Falsifying Baryogenesis Mechanisms through Observation of Lepton Number and Flavour Violation

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in collaboration with

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

27/09/2016

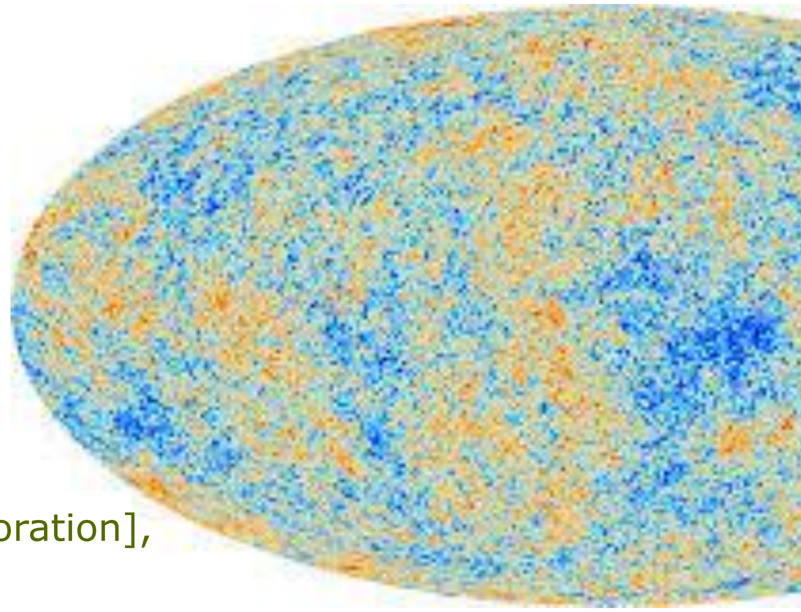
DESY Theory Workshop

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

Baryon Asymmetry



- observation of a baryon asymmetry of the Universe (BAU)

$$\eta_B^{\rm obs} = \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$$

P. A. R. Ade et al. [Planck Collaboration], arXiv:1502.01589 [astro-ph.CO]

- theoretical requirements for generating a baryon asymmetry: 3 Sakharov conditions

A. D. Sakharov, JETP Lett. 5, 24 (1967)

  - *C* and *CP* violation
  - departure from thermal equilibrium
  - (B-L)-violation

} not fully fulfilled within the Standard Model

⇓

physics beyond the Standard Model

- popular scenarios for explaining baryon asymmetry:
  - electroweak baryogenesis, leptogenesis, etc. …

How can we shed light on the underlying mechanism that generated the baryon asymmetry with current experiments?

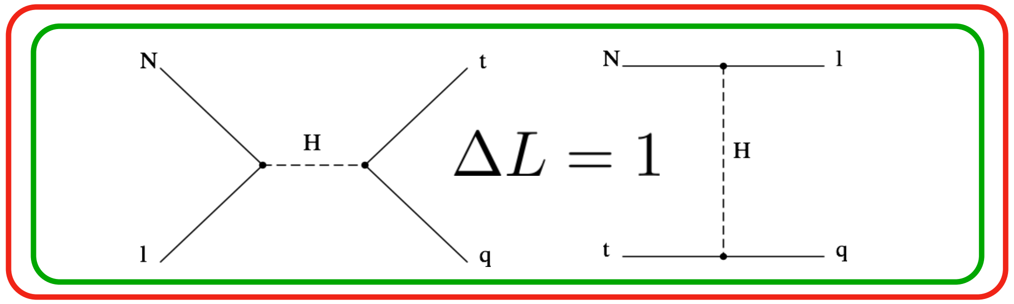
Example: Leptogenesis

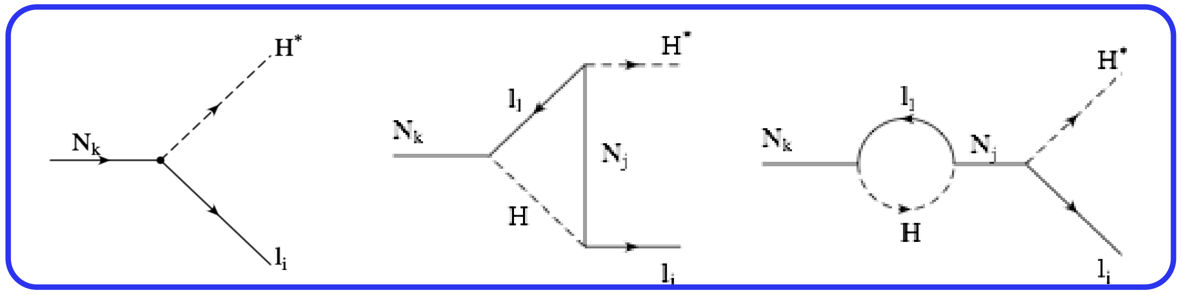
- generation of lepton asymmetry via heavy neutrino decays
- competition with lepton number violating (LNV) washout processes
- conversion to baryon asymmetry via sphaleron processes

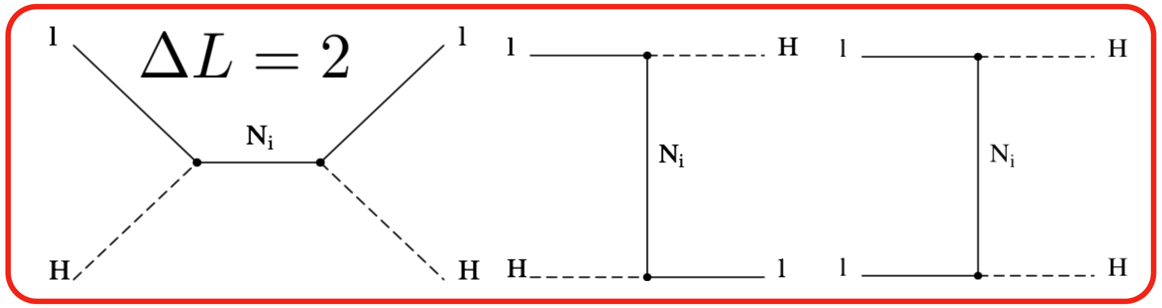
$$Hz\frac{dN_{N_1}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{\mathrm{eq}})$$

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

source of CP-asymmetry







washout processes

~~B-L~~

~~B+L~~

B asymmetry

washout highly efficient if: $\frac{\Gamma_W}{H} > 1$

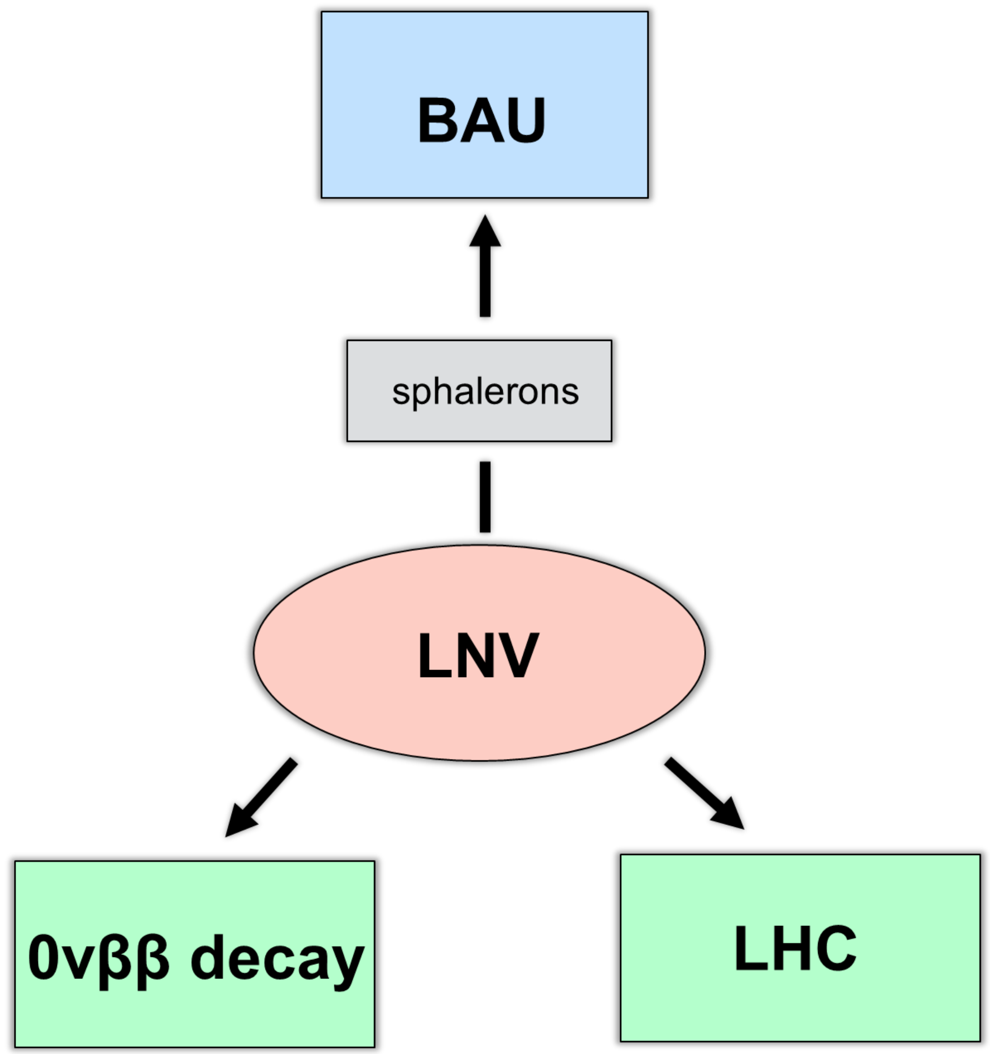
Lepton Number Violation (LNV)

- experimental observation of LNV implies existence of washout processes in the Early Universe
- due to sphaleron processes this allows for a measure of the corresponding baryon asymmetry washout

~~B-L~~

~~B+L~~

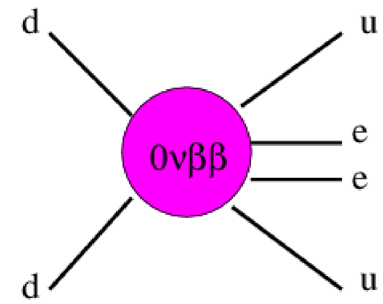
B washout



observation of low energy LNV will have far-reaching consequences on mechanisms of baryogenesis

Neutrinoless Double Beta Decay (0vbb)

- 0vββ ($2n \to 2p + 2e^-$) is a sensitive probe of low energy LNV



$\Delta L = 2$

- current experimental limits on the half life of 0vββ:

$T_{1/2}^{^{76}\mathrm{Ge}} > (1.1 - 1.9) \times 10^{25}$ y (EXO-200, KamLAND-Zen)

$T_{1/2}^{^{136}\mathrm{Xe}} > 2.1 \times 10^{25}$ y (GERDA)

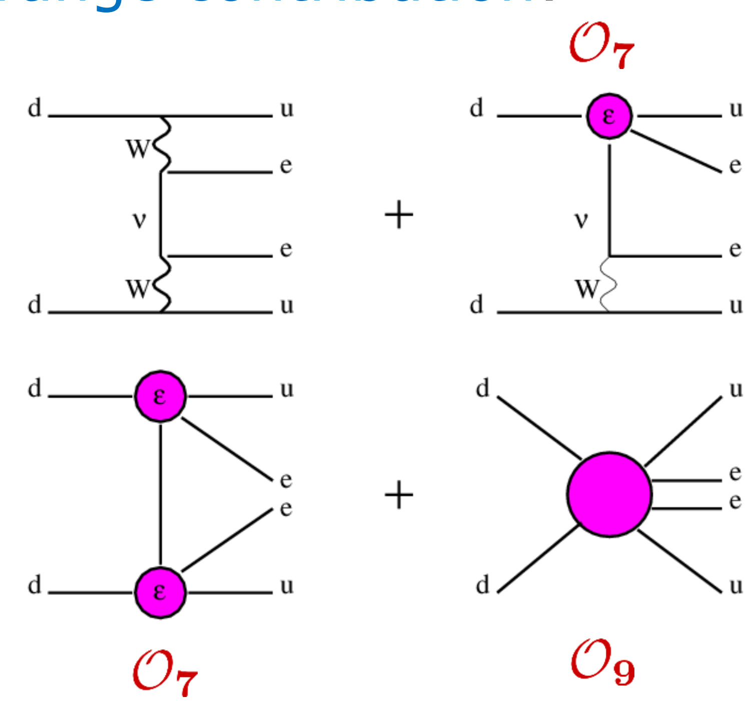
- general Lagrangian describing different non-SM contributions to 0vββ can be written in terms of effective couplings ϵ_α^β , e.g. for the long range contribution:

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

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

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

$$T_{1/2}^{-1} = |\epsilon_\alpha^\beta|^2 G_i |M_i|^2$$



Isotope	$\lvert\epsilon_{V-A}^{V+A}\rvert$	$\lvert\epsilon_{V+A}^{V+A}\rvert$	$\lvert\epsilon_{S-P}^{S+P}\rvert$	$\lvert\epsilon_{S+P}^{S+P}\rvert$	$\lvert\epsilon_{TL}^{TR}\rvert$	$\lvert\epsilon_{TR}^{TR}\rvert$
^{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	$2.6 \cdot 10^{-9}$	$5.1 \cdot 10^{-7}$	$6.2 \cdot 10^{-9}$	$6.2 \cdot 10^{-9}$	$4.4 \cdot 10^{-10}$	$7.4 \cdot 10^{-10}$

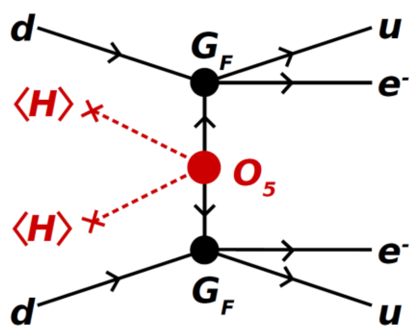
F. Deppisch, M. Hirsch, H. Päs, J. Phys. G 39 (2012) 124007, arXiv:1208.0727 [hep-ph], updated

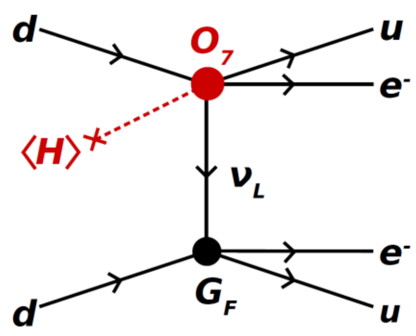
0vββ half life sets constraints on effective couplings ϵ_α^β

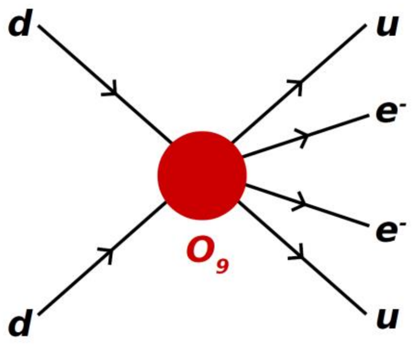
Possible underlying LNV Operators

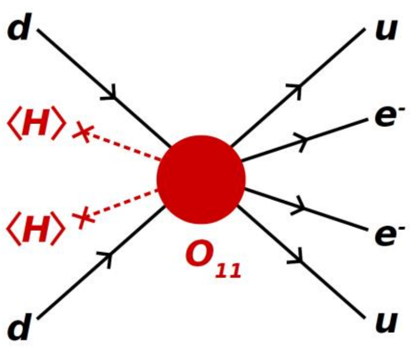
- four examples from the complete list of all possible LNV $\Delta L = 2$ effective operators

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 was observed, the scale of the underlying operator can be determined

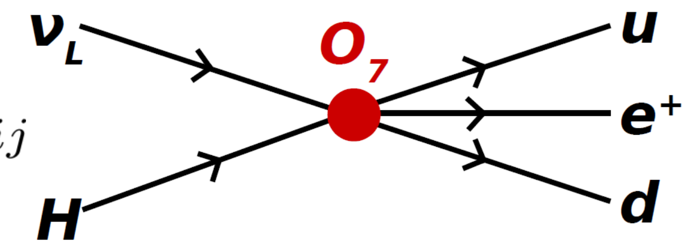
$$m_e \epsilon_5 = \frac{g^2 v^2}{\Lambda_5} \qquad \frac{G_F \epsilon_7}{\sqrt{2}} = \frac{g^3 v}{2{\Lambda_7}^3} \qquad \frac{G_F^2 \epsilon_{\{9,11\}}}{2 m_p} = \left\{ \frac{g^4}{{\Lambda_9}^5}, \frac{g^6 v^2}{{\Lambda_{11}}^7} \right\}$$

$\mathcal{O}_D$	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 – we take now as an example $\mathcal{O}_7$

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



$$zHn_\gamma \frac{d\eta_N}{dz} = -\sum_{a,i,j,\cdots}\left(\frac{n_N n_a \cdots}{n_N^{\rm eq} n_a^{\rm eq}\cdots} - \frac{n_i n_j \cdots}{n_i^{\rm eq} n_j^{\rm eq}\cdots}\right)\gamma^{\rm eq}(Na\cdots \leftrightarrow ij\cdots)$$

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

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

c_D operator specific factor

η_L lepton density

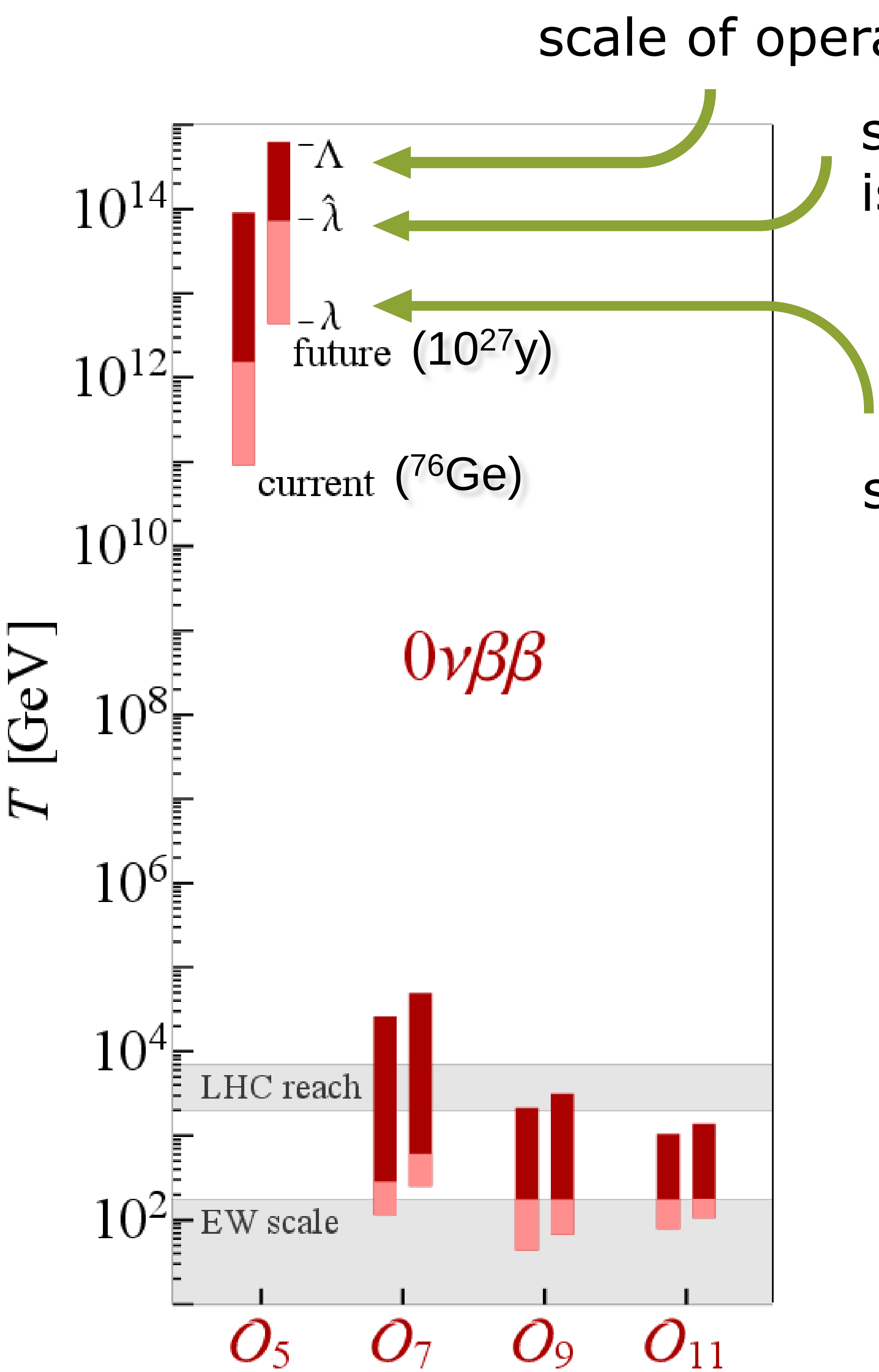
- washout effective if

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

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

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

Results



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

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

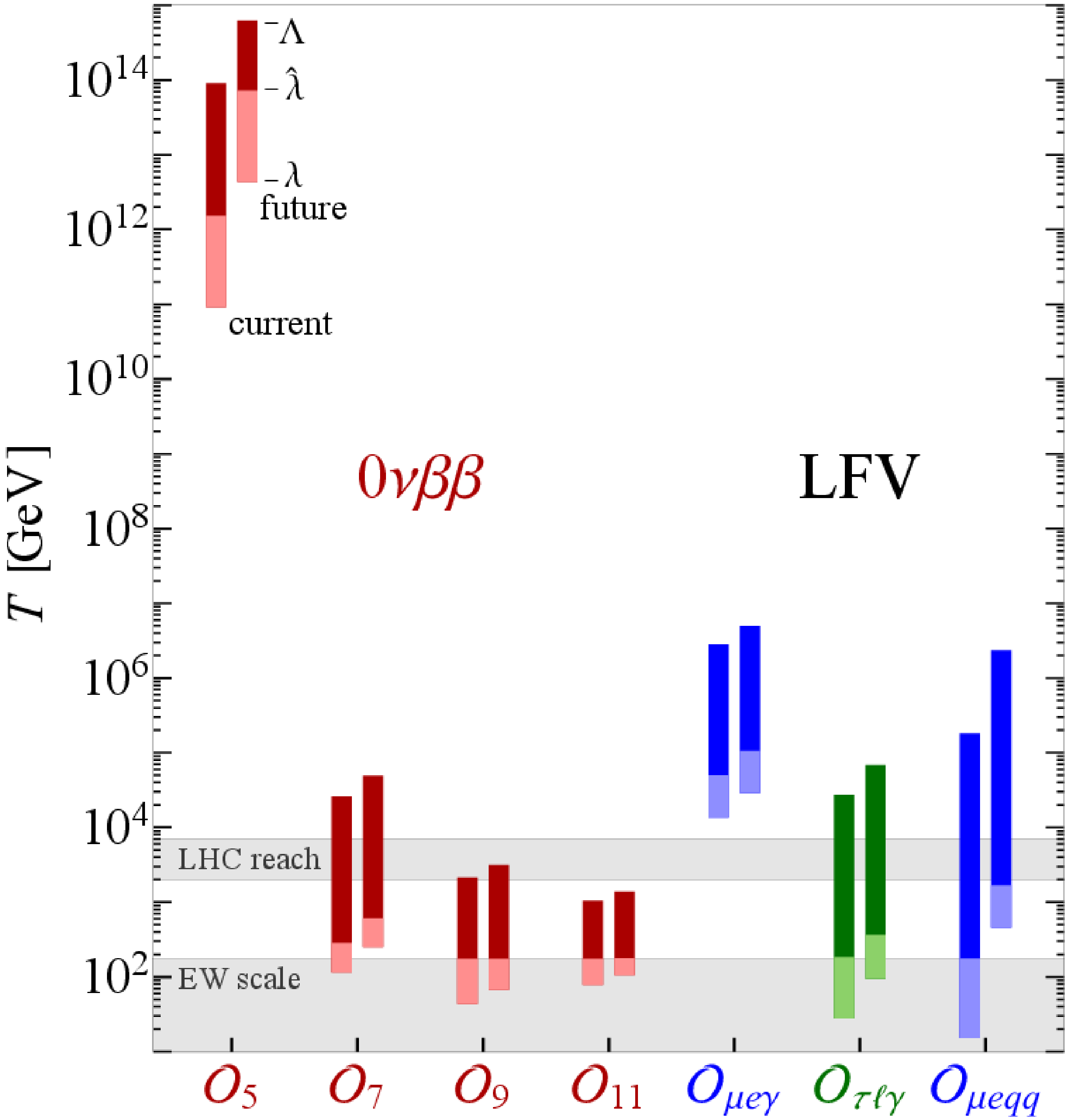
scale above which washout highly effective $\frac{\Gamma_W}{H} > 1$

- 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

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

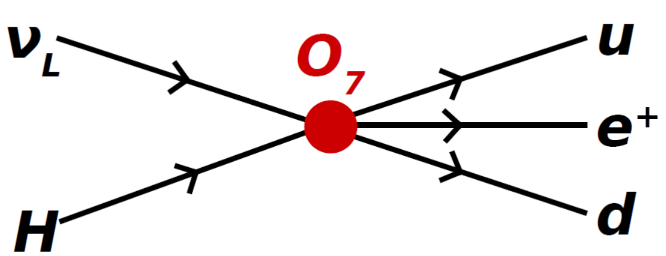
$$\mathcal{O}_{\ell\ell qq} = \mathcal{C}_{\ell\ell qq} (\bar{\ell}\, \Pi_1 \ell)(\bar{q}\, \Pi_2 q)$$

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

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

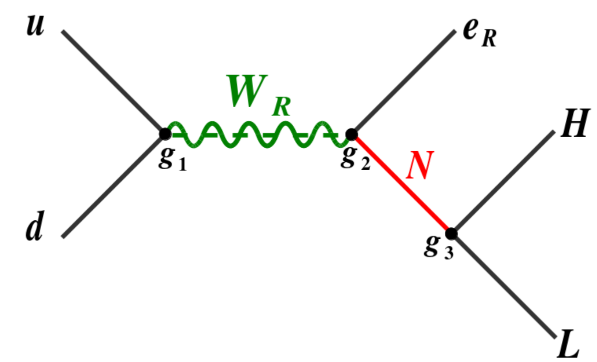
- IF LFV processes are observed as well, loophole of asymmetry being stored in another flavour sector is ruled out

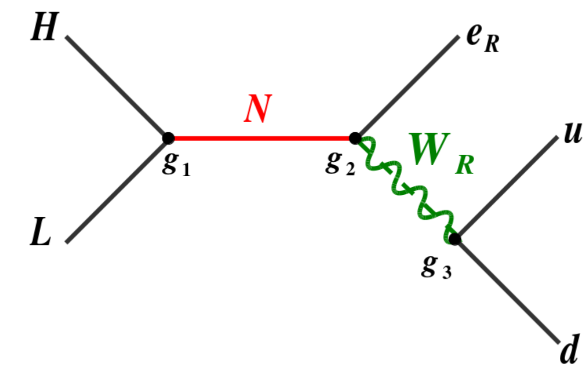
Comparison with UV completed Model

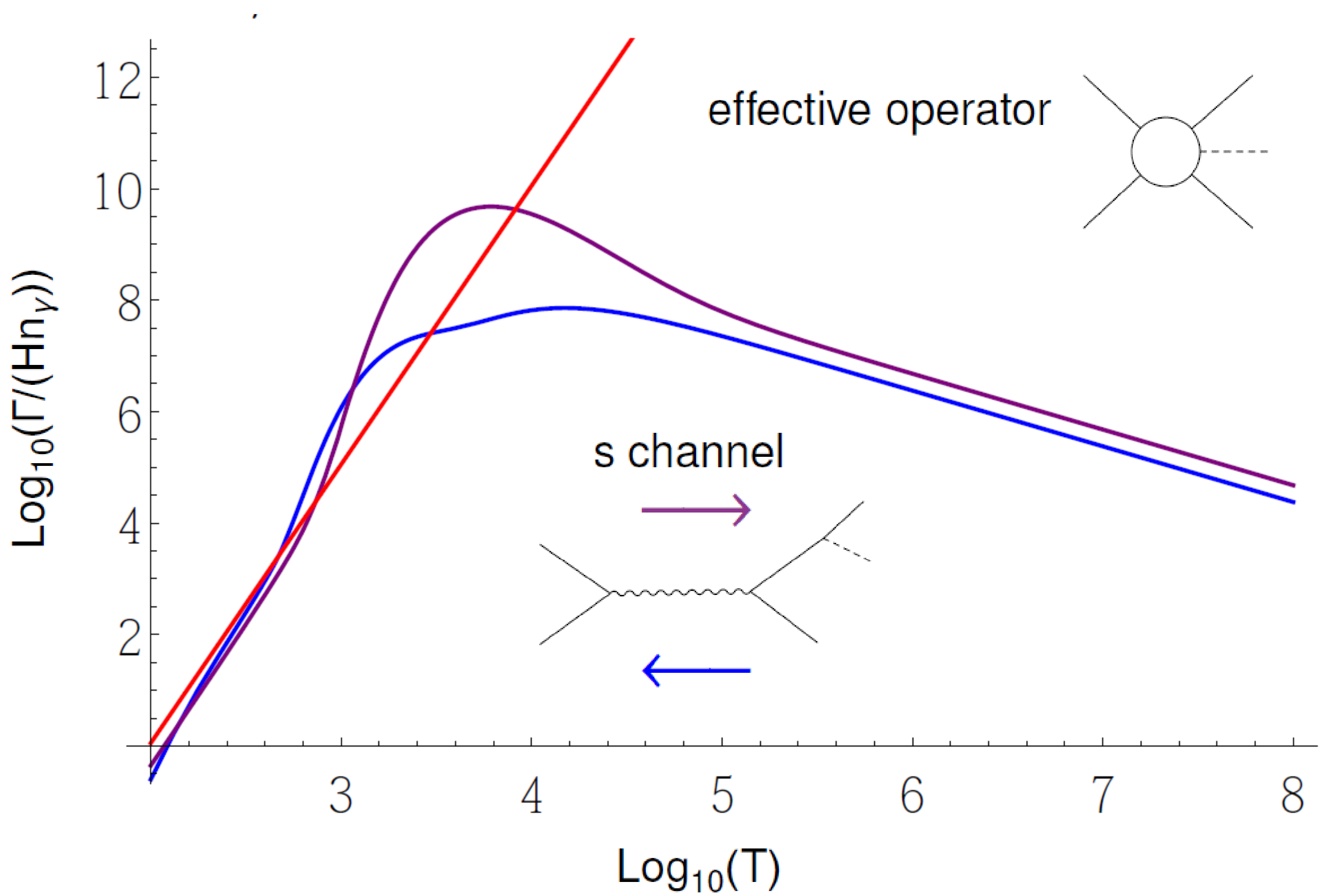


$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c})H^j \epsilon_{ij}$$

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



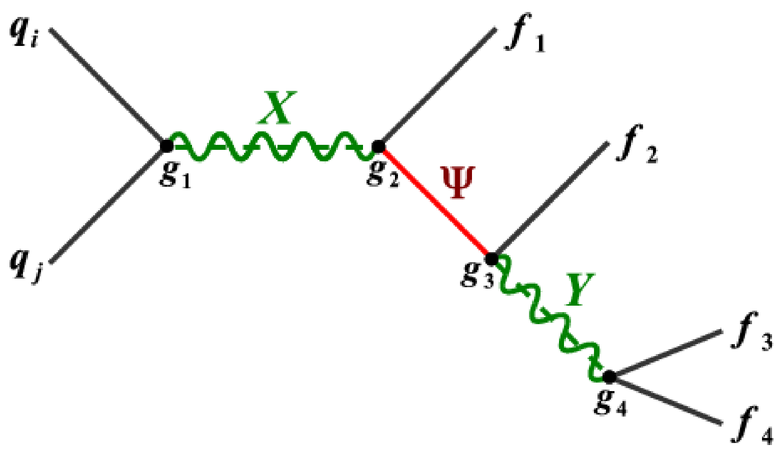


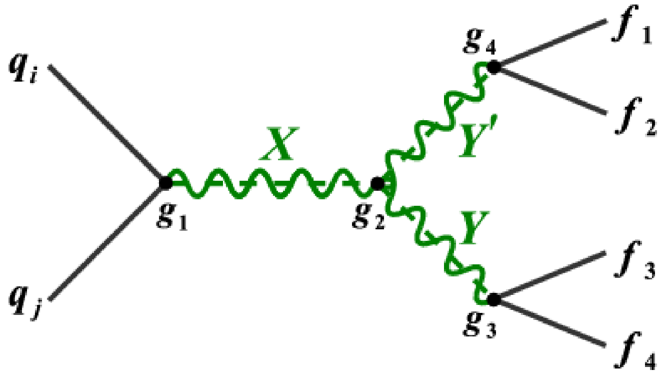


effective operator approach is a conservative estimation of washout rate

LNV at the LHC

- **Signature:** $\Delta L = 2$ LNV at LHC through resonant process $pp \to l^\pm l^\pm + 2\,\text{jets}$ with two same-sign leptons and two jets without missing energy





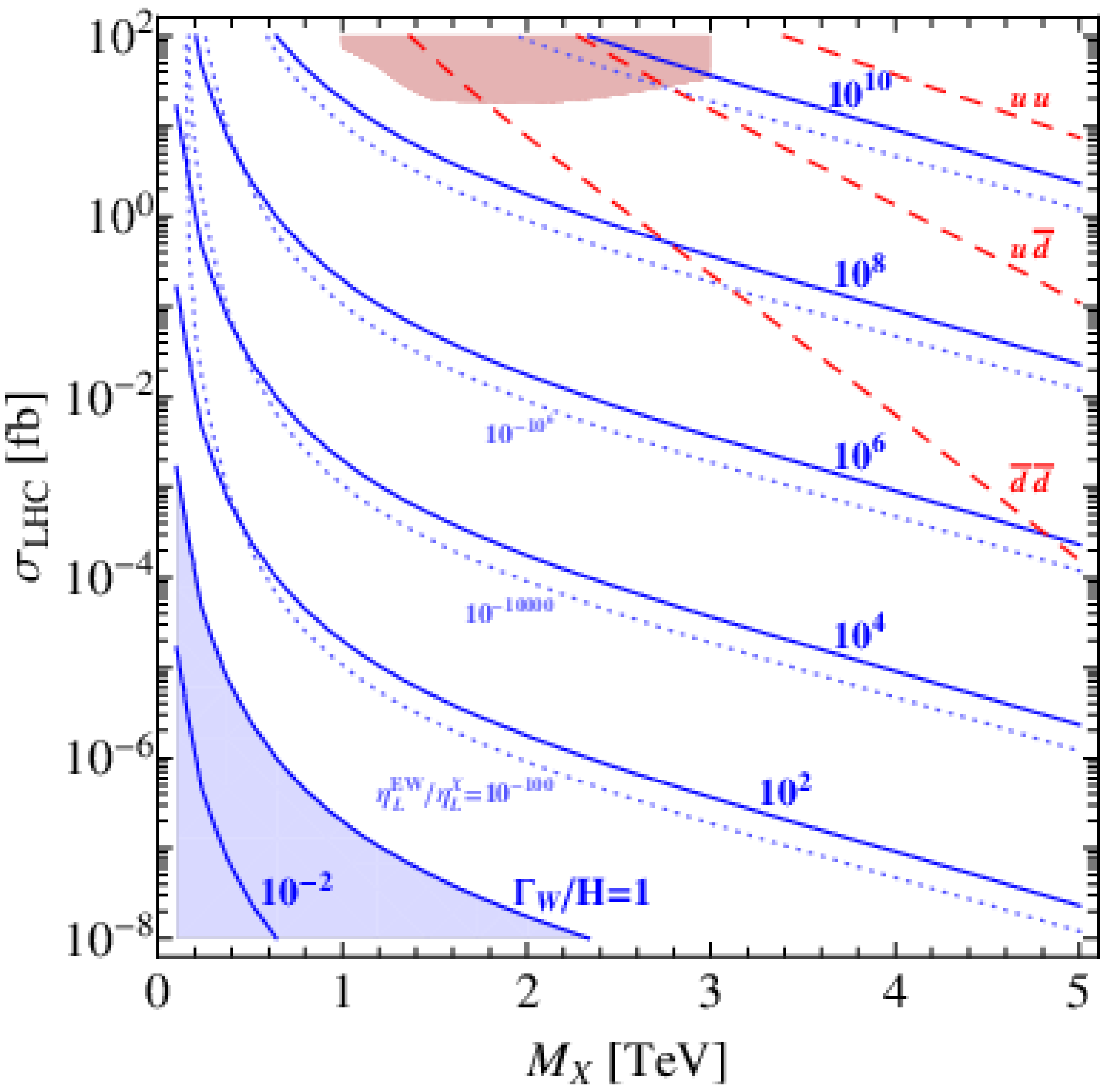
$$\frac{\Gamma_W}{H} = \frac{1}{n_\gamma H} \frac{T}{32\pi^4} \int_0^\infty ds\; s^{3/2} \sigma(s) K_1\left(\frac{\sqrt{s}}{T}\right) \qquad \sigma(s) = \frac{4 \cdot 9 \cdot s}{f_{q_1 q_2}(M_X/\sqrt{s})} \sigma_{\text{LHC}}$$

Measureable LNV signal at LHC and corresponding resonant mass sets lower limit on baryon asymmetry washout

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

LNV at the LHC

- assuming pre-existing lepton asymmetry generated at high scale

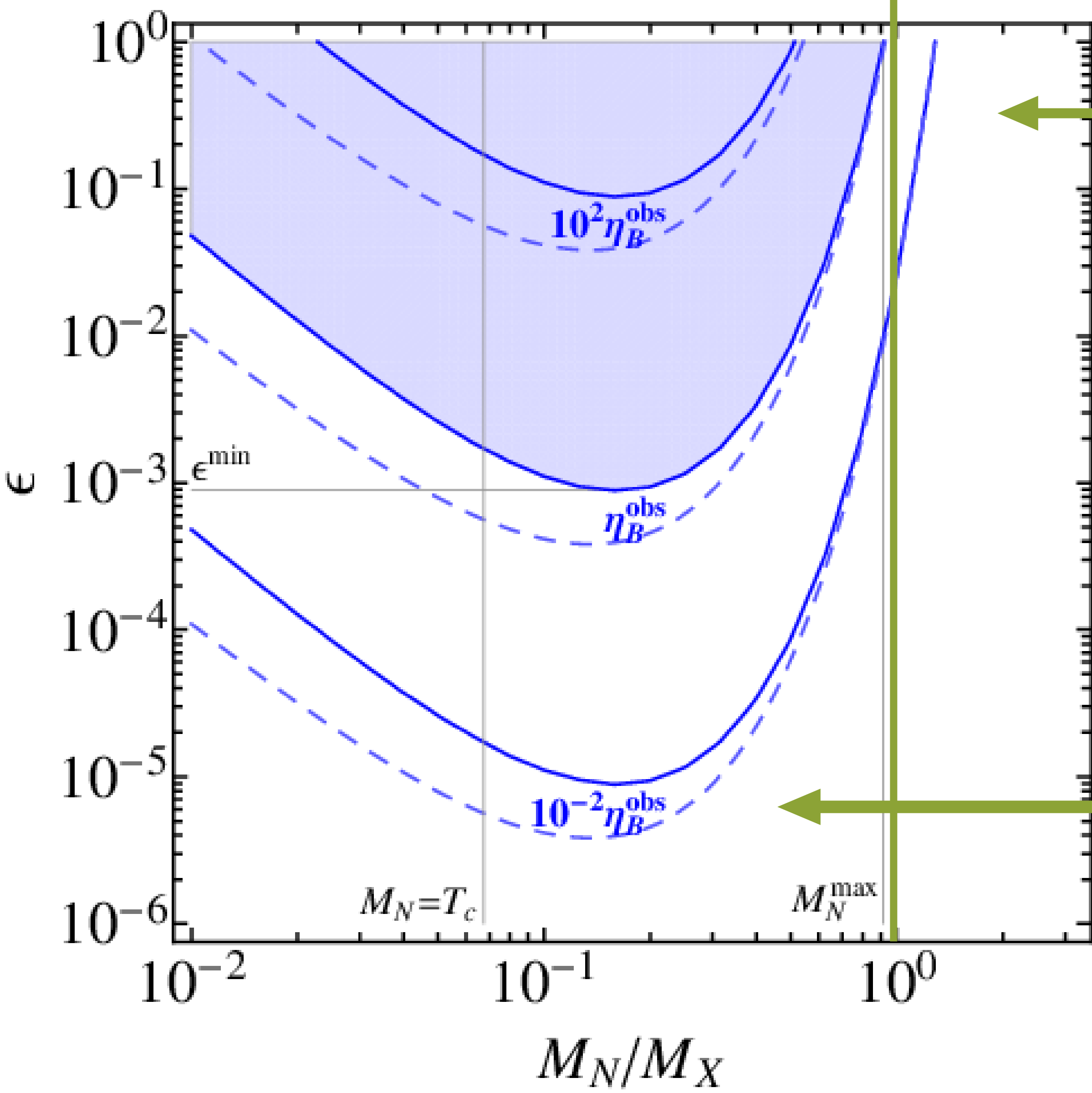


$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\text{LHC}}}{\text{fb}}$$

observation of LNV process at the LHC implies very strong washout

LNV at the LHC

- assuming CP asymmetry ϵ is created at scale M_N



$M_N > M_X$
not possible to generate large enough baryon asymmetry at all

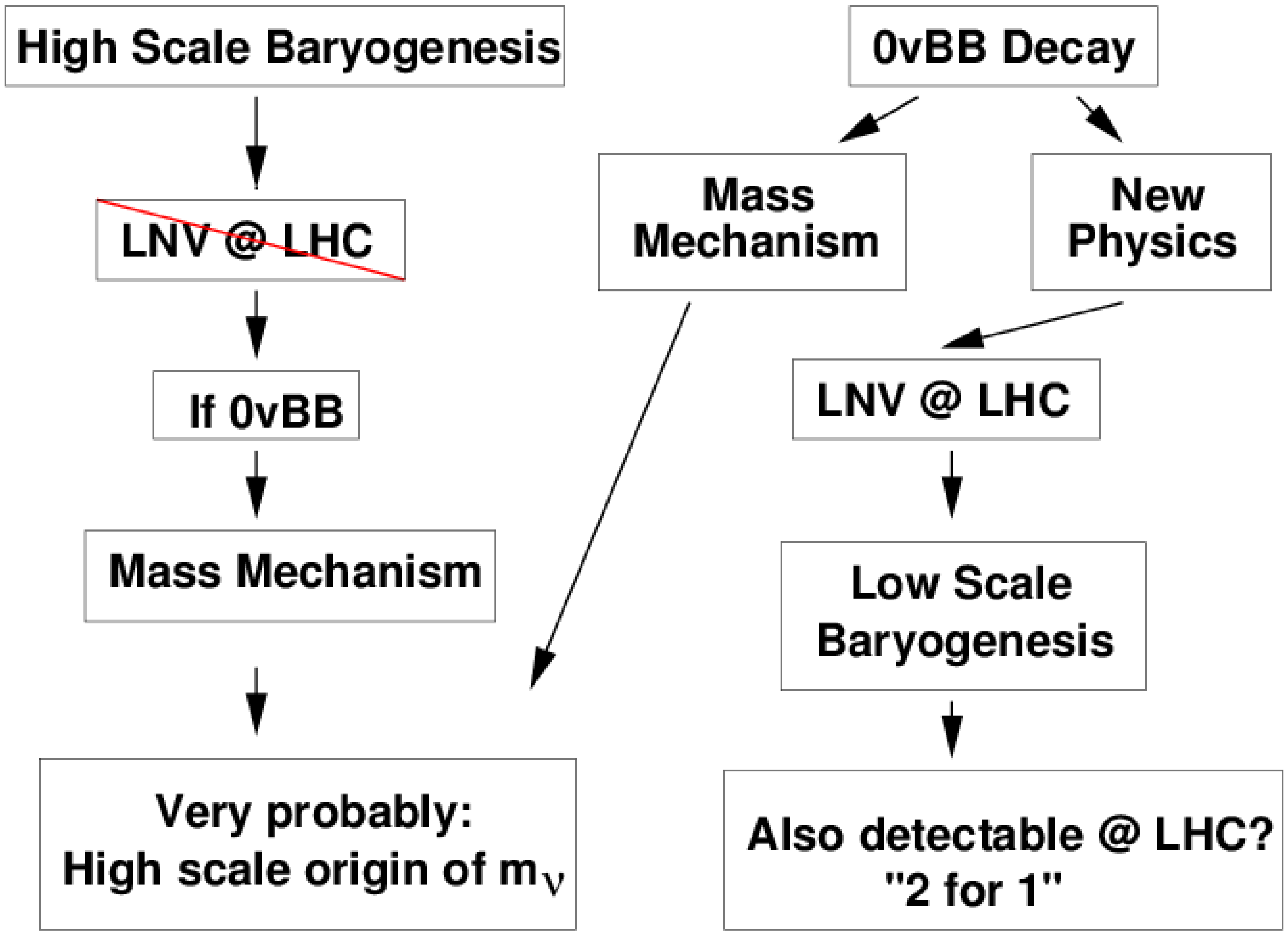
$M_N < M_X$
lower limit on CP-asymmetry

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

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

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

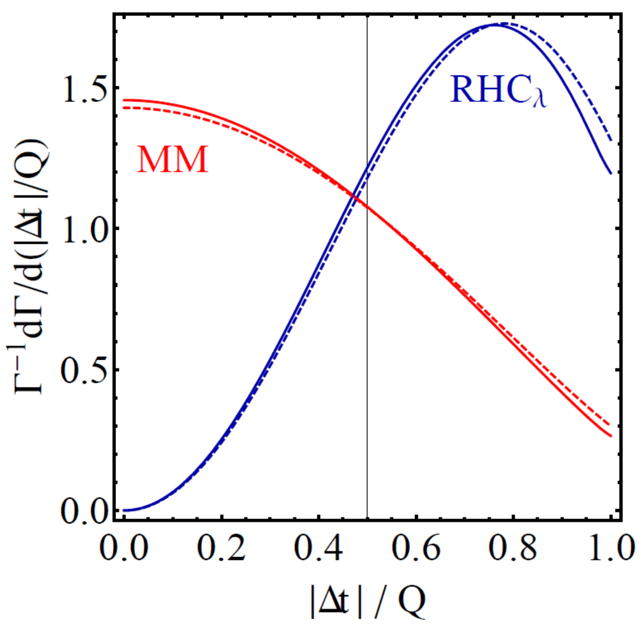
Conclusions

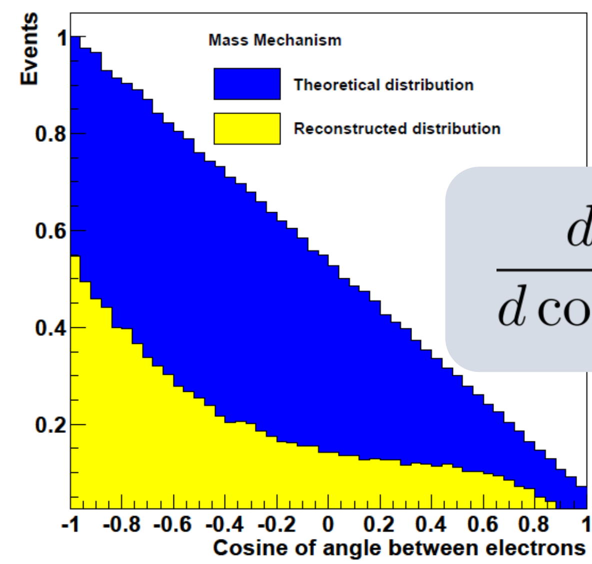


observation of low energy LNV processes (e.g. in 0vbb or LHC) indicates a washout of any pre-existing baryon asymmetry irrespective of the baryogenesis mechanism

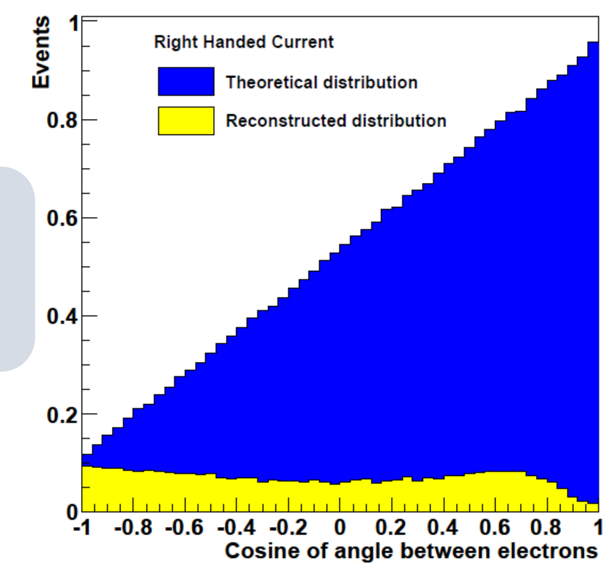
Distinguishing between different Operators

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





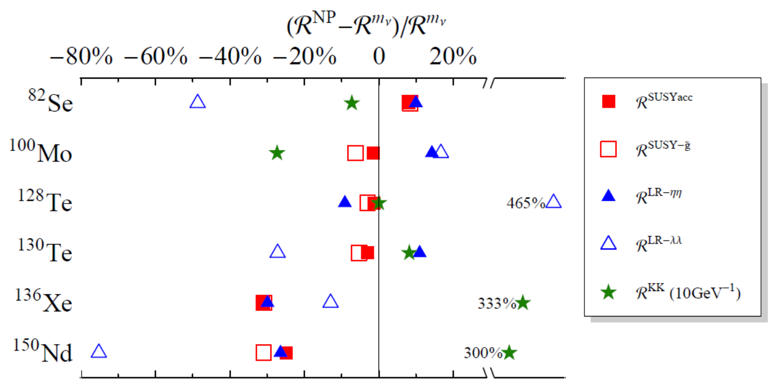
$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$



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)

- comparison of $0\nu\beta^-\beta^-$ with $0\nu\beta^+\beta^+$ Hirsch, Muto, Oda, Klapdor-Kleingrothaus, Z. Phys A347 (1994)
- observation of $0\nu\beta\beta$ via O_9 and O_{11} will imply observation of LNV at LHC