Probing Baryogenesis

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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

How can we probe Baryogenesis models?

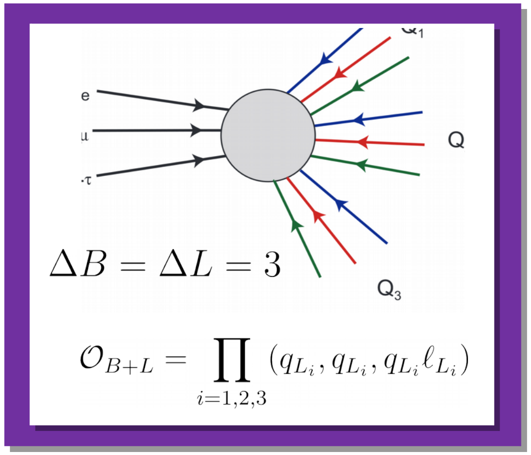
Baryogenesis via Leptogenesis

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

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

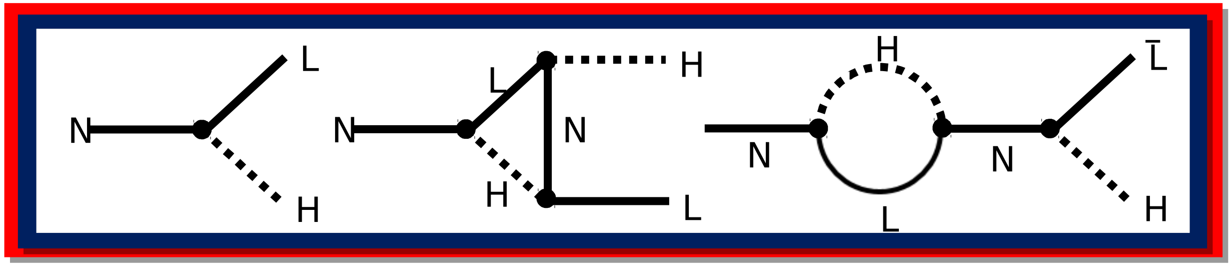
$$Hz\frac{dN_L}{dz} = \epsilon_1 \Gamma_D (N_{N_1} - N_{N_1}^{\mathrm{eq}}) - \Gamma_W N_L$$

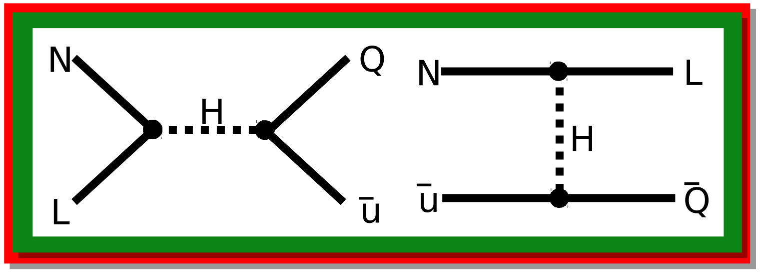
$T \approx 100\mathrm{GeV}$

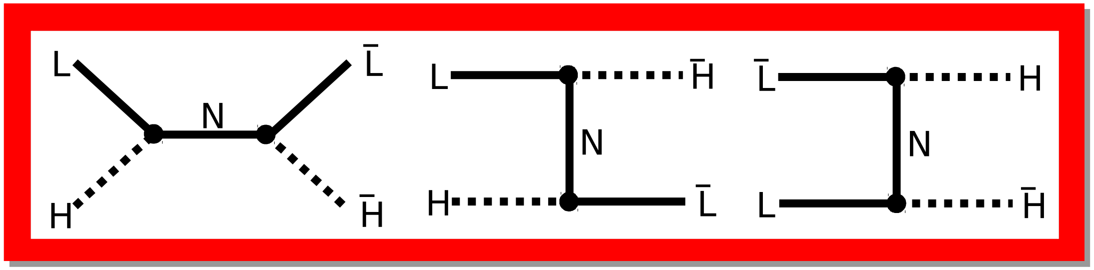


sphaleron processes

$\Delta L = 1$ source of CP violation

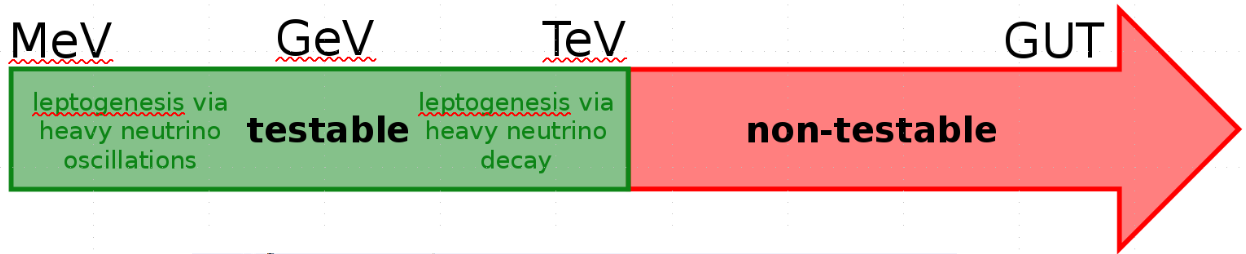


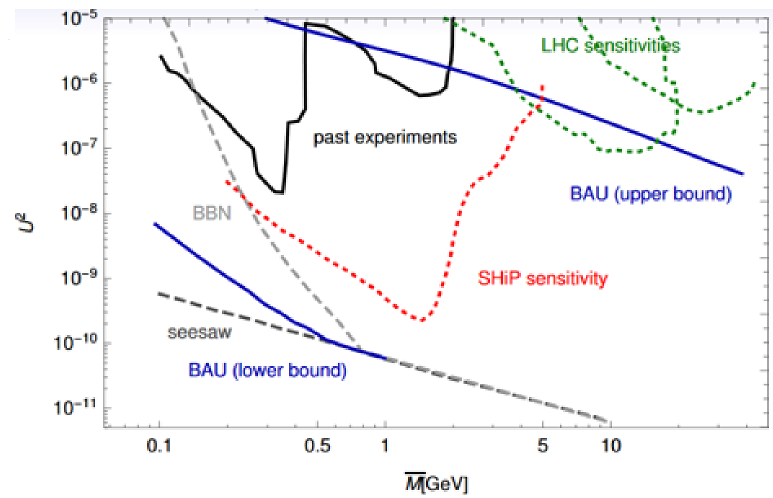


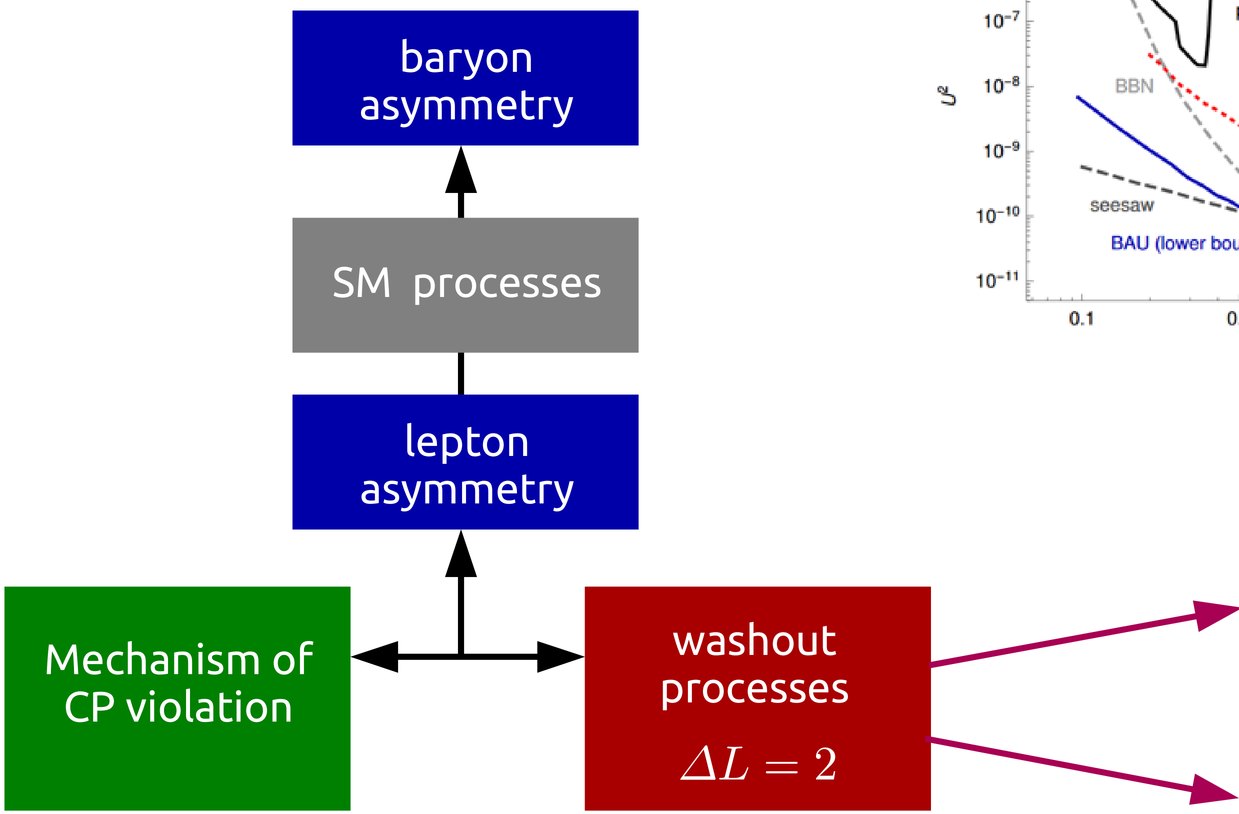


$\Delta L = 2$ scattering processes $\Delta L = 2$ washout processes

How can we test what generates the BAU?



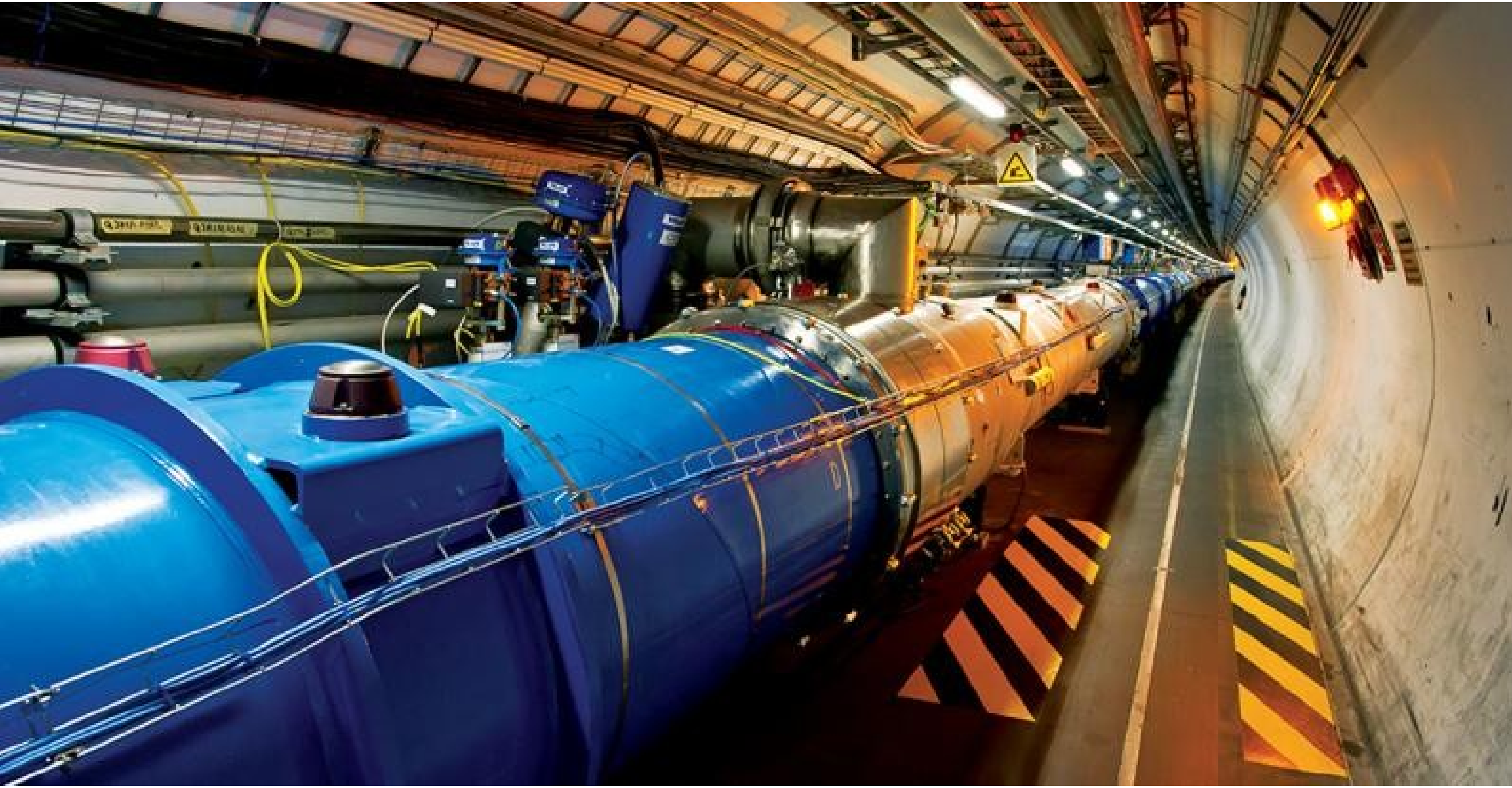




LHC

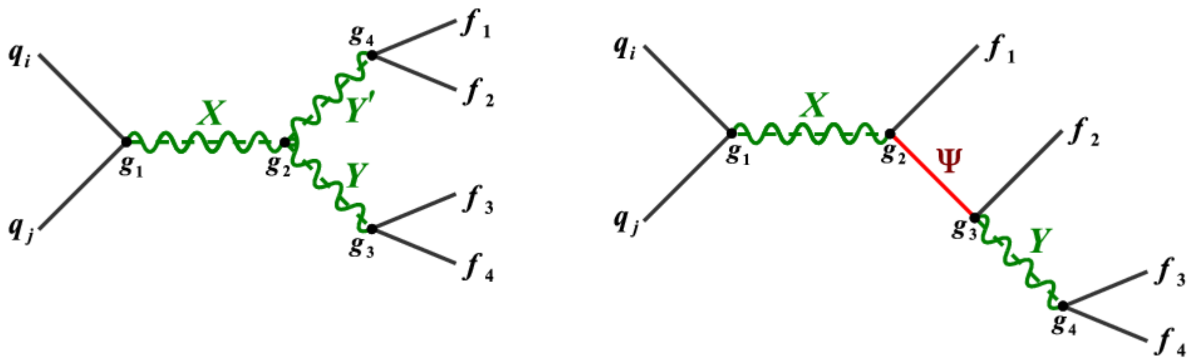
neutrinoless double beta decay experiments

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

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

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

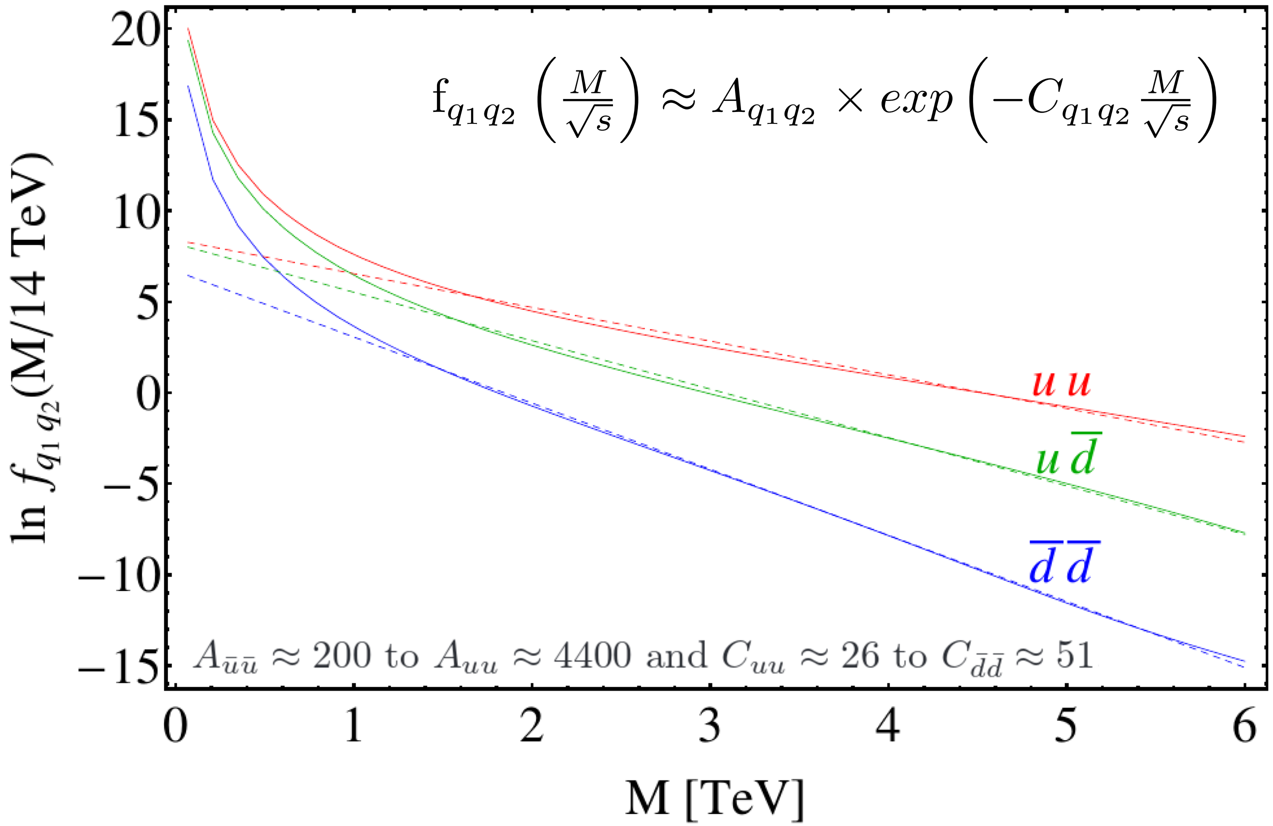
cross section possibly measured at LHC

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

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

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

LNV at the LHC

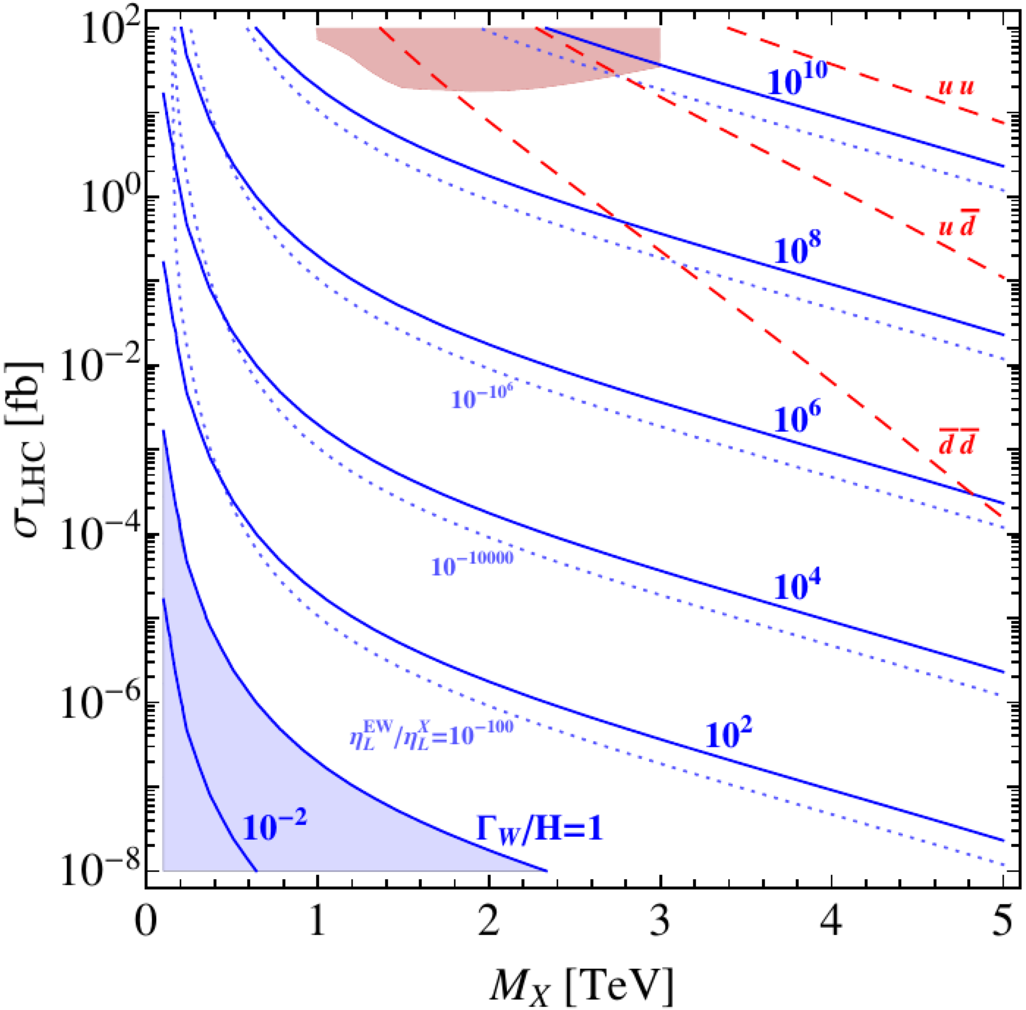


pick most conservative choice $A_{qq} = 5000$ and $C_{qq} = 26$

$$\frac{\Gamma_W}{H} = \frac{0.028}{\sqrt{g_*}} \frac{M_P {M_X}^3}{T^4} \frac{K_1\left(M_X/T\right)}{f_{q_1 q_2}\left(M_X/\sqrt{s_{\mathrm{LHC}}}\right)} \times \left(s_{\mathrm{LHC}} \sigma_{\mathrm{LHC}}\right)$$

LNV at the LHC

- Assuming pre-existing lepton asymmetry generated at high scale

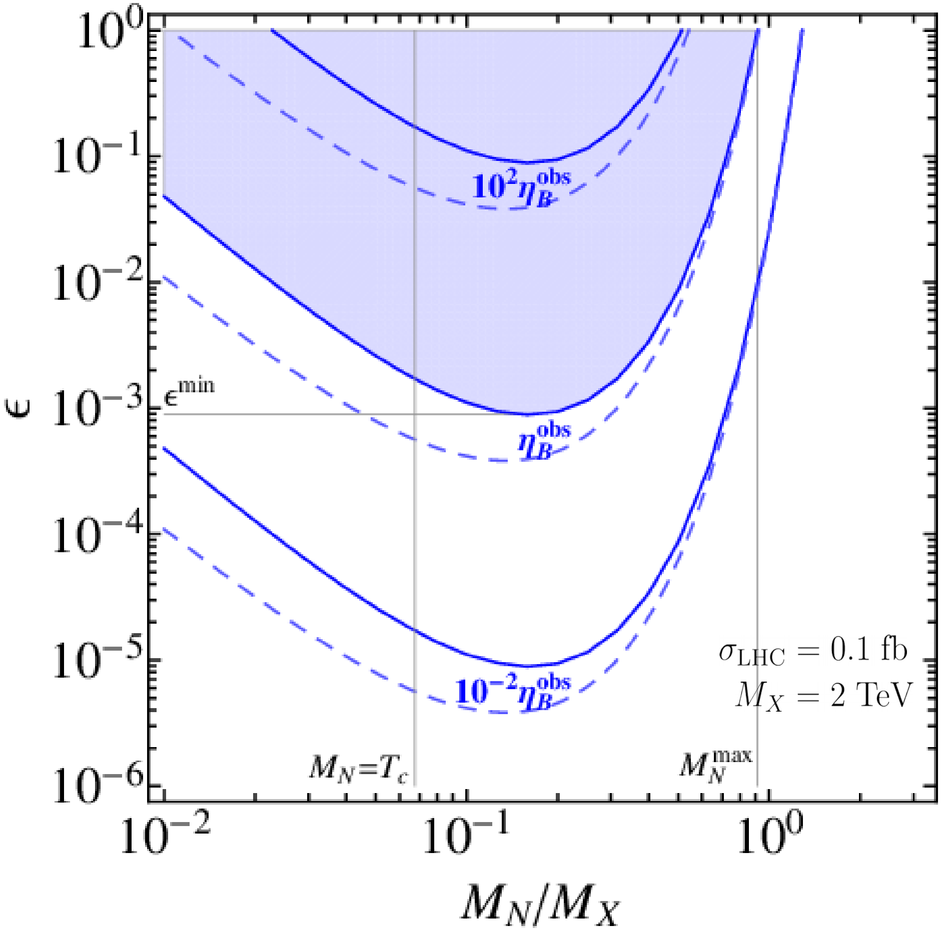


$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\rm TeV} - 1\right) + \log_{10}\frac{\sigma_{\rm LHC}}{\rm fb}$$

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



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

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

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

scale of CP-asymmetry generation (M_N)

scale of LNV observation (M_X)

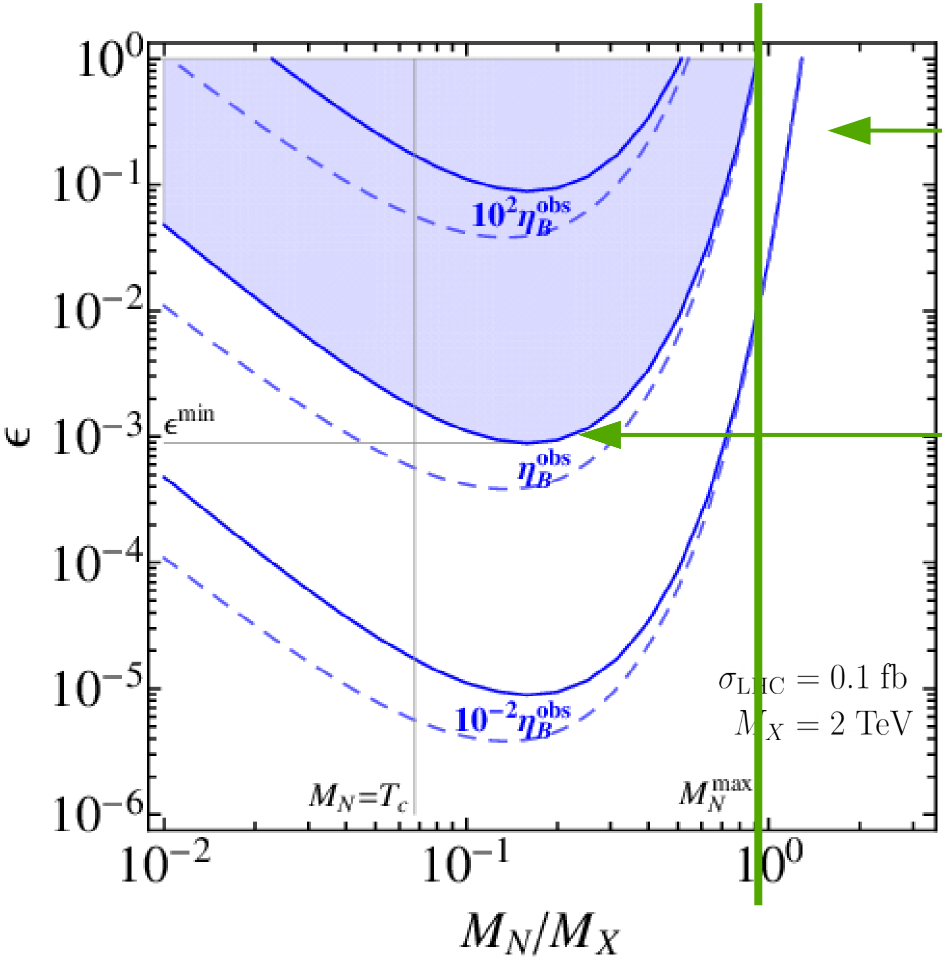
observation of LNV process at the LHC

- 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

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

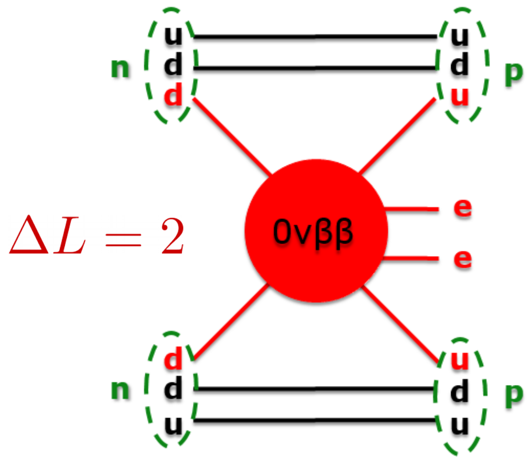
Caveats

- 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

LNV at 0vbb decay experiments

Neutrinoless double beta decay (0vbb)

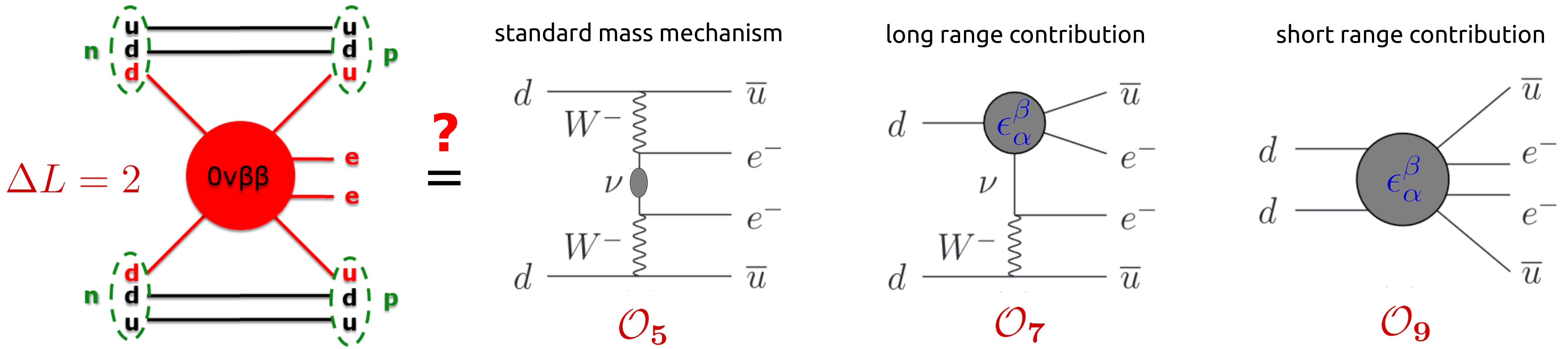


Most stringent limits are currently from GERDA and Kamland-Zen:

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

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)



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

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

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

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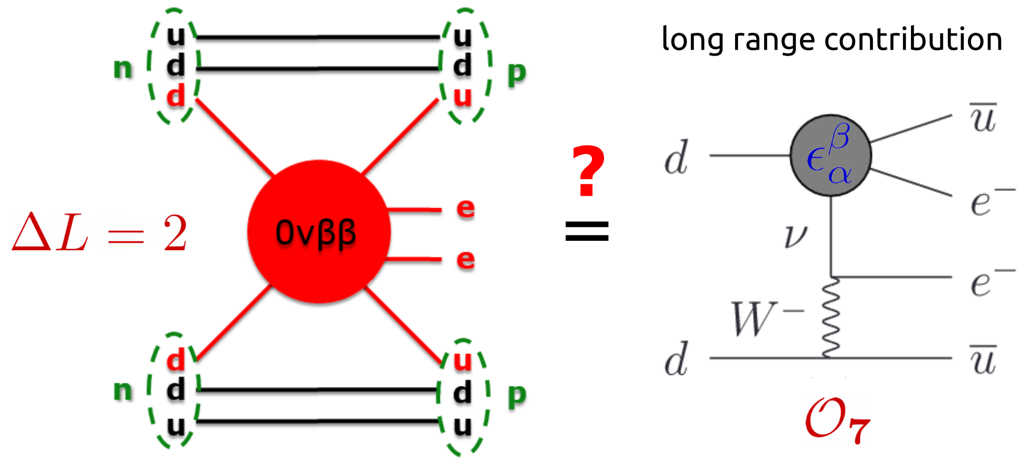
Neutrinoless double beta decay (0vbb)

Long range contribution:

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



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

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

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

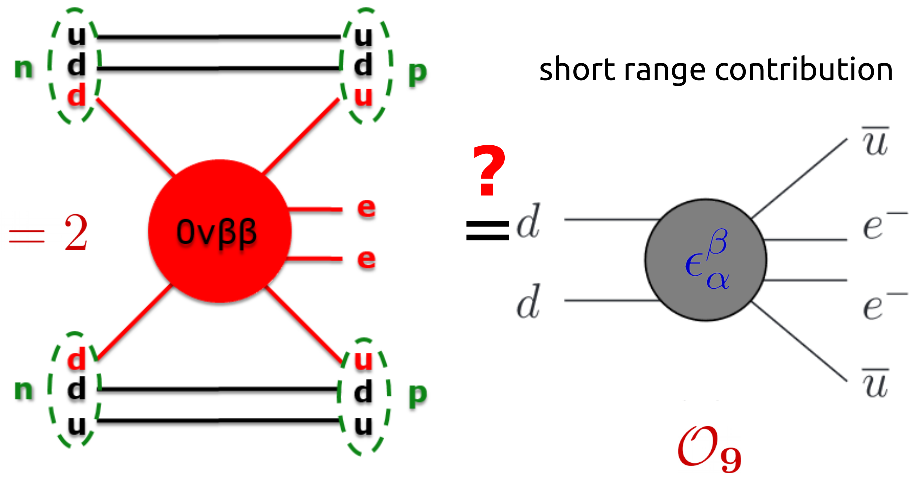
$\lvert\epsilon\rvert \times 10^8$	ϵ_{ν}	ϵ^{V+A}_{V-A}	ϵ^{V+A}_{V+A}	$\epsilon^{S+P}_{S\pm P}$	$\epsilon^{T_R}_{T_R}$
^{76}Ge	41	0.21	37	0.66	0.07
^{76}Xe	26	0.11	22	0.26	0.03

Neutrinoless double beta decay (0vbb)

Short range contribution:

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

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



Leptonic and hadronic current with different chirality structure:

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

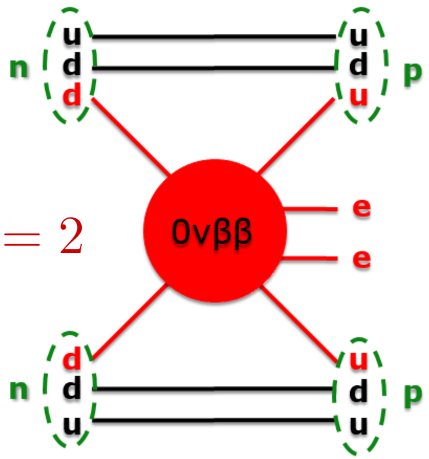
$$j = \overline{e}(1 \pm \gamma_5)e^C, \; j^{\mu} = \overline{e}\gamma^{\mu}(1 \pm \gamma_5)e^C$$

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

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

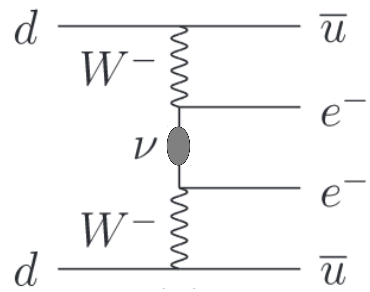
Possible underlying LNV operators

$\Delta L = 2$



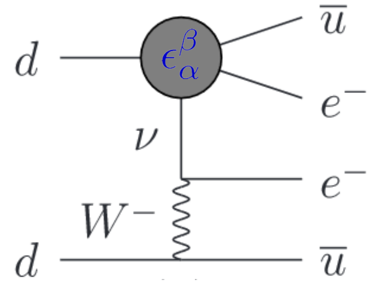
$\stackrel{?}{=}$

standard mass mechanism



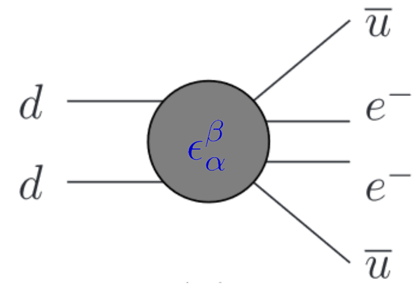
$\mathcal{O}_5$

long range contribution



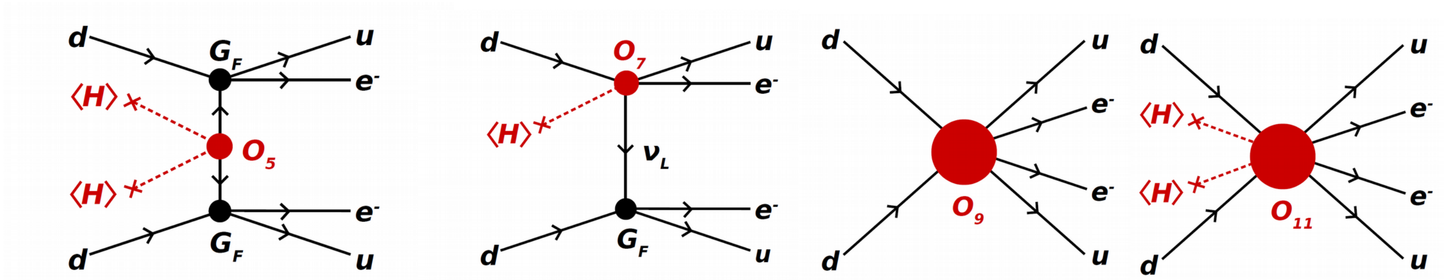
$\mathcal{O}_7$

short range contribution

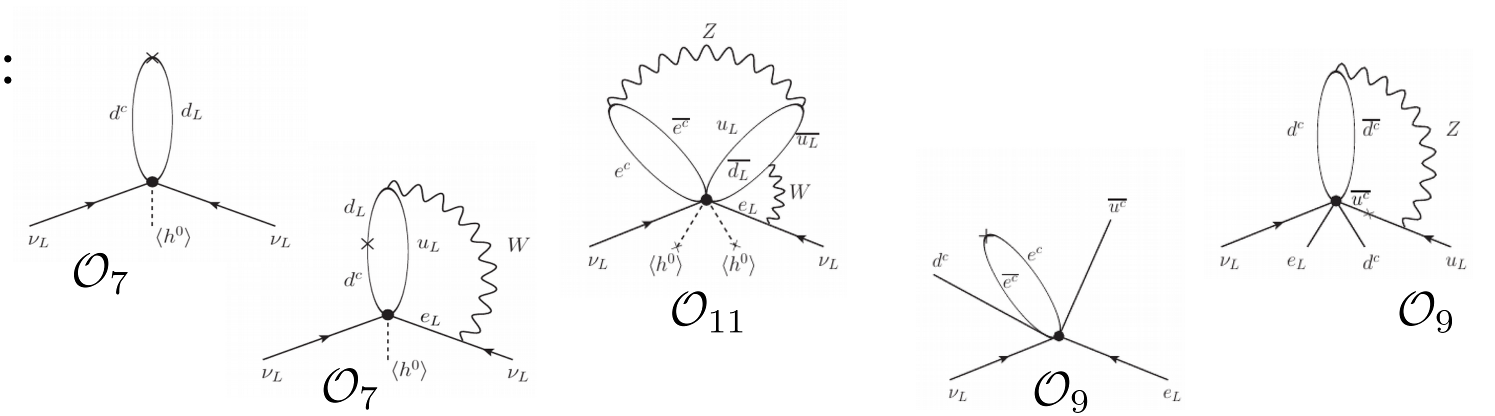


$\mathcal{O}_9$

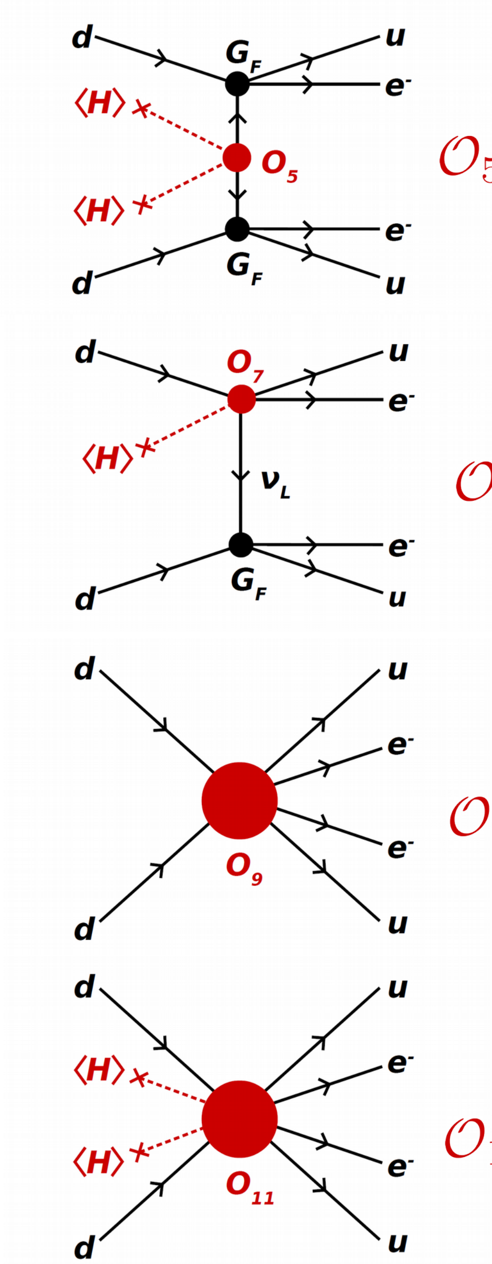
possibilities at tree level:



possibilities at loop level:



Constraining the effective operator scale



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

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

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

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

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

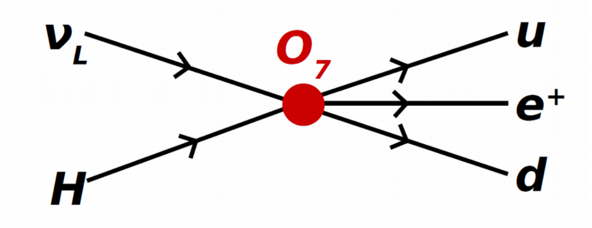
$$\mathcal{O}_{11} = (L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk}\epsilon_{lm}$$

$\mathcal{O}_D$	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



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

$$\begin{aligned}
zHn_\gamma \frac{d\,\eta_{L_e}}{d\,z} &= -\left[L_e\bar{e^c} \leftrightarrow u^c\bar{d^c}\bar{H}\right] + (\text{other permutations}) \\
&= -\left(\frac{n_{L_e} n_{\bar{e^c}}}{n^{\text{eq}}_{L_e} n^{\text{eq}}_{\bar{e^c}}} - \frac{n_{u^c} n_{\bar{d^c}} n_{\bar{H}}}{n^{\text{eq}}_{u^c} n^{\text{eq}}_{\bar{d^c}} n^{\text{eq}}_{\bar{H}}}\right) \gamma^{\text{eq}}(L_e\bar{e^c} \to u^c\bar{d^c}\bar{H}) + \cdots \\
&= -\frac{22\,\mu_{L_e}}{7\,T}\gamma^{\text{eq}}(L_e\bar{e^c} \to u^c\bar{d^c}\bar{H}) + \cdots \\
&= -\frac{11}{7}\eta_{\Delta L_e}\gamma^{\text{eq}}(L_e\bar{e^c} \to u^c\bar{d^c}\bar{H}) + \cdots\,,
\end{aligned}$$

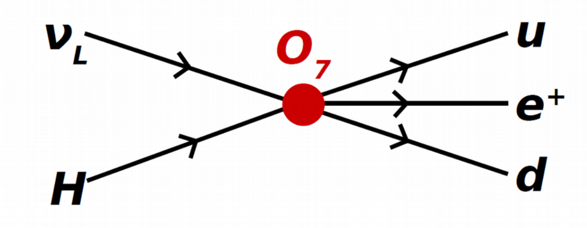
$$\mu_H = \frac{4}{21}\sum_\ell \mu_{L_\ell}, \qquad \mu_{\bar{u^c}} = \frac{5}{63}\sum_\ell \mu_{L_\ell},$$

$$\mu_{\bar{e^c_\ell}} = \mu_{L_\ell} - \frac{4}{21}\sum_\ell \mu_{L_\ell}, \qquad \mu_{\bar{d^c}} = -\frac{19}{63}\sum_\ell \mu_{L_\ell}$$

$$zHn_\gamma \frac{d\eta_{\Delta L_e}}{dz} = -\frac{11\sqrt{195}\,T^{10}}{7\pi^7\Lambda^6}\eta_{\Delta L_e}$$

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

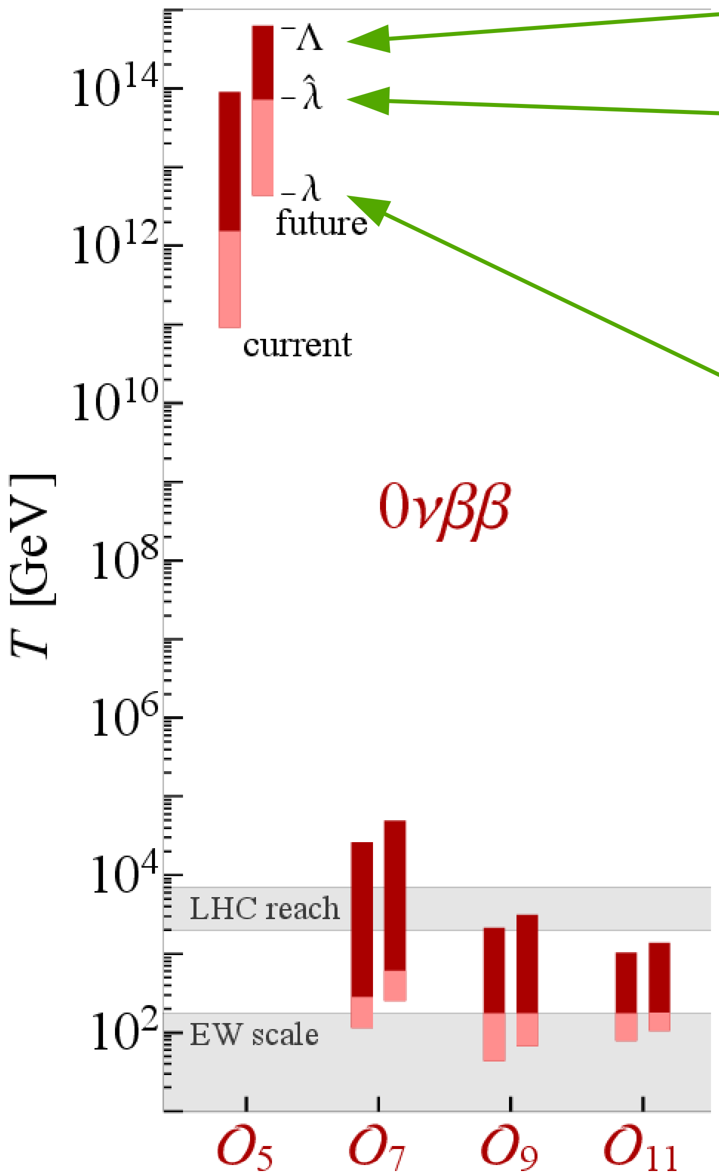
- washout efficient if

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

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)

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

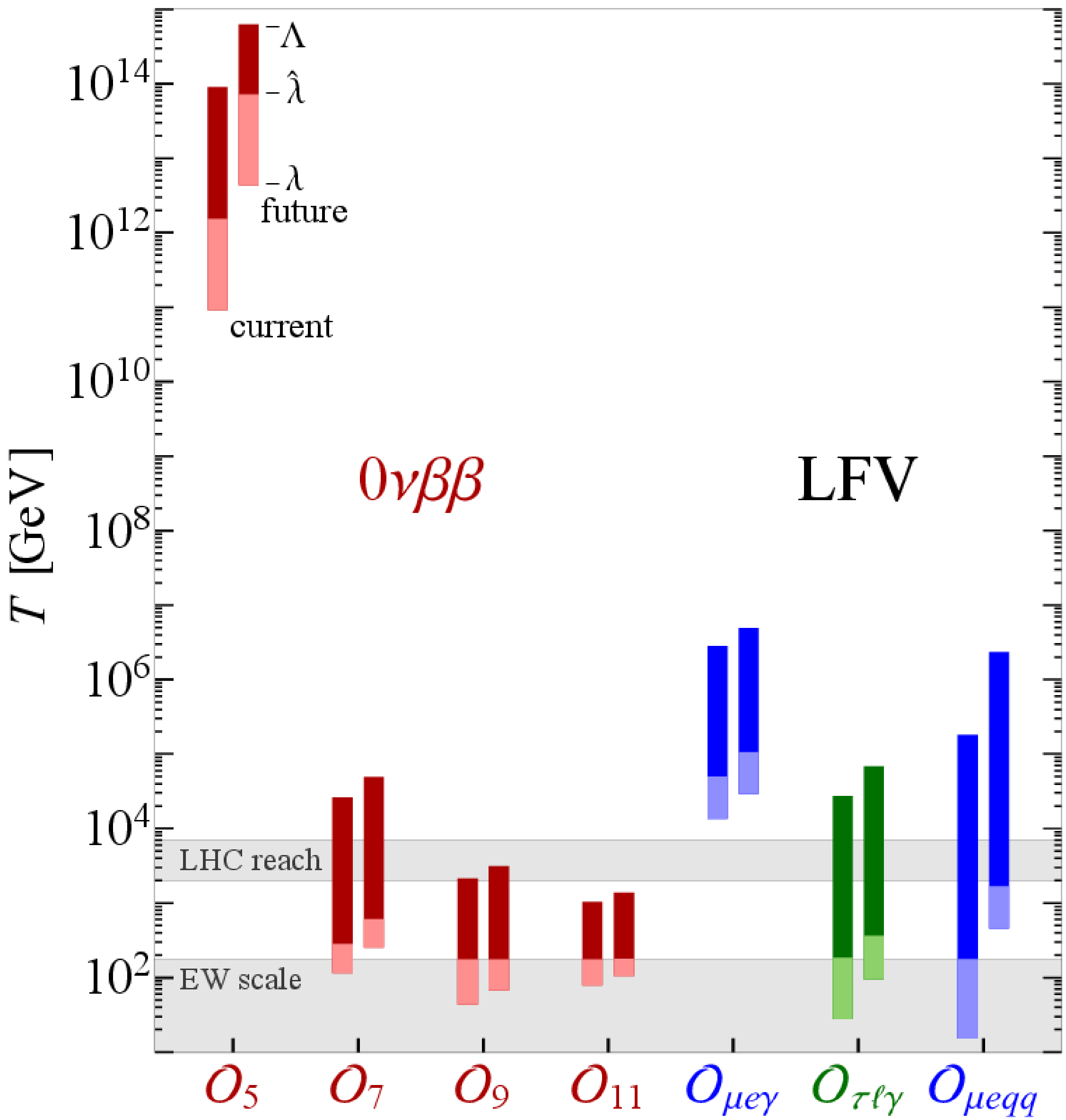
scale above which washout is highly effective $\frac{\Gamma_W}{H} > 1$

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

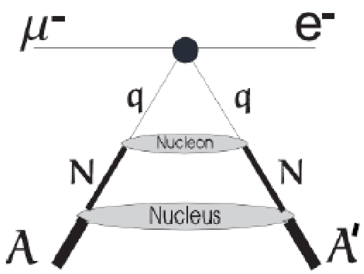
However:
0vßß decay probes only electron component of LNV operators:

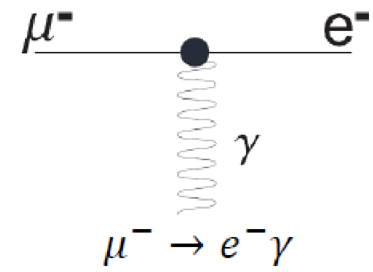
$$\frac{1}{\Lambda_9^5} \to \frac{c_{\alpha\beta}}{\Lambda_9^5}$$

Extending the impact with LFV



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





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

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

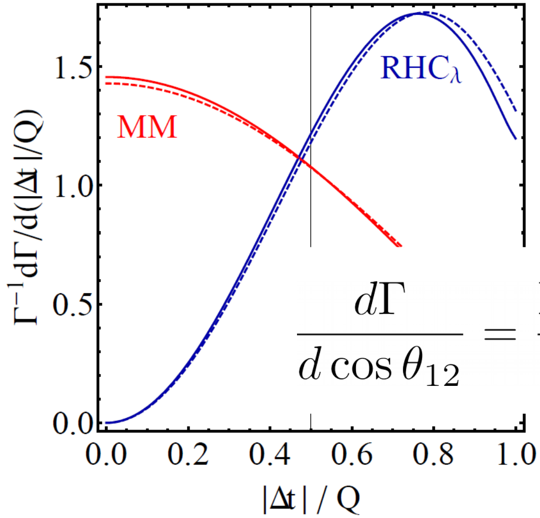
$$\mathcal{C}_{\ell\ell qq} = \frac{g^2}{\Lambda^2_{\ell\ell qq}} \qquad \mathcal{C}_{\ell\ell\gamma} = \frac{e g^3}{16\pi^2 \Lambda^2_{\ell\ell\gamma}}$$

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

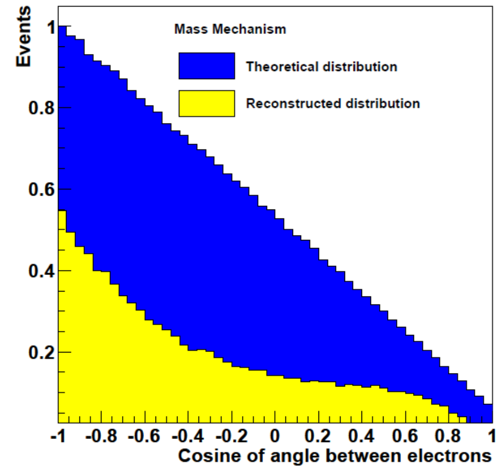
IF LFV processes are observed as well, loophole of asymmetry being stored in another flavour sector is ruled out

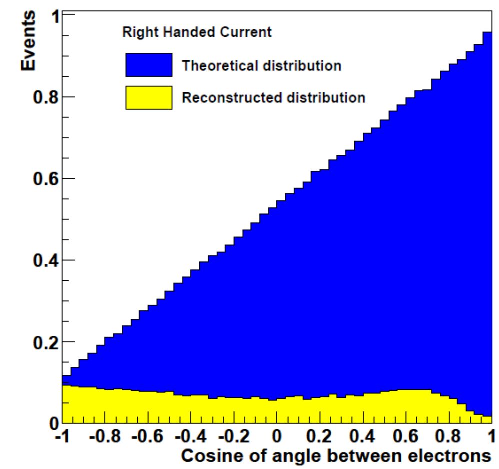
Distinguishing between different operators

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



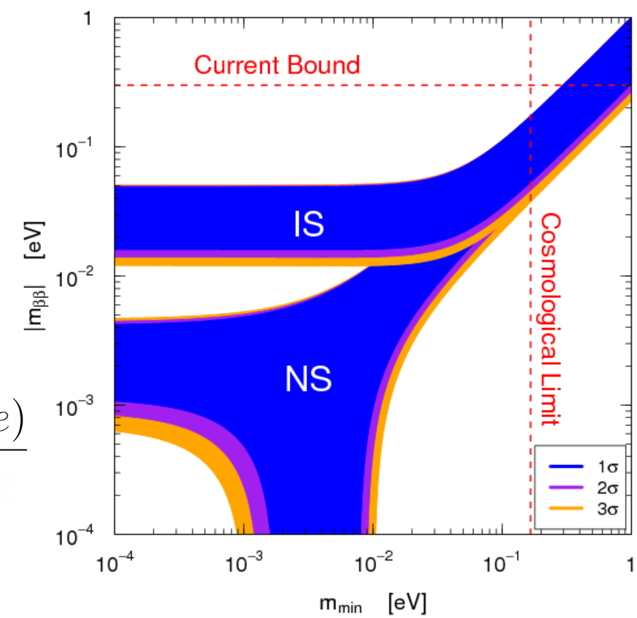
$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$

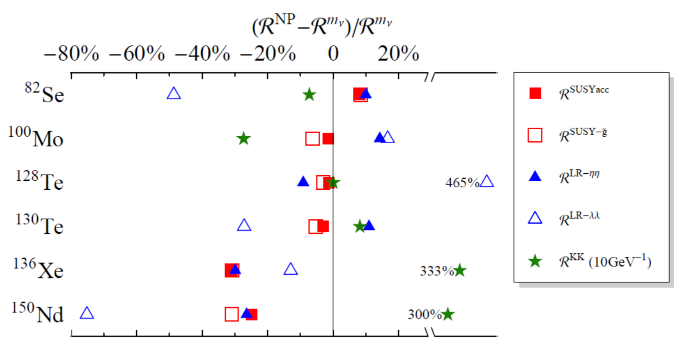




- potential discrepancy between neutrino mass (cosmology) and 0vbb half live measurement could be an indication for 0vbb triggered by non-standard mechanism

- 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

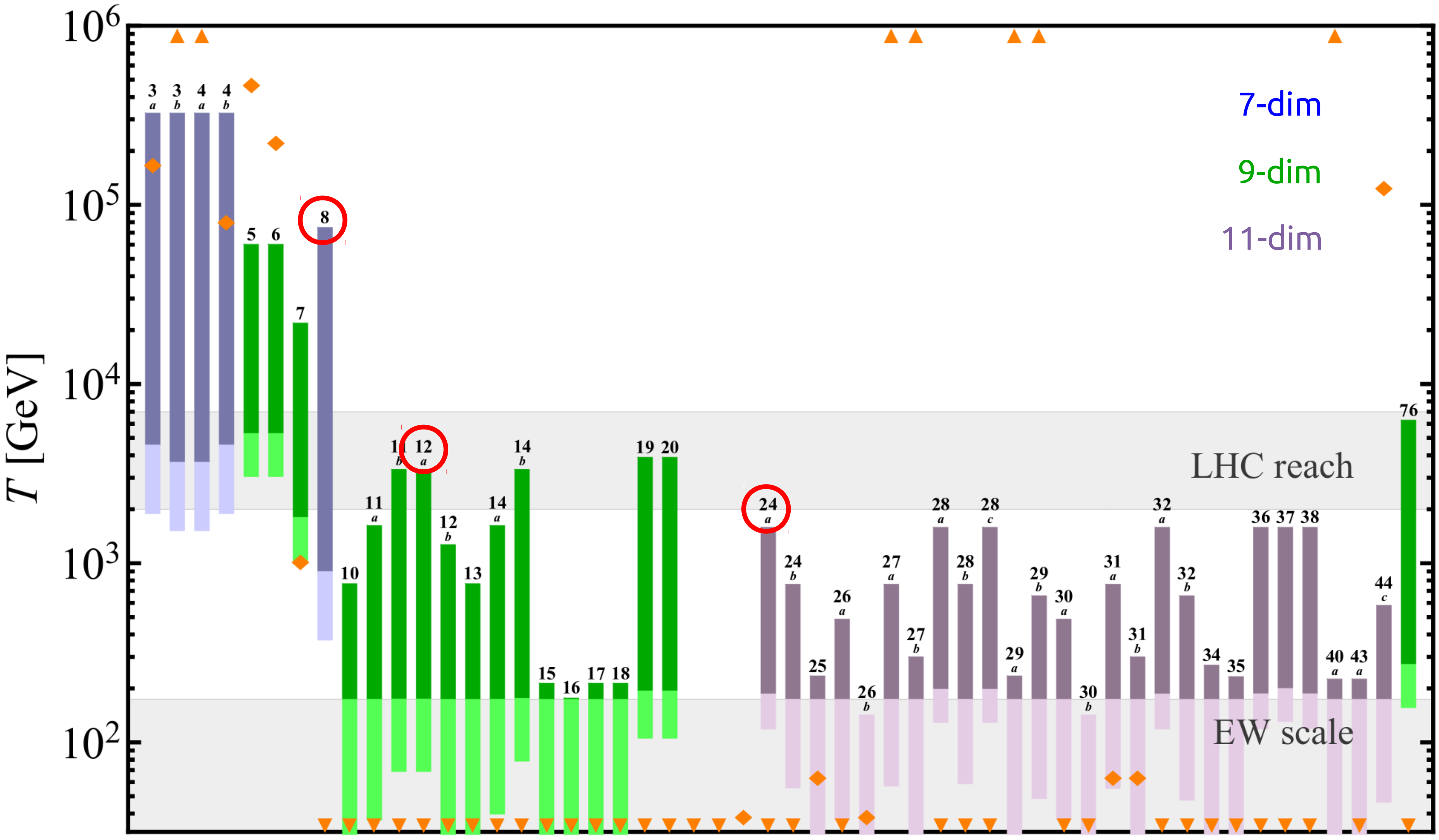
The full picture

$\mathcal{O}$	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	$L^iL^j\overline{Q}_k\bar{u}^cH^k\epsilon_{ij}$
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$
6	$L^iL^j\overline{Q}_k\bar{u}^cH^lH^k\overline{H}_i\epsilon_{jl}$
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	$L^iL^jQ^kd^c\overline{Q}_ju^cH^l\overline{H}_i\epsilon_{kl}$
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	$L^iL^jQ^ku^c\overline{Q}_k\bar{u}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
29_b	$L^iL^jQ^ku^c\overline{Q}_lu^cH^lH^m\epsilon_{ik}\epsilon_{jm}$
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	$L^iL^j\overline{Q}_id^c\overline{Q}_k\bar{u}^cH^kH^l\epsilon_{jl}$
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	$L^iL^j\overline{Q}_m\bar{u}^c\overline{Q}_n\bar{u}^cH^k\overline{H}_i\epsilon_{jk}\epsilon^{mn}$
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	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$
47_b	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_kH^mH^n\epsilon_{jm}\epsilon_{ln}$
47_c	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_lH^mH^n\epsilon_{km}\epsilon_{jn}$
47_d	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
47_e	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jm}\epsilon_{kl}$
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	$L^iQ^jQ^kd^c\overline{Q}_ie^cH^lH^m\epsilon_{jl}\epsilon_{km}$
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	
67	
68_a	
68_b	
69_a	$L^iL^j\overline{Q}_i\bar{u}^cH^kQ^rd^c\overline{H}_r\epsilon_{jk}$
69_b	$L^iL^j\overline{Q}_k\bar{u}^cH^kQ^rd^c\overline{H}_r\epsilon_{ij}$
70	$L^ie^cu^cd^cH^jQ^rd^c\overline{H}_r\epsilon_{ij}$
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	$L^i\bar{e}^c\bar{u}^cd^cH^jQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$

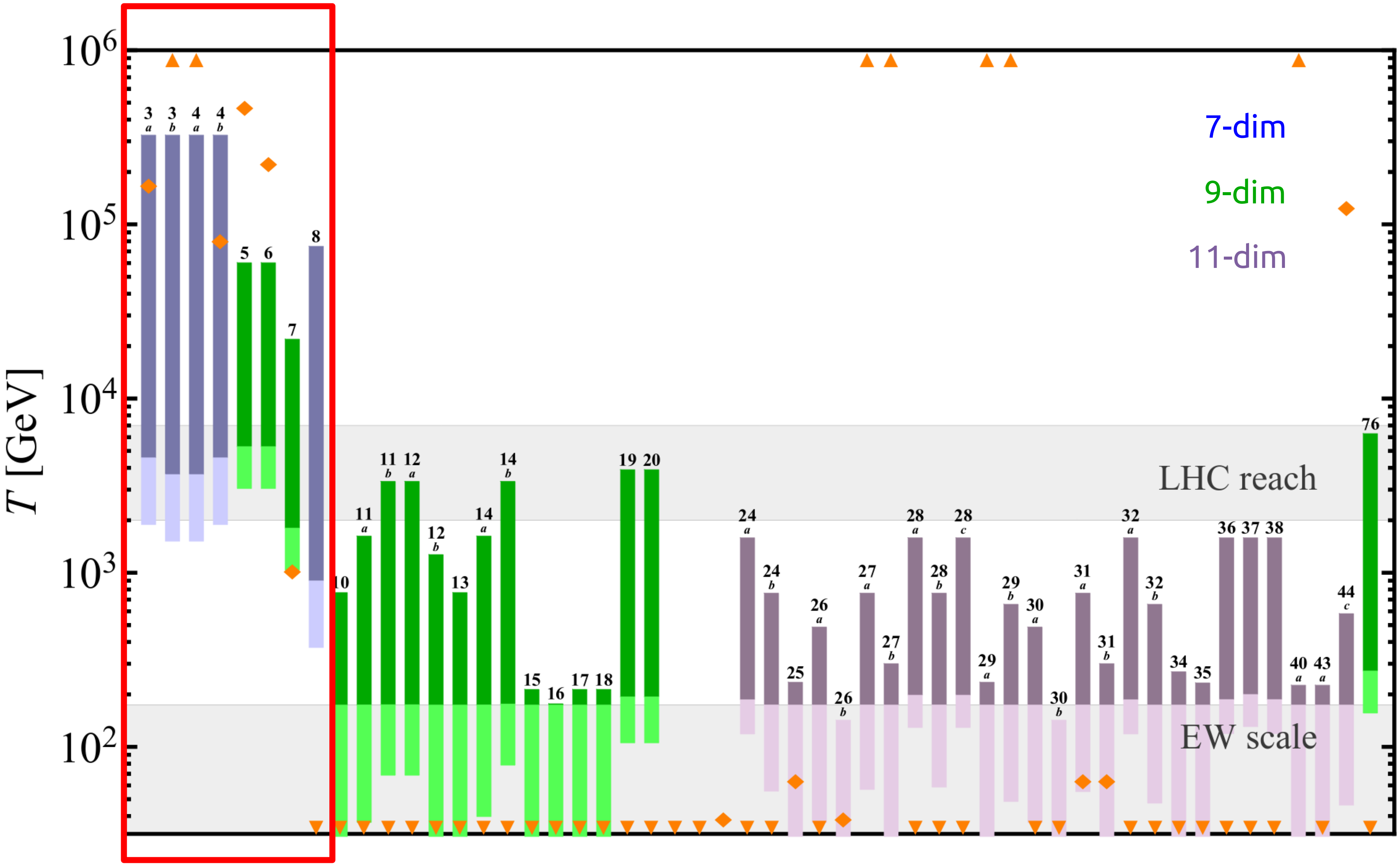
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_5}\mathcal{O}_5 + \sum_i \frac{1}{\Lambda_{7_i}^3}\mathcal{O}_7^i + \sum_i \frac{1}{\Lambda_{9_i}^5}\mathcal{O}_9^i + \sum_i \frac{1}{\Lambda_{11_i}^7}\mathcal{O}_{11}^i$$

The full picture

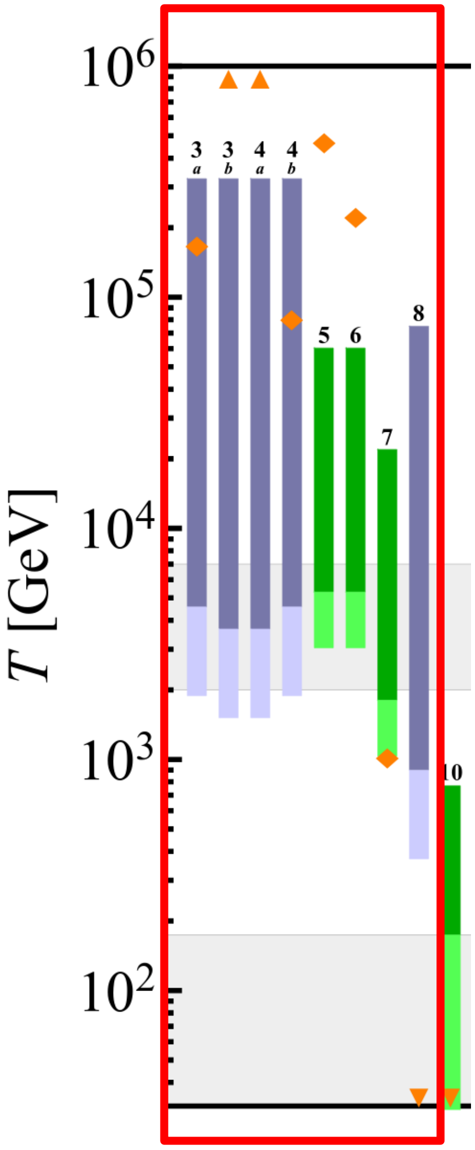
BUT: There are 129 LNV operators...



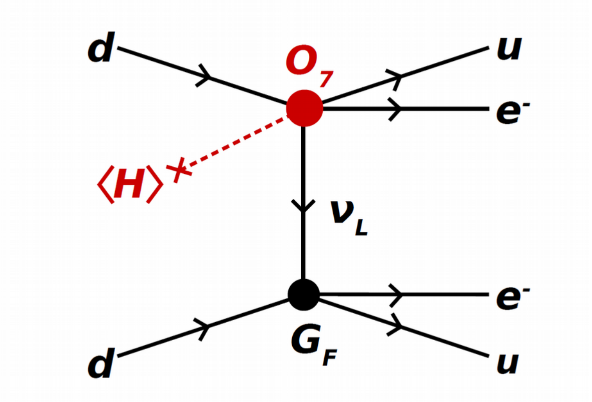
The full picture



Impact of sensitivity on effective couplings



$$\frac{G_F \epsilon_7^{3a,3b,4a,8}}{\sqrt{2}} = \frac{v}{\Lambda_7^3}$$



$$\mathcal{O}_7^{3a} = L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl} \qquad \epsilon_7^{3a} = \epsilon_{S+P}^{S+P}$$

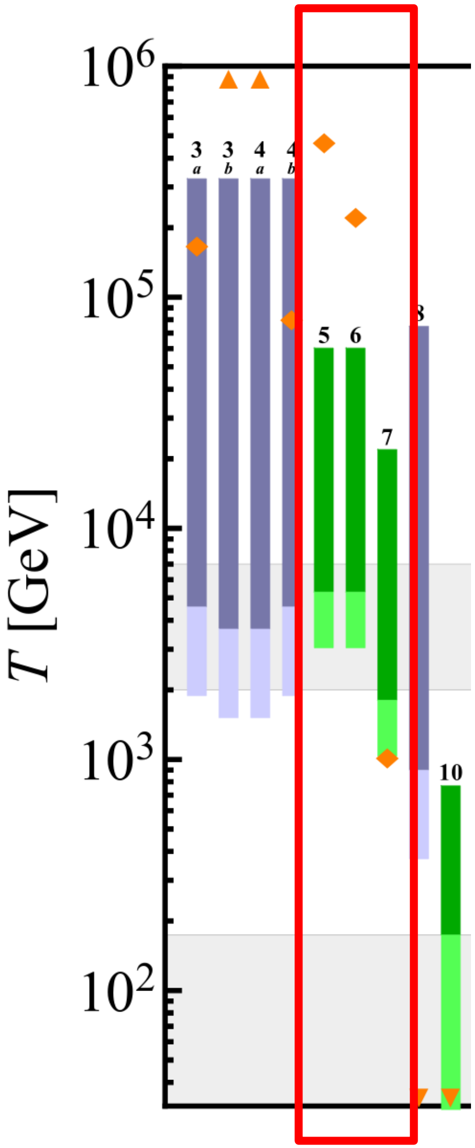
$$\mathcal{O}_7^{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl} \qquad \epsilon_7^{3b} = \epsilon_{S+P}^{S+P}$$

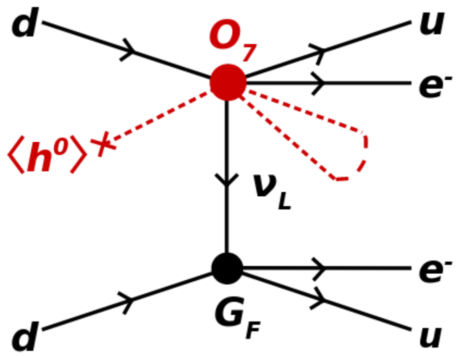
$$\mathcal{O}_7^{4a} = L^i L^j \overline{Q}_i \bar{u}^c H^k \epsilon_{jk} \qquad \epsilon_7^{4a} = \epsilon_{S-P}^{S+P}$$

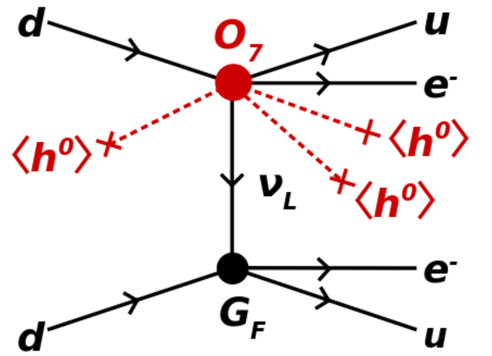
$$\mathcal{O}_7^{8} = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij} \qquad \epsilon_7^{8} = 2\epsilon_{V+A}^{V+A}$$

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

Impact of sensitivity on effective couplings







$$\mathcal{O}_5 = L^i L^j Q^k d^c H^l H^m \overline{H}_i \epsilon_{jl} \epsilon_{km}$$

$$\mathcal{O}_6 = L^i L^j \overline{Q}_k \bar{u^c} H^l H^k \overline{H}_i \epsilon_{jl}$$

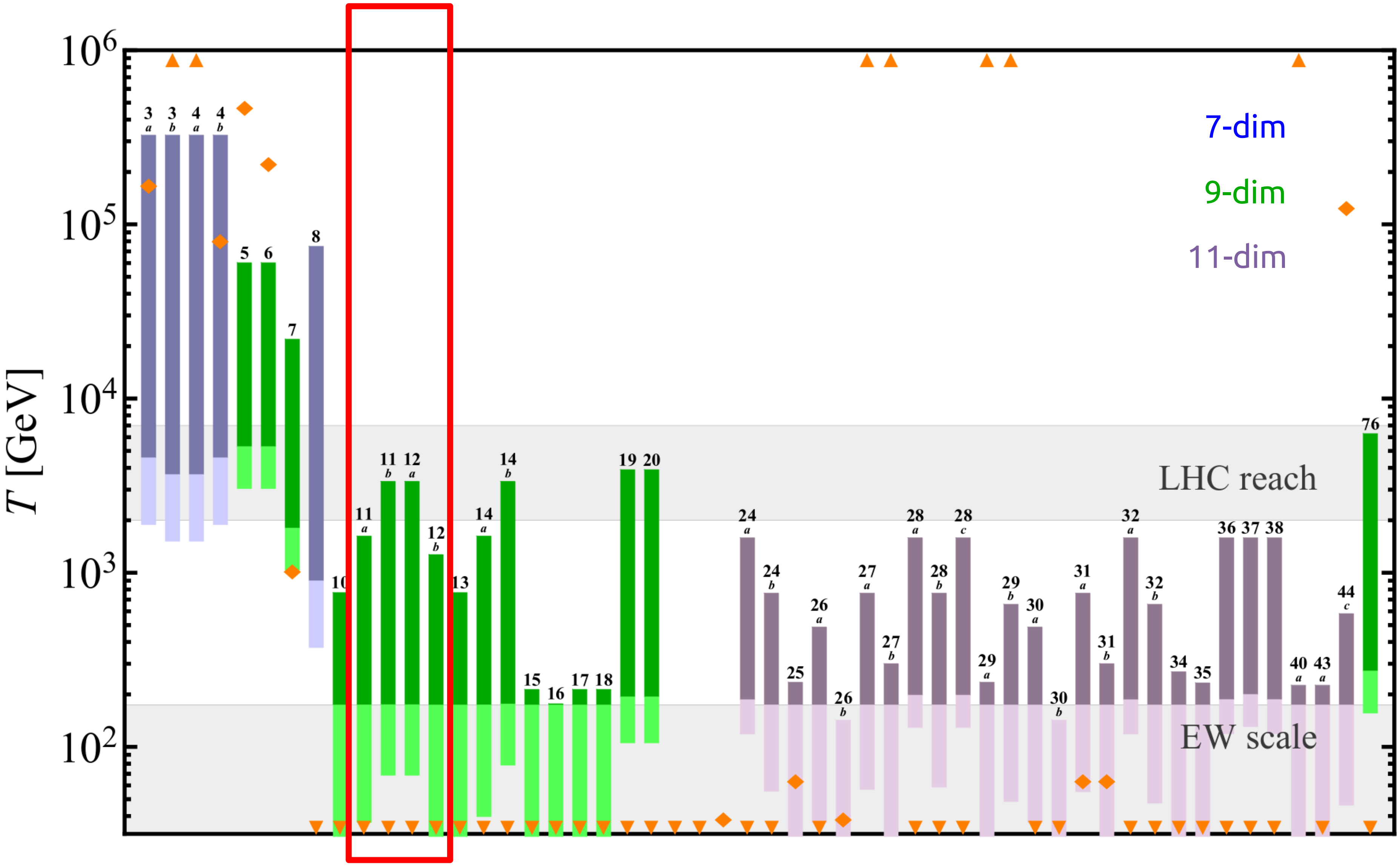
$$\frac{G_F \epsilon_7^{5,6}}{\sqrt{2}} = \boxed{\frac{v}{16\pi^2 \Lambda^3}} + \frac{v^3}{\Lambda^5}$$

$$\Lambda > 4\pi v$$

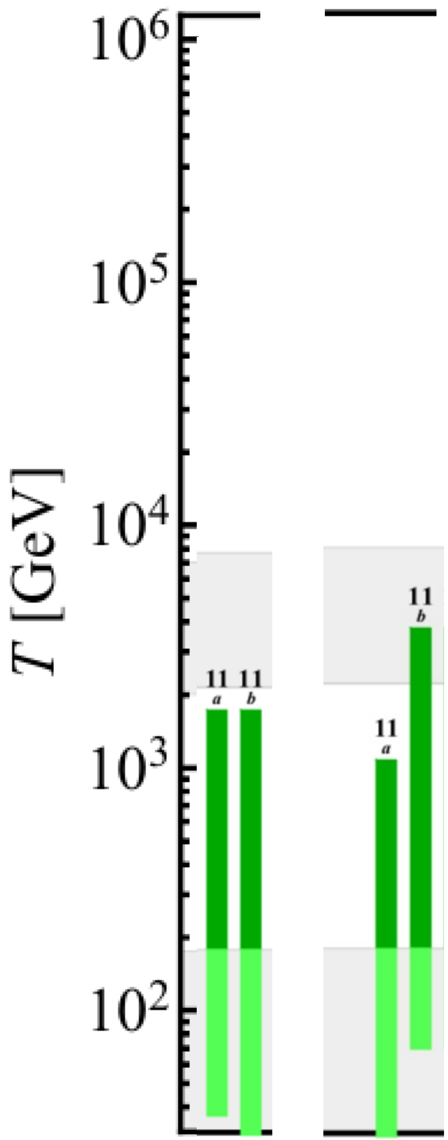
$$\mathcal{O}_7 = L^i Q^j \bar{e^c} \overline{Q}_k H^k H^l H^m \epsilon_{il} \epsilon_{jm}$$

$$\frac{G_F \epsilon_7^{7}}{\sqrt{2}} = \boxed{\frac{v^3}{\Lambda^5}}$$

The full picture



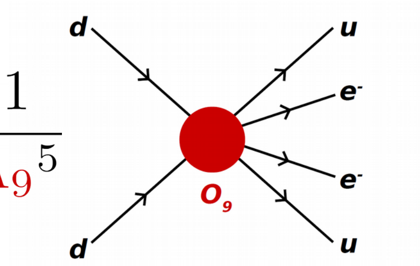
Competition between long- and short-range



Short-range contribution:

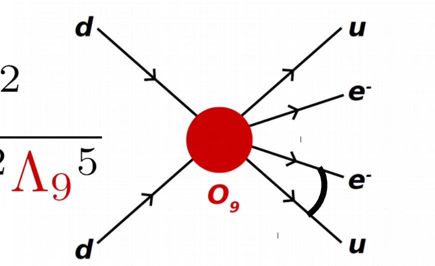
$$\mathcal{O}_9{}^{11b} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}$$

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



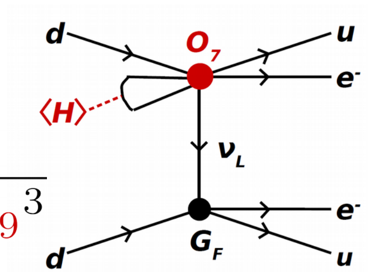
$$\mathcal{O}_9{}^{11a} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}$$

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



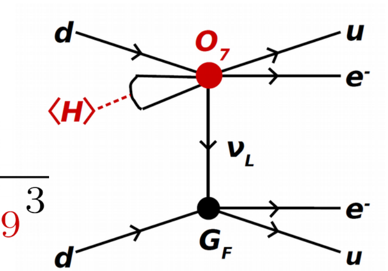
Long-range contribution:

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



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

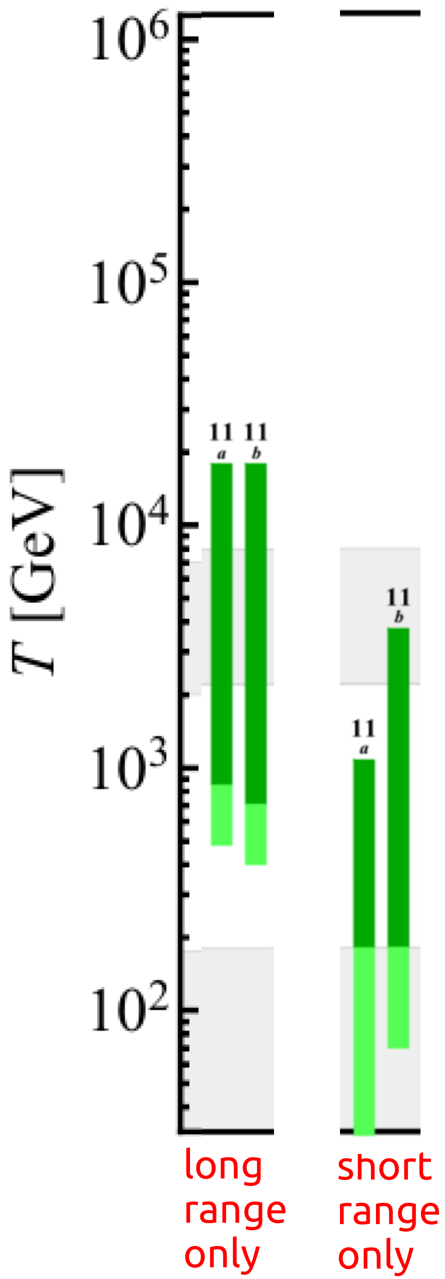
$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_d v}{16\pi^2 \Lambda_9{}^3}$$



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

only first generation Yukawa couplings

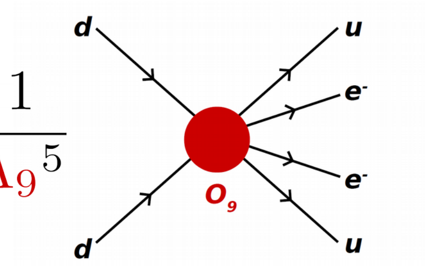
Competition between long- and short-range



Short-range contribution:

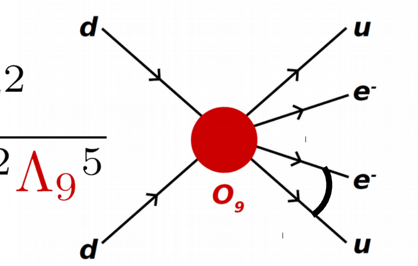
$$\mathcal{O}_9{}^{11b} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl}$$

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



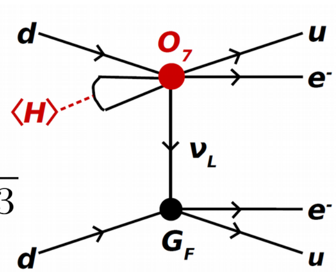
$$\mathcal{O}_9{}^{11a} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}$$

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



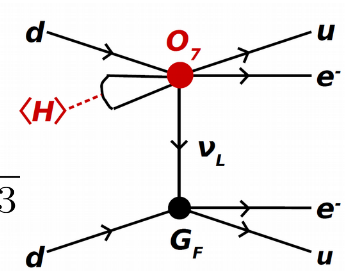
Long-range contribution:

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



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

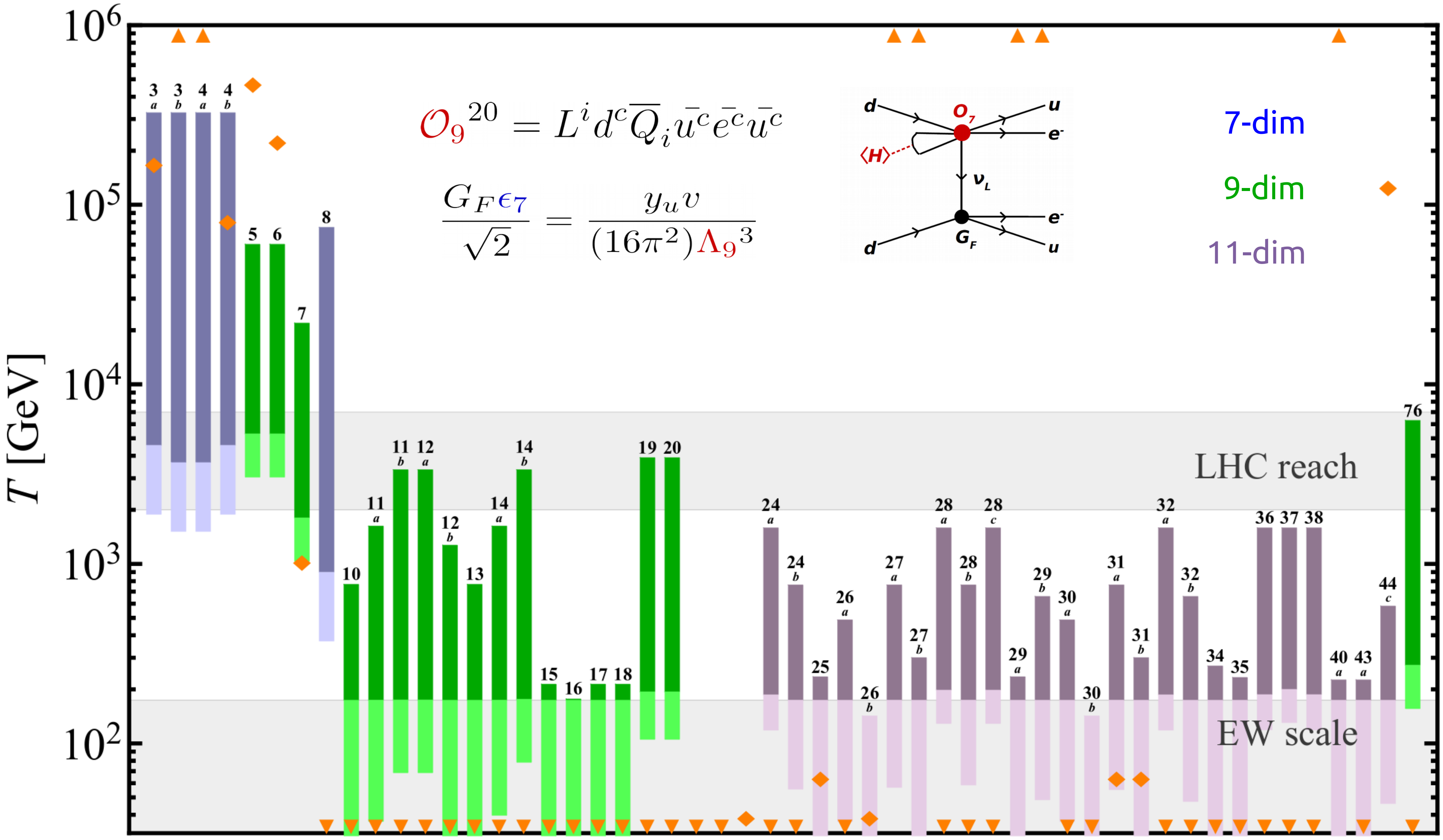
$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_d v}{16\pi^2 \Lambda_9{}^3}$$



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

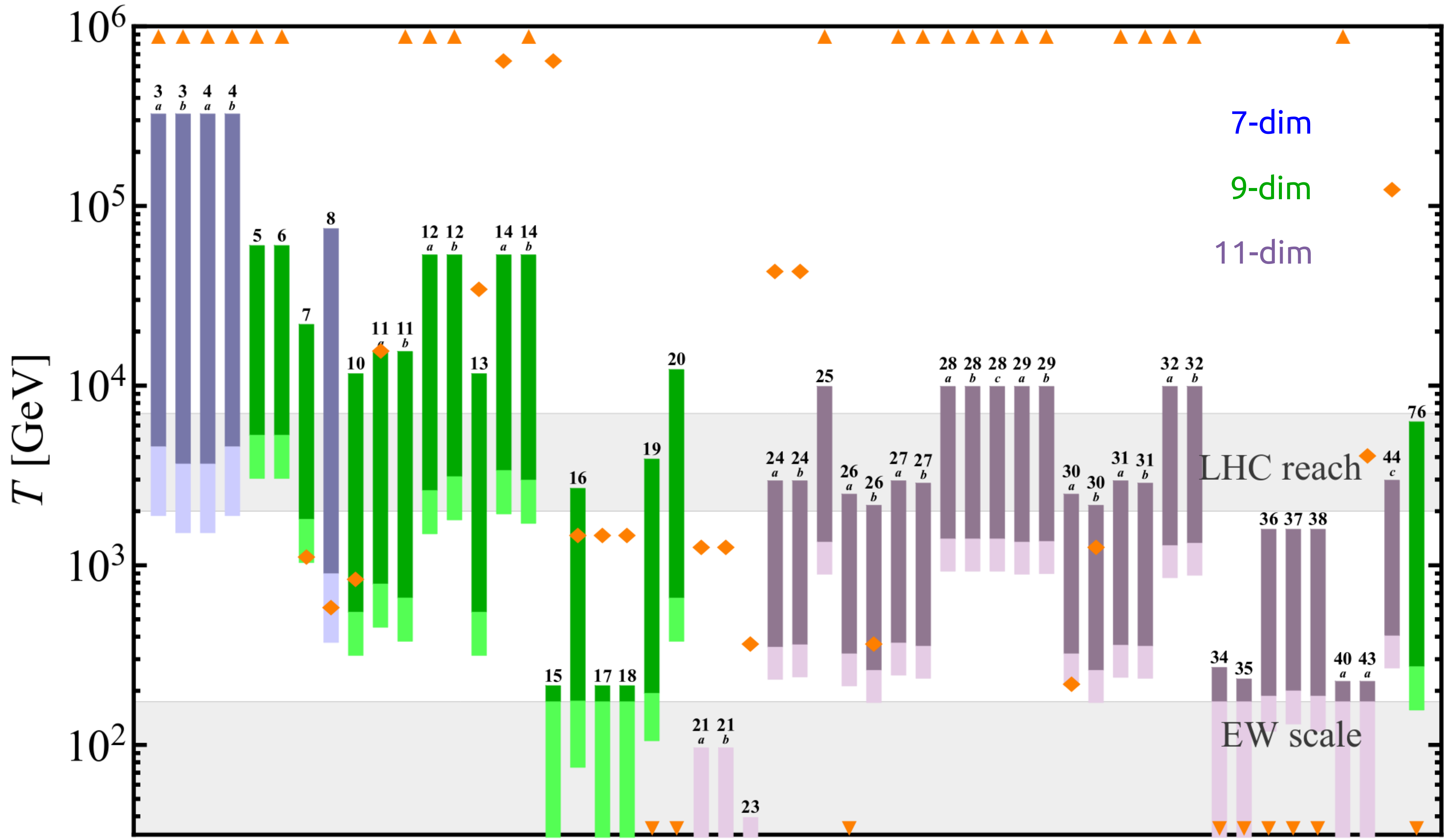
allow third generation Yukawa couplings

The full picture



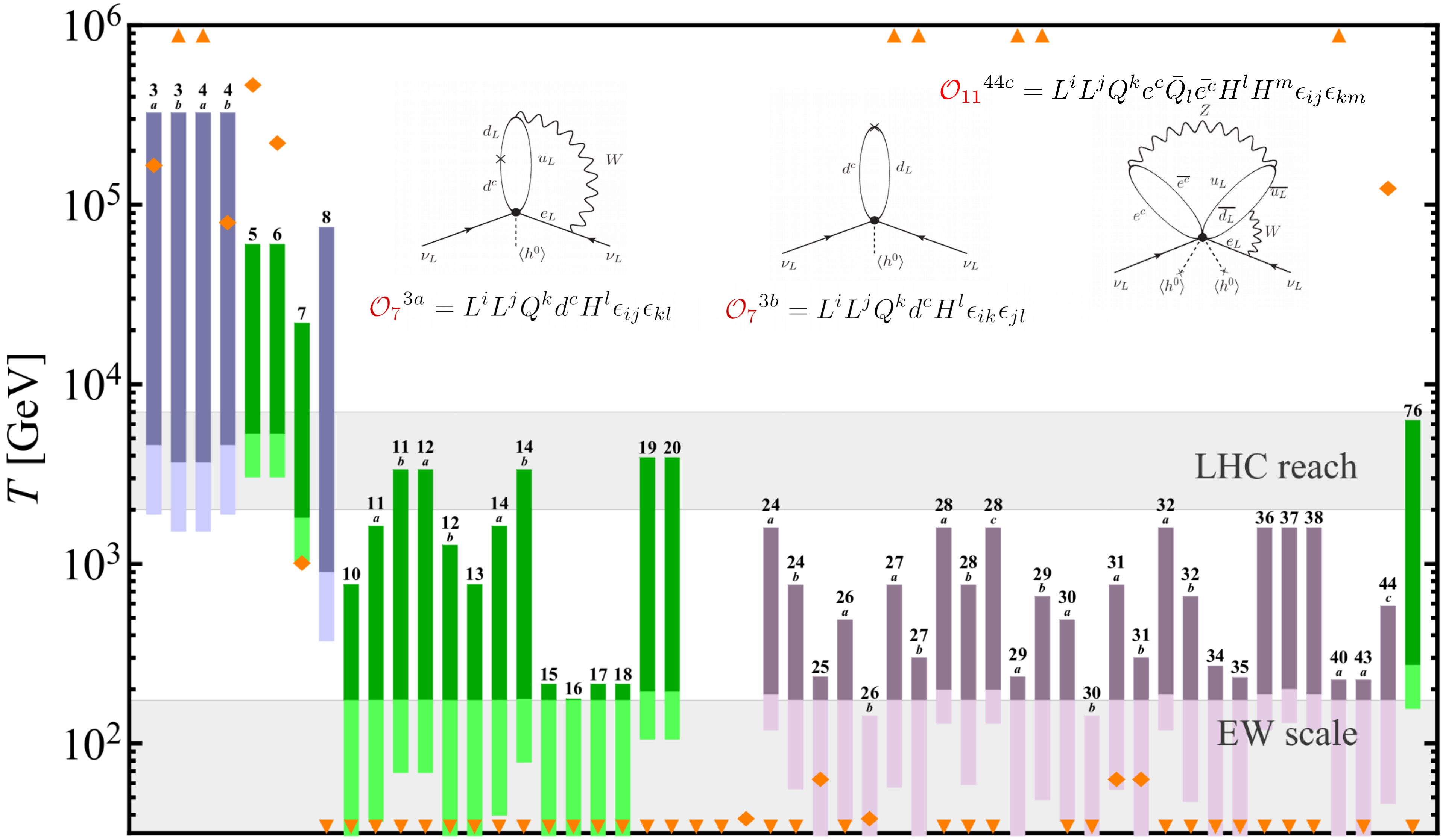
first generation only

The full picture



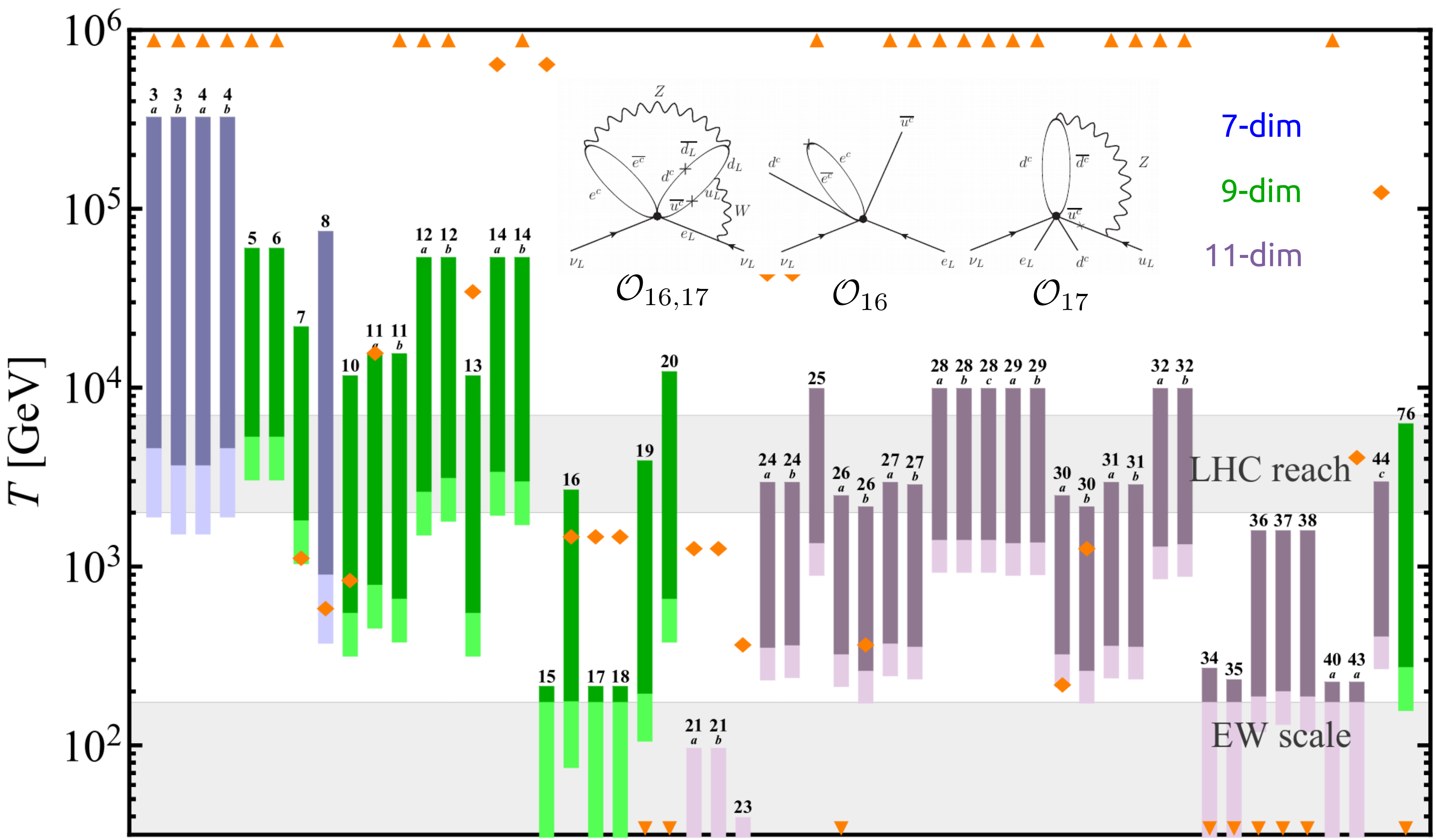
incl. third generation

Comparison with mass mechanism



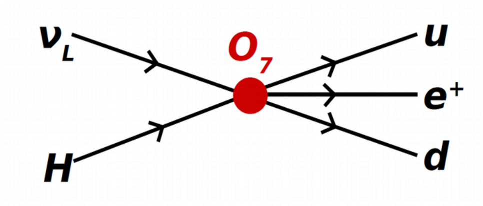
first generation only

Comparison with mass mechanism

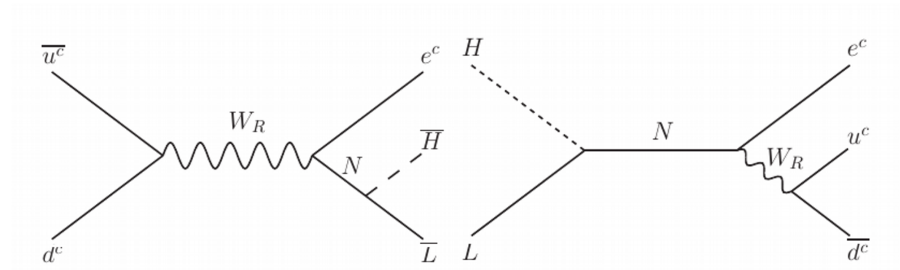


incl. third generation

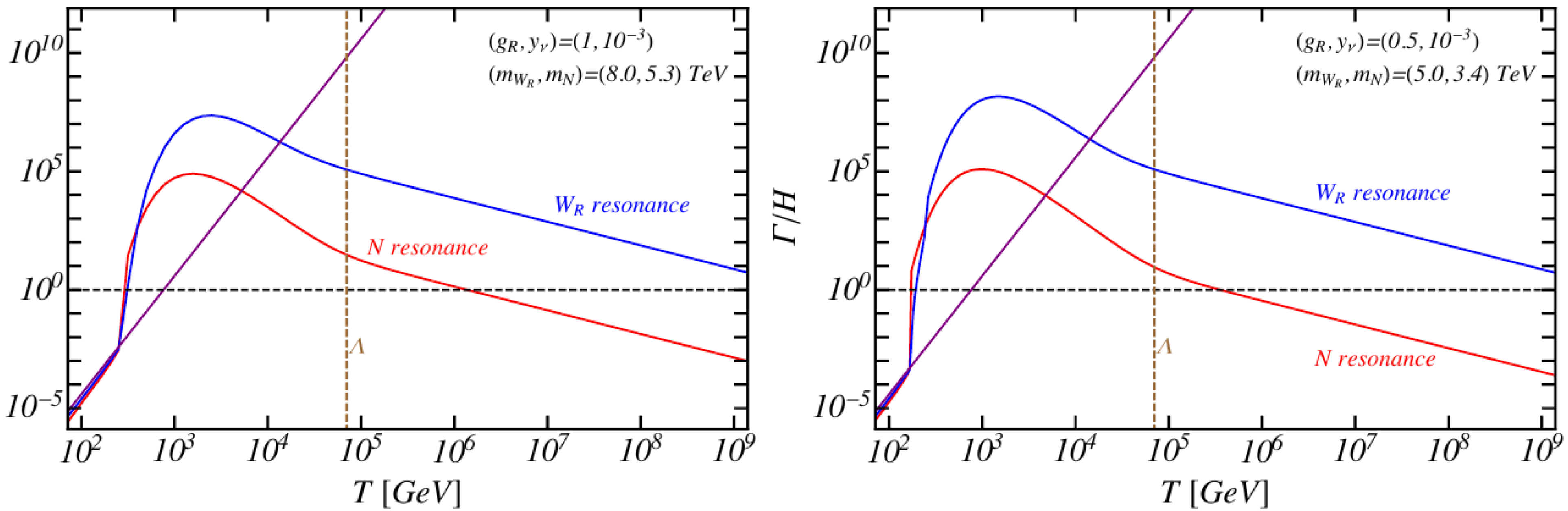
Validity of the effective operator approach



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

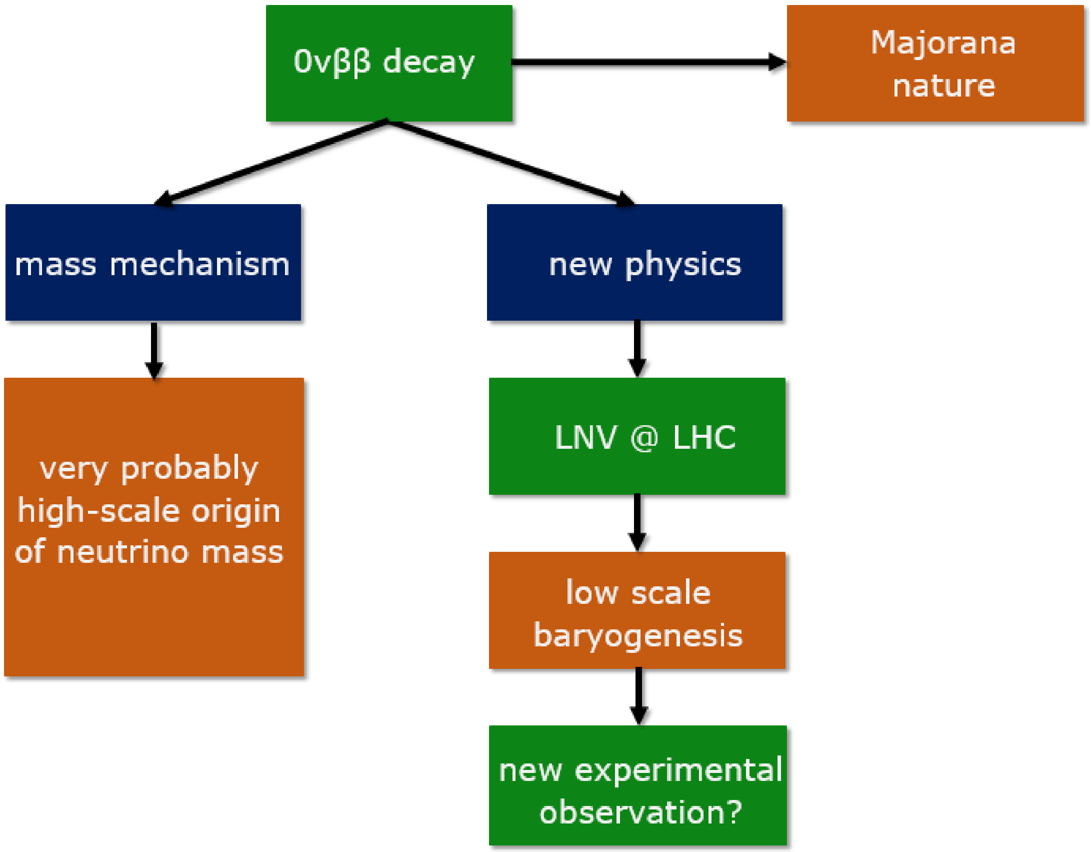


$\bar{u^c} d^c \leftrightarrow \bar{L} e^c \bar{H}$ $\qquad$ $LH \leftrightarrow e^c u^c \bar{d^c}$



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

Conclusions



- LNV processes are of high interest with respect to baryogenesis
- tight connection of high intensity and energy frontier
- possibility to falsify / probe BG models!