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CP3 Origins
Cosmology & Particle Physics

Implications of lepton number violation on high-scale baryogenesis and dark matter

CP^3 Origins
Wei-Chih Huang
03.01.2018
IOP Academia Sinica

F. Deppisch, J. Harz, WCH, M. Hirsch, H. Päs, Phys. Rev. D92 (2015) 036005
F. Deppisch, L. Graf, J. Harz, WCH, arXiv:1711.10432
M. T. Frandsen, C. Hagedorn, WCH, E. Molinaro, H. Päs, arXiv:1801.XXXXX

Outline

- Motivations
- Sakharov Conditions
- Introduction on mechanisms for baryon asymmetry generation
- L-violation responsible for $0\nu\beta\beta$ decay and wash-out on L and B
- Tree- and loop-level contributions to $0\nu\beta\beta$ decay
- Connection to asymmetric dark matter (ADM)
- Conclusions

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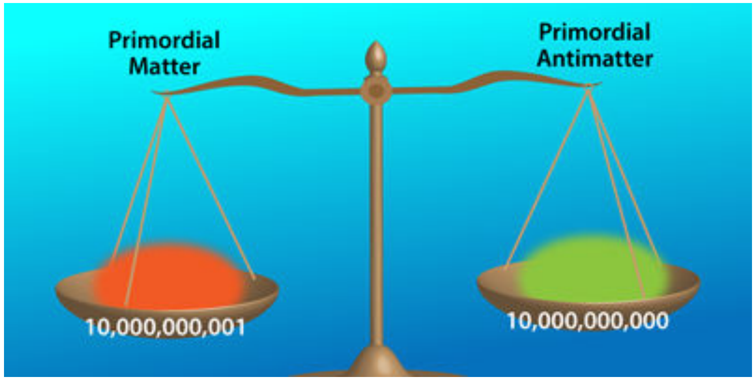
Motivation



Sakharov Conditions

- B violation
- C and CP violation:

$$X \to B$$

$$\overline{X} \to \overline{B}$$

➔ Total baryon number is still conserved if C or CP is conserved.

Sakharov Conditions

- C and CP violation:

$$iM_1(X->B+Y)=a$$
$$iM_2(X->B+Y)=B\times Ce^{i\theta}$$
$$i\overline{M}_1(\overline{X}->\overline{B}+\overline{Y})=a^*$$
$$i\overline{M}_2(\overline{X}->\overline{B}+\overline{Y})=B^*\times Ce^{i\theta}$$

$$\Gamma(X->B+Y)-\Gamma(\overline{X}->\overline{B}+\overline{Y})=4\int d\Pi_f\left|AB^*\right|\sin\phi_{AB}\sin\theta$$

$$AB^*=\left|AB^*\right|e^{i\phi_{AB}}$$

Sakharov Conditions

- Out of equilibrium dynamics since in thermal equilibrium, we have <B>=0

Baryon number B is odd under C, even under P and T
$\Rightarrow$ B is odd under $CPT \equiv \theta$

$$
\begin{aligned}
\langle B \rangle_T &= \mathrm{Tr}\left(\mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\theta^{-1}\theta\,\mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\mathrm{e}^{-H/T}\,\theta B \theta^{-1}\right) \\
&= -\langle B \rangle_T
\end{aligned}
$$

M. Plümacher ’09

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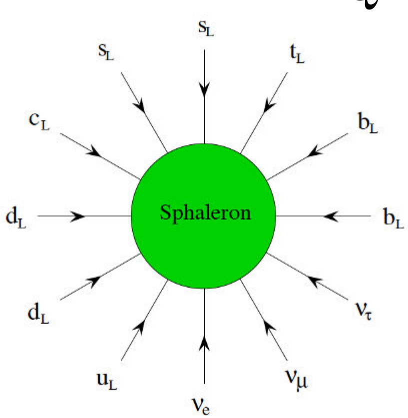
Sphalerons

•Sphaleron processes (Klinkhammer & Manton ’84; Kuzmin et al. ’85) convert lepton asymmetry into baryon asymmetry

$$j_5^\mu = \overline{\psi}\gamma_5\gamma^\mu\psi, \qquad \partial_\mu j_5^\mu = \frac{1}{16\pi^2}\widetilde{F}_{\mu\nu}F^{\mu\nu} = \frac{\epsilon_{\rho\sigma\mu\nu}}{16\pi^2}F^{\rho\sigma}F^{\mu\nu}\ .$$

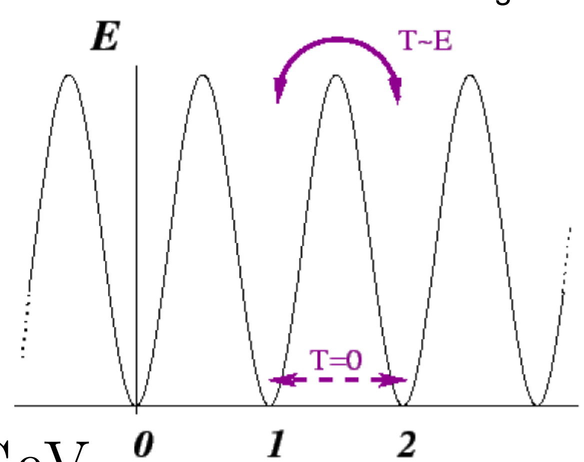
$$\Delta Q^{\ i} = \frac{1}{64\pi^2}\int d^4x F^A_{\mu\nu}\widetilde{F}^{\mu\nu A}$$

Winding or Chern-Simons number of the field configuration



$$\Delta B = \Delta L = 3$$

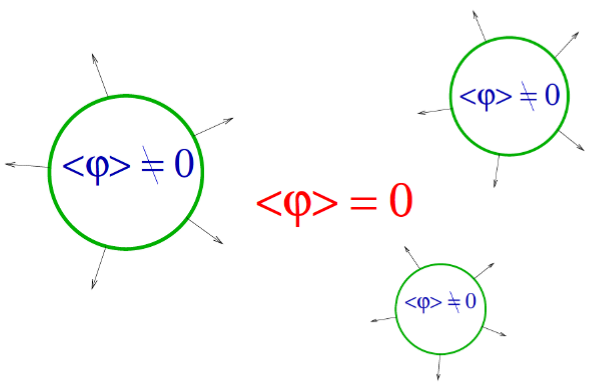
$$\mathcal{O}_{B+L} = \prod_{i=1,2,3}(q_{L_i}, q_{L_i}, q_{L_i}\ell_{L_i})$$

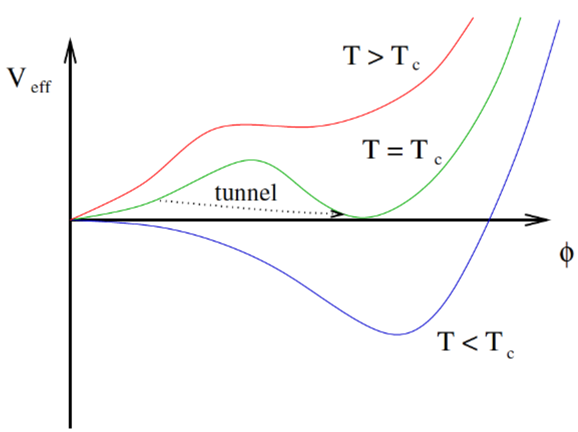


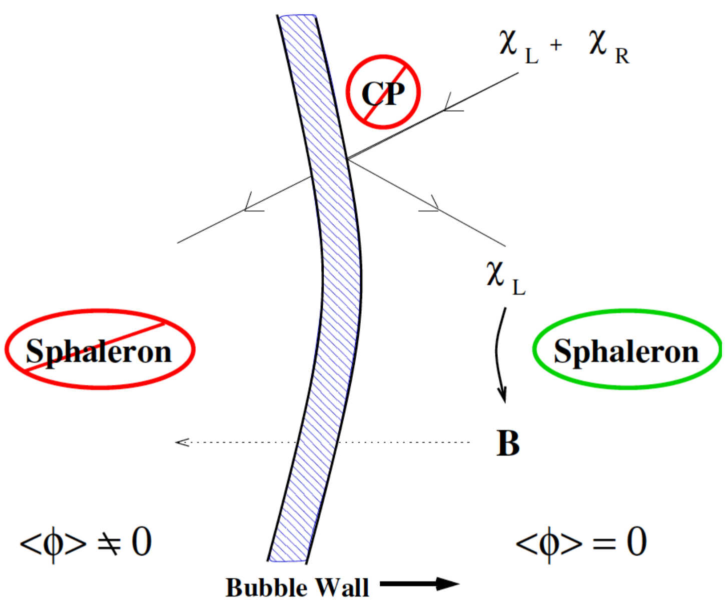
$$\Gamma_{\not{B+L}} \simeq 250\,\alpha_W^5\,T \Rightarrow 100 \lesssim T \lesssim 10^{12}\ \text{GeV}$$

Baryogenesis

- Baryogenesis occurs at the boundary between different vacuum states (Kuzmin, Rubakov, Shaposhnikov '85 '86 '87)



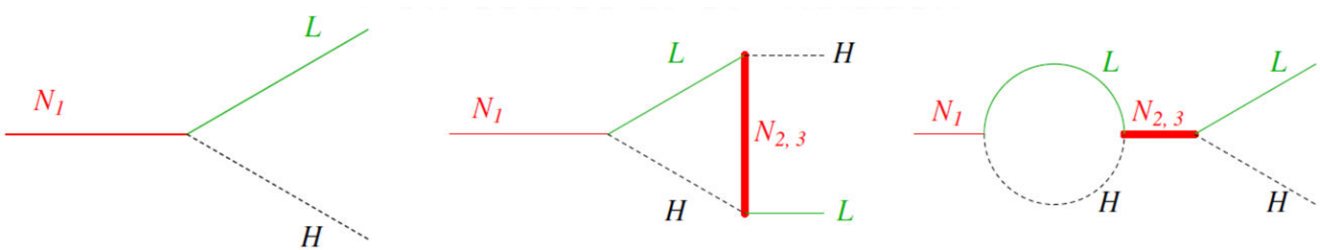




Morrissey et al,1206.2942

Leptogenesis

- A heavy neutrino decays out of equilibrium into leptons and anti-leptons unevenly (Fukugita,Yanagida '86)



A. Strumia, hep-ph/0608347 (2006)

$$\varepsilon_1 \equiv \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \overline{L}\,\overline{H})}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \overline{L}\,\overline{H})} \approx -\frac{3}{8\pi}\frac{1}{(hh^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}(hh^\dagger)^2_{li} \frac{M_1}{M_i}$$

$$\Delta L \neq 0 \;\to\; \text{sphalerons} \;\to\; \Delta B \neq 0$$

Leptogenesis (Alternatives)

- Resonant leptogenesis
- Soft leptogenesis via oscillations
- Non-thermal leptogenesis
- CP-violation scattering
- $\boldsymbol{\nu}$-N Level-crossing
- …..

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Upper bound on baryogenesis scale from neutrino masses

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Received 4 June 1990

We examine the constraints on baryogenesis if anomalous weak baryon violation is in thermal equilibrium at high temperatures. If neutrinos have Majorana masses, there is an upper bound on the scale of baryogenesis: $T_0 \lesssim 10^{12}\,\text{GeV}(1\,\text{eV}/m_\nu)^2$, where m_ν is the mass of the *lightest* neutrino, and no baryon number is generated at temperatures below T_0.

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Chemical potential equilibirum

$$- \mu_q + \mu_H + \mu_{d_R} = 0 \ , \ \ -\mu_q - \mu_H + \mu_{u_R} = 0 \ , \ \ -\mu_\ell + \mu_H + \mu_{e_R} = 0 \ ,$$

$$3\,(3\,\mu_q + \mu_\ell) = 0 \ , \ \ \mu_q + 2\mu_{u_R} - \mu_{d_R} - \mu_\ell - \mu_{e_R} + \frac{2}{3}\mu_H = 0 \ ,$$

All chemical potentials vanish after ΔL=2 kicks in !

$$\mu_\ell + \mu_H = 0$$

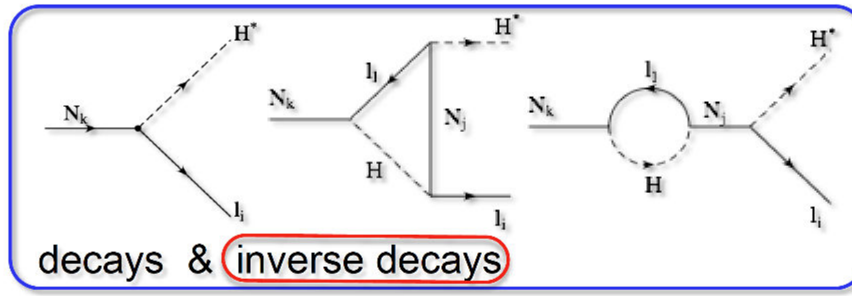
Wash-out Effects on Leptogenesis

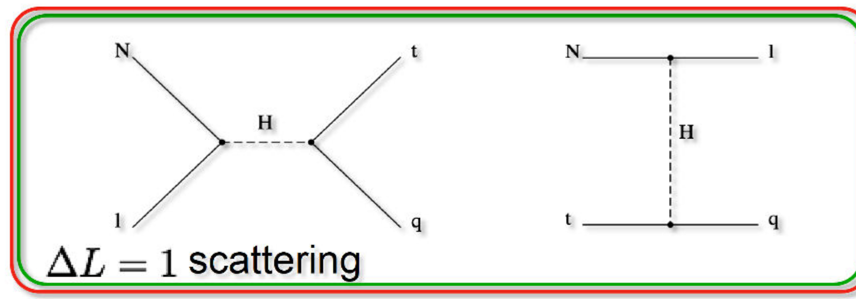
- Boltzmann equations describe evolution of N / L number density

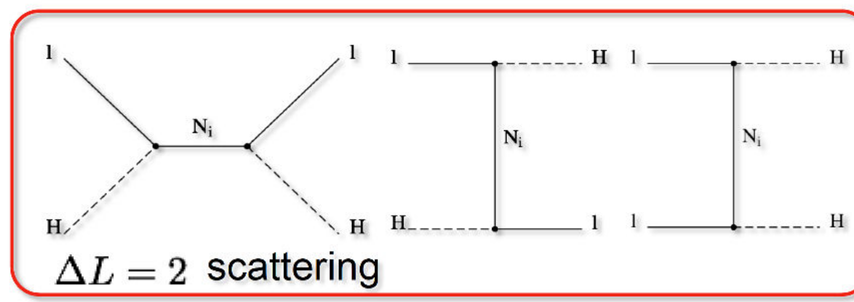
$$Hz\frac{dN_{N_1}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{\rm eq})$$

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

with $z = \frac{M_{N_1}}{T}$





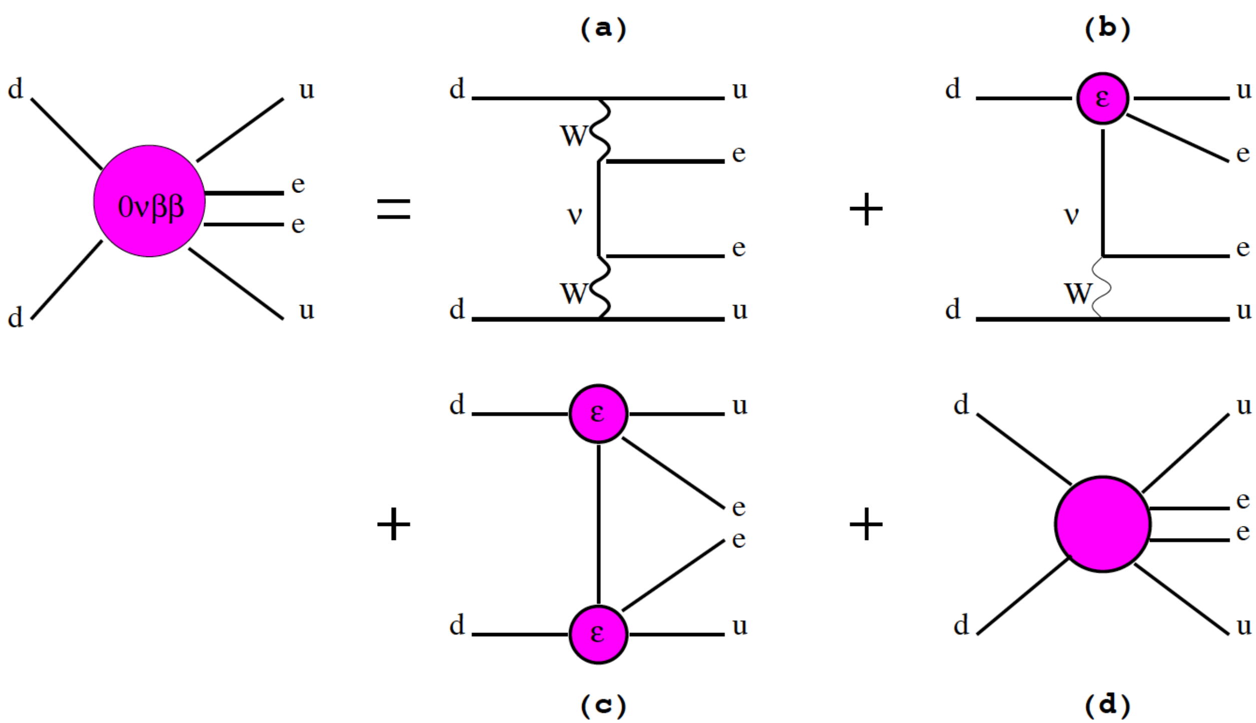


➤ L violation and the (L+B)-violating sphalerons erase both L and B

J. Harz Helmholtz Alliance meeting, DESY

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

- Lepton number is violated if $0\nu\beta\beta$ is observed and SM neutrinos contains a Majorana component. It would wash out not only L and but also B in light of the sphalerons



Deppisch et al. 1208.0727

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Lepton Number Violation (LNV) Operators

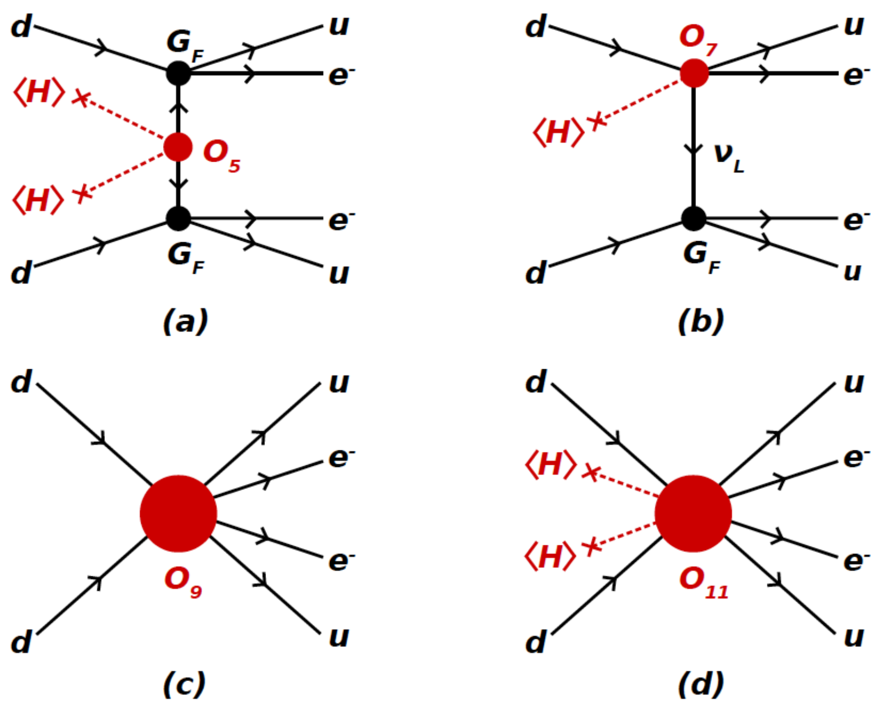


FIG. 1: Contributions to $0\nu\beta\beta$ decay generated by the operators in Eq. (2) in terms of effective vertices, point-like at the nuclear Fermi momentum scale.

- We single out operators which contribute $0\nu\beta\beta$ with short- and long-range interactions.

$$\mathcal{O}_5 = \frac{1}{\Lambda}(L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl},$$

$$\mathcal{O}_7 = \frac{1}{\Lambda^3}(L^i d^c)(\bar{e^c}\bar{u^c}) H^j \epsilon_{ij},$$

$$\mathcal{O}_9 = \frac{1}{\Lambda^5}(L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}),$$

$$\mathcal{O}_{11} = \frac{1}{\Lambda^7}(L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk}\epsilon_{lm},$$

Lepton Flavor Violation (LFV)

- Since we only study wash-out effects resulting from the $0\nu\beta\beta$ operators, only e-lepton asymmetry will be eliminated.
- In order to washout other flavor asymmetries, one would need LFV operators together with the $0\nu\beta\beta$ operators.
- We study $\ell_i \to \ell_j + \gamma$ and $\ell_i \to \ell_j$ conversion

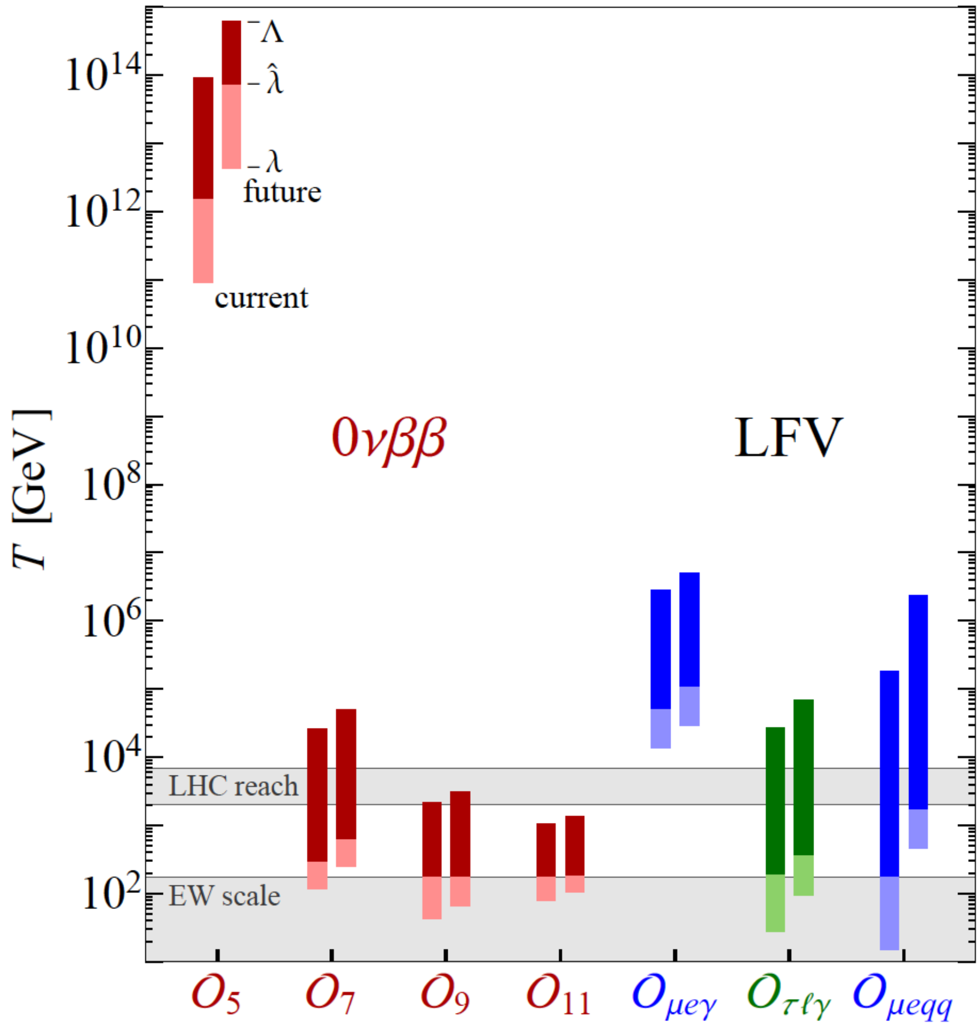
$$\mathcal{O}_{\ell\ell\gamma} = \mathcal{C}_{\ell\ell\gamma} \bar{L}_\ell \sigma^{\mu\nu} \bar{\ell}^c H F_{\mu\nu}$$

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

Π : Lorentz structures

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

Results



- From , one can not differentiate O_9 and O_{11} from O_5
- However, O_9 and O_{11} can be probed at the LHC

$$\mathcal{O}_5 = \frac{1}{\Lambda}(L^i L^j)H^k H^l \epsilon_{ik}\epsilon_{jl},$$

$$\mathcal{O}_7 = \frac{1}{\Lambda^3}(L^i d^c)(\bar{e^c}\bar{u^c})H^j \epsilon_{ij},$$

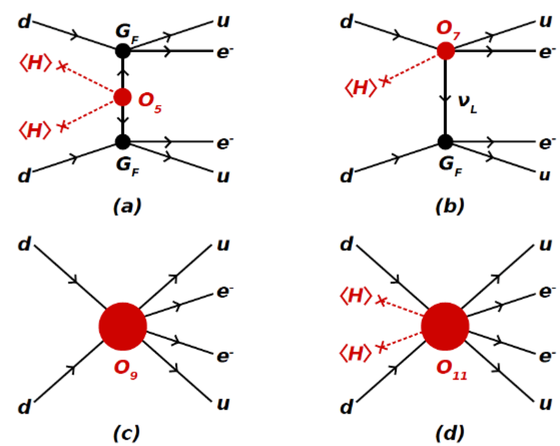
$$\mathcal{O}_9 = \frac{1}{\Lambda^5}(L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}),$$

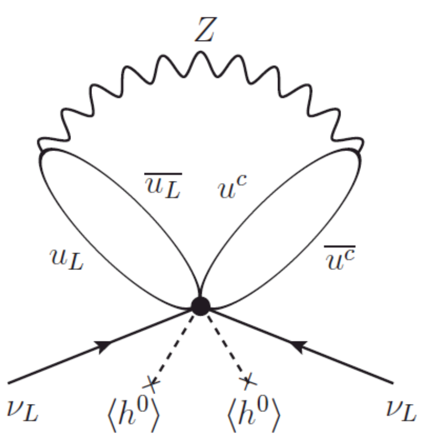
$$\mathcal{O}_{11} = \frac{1}{\Lambda^7}(L^i L^j)(Q_k d^c)(Q_l d^c)H_m \bar{H}_i \epsilon_{jk}\epsilon_{lm},$$

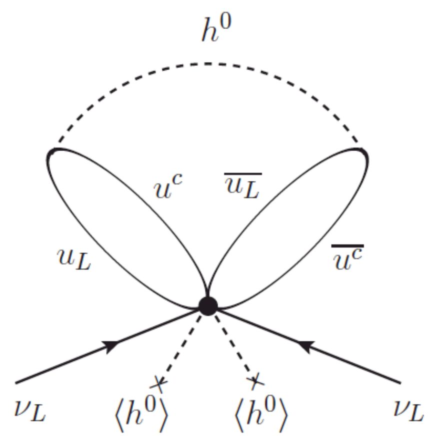
Tree- and loop-level contributions

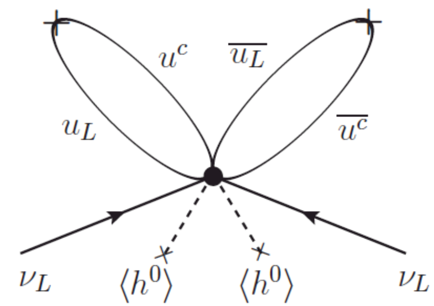
- In the following, we try to find all contributions to $0\nu\beta\beta$, given an operator.

$$L^i L^j Q^k u^c \overline{Q}_l \bar{u^c} H^l H^m \epsilon_{ik}\epsilon_{jm}$$









Automation

f_L	$\bar{f}_L$	Z	$g/(16\pi^2)$
f_L	$\bar{f}'_L$	W^-	$g/(16\pi^2)$
$\bar{f}^c$	$\bar{f}'_L$	H^-	$y_f/(16\pi^2)$
$\bar{f}^c$	$\bar{f}_L$	h^0	$y_f/(16\pi^2)$
Z	$\bar{f}_L$	$\bar{f}_L$	$g/(16\pi^2)$
W^-	$\bar{f}_L$	$\bar{f}'_L$	$g/(16\pi^2)$
H^-	f^c	$\bar{f}'_L$	$y_f/(16\pi^2)$
h^0	$\bar{f}_L$	f^c	$y_f/(16\pi^2)$
$\langle h \rangle$	$\bar{f}_L$	f^c	$vy_f/(16\pi^2)$
$h^0\|W^-\|H^-$	$\bar{h}^0\|W^+\|H^+$	$-$	$1/(16\pi^2)$

f_L	f^c	h^0	$y_f/(16\pi^2)^2$
f^c	f'_L	H^+	$y_f/(16\pi^2)^2$
f_L	$\bar{f}'_L$	W^+	$g/(16\pi^2)^2$
f_L	$\bar{f}_L$	Z	$g/(16\pi^2)^2$
h	$Z\ \|W^+$	$Z\ \|W^-$	$vg^2/(16\pi^2)^2$
Z	$H^+\|W^+$	$W^-\|H^-$	$2vg^2/(16\pi^2)^2$

Operator lists

$\mathcal{O}$	Operator	m_ν	LR	$\epsilon_{\rm LR}$
1^{H^2}	$L^iL^jH^kH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$	$\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	–	–
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$	$\frac{y_e}{16\pi^2}\frac{v^2}{\Lambda}$	–	–
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$	$\frac{y_d g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}
3_b	$L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}
4_a	$L^iL^j\overline{Q}_i\bar{u}^cH^k\epsilon_{jk}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}
4_b^*	$L^iL^j\overline{Q}_k\bar{u}^cH^k\epsilon_{ij}$	$\frac{y_u g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$	$\frac{y_e^{\rm ex}y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$

Table 4: Effective $\Delta L = 2$ SM operators at dimension 7. Dominant contributions to $0\nu\beta\beta$ decay via the effective neutrino mass (m_ν) and long-range (LR) mechanisms are shown. The $0\nu\beta\beta$ long-range interaction excited by a particular operator is denoted in column $\epsilon_{\rm LR}$. The notation of the contributions is explained in Sec. 4.3.

Operator lists

$\mathcal{O}$	Operator	m_ν	LR	$\epsilon_{\rm LR}$	SR	$\epsilon_{\rm SR}$
1^{H^4}	$L^iL^jH^kH^lH^tH_tH^uH_u\epsilon_{ik}\epsilon_{jl}$	$\frac{v^2}{\Lambda}f^2\left(\frac{v}{\Lambda}\right)$	–	–	–	–
1^{y_e}	$L^iL^jH^kH^l(\overline{L}^tH_t\overline{e^c})\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	–	–	–	–
1^{y_d}	$L^iL^jH^kH^l(\overline{Q}^tH_t\overline{d^c})\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_dy^{\rm ex}_{d\vert u}}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
2^{H^2}	$L^iL^jL^ke^cH^l\overline{H}^tH_t\epsilon_{ij}\epsilon_{kl}$	$\frac{y_e}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	–	–	–	–
$3_a^{H^2}$	$L^iL^jQ^kd^cH^l\overline{H}^tH_t\epsilon_{ij}\epsilon_{kl}$	$\frac{y_dg^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
$3_b^{H^2}$	$L^iL^jQ^kd^cH^l\overline{H}^tH_t\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
$4_a^{H^2}$	$L^iL^j\overline{Q}_i\overline{u^c}H^k\overline{H}^tH_t\epsilon_{jk}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	–	–
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
6	$L^iL^j\overline{Q}_k\overline{u^c}H^lH^k\overline{H}_i\epsilon_{jl}$	$\frac{y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	–	–
7	$L^iQ^j\overline{e^c}Q_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_e^{\rm ex}g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V-A}$	–	–
8^{H^2}	$L^i\overline{e^c}\overline{u^c}d^cH^j\overline{H}^tH_t\epsilon_{ij}$	$\frac{y_e^{\rm ex}y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$2\epsilon^{V+A}_{V+A}$	–	–
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_e^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	–	–	–	–
10	(2) $L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_ey_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	–	–
11_a	(2) $L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$	$\frac{y_d^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{g^2}{16\pi^2}\frac{1}{\Lambda^5}$	ϵ_1
11_b	(2) $L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{1}{\Lambda^5}$	ϵ_1
12_a	$L^iL^j\overline{Q}_i\overline{u^c}\overline{Q}_j\overline{u^c}$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{1}{\Lambda^5}$	ϵ_1
12_b^*	$L^iL^j\overline{Q}_k\overline{u^c}\overline{Q}_l\overline{u^c}\epsilon_{ij}\epsilon^{kl}$	$\frac{y_u^2g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{g^2y_d^{\rm ex}y_u^{\rm ex}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
13	$L^iL^jQ_i\overline{u^c}L^le^c\epsilon_{jl}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	–	–
14_a	(2) $L^iL^j\overline{Q}_k\overline{u^c}Q^kd^c\epsilon_{ij}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_{u\vert d}}{16\pi^2}\frac{v}{\Lambda^3}$	$\epsilon^{S+P}_{S\pm P}$	$\frac{g^2}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
14_b	(2) $L^iL^j\overline{Q}_i\overline{u^c}Q^ld^c\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	$\frac{y_{u\vert d}}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{1}{\Lambda^5}$	ϵ_1
15	$L^iL^jL^kd^cL_i\overline{u^c}\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	–	–
16	$L^iL^je^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	–	–
17	$L^iL^jd^cd^c\overline{d^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	$\frac{y_d^{\rm ex}y_e^{\rm ex}}{16\pi^2}\frac{1}{\Lambda^5}$	$2\epsilon_5$
18	$L^iL^jd^cu^c\overline{u^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_dy_ug^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	$\frac{y_e^{\rm ex}y_u^{\rm ex}}{16\pi^2}\frac{1}{\Lambda^5}$	$2\epsilon_5$
19	(2) $L^iQ^jd^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_e^{\rm ex}y_d^2y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}$	$2\epsilon_5$
20	(2) $L^id^c\overline{Q}_i\overline{u^c}\overline{e^c}\overline{u^c}$	$\frac{y_e^{\rm ex}y_dy_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}$	$2\epsilon_5$
61	$L^iL^jH^kH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	–	–	–	–
66	$L^iL^jH^kH^l\epsilon_{ik}Q^rd^c\overline{H}_r\epsilon_{jl}$	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{1}{16\pi^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	–	–
71	$L^iL^jH^kH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_uy^{\rm ex}_{d\vert u}}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
76	$\overline{e^c}\overline{e^c}d^cd^c\overline{u^c}\overline{u^c}$	$\frac{y_e^{\rm ex2}y_d^2y_u^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_dy_uy_e^{\rm ex}}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}$	$2\epsilon_3^{LLz}$

Table 5: Effective $\Delta L = 2$ SM operators at dimension 9. Dominant contributions to $0\nu\beta\beta$ decay via the effective neutrino mass (m_ν) as well as long-range (LR) and short-range (SR) mechanisms are shown. The $0\nu\beta\beta$ long-range and short-range interactions excited by a particular operator are denoted in column $\epsilon_{\rm LR}$ and $\epsilon_{\rm SR}$. The notation of the contributions is explained in Sec. 4.3.

$\mathcal{O}$	Operator	m_ν	LR	$\epsilon_{\rm LR}$	SR	$\epsilon_{\rm SR}$
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_ey_e^{\rm ex}y_u^{\rm ex}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V-A}$	–	–
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_ey_e^{\rm ex}y_u^{\rm ex}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V-A}$	–	–
23	$L^iL^jL^ke^c\overline{Q}_k\overline{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_ey_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y^{\rm ex}_{d\vert(e)}y_d^{\rm ex}y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S-P}\vert\epsilon^{V+A}_{V+A}$	–	–
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{g^2}{(16\pi^2)}\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{y_u^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
26_a	$L^iL^jQ^kd^c\overline{L}_i\overline{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{y_ey_d}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	–	–
26_b	$L^iL^jQ^kd^cL_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_ey_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	–	–
27_a	$L^iL^jQ^kd^cQ_i\overline{d^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
27_b	$L^iL^jQ^kd^c\overline{Q}_k\overline{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S+P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
28_a	$L^iL^jQ^kd^c\overline{Q}_j\overline{u^c}H^l\overline{H}_i\epsilon_{kl}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S+P}	$\frac{v^2}{\Lambda^7}$	ϵ_1
28_b	$L^iL^jQ^kd^c\overline{Q}_k\overline{u^c}H^l\overline{H}_i\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_{u\vert d}}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}$	$\frac{g^2}{(16\pi^2)}\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
28_c	$L^iL^jQ^kd^c\overline{Q}_l\overline{u^c}H^l\overline{H}_i\epsilon_{jk}$	$\frac{y_dy_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
29_a	$L^iL^jQ^ku^c\overline{Q}_k\overline{u^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\rm ex}y_u^{\rm ex}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
29_b	$L^iL^jQ^ku^cQ_l\overline{u^c}H^lH^m\epsilon_{ik}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\rm ex}y_u^{\rm ex}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
30_a	$L^iL^j\overline{L}_i\overline{e^c}\overline{Q}_k\overline{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_ey_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	–	–
30_b	$L^iL^j\overline{L}_m\overline{e^c}\overline{Q}_n\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$	$\frac{y_ey_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_e}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	–	–
31_a	$L^iL^j\overline{Q}_i\overline{d^c}\overline{Q}_k\overline{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_d}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
31_b	$L^iL^j\overline{Q}_m\overline{d^c}\overline{Q}_n\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$	$\frac{y_dy_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}f\left(\frac{v}{\Lambda}\right)$	$\frac{y_d}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
32_a	$L^iL^j\overline{Q}_j\overline{u^c}\overline{Q}_k\overline{u^c}H^k\overline{H}_i$	$\frac{y_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
32_b	$L^iL^jQ_m\overline{u^c}Q_n\overline{u^c}H^kH_i\epsilon_{jk}\epsilon^{mn}$	$\frac{y_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	ϵ^{S+P}_{S-P}	$\frac{y_d^{\rm ex2}}{(16\pi^2)^2}\frac{1}{\Lambda^5}$	ϵ_1
34	$\overline{e^c}\overline{e^c}L^iQ^je^cd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e^{\rm ex}y_dg^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{e\vert u\vert(d)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S+P}\vert 2\epsilon^{V+A}_{V+A}$	–	–
35	$\overline{e^c}\overline{e^c}L^ie^cQ_j\overline{u^c}H^jH^k\epsilon_{ik}$	$\frac{y_e^{\rm ex}y_ug^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{e\vert d\vert(u)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S-P}\vert 2\epsilon^{V+A}_{V\pm A}$	–	–
36	$\overline{e^c}\overline{e^c}Q^id^cQ^jd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$	$\frac{y_e^{\rm ex2}y_d^2g^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{y_dy_e^{\rm ex}y^{\rm ex}_{e\vert u\vert(d)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S+P}\vert 2\epsilon^{V+A}_{V\pm A}$	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
37	$\overline{e^c}\overline{e^c}Q^id^c\overline{Q}_j\overline{u^c}H^jH^k\epsilon_{ik}$	$\frac{y_e^{\rm ex2}y_dy_ug^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{g^2y_e^{\rm ex}}{(16\pi^2)^2}\frac{v^3}{\Lambda^5}$	$2\epsilon^{V+A}_{V+A}$	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
38	$\overline{e^c}\overline{e^c}\overline{Q}_i\overline{u^c}\overline{Q}_j\overline{u^c}H^iH^j$	$\frac{y_e^{\rm ex2}y_u^2g^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{y^{\rm ex}_{e\vert d\vert(u)}y_e^{\rm ex}y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S-P}\vert 2\epsilon^{V+A}_{V\pm A}$	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	ϵ_1
40_a	$L^iL^jL^kQ^lL_iQ_jH^mH^n\epsilon_{km}\epsilon_{ln}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{d\vert u\vert u\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V\pm A}$	–	–
43_a	$L^iL^jL^kd^c\overline{L}_l\overline{u^c}H^l\overline{H}_i\epsilon_{jk}$	$\frac{y_dy_ug^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	–	–
44_c	$L^iL^jQ^ke^c\overline{Q}_l\overline{e^c}H^lH^m\epsilon_{ij}\epsilon_{km}$	$\frac{g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_e}{16\pi^2}\frac{v^3}{\Lambda^5}$	ϵ^{V+A}_{V-A}	–	–
47_a	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{d\vert u\vert(e)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S+P}\vert 2\epsilon^{V+A}_{V-A}$	$\frac{v^2}{\Lambda^7}$	$2\epsilon_3^a$
47_d	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{d\vert u\vert(e)}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V-A}$	$\frac{v^2}{\Lambda^7}$	$2\epsilon_3^a$
53	$L^iL^jd^cd^c\overline{u^c}\overline{u^c}\overline{H}_i\overline{H}_j$	$\frac{y_d^2y_u^2g^2}{(16\pi^2)^5}\frac{v^2}{\Lambda}$	$\frac{y_dy_uy^{\rm ex}_{u\vert d\vert e}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S\pm P}\vert 2\epsilon^{V+A}_{V+A}$	$\frac{v^2}{\Lambda^7}$	$2\epsilon_3^a$
54_a	$L^iQ^jQ^kd^c\overline{Q}_i\overline{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{y_e^{\rm ex}y_dg^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{g^2y^{\rm ex}_{e\vert(d)\vert u}}{(16\pi^2)^2}\frac{v}{\Lambda^3}f\left(\frac{v}{\Lambda}\right)$	$\epsilon^{S+P}_{S+P}\vert 2\epsilon^{V+A}_{V+A}$	–	–
54_d	$L^iQ^jQ^kd^cQ_l\overline{e^c}H^lH^m\epsilon_{ij}\epsilon_{km}$	$\frac{y_e^{\rm ex}y_dg^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_d}{16\pi^2}\frac{v^3}{\Lambda^5}$	ϵ^{V+A}_{V-A}	$\frac{v^2}{\Lambda^7}$	$2\epsilon_5$
55_a	$L^iQ^jQ_iQ_k\overline{e^c}\overline{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_e^{\rm ex}y_ug^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_u}{16\pi^2}\frac{v^3}{\Lambda^5}$	ϵ^{V+A}_{V-A}	$\frac{v^2}{\Lambda^7}$	$2\epsilon_5$
59	$L^iQ^jd^cd^c\overline{e^c}\overline{u^c}H^kH_i\epsilon_{jk}$	$\frac{y_e^{\rm ex}y_d^2y_u}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_d}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{V+A}_{V+A}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	$2\epsilon_5$
60	$L^id^c\overline{Q}_j\overline{u^c}\overline{e^c}\overline{u^c}H^j\overline{H}_i$	$\frac{y_e^{\rm ex}y_dy_u^2}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	$\frac{y_u}{(16\pi^2)^2}\frac{v}{\Lambda^3}$	ϵ^{V+A}_{V+A}	$\frac{1}{\Lambda^5}f\left(\frac{v}{\Lambda}\right)$	$2\epsilon_5$

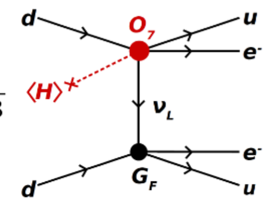
Table 6: As Tab. 5 but showing selected effective $\Delta L = 2$ SM operators at dimension 11.

Comparison

Why is it of interest?

Dependence on experimental sensitivity

$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{v}{\Lambda_7{}^3}$$



$$\left.\begin{aligned} \mathcal{O}_7{}^{3a} &= L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl} \\ \mathcal{O}_7{}^{3b} &= L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl} \\ \mathcal{O}_9{}^{5} &= L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km} \end{aligned}\right\} \quad e_L \nu_L u_L d^c \quad \Rightarrow \quad \epsilon^{S+P}_{S+P}$$

$$\left.\begin{aligned} \mathcal{O}_7{}^{4a} &= L^i L^j \overline{Q}_i \bar{u}^c H^k \epsilon_{jk} \\ \mathcal{O}_7{}^{4b} &= L^i L^j \overline{Q}_k \bar{u}^c H^k \epsilon_{ij} \\ \mathcal{O}_9{}^{6} &= L^i L^j \overline{Q}_k \bar{u}^c H^l H^k \bar{H}_i \epsilon_{jl} \end{aligned}\right\} \quad e_L \nu_L \bar{d}_L \bar{u}^c \quad \Rightarrow \quad \epsilon^{S+P}_{S-P}$$

$$\mathcal{O}_9{}^{7} = L^i Q^j \bar{e}^c \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm} \quad \Big\} \quad \nu_L u_L \bar{e}^c \bar{d}_L \quad \Rightarrow \quad \frac{1}{2}\epsilon^{V+A}_{V-A}$$

$$\mathcal{O}_7{}^{8} = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij} \quad \Big\} \quad \nu_L \bar{e}^c \bar{u}^c d^c \quad \Rightarrow \quad \frac{1}{2}\epsilon^{V+A}_{V+A}$$

Isotope	$\lvert\epsilon^{V+A}_{V-A}\rvert$	$\lvert\epsilon^{V+A}_{V+A}\rvert$	$\lvert\epsilon^{S+P}_{S-P}\rvert$	$\lvert\epsilon^{S+P}_{S+P}\rvert$	$\lvert\epsilon^{TR}_{TL}\rvert$	$\lvert\epsilon^{TR}_{TR}\rvert$
^{76}Ge	$3.3 \cdot 10^{-9}$	$5.9 \cdot 10^{-7}$	$1.0 \cdot 10^{-8}$	$1.0 \cdot 10^{-8}$	$6.4 \cdot 10^{-10}$	$1.0 \cdot 10^{-9}$
^{136}Xe	$2.6 \cdot 10^{-9}$	$5.1 \cdot 10^{-7}$	$6.2 \cdot 10^{-9}$	$6.2 \cdot 10^{-9}$	$4.4 \cdot 10^{-10}$	$7.4 \cdot 10^{-10}$

F. Deppisch, M. Hirsch, H. Päs, J. Phys. G 39 (2012) 124007, arXiv:1208.0727 [hep-ph], updated

J. Harz, ACFI Workshop 2017

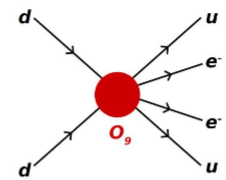
Comparison

Why is it of interest?

Crucial dependence on SU(2) structure and Yukawa couplings

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

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

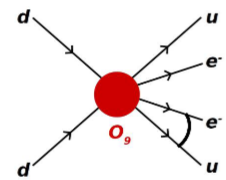


at tree level

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

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

(flavour structure!)

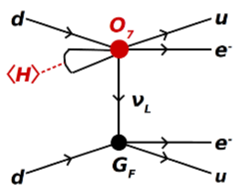


only at one loop

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

$\mathcal{O}_7{}^{3b}$ H^l

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

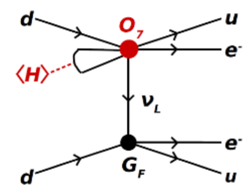


same

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

$\mathcal{O}_7{}^{3a}$ H^l

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



$\mathcal{O}_9{}^{20} = L^i d^c \overline{Q}_i \overline{u^c}\,\overline{e^c}\,\overline{u^c}$

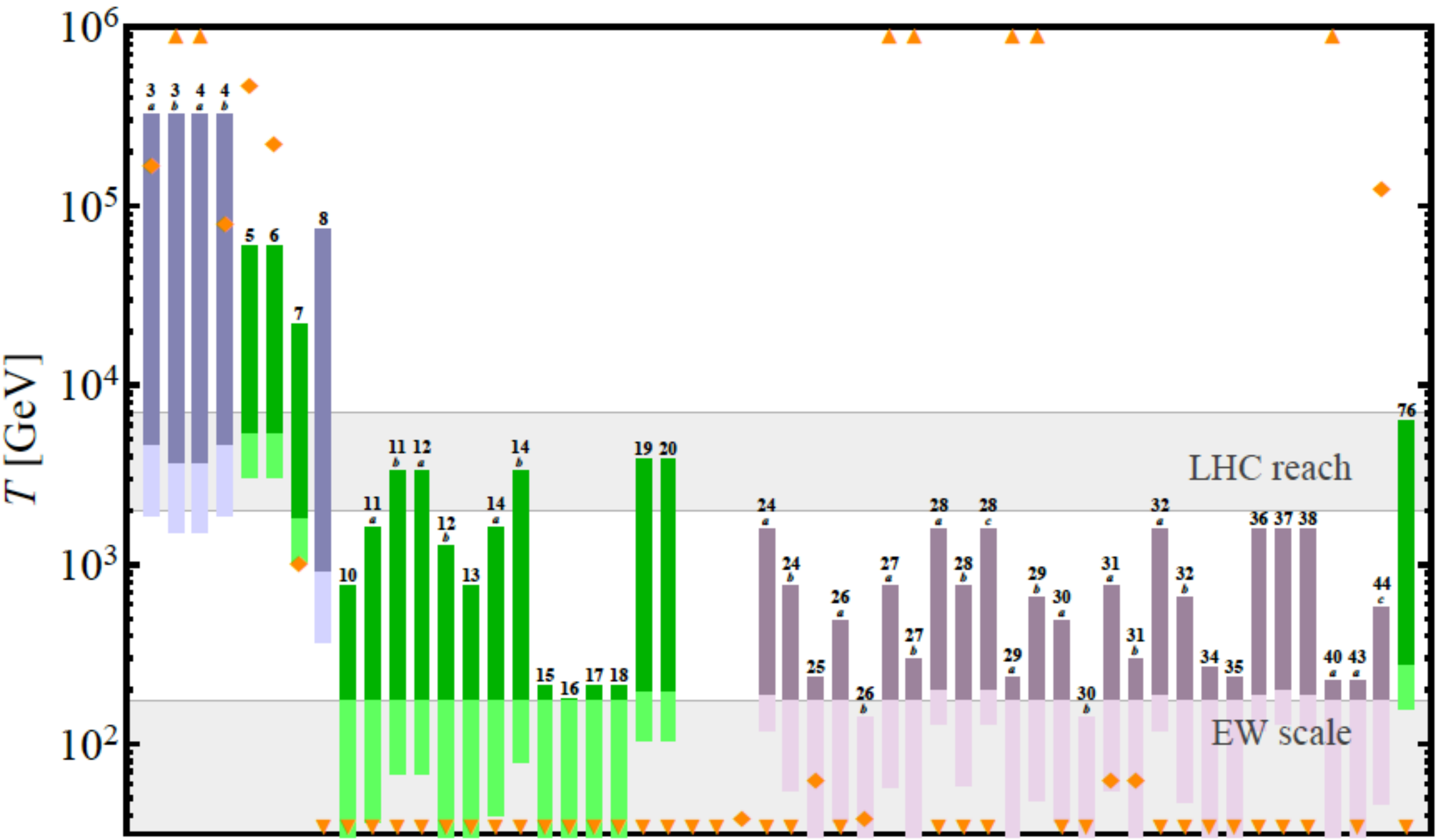
$H_r \epsilon_{ri}$

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

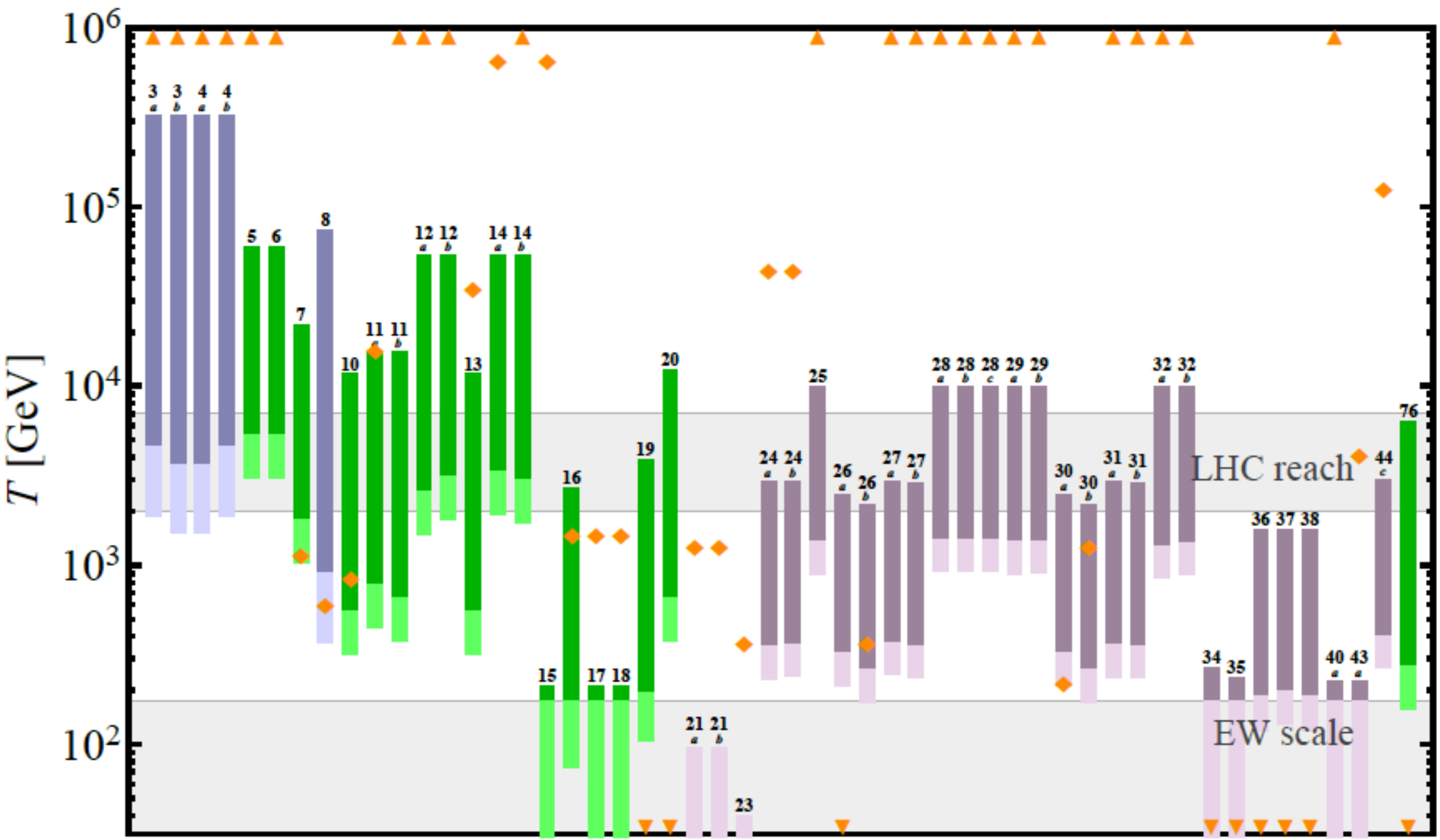
$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_u v}{(16\pi^2)\Lambda_9{}^3}$$

J. Harz, ACFI Workshop 2017

Results (1st Gen)



Results (3rd Gen)



Beyond EFT approach

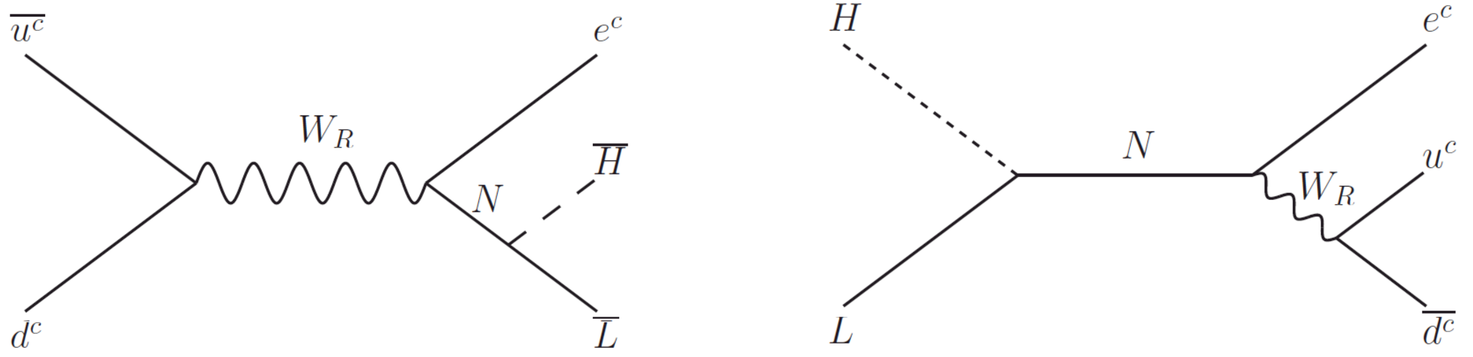
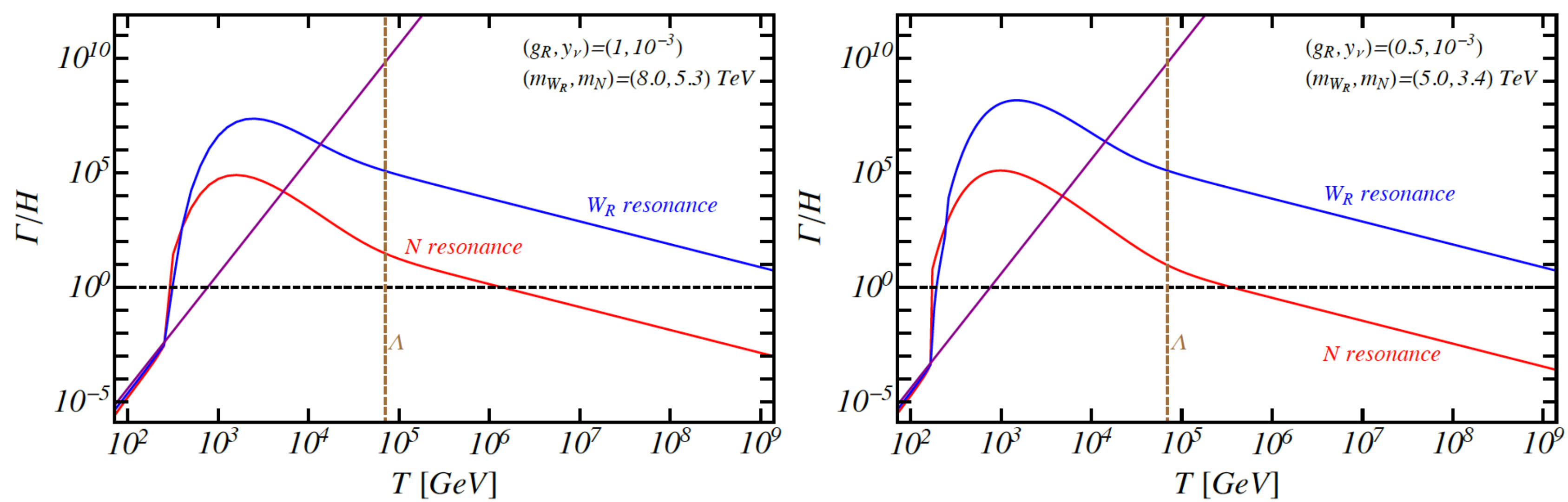


Figure 19: Two example diagrams in a left-right symmetric model framework that give rise to the effective operator $\mathcal{O}_8 = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}$.



Caveats

- $0\nu\beta\beta$ decays only probe the electron flavor, so LFV is needed to wash out asymmetries stored in μ and τ flavors

- To carry out the analysis in a model-independent way, we assume no correlation between the generation mechanism and washout

- The existence of a decoupled sector can protect asymmetries from washout in the visible sectors (Phys. Lett. B207, 210 (1988) and 1309.4770)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CP3 Origins
Cosmology & Particle Physics

Can ADM save world?

$$-\mu_q + \mu_H + \mu_{d_R} = 0 \ , \ -\mu_q - \mu_H + \mu_{u_R} = 0 \ , \ -\mu_\ell + \mu_H + \mu_{e_R} = 0 \ ,$$

$$3\,(3\,\mu_q + \mu_\ell) = 0 \ , \ \mu_q + 2\mu_{u_R} - \mu_{d_R} - \mu_\ell - \mu_{e_R} + \frac{2}{3}\mu_H = 0 \ ,$$

All chemical potentials vanish after ΔL=2 kicks in !

$$\mu_\ell + \mu_H = 0$$

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Can ADM save world?

$$-\mu_q + \mu_H + \mu_{d_R} = 0\ , \quad -\mu_q - \mu_H + \mu_{u_R} = 0\ , \quad -\mu_\ell + \mu_H + \mu_{e_R} = 0\ ,$$

$$\cancel{3\,(3\,\mu_q + \mu_\ell) = 0}, \quad \mu_q + 2\mu_{u_R} - \mu_{d_R} - \mu_\ell - \mu_{e_R} + \frac{2}{3}\mu_H = 0\ ,$$

$$\mu_\ell + \mu_H = 0\ ,$$

If particles in the dark sector are also charged under $SU(2)_L$, then the sphalerons can transfer symmetry between B, L and X (dark charge) => Asymmetric DM

$$3\,(3\,\mu_q + \mu_\ell) + n_X \mu_X = 0,$$

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Can ADM save world?

$$-\mu_q + \mu_H + \mu_{d_R} = 0 \ , \ \ -\mu_q - \mu_H + \mu_{u_R} = 0 \ , \ \ -\mu_\ell + \mu_H + \mu_{e_R} = 0 \ ,$$

$$3\,(3\,\mu_q + \mu_\ell) = 0 \ , \ \ \mu_q + 2\mu_{u_R} - \mu_{d_R} - \mu_\ell - \mu_{e_R} + \frac{2}{3}\mu_H = 0 \ ,$$

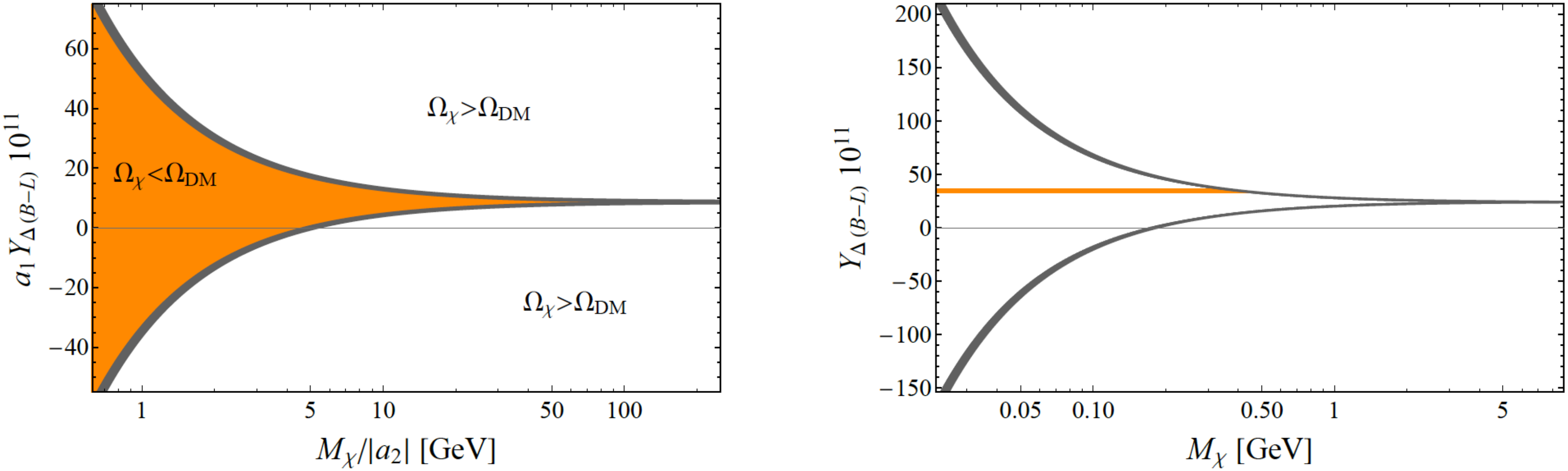
$$\mu_\ell + \mu_H = 0 \, ,$$

If models need an extra asymmetry-transfer interaction, then DM asymmetry will also vanish!

$$X_{\rm DM}^2\,(\ell H)^2 \ , \ \ X_{\rm DM} d_R d_R u_R \ (\text{or } X_{\rm DM}^2 d_R d_R u_R)$$

Can ADM save world?

$$Y_{\Delta B} = a_1 Y_{\Delta(B-L)} + a_2 Y_{\Delta X} \quad \Rightarrow \quad M_\chi \leq M_p \frac{|a_2|}{\left|1 - a_1 \frac{Y_{\Delta(B-L)}}{Y_{\Delta B}}\right|} \frac{\Omega_{\rm DM}}{\Omega_{\rm B}}$$



$$Y_{\Delta L} = a_2\, a_3\, Y_{\Delta X}$$

Conclusions and Outlook

- Observation of LNV via 0vbb decay or at colliders together with LFV can falsify high-scale baryogenesis/leptogenesis
- A single LNV operator may induce at tree- and loop-level to short- and long-range contributions to 0vbb decay
- In certain ADM models, the existence of DM can *revive* high-scale baryon or lepton asymmetry generation mechanisms and realize the connection of the baryon and DM density