Neutrino Physics (Theory) – 2

2024 BND school, Blankenberge, België

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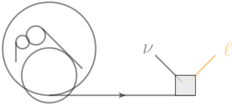
Institute of Nuclear Physics – Polish Academy of Science (IFJ PAN)

2 September 2024



Lecture Plan (one-day show!)

Lecture I:

- Pt 1: The **Standard Model (SM)** neutrino
- Pt 2: The neutrino that nature gave us: intro to ν oscillations

Coffee break at 10:30ish

Lecture II:

- Pt1. Consequences of neutrino masses (theory perspective)
- Pt2. Neutrino mass models (highlights)

Lunch at 12:30ish

Pt1. Consequences of neutrino masses

The massless ν hypothesis (recap)

In quantum field theory: we learn about three types of fermions

$$\mathcal{L}_{\text{Kin.}} = \overline{\psi} i \not{\partial} \psi \qquad \mathcal{L}_{\text{Kin.}} = \overline{\psi} \left(i \not{\partial} - m \right) \psi \qquad \mathcal{L}_{\text{Kin.}} = \frac{1}{2} \overline{\psi} \left(i \not{\partial} - m \right) \psi$$

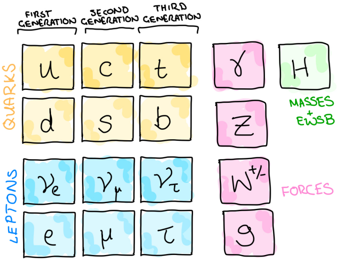
Weyl fermion $(m = 0)$ **Dirac fermion** $(m \neq 0)$ **Majorana fermion** $(m \neq 0)$

- **SM** hypothesizes 3 massless, chiral ν_L

  (no evidence for $m_\nu \neq 0$)

- **Data** only say $m_\nu \neq 0$, but not whether ν is Dirac or Majorana

- **The** 1/2 **Problem**: cannot write $\mathcal{L}_{\text{Kin.}}$ without first knowing D vs M nature



$\Longrightarrow$ **existence of ν masses remain physics beyond the SM** ('15)

consider "The $1/2$ Problem" from a different perspective

Fermion masses and chirality

For fermions chirality and masses are linked

[1] friendly reminder: $\overline{\psi} = \psi^\dagger \gamma^0$ and $P_L \gamma^0 = \gamma^0 P_R$.
we also have $P_L P_L \psi_L = P_L \psi_L = \psi_L$ (also true for R).

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Example: consider the **chiral projection operators**[1] $P_L + P_R = \mathbb{1}$

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$$= m\ (\overline{\psi_L} P_R + \overline{\psi_R} P_L)\ (P_L \psi_L + P_R \psi_R) = m\ (\overline{\psi_L}\psi_R\ +\ \overline{\psi_R}\psi_L)$$

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Conclusion: only (LR) and (RL) survive since $P_L \cdot P_R = P_R \cdot P_L = 0$

- if $\psi_R = (\psi_L)^c$, then ψ is a Majorana fermion
- if $\psi_R \neq (\psi_L)^c$, then ψ is a Dirac fermion

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Example: consider the **chiral projection operators**[2] $P_L + P_R = \mathbb{1}$

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In SM: Higgs field $(\Phi_{\rm SM})$ couples LH and RH chiral fermions

- Yukawa couple **opposite chirality**, e.g., $\mathcal{L}_{\rm Yuk.} = y_e^{ij}\,\overline{L_L^i}\,\Phi\,e_R^j + {\rm H.c.}$
- Covariant derivatives couple **same chirality**, e.g., $\mathcal{L}_{\rm Kin.} = \overline{L_L}\,i\,\not{D}\,L_L$

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accommodating Dirac masses in the SM (1/2)

To generate Dirac masses for ν like other SM fermions, we need ν_R

$$\mathcal{L}_{\nu\ \mathrm{Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + \mathrm{H.c.}$$

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$$= \underbrace{-y_\nu \langle \Phi \rangle}_{=m_D} \overline{\nu_L}\nu_R \ + \ \text{H.c.} \ + \ \ldots$$

accommodating Dirac masses in the SM (2/2)

Adding ν_R's to SM seems trivial but...

- ν_R's are neutral under all SM gauge interactions (before and after EWSB)
- If ν_R's are **Majorana fermions**, must **include** RH Majorana masses

$$\mathcal{L}_M = \frac{1}{2}\mu_R \overline{\nu_R^c}\nu_R + \mathrm{H.c.}$$

- If ν_R's are **Dirac fermions**, must **forbid** RH Majorana masses by imposing some new symmetry/conservation law

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Adding ν_R's to the **SM** means:

- a new scale μ_R that **breaks lepton number** symmetry
- a new symmetry that **conserves lepton number** symmetry
- both e.g., spontaneous $B-L$ breaking

However, the origin of $m_\nu \neq 0$ might not even involve ν_R

to date, data gives no preference for Dirac or Majorana nature

the SM does provide some theoretical guidance!

$m_\nu \neq 0 \implies$ **new physics must exist**

Ma('98) + others

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$$m_\nu \neq 0 + \mathrm{left-handed\ (LH)\ weak\ currents}$$

(renormalizability)

LH Majorana mass : $\frac{1}{2} m_\nu^L \overline{\nu_L} \nu_L^c$

Dirac mass : $m_\nu^D \overline{\nu_L} \nu_R$

(gauge invariance)

$m_\nu^L = y\langle\Delta\rangle$ or new dynamics

$m_\nu^D = y\langle\Phi_{\mathrm{SM}}\rangle$

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$m_\nu^L = y\langle\Delta\rangle$ or new dynamics

$m_\nu^D = y\langle\Phi_{\rm SM}\rangle$

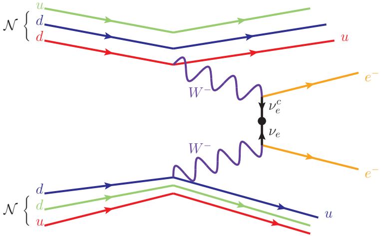
$m_\nu \neq 0$ **+ renormalizability + gauge inv.** $\implies$ **new particles**

New particles must couple to $\Phi_{\rm SM}$ and L, often inducing non-conservation of **lepton number** and/or **lepton flavor**

friendly reminder of lepton symmetries

Lepton Number Violation (LNV) $=$
(#leptons – #antileptons) not conserved

e.g, nuclear $0\nu\beta\beta$ decay of heavy isotopes $(A, Z) \to (A, Z+2) + e^- e^-$



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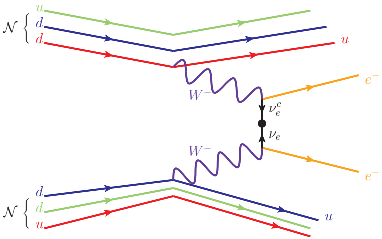
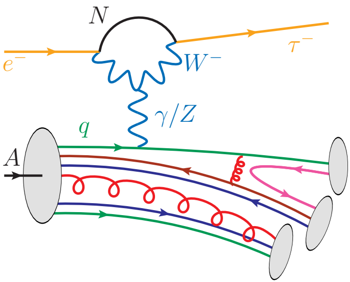




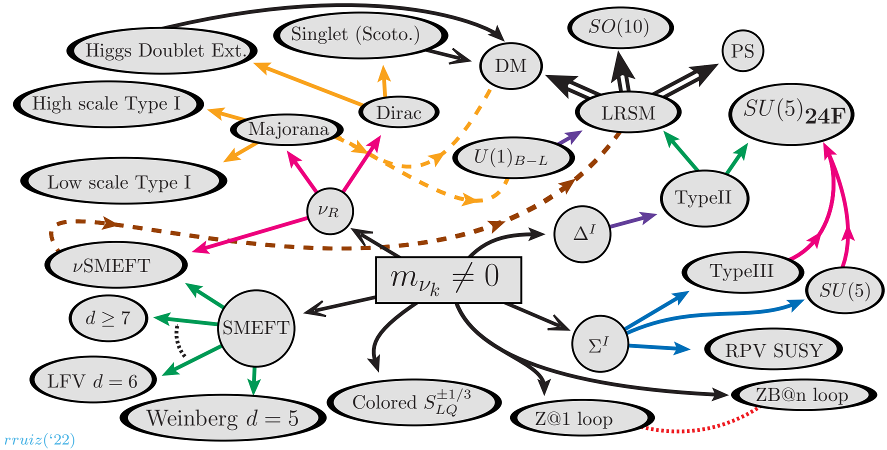
Lepton Flavor Violation (LFV) =
(#lepton species – #antilepton species)
not conserved,

e.g, $e^- \to \tau^-$ conversion in deeply inelastic scattering (DIS)

lepton number and **lepton flavor** are **accidentally** conserved **in the SM**

Solution to $m_\nu \neq 0$ can be realized in ***many*** ways!

Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



New particles must couple to Φ_{SM} and L, often inducing **lepton number violation (LNV)** and **lepton flavor violation (LFV)** in experiments

why the obsession with LNV?

The Black Box Theorem

In '82, Schechter & Valle published (PRD'82) a seminal finding:

- Suppose $0\nu\beta\beta$ is mediated within "a 'natural' gauge theory" a $\Delta L = -2$ process →
- u, d and e^- all carry weak charges

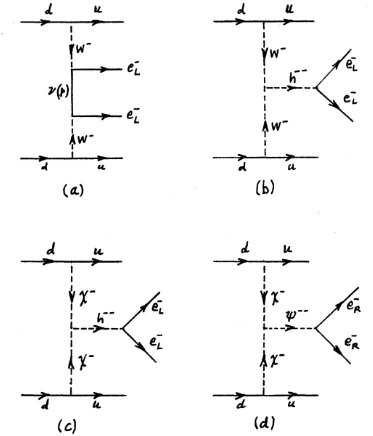


FIG. 1. Diagrams for neutrinoless double-β decay in an SU(2)×U(1) gauge theory. The standard diagram is Fig. 1(a). It is the only one which contains a virtual neutrino (of four-momentum p). d and u are the down and up quarks.

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- Suppose $0\nu\beta\beta$ is mediated within "a 'natural' gauge theory" a $\Delta L = -2$ process →
- u, d and e^- all carry weak charges
- always possible to build a many-loop, 2-point graph with external ν_L, ν_L^c
- $0\nu\beta\beta$ generates a **Majorana mass** for ν
- holds generally for other $\Delta L \neq 0$ process

for further discussions, see:

Hirsch, et al [hep-ph/0608207] and Pascoli, et al [1712.07611]

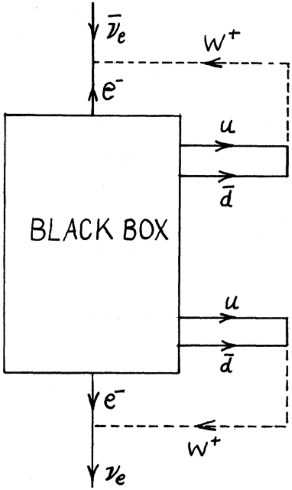


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

LNV $\Longleftrightarrow$ Majorana nature of ν

well, why not look for $0\nu\beta\beta$?

... is it hard? ☺

☺☺☺

quick review from this morning (1 slide)

The SM $W^\pm$ boson coupling to **leptons** in the **flavor eigenbasis** is

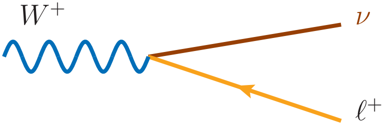
$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{l=1}^{3} \left[\overline{\nu_{lL}} \gamma^\mu P_L l^- \right] \ + \ \text{H.c.}$$

The SM $W^\pm$ boson coupling to **leptons** in the **mass eigenbasis** is

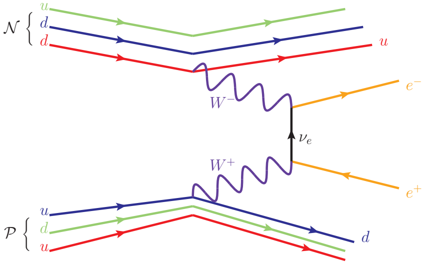
$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e}^{\tau} \sum_{m=1}^{3} \left[\overline{\nu_m} \underbrace{U_{m\ell}^*}_{U_{m\ell}^* \equiv \sum_l \Omega_{ml}^* \Omega_{l\ell}} \gamma^\mu P_L \ell^- \right] \ + \ \text{H.c.}$$

Like the CKM, SM Feynman rules are modified by **PMNS** mixing factor:

$$\Gamma^\mu = \frac{-ig}{\sqrt{2}} \gamma^\mu P_L \rightarrow \tilde{\Gamma}^\mu = \frac{-ig}{\sqrt{2}} U_{m\ell}^* \gamma^\mu P_L$$



Consider the LNC process $\mathcal{N}\mathcal{P} \to \mathcal{P}'\mathcal{N}' e^+ e^-$ as governed by the SM



The helicity amplitude for the LNC subprocess $q_1 q_2 \to \ell_1^- \ell_2^+ q_1' q_2'$ is

$$\mathcal{M}_{LNC} = J^{\mu}_{q_1 q_1'} J^{\nu}_{q_2 q_2'} \Delta^{W}_{\mu\rho} \Delta^{W}_{\nu\sigma} T^{\rho\sigma}_{LNC} \mathcal{D}(p_N)$$

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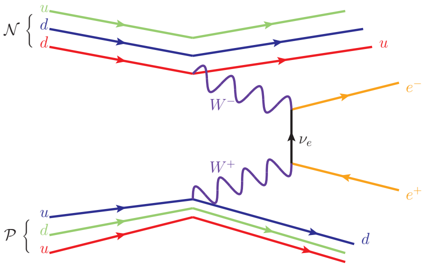

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$$T^{\rho\sigma}_{LNC} = \overline{u_L}(p_1) U_{ek} \gamma^\rho P_L \times (\underbrace{\not{p}_k}_{\text{LH helicity state}} + \underbrace{m_k}_{P_L m_k P_R = 0}) \times U_{ek} \gamma^\sigma P_L v_R(p_2)$$

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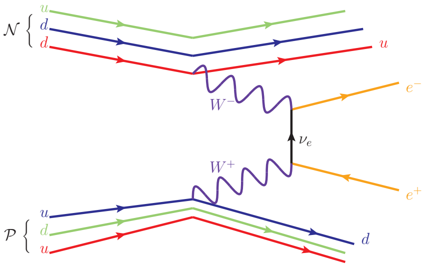

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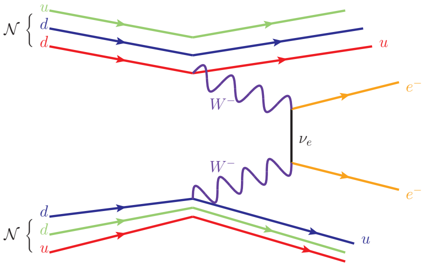
$$\implies \mathcal{M}_{LNC} \sim \frac{p_k}{(p_k^2 - m_k^2)} U_{ek}^2$$

scales with momentum transfer!

Consider the LNV process $\mathcal{N}\mathcal{N} \to \mathcal{P}'\mathcal{P}' e^- e^-$ in minimal SM+m_ν



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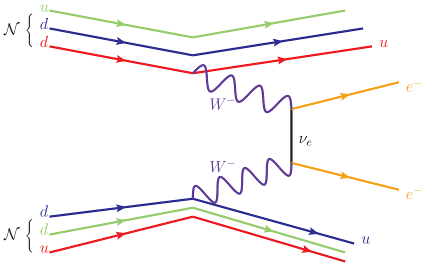

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Intuition: CPT Theorem $\implies$ CT-inversion = P-inversion

$$T^{\rho\sigma}_{LNV} = \overline{u_R}(p_1) U_{ek} \gamma^\rho \underbrace{P_R}_{CPT:\ P_L \to P_R} \times \Big(\underbrace{\not{p}_k}_{P_R\ \not{p}_k\ P_R = 0} + \underbrace{m_k}_{\text{RH helicity state}} \Big) \times U_{ek} \gamma^\sigma P_L v_R(p_2)$$

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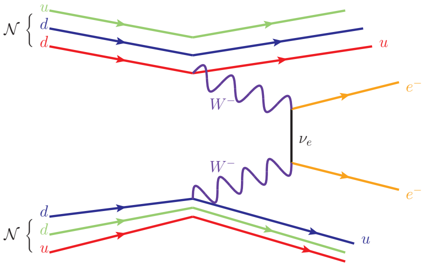

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$$\implies \mathcal{M}_{LNV} \sim \frac{m_k}{(p_k^2 - m_k^2)}\ U_{ek}^2$$

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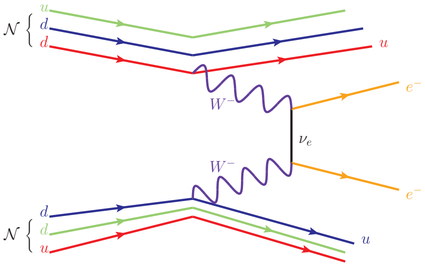

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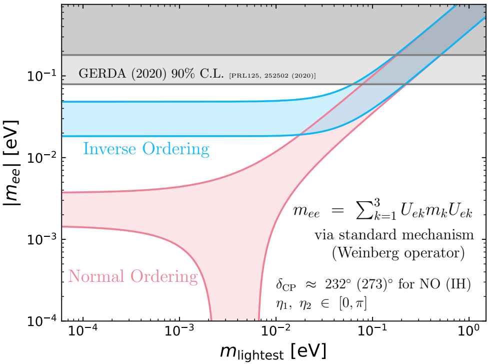
$$T^{\rho\sigma}_{LNV} = \overline{u_R}(p_1) U_{ek} \gamma^\rho \underbrace{P_R}_{CPT:\ P_L \to P_R} \times \Big(\underbrace{\not{p}_k}_{P_R\ \not{p}_k\ P_R = 0} + \underbrace{m_k}_{\text{RH helicity state}} \Big) \times U_{ek} \gamma^\sigma P_L v_R(p_2)$$

$$\implies \mathcal{M}_{LNV} \sim \frac{m_k}{(p_k^2 - m_k^2)} U_{ek}^2 \approx \frac{m_k}{p_k^2} U_{ek}^2 \times \left[1 + \mathcal{O}\left(\frac{m_k^2}{p_k^2} \right) \right]$$

scales with mass!

Plotted: Excluded/allowed "effective $\beta\beta$ Majorana mass" vs lightes m_ν

$$1/T_{1/2}^{0\nu\beta\beta} = \underbrace{G_{0\nu\beta\beta}}_{\text{phase space}} \; m_p^2 \; \underbrace{|\mathcal{A}|^2 \; |m_{ee}|^2}_{\text{matrix element}}, \qquad m_{ee} = \sum_{k=1}^{3} U_{ek} m_k U_{ek}$$



gitlab.cern.ch/riruiz/public-projects/-/tree/master/NuPhysSandbox

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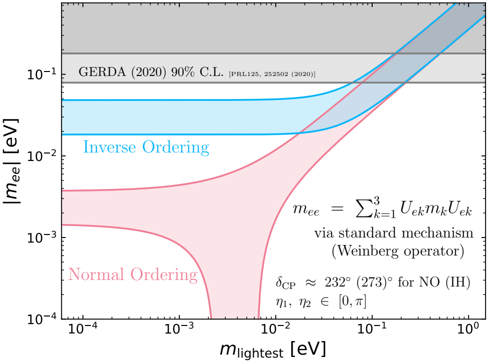

Weinberg operator only SMEFT operator at $d = 5$:

$$\mathcal{L} = \frac{C_5^{\ell\ell'}}{\Lambda} [\Phi \cdot \overline{L_\ell^c}][L_{\ell'} \cdot \Phi]$$

generates ν mass matrix:

$$m_{\ell\ell'} = C_5^{\ell\ell'} \langle \Phi \rangle^2 / 2\Lambda$$

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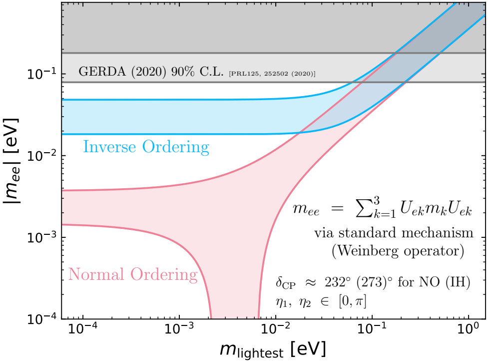

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Searches for nuclear $0\nu\beta\beta$ decay set stringent constraints, e.g.,

GERDA [2009.06079]

$$C_5^{ee}/\Lambda \gtrsim (3.3 - 7.6) \times 10^{14} \text{ GeV}$$

Important: sensitivity is model dependent!!!

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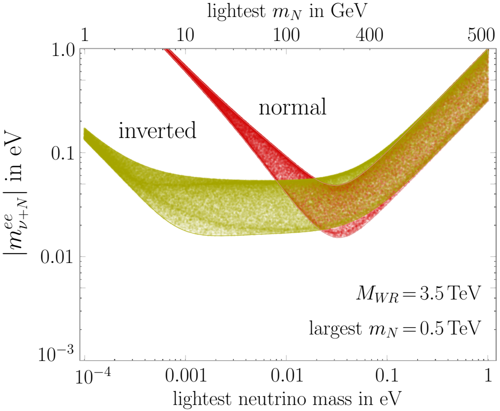
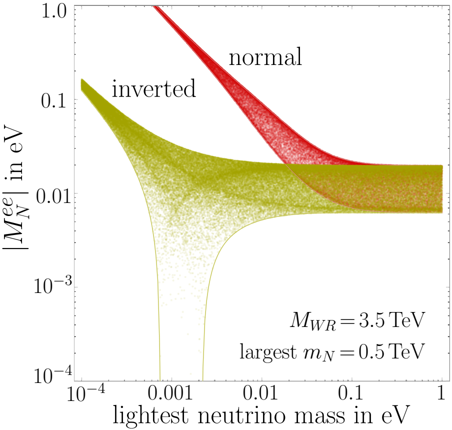




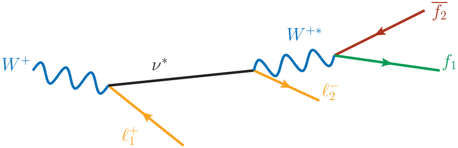
eg., Left-Right Symm. Model, Tello, et al [1011.3522]

how about looking for LNV elsewhere?

The Dirac-Majorana Confusion Theorem

In '82, Kayser also published (PRD'82) a seminal finding:

refined later by Mohapatra & Pal ('98)



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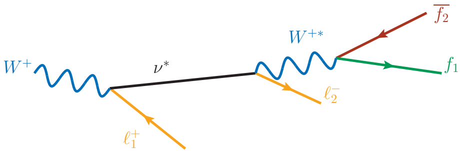

The helicity amplitude for the LNC process $W^+ \to \ell_1^+ \ell_2^- f \overline{f'}$ is

$$\mathcal{M}_{LNC} = \varepsilon_\mu \, T^{\rho\mu}_{LNC} \, \Delta^W_{\nu\rho} \, J^\nu_{f_1 f_2} \mathcal{D}(p_\nu)$$

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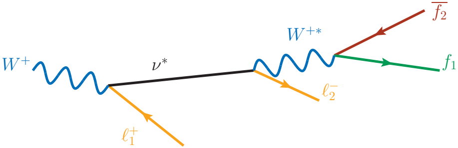

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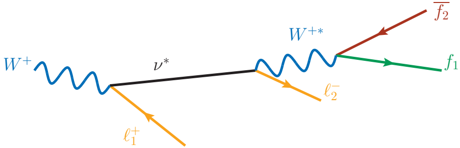

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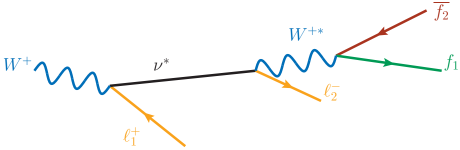

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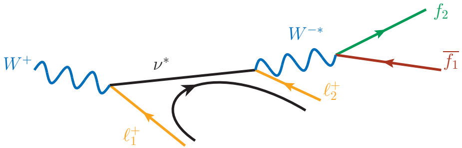

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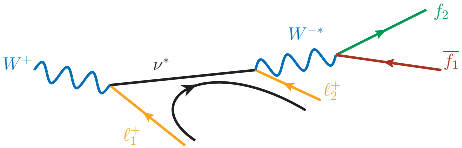

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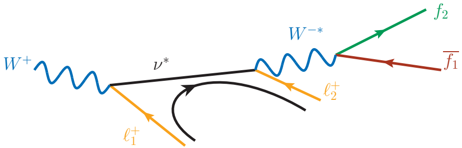

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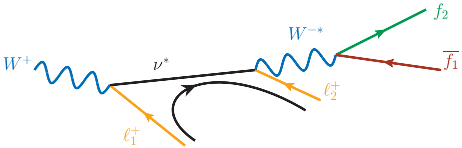

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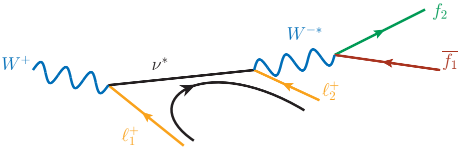

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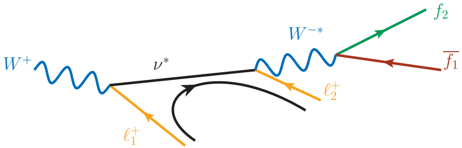

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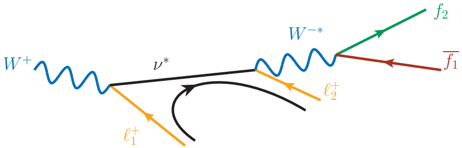

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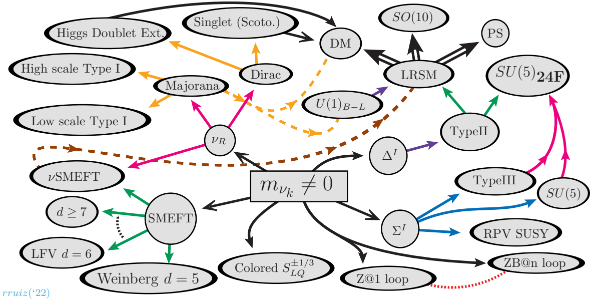
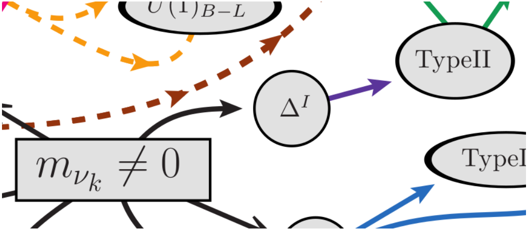
holds for other gauge theories with Majorana fermions Han, RR, et al [1211.6447]; RR [2008.01092]

Pt2. ν mass models



Type II Seesaw[3]



[3] Konetschny and Kummer ('77); Schechter and Valle ('80); Cheng and Li ('80); Lazarides, et al ('81); Mohapatra and Senjanovic ('81)

The Type II Seesaw is special: generates m_ν ***without*** hypothesizing ν_R

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Hypothesize a **scalar** $SU(2)_L$ triplet with **lepton number** $L = -2$

$$\hat{\Delta} = \frac{1}{\sqrt{2}}\begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \sqrt{2}\Delta^0 & -\Delta^+ \end{pmatrix}, \quad \text{with} \quad \mathcal{L}_{\Delta\Phi} \ni \mu_{h\Delta}\left(\Phi_{\rm SM}{}^\dagger \hat{\Delta} \cdot \Phi_{\rm SM}{}^\dagger + \text{H.c.}\right)$$

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$\implies$ **left-handed** Majorana masses for ν

$$\Delta\mathcal{L} = -\frac{y_\Delta^{ij}}{\sqrt{2}}\overline{L^c}\hat{\Delta}L = -\frac{y_\Delta^{ij}}{\sqrt{2}}\begin{pmatrix}\overline{\nu^{jc}} & \overline{\ell^{jc}}\end{pmatrix}\begin{pmatrix} 0 & 0 \\ v_\Delta & 0 \end{pmatrix}\begin{pmatrix}\nu^i \\ \ell^i\end{pmatrix}$$

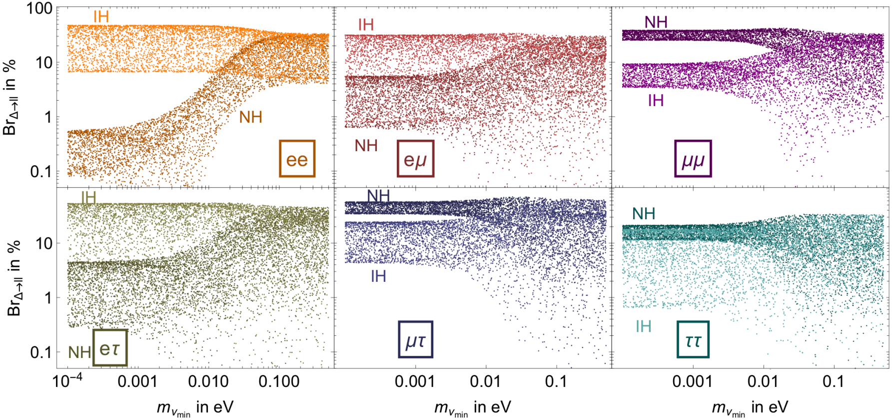
$$\ni -\frac{1}{2}\underbrace{\left(\sqrt{2}y_\Delta^{ij} v_\Delta\right)}_{=m_\nu^{ij}}\overline{\nu^{jc}}\nu^i$$

Fewer free parameters $\Longrightarrow$ richer experimental predictions

Fileviez Perez, Han, Li, et al, [0805.3536], Crivellin, et al [1807.10224], Fuks, Nemevšek, RR [1912.08975] + others

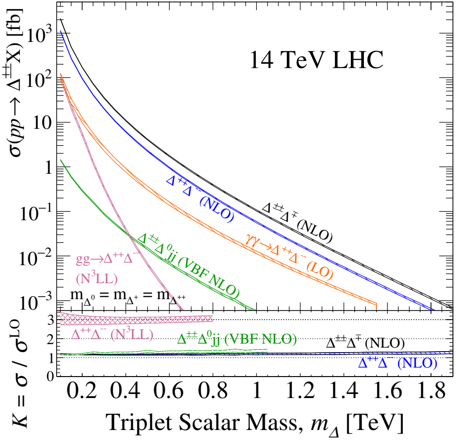
- **Example:** Δ decay rates encode inverse (IH) vs normal (NH) ordering of light neutrino masses

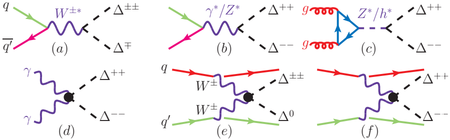
$$\Gamma(\Delta^{\pm\pm} \to \ell_i^\pm \ell_j^\pm) \sim y_\Delta^{ij} \sim \left(U^*_{\rm PMNS}\, \tilde{m}_\nu^{\rm diag}\, U^\dagger_{\rm PMNS}\right)_{ij}$$



$\Delta^{\pm\pm}$, $\Delta^{\pm}$, Δ^{0}, ξ^{0} all couple to W, Z, γ via gauge couplings

($\implies$ unambiguous xsec prediction!)





Fuks, Nemevšek, RR [1912.08975]

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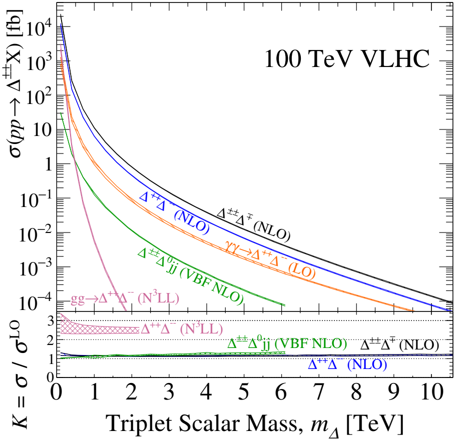

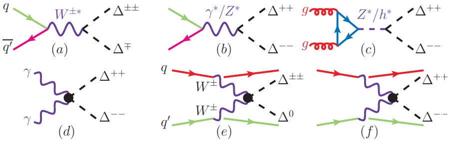

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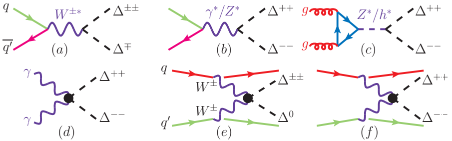

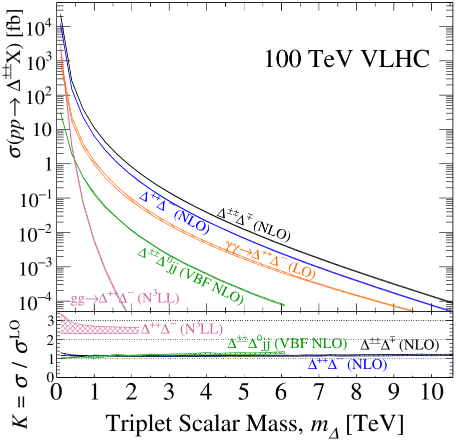

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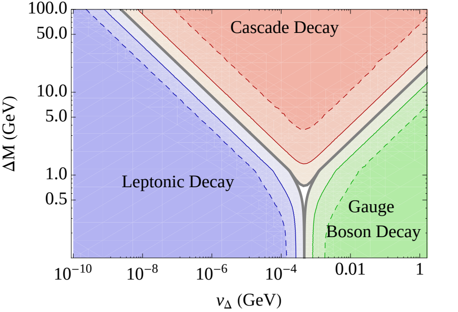
Preferred decay modes of $\Delta^{\pm\pm}$

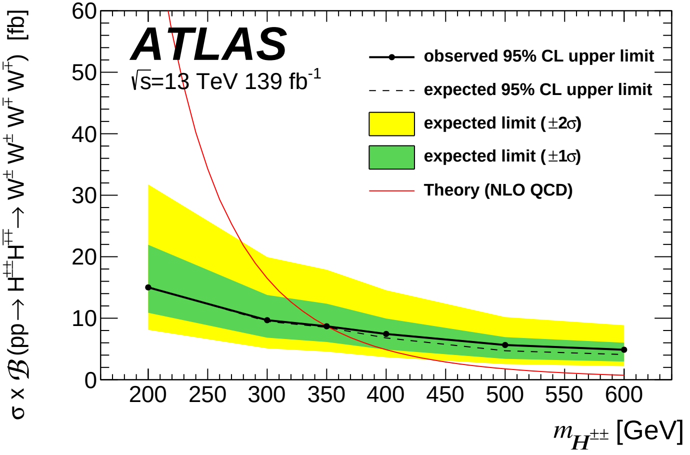
($\Delta M = m_{++} - m_{+}$)



Melfo, Nemevšek, Nesti, Senjanovic, Zhang [1108.4416]

LHC limits on pair production

$$pp \rightarrow \Delta^{++}\Delta^{--} \rightarrow 4W^{\pm} \rightarrow 2-4\ell^{\pm} + \not{E}_T + X \qquad (\ell = e, \mu) \text{ [2101.11961]}$$



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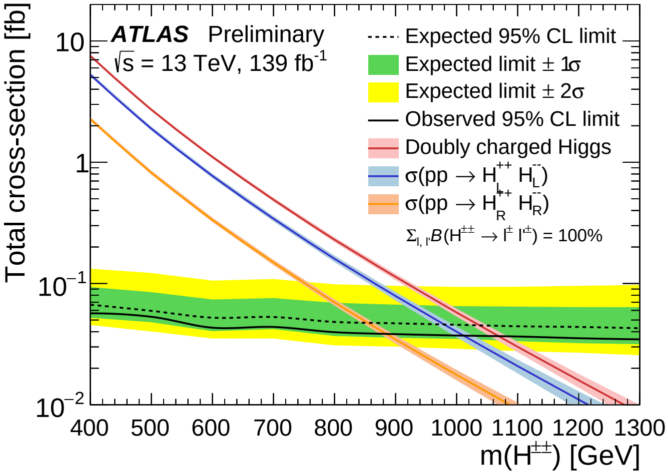


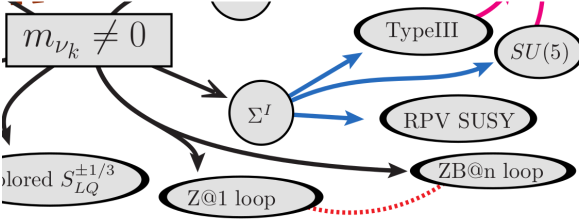
What if $\Delta^{\pm\pm}$, $\Delta^{\pm}$ are discovered?

celebrate! ☺

except... ☹

$\Delta^{\pm\pm},\ \Delta^{\pm}$ are not unique in new physics models

Zee-Babu Model[4]



[4] Zee ('85×2), Babu ('88)

Zee-Babu model generates m_ν radiatively ***without*** hypothesizing ν_R

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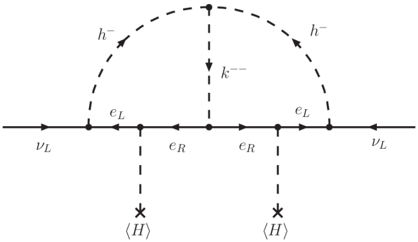
Zee-Babu model generates m_ν radiatively ***without*** hypothesizing ν_R

Hypothesize two **scalar** $SU(2)_L$ singlets k, h with weak hypercharge $Y = -2, -1$ ($\implies Q_k = -2, Q_h = -1$) with **lepton number** $L = -2$

$$\mathcal{L}_{\rm ZB} = \mathcal{L}_{\rm SM} + (D_\mu k)^\dagger (D^\mu k) + (D_\mu h)^\dagger (D^\mu h) + + \left(\mu_{\not L}\ hhk^\dagger + \text{H.c.}\right)$$
$$\left[f_{ij}\ \overline{\tilde{L}^i} L^j h^\dagger + g_{ij}\ \overline{(e_R^c)^i} e_R{}^j k^\dagger + \text{H.c.}\right] + \ldots$$



[1402.4491]

The mass scale $\mu_{\not L}$ breaks lepton number, and induces $m_\nu \neq 0$:

$$\left(\mathcal{M}_\nu^{\rm flavor}\right)_{ij} = 16\mu_{\not L}\ f_{ia}\ m_a\ g^*_{ab}\ \mathcal{I}_{ab}(r)\ m_b\ f_{jb}.$$

Few free parameters $\Longrightarrow$ ric experimental predictions

Nebot,et al [0711.0483]; Ohlsson, Schwetz, Zhang [0909.0455]; Herrero-Garcia, Nebot, Rius, et al [1402.4491]; + others

- E.g., $k^{\pm\pm}$, $h^{\pm}$ couplings to leptons encode oscillation physics

Normal ordering:

$$\frac{f_{e\tau}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} + \tan\theta_{13}\sin\theta_{23}e^{-i\delta}$$

$$\frac{f_{e\mu}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} - \tan\theta_{13}\sin\theta_{23}e^{-i\delta}$$

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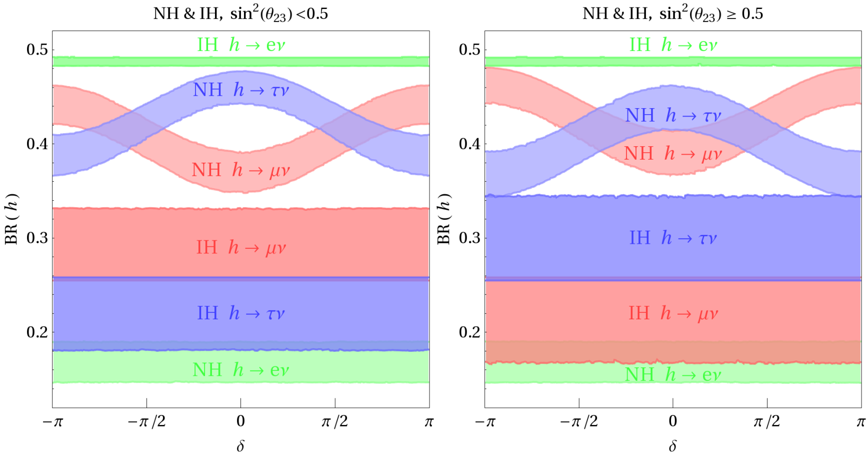
Inverse ordering:

$$\frac{f_{e\tau}}{f_{\mu\tau}} = -\frac{\sin\theta_{23}}{\tan\theta_{13}}e^{-i\delta},$$
$$\frac{f_{e\mu}}{f_{\mu\tau}} = \frac{\cos\theta_{23}}{\tan\theta_{13}}e^{-i\delta},$$
$$\frac{f_{e\tau}}{f_{e\mu}} = -\tan\theta_{23}.$$

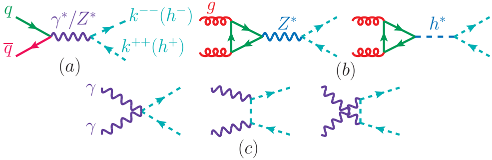
Few free parameters $\Longrightarrow$ ric experimental predictions

Nebot,et al [0711.0483]; Ohlsson, Schwetz, Zhang [0909.0455]; Herrero-Garcia, Nebot, Rius, et al [1402.4491]; + others

- E.g., $k^{\pm\pm}$, $h^{\pm}$ decay rates encode IH vs NO



$k^{\pm\pm}$, $h^{\pm}$ couple directly to Z, γ via gauge couplings ($\Longrightarrow$ unambiguous xsec prediction!)

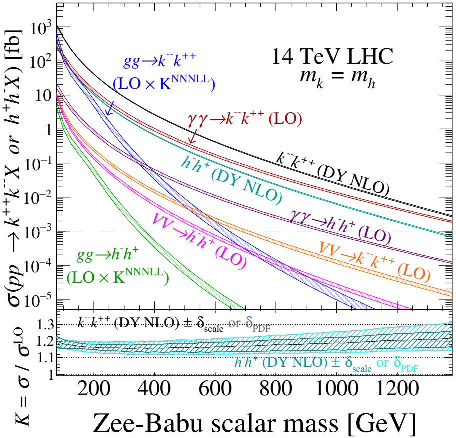


Many production channels but most studies focus on $pp \to k^{++}k^{--}$

If $k^{\pm\pm}$ is the lightest state, then decay rates set by oscillation parameters

(I find this really, really cool ☺)

Discerning from Type II Seesaw is actually difficult



RR [2206.14833]

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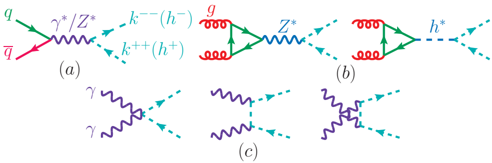

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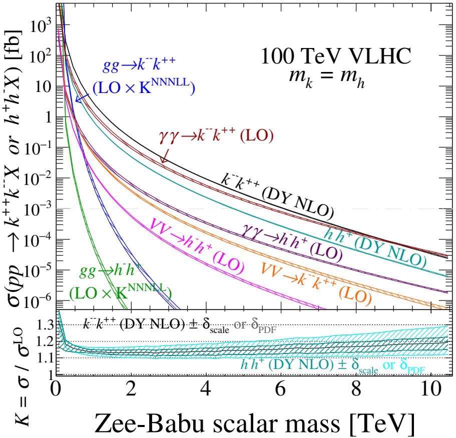

RR [2206.14833]

Guidance from oscillation data

The ratios of $h^{\pm} \to \ell\nu$ couplings are fixed by oscillation data

- ν cannot be tagged at the LHC
- LHC only sensitive to sum over $\nu \implies$ inclusive w.r.t. ν

From flavor-exclusive decay rates:

$$\Gamma(h^{\pm} \to \ell\nu_{\ell}') = \frac{|f_{\ell\ell'}|^2}{4\pi}\, m_h \left(1 - \frac{m_\ell^2}{m_h^2}\right)$$

define flavor-inclusive decay rates:

$$\Gamma(h^{\pm} \to e^{\pm}\nu_X) = \sum_{\ell=e}^{\tau} \Gamma(h^{\pm} \to e^{\pm}\nu_\ell)$$

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$$\mathcal{R}^h_{e\mu} = \frac{\mathrm{BR}(h^\pm \to e^\pm\nu_X)}{\mathrm{BR}(h^\pm \to \mu^\pm\nu_X)} = \frac{|f_{e\mu}|^2 + |f_{e\tau}|^2}{|f_{e\mu}|^2 + |f_{\mu\tau}|^2} = \frac{|\frac{f_{e\mu}}{f_{\mu\tau}}|^2 + |\frac{f_{e\tau}}{f_{\mu\tau}}|^2}{|\frac{f_{e\mu}}{f_{\mu\tau}}|^2 + 1}$$

(equivalent to measuring cross section ratio!)

Using `NuFit`(v5.1)

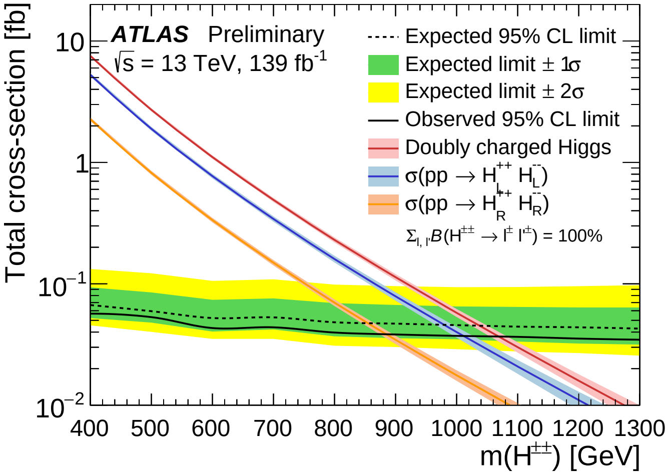
$\mathcal{R}^h_{e\mu}\Big|_{\mathrm{NO}} \approx 0.313^{+55\%}_{-20\%}$ at 3σ

$\mathcal{R}^h_{e\mu}\Big|_{\mathrm{IO}} \approx 0.715^{+3\%}_{-11\%}$ at 3σ

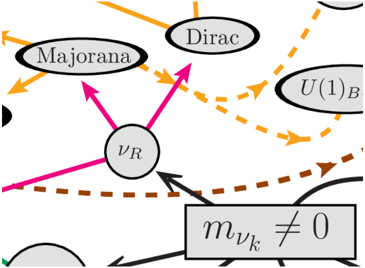
LHC limits on pair production

first direct search for ZB scalars at colliders

$$pp \rightarrow \Delta^{++}\Delta^{--} \rightarrow 4\ell^{\pm} + X \quad (\ell = e, \mu)$$ [2211.07505]



right-handed neutrinos[5]



[5] For reviews at colliders, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]

1 slide for non-experts

To generate Dirac masses for ν like other SM fermions, we need ν_R

$$\mathcal{L}_{\nu \text{ Yuk.}} = -y_\nu \overline{L}\tilde{\Phi}\nu_R + H.c. = -y_\nu \begin{pmatrix} \overline{\nu_L} & \overline{\ell_L} \end{pmatrix} \begin{pmatrix} \langle \Phi \rangle + h \\ 0 \end{pmatrix} \nu_R + H.c.$$

$$= \underbrace{-y_\nu \langle \Phi \rangle}_{=m_D} \overline{\nu_L} \nu_R + H.c. + ...$$

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ν_R do not exist in the SM, so **hypothesize** that they do and $\nu_R = \nu_R^c$:

$$\implies \mathcal{L}_{\text{mass}} = \frac{-1}{2} \underbrace{\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}}_{\text{chiral state}} \underbrace{\begin{pmatrix}0 & m_D \\ m_D & \mu_{\not{L}}\end{pmatrix}}_{\text{mass matrix (chiral basis)}} \begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}$$

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After diagonalizing the mass matrix, identify ν_L (chiral eigenstate) in the SM as a linear combination of mass eigenstates:

$$\underbrace{|\nu_L\rangle}_{\text{chiral state}} = \cos\theta \underbrace{|\nu\rangle}_{\text{light mass state}} + \sin\theta \underbrace{|N\rangle}_{\text{heavy mass state (this is a prediction!)}}$$

technical comments on high- and low-scale Seesaws (for experts)

In pure Type I scenarios (SM+ν_R), tiny m_ν obtained in two ways:

greatly clarified by Pascoli, et al, [1712.07611]

1. **High-scale seesaw**:

$$\Lambda_{LNV} \gg y_\nu \langle \Phi_{SM} \rangle \implies m_\nu \sim m_D \left(\frac{m_D}{\Lambda_{LNV}} \right), \quad m_N \sim \Lambda_{LNV}$$

Generically leads to decoupling of N and LNV from colliders

2. **Low-scale seesaw**:

$$\Lambda_{LNV} \ll y_\nu \langle \Phi_{SM} \rangle \implies m_\nu \sim \Lambda_{LNV} \left(\frac{m_D}{m_R} \right)^2, \quad m_N \sim m_R$$

Known also in literature as Inverse Seesaw, Linear Seesaw, Protective Symmetries, etc.

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- **Corollary for low-scale Type I:** if $m_\nu \approx 0$ experimental scale, i.e., $(\tilde{m}_\nu^2/Q^2) \approx 0 \implies$ approx. L conservation

  Pilaftsis, et al [hep-ph/9901206]; Kersten & Smirnov [0705.3221]; Pascoli, et al, [1712.07611]; w/ Pascoli [1812.08750]

  warning: limits from **LNV** searches not applicable to Dirac N

- **Corollary:** Collider LNV via $N_i \implies$ more new particles! RR [1703.04669]

What about quasi-degenerate Majorana neutrinos?

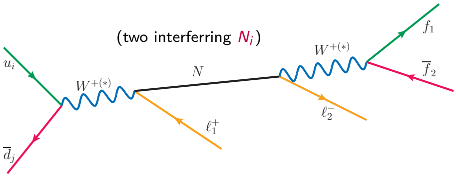
Wolfenstein ('81), Petcov ('82)

Low-scale Seesaws assume SM+ν_R+S $\implies$ 3 mass states per generation:

(for a review, see C. Weiland's thesis [1311.5860])

$$m_\nu \sim \underbrace{\Lambda_{LNV}}_{\text{this is small!!}} \left(\frac{m_D}{m_R}\right)^2 \qquad m_{N_{1,2}} \sim \pm\left(\sqrt{m_R^2 + m_D^2} \mp \mathcal{O}(\Lambda_{LNV})\right)$$

(two interferring N_i)



For super experts (1 slide)

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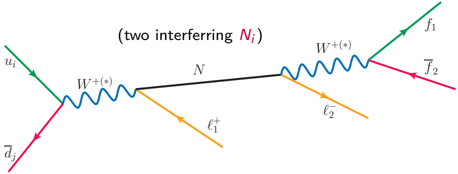
Minus sign $\Longleftrightarrow$ a CP phase $\Longrightarrow$ destructive interference

$$-i\mathcal{M}_{\rm LNV}(W \to \ell^\pm \ell^\pm X) \sim m_{N_1} + e^{i\Delta\phi} m_{N_2} \sim \mathcal{O}(\Lambda_{LNV}) \sim m_\nu$$

(this is small!!)

(two interferring N_i)



Bray,Lee, Pilaftsis [hep-ph/0702294]

In $m_\nu \to 0$ limit (typical for LHC), $m_{N_2} \to m_{N_1}$ and $\Delta\phi \to \pi$:

2 quasi-degenerate, Majorana N_i with opposite CP phase $\approx$ 1 Dirac N_i

For ***discovery purposes***, paramerize active-sterile neutrino mixing :

Atre, Han, et al [0901.3589]

$$\underbrace{\nu_{\ell L}}_{\text{flavor basis}} \approx \underbrace{\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell m'=4} N_{m'=4}}_{\text{mass basis. can be Dirac or Maj.}} \quad \text{(neglect heavier } N_{m'}\text{)}$$

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The SM W couplings to **leptons** in the **flavor basis** are

$$\mathcal{L}_{\rm Int.} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\overline{\ell}\gamma^\mu P_L \nu_\ell\right] + {\rm H.c.}, \qquad \text{where } P_L = \frac{1}{2}(1-\gamma^5)$$

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$\implies$ W couplings to ν and N in the **mass basis** are

$$\mathcal{L}_{\text{Int.}} = -\frac{g_W}{\sqrt{2}} W_\mu^- \sum_{\ell=e}^{\tau} \left[\overline{\ell}\gamma^\mu P_L \left(\sum_{m=1}^{3} U_{\ell m}\nu_m + V_{\ell N} N\right)\right] + \text{H.c.}$$

$\implies$ N is **accessible through** $W/Z/h$ bosons

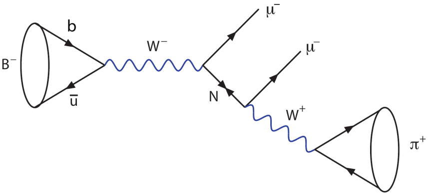
searches for low-mass

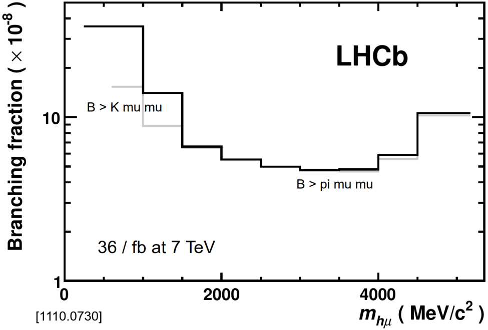
heavy neutrinos (N)

Searches for low-mass N

For $m_N \ll M_W$, N can appear in decays of baryons, mesons, and $\tau^\pm$!

Atre, Han, Pascoli, & Zhang [0901.3589]; Castro & Quintero [1302.1504]; Yuan, Wang ×2 , Ju, & Zhang [1304.3810]; + others





Production rate of mesons $(\pi^\pm, \mathcal{D}, \mathcal{B})$ at colliders is ***big*** $(\sigma_{bX}^{\rm LHC} \sim 0.1$ mb$)$

- sufficient to probe ***tiny*** rates of LNV
- sufficient to probe LFV

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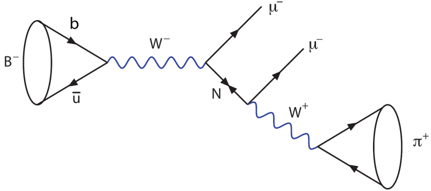

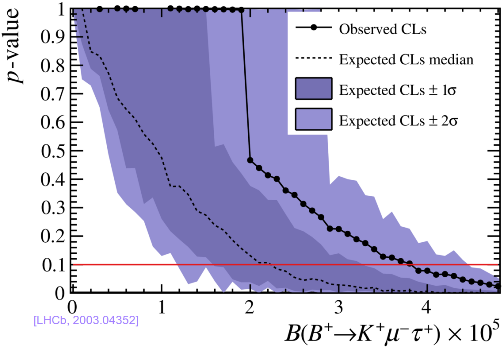

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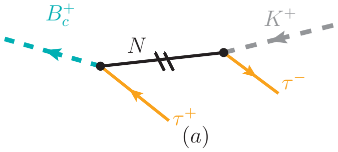
Confusion Theorem $\Longrightarrow$ relative helicity inversion of N

Kayser ('82) , Mohapatra & Pal ('98), Denner, et al (NPB'92, PLB'92)

$\Longrightarrow$ shifts in kinematic distributions

Many dedicated works, e.g., Han, RR, et al [1211.6447]; RR [2008.01092]

Shifts can occur at all scales, e.g., meson decays



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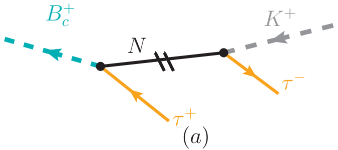
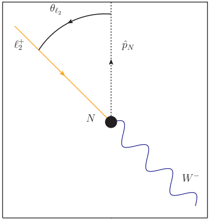
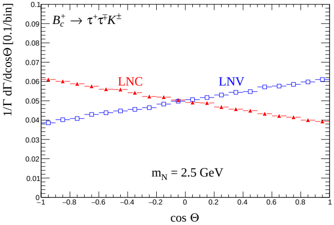


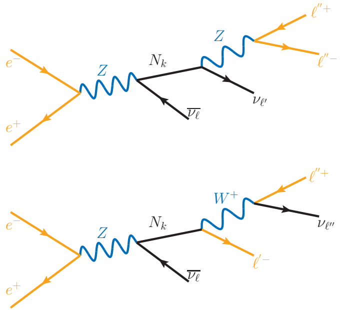


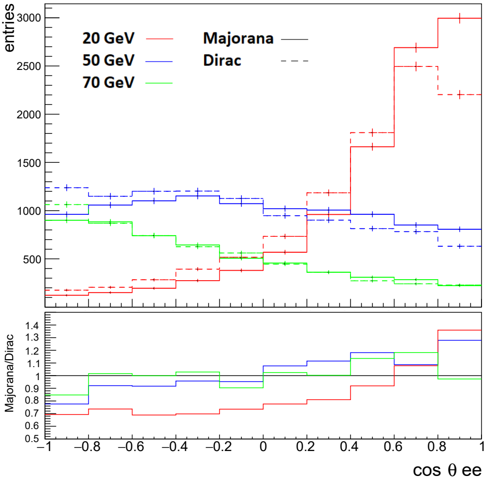


w/ Jeon, Fernandez-Martinez, Kulkarni, et al [(*to appear*)]

Shifts in kinematic distributions also appear when event is not fully reconstructable, e.g. $e^+e^- \to Z \to N\nu \to e^+e^-\nu\nu$

lots of recent activity! E.g., de Gouvea, et al [1808.10518, 2104.05719, 2105.06576 (FCC-ee), 2109.10358]





θ_{ee} = opening between final-state e^+e^-

– Dirac = LNC
– Majorana = LNC+LNV

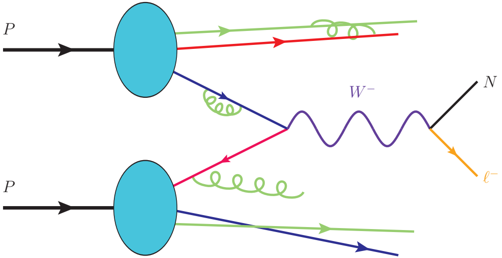
w/ Alimena, Gonzalez Suarez, Sfyrla, Sharma, et al [2203.05502]

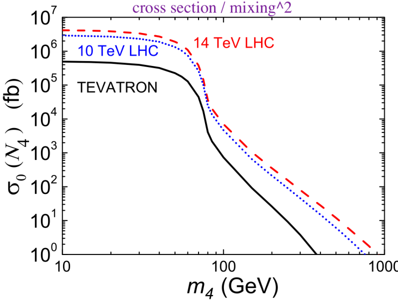
searches for intermediate

heavy neutrinos (N)

Historically, searches for N with $m_N \sim M_W$ relied on decays of $W^{\pm}$, or more generally $(q\overline{q})$ annihilation

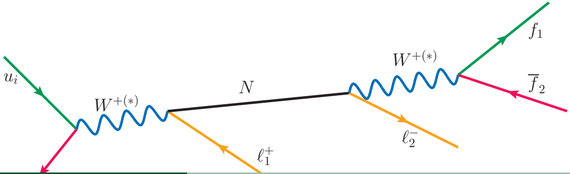
Keung & Senjanovic (PRL'83)





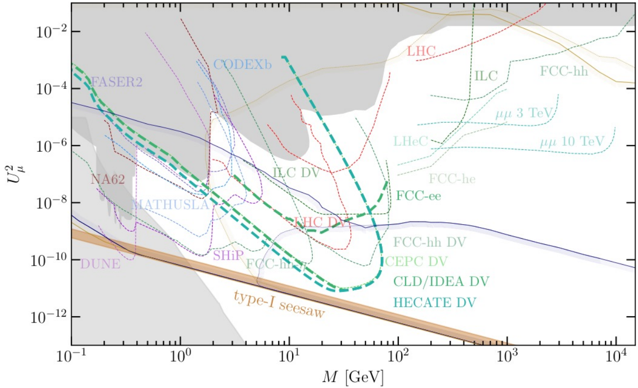
At **ATLAS** and **CMS**, search for $pp \to \ell_i \ell_j$+jets or $\ell_i \ell_j \ell_k$ + nothing

based on seminal works by K&S, del Aguila & Aguilar-Saavedra [0808.2468], and Atre, et al [0901.3589]



Outlook for Current and Future Machines

Community Message: Current + next-gen. facilities can probe *simplest* ($m_{\nu_1} = 0$) leptogenesis scenario w/ ν_R Abdullahi, et al [2203.08039]; w/ Alimena, et al [2203.05502]

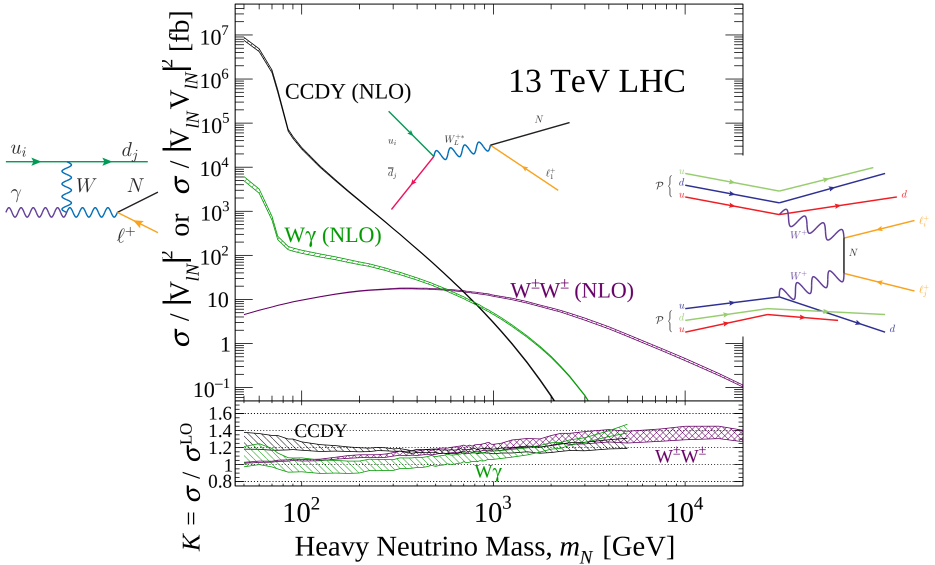


Note: LHC picture evolving with new strategies and channels

Cottin, Helo, Hirsch [1806.05191]; Abada, Bernal, Losada, Marcano [1812.01720]; K. Cheung, H. Ishida, et al [2004.11537] searches for high-mass

heavy neutrinos (N)

Plotted: Normalized production rate $(\sigma/|V|^{2\ (4)})$ vs m_N

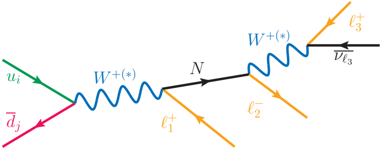


$\gamma W^{\pm}$ and $W^{\pm}W^{\pm}$ scattering drive high-mass scattering rates!

w/ Fuks, Neundorf, Peters, Saimpert [2011.02547; 2012.09882]

what do ATLAS and CMS say?

ATLAS experiment's search for light N with full Run II data



Plotted: Limits on $|V_{\ell N}|^2$ in search for $pp \to 3\ell$+MET

MET $= -|\sum_k \vec{p}_T^{\,k}|$, k=anything

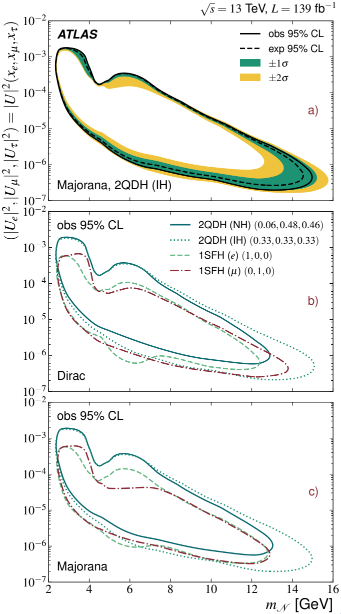
(top) 2 Majorana N

(mid) 1 Dirac N

(btm) 1 Majorana N

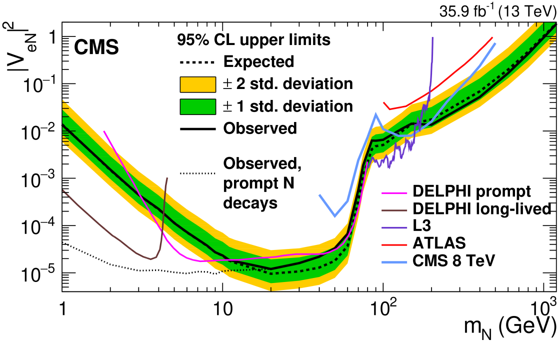
No discovery ☹

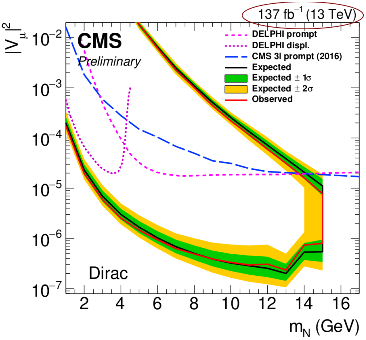
[2204.11988]



CMS experiment's search for light N with Run II data

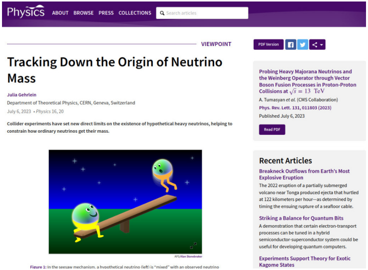
Plotted: Limits on $|V_{\ell N}|^2$ in search for $pp \to 3\ell+\text{MET}$ $\quad (\ell = e, \mu)$



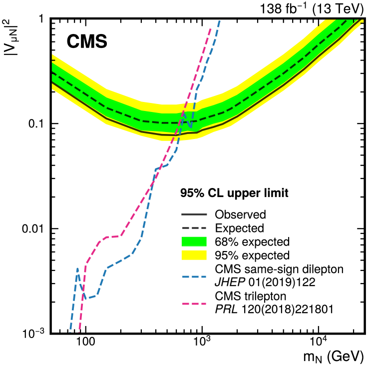


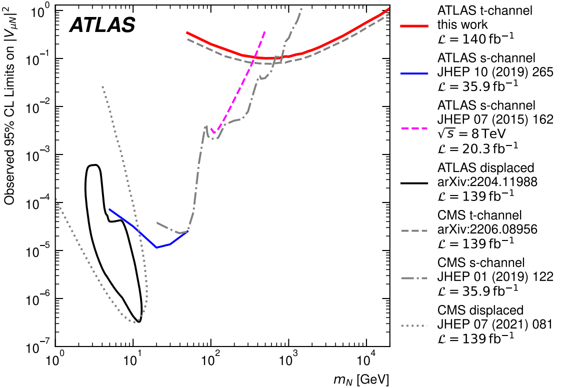
No discovery ☹ but there is hope with $20-30\times$ **more data! ☺**

- (L)CMS experiments's trilepton search for short-lived N [1802.02965]
- (R)CMS search for long-lived N [2201.05578]
- (not shown) same-sign dilepton searches [1806.10905]



Search for $W^\pm W^\pm \to \ell^\pm \ell'^\pm$ quickly adopted by **ATLAS** and **CMS** experiments!



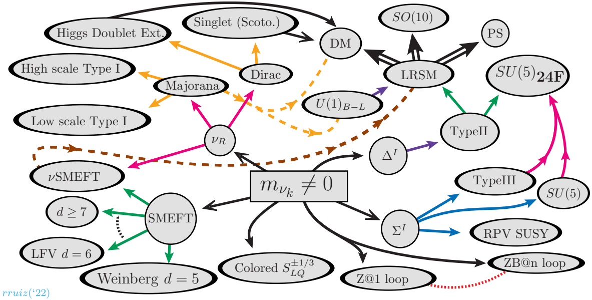


ATLAS (EPJC'23) [2305.14931]

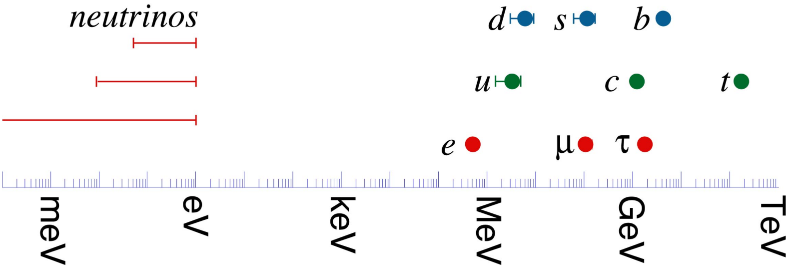
$ee/e\mu$ [2403.15016]

← CMS (PRL'22) [2206.08956]

so much not covered



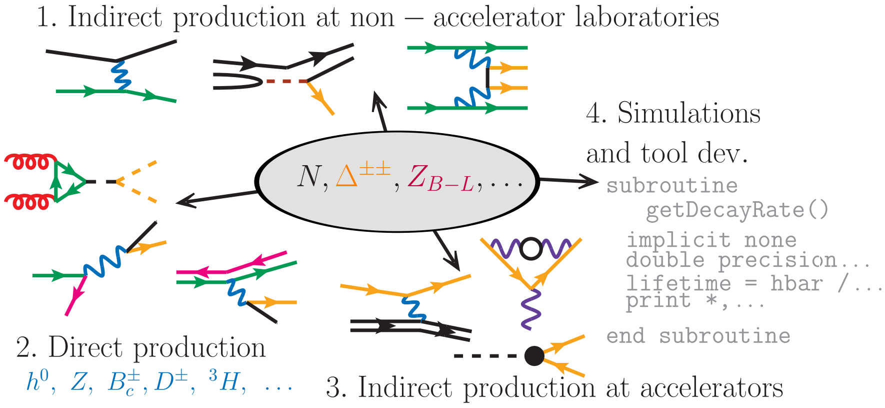
Summary and Outlook



Unambiguous data that neutrino have nonzero masses

- contrary to the Standard Model (SM) of particle physics
- general arguments, more new particles must exist (unclear what kind)

broad implications for experimental physics



Many complementary ways to explore consequences of m_ν

- colliders and ℓ-DIS facilities $\ell\ell$, ℓh, hh ☺
- short and long baseline experiments and νDIS facilities ☺
- space! (underground-, ground-, water-, ice-based telescopes) ☺

Thank you for your time.