

The neutrinoless $\beta\beta$ process at the LHC and Beyond¹

LIO 2021: Future colliders and the origin of mass

Richard Ruiz

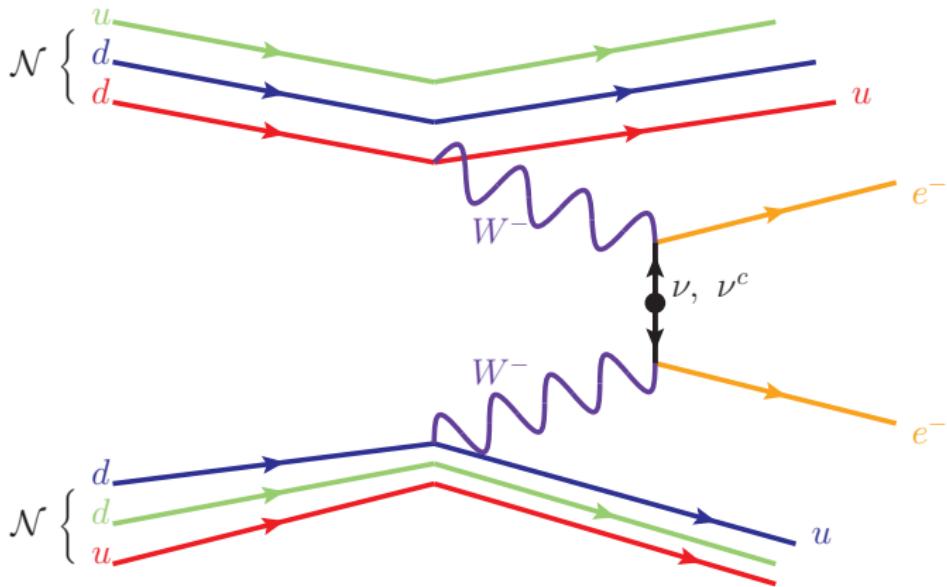
Institute of Nuclear Physics – Polish Academy of Science (IFJ PAN)

22 June 2021



¹w/ B. Fuks, J. Neundorf, K. Peters, M. Saimpert [2011.02547; 2012.09882]

a fun idea: is it possible to see the (standard mechanism for) neutrinoless $\beta\beta$ process ($0\nu\beta\beta$) at accelerators?



Why? Colliders, beam dumps, etc., can access μ and τ sectors!

for reviews on LNV/LFV at colliders, see w/ Y. Cai, T. Li, T. Han [1711.02180], and w/ S. Pascoli, et.al. [1812.08750]

Many ways to explain $m_\nu \neq 0$, so take an effective field theory approach:

The **Weinberg operator** is the only SMEFT operator at $d = 5$: Weinberg ('97)

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

Can be generated in **many** ways at tree- and loop-level

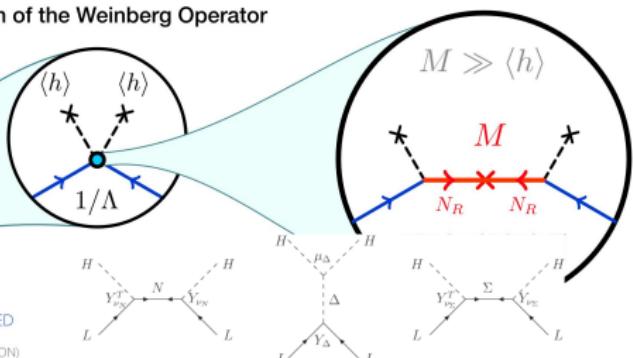
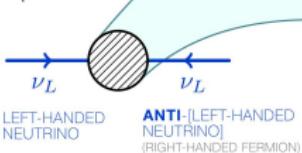
Eg. Ma ('98), Bonnet, et al [1204.5862]

Importantly, after EWSB, generates a Majorana mass matrix for ν

$$m_{\ell\ell'} = C_5^{\ell\ell'} \langle \Phi \rangle^2 / 2\Lambda \quad \leftarrow (\text{flavor basis!})$$

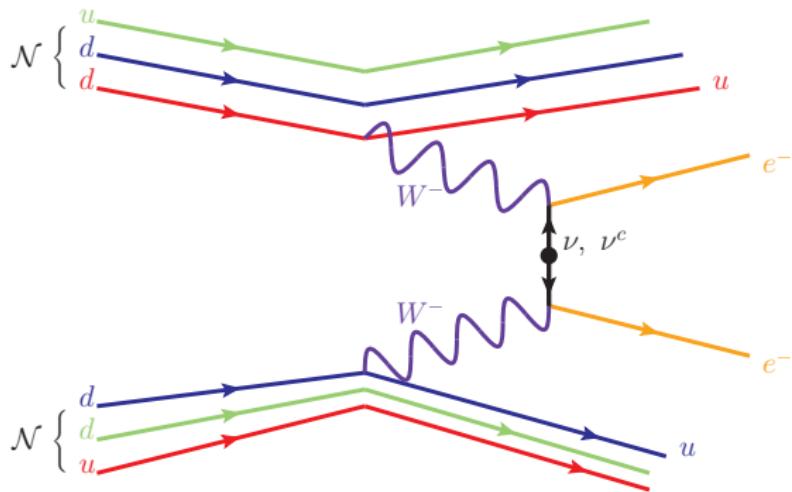
Type-I See-Saw Completion of the Weinberg Operator

one interesting way to generate the Weinberg operator is if a heavy gauge-singlet fermion has Yukawa couplings to the left-handed leptons



F.Tanedo

constraints on the Weinberg operator from nuclear $0\nu\beta\beta$ decay



The Weinberg operator:

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

generates ν mass matrix:

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

since

$$|m_{ee}| = \left| \sum_{k=1}^3 U_{ek} m_{\nu_k} U_{ek} \right|$$

"mass" in flavor space

⇒ nuclear $0\nu\beta\beta$ decay rate:

$$1/T_{1/2}^{0\nu\beta\beta} \sim |\mathcal{M}^{0\nu\beta\beta}|^2 \sim |m_{ee}|^2$$

The Weinberg operator:

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

generates ν mass matrix:

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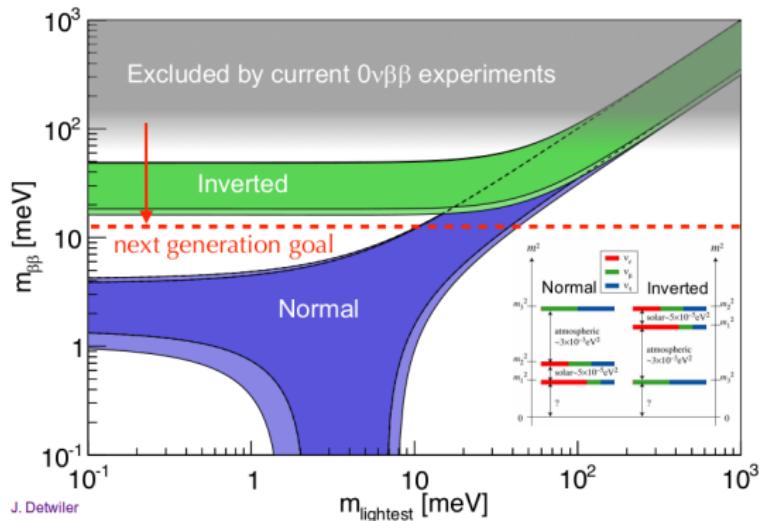
$$|m_{ee}| = \left| \sum_{k=1}^3 U_{ek} m_{\nu_k} U_{ek} \right|$$

"mass" in flavor space

\implies nuclear $0\nu\beta\beta$ decay rate:

$$1/T_{1/2}^{0\nu\beta\beta} \sim |\mathcal{M}^{0\nu\beta\beta}|^2 \sim |m_{ee}|^2$$

Plotted: Excluded/allowed "effective Majorana mass" vs lightest m_ν
 (assumes no other new physics)



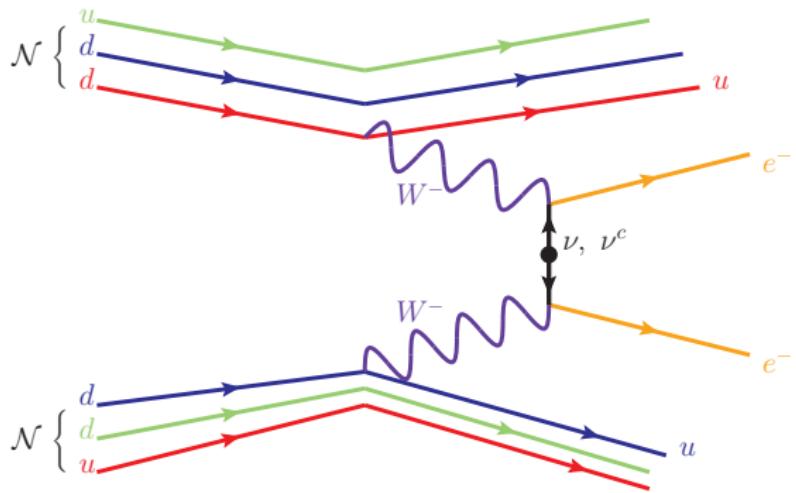
Searches for nuclear $0\nu\beta\beta$ set strong constraints, e.g., GERDA [2009.06079]

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

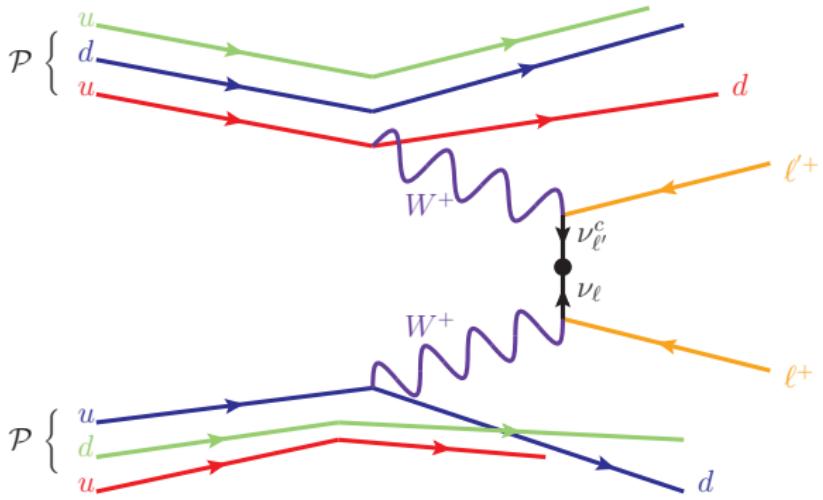
C_5^{ee} can naturally be zero/small

Eg. symmetry [0810.1263] or interference [Asaka('20)x3]

So what about the other $C_5^{\ell\ell'}$?



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



a moment of perspective

Our goal was to calculate $W^\pm W^\pm \rightarrow \ell_i^\pm \ell_j^\pm$ at $d = 5$ at the LHC

limited intuition since calculation was (to our knowledge!) absent in literature

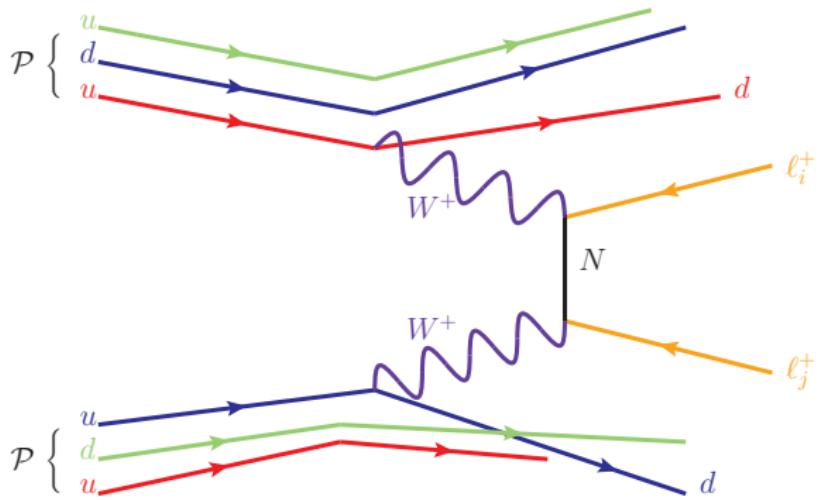
To build intuition, we considered first the $d = 4$ case with a Majorana N

interesting in its own right and exists in the literature! Dicus, et al (PRD'91),

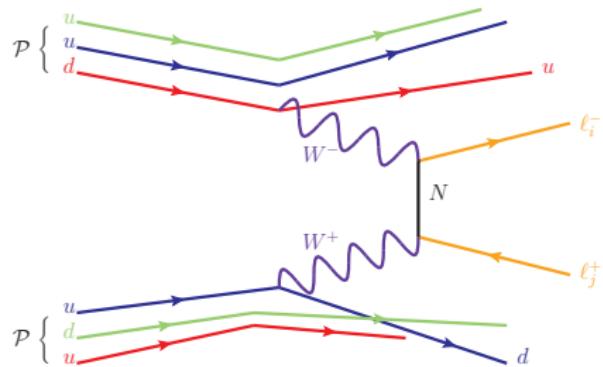
This turned out to be a very good idea. :)

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

w/ B. Fuks, J. Neundorf, K. Peters, M. Saimpert [2011.02547]



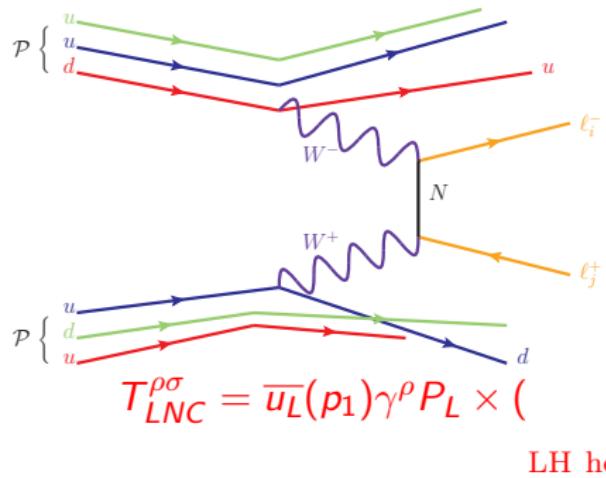
helicity preservation in $W^- W^+ \rightarrow \ell_i^- \ell_j^+$ (LNC+LFV!)



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

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

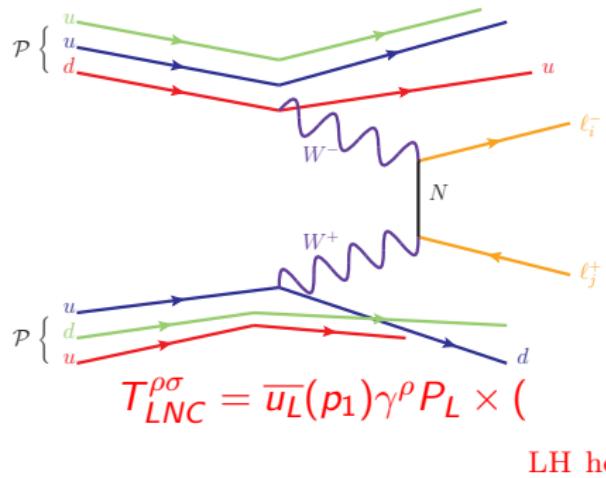
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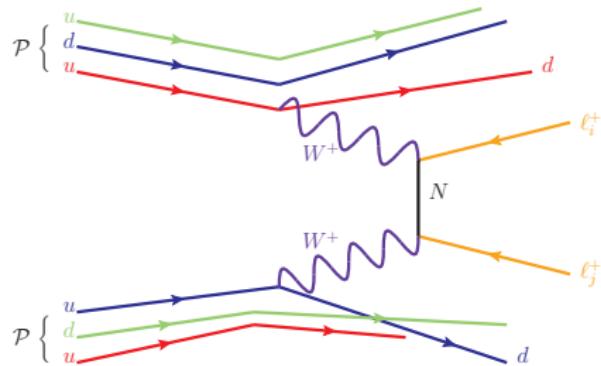
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The helicity amplitude for the LNC process $q_1 q_2 \rightarrow \ell_1^- \ell_2^+ q'_1 q'_2$ is

$$\Rightarrow \mathcal{M}_{LNC} \sim \frac{p_N}{(p_N^2 - m_N^2)} \quad \text{scales with momentum transfer!}$$

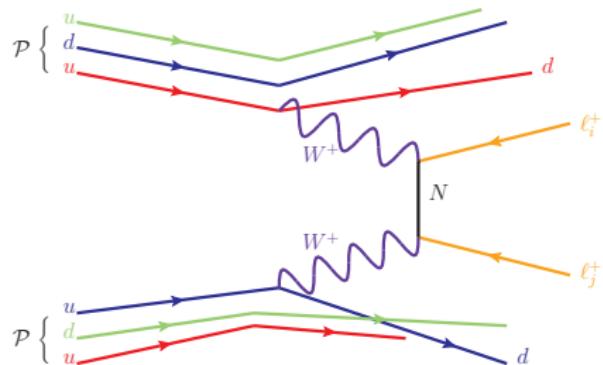
helicity inversion in $W^+W^+ \rightarrow \ell_i^+\ell_j^+$ (LNC+LFV!)



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

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

helicity inversion in $W^+W^+ \rightarrow \ell_i^+\ell_j^+$ (LNC+LFV!)



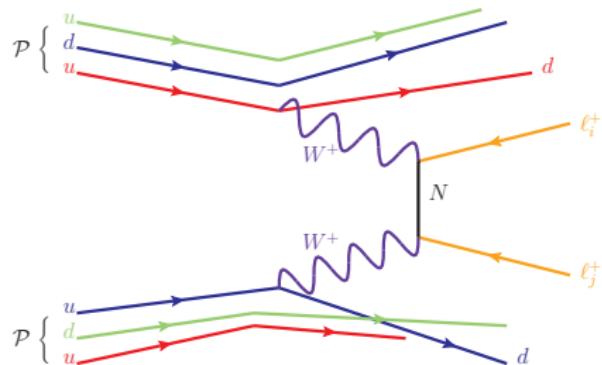
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Intuition: CPT Theorem \implies CT-inversion = P -inversion

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

helicity inversion in $W^+W^+ \rightarrow \ell_i^+\ell_j^+$ (LNC+LFV!)



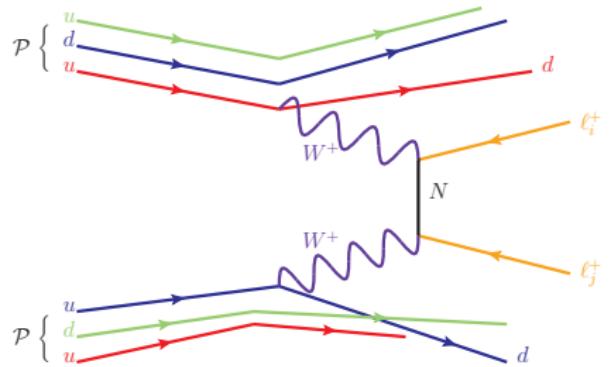
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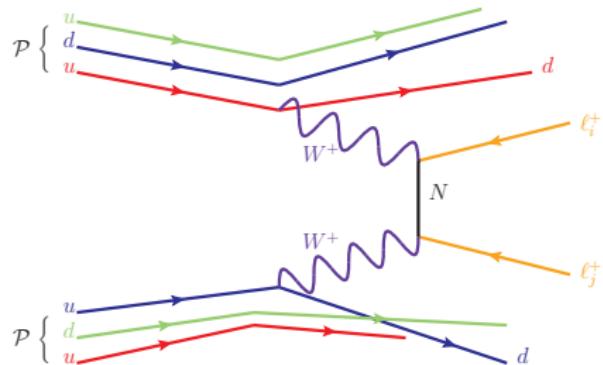
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$$\implies \mathcal{M}_{LNV} \sim \frac{m_N}{(p_N^2 - m_N^2)} \quad \text{scales with mass!}$$



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

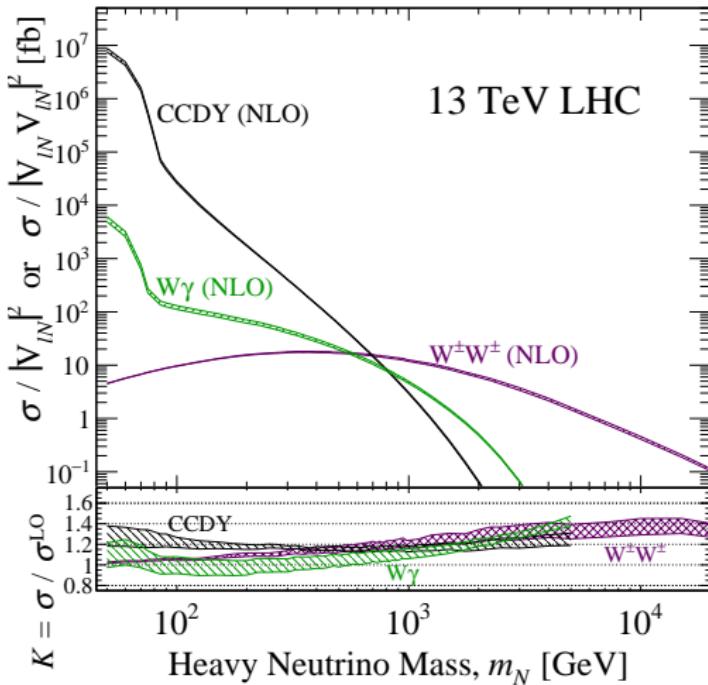
Used mg5amc + HeavyN UFO libraries

“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 ($M_{WW} \ll m_N$):
 $\hat{\sigma}(W^+W^+ \rightarrow \ell^+\ell^+)$

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



Reproduce LO results from Dicus, et al (PRD'91),

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 next few 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, μ_f, μ_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})	σ^{SR} [fb] (ε)
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%)

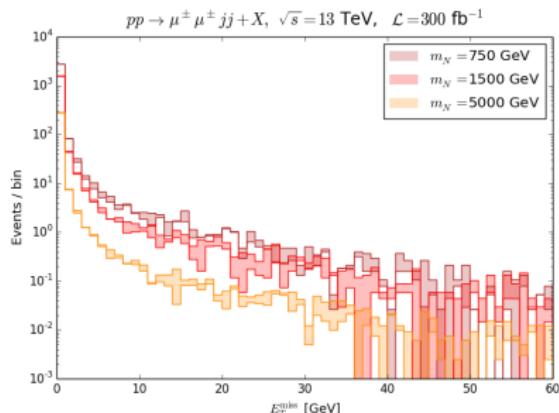
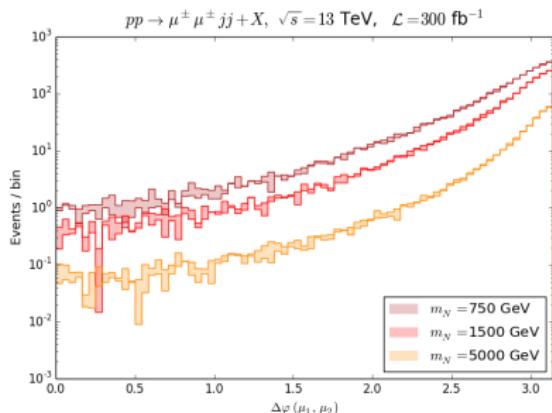
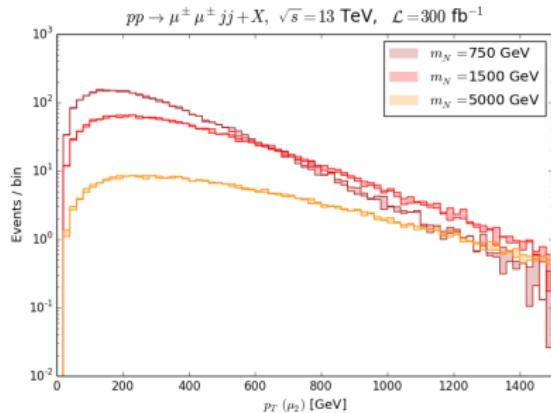
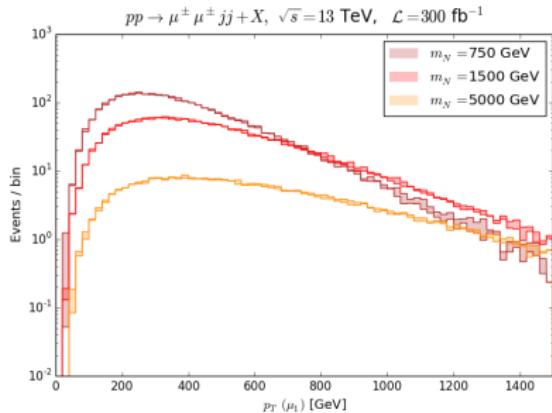
TABLE V. Expected number of SM background events in the Signal Region at the (HL-)LHC with $\mathcal{L} = 300$ fb $^{-1}$ (3 ab $^{-1}$).

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

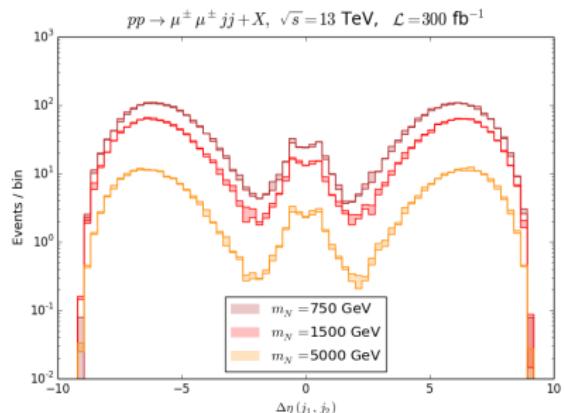
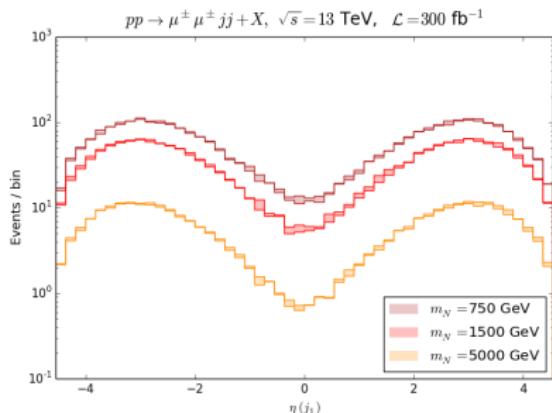
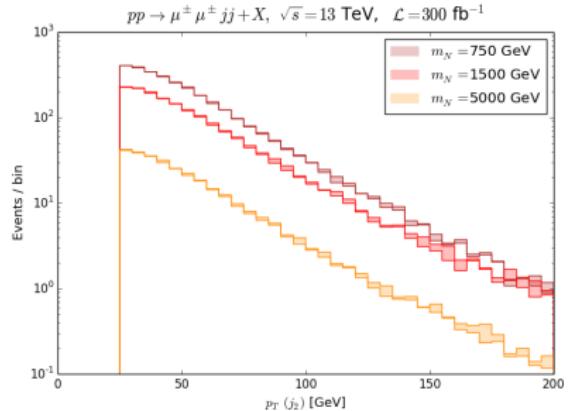
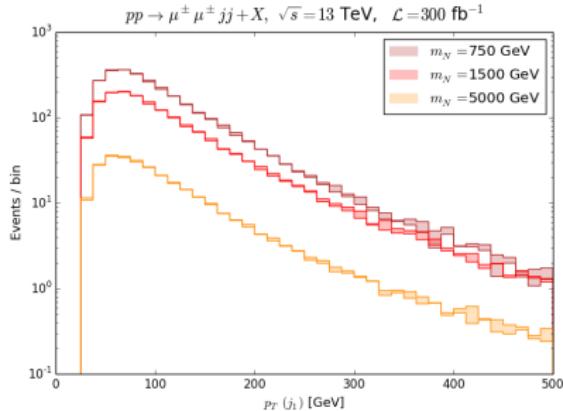
Kinematics at NLO+PS

after basis pre-selection

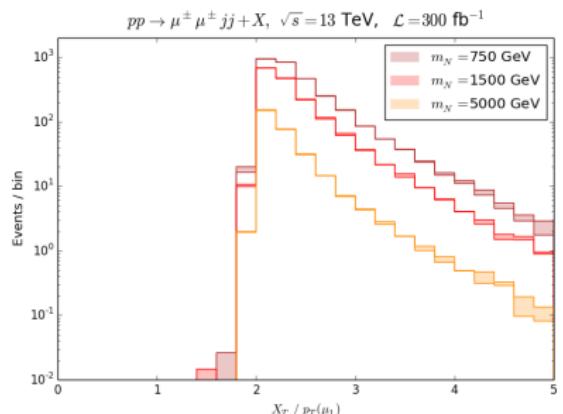
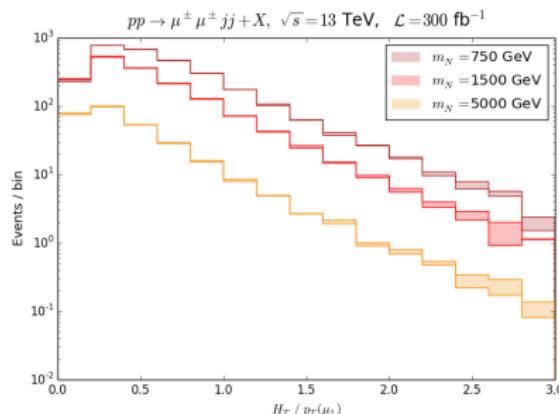
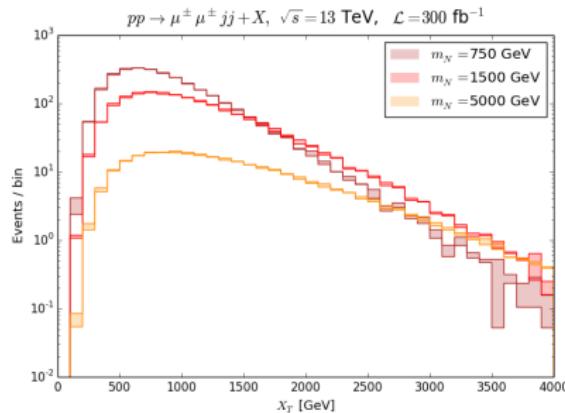
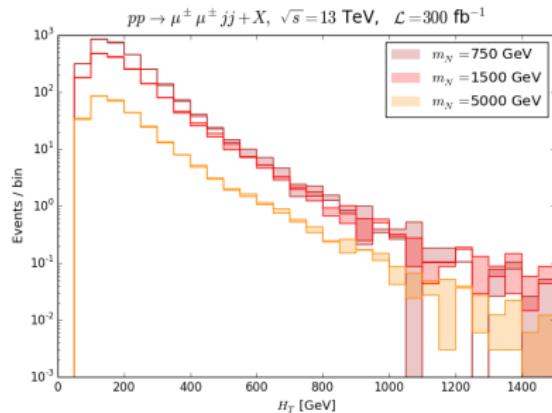
Top: $p_T^{\mu_1}$, $p_T^{\mu_2}$, Btm: $\Delta\varphi(\mu_1, \mu_2)$, MET



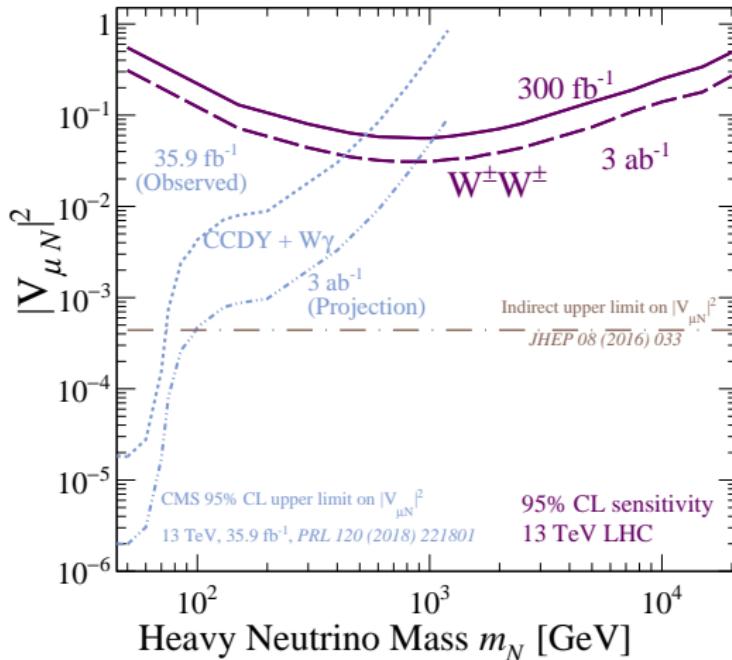
Top: $p_T^{j_1}$, $p_T^{j_2}$, **Btm:** η^{j_1} , $\Delta\eta(j_1, j_2)$



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



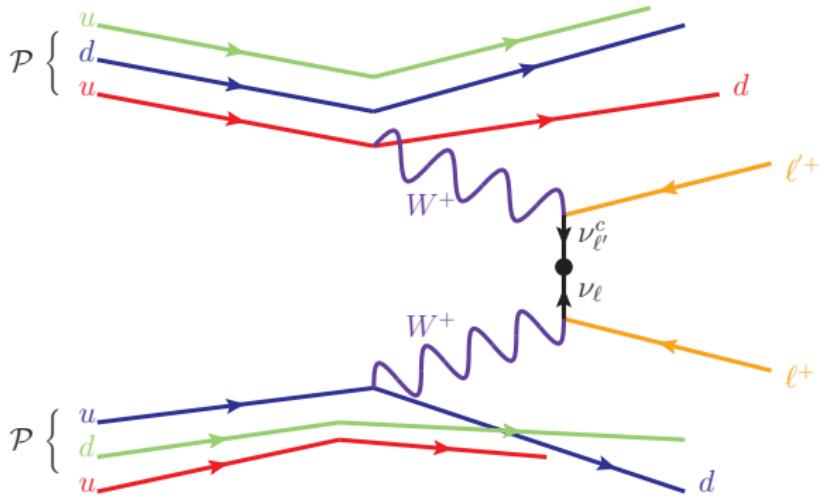
Plotted: LHC 13 sensitivity to active-sterile neutrino mixing (coupling) vs heavy neutrino mass (m_N)

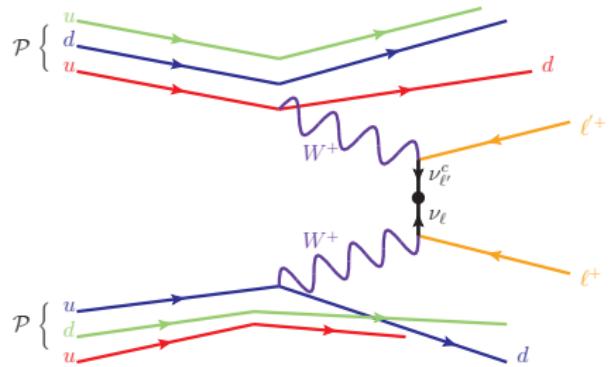


$W^\pm W^\pm \rightarrow \ell_i^\pm \ell_j^\pm$ allows direct probe $m_N \sim 1 - 10 \text{ TeV}$ at $|V|^2 \lesssim 0.1$

- Simplified analysis = room for improvement!

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





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

$$\mathcal{M}_{LNV} = J_{f_1 f'_1}^\mu J_{f_2 f'_2}^\nu \Delta_{\mu\alpha}^W \Delta_{\nu\beta}^W \underbrace{T_{LNV}^{\alpha\beta}}_{\text{lepton current}} \mathcal{D}(p_\nu)$$

Difficult to simulate events since Weinberg op. modifies propagator of ν_ℓ

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

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

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

recovers right behavior!

$$T_{LNV}^{\alpha\beta} \mathcal{D}(p_\nu) \propto \gamma^\alpha P_L \frac{i(p + m_{\ell\ell'})}{p^2 - m_{\ell\ell'}^2} \gamma^\beta P_R = \gamma^\alpha P_L \frac{i m_{\ell\ell'}}{p^2} P_L \gamma^\beta \times \left[1 + \mathcal{O}\left(\left|\frac{m_{\ell\ell'}}{p^2}\right|\right) \right]$$

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

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

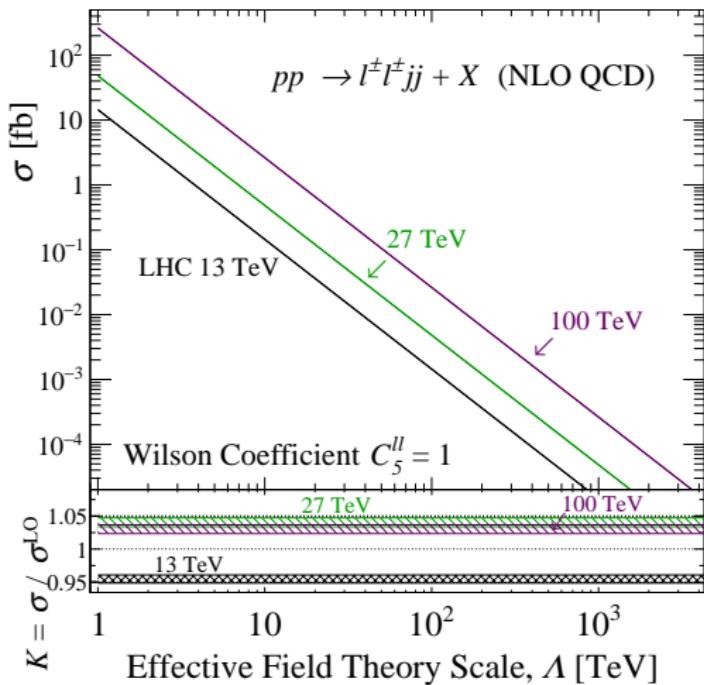
Full $2 \rightarrow 4$ calculation at NLO(+PS)
in QCD is more involved

Used mg5amc + NEW SMWeinberg UFO libraries

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

Once σ is obtained for a “high”
scale, i.e., $C_5^{\ell\ell'} = 1, \Lambda = 200$ TeV,
rescale for other Λ/C_5 .

C_5^{ee}/Λ is heavily constrained. **What**
can the LHC say about $C_5^{\ell\ell'}$?

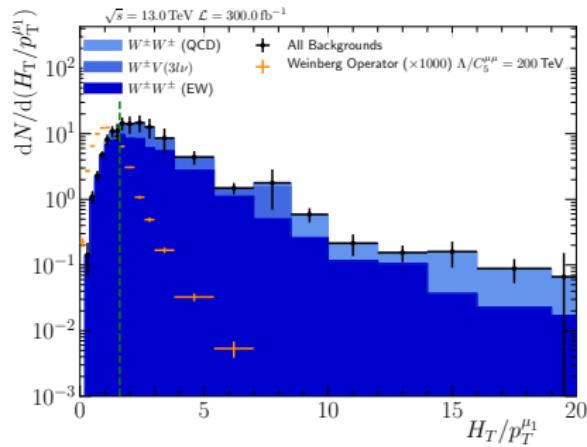
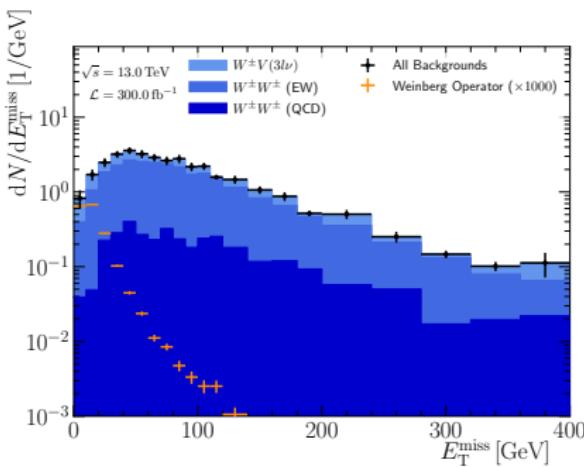


The collider signature exhibits both LNV and VBS characteristics

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

(L) E_T^{miss}

(R) $H_T/p_T^{\mu_1}$



The collider signature exhibits both LNV and VBS 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 II. Particle identification and signal region definitions

Particle Identification Cuts	
$p_T^{e(\mu)} [j] > 10$ (10) [25] GeV,	Anti- k_T ($R=0.4$)
$ \eta^{e(\mu)} [j] < 2.5$ (2.7) [4.5]	
Signal Region Cuts	
$p_T^{\mu_1(\mu_2)} > 27$ (10) GeV, $n_\mu = 2$, $n_j \geq 2$,	
$n_e = n_{\tau_{had}} = 0$, $Q_{\mu_1} \times Q_{\mu_2} = 1$, $M(j_1, j_2) > 700$ GeV	
$E_T^{\text{miss}} < 30$ GeV, $(H_T/p_T^{\mu_1}) < 1.6$	

TABLE III. Expected number of background and $0\nu\beta\beta$ signal events in the signal region with $\mathcal{L} = 300$ fb^{-1} (3 ab^{-1}).

Collider	$W^\pm W^\pm jj$	EW	$W^\pm W^\pm jj$	$W^\pm V$	Total	Signal
LHC	< 0.01		6.40	1.16	7.56	0.013
HL-LHC	< 0.01		64.0	11.6	75.5	0.13

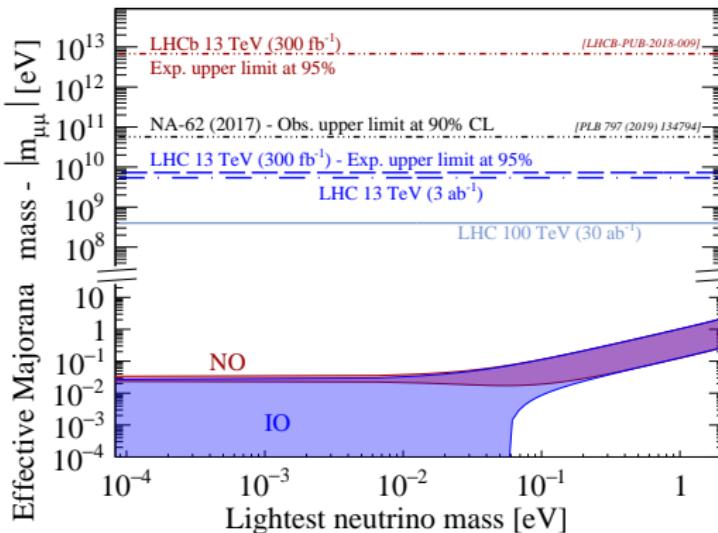
the big picture

With a minimal cuts (= can be improved) $\mathcal{L} = 300$ (3000) fb^{-1}

$$\Lambda / |C_5^{\mu\mu}| \lesssim 8.3 \text{ (11)} \text{ TeV} \implies |m_{\mu\mu}| \gtrsim 7.3 \text{ (5.4)} \text{ GeV}$$

Plotted: Allowed and projected reach of $|m_{\mu\mu}|$ vs lights ν mass

$$|m_{\ell\ell'}| = |C_5^{\ell\ell'}| \langle \Phi \rangle^2 / 2\Lambda = \left| \sum_{k=1}^3 U_{\ell k} m_{\nu_k} U_{\ell' k} \right|$$



LHC is most competitive but all can be improved!

Summary

- Colliders are **incredibly complementary** to oscillation facilities:
 - ▶ Direct production of **Seesaw** and **heavy flavors** particles
 - ▶ Test both neutrino **NSIs** and **UV** realizations of EFTs
- If BSM is **heavy**, the **Weinberg op.** parametrizes the origin of **m_ν**
 - ▶ $0\nu\beta\beta$ experiments **strongly constrain** Λ/C_5^{ee} but insensitive to μ, τ
 - ▶ For high-energy scattering and decay processes, a prescription for describing the **Weinberg op.** has been developed (and implemented into a **UFO!**)
w/ B. Fuks, J. Neundorf, K. Peters, M. Sainpert [[2012.09882](#)]
 - ▶ For first time, there is a **roadmap** for probing **Weinberg op.** with μ, τ at accelerators (LHC, HL-LHC, beam dumps, etc.)
- Along the way, learned a lot about **N** at $d = 4$ and $d = 6$ (backup!) Lots not covered, so see papers for details! [[2011.02547](#); [2012.09882](#)]

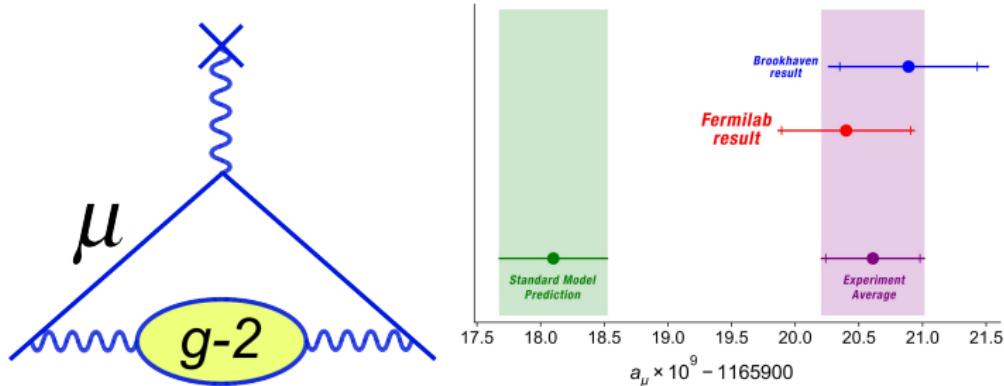


Thank you.

Backup

NEW:² Sterile neutrinos N at $d = 6$ and Δa_μ

Anomalous magnetic moment of the μ



Fermilab's Muon g-2 has *confirmed* that $a_\mu = (g_\mu - 2)/2$ is *a bit* large

[2104.03281]

$$a_\mu^{\text{average}} = (116\,592\,061 \pm 41) \cdot 10^{-11}$$

$$a_\mu^{\text{SM}} = (116\,591\,810 \pm 43) \cdot 10^{-11}$$

The difference? Large enough to start taking BSM solutions seriously.

$$\Delta a_\mu = (251 \pm 59) \cdot 10^{-11} \text{ or about } 4.2\sigma!$$

Can new N interactions account for this?

Yes, in a surprisingly succinct manner.

ν SMEFT is the Standard Model Effective Field Theory extended by ν_R

$\psi^2 H^3$		$\psi^2 H^2 D$		$\psi^2 H X (+\text{H.c.})$	
$\mathcal{O}_{L\nu H} (+\text{H.c.})$	$(\bar{L}\nu_R)\bar{H}(H^\dagger H)$	$\mathcal{O}_{H\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\bar{H}B^{\mu\nu}$
		$\mathcal{O}_{H\nu e} (+\text{H.c.})$	$(\bar{\nu}_R\gamma^\mu e)(\bar{H}^\dagger iD_\mu H)$	$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I \bar{H}W^{I\mu\nu}$
$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R) (+\text{H.c.})$	
$\mathcal{O}_{\nu\nu}$	$(\bar{\nu}_R\gamma^\mu\nu_R)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu}$	$(\bar{L}\gamma^\mu L)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Le}$	$(\bar{L}\nu_R)e(\bar{L}e)$
$\mathcal{O}_{e\nu}$	$(\bar{e}\gamma^\mu e)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{Q\nu}$	$(\bar{Q}\gamma^\mu Q)(\bar{\nu}_R\gamma_\mu\nu_R)$	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}\nu_R)e(\bar{Q}d)$
$\mathcal{O}_{u\nu}$	$(\bar{u}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu\nu_R)$			$\mathcal{O}_{LdQ\nu}$	$(\bar{L}d)e(\bar{Q}\nu_R)$
$\mathcal{O}_{d\nu}$	$(\bar{d}\gamma^\mu d)(\bar{\nu}_R\gamma_\mu\nu_R)$				
$\mathcal{O}_{duwe} (+\text{H.c.})$	$(\bar{d}\gamma^\mu u)(\bar{\nu}_R\gamma_\mu e)$				
$(\bar{L}R)(\bar{R}L)$		$(\bar{L} \cap B) (+\text{H.c.})$		$(\bar{L} \cap \mathcal{B}) (+\text{H.c.})$	
$\mathcal{O}_{Qu\nu L} (+\text{H.c.})$	$(\bar{Q}u)(\bar{\nu}_R L)$	$\mathcal{O}_{\nu\nu\nu\nu}$	$(\bar{\nu}_R^\ell\nu_R)(\bar{\nu}_R^\ell\nu_R)$	$\mathcal{O}_{QQd\nu}$	$\epsilon_{ij}\epsilon_{\alpha\beta\sigma}(Q_\alpha^\ell C Q_\beta^\ell)(d_\sigma C\nu_R)$
				$\mathcal{O}_{udd\nu}$	$\epsilon_{\alpha\beta\sigma}(u_\alpha C d_\beta)(d_\sigma C\nu_R)$

Table 1: The complete basis of dimension-six operators involving ν_R taken from Ref. [24]. The operators are expressed in terms of a column vector of n gauge singlet fields, ν_R , and of SM fields, the lepton and Higgs doublets, L and H , the quark left-handed doublet $Q = (u_L, d_L)^T$, and the right-handed fields e , u , and d .

Unexpectedly, only one ν SMEFT can generate the right Δa_μ

$$\mathcal{L}_{H\nu e} \approx \frac{gv^2}{2\sqrt{2}\Lambda^2} \sum_{k=1}^3 [\bar{C}_{H\nu e}]_{k\ell} (\bar{N}_k \gamma^\mu P_R \ell_R) W_\mu^+ (1 + \frac{h}{v})^2 + \text{H.c.}$$

This generates Δa_μ of the form

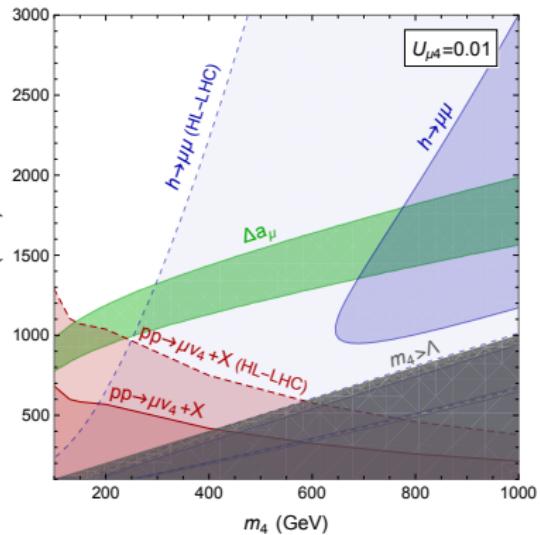
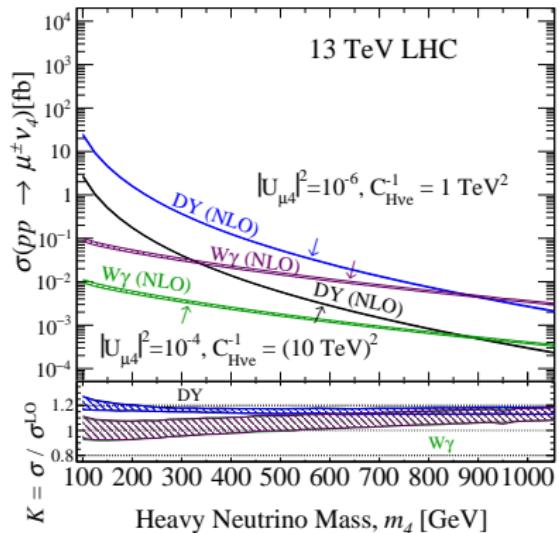
$$\Delta a_\mu \sim -\frac{2m_\mu m_N}{(4\pi)^2 \Lambda^2} \text{Re} \left(V_{\mu N} [\bar{C}_{H\nu e}]_{N\mu} \right)$$

(see [2105.11462] for exact formula!)

Δa_μ at the LHC

We created a new UFO HeavyN_vSMEFTdim6 containing $\mathcal{O}_{H\nu e}$

Already available from the FeynRules UFO database: feynrules.irmp.ucl.ac.be/wiki/HeavyN



Conclusion: If N are involved in Δa_μ , then expect something in

$$pp \rightarrow N\mu^\pm + X \text{ and } H \rightarrow \mu^+ \mu^-$$

in Run III data and at the HL-LHC (see the paper for more details! [\[2105.11462\]](#))