Low-scale Lepton Number Violation and Leptogenesis

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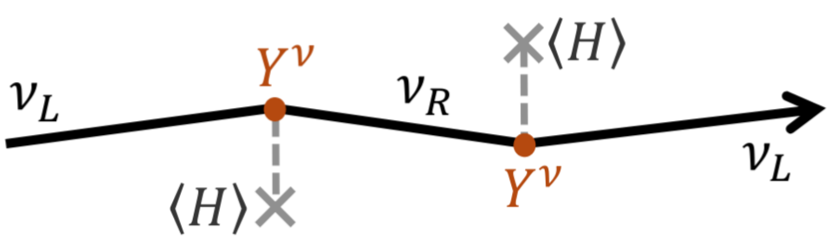
F. Deppisch, L. Graf, JH, W. Huang, arxiv:1711.10432
F. Deppisch, JH, W. Huang, M. Hirsch, H. Päs, Phys. Rev. D92 (2015) 036005
F. Deppisch, JH, M. Hirsch, PRL 112 (2014) 221601

Why is Lepton Number Violation that interesting and powerful?

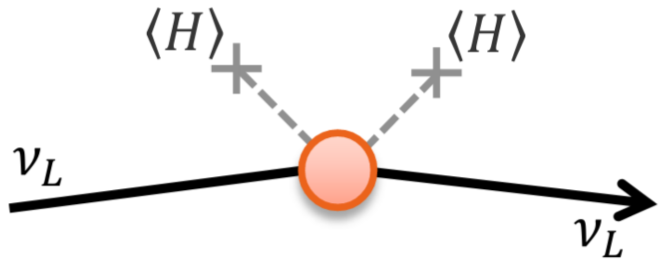
Neutrino mass mechanism

- The origin of neutrino masses lies beyond the standard model



Dirac

vs.



Majorana

- Dirac masses
- Additional right handed neutrinos
- tiny Yukawa couplings $m_\nu/\Lambda_{EW} \leq 10^{-12}$

- Majorana neutrino mass
- Only left handed neutrinos
- Lepton number violation (LNV)

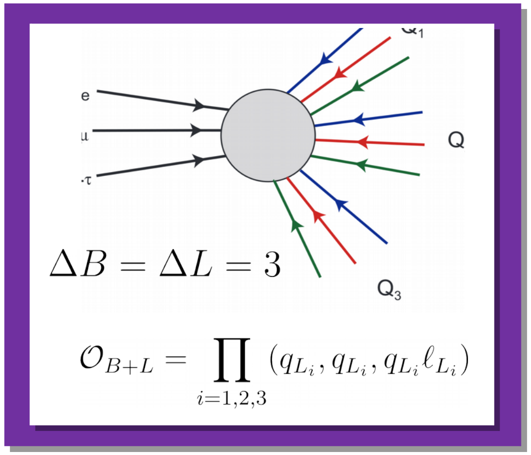
LNV as a probe of baryogenesis models

- generation of lepton asymmetry via heavy neutrino decays
- competition with lepton number violating (LNV) washout processes
- conversion to baryon asymmetry via sphaleron processes at

$$Hz\frac{dN_{N_1}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{\rm eq})$$

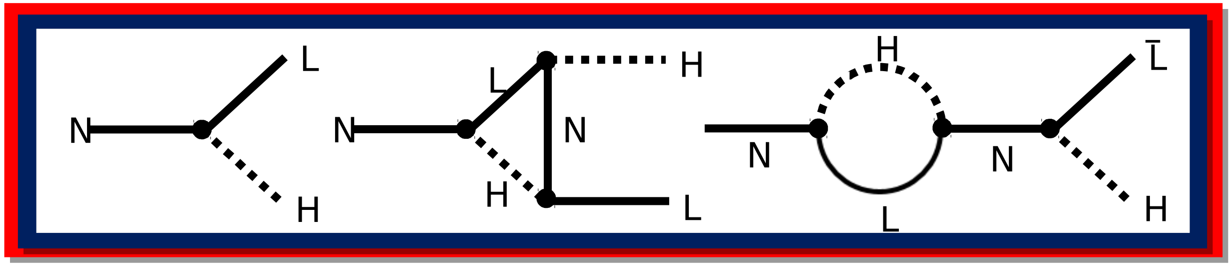
$$Hz\frac{dN_L}{dz} = \epsilon_1 \Gamma_D (N_{N_1} - N_{N_1}^{\rm eq}) - \Gamma_W N_L$$

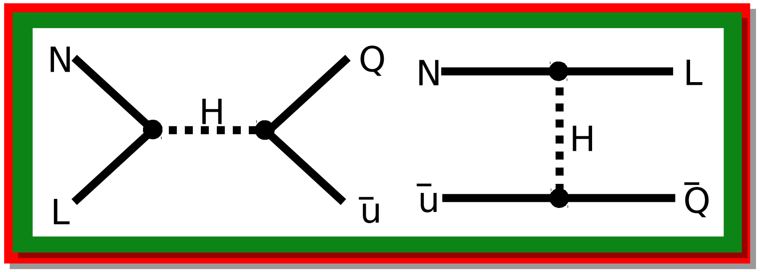
$T \approx 100\mathrm{GeV}$

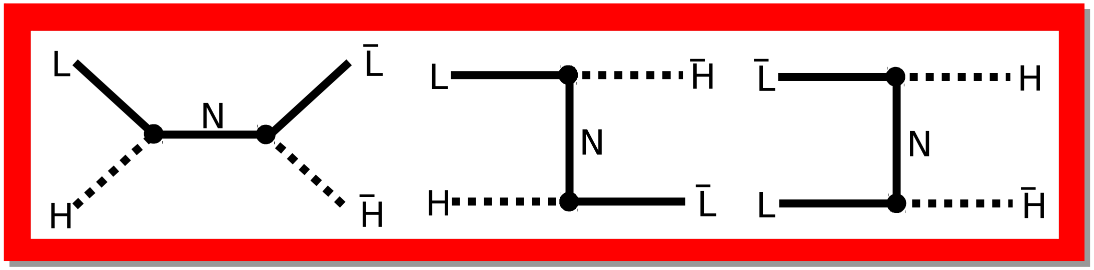


sphaleron processes

$\Delta L = 1$ source of CP violation

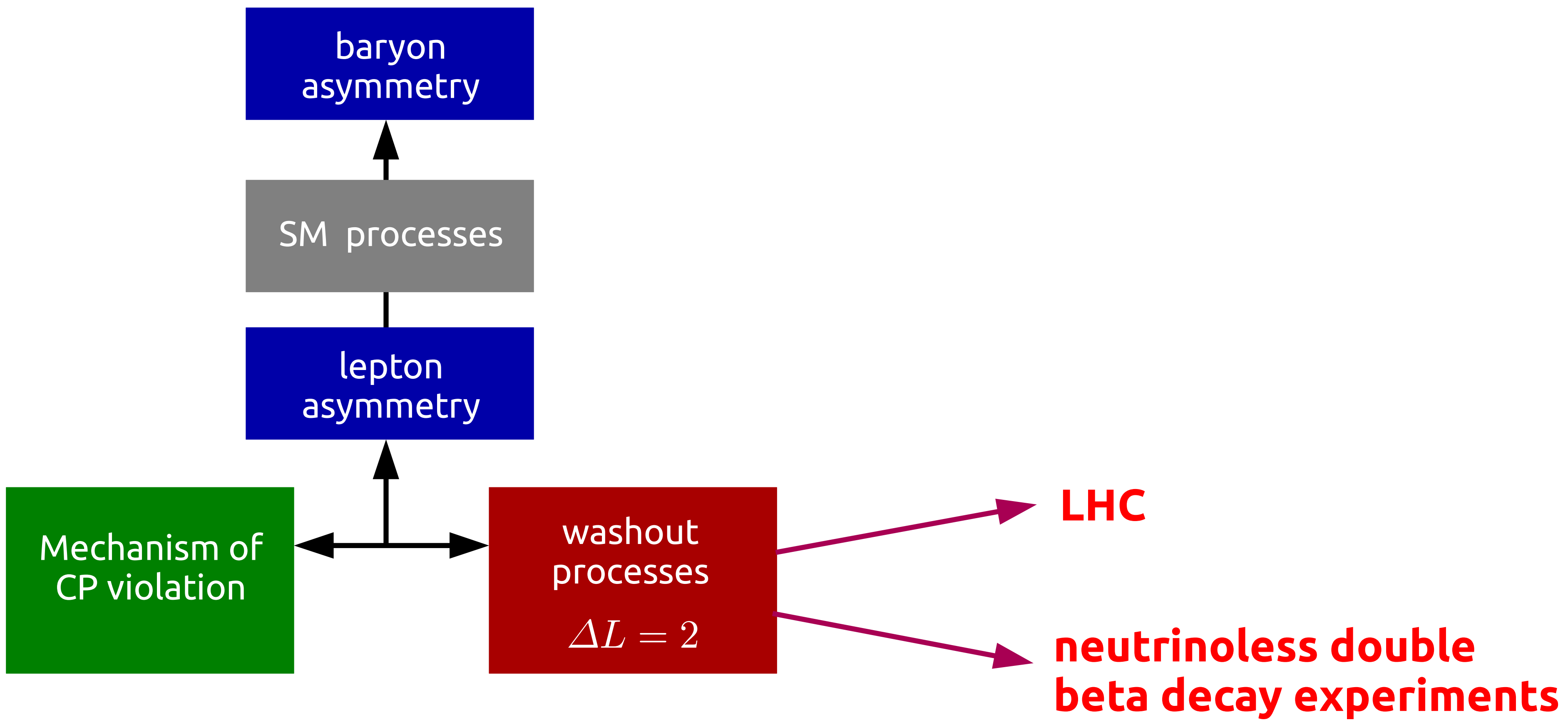






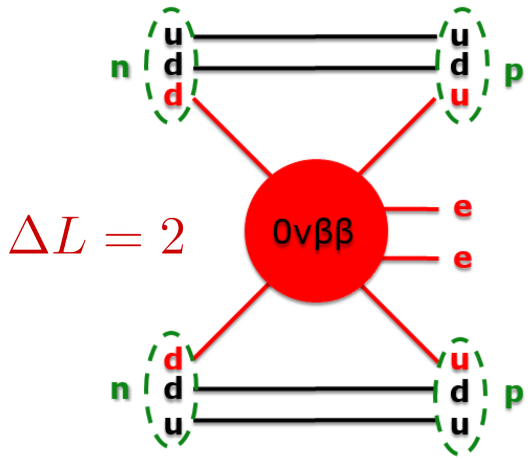
$\Delta L = 2$ scattering processes $\Delta L = 2$ washout processes

LNV as a probe of baryogenesis models



LNV at 0vbb decay experiments

Neutrinoless double beta decay (0vbb)

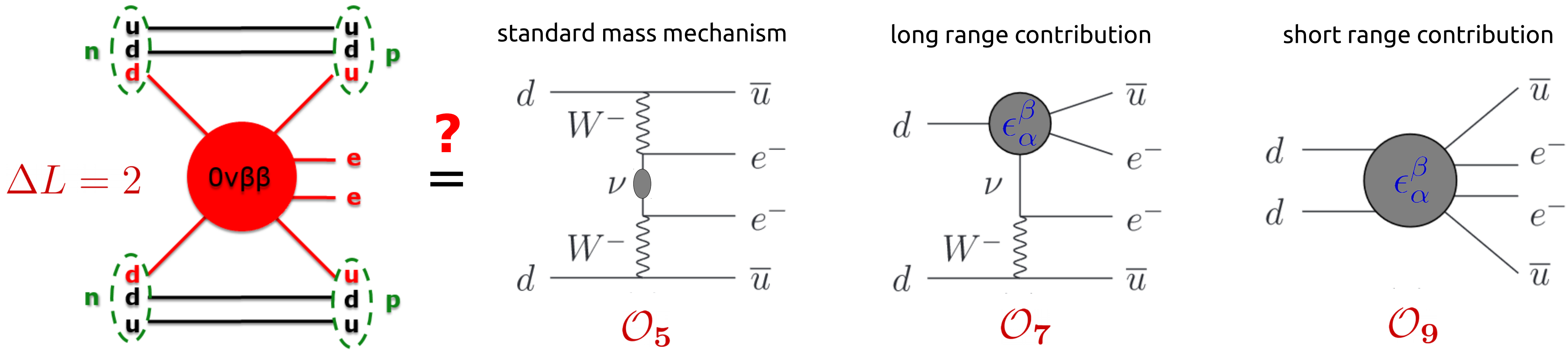


Most stringent limits are currently from GERDA and Kamland-Zen:

$$T_{1/2}^{\rm Ge} \geq 5.3 \times 10^{25}\ \rm y \qquad\qquad T_{1/2}^{\rm Xe} \geq 1.07 \times 10^{26}\ \rm y$$

Experiment	Iso.	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]
LEGEND 200 [60, 61]	^{76}Ge	$8.4 \cdot 10^{26}$	40–73
LEGEND 1k [60, 61]	^{76}Ge	$4.5 \cdot 10^{27}$	17–31
SuperNEMO [67, 68]	^{82}Se	$6.1 \cdot 10^{25}$	82–138
CUPID [57, 58, 69]	^{82}Se	$1.8 \cdot 10^{27}$	15–25
CUORE [51, 52]	^{130}Te	$5.4 \cdot 10^{25}$	66–164
CUPID [57, 58, 69]	^{130}Te	$2.1 \cdot 10^{27}$	11–26
SNO+ Phase I [65, 70]	^{130}Te	$1.1 \cdot 10^{26}$	46–115
SNO+ Phase II [66]	^{130}Te	$4.8 \cdot 10^{26}$	22–54
KamLAND-Zen 800 [59]	^{136}Xe	$1.6 \cdot 10^{26}$	47–108
KamLAND2-Zen [59]	^{136}Xe	$8.0 \cdot 10^{26}$	21–49
nEXO [71]	^{136}Xe	$4.1 \cdot 10^{27}$	9–22
NEXT 100 [63, 72]	^{136}Xe	$5.3 \cdot 10^{25}$	82–189
PandaX-III 200 [64]	^{136}Xe	$8.3 \cdot 10^{25}$	65–150
PandaX-III 1k [64]	^{136}Xe	$9.0 \cdot 10^{26}$	20–46

Neutrinoless double beta decay (0vbb)



Most stringent limits are currently from GERDA and Kamland-Zen:

$$T_{1/2}^{\mathrm{Ge}} \geq 5.3 \times 10^{25}\ \mathrm{y} \qquad T_{1/2}^{\mathrm{Xe}} \geq 1.07 \times 10^{26}\ \mathrm{y}$$

All ΔL=2 LNV operators contribute to 0vbb

The inverse half life can be expressed in terms of effective couplings:

$$T_{1/2}^{-1} = G_{0\nu}\,|\,\mathcal{M}\,|^2|\,m_{\beta\beta}\,|^2$$

$$T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2$$

All ΔL=2 LNV effective operators up to dim 11

$\mathcal{O}$	Operator
1	$L^iL^jH^kH^l\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
4_b	$L^iL^j\overline{Q}_k\overline{u^c}H^k\epsilon_{ij}$
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$
6	$L^iL^j\overline{Q}_k\overline{u^c}H^lH^k\overline{H}_i\epsilon_{jl}$
7	$L^iQ^j\overline{e^c}\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$
8	$L^i\overline{e^c}\overline{u^c}d^cH^j\epsilon_{ij}$
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$
12_a	$L^iL^j\overline{Q}_i\overline{u^c}\overline{Q}_j\overline{u^c}$
12_b	$L^iL^j\overline{Q}_k\overline{u^c}\overline{Q}_l\overline{u^c}\epsilon_{ij}\epsilon^{kl}$
13	$L^iL^j\overline{Q}_i\overline{u^c}L^le^c\epsilon_{jl}$
14_a	$L^iL^j\overline{Q}_k\overline{u^c}Q^kd^c\epsilon_{ij}$
14_b	$L^iL^j\overline{Q}_i\overline{u^c}Q^ld^c\epsilon_{jl}$
15	$L^iL^jL^kd^c\overline{L}_i\overline{u^c}\epsilon_{jk}$
16	$L^iL^je^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$
17	$L^iL^jd^cd^c\overline{d^c}\overline{u^c}\epsilon_{ij}$
18	$L^iL^jd^cu^c\overline{u^c}\overline{u^c}\epsilon_{ij}$
19	$L^iQ^jd^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$
20	$L^id^c\overline{Q}_i\overline{u^c}\overline{e^c}\overline{u^c}$
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$
22	$L^iL^jL^ke^c\overline{L}_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$
23	$L^iL^jL^ke^c\overline{Q}_k\overline{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$
26_a	$L^iL^jQ^kd^c\overline{L}_i\overline{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$
26_b	$L^iL^jQ^kd^c\overline{L}_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$
27_a	$L^iL^jQ^kd^c\overline{Q}_i\overline{d^c}H^lH^m\epsilon_{jl}\epsilon_{km}$
27_b	$L^iL^jQ^kd^c\overline{Q}_k\overline{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$
28_a	$L^iL^jQ^kd^c\overline{Q}_ju^cH^l\overline{H}_i\epsilon_{kl}$
28_b	$L^iL^jQ^kd^c\overline{Q}_ku^cH^l\overline{H}_i\epsilon_{jl}$
28_c	$L^iL^jQ^kd^c\overline{Q}_lu^cH^l\overline{H}_i\epsilon_{jk}$
29_a	$L^iL^jQ^ku^c\overline{Q}_k\overline{u^c}H^lH^m\epsilon_{il}\epsilon_{jm}$
29_b	$L^iL^jQ^ku^c\overline{Q}_l\overline{u^c}H^lH^m\epsilon_{ik}\epsilon_{jm}$
30_a	$L^iL^j\overline{L}_ie^c\overline{Q}_ku^cH^kH^l\epsilon_{jl}$
30_b	$L^iL^j\overline{L}_me^c\overline{Q}_nu^cH^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
31_a	$L^iL^j\overline{Q}_id^c\overline{Q}_k\overline{u^c}H^kH^l\epsilon_{jl}$

$\mathcal{O}$	Operator
31_b	$L^iL^j\overline{Q}_md^c\overline{Q}_n\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
32_a	$L^iL^j\overline{Q}_j\overline{u^c}\overline{Q}_k\overline{u^c}H^k\overline{H}_i$
32_b	$L^iL^j\overline{Q}_mu^c\overline{Q}_n\overline{u^c}H^k\overline{H}_i\epsilon_{jk}\epsilon^{mn}$
33	$\overline{e^c}\overline{e^c}L^iL^je^ce^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
34	$\overline{e^c}\overline{e^c}L^iQ^je^cd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
35	$\overline{e^c}\overline{e^c}L^ie^c\overline{Q}_j\overline{u^c}H^jH^k\epsilon_{ik}$
36	$\overline{e^c}\overline{e^c}Q^id^cQ^jd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
37	$\overline{e^c}\overline{e^c}Q^id^c\overline{Q}_j\overline{u^c}H^jH^k\epsilon_{ik}$
38	$\overline{e^c}\overline{e^c}\overline{Q}_i\overline{u^c}\overline{Q}_j\overline{u^c}H^iH^j$
39_a	$L^iL^jL^kL^l\overline{L}_i\overline{L}_jH^mH^n\epsilon_{km}\epsilon_{ln}$ †
39_b	$L^iL^jL^kL^l\overline{L}_m\overline{L}_nH^mH^n\epsilon_{ij}\epsilon_{kl}$
39_c	$L^iL^jL^kL^l\overline{L}_i\overline{L}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
39_d	$L^iL^jL^kL^l\overline{L}_p\overline{L}_qH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
40_a	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$
40_b	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_lH^mH^n\epsilon_{jm}\epsilon_{kn}$
40_c	$L^iL^jL^kQ^l\overline{L}_l\overline{Q}_iH^mH^n\epsilon_{jm}\epsilon_{kn}$
40_d	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
40_e	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_mH^mH^n\epsilon_{jl}\epsilon_{kn}$
40_f	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_iH^mH^n\epsilon_{jk}\epsilon_{ln}$
40_g	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_iH^mH^n\epsilon_{jl}\epsilon_{kn}$
40_h	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^mH^n\epsilon_{ij}\epsilon_{kl}$
40_i	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^pH^q\epsilon_{ip}\epsilon_{jq}\epsilon_{kl}\epsilon^{mn}$
40_j	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^pH^q\epsilon_{ip}\epsilon_{lq}\epsilon_{jk}\epsilon^{mn}$
41_a	$L^iL^jL^kd^c\overline{L}_i\overline{d^c}H^lH^m\epsilon_{jl}\epsilon_{km}$
41_b	$L^iL^jL^kd^c\overline{L}_l\overline{d^c}H^lH^m\epsilon_{ij}\epsilon_{km}$
42_a	$L^iL^jL^ku^c\overline{L}_i\overline{u^c}H^lH^m\epsilon_{jl}\epsilon_{km}$
42_b	$L^iL^jL^ku^c\overline{L}_l\overline{u^c}H^lH^m\epsilon_{ij}\epsilon_{km}$
43_a	$L^iL^jL^kd^c\overline{L}_l\overline{u^c}H^l\overline{H}_i\epsilon_{jk}$
43_b	$L^iL^jL^kd^c\overline{L}_j\overline{u^c}H^l\overline{H}_i\epsilon_{kl}$
43_c	$L^iL^jL^kd^c\overline{L}_l\overline{u^c}H^m\overline{H}_n\epsilon_{ij}\epsilon_{km}\epsilon^{ln}$
44_a	$L^iL^jQ^ke^c\overline{Q}_i\overline{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$
44_b	$L^iL^jQ^ke^c\overline{Q}_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$
44_c	$L^iL^jQ^ke^c\overline{Q}_l\overline{e^c}H^lH^m\epsilon_{ij}\epsilon_{km}$
44_d	$L^iL^jQ^ke^c\overline{Q}_l\overline{e^c}H^lH^m\epsilon_{ik}\epsilon_{jm}$
45	$L^iL^je^cd^c\overline{e^c}\overline{d^c}H^kH^l\epsilon_{ik}\epsilon_{jl}$
46	$L^iL^je^cu^c\overline{e^c}\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}$
47_a	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$

$\mathcal{O}$	Operator
47_b	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_kH^mH^n\epsilon_{jm}\epsilon_{ln}$
47_c	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_lH^mH^n\epsilon_{im}\epsilon_{jn}$
47_d	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
47_e	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jn}\epsilon_{kl}$
47_f	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_mH^mH^n\epsilon_{ij}\epsilon_{ln}$
47_g	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_mH^mH^n\epsilon_{il}\epsilon_{jn}$
47_h	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
47_i	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{ik}\epsilon_{jm}\epsilon_{ln}\epsilon^{pq}$
47_j	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}\epsilon^{pq}$
48	$L^iL^jd^cd^c\overline{d^c}\overline{d^c}H^kH^l\epsilon_{ik}\epsilon_{jl}$
49	$L^iL^jd^cu^c\overline{d^c}\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}$
50	$L^iL^jd^cd^c\overline{d^c}\overline{u^c}H^k\overline{H}_i\epsilon_{jk}$
51	$L^iL^ju^cu^c\overline{u^c}\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}$
52	$L^iL^jd^cu^c\overline{u^c}\overline{u^c}H^k\overline{H}_i\epsilon_{jk}$
53	$L^iL^jd^cd^c\overline{u^c}\overline{u^c}\overline{H}_i\overline{H}_j$
54_a	$L^iQ^jQ^kd^c\overline{Q}_i\overline{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$
54_b	$L^iQ^jQ^kd^c\overline{Q}_j\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{km}$
54_c	$L^iQ^jQ^kd^c\overline{Q}_l\overline{e^c}H^lH^m\epsilon_{im}\epsilon_{jk}$
54_d	$L^iQ^jQ^kd^c\overline{Q}_l\overline{e^c}H^lH^m\epsilon_{ij}\epsilon_{km}$
55_a	$L^iQ^j\overline{Q}_i\overline{Q}_k\overline{e^c}\overline{u^c}H^kH^l\epsilon_{jl}$
55_b	$L^iQ^j\overline{Q}_j\overline{Q}_k\overline{e^c}\overline{u^c}H^kH^l\epsilon_{il}$
55_c	$L^iQ^j\overline{Q}_m\overline{Q}_n\overline{e^c}\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
56	$L^iQ^jd^cd^c\overline{e^c}\overline{d^c}H^kH^l\epsilon_{ik}\epsilon_{jl}$
57	$L^id^c\overline{Q}_j\overline{u^c}\overline{e^c}\overline{d^c}H^jH^k\epsilon_{ik}$
58	$L^iu^c\overline{Q}_j\overline{u^c}\overline{e^c}\overline{u^c}H^jH^k\epsilon_{ik}$
59	$L^iQ^jd^cd^c\overline{e^c}\overline{u^c}H^k\overline{H}_i\epsilon_{jk}$
60	$L^id^c\overline{Q}_j\overline{u^c}\overline{e^c}\overline{u^c}H^j\overline{H}_i$
61	$L^iL^jH^kH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
62	$L^iL^jL^ke^cH^lL^re^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
63_a	$L^iL^jQ^kd^cH^lL^re^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
63_b	$L^iL^jQ^kd^cH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
64_a	$L^iL^j\overline{Q}_i\overline{u^c}H^kL^re^c\overline{H}_r\epsilon_{jk}$
64_b	$L^iL^j\overline{Q}_k\overline{u^c}H^kL^re^c\overline{H}_r\epsilon_{ij}$
65	$L^i\overline{e^c}\overline{u^c}d^cH^jL^re^c\overline{H}_r\epsilon_{ij}$
66	$L^iL^jH^kH^l\epsilon_{ik}Q^rd^c\overline{H}_r\epsilon_{jl}$
67	$L^iL^jL^ke^cH^lQ^rd^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
68_a	$L^iL^jQ^kd^cH^lQ^rd^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
68_b	$L^iL^jQ^kd^cH^lQ^rd^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
69_a	$L^iL^j\overline{Q}_iu^cH^kQ^rd^c\overline{H}_r\epsilon_{jk}$
69_b	$L^iL^j\overline{Q}_k\overline{u^c}H^kQ^rd^c\overline{H}_r\epsilon_{ij}$

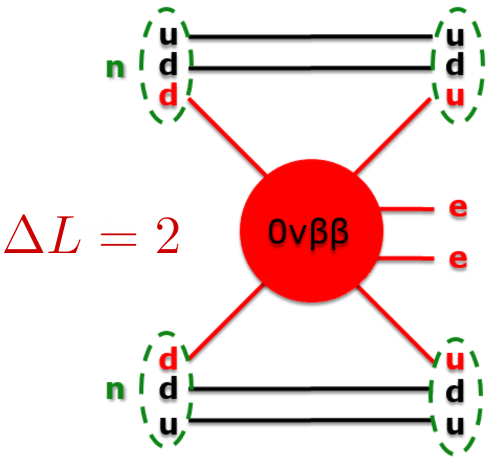
$\mathcal{O}$	Operator
70	$L^i\overline{e^c}\overline{u^c}d^cH^jQ^rd^c\overline{H}_r\epsilon_{ij}$
71	$L^iL^jH^kH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
72	$L^iL^jL^ke^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_a	$L^iL^jQ^kd^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_b	$L^iL^jQ^kd^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
74_a	$L^iL^j\overline{Q}_i\overline{u^c}H^kQ^ru^cH^s\epsilon_{rs}\epsilon_{jk}$
74_b	$L^iL^j\overline{Q}_k\overline{u^c}H^kQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$
75	$L^i\overline{e^c}\overline{u^c}d^cH^jQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$

Babu, Leung (2001)

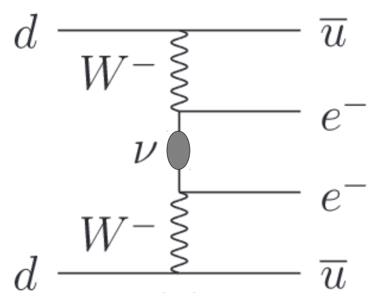
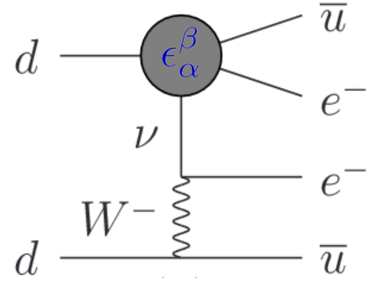
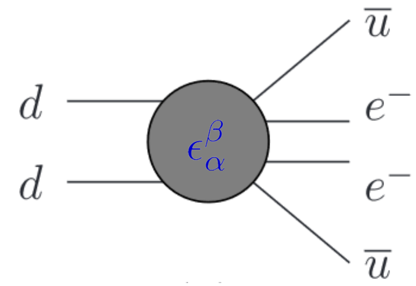
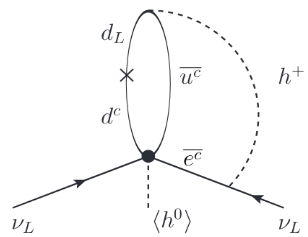
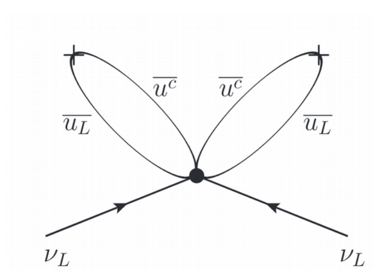
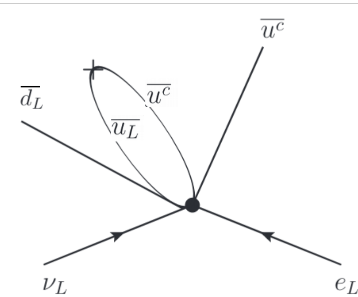
deGouvea, Jenkins (2007)

Deppisch, Graf, Harz, Huang (2017)

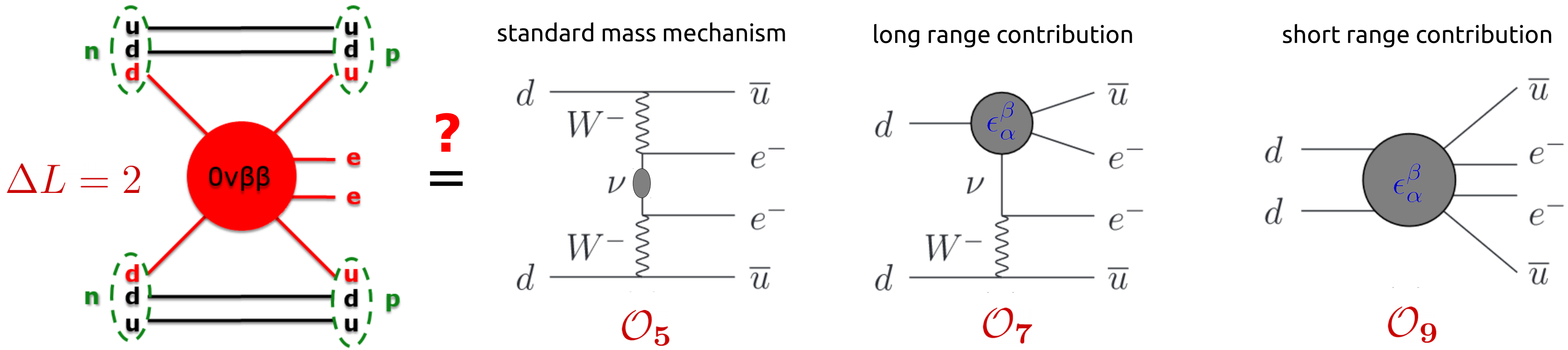
Possible underlying LNV operators

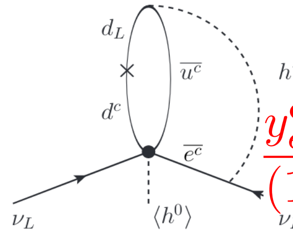
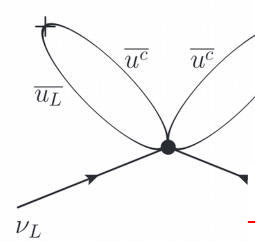
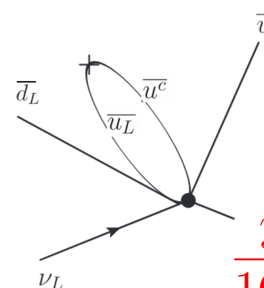


$\overset{?}{=}$

	standard mass mechanism	long range contribution	short range contribution
	 $\mathcal{O}_5$	 $\mathcal{O}_7$	 $\mathcal{O}_9$
$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$	tree level		
$\mathcal{O}_8 = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$		tree level	
$\mathcal{O}_{12a} = L^i L^j \overline{Q}_i \bar{u^c} \overline{Q}_j \bar{u^c}$			tree level

Possible underlying LNV operators

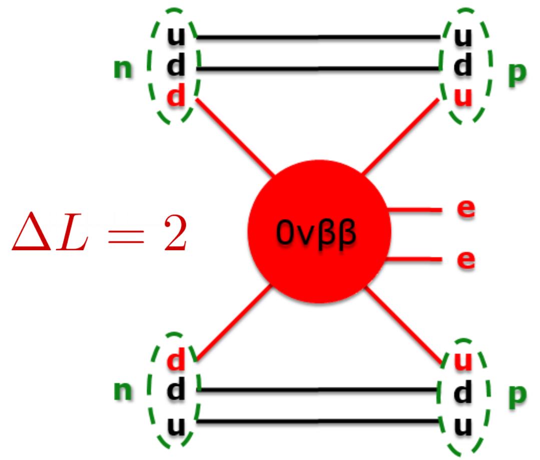


$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$	tree level $\frac{1}{\Lambda}$		
$\mathcal{O}_8 = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}$	 $\frac{y_e^{\text{ex}} y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	tree level $\frac{1}{\Lambda^3}$	
$\mathcal{O}_{12a} = L^i L^j \overline{Q}_i \bar{u}^c \overline{Q}_j \bar{u}^c$	 $\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	 $\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}$	tree level $\frac{1}{\Lambda^5}$

Neutrinoless double beta decay (0vbb)

Long range contribution:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \{ j^{\mu}_{V-A} J^{\dagger}_{V-A,\mu} + \sum_{\alpha,\beta} \epsilon^{\beta}_{\alpha} j_{\beta} J^{\dagger}_{\alpha} \}$$



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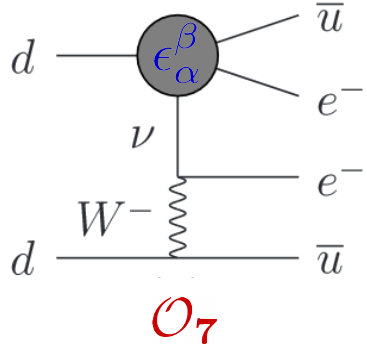


Leptonic and hadronic current with different chirality structure:

$$j_{\beta} = \bar{e}\mathcal{O}_{\beta}\nu$$
$$J^{\dagger}_{\alpha} = \bar{u}\mathcal{O}_{\alpha}d$$

with

$$\mathcal{O}_{V\pm A} = \gamma^{\mu}(1 \pm \gamma_5)$$
$$\mathcal{O}_{S\pm P} = (1 \pm \gamma_5)$$
$$\mathcal{O}_{T_{R,L}} = \frac{i}{2}[\gamma_{\mu}, \gamma_{\nu}](1 \pm \gamma_5)$$

$$T^{-1}_{1/2} = G_{0\nu} |\mathcal{M}|^2 |\epsilon^{\beta}_{\alpha}|^2$$

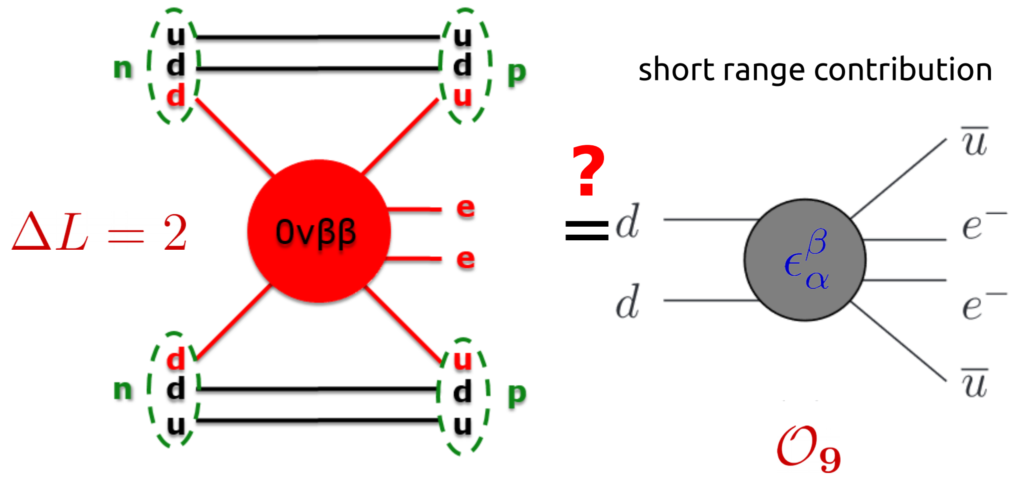
$\lvert\epsilon\rvert \times 10^8$	ϵ_ν	ϵ^{V+A}_{V-A}	ϵ^{V+A}_{V+A}	$\epsilon^{S+P}_{S\pm P}$	$\epsilon^{T_R}_{T_R}$
^{76}Ge	41	0.21	37	0.66	0.07
^{76}Xe	26	0.11	22	0.26	0.03

Neutrinoless double beta decay (0vbb)

Short range contribution:

$$\mathcal{L}^{\text{eff}} = \frac{G_F^2}{2} m_P^{-1} \left[\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j \right.$$

$$\left. + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu \right]$$



Leptonic and hadronic current with different chirality structure:

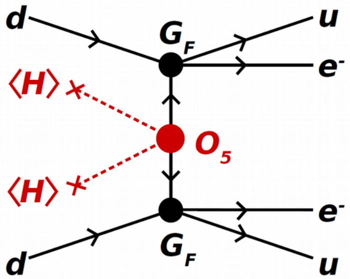
$$J = \overline{u}(1 \pm \gamma_5)d, \; J^\mu = \overline{u}\gamma^\mu(1 \pm \gamma_5)d, \; J^{\mu\nu} = \overline{u}\tfrac{i}{2}[\gamma^\mu, \gamma^\nu](1 \pm \gamma_5)d$$

$$j = \overline{e}(1 \pm \gamma_5)e^C, \; j^\mu = \overline{e}\gamma^\mu(1 \pm \gamma_5)e^C$$

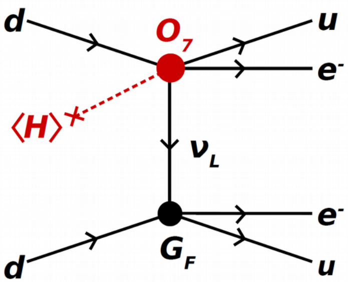
$$T_{1/2}^{-1} = G_{0\nu} |\mathcal{M}|^2 |\epsilon_\alpha^\beta|^2$$

ϵ_1	ϵ_2	ϵ_3^a	ϵ_3^b	ϵ_4	ϵ_5
19	0.11	1.30	0.83	0.90	9.0
10	0.05	0.43	0.66	0.46	4.6

Constraining the effective operator scale

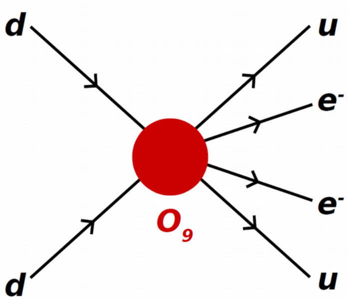


$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl} \longrightarrow m_e \epsilon_5 = \frac{g^2 v^2}{\Lambda_5} = |m_{\beta\beta}|$$



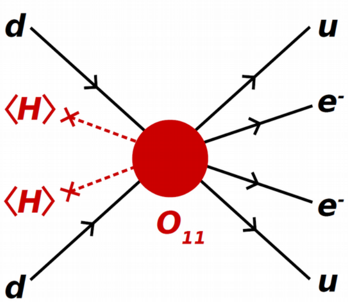
$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \{ j^{\mu}_{V-A} J^{\dagger}_{V-A,\mu} + \sum_{\alpha,\beta} \epsilon^{\beta}_{\alpha} j_{\beta} J^{\dagger}_{\alpha} \}$$

$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c} \bar{u^c}) H^j \epsilon_{ij} \longrightarrow \frac{G_F \epsilon_7}{\sqrt{2}} = \frac{g^3 v}{2 {\Lambda_7}^3}$$



$$\mathcal{L}^{\text{eff}} = \frac{G_F^2}{2} m_P^{-1} \left[\epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu} \right]$$

$$\mathcal{O}_9 = (L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}) \longrightarrow \frac{G_F^2 \epsilon_{\{9,11\}}}{2 m_p} = \left\{ \frac{g^4}{{\Lambda_9}^5}, \frac{g^6 v^2}{{\Lambda_{11}}^7} \right\}$$



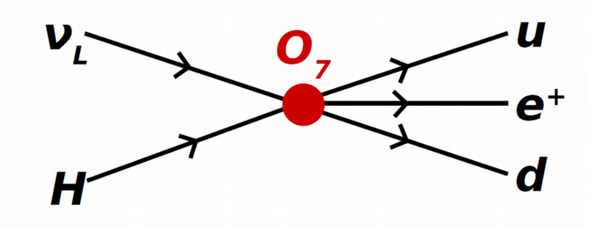
$$\mathcal{O}_{11} = (L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk} \epsilon_{lm}$$

$\mathcal{O}_D$	Λ_D^0 [GeV]
$\mathcal{O}_5$	9.1×10^{13}
$\mathcal{O}_7$	2.6×10^{4}
$\mathcal{O}_9$	2.1×10^{3}
$\mathcal{O}_{11}$	1.0×10^{3}

If 0νββ is observed, the scale of the underlying operator can be determined

Lepton Asymmetry Washout

- LNV operator would cause washout of pre-existing net lepton asymmetry in the early Universe



$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c})H^j \epsilon_{ij}$$

$$zHn_\gamma \frac{d\,\eta_{L_e}}{d\,z} = -\left(\frac{n_{L_e} n_{\bar{e^c}}}{n^{\rm eq}_{L_e} n^{\rm eq}_{\bar{e^c}}} - \frac{n_{u^c} n_{\bar{d^c}} n_{\bar{H}}}{n^{\rm eq}_{u^c} n^{\rm eq}_{\bar{d^c}} n^{\rm eq}_{\bar{H}}}\right)\gamma^{\rm eq}(L_e\bar{e^c} \to u^c \bar{d^c}\bar{H})$$

$$zHn_\gamma \frac{d\eta_{\Delta L_e}}{dz} = -c_D \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}}\eta_{\Delta L_e}$$

$$\gamma^{eq} \propto \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}}$$

c_D operator specific factor

η_L lepton density

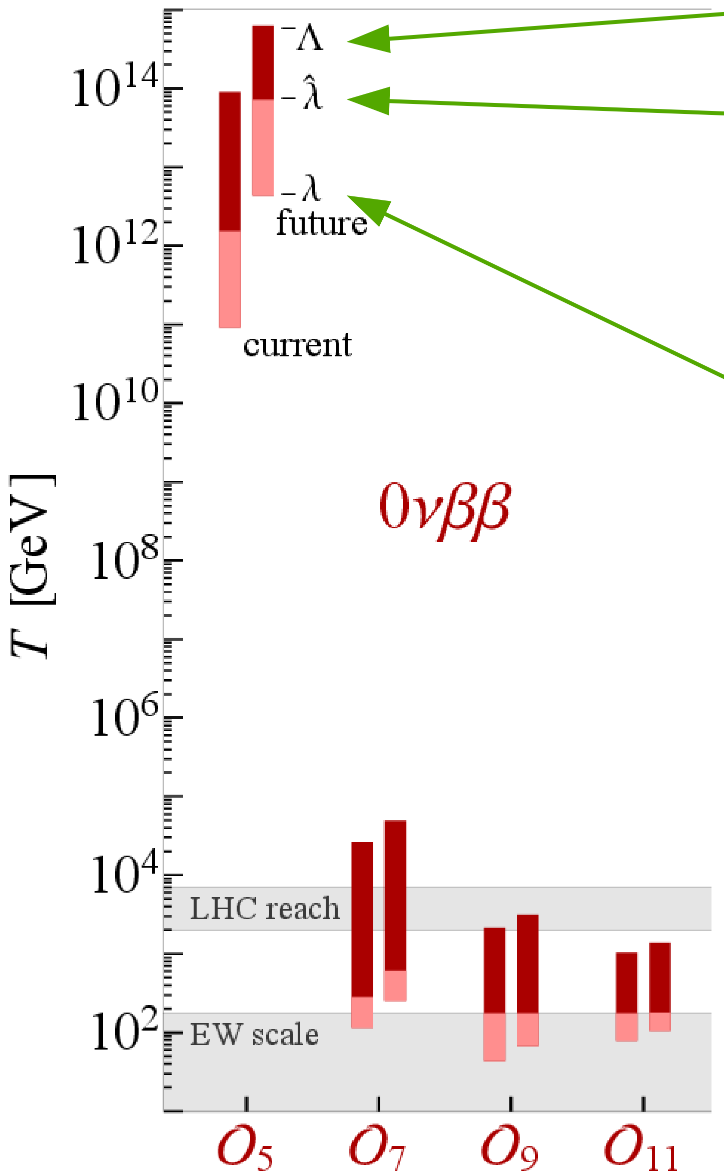
- washout efficient if

$$\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H}\frac{T^{2D-4}}{\Lambda_D{}^{2D-8}} = c'_D \frac{\Lambda_{\rm Pl}}{\Lambda_D}\left(\frac{T}{\Lambda_D}\right)^{2D-9} > 1$$

If 0νßß is observed, washout efficient in the temperature interval

$$\Lambda_D\left(\frac{\Lambda_D}{c'_D \Lambda_{\rm Pl}}\right)^{\frac{1}{2D-9}} \equiv \lambda_D < T < \Lambda_D$$

Impact on Baryogenesis models



scale of operator

scale above which a maximal lepton asymmetry of 1 is washout out to the observed baryon asymmetry (or less)

$$\hat{\lambda}_D \approx \left[(2D-9)\ln\left(\frac{10^{-2}}{\eta_B^{\text{obs}}}\right)\lambda_D^{2D-9} + v^{2D-9}\right]^{\frac{1}{2D-9}}$$

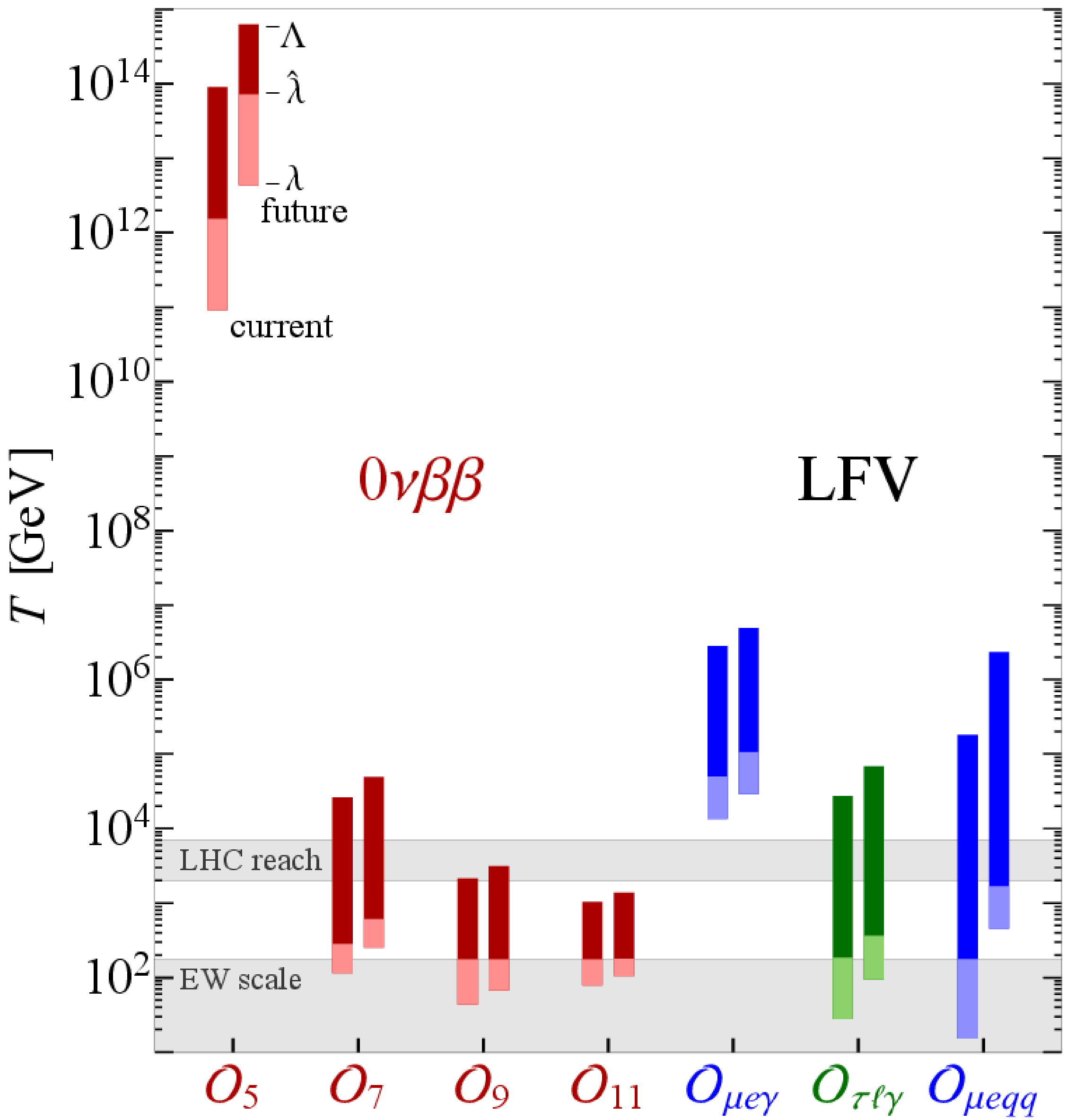
scale above which washout is highly effective $\frac{\Gamma_W}{H} > 1$

If was observed via non-standard mechanism, resulting washout would rule out baryogenesis mechanisms above λ

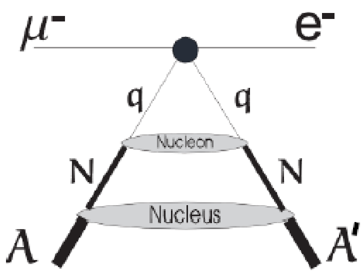
However:
0νßß decay probes only electron component of LNV operators:

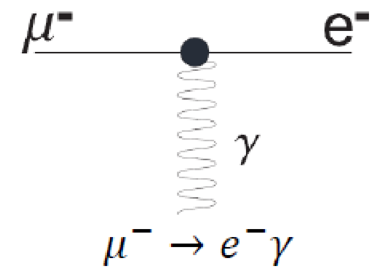
$$\frac{1}{\Lambda_9^5} \to \frac{c_{\alpha\beta}}{\Lambda_9^5}$$

Extending the impact with LFV



- Most stringent limits on LFV set by 6-dim $\Delta L = 0$ operators





$$\mathcal{O}_{\ell\ell\gamma} = \mathcal{C}_{\ell\ell\gamma} \bar{L}_\ell \sigma^{\mu\nu} \bar{\ell}^c H F_{\mu\nu}$$

$$\mathcal{O}_{\ell\ell qq} = \mathcal{C}_{\ell\ell qq} (\bar{\ell}\, \Pi_1 \ell)(\bar{q}\, \Pi_2 q)$$

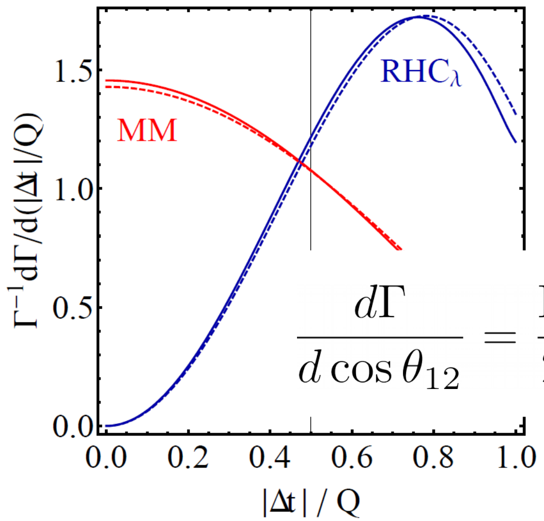
$$\mathcal{C}_{\ell\ell qq} = \frac{g^2}{\Lambda^2_{\ell\ell qq}} \qquad \mathcal{C}_{\ell\ell\gamma} = \frac{e g^3}{16\pi^2 \Lambda^2_{\ell\ell\gamma}}$$

- Determine interval in which LFV process equilibrate pre-existing flavour asymmetry

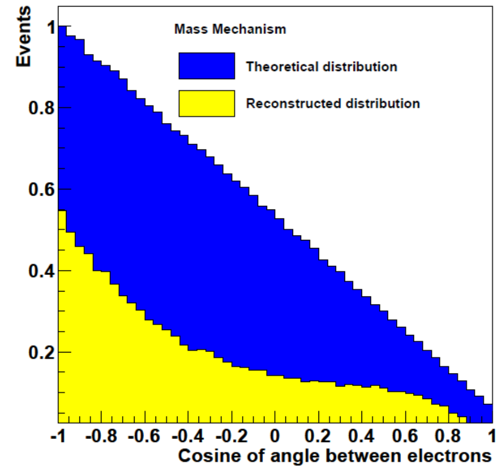
IF LFV processes are observed as well, loophole of asymmetry being stored in another flavour sector is ruled out

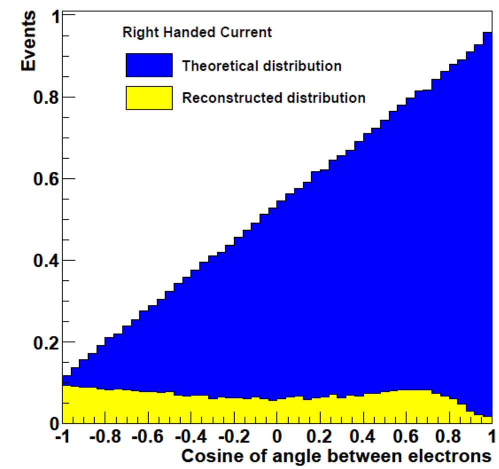
Distinguishing between different operators

- SuperNEMO will be able to discriminate O_7 from others, due to e^-_R and e^+_L in the final state



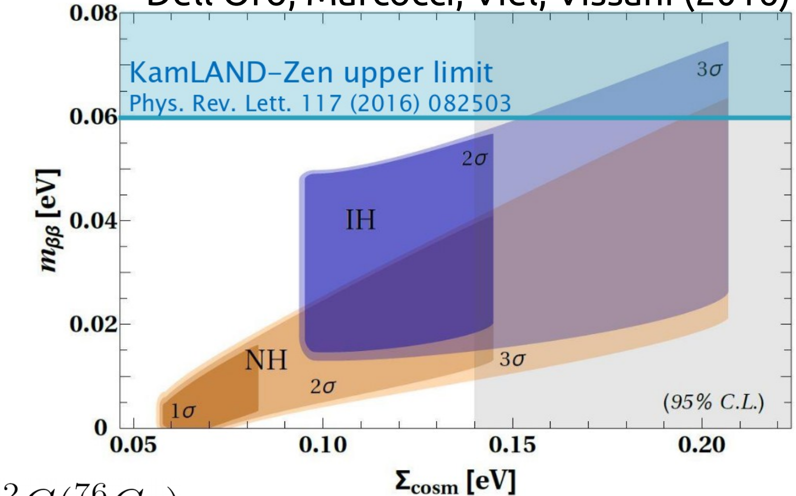
$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$



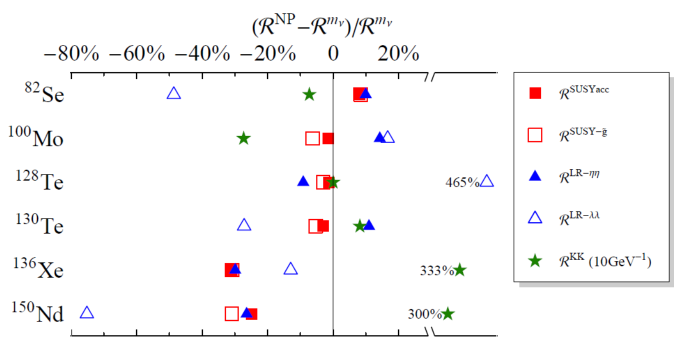


- potential discrepancy between neutrino mass (cosmology) and 0vbb half live measurement could be an indication for 0vbb triggered by non-standard mechanism

Dell'Oro, Marcocci, Viel, Vissani (2016)



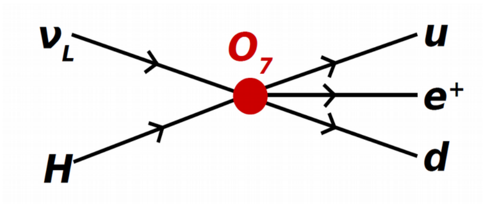
- distinguishing between different mechanisms via measurements in different isotopes



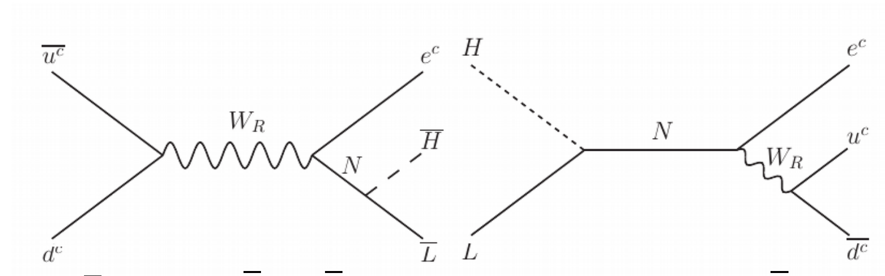
$$\frac{T_{1/2}(^AX)}{T_{1/2}(^AX)}) = \frac{|\mathcal{M}(^{76}Ge)|^2 G(^{76}Ge)}{|\mathcal{M}(^AX)|^2 G(^AX)}$$

- observation of 0vββ via O_9 and O_{11} will imply observation of LNV at LHC

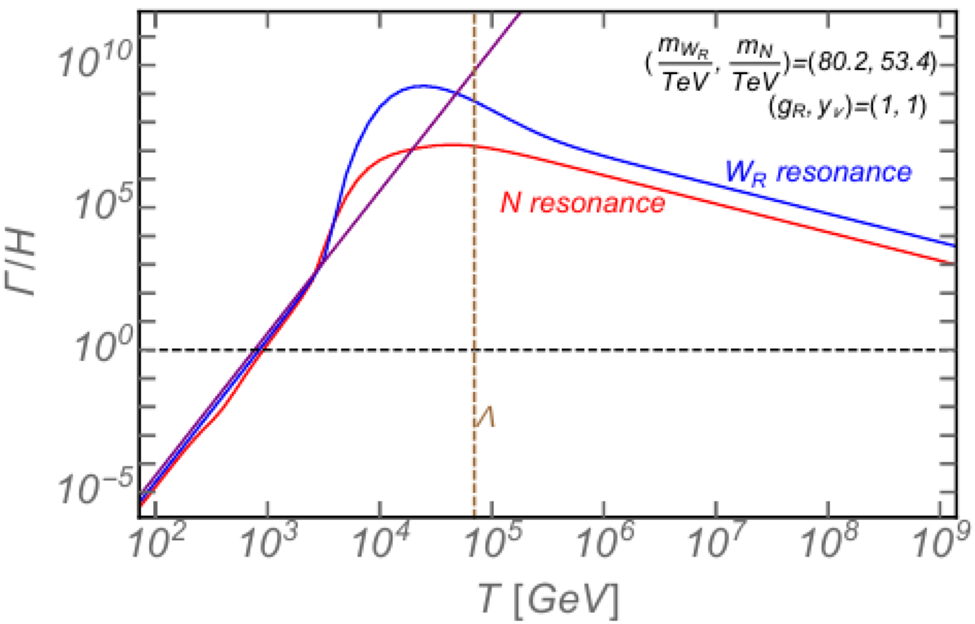
Validity of the effective operator approach

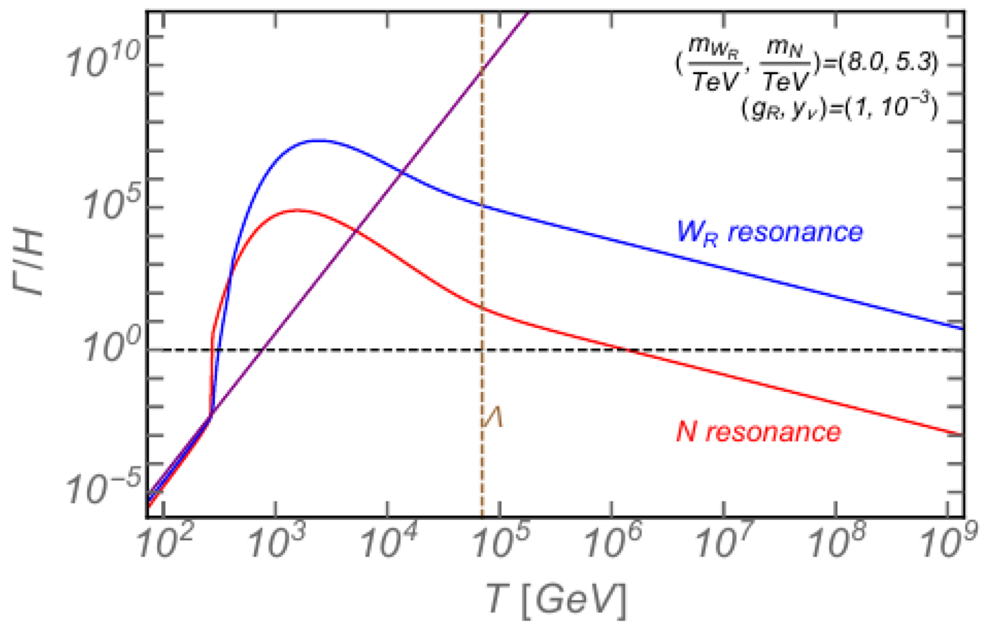


$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c})H^j\epsilon_{ij}$$



$$\bar{u^c}d^c \leftrightarrow \bar{L}e^c\bar{H} \qquad LH \leftrightarrow e^c u^c \bar{d^c}$$





$$\frac{1}{\Lambda^3} = \frac{g_R^2 y_\nu}{m_{W_R}^2 m_N} \quad \text{with} \quad m_{W_R} = 1.5 m_N$$

Little summary

- We can distinguish experimentally the different interactions contributing to 0vbb (mass mechanism, long-range interaction, short-range interaction)

- If 0vbb is observed and triggered by a non-standard operator, we can falsify high-scale leptogenesis (and baryogenesis!)

- In order to be sure that no asymmetry is stored in another flavour, LFV should be observed as well

Little summary

- We can distinguish experimentally the different interactions contributing to 0vbb (mass mechanism, long-range interaction, short-range interaction)
- If 0vbb is observed and triggered by a non-standard operator, we can falsify high-scale leptogenesis (and baryogenesis!)
- In order to be sure that no asymmetry is stored in another flavour, LFV should be observed as well

➡ **So far we only considered tree level contributions – what about loop induced contributions?**

How does this compare with the mass mechanism? Radiative neutrino mass models?

All ΔL=2 LNV effective operators up to dim 11

$\mathcal{O}$	Operator
1	$L^iL^jH^kH^l\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
[illegible]	[illegible]
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$
6	$L^iL^j\overline{Q}_k\bar{u}^cH^lH^k\overline{H}_i\epsilon_{jl}$
7	$L^iQ^j\bar{e}^c\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$
12_a	$L^iL^j\overline{Q}_i\bar{u}^c\overline{Q}_j\bar{u}^c$
12_b	$L^iL^j\overline{Q}_k\bar{u}^c\overline{Q}_l\bar{u}^c\epsilon_{ij}\epsilon^{kl}$
13	$L^iL^j\overline{Q}_i\bar{u}^cL^le^c\epsilon_{jl}$
14_a	$L^iL^j\overline{Q}_k\bar{u}^cQ^kd^c\epsilon_{ij}$
14_b	$L^iL^j\overline{Q}_i\bar{u}^cQ^ld^c\epsilon_{jl}$
15	$L^iL^jL^kd^c\overline{L}_i\bar{u}^c\epsilon_{jk}$
16	$L^iL^je^cd^c\bar{e}^c\bar{u}^c\epsilon_{ij}$
17	$L^iL^jd^cd^c\bar{d}^c\bar{u}^c\epsilon_{ij}$
18	$L^iL^jd^cu^c\bar{u}^c\bar{u}^c\epsilon_{ij}$
19	$L^iQ^jd^cd^c\bar{e}^c\bar{u}^c\epsilon_{ij}$
20	$L^id^c\overline{Q}_i\bar{u}^c\bar{e}^c\bar{u}^c$
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$
22	$L^iL^jL^ke^c\overline{L}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
23	$L^iL^jL^ke^c\overline{Q}_k\bar{d}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$
26_a	$L^iL^jQ^kd^c\overline{L}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
26_b	$L^iL^jQ^kd^c\overline{L}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
27_a	$L^iL^jQ^kd^c\overline{Q}_i\bar{d}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
27_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{d}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
28_a	$L^iL^jQ^kd^c\overline{Q}_j\bar{u}^cH^l\overline{H}_i\epsilon_{kl}$
28_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{u}^cH^l\overline{H}_i\epsilon_{jl}$
28_c	$L^iL^jQ^kd^c\overline{Q}_l\bar{u}^cH^l\overline{H}_i\epsilon_{jk}$
29_a	$L^iL^jQ^ku^c\overline{Q}_k\bar{u}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
29_b	$L^iL^jQ^ku^c\overline{Q}_l\bar{u}^cH^lH^m\epsilon_{ik}\epsilon_{jm}$
30_a	$L^iL^j\overline{L}_ie^c\overline{Q}_ku^cH^kH^l\epsilon_{jl}$
30_b	$L^iL^j\overline{L}_me^c\overline{Q}_nu^cH^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
31_a	$L^iL^j\overline{Q}_id^c\overline{Q}_k\bar{u}^cH^kH^l\epsilon_{jl}$

$\mathcal{O}$	Operator
31_b	$L^iL^j\overline{Q}_md^c\overline{Q}_n\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
32_a	$L^iL^j\overline{Q}_j\bar{u}^c\overline{Q}_k\bar{u}^cH^k\overline{H}_i$
32_b	$L^iL^j\overline{Q}_m\bar{u}^c\overline{Q}_n\bar{u}^cH^k\overline{H}_l\epsilon_{ik}\epsilon^{mn}$
33	$\bar{e}^c\bar{e}^cL^iL^je^ce^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
34	$\bar{e}^c\bar{e}^cL^iQ^je^cd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
35	$\bar{e}^c\bar{e}^cL^ie^c\overline{Q}_j\bar{u}^cH^jH^k\epsilon_{ik}$
36	$\bar{e}^c\bar{e}^cQ^id^cQ^jd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
37	$\bar{e}^c\bar{e}^cQ^id^c\overline{Q}_j\bar{u}^cH^jH^k\epsilon_{ik}$
38	$\bar{e}^c\bar{e}^c\overline{Q}_i\bar{u}^c\overline{Q}_j\bar{u}^cH^iH^j$
39_a	$L^iL^jL^kL^l\overline{L}_i\overline{L}_jH^mH^n\epsilon_{km}\epsilon_{ln}$ †
39_b	$L^iL^jL^kL^l\overline{L}_m\overline{L}_nH^mH^n\epsilon_{ij}\epsilon_{kl}$
39_c	$L^iL^jL^kL^l\overline{L}_i\overline{L}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
39_d	$L^iL^jL^kL^l\overline{L}_p\overline{L}_qH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
40_a	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$
40_b	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_lH^mH^n\epsilon_{jm}\epsilon_{kn}$
40_c	$L^iL^jL^kQ^l\overline{L}_l\overline{Q}_iH^mH^n\epsilon_{jm}\epsilon_{kn}$
40_d	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
40_e	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_mH^mH^n\epsilon_{jl}\epsilon_{kn}$
40_f	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_iH^mH^n\epsilon_{jk}\epsilon_{ln}$
40_g	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_iH^mH^n\epsilon_{jl}\epsilon_{kn}$
40_h	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^mH^n\epsilon_{ij}\epsilon_{kl}$
40_i	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^pH^q\epsilon_{ip}\epsilon_{jq}\epsilon_{kl}\epsilon^{mn}$
40_j	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^pH^q\epsilon_{ip}\epsilon_{lq}\epsilon_{jk}\epsilon^{mn}$
41_a	$L^iL^jL^kd^c\overline{L}_i\bar{d}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
41_b	$L^iL^jL^kd^c\overline{L}_l\bar{d}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
42_a	$L^iL^jL^ku^c\overline{L}_i\bar{u}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
42_b	$L^iL^jL^ku^c\overline{L}_l\bar{u}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
43_a	$L^iL^jL^kd^c\overline{L}_l\bar{u}^cH^l\overline{H}_i\epsilon_{jk}$
43_b	$L^iL^jL^kd^c\overline{L}_j\bar{u}^cH^l\overline{H}_i\epsilon_{kl}$
43_c	$L^iL^jL^kd^c\overline{L}_l\bar{u}^cH^m\overline{H}_n\epsilon_{ij}\epsilon_{km}\epsilon^{ln}$
44_a	$L^iL^jQ^ke^c\overline{Q}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
44_b	$L^iL^jQ^ke^c\overline{Q}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
44_c	$L^iL^jQ^ke^c\overline{Q}_l\bar{e}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
44_d	$L^iL^jQ^ke^c\overline{Q}_l\bar{e}^cH^lH^m\epsilon_{ik}\epsilon_{jm}$
45	$L^iL^je^cd^c\bar{e}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
46	$L^iL^je^cu^c\bar{e}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
47_a	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$

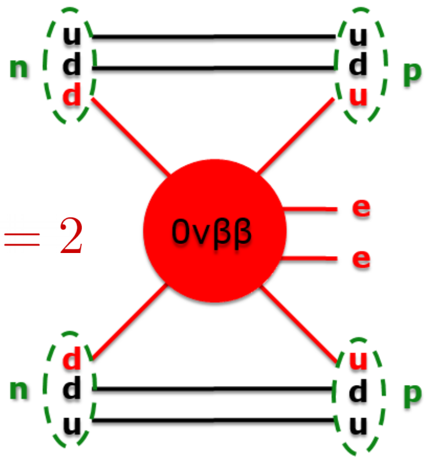
$\mathcal{O}$	Operator
47_b	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_kH^mH^n\epsilon_{jm}\epsilon_{ln}$
47_c	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_lH^mH^n\epsilon_{im}\epsilon_{jn}$
47_d	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
47_e	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jn}\epsilon_{kl}$
47_f	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_mH^mH^n\epsilon_{ij}\epsilon_{ln}$
47_g	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_mH^mH^n\epsilon_{il}\epsilon_{jn}$
47_h	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
47_i	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{ik}\epsilon_{jm}\epsilon_{ln}\epsilon^{pq}$
47_j	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}\epsilon^{pq}$
48	$L^iL^jd^cd^c\bar{d}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
49	$L^iL^jd^cu^c\bar{d}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
50	$L^iL^jd^cd^c\bar{d}^c\bar{u}^cH^k\overline{H}_i\epsilon_{jk}$
51	$L^iL^ju^cu^c\bar{u}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
52	$L^iL^jd^cu^c\bar{u}^c\bar{u}^cH^k\overline{H}_i\epsilon_{jk}$
53	$L^iL^jd^cd^c\bar{u}^c\bar{u}^c\overline{H}_i\overline{H}_j$
54_a	$L^iQ^jQ^kd^c\overline{Q}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
54_b	$L^iQ^jQ^kd^c\overline{Q}_j\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{km}$
54_c	$L^iQ^jQ^kd^c\overline{Q}_l\bar{e}^cH^lH^m\epsilon_{im}\epsilon_{jk}$
54_d	$L^iQ^jQ^kd^c\overline{Q}_l\bar{e}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
55_a	$L^iQ^j\overline{Q}_i\overline{Q}_k\bar{e}^c\bar{u}^cH^kH^l\epsilon_{jl}$
55_b	$L^iQ^j\overline{Q}_j\overline{Q}_k\bar{e}^c\bar{u}^cH^kH^l\epsilon_{il}$
55_c	$L^iQ^j\overline{Q}_m\overline{Q}_n\bar{e}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
56	$L^iQ^jd^cd^c\bar{e}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
57	$L^id^c\overline{Q}_j\bar{u}^c\bar{e}^c\bar{d}^cH^jH^k\epsilon_{ik}$
58	$L^iu^c\overline{Q}_j\bar{u}^c\bar{e}^c\bar{u}^cH^jH^k\epsilon_{ik}$
59	$L^iQ^jd^cd^c\bar{e}^c\bar{u}^cH^k\overline{H}_i\epsilon_{jk}$
60	$L^id^c\overline{Q}_j\bar{u}^c\bar{e}^c\bar{u}^cH^j\overline{H}_i$
61	$L^iL^jH^kH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
62	$L^iL^jL^ke^cH^lL^re^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
63_a	$L^iL^jQ^kd^cH^lL^re^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
63_b	$L^iL^jQ^kd^cH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
64_a	$L^iL^j\overline{Q}_i\bar{u}^cH^kL^re^c\overline{H}_r\epsilon_{jk}$
64_b	$L^iL^j\overline{Q}_k\bar{u}^cH^kL^re^c\overline{H}_r\epsilon_{ij}$
65	$L^i\bar{e}^c\bar{u}^cd^cH^jL^re^c\overline{H}_r\epsilon_{ij}$
66	[illegible]
67	[illegible]
68_a	[illegible]
68_b	[illegible]
69_a	$L^iL^j\overline{Q}_i\bar{u}^cH^kQ^rd^c\overline{H}_r\epsilon_{jk}$
69_b	$L^iL^j\overline{Q}_k\bar{u}^cH^kQ^rd^c\overline{H}_r\epsilon_{ij}$

$\mathcal{O}$	Operator
70	$L^i\bar{e}^c\bar{u}^cd^cH^jQ^rd^c\overline{H}_r\epsilon_{ij}$
71	$L^iL^jH^kH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
72	$L^iL^jL^ke^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_a	$L^iL^jQ^kd^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_b	$L^iL^jQ^kd^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
74_a	$L^iL^j\overline{Q}_i\bar{u}^cH^kQ^ru^cH^s\epsilon_{rs}\epsilon_{jk}$
74_b	$L^iL^j\overline{Q}_k\bar{u}^cH^kQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$
75	$L^i\bar{e}^c\bar{u}^cd^cH^jQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_5}\mathcal{O}_5 + \sum_i \frac{1}{\Lambda_{7_i}^3}\mathcal{O}_7^i + \sum_i \frac{1}{\Lambda_{9_i}^5}\mathcal{O}_9^i + \sum_i \frac{1}{\Lambda_{11_i}^7}\mathcal{O}_{11}^i$$

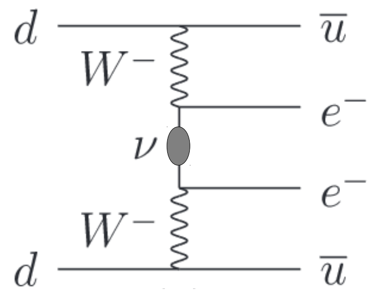
Possible underlying LNV operators

$\Delta L = 2$



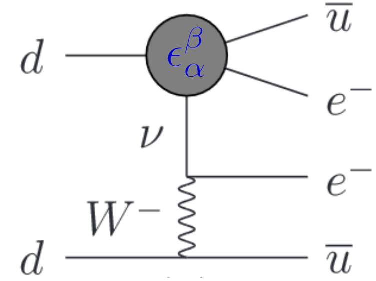
? $=$

standard mass mechanism



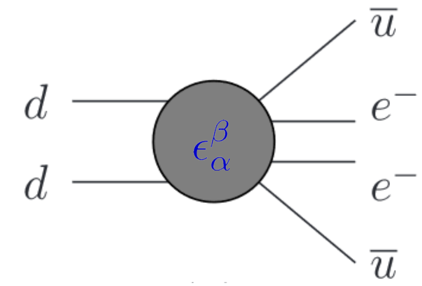
$\mathcal{O}_5$

long range contribution

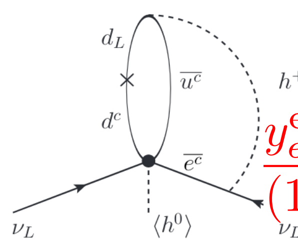
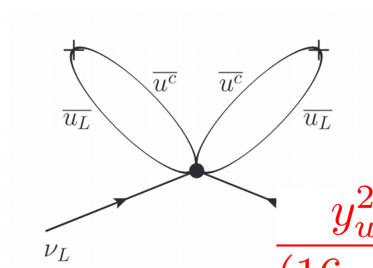
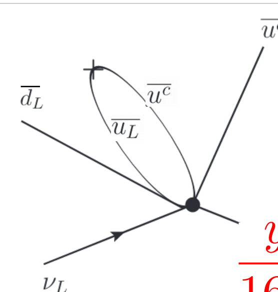


$\mathcal{O}_7$

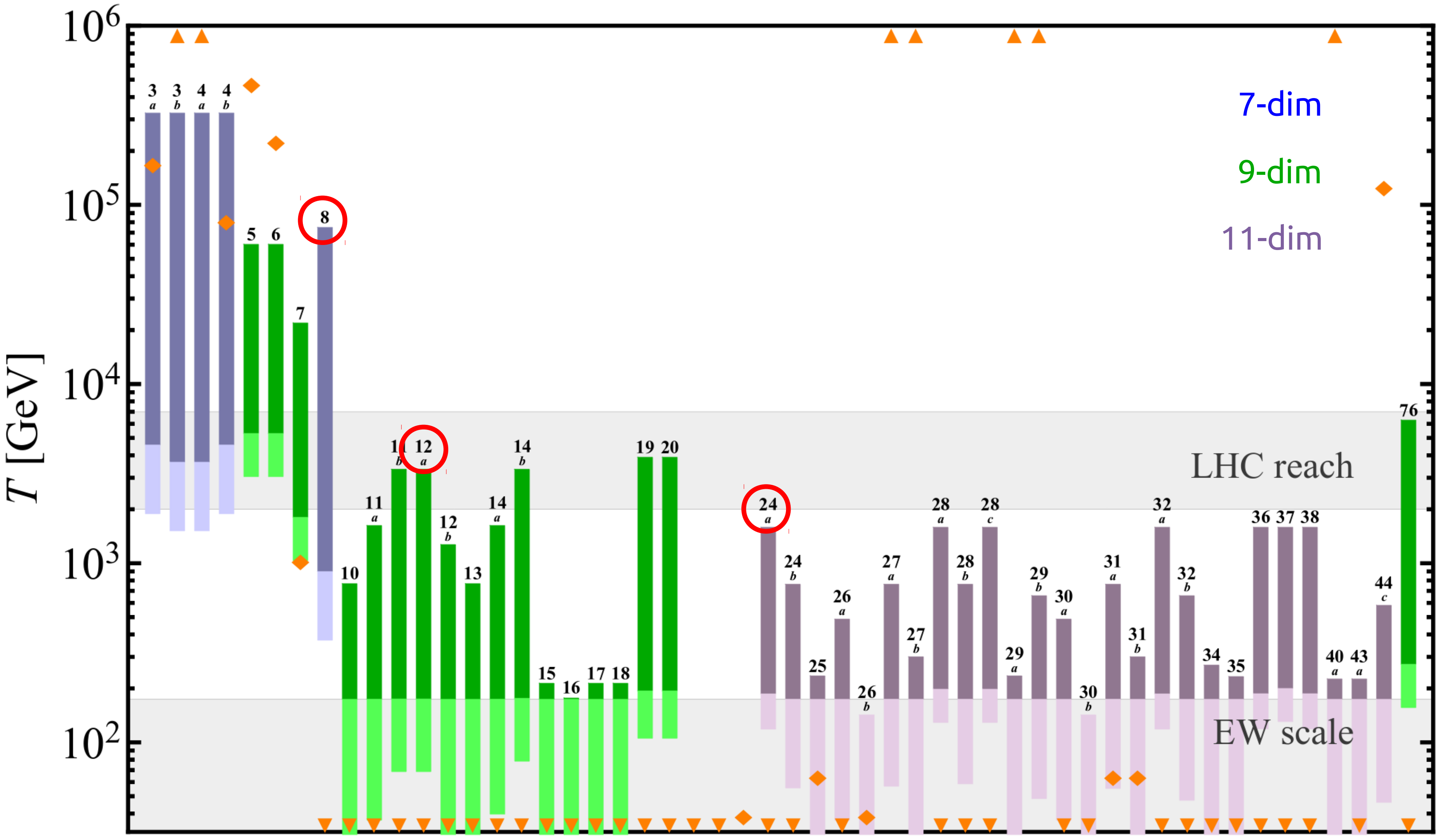
short range contribution



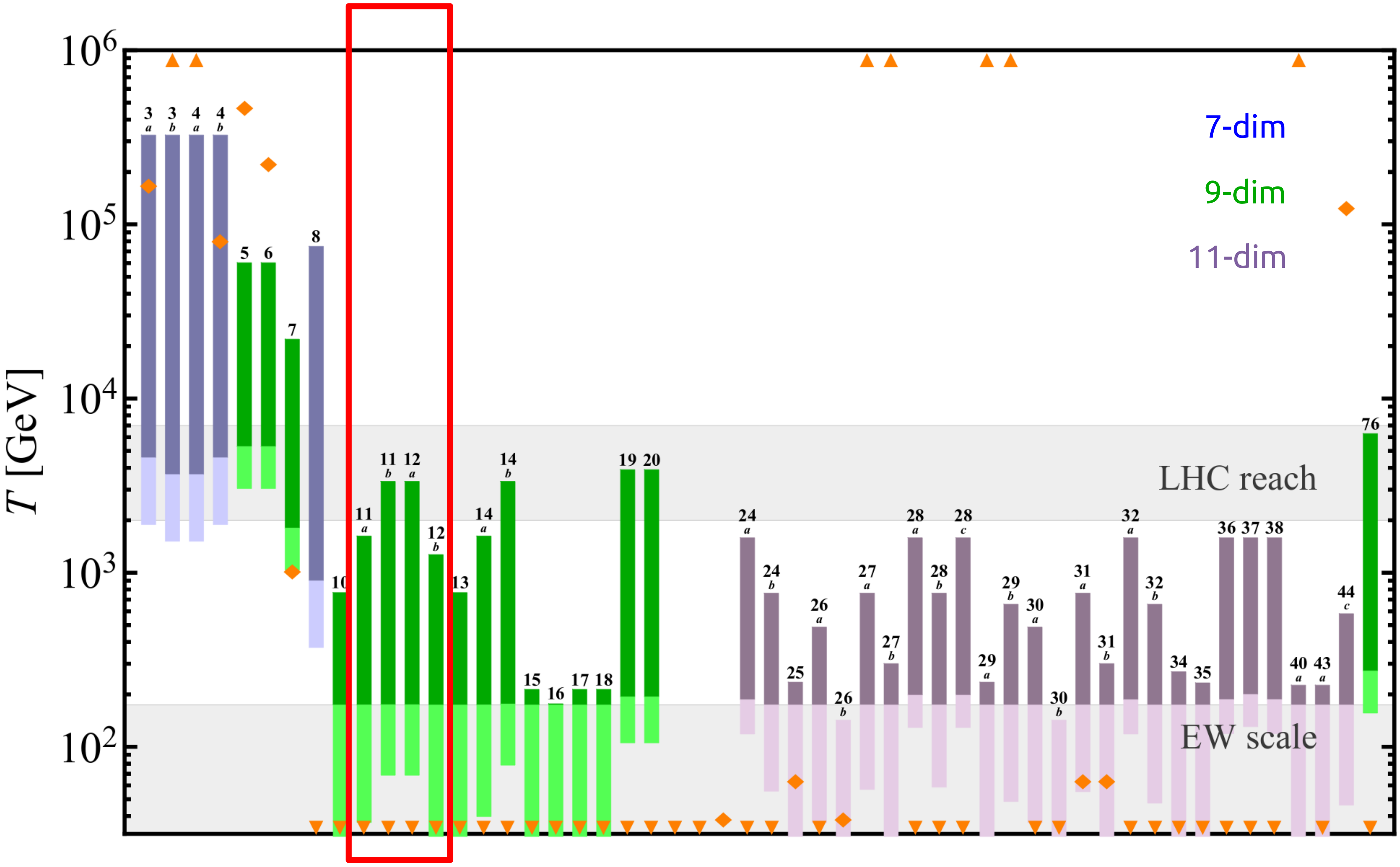
$\mathcal{O}_9$

$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$	tree level $\frac{1}{\Lambda}$		**What is the dominant contribution to 0vbb?**
$\mathcal{O}_8 = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$	 $\frac{y_e^{\mathrm{ex}} y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	tree level $\frac{1}{\Lambda^3}$	
$\mathcal{O}_{12a} = L^i L^j \overline{Q}_i \bar{u^c} \overline{Q}_j \bar{u^c}$	 $\frac{y_u^2}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	 $\frac{y_u}{16\pi^2} \frac{v}{\Lambda^3}$	tree level $\frac{1}{\Lambda^5}$

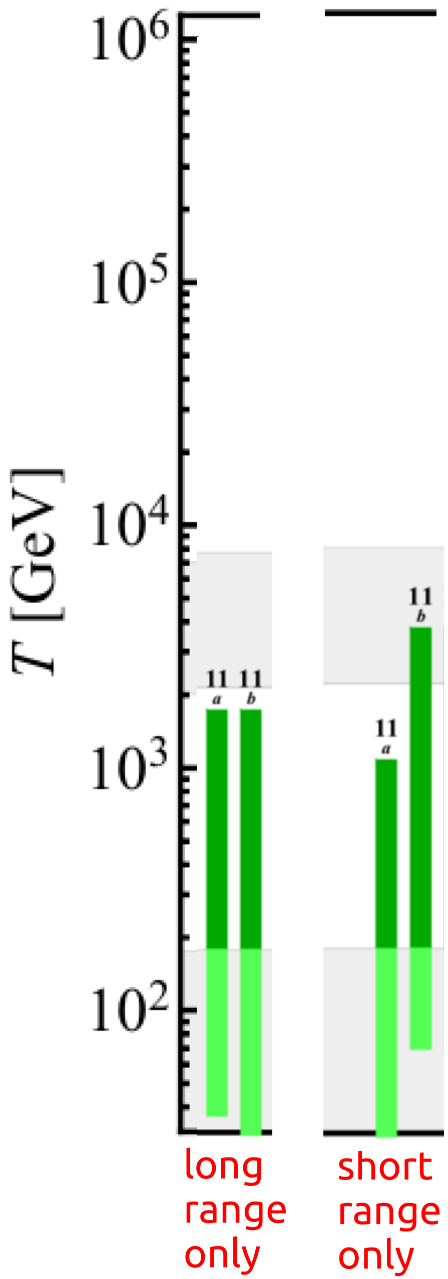
The full picture



Competition between long- and short-range



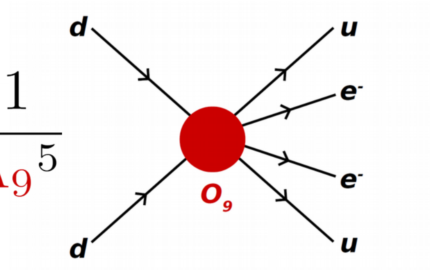
Competition between long- and short-range



Short-range contribution:

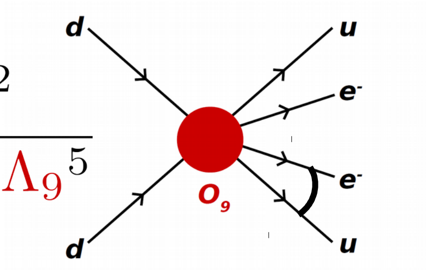
$$\mathcal{O}_9{}^{11b} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}$$

$$\frac{G_F^2 \epsilon_9}{2m_p} = \frac{1}{\Lambda_9{}^5}$$



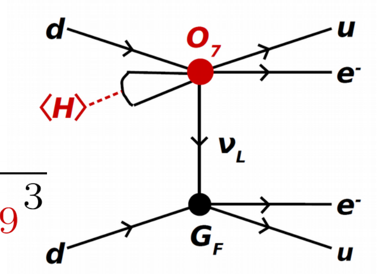
$$\mathcal{O}_9{}^{11a} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}$$

$$\frac{G_F^2 \epsilon_9}{2m_p} = \frac{g^2}{16\pi^2 \Lambda_9{}^5}$$



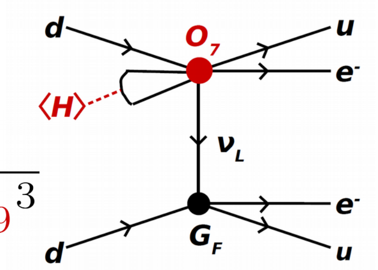
Long-range contribution:

$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_d v}{16\pi^2 \Lambda_9{}^3}$$



$$\epsilon_7^{11b} = \epsilon_{S+P}^{S+P}$$

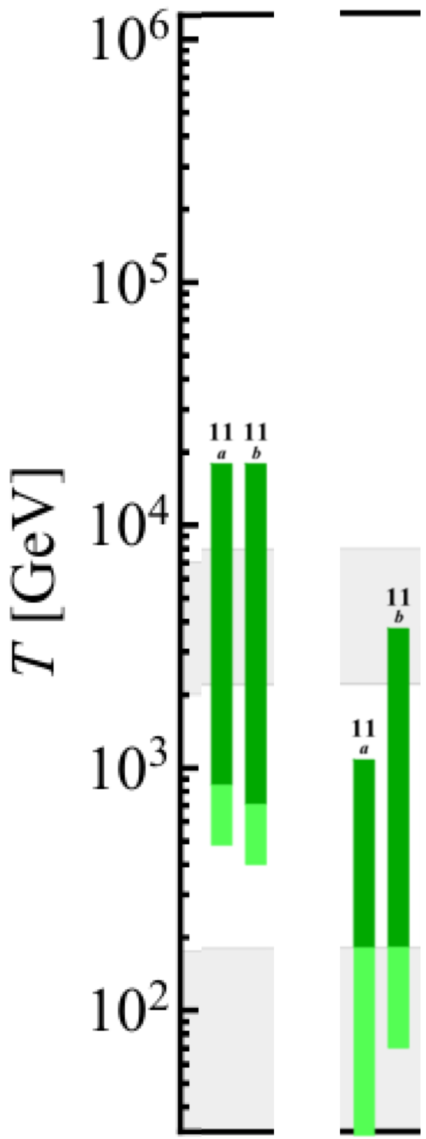
$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_d v}{16\pi^2 \Lambda_9{}^3}$$



$$\epsilon_7^{11a} = \epsilon_{S+P}^{S+P}$$

only first generation Yukawa couplings

Competition between long- and short-range

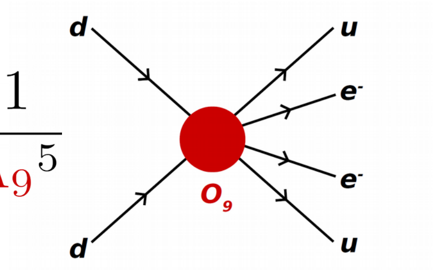


Short-range contribution:

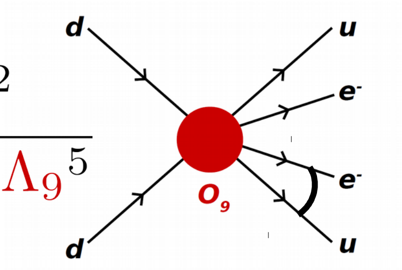
$\mathcal{O}_9{}^{11b} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}$

$\mathcal{O}_9{}^{11a} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}$

$$\frac{G_F^2 \epsilon_9}{2m_p} = \frac{1}{\Lambda_9{}^5}$$

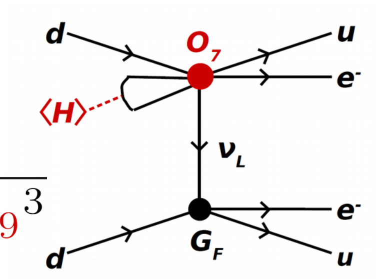


$$\frac{G_F^2 \epsilon_9}{2m_p} = \frac{g^2}{16\pi^2 \Lambda_9{}^5}$$

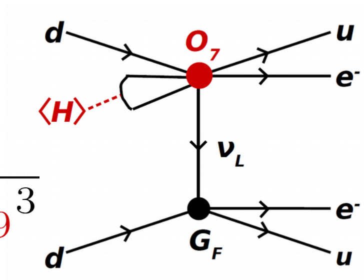


Long-range contribution:

$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_d v}{16\pi^2 \Lambda_9{}^3}$$



$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_d v}{16\pi^2 \Lambda_9{}^3}$$

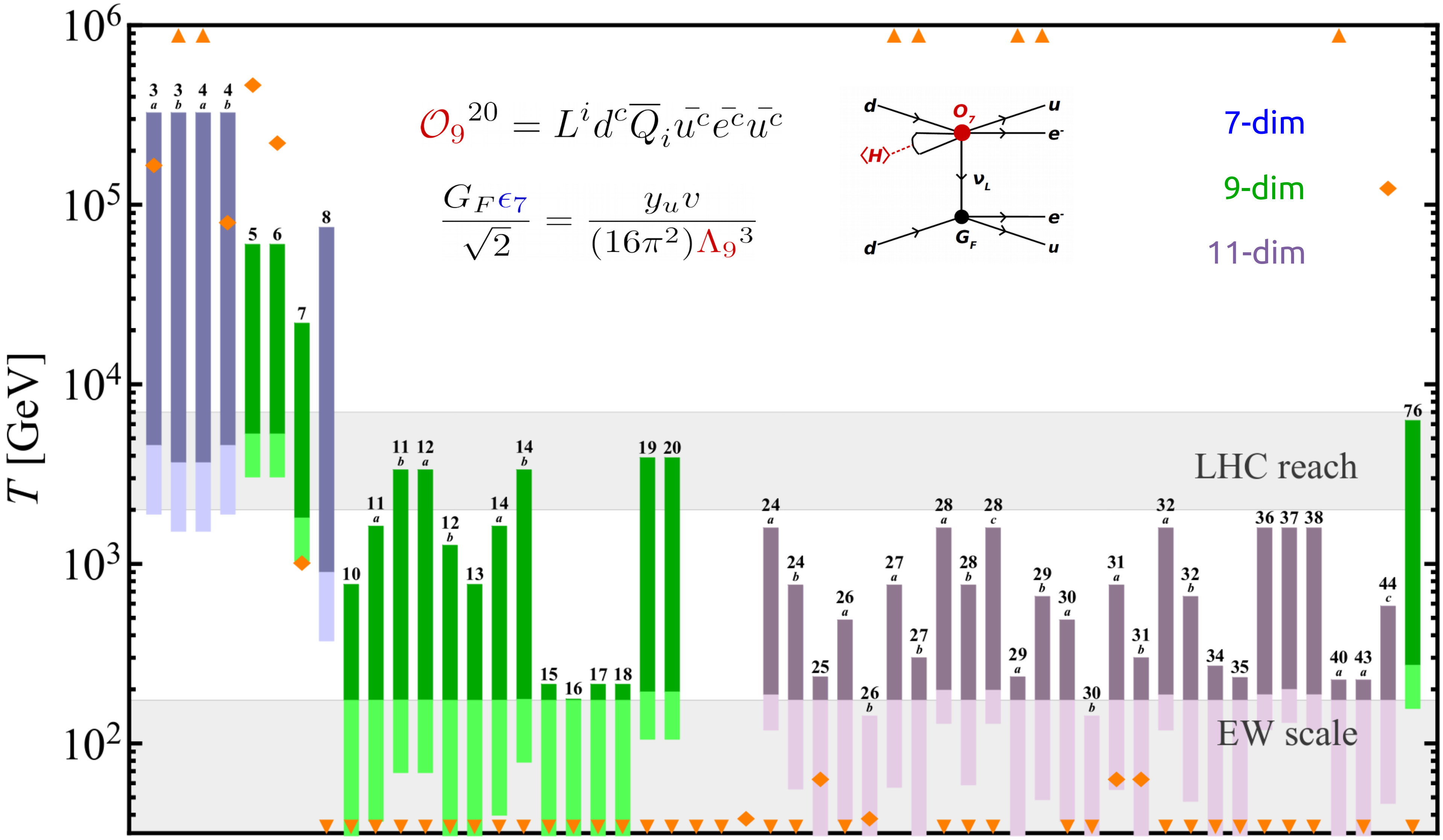


$\epsilon_7^{11b} = \epsilon_{S+P}^{S+P}$

$\epsilon_7^{11a} = \epsilon_{S+P}^{S+P}$

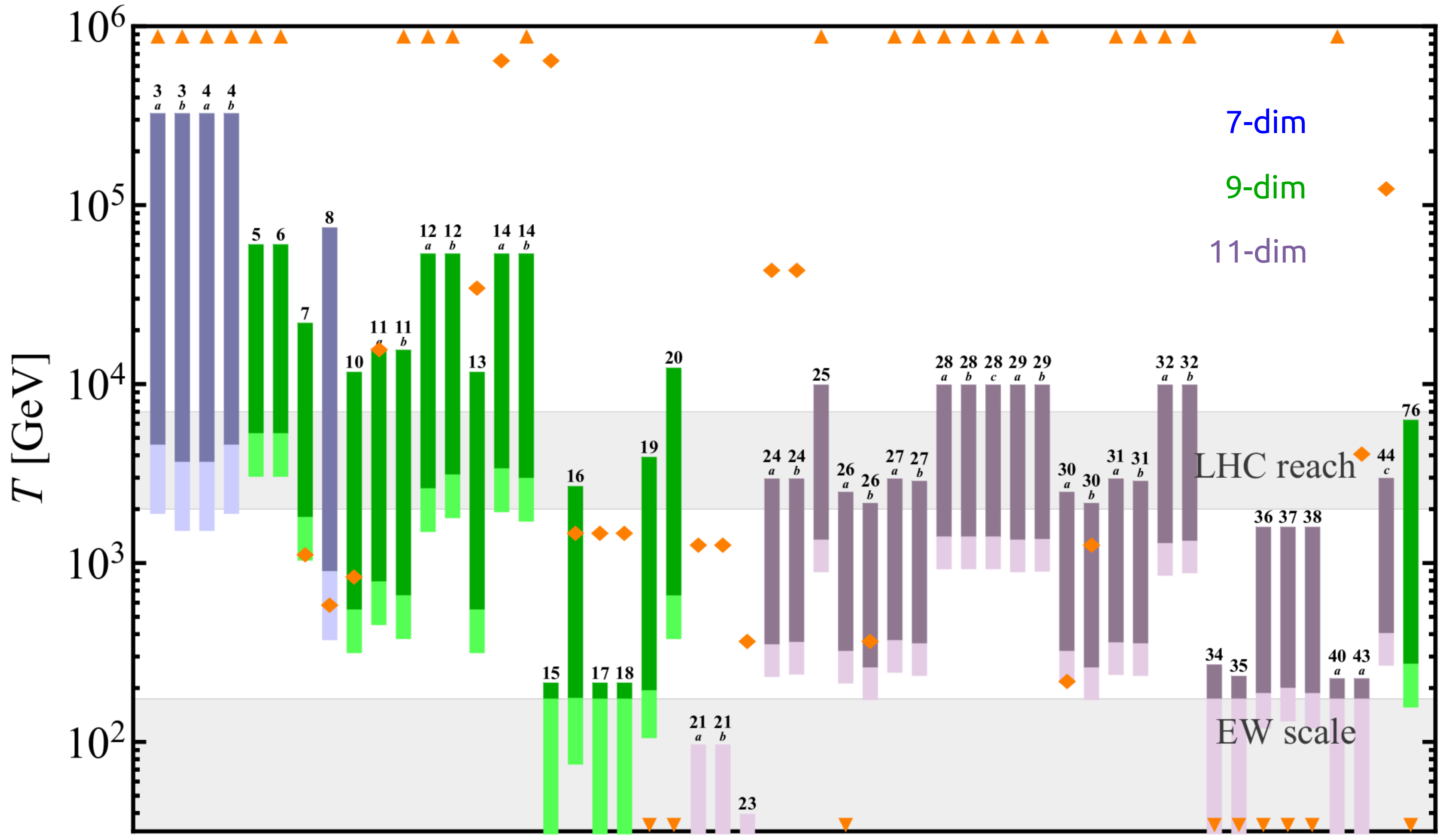
allow third generation Yukawa couplings

Impact of flavour structure



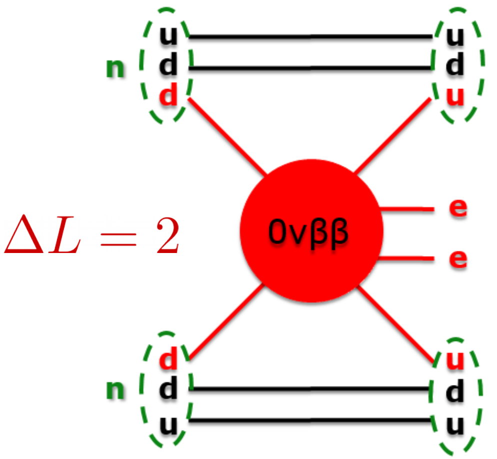
first generation only

Impact of flavour structure

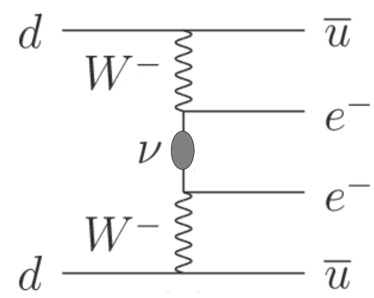
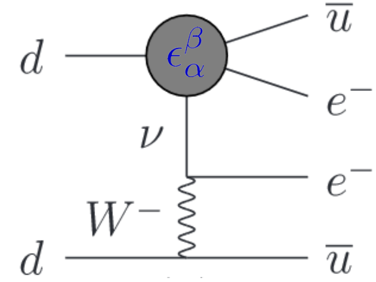
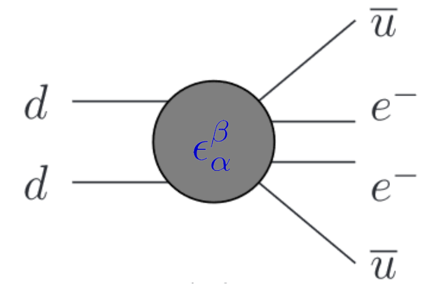
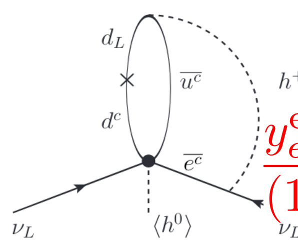
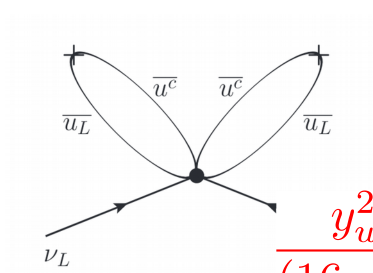
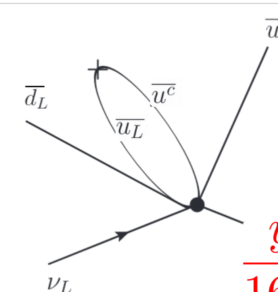


incl. third generation

Possible underlying LNV operators

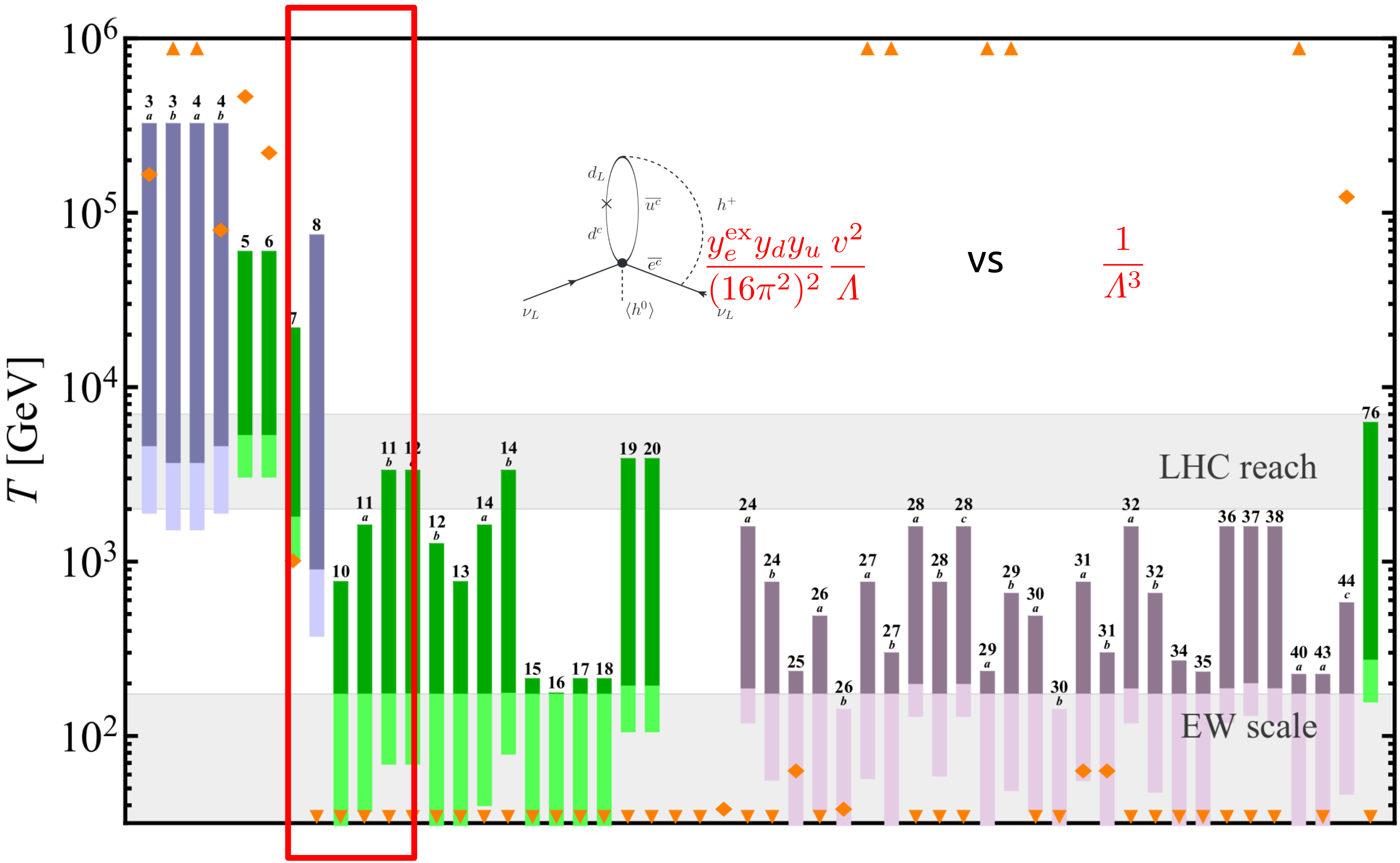


? =

	standard mass mechanism  $\mathcal{O}_5$	long range contribution  $\mathcal{O}_7$	short range contribution  $\mathcal{O}_9$
$\mathcal{O}_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl}$	tree level $\frac{1}{\Lambda}$		
$\mathcal{O}_8 = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$	 $\frac{y_e^{\text{ex}} y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	tree level $\frac{1}{\Lambda^3}$	
$\mathcal{O}_{12a} = L^i L^j \overline{Q}_i \bar{u^c} \overline{Q}_j \bar{u^c}$	 $\frac{y_u^2}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	 $\frac{y_u}{16\pi^2} \frac{v}{\Lambda^3}$	tree level $\frac{1}{\Lambda^5}$

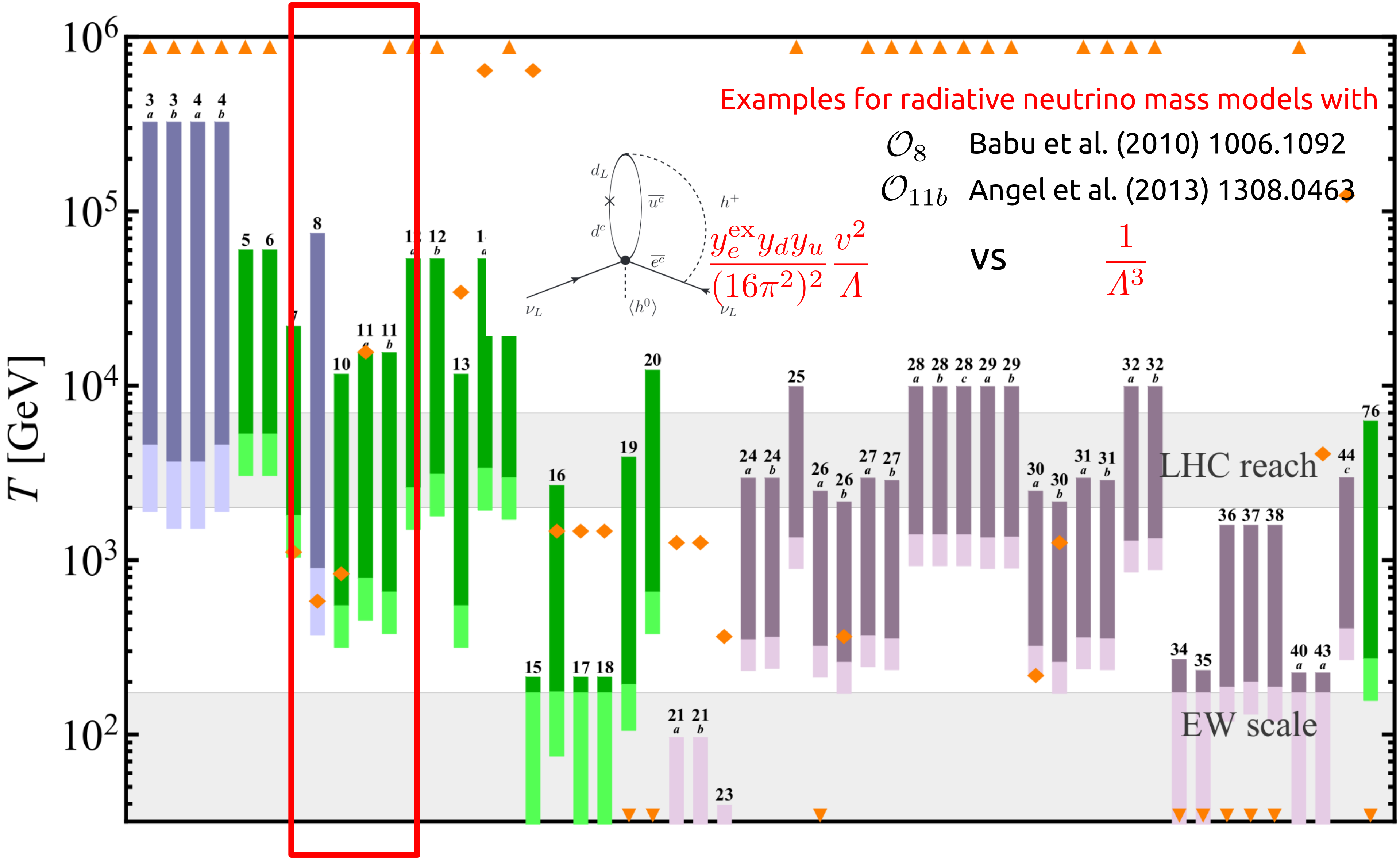
What is the dominant contribution to 0vbb?

Competition with the mass mechanism



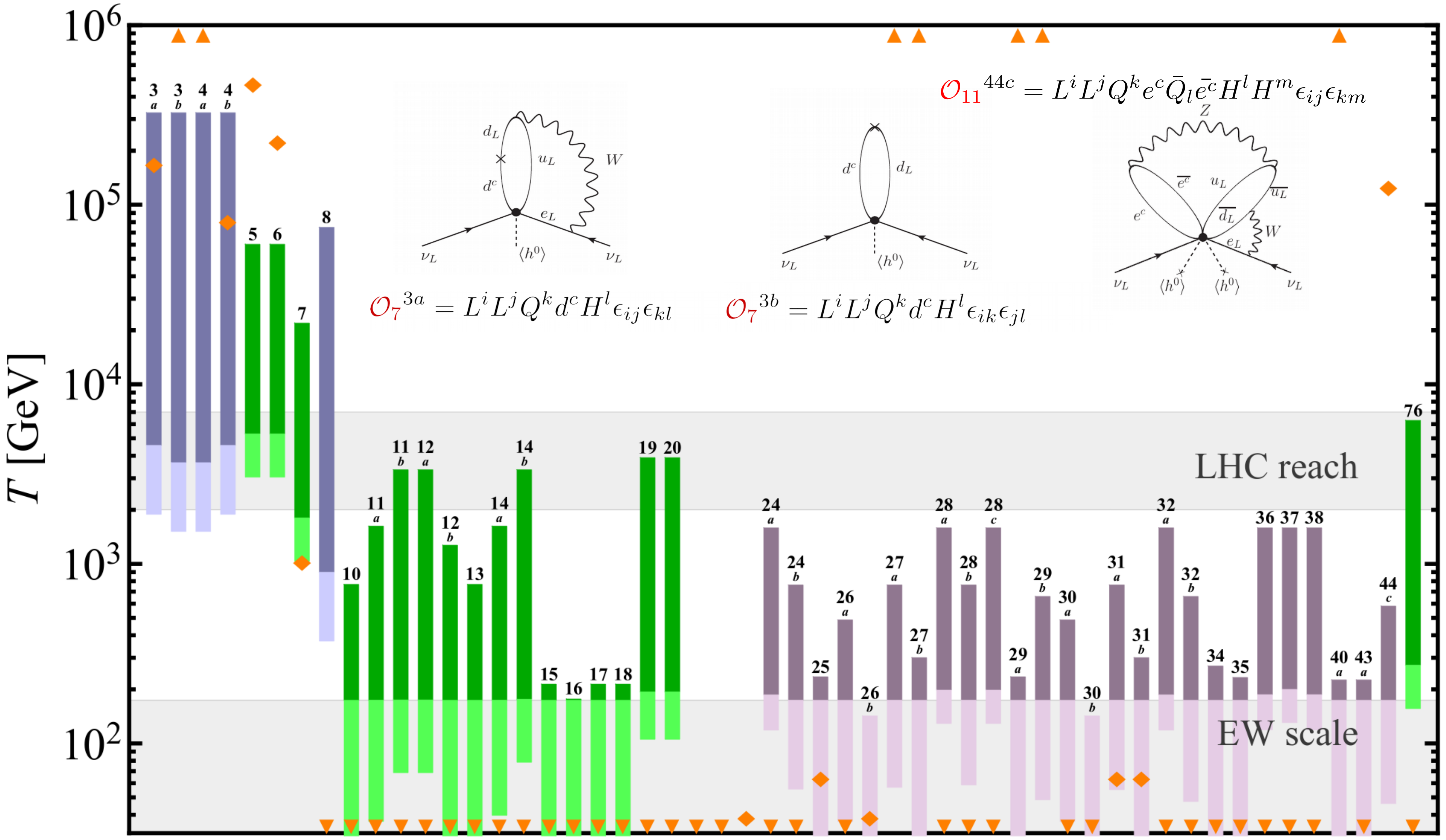
first generation only

Competition with the mass mechanism



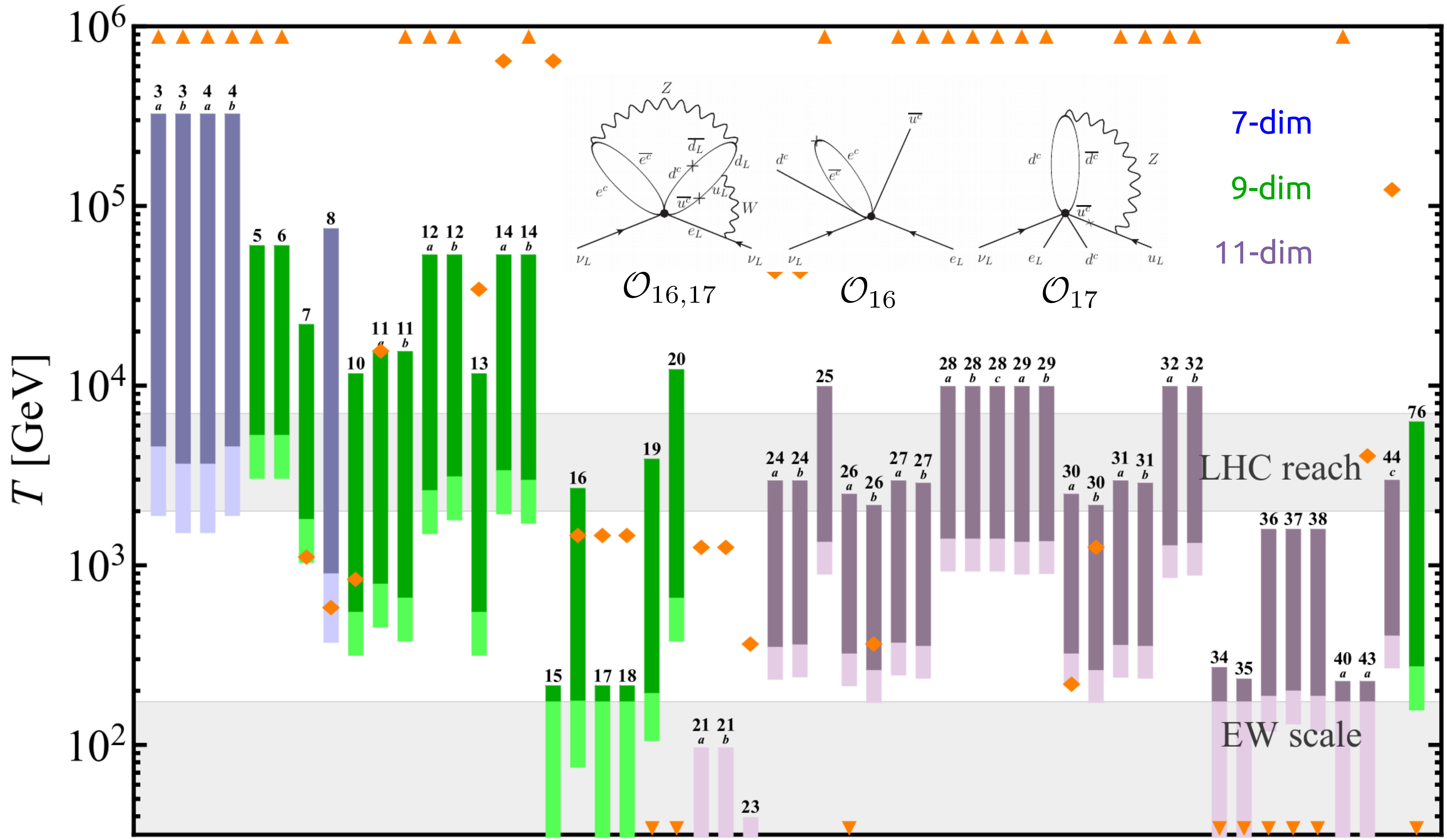
incl. third generation

Competition with the mass mechanism



first generation only

Competition with the mass mechanism



incl. third generation

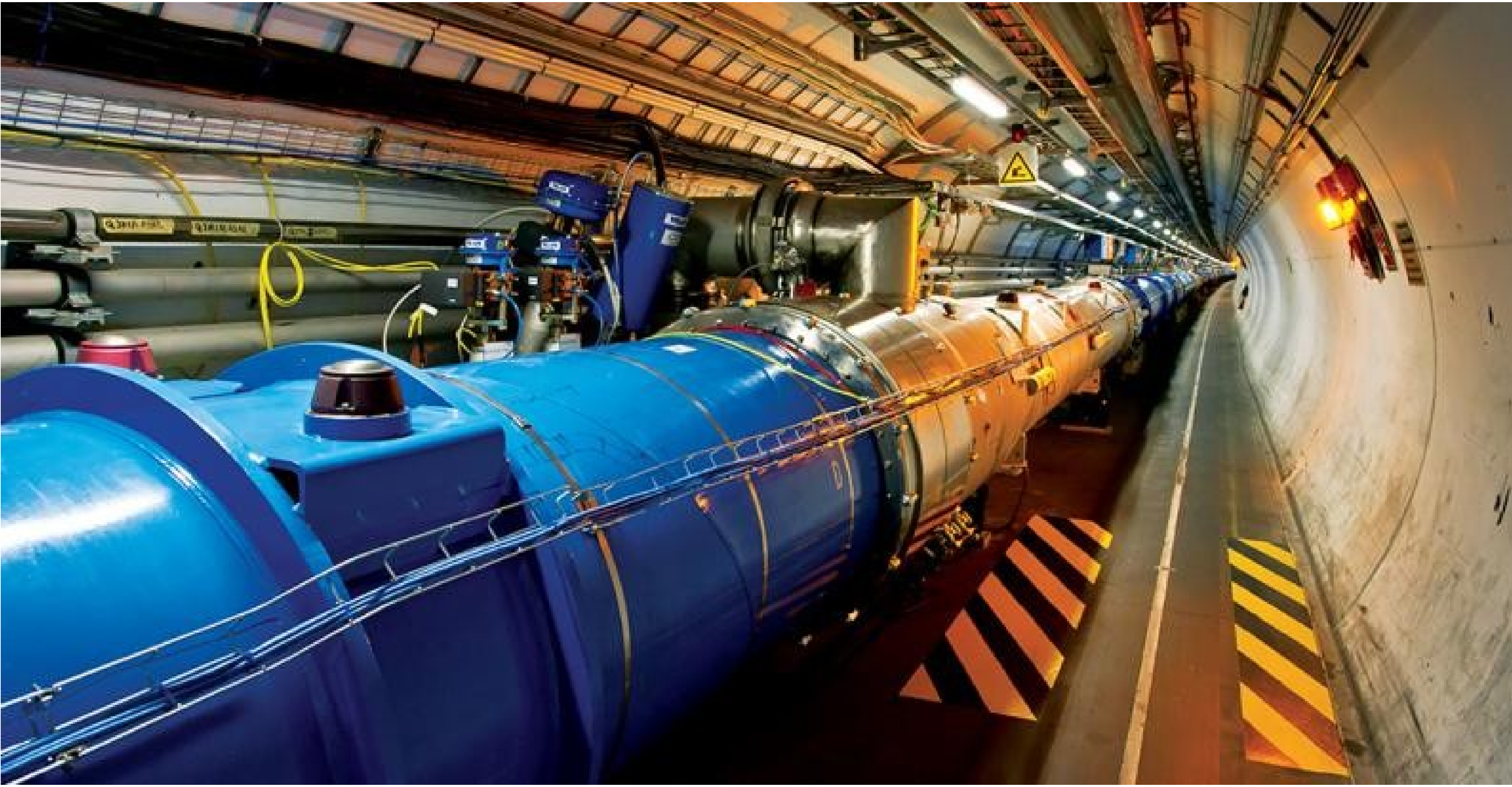
Little summary

- Higher dimensional operators can dominantly contribute via loops to lower dimensional 0vbb contributions

- Underlying flavour structure can impact this picture

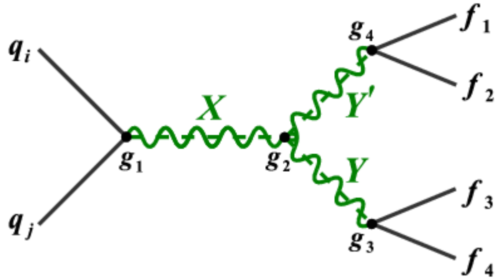
- Survey tells us if existence of specific UV complete radiative neutrino mass models would falsify high scale baryogenesis models

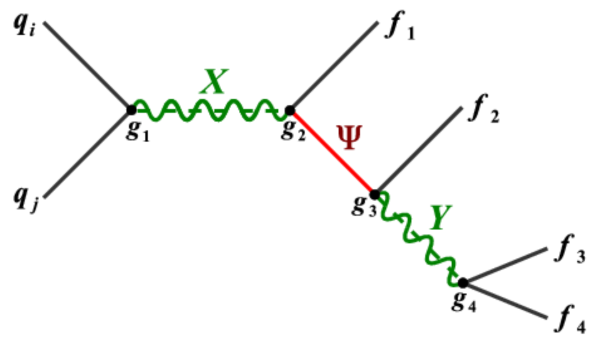
LNV at the LHC



LNV at the LHC

signature: $pp \to l^{\pm}l^{\pm} + 2\text{ jets}$





$$\frac{\Gamma_W}{H} = \frac{1}{n_\gamma H}\frac{T}{32\pi^4}\int_0^\infty ds\ s^{3/2}\sigma(s)K_1\left(\frac{\sqrt{s}}{T}\right)$$

cross section in early universe determines washout strength

$$\sigma(Q^2) = \frac{4\pi}{9}(2J_X+1)\frac{\Gamma(X\to q_1q_2)\Gamma(X\to 4f)}{(Q^2-M_X^2)^2+M_X^2\Gamma_X^2}$$

$$\sigma_{\mathrm{LHC}} = \frac{4\pi^2}{9s}(2J_X+1)\frac{\Gamma_X}{M_X}f_{q_1q_2}\left(\frac{M_X}{\sqrt{s}}, M_X^2\right)\times \mathrm{Br}(X\to q_1q_2)\mathrm{Br}(X\to 4f)$$

cross section possibly measured at LHC

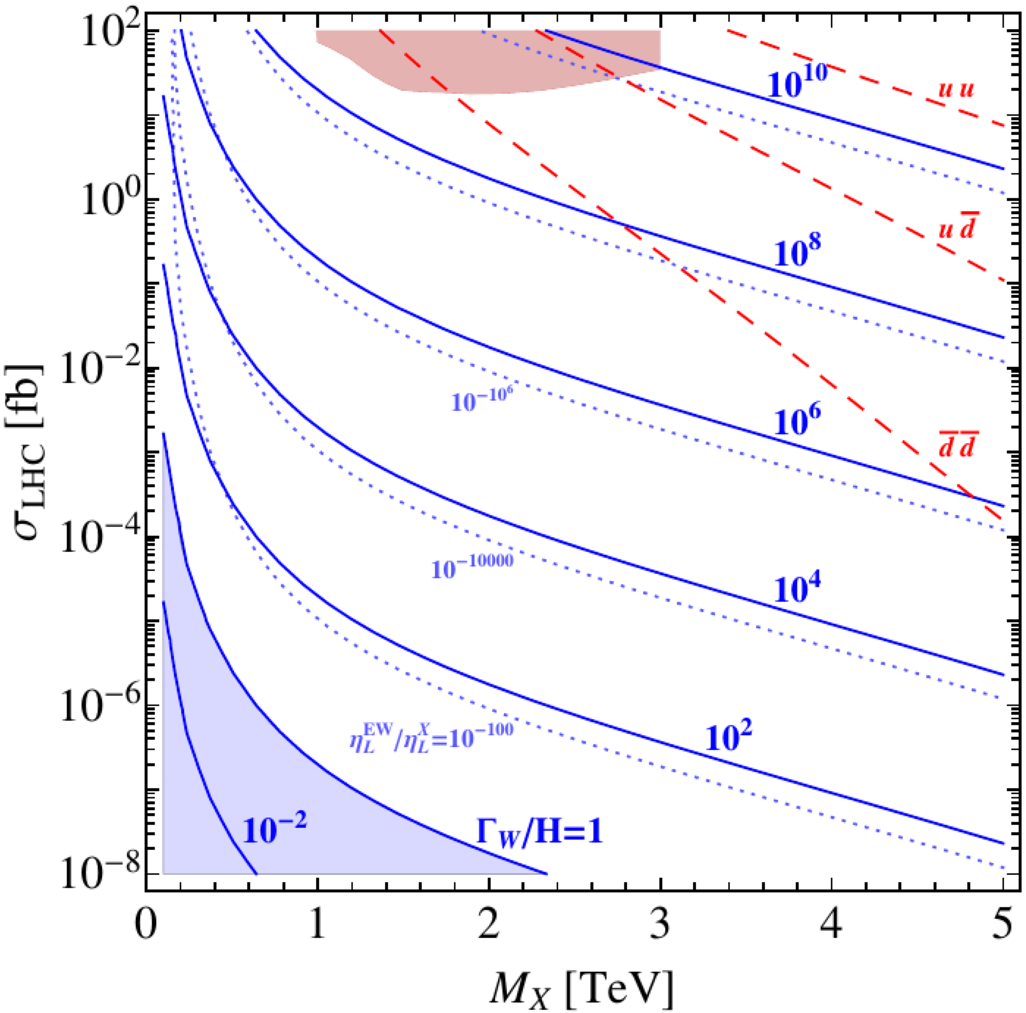
$$\sigma(s) = \frac{4\cdot 9\cdot s_{\mathrm{LHC}}}{f_{q_1q_2}\left(M_X/\sqrt{s_{\mathrm{LHC}}}\right)}\cdot\sigma_{\mathrm{LHC}}\cdot\delta(s-M_X^2)$$

Observable LNV signal at LHC and corresponding resonant mass can be directly related to baryon asymmetry washout

$$\frac{\Gamma_W}{H} = \frac{0.028}{\sqrt{g_*}}\frac{M_P M_X{}^3}{T^4}\frac{K_1\left(M_X/T\right)}{f_{q_1q_2}\left(M_X/\sqrt{s_{\mathrm{LHC}}}\right)}\times\left(s_{\mathrm{LHC}}\sigma_{\mathrm{LHC}}\right)$$

LNV at the LHC

- Assuming pre-existing lepton asymmetry generated at high scale

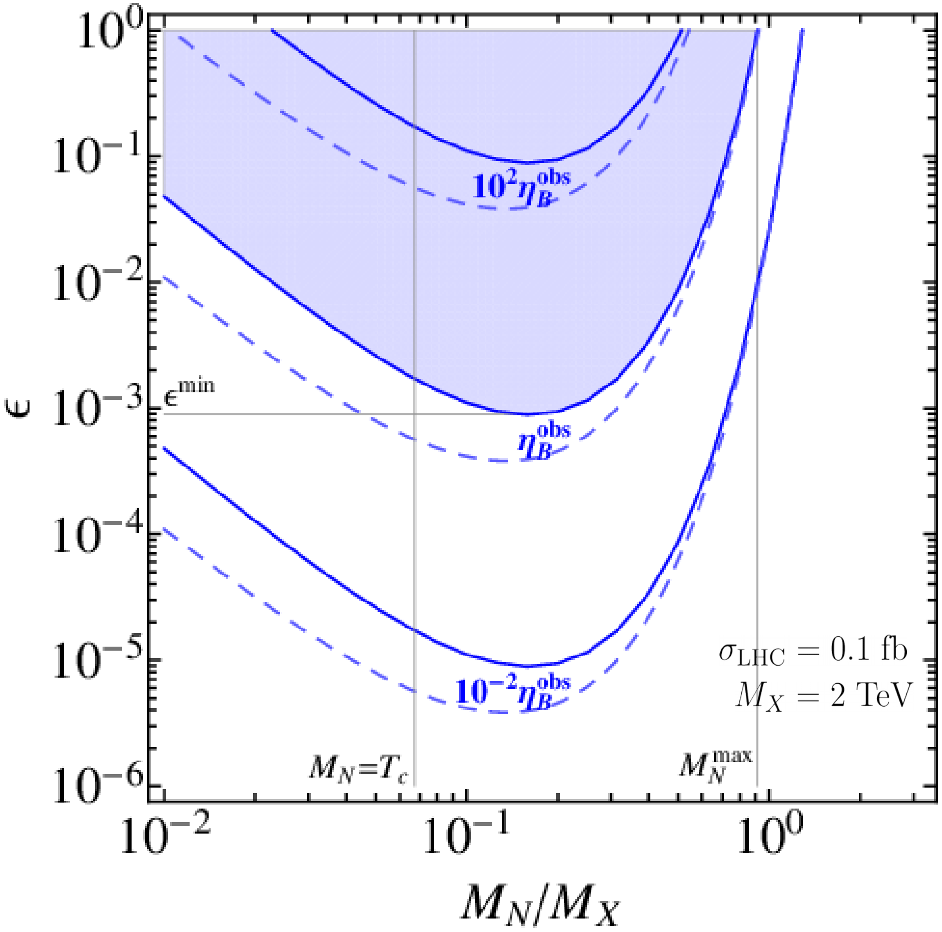


$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\rm TeV} - 1\right) + \log_{10}\frac{\sigma_{\rm LHC}}{\rm fb}$$

Observation of LNV process at the LHC implies a strong washout that it excludes leptogenesis models that generate an asymmetry above M_x

LNV at the LHC

- NOW: assumption that CP-asymmetry ϵ is created at scale M_N



$$\frac{d\delta\eta_N}{dz} = \frac{K_1(r_N z)}{K_2(r_N z)}\left[r_N + \left(1 - r_N{}^2 K_D z\right)\delta\eta_N\right]$$

$$\frac{d\eta_L}{dz} = \epsilon K_D r_N{}^4 z^3 K_1(r_N z)\delta\eta_N - K_W z^3 K_1(z)\eta_L$$

$$r_N = \frac{M_N}{M_X}$$

M_N: scale of CP-asymmetry generation

M_X: scale of LNV observation

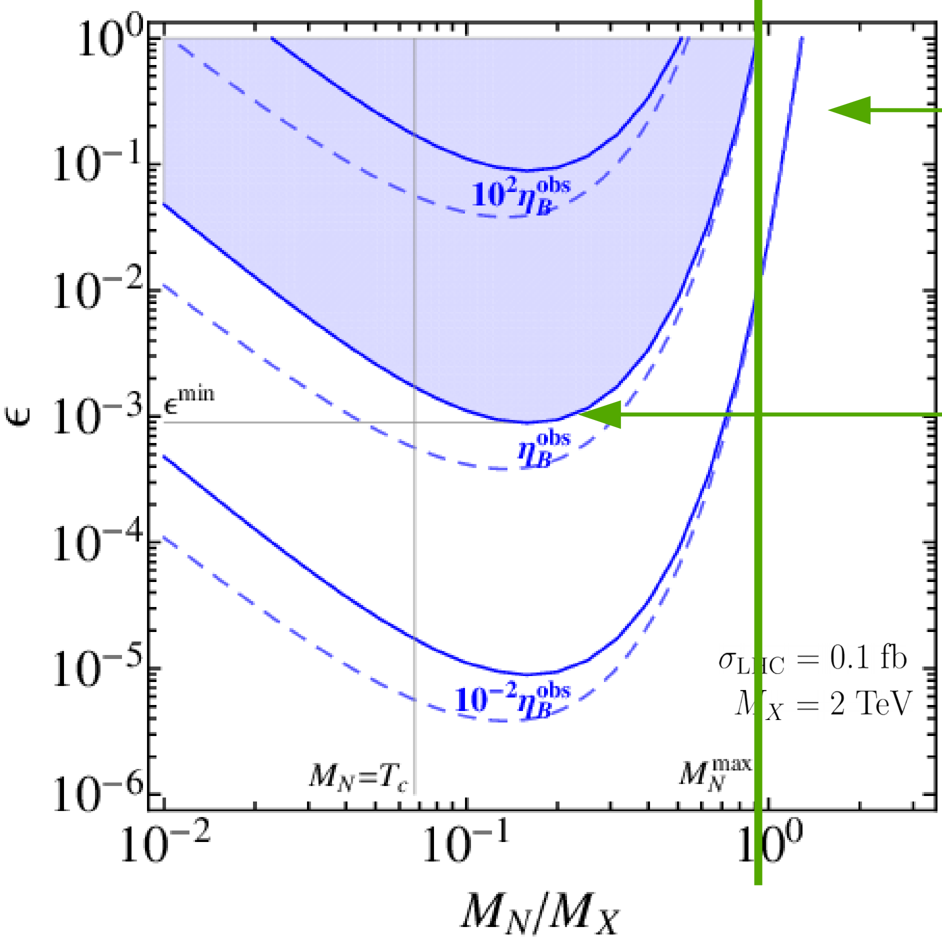
observation of LNV process at the LHC

- excludes high-scale baryogenesis models
- sets lower limit on the baryon asymmetry of a low-scale leptogenesis model

$$\log_{10}\left|\frac{\eta_B}{\eta_B^{obs}}\right| < 2.4\frac{M_X}{\text{TeV}}\left(1 - \frac{4}{3}\frac{M_N}{M_X}\right) + \log_{10}\left[|\epsilon|\left(\frac{\sigma_{LHC}}{\text{fb}}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^2\right]$$

LNV at the LHC

- NOW: assumption that CP-asymmetry ϵ is created at scale M_N



$M_N > M_X$

not possible to generate large enough baryon asymmetry at all

$M_N < M_X$

lower limit on CP-asymmetry

observation of LNV process at the LHC

- excludes high-scale baryogenesis models
- sets lower limit on the baryon asymmetry of a low-scale leptogenesis model

$$\log_{10}\left|\frac{\eta_B}{\eta_B^{obs}}\right| < 2.4\,\frac{M_X}{\text{TeV}}\left(1-\frac{4}{3}\frac{M_N}{M_X}\right) + \log_{10}\left[|\epsilon|\left(\frac{\sigma_{LHC}}{\text{fb}}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^2\right]$$

Caveats

- Asymmetries can be protected from washout in models where lepton asymmetry can be transferred in a hidden sector and decouple

- only the observation of LNV in **all** flavours allows for a conclusive statement

- Baryon asymmetry could be generated below the electroweak scale where sphaleron processes are not efficient

  → in that case: lepton asymmetry washout does NOT imply baryon asymmetry washout

Conclusions