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Falsifying Baryogenesis Models via Observation of LNV (and LFV)

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Baryon Asymmetry
Generation and Washout

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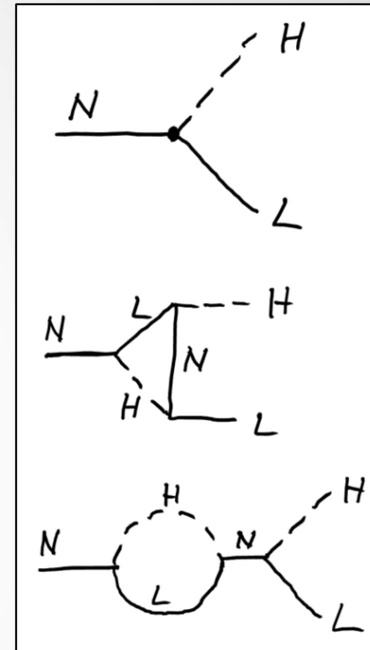
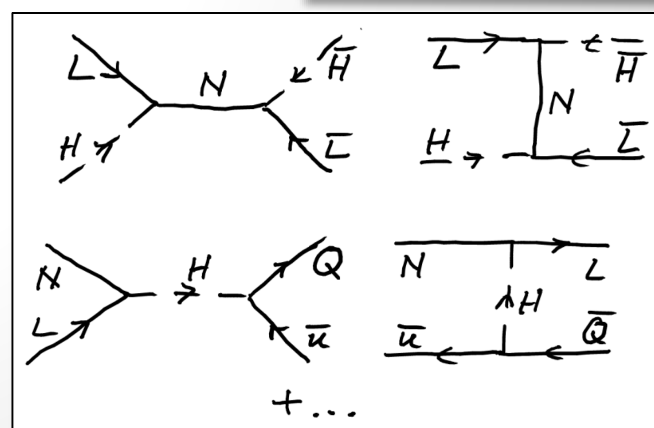
- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$



- Other possible scenarios
  - For us only important: $(B - L)$ asymmetry generated above LHC scale



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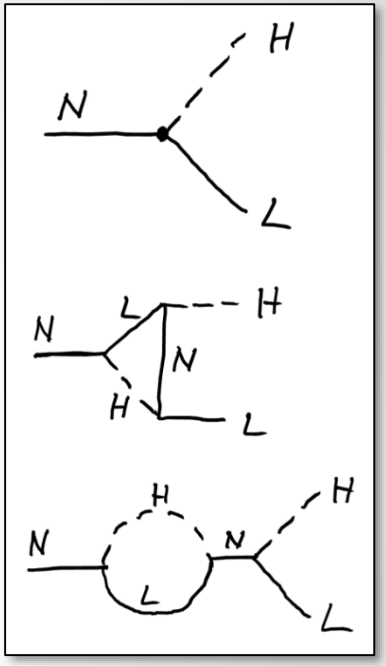
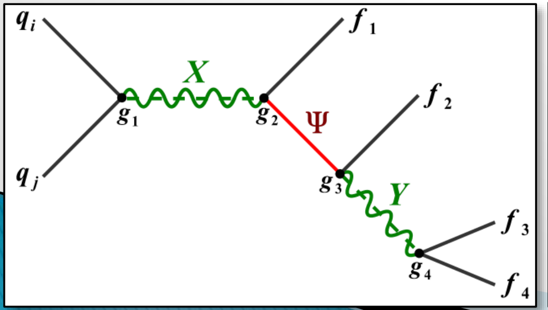
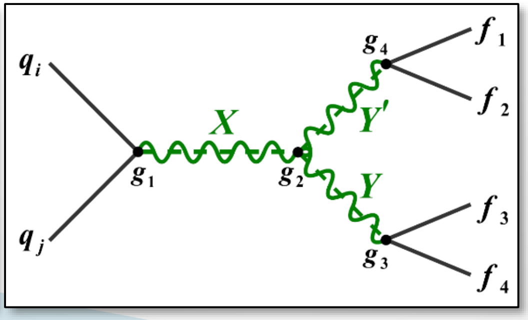
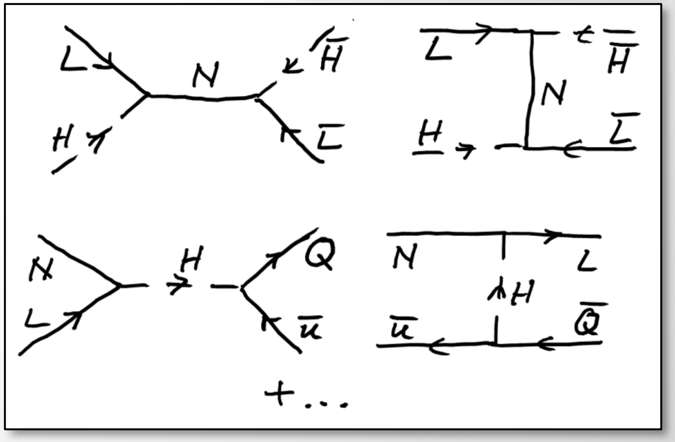


- What if we observe lepton number violating processes at the LHC or in $0\nu\nu\beta$?







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Induced Washout

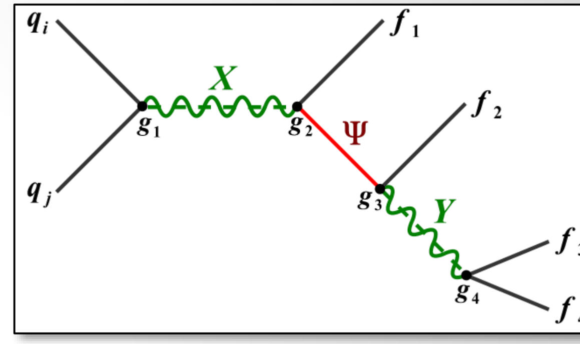
- Compare LHC cross section with lepton number asymmetry washout

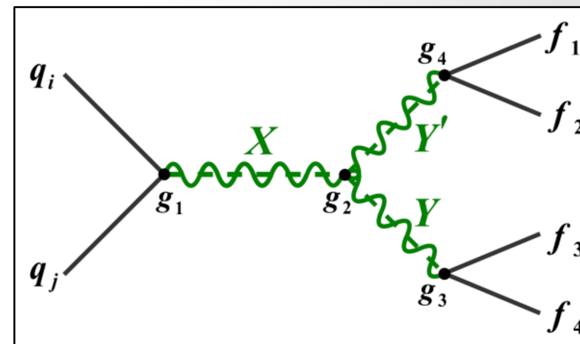
$$\frac{\Gamma_W}{H} > 3\times 10^{-3}\,\frac{M_P M_X^3}{T^4}\,\frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})}\times(s\,\sigma_{\rm LHC})$$

  - Lower limit on total washout rate
    - Neglecting other washout processes

$$\log_{10}\frac{\Gamma_W}{H} > 7 + 0.6\left(\frac{M_X}{\rm TeV} - 1\right) + \log_{10}\frac{\sigma_{\rm LHC}}{\rm fb}$$

  - Observation of LNV @ LHC corresponds to highly effective washout $\Gamma_W/H \gg 1$
    - Excludes Leptogenesis models that generate asymmetry above M_X





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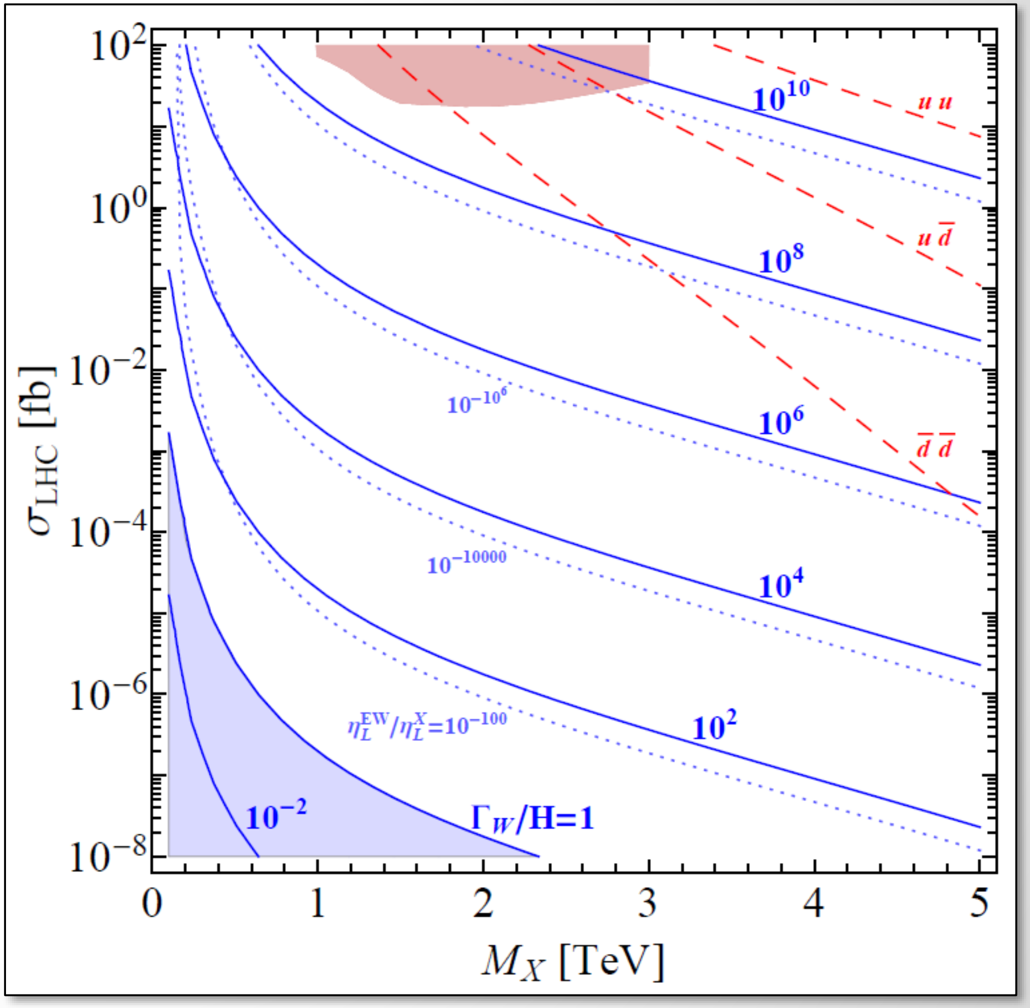

Baryon Asymmetry Limit

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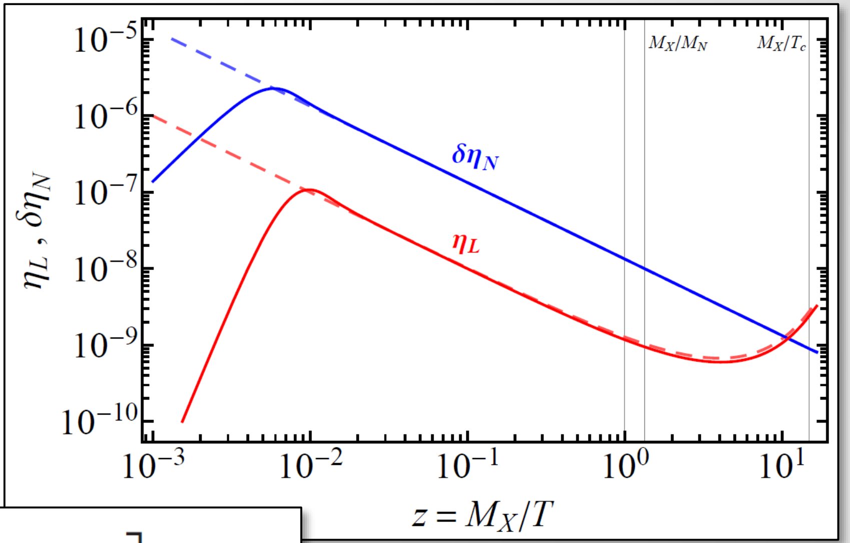
- Classic Leptogenesis with one heavy neutrino N, neglecting flavour
  - Solve Boltzmann equations for η_N and η_L with LHC process as only washout source



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

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

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

M_N = Scale of CP asymmetry generation,

M_X = Scale of LNV observation

Baryon Asymmetry Limit

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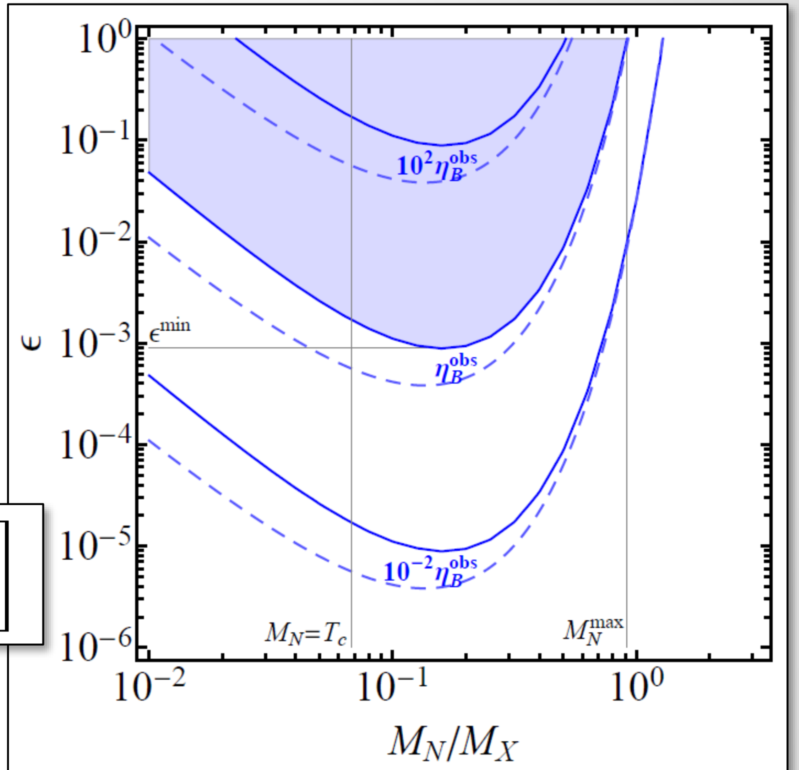
- Classic Leptogenesis with one heavy neutrino N, neglecting flavour
  - Solve Boltzmann equations for η_N and η_L with LHC process as only washout source
  - Upper limit on baryon asymmetry

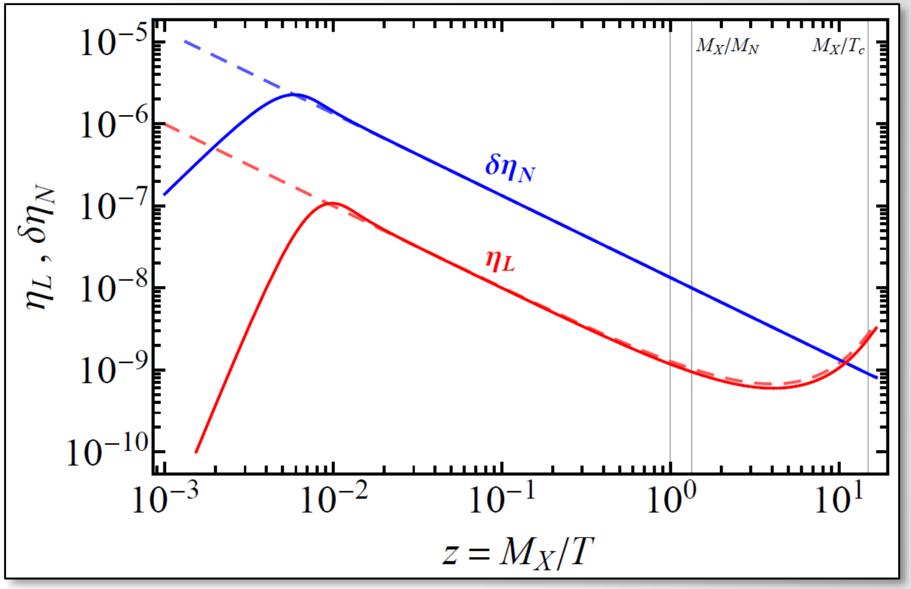
$$\log_{10}\left|\frac{\eta_B}{\eta_B^{\rm obs}}\right| < 2.4\frac{M_X}{\rm TeV}\left(1-\frac{4}{3}\frac{M_N}{M_X}\right) + \log_{10}\left[|\epsilon|\left(\frac{\sigma_{\rm LHC}}{\rm fb}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^2\right]$$



  - LNV is observed at LHC
    → High scale Leptogenesis ($M_N > M_X$) is not viable
    → Strong limit on CP asymmetry ϵ for low scale Leptogenesis ($M_{EW} < M_N < M_X$)

Caveats

- Cannot exclude scenarios that generate a lepton number asymmetry below observed scale M_X
  - But strong limits still apply
- Asymmetry can be present in one lepton generation only
  - Unambiguous falsification requires observation of LNV in all flavours (or observation of low energy LFV such as $\tau \to e\gamma$)



- Sphalerons only affect LH leptons… What if LNV is observed for RH leptons only?
  - Not an issue as all LH and RH charged fermions are in thermal equilibrium $\approx M_{EW}$
- Symmetry in new sector coupled via hypercharge induces $(B - L)$ chemical potential (Antaramian, Hall, Rašin '93)

Displaced Vertices

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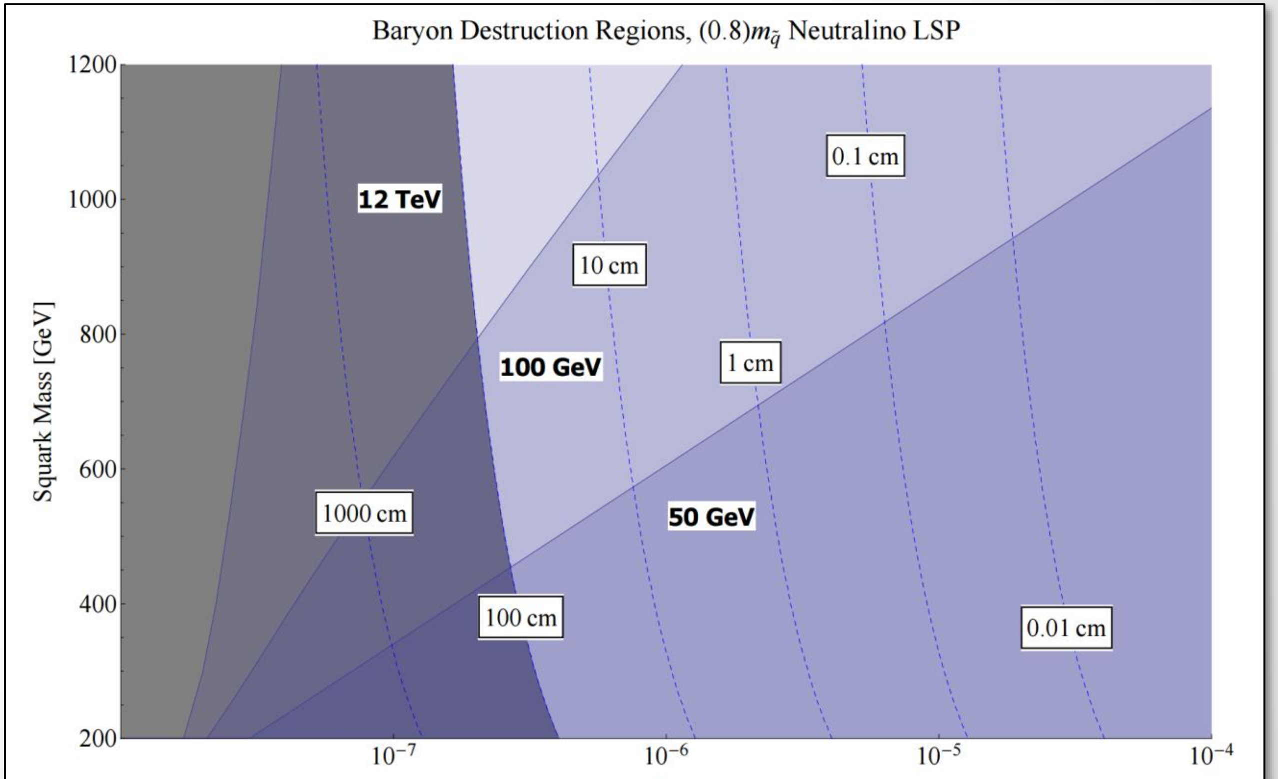
- Avoiding strong washout requires e.g. small couplings
  - Can lead to displaced vertices at the LHC
  - Example: R-Parity violating SUSY coupling UUD (Barry, Graham, Rajendran '13)
  - Upper limit on baryogenesis scale related to decay length



Barry, Graham, Rajendran '13

Other High Energy LNV Processes

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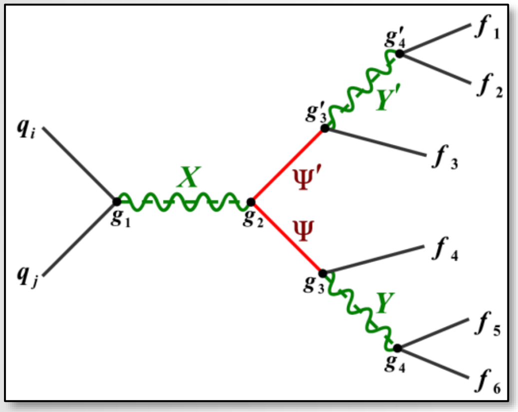
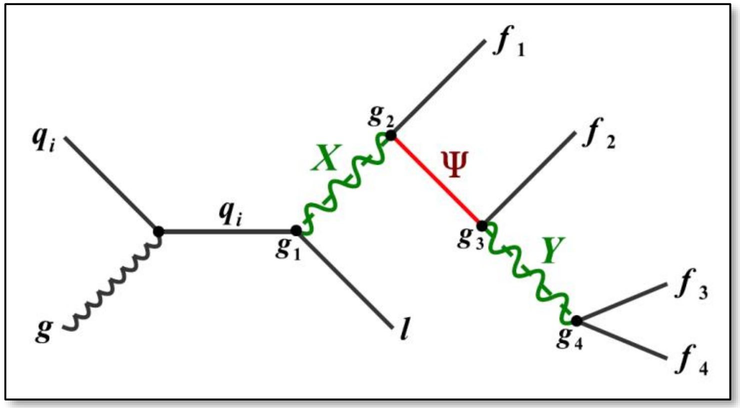
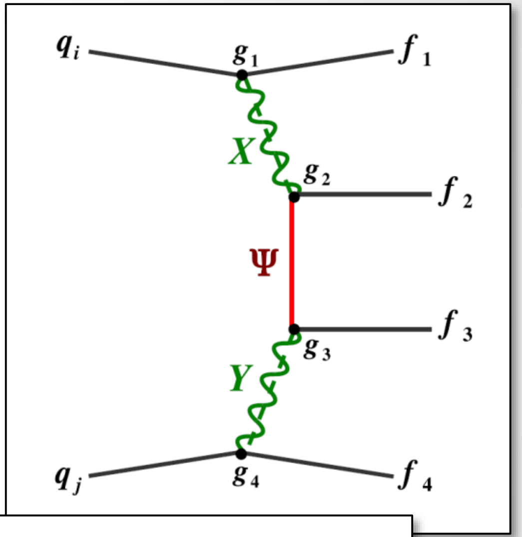
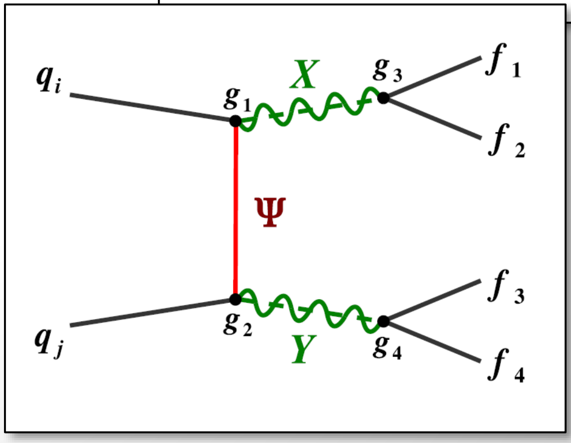
- The argument can be extended to
  - other resonant and non-resonant LNV processes at the LHC







  - LNV processes at other, future colliders



Washout via $0\nu\beta\beta$ operators

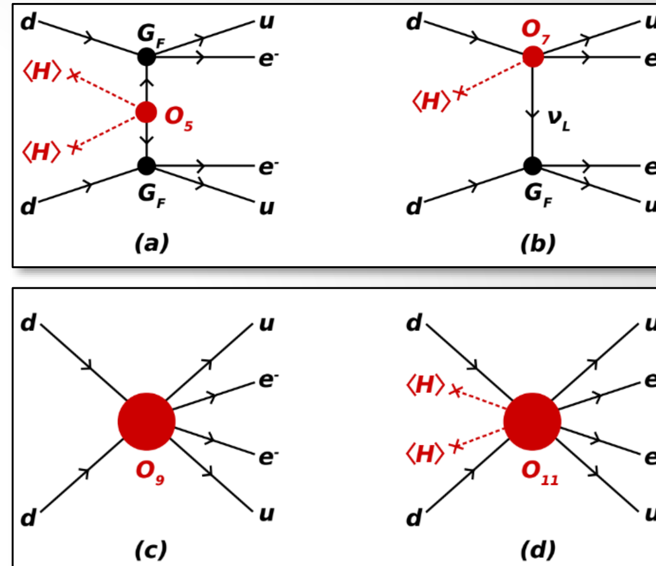
- Analogous analysis using LNV effective operators of mass dimensions 5, 7, 9, 11
  - 129 Operators (Babu, Leung '01, de Gouvea, Jenkins '08)
  - Examples

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

  - Matching to $0\nu\beta\beta$ operators

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

$$T_{1/2} = 2.1\times 10^{25}\ \mathrm{y}\cdot\left(\Lambda_D/\Lambda_D^0\right)^{2d-8}$$



$\mathcal{O}_D$	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}

Washout via $0\nu\beta\beta$ operators

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- Boltzmann equation including washout of D-dim effective operator

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

  - $c_{\{5,7,9,11\}} = \{\frac{8}{\pi^5}, \frac{27}{2\pi^7}, \frac{3.2\times10^4}{\pi^9}, \frac{3.9\times10^5}{\pi^{13}}\}$

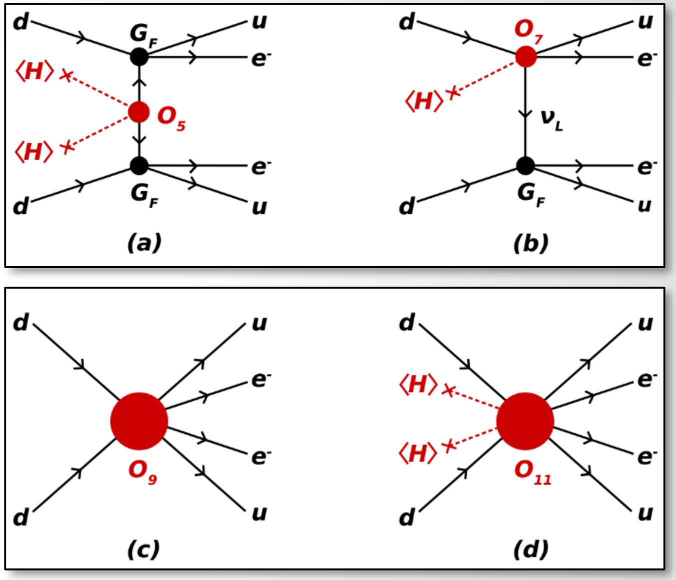
- Effective washout if

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

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

- Better: Solve Boltzmann such that initial asymmetry is washed out at the EW scale

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



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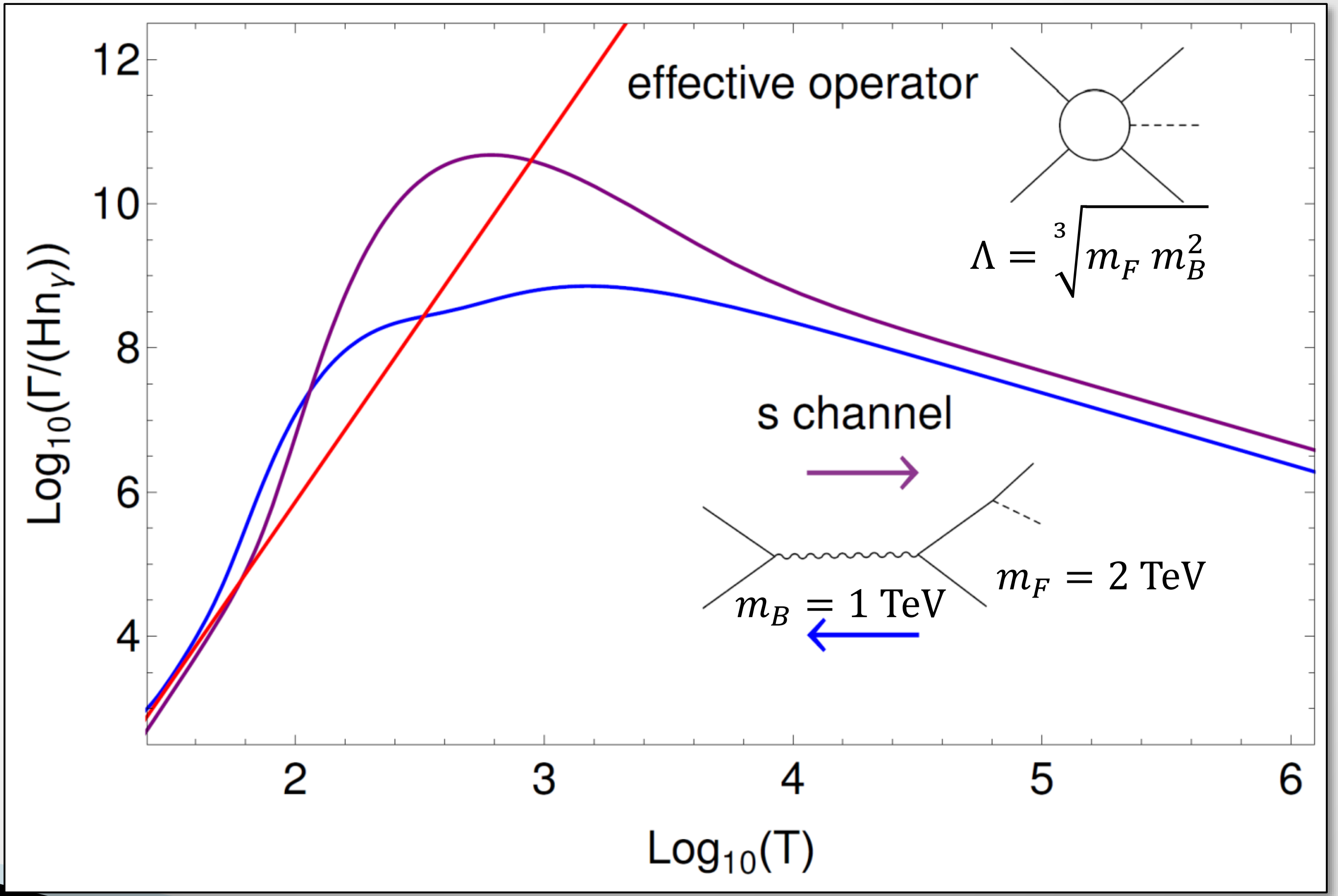
Washout via $0\nu\beta\beta$ operators

- Even better:
  UV-completed operators for behaviour around Λ



Effect of LFV operators

- Analogous analysis for eff. 6-dim LFV operators

$$\mathcal{O}_6(ll\gamma H) = \bar{L}_i \sigma^{\mu\nu} e_j^c H^+ F_{\mu\nu}$$

$$\mathcal{O}_6(llll) = (\bar{L}_i \gamma^\mu L_j)(\bar{L}_k \gamma^\mu L_l)$$

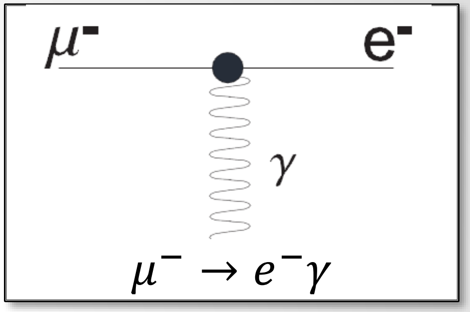
$$\mathcal{O}_6(llqq) = (\bar{L}_i \gamma^\mu L_j)(\bar{Q}_k \gamma^\mu Q_l)$$

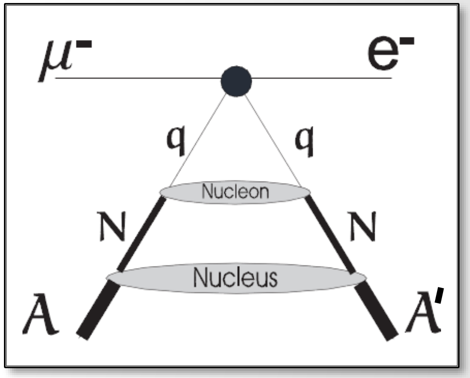
  - Do not washout total lepton number asymmetry but equilibrate lepton flavours

- Matching to LFV process rate

$$C_{\ell\ell\gamma} = \frac{eg^3}{16\pi^2 \Lambda^2_{\ell\ell\gamma}}, \quad C_{\ell\ell qq} = \frac{g^2}{\Lambda^2_{\ell\ell qq}}$$

$$\mathrm{Br}_{\mu\to e\gamma} = 5.7 \times 10^{-13} \cdot \left(\Lambda^0_{\mu e\gamma}/\Lambda_{\mu e\gamma}\right)^4$$



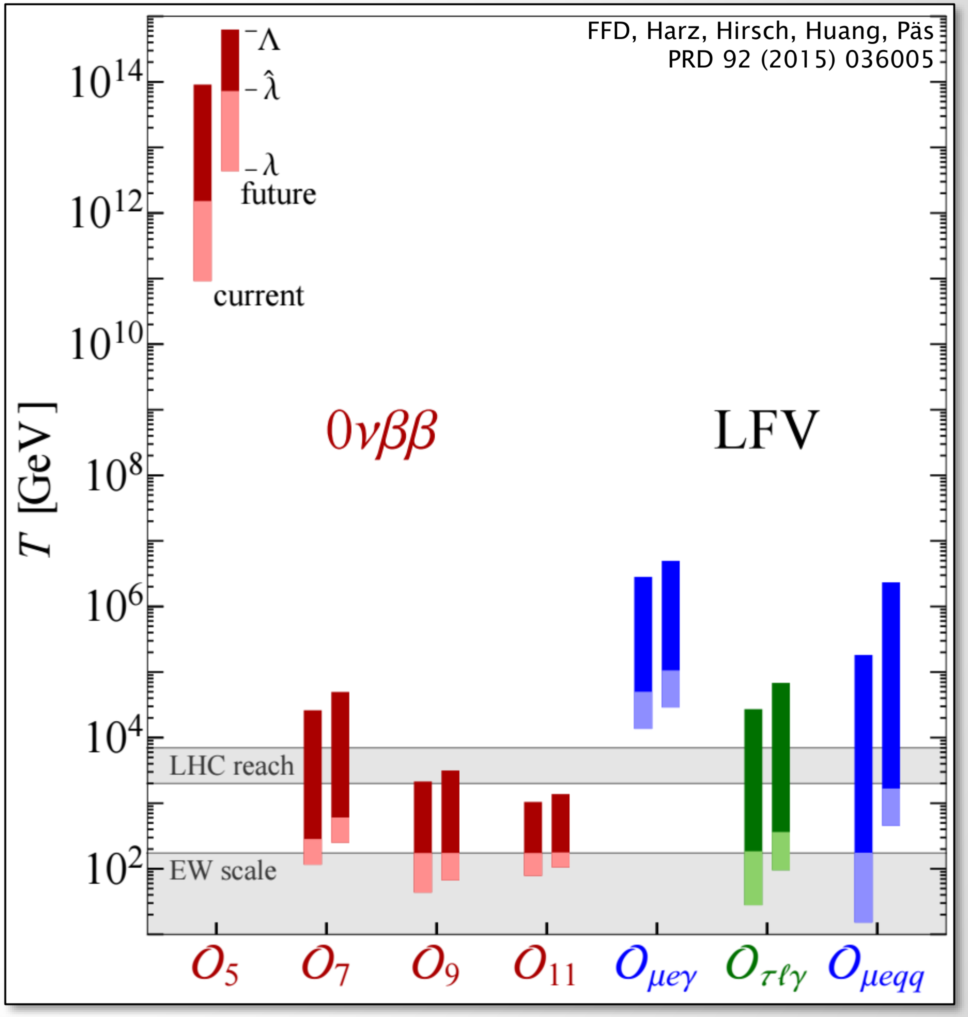


$\mu^- \to e^-$ conversion in nuclei

$\mathcal{O}_i$	λ_i^0 [GeV]	Λ_i^0 [GeV]
$\mathcal{O}_{\mu e\gamma}$	1.4×10^4	2.8×10^6
$\mathcal{O}_{\tau\ell\gamma}$	2.8×10^1	2.7×10^4
$\mathcal{O}_{\mu eqq}$	1.5×10^1	1.8×10^5

Observation of $0\nu\beta\beta$ / LFV

- Temperature ranges of strong washout or flavour equilibration
  - Assumes observation of corresponding process!!
- Crucial to distinguish non-standard $0\nu\beta\beta$ operators



Conclusion

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- **LNV a crucial BSM signature**
  - Majorana neutrino mass models
  - Baryogenesis via Leptogenesis
- **Observations of LNV and LFV processes**
  - Tell us the temperature regime where leptons-antileptons and different flavours are equilibrated
  - Can falsify high scale baryogenesis scenarios
- **Bottom-up approach**
  - Experimental data → Constrained model-landscape(data)
- **Important information for model selection, e.g.**
  - Observation of $0\nu\beta\beta$
  - Observation of LNV @ LHC

  } LNV @ TeV Scale
Disfavours high-scale seesaw

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- **Bottom-up approach**
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- **Important information for model selection, e.g.**
  - Observation of $0\nu\beta\beta$
  - No observation of LNV @ LHC

  } Improved confidence in standard $0\nu\beta\beta$ mechanism