Probing charged lepton number violation via $\ell\ell' WW$

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Based on Mayumi Aoki, KE, Shinya Kanemura, PRD 101 (2020) 115019 and the work in progress.

I. Introduction ($\ell\ell' WW$ operator)

■ The origin of tiny neutrino masses is still unknown.

A key to solving the mystery

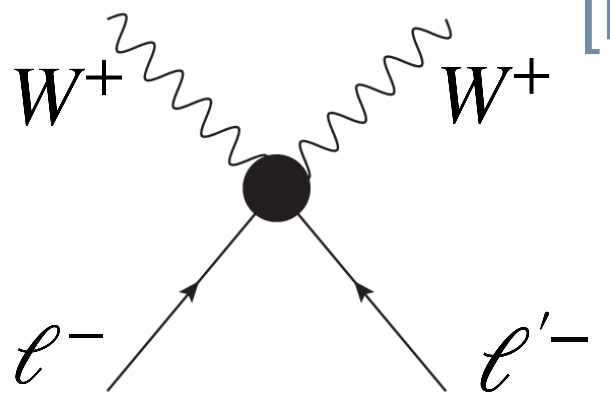
Lepton Number Violation (LNV)

LNV at high energies = LNV higher dimensional operators

[Weinberg, PRL(1979)], [Babu, Leung, NPB(2001)]

$\ell\ell' WW$ operators

[F. del Aguila, et al, JHEP 05 (2012); JHEP 06 (2012)]



$$\overline{\ell^c_L}\ell'_L W^+_\mu W^{+\mu}, \quad \overline{\ell^c_R}\ell'_R W^+_\mu W^{+\mu}$$

■ They include only charged leptons (not ν)

■ Rich phenomenology would be expected.

II. Lagrangian

■ $\ell\ell' WW$ oeps. are from gauge invariant $d=7$ or $d=9$ LNV opes.

[F. del Aguila, et al, JHEP(2012)], [M. Gustafsson, PRL(2013)]

Left-Handed (LH) $\ell\ell' WW$

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{C_5^{\ell\ell'}}{\Lambda}\left(\overline{\tilde{L}_\ell} H\right)\left(\tilde{H}^\dagger L_{\ell'}\right) + \frac{C_7^{\ell\ell'}}{\Lambda^3}\left(\overline{\tilde{L}_\ell} D_\mu L_{\ell'}\right)\left(\tilde{H}^\dagger D^\mu H\right)$$

Weinberg ope.

Right-Handed (RH) $\ell\ell' WW$

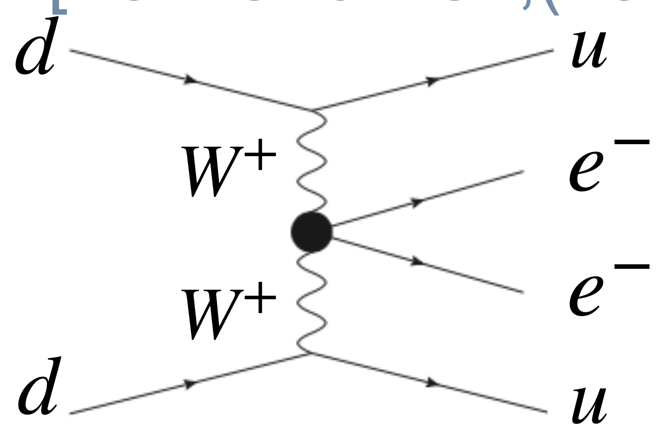
$$\mathscr{L} = \mathscr{L}_{SM} + \frac{C_5^{\ell\ell'}}{\Lambda}\left(\overline{\tilde{L}_\ell} H\right)\left(\tilde{H}^\dagger L_{\ell'}\right) + \frac{C_9^{\ell\ell'}}{\Lambda^5}\left(\overline{\ell^c_R}\ell'_R\right)\left(\tilde{H}^\dagger D_\mu H\right)^2$$

■ Neutrino masses are generated by Weinberg ope. at tree level.

■ $d=7,9$ opes. contribute to ν masses at loop level (Sec.IV)

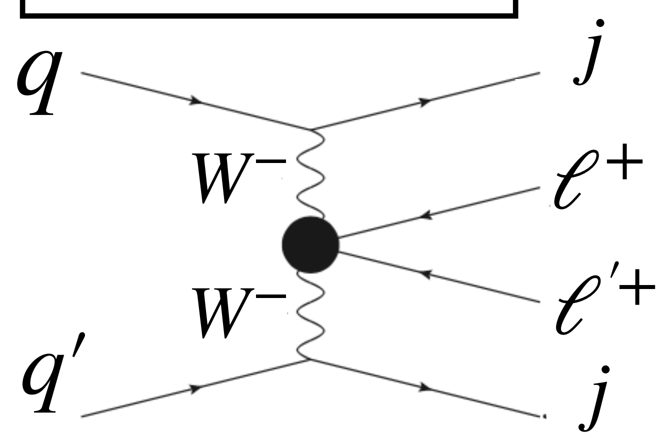
III. $\ell\ell' WW$ in $0\nu\beta\beta$ and hadron colliders

$\boxed{0\nu\beta\beta}$ $T_{1/2} > 10^{26}$ years [Kamland-Zen,(2018)]



	Lower limit
LH	$\Lambda \gtrsim 8.4$ TeV
RH	$\Lambda \gtrsim 1.8$ TeV

$\boxed{pp \to \ell^+\ell'^+ jj}$ at HL-LHC



$\sqrt{s} = 14$ TeV

$L = 3000\ \mathrm{fb}^{-1}$

With Background reduction(Backup)

	Lower limit	
	$\ell = \ell'$	$\ell \neq \ell'$
LH	$\Lambda \gtrsim 1.8$ TeV	2.3 TeV
RH	$\Lambda \gtrsim 0.71$ TeV	0.82 TeV

■ $\ell\ell' WW$ opes. can be directly tested at HL-LHC.

■ For (e, e) channel, current $0\nu\beta\beta$ limit is very stringent, however, HL-LHC can be useful to test other flavor channels.

IV. Loop-level analysis (Work in progress)

■ The above results are tree level analysis.

■ The origin of $\ell\ell' WW$ operators ($d = 7,9$) contribute to Majorana ν masses at loop level.

■ To consider the constraints from ν mass matrix data, loop level analysis is needed.

■ It is the work in progress, and current status is explained in Backup

Backup slide1

A. Details of Background reduction

SM backgrounds

1. $pp \to \ell^+\ell^- jj$ with charge mis-id.
2. $pp \to \ell^+\ell'^+\nu_\ell\nu_{\ell'} jj$

Background for only flavor diagonal channel

Kinematical cuts

Basic cuts (due to detector performance)

$$p_T^j > 30\ \mathrm{GeV},\quad |\eta_j| < 5.0,\quad p_T^\ell > 20\ \mathrm{Gev},\quad |\eta_\ell| < 2.5$$

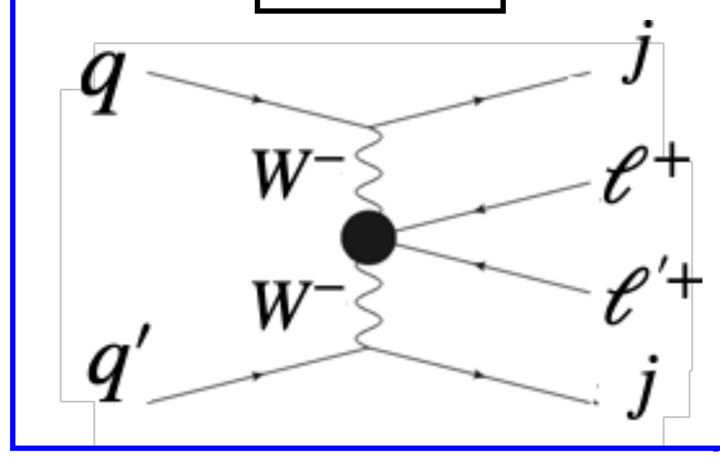
VBF cuts

$$m_{jj} > 500\ \mathrm{GeV},\quad |\Delta\eta_{jj}| > 2.5$$

Other cuts

$$p_T^\ell > 500\ \mathrm{GeV},\quad \not{p}_T < 20\ \mathrm{GeV}$$

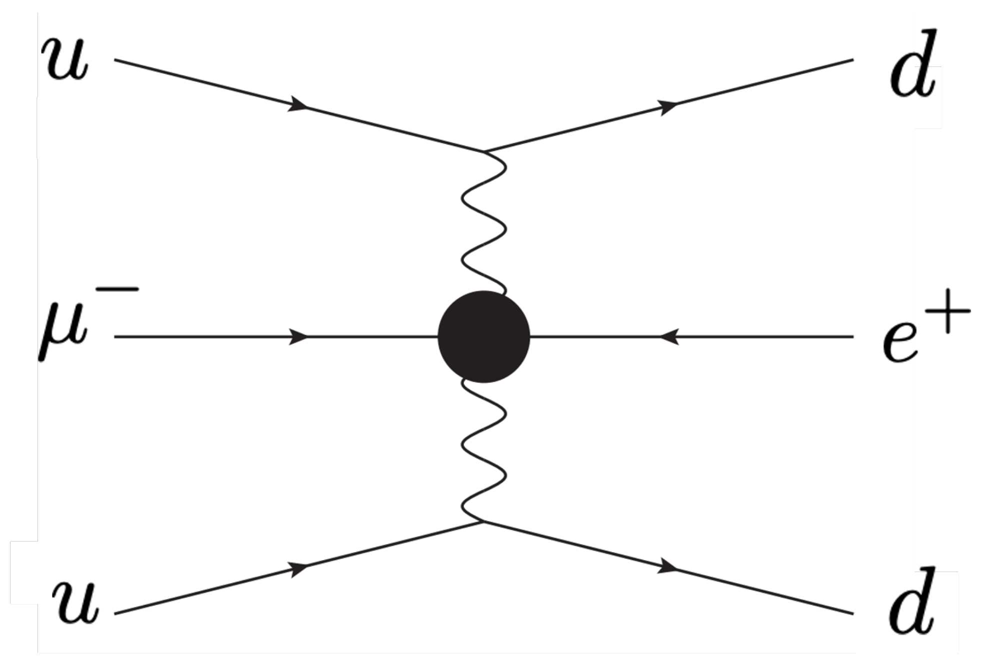
Signal



$C/\Lambda = 1\ \mathrm{TeV}^{-1}$	Basic cut	$+$VBF cut	$+\not{p}_T$ cut	$+p_T^\ell$ cut
Signal (pb)	4.69	4.5	4.5	2.9
eff.	-	96 %	100 %	64 %
$\mu^+\mu^- jj$ (pb)	117	4.1	4.1	5.3×10^{-5}
eff.	-	3.5%	100%	1.3×10^{-3} %
$\mu^+\mu^+\nu_\mu\nu_\mu jj$ (pb)	3.71×10^{-3}	1.40×10^{-3}	6.5×10^{-5}	6×10^{-9}
eff.	-	38 %	4.6 %	0.01 %

※C/Λ is coefficient of $d=5$ $\ell\ell' WW$ ope.

B. $\ell\ell' WW$ in μ^--e^+ conversion

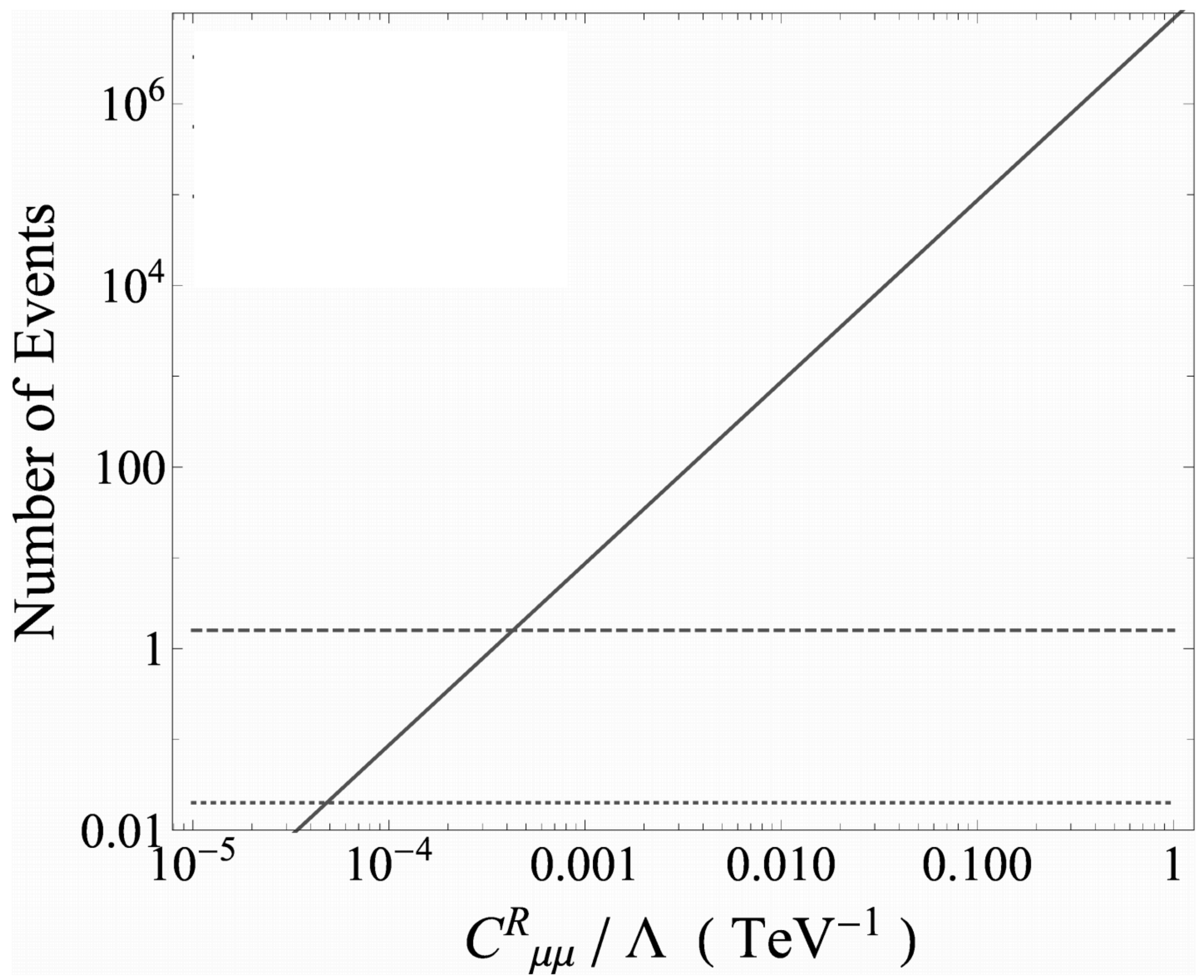


	Lower limit
LH	$\Lambda \gtrsim 3.3\times10^{-4}$ TeV
RH	$\Lambda \gtrsim 4.1\times10^{-3}$ TeV

Too weak limit

$$\frac{\Gamma(\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca})}{\Gamma(\mu^- + \mathrm{Ti} \to \nu_\mu + \mathrm{Sc})} < 1.7\times10^{-12}$$

[SINDRUM-II, (1998)]



We assume that the charge mis-id rate $r = 1\,\%$

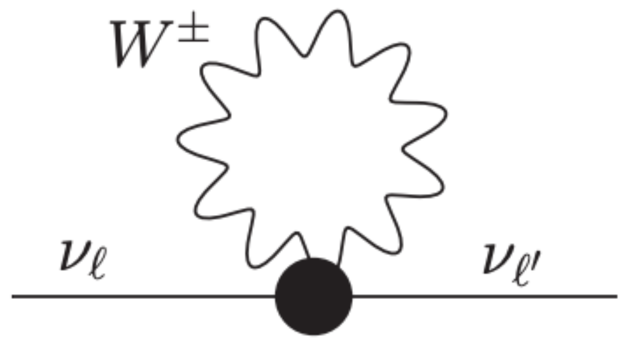
- $\mu^+\mu^+ jj$ (signal)
- $\mu^+\mu^- jj \times r$
- $\mu^+\mu^+\nu_\mu\nu_\mu jj$

Backup slide2

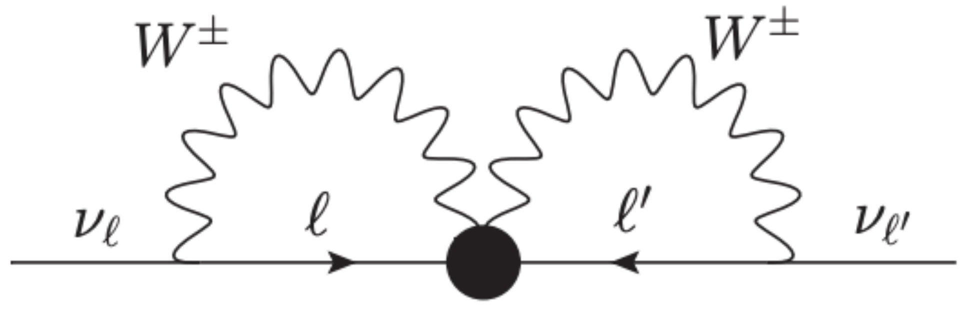
C. Loop-level analysis (Work in progress)

■ $d=7\ (9)$ operators contribute Majorana ν masses at one- (two-) loop level.

$(\tilde{\overline{L}}_\ell D_\mu L_{\ell'})(\tilde{H}^\dagger D^\mu H) \to \overline{\nu^c_{\ell L}}\nu_{\ell' L} W^{+\mu} W^+_\mu$



$d=7$



$d=9$

$$M_\nu^{1(2)\text{-loop}} = \boxed{\frac{v^2}{\Lambda} C_5^{\ell\ell'}} \boxed{+\,\delta\left(\frac{v^2}{\Lambda} C_5^{\ell\ell'}\right) + \left(\text{Contributions from } d=7\ (9) \text{ LNV opes.}\right)}$$

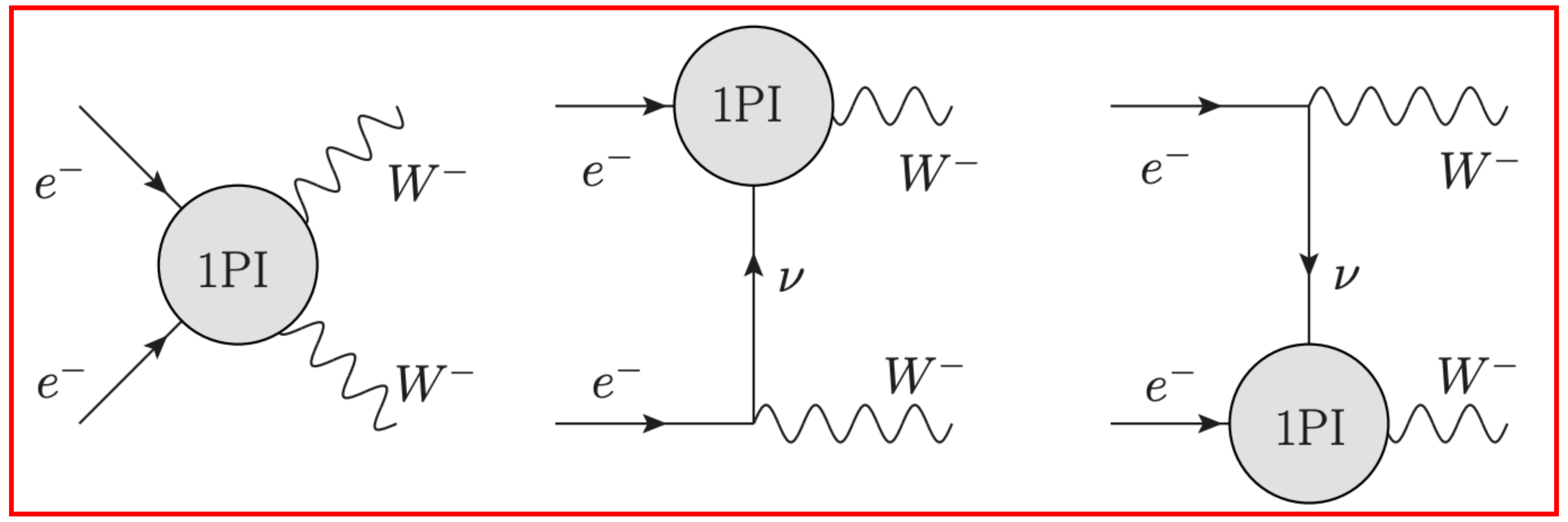
tree level:
Weinberg ope.

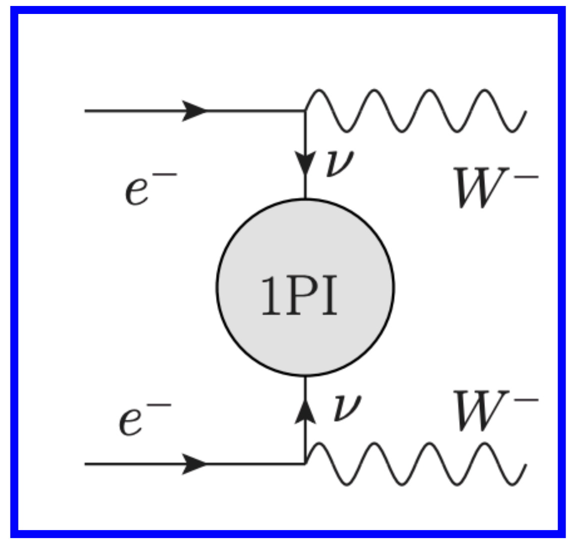
1-loop (2-loop) level

■ The counter term $\delta\left(\frac{v^2}{\Lambda} C_5^{\ell\ell'}\right)$ can be determined by <u>on-shell condition</u> to neutrino two point function.

Neutrino mass matrix data

To answer the question, we must to be decide other counter terms.





At loop level,
the counter terms of $d \geq 7$ LNV opes. contribute.

$\delta\left(\frac{v^2}{\Lambda} C_5^{\ell\ell'}\right)$

■ In general, it is not possible to determine all of counter terms of other LNV opes with physical renormalization condition.

EFT is NOT renormalizable theory

■ Is it possible to determine these counter terms under an appropriate assumption about new physics ? (e.g. flavor symmetries)

Now, we are investigating.

Q. How does the counter terms $\delta\left(\frac{v^2}{\Lambda} C_5^{\ell\ell'}\right)$ determined by neutrino mass matrix data change the results in the tree level analyses (in my presentation) ?