

# New probes of Lepton Number Violation and Lepton Flavor Violation at the LHC

Matter to the Deepest, Ustroń

Richard Ruiz

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

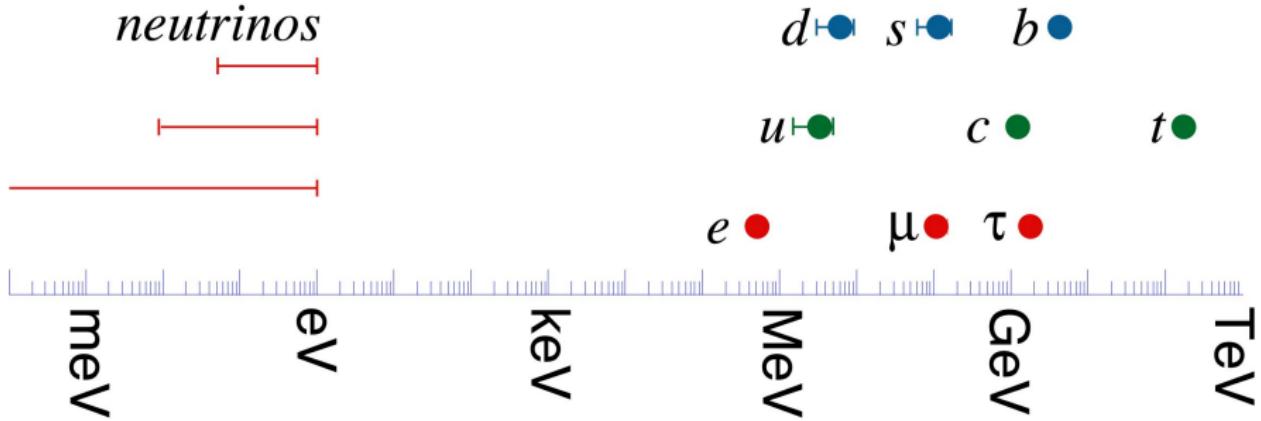
20 September 2023



**thank you for the invitation!**

# **motivation**

**Problem:** according to the SM,  $m_\nu = 0$ . (Not enough ingredients!)



**Discovery of neutrino masses  $\implies$  opens several questions:**

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

**the SM provides some theoretical guidance!**

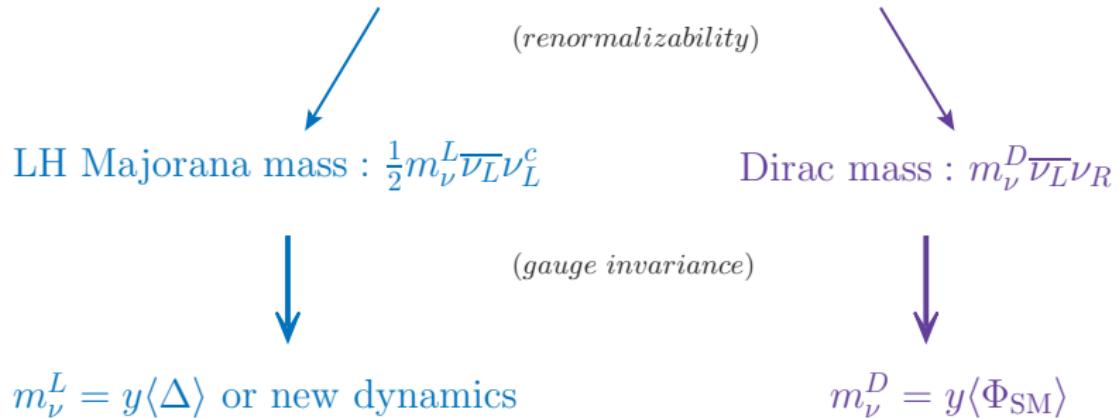
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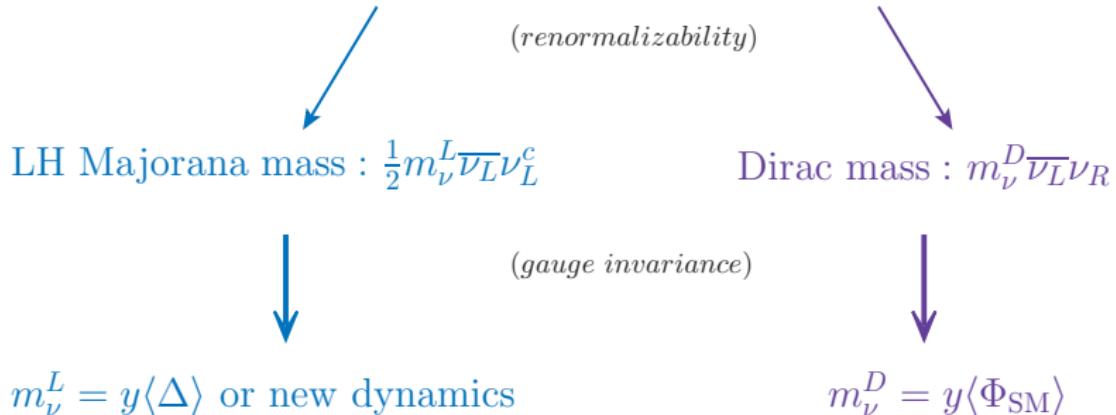
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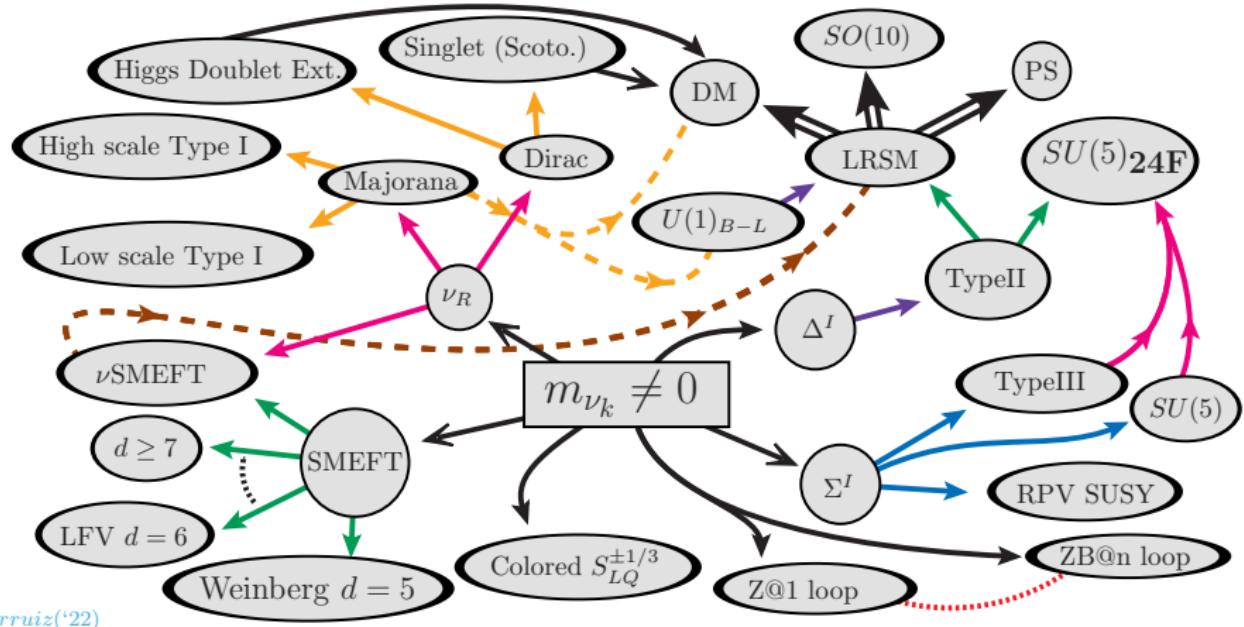


$m_\nu \neq 0 +$  renormalizability + gauge inv.  $\implies$  new particles

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

# Solution (and problem): this can be realized in *many* ways!

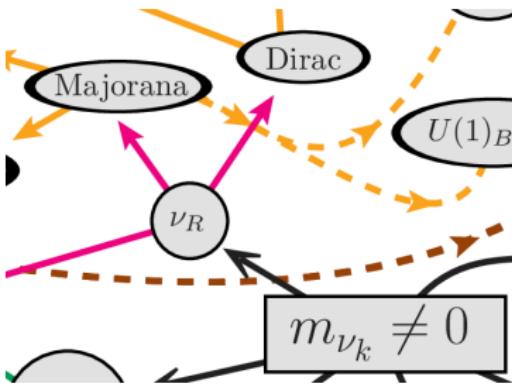
Minkowski ('77); Yanagida ('79); Glashow & Levy ('80); Gell-Mann et al., ('80); Mohapatra & Senjanović ('82); + many others



rruiz('22)

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

## right-handed neutrinos at the LHC<sup>1</sup>



<sup>1</sup> For reviews at colliders, see Cai, Han, Li, RR [1711.02180] and Pascoli, RR, Weiland [1812.08750]

## adding $\nu_R$ to the SM

To generate Dirac masses for  $\nu$  like other SM fermions, we need  $\nu_R$

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

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

$$\Rightarrow \mathcal{L}_{\text{mass}} = \frac{-1}{2} \underbrace{\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix}}_{\text{chiral state}} \underbrace{\begin{pmatrix} 0 & m_D \\ m_D & \mu_{\chi} \end{pmatrix}}_{\text{mass matrix (chiral basis)}} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

(sizes of  $m_D$  &  $\mu_{\chi}$  have major impact on pheno; see Pascoli, et al [1712.07611])

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(sizes of  $m_D$  &  $\mu_{\chi}$  have major impact on pheno; see Pascoli, et al [1712.07611])

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

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

# For the experts (1 slide)

Generically parameterize active-sterile neutrino mixing via

Atre, et al [0901.3589]

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

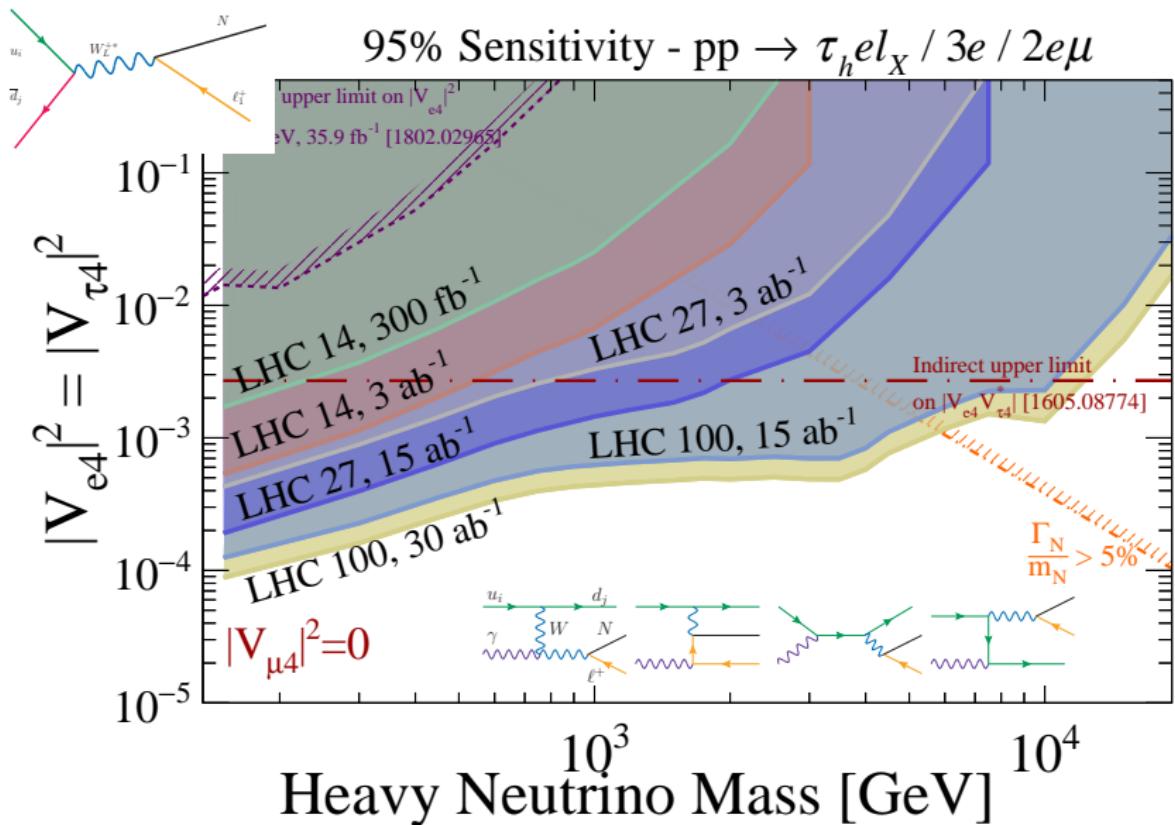
The SM  $W$  coupling to **leptons** in the **flavor basis** is

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

$\implies$   $W$  coupling to  $N$  in the **mass basis** is

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

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

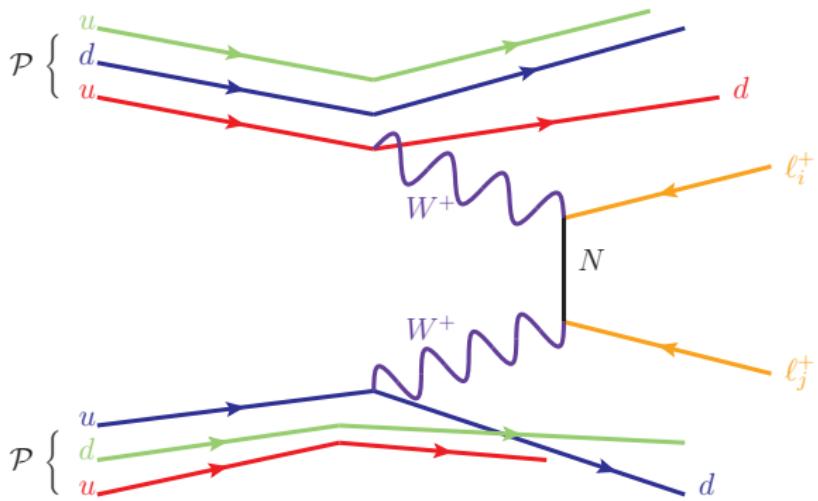


**Major improvements since Snowmass 2013:**  $> 10\times$  better sensitivity to LNV + LFV

Only one plot; see [1812.08750] for various flavor, Dirac vs Majorana, and  $\sqrt{s}$  permutations

**how heavy can we go at the LHC?**

## $N$ from $W^\pm W^\pm$ scattering



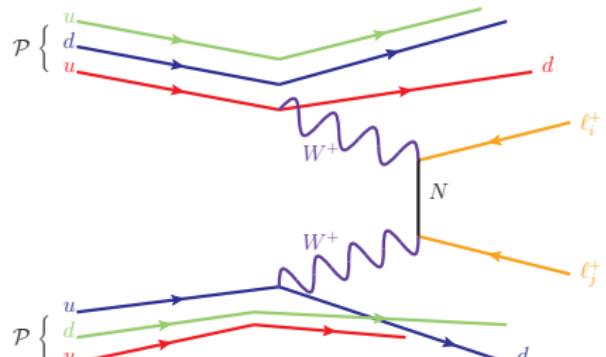
$0\nu\beta\beta$ @LHC

**VBS** probes spin & charge configurations inaccessible with **quarks/gluons**  
⇒ **VBS is uniquely sensitive** to Standard Model and new physics!

See review by Buarque (ed.), Gallinaro (ed.), RR (ed.), et al, Rev. Physics ('22) [2106.01393]

$W^\pm W^\pm \rightarrow \ell_i^\pm \ell_j^\pm$  is the high-energy realization of nuclear  $0\nu\beta\beta$  decay

Dicus, et al (PRD'91)



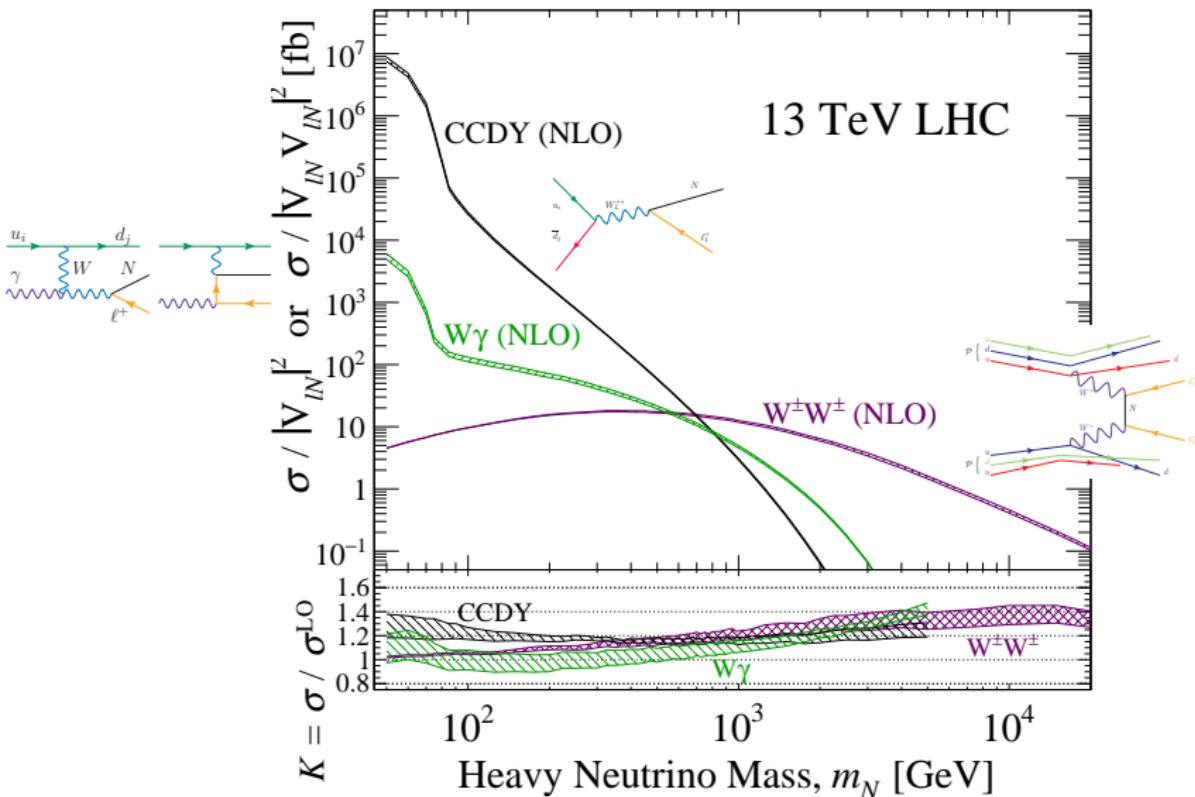
#### Lost in the literature but revived:

- Majorana  $N$  (SMEFT@dim-7) at LHC  
w/ Fuks, Neundorf, Peters, Saimpert [2011.02547]
  - Weinberg operator (SMEFT@dim-5) at LHC/100 TeV  
w/ Fuks, Neundorf, et al [2012.09882]
  - Majorana  $N$  +  $W$  PDFs at 100 TeV

Schubert & Ruchayskiy [2210.11294]

**so we ran the numbers!**

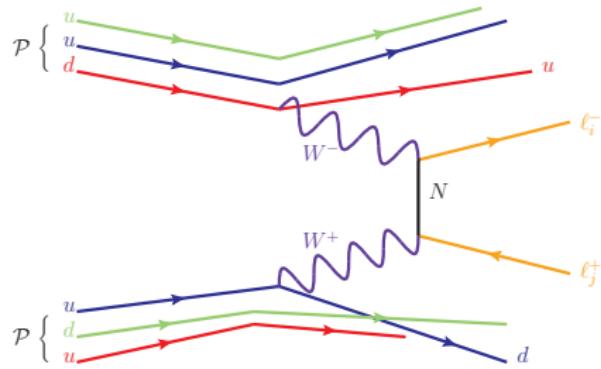
**Plotted:** Normalized production rate ( $\sigma/|V|^2$ ) vs  $m_N$



$W^\pm W^\pm \rightarrow \ell_i^\pm \ell_j^\pm$  phenomenology is **wild** and rate is **competitive**

## anatomy of the $0\nu\beta\beta$ process

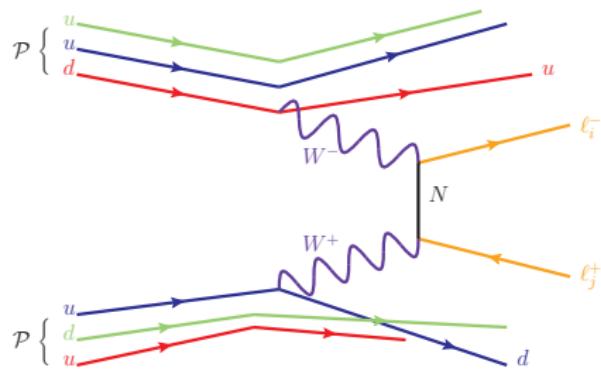
# helicity preservation in $W^- W^+ \rightarrow \ell_i^- \ell_j^+$



The helicity amplitude for the LNC process  $q_1 q_2 \rightarrow \ell_1^- \ell_2^+ q'_1 q'_2$  is

$$\mathcal{M}_{LNC} = J_{q_1 q'_1}^\mu J_{q_2 q'_2}^\nu \Delta_{\mu\rho}^W \Delta_{\nu\sigma}^W T_{LNC}^{\rho\sigma} \mathcal{D}(p_N)$$

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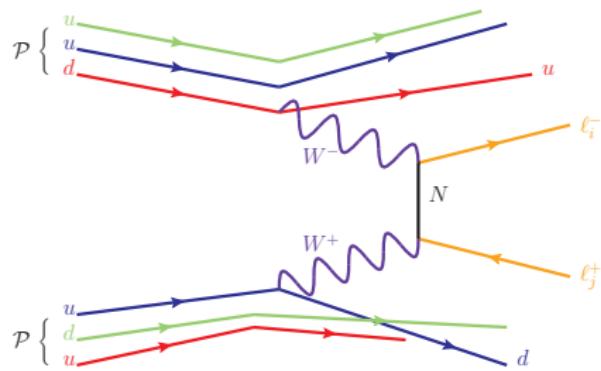


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$$T_{LNC}^{\rho\sigma} = \overline{u_L}(p_1) \gamma^\rho P_L \times \left( \underbrace{\not{p}_N}_{\text{LH helicity state}} + \underbrace{\not{m}_N}_{P_L m_N P_R = 0} \right) \times \gamma^\sigma P_L v_R(p_2)$$

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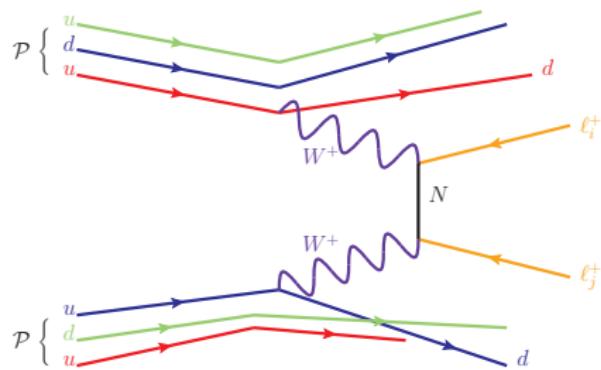
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$$\implies \mathcal{M}_{LNC} \sim \frac{\not{p}_N}{(\not{p}_N^2 - m_N^2)} \quad \text{scales with momentum transfer!}$$

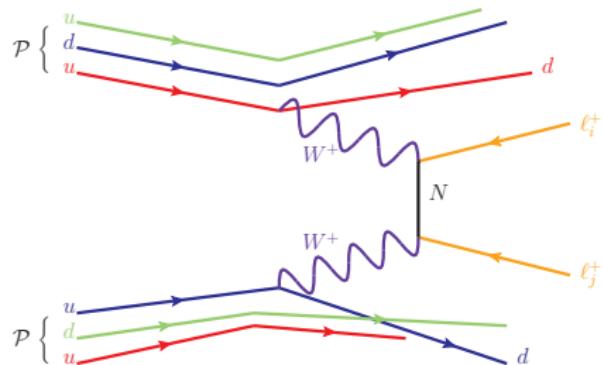
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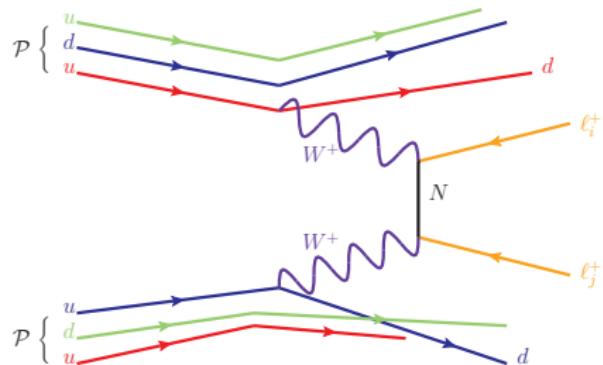
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Intuition: CPT Theorem  $\implies$  CT-inversion =  $P$ -inversion

$$T_{LNV}^{\rho\sigma} = \overline{u_R}(p_1) \gamma^\rho \underbrace{P_R}_{CPT: P_L \rightarrow P_R} \times \left( \underbrace{\not{p}_N}_{P_R \not{p}_N' P_R=0} + \underbrace{\not{m}_N}_{RH \text{ helicity state}} \right) \times \gamma^\sigma P_L v_R(p_2)$$

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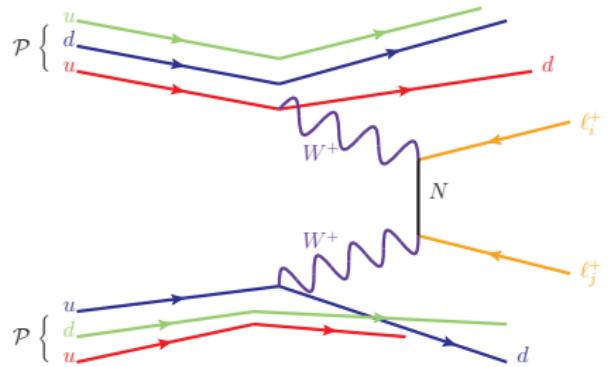
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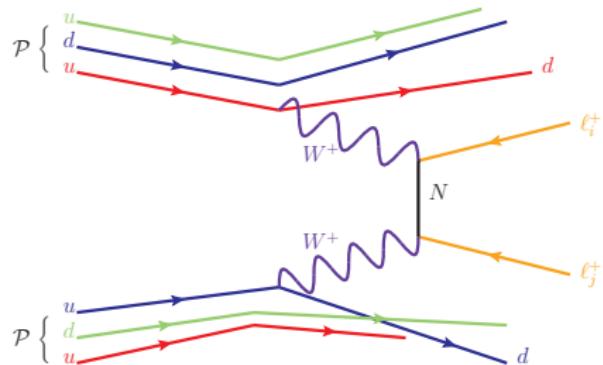
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$$\implies \mathcal{M}_{LNV} \sim \frac{\not{m}_N}{(\not{p}_N - \not{m}_N^2)} \quad \text{scales with mass!}$$



The remainder of  $\mathcal{M}_{LNV}$  depends on:

- $WW$  scattering system
- $N$ 's pole structure



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- $WW$  scattering system
- $N$ 's pole structure

Explicit computation shows amplitude is driven by  $W_0^\pm W_0^\pm$  scattering

$$\mathcal{M}_{LNV} \sim \varepsilon_\mu^{W_1}(\lambda_1) \varepsilon_\mu^{W_2}(\lambda_2) \sim \frac{M_{WW}^2}{M_W^2}$$

“Low-mass” limit ( $M_{WW} \gg m_N$ ):

$$\frac{m_N}{(p_N^2 - m_N^2)} \sim \frac{m_N}{(M_{WW}^2 - m_N^2)} \sim \frac{m_N}{M_{WW}^2} + \mathcal{O}\left(\frac{m_N^2}{M_{WW}^2}, \frac{M_W^2}{M_{WW}^2}, \dots\right)$$

(amplitude grows with mass!)

“High-mass” limit ( $M_{WW} \ll m_N$ ):

$$\frac{m_N}{(p_N^2 - m_N^2)} \sim \frac{m_N}{(M_{WW}^2 - m_N^2)} \sim \frac{-m_N}{m_N^2} + \mathcal{O}\left(\frac{M_{WW}^2}{m_N^2}\right)$$

(slower decoupling since  $d = 7$ , not  $d = 8$ )

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

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

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

Used mg5amc + HeavyN UFO libraries

“Low-mass” limit ( $M_{WW} \gg m_N$ ):

$$\hat{\sigma}(W^+ W^+ \rightarrow \ell^+ \ell^+)$$

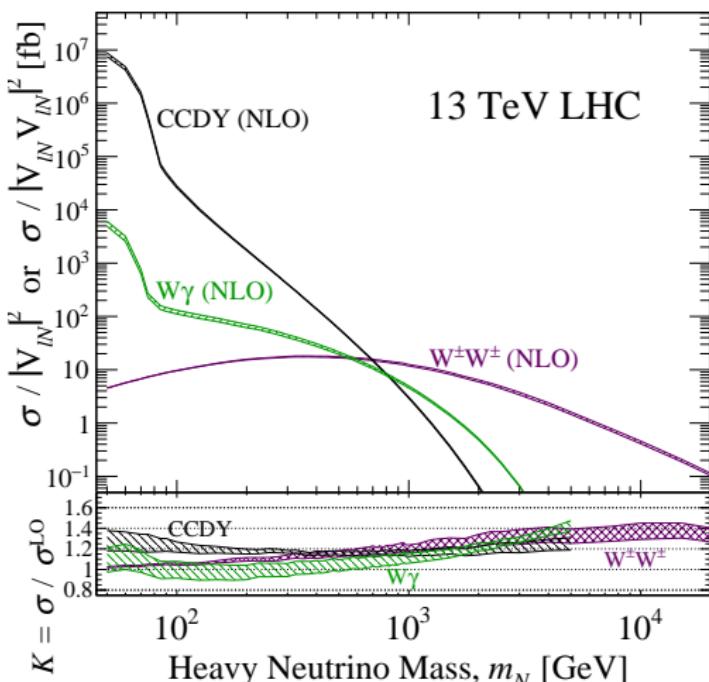
$$\sim g_W^4 |V_{\ell N}|^4 \frac{m_N^2}{m_W^4}$$

“High-mass” limit ( $M_{WW} \ll m_N$ ):

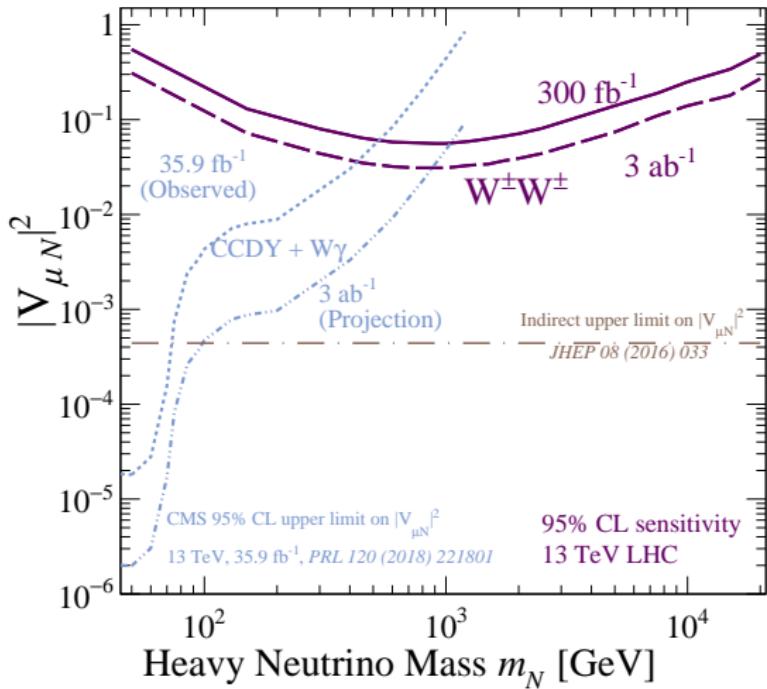
$$\hat{\sigma}(W^+ W^+ \rightarrow \ell^+ \ell^+)$$

$$\sim g_W^4 \frac{|V_{\ell N}|^4}{m_N^2} \frac{M_{WW}^4}{m_W^4}$$

**Take away:**  $W^\pm W^\pm \rightarrow \ell^\pm \ell^\pm$  has largest rate from  $m_N \gtrsim 1 - 3$  TeV!



**Plotted:** LHC 13 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass ( $m_N$ )



$W^\pm W^\pm \rightarrow \ell_i^\pm \ell_j^\pm$  allows direct probe  $m_N \sim 1 - 10$  TeV at  $|V|^2 \lesssim 0.1$

# Search for $W^\pm W^\pm \rightarrow \ell^\pm \ell^\pm$ quickly adopted by LHC groups!

## Tracking Down the Origin of Neutrino Mass

Jutta Gehrlein  
Department of Theoretical Physics, CERN, Geneva, Switzerland

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



Figure 1: In the seesaw mechanism, a hypothetical neutrino (left) is “reduced” with an ordinary neutrino

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

A. Tumasyan et al. (CMS Collaboration)

Phys. Rev. Lett. 133, 031809 (2024)

Published July 6, 2023

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Breakaway Outflows from Earth’s Most Explosive Eruption

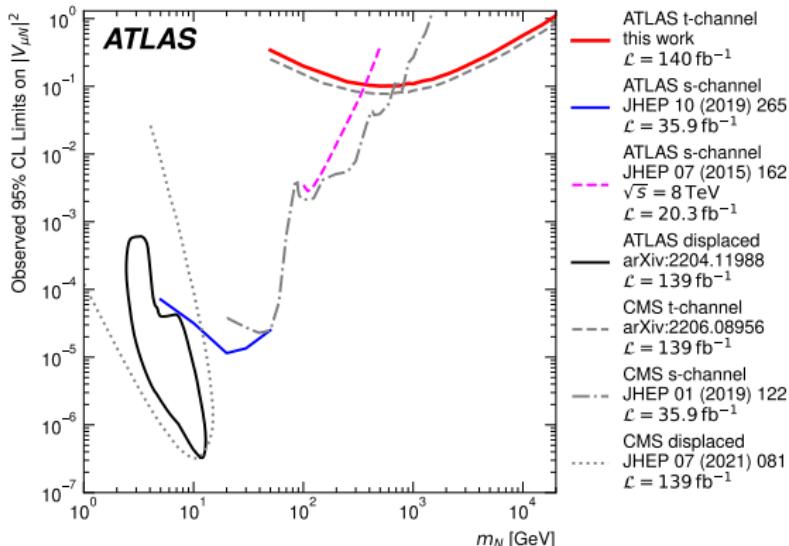
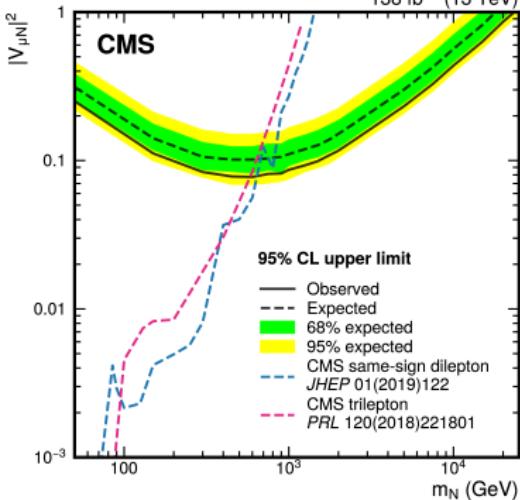
The 2022 eruption of a partially submerged volcano near Tonga produced spectra that horrified at 322 kilometers per hour—as determined by fitting the resulting points of a scatter plot.

Striking a Balance for Quantum Bits

A quantum computer based on charge transport processes can be built in a hybrid semiconductor-superconductor system could be useful for developing quantum computers.

Experiments Support Theory for Exotic Kagome States

ATLAS and CMS find evidence for a theoretical prediction of exotic magnetic states in a material.

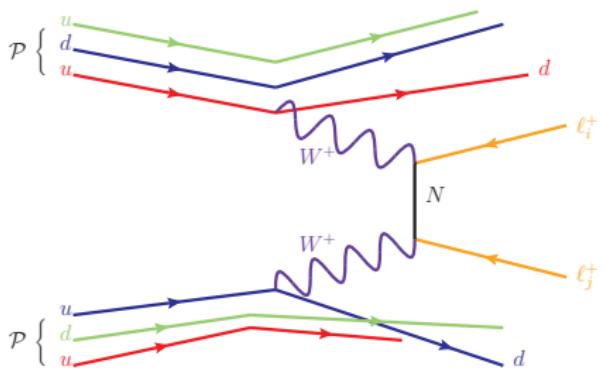


ATLAS ('23) [2305.14931]

← CMS ('22) [2206.08956]

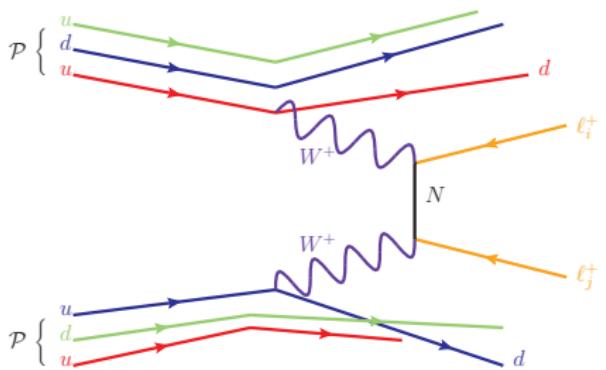
**something interesting**

# $W^+ W^+ \rightarrow \ell^+ \ell^+$ at high energies



$W_0^\pm W_0^\pm$  scattering dominates when  $m_\nu \ll M_W \ll M_{WW} \ll m_N$ :  
 $\mathcal{M} \sim g_W^2 \left( \frac{V_{\ell N}^2}{2m_N M_W^2} \right) M_{WW}^3$

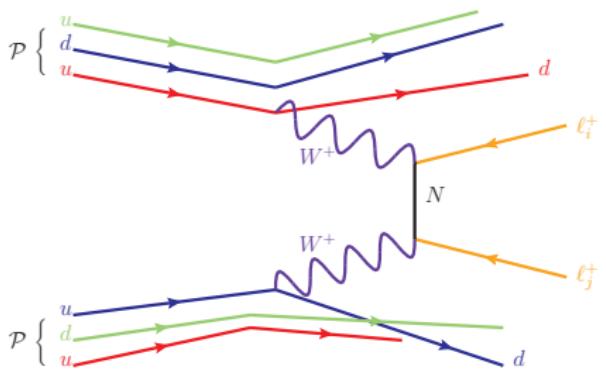
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Now,  $J = 0$  partial wave is given by:  
 $a_{J=0} = \frac{1}{32\pi} \int_{-1}^1 d \cos \theta_W \mathcal{M}$

$W^+ W^+ \rightarrow \ell^+ \ell^+$  at high energies



$W_0^\pm W_0^\pm$  scattering dominates when  
 $m_\nu \ll M_W \ll M_{WW} \ll m_N$ :  
 $\mathcal{M} \sim g_W^2 \left( \frac{v_{eN}^2}{2m_N M_W^2} \right) M_{WW}^3$

Now,  $J = 0$  partial wave is given by:

Req. that  $|a_{J=0}| < 1$ , means:

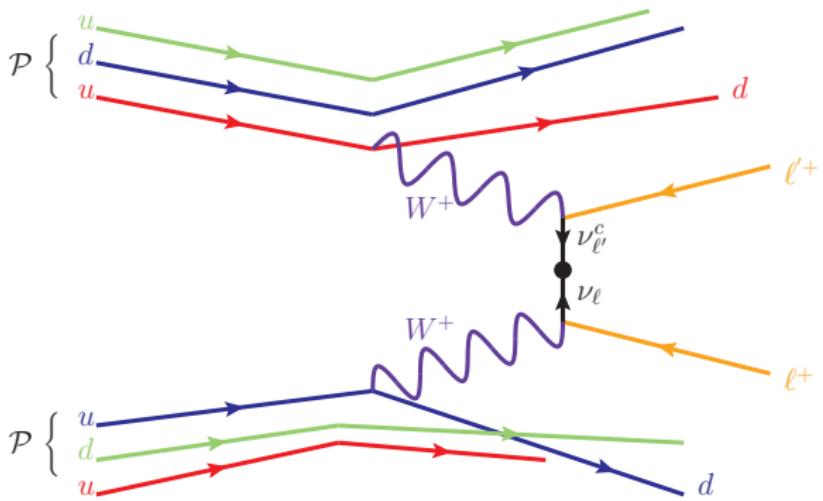
$$E_U^3 = \frac{16\pi M_W^2/g_W^2}{|\sum_k V_{eN_k} m_{N_k} V_{\ell N_k}|}$$

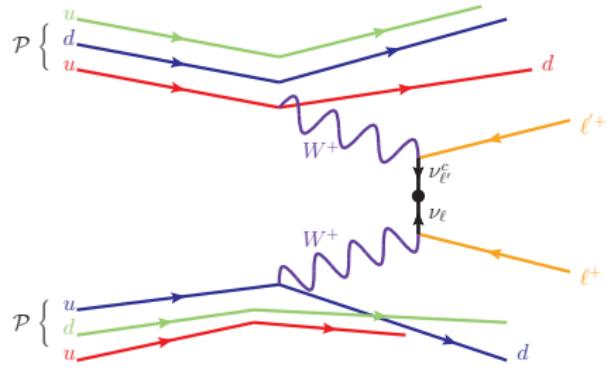
$E_U$  is the  $W_0^\pm W_0^\pm$  scattering scale ( $M_{WW}$ ) above which pert. unitarity is violated 😊 Maltoni, Niczyporuk, Willenbrock [PRL'01]; Fuks, Neundorf, Peters, RR, Sajmpert [2011.02547]

Maltoni, Niczyporuk, Willenbrock [PRL'01]; Fuks, Neundorf, Peters, RR, Saimpert [2011.02547]

**Interesting** that  $E_U$  is finite. Using GERDA('20) limits:  $E_U = 72\text{-}87 \text{ TeV}$

## $W^\pm W^\pm$ scattering at dimension five





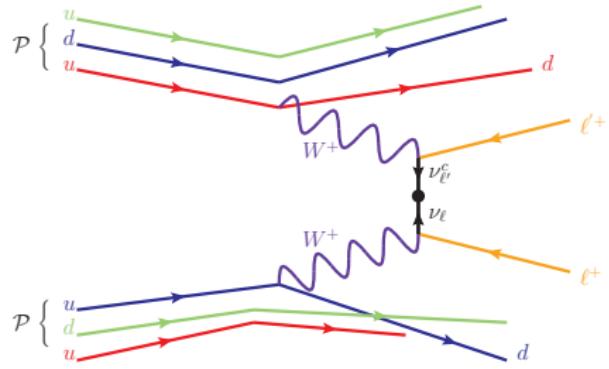
Weinberg operator is the only SMEFT operator at  $d = 5$ :

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

contributes to  $\nu$  masses after EWSB:

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

Nuclear  $0\nu\beta\beta$  only sensitive to  $\ell\ell' = ee$ !



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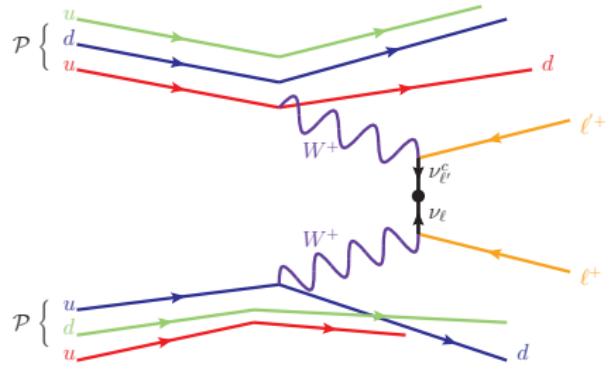
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Nuclear  $0\nu\beta\beta$  only sensitive to  $\ell\ell' = ee$ !

Difficult to simulate since Weinberg op. modifies propagator of  $\nu_\ell$

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

$$\frac{\nu_\ell(p)}{p} \frac{\nu_{\ell'}^c(-p)}{p} = \frac{ip}{p^2} \frac{-iC_5^{\ell\ell'} v^2}{\Lambda} \frac{ip}{p^2} = \frac{im_{\ell\ell'}}{p^2}$$



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

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

contributes to  $\nu$  masses after EWSB:

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

Nuclear  $0\nu\beta\beta$  only sensitive to  $\ell\ell' = ee$ !

Difficult to simulate since Weinberg op. modifies propagator of  $\nu_\ell$

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

$$\frac{\nu_\ell(p)}{p} \frac{\nu_{\ell'}^c(-p)}{p} = \frac{ip}{p^2} \frac{-iC_5^{\ell\ell'} v^2}{\Lambda} \frac{ip}{p^2} = \frac{im_{\ell\ell'}}{p^2}$$

**Solution (highly nontrivial):** Invent an unphysical Majorana fermion with (small) mass  $m_{\ell\ell'}$  that couples to all lepton flavors

recovers right behavior!

$$\gamma^\alpha P_L \frac{i(p+m_{\ell\ell'})}{p^2-m_{\ell\ell'}^2} \gamma^\beta P_R = \gamma^\alpha P_L \frac{im_{\ell\ell'}}{p^2} P_L \gamma^\beta \times \left[ 1 + \mathcal{O}\left(\left|\frac{m_{\ell\ell'}^2}{p^2}\right|\right) \right],$$

# Plotted: Normalized production rate ( $C_5 = 1$ ) vs scale ( $\Lambda$ )

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

Full  $2 \rightarrow 4$  calculation at NLO(+PS)  
in QCD      Used mg5amc + NEW SMWeinberg UFO libraries

Driven by  $W_0^+ W_0^+$  scattering  
 $\hat{\sigma}(W^+ W^+ \rightarrow \ell^+ \ell^+) \sim \frac{|C_5^{\ell\ell}|^2}{18\pi\Lambda^2}$

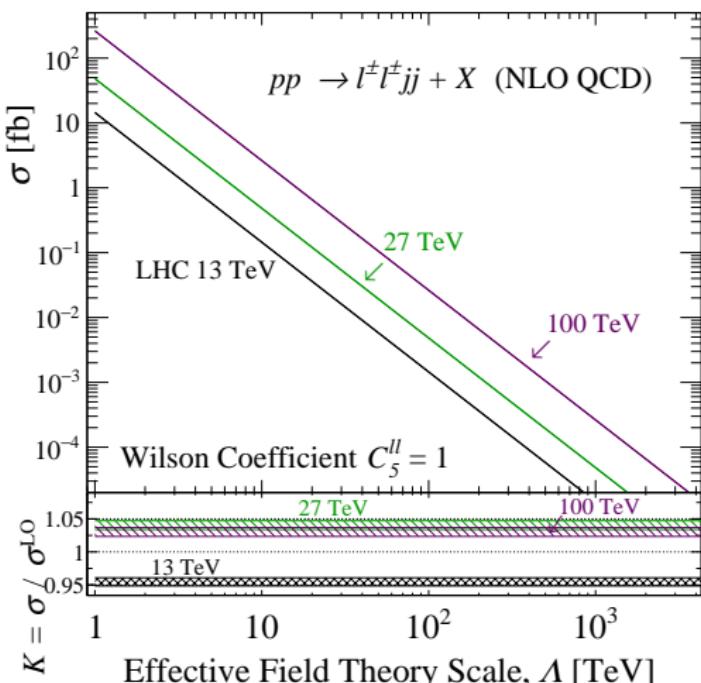
**Take away:** sensitivity with a simple cuts at  $\mathcal{L} = 300$  (3000)  $\text{fb}^{-1}$ :

$$\Lambda / |C_5^{\mu\mu}| \lesssim 8.3 \text{ (13) TeV} \\ \implies |m_{\mu\mu}| \gtrsim 7.3 \text{ (5.4) GeV}$$

LHC 95% CL upper limits:

**CMS:**  $|m_{\mu\mu}| < 10.8 \text{ GeV}$  [2206.08956]

**ATLAS:**  $|m_{\mu\mu}| < 16.7 \text{ GeV}$  [2305.14931]

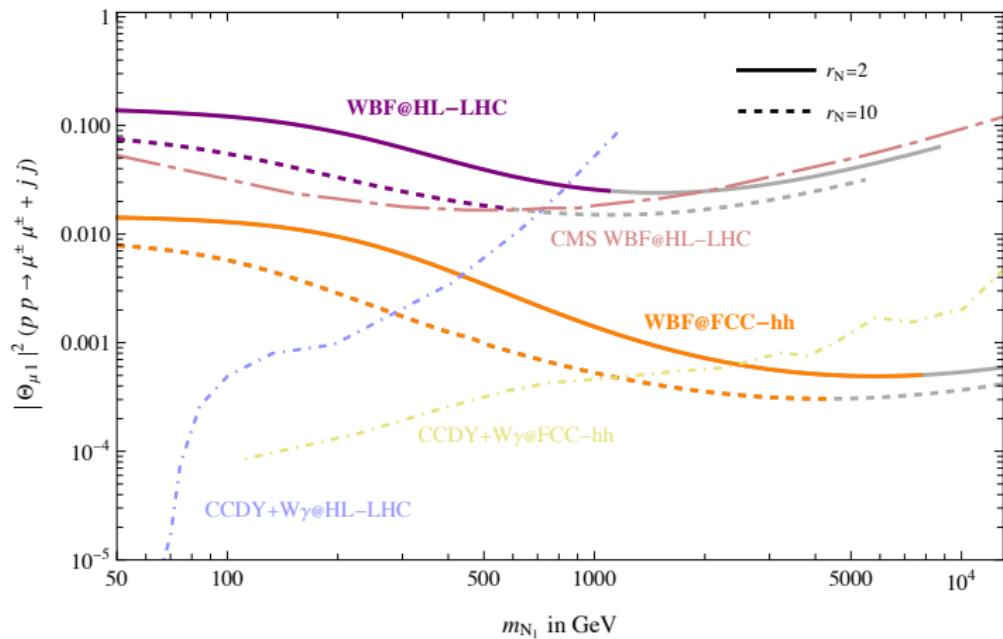


## **brief outlook for future colliders**

# $W^+W^+ \rightarrow \ell_i^+\ell_j^+$ @ 100 TeV

**Plotted:** sensitivity to active-sterile mixing vs  $m_N$

Schubert & Ruchayskiy [2210.11294]



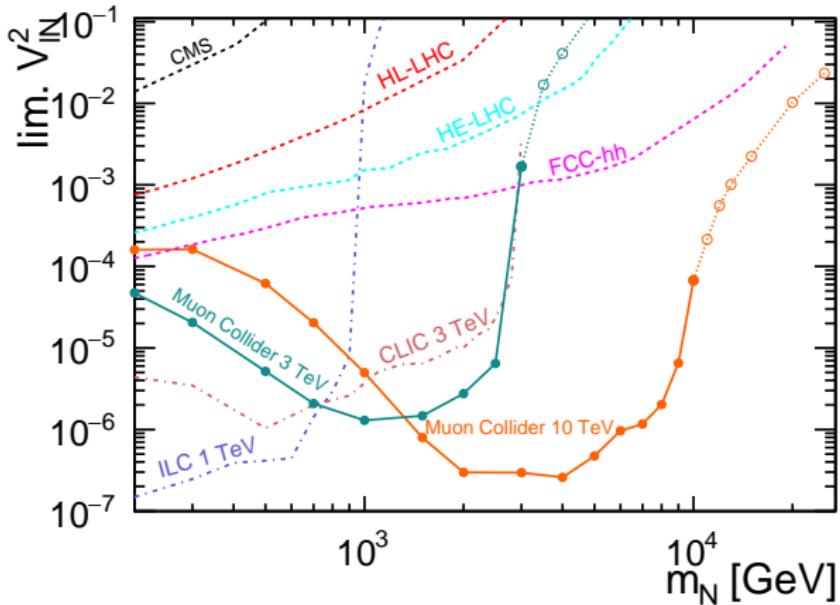
**caveat:** study employs effective  $W$  approximation ( $W$  PDF of proton)

- unsure assumptions for EWA are met see, Ruiz, Costantini, Maltoni, Mattelaer [2111.02442]

# $\mu^+ \mu^-$ collider

Plotted: sensitivity to active-sterile mixing vs  $m_N$

Mekala, Reuter, Zarnecki [2301.02602]



note: **great** outlook for high-mass sensitivity in  $s$ -channel

- conjecture:  $W^+ W^- \rightarrow \ell_i^+ \ell_j^-$  can do better

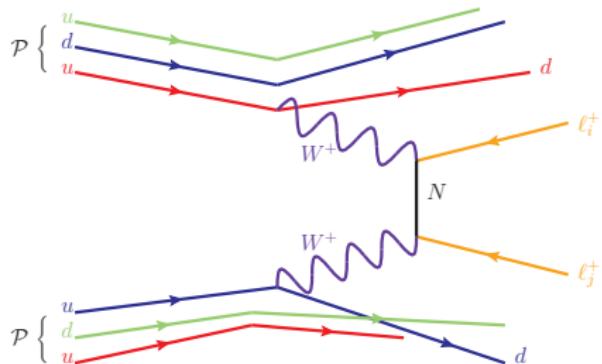
se, Costantini, Ruiz, et al [2005.10289]

# summary and conclusions

VBS/VBF probes neutrino mass models  
configurations inaccessible to  $q/g$

$\nu$ @colliders review [1711.02180]

VBS/VBF review [2106.01393]

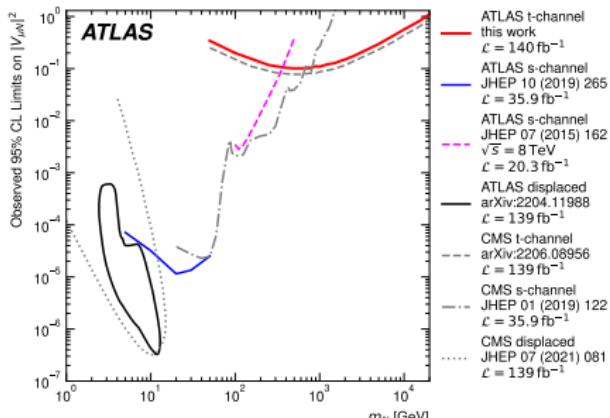


ATLAS and CMS are using VBS to  
search for LNV and LFV

- same-sign  $e/\mu$  in the pipeline ('23/'24)
- same-sign  $\tau$  on the agenda ('24/'25)
- wanted: add'l interpretations of results

Future colliders  $\implies$  interesting results

- worth further investigations!



**Thank you!**

# **Backup**

## **VBF vs s-channel**

## Evidence for trend that VBF/S rates will always exceed s-ch. rates

Is this obvious? (not to me at first!) Is there intuition for this? (yes!)

w/ A. Costantini, et al [2005.10289]

**Idea:** crudely compare the production of  $X$  by writing generically

$$\sigma^{s-ch.} \sim \frac{(s - M_X^2)}{(s - M_V^2)^2} \sim \frac{(s - M_X^2)}{s^2} \quad \leftarrow \text{assumes } s \gg M_V^2$$

$$\frac{d\sigma^{VBF}}{dz_1 dz_2} \sim \underbrace{f_V(z_1) f_{V'}(z_2)}_{\text{"PDFs"}} \underbrace{\frac{(M_{VV'}^2 - M_X^2)}{(M_{VV'}^2 - M_V^2)^2}}_{M_{VV'}^2 = z_1 z_2 s \gg M_V^2} \sim f_V(z_1) f_{V'}(z_2) \frac{(z_1 z_2 s - M_X^2)}{(z_1 z_2)^2} \frac{\sigma^{s-ch.}}{(s - M_X^2)}$$

**PDFs are largest** when  $z = E_V/E_\mu \ll 1$  but  $E_V \sim \sqrt{s} \gg M_V$

$$\implies f_V(z_i) \sim \frac{g_W^2}{4\pi} \frac{1}{z_i} \log\left(\frac{s}{M_V^2}\right) \quad \leftarrow \text{crude approximation}$$

**Observation:**  $\sigma^{VBF} = \sigma^{s-ch.} \times \int dz_1 dz_2 \dots$  is solvable for  $M_{VV'} \gg M_X$ !

**Universal behavior:** when production of  $X$  by VBF and annihilation are driven by same physics, VBF **dominates** when  $\sqrt{s}$  satisfies

$$\frac{\sigma^{\text{VBF}}}{\sigma^{s-ch.}} \sim \mathcal{S} \left( \frac{g_W^2}{4\pi} \right)^2 \left( \frac{s}{M_X^2} \right) \log^2 \frac{s}{M_V^2} \log \frac{s}{M_X^2} > 1$$

Scaling estimate not so bad if  $M_X \gg M_V$ . Difference is about  $\mathcal{O}(10\%)$

mass ( $M_X$ ) [TeV]	$SZ$ (Singlet)	$H_2Z$ (2HDM)	$t\bar{t}$ (VLQ)	$t\bar{t}$ (MSSM)	$\tilde{\chi}^0\tilde{\chi}^0$ (MSSM)	$\tilde{\chi}^+\tilde{\chi}^-$ (MSSM)	Scaling (Eq. 7.7)
400 GeV	2.1 TeV	2.1 TeV	11 TeV	2.9 TeV	3.2 TeV	7.5 TeV	1.0 (1.7) TeV
600 GeV	2.5 TeV	2.5 TeV	16 TeV	3.8 TeV	3.8 TeV	8.1 TeV	1.3 (2.4) TeV
800 GeV	2.8 TeV	2.8 TeV	22 TeV	4.3 TeV	4.3 TeV	8.5 TeV	1.7 (3.1) TeV
2.0 TeV	4.0 TeV	4.0 TeV	>30 TeV	7.8 TeV	6.9 TeV	11 TeV	3.7 (6.8) TeV
3.0 TeV	4.8 TeV	4.8 TeV	>30 TeV	10 TeV	9.0 TeV	13 TeV	5.3 (9.8) TeV
4.0 TeV	5.5 TeV	5.5 TeV	>30 TeV	13 TeV	11 TeV	15 TeV	6.8 (13) TeV

**Table 9.** For representative processes and inputs, the required muon collider energy  $\sqrt{s}$  [TeV] at which the VBF production cross section surpasses the  $s$ -channel, annihilation cross section, as shown in figure 17. Also shown are the cross over energies as estimated from the scaling relationship in equation (7.7) assuming a mass scale  $M_X$  ( $2M_X$ ).

**Evidence that PDF prescription works quantitatively**

# **Kinematics at NLO+PS**

## **after baseline cuts / pre-selection**

# The collider signature exhibits both LNV and VBS/F characteristics

$$pp \rightarrow \mu^\pm \mu^\pm jj + X$$

- same-sign, high- $p_T$  charged leptons without MET and back-to-back
- forward, high- $p_T$  with rapidity gap
- See backup slides for kinematic distributions at NLO+PS

## Built simplified analysis for expedience:

TABLE III. Pre-selection and signal region cuts.

Pre-selection Cuts		
$p_T^{\mu_1} (\mu_2) > 27 (10)$ GeV,	$ \eta^\mu  < 2.7$ ,	$n_\mu = 2$ ,
$p_T^j > 25$ GeV,	$ \eta^j  < 4.5$ ,	$n_j \geq 2$ ,
$Q_{\mu_1} \times Q_{\mu_2} = 1$ ,	$M(j_1, j_2) > 700$ GeV	
Signal Region Cuts		
$p_T^{\mu_1}, p_T^{\mu_2} > 300$ GeV		

TABLE I. Generator-level cross sections [fb] and cuts,  $\mu_f, \mu_r$  scale uncertainty [%], PDF uncertainties [%], and perturbative order for leading backgrounds at  $\sqrt{s} = 13$  TeV.

Process	Order	Cuts	$\sigma^{\text{Gen.}}$ [fb]	$\pm \delta_{\mu_f, \mu_r}$	$\pm \delta_{\text{PDF}}$
$W^\pm W^\pm jj$ (QCD)	NLO in QCD	Eq. (4.2)	385	+10% -10%	+1% -1%
$W^\pm W^\pm jj$ (EW)	NLO in QCD	Eq. (4.2) + diagram removal	254	+1% -1%	+1% -1%
Inclusive $W^\pm V$ (3 $\ell\nu$ )	FxFx (1j)	Eqs. (4.3), (4.4)	2,520	+5% -6%	+1% -1%

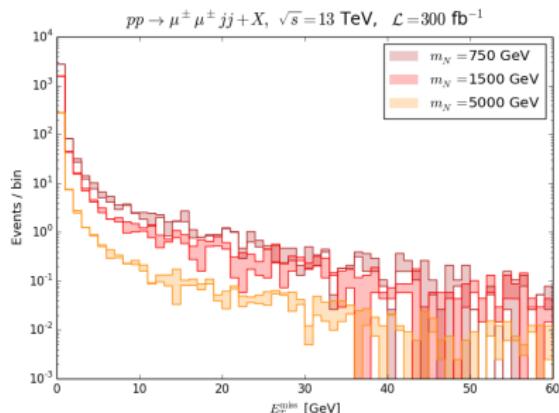
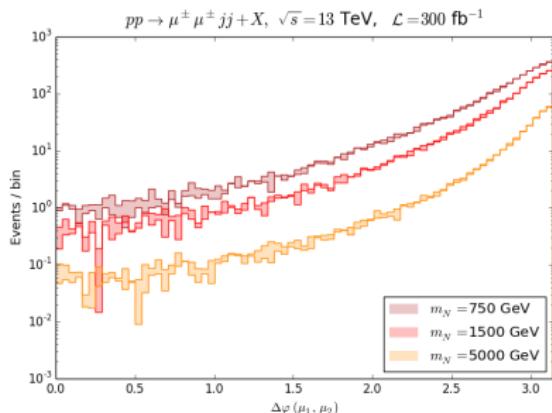
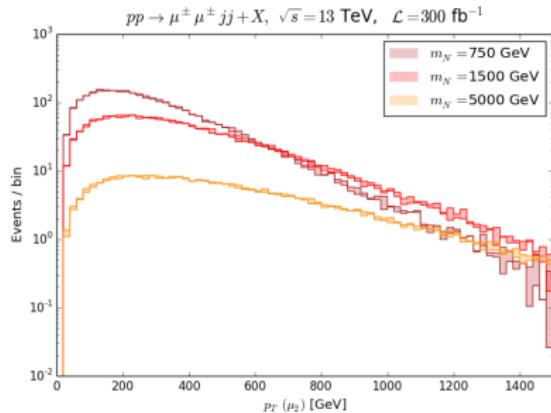
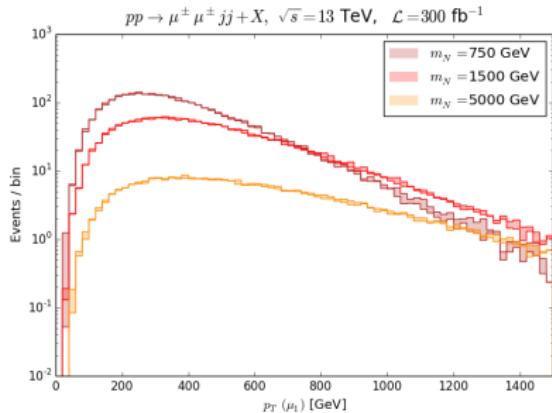
TABLE IV. Visible signal cross sections (and efficiencies) after applying different selections to the simulated events.

$m_N$	$\sigma^{\text{Gen.}}$ [fb]	$\sigma^{\text{Pre.}}$ [fb] ( $\mathcal{A}$ )	$\sigma^{\text{SR}}$ [fb] ( $\varepsilon$ )
150 GeV	13.3	3.7 (28%)	0.5 (14%)
1.5 TeV	8.45	3.18 (38%)	1.9 (63%)
5 TeV	1.52	0.58 (38%)	0.46 (79%)
15 TeV	0.190	0.072 (38%)	0.056 (78%)

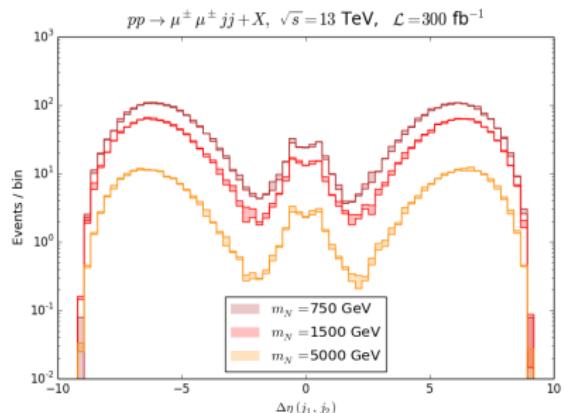
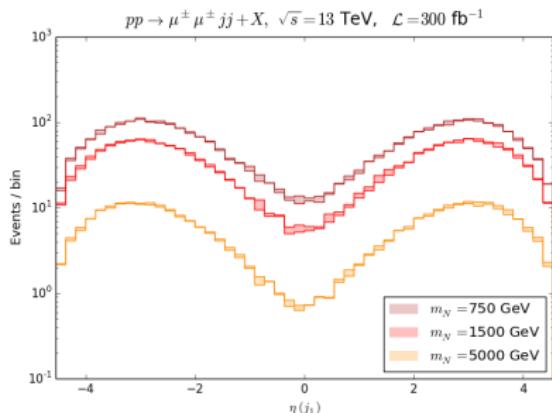
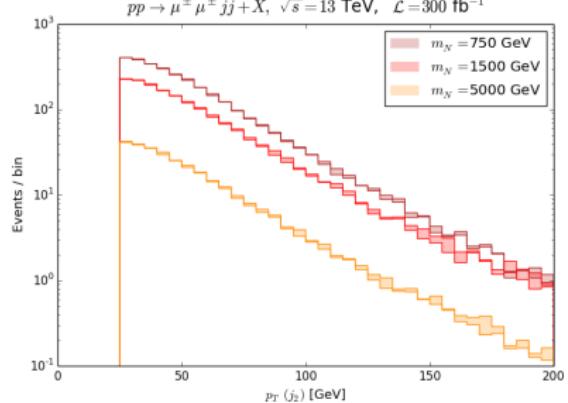
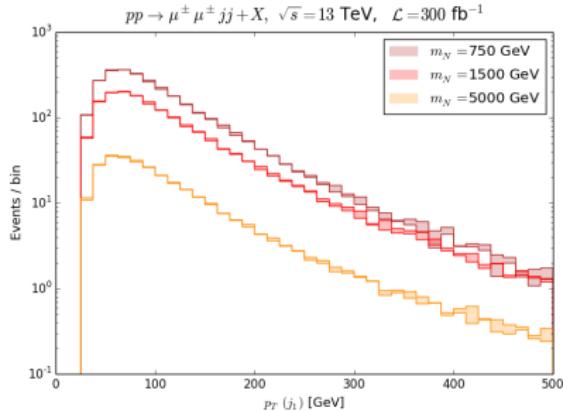
TABLE V. Expected number of SM background events in the Signal Region at the (HL-)LHC with  $\mathcal{L} = 300$  fb $^{-1}$  (3 ab $^{-1}$ ).

Collider	$QCD\ W^\pm W^\pm jj$	$EW\ W^\pm W^\pm jj$	$W^\pm V(3\ell\nu)$	Total
LHC	0.05	0.52	0.14	0.71
HL-LHC	0.49	5.17	1.40	7.10

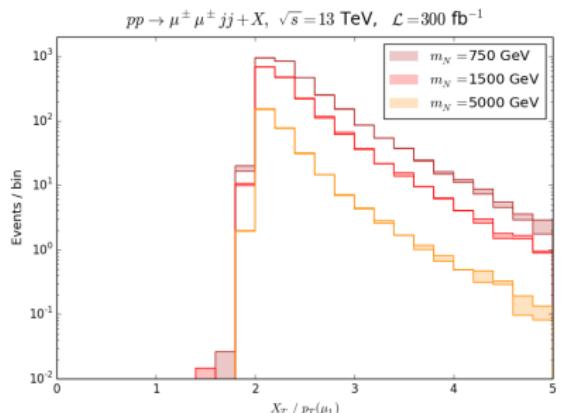
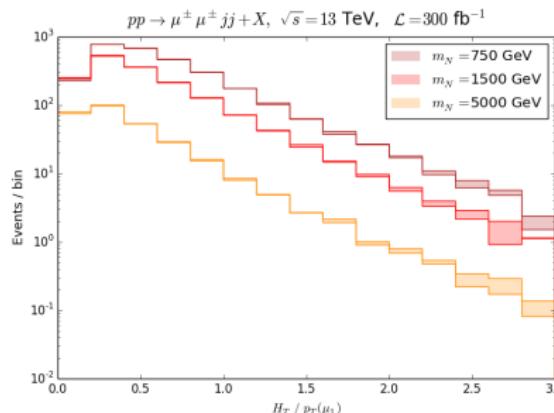
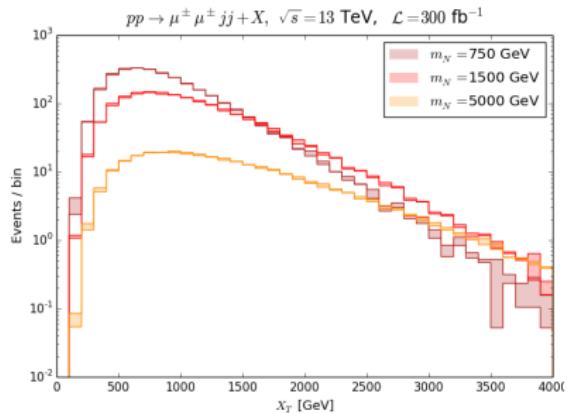
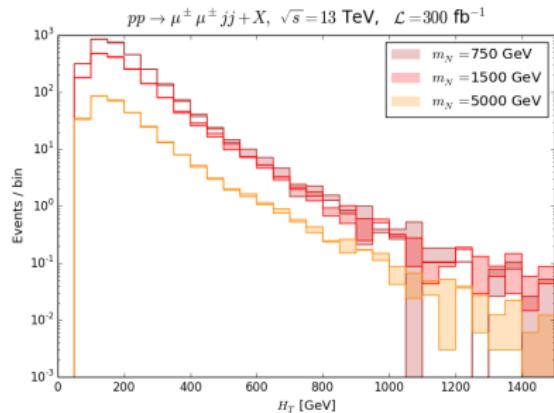
# Top: $p_T^{\mu_1}$ , $p_T^{\mu_2}$ , Btm: $\Delta\varphi(\mu_1, \mu_2)$ , MET



**Top:**  $p_T^{j_1}$ ,  $p_T^{j_2}$ , **Btm:**  $\eta^{j_1}$ ,  $\Delta\eta(j_1, j_2)$



**Top:**  $H_T = \sum |p_T^j|$ ,  $X_T = H_T + \sum |p_T^\mu|$ , **Btm:**  $H_T/p_T^{\mu_1}$ ,  $X_T/p_T^{\mu_1}$



# Tools

## HeavyN : The Standard Model + Heavy Neutrinos at NLO in QCD

### Contact Author

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In collaboration with:

D. Alva and T. Han [ 1 ]; C. Degrande, O. Mattelear, and J. Turner [ 2 ]; S. Pascoli and C. Weiland [ 3, 4 ]; and V. Cirigliano, W. Dekens, J. de Vries, K. Fuyuto, E. Mere

### Usage resources

- For detailed instructions and examples on using the HeavyN UFO libraries, see C. Degrande, et al, [arXiv:1602.06957](#) and S. Pascoli, et al, [arXiv:1812.08750](#).
- **\*New\*** For heavy neutrinos in vSMEFT, see V. Cirigliano, et al, [arXiv:2105.11462](#).
- See **Validation** section below for additional information

### Citation requests

- For studies of heavy Majorana neutrinos, please consider citing [ 6 ] for the Lagrangian and [ 1, 2 ] for the Majorana FR/UFO files.
- For studies of heavy Dirac neutrinos, please also consider citing [ 4 ].
- **\*New\*** For studies of heavy neutrinos in vSMEFT, please consider citing [ 5 ].

## Model Description

### Majorana N

This effective/simplified model extends the Standard Model (SM) field content by introducing three right-handed (RH) neutrinos, which are singlets under the SM gauge symmetries. After electroweak symmetry breaking, the Lagrangian with three heavy Majorana neutrinos  $N_i$  (for  $i=1,2,3$ ) is given by [ 6 ]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_N + \mathcal{L}_{N \text{ Int.}} \quad (1)$$

The first term is the Standard Model Lagrangian. In the mass basis, i.e., after mixing with active neutrinos, the heavy Majorana neutrinos' kinetic and mass terms are

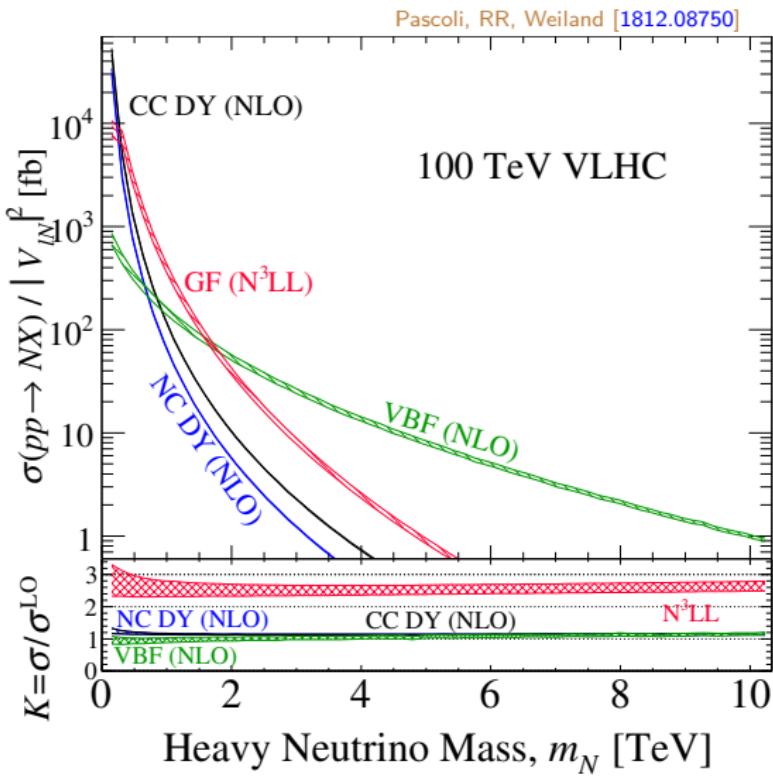
$$\mathcal{L}_N = \frac{1}{2} \overline{N_k} i \not{\partial} N_k - \frac{1}{2} m_{N_k} \overline{N_k} N_k, \quad k = 1, \dots, 3, \quad (1)$$

# FeynRules to MadGraph5aMC@NLO

Given a *Universal FeynRules Object* (UFO) file, run `mg5amc` out of the box

```
$ ./bin/mg5_aMC
> import model SM_HeavyN_NLO
> define p = g u c d s b u~ c~
d~ s~ b~ a
> define ell = mu+ mu-
> generate p p > n2 ell [QCD]
> output PP_Nmu_NLO
> launch PP_Nmu_NLO
> order=NLO
> fixed_order=ON
> set LHC 100
> set vmun2 1.0
> set mn2 scan:range(5,1001,25)
> set wn2 auto
```

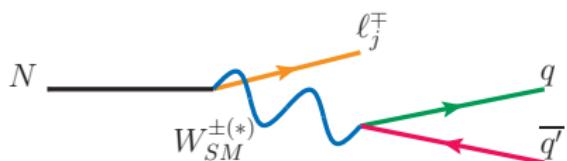
$\mathcal{O}(10)$  lines to get each curve →



# mg5amc+MadSpin+Parton Shower

If the **narrow width approximation** is justified ( $\Gamma_N/m_N \ll 1$ ), efficient generation of  $e^+e^- \rightarrow Z \rightarrow \nu N \rightarrow \nu \ell^\pm q\bar{q}'$  possible with MadSpin:

Spin-correlation fully treated, RR [2008.01092]



In `madspin_card.dat`, write:

```
set spinmode onshell  
  
define q = u c d s u~ c~ d~ s~  
  
define ee = e+ e-  
  
decay n1 > ee q q  
  
launch
```

Parton showering with PY8 or HERWIG straightforward

**Fun Fact:** possible to steer entire process with a script →

```
rruiz@mac-1R0-359:~/Scripts/MG5aMC$ more runEffLRSMnlo_pp_Ne_NLO_update.txt  
launch EffLRSMnlo_pp_wr_Ne_NLO  
order=NLO  
shower=PY8  
madspin=ON  
done  
set mwr 4000  
set mn1 100  
compute_widths wr+  
compute_widths n1  
set no_parton_cut  
set nevents 100k  
set LHC 13  
set shower_card nsplit_jobs 100  
set shower_card ue_enabled true  
  
launch EffLRSMnlo_pp_wr_Ne_NLO  
order=L0  
shower=ON
```