LNV@FCC-ee and hh

BLV 2024, Karlsruhe, Germany

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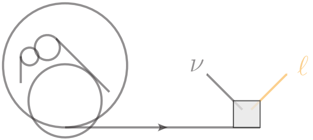

NARODOWE CENTRUM NAUKI

apologies: this is only a subset of available results

the big picture

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

Ma('98) + others

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

$(renormalizability)$

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

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

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

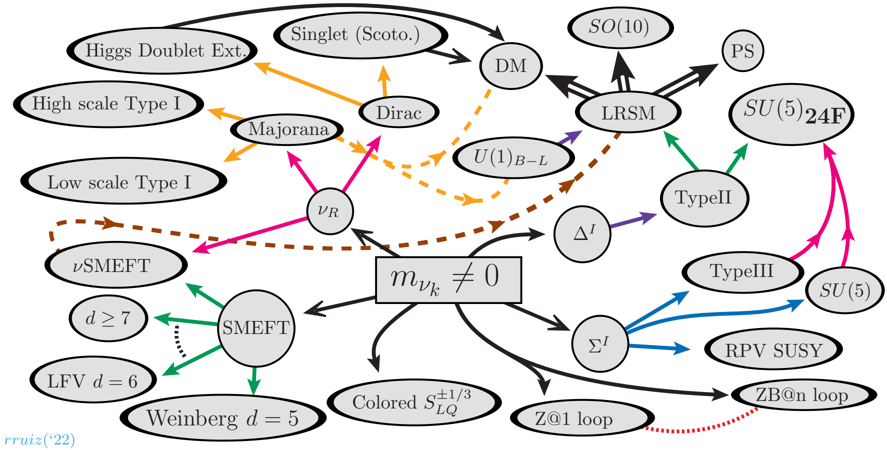
$m_\nu^D = y\langle\Phi_{\rm SM}\rangle$

$m_\nu \neq 0$ **+ 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**

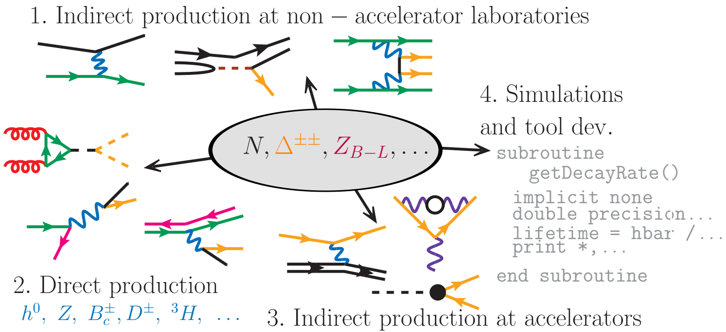
Solution to $m_\nu \neq 0$ can be realized in ***many*** ways!

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



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

broad implications for laboratory-based physics



Many complementary ways to explore consequences of m_ν

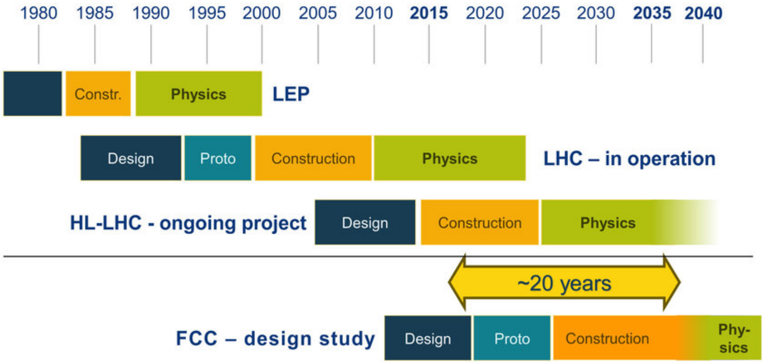
- short and long baseline experiments and νDIS facilities ☺
- rare decay and *in situ* experiments ☺
- colliders and ℓ-DIS facilities $\ell\ell$, ℓh, hh ☺

European Strategy Update (2024-)

Ongoing discussions on European HEP program and future initiatives

European Strategy Update ('20); Snowmass ('21) [2209.14872]; P5 ('23) [2407.19176]

Future Circular Collider (FCC) program
– phase 1: e^+e^- collisions
– phase 2: $pp/p\mathcal{A}/\mathcal{A}\mathcal{A}$ collisions

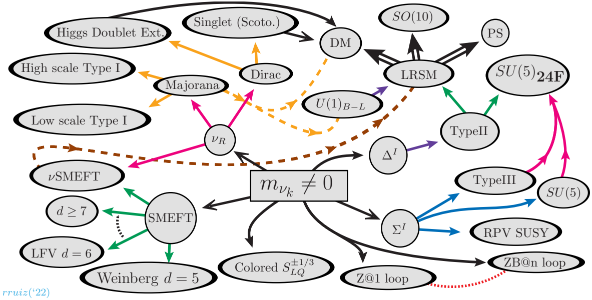


European Strategy Update (2024-)

Topics of discussions:

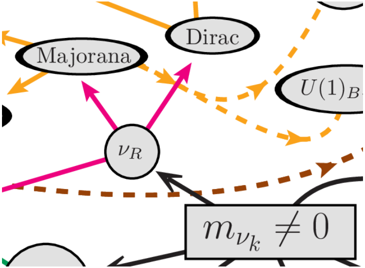
- anticipated timeline of High Luminosity LHC (HL-LHC) milestones ☺
- objectives/milestones and timeline of FCC-*ee* ☺
- objectives/milestones and timeline of FCC-hh ☺
- cost/benefit of accelerated/alternative timelines ☺

collider strategy: infer Majorana nature[1] of ν from LNV via new particles



[1] Black Box Theorem: LNV $\iff$ Majorana ν

right-handed neutrinos[2]



[2] 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

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

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

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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 high-mass 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 #1: In low-scale Type I, if $m_\nu \approx 0$ on scale of expt. i.e., $(m_\nu^2/Q^2)^k \approx 0$
$\implies$ **approx. L conservation**

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

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Corollary #2: Collider-scale LNV via N_i with $m_N \gtrsim M_W$
$\implies$ **larger active particle spectrum!** RR [1703.04669]

the benchmark setup

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

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

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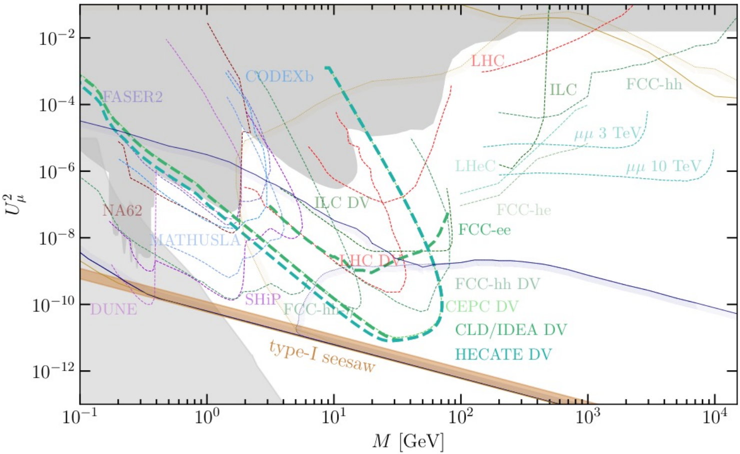
$\implies$ W couplings to ν and N in the **mass basis** are

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

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

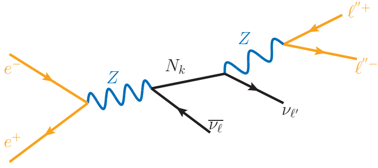
heavy neutrinos@FCC-ee

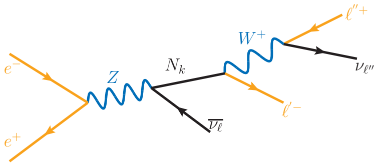
Community Message: Current + next-gen. facilities can probe *simplest* $(m_{\nu_1} = 0)$ leptogenesis scenario w/ ν_R Abdullahi, et al [2203.08039]; w/ Alimena, et al [2203.05502]



Polarization measurements are priority: subtle helicity inversion $\Longrightarrow$ differences in kinematics for Dirac LNC vs Majorana LNC+LNV

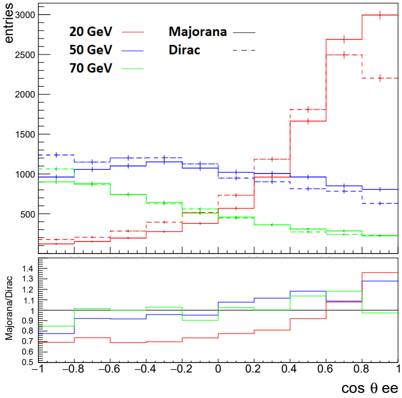
Kayser ('82) , Mohapatra & Pal ('98), Denner, et al (NPB'92, PLB'92); Han, RR, et al [1211.6447]; RR [2008.01092]





w/ Alimena, Gonzalez Suarez, Sfyrla, Sharma, et al [2203.05502]; see also de Gouvea, et al [1808.10518, 2104.05719, 2105.06576 (FCC-ee), 2109.10358]

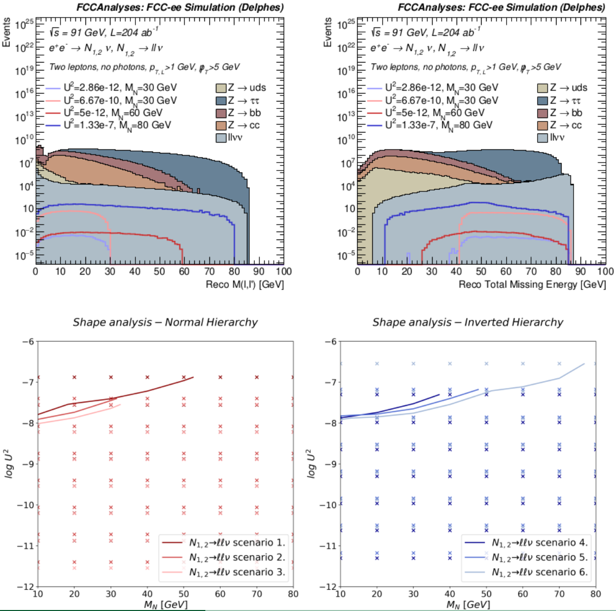
θ_{ee} = opening between outgoing $\ell^+\ell^-$



– Dirac = LNC
– Majorana = LNC+LNV

NEW: update with FCC-ee reconstruction framework for two-N_k setup

Ajmal, et al [2410.03615]

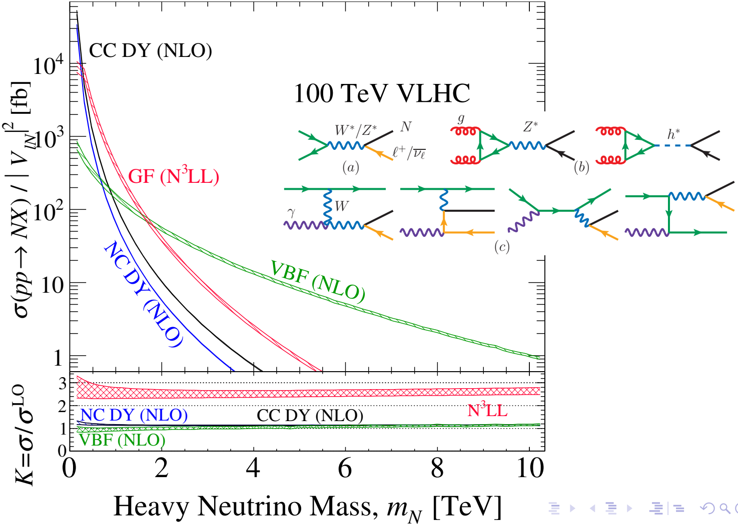


what about heavier N?

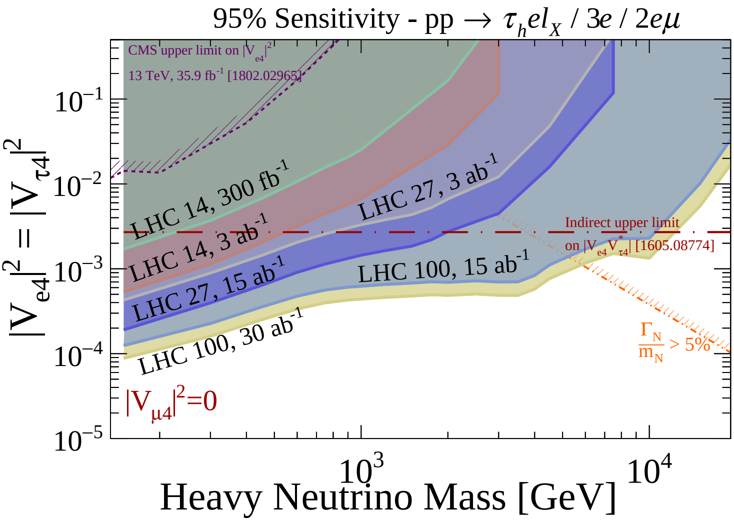
heavy neutrinos@FCC-hh

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

w/ Pascoli, et al [1812.08750]

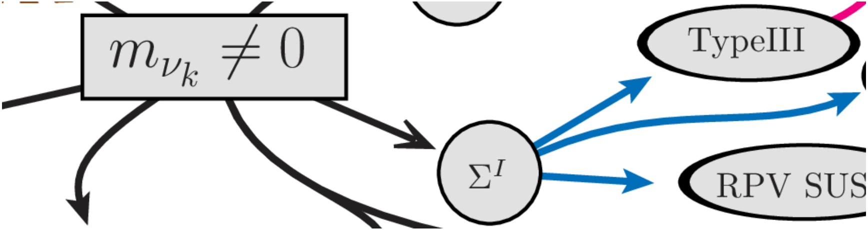


heavy neutrinos@FCC-hh



Only a few results. See the big paper for various flavor, Dirac vs Majorana, and $\sqrt{s}$ permutations [1812.08750]

Type III Seesaw[3]

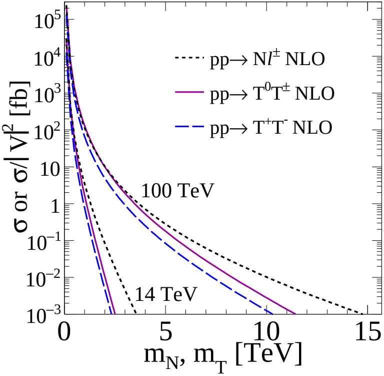


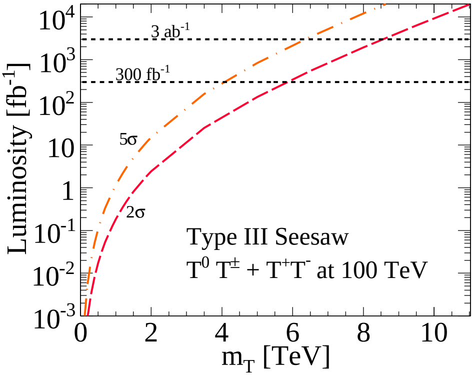
[3] Foot, et al ('89)

Type III Seesaw postulates $SU(2)_L$ letponic triplet (T^+, N^0, T^-)

lots of rich physics Bajc, Senjanovic [hep-ph/0612029]; PF Perez [hep-ph/0702287]; Abada, et al [0707.4058, 0803.0481]; +++

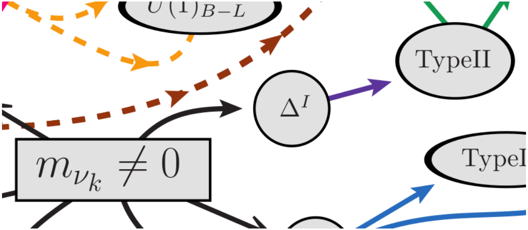
- heavy electron and heavy neutrino carry weak isospin charges
- $\Longrightarrow$ couples to $W/Z/\gamma$ via gauge charges
- typical decay modes $T^\pm, N \to \ell^\pm/\nu + V$





w/ Cai, Han, Li [1711.02180]

Type II Seesaw[4]



[4] 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

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

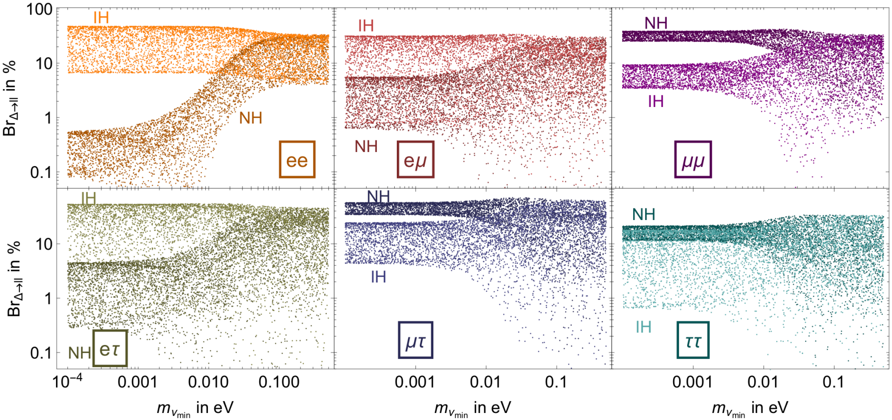
$$\ni -\frac{1}{2}\underbrace{\left(\sqrt{2}y_\Delta^{ij}v_\Delta\right)}_{=m_\nu^{ij}}\overline{\nu^{jc}}\nu^i$$

Few free parameters $\implies$ rich 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

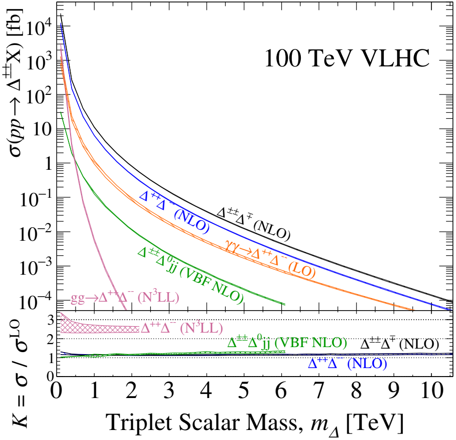
$$\Gamma(\Delta^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim y_{\Delta}^{ij} \sim (U^*_{\rm PMNS}\tilde{m}_{\nu}^{\rm diag}U^{\dagger}_{\rm PMNS})_{ij}$$

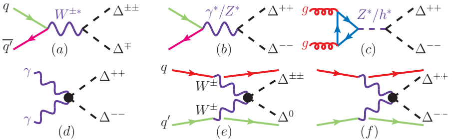


Type II@FCC-hh

$\Delta^{\pm\pm}$, $\Delta^{\pm}$, Δ^{0}, ξ^{0} production
driven by gauge couplings to W, Z, γ

($\Longrightarrow$ unambiguous xsec prediction!)





Fuks, Nemevšek, RR [1912.08975]

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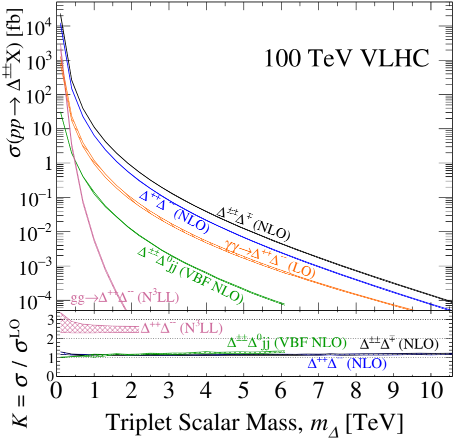

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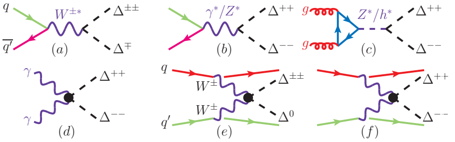
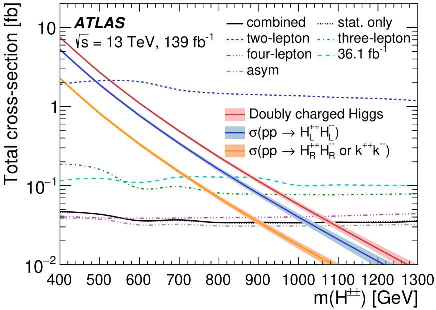


$$pp \to \Delta^{++}\Delta^{--} \to 4\ell^{\pm} + X$$

($\ell = e, \mu$) [2211.07505]



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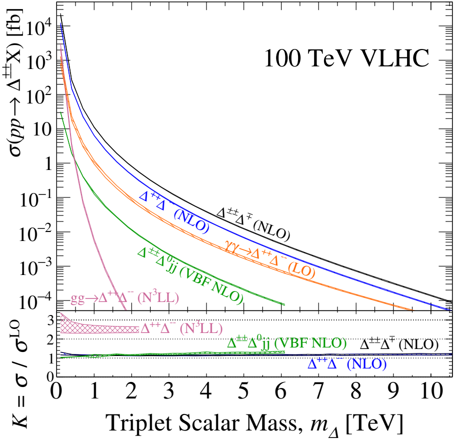
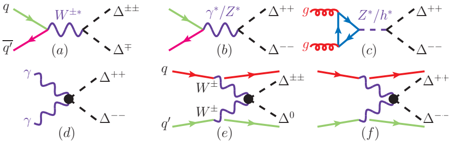
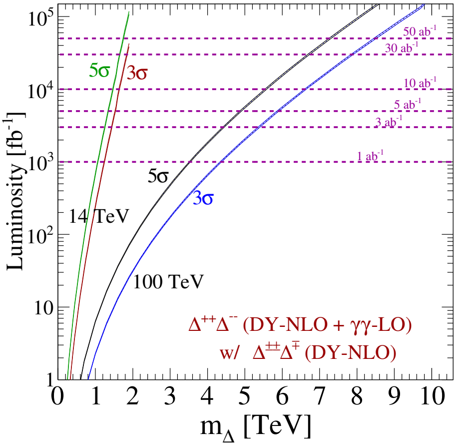
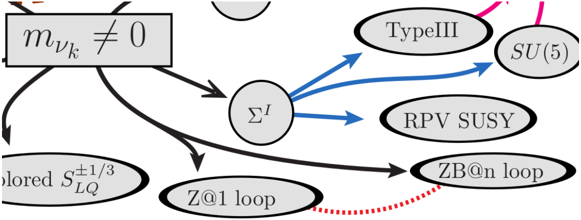






Fuks, Nemevšek, RR [1912.08975]

Zee-Babu Model[5]



[5] Zee ('85×2), Babu ('88)

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

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

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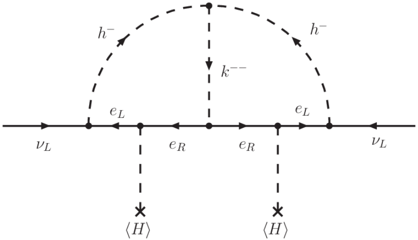
$$\mathcal{L}_{\rm ZB} = \mathcal{L}_{\rm SM} + (D_\mu k)^\dagger (D^\mu k) + (D_\mu h)^\dagger (D^\mu h) + + \left(\mu_{\not{L}}\ hhk^\dagger + \text{H.c.}\right)$$
$$\left[f_{ij}\ \overline{\tilde{L}^i} L^j h^\dagger + g_{ij}\ \overline{(e_R^c)^i} e_R{}^j k^\dagger + \text{H.c.}\right] + \ldots$$



[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 $\implies$ rich 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:

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

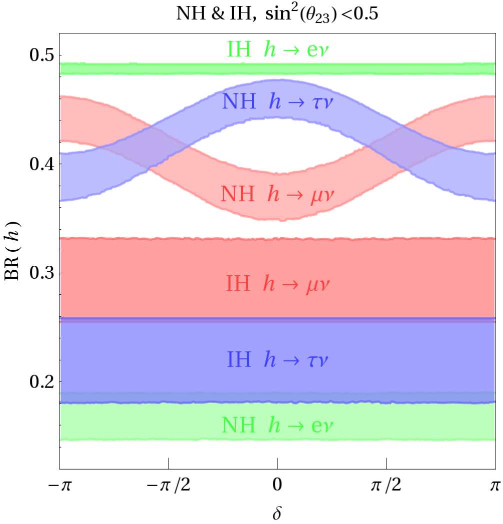
$$\frac{f_{e\mu}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} - \tan\theta_{13}\sin\theta_{23}e^{-i\delta}$$

Inverse ordering:

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

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

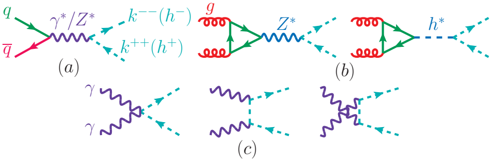
$$\frac{f_{e\tau}}{f_{e\mu}} = -\tan\theta_{23}.$$

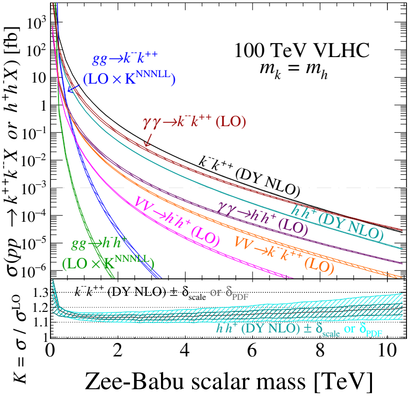


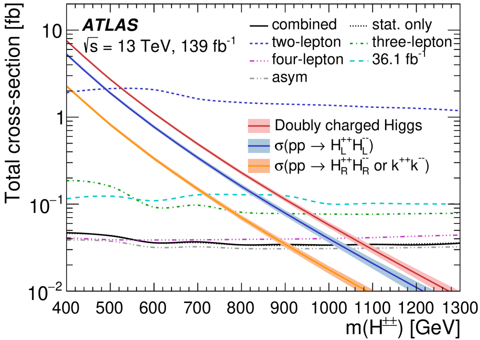
Zee-Babu@FCC-hh

$k^{\pm\pm}$, $h^{\pm}$ couple directly to Z, γ via gauge couplings

($\Longrightarrow$ unambiguous xsec prediction!)



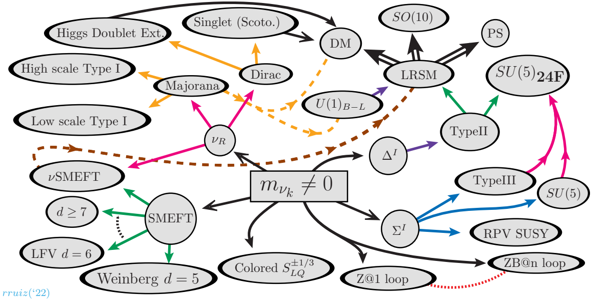


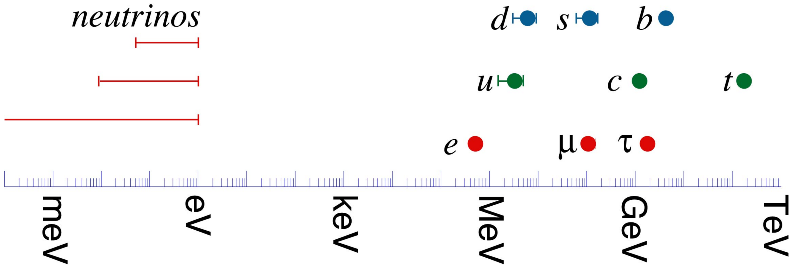


RR [2206.14833]

FCC-hh: $m_k \sim 4 - 5$ TeV with $\mathcal{L} = 10 - 50$ fb^{-1} at $\sqrt{s} = 100$ TeV

so much not covered





Unambiguous data that neutrino have nonzero masses

- general arguments, more new physics must exist (unclear what kind)
- reach of FCC-ee/hh known for many popular Seesaw models

(more work still needed!)

- until clear guidance from TH or EXP, important to explore broadly

for a review, see Cai, Han, Li, RR [1711.02180]

one more thing

senior postdoc vacancy in Krakow

3-year Adv/Senior Postdoctoral Researcher in Theoretical Particle Physics

Cracow, INP • Europe

hep-ph hep-th nucl-th PostDoc

Deadline on Nov 15, 2024

Job description:
Job Title: Adv/Senior Postdoctoral Researcher

The Department of Theoretical Particle Physics (NZ42) at the **Institute of Nuclear Physics – Polish Academy of Sciences** (IFJ PAN) in Krakow, Pola
postdoctoral appointment ("adjunct" in Polish) in the group of Prof. Richard Ruiz.

inspirehep.net/jobs/2829053

Thank you for your time.

backup

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 $\rightarrow$

- u, d and e^- all carry weak charges

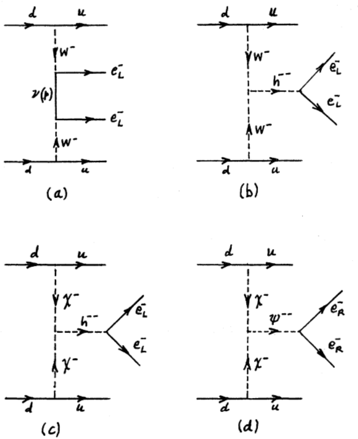


FIG. 1. Diagrams for neutrinoless double-β decay in an SU(2)×U(1) gauge theory. The standard diagram is Fig. 1(a). It is the only one which contains a virtual neutrino (of four-momentum p). d and u are the down and up quarks.

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 $\rightarrow$
- 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]

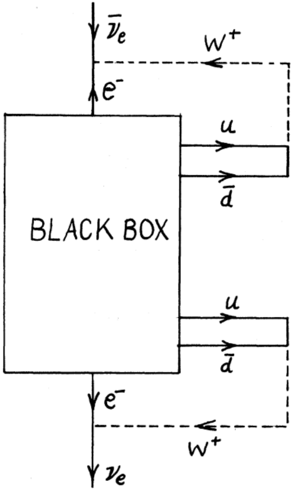
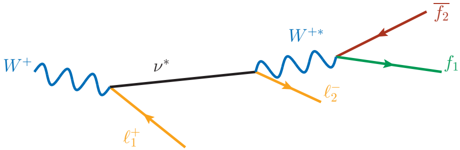


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

The Dirac-Majorana Confusion Theorem

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

refined later by Mohapatra & Pal ('98)



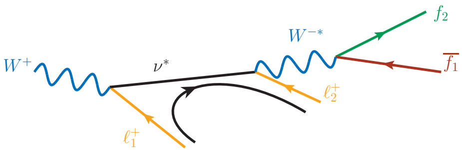
The helicity amplitude for the LNC process $W^+ \to \ell_1^+ \ell_2^- f\overline{f'}$ is

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

Intuition: successive LH chiral interactions $\implies$ LH helicity eigenstate

$$T^{\rho\mu}_{LNC} = \overline{u_L}(p_2)\gamma^\rho P_L \times (\underbrace{\not{p}_\nu}_{\text{LH helicity state}} + \underbrace{m_\nu}_{P_L m_\nu P_R = 0}) \times \gamma^\mu P_L v_R(p_1)$$

$$\implies \mathcal{M}_{LNC} \sim \frac{p_\nu}{p_\nu^2 - m_\nu^2}$$



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

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

Intuition: CPT Theorem $\implies$ C-inversion = PT-inversion

$$T^{\rho\mu}_{LNV} = \overline{u_R}(p_2)\gamma^\rho \underbrace{P_R}_{CPT:\ P_L \to P_R} \times \big(\underbrace{\not{p}_\nu}_{P_R \not{p}_\nu P_R = 0} + \underbrace{m_\nu}_{\text{RH helicity state}} \big) \times \gamma^\mu P_L v_R(p_j)$$

$$\implies \mathcal{M}_{LNV} \sim \frac{m_\nu}{p_\nu^2 - m_\nu}$$

Confusion Theorem: In SM + Majorana ν, the rate of **LNV** $\sim \mathcal{O}(m_\nu)$; in the limit where $(m_\nu^2/M_W^2) \to 0$, Dirac behavior recovered

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

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

What about quasi-degenerate Majorana neutrinos?

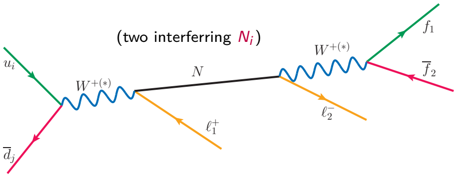
Wolfenstein ('81), Petcov ('82)

Low-scale Seesaws assume SM$+\nu_R+$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

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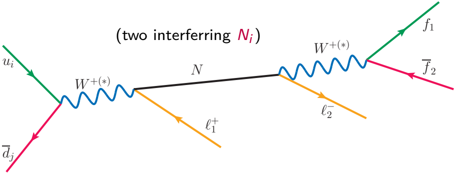
Minus sign $\iff$ a CP phase $\implies$ destructive interference

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

(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