Falsifying High-Scale Baryogenesis with $0\nu\beta\beta$, LFV and the LHC

Frank F. Deppisch, JH, Martin Hirsch,
Phys. Rev. Lett. 112, 221601 (2014), arXiv: 1312.4447 [hep-ph]

Frank F. Deppisch, JH, Martin Hirsch, Wei-Chih Huang, Heinrich Päs,
arXiv: 1503.04825 [hep-ph]

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University College London

June 12th 2015
WIN 2015, MPIK Heidelberg

Baryogenesis and Leptogenesis

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

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

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

- Theoretical requirements: 3 Sakharov conditions

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

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

} not fulfilled within the Standard Model

⇓

Physics beyond the Standard Model?

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

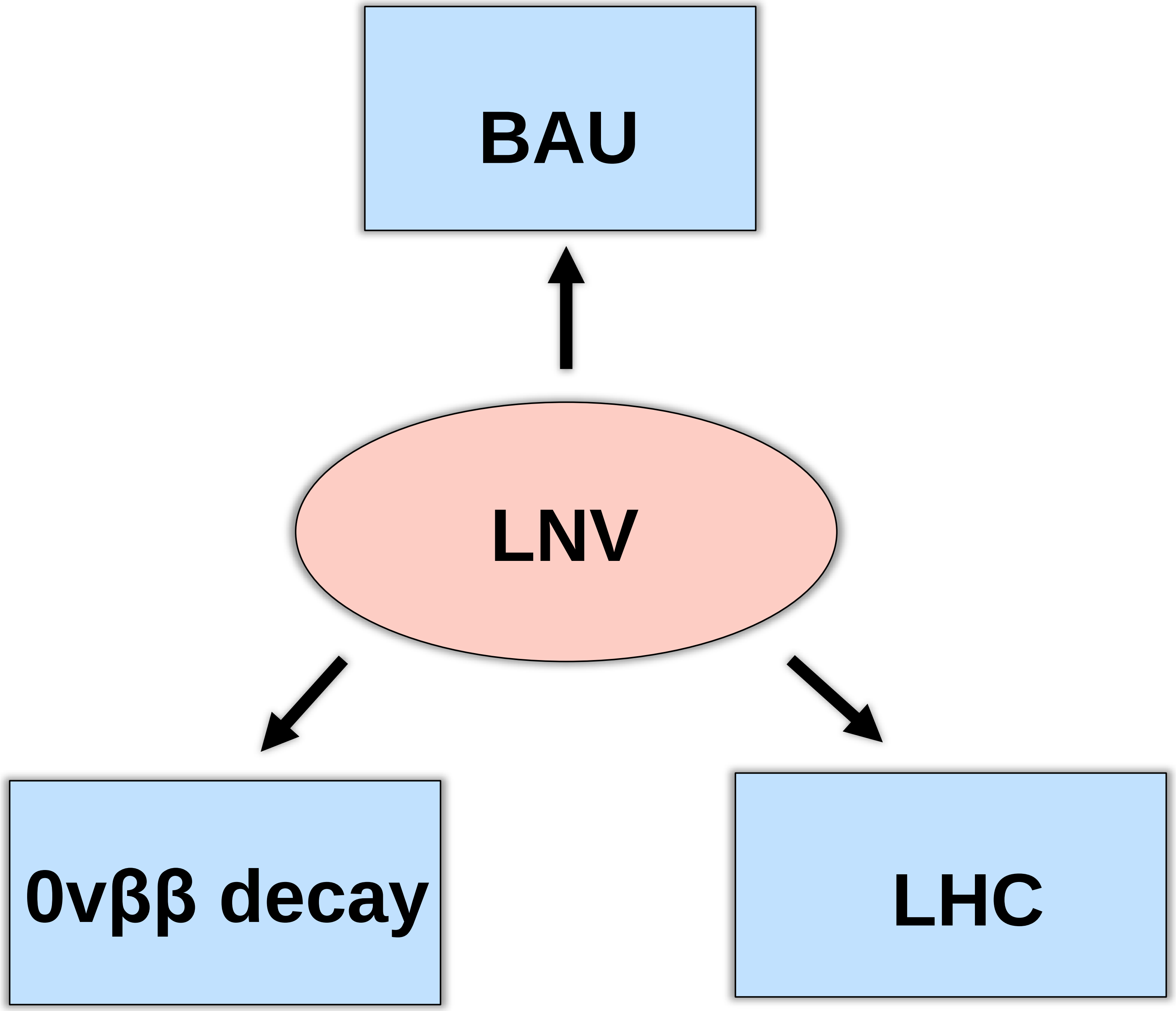
~~B-L~~ → ~~B+L~~ → B asymmetry

- In reverse:

⇒
- LNV processes as a probe of the strength of the washout
- probe if observable BAU still reachable

~~B-L~~ → ~~B+L~~ → B washout

Connection between BAU, 0vbb & LHC

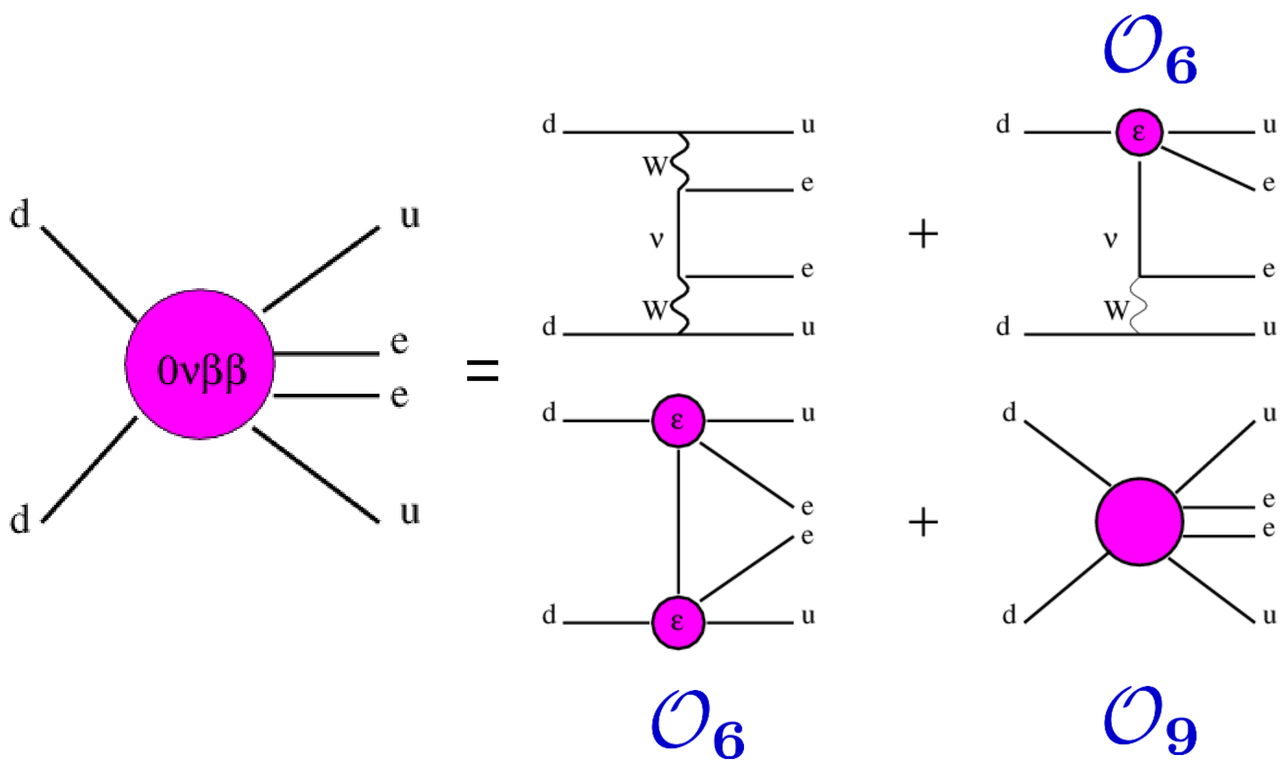


⇨ Observation of low energy LNV will have far-reaching consequences on mechanisms of baryogenesis

Neutrinoless Double Beta Decay (0vbb)

- current limits on 0νββ: $T_{1/2}^{76\mathrm{Ge}} > (1.1 - 1.9) \times 10^{25}$ y EXO-200, KamLAND-Zen

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



long range contributions:

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

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

$$T^{-1}_{1/2} = |\epsilon^{\beta}_{\alpha}|^2 G_i |M_i|^2$$

similar treatment for short range contribution …

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	$2.6 \cdot 10^{-9}$	$5.1 \cdot 10^{-7}$	$6.2 \cdot 10^{-9}$	$6.2 \cdot 10^{-9}$	$4.4 \cdot 10^{-10}$	$7.4 \cdot 10^{-10}$

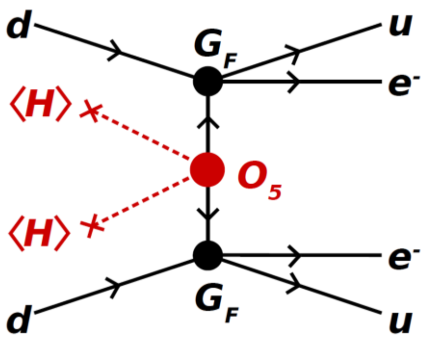
F. Deppisch, M. Hirsch, H. Päs, J. Phys. G 39 (2012) 124007, arXiv:1208.0727 [hep-ph], updated

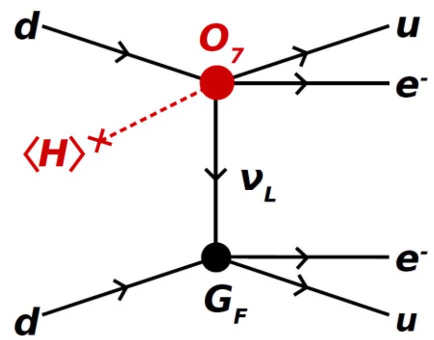
half life sets constraints on effective coupling parameters

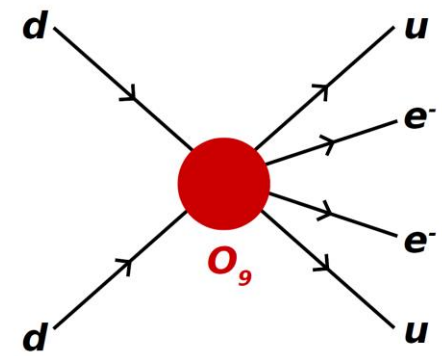
Lepton Number Violating Operators

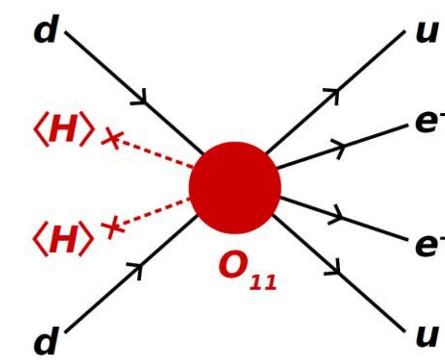
- Complete list of all LNV $\Delta L = 2$ effective operators

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]









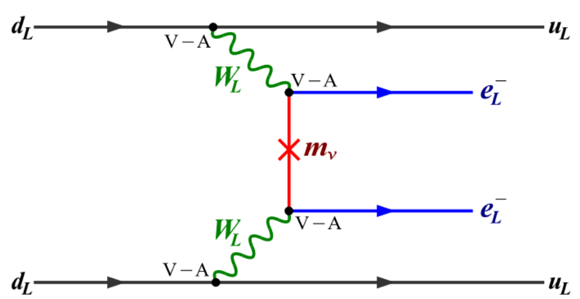
$$\mathcal{O}_5 = (L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl}$$

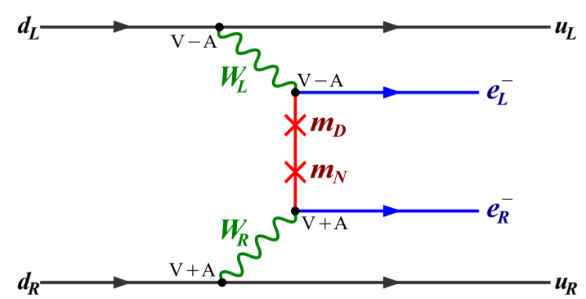
$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c}) H^j \epsilon_{ij}$$

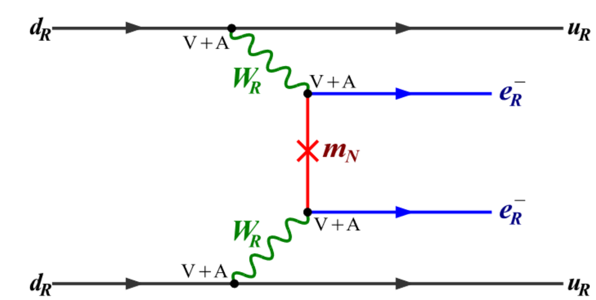
$$\mathcal{O}_9 = (L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c})$$

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

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







- If 0vββ was observed, the scale of the underlying operator can be determined

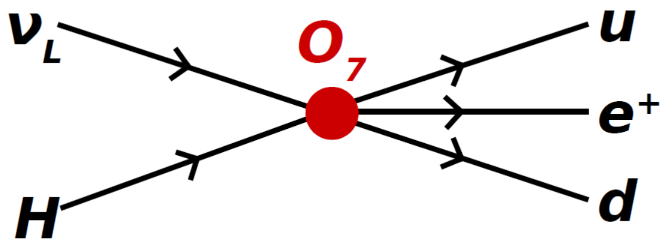
$$m_{e\epsilon_5} = \frac{g^2 v^2}{\Lambda_5} \qquad \frac{G_F \epsilon_7}{\sqrt{2}} = \frac{g^3 v}{2\Lambda_7{}^3} \qquad \frac{G_F^2 \epsilon_{\{9,11\}}}{2 m_p} = \left\{ \frac{g^4}{\Lambda_9{}^5}, \frac{g^6 v^2}{\Lambda_{11}{}^7} \right\}$$

$\mathcal{O}_D$	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

F. Deppisch, JH, W. Huang, M. Hirsch, H. Päs, arXiv:1503.07632 [hep-ph]

Lepton Asymmetry Washout

- Study washout of pre-existing net lepton asymmetry introduced by single D-dim operator



- 20 combinations of O_7 to create 2 → 3 and 3→ 2 processes
- 1→ 4 phase space suppressed

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

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

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

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

c_D operator specific factor

η_L lepton density

- Washout effective if

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

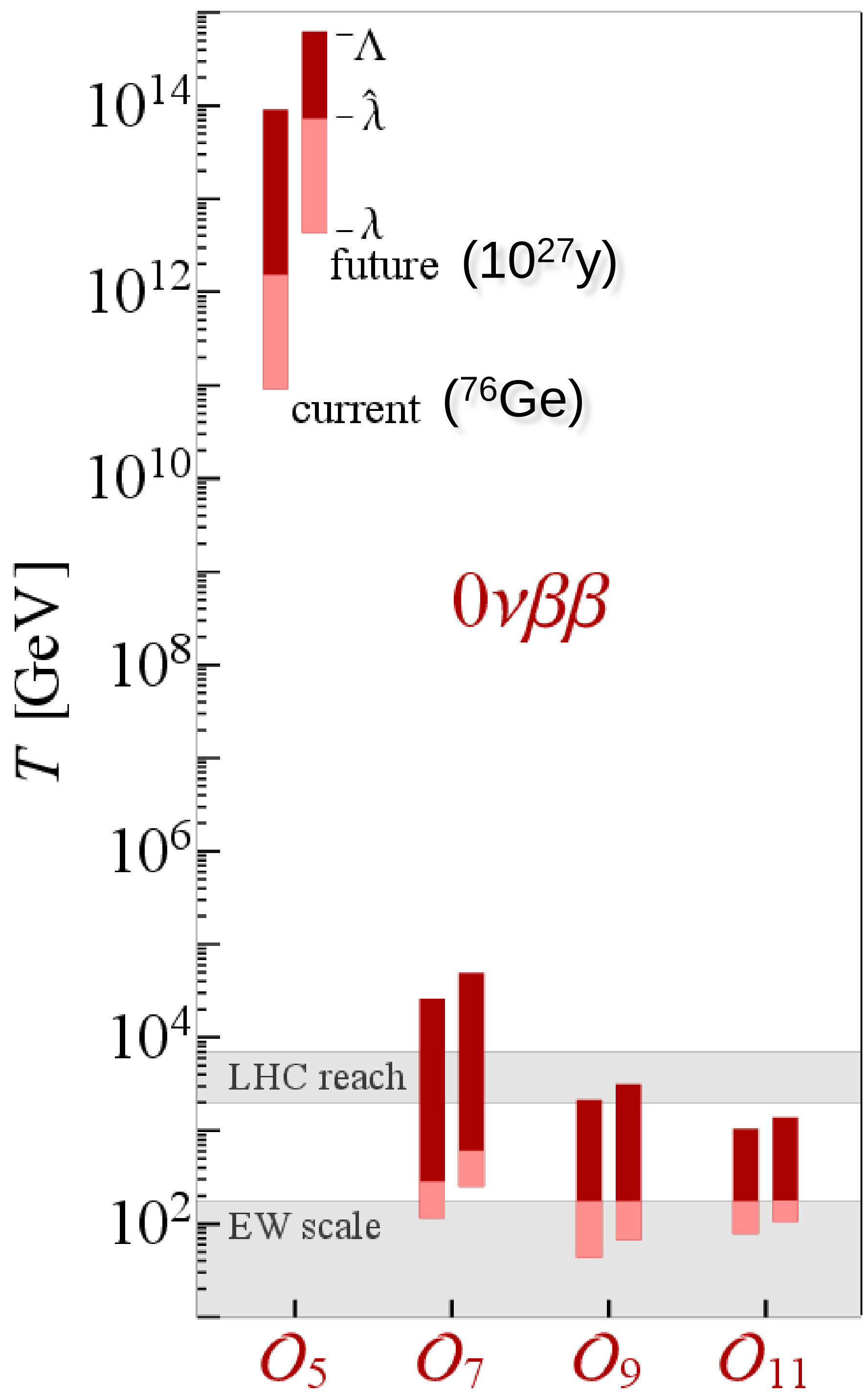
- This is the case in the temperature interval

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

$\mathcal{O}_D$	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, arXiv:1503.07632 [hep-ph]

Lepton Asymmetry Washout - 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

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

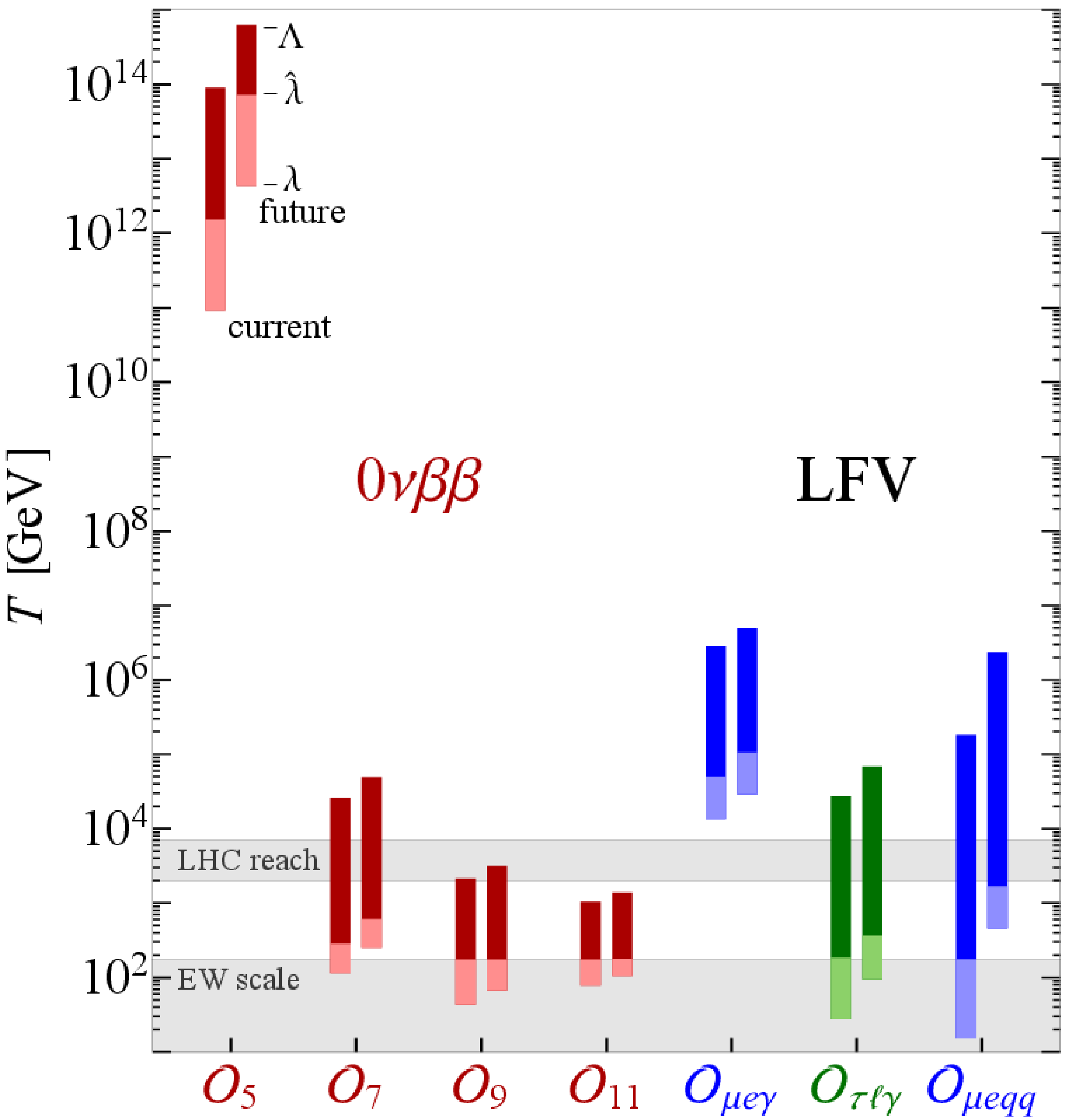
- IF 0vββ was observed via non-standard mechanism, resulting washout would rule out baryogenesis mechanisms above λ

- observation of 0vββ via O_9 and O_{11} will imply observation of LNV at LHC

- 0vββ decay probes only electron-electron component of LNV operators $\frac{1}{\Lambda_9^5} \to \frac{c_{\alpha\beta}}{\Lambda_9^5}$

F. Deppisch, JH, W. Huang, M. Hirsch, H. Päs, arXiv:1503.07632 [hep-ph]

Lepton Flavour Violation – Results



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

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

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

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

- Current & future limits:

$$\mathrm{Br}_{\mu\to e\gamma} < 5.7 \times 10^{-13} \quad (6.0 \times 10^{-14})$$

$$\mathrm{Br}_{\tau\to \ell\gamma} < 4.0 \times 10^{-8} \quad (1.0 \times 10^{-9}),\ \ell = e, \mu$$

$$\mathrm{R}^{\mathrm{Au}}_{\mu\to e} < 7.0 \times 10^{-13} \quad (2.7 \times 10^{-17})$$

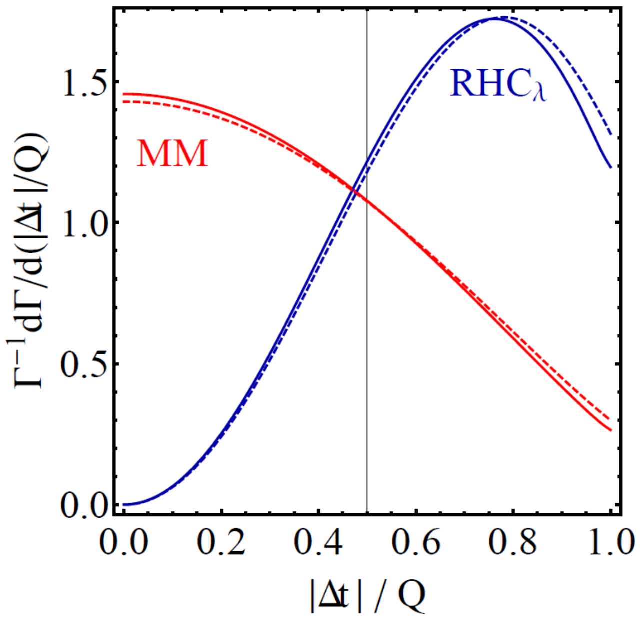
- determine temperature interval in which LFV process equilibrate pre-existing flavour asymmetry

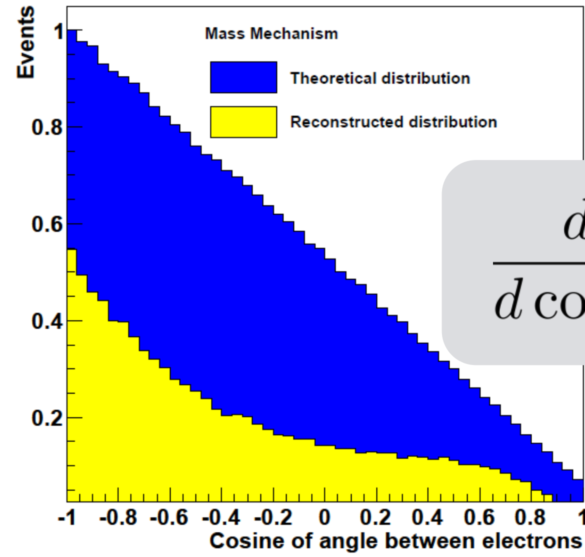
- IF LFV processes are observed as well, loophole of asymmetry being stored in another flavour sector is ruled out

F. Deppisch, JH, W. Huang, M. Hirsch, H. Päs, arXiv:1503.07632 [hep-ph]

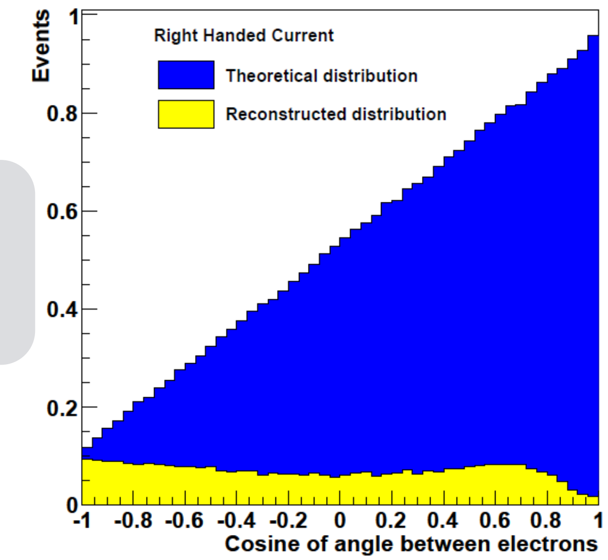
Discrimination of different Operators

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





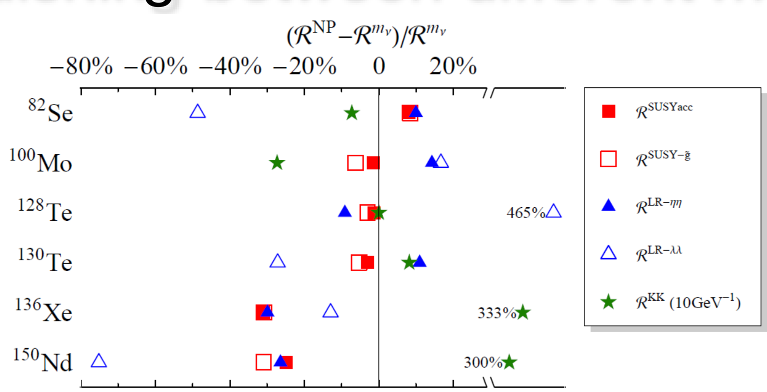
$$\frac{d\Gamma}{d\cos\theta_{12}} = \frac{\Gamma}{2}(1 - k_\theta \cos\theta_{12})$$



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

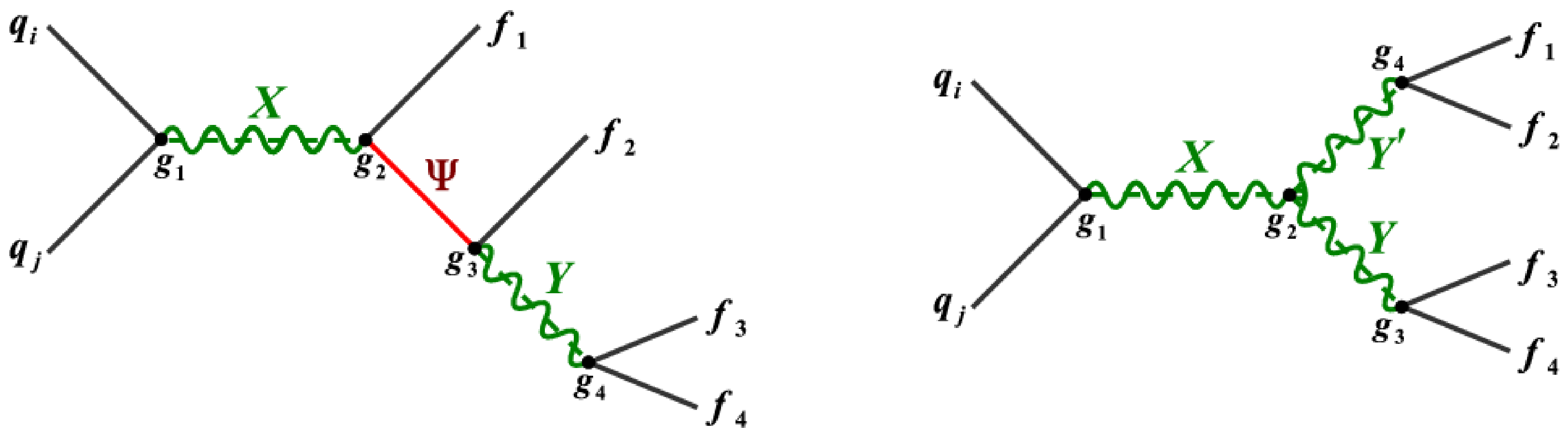


$$\frac{T_{1/2}(^AX)}{T_{1/2}(^AX)}) = \frac{|\mathcal{M}(^{76}Ge)|^2 G(^{76}Ge)}{|\mathcal{M}(^AX)|^2 G(^AX)}$$

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

- **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



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

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

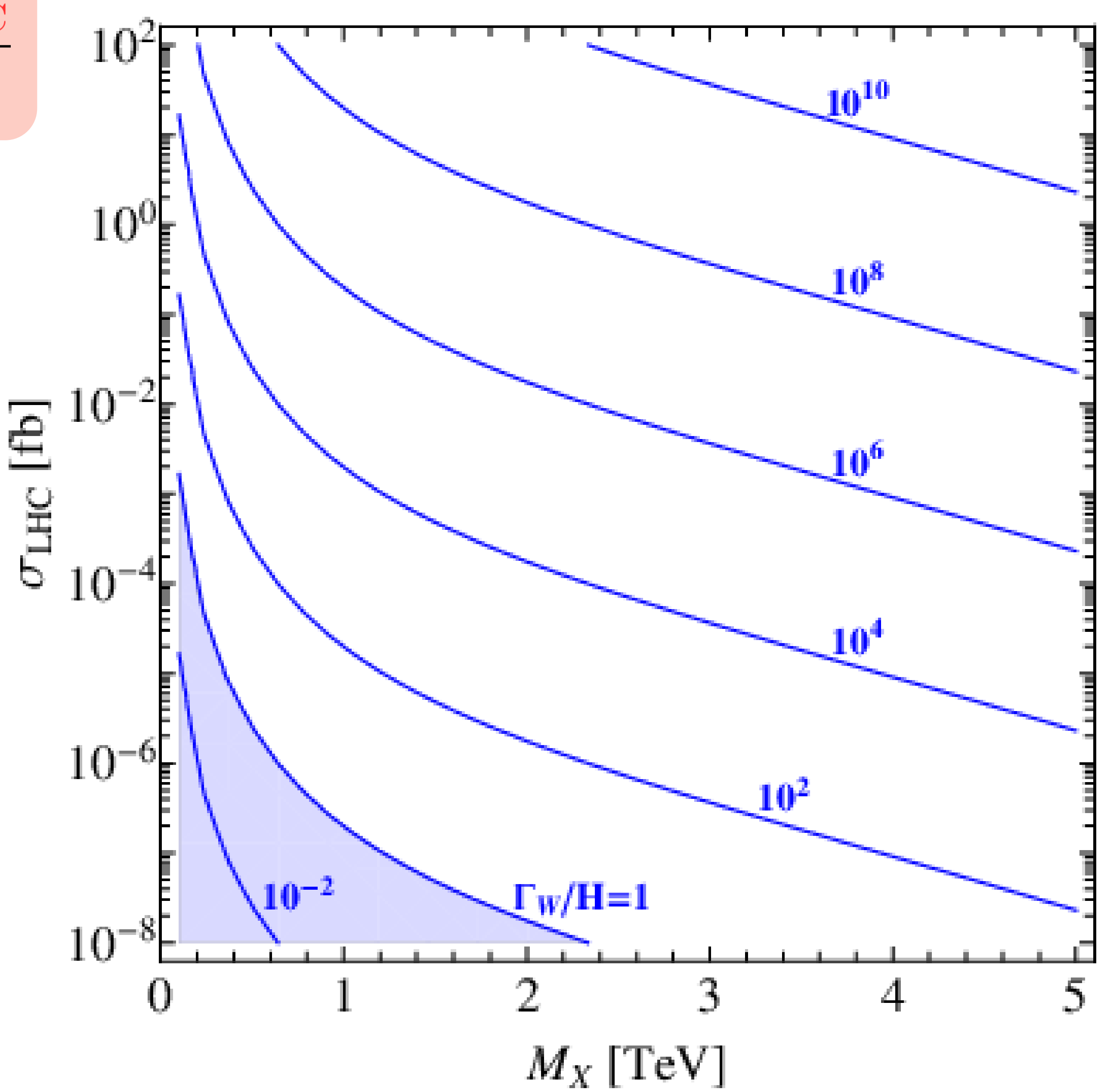
$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\rm TeV} - 1\right) + \log_{10}\frac{\sigma_{\rm LHC}}{\rm fb}$$

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 $\sigma_{\text{LHC}} > 10^{-2}$ fb washout highly effective

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



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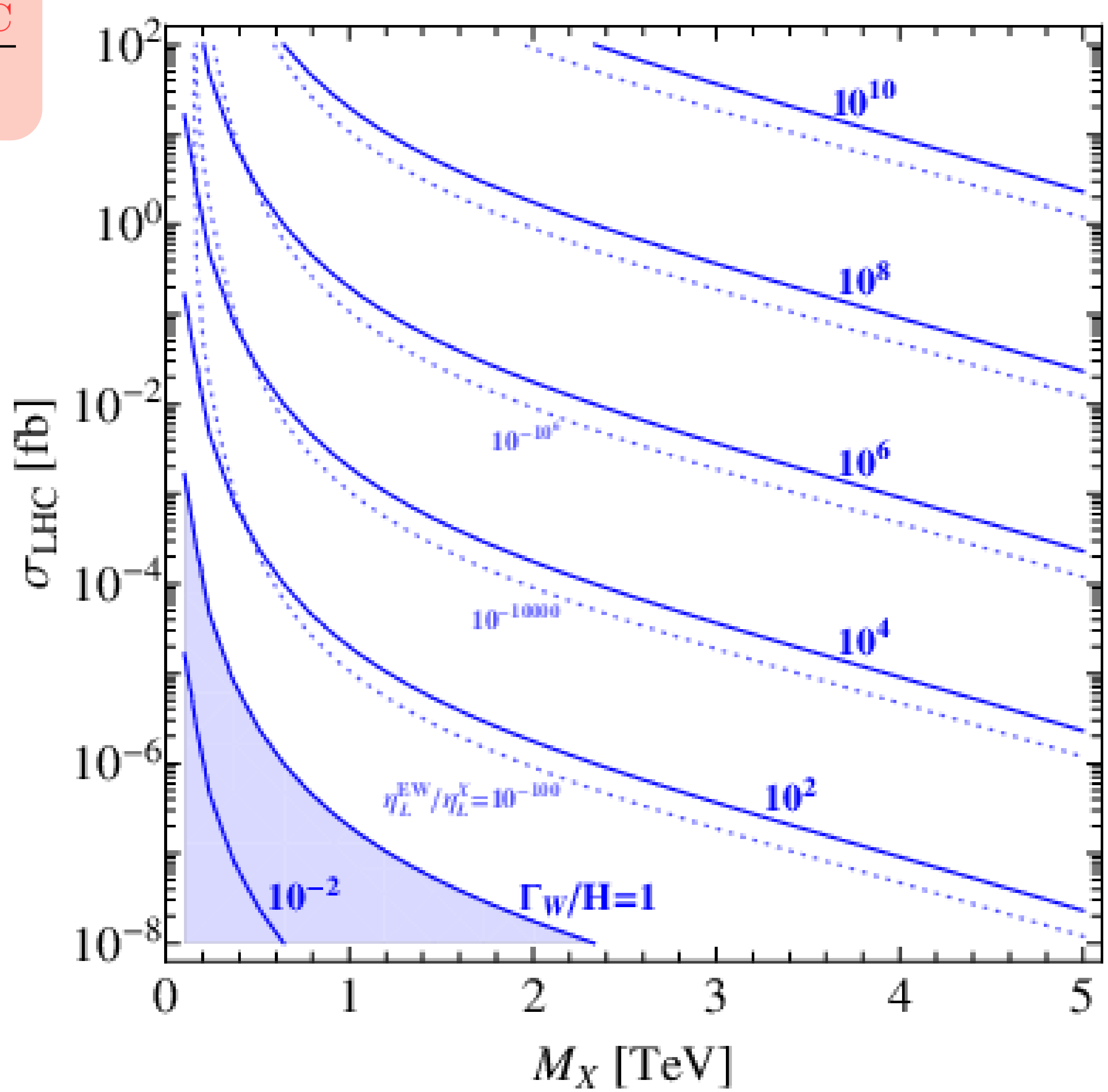
$$\frac{\Gamma_W}{H} >> 1$$

- enormous washout of any pre-existing lepton asymmetry

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



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

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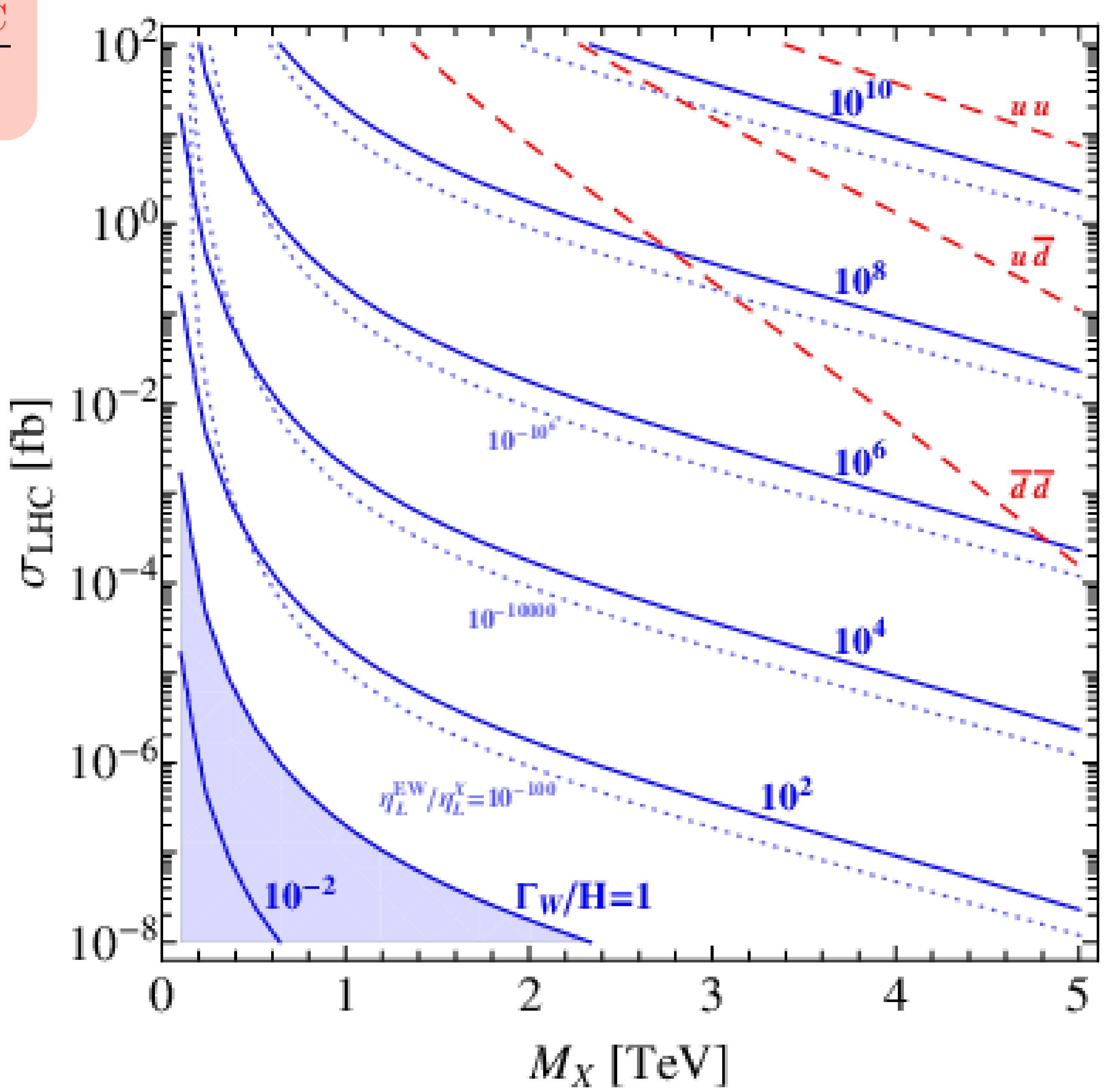

F. Deppisch, JH, M. Hirsch, PRL 112 (2014) 221601, arXiv:1312.4447 [hep-ph]

Lepton Number Violation at the LHC

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

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

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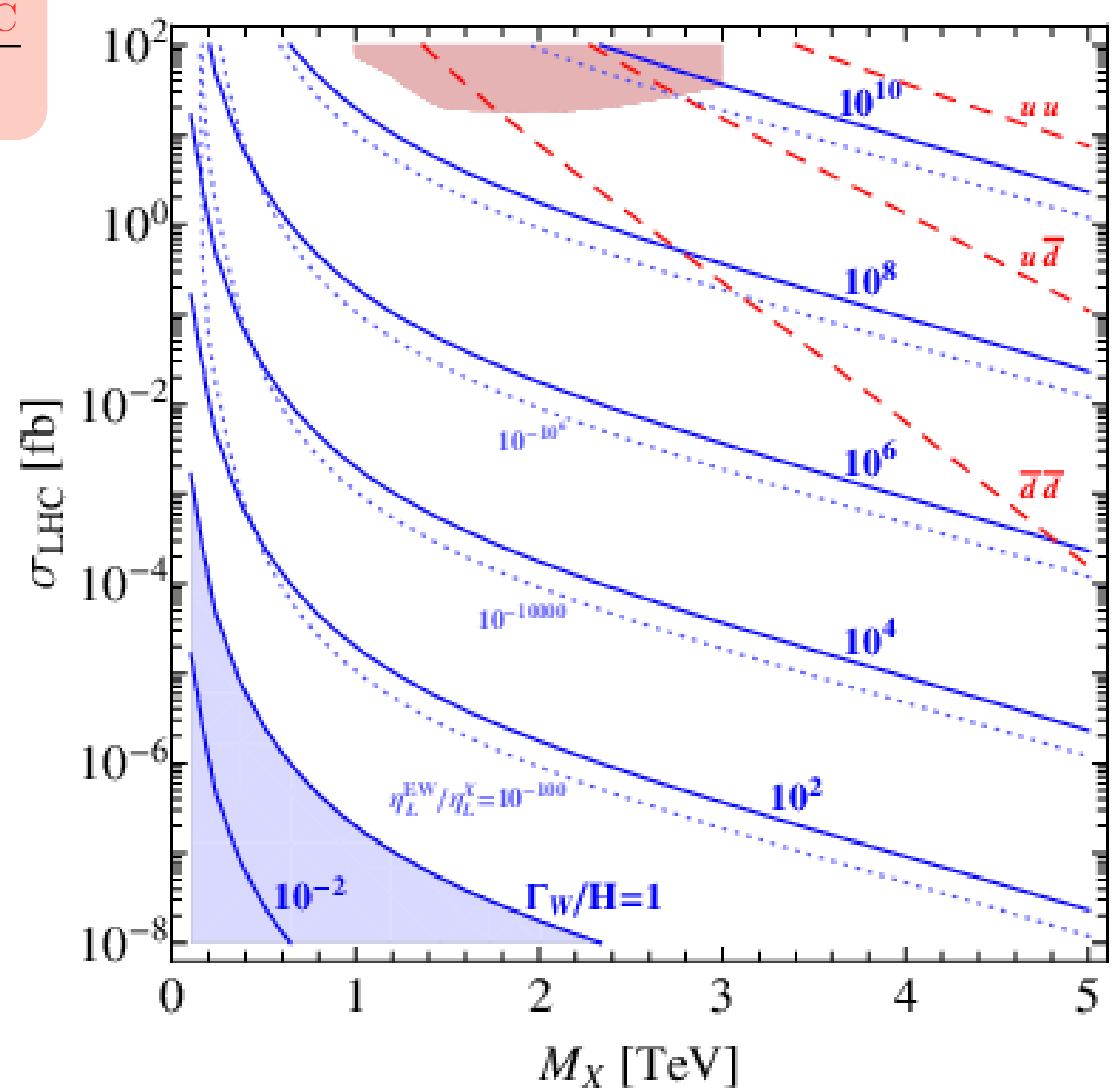


- LHC starts to exclude top of parameter plane

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

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

Caveats

- LNV process at LHC involves right-handed leptons, but SM sphaleron processes only affect EW fermion doublets

  → left- and right-handed fermions are in thermal equilibrium around EW-scale

- Possible generation of LNV only in one flavour family

  → observation of same-sign signatures in different flavours

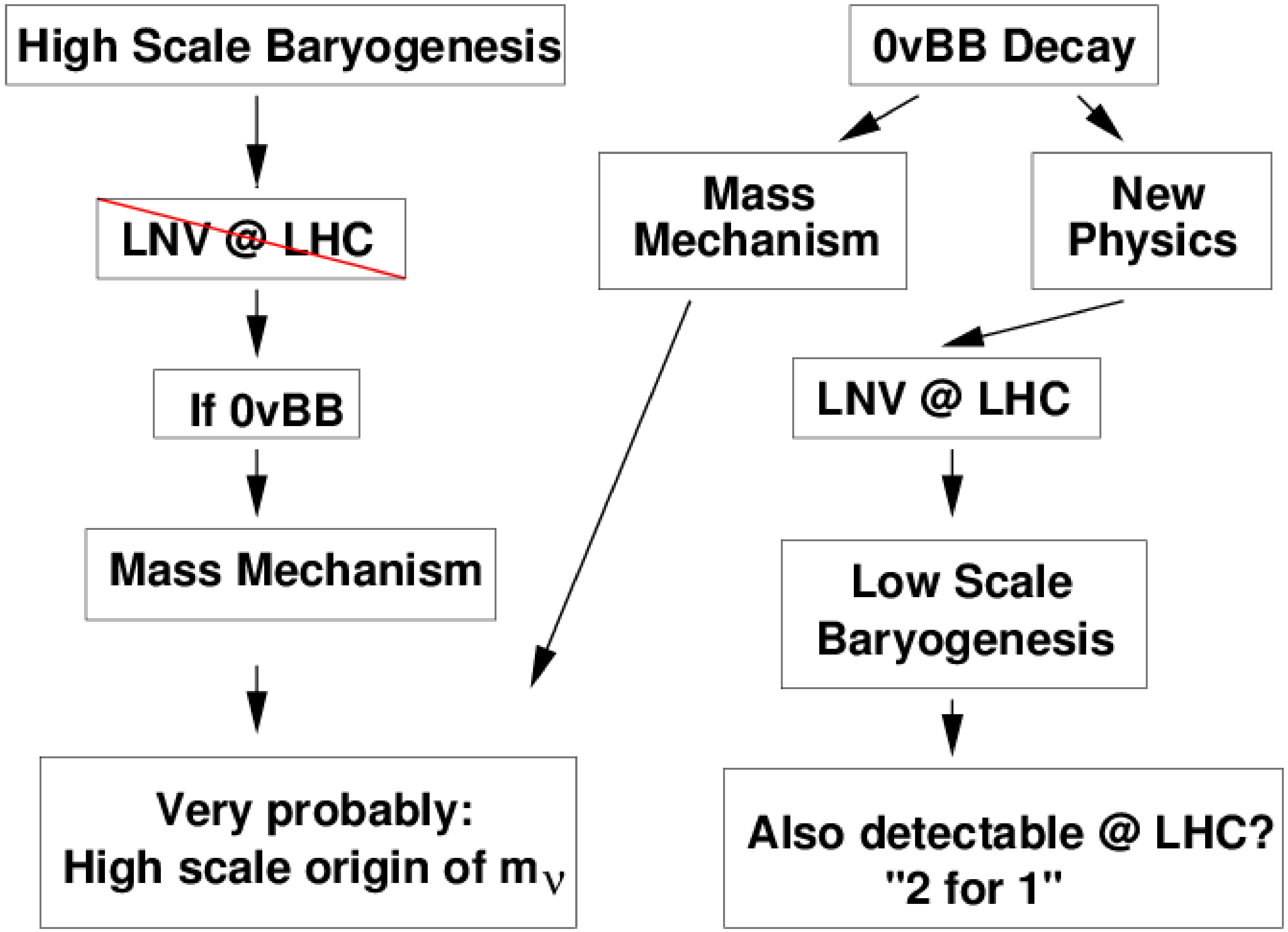
  → observation of LFV processes

- LNV models with new conserved quantum numbers or hidden sectors may be exempt

S. Weinberg, PRD 22 (1980)
A. Antaramian, L. Hall, A. Rasin, PRD 49 (1994), arXiv:9311279 [hep-ph]

- Baryon asymmetry could be generated below the EW scale

Conclusions



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

Thank you!