

Impact of Neutrinoless Double Beta Decay on Models of Baryogenesis

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RPP Annecy

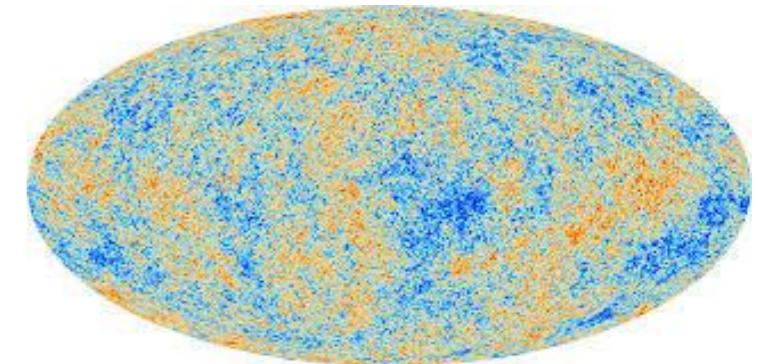
25/1/2016



What explains the Baryon Asymmetry?

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

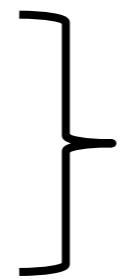
$$\eta_B^{\text{obs}} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$$



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

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

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



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

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 mechanism that generated the baryon asymmetry with current experiments?

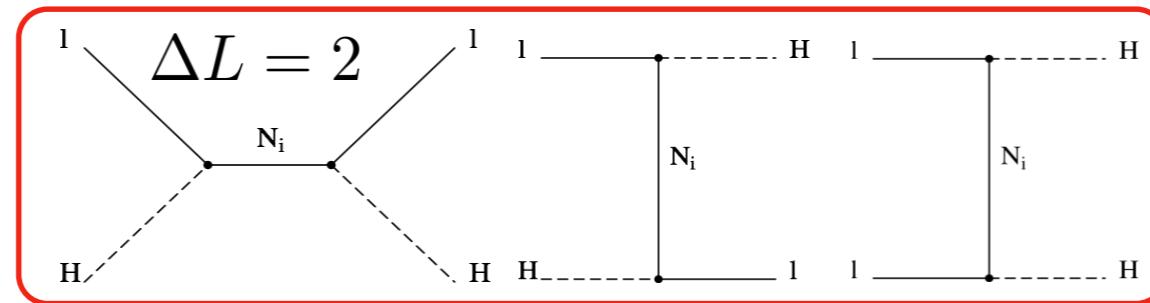
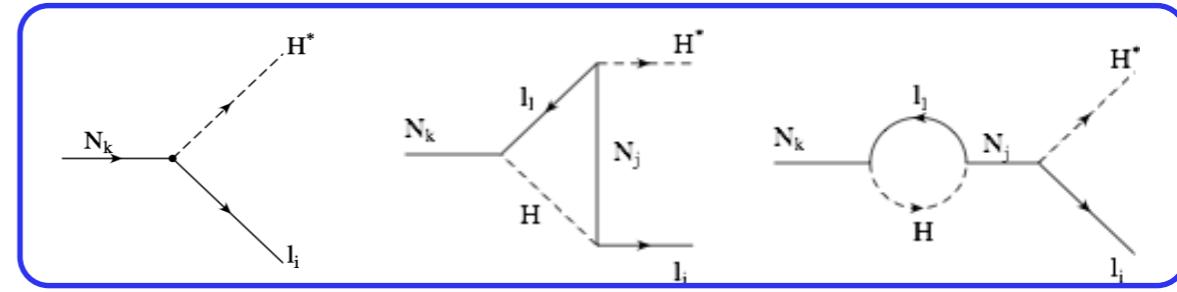
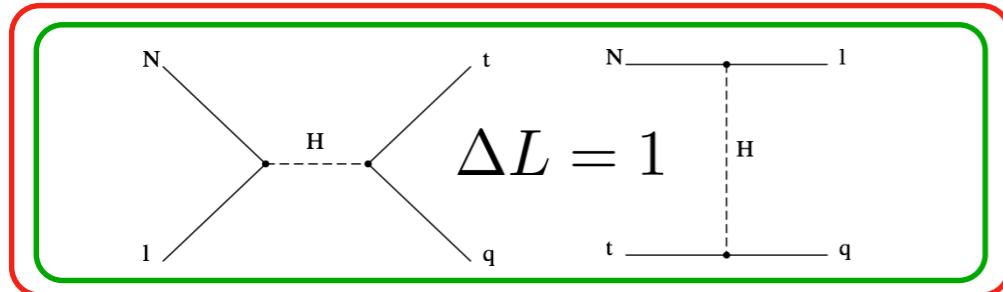
Leptogenesis

- Reminder: concept of 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

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

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

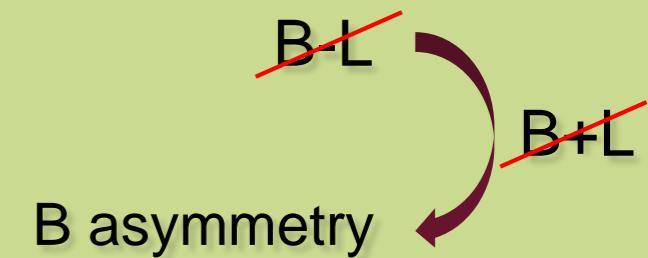
source of CP-asymmetry



washout processes

Washout highly efficient if:

$$\frac{\Gamma_W}{H} > 1$$

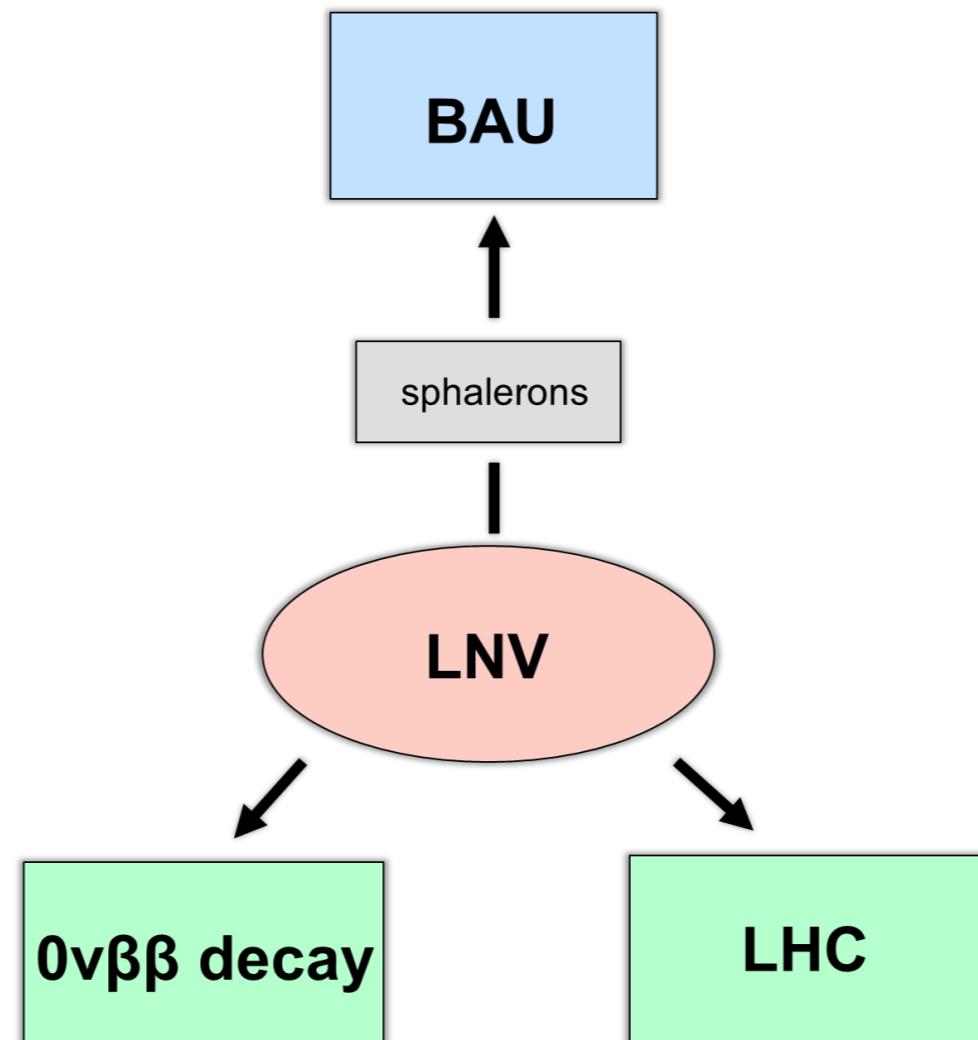


Lepton Number Violation

- In reverse:

- experimental observation of LNV corresponds to a certain washout strength
- due to sphaleron processes this allows for a measure of the corresponding baryon asymmetry washout

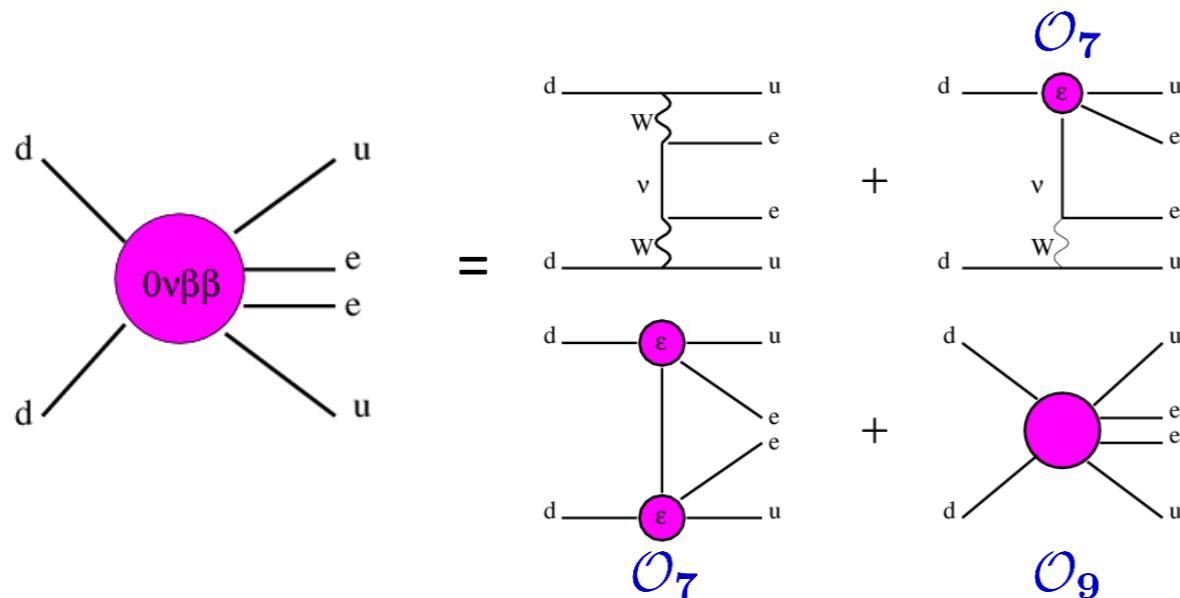
$B-L$
 $B+L$
B washout



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

Different Contributions to ovbb

- $0\nu\beta\beta$ ($2n \rightarrow 2p + 2e^-$) is a sensitive probe of low energy LNV
 - current limits on the half life of $0\nu\beta\beta$: $T_{1/2}^{^{76}\text{Ge}} > (1.1 - 1.9) \times 10^{25}$ y (EXO-200, KamLAND-Zen)
 $T_{1/2}^{^{136}\text{Xe}} > 2.1 \times 10^{25}$ y (GERDA)
 - general Lagrangian can be written in terms of effective couplings ϵ_α^β which correspond to pointlike vertices at the Fermi scale, e.g. for the long range contribution:



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

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

Isotope	$ \epsilon_{V-A}^{V+A} $	$ \epsilon_{V+A}^{V+A} $	$ \epsilon_{S-P}^{S+P} $	$ \epsilon_{S+P}^{S+P} $	$ \epsilon_{TL}^{TR} $	$ \epsilon_{TR}^{TR} $
^{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

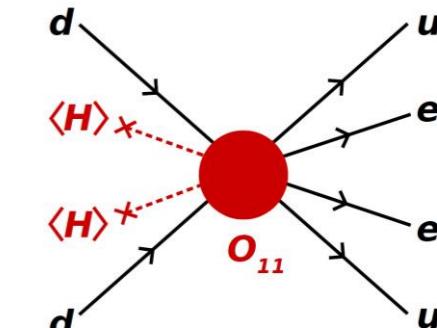
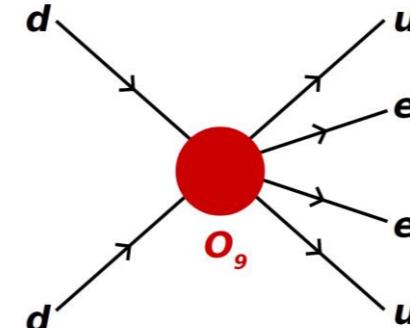
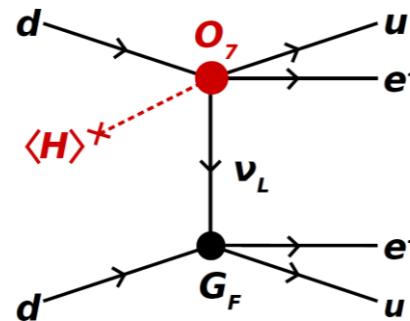
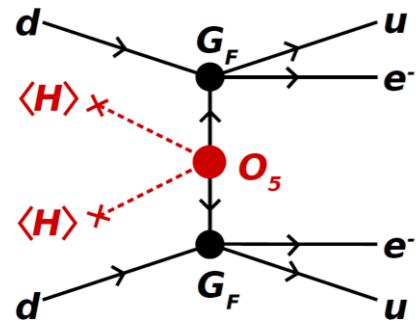
A red right-pointing arrow indicating the next step in the process.

0v $\beta\beta$ half life sets constraints on effective couplings ϵ_α^β

Constraining the Scale of Effective Operators

- Complete list of all 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]



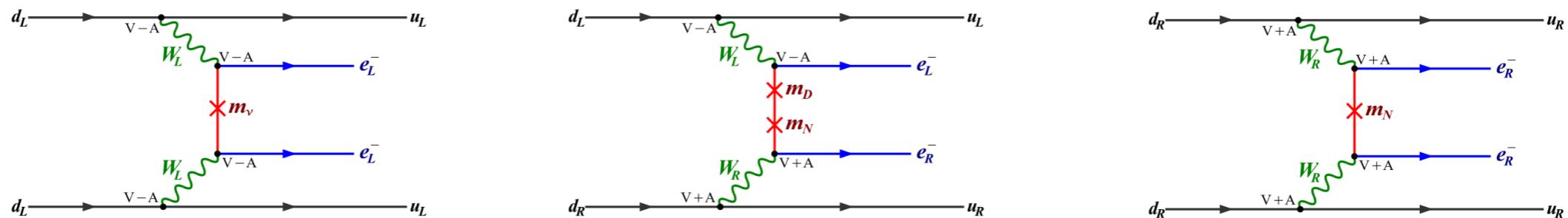
$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik} \epsilon_{jl}$$

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

$$\mathcal{O}_9 = (\bar{Q}_i \bar{u}^c) (\bar{Q}_j \bar{u}^c)$$

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

- Example for an UV completion: Left-right symmetric model



- If $0\nu\beta\beta$ was observed, the scale of the underlying operator can be determined

$$m_e \epsilon_5 = \frac{g^2 v^2}{\Lambda_5}$$

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

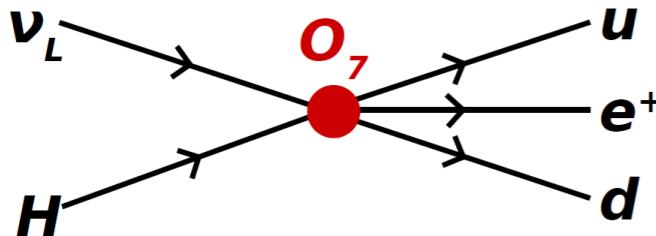
$$\frac{G_F^2 \epsilon_{\{9,11\}}}{2m_p} = \left\{ \frac{g^4}{\Lambda_9^5}, \frac{g^6 v^2}{\Lambda_{11}^7} \right\}$$

\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

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

Lepton Asymmetry Washout

- Study washout of pre-existing net lepton asymmetry introduced by single D-dim operator, e.g. \mathcal{O}_7



- 20 combinations of \mathcal{O}_7 to create $2 \rightarrow 3$ and $3 \rightarrow 2$ processes
- $1 \rightarrow 4$ phase space suppressed

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

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

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

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

c_D operator specific factor

η_L lepton density

- Washout effective if

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

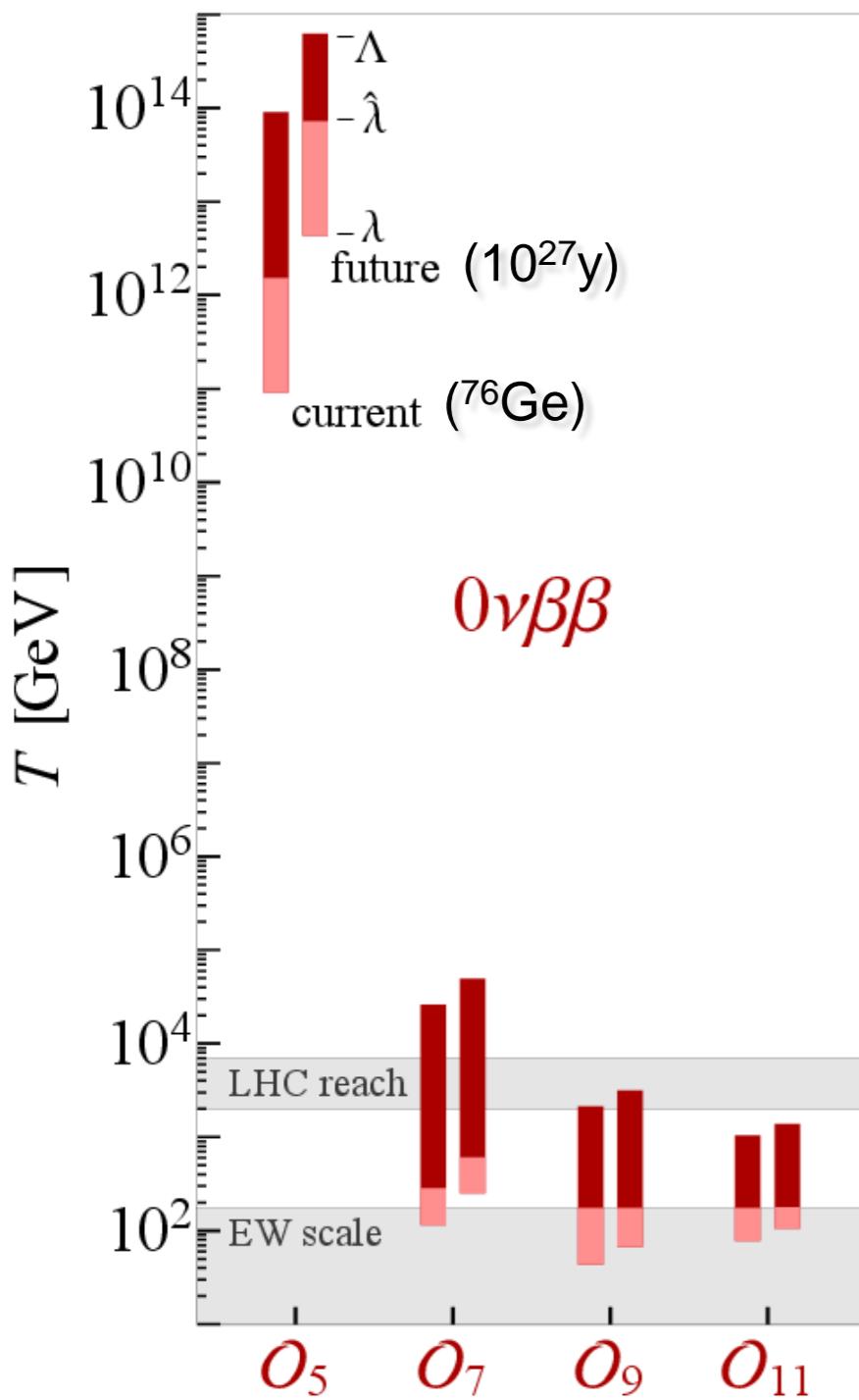
- If $0\nu\beta\beta$ is observed, washout effective in the temperature interval

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

\mathcal{O}_D	λ_D^0 [GeV]	Λ_D^0 [GeV]
\mathcal{O}_5	9.2×10^{10}	9.1×10^{13}
\mathcal{O}_7	1.2×10^2	2.6×10^4
\mathcal{O}_9	4.3×10^1	2.1×10^3
\mathcal{O}_{11}	7.8×10^1	1.0×10^3

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

Results



- Λ scale of operator
- λ scale above which washout highly effective $\frac{\Gamma_W}{H} > 1$
- $\hat{\lambda}$ scale above which a max. lepton asymmetry of 1 is washed out to η_B^{obs} or less

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

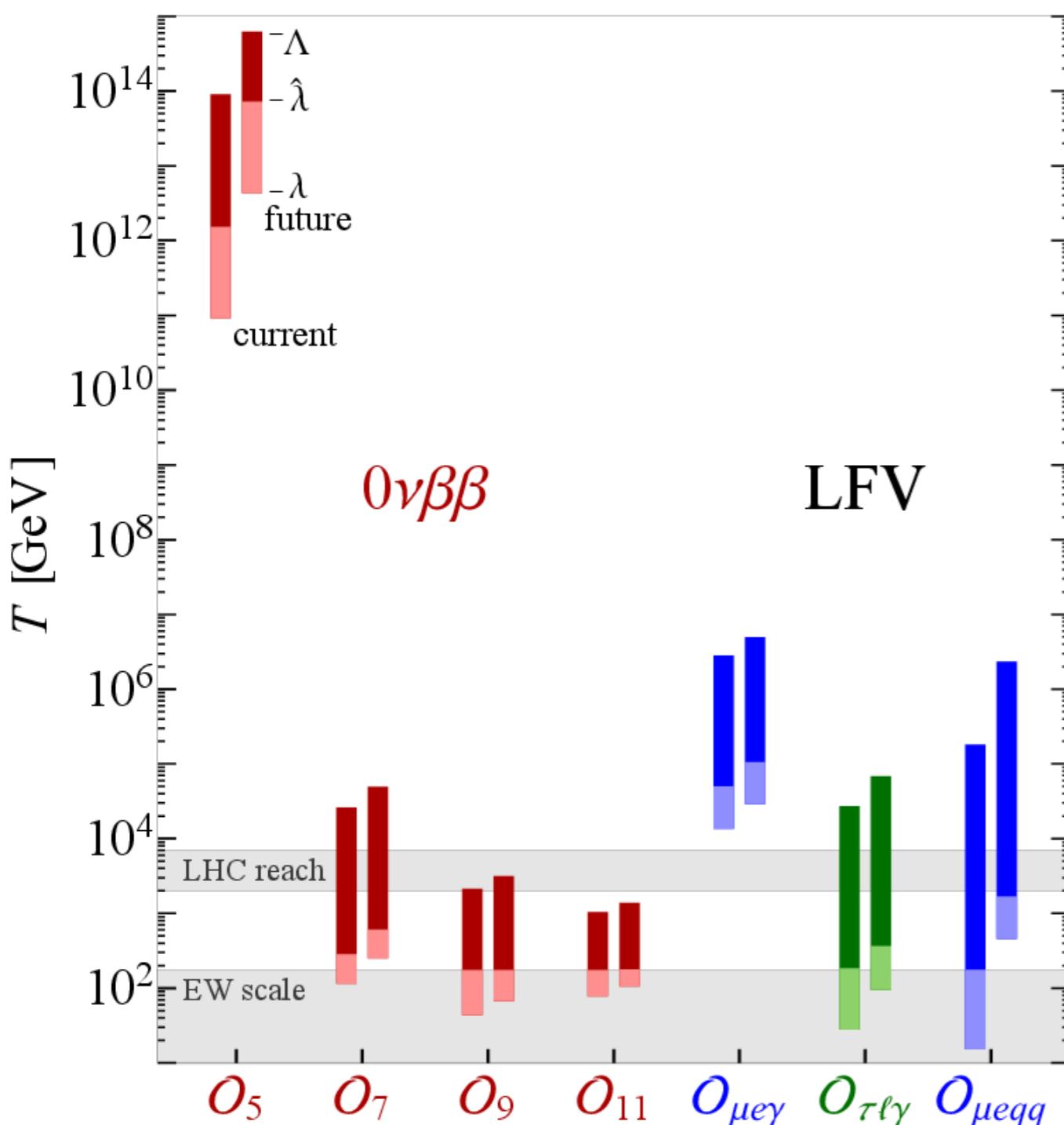
- **IF** $0\nu\beta\beta$ was observed via a non-standard mechanism, resulting washout would rule out baryogenesis mechanisms above λ
- observation of $0\nu\beta\beta$ via O_9 and O_{11} will imply observation of LNV at LHC

- $0\nu\beta\beta$ decay probes only electron-electron component of LNV operators

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

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

Extension to other Flavours by considering LFV



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

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

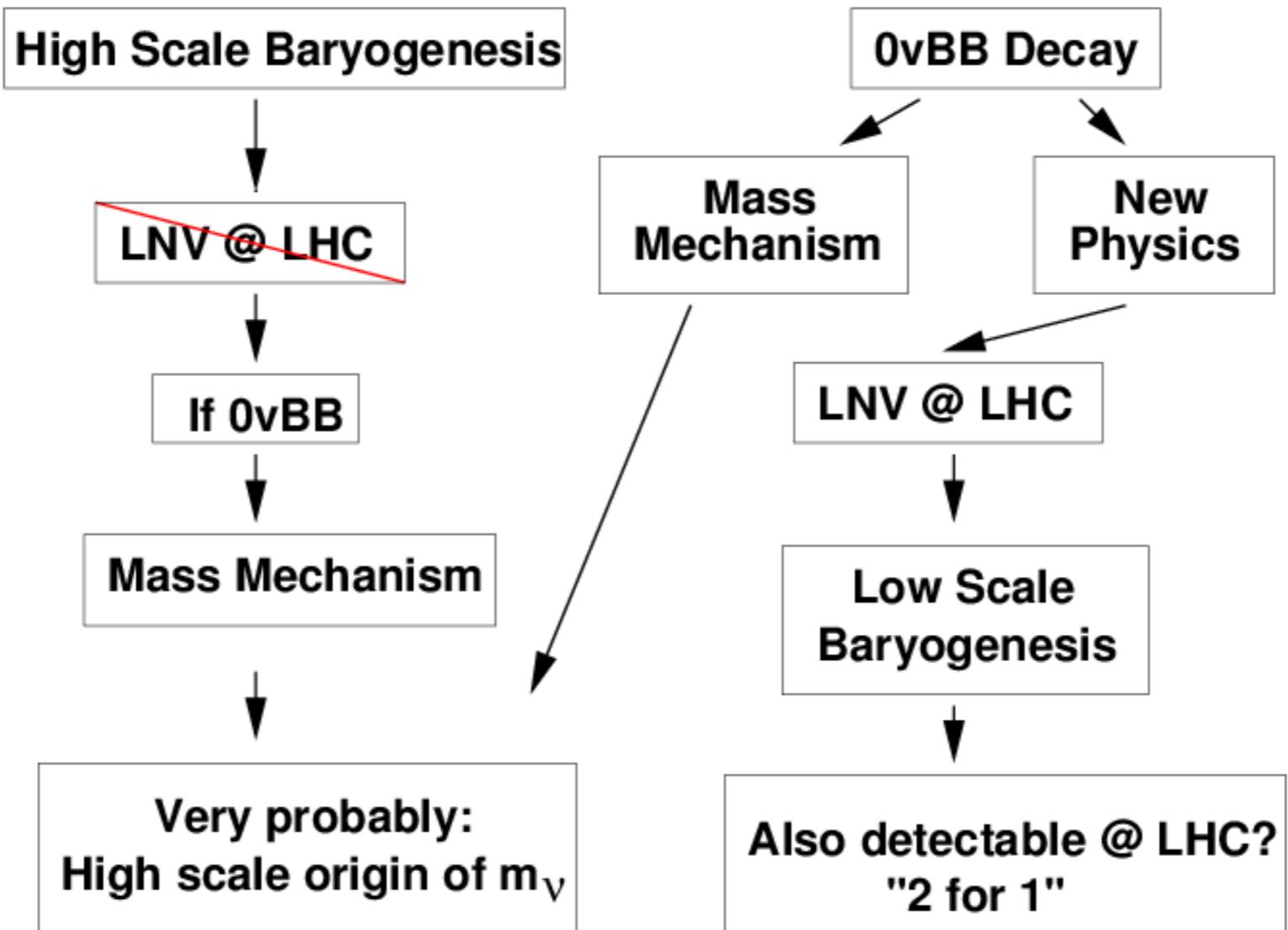
$$\mathcal{O}_{\ell\ell qq} = \mathcal{C}_{\ell\ell qq} (\bar{\ell} \Pi_1 \ell) (\bar{q} \Pi_2 q)$$

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

- Current & future limits:
 - $\text{Br}_{\mu \rightarrow e\gamma} < 5.7 \times 10^{-13}$ (6.0×10^{-14})
 - $\text{Br}_{\tau \rightarrow \ell\gamma} < 4.0 \times 10^{-8}$ (1.0×10^{-9}), $\ell = e, \mu$
 - $R_{\mu \rightarrow e}^{\text{Au}} < 7.0 \times 10^{-13}$ (2.7×10^{-17})
- 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

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

Conclusions



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

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

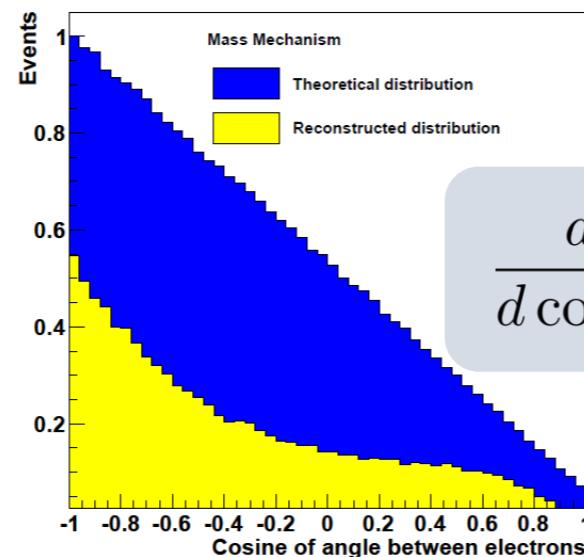
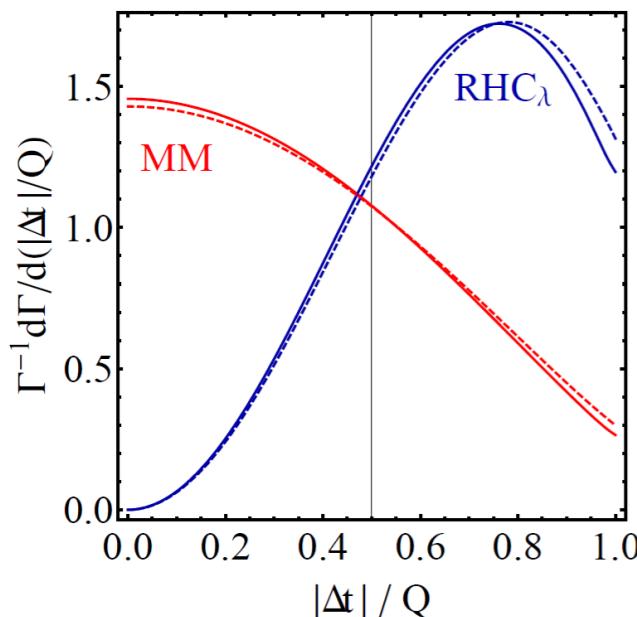
JH, W. Huang, H. Päs, Int. J. Mod. Phys. A 30 (2015) 17, 1530045



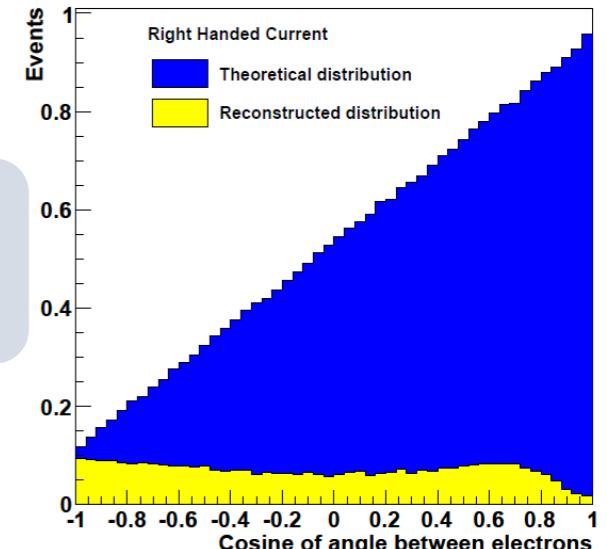
observation of low energy LNV processes (e.g. in 0vbb or LHC) indicates a washout of any pre-existing baryon asymmetry irrespective of the baryogenesis mechanism

Distinguishing between different Operators

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

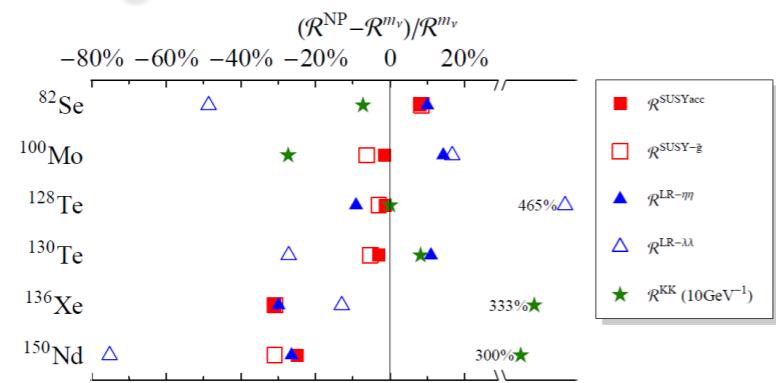


$$\frac{d\Gamma}{d \cos \theta_{12}} = \frac{\Gamma}{2} (1 - k_\theta \cos \theta_{12})$$



SuperNEMO collaboration, arXiv:1005.1241 [hep-ex]

- potential discrepancy between neutrino mass (cosmology) and 0vbb half live measurement could be an indication for 0vbb being triggered by non-standard mass mechanism
- distinguishing between different mechanisms via measurements in different isotopes

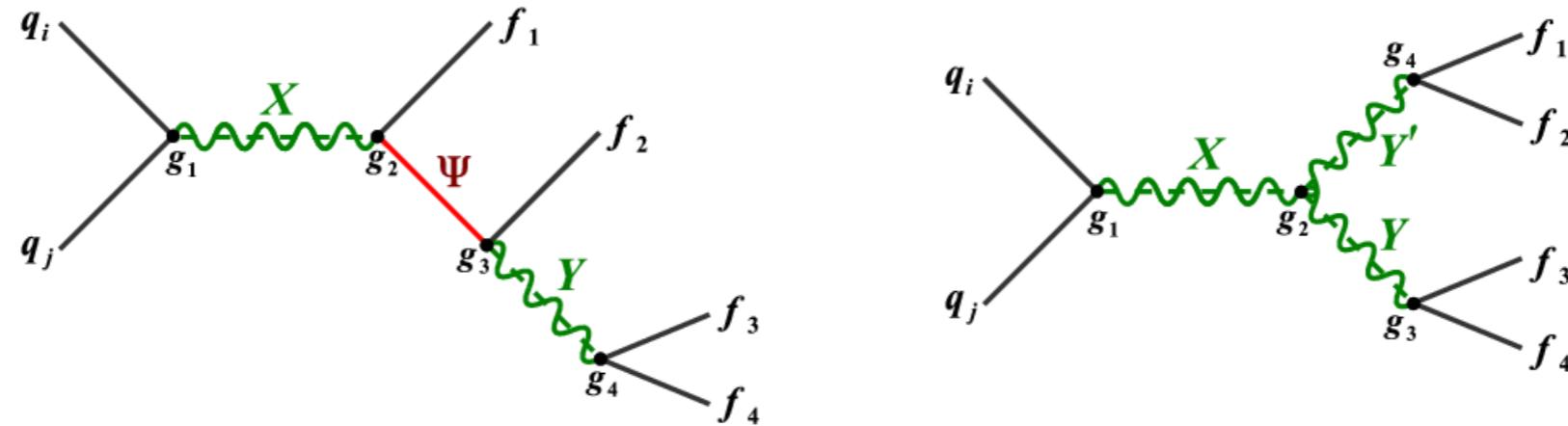


$$\frac{T_{1/2}(^A X)}{T_{1/2}(^A X)} = \frac{|\mathcal{M}(^{76}Ge)|^2 G(^{76}Ge)}{|\mathcal{M}(^A X)|^2 G(^A X)}$$

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

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



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

$$\sigma(s) = \frac{4 \cdot 9 \cdot s}{f_{q_1 q_2} (M_X / \sqrt{s})} \sigma_{\text{LHC}}$$

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

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

F. Deppisch, JH, M. Hirsch, PRL 112 (2014) 221601, arXiv:1312.4447 [hep-ph]

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

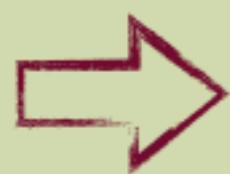
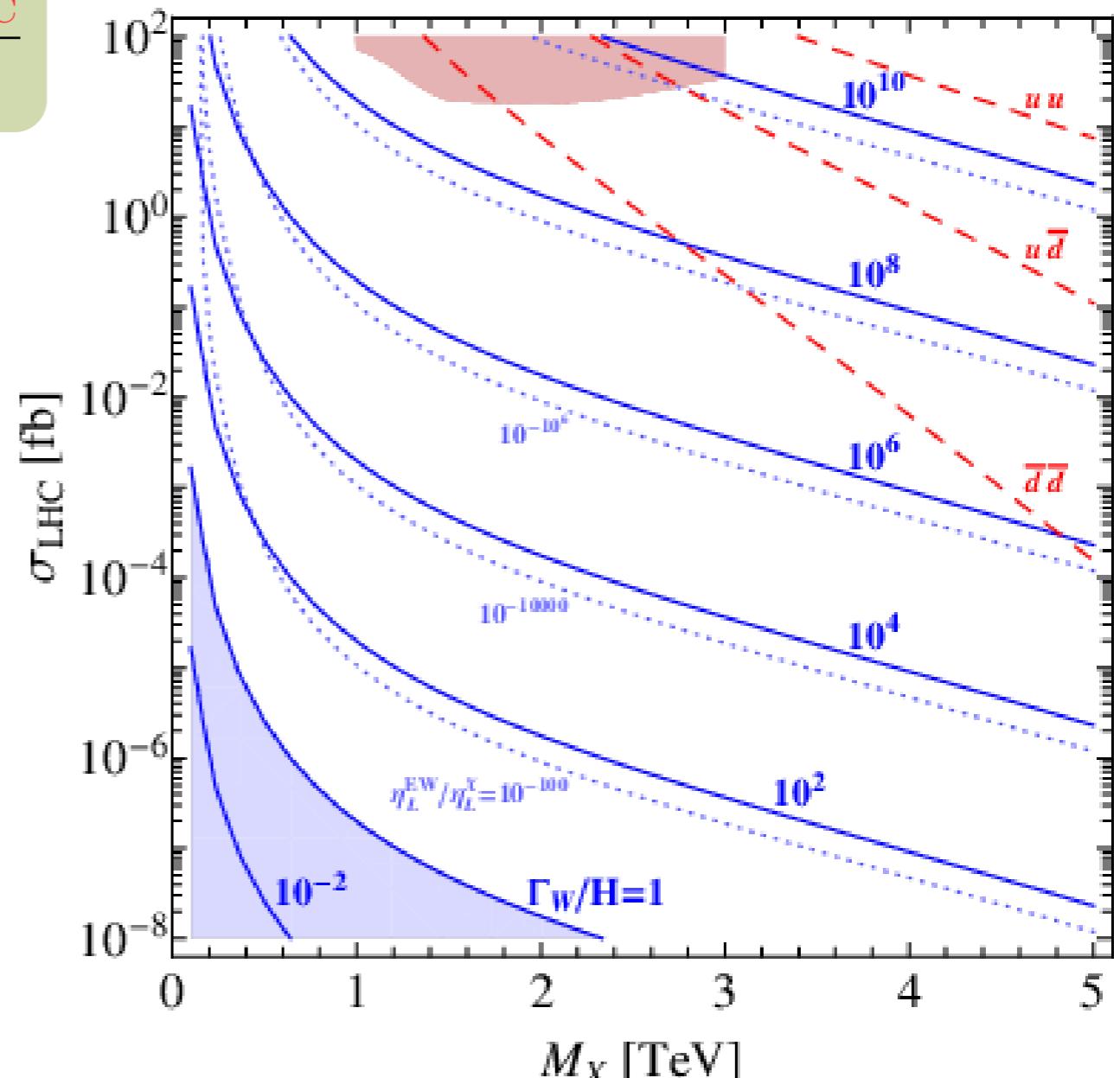
- For any realistic cross section at LHC with $\sigma_{\text{LHC}} > 10^{-2} \text{ fb}$ washout highly effective

$$\frac{\Gamma_W}{H} \gg 1$$

- enormous washout of any pre-existing lepton asymmetry

$$\eta_L^{\text{EW}} / \eta_L^X \approx \exp(-\Gamma_W/H)$$

- LHC starts to exclude top of parameter plane



- observation of LNV processes sets serious bounds on washout
- excludes LG models which generate asymmetry above