Probing heavy neutrino oscillation and associated CP violation at future hadron colliders

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based on

P. S. B. Dev, R. N. Mohapatra & YCZ, 1904.04787

Seesaw mechanism

Minkowski, '77; Mohapatra & Senjanovic, '80; Yanagida, '79;
Gell-Mann, Ramond & Slansky, '79; Glashow, '80

$$m_\nu \simeq -m_D M_N^{-1} m_D^{\mathsf{T}}$$

At least two heavy right-handed neutrinos (RHNs)
to generate the tiny neutrino masses.
("fair-play rule")

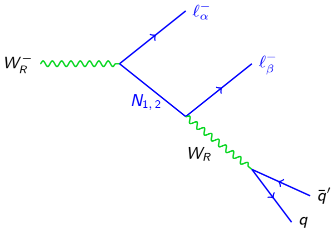
Seesaw scenarios

- In pure type-I seesaw and $U(1)_{B-L}$ gauge extension of SM, RHN mixing and associated CP violation signatures depend on heavy-light neutrino mixing. Thanks to the discussions with Shun Zhou [Chao, Si, Zheng, Zhou '09]
- In the left-right model based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$:
  [Pati & Salam, '74; Mohapatra & Pati, '75; Senjonavić & Mohapatra, '75]

$$
\begin{aligned}
Q_L &= \begin{pmatrix} u_L \\ d_L \end{pmatrix} \in \left(\mathbf{2}, \mathbf{1}, \frac{1}{3}\right) \overset{\mathcal{P}}{\longleftrightarrow} Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \in \left(\mathbf{1}, \mathbf{2}, \frac{1}{3}\right) \\
\Psi_L &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \in (\mathbf{2}, \mathbf{1}, -1) \overset{\mathcal{P}}{\longleftrightarrow} \Psi_R = \begin{pmatrix} N_R \\ e_R \end{pmatrix} \in (\mathbf{1}, \mathbf{2}, -1)
\end{aligned}
$$

  The RHN mixing and CP violation can be measured at colliders.
- This can be used to directly test TeV-scale leptogenesis at future hadron colliders!

Flavor dependence of same-sign dilepton signals



- The "smoking-gun" signal of W_R and N! [Keung & Senjanović, '83]
- With only one RHN, or the production and decays of RHNs not interfering coherently:

$$\Gamma(N \to \ell^+ jj) = \Gamma(N \to \ell^- jj) \quad \Longrightarrow \quad \mathcal{N}(\ell^\pm \ell^\pm) = \mathcal{N}(\ell^+ \ell^-)$$

- If we have more than one RHNs, and there are mixing and CPV in the RHN sector [Dev & Mohapatra, '15; Gluza, Jelinski & Szafron, '16; Anamiati, Hirsch & Nardi, '16; Antusch, Cazzato & Fischer, '17; Das, Dev & Mohapatra, '17]

$$\Gamma(N_\alpha \to \ell_\beta^+ jj) = \Gamma(N_\alpha \to \ell_\beta^- jj)\,, \quad \text{but} \quad \mathcal{N}(\ell_\alpha^\pm \ell_\beta^\pm) \neq \mathcal{N}(\ell_\alpha^+ \ell_\beta^-)\,,$$

$$\mathcal{N}(\ell_\alpha^+ \ell_\beta^+) \neq \mathcal{N}(\ell_\alpha^- \ell_\beta^-) \text{ (CP-induced effects)}$$

RHN mixing and CP violation

Some assumptions

- Only two RHNs $N_{e,\,\mu}$ mixing with each other;
  the third one N_τ does not mix with $N_{e,\,\mu}$:

$$\begin{pmatrix} N_e \\ N_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_R & \sin\theta_R e^{-i\delta_R} \\ -\sin\theta_R e^{i\delta_R} & \cos\theta_R \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} ,$$

- The mass relation $M_{1,\,2} < M_{W_R}$ (and $M_3 > M_{W_R}$):

on-shell production of RHNs from W_R decay: $W_R^\pm \to \ell_\alpha^\pm N_\alpha$

Same-sign charge asymmetry (SSCA)

Define the same-sign charge asymmetry (SSCA)

$$\mathcal{A}_{\alpha\beta} \equiv \frac{\mathcal{N}(\ell_\alpha^+\ell_\beta^+) - \mathcal{N}(\ell_\alpha^-\ell_\beta^-)}{\mathcal{N}(\ell_\alpha^+\ell_\beta^+) + \mathcal{N}(\ell_\alpha^-\ell_\beta^-)} = \frac{\sigma(pp \to W_R^+)\mathcal{R}(\ell_\alpha^+\ell_\beta^+) - \sigma(pp \to W_R^-)\mathcal{R}(\ell_\alpha^-\ell_\beta^-)}{\sigma(pp \to W_R^+)\mathcal{R}(\ell_\alpha^+\ell_\beta^+) + \sigma(pp \to W_R^-)\mathcal{R}(\ell_\alpha^-\ell_\beta^-)}$$

Combing both the three-body decays of N_α through the gauge couplings to W_R boson $(1 - \mathrm{BR}_y)$ and two-body decays of N_α through the Yukawa couplings via heavy-light neutrino mixing (BR_y)

$$\mathcal{R}(\ell_\alpha^\pm\ell_\beta^\pm) \simeq \underbrace{(1 - \mathrm{BR}_y)R(\ell_\alpha^\pm\ell_\beta^\pm)}_{\text{3-body decay ctrb.}} + \underbrace{\frac{1}{4}\mathrm{BR}_y B_{\alpha\beta}}_{\text{2-body decay ctrb.}}$$

3-body and 2-body decay contributions

- Three-body decays $N_\alpha \to \ell_\beta^\pm jj$, in the limit of $\Gamma_1 = \Gamma_2$, with $x \equiv \Delta E_N/\Gamma_{\rm avg}$ [normalization condition $\sum_{\alpha,\beta=e,\mu} R(\ell_\alpha^\pm \ell_\beta^\pm) = 1$]

$$R(e^\pm \mu^\pm) = R(\mu^\pm e^\pm) \simeq \frac{1}{4}\sin^2 2\theta_R \left(1 - \frac{\cos 2\delta_R \pm x \sin 2\delta_R}{1+x^2}\right),$$
$$R(e^\pm e^\pm) \simeq R(\mu^\pm \mu^\pm) \simeq \frac{1}{2} - R(e^\pm \mu^\pm),$$

- Two-body decays $N_\alpha \to \ell_\beta^\pm W^\mp$ ($\alpha = e, \mu,\ \beta = e, \mu, \tau$)

$$\mathcal{N}(\ell_\alpha^\pm \ell_\beta^\pm) \propto \left[R(e^\pm e^\pm) + R(e^\pm \mu^\pm)\right] B_{e\beta} = \frac{1}{2} B_{e\beta}$$
$$B_{\alpha\beta} = \Gamma(N_\alpha \to \ell_\beta^\pm W^\mp)/\Gamma(N_\alpha \to \sum_\beta \ell_\beta^\pm W^\mp)$$

In most of the parameter space of interest, the dependence of SSCAs on θ_R and δ_R is negligible.

Some comments

- $\mathcal{A}_{ee,\,\mu\mu}$ depend both on θ_R and δ_R, while $\mathcal{A}_{e\mu}$ depends only on δ_R.
- We expect the relation, in the limit of $(1 - \mathrm{BR}_y) \gg \mathrm{BR}_y$,

$$\mathcal{A}_{e\mu}(\delta_R) \; = \; \mathcal{A}_{ee,\,\mu\mu} \left(\theta_R = \frac{\pi}{4}, \delta_R + \frac{\pi}{2} \right) \, .$$

- $A_{ee,\,\mu\mu,\,e\mu}$ can be used to determine the RHN mixing angle θ_R and CP phase δ_R at future colliders.

- If the two-body decay dominates, the CP-induced SSCAs will be suppressed.
- If the three-body decay dominates, the TeV-scale leptogenesis efficiency will be suppressed.

Dominant (reducible) backgrounds

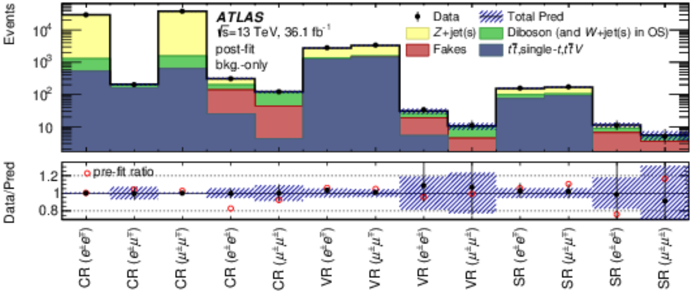


Figure: From ATLAS, 1809.11105, with $\mathcal{L} = 36.1\,\mathrm{fb}^{-1}$. [See also CMS, 1803.11116; Mitra, Ruiz, Scott & Spannowsky, '16; Nemevsek, Nesti & Popara, '18]

Production cross sections

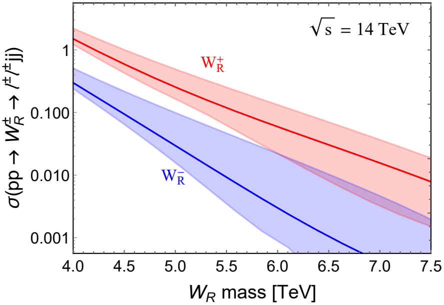


Figure: Using a conservative k-factor of 1.1. Mitra, Ruiz, Scott & Spannowsky, '16

Even if there is no CPV in the RHN sector,
we can still expect non-zero SSCAs:

$$\sigma(pp \to W_R^+) > \sigma(pp \to W_R^-)$$

The proton PDF uncertainties are more important...

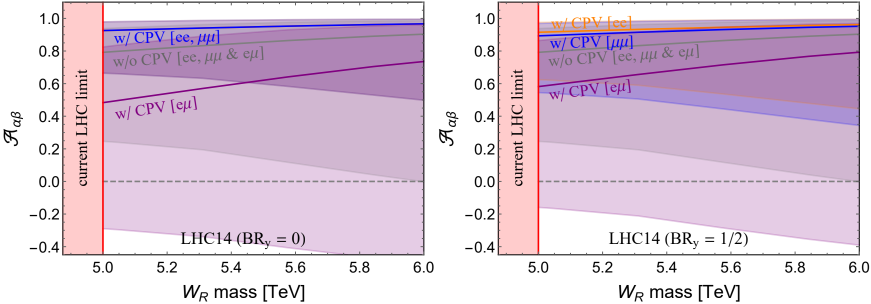


Figure: Using NNPDF3.1 and $\theta_R = \delta_R = \pi/4$. *Left*: $\mathrm{BR}_y = 0$ and *Right*: $\mathrm{BR}_y = 1/2$.

- The proton parton energy fraction

$$x_1 x_2 = \frac{\hat{s}}{s} \simeq \frac{M_{W_R}^2}{s} \gtrsim 0.1 \quad \text{for } M_{W_R} \gtrsim 5\,\mathrm{TeV}$$

We need a higher-energy collider!

Prospects @ HE-LHC $\sqrt{s} = 27$ TeV

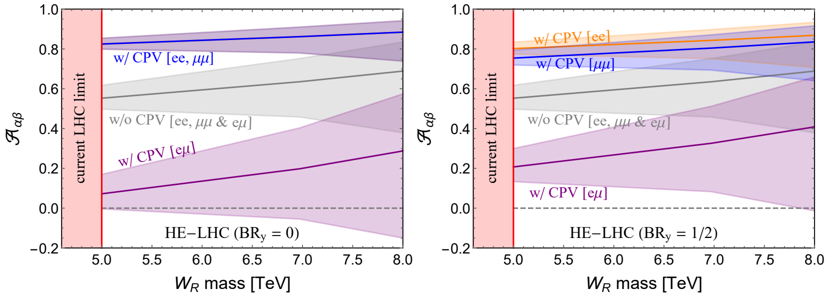


Figure: *Left*: $\mathrm{BR}_y = 0$ and *Right*: $\mathrm{BR}_y = 1/2$.

- One could measure the RHN mixing and CPV at future high energy colliders by using the SSCA signals.
- The maximal CPV case ($\theta_R = \delta_R = \pi/4$) can be measured at $\sqrt{s} = 27$ TeV, for a W_R mass up to 7.2 TeV.
- We need only $\mathcal{O}(100\,\mathrm{fb}^{-1})$ of data to have at least 100 events of both $\ell^+\ell^+$ and $\ell^-\ell^-$ at HE-LHC for a W_R mass of 5 TeV.

Prospects @ FCC-hh/SPPC $\sqrt{s} = 100$ TeV

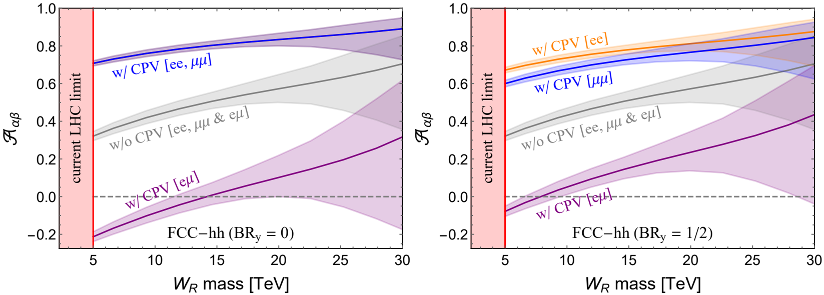
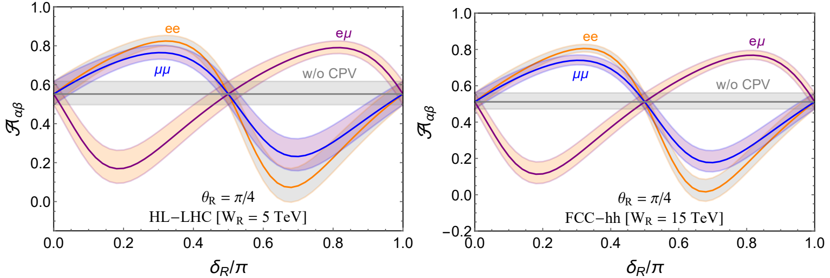


Figure: *Left*: $\mathrm{BR}_y = 0$ and *Right*: $\mathrm{BR}_y = 1/2$.

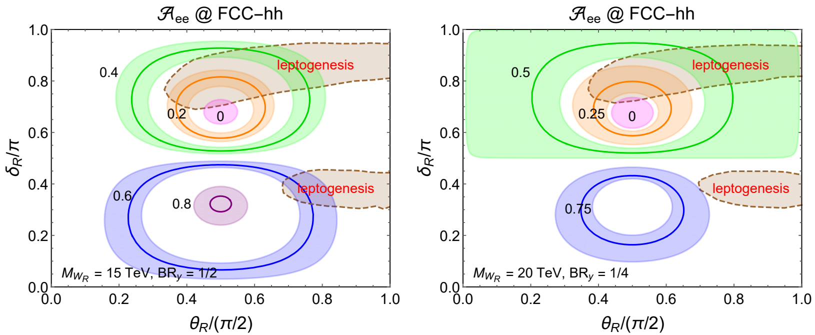
- One could measure the RHN mixing and CPV at future high energy colliders by using the SSCA signals.
- The maximal CPV case ($\theta_R = \delta_R = \pi/4$) can be measured at $\sqrt{s} = 100$ TeV, for a W_R mass up to 26 TeV.
- We need only $\mathcal{O}(100\,\mathrm{fb}^{-1})$ of data to have at least 100 events of both $\ell^+\ell^+$ and $\ell^-\ell^-$ at FCC-hh/SPPC for a W_R mass of 10 TeV.

Expected SSCAs: benchmark points



- The $\mathcal{A}_{e\mu}$ does not depend on θ_R, thus one can use $\mathcal{A}_{e\mu}$ to first determine the phase δ_R, up to a twofold ambiguity.
- Then one can use $\mathcal{A}_{ee,\,\mu\mu}$ to determine the mixing angle θ_R (and potentially remove the ambiguity of δ_R).
- By comparing the $\mathcal{A}_{ee}$ and $\mathcal{A}_{\mu\mu}$ data, we can get information on the BRs of 3- and 2-body decays of RHNs.

Expected SSCAs: benchmark points



- With only $\mathcal{A}_{ee}$ (or $\mathcal{A}_{\mu\mu}$), one can limit θ_R and δ_R to a circle (band).
- Then one can use $\mathcal{A}_{e\mu}$ to determine θ_R and δ_R (to a limited range).

Casas-Ibarra parameterization

Casas & Ibarra, '01; Nemevšek, Senjanović, Tello, '12 PRL

- For simplicity, we "decouple" N_τ, with one of the active neutrinos being massless.
- Casas-Ibarra parameterization of the M_D matrix (equiv. to Nemevšek-Senjanović-Tello form in the LRSM)

$$M_D = i V_{\rm PMNS}\, \widehat{m}_\nu^{1/2} \mathcal{O} M_N^{1/2}$$

- The arbitrary matrix

$$\mathcal{O} = \begin{pmatrix} 0 & 0 \\ \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix}, \quad \mathcal{O}\mathcal{O}^{\sf T} = \begin{pmatrix} 0 & 0 \\ 0 & \mathbf{1}_{2\times2} \end{pmatrix} \text{ for NH}\,,$$

$$\mathcal{O} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \\ 0 & 0 \end{pmatrix}, \quad \mathcal{O}\mathcal{O}^{\sf T} = \begin{pmatrix} \mathbf{1}_{2\times2} & 0 \\ 0 & 0 \end{pmatrix} \text{ for IH}\,.$$

- ζ could be complex, enhancing largely the couplings $y = M_D / v_{\rm EW}$.

Leptogenesis

- The lepton asymmetry generated from RHN decay, with $K_\alpha^{\rm eff}$ the washout factor [Dev, Lee & Mohapatra, '14]

$$\eta_i^{\Delta L} \simeq \frac{3}{2 z_c K_\alpha^{\rm eff}} \sum_\alpha \varepsilon_{i\alpha} d_i ,$$

- The dilution factor due to the right-handed gauge interactions of RHNs,

$$d_i = \gamma_{L\phi}^{N_i} / \left(\gamma_{L\phi}^{N_i} + \gamma_{Lqq}^{N_i} + \gamma_{W_R}^{N_i} \right)$$

- The flavor-dependent CP asymmetry contains the information of RHN mixing and CPV, with $i \neq j$,

$$\varepsilon_{i\alpha} \simeq \frac{(M_i^2 - M_j^2) {\rm Im}[y_{\alpha i}^* y_{\alpha j}] {\rm Re}[(y^\dagger y)_{ij}]}{4\pi [4(M_i - M_j)^2 + \Gamma_j^2](y^\dagger y)_{ii}} \times {\rm BR}_y(N_i)$$

Complex ζ

Frerè, Hambye & Vertongen, '08; Dev, Lee & Mohapatra, '14; Dhuria, Hati, Rangarajan & Sarkar, '15

- Without any significant cancellation or fine-tuning in the M_D matrix,

$$|y| \sim \sqrt{|m_\nu M_N|} \sim 10^{-6} \ll g_R$$

This sets a lower bound on the W_R boson mass

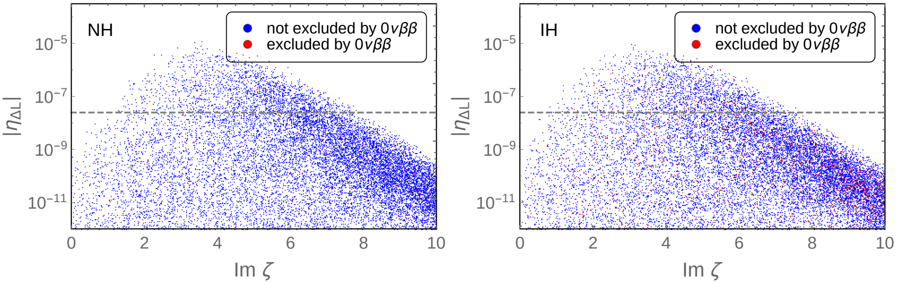
$$M_{W_R} \gtrsim 50\,\mathrm{TeV} \quad \Longrightarrow \quad \text{no CPV prospect @ 100 TeV collider}$$

- The W_R mass could be significantly smaller, if

$$|\sin\zeta|,\ |\cos\zeta| \gg 1 \quad \Rightarrow \quad y \gg 10^{-6}$$

- However, $\mathrm{Im}\zeta$ can not be too large
  - The $\Delta L = 0$ processes $L\phi \leftrightarrow L\phi$, $\Delta L = 2$ process $L\phi \leftrightarrow \bar{L}\phi^\dagger$ and/or the inverse decay $L\phi \to N_i$ induce significant dilution/washout effects.
  - It is potentially constrained by high-precision low-energy constraints, such as $\mu \to e\gamma$, $0\nu\beta\beta$ and electron EDM (almost no limit in our case).

Imζ ranges



Ranges of parameters, with RHN mass splitting $\varepsilon = \Gamma_{\rm avg}/2$ to have the maximal lepton asymmetry:

$$\delta_\nu \in [0,\, 2\pi]\,, \quad \alpha \in [0,\, 2\pi]\,, \quad \zeta \in [0,\, 10]i\,,$$
$$M_N \in [0.15,\, 10]\,{\rm TeV}\,, \quad M_{W_R} \in [3,\, 50]\,{\rm TeV}\,, \quad \theta_R \in [0,\, 2\pi]\,, \quad \delta_R \in [0,\, 2\pi]\,.$$

The limits from LFV decay $\mu \to e\gamma$ and electron EDM can not provide any limits in our case.

$\mathrm{Im}\zeta$ ranges and Yukawa couplings

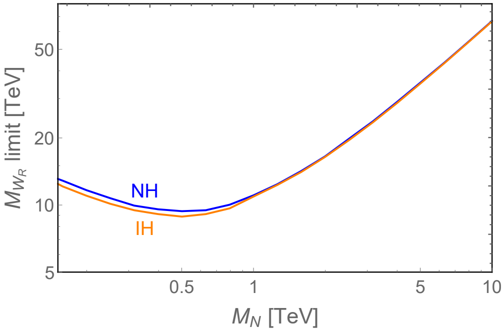
The ranges of $\mathrm{Im}\zeta$ we found:

$$\begin{cases} 1.3 \lesssim \mathrm{Im}\zeta \lesssim 7.8\,, & \text{for NH}\,, \\ 0.8 \lesssim \mathrm{Im}\zeta \lesssim 7.7\,, & \text{for NH}\,, \end{cases}$$

and the resultant magnitudes of Yukawa couplings $y = M_D / v_{\rm EW}$:

$$\begin{cases} 1.3 \times 10^{-6} \lesssim |y|_{\rm max} \lesssim 7.2 \times 10^{-4}\,, & \text{for NH}\,, \\ 1.0 \times 10^{-6} \lesssim |y|_{\rm max} \lesssim 8.6 \times 10^{-4}\,, & \text{for IH}\,. \end{cases}$$

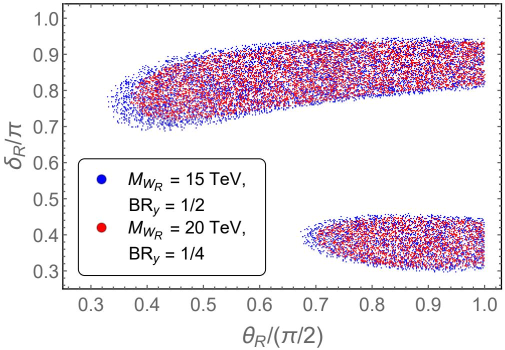
Absolute W_R mass limits



$$M_{W_R} > 9.38\,(8.87)\,\mathrm{TeV} \text{ for NH (IH) at } M_N \simeq 500\,\mathrm{GeV}$$

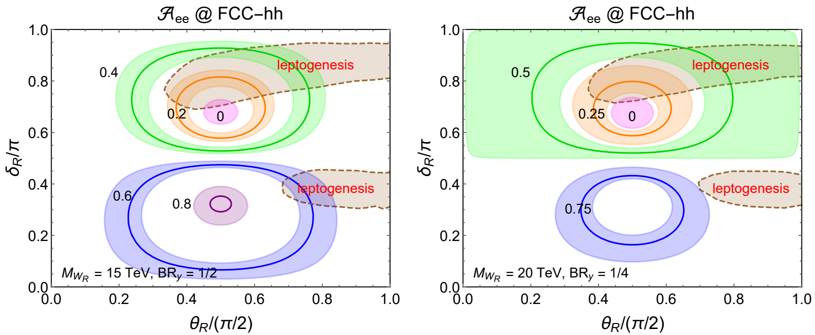
Leptogenesis lmits on W_R mass depend on RHN masses as well as active neutrino data and other parameters.

Leptogenesis limits on θ_R & δ_R



The neutrino data within their 2σ ranges, and $M_N = 1$ TeV
$\Delta M_N = \Gamma_{\rm avg}/2$ to maximize the CP asymmetry.

Testing leptogenesis @ colliders



Other methods to measure RHN CPV and test leptogenesis at colliders:

- Model-independent analysis of LNV signals $pp \to \ell^\pm \ell^\pm jj$ [Deppisch, Harz, Hirsch, '13]
- LNV decays of right-handed doubly-charged scalar [Vasquez, '14]
- The decays $N \to \ell^\pm H^\mp$ ($H^\pm$ being charged mesons) [Caputo, Hernandez, Kekic, Lopez-Pavon & Salvado, '16]
- Heavy-light neutrino mixing at future lepton colliders [Antusch, Cazzato, Drewes, Fischer, Garbrecht, Gueter, Klaric, '17]

Conclusion

- The mixing and CP violation in the RHN sector of TeV-scale left-right models can be directly probed at future high-energy hadron colliders, by measuring the same-sign charge asymmetries (SSCAs).
- In the case with only $N_{e,\mu}$, the $e^{\pm}\mu^{\pm}$ channel can be used to measure the CP phase δ_R, which is independent of the RHN mixing angle; using the channels $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, one can then determine the mixing angle θ_R.
- The future 100 (27) TeV collider could probe the RHN mixing and CPV, for W_R mass up to 26 (7.2) TeV.
- TeV-scale resonant leptogenesis can be directly tested at future hadron colliders by measuring the SSCAs.
- There is an absolute lower bound around 9 TeV on the W_R boson mass to make leptogenesis work in the case with effectively only two RHNs.

Thank you very much!

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Absolute W_R mass limit

- In the large M_N limit, the dependence is respectively (for the 2-body decays we have taken into account also the dependence $M_D \propto M_N^{1/2}$)

$$\Gamma(N \to \ell q \bar{q}') \propto M_N^5 / M_{W_R}^4 \,, \quad \Gamma(N \to L\phi) \propto M_N^2 \,.$$

  When M_N gets larger, the 3-body width grows faster than the 2-body decays, therefore the W_R mass has to be larger to make leptogenesis work.

- When RHN masses get smaller $\downarrow$ ($\lesssim$ 500 GeV),

$$K_{\rm eff} \uparrow, \ \ d_i \downarrow, \ \ \varepsilon_{i\alpha} \uparrow \ \Rightarrow M_{W_R} \text{ limits } \uparrow$$