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Heavy neutrinos at the FCC-hh in the $U(1)_{B-L}$ model

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Work in collaboration with **Suchita Kulkarni, Frank F. Deppisch**
Eleventh workshop of the LLP Community

Neutrino Mass

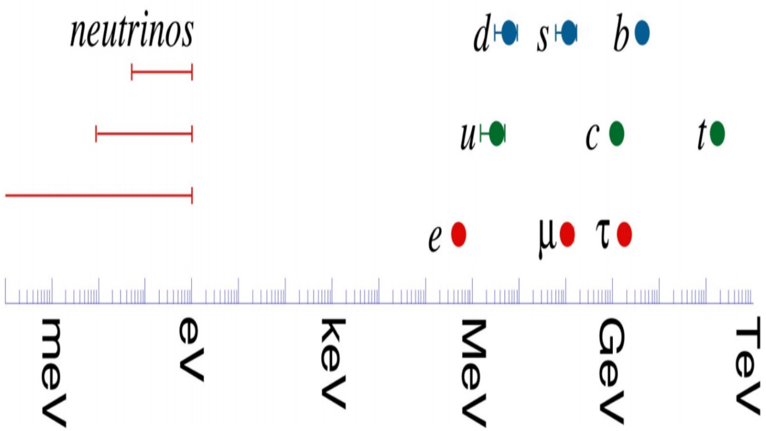


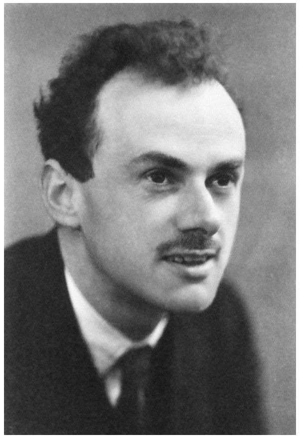
Figure from Hitoshi Murayama

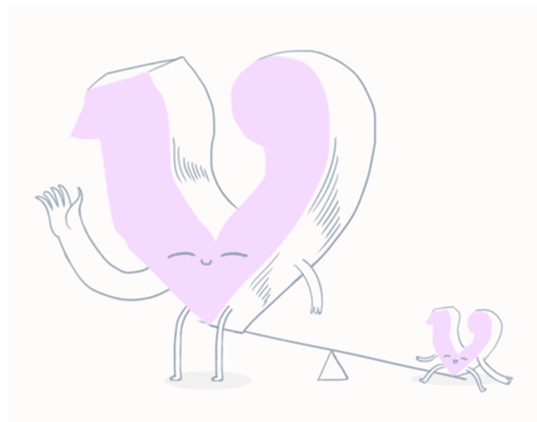
The masses of the neutrinos are **much smaller** than the other fermions!

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

$L_{\mathrm{Dirac}} = -y\overline{l_L}\widetilde{H}\nu_R$

$L_{Majorana} = -M\overline{\nu_R{}^c}\nu_R$

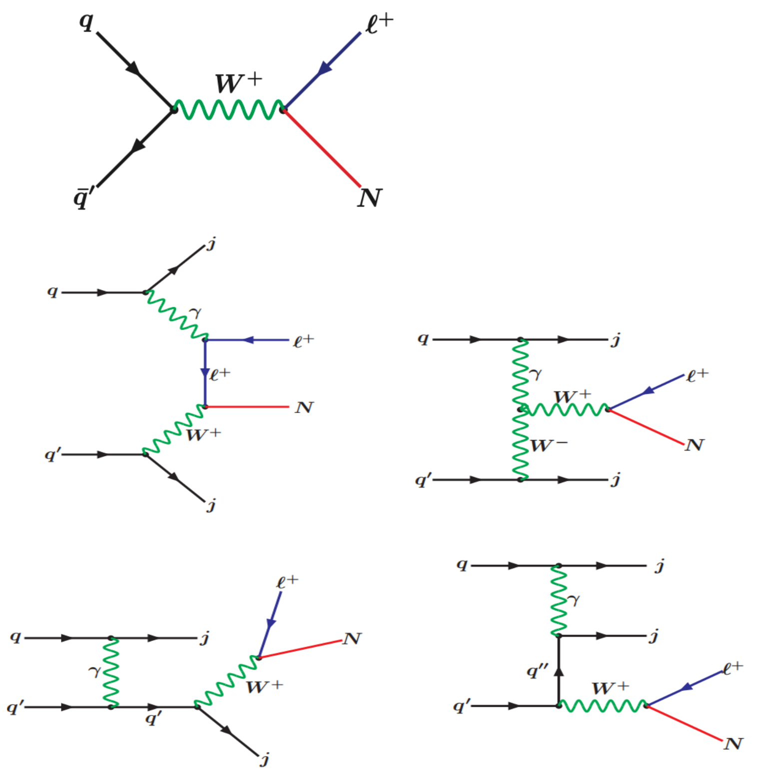
Tiny Yukawa coupling $\sim 10^{-12}$ for pure Dirac mass!

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? $\boldsymbol{\nu MSM}$

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!

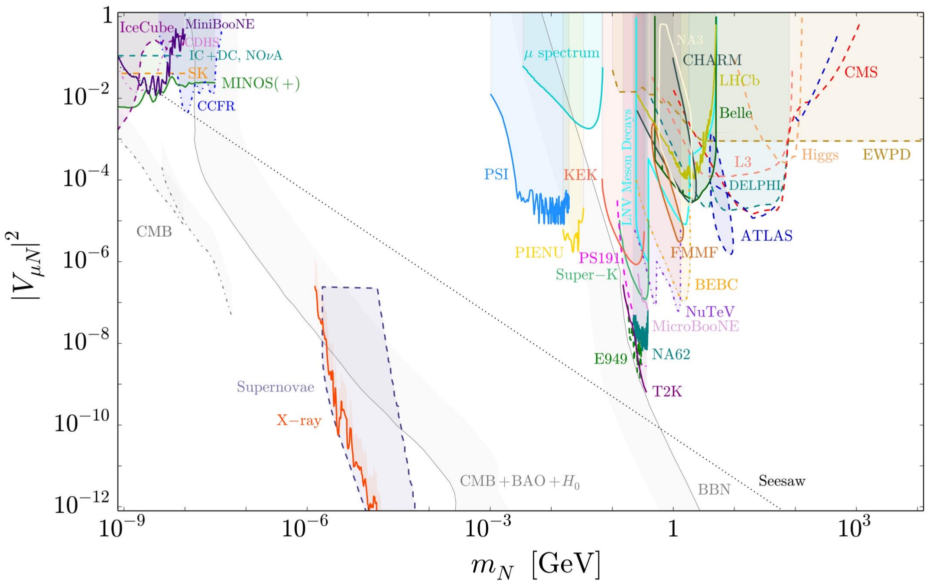
Within the $\boldsymbol{\nu MSM}$ model, the heavy neutrinos can be produced either via the s and t channel.

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

Both cannot reach low V_{lN}!

$10^7 pb \times V_{lN}^2 <$ 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 $\boldsymbol{\nu MSM}$ model **cannot reach the type-I seesaw** due to the low mixing at the EW scale

$$\begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix} = \begin{bmatrix} V_{LL} & V_{RL} \\ V_{LR} & V_{RR} \end{bmatrix} \begin{bmatrix} \nu \\ N \end{bmatrix}$$

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

Natural Type-I Seesaw at the $U(1)_{B-L}$ model

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

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

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

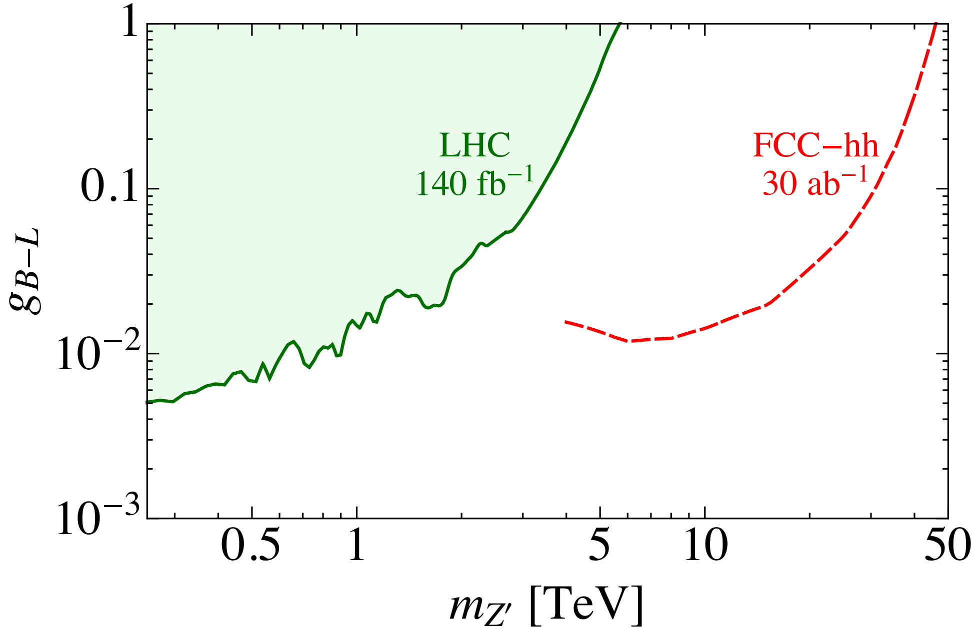
One of the simplest model UV complete and anomaly free model is the $U(1)_{B-L}$ model, other $U(1)$ models such as $U(1)_{L_\mu - L_\tau}$ is also possible.

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

Additional $\boldsymbol{B-L}$ gauge boson $\boldsymbol{Z'}$ with interactions

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

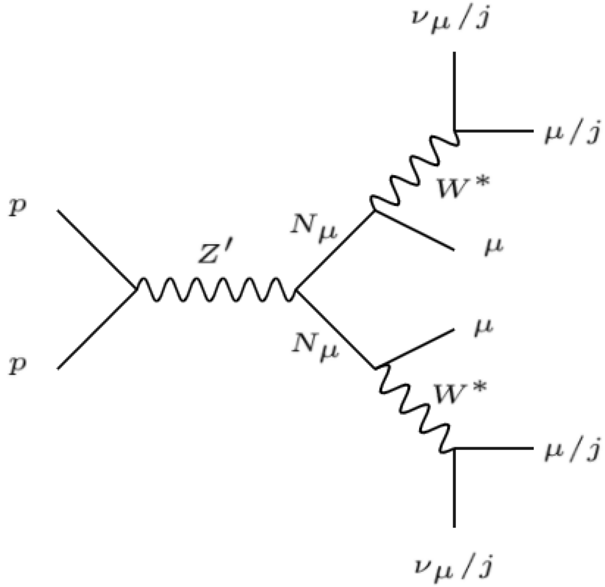
Experimental limits on the $U(1)_{B-L}$ model

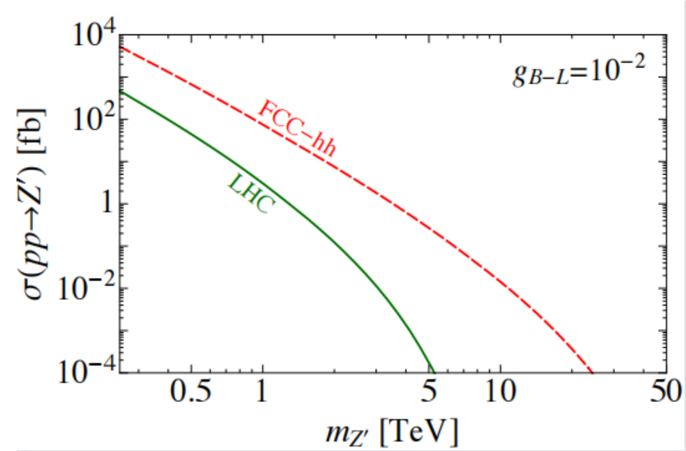


The gauge portal is well-constrained for sub-TeV Z' at the LHC.

However, TeV Z' is still possible, and FCC-hh has very good coverage.

Pair-Production of *N* at the FCC-hh

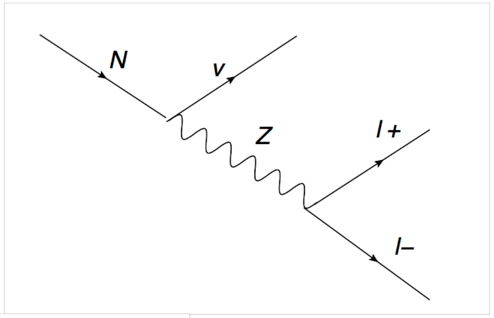


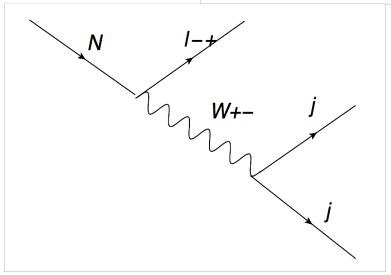


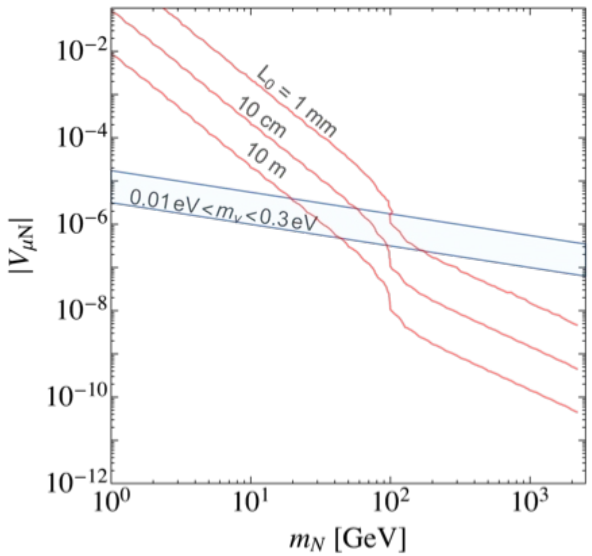
Heavy neutrinos can be pair-produced from a Z' decays at the FCC-hh, if the gauge coupling is appreciable.

Setting $g_{B-L} = 10^{-2}$ as a conservative benchmark. FCC-hh can still **100s** of heavy neutrinos from a very heavy Z'.

Heavy Neutrino, a Natural LLP







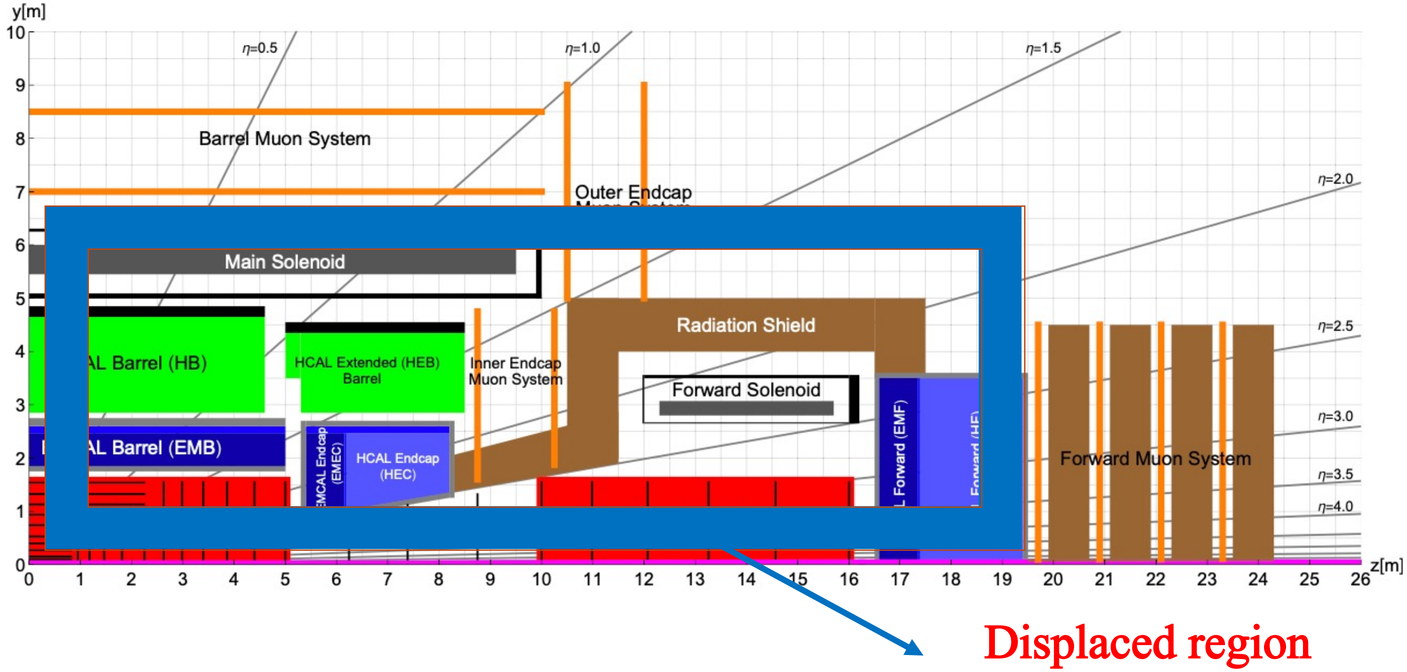
At the EW scale, the **heavy neutrinos are natural LLPs** predicted by the type-I seesaw.

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

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

At least one neutrino has mass within [0.01eV, 0.3 eV].

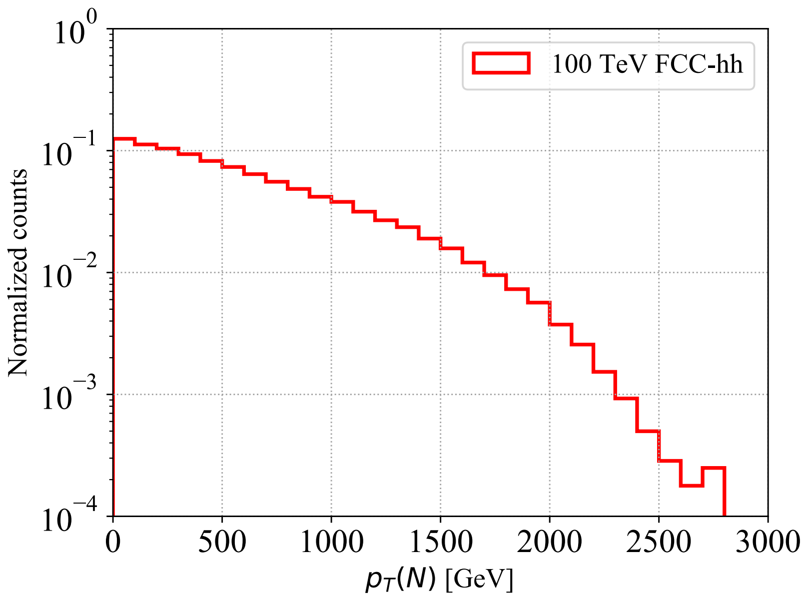
LLP signal at the FCC-hh

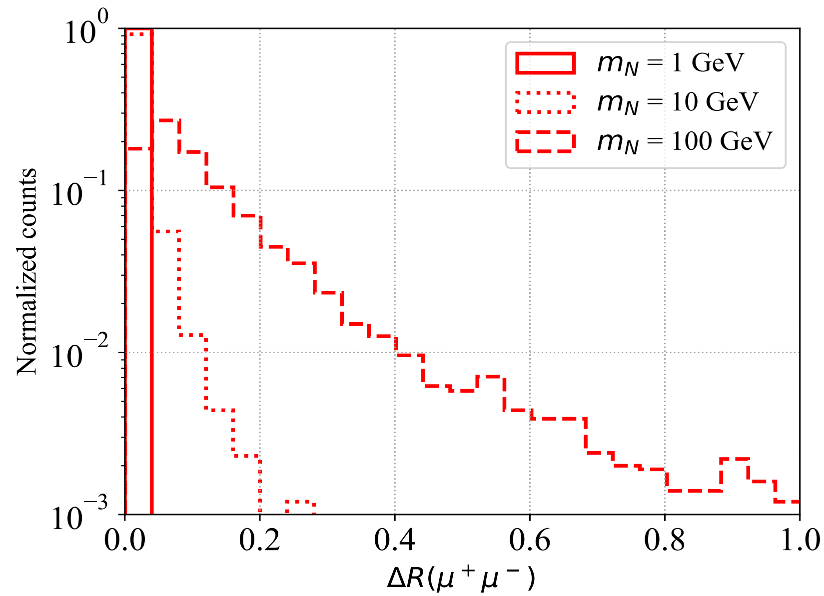


Figures from FCC collaboration, FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3.

Heavy neutrinos decay at a macroscopic distance from the IP, roughly within the tracker and calorimeter system (possibly the muon system), are regard as a LLP.

Kinematical Distribution

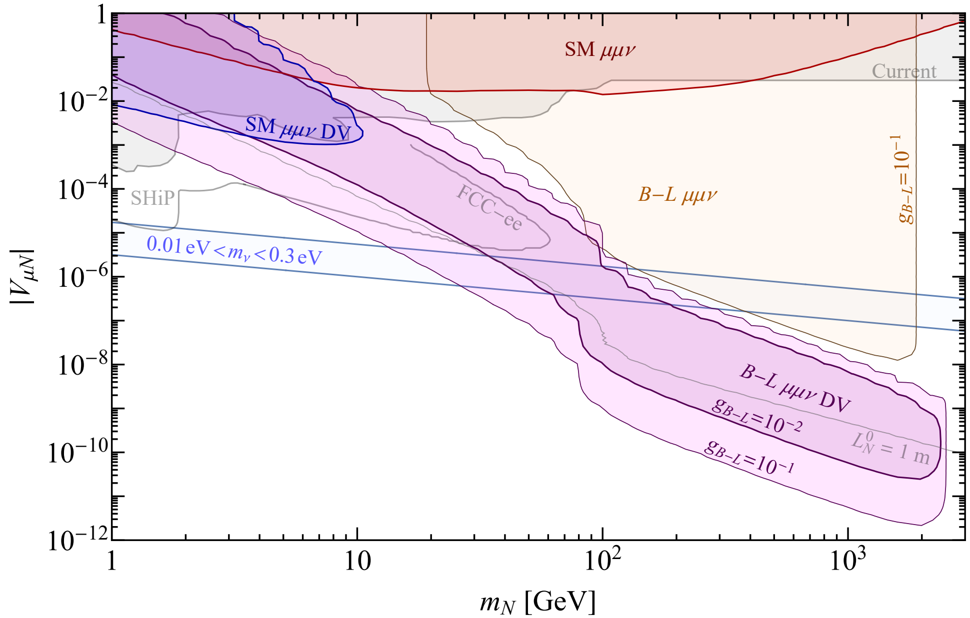




The heavy neutrinos from 5 TeV ***Z′*** are largely boosted.

The final states can be **very collimated**, the detailed analysis can be see at Padhan, Rojalin et al, arxiv: 2203.06114.

Sensitivity



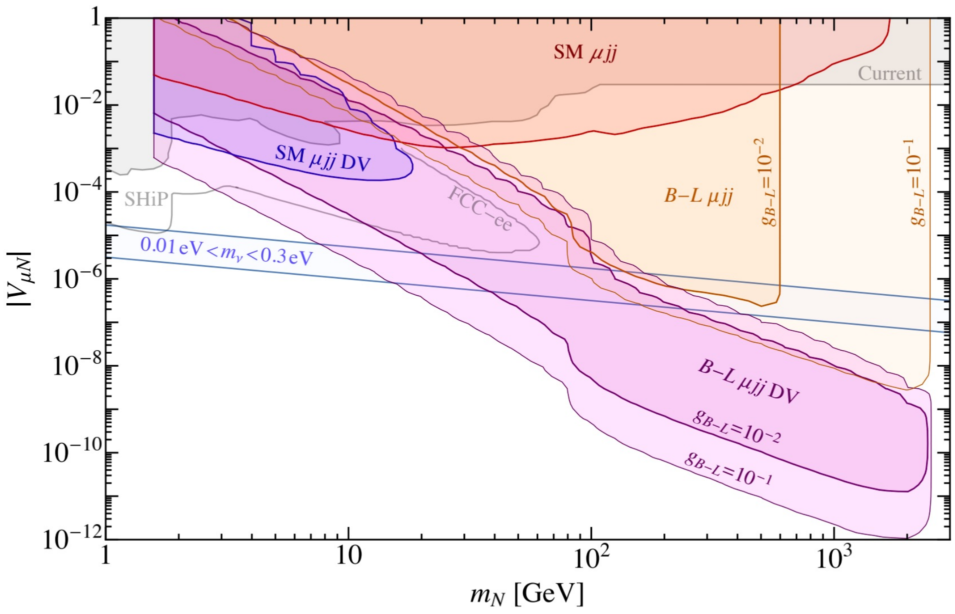
The SM prompt analyses suffer in large SM background, can not probe lower $V_{\mu N}$ than the current limits, while the B-L prompt can.

Due to the larger production cross section, the LLP analyses can test the seesaw, and reach lower $V_{\mu N}$ comparing to the LHC.

m_N < 5 GeV should be dominantly produced by meson decays, performed at the SHiP.

The gauge portal at the FCC-hh can test the seesaw!

Sensitivity



$m_N < 5$ GeV should be dominantly produced by meson decays, performed at the SHiP.

Due to larger $Br(N \to \mu jj)$ μjj channel can reach even lower $V_{\mu N}$.

The prompt analyses suffer in large SM background, but can still probe lower $V_{\mu N}$ than the current limits.

Due to the larger production cross section, the LLP analyses can test the seesaw, and reach lower $V_{\mu N}$ comparing to the LHC.

The gauge portal at the FCC-hh can test the seesaw!

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**, we seek to test the this problem at colliders.

- By adding a **B-L gauge**, the pair-production of right-handed neutrinos can be probed at colliders

- Via their **LLP signals** at the **lifetime frontier of the FCC-hh**, **we can test the type-I seesaw**

Heavy Neutrino Searches

- GUT points out $M_N \sim 10^{14}$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,

$$y_D \sim 10^{-6},\ M_N \sim \text{GeV}$$

- Inverse seesaw can yield natural Yukawa couplings.
- **Colliders probes of heavy neutrinos are resonable!**

Prompt signal at the FCC-hh

	$3\mu + \not{E}_T$	$2\mu + 2j$ (OS/SS)	$2\mu + 4j$ (OS/SS)	$4\mu + \not{E}_T$
Common cuts	$p_T(\mu_1) > 150\,\mathrm{GeV}$, $p_T(\mu) > 20\,\mathrm{GeV}$ $p_T(j) > 20\,\mathrm{GeV}$, $\lvert\eta(\mu, j)\rvert \leq 4$			
Lepton charge	N.A.	$\mu^+\mu^-/\mu^\pm\mu^\pm$	$\mu^+\mu^-/\mu^\pm\mu^\pm$	N.A.
Number of light jets	0	$= 2$	$= 4$	0
b-jet veto	No	Yes	Yes	No
$\not{E}_T$	N.A.	$< 20\,\mathrm{GeV}$	$< 20\,\mathrm{GeV}$	$> 100\,\mathrm{GeV}$
M_{inv}	N.A.	$> 4\,\mathrm{TeV}$	$> 4\,\mathrm{TeV}$	N.A.

Table 2: Different cuts on final states for various prompt signal categories considered.

LLP detectors have been proposed with different coverage sensitive to certain masses of LLPs. FASER and MoEDAL-MAPP already in installation.

The outer region of the CMS/ATLAS, LHCb as well as the detector for the FCC-hh can be used to detect LLP from displaced vertex.

Prompt signal at the FCC-hh

SM Prompt	Background	σ(fb)	M($t\bar{t}$)	N_{B}
Leptonic ($\mu\mu\mu\not{E}_T$)	$\mu^{\pm}\nu Z$	11.9	-	3.55×10^5
Hadronic OS ($\mu^{\pm}\mu^{\mp}jj$)	$t\bar{t}$ (leptonic decay)	1.84	-	5.52×10^4
Hadronic SS ($\mu^{\pm}\mu^{\pm}jj$)	$t\bar{t}$ (leptonic decay)	1.84×10^{-3}	-	55.2
$B-L$ Prompt	Background	σ(fb)	M($t\bar{t}$)	N_{B}
Leptonic ($\mu\mu\mu\mu\not{E}_T$)	ZWW	5.92×10^{-2}	-	1.78×10^3
Hadronic OS ($\mu^{\pm}\mu^{\mp}jjjj$)	$t\bar{t}$ (leptonic decay)	1.85	8.73×10^{-2}	2.62×10^3
Hadronic SS ($\mu^{\pm}\mu^{\pm}jjjj$)	$t\bar{t}$ (leptonic decay)	1.85×10^{-3}	Negligible	Negligible
Displaced Vertex	Background	σ(fb)	M($t\bar{t}$)	N_{B}
Leptonic ($\mu\mu\not{E}_T$)	-	-	-	Negligible
Hadronic (μjj)	-	-	-	Negligible

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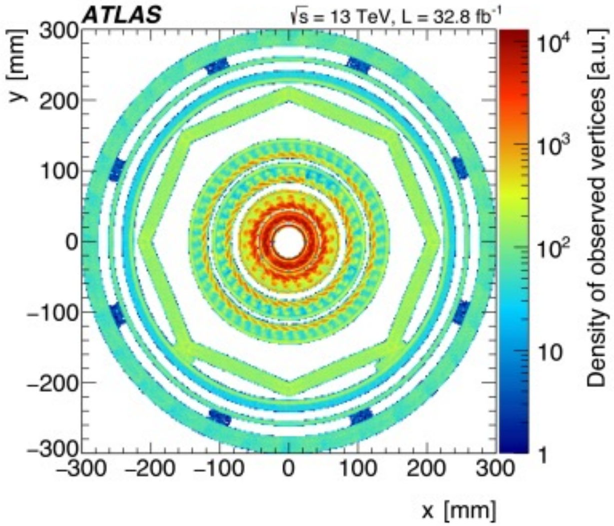
LLP Background



Juliette Alimena, James Beacham, Martino Borsato, Yangyang Cheng , Xabier Cid Vidal et al. J.Phys.G 47 (2020) 9, 090501.

In general, very low background.

Not modelled, needs to be measured experimentally.

- Long-lived SM particles:

Cut away by mass fit

- Real particles interact with detectors

Material map, can be available in Delphes

- Real particles outside the detectors

Can use control experiment to measure

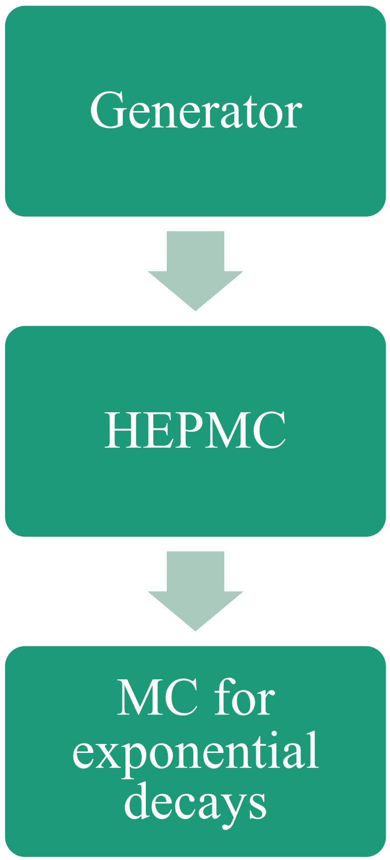
- Fake-particle signatures

control experiment

- Algorithmically induced fakes

control experiment

LLP Simulation



Simple MC:

Use inverse sampling of the exponential decays.

Easy to rescale for different proper decay length.

Detector level simulation:
Taking enormous time to get distribution of exponential decays!
No information for new detectors.