Falsifying highscale Baryogenesis

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in collaboration with

F. Deppisch, L. Graf, W. Huang, M. Hirsch, H. Päs

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ACFI Workshop

F. Deppisch, JH, M. Hirsch, PRL 112 (2014) 221601

F. Deppisch, JH, W. Huang, M. Hirsch, H. Päs, Phys. Rev. D92 (2015) 036005

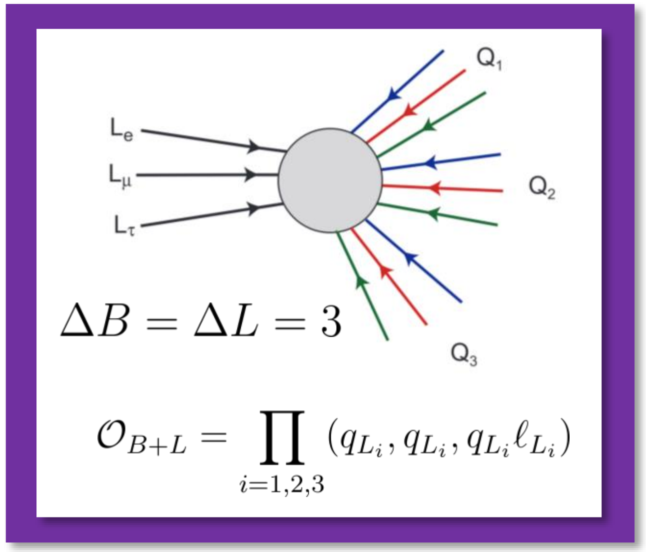
F. Deppisch, L. Graf, JH, W. Huang, work in progress

Recap: 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 $T \approx 100\text{GeV}$

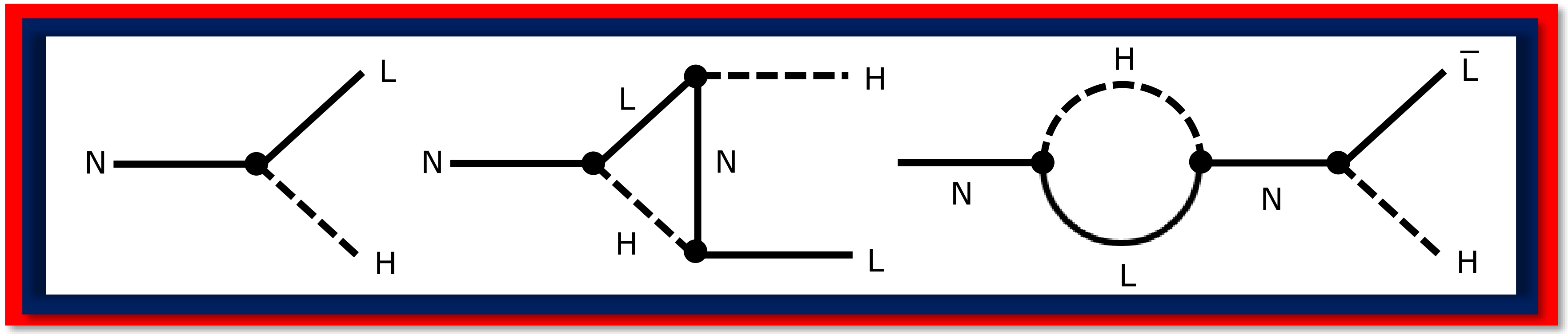
$$Hz\frac{dN_{N_1}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{\text{eq}})$$

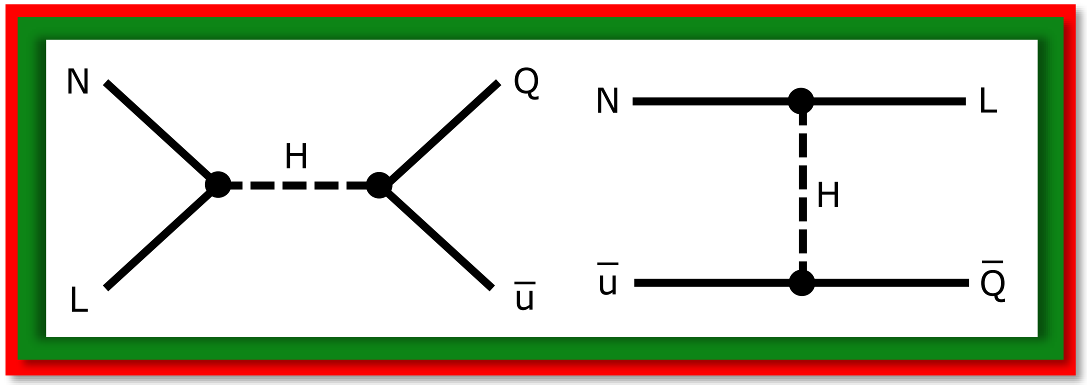
$$Hz\frac{dN_L}{dz} = \epsilon_1 \Gamma_D (N_{N_1} - N_{N_1}^{\text{eq}}) - \Gamma_W N_L$$



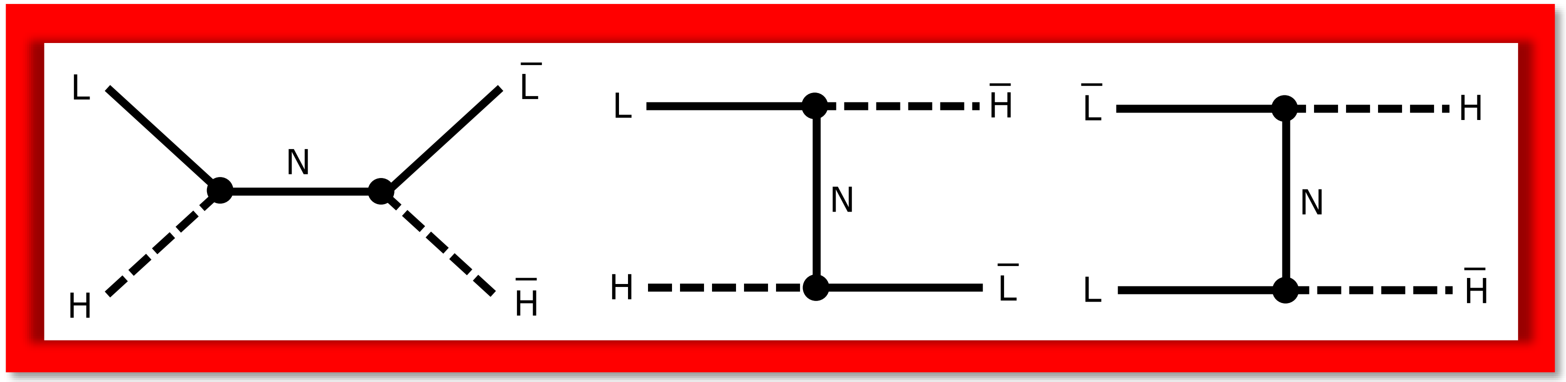
sphaleron processes

$\Delta L = 1$ source of CP-asymmetry



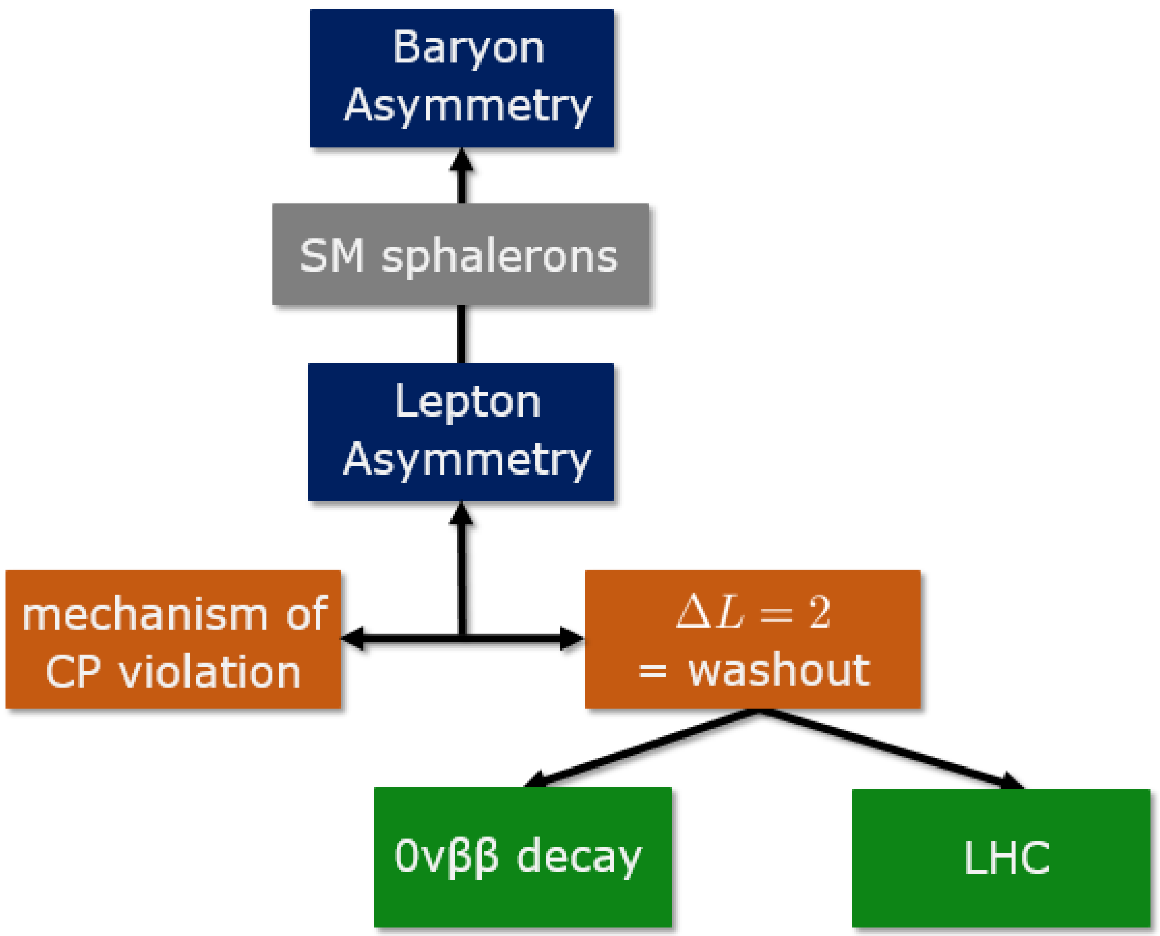


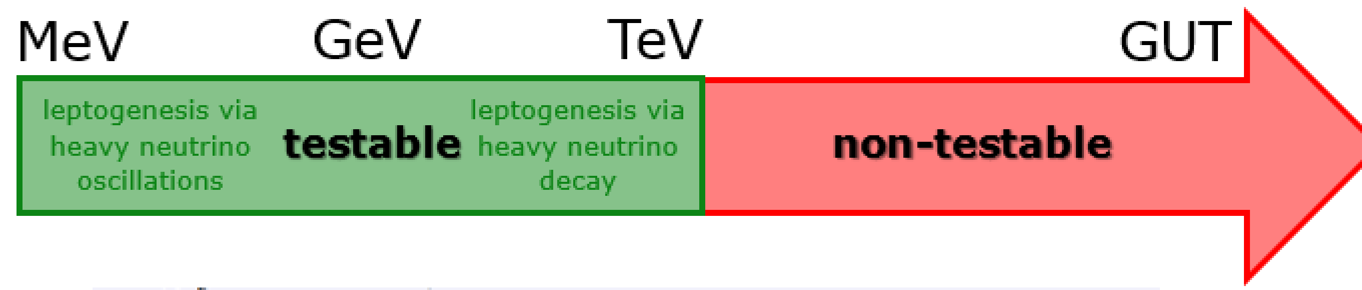
$\Delta L = 1$ scattering processes

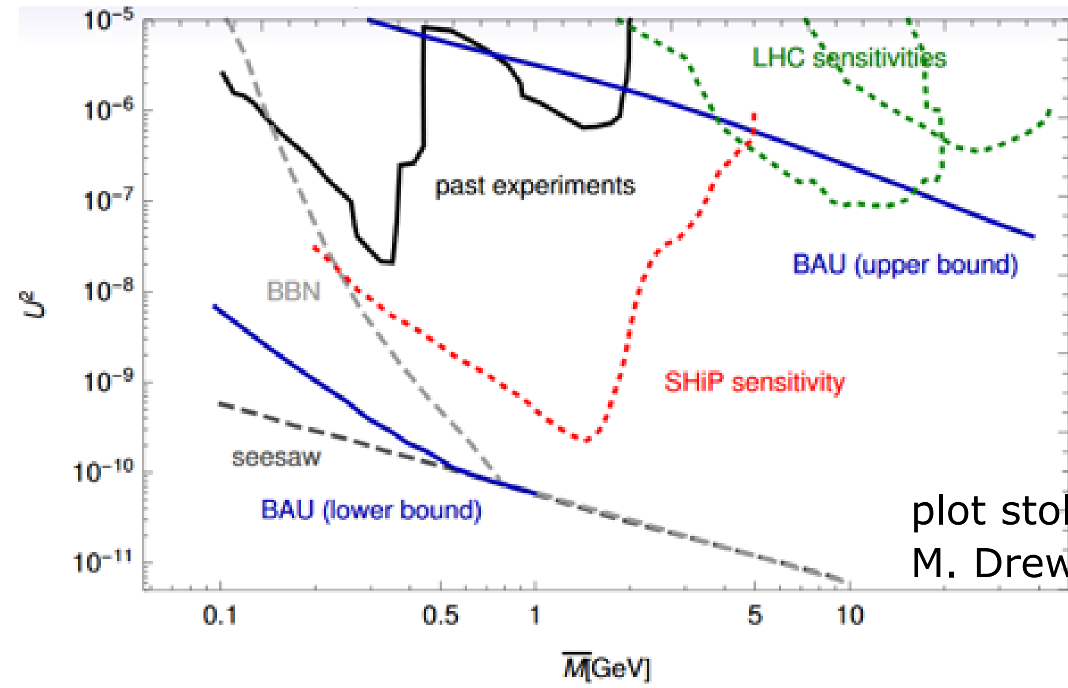


$\Delta L = 2$ washout processes

What generates the Baryon Asymmetry?





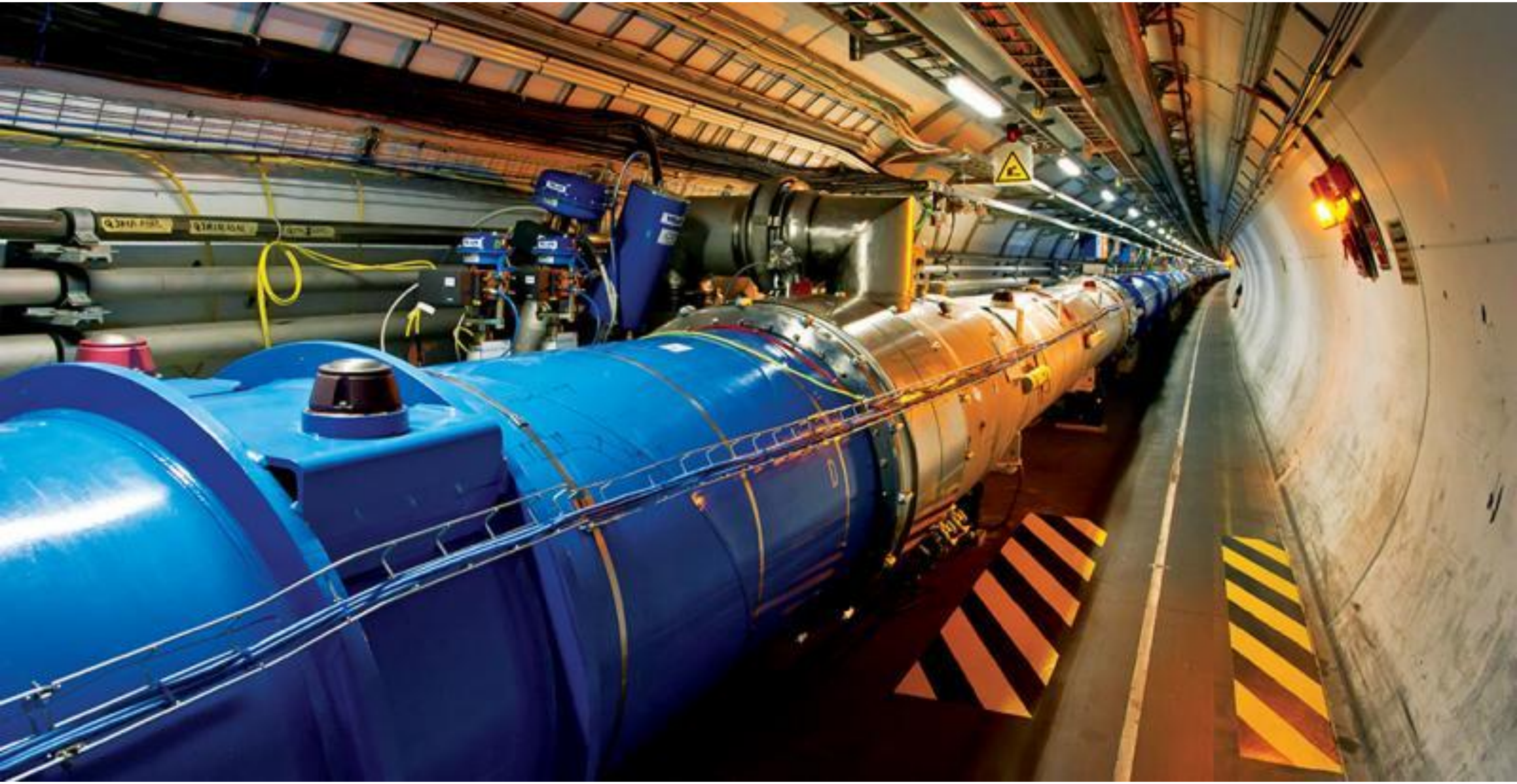


plot stolen from M. Drewes

If we cannot test high-scale Baryogenesis models, can we somehow falsify them?

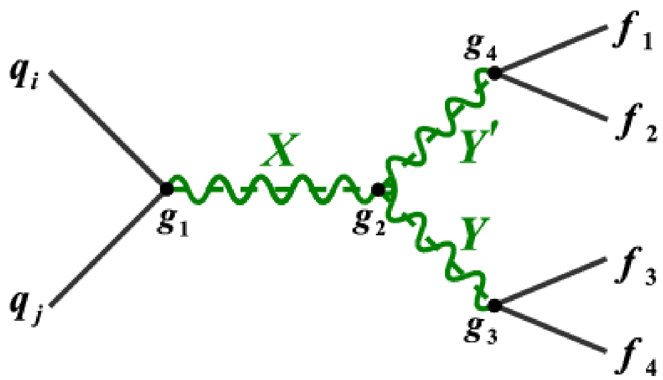
Yes, we can!

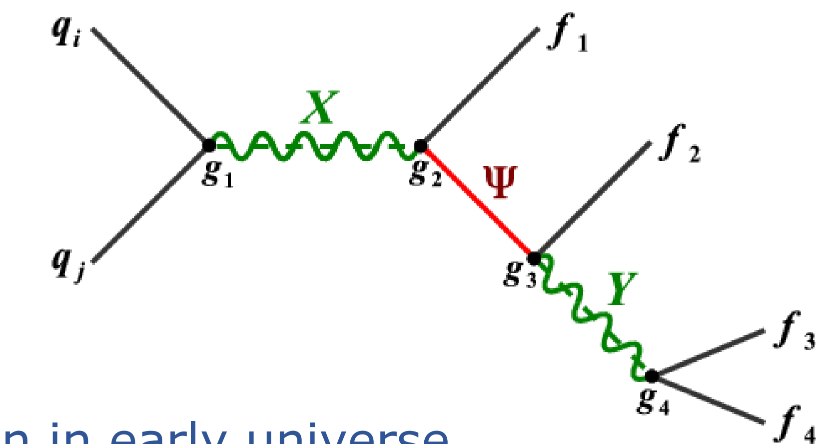
Falsifying Baryogenesis at the LHC



LNV at the LHC

signature: $pp \to l^{\pm} l^{\pm} + 2\,\text{jets}$ (w/o missing energy!)





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

cross-section in early universe determines washout strength

$$\sigma(Q^2) = \frac{4\pi}{9}(2J_X+1)\frac{\Gamma(X \to q_1 q_2)\Gamma(X \to 4f)}{(Q^2 - M_X^2)^2 + M_X^2 \Gamma_X^2}$$

$$\sigma_{\text{LHC}} = \frac{4\pi^2}{9s}(2J_X+1)\frac{\Gamma_X}{M_X} f_{q_1 q_2}\left(\frac{M_X}{\sqrt{s}}, M_X^2\right) \times \text{Br}(X \to q_1 q_2)\text{Br}(X \to 4f)$$

$$\sigma(s) = \frac{4 \cdot 9 \cdot s_{\text{LHC}}}{f_{q_1 q_2}\left(M_X/\sqrt{s_{\text{LHC}}}\right)} \cdot \sigma_{\text{LHC}} \cdot \delta(s - M_X^2)$$

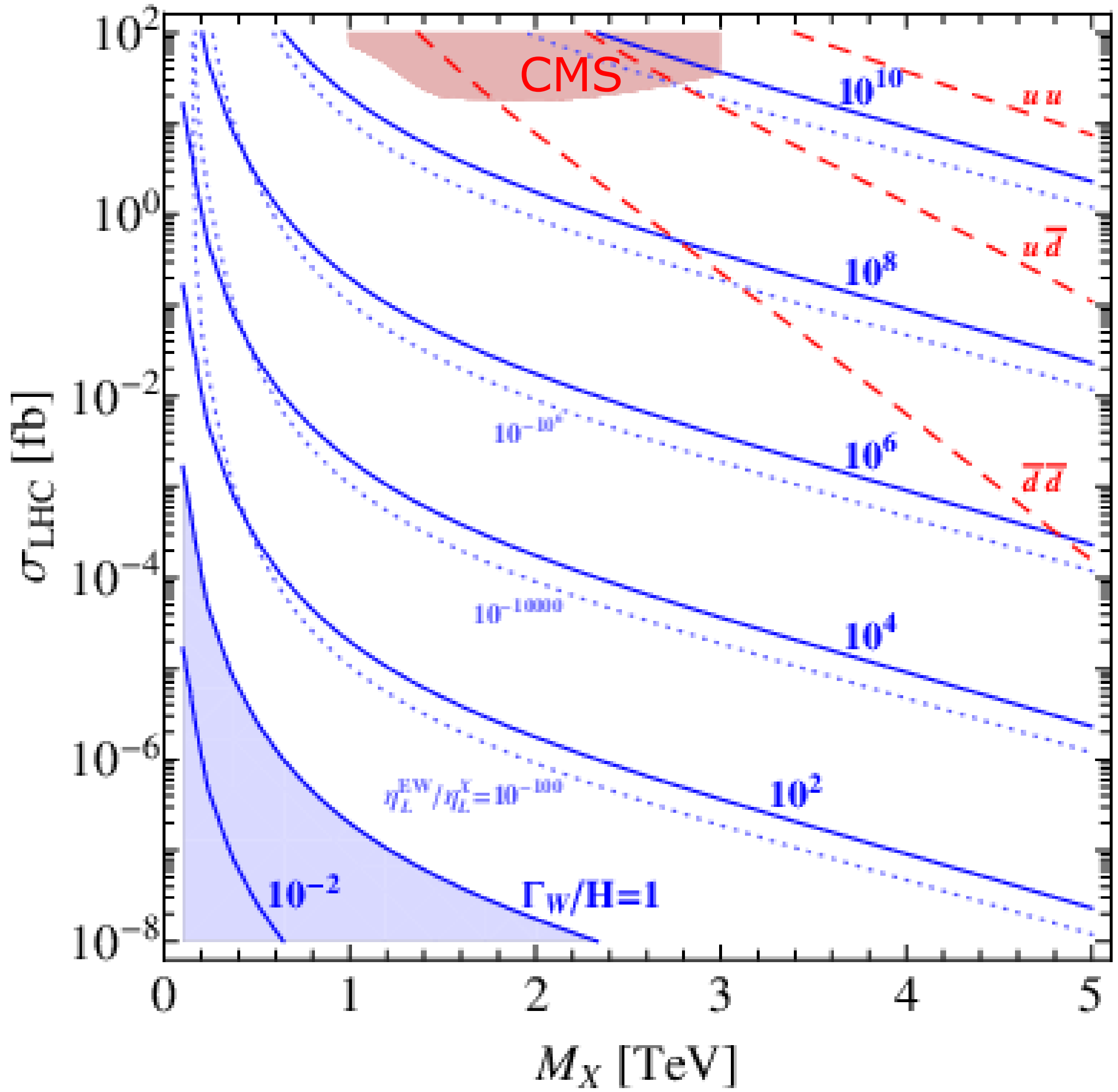
cross section measured at LHC

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

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

LNV at the LHC

- assuming pre-existing lepton asymmetry generated at high scale

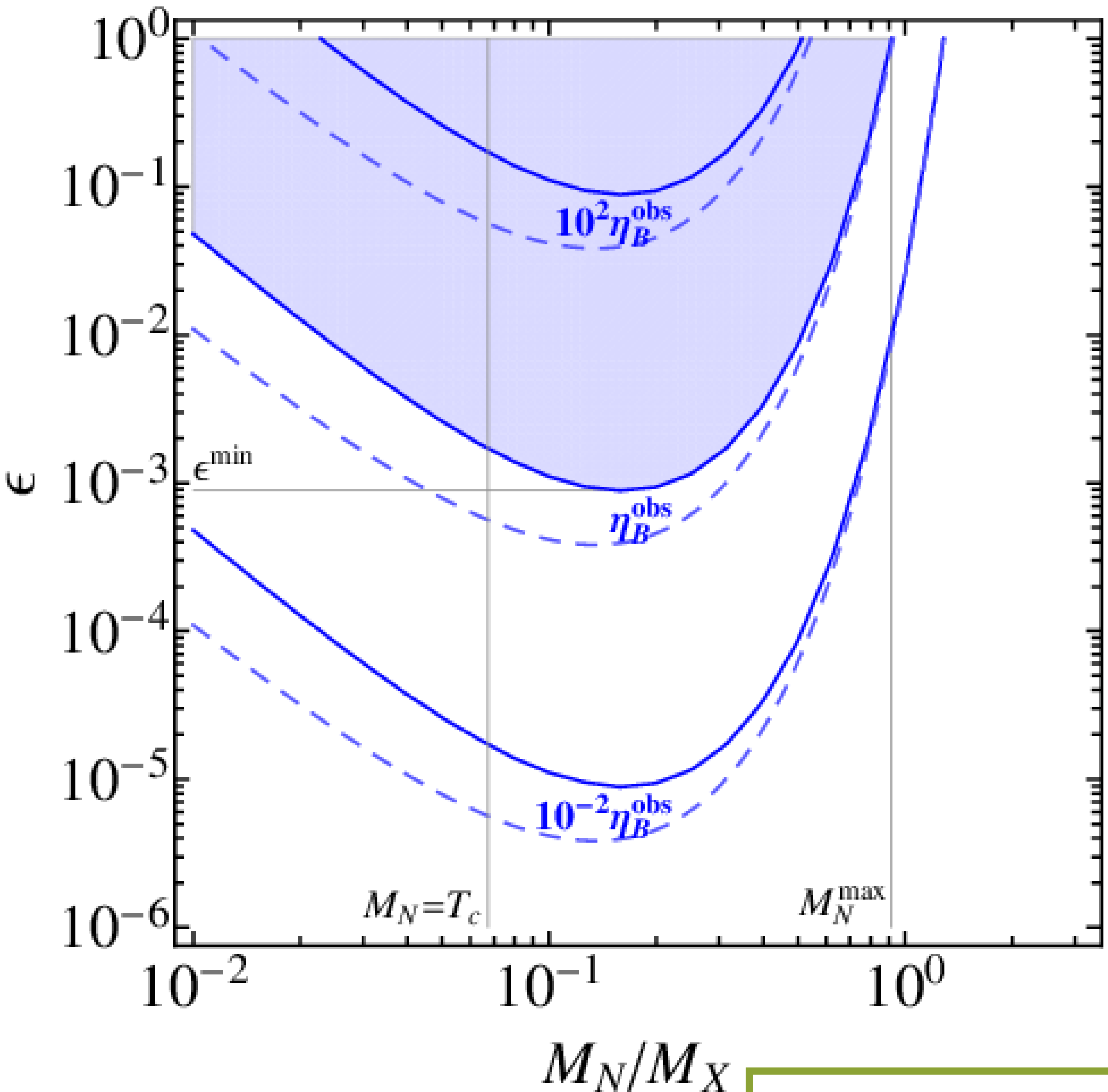


$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\mathrm{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}$$

observation of LNV process at the LHC implies very strong washout, excludes Leptogenesis models that generate asymmetry above M_x

LNV at the LHC

- NOW: assumption 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

scale of LNV observation

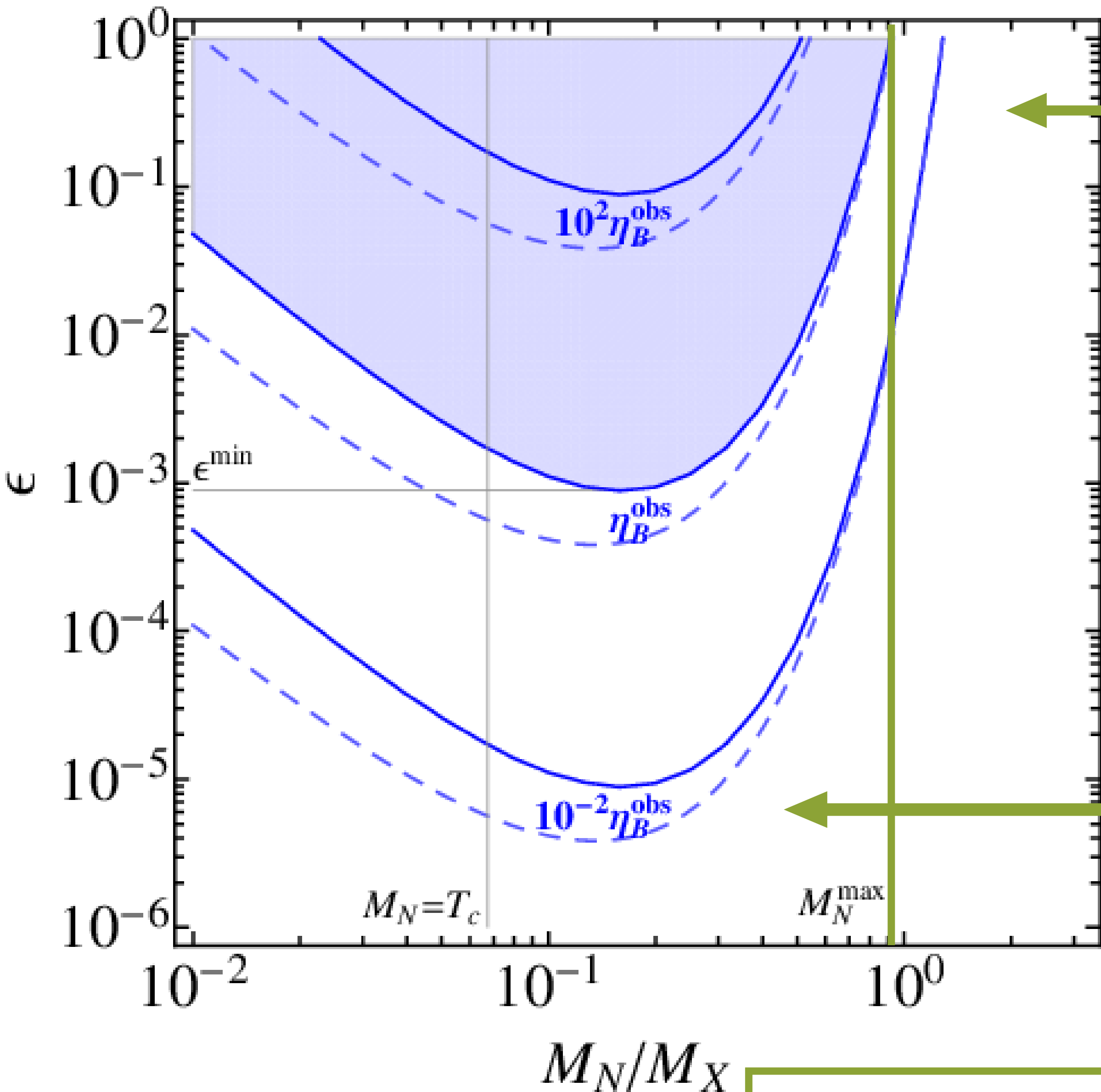
$$\sigma_{\rm LHC} = 0.1 \text{ fb}$$
$$M_X = 2 \text{ TeV}$$

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

observation of LNV process at the LHC excludes high-scale baryogensis models and sets lower limit on the baryon asymmetry of a low-scale leptogenesis model

LNV at the LHC

- NOW: assumption 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

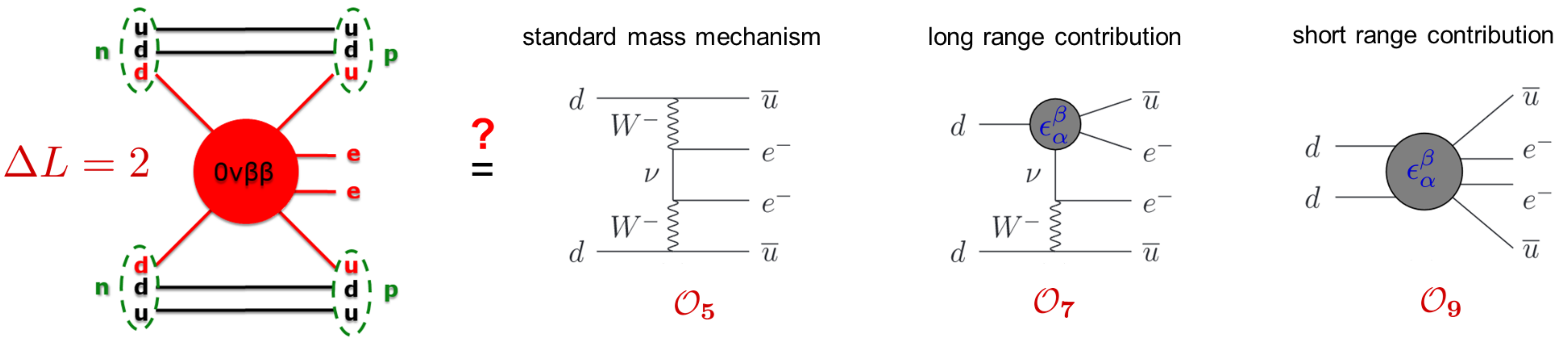
$\sigma_{\mathrm{LHC}} = 0.1$ fb
$M_X = 2$ TeV

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

observation of LNV process at the LHC excludes high-scale baryogensis models and sets lower limit on the baryon asymmetry of a low-scale leptogenesis model

Falsifying Baryogensis at $0\nu\beta\beta$ experiments

Neutrinoless Double Beta Decay (0νββ)

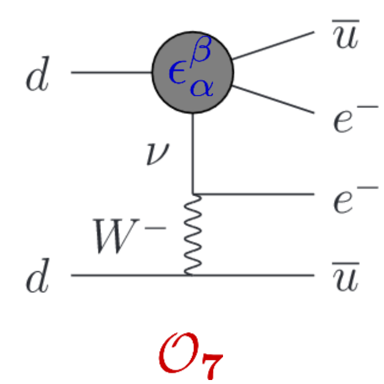


The general Lagrangian which describes different non-SM contributions to 0νββ can be written in terms of effective couplings ϵ_α^β, e.g. for the long range contribution:

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

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

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



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	$3.3\cdot10^{-9}$	$5.9\cdot10^{-7}$	$1.0\cdot10^{-8}$	$1.0\cdot10^{-8}$	$6.4\cdot10^{-10}$	$1.0\cdot10^{-9}$
^{136}Xe	$2.6\cdot10^{-9}$	$5.1\cdot10^{-7}$	$6.2\cdot10^{-9}$	$6.2\cdot10^{-9}$	$4.4\cdot10^{-10}$	$7.4\cdot10^{-10}$

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

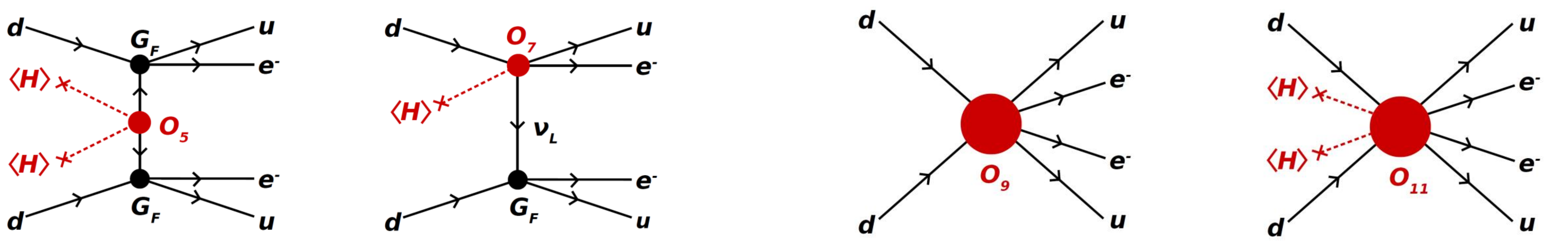
$$T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2$$

0νββ half life sets constraints on effective couplings

Possible underlying LNV Operators

- four examples from the complete list of all possible LNV $\Delta L = 2$ effective operators

K. S. Babu, C. N. Leung, Nucl. Phys. B 619 (2001), arxiv:0106054 [hep-ph]
A. de Gouvea, J. Jenkins, PRD 77 (2008), arXiv:0708.1344 [hep-ph]



$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl}$$
$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c}) H^j \epsilon_{ij}$$
$$\mathcal{O}_9 = (L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c})$$
$$\mathcal{O}_{11} = (L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk}\epsilon_{lm}$$

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

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\{ j^{\mu}_{V-A} J^{\dagger}_{V-A,\mu} + \sum_{\alpha,\beta} \epsilon^{\beta}_{\alpha} j_{\beta} J^{\dagger}_{\alpha} \}$$
$$j_\beta = \bar{e}\mathcal{O}_\beta \nu \qquad J^{\dagger}_{\alpha} = \bar{u}\mathcal{O}_\alpha d$$

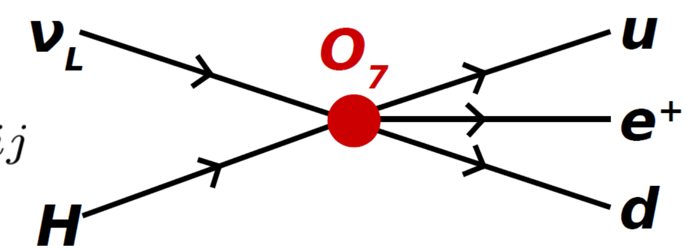
$$m_e \epsilon_5 = \frac{g^2 v^2}{\Lambda_5} \qquad \frac{G_F \epsilon_7}{\sqrt{2}} = \frac{g^3 v}{2{\Lambda_7}^3} \qquad \frac{G_F^2 \epsilon_{\{9,11\}}}{2 m_p} = \{ \frac{g^4}{{\Lambda_9}^5}, \frac{g^6 v^2}{{\Lambda_{11}}^7} \}$$

$\mathcal{O}_D$	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}

Lepton Asymmetry Washout

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

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



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

$$n_\gamma HT \frac{d\eta_L}{dT} = c_D \frac{T^{2D-4}}{{\Lambda_D}^{2D-8}} \eta_L$$

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

c_D operator specific factor

η_L lepton density

- washout efficient if

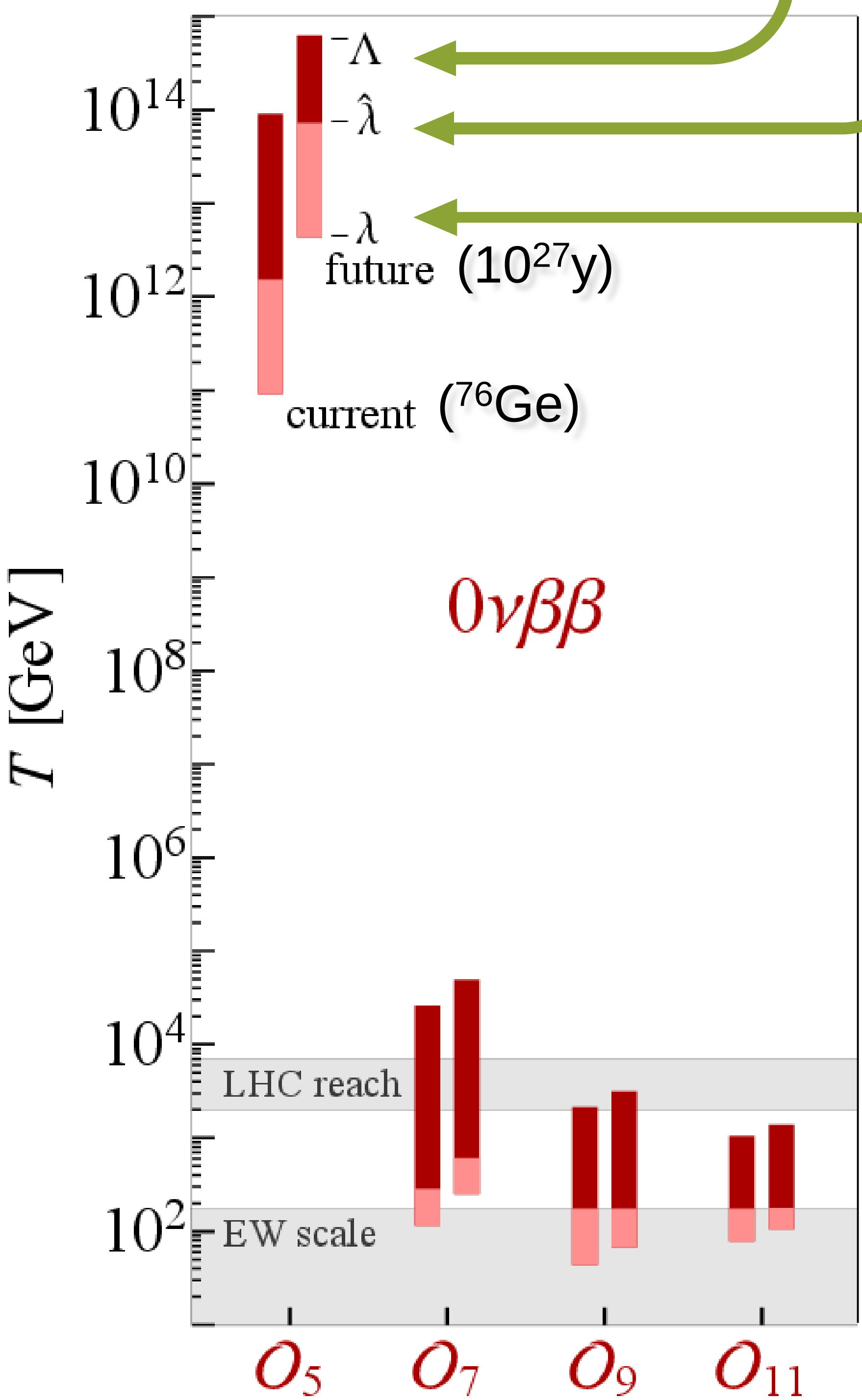
$$\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H} \frac{T^{2D-4}}{{\Lambda_D}^{2D-8}} = c'_D \frac{\Lambda_{\text{Pl}}}{\Lambda_D} \left(\frac{T}{\Lambda_D}\right)^{2D-9} > 1$$

- **If** 0νββ is observed, washout efficient in the temperature interval

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

Impact on Baryogenesis Models

scale of operator



scale above which a max. lepton asymmetry of 1 is washed out to η_B^{obs} or less

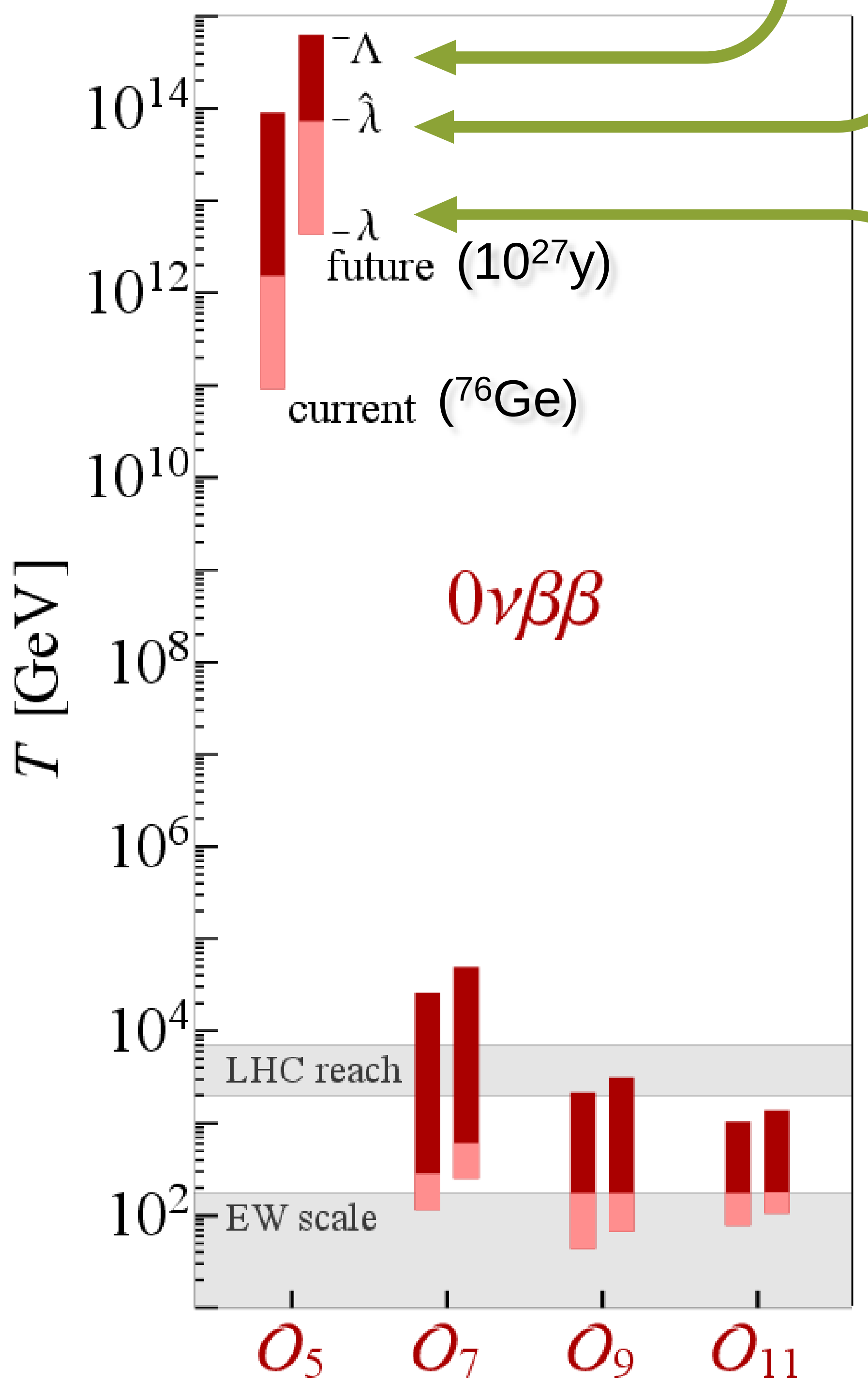
$$\hat{\lambda}_D \approx \left[(2D-9)\ln\left(\frac{10^{-2}}{\eta_B^{\mathrm{obs}}}\right)\lambda_D^{2D-9} + v^{2D-9}\right]^{\frac{1}{2D-9}}$$

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

- IF 0νββ was observed via a non-standard mechanism, resulting washout would rule out baryogenesis mechanisms above λ
- observation of 0νββ via O_9 and O_{11} will imply observation of LNV at LHC

Impact on Baryogenesis Models

scale of operator



scale above which a max. lepton asymmetry of 1 is washed out to $\eta_B^{\rm obs}$ or less

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

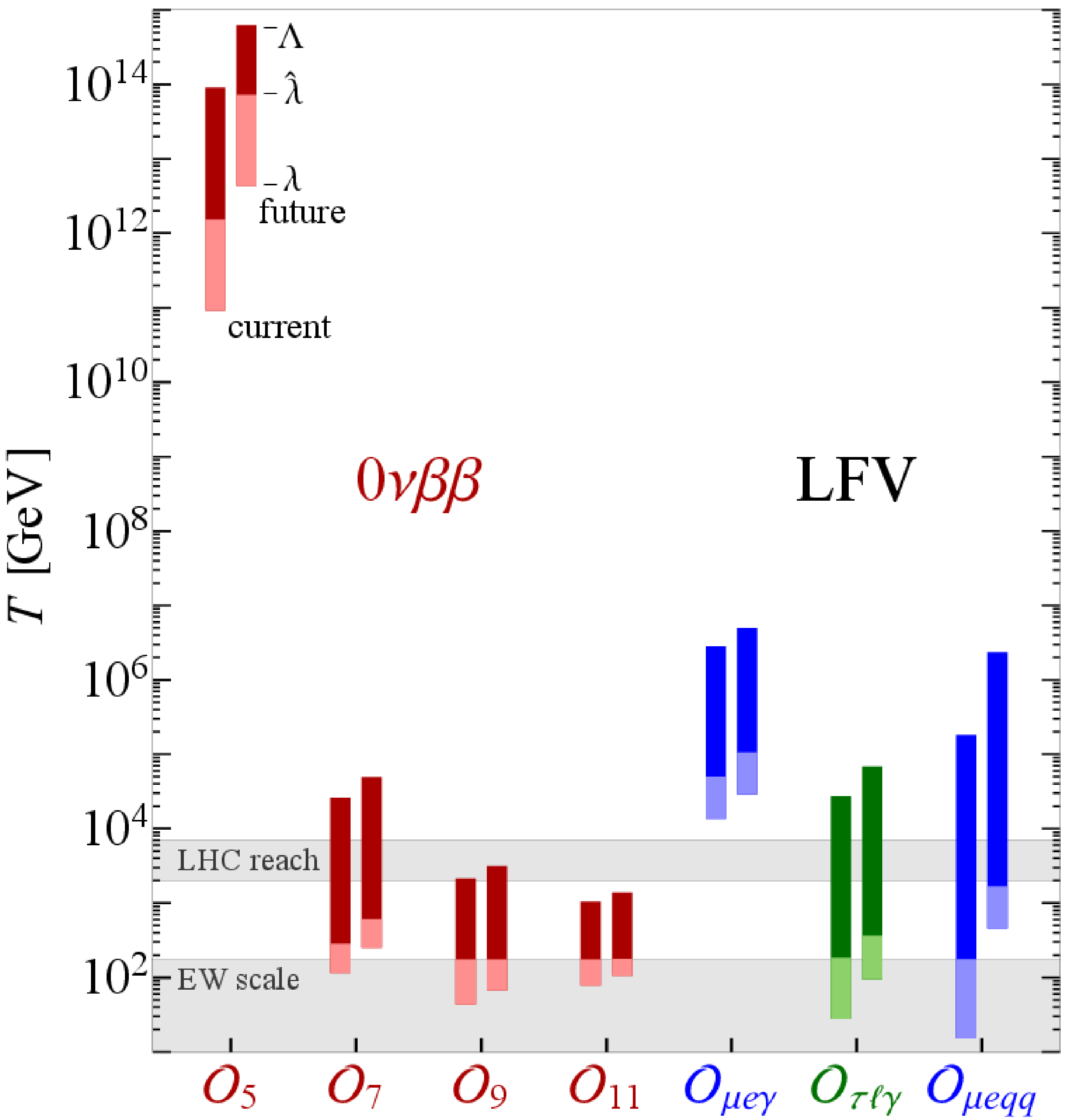
scale above which washout highly effective $\frac{\Gamma_W}{H} > 1$

- IF 0νββ was observed via a non-standard mechanism, resulting washout would rule out baryogenesis mechanisms above λ
- observation of 0νββ via O_9 and O_{11} will imply observation of LNV at LHC

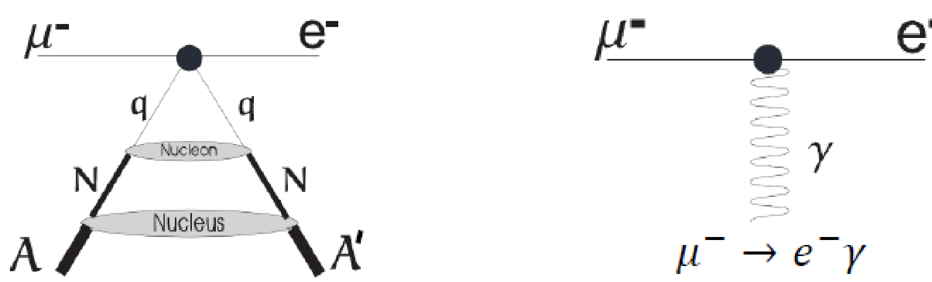
- 0νββ decay probes only electron-electron component of LNV operators

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

Considering Lepton Flavour Violation (LFV)



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



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

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

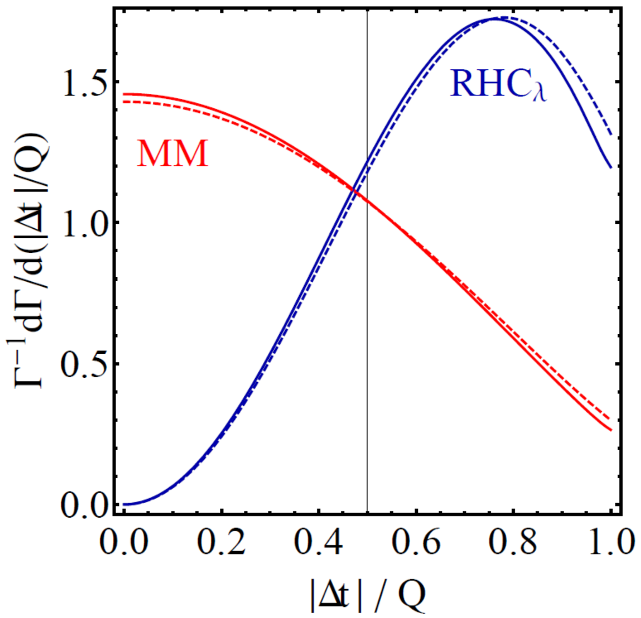
$$\mathcal{C}_{\ell\ell qq} = \frac{g^2}{\Lambda^2_{\ell\ell qq}} \qquad \mathcal{C}_{\ell\ell\gamma} = \frac{eg^3}{16\pi^2 \Lambda^2_{\ell\ell\gamma}}$$

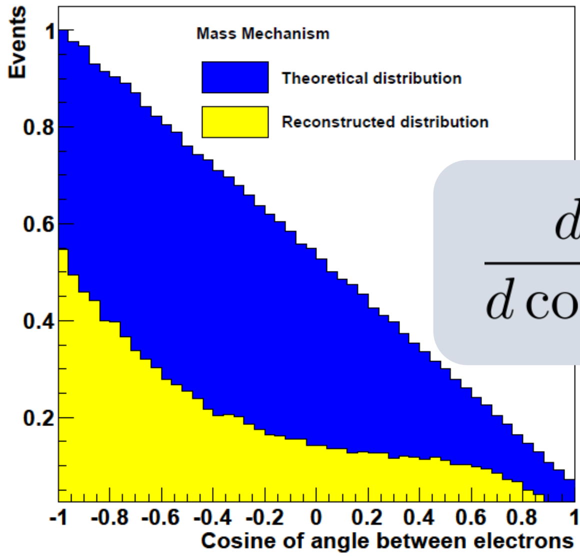
- determine interval in which LFV process equilibrate pre-existing flavour asymmetry

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

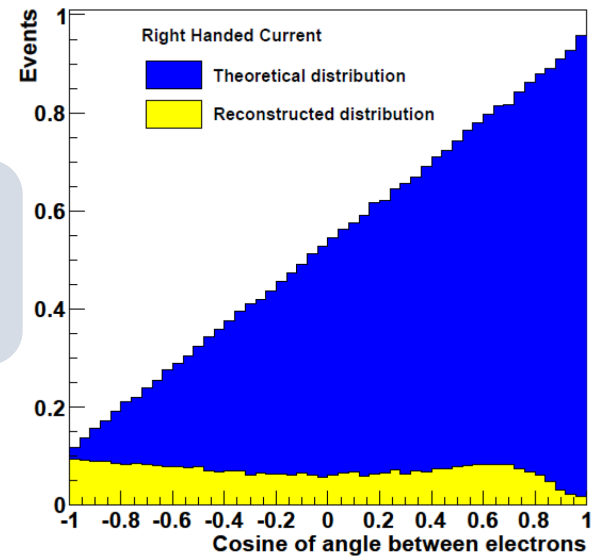
Distinguishing between different Operators

- SuperNEMO can discriminate O_7 from others, due to e^-_R and e^-_L in final state





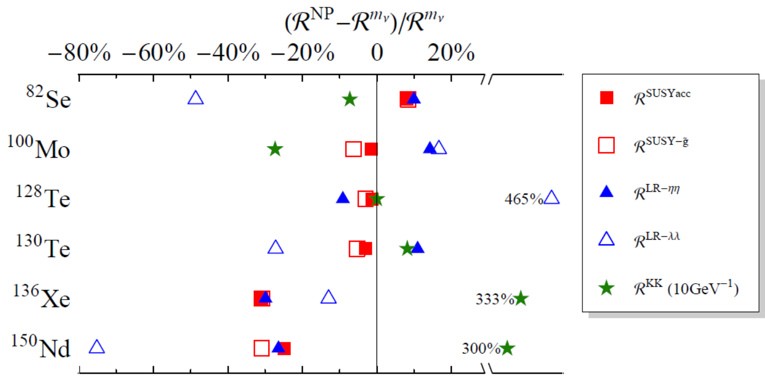
$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$



SuperNEMO collaboration, arXiv:1005.1241 [hep-ex]

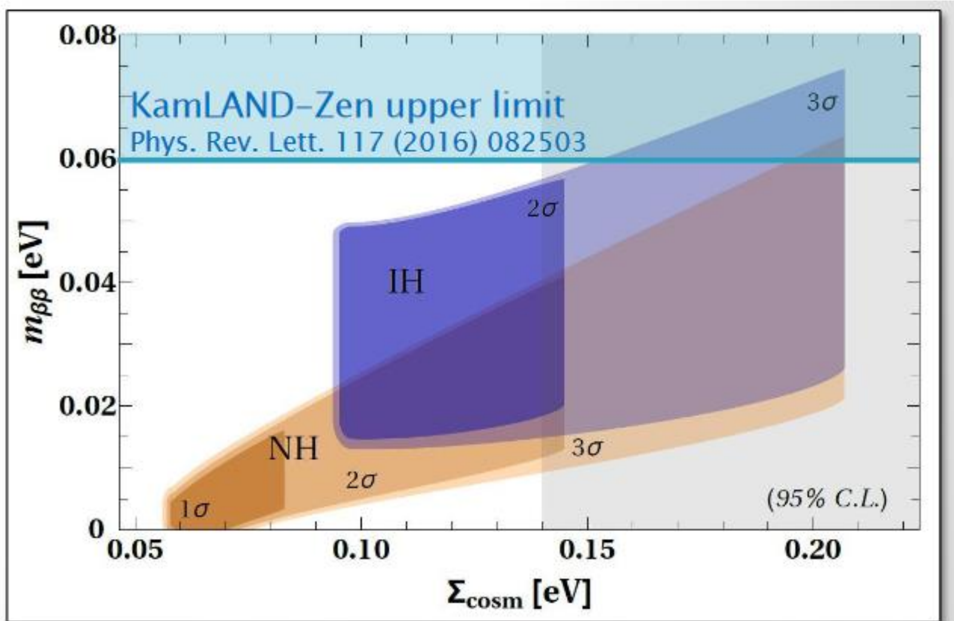
- potential discrepancy between neutrino mass (cosmology) and 0vbb half live measurement could be an indication for 0vbb triggered by non-standard mechanism

- distinguishing between different mechanisms via measurements in different isotopes



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

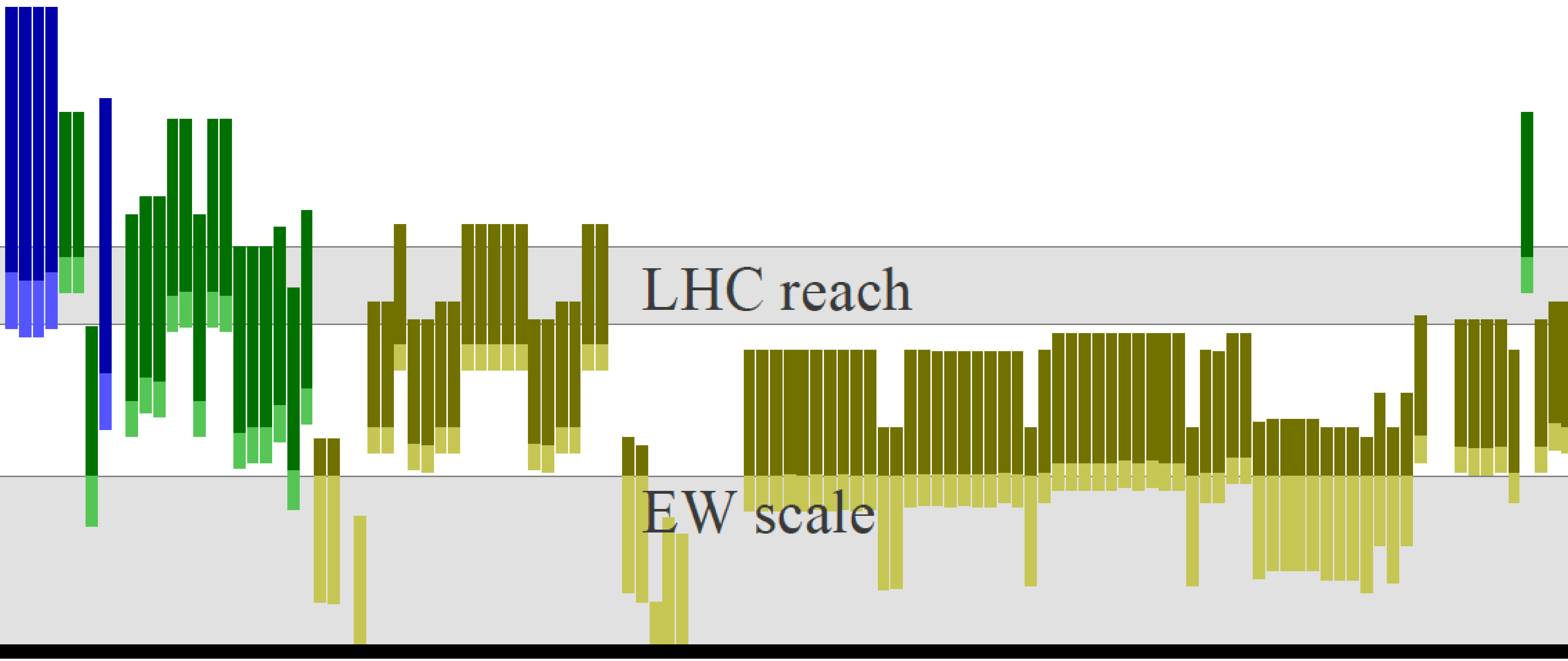
Deppisch, Paes, PRL 98 (2007)
Gehmann, Elliott, J. Phys G 34 (2007)



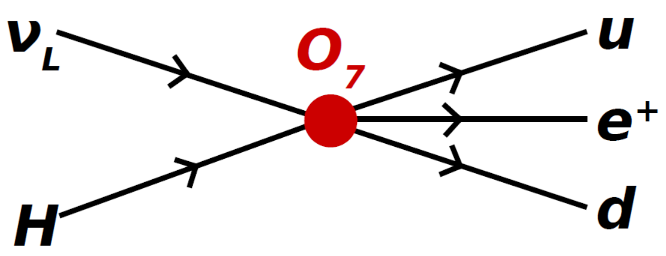
Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

- observation of $0\nu\beta\beta$ via O_9 and O_{11} will imply observation of LNV at LHC

Falsifying Baryogenesis refined

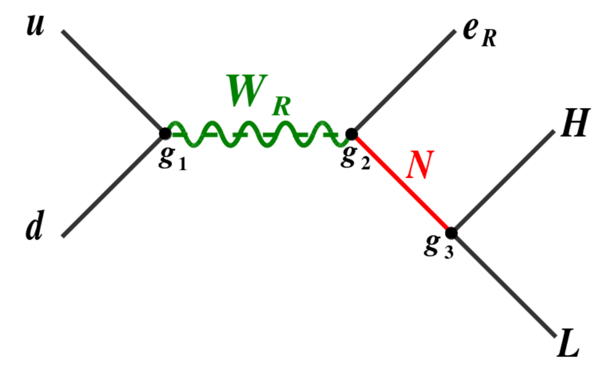


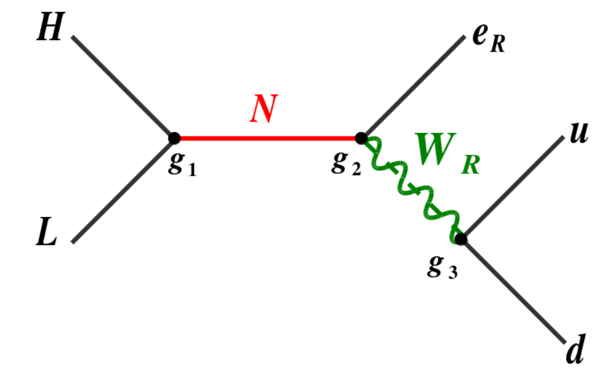
Comparison with UV complete Model

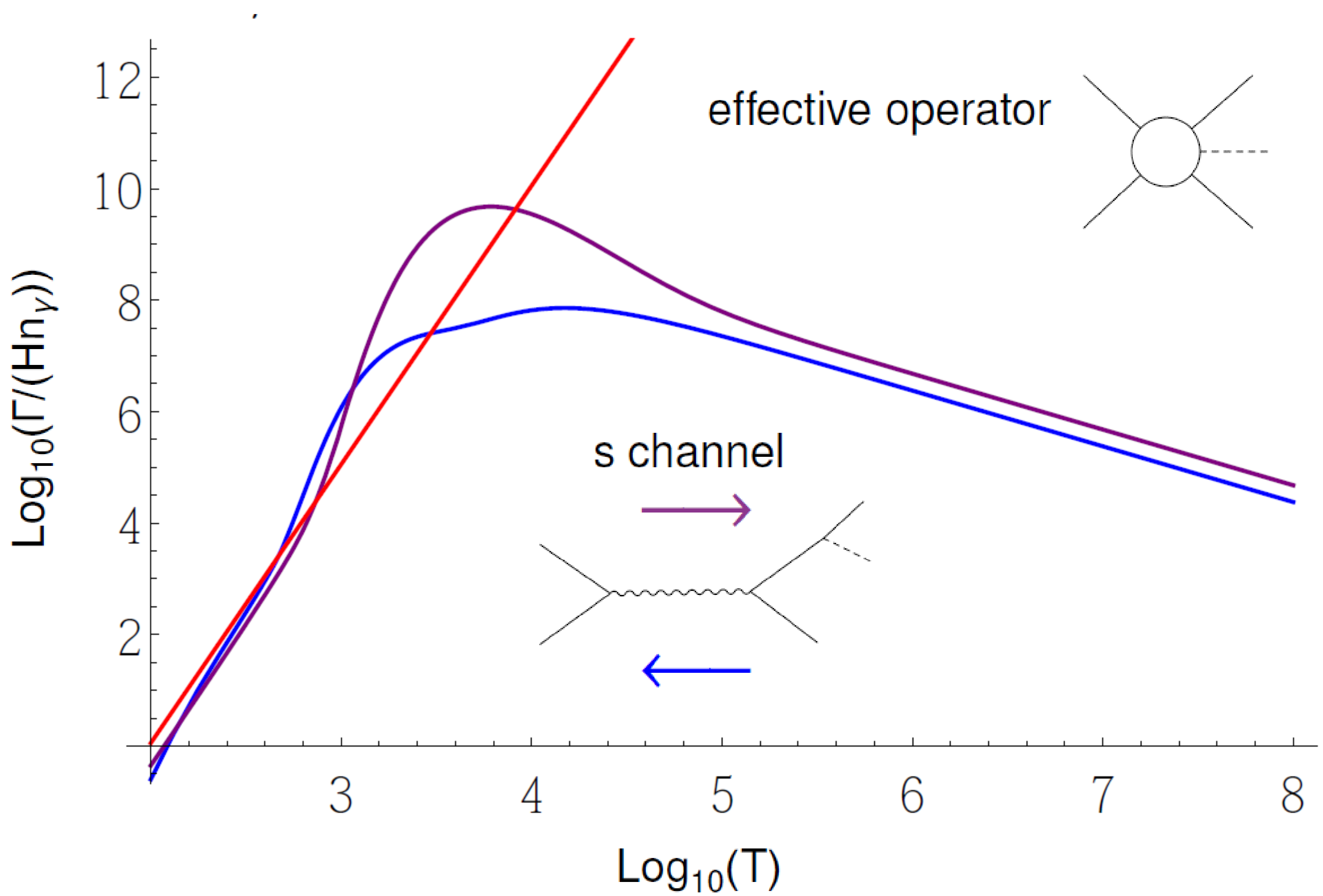


$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c})H^j\epsilon_{ij}$$

$$\Lambda_7^6 = m_{W_R}^4 m_N^2$$







effective operator approach is a conservative estimation of washout rate

Lepton Number violating effective operators

So far, we studied for **each** dimension **one** operator to show the impact exemplarily

$\mathcal{O}$	Operator
1	$L^iL^jH^kH^l\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
3_b	$L^iL^jQ^kd^cH^l\epsilon_{ik}\epsilon_{jl}$
4_a	$L^iL^j\overline{Q}_i\overline{u^c}H^k\epsilon_{jk}$
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	$L^iL^jQ^kd^c\overline{Q}_j\overline{u^c}H^l\overline{H}_i\epsilon_{kl}$
28_b	$L^iL^jQ^kd^c\overline{Q}_k\overline{u^c}H^l\overline{H}_i\epsilon_{jl}$
28_c	$L^iL^jQ^kd^c\overline{Q}_l\overline{u^c}H^l\overline{H}_i\epsilon_{jk}$
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	$L^iL^j\overline{L}_i\overline{e^c}\overline{Q}_k\overline{u^c}H^kH^l\epsilon_{jl}$
30_b	$L^iL^j\overline{L}_m\overline{e^c}\overline{Q}_n\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
31_a	$L^iL^j\overline{Q}_i\overline{d^c}\overline{Q}_k\overline{u^c}H^kH^l\epsilon_{jl}$

$\mathcal{O}$	Operator
31_b	$L^iL^j\overline{Q}_m\overline{d^c}\overline{Q}_n\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
32_a	$L^iL^j\overline{Q}_j\overline{u^c}\overline{Q}_k\overline{u^c}H^k\overline{H}_i$
32_b	$L^iL^j\overline{Q}_m\overline{u^c}\overline{Q}_n\overline{u^c}H^k\overline{H}_i\epsilon_{jk}\epsilon^{mn}$
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	$L^iL^j\overline{Q}_i\overline{u^c}H^kQ^rd^c\overline{H}_r\epsilon_{jk}$
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	$L^i\overline{e^c}\overline{u^c}d^cH^jQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$

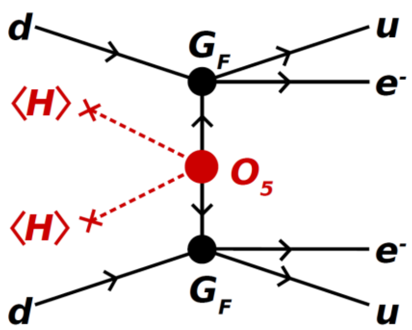
Exhaustive study:

- Study them **all**
- contribution to lower dimensional operator (**loop effects**)
- compile **complete list** of **washout strength** for each operator

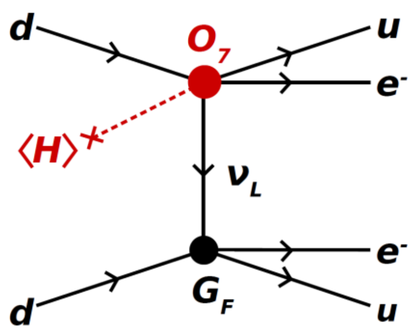
K. S. Babu, C. N. Leung, Nucl. Phys. B 619 (2001), arxiv:0106054 [hep-ph]
A. de Gouvea, J. Jenkins, PRD 77 (2008), arXiv:0708.1344 [hep-ph]

Lepton Number violating effective operators

at tree level



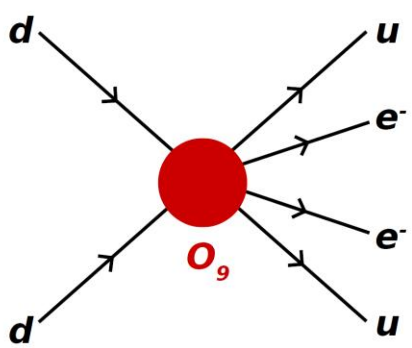
$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik} \epsilon_{jl}$$



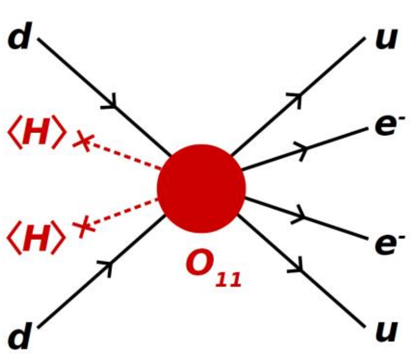
$$\mathcal{O}_7{}^{3a} = L^i L^j Q^k d^c H^l \epsilon_{ij} \epsilon_{kl} \quad \mathcal{O}_7{}^{4a} = L^i L^j \overline{Q}_i \bar{u^c} H^k \epsilon_{jk}$$

$$\mathcal{O}_7{}^{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik} \epsilon_{jl} \quad \mathcal{O}_7{}^{4b} = L^i L^j \overline{Q}_k \bar{u^c} H^k \epsilon_{ij}$$

$$\mathcal{O}_7{}^{8} = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$$



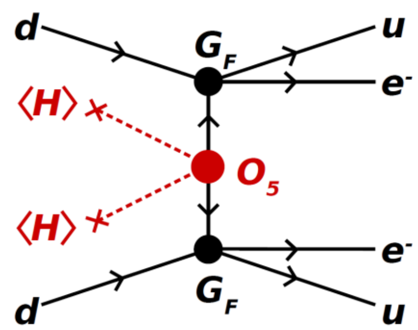
18 different 9-dim operators



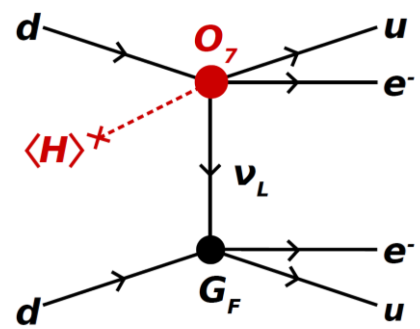
105 different 11-dim operators

Lepton Number violating effective operators

including loop effects



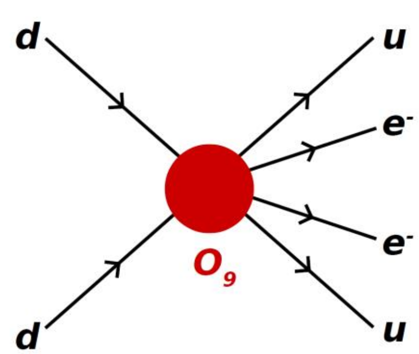
$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik} \epsilon_{jl}$$



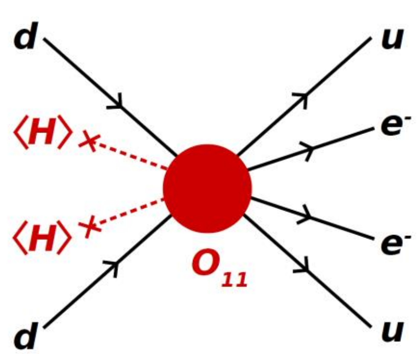
$$\mathcal{O}_7{}^{3a} = L^i L^j Q^k d^c H^l \epsilon_{ij} \epsilon_{kl} \quad \mathcal{O}_7{}^{4a} = L^i L^j \overline{Q}_i \bar{u^c} H^k \epsilon_{jk}$$

$$\mathcal{O}_7{}^{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik} \epsilon_{jl} \quad \mathcal{O}_7{}^{4b} = L^i L^j \overline{Q}_k \bar{u^c} H^k \epsilon_{ij}$$

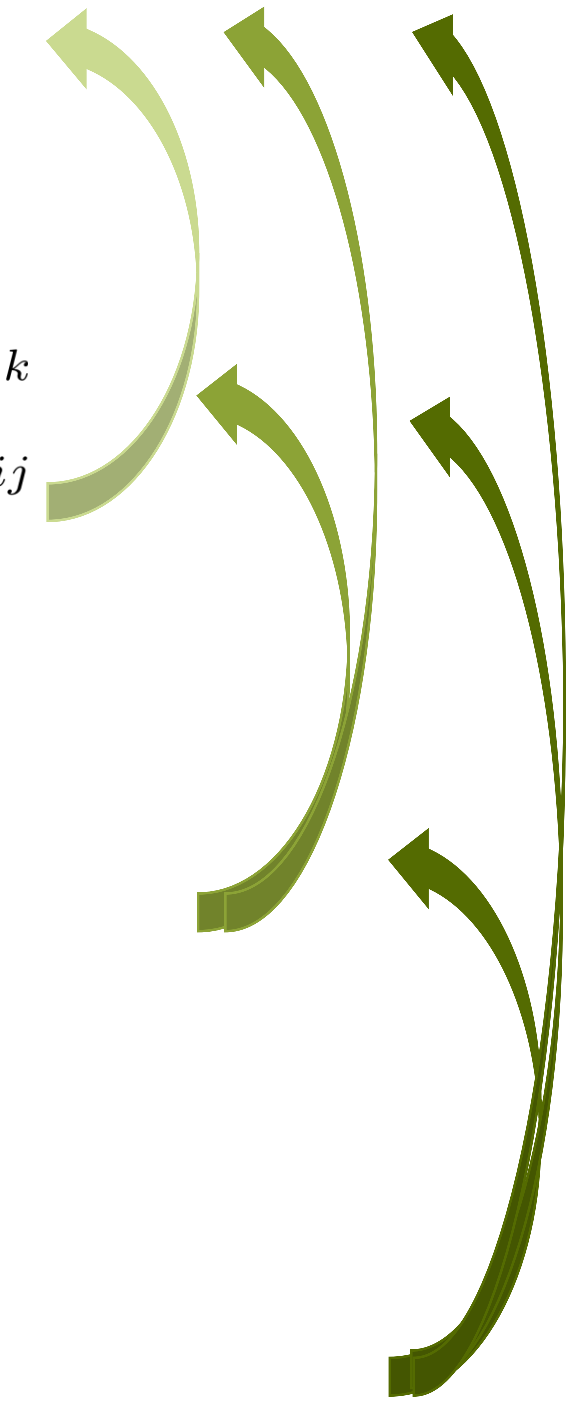
$$\mathcal{O}_7{}^{8} = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$$



18 different 9-dim operators



105 different 11-dim operators



Why is it of interest?

Many different effects do interplay!

7 dim – tree level

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

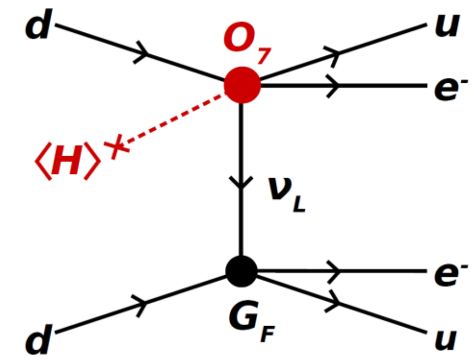
$$\mathcal{O}_7{}^{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}$$

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

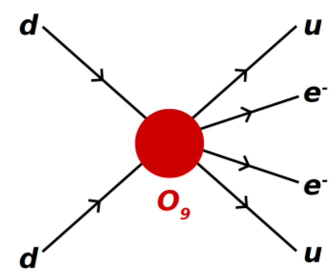
$$\mathcal{O}_7{}^{4b} = L^i L^j \overline{Q}_k \bar{u^c} H^k \epsilon_{ij}$$

$$\mathcal{O}_7{}^{8} = L^i \bar{e^c} \bar{u^c} d^c H^j \epsilon_{ij}$$

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



9 dim with 3 Higgs doublets



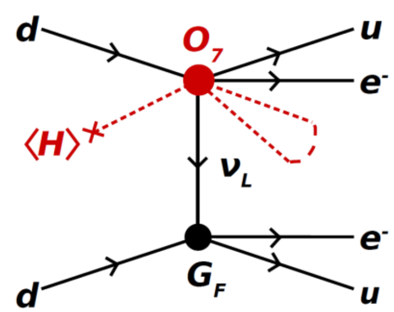
$$\mathcal{O}_9{}^{5} = L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km}$$

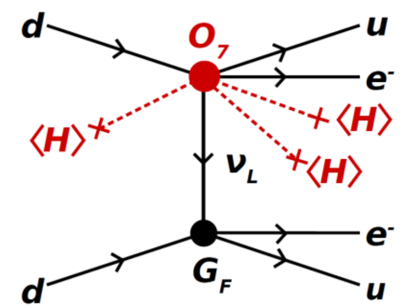
$$e_L \nu_L u_L d^c h^0 h^0 \bar{h}^0$$

$$\mathcal{O}_9{}^{6} = L^i L^j \overline{Q}_k \bar{u^c} H^l H^k \bar{H}_i \epsilon_{jl}$$

$$e_L \nu_L \bar{d}_L \bar{u}^c h^0 h^0 \bar{h}^0$$

$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{v}{16\pi^2 \Lambda_9{}^3} + \frac{v^3}{\Lambda_9{}^5}$$





comparable if $\Lambda < 2187\text{GeV}$

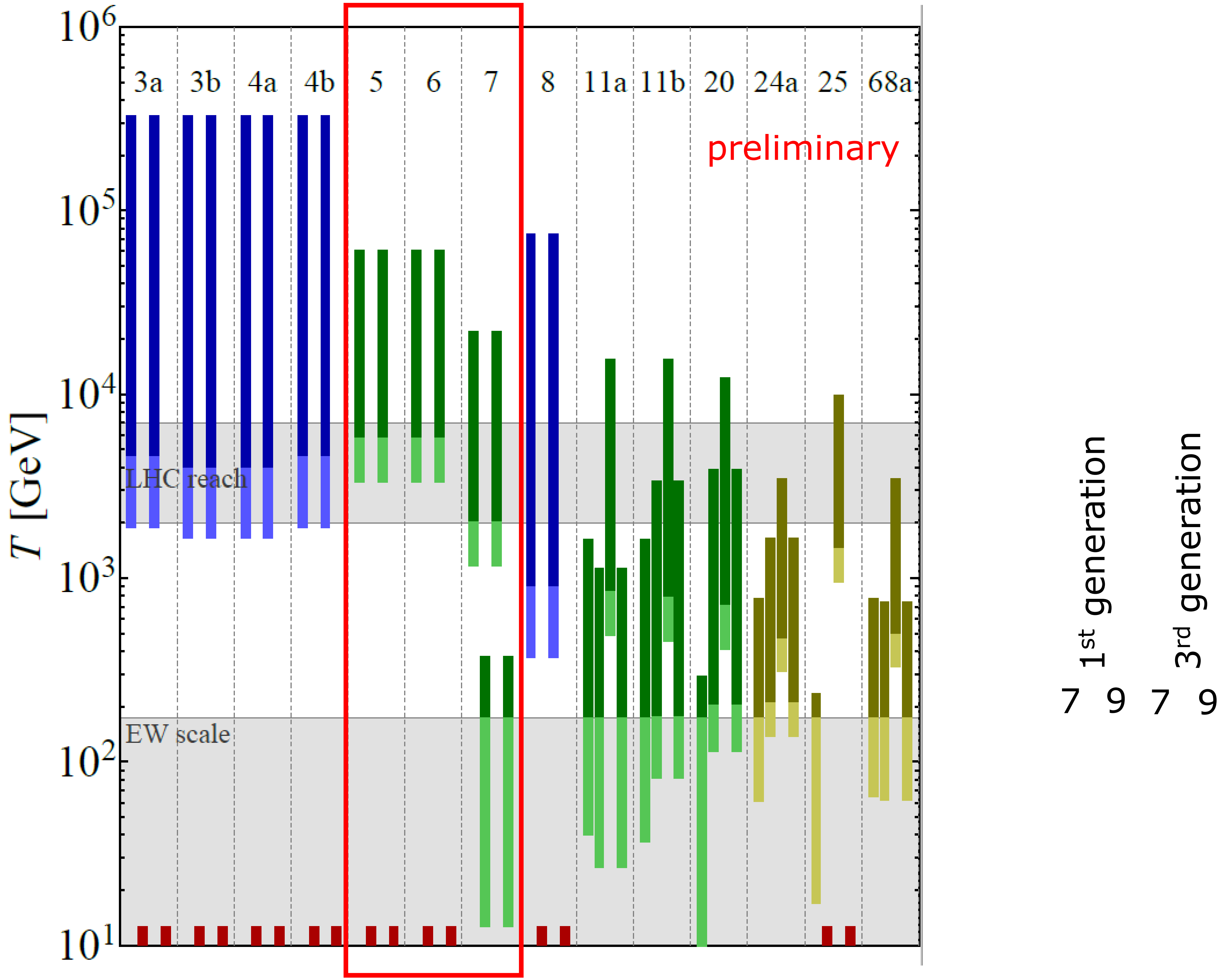
$$\mathcal{O}_9{}^{7} = L^i Q^j \bar{e}^c \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm}$$

$$\nu_L u_L \bar{e}^c \bar{d}_L h^0 h^0 h^0$$

$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{v^3}{\Lambda_9{}^5}$$

short range contribution suppressed,
long range dominant

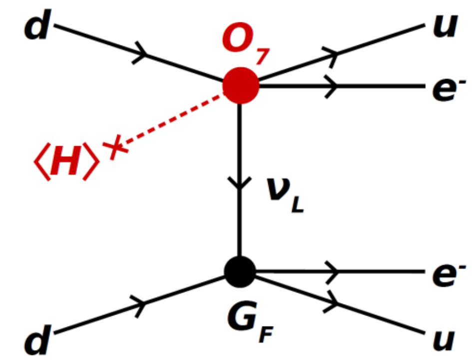
Effective washout range



Why is it of interest?

Dependence on experimental sensitivity

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



$$\mathcal{O}_7{}^{3a} = L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}$$
$$\mathcal{O}_7{}^{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}$$
$$\mathcal{O}_9{}^{5} = L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{jl}\epsilon_{km}$$

$\Big\}\; e_L \nu_L u_L d^c \;\Rightarrow\; \epsilon^{S+P}_{S+P}$

$$\mathcal{O}_7{}^{4a} = L^i L^j \overline{Q}_i \bar{u}^c H^k \epsilon_{jk}$$
$$\mathcal{O}_7{}^{4b} = L^i L^j \overline{Q}_k \bar{u}^c H^k \epsilon_{ij}$$
$$\mathcal{O}_9{}^{6} = L^i L^j \overline{Q}_k \bar{u}^c H^l H^k \bar{H}_i \epsilon_{jl}$$

$\Big\}\; e_L \nu_L \bar{d}_L \bar{u}^c \;\Rightarrow\; \epsilon^{S+P}_{S-P}$

$$\mathcal{O}_9{}^{7} = L^i Q^j \bar{e}^c \bar{Q}_k H^k H^l H^m \epsilon_{il}\epsilon_{jm}$$

$\Big\}\; \nu_L u_L \bar{e}^c \bar{d}_L \;\Rightarrow\; \frac{1}{2}\epsilon^{V+A}_{V-A}$

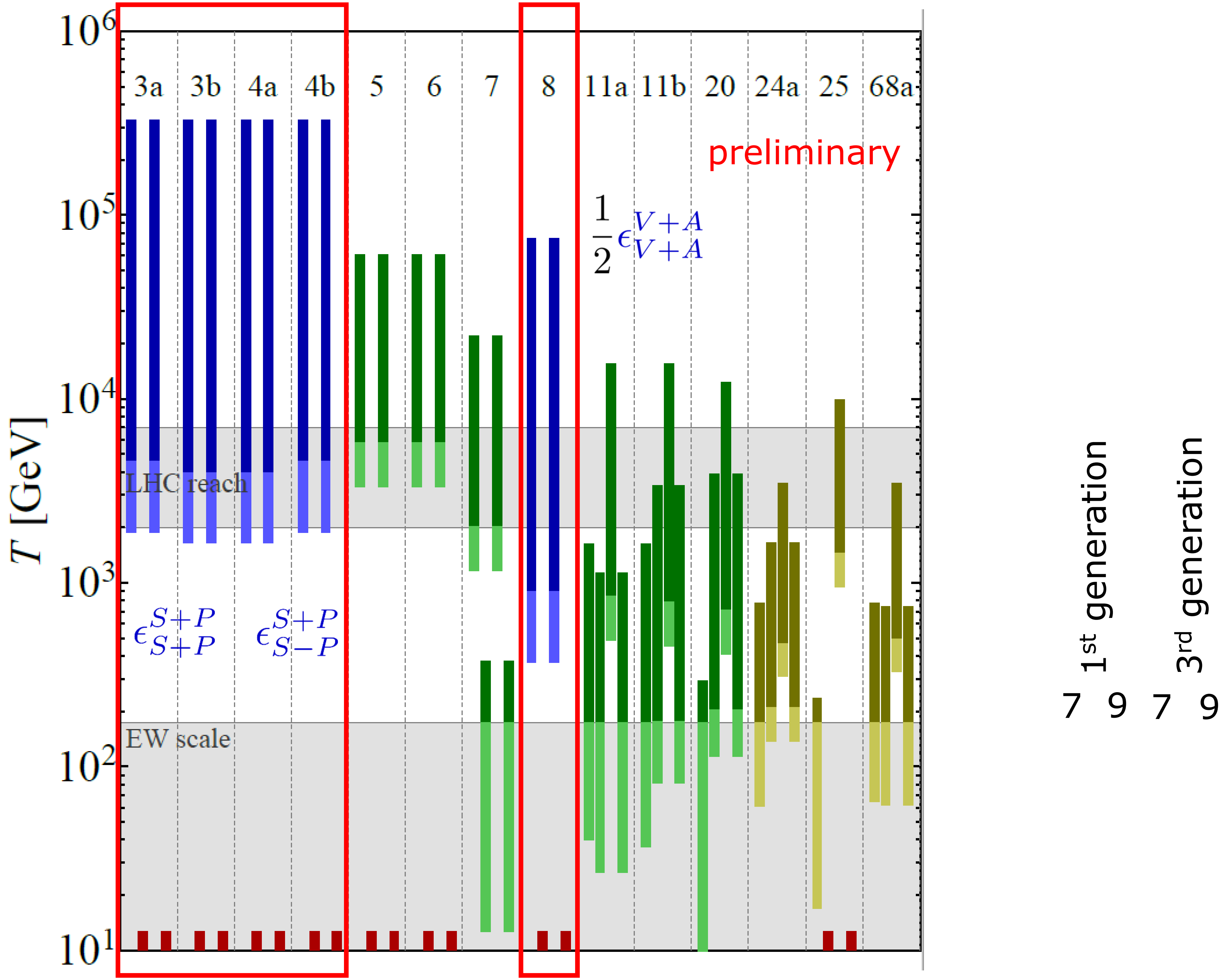
$$\mathcal{O}_7{}^{8} = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}$$

$\Big\}\; \nu_L \bar{e}^c \bar{u}^c d^c \;\Rightarrow\; \frac{1}{2}\epsilon^{V+A}_{V+A}$

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	$3.3\cdot10^{-9}$	$5.9\cdot10^{-7}$	$1.0\cdot10^{-8}$	$1.0\cdot10^{-8}$	$6.4\cdot10^{-10}$	$1.0\cdot10^{-9}$
^{136}Xe	$2.6\cdot10^{-9}$	$5.1\cdot10^{-7}$	$6.2\cdot10^{-9}$	$6.2\cdot10^{-9}$	$4.4\cdot10^{-10}$	$7.4\cdot10^{-10}$

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

Effective washout range

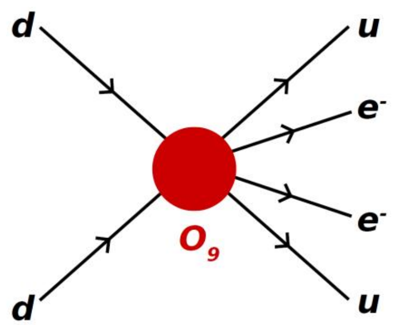


Why is it of interest?

Crucial dependence on SU(2) structure and Yukawa couplings

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

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

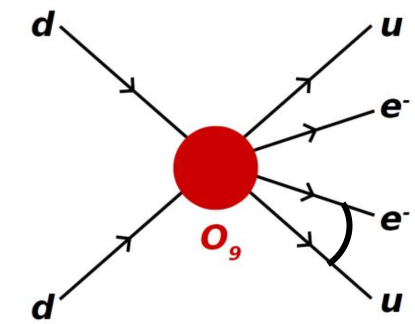


at tree level

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

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

(flavour structure!)

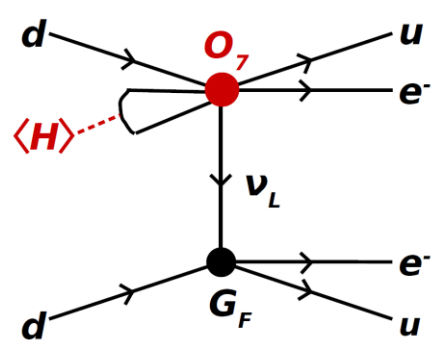


only at one loop

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

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

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

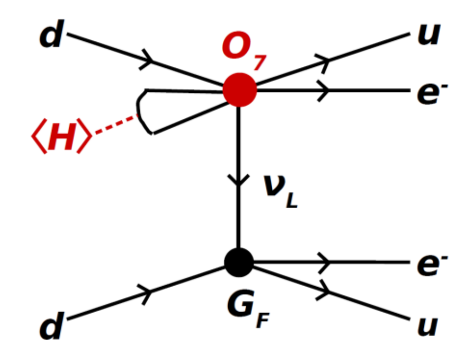


same

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

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

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



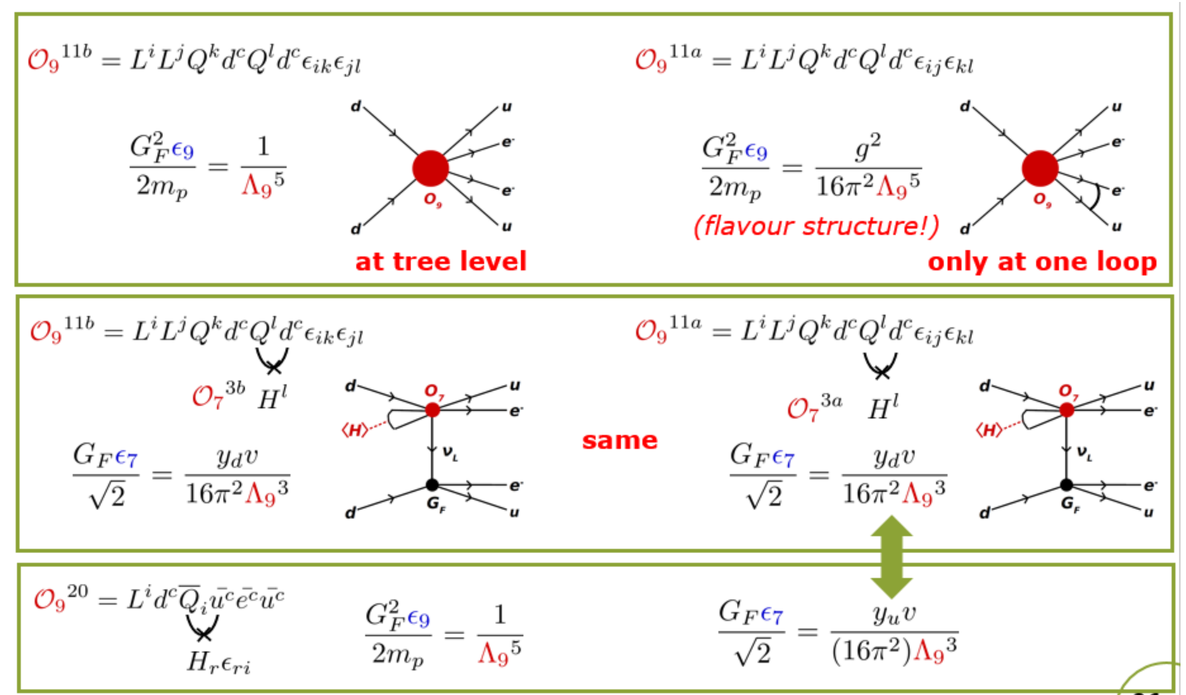
$\mathcal{O}_9{}^{20} = L^i d^c \overline{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c$

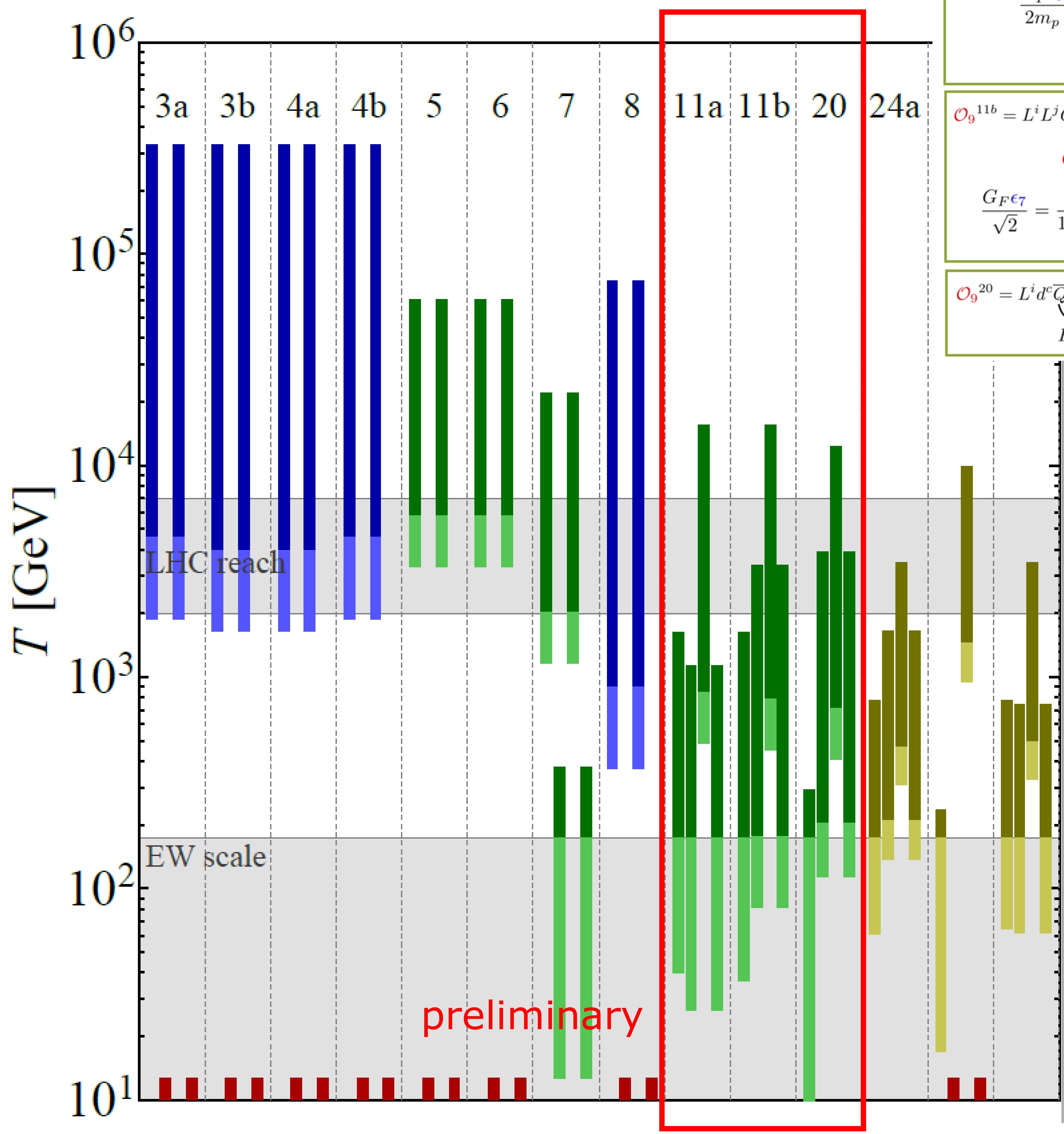
$H_r \epsilon_{ri}$

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

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

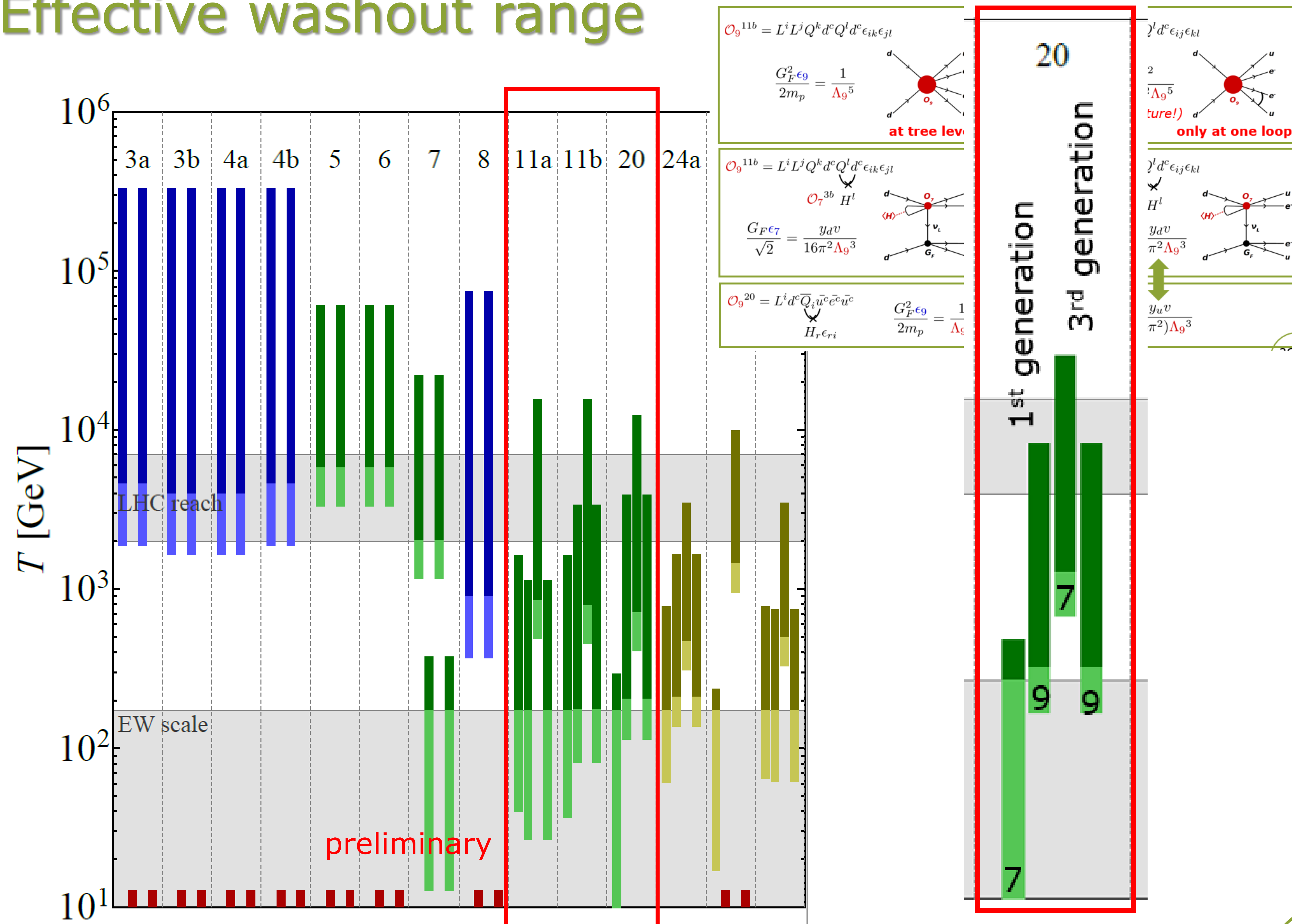
Effective washout range





1st generation
3rd generation
7 9 7 9

Effective washout range



Why is it interesting?

Same for 11dim…

$$\mathcal{O}_{11}{}^{24a} = L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{jk} \epsilon_{lm}$$

11D to 9D

$$\mathcal{O}_{11}{}^{24a} = L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{jk} \epsilon_{lm}$$

$$e_L e_L \bar{h}^0 u_L d^c u_L d^c h^0$$

$$\frac{G_F^2 \epsilon_9}{2 m_p} = \frac{1}{16\pi^2 \Lambda_{11}{}^5} + \frac{v^2}{\Lambda_{11}{}^7}$$

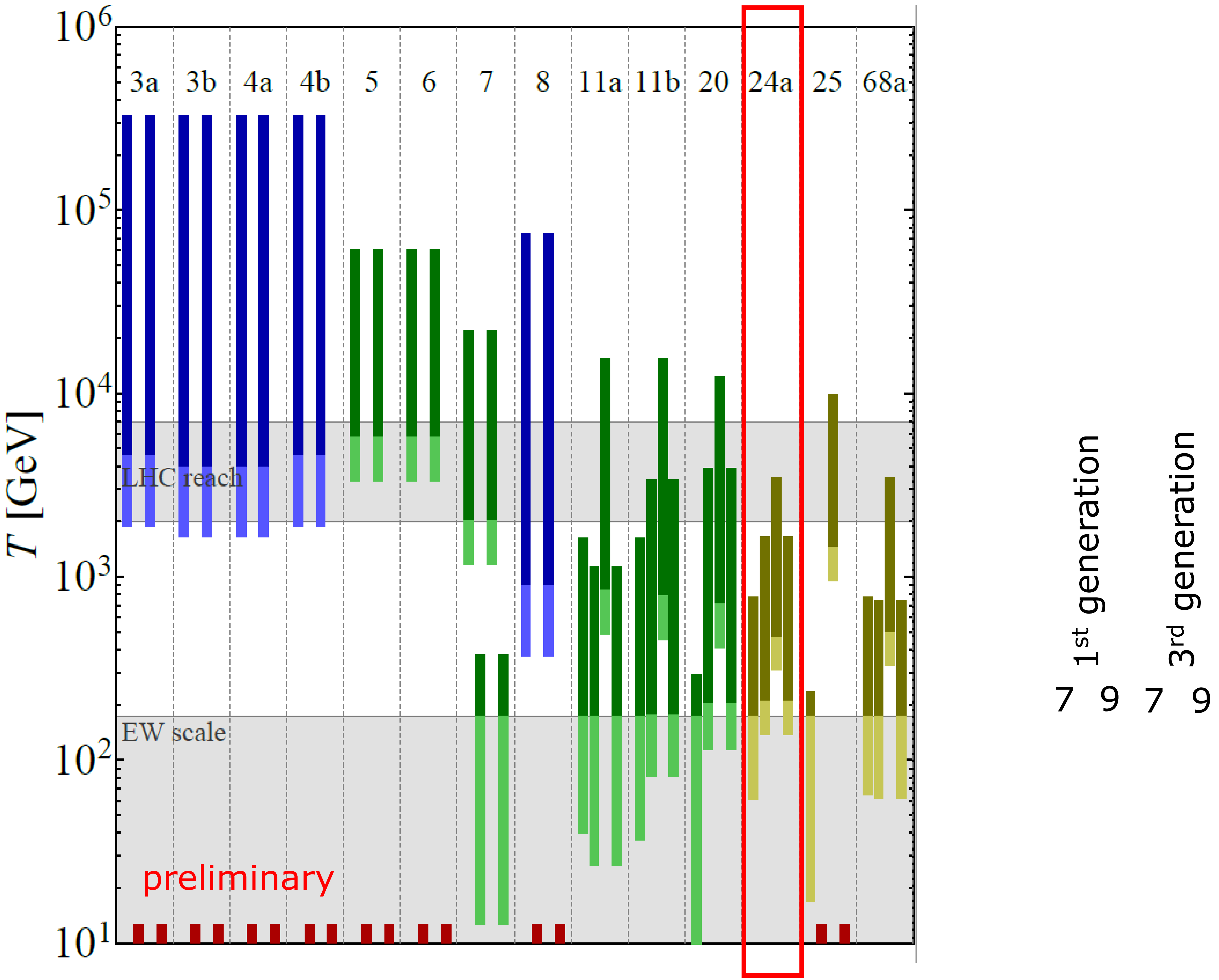
11D to 7D

$$\mathcal{O}_{11}{}^{24a} = L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{jk} \epsilon_{lm}$$

$$e_L \nu_L h^0 d^c \bar{h}^0 u_L h^0$$

$$\frac{G_F \epsilon_7}{\sqrt{2}} = \frac{y_d v}{(16\pi^2)^2 \Lambda_{11}{}^3} + \frac{y_d v^3}{16\pi^2 \Lambda_{11}{}^5}$$

Effective washout range



Automatization

(A) Constraining the operator scale

1) SU(2) decomposition

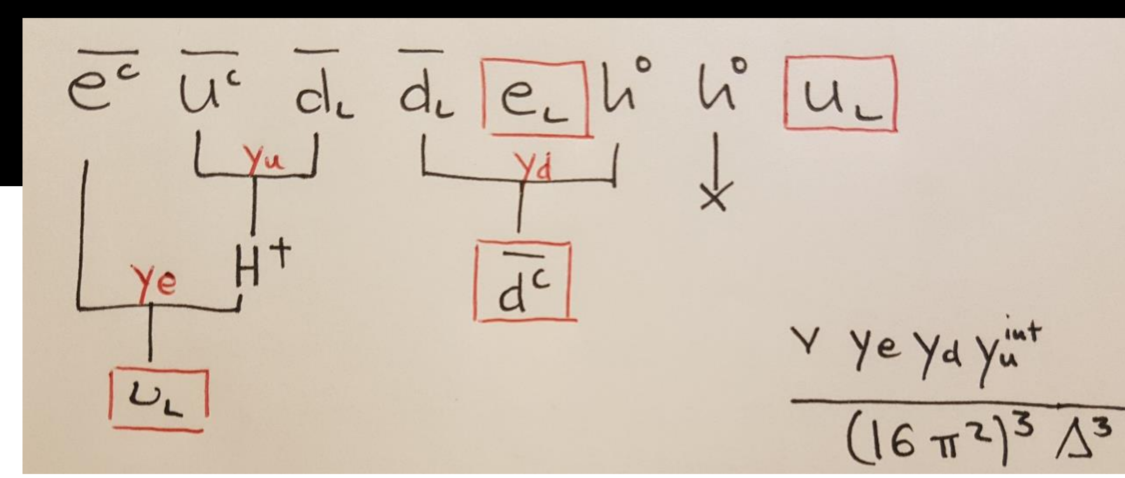
2) Reduce every operator to every operator equal and lower in dimension

3) find the dominant contribution for every combination
   (*start and ending operator*)

```
# 1,2,1,1,1,9,9|1,3,1,1,1,9,9|1,4,1,0,1,9,9|1,4,1,0,1,9,9|1,2,1,0,0,9,9|0,0,0,0,0,9,0|0,0,0,0,0,9,0|1,3,1,0,0,9,9

# 1,4,1,1,0,9,9|1,2,1,0,0,9,9|1,3,1,0,0,9,9|1,1,1,0,0,9,9

{{1,0} "(1/(16Pi^2)^3 vev^1 ye^1 yu^1 yd^1 " {2,1,0,0}[4, 1]{3,1,0,0}[7, 1]{1,1,0,0}[10, 4]{4,1,1,0}[11, 2] {11 23 27 28}
{11}
11|  {h}[5, 0]     |  {$}[-1, 0]
23|  {3,1,1,1}[1, 1]  {4,1,0,1}[2, 1]    |  {H+}[9, 2]
27|  {2,1,1,1}[0, 1]  {H+}[9, 2]    |  {1,1,0,0}[10, 4]
28|  {4,1,0,1}[3, 1]  {h}[6, 0]    |  {4,1,1,0}[11, 2]
```



4) Fierz transform (if necessary) to get the right effective coupling

5) identify the scale of the operator

Automatization

(A) Calculation of the Washout

1) Consider the reaction density of all different n to m processes

$$zHn_\gamma \frac{d\eta_N}{dz} = -\sum_{a,i,j,\cdots} [Na\cdots \leftrightarrow ij\cdots]$$

$$= -\sum_{a,i,j,\cdots} \frac{n_N n_a \cdots}{n_N^{\text{eq}} n_a^{\text{eq}} \cdots} \gamma^{\text{eq}}(Na\cdots \to ij\cdots) - \frac{n_i n_j}{n_i^{\text{eq}} n_j^{\text{eq}} \cdots} \gamma^{\text{eq}}(ij\cdots \to Na\cdots)$$

$$\gamma^{\text{eq}}(Na\cdots \to ij\cdots) = \prod_{a=1}^{n} \left[\int \frac{\mathrm{d}^3 p_a}{2E_a(2\pi)^3} e^{-\frac{E_a}{T}} \right] \times \prod_{i=1}^{m} \left[\int \frac{\mathrm{d}^3 p_i}{2E_i(2\pi)^3} e^{-\frac{E_i}{T}} \right]$$

$$\times (2\pi)^4 \delta^4 \left(\sum_{a=1}^{n} p_a - \sum_{i=1}^{m} p_i \right) |M|^2$$

$$\gamma^{\text{eq}}(Na\cdots \to ij\cdots) = \frac{2^{N_f-2}}{(2\pi)^{2N-3}} \times \bar{c}_{a,b} \times \frac{\Gamma(N+N_f/2-3)\,\Gamma(N+N_f/2-2)}{\Gamma(n)\Gamma(n-1)\Gamma(N-n)\Gamma(N-n-1)} \times \frac{T^{2N+N_f-4}}{\Lambda^{2N+N_f-8}}$$

$$\bar{c}_a = 1 \qquad \text{or} \qquad \bar{c}_b = \frac{1}{n^{n_f}(N-n)^{N_f-n_f}}$$

Automatization

(A) Calculation of the Washout

1) Consider the reaction density of all different n to m processes
2) relate chemical potentials

$$zHn_\gamma \frac{d\,\eta_{L_e}}{d\,z} = -[\nu_L \bar{d}^c \bar{u}_L \leftrightarrow u^c e^c u^c]$$
$$= -\left(\delta n_{\nu_L} + \delta n_{d^c} + \delta n_{u_L} - \delta n_{u^c} - \delta n_{e^c} - \delta n_{u^c}\right) \gamma^{\mathrm{eq}}(L_e \bar{e^c} \to \bar{u^c} \bar{d^c} H)$$

$$\mu_H = \frac{4}{21} \sum_{\ell=e,\mu,\tau} \mu_{L_\ell}, \quad \mu_{\bar{u^c}} = \frac{5}{63} \sum_{\ell=e,\mu,\tau} \mu_{L_\ell},$$
$$\mu_{\bar{e^c_\ell}} = \mu_{L_\ell} - \frac{4}{21} \sum_{\ell=e,\mu,\tau} \mu_{L_\ell}, \quad \mu_{\bar{d^c}} = -\frac{19}{63} \sum_{\ell=e,\mu,\tau} \mu_{L_\ell}.$$

3) Consider different channels and symmetry factors

(a) contractions

(b) same particles in initial / final state

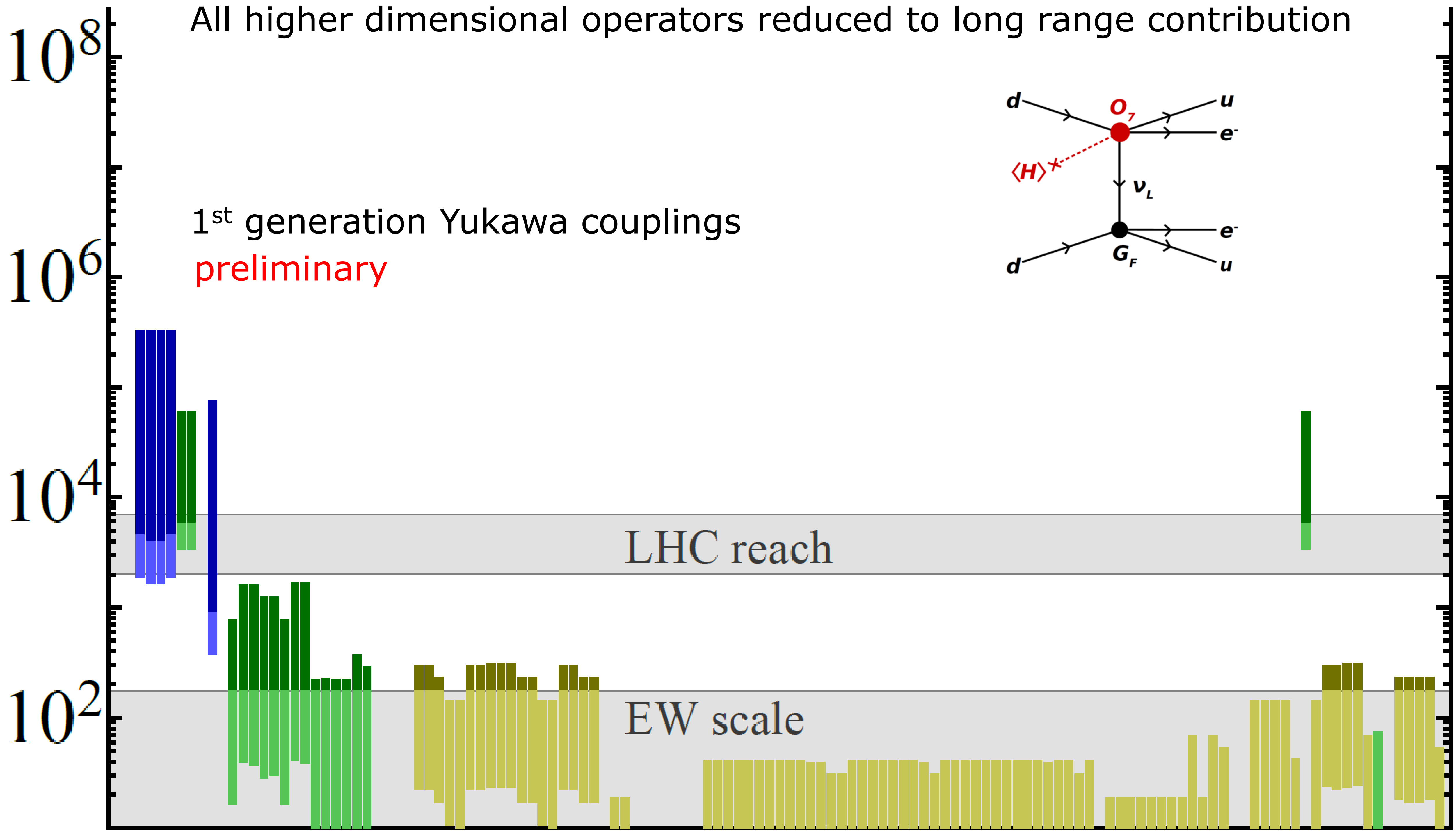
(c) flavour structure

$$\mathcal{O}_{911a} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ij} \epsilon_{kl}$$
$$\mathcal{O}_{911b} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ik} \epsilon_{jl}$$

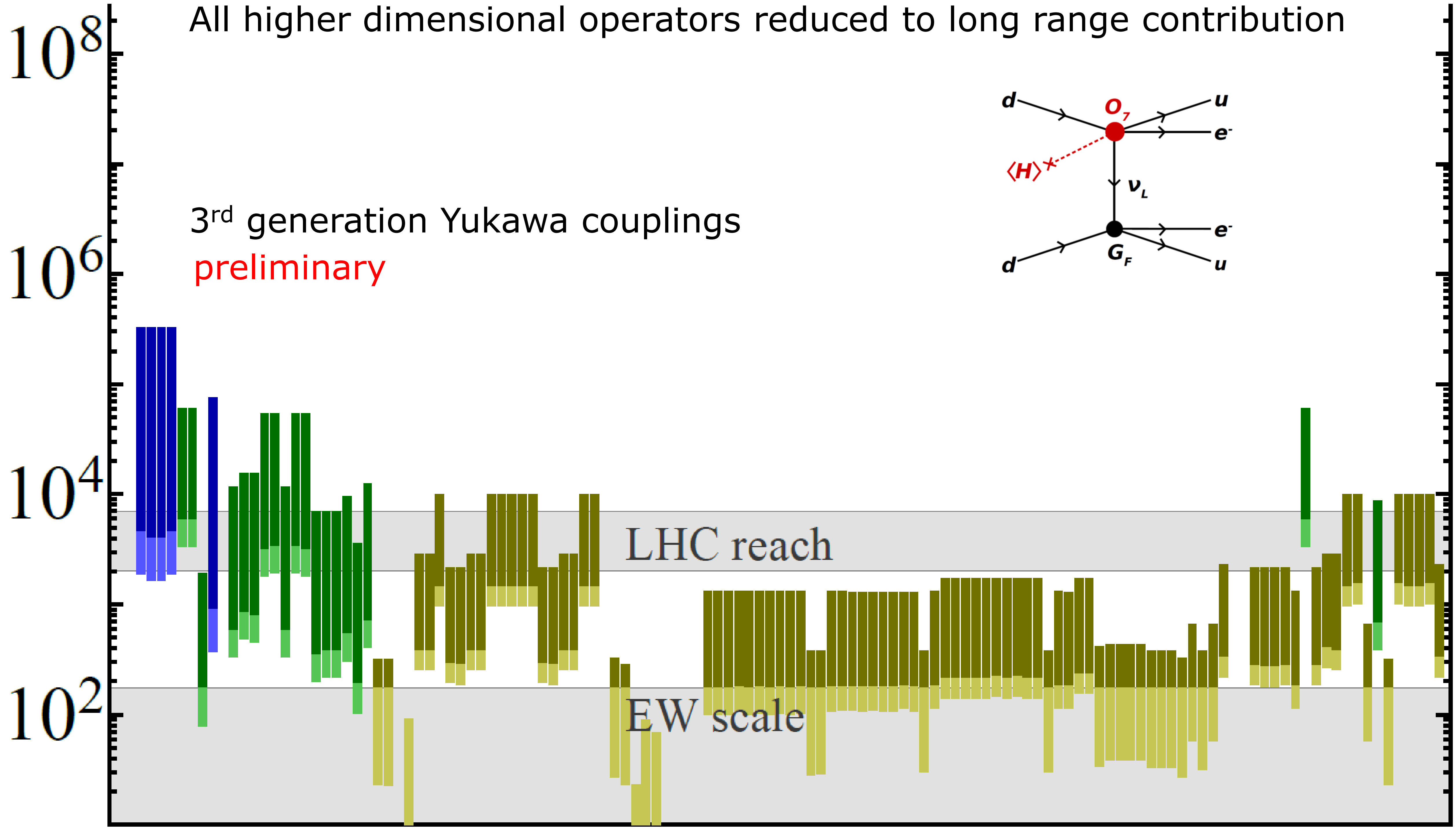
Finally result:

$$c_{20} = \frac{0.075\, T^{14}}{\Lambda^{10}}$$

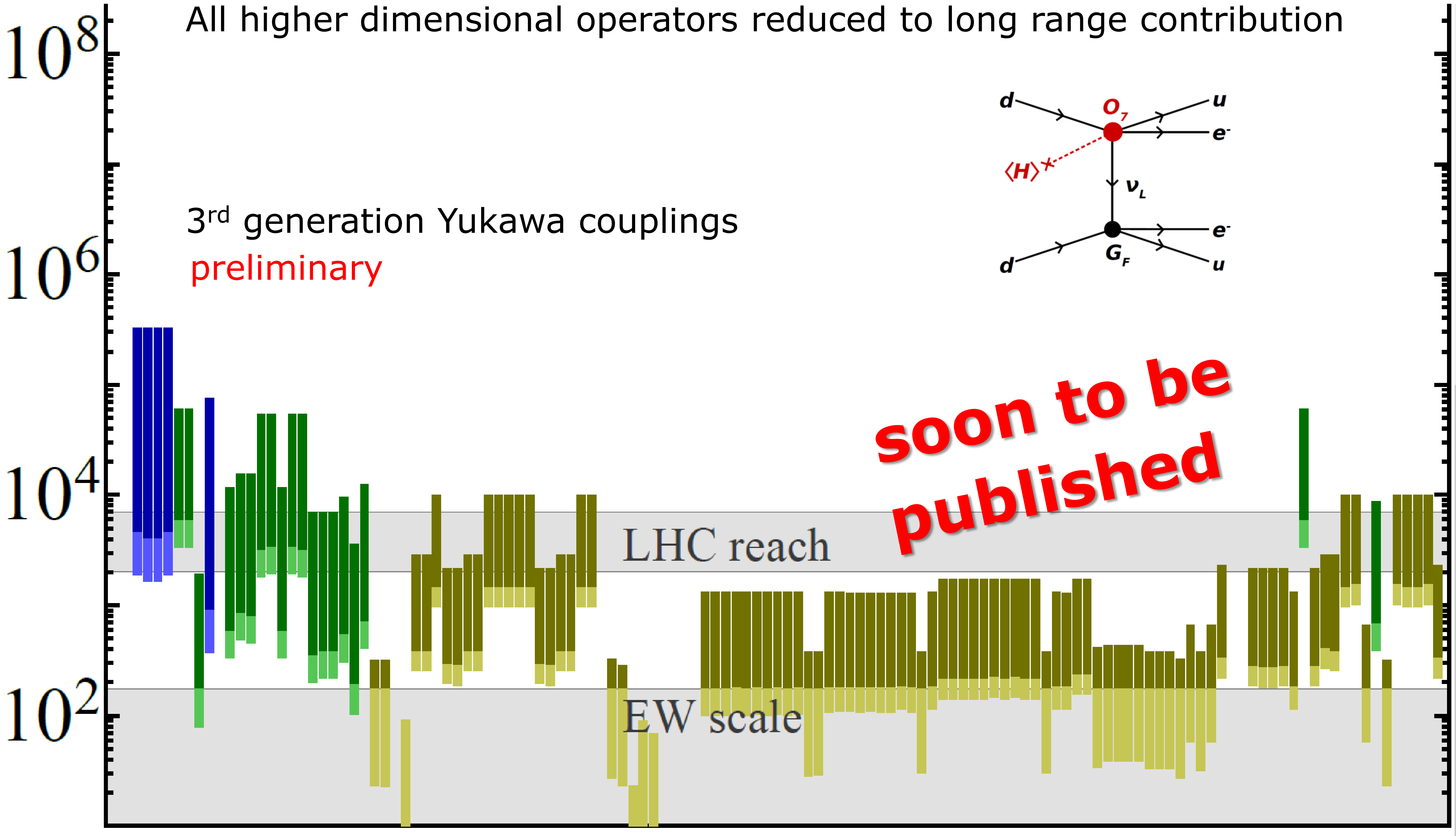
There are 129 of them…



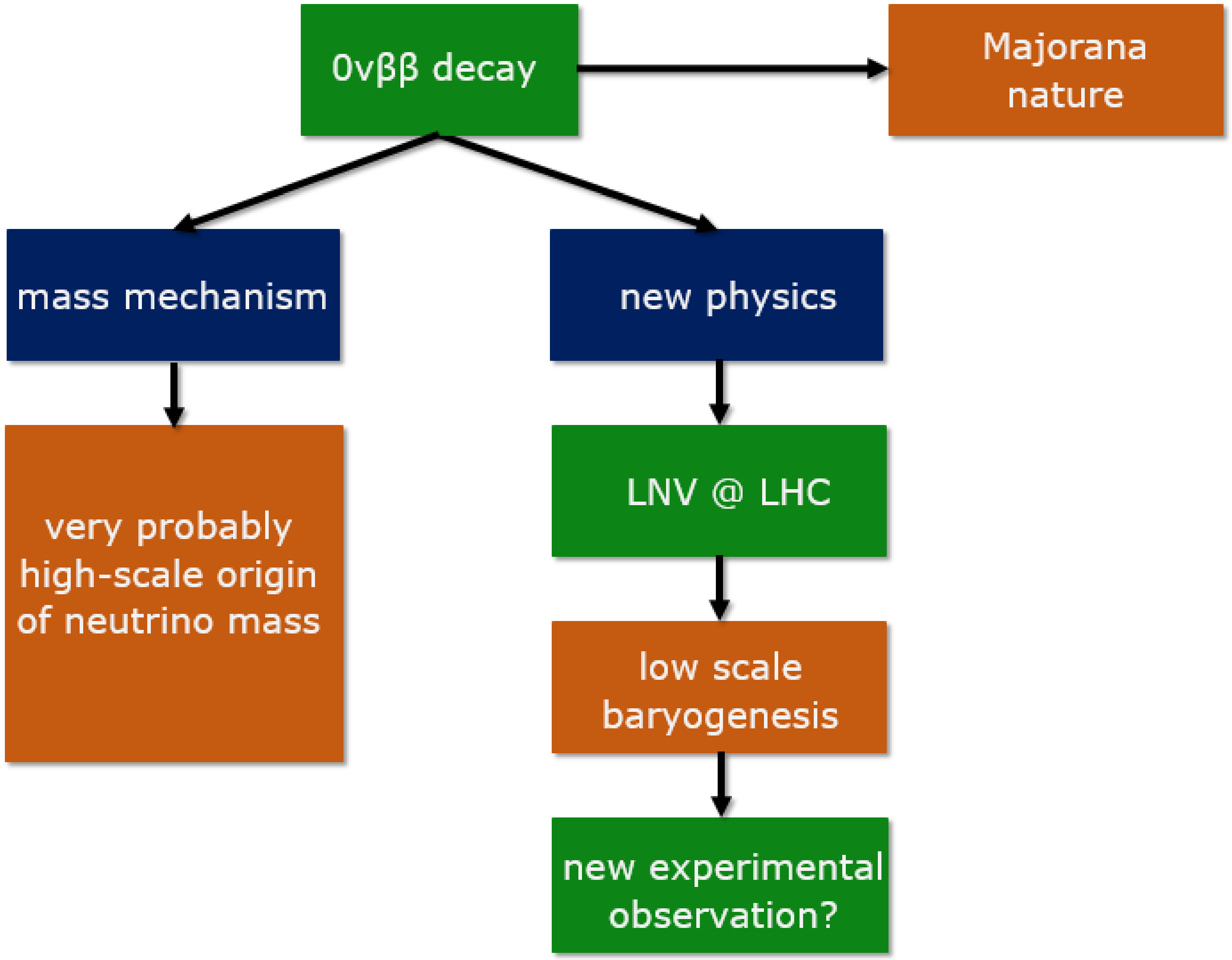
There are 129 of them…



There are 129 of them…



Conclusions



- LNV processes are of high interest with respect to the nature of baryogenesis
- possibility to falsify baryogenesis models!
- tight connection between different frontiers
- LNV and LFV interesting to look and search for