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Revealing the Origin of Neutrino Masses through Displaced Shower Searches in the CMS Muon System

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2407.20676

In collaboration with

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Neutrino Mass

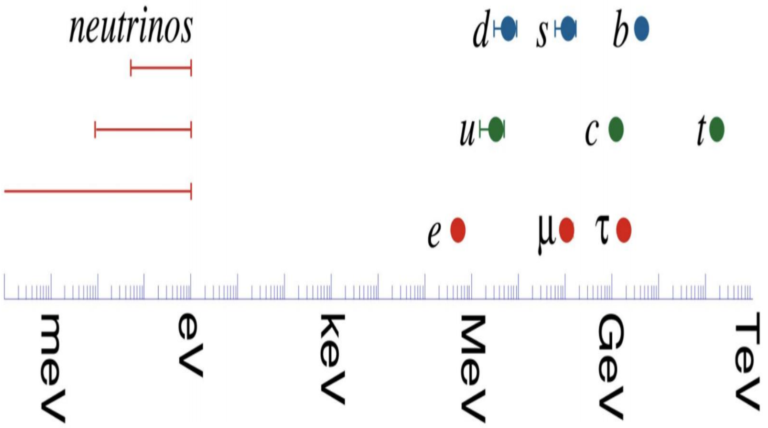


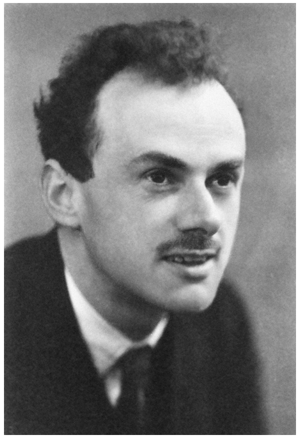
Figure from Hitoshi Murayama

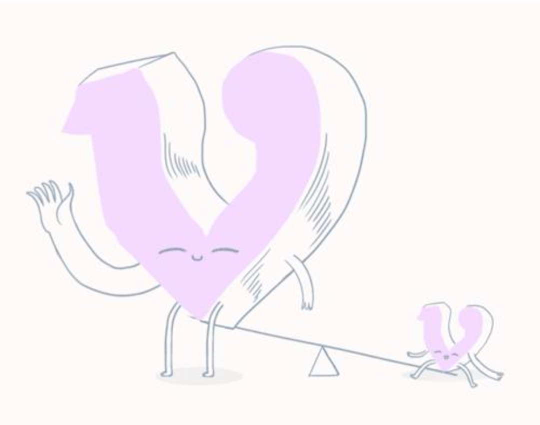
The masses of the neutrinos are much smaller than the other fermions!

Neutrinos are the only neutral fermions.

The nature of the neutrino masses can be different!

Type-I Seesaw Mechanisms





Artwork by Sandbox Studio, Chicago with Ana Kova

$L_{Dirac} = -y\overline{l_L}\tilde{H}\nu_R$ $L_{Majorana} = -M\overline{\nu_R}^c\nu_R$

Tiny Yukawa coupling $\sim 10^{-12}$ for pure Dirac mass!

Can the neutrino masses induced by both?

$$\begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix} \qquad m_1 \approx -\frac{{M_D}^2}{M_R} \sim eV \qquad m_2 \approx M_R \gg GeV$$

Seesaw Mechanism by hand? *υMSM*

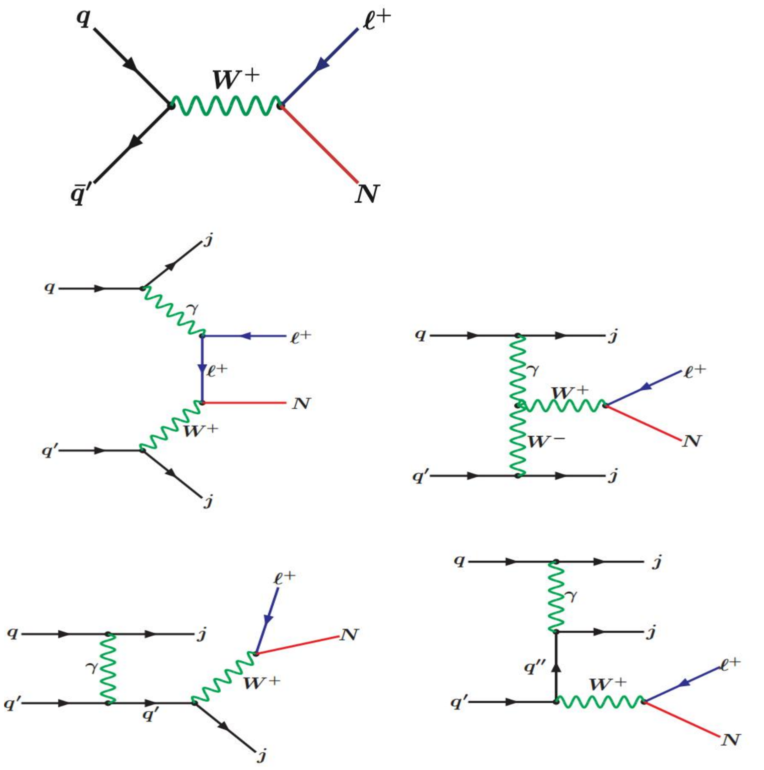
Heavy Neutrino Searches

- GUT points out $M_N \approx \frac{M_D^2}{m_\nu} \sim 10^{14}$GeV

  $y_D \sim 1$
- Leptogenesis favors $M_N \sim 10^9$ GeV
- **Can we still probe heavy neutrinos at colliders?**
- Such heavy degree of freedom leads to non-stable Higgs masses, $M_N < 10^7$ GeV.
- Larger CP violation can be produced if heavy neutrinos are degenerate, or the PMNS has CP violations, i.e. **resonant leptogenesis** or **leptogenesis via oscillations**. $M_N \sim 10^3(1)$GeV.
- The Yukawa couplings can be electron like,

  $y_D \sim 10^{-6}$, $M_N \sim$ 100 GeV
- Inverse seesaw can yield natural Yukawa couplings.
- **Colliders probes of heavy neutrinos are resonable!**

Heavy Neutrino Searches



The main production processes of the heavy neutrinos at the LHC. Figures from P.S.Bhupal Dev, Apostolos Pilaftsis, Un-ki Yang, Phys.Rev.Lett. 112 (2014) 8, 081801.

Our goal is to search the heavy neutrinos colliders!

Within the ***υMSM*** model, the heavy neutrinos can be produced either via the s and t channel.

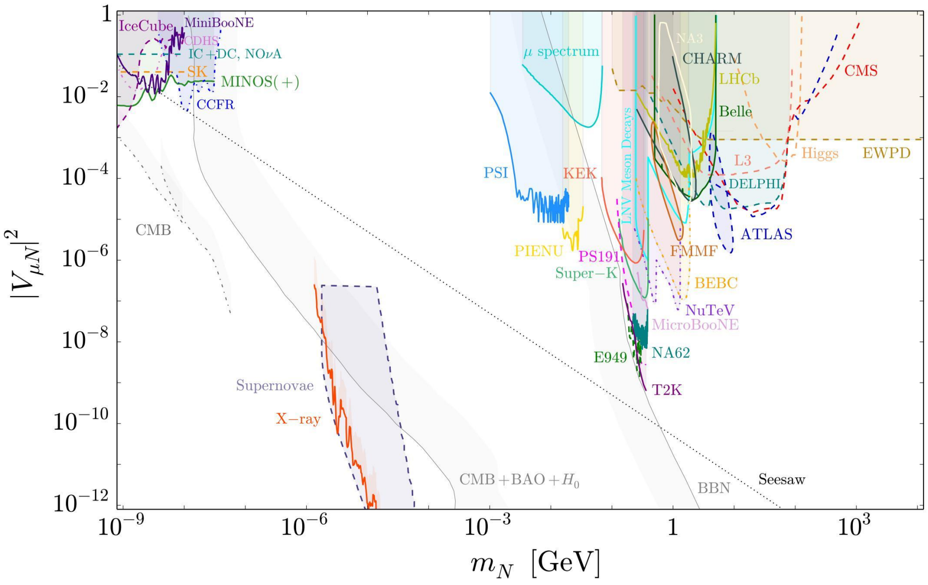
The s channel production from the Drell-Yan processes are the dominant processes for $m_N \leq 1$ TeV, otherwise by the t channel.

Both cannot reach low V_{IN}!

$$\propto V_{IN}^{-2}$$

$$10^7 pb \times V_{IN}^2 < \text{fb}$$

Heavy Neutrino Searches



Limits on the seesaw parameters (m_N, V_{lN}) from the collider searches for heavy neutrinos and other probes. Figure from Patrick D. Bolton, Frank F. Deppisch, P.S. Bhupal Dev, JHEP 03 (2020), 170.

We need to look for other production channels!

Our goal is to search the heavy neutrinos and test the type-I seesaw, the origin of the neutrino masses!

However, direct probes of the heavy neutrinos within the ***υMSM*** model **cannot reach the type-I seesaw** due to the low mixing at the EW scale

$$\begin{bmatrix} v_L \\ v_R \end{bmatrix} = \begin{bmatrix} V_{LL} & V_{RL} \\ V_{LR} & V_{RR} \end{bmatrix} \begin{bmatrix} v \\ N \end{bmatrix}$$

$$V_{lN}^2 \approx \frac{m_v}{mN} < \frac{eV}{GeV} < 10^{-10}$$

Natural Type-I Seesaw

The Majorana mass terms can be generated more naturally by the spontaneous breaking of a $U(1)$ gauge.

$$\mathcal{L} \supset -y_D \overline{l_L} \tilde{H} \nu_R - y_M \bar{\nu}_R^c \chi \nu_R .$$

Therefore, $m_N \approx y_M v_\chi \sim$TeV.

One of the simplest model UV complete and anomaly free model is the $U(1)_{B-L}$ model, other $U(1)$ models such as $U(1)_{L_\mu - L_\tau}$ is also possible.

Baryon and Lepton numbers
Accidental symmetries in the SM, can be broken by anomalies

B-L **number**
Anomaly free

$U(1)_{B-L}$ model

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
R. N. Mohapatra and R. E. Marshak
Phys. Rev. Lett. 44 (1980) 1316

Additional scalar singlet χ with the scalar potential

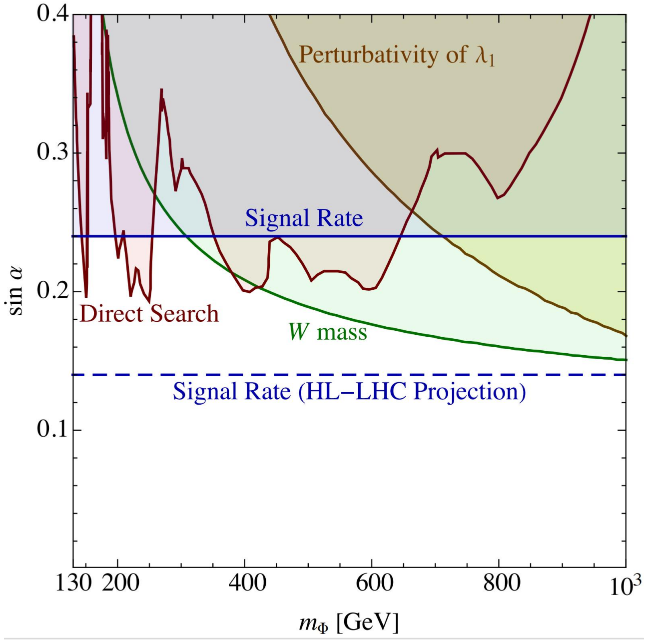
$$V(H,\chi) = m^2 H^+ H + \mu^2 |\chi|^2 + \lambda_1 (H^+ H)^2 + \lambda_2 |\chi|^4$$

Additional $B-L$ gauge boson Z' with interactions

$$\mathcal{L} \supset \sum i g_{B-L} Y_{B-L} Z' f \bar{f}$$

The $B-L$ gauge interactions can have suppressed kinetic mixings to the hypercharge in the loop level.

Experimental limits on Higgs mixing



Higgs mixing

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} H \\ \chi \end{bmatrix}$$

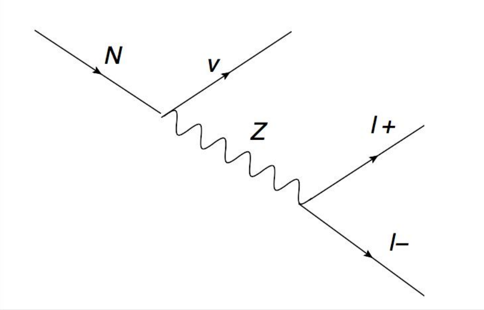
$$\lambda_{h_x XX} = \sin\theta(\cos\theta)\lambda_{HXX}$$

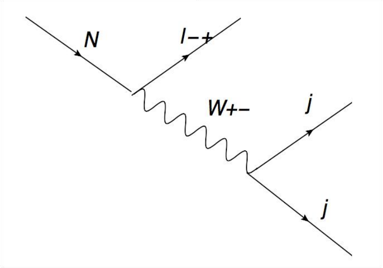
$$\sigma_{h_x} = \sin^2\theta(\cos^2\theta)\sigma_{h_{SM}}$$

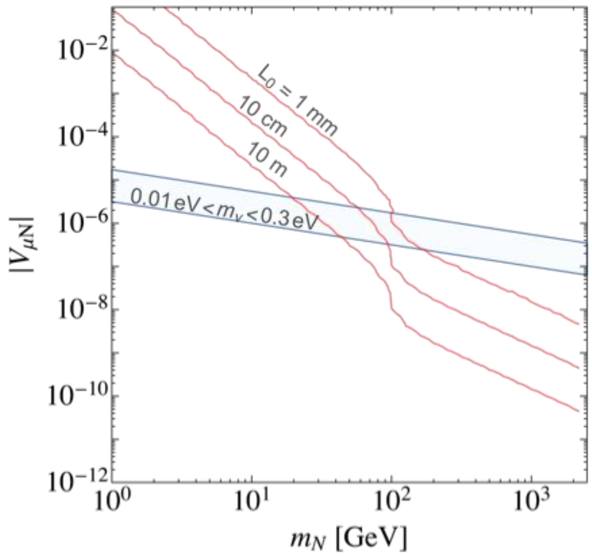
The most stringent limits on heavy scalar is the W boson mass measurement.

Still have room for production of the additional scalars at colliders!

Heavy Neutrino, a Natural LLP







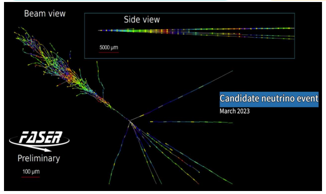
At the EW scale, the **heavy neutrinos are natural LLPs** predicted by the type-I seesaw.

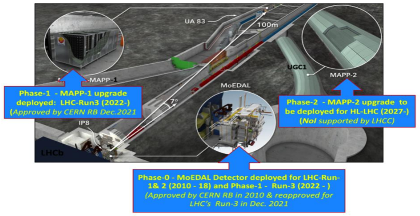
$$L \approx 3\ cm \times (\frac{10^{-6}}{V_{\mu N}})^2 \times (\frac{100\ GeV}{M_N})^5.$$

$$V_{lN}^2 \approx \frac{m_\nu}{mN} < \frac{eV}{GeV} < 10^{-10}.$$

LLP detectors at the LHC

2019.03	2021	2022	2024.03	2031
FASER Approved	FASER Run MoEDAL-MAPP Approved	MOEDAL-MAPP Run	SHiP Approved	SHiP Run

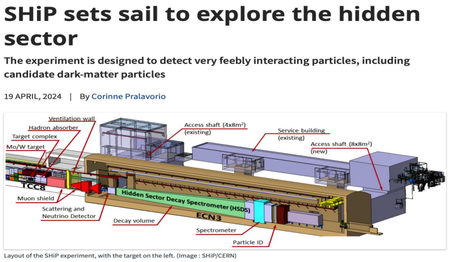




Phase-1 - MAPP-1 upgrade deployed: LHC-Run3 (2022-)
(Approved by CERN RB Dec.2021

Phase-2 - MAPP-2 upgrade to be deployed for HL-LHC (2027-)
(Not supported by LHCC)

Phase-0 - MoEDAL Detector deployed for LHC-Run-1& 2 (2010 - 18) and Phase-1 - Run-3 (2022 -)
(Approved by CERN RB in 2010 & reapproved for LHC's Run-3 in Dec. 2021



SHiP sets sail to explore the hidden sector

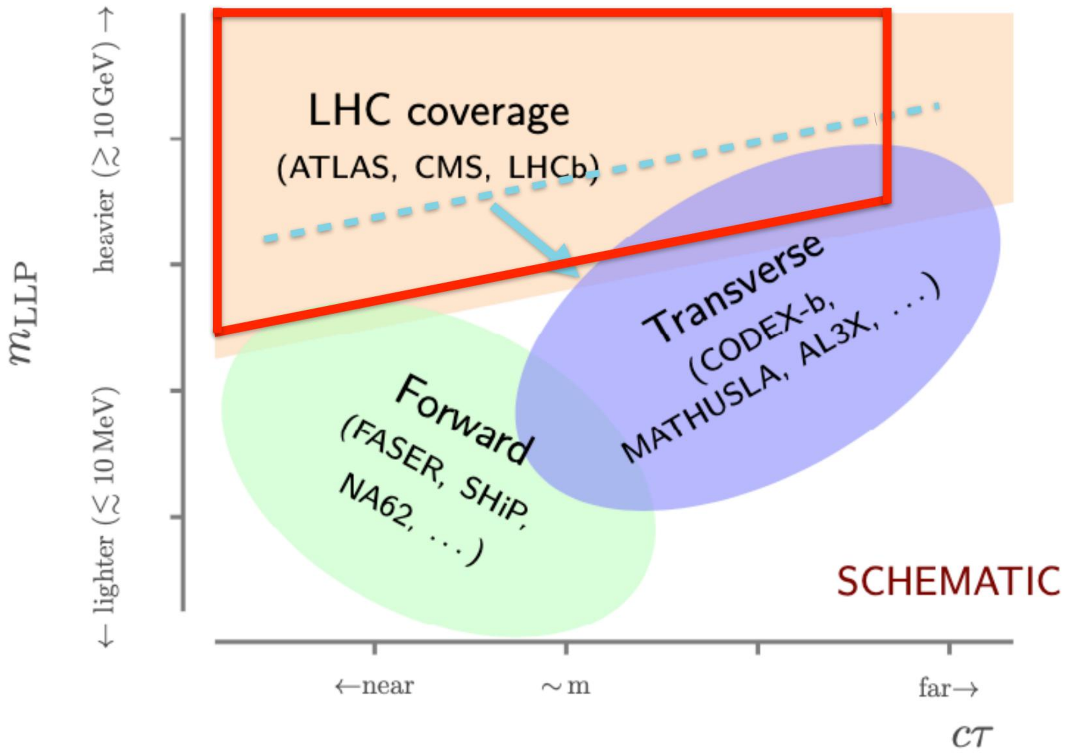
The experiment is designed to detect very feebly interacting particles, including candidate dark-matter particles

19 APRIL, 2024 | By Corinne Pralavorio

Layout of the SHiP experiment, with the target on the left. (Image : SHiP/CERN)

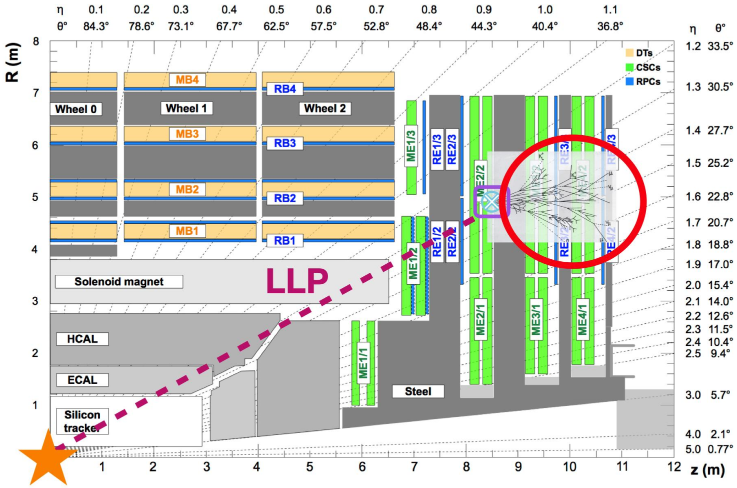
- LLP detectors include CODEX-b, FASER, FACET, SHiP, MoEDAL-MAPP and MATHUSLA, etc.
- **FASER, MoEDAL-MAPP collecting data since Run3,**
- **SHiP approved**, run from 2031

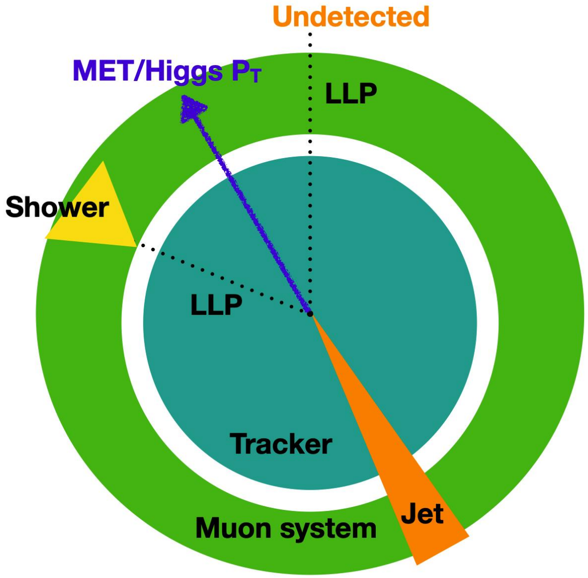
LLP Search at the LHC



- CMS/ATLAS, LHCb can probe **heavy** LLPs, with **high coverage, high background**
- Forward LLP detectors for **light** LLPs, **high events** from meson decay
- Transverse LLP detectors can suffer in **low coverage, low background**

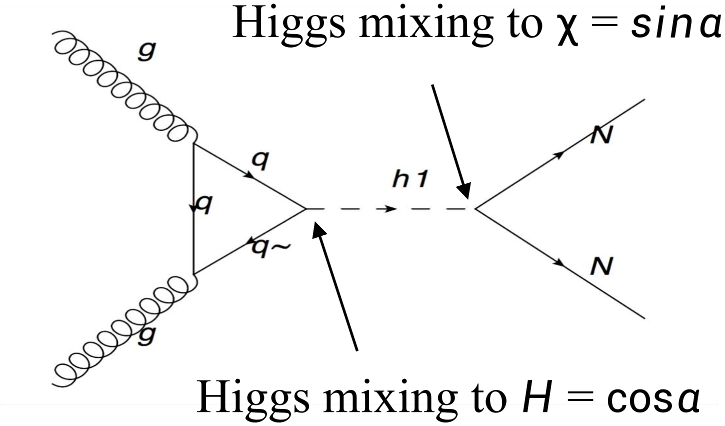
CMS Muon System for LLP





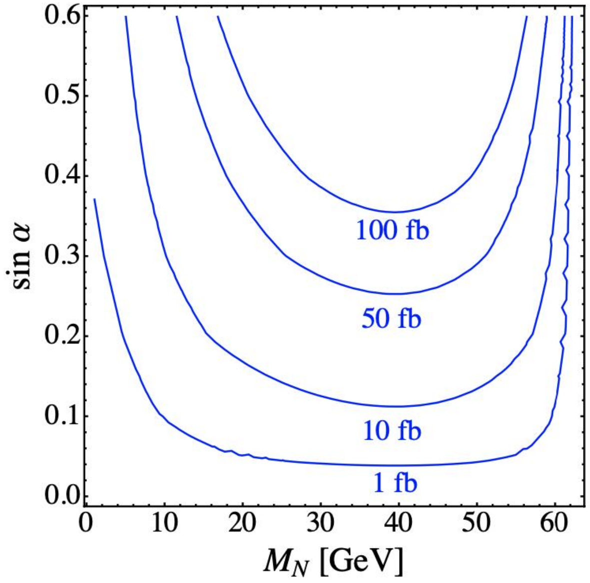
- We focus on heavy *N* as LLP
- LLP can also be searched with **CMS muon system** since **Run2**.
- No Dedicated trigger, require **high MET** to trigger, MET > 200 GeV
- New trigger since Run3, higher efficiency.

Higgs to pairs of *N* at the LHC



Higgs mixing to χ = *sinα*

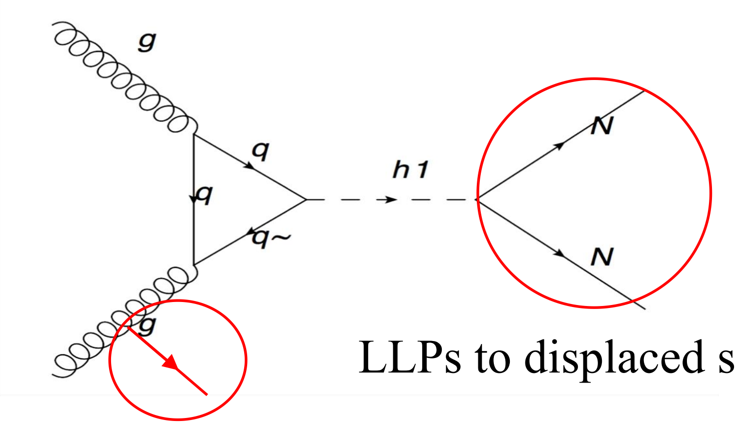
Higgs mixing to *H* = cos*α*



Heavy neutrinos can be pair-produced as exotic Higgs decays if the mixing is appreciable.

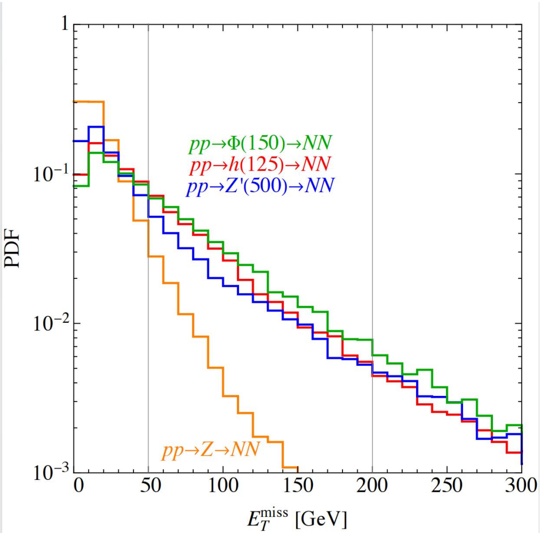
This channel can still have 10s fb of cross section.

Higgs to pairs of *N* at the LHC



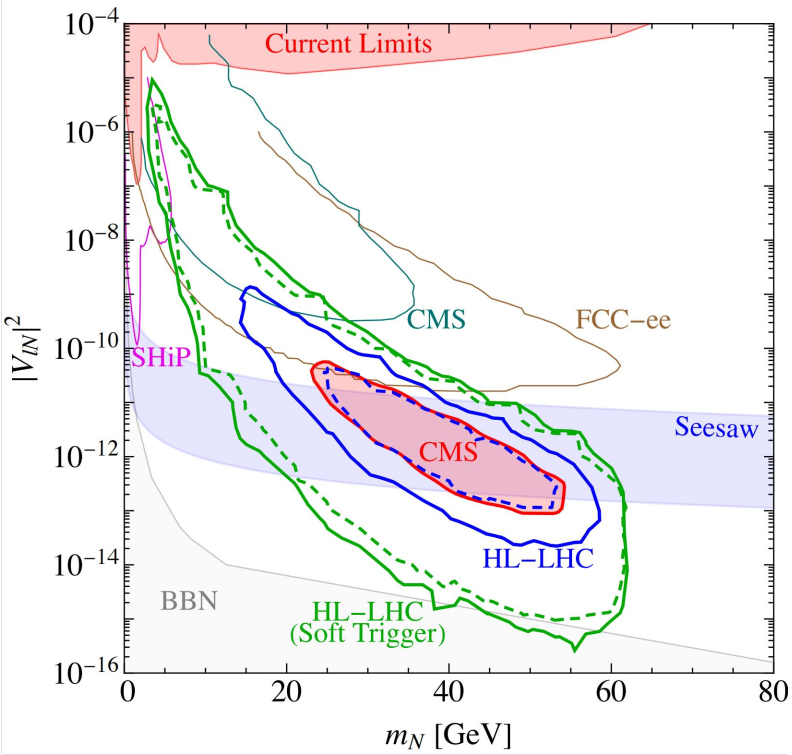
LLPs to displaced shower

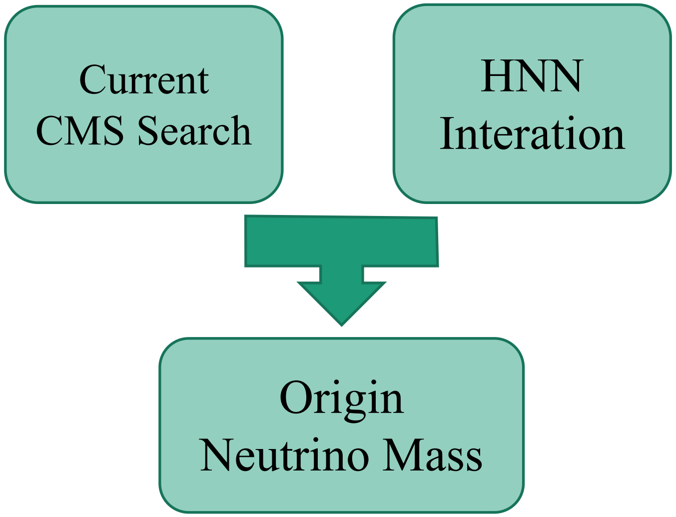
ISR jets to **trigger** MET



- ISR jets from **gluon fusion** to trigger MET
- **Low** efficiency from **W/Z** decays.
- **RHNs** as **LLP**s to **displaced shower** signals at CMS muon system.

Sensitivity





Current CMS Search

HNN Interation

Origin Neutrino Mass

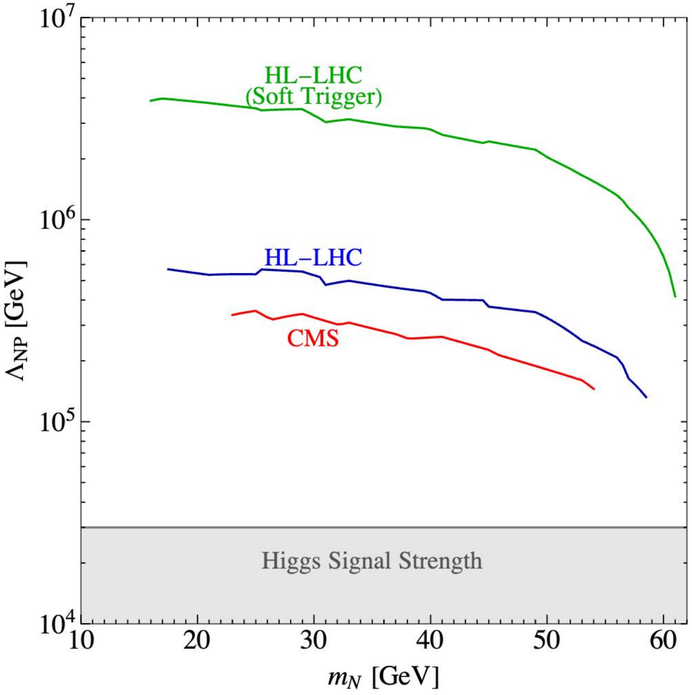
- Higgs mixing at current limits, only require $\sin\alpha > 0.02$ (HL-LHC)
- **Existing** CMS Search **can test Seesaw**!
- Dedicated trigger since Run3, **better** sensitivity expected
- **$Br(H \rightarrow NN) \approx 10^{-5}$** is required to test seesaw.

EFT

- More General Description in **N_RSMEFT(0806.0876).**

$$\mathcal{L}_5 = \frac{(\alpha_W^\dagger)_{ab}}{\Lambda}(\bar{L}_a\tilde{\phi})(\phi^\dagger \tilde{L}_b^c) + \frac{(\alpha_{N\phi})_{ss'}}{\Lambda}(\phi^\dagger\phi)\,\bar{\nu}_{Rs}\,\nu_{Rs'}^c + \frac{(\alpha_{NB})_{ss'}}{\Lambda}\bar{\nu}_{Rs}\,\sigma^{\mu\nu}\nu_{Rs'}^c\,B_{\mu\nu} + h.c.$$

- Only three in Dim-5
- Weinberg Operator for Neutrino Mass, Dipole for W/Z decay to N



- **Anisimov-Graesser Operator** for HNN
- Current limits from Higgs signal strength (2210.16279, 2304.06772)

$$\Lambda \geq 30 \text{ TeV}$$

- **Large parameter space in EFTs to probe seesaw**
- Limits from this work **surpass** current limits by **more than 10 times**

Leptogenesis to explain the BAU

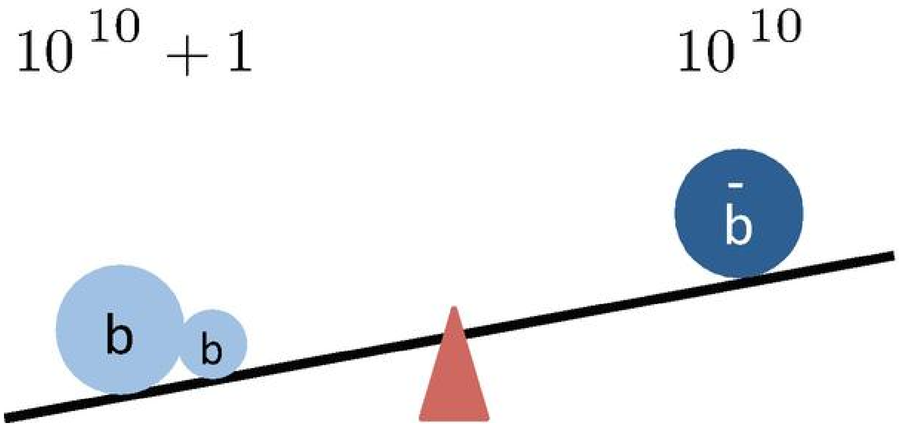


Figure from Kaori Fuyuto

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

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

from Planck satellite and the CMB.

Sakhorov's criteria

1. Baryon number violating process,

2. C and CP violations,

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

3. Out of equilibrium.

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

Leptogenesis to explain the BAU

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,

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

$$Y_B \simeq 10^{-2} \times \epsilon \times \eta$$

- CP Asymmetry
- Thermal efficiency
- Consider $B - L$ gauge boson

Resonant Leptogenesis

- ϵ_{aa} is the CP asymmetry in N_1 decay,
  comes from the interference between the tree-level and one loop amplitude.

- Hierarchical RH neutrinos,
  $\epsilon \lesssim 10^{-15} M_{N_1}$, $Y_{\Delta B} \simeq 10^{-2} \times \epsilon \times \eta \simeq 10^{-10}$.
  As $\eta \sim 0.1, \epsilon \simeq 10^{-7}$, 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**.

.

CP Asymmetry

- ϵ_{aa} is the CP asymmetry in N_1 decay, **without quantum effect**

$$-\epsilon_{i\ell} = \sum_{j\neq i} \frac{\mathrm{Im}\left([\lambda_D^\dagger]_{i\ell}[\lambda_D]_{\ell j}[\lambda_D^\dagger\lambda_D]_{ij}\right) + \frac{M_{N_i}}{M_{N_j}}\mathrm{Im}\left([\lambda_D^\dagger]_{i\ell}[\lambda_D]_{\ell j}[\lambda_D^\dagger\lambda_D]_{ji}\right)}{[\lambda_D^\dagger\lambda_D]_{ii}[\lambda_D^\dagger\lambda_D]_{jj}}\left(f_{ij}^{\mathrm{mix}} + f_{ij}^{\mathrm{osc}}\right),$$

- Yukawa can be expressed by Casas-Ibarra paramterasation.

$$\lambda_D = \frac{1}{v_{\mathrm{EW}}} U\sqrt{\hat{m_\nu}}R^T\sqrt{\hat{M_N}},$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}.$$

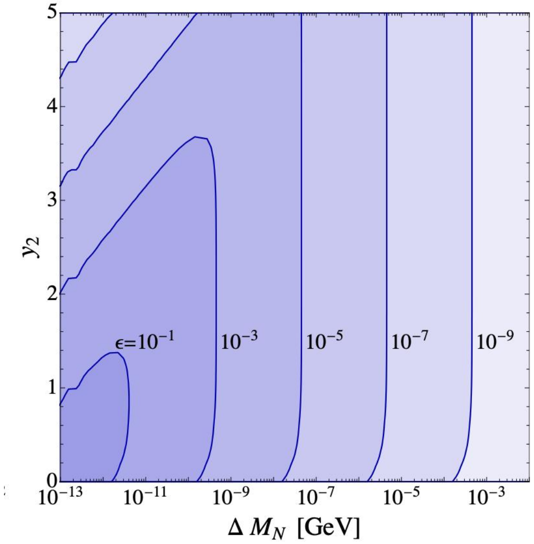
$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\omega_1} & s_{\omega_1} \\ 0 & -s_{\omega_1} & c_{\omega_1} \end{pmatrix} \begin{pmatrix} c_{\omega_2} & 0 & s_{\omega_2} \\ 0 & 1 & 0 \\ -s_{\omega_2} & 0 & c_{\omega_2} \end{pmatrix} \begin{pmatrix} c_{\omega_3} & s_{\omega_3} & 0 \\ -s_{\omega_3} & c_{\omega_3} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

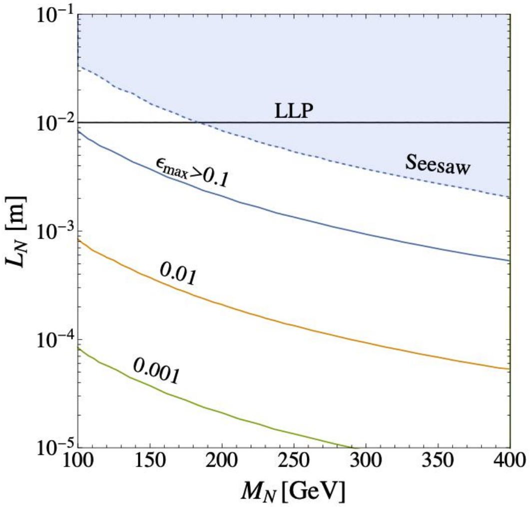
CP Asymmetry

- Connection to seesaw

$$|V|^2 \equiv \Sigma_{i=1,2,\ell=e,\mu,\tau}|V_{\ell N_i}|^2 = \frac{\Sigma_i m_{\nu_i}}{M_N}\cosh(2y_2) \approx 2\Sigma_{\ell=e,\mu,\tau}|V_{\ell N_{1/2}}|^2.$$

- V^2 is tiny from seesaw→LLPs
- Tiny V^2 →tiny y_2
- Large $\epsilon_{\alpha\alpha}$ require tiny y_2
- **Both Leptogenesis and Seesaw prefer *N* as LLPs**





Free Parameters

Consider neutrino oscillation data, -5 parameters

$$\theta_{12} = 33.44^\circ \quad \theta_{13} = 8.57^\circ, \quad \theta_{23} = 49.20^\circ,$$

$$m_{\nu_2} = \sqrt{\Delta m^2_{\rm sol}} = 8.6 \times 10^{-3}\ \text{eV}, \quad m_{\nu_3} = \sqrt{\Delta m^2_{\rm atm}} = 5.0 \times 10^{-2}\ \text{eV}.$$

Take the massless lightest neutrino, decouple the heaviest *N,* -6 parameters

$$\omega_{1,3} = \pi/2,\ \omega_2 = x_2 + i y_2$$

One free parameter rotate away, -1

Consider couplings with $B - L$ gauge boson Z'
add two free parameters

$$m_{Z'}, g_{B-L}$$

Free parameters,

$$3x3x2 - 5 - 6 - 1 + 2 = 8$$

Free Parameters

Benchmark for free parameters

$$M_N = 1 - 1000\ \text{GeV}, \quad \Delta M_N = 10^{-17} - 10^{-4}\ \text{GeV},$$
$$M_{Z'} = 5\ \text{TeV}, \quad g_{B-L} = 0.025, 0.05, 0.15,$$
$$x_2 = \pi/4, \quad y_2 = 0 - 5, \quad \delta = 3\pi/2, \quad \alpha_{23} = \pi.$$

$$U = \begin{pmatrix} 0.825 & 0.545i & 0.149i \\ -0.360 + 0.094i & 0.062 + 0.545i & 0.749 \\ 0.417 + 0.081i & 0.054 - 0.632i & 0.646 \end{pmatrix},$$

$$|V_{\ell N_i}|^2 \approx 10^{-13} \times \frac{100\ \text{GeV}}{M_N}$$
$$\times \begin{pmatrix} |0.59e^{-1.57i}\cosh y_2 + 0.12\sinh y_2|^2 & |0.12e^{1.57i}\cosh y_2 + 0.59\sinh y_2|^2 & 0 \\ |1.20e^{0.3i}\cosh y_2 + 1.28e^{1.29i}\sinh y_2|^2 & |1.28e^{-0.28i}\cosh y_2 + 1.20e^{-1.27i}\sinh y_2|^2 & 0 \\ |1.07e^{-0.4i}\cosh y_2 - 1.14e^{-1.20i}\sinh y_2|^2 & |1.14e^{0.37i}\cosh y_2 - 1.07e^{1.17i}\sinh y_2|^2 & 0 \end{pmatrix}.$$

Thermal Efficiency

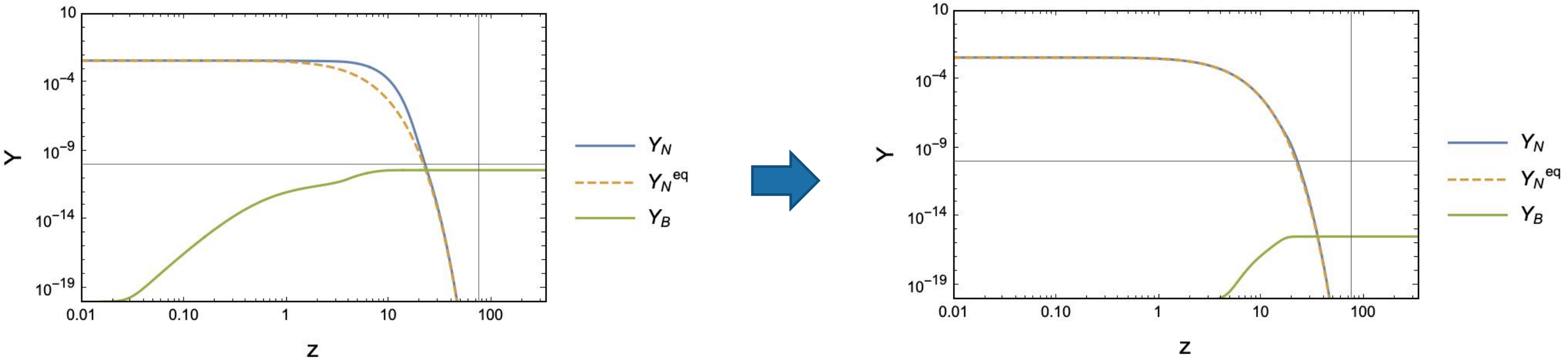
Corrections on the Boltzmann equations,

$$\frac{\mathrm{d}N_{N_i}}{\mathrm{d}z} = -(D(K_i) + S_{h/A})(N_{N_i} - N_{N_i}^{\mathrm{eq}}) - 2\, S_{Z'}/N_{N_i}^{\mathrm{eq}}(N_{N_i}^2 - (N_{N_i}^{\mathrm{eq}})^2) \,,$$
$$\frac{\mathrm{d}N_{\Delta_\ell}}{\mathrm{d}z} = \sum_i \varepsilon_{i\ell}\, D(K_i)\,(N_{N_i} - N_{N_i}^{\mathrm{eq}}) - \sum_i W^0(K_{i\ell}) N_{\Delta_\ell} \,,$$

Large washout from Z' scattering
Thermal efficiency can be analytically expressed

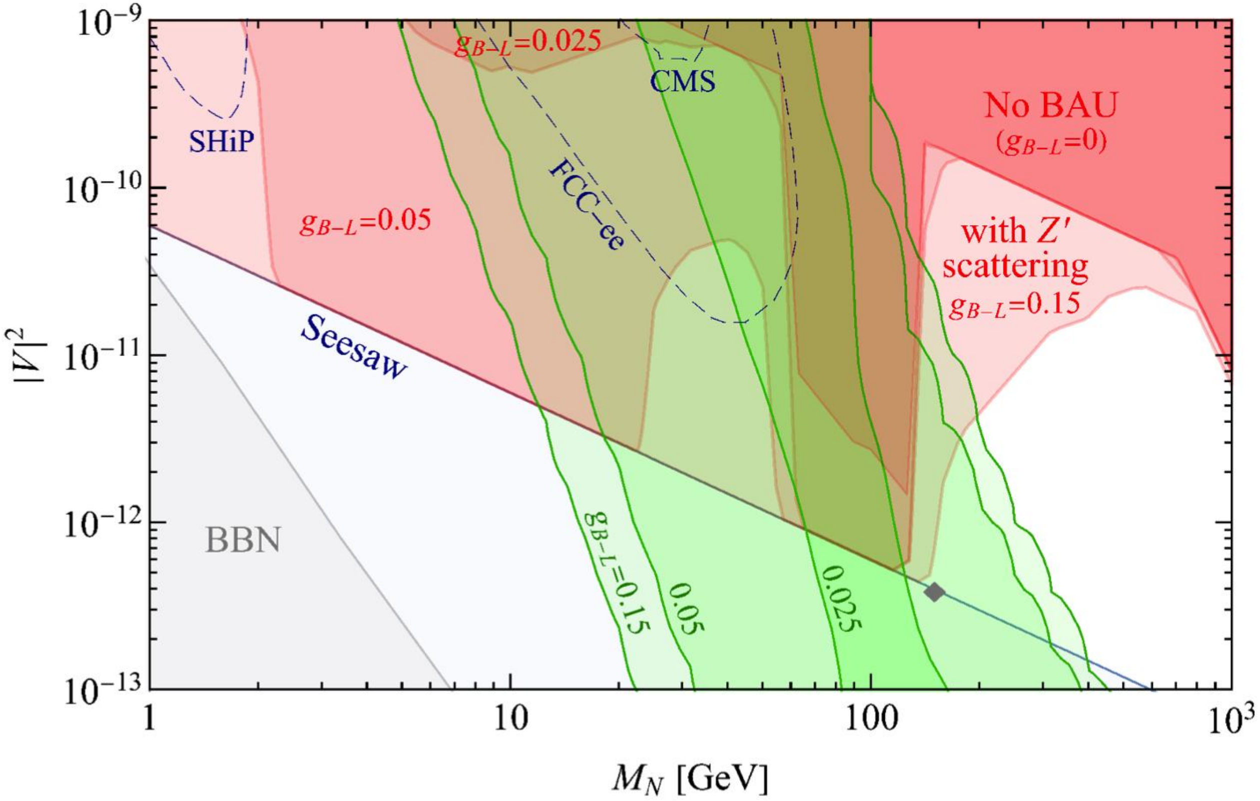
$$\kappa_{i\ell}(z, z_{\mathrm{in}}) \approx \int_{z_{\mathrm{in}}}^{z} \mathrm{d}z' \frac{\mathrm{d}N_{N_i}^{\mathrm{eq}}}{\mathrm{d}z'} \frac{D(K_i, z')}{D(K_i, z') + S_{h/A}(z') + 4S_{Z'}(z')} \times \exp\left[-\int_{z'}^{z} \mathrm{d}z'' \sum_i W^0(K_{i\ell}, z'') \right] ,$$

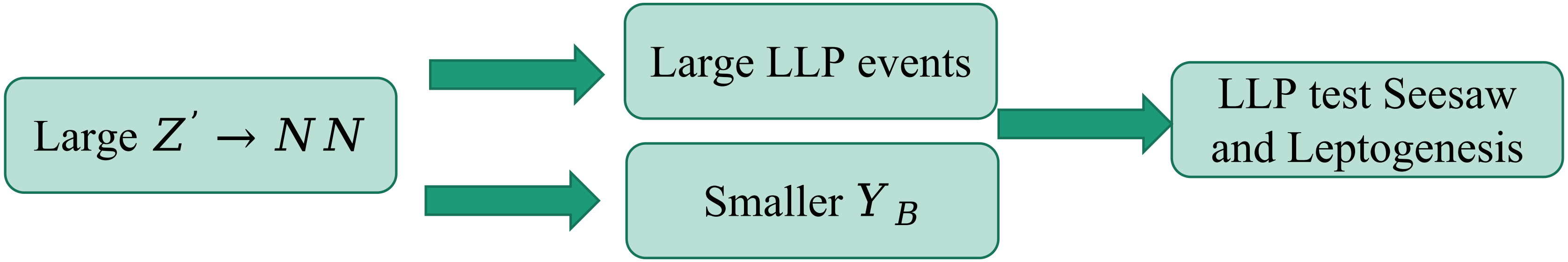
Wash-out from Pair-production



The scattering mediated via Z'
makes the N **closer to the equilibrium.**
The BAU is diluted due to the scatterings.

Test Leptogenesis by LLP searches





Large $Z' \rightarrow N\,N$

Large LLP events

Smaller Y_B

LLP test Seesaw and Leptogenesis

Conclusion

- There are still a lot unknown in the neutrino physics. The origin of the neutrino masses are one of the most interesting.
- Right-handed neutrinos can explain the neutrino masses via the type-I seesaw, and the BAU via the leptogenesis.
- By adding a B-L gauge, the pair-production of right-handed neutrinos can be probed at colliders
- We show **current CMS displaced shower** search can **test seesaw** whenever there is tiny **HNN** interaction
- We show future LLP searches might test **both leptogenesis and seesaw** with **B-L gauge** interactions.