Implications of $0\nu\beta\beta$ on Mechanisms of Baryogenesis

based on Phys.Rev.Lett.112 (2014) 221601, Phys.Rev.D92 (2015) 3, 036005, WIP
with L. Graf, J. Harz, W.-C. Huang, M. Hirsch, H. Päs

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Dirac vs Majorana

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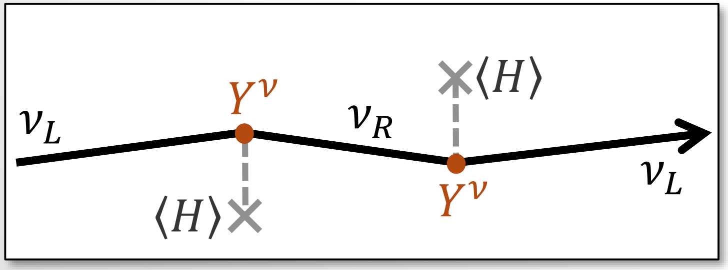
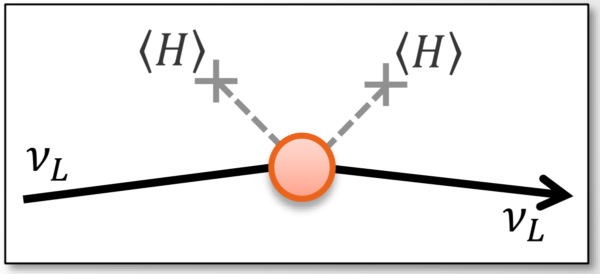
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs



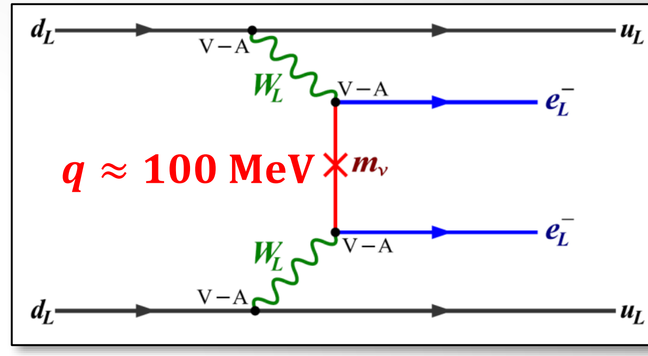
Majorana mass, using only a left-handed neutrino → Lepton Number Violation



$0\nu\beta\beta$

- Half-life

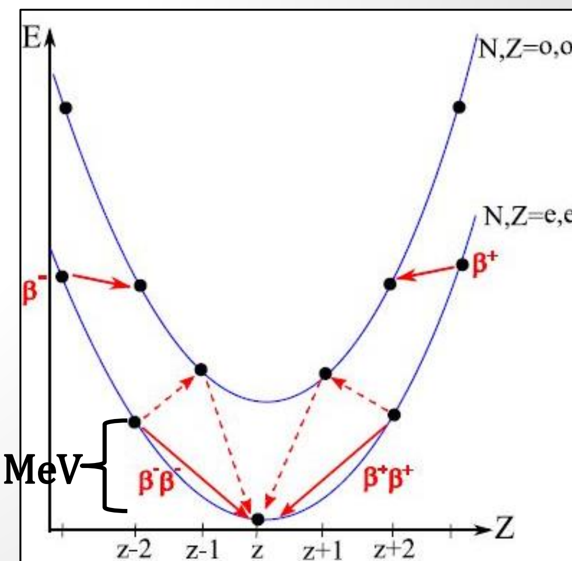
$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$



- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5) \gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu}$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu}$



$$T_{1/2}^{-1} \propto \frac{|m_{\beta\beta}|^2}{q^4} G_F^4 Q^5$$

$$\frac{10^{25}\text{yr}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{eV}\right)^2$$

$Q \approx 2\text{–}4$ MeV

Three Active Neutrinos

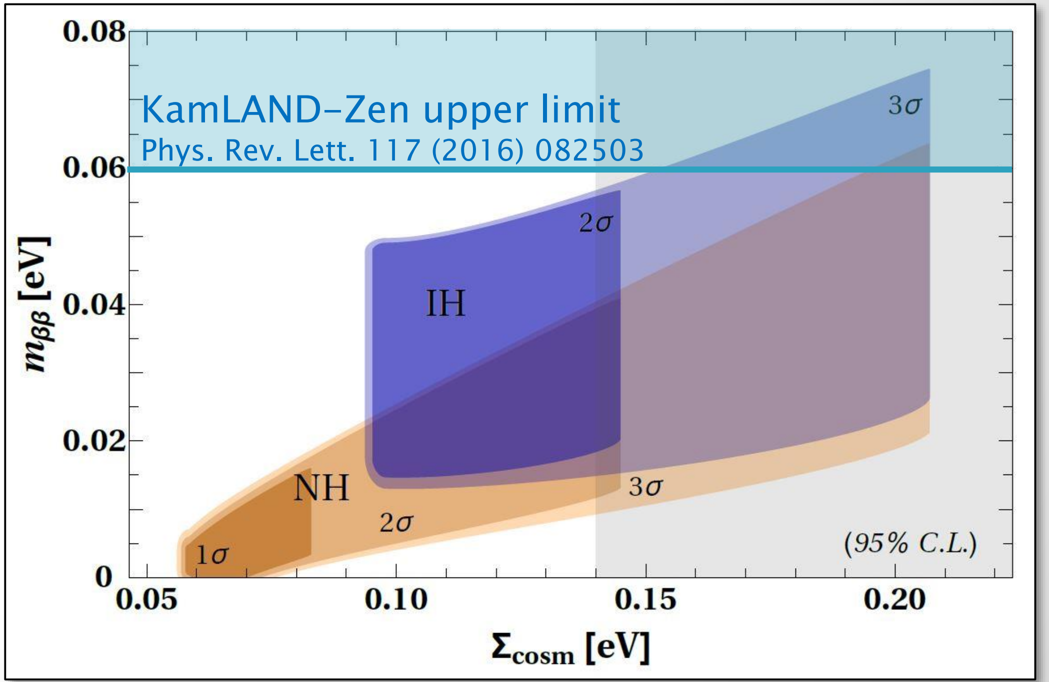
- Effective $0\nu\beta\beta$ Mass

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i(\phi_{13}-2\delta)}$$

- Degenerate Regime

$$|m_{\beta\beta}| = m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\phi_{12}}{2}\right)}$$

- Uncertainty from unknown Majorana phases
- Accidental cancellation for NH possible



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

New Physics and $0\nu\beta\beta$

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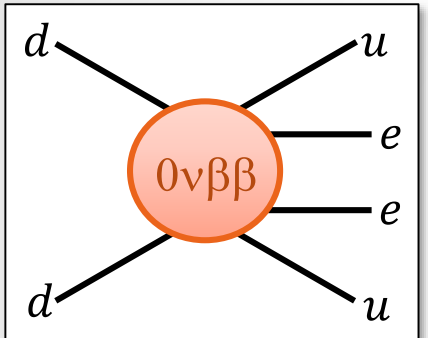
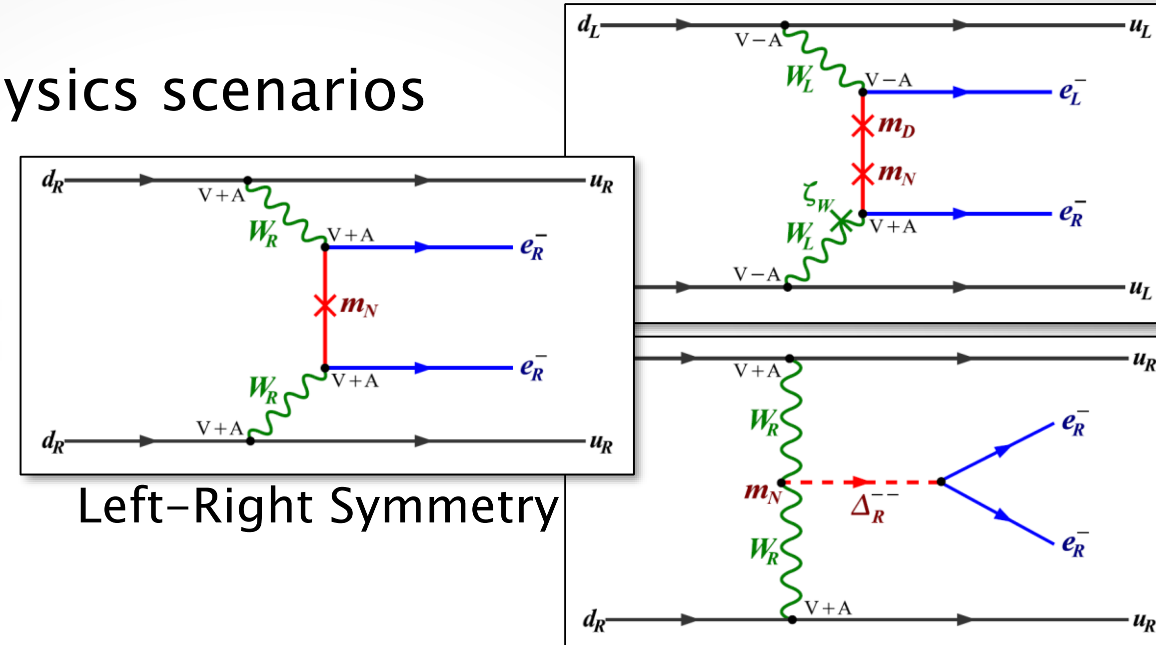
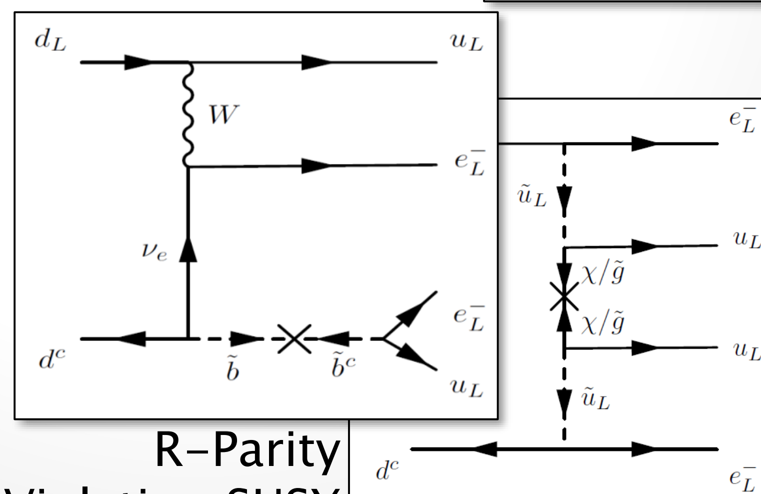
- Plethora of New Physics scenarios



$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$



Left-Right Symmetry



R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

...

New Physics and $0\nu\beta\beta$

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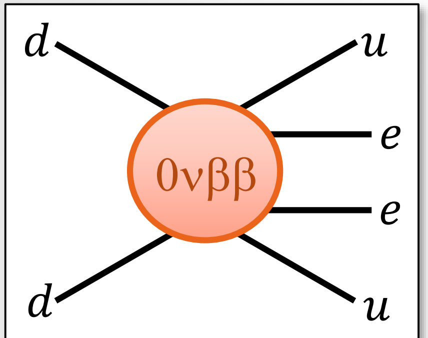

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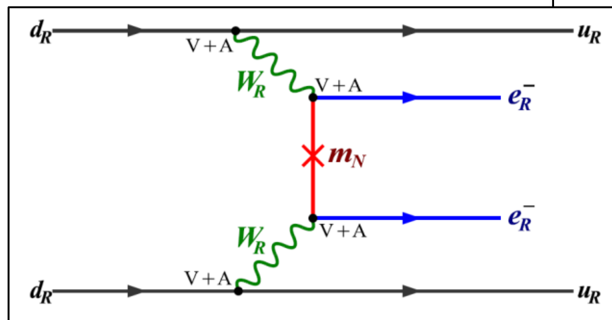
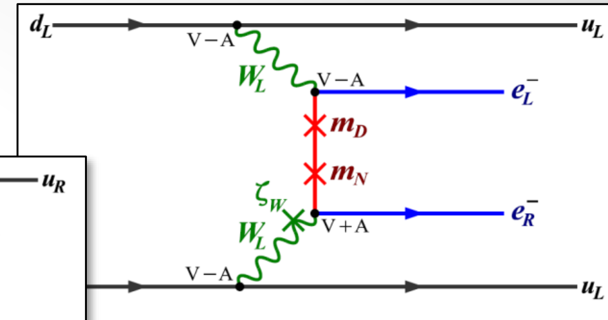
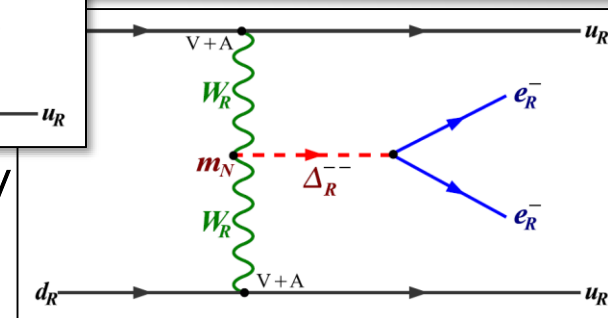
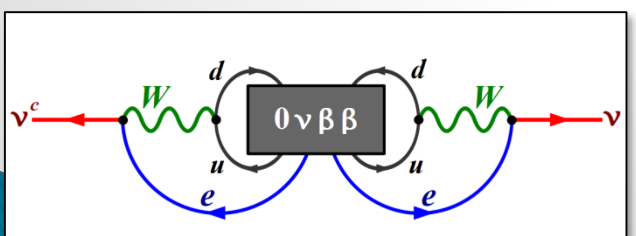


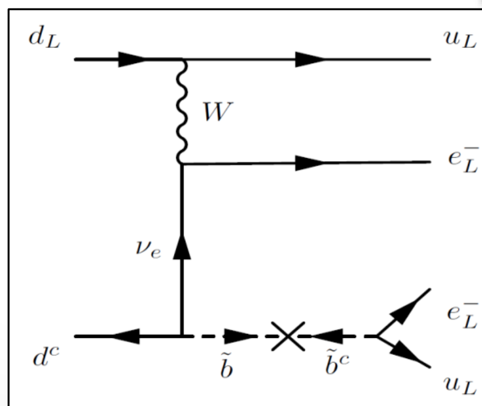


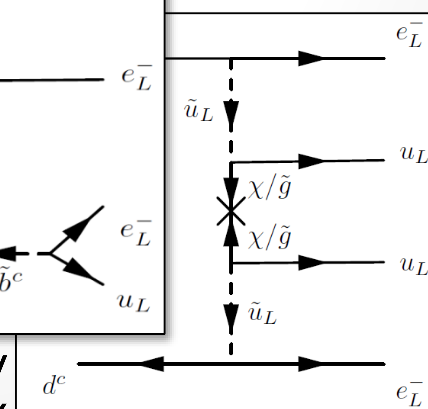


Left-Right Symmetry

- Neutrinos still Majorana







R-Parity Violating SUSY

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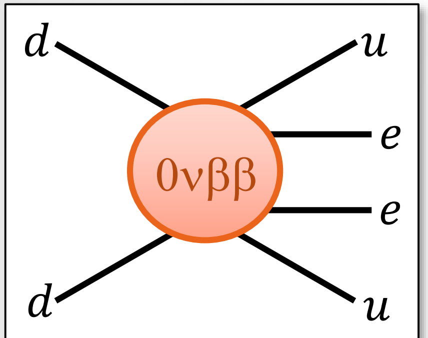
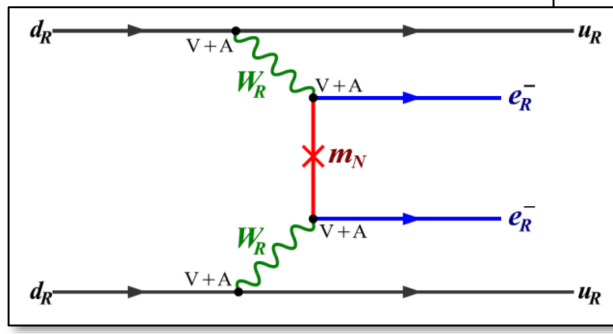
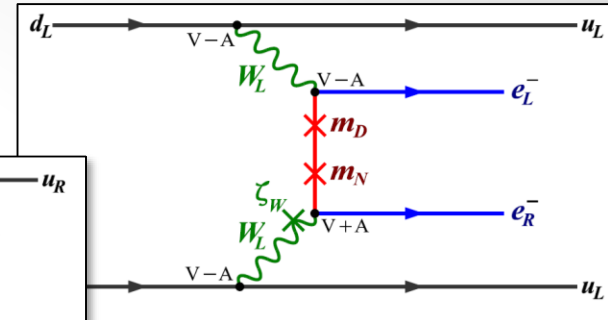
New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry







$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \mathrm{TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale

New Physics and $0\nu\beta\beta$

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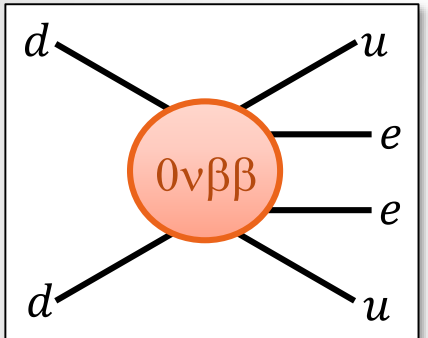

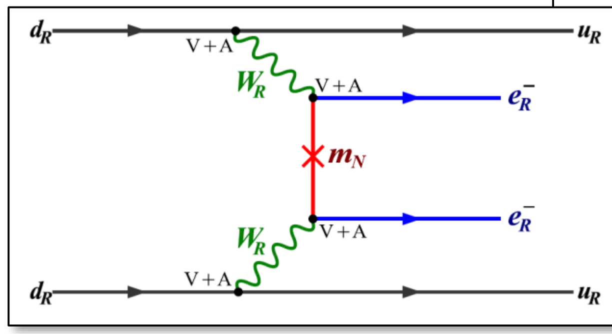

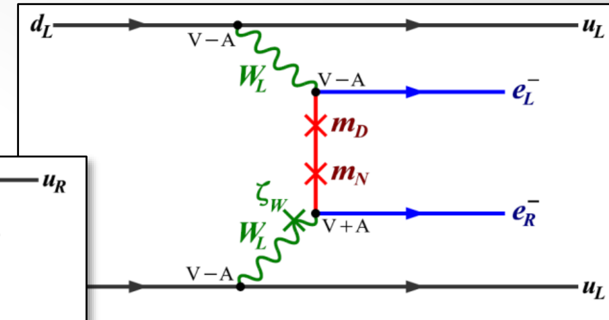

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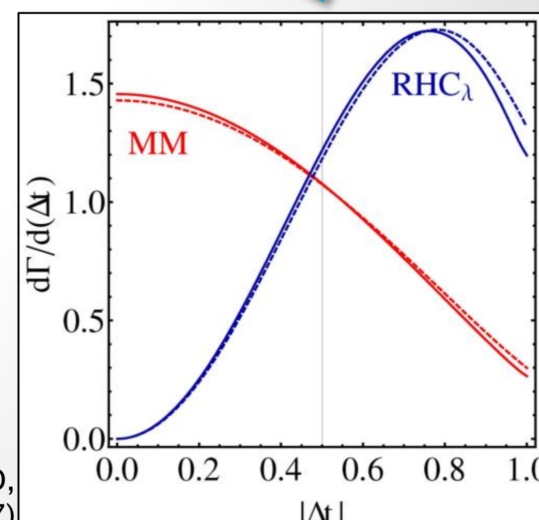
- $0\nu\beta\beta$ probes the TeV scale

Modified angular and energy distribution of emitted electrons
(Doi et al. '83; Ali et al. '06)



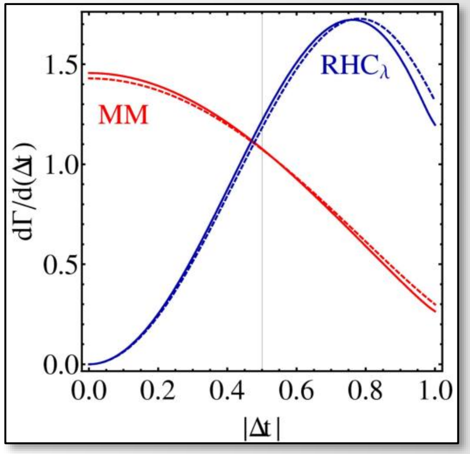
FFD, SuperNEMO, Eur.Phys.J. C70 (2010) 927)

Disentangling New Physics Contributions

- Angular and energy distribution of emitted electrons
  (Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner-Rembold '10)

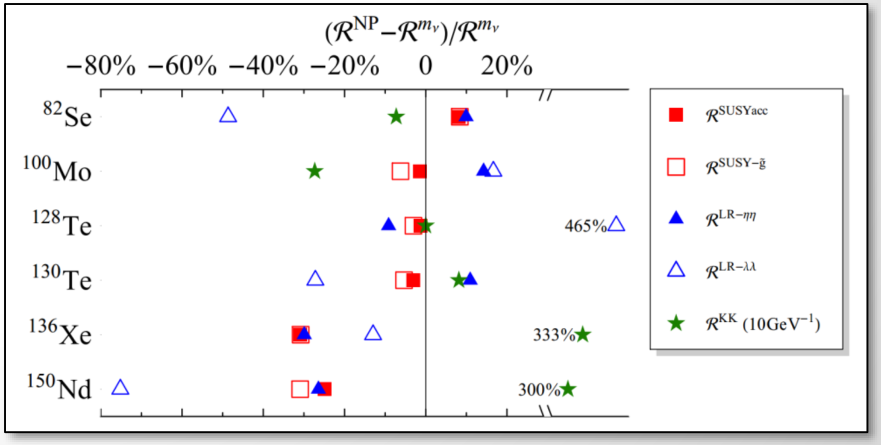
$$\frac{d\Gamma}{dE_{e_1} dE_{e_2} d\cos\theta} = \frac{\Gamma}{2}\left(1 - k\left(E_{e_1}, E_{e_2}\right)\cos\theta\right), \qquad -1 < k < 1$$

  - Linear in $\cos\theta$
  - $k(E_{e_1}, E_{e_2})$ depends on $0\nu\beta\beta$ mechanism



- Comparison of $0\nu\beta\beta$ in multiple isotopes
  (FFD, Päs PRL 2007, Meroni et al. 2013)
  - Depends on $0\nu\beta\beta$ mechanism
  - Independent of details of new physics (if one mechanism dominates)

$$\frac{T_{1/2}(X)}{T_{1/2}(Y)} = \frac{G(Y)|M(Y)|^2}{G(X)|M(X)|^2}$$



Baryon Asymmetry

- The Universe is not matter-antimatter symmetric
  - CMB Anisotropy
  - Primordial Nucleosynthesis
  - No matter-antimatter annihilation
- Observed asymmetry

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

  - Very small… Universe may have begun symmetric
  - Still too large… to be compatible with the Standard Model

Baryon Asymmetry

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- Dynamic generation of baryon asymmetry requires (Sakharov '66)
  - Baryon number violation
  - C and CP Violation
  - Out-of-equilibrium dynamics
- Standard Model
  - Baryon number violated at quantum level (Sphalerons)
  - C and CP violated but effect too small

$$\frac{\mathrm{Im}\,\det(m_u m_u^+ m_d m_d^+)}{v^{12}} = J\,\frac{m_t^4 m_c^2 m_b^4 m_s^2}{v^{12}} \approx 10^{-19}$$

  - Electroweak phase transition out-of-equilibrium if first order but requires

$$m_h < 60 - 80\ \mathrm{GeV}$$

Sphalerons

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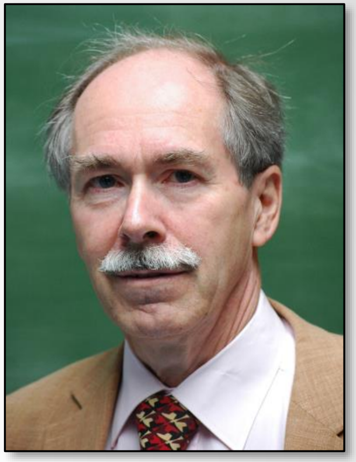
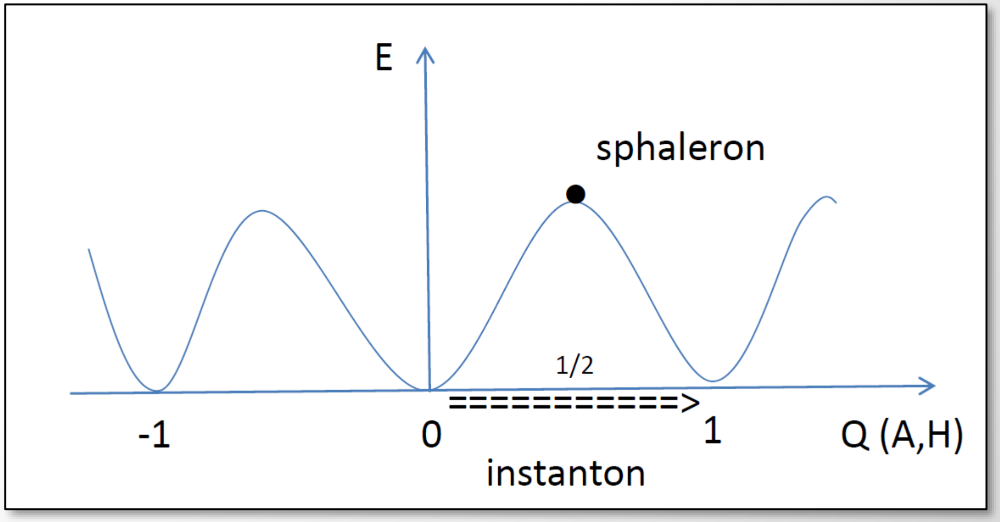


- Baryon and Lepton numbers accidental, classical symmetries in the Standard Model
- Violated at the quantum level (t' Hooft '76)

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

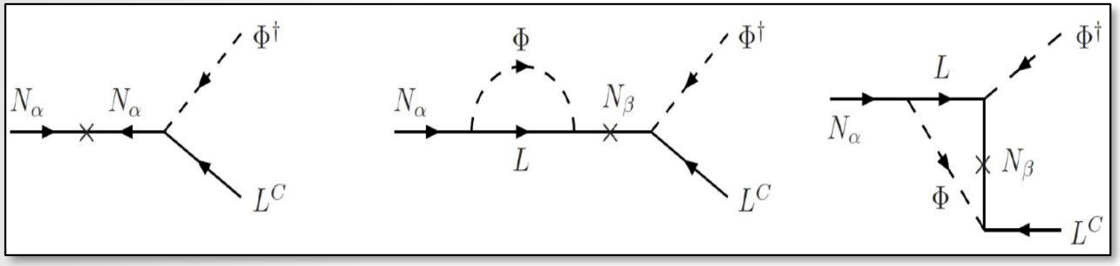
  - $B + L$ violated
  - $B - L$ remains conserved
- Sphaleron transitions in equilibrium $\frac{\Gamma_{Sph}}{H} > 1$ for

$$\Lambda_{EW} \approx 10^2 \text{GeV} < T < 10^{12}\ \text{GeV}$$



Leptogenesis

- Decays of heavy Majorana neutrinos violating L and CP (Fukugita, Yanagida '86)

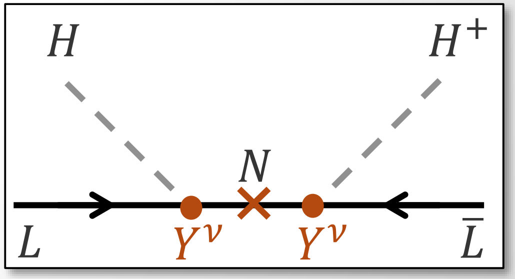


  - CP asymmetry

$$\epsilon_1 = \frac{\Gamma(N_1 \to LH^+) - \Gamma(N_1 \to \bar{L}H)}{\Gamma(N_1 \to LH^+) + \Gamma(N_1 \to \bar{L}H)} \approx \frac{3}{8\pi} \frac{\mathrm{Im}\left[(Y_\nu Y_\nu^+)^2_{1k}\right]}{(Y_\nu Y_\nu^+)_{11}} \frac{M_1}{M_k} \approx 10^{-6} \frac{M_1}{10^{10}\ \mathrm{GeV}} \frac{m_3}{0.05\ \mathrm{eV}}$$

- Competition with washout processes eradicating L asymmetry

$$m_\nu < O(0.1)\ \mathrm{eV}$$



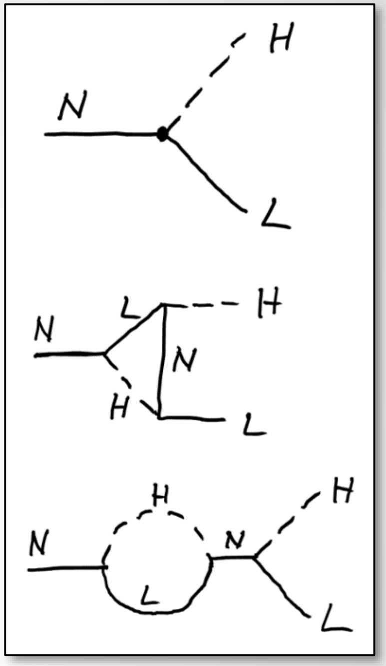
- Conversion to baryon asymmetry via sphaleron processes

$$\eta_B \approx \eta_L$$

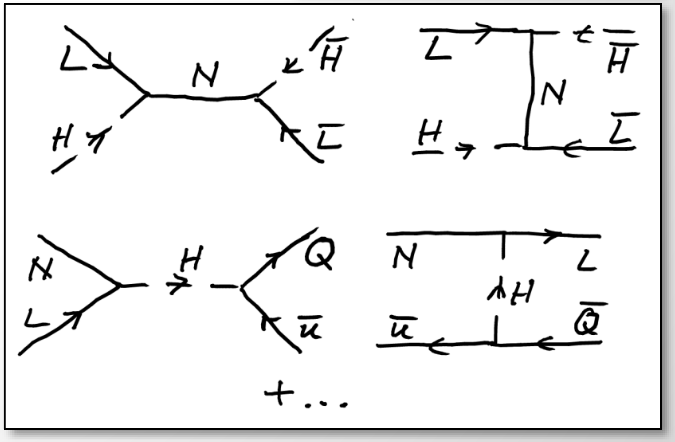
Baryon Asymmetry
Generation and Washout

- 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



Baryon Asymmetry
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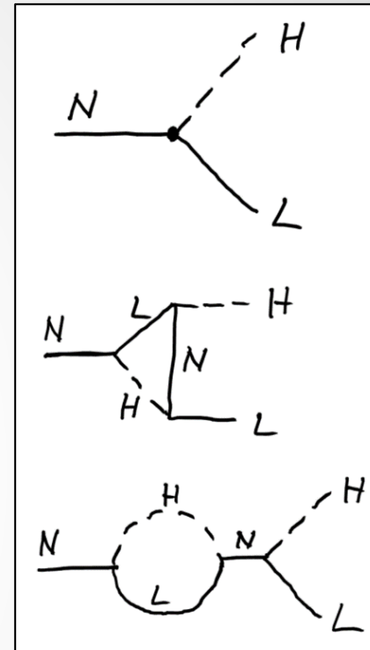
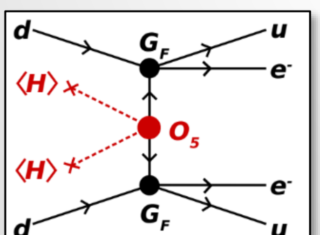
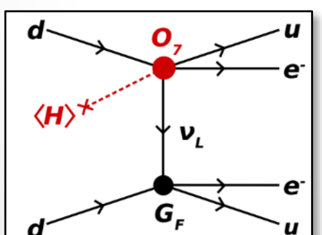
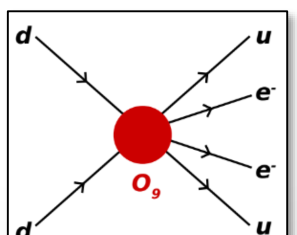
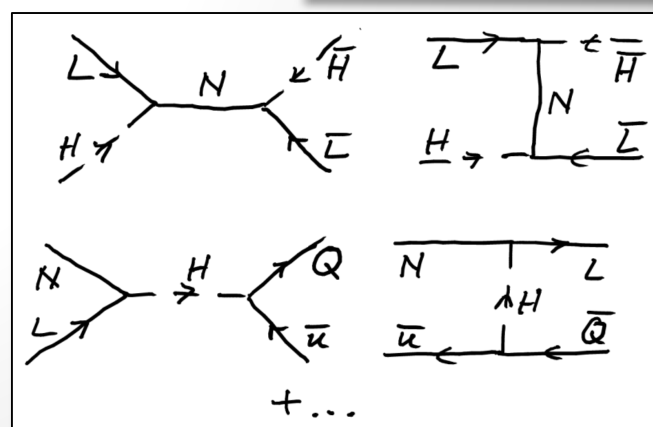


- What if we observe lepton number violating processes in $0\nu\beta\beta$?





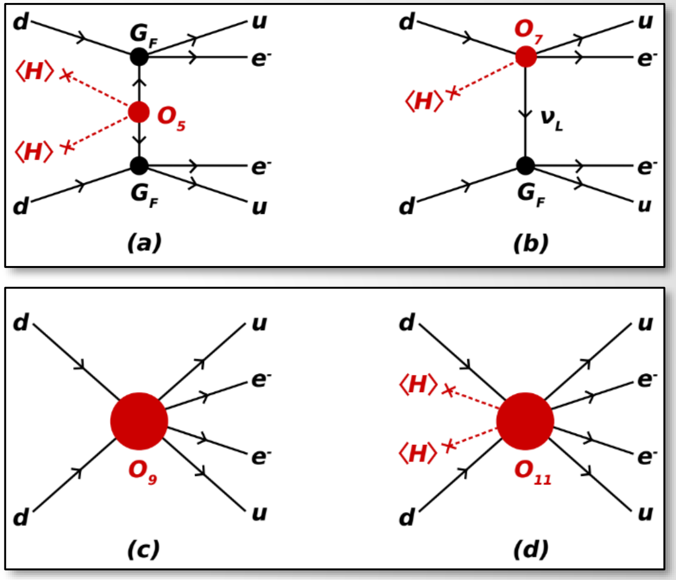




Washout via $0\nu\beta\beta$ operators

- 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

- Boltzmann equation including washout of D-dim effective operator

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

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

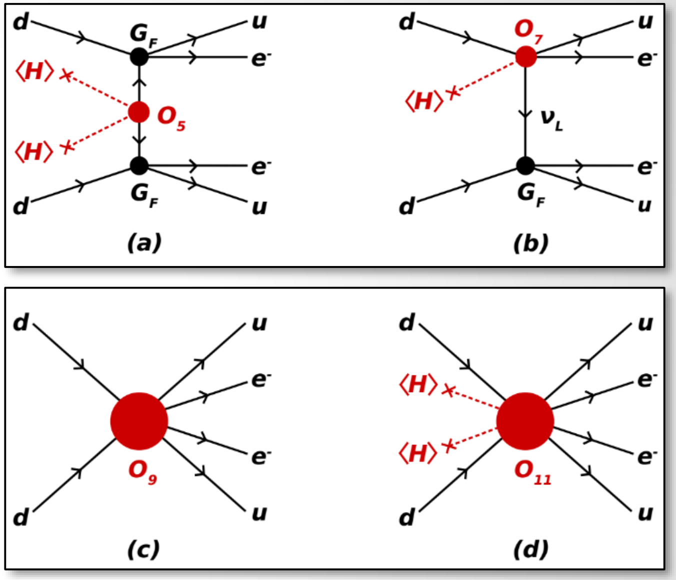
- Effective washout if

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

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

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

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



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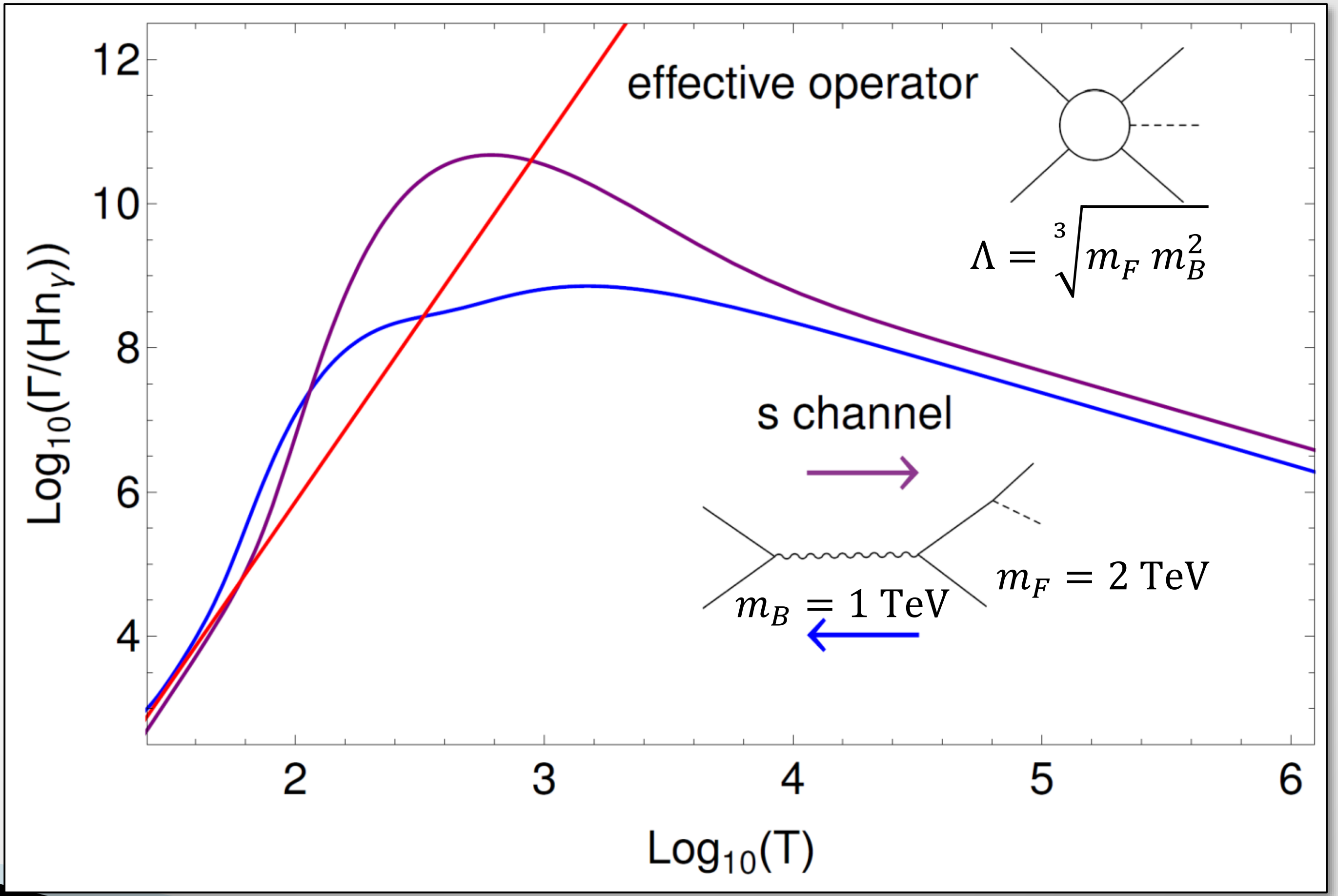
Washout via $0\nu\beta\beta$ operators

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



Effect of LFV operators

- Analogous analysis for eff. 6-dim LFV operators

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

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

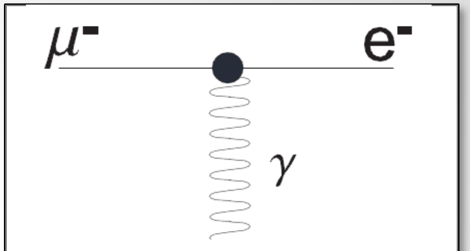
$$\mathcal{O}_6(llqq) = (\bar{L}_i \gamma^\mu L_j\ )(\bar{Q}_k \gamma^\mu Q_l\ )$$

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

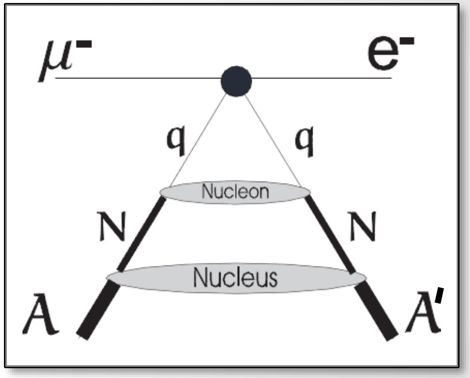
- Matching to LFV process rate

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

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



$\mu^- \to e^-\gamma$



$\mu^- \to e^-$ 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

Baryon Asymmetry
Lepton Asymmetry Washout

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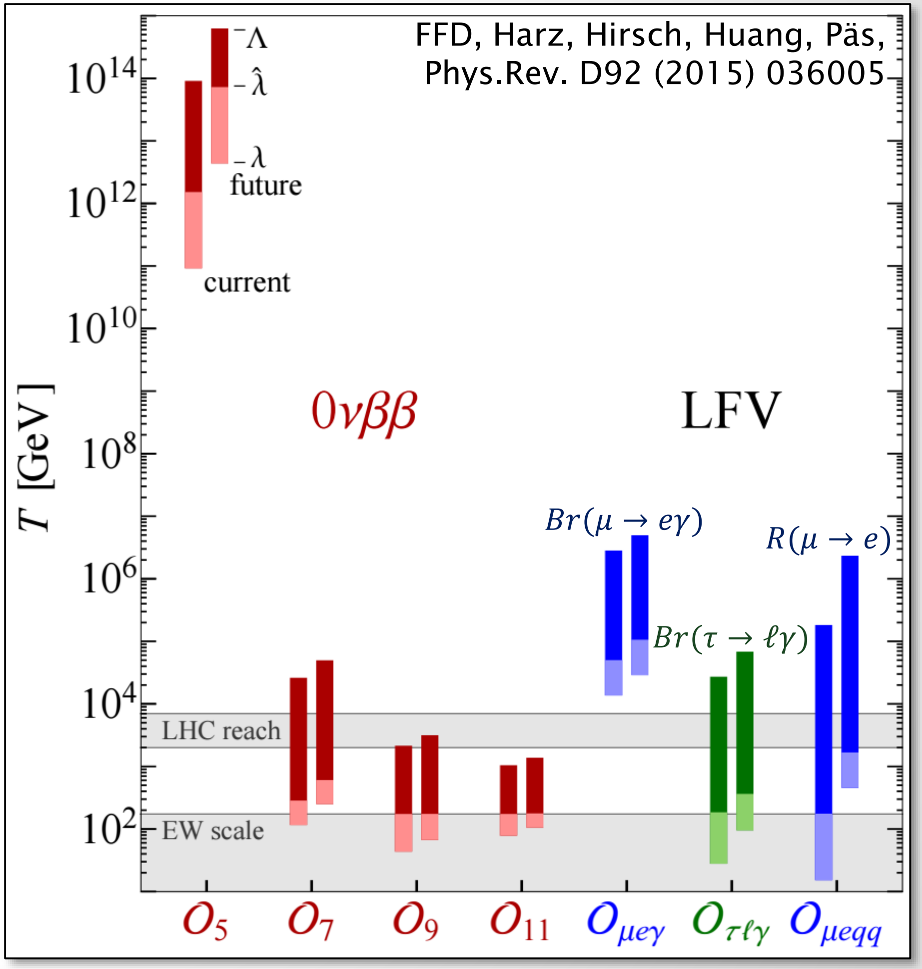
- Temperature ranges of strong equilibration
  - **Assumes observation of corresponding process!**
- Observation of LN(F)V
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**



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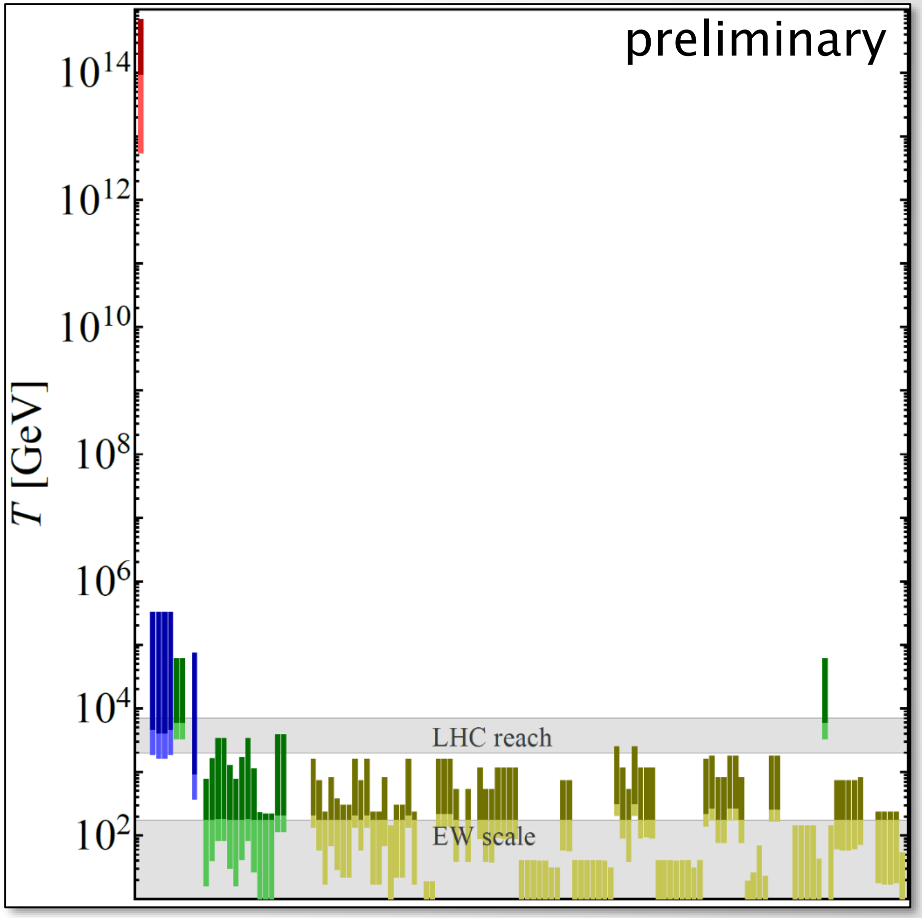


LNV @ LHC

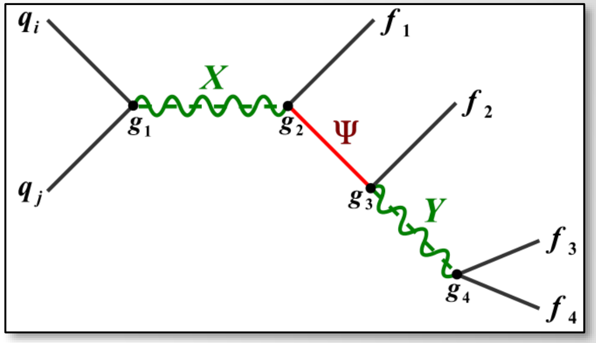
- Compare LHC cross section with lepton number asymmetry washout

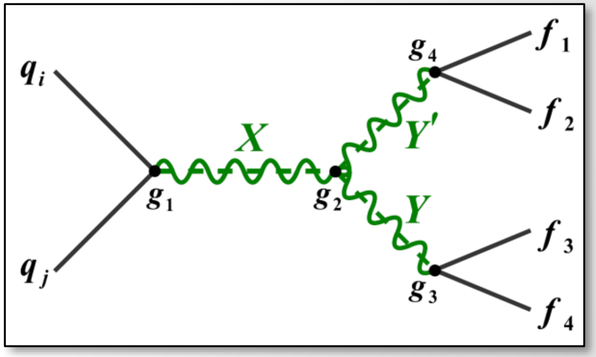
$$\frac{\Gamma_W}{H} > 3 \times 10^{-3} \frac{M_P M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})} \times (s\,\sigma_{\mathrm{LHC}})$$

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

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

  - 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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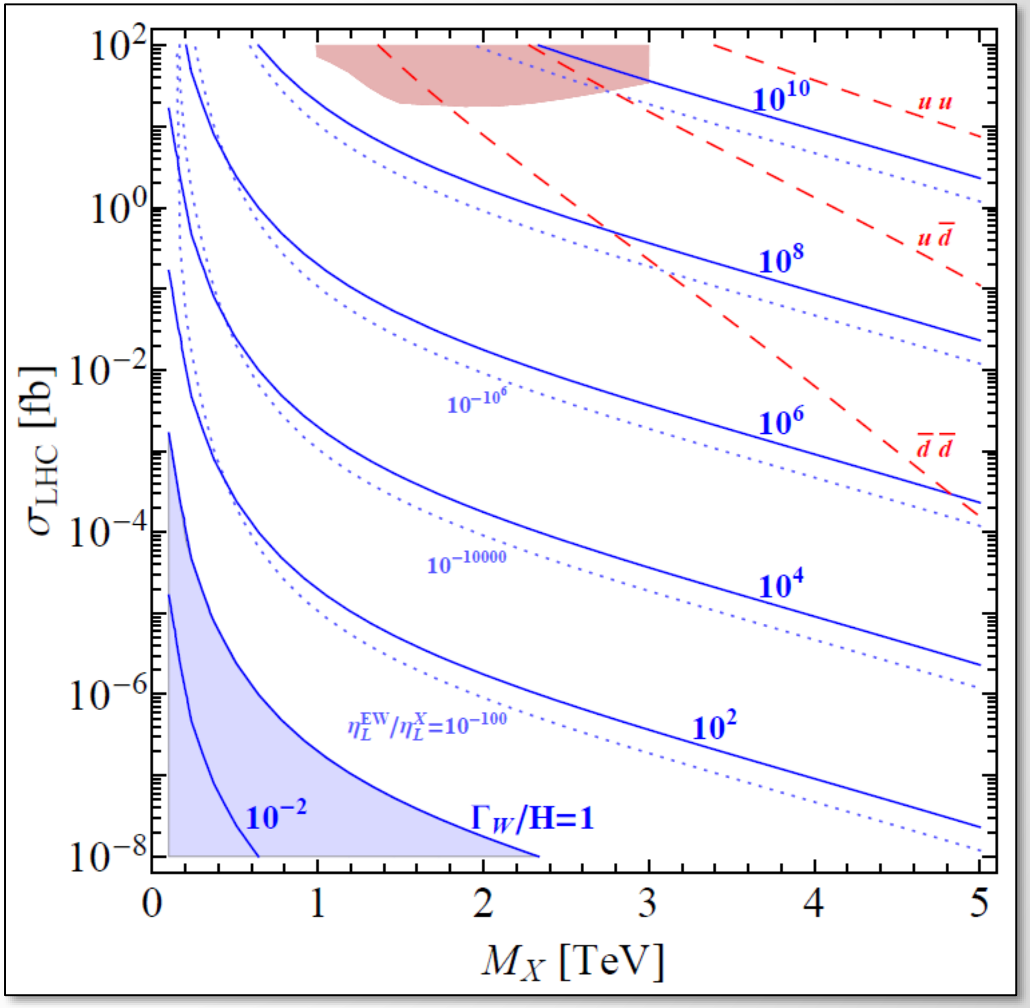
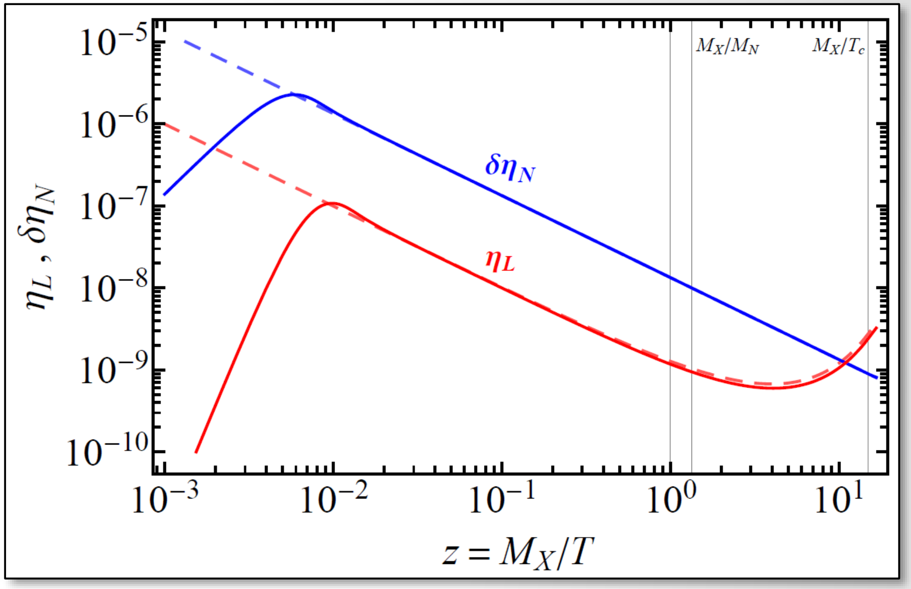


Caveats

- 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)

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
- **Important information for model selection, e.g.**
  - Observation of $0\nu\beta\beta$
  - Observation of LNV @ LHC

  } LNV @ TeV Scale
  Disfavours high-scale seesaw

Conclusion

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