Collider Signatures of Neutrino Models[1]

Snowmass Intensity Frontier Workshop, ANL

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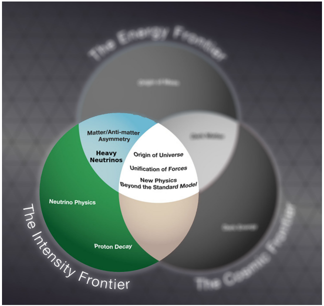
April 26, 2013



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[1] Silent Plug: Snowmass Young: http://tinyurl.com/snomassyoung

What This Talk Is.

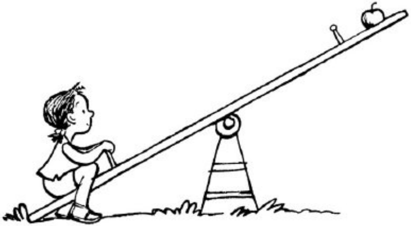
It is a gross, unjust summary of heavy neutrino searches at colliders.

It focuses on two complimentary perspectives:

- Low Energy Colliders: B, D, τ Factories
- High Energy Colliders: The ILC, LHC, and beyond.

The Higgs will make an appearance

... but first, a very brief review at how neutrino masses can be small and large



The Seesaw Mechanism[2] in a Nutshell

Massive, left-handed neutrinos exist. By Lorentz-invariance, ν_R exist too! Hence, below the EW scale

$$\mathcal{L} \ni -m_D \overline{\nu_R} \nu_L + h.c.$$

Suppose some spin-1/2 fermion with zero charge under any exact symmetry below EW scale (singlet!). We are allowed to write

$$-m_M \overline{S^c} S$$

However, below the EW scale, ν and S have the same spacetime and good, internal q numbers, so they mix! The mass eigenvalues are

$$m_1 \approx m_D \frac{m_D}{m_M}, \quad m_2 \approx m_M \qquad (m_D \ll m_M)$$

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[2] Yanagita (1979); Gell-Mann, Ramond, Slansky (1979); S.L. Glashow (1980); Mohapatra, Senjanovic (1980)

Several Ways to Generate $m_{D/M}$

Type(I)[3]: Add a spin-$1/2$ singlet with a Majorana mass term:

- $\mathcal{L} \ni \; m_M \overline{S^c} S \implies \; m_\nu^{ij} \propto m_D^i m_D^j / m_M$
- N_R can be singlet

Type(II)[4]: Add Higgs $SU(2)_L$ triplet $(H^{0,\pm,\pm\pm})$

- $\mathcal{L} \ni \; y\overline{L^c}(i\sigma_2)\Phi L \implies \; m_M \overline{\nu^c}\nu \implies$ same as above

Type(III)[5]: Introduce fermion $SU(2)_L$ triplet $(T^{0,\pm})$

- $m_\nu^{ij} \propto m_D^i m_D^j / M_T$

Lepton number violation (LNV) is present in all these mechanisms.

Punchline: There are many different ways to generate $m_{D/M}$, and each results in rich collider phenomenology.

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[3] Minkowski ('77); Gell-Mann, Ramond, Slansky ('79); etc...

[4] Mohapatra, Senjanovic ('80,'81); Magg, Wetterich ('80); Lazarides, Shafi ('81); etc...

[5] Foot, Lew, He, Joshi (1989); G. Senjanovic et al. ...

A Quick Note for Experiments

If there are 3 ν_L with light mass eigenstates, m, and n ν_R with heavy mass eigenstates, m', then the mixing gets complicated[6]

$$\begin{pmatrix} \nu_L \\ N_L^c \end{pmatrix} = \begin{pmatrix} U_{3\times 3} & V_{3\times n} \\ X_{n\times 3} & Y_{n\times n} \end{pmatrix} \begin{pmatrix} \nu_m \\ \nu_{m'} \end{pmatrix}$$

- $U_{3\times 3}$ is the PMNS matrix
- $UU^\dagger, YY^\dagger \sim \mathcal{O}(1)$ and $VV^\dagger, XX^\dagger \sim \mathcal{O}(m_m/m_{m'}) \sim \mathcal{O}(10^{-3})$[7]
- New CP phases and mixing angles will be present
- A job for high intensity experiments

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[6] Atre, Han, Pascoli, Zhang, arXiv.0901.3589; Han, Lewis, Ruiz, Si, arXiv:1211.6447

[7] W.-Y. Keung and G. Senjanovic, Phys. Rev. Lett. 50, 1427 (1983).

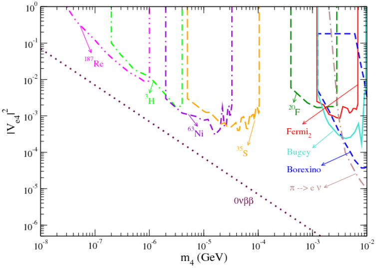
Heavy Neutrinos at Low Energy Colliders:

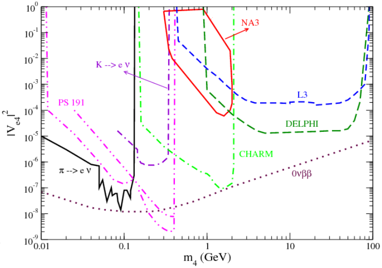
Mesons Factories

Heavy Neutrinos at Meson Factories

$0\nu\beta\beta$ decay greatly restricts[8] $\sum_{m'} \frac{|V_{em'}|^2}{m_{m'}}$,

- GeV-scale N is very much still possible if $|V_{\ell m'}|$ is small
- In this case, more energy buys little; luminosity is needed





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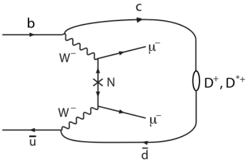
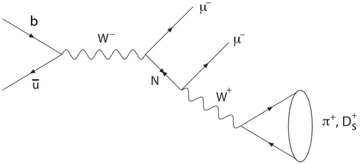
[8] Olness, Ebel (1984); Langacker, Sankar (1989); Belanger, et al, arXiv:hep-ph/9508317; London, arXiv:hep-ph/9907419; Benes, et al., arXiv:hep-ph/0501295; Atre, et al., arXiv:0901.3589

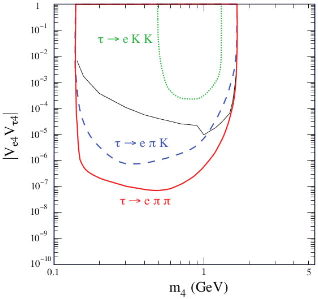
3-Body τ/Meson Decays

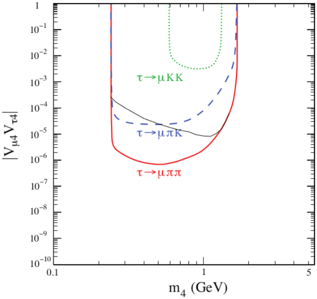
Majorana N contribute to τ/meson decays through s/t-channels[9]

- Sensitive to products of $V_{\ell m'}$ and compliments $0\nu\beta\beta$









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[9] Atre, Han, Pascoli, Zhang, arXiv:0901.3589

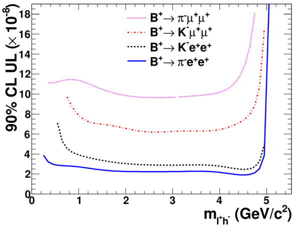
3-Body Meson Search Results

Belle: 7.7×10^8 $B\overline{B}$ pairs at $\Upsilon(4S)$ (arXiv:1107.0642)

Mode	ϵ [%]	N_{obs}	$N_{\text{exp}}^{\text{bkg}}$	U.L. [10^{-6}]
$B^+ \to D^- e^+ e^+$	1.2	0	0.18±0.13	< 2.6
$B^+ \to D^- e^+ \mu^+$	1.3	0	0.83±0.29	< 1.8
$B^+ \to D^- \mu^+ \mu^+$	1.9	0	1.44±0.43	< 1.0

Belle II Goal: 50 ab^{-1} ($\times 40$ higher int. lumi.!)

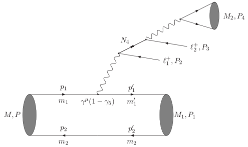
BABAR: 4.7×10^8 $B\overline{B}$ (arXiv:1202.3650): Limit on BR vs m_N

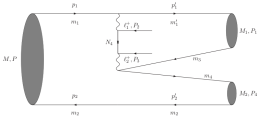


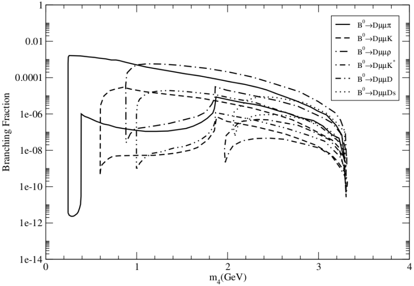
Mode	Events	Fit Bias	Yield	η (%)	$\mathcal{S}$ (σ)	$\mathcal{B}$ ($\times 10^{-8}$)	$\mathcal{B}_{UL}$ ($\times 10^{-8}$)
$B^+ \to \pi^- e^+ e^+$	123	$+0.15 \pm 0.09$	$0.6^{+2.5}_{-2.7}$	47.8 ± 0.1	0.4	$0.27^{+1.1}_{-1.2} \pm 0.1$	2.3
$B^+ \to K^- e^+ e^+$	42	-0.30 ± 0.15	$0.7^{+1.8}_{-1.2}$	30.9 ± 0.1	0.5	$0.49^{+1.3}_{-0.8} \pm 0.1$	3.0
$B^+ \to \pi^- \mu^+ \mu^+$	228	-0.01 ± 0.05	$0.0^{+3.2}_{-2.0}$	13.1 ± 0.1	0.0	$0.03^{+5.1}_{-3.2} \pm 0.6$	10.7
$B^+ \to K^- \mu^+ \mu^+$	209	$+0.02 \pm 0.04$	$0.5^{+3.5}_{-2.5}$	23.0 ± 0.1	0.2	$0.45^{+3.2}_{-2.7} \pm 0.4$	6.7

4-Body Meson Decays: $M_1 \to M_2\ \ell_1^\pm\ \ell_2^\pm\ M_3$

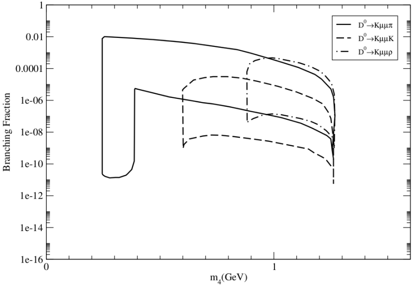
Plenty to do: **75** four-body LNV processes with rates comparable to three-body decays, most were previously unconsidered[10]







$B^0 \to D^- \mu^+ \mu^+ M_2^-$



$D^0 \to K^- \mu^+ \mu^+ M_2^-$

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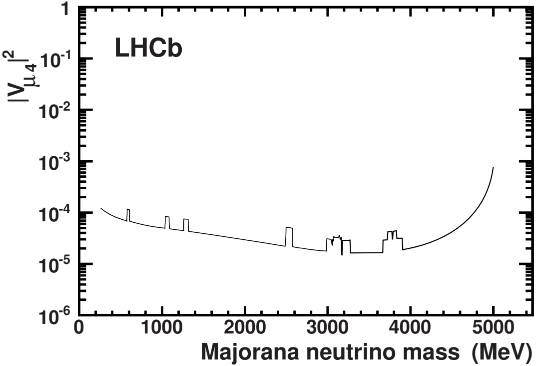
[10] Yuan, et al., arXix:1304.3810

4-Body Meson Search Results

LHCb is now searching for four-body LNV processes but collects only a fraction of luminosity compared to other LHC expts [11]

$$\mathcal{B}(B^- \to D^0\pi^+\mu^-\mu^-) < 1.5\times10^{-6} \text{ at 95\% CL}$$



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[11] LHCb, arXiv:1201.5600

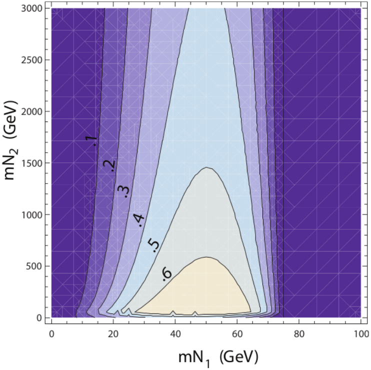
Heavy Neutrinos at the ILC:

A Higgs Factory as a Portal to Heavy Neutrinos

Enhanced (In)Visible Higgs Width at ILC

In the most general case, fourth generation neutrinos may have both a Dirac and a Majorana mass terms

- $BR(H \to N_1 N_1) \propto |V_{N_1 \ell_4}|^2$ can be quite large![12]
- N_1 is "light" state; N_2 is heavy state; $m_H = 150$ GeV.



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[12] Carpenter, Whiteson, arXiv:1107.2123

Enhanced (In)Visible Higgs Width at ILC

$BR(H \to N_1 N_1) \propto |V_{N_1 \ell_4}|^2$ can be quite large![13]

If $BR(N_1 \to W^+ \ell^-_{1..3}) \propto |V_{N_1 \ell_{1..3}}|^2$ is not too small,

- $H \to N_1 N_1 \to W^+ \ell^-_{1..3} W^+ \ell'^-_{1..3}$ is a viable ILC/LHC channel

If $|V_{N_1 \ell_{1..3}}|^2$ is too small,

- $H \to N_1 N_1$ contributes to the invisible Higgs decay modes, which is a prerogative of ILC.

High luminosity is absolutely necessary for this.

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[13] Carpenter, Whiteson, arXiv:1107.2123

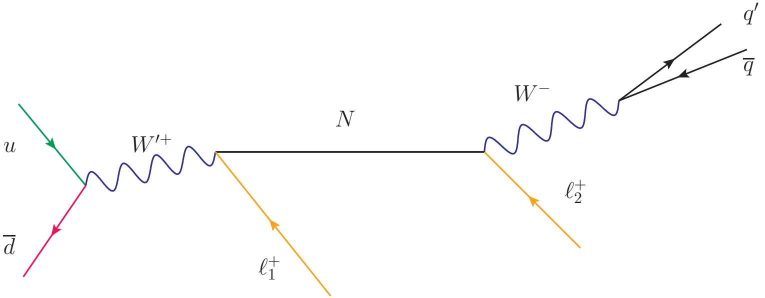
Heavy Neutrinos at High Energy Colliders:

Taking a Crack at the Seesaw Itself

Resonant Majorana *N* Production at the LHC

Resonant production of *N* through $pp \to N\ell_1^\pm \to \ell_1^\pm \ell_2^\pm jj$ is

- Clean, direct, and unambiguous[14]
- The Holy Grail of LNV at the LHC
- No missing E_T, $m_{jj} = M_W$, prominent signal over small background[15]



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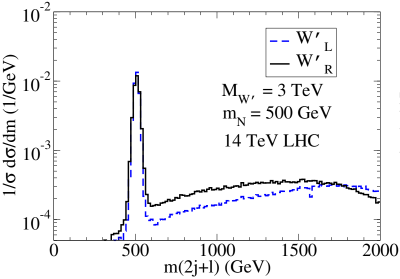
[14] Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); F. Almeida et al. (2000); F. del Aguila et al. (2007)

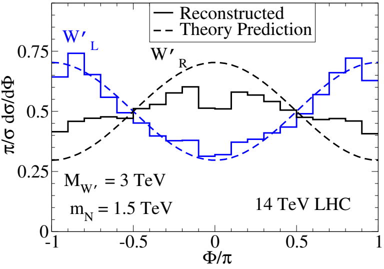
[15] Atre, Han, Pascoli, Zhang, arXiv.0901.3589

Resonant Majorana *N* Production at the LHC

Resonant production of *N* through $pp \to N\ell_1^\pm \to \ell_1^\pm \ell_2^\pm jj$ is[16]

- Fully reconstructible; m_N peak is observable
- Generalized to discriminate between different production modes, e.g. $W_{R/L} \to N\ell$ vs $W' \to N\ell$
- Majorana nature of *N* can be verified by two methods: LNV and by angular distributions





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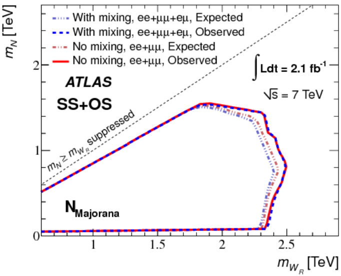
[16] Han, Lewis, Ruiz, Si, arXiv:1211.6447

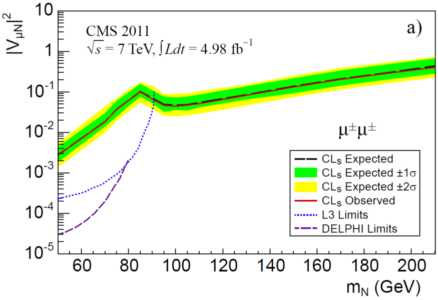
$pp \rightarrow \ell_1^\pm \ell_2^\pm jj$ Searches at ATLAS and CMS

Searches at the LHC are complimentary[17]

- Same-sign and Opposite-sign leptons signals are investigated
- ATLAS & CMS search for N coupling to W_R only
  - $m_N > 1.9$ TeV $(M_{W_R} \approx 2.4$ TeV$)$
  - $M_{W_R} > 2.5$ TeV $(m_N \approx 0.8$ TeV$)$
  - CMS has comparable numbers

- CMS also searches for N coupling to W_L only





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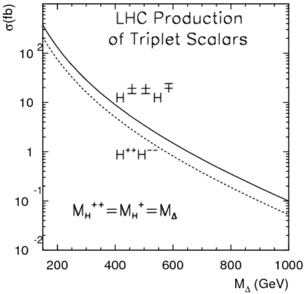
[17] ATLAS, arXiv:1203.5420; CMS, arXiv:1207.6079

Testing Type(II) Seesaw: $H^{\pm\pm}$ Production

$H^{\pm\pm}$ production is a robust test of Type(II)[18]

- $pp \to W^{\pm *} \to H^{\pm\pm} H^{\mp}$ has sizable production rate
- $H^{\pm\pm}$ decay modes are sensitive to neutrino hierarchy



Spectrum	Relations
NH	$\mathrm{Br}(\tau^+\tau^+), \mathrm{Br}(\mu^+\mu^+) \gg \mathrm{Br}(e^+e^+)$
$\Delta m^2_{31} > 0$	$\mathrm{Br}(\mu^+\tau^+) \gg \mathrm{Br}(e^+\tau^+), \mathrm{Br}(e^+\mu^+)$
	$\mathrm{Br}(\tau^+\bar{\nu}), \mathrm{Br}(\mu^+\bar{\nu}) \gg \mathrm{Br}(e^+\bar{\nu})$
IH	$\mathrm{Br}(e^+e^+) > \mathrm{Br}(\mu^+\mu^+), \mathrm{Br}(\tau^+\tau^+)$
$\Delta m^2_{31} < 0$	$\mathrm{Br}(\mu^+\tau^+) \gg \mathrm{Br}(e^+\tau^+), \mathrm{Br}(e^+\mu^+)$
	$\mathrm{Br}(e^+\bar{\nu}) > \mathrm{Br}(\mu^+\bar{\nu}), \mathrm{Br}(\tau^+\bar{\nu})$
QD	$\mathrm{Br}(e^+e^+) \approx \mathrm{Br}(\mu^+\mu^+) \approx \mathrm{Br}(\tau^+\tau^+)$
	$\mathrm{Br}(\mu^+\tau^+) \approx \mathrm{Br}(e^+\tau^+) \approx \mathrm{Br}(e^+\mu^+)$ (suppressed)
	$\mathrm{Br}(e^+\bar{\nu}) \approx \mathrm{Br}(\mu^+\bar{\nu}) \approx \mathrm{Br}(\tau^+\bar{\nu})$

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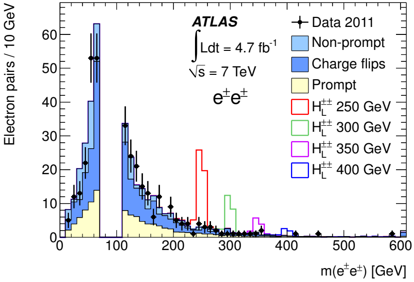
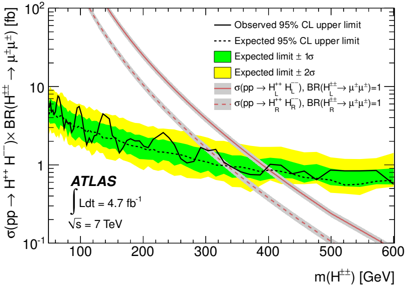
[18] Fileviez-Perez, Han, Huang, Li, Wang, arXiv:0803.3450

$H^{\pm\pm}$ Searches at the LHC

The ATLAS and CMS Experiments are actively searching for resonant production of $H^{\pm\pm}$[19]

- $pp \to W^\pm W^\pm \to \ell_1^\pm \ell_2^\pm \nu\nu$ has very few background processes
- Detector behavior, e.g., charge flip/misidentification, is critical
- $m_{H^{\pm\pm}} \lesssim 400$ GeV is excluded for all $e^\pm\mu^\pm$ permutations
- CMS has searched for $pp \to H^{++}H^{--}/H^{++}H^{-} \to 4/3\ell$





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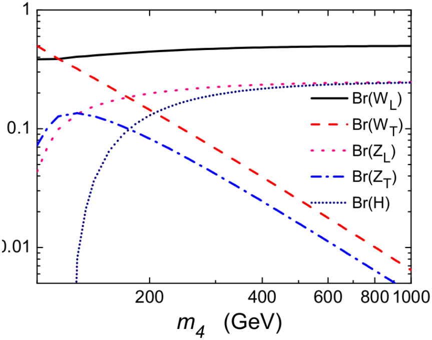
[19] ATLAS, arXiv:1210.5070; CMS, arXiv:1207.2666

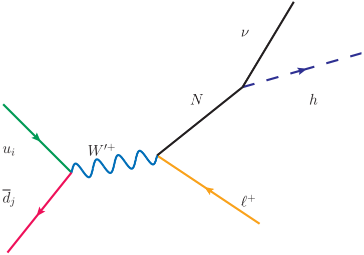
Anything else? Yes.

LHC Neutrino Physics with a 126 GeV Higgs[21]

A 126 GeV Higgs boson is interesting

- If N is heavier than H, then the decay to H will be present[20]
- $\Gamma(N \to \nu_\ell H) = \frac{g^2}{64\pi M_W^2}|V_{\ell N}|^2 m_N^3 (1-(m_H/m_N)^2)^2$
- $pp \to \ell N \to \ell \nu H$ has well studied backgrounds (WH)





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[20] Atre, Han, Pascoli, Zhang, arXiv.0901.3589

[21] Han, Ruiz, In Progress

Summary

1. Solutions to the "Smallness Problem" invoke lepton number violation
2. Meson Factories: Super high lumi. factories can push beyond $0\nu\beta\beta$ limits on $\mathcal{O}(1)$ GeV neutrinos
3. ILC: $\mathcal{O}(10)$ GeV neutrinos may contribute to Higgs (in)visible decay modes and can be observed at Higgs factories
4. LHC: $\mathcal{O}(10^2 \sim 10^3)$ GeV neutrinos can be unambiguously identified

Conclusion & Beyond[22]

The search for heavy Dirac/Majorana neutrinos is a very active and very healthy program at colliders

L/HE colliders are incredibly complimentary to each other, and to dedicated neutrino experiments, providing

- Independent measurements of neutrino mixing parameters
- Direct measurements of heavy mass eigenstates
- Literally, $\mathcal{O}(100)$ of channels sensitive to LNV

Beyond: Much work has been done at the intersection of the Energy and Intensity Frontiers, and much more work will be done as we continue to push **forward** on higher **luminosity**, higher **energy**, and higher **computing**.

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[22] Silent Plug: Snowmass Young: http://tinyurl.com/snomassyoung