$$

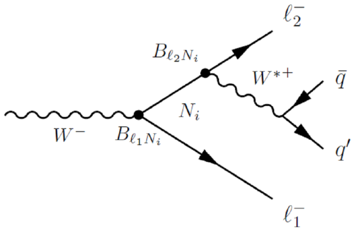
$$\text{with} \qquad \tan\eta_i = \frac{-M_{N_i}\Gamma_{N_i}}{(p_N^2 - M_{N_i}^2)} ~.$$

N_1 and N_2 do not have exactly the same mass $\Longrightarrow \eta_1 - \eta_2 \neq 0$. E.g., if $\eta_1 = -\pi/2$ (N_1 on-shell), then $|\eta_2| < \pi/2$. This is *resonant CP violation*.

Note: since the N_i are nearly degenerate., the two amplitudes are of similar size, and $A_{\rm CP}$ can be sizeable.

Second, $\exists$ oscillations of heavy neutrinos. The time evolution of a heavy N_i mass eigenstate involves e^{-iE_it}. $M_{N_1} \neq M_{N_2} \Longrightarrow E_1 \neq E_2 \Longrightarrow$ different e^{-iE_it} factors. This is another type of CP-even phase difference, and can also lead to CP violation.

$\mathcal{M}(W^- \to \ell_1^- \bar{N}_i, N_i \to \ell_2^- W^{*+}(\to (q'\bar{q})^+)$



The decay amplitude is

$$\mathcal{M}_i^{\mu\nu} = \bar{\ell}_1 \gamma^\mu P_L \left(\frac{g}{\sqrt{2}} B_{\ell_1 N_i} \right) N_i \times e^{-\Gamma_i t/2} e^{-iE_i t} \times \bar{\ell}_2 \gamma^\nu P_L \left(\frac{g}{\sqrt{2}} B_{\ell_2 N_i} \right) N_i$$

$$\to \frac{\frac{g^2}{2} B_{\ell_1 N_i} B_{\ell_2 N_i} M_i \, e^{-\Gamma_i t/2} e^{-iE_i t}}{p_N^2 - M_i^2 + i\Gamma_i M_i} L^{\mu\nu} ,$$

where $L^{\mu\nu} = \bar{\ell}_1 \gamma^\mu \gamma^\nu P_R \ell_2^c$.

The total amplitude is $\mathcal{M}^{\mu\nu} = \mathcal{M}_1^{\mu\nu} + \mathcal{M}_2^{\mu\nu}$.

Writing $B_{\ell_1 N_1} B_{\ell_2 N_1} = B_1 e^{i\phi_1}$, $B_{\ell_1 N_2} B_{\ell_2 N_2} = B_2 e^{i\phi_2}$, we have

$$\mathcal{M}^{\mu\nu} = \frac{g^2}{2} \left(\frac{M_1 B_1 e^{i\phi_1} e^{-\Gamma_1 t/2} e^{-iE_1 t}}{p_N^2 - M_1^2 + i\Gamma_1 M_1} + \frac{M_2 B_2 e^{i\phi_2} e^{-\Gamma_2 t/2} e^{-iE_2 t}}{p_N^2 - M_2^2 + i\Gamma_2 M_2} \right) L^{\mu\nu} \ .$$

Note the two amplitudes have relative CP-odd phases and (2 sources of) relative CP-even phases $\Longrightarrow \exists$ CP violation.

With this expression, we (i) compute $|\mathcal{M}^{\mu\nu}|^2$ using the narrow-width approximation, (ii) integrate over time (we do not aim to measure the neutrino oscillations), (iii) perform the phase-space integrals, and (iv) construct $A_{\rm CP}$.

$A_{\rm CP}$

With the assumption that $B_1 = B_2$, we find

$$A_{\rm CP} = \frac{2(2y - x)\sin\delta\phi}{(1 + x^2)(1 + 4y^2) + 2(1 - 2xy)\cos\delta\phi} ,$$

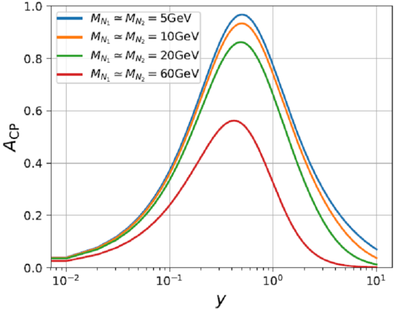
with

$$x \equiv \frac{\Delta E}{\Gamma} \quad , \qquad y \equiv \frac{\Delta M}{\Gamma} \qquad \text{with} \qquad x = y\,\frac{M_N}{M_W} \ .$$

x and y each play the role of the CP-even phase-difference term $\sin(\delta_A - \delta_B)$. x arises from neutrino oscillations (ΔE); y is due to the neutrino propagator (ΔM).

y is always present; x is generally subdominant, except for large values of M_N. $|2y - x| \le |2y| \Longrightarrow$ as $|x|$ increases, $A_{\rm CP}$ decreases. We therefore expect to see smaller CP-violating effects for larger values of M_N.

Estimate potential size of $A_{\rm CP}$: set $\delta\phi = \pi/2$, plot $A_{\rm CP}$ as a function of y, for various values of M_N:



Find

- Large values of $|A_{\rm CP}|$ (≥ 0.9) can be produced for light M_N.
- Maximal values of $|A_{\rm CP}|$ are found when $y \simeq \pm\frac{1}{2}$, with $|A_{\rm CP}|$ decreasing for larger/smaller values of $|y|$.
- As expected, the size of $|A_{\rm CP}|$ decreases as M_N increases, with $|A_{\rm CP}|_{\rm max} < 0.6$ for larger values of M_N.

Experimental Prospects

$A_{\rm CP}$: compare N_{--} (# events of $W^- \to \ell_1^- \ell_2^- (q'\bar{q})^+$) and N_{++} (# events of $W^+ \to \ell_1^+ \ell_2^+ (q\bar{q}')^-$). Take into account fact that number of W^- and W^+ bosons produced is not the same: $R_W \equiv \sigma^+/\sigma^- = 1.295 \pm 0.003\ (stat) \pm 0.010\ (syst)$ at $\sqrt{s} = 13$ TeV.

Given an $A_{\rm CP}$, number of events required to show it is nonzero at $n\sigma$ is

$$N_{\rm events} = \frac{n^2}{A_{CP}^2\, \epsilon} ~,$$

where ϵ is the experimental efficiency $\Longrightarrow$ given $N_{\rm events}$, can compute smallest value of $|A_{\rm CP}|$ measurable at $n\sigma$.

Consider three versions of the LHC: (i) the high-luminosity LHC (HL-LHC, $\sqrt{s} = 14$ TeV), (ii) the high-energy LHC (HE-LHC, $\sqrt{s} = 27$ TeV), (iii) the future circular collider (FCC-hh, $\sqrt{s} = 100$ TeV). Use `FeynRules` and `MadGraph` to generate events, take $|B_{\ell N}|^2 \leq 10^{-5}$.

Note: $N_{\rm events}$ not whole story, need number of *measurable* events $\Longrightarrow$ look at the N lifetime and determine what percentage of the heavy neutrinos actually decay in the detector. E.g., CMS: for $M_N = 1$ GeV, 5 GeV and 10 GeV, multiplicative reduction factor was 10^{-3}, 0.1 and $\simeq 1$.

Results using overall efficiency of $\epsilon \sim 1\%$ (CMS):

Minimum $A_{\rm CP}$ measurable at 3σ			
Machine	$M_N = 5$ GeV	$M_N = 10$ GeV	$M_N = 50$ GeV
HL-LHC	15.0%	4.8%	7.4%
HE-LHC	5.1%	1.6%	2.5%
FCC-hh	2.1%	0.7%	1.0%

- As LHC increases in energy and integrated luminosity, smaller values of $A_{\rm CP}$ are measurable.
- At a given machine, measurable $A_{\rm CP}$ decreases as M_N increases. (But there is a reduction factor due to the N lifetime for small M_N.
- Most promising results are for $M_N = 10$ GeV, but in all cases reasonably small values of $A_{\rm CP}$ can be probed.

Conclusions

In many leptogenesis models, a lepton-number asymmetry arises through CP-violating decays of a pair of nearly-degenerate heavy neutrinos N_1 and N_2. Intriguing: the masses of $N_{1,2}$ can be small, $O(\mathrm{GeV})$.

Heavy-light neutrino mixing leads to LNV processes at the LHC such as $W^\pm \to \ell_1^\pm \ell_2^\pm (q'\bar{q})^\mp$. A CPV rate asymmetry A_{CP} between the W^- and W^+ decays can arise due to the interference of the N_1 and N_2 contributions. The different W-ℓ-N_1 and W-ℓ-N_2 couplings produces the CP-odd phase difference; The CP-even phase difference is generated via propagator effects or oscillations of the heavy neutrino.

We consider $5\ \mathrm{GeV} \leq M_N \leq 80\ \mathrm{GeV}$ and examine three versions of the LHC: (i) HL-LHC ($\sqrt{s} = 14$ TeV), (ii) HE-LHC ($\sqrt{s} = 27$ TeV), (iii) FCC-hh ($\sqrt{s} = 100$ TeV). Most promising result: FCC-hh with $M_N = 10$ GeV, $A_{\mathrm{CP}} = O(1\%)$ is measurable. But even in worst case, HL-LHC with $M_N = 5$ GeV, $A_{\mathrm{CP}} = O(10\%)$ can be measured.