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Testing Leptogenesis at the LHC and Future Muon Colliders: a Z' Scenario

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Work in collaboration with **Ke-pan Xie**

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Outline

1. Introduction
- Baryon Asymmetry of the Universe
- Orgin of the Neutrino Masses

2. Model

3. Boltzmann Equations During the Early Universe

4. Collider Signatures

5. Sensitivities

6. Conclusion

Baryon Asymmetry of the Universe

$$\frac{n_{\Delta B}}{s} \approx (8.59 \pm 0.11)\times 10^{-11}$$

from Planck satellite [1]

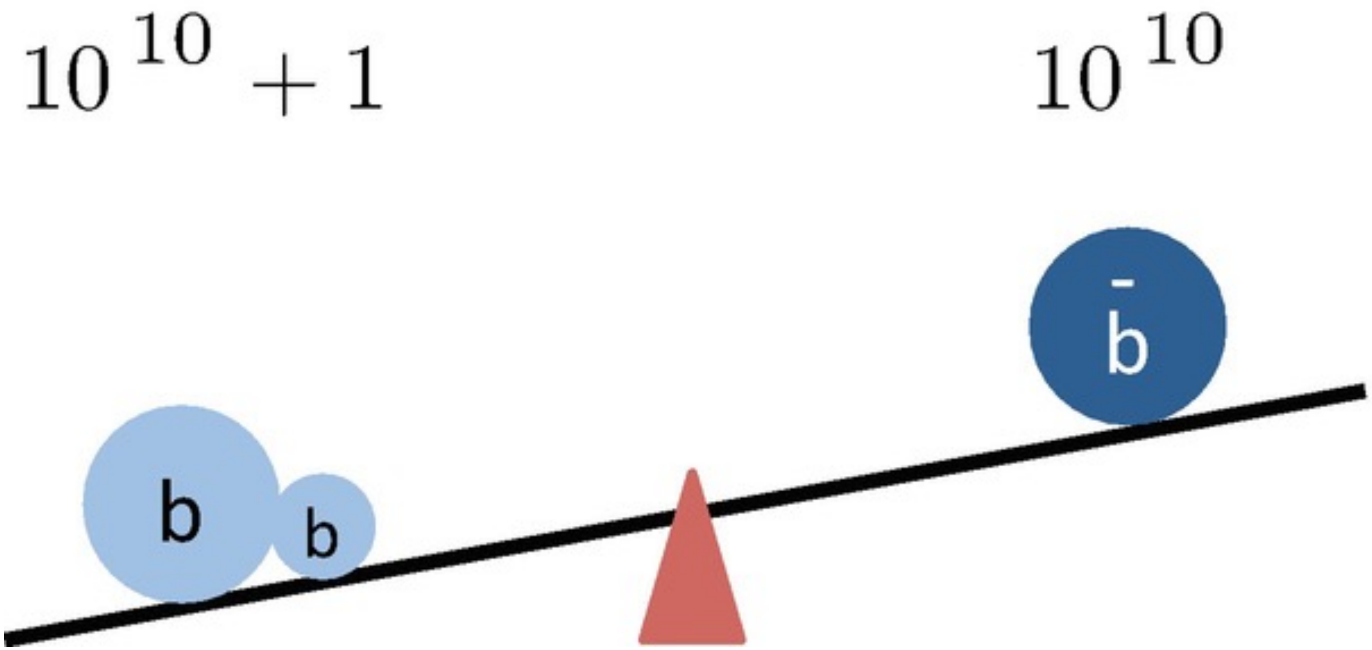


Figure from Kaori Fuyuto [2]

Baryon Asymmetry of the Universe

Sakhorov's criteria

1. Baryon number violating process,

   Generate $n_{\Delta B}$.

   Triangle Anomoly

2. C and CP violations,

   $\Gamma(X \to Y + b) \neq \Gamma(\overline{X} \to \overline{Y} + \overline{b})$*, L and R.*

   CKM

3. Out of equilibrium.

   $\Gamma(X \to Y + b) \neq \Gamma(Y + b \to X)$.

   Electroweak phase transition

Way too small to explain the observed BAU within the SM. **We need new physics!**

Baryon Asymmetry of the Universe

Potential solutions:

1. GUT baryogenesis

2. Electroweak baryogenesis,

3. The Affleck-Dine mechanism

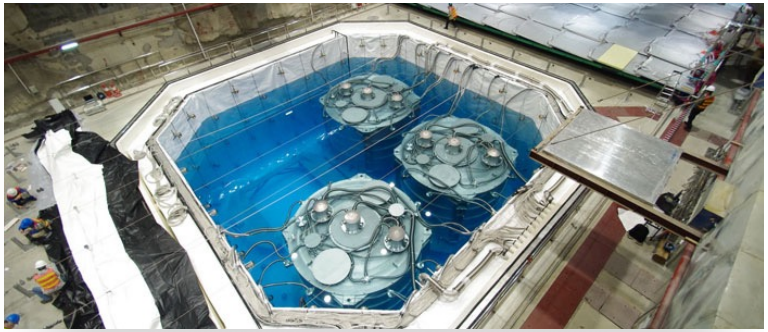
4. Leptogenesis

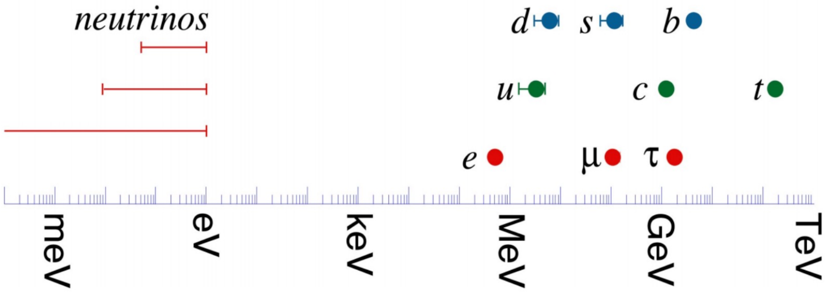
We focus on the **leptogenesis** due to the **neutrino mass** problems.

Origin of the Neutrino Masses

$$\sum m_{\nu} \lesssim 0.12\ eV$$

from Planck satellite [1]





https://physicsworld.com/a/daya-bay-nails-neutrino-oscillation/

From Hitoshi Murayama

Origin of the Neutrino Masses

Seesaw mechanism

$$L \supset -y_D \overline{l_L} \widetilde{H} \nu_R - M_R \overline{\nu_R{}^c} \nu_R$$
$$M = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$
$$m_1 \approx \frac{-M_D^2}{M_R}, m_2 \approx M_R.$$

The lightness of the observed neutrinos is explained by heavy right-handed neutrinos, with $M_R \approx 10^{14}$ GeV to make y_D natural. **Not required by the inverse seesaw.**

Additional CP violations can exists in the **neutrino mass matrix.**

Leptogenesis

BAU from neutrino!

1. Lepton number is violated within the neutrino masses terms.

2. **Additional CP violations** can exists in the **neutrino mass matrix.**

3. Right-handed neutrinos decay out of equilibrium potentially.

And EW sphaleron to transfer $n_{\Delta L}$ into $n_{\Delta B}$ during EW phase transition,

$$Y_B = \frac{28}{79} Y_{B-L}$$

Leptogenesis

Main ideas

$$Y_{\Delta B} \simeq \frac{135\zeta(3)}{4\pi g_*} \sum_{\alpha} \epsilon_{\alpha\alpha} \times \eta_{\alpha} \times C$$

BAU is generated mainly by the lightest RH neutrinos, N_1.

$\frac{135\zeta(3)}{4\pi g_*} \sim 10^{-3}$ is the equilibrium N_1 number density by entropy.

$\epsilon_{\alpha\alpha}$ is the CP asymmetry in N_1 decay.

η_{α} describe the efficiencies, including the production and washout effects.

Leptogenesis

$\epsilon_{\alpha\alpha}$ is the CP asymmetry in N_1 decay,
comes from the interference between the tree-level and one loop amplitude.

Hierarchical RH neutrinos,

$\epsilon \lesssim 10^{-15} M_{N_1}$, $Y_{\Delta B} \simeq 10^{-3} \times \epsilon \times \eta \simeq 10^{-10}$.

As $\eta \sim 0.1, \epsilon \simeq 10^{-6}$, so $\boldsymbol{M_{N_1} \geq 10^9}$**GeV**.

Davidson-Ibarra Bound, no possible collider signatures.

Resonant leptogenesis (what we focus on)

if **at least two of the RH neutrinos masses are degenerate**, as $\Delta M \lesssim \Gamma$.

$\epsilon \lesssim \frac{1}{2}$, only needs $\boldsymbol{M_{N_1} \geq T_{sph} \approx 130}$ **GeV**.

B-L Model

Natural Seesaw mechanism if B-L number is gauged

$$M_R = y_M x$$

Where x is the vev of the B-L Higgs. RH neutrinos masses are generated via the spontaneous symmetry breaking of the $U(1)_{B-L}$.

Additional ***Z'* gauge boson** might **interfere the leptogenesis via the scatterings**.

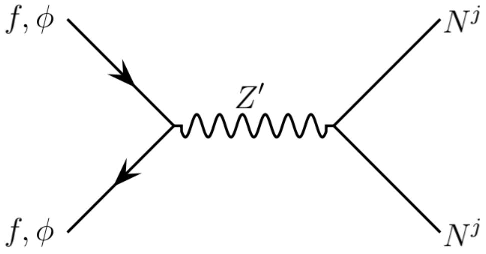


Figure from Ref. [3]

Boltzmann Equations

Corrections on the Boltzmann equations,

$$\frac{s_N H_N}{z^4}\frac{dY_N}{dz} = -\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\left(\gamma_D + 2\gamma_{h,s} + 4\gamma_{h,t}\right)$$

$$-\left(\frac{Y_N^2}{(Y_N^{eq})^2} - 1\right)2\gamma_{Z'},$$

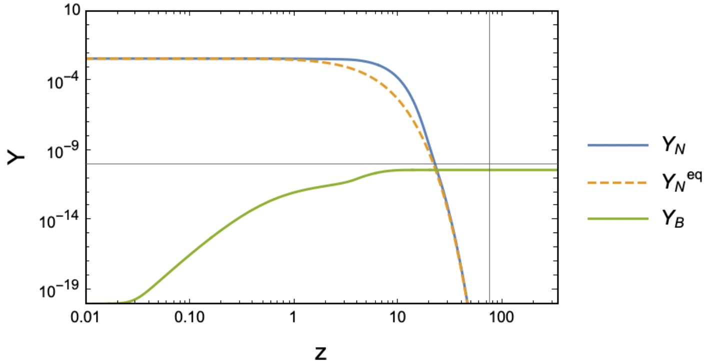
$$\frac{s_N H_N}{z^4}\frac{dY_{B-L}}{dz} = -\epsilon\left(\frac{Y_N}{Y_N^{eq}} - 1\right) - \frac{Y_{B-L}}{Y_l^{eq}}\left(\frac{1}{2}\gamma_D + \right.$$

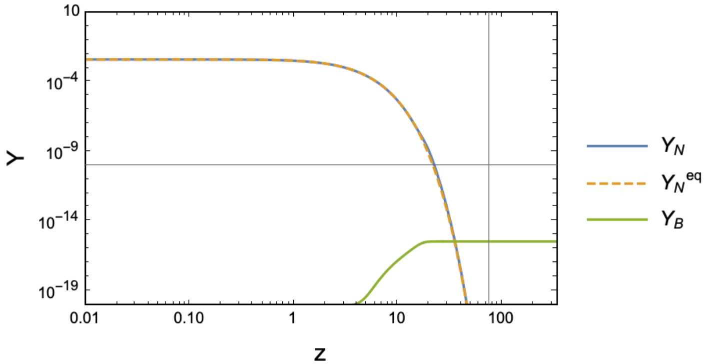
$$\left. 2\left(\gamma_{N,s} + \gamma_{N,s} + \gamma_{h,t}\right) + \frac{Y_N}{Y_N^{eq}}\gamma_{h,s}\right),$$

$$Y_{B-L} \equiv \frac{1}{2}(Y_l - Y_{\bar{l}}).$$

BAU and CP Violations

The scattering mediated via Z'
makes the N **closer to the equilibrium**





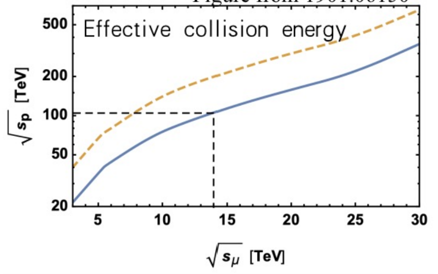
The BAU is diluted due to the scatterings.
Large CP violation in need!

Signatures at Colliders

Muon colliders

Precision and energy frontier!

Figure from 1901.06150



Compared to the e^+e^- machine:

Synchrotron radiation is suppressed by 10^9, hence the collision energy can reach O(10) TeV;

Also very clean, as long as the beam-induced-background is controllable (main challenge).

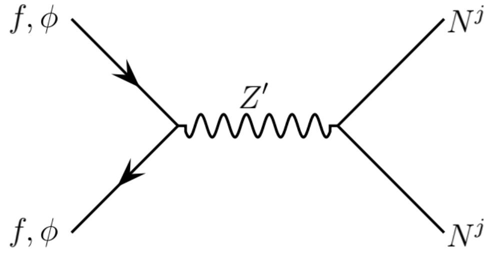
Compared to the *pp* machine:

The entire collision energy can be used to probe hard process;

Much cleaner due to the small QCD background.

Signatures at Colliders

The same processes are detectable at colliders.

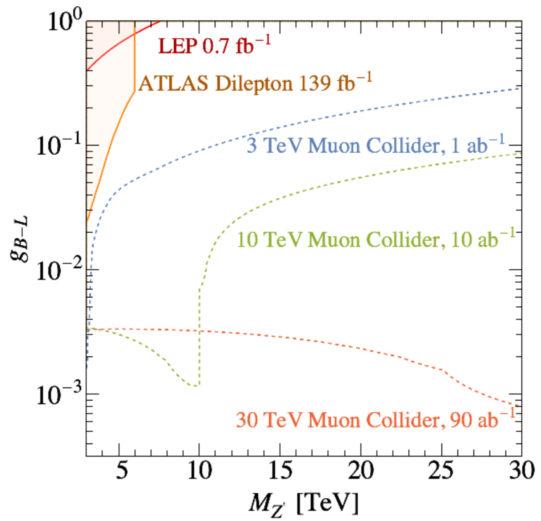


corresponds to $pp(\mu\mu) \rightarrow Z'(\gamma) \rightarrow NN$

The CP violations can be measured by the **same-sign dilepton** signatures from the N decays.

Signatures at Colliders

Projections on the **sensitivities of Z'**



HL-LHC should be less than one magnitude better the current LHC.
Muon colliders can push the sensitivities to heavier Z' and weaker couplings (g_{B-L}).
We focus on $\boldsymbol{M_{Z'} > 6}$ **TeV**, and fix $\boldsymbol{g_{B-L} = 0.8}$ as our benchmarks to get maximal number of RH neutrinos.

Signatures at Colliders

Same-sign dileptons from RH neutrinos decay

$$pp(\mu\mu) \to Z'(\gamma) \to NN \to l^{\pm}l^{\pm} + W^{\mp}W^{\mp}(\text{jets})$$

$$BR(N \to l^{+}W^{-}) \approx 25\% \text{ for } \epsilon \sim 0$$

CP violations from the final states

$$\epsilon = \frac{\Gamma(N \to l^{+}W^{-}) - \Gamma(N \to l^{-}W^{+})}{\Gamma(N \to l^{+}W^{-}) + \Gamma(N \to l^{-}W^{+})}$$

The limits are put assuming the number of signal events follows a **Poisson distribution**.

We only focus on the N interacts with the **electrons**, and assume other Ns' contribution to the BAU is subdominant. (Discussions on the other Ns can be seen at Ref. [4])

Signatures at Colliders

Backgrounds

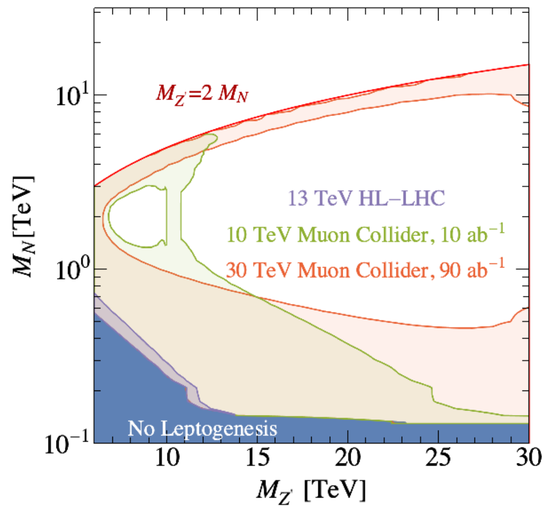
mainly arise from leptonic final states with charge misidentification. The rate is ~0.1% at the current LHC.

LHC	Trigger cut [fb]	Same-sign lepton [fb]	W-jet [fb]
Signal	$\sim 10^{-3}$	$\sim 10^{-3}$	$\sim 10^{-4}$
$t\bar{t}$	$\sim 10^{-4}$ $(*)$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$W^\pm W^\pm jj$	$\lesssim 10^{-2}$	$\lesssim 10^{-4}$	$\lesssim 10^{-7}$
10 TeV muon collider	**Trigger cut [fb]**	**Same-sign lepton [fb]**	**W-jet [fb]**
Signal	~ 1	~ 1	$\sim 10^{-1}$
$\mu^+\mu^- \to e^+e^-W^+W^-$	$\sim 10^{-2}$	$\sim 10^{-5}$	$\sim 10^{-6}$
$\mu^+\mu^- \to e^+e^-W^+W^-\gamma/Z$	$\sim 10^{-2}$	$\sim 10^{-5}$	$\sim 10^{-6}$
$\mu^+\mu^- \to W^+W^-jj$	$\sim 10^{-1}$	$\sim 10^{-6}$	$\sim 10^{-9}$

Mistag rate 5% for QCD jets faking W-jets.
$t\bar{t}$ is further required to have $M_{t\bar{t}} > 6$ TeV
Clean after cuts.

Sensitivities of the Leptogenesis at Colliders

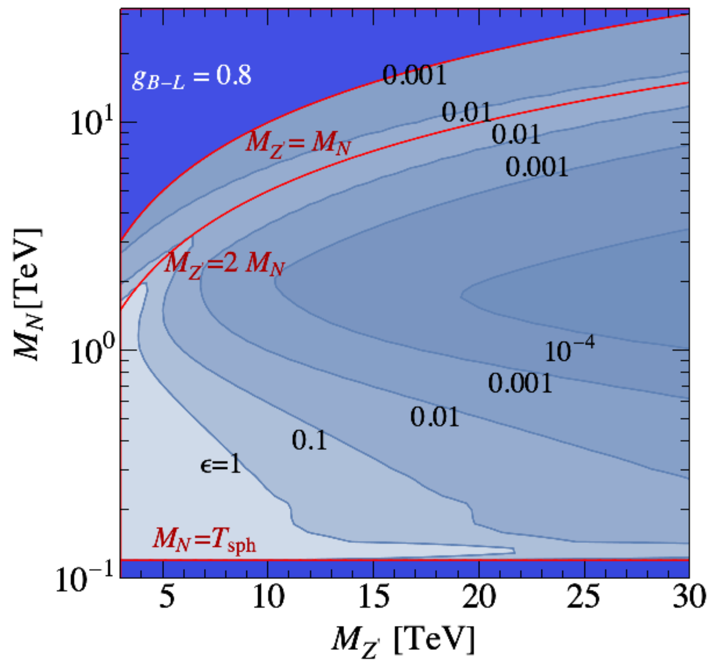
HL-LHC has merely no sensitivities



10 TeV muon collider can test leptogenesis with $M_{Z'} \lesssim 30$ TeV.

30 TeV muon collider can test leptogenesis with $M_{Z'} \lesssim 100$ TeV potentially.

BAU and CP Violations



Fixed M_N, $\quad M_{Z'}\uparrow \rightarrow\ \sigma_{Z'}\downarrow \rightarrow \eta \uparrow \rightarrow \epsilon \downarrow$

Fixed $M_{Z'}$, $A.\ M_N \uparrow \rightarrow\ \Delta t \uparrow \rightarrow \eta \uparrow \rightarrow \epsilon \downarrow$

$B.\ M_N \uparrow \rightarrow \boldsymbol{Washout} \uparrow \rightarrow \eta \downarrow \rightarrow \epsilon \uparrow$

Larger CP violations in need to compensate the inefficiencies due to the scatterings, and $\epsilon \gtrsim 1$ is **forbidden**.

Conclusion

In this work

- Derive the CP violations ϵ within a Z' scenario and resonant leptogenesis, via solving Boltzmann Equations.
- Obtain the sensitivities of CP violations ϵ at the HL-LHC and muon colliders via same-sign dilepton signals.
- Testing the resonant leptogenesis at colliders by comparison.

Conclusion

- Leptogenesis is the natural solution to the BAU problem, once the origins of the neutrino masses are considered.
- Resonant leptogenesis can be tested at colliders.
- U(1) gauge bosons lead to additional RH neutrinos pair scatterings, might dilute the BAU, larger CP violations in need, detectable at colliders.
- Both the HL-LHC and muon colliders can test the resonant leptogenesis via the same-sign dilepton signatures, while muon colliders show much better sensitivities.

References

[1] Planck Collaboration, Astron.Astrophys. 594 (2016), A13

[2] Kaori Fuyuto, PhD Nagoya U.

[3] Michael Plumacher, Z.Phys.C 74 (1997), 549-559.

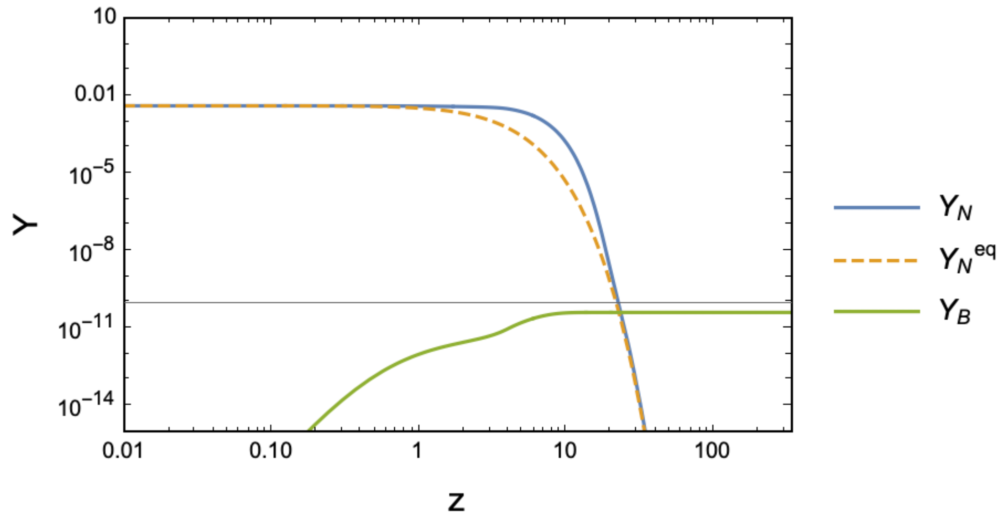
[4] Satoshi Iso, Nobuchika Okada, Yuta Orikasa, Phys.Rev.D 83 (2011), 093011.

[5] Steve Blanchet, Z. Chacko, Rabindra N. Mohapatra, Phys.Rev.D 82 (2010), 076008.

Leptogenesis

Precise evolutions need solving Boltzmann equations

Results of one example



Shapes controlled by m_N and washout parameters, including **thermal neutrino masses ($\widetilde{m}$),** and **effective neutrino masses (m_*).**

Signatures at Colliders

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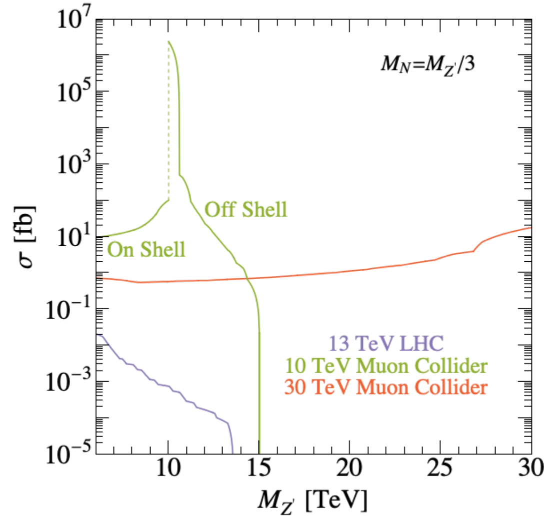
RH neutrinos production via **Z' decays**



Muon colliders has much larger cross section, and can produce RH neutrinos **off-shell**, beyond their collision energies.

Signatures at Colliders

Cuts on the two electrons (Parton)

LHC

$$p_T^e > 100 \text{ GeV}, |\eta_e| < 2.5,$$

Muon colliders

$$p_T^e > 30 \text{ GeV}, |\eta_e| < 2.43.$$

Cuts on the two W-jets (Parton)

LHC

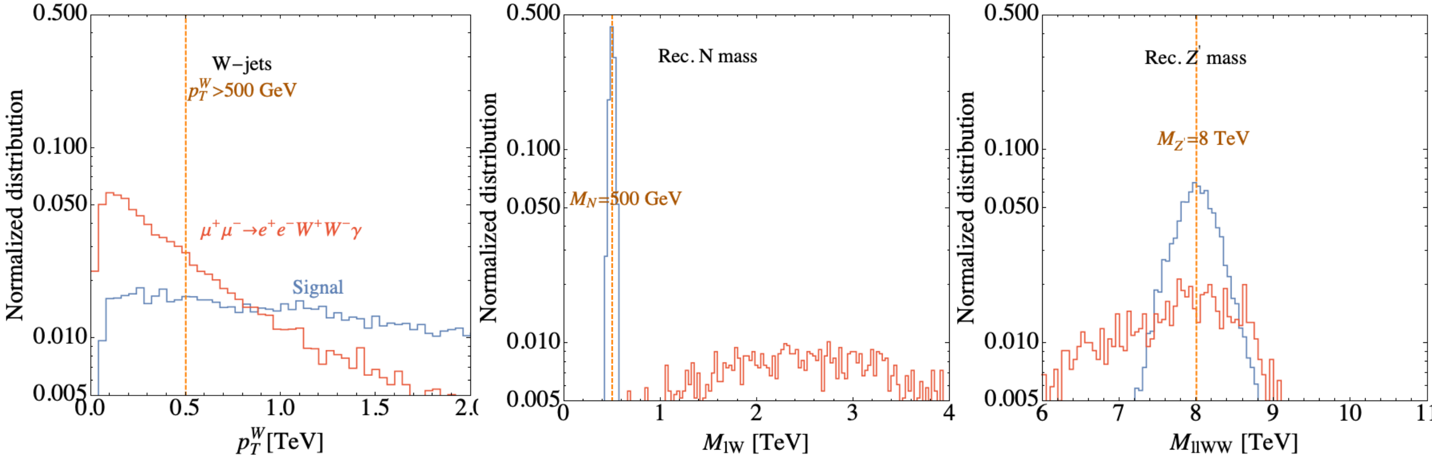
$$p_T^W > 500 \text{ GeV}, |\eta_W| < 2,$$

Muon colliders

$$p_T^W > 500 \text{ GeV}, |\eta_W| < 2.43.$$

Signatures at Colliders

Kinematics at the 10 TeV muon colliders



Excellent separation between signal and background.

Reconstruction on N mass is powerful.