LNV and LFV @ FCC and HL-LHC (without ν_R)

νPhysics, IPPP, Durham

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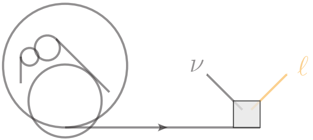
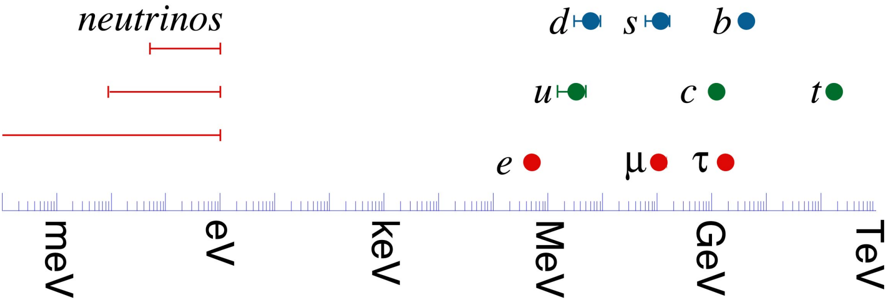


this talk:

- summary of HL-LHC + FCC sensitivity to ν mass models ☺
  - scenarios without ν_R (see talks by S. King, T. Schwetz-Mangold, M. Mitra, & A. Titov!)
- many numbers already available from previous ESU/Snowmass ☺
  - broad review on LNV@Colliders (Front.'17) [1711.02180]
  - review for (pseudo)Dirac and Majorana N (JHEP'18) [1812.08750]
  - lots of newer works by the community
- 20' too little time for everything ☹

the big picture

Problem: according to the SM, $m_\nu = 0$. (too few ingredients but data obviously disagree!)



Discovery of neutrino masses $\Longrightarrow$ **several open questions:**

- ν have mass. What is generating m_ν?
- ν masses are *tiny*. What sets the scale of m_ν?
- m_ν are nearly degenerate. What sets the pattern of m_ν?
- ν carry no QCD/QED charge. Are $\nu, \overline{\nu}$ the same (Majorana)?

guidance from theory

$m_\nu \neq 0 \implies$ 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

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

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

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$(renormalizability)$

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

$(gauge\ invariance)$

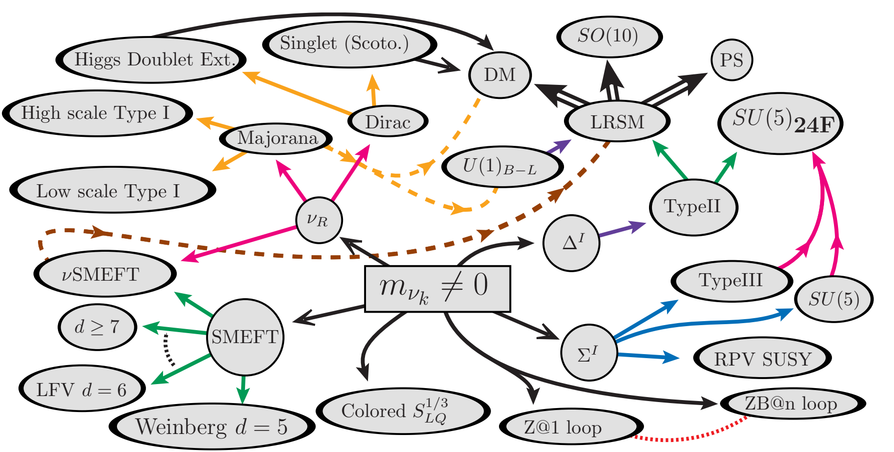
$m_\nu^L = y \langle \Delta \rangle$ or new dynamics — $m_\nu^D = y \langle \Phi_{SM} \rangle$

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

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

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

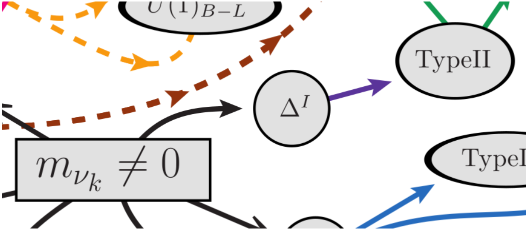
Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + *many* others



collider strategy: infer Majorana nature[1] or mass mechanism of ν from LNV+LFV with new particles

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

Type II Seesaw[2]



[2] 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** $\text{SU}(2)_L$ triplet with **lepton number** $L = -2$

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

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The mass scale $\mu_{h\Delta}$ breaks lepton number, and induces $\langle\Delta\rangle \neq 0$:

$$\langle\hat{\Delta}\rangle = v_\Delta \approx \frac{\mu_{h\Delta} v_{\rm EW}^2}{\sqrt{2} m_\Delta^2}$$

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

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

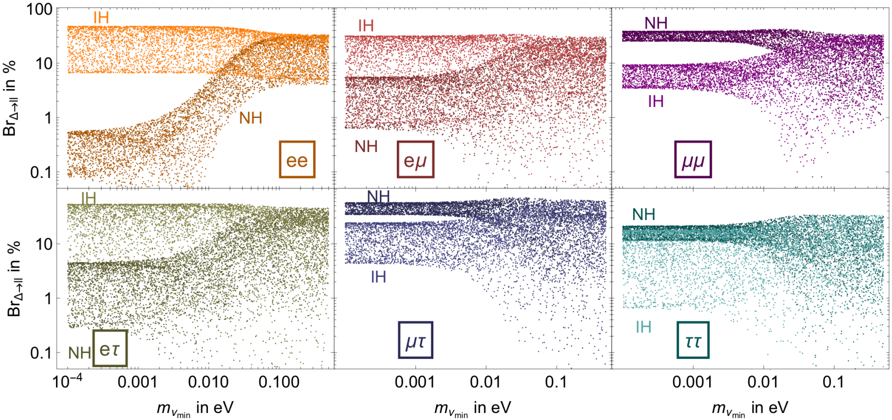
$$\ni -\frac{1}{2}\underbrace{\left(\sqrt{2} y_\Delta^{ij} v_\Delta\right)}_{=m_\nu^{ij}}\overline{\nu^{jc}}\nu^i$$

Few free parameters $\Longrightarrow$ 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

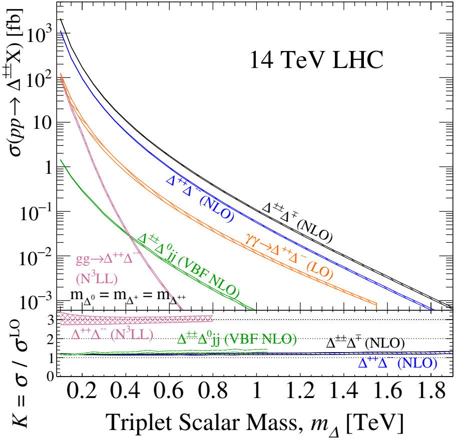
$$\Gamma(\Delta^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}) \sim y_{\Delta}^{ij} \sim (U^{*}_{\rm PMNS}\,\tilde{m}_{\nu}^{\rm diag}\,U^{\dagger}_{\rm PMNS})_{ij}$$

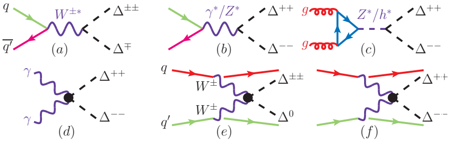


Type II@HL-LHC

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

($\implies$ unambiguous xsec prediction!)





Fuks, Nemevšek, RR [1912.08975]

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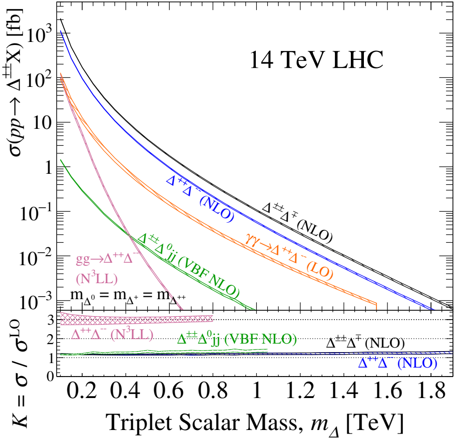

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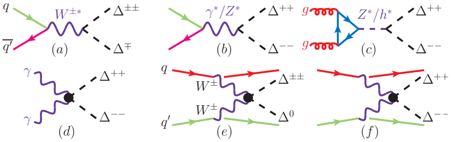
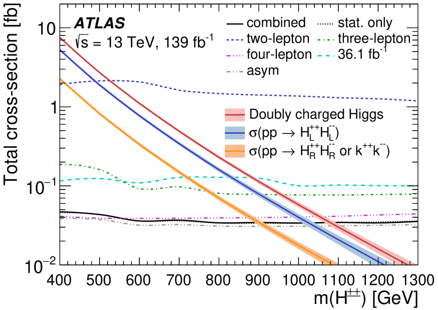


$$pp \rightarrow \Delta^{++}\Delta^{--} \rightarrow 4\ell^{\pm} + X$$

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



Type II@FCC-hh

$\Delta^{\pm\pm}$, $\Delta^{\pm}$, Δ^{0}, ξ^{0} production
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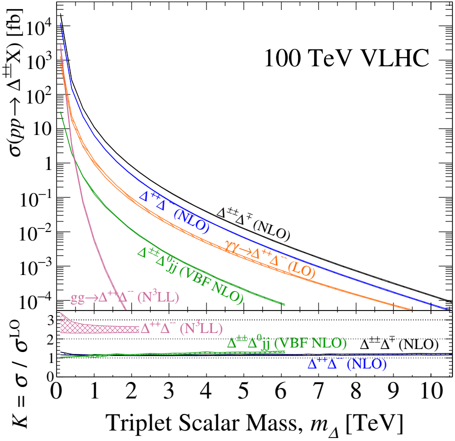
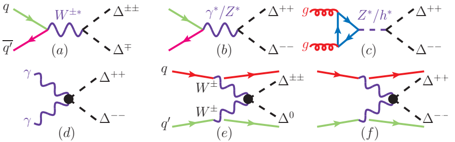
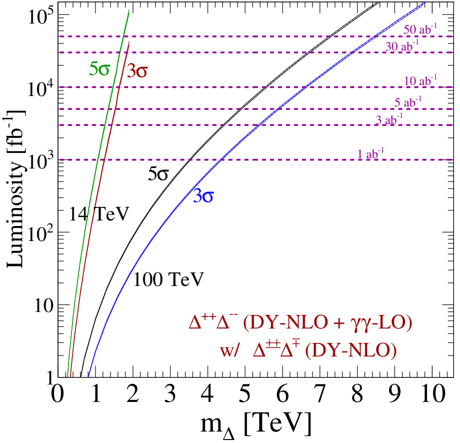






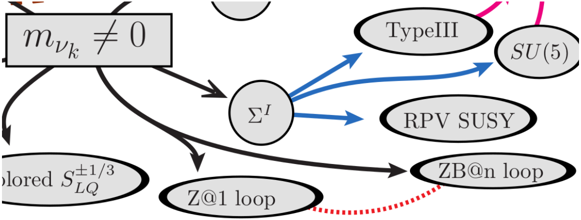
Fuks, Nemevšek, RR [1912.08975]

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

celebrate! ☺

charged scalars $H^{\pm\pm}$, $H^{\pm}$ are not unique

Zee-Babu Model[3]



[3] 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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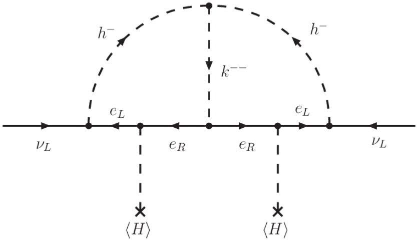
$$\mathcal{L}_{\rm ZB} = \mathcal{L}_{\rm SM} + (D_\mu k)^\dagger (D^\mu k) + (D_\mu h)^\dagger (D^\mu h) + + \left(\mu_{\not{L}}\ hhk^\dagger + \text{H.c.}\right)$$
$$\left[f_{ij}\ \overline{\tilde{L}^i} L^j h^\dagger + g_{ij}\ \overline{(e_R^c)^i} e_R{}^j k^\dagger + \text{H.c.}\right] + \dots$$



[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 $\Longrightarrow$ 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:

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

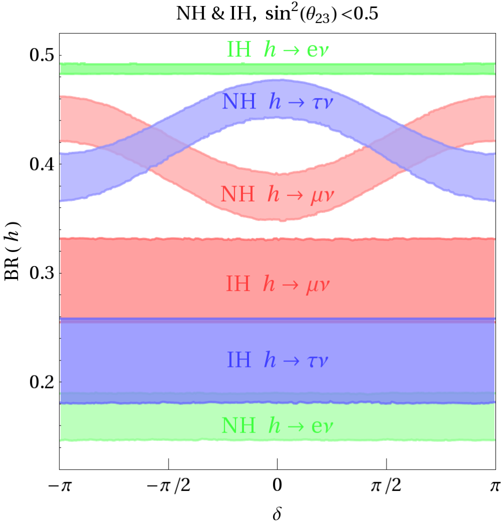
$$\frac{f_{e\mu}}{f_{\mu\tau}} = \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} - \tan\theta_{13}\sin\theta_{23}e^{-i\delta}$$

Inverse ordering:

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

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

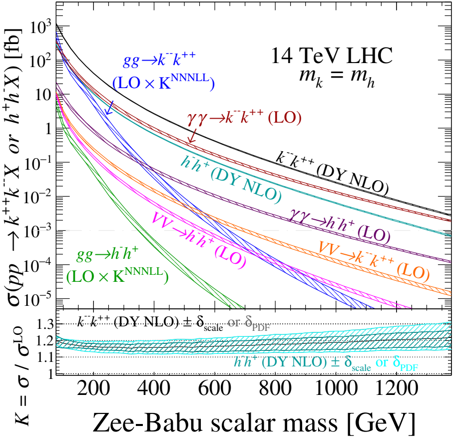
$$\frac{f_{e\tau}}{f_{e\mu}} = -\tan\theta_{23}.$$

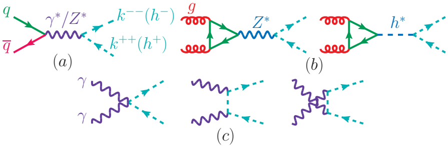


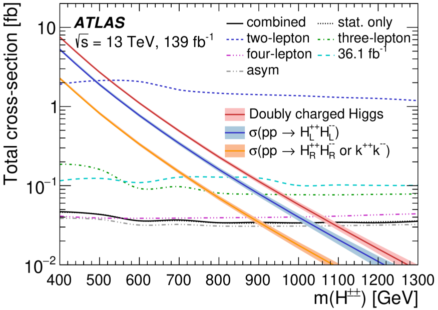
Zee-Babu@HL-LHC

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

($\Longrightarrow$ unambiguous xsec prediction!)







HL-LHC: up to $m_k \sim 1$ TeV with $\mathcal{L} = 3$ ab^{-1} at $\sqrt{s} = 14$ TeV

RR (JHEP'22) [2206.14833]

Zee-Babu@FCC-hh

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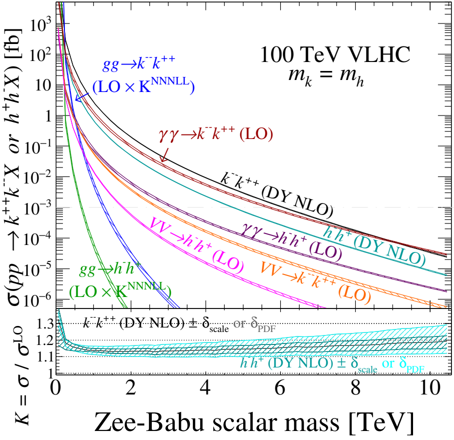
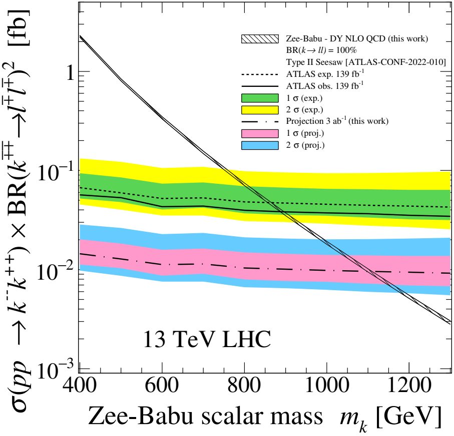




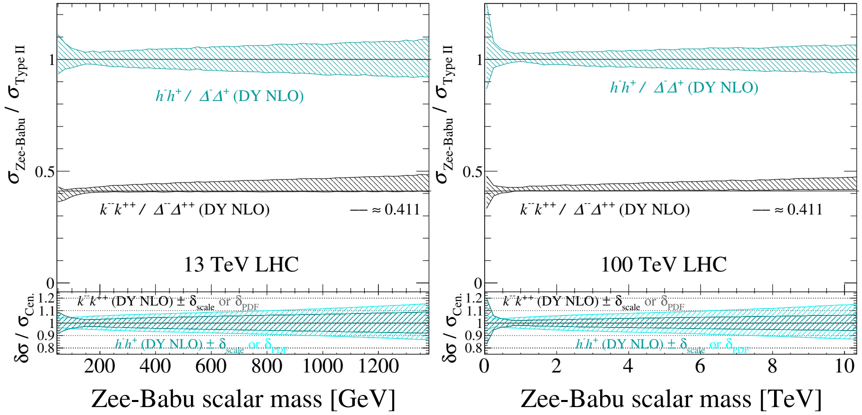
FCC-hh: up to $m_k \sim 4 - 5$ TeV with $\mathcal{L} = 10 - 50$ ab^{-1} at $\sqrt{s} = 100$ TeV

RR (JHEP'22) [2206.14833]

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

Usual argument: Different gauge quantum numbers $\implies$ different σ

- In principle, this is a good arguement
- ... but difference ($1\times$ or $2\times$) can be absorbed by BR **(via LNV coupling)**



silver lining

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:

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

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

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

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

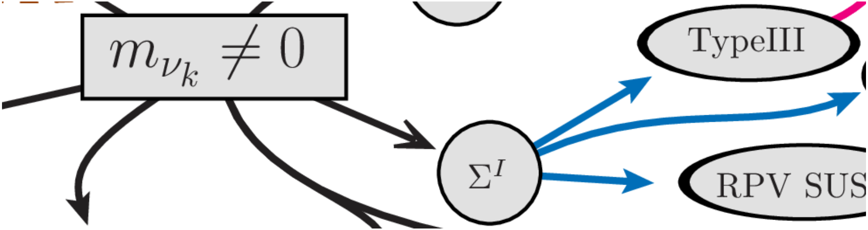
(equivalent to measuring cross section ratio!)

Using NuFit(v5.1)

$$\mathcal{R}^h_{e\mu}\Big|_{\mathrm{NO}} \approx 0.313 \quad \text{(+smallish unc.)}$$

$$\mathcal{R}^h_{e\mu}\Big|_{\mathrm{IO}} \approx 0.715 \quad \text{(+smallish unc.)}$$

Type III Seesaw[4]

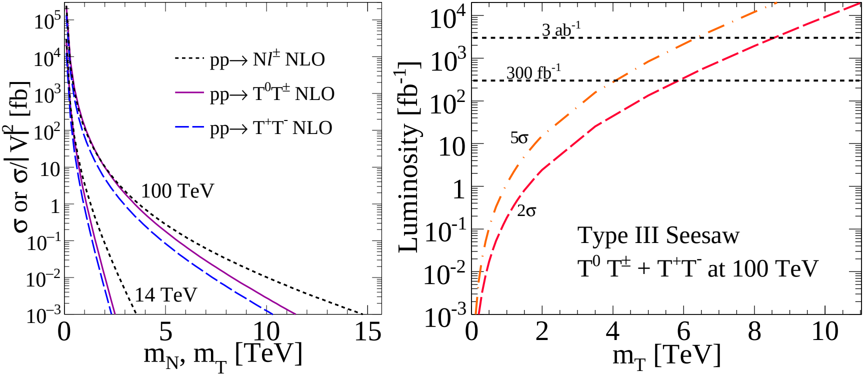


[4] Foot, et al ('89)

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

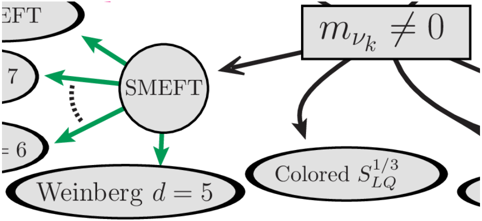
lots of rich physics Bajc, Senjanovic [hep-ph/0612029]; PF Perez [hep-ph/0702287]; Abada, et al [0707.4058, 0803.0481]; +++

- heavy electron and heavy neutrino carry weak isospin charges
- $\implies$ 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]

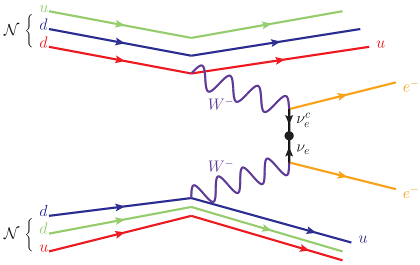
Weinberg Operator[5]



[5] Weinberg ('79); w/ Fuks, et al PRD('21)[2012.09882]

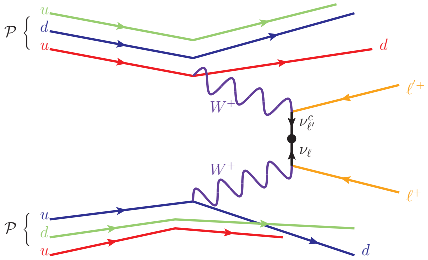
Weinberg operator at the LHC

In many ways $W^\pm W^\pm \to \ell^\pm \ell'^\pm$ is the high-energy realization of $0\nu\beta\beta$



First constraints of Weinberg operator ever for $\mu\mu$ [2206.08956; 2305.14931] and $e\mu$ [2403.15016] (**new!**), and outside nuclear environment for ee [2403.15016] (**new!**)

$$\Lambda/|C_{\ell\ell'}| \gtrsim 2.5 - 5.6 \text{ TeV} \iff |m_{\ell\ell'}| \lesssim 11 - 24 \text{ GeV for } ee, e\mu, \mu\mu$$

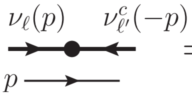


The helicity amplitude for the $0\nu\beta\beta$ process $q\overline{q'} \to \ell_1^+\ell_2^+\overline{f}\overline{f'}$ is

$$\mathcal{M}_{LNV} = J^{\mu}_{f_1 f_1'} J^{\nu}_{f_2 f_2'} \Delta^{W}_{\mu\alpha}\Delta^{W}_{\nu\beta} \underbrace{T^{\alpha\beta}_{LNV}\mathcal{D}(p_\nu)}_{\text{lepton current}}$$

Difficult to simulate since Weinberg op. modifies propagator of ν_ℓ

modern Monte Carlo tools work in mass basis and do not like the idea of modifying $\langle 0|\overline{\nu_{\ell'}}\nu_\ell|0\rangle$



$$= \frac{i\not{p}}{p^2}\ \frac{-iC_5^{\ell\ell'}v^2}{\Lambda}\ \frac{i\not{p}}{p^2} = \frac{im_{\ell\ell'}}{p^2}$$

Solution: Treat vertex as a particle! Invent unphysical Majorana fermion with (small) mass $m_{\ell\ell}$ that couples to all lepton flavors

recovers right behavior!

$$T^{\alpha\beta}_{LNV}\mathcal{D}(p_\nu) \propto \gamma^\alpha P_L \frac{i(\not{p}+m_{\ell\ell'})}{p^2-m^2_{\ell\ell'}}\gamma^\beta P_R = \gamma^\alpha P_L \frac{im_{\ell\ell'}}{p^2} P_L \gamma^\beta \times \left[1 + \mathcal{O}\left(\left|\frac{m^2_{\ell\ell'}}{p^2}\right|\right)\right]$$

Plotted: Normalized production rate $(C_5 = 1)$ vs scale (Λ)

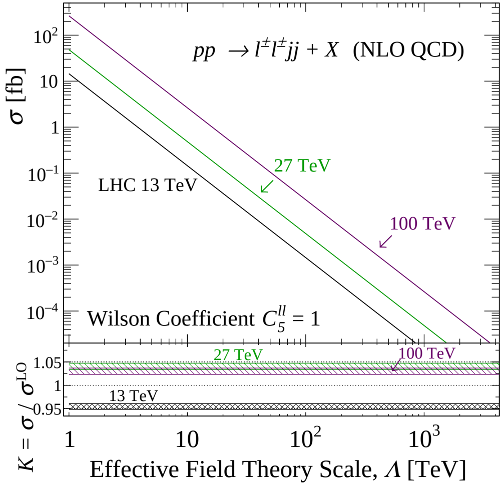
w/ Fuks, Saimpert, et al (PRD'21) [2012.09882]

Full $2 \to 4$ calculation at NLO(+PS) in QCD is more involved

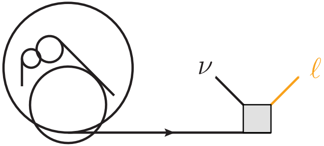
Used mg5amc + SMWeinberg UFO libraries

Driven by $W_0^+ W_0^+$ scattering

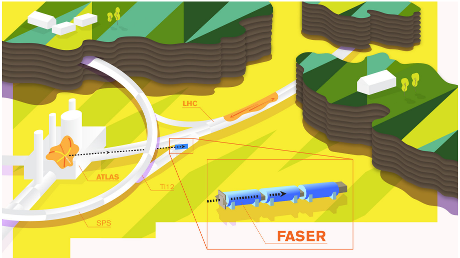
$\hat{\sigma}(W_0^+ W_0^+ \to \ell^+ \ell^+) \sim \frac{|C_5^{\ell\ell}|^2}{18\pi\Lambda^2}$

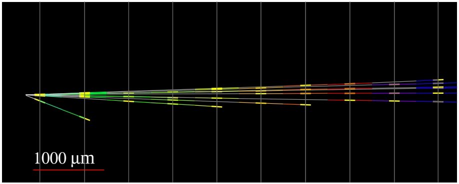


what is on the horizon?



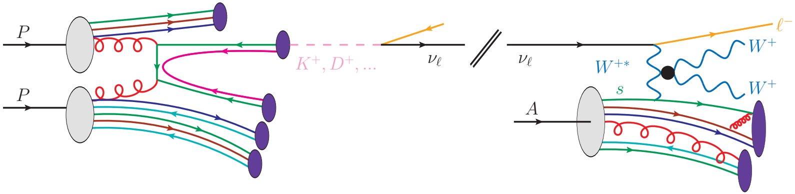
Over past few years, the LHC has been established as an intense (laboratory) source of TeV-scale neutrinos (ν) **(a remarkable expt. achievement!)**





Candidate LHC neutrino event from FASER's pilot run

New programs (FASER, SND@LHC) **now collecting ν-nucleus scattering data**



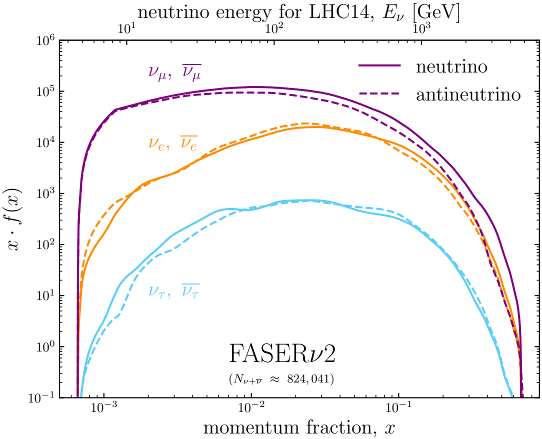
ν **fluxes** from LHC **(a) are large** and **(b) span $1-4$ TeV in energy**

ν **fluxes** from LHC **(a) are large** and **(b) span $1 - 4$ TeV in energy**

Kling & Nevay (PRD'21)

ν **fluxes can be normalized to be likelihood functions $f_\nu(x)$ ...** ☺

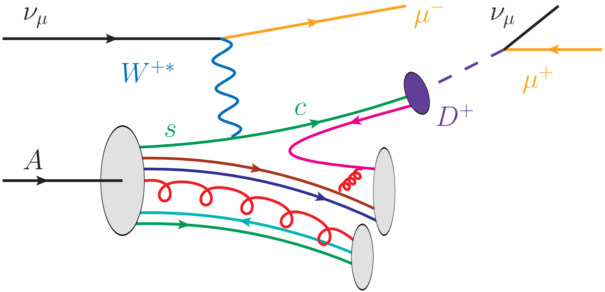
see, e.g., van Groenendijk, Krack, Rojo, et al [2407.09611]



[in progress]

... and used to calculate arbitrary high-p_T processes

$$d\sigma(\nu\mathcal{A}\to\ell X) = \underbrace{\sum_{f,k,X_n}}_{inclusive} \underbrace{\Delta_{kk'}}_{\text{shower/RGE}} \otimes \underbrace{f_{\nu_f}\otimes f_{k'}}_{\text{PDF}} \otimes \underbrace{d\hat{\sigma}_{\nu_f k'\to X_n}}_{\text{hard scattering}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{\rm NP}^{2+k}}{Q^{2+k}}\right)}_{\text{HT}}$$



… and used to calculate arbitrary high-p_T processes

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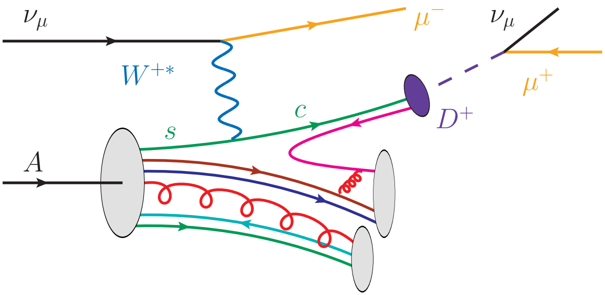
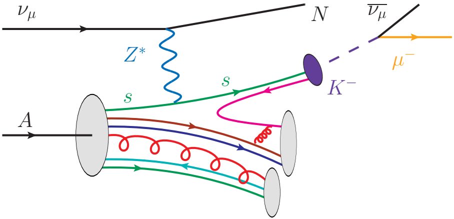
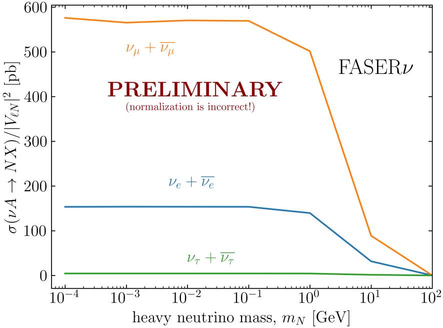


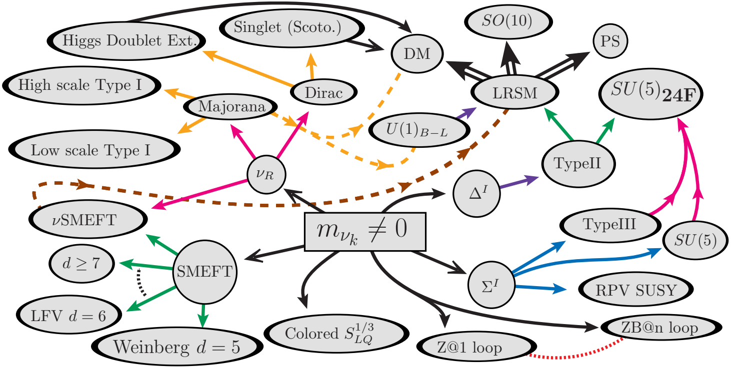

```
  === Results Summary for run: run_01 tag: tag_1 ===

     Cross-section :   12.26 +- 0.1384 pb
     Nb of events :  100

store_events
INFO: Storing parton level results
INFO: End Parton
reweight -from_cards
decay_events -from_cards
INFO: Running Pythia8 [arXiv:1410.3012]
Splitting .lhe event file for PY8 parallelization...
Submitting Pythia8 jobs...
Pythia8 shower jobs: 1 Idle, 0 Running, 0 Done [0 second]
Pythia8 shower jobs: 0 Idle, 0 Running, 1 Done [0 second]
Merging results from the split PY8 runs...
INFO: Pythia8 shower finished after 0 second.
  === Results Summary for run: run_01 tag: tag_1 ===

     Cross-section :   12.26 +- 0.1384 pb
     Nb of events :  100

INFO: storing files of previous run
INFO: Storing Pythia8 files of previous run
INFO: Done
```

… including BSM processes in `mg5amc`

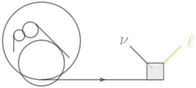




so much not covered



thank you for your time!



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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

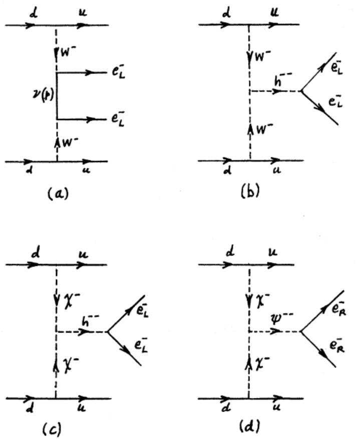


FIG. 1. Diagrams for neutrinoless double-β decay in an SU(2)×U(1) gauge theory. The standard diagram is Fig. 1(a). It is the only one which contains a virtual neutrino (of four-momentum p). d and u are the down and up quarks.

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]

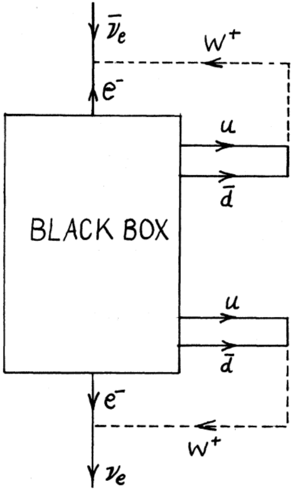
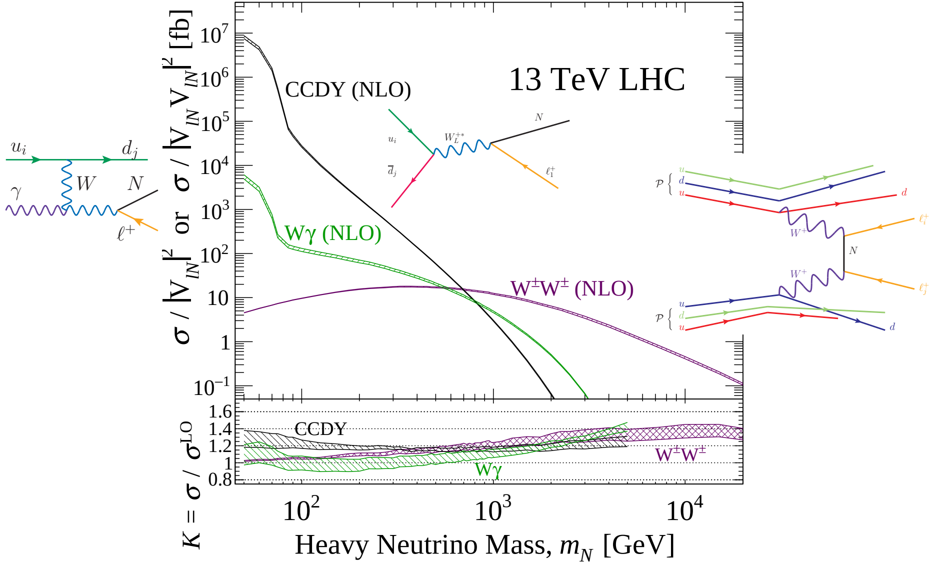


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

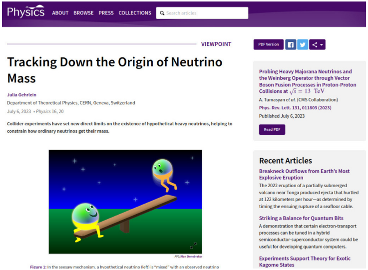
Plotted: Normalized production rate $(\sigma/|V|^{2\ (4)})$ vs m_N



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

Dicus, et al (PRD'91); Datta, Guchait, Pilaftsis (PRD'94); w/ Fuks, Neundorf, Peters, Saimpert (PRD'21) [2011.02547]

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

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Tracking Down the Origin of Neutrino Mass

Julia Gehrlein

Department of Theoretical Physics, CERN, Geneva, Switzerland

July 6, 2023 • *Physics* 16, 20

Collider experiments have set new direct limits on the existence of hypothetical heavy neutrinos, helping to constrain how ordinary neutrinos get their mass.

APS/Alan Stonebraker

Figure 1: In the seesaw mechanism, a hypothetical neutrino (left) is "mixed" with an observed neutrino

Probing Heavy Majorana Neutrinos and the Weinberg Operator through Vector Boson Fusion Processes in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Tumasyan *et al.* (CMS Collaboration)

Phys. Rev. Lett. 131, 011803 (2023)

Published July 6, 2023

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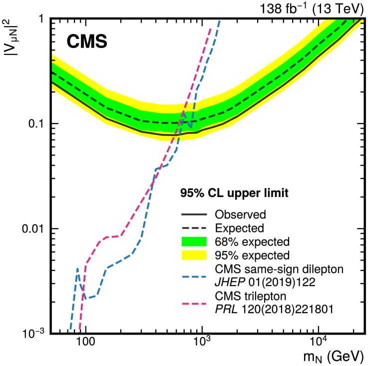

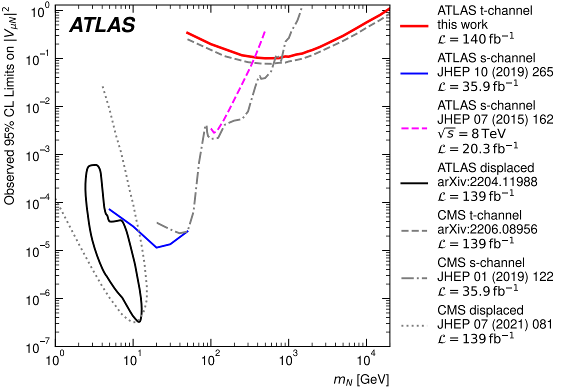

ATLAS (EPJC'23) [2305.14931]

$ee/e\mu$ **(PLB'24) [2403.15016]**

← **CMS (PRL'22) [2206.08956]**