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Neutrinoless Double Beta Decay and Baryogenesis

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$0\nu\beta\beta$ Progress + Challenges | ECT* Trento | 15 – 19/7/2019

Fluff Ahead


CONTAINS CORN SYRUP, SUGAR, DRIED EGG WHITE, VANILLIN
Marshmallow
fluff

Dirac vs Majorana

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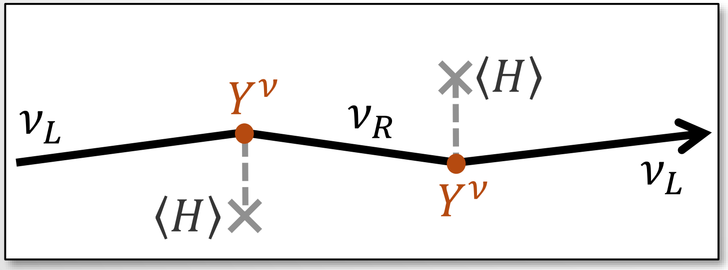
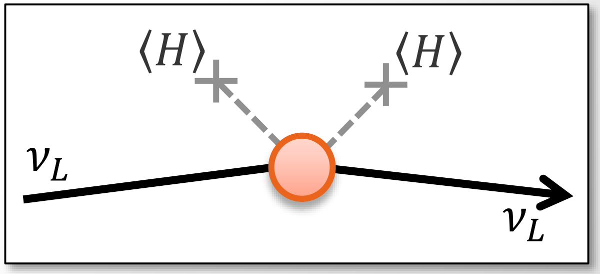
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

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



$0\nu\beta\beta$

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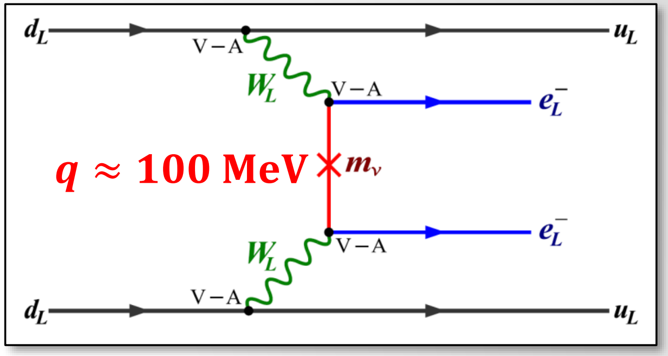
- Half-life

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



- Particle Physics

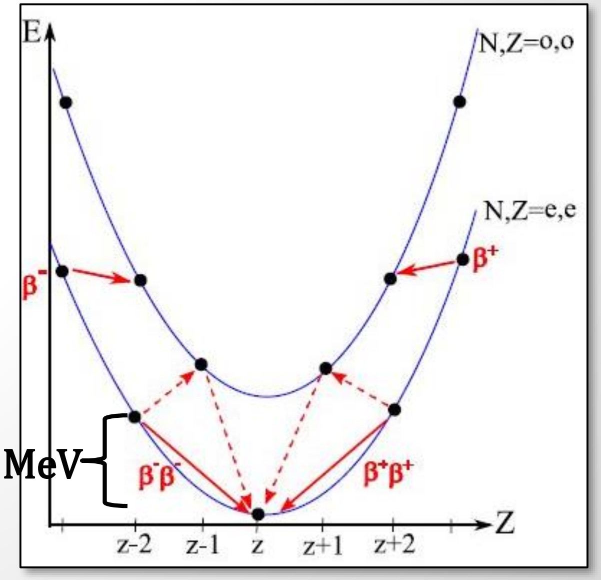
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

- 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

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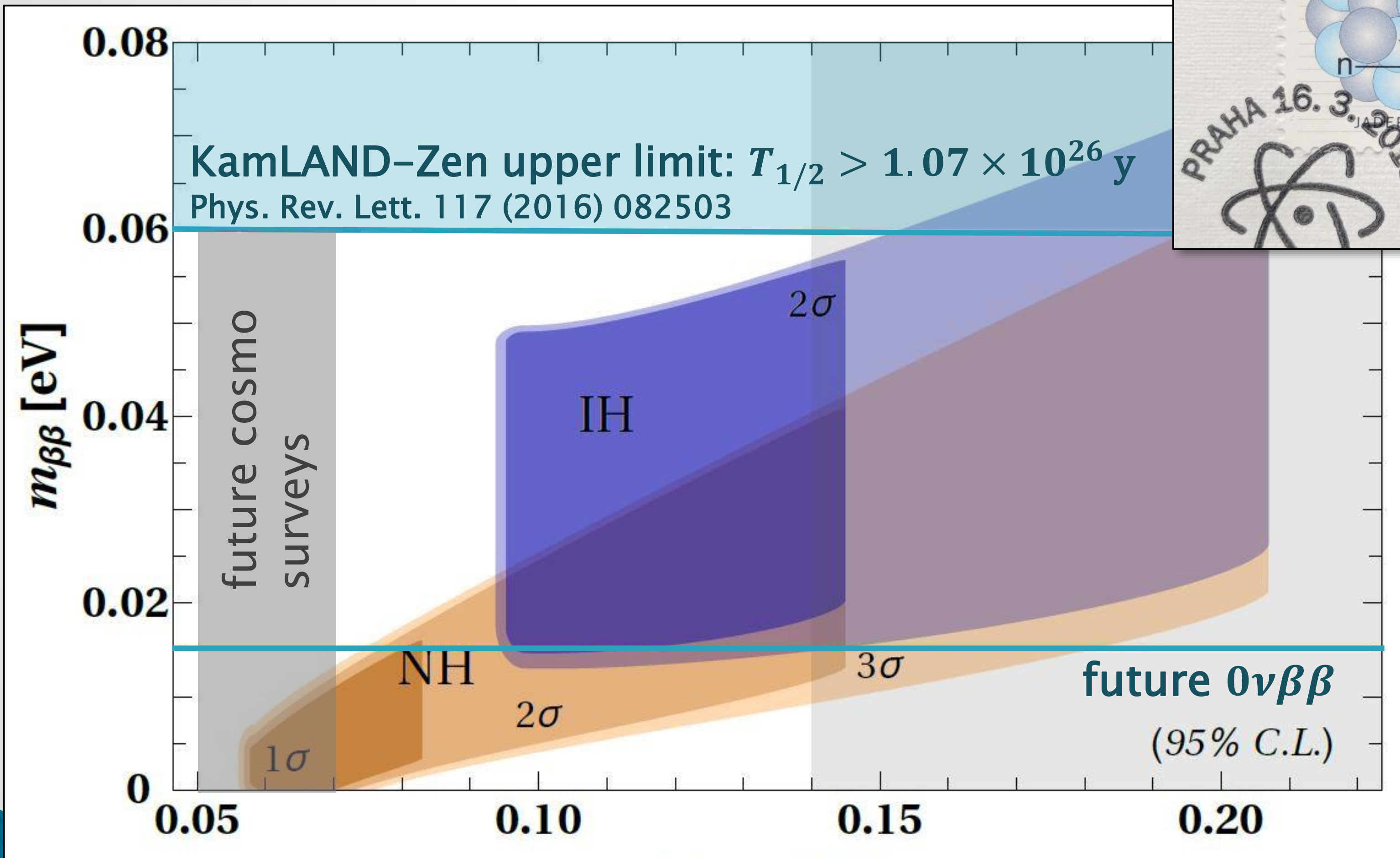
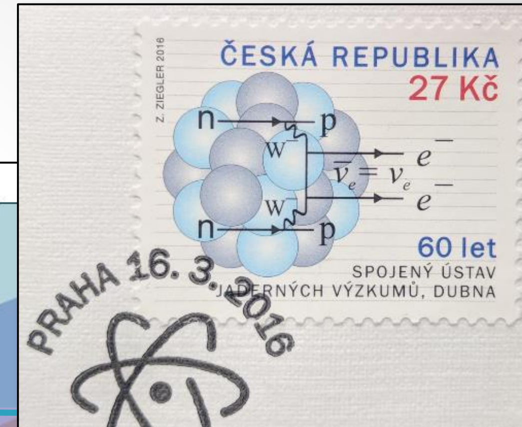
- Effective $0\nu\beta\beta$ Mass

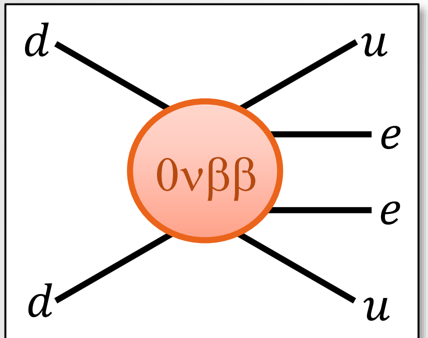


Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

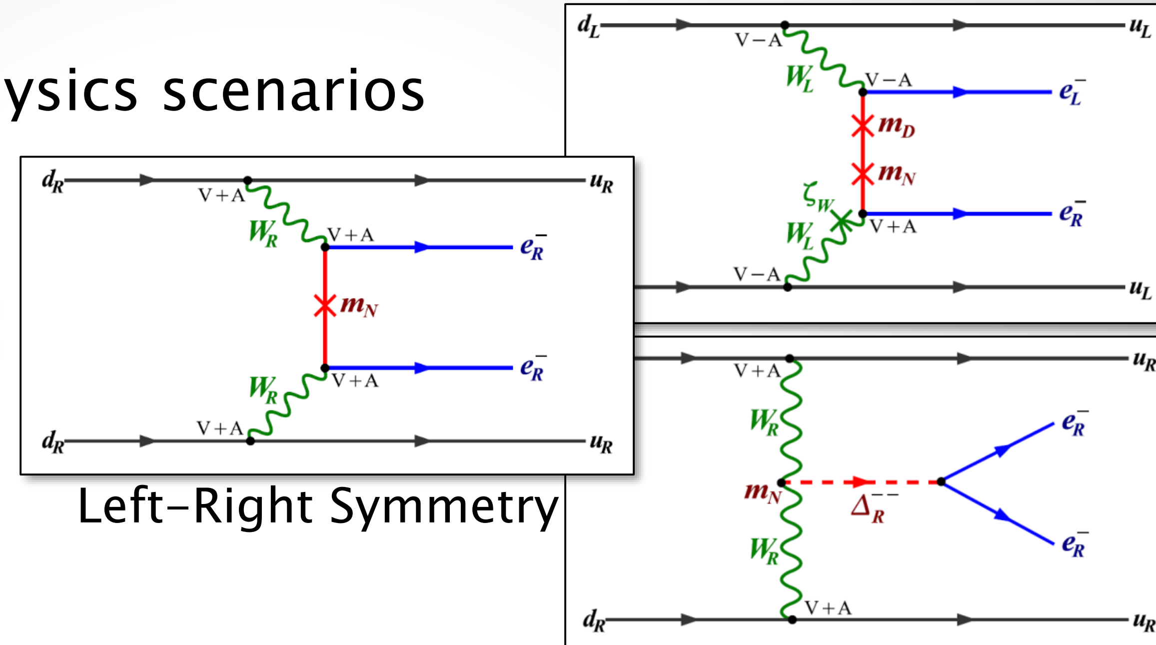


New Physics and $0\nu\beta\beta$

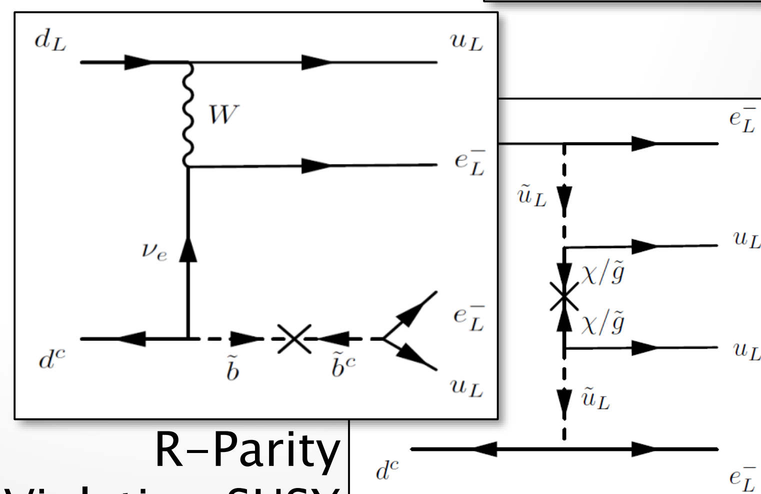
- Plethora of New Physics scenarios



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



Left-Right Symmetry



R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

...

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

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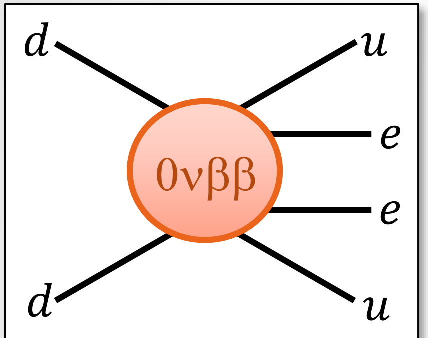
- Plethora of New Physics scenarios



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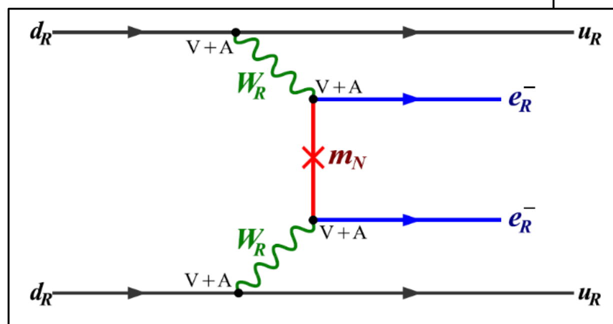
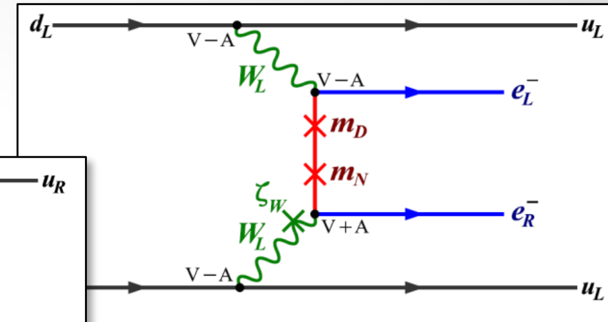
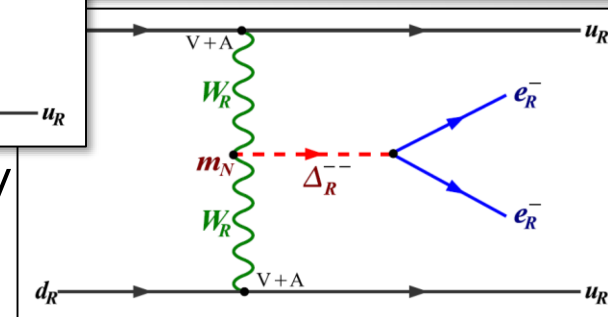
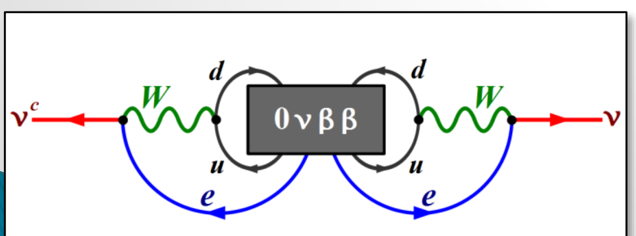


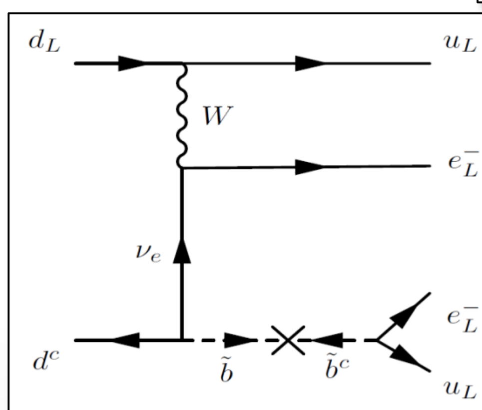


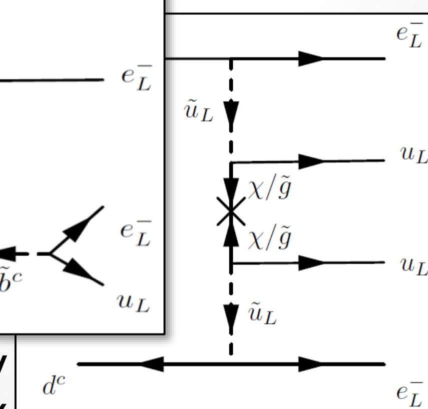


Left-Right Symmetry

- Neutrinos still Majorana





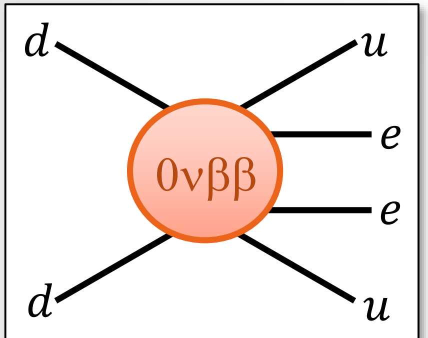


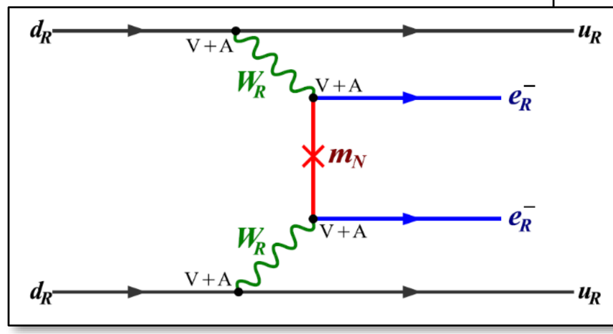
R-Parity Violating SUSY

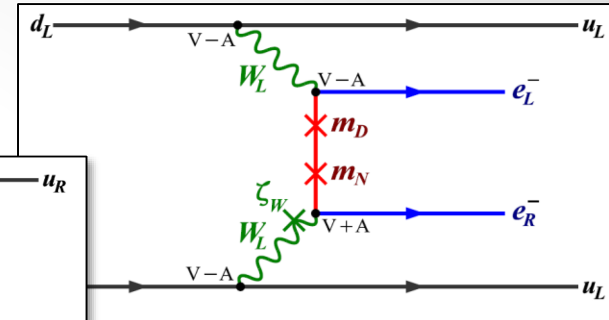
- Extra Dimensions
- Majorons
- Leptoquarks
- ...

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

- Examples in Left–Right Symmetry





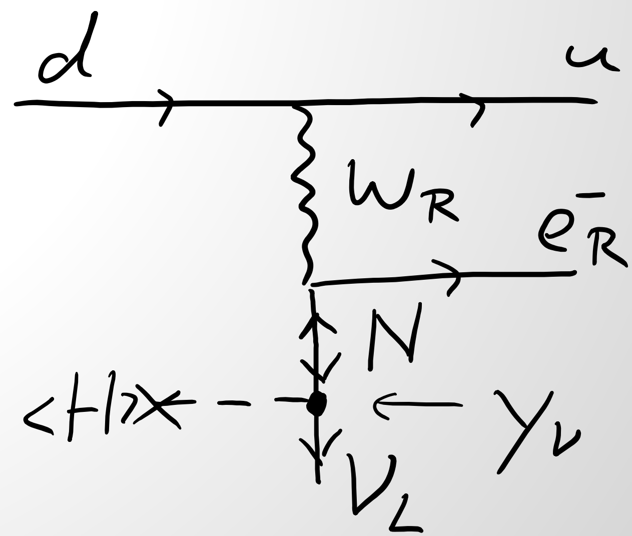


$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

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

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/100\ \mathrm{TeV})^3}$$

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



Disentangling New Physics

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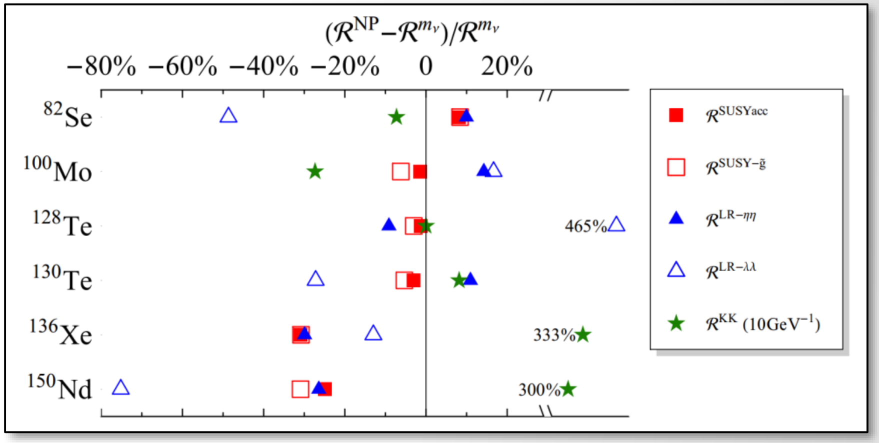
- Comparison of $0\nu\beta\beta$ in multiple isotopes
  (FFD, Päs PRL 2007, Meroni et al. 2013)
  - Depends on $0\nu\beta\beta$ mechanism
  - Independent of details of new physics (if one mechanism dominates)

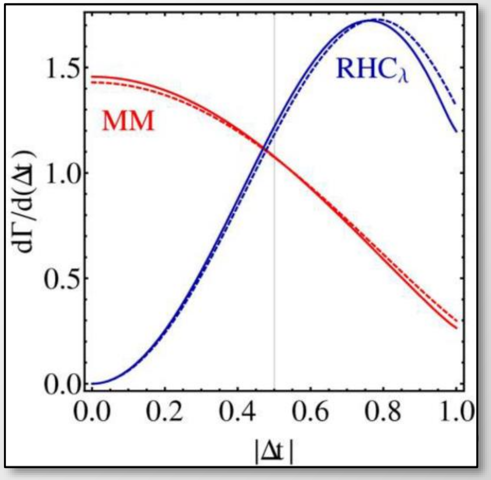
$$\frac{T_{1/2}(X)}{T_{1/2}(Y)} = \frac{G(Y)|M(Y)|^2}{G(X)|M(X)|^2}$$



- 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



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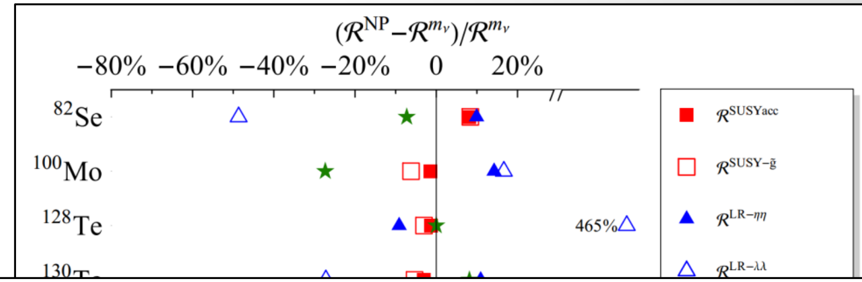

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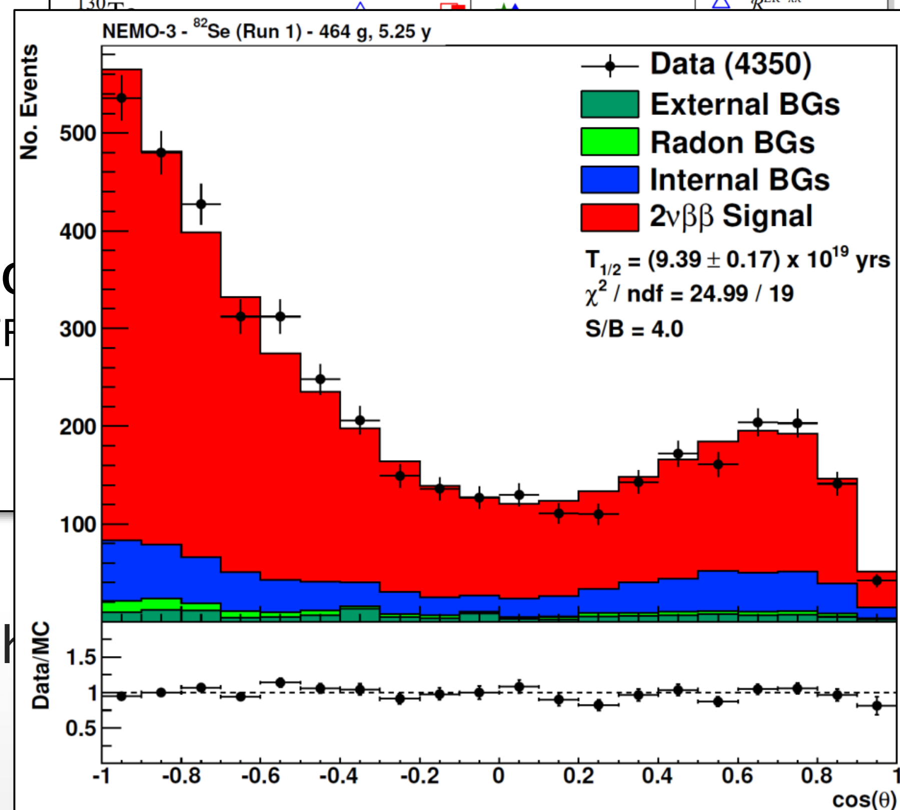

Baryon Asymmetry

- 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

$$m_h < 60 \; - 80 \text{ GeV}$$

Sphalerons

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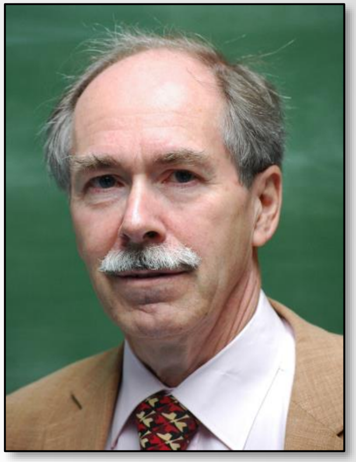
- Baryon and Lepton numbers accidental, classical symmetries in the Standard Model
- Violated at the quantum level (t' Hooft '76)

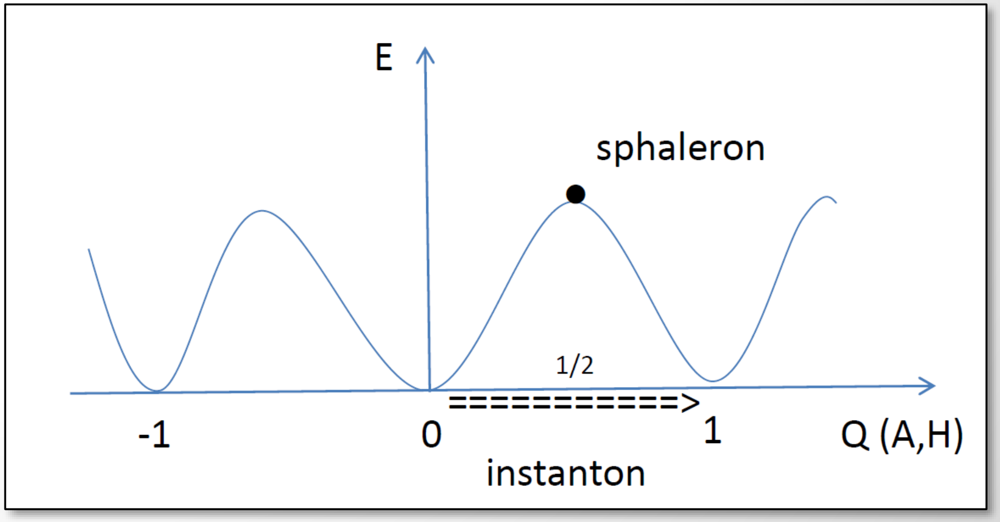


$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

  - $B + L$ violated
  - $B - L$ remains conserved

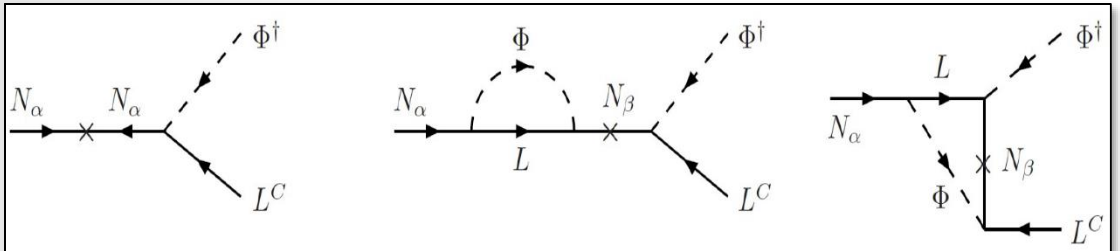
- Sphaleron transitions in equilibrium $\frac{\Gamma_{Sph}}{H} > 1$ for

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



Leptogenesis – Vanilla

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

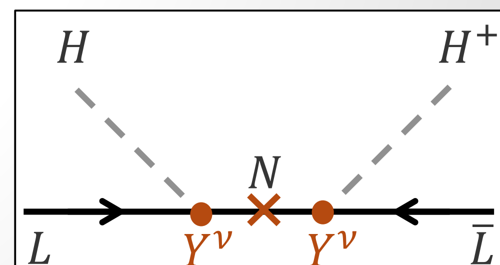


  - CP asymmetry

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

- Competition with washout processes eradicating L asymmetry

$$M_N \gtrsim 10^8 \left(\frac{\eta_B}{5 \times 10^{-11}}\right) \left(\frac{0.06\mathrm{eV}}{m_3}\right) \mathrm{GeV}$$

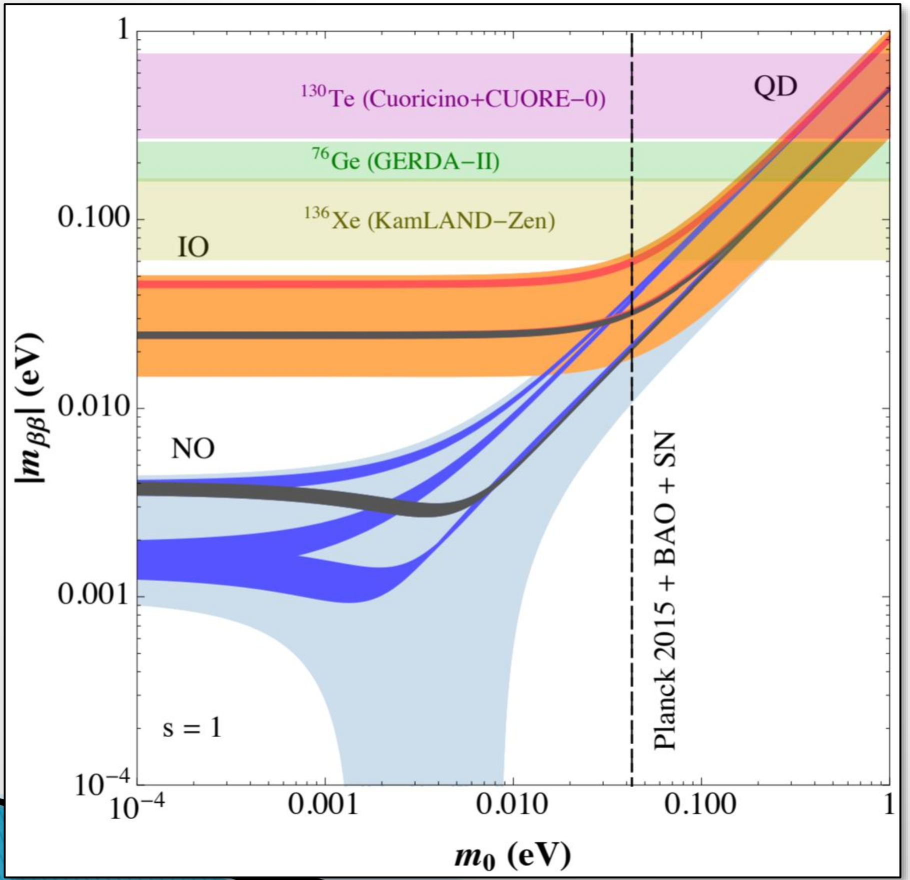


- Conversion to baryon asymmetry via sphaleron processes

$$\eta_B \approx \eta_L$$

Leptogenesis – Vanilla

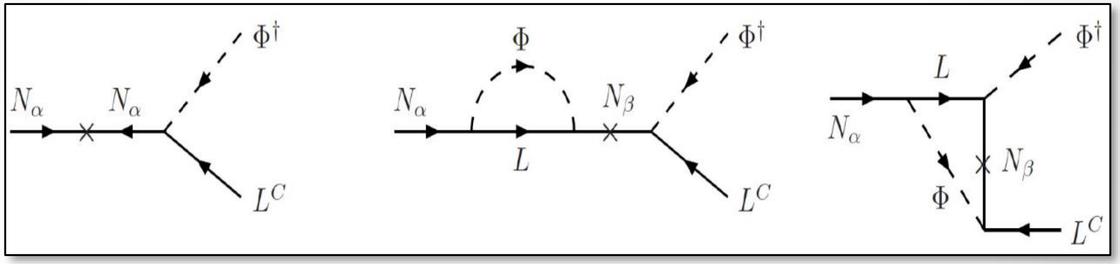
- Consequence for $0\nu\beta\beta$
  - Only standard light neutrino exchange
  - But CP Majorana phases expected?



Hagedorn, Molinaro '17

Leptogenesis – Resonant

- Dominance of self-energy loop for small mass difference between heavy neutrinos (Pilaftsis '97)



  - CP asymmetry can be $O(1)$ for $\Delta M_N \approx \Gamma_N$
  - Viable leptogenesis for neutrino masses as light as $M_N \approx 100\ \mathrm{GeV}$

Leptogenesis – Resonant

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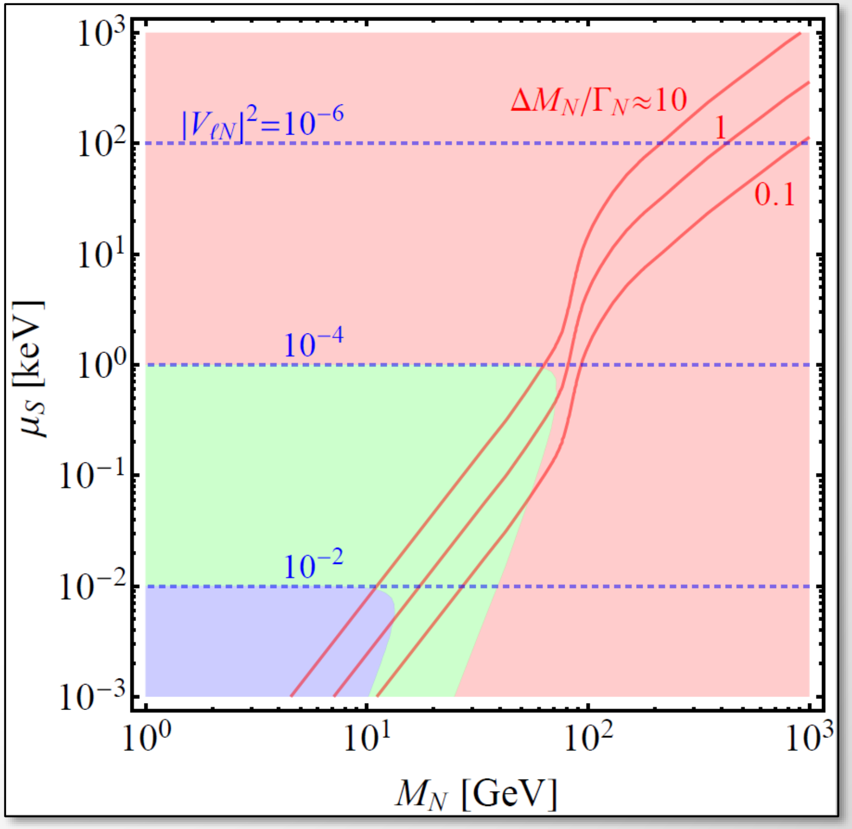
- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings $Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}$
  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

$$\begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

    - LNV in $0\nu\beta\beta$ suppressed by $\frac{\Delta m_N}{m_N}$
    - LNV in resonant N production suppressed by $\frac{\Delta m_N}{\Gamma_N} \approx \frac{\mu}{\Gamma_N}$



Leptogenesis – Oscillations

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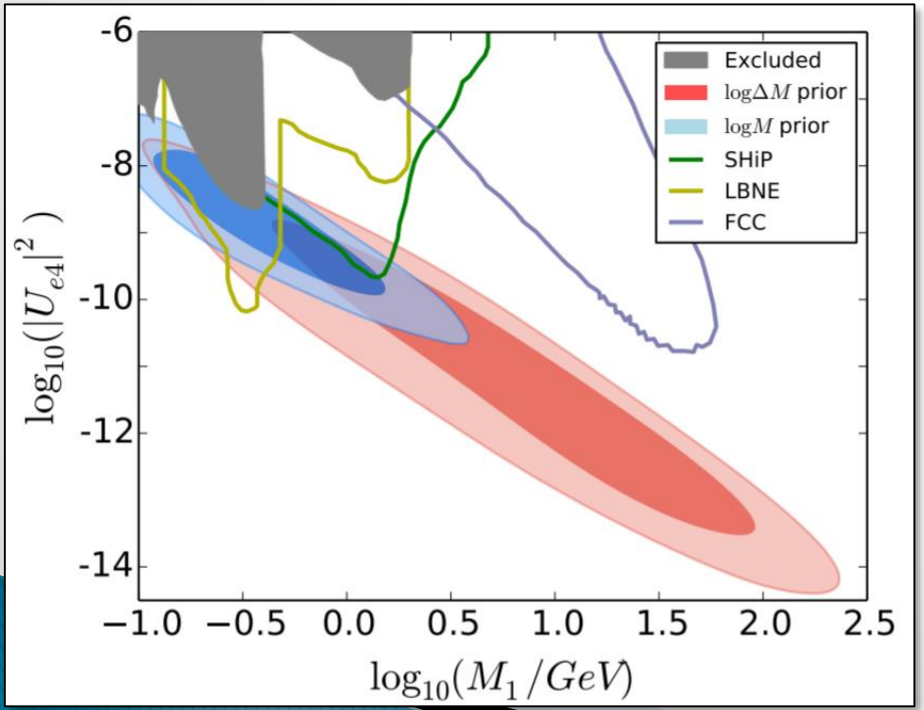
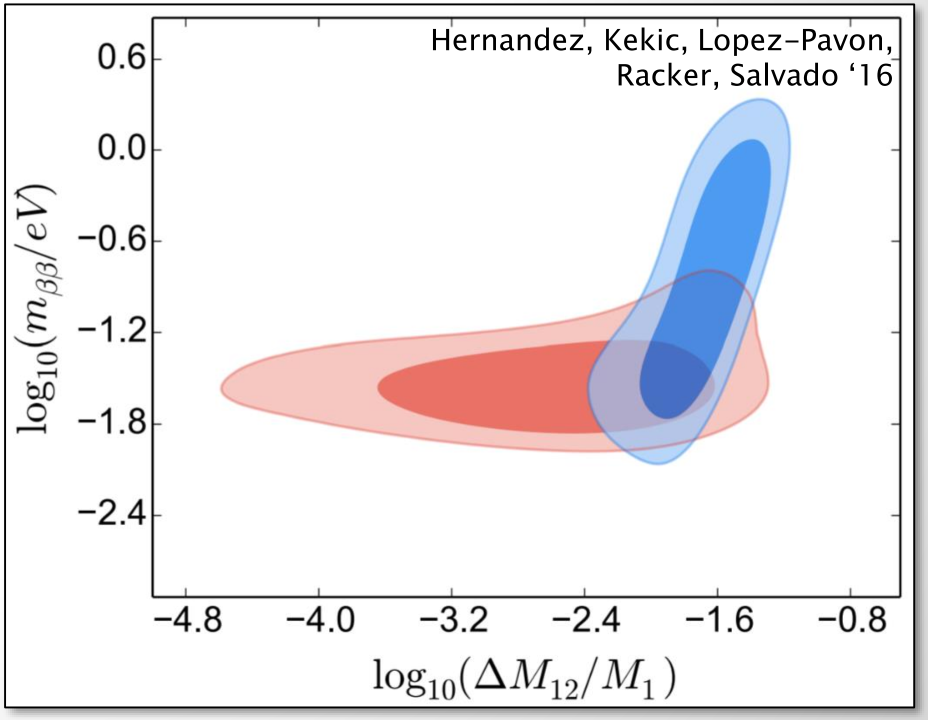
- Sterile neutrinos with small hierarchical Yukawa couplings (Akhmedov, Rubakov, Smirnov '98)
  - One neutrino not in equilibrium before critical sphaleron T
  - CP and flavor violating oscillations between sterile neutrinos generate asymmetry
  - Viable mechanism for $m_N \approx 1 - 100\ \mathrm{GeV}$





Leptogenesis – Oscillations

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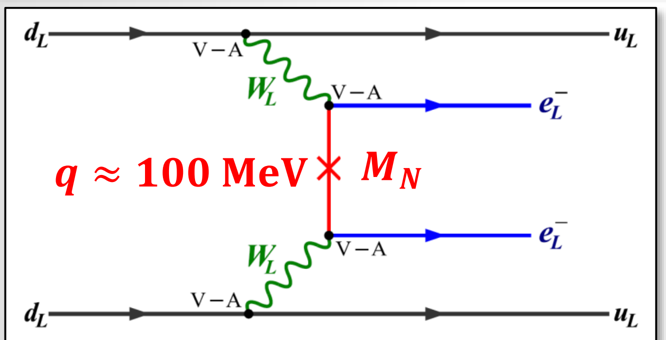
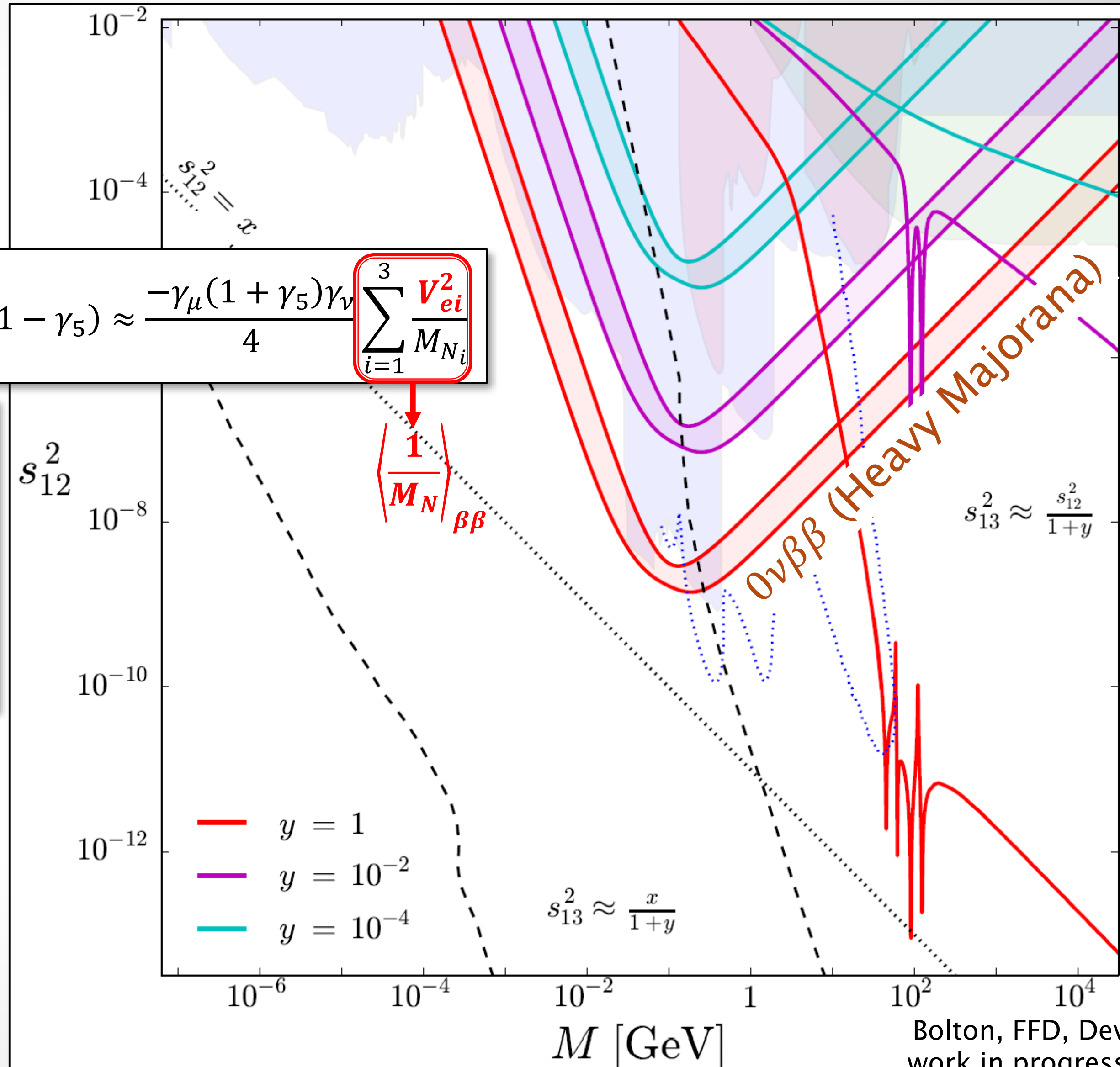
- Heavy neutrinos with masses larger than ≈ 100 MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2\, \gamma_\mu (1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\sum_{i=1}^{3}\frac{V_{ei}^2}{M_{N_i}}$$

$$\left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$



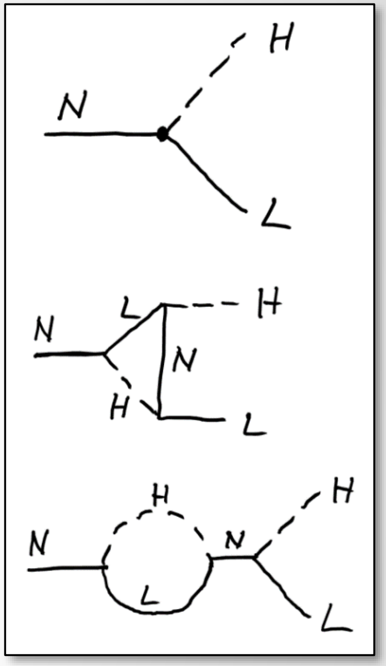


- Different nuclear matrix elements
  - Short-range operator

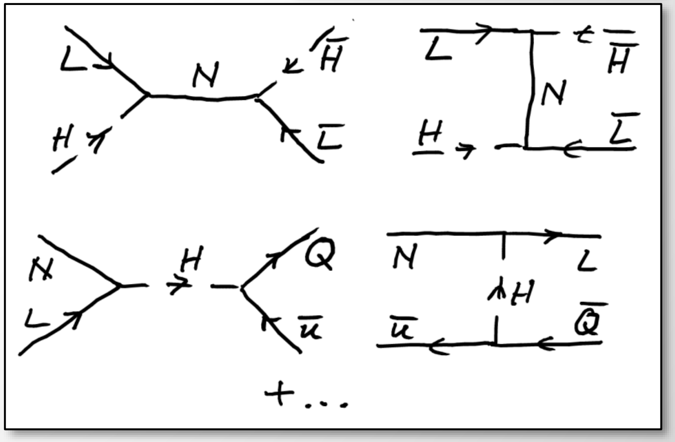
Baryon Asymmetry Generation and Washout

- 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



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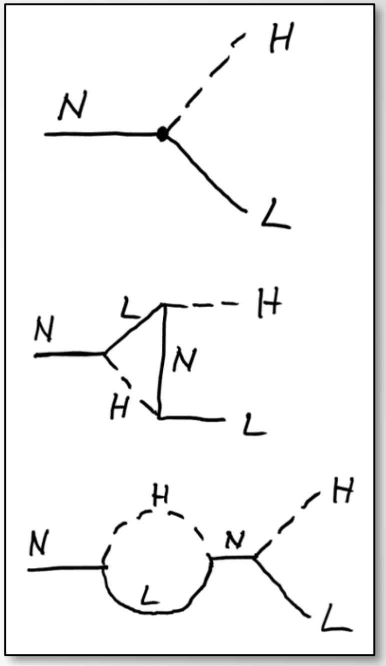
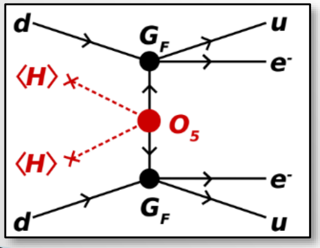
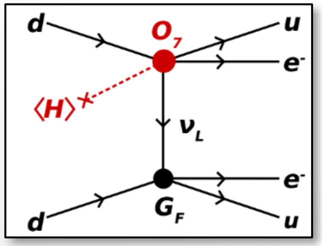
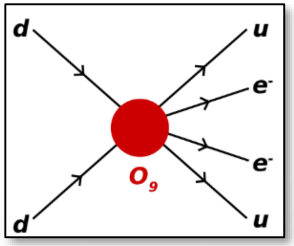
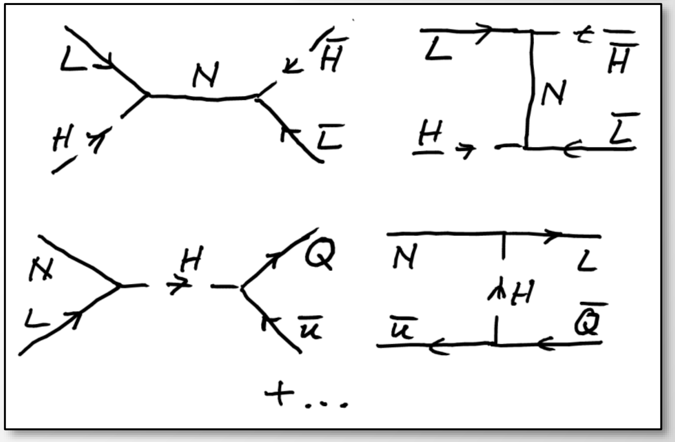


- What if we observe lepton number violating processes in $0\nu\beta\beta$?





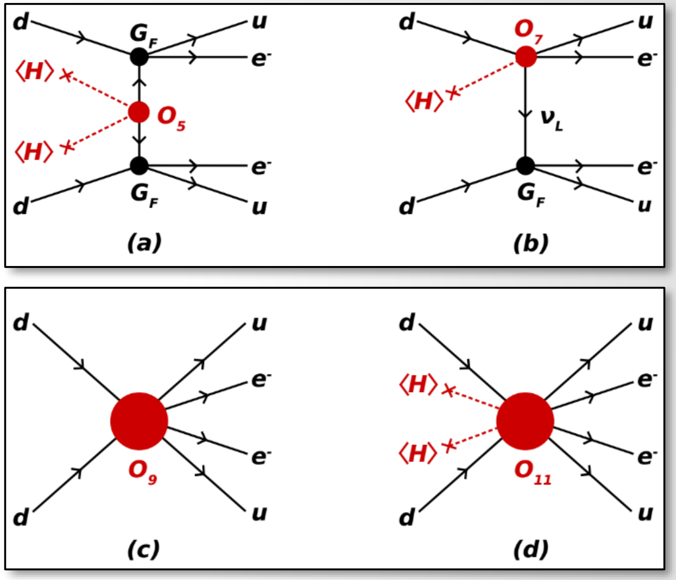




Washout via $0\nu\beta\beta$ operators

- 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

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

- Boltzmann equation including washout of D-dim effective operator

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

  - $c_{\{5,7,9,11\}} = \{\frac{8}{\pi^5}, \frac{27}{2\pi^7}, \frac{3.2\times 10^4}{\pi^9}, \frac{3.9\times 10^5}{\pi^{13}}\}$

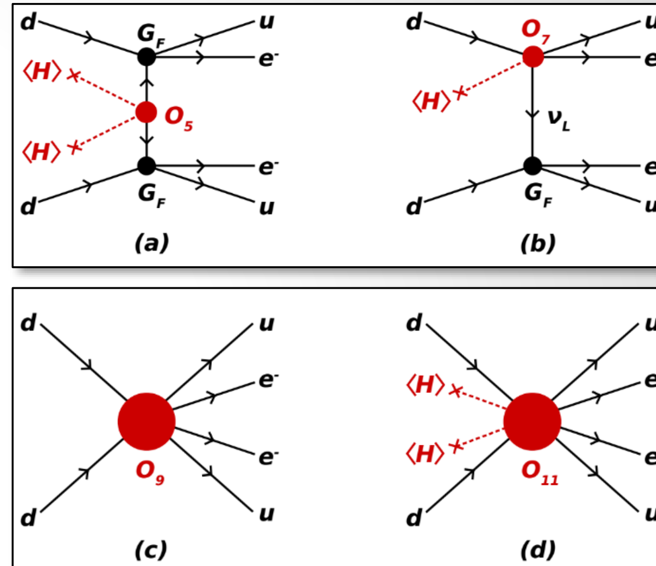
- Effective washout if

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

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

- 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

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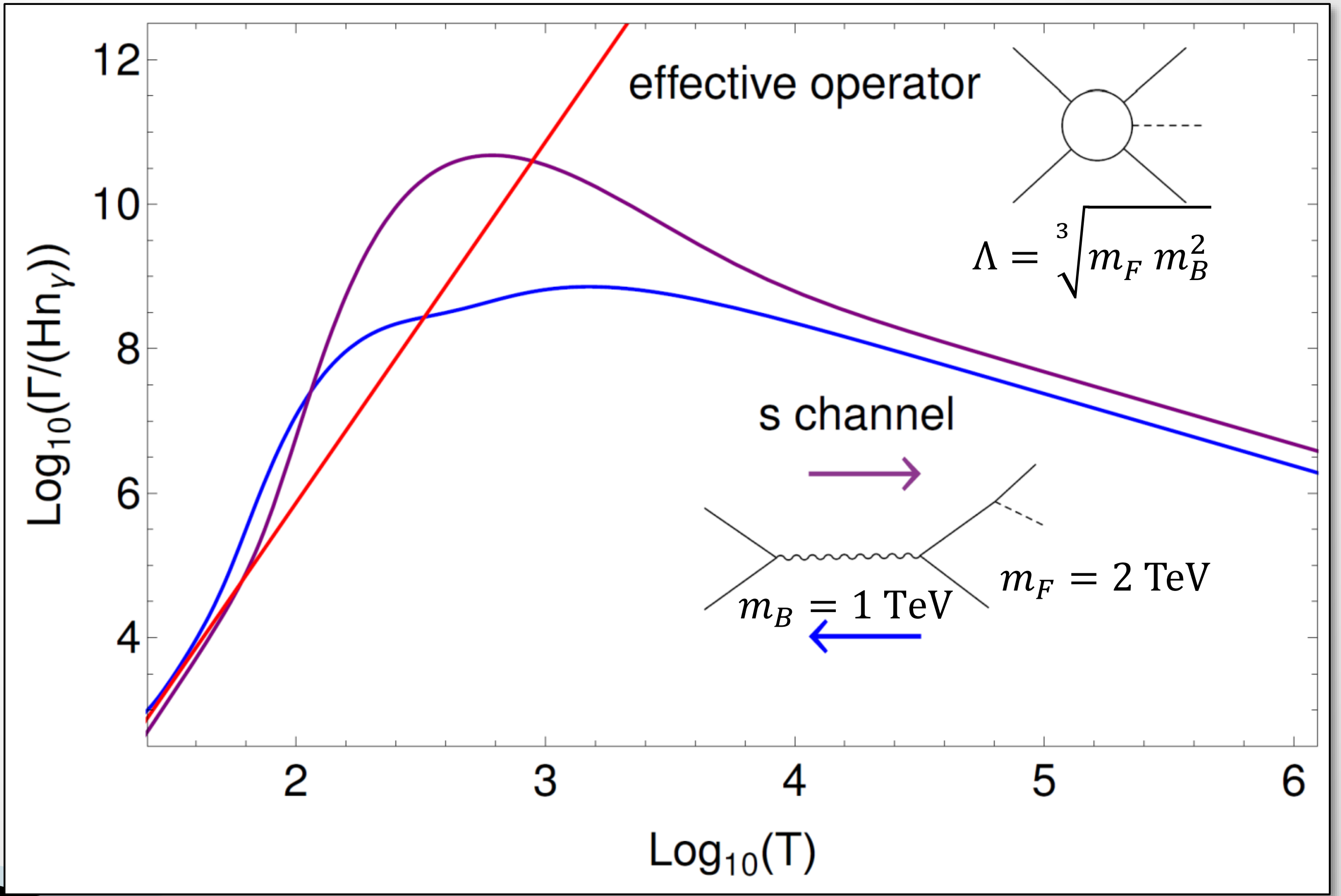
- Even better:
  UV-completed operators for behaviour around Λ



Effect of LFV operators

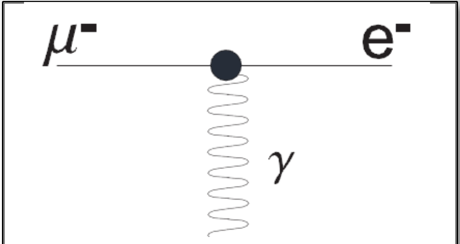
- Analogous analysis for eff. 6-dim LFV operators

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

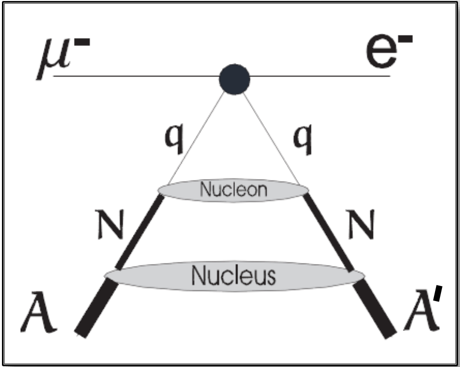
$$\mathcal{O}_6(llll) = (\bar{L}_i \gamma^\mu L_j)(\bar{L}_k \gamma^\mu L_l)$$

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

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



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



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

- Matching to LFV process rate

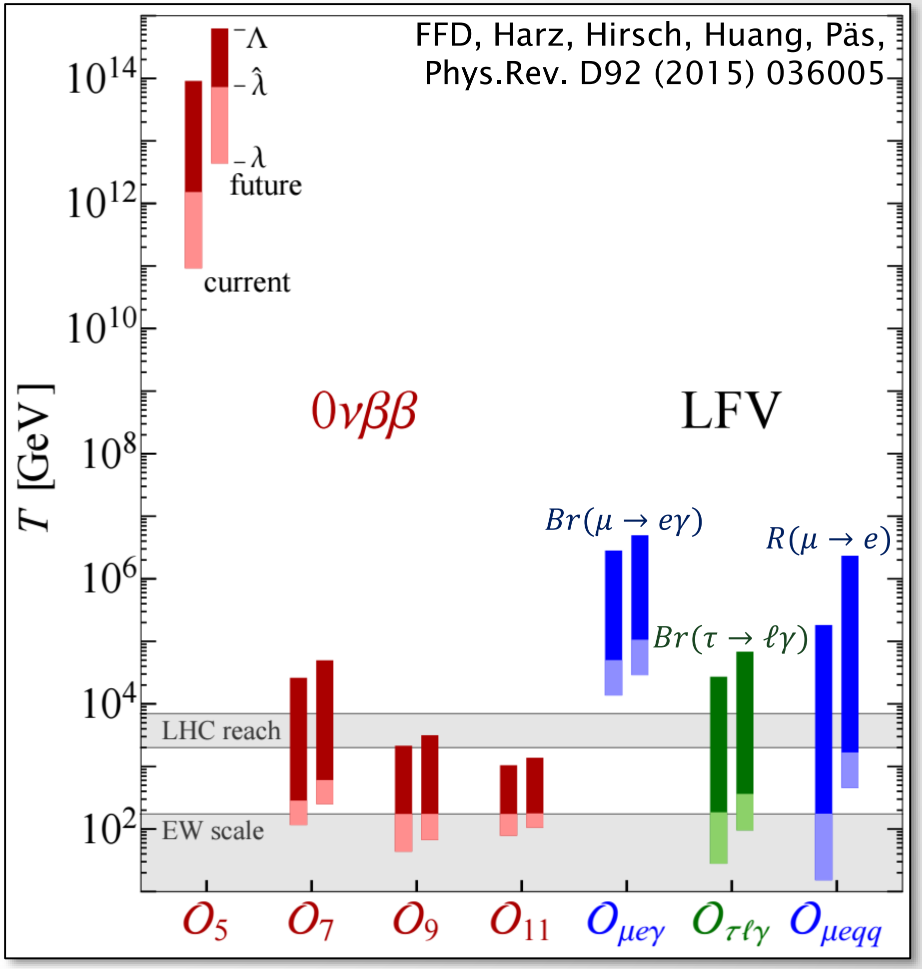
$$C_{\ell\ell\gamma} = \frac{eg^3}{16\pi^2 \Lambda^2_{\ell\ell\gamma}}, \quad C_{\ell\ell qq} = \frac{g^2}{\Lambda^2_{\ell\ell qq}}$$

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

$\mathcal{O}_i$	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

- 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**



Baryon Asymmetry
Lepton Asymmetry Washout

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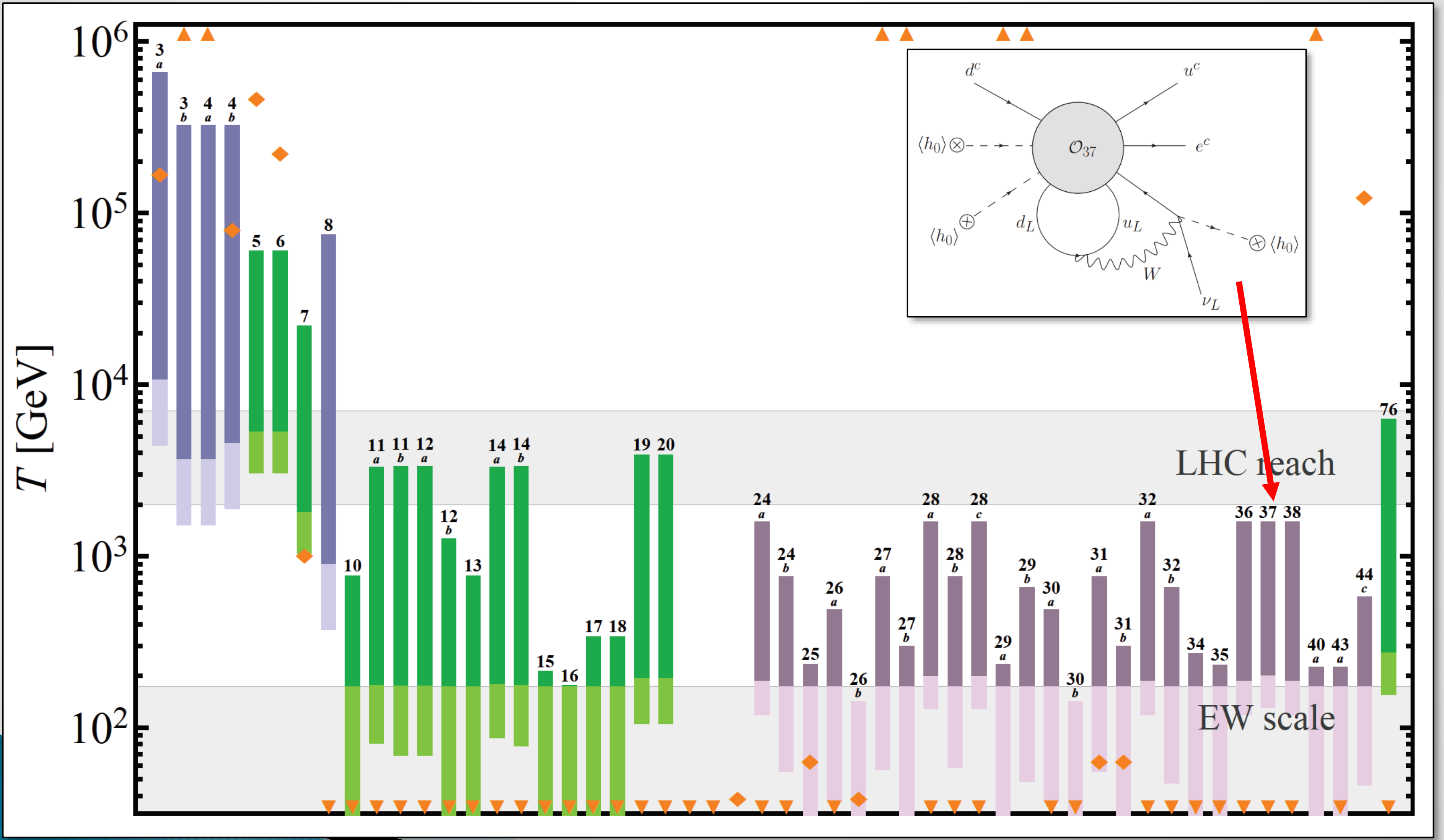

Baryon Asymmetry
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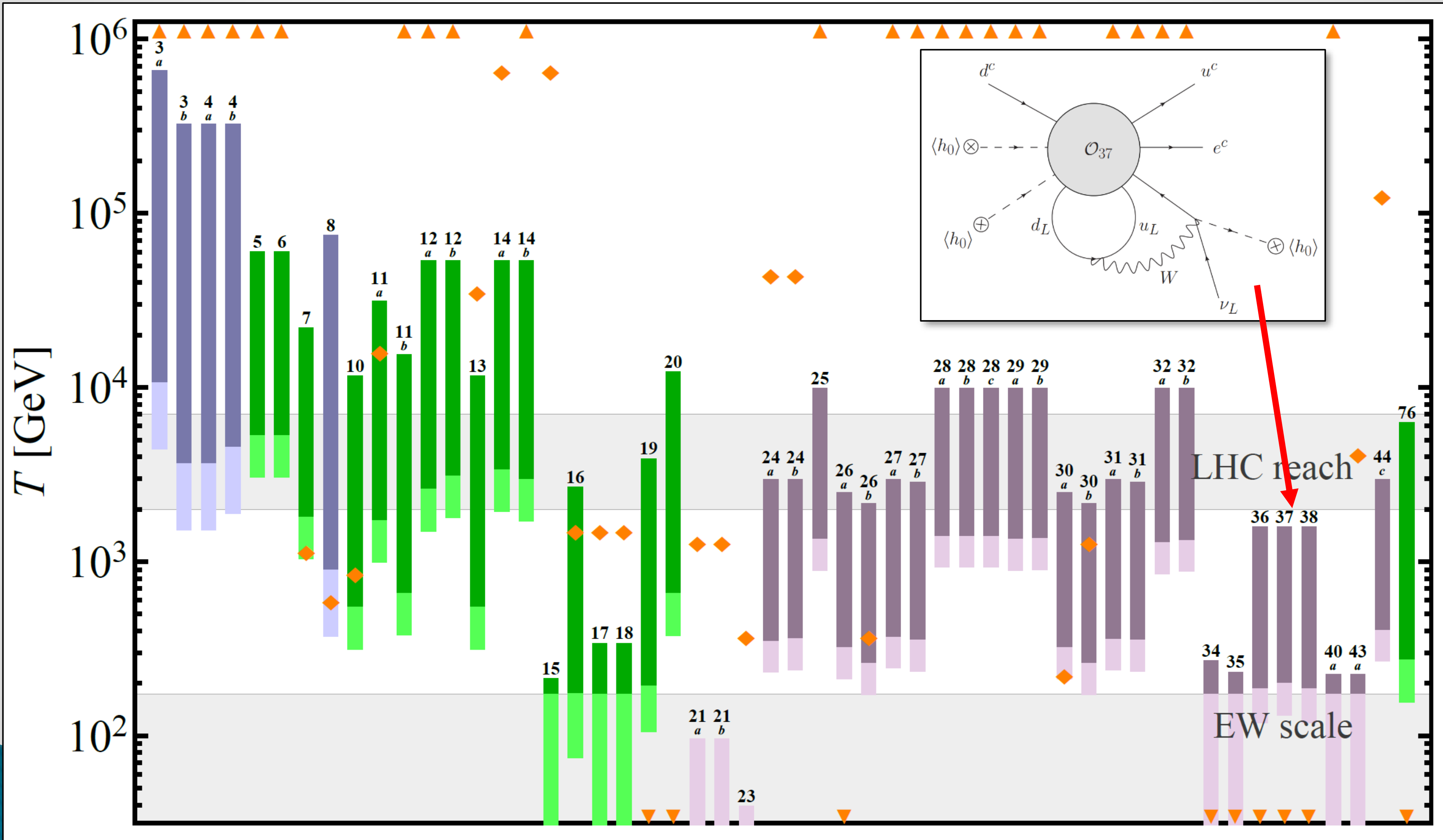

LNV @ LHC

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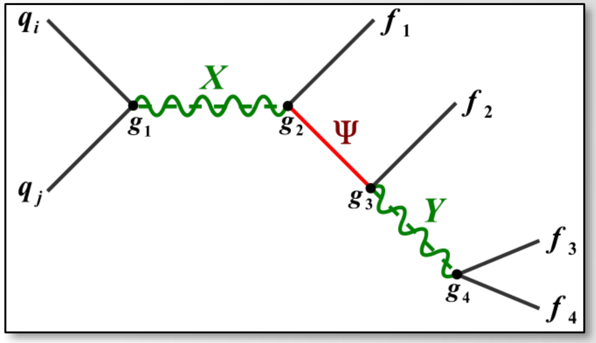
- Compare LHC cross section with lepton number asymmetry washout

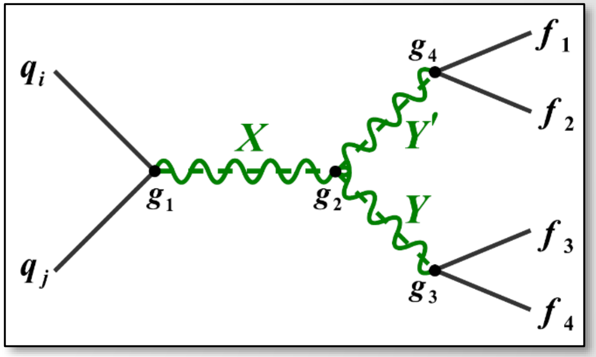
$$\frac{\Gamma_W}{H} > 3 \times 10^{-3} \frac{M_P M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})} \times (s\, \sigma_{\mathrm{LHC}})$$

  - 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





LNV @ LHC

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- Compare LHC cross section with lepton number asymmetry washout
  - Lower limit on total washout rate
  - Observation of LNV @ LHC corresponds to highly effective washout $\Gamma_W/H \gg 1$
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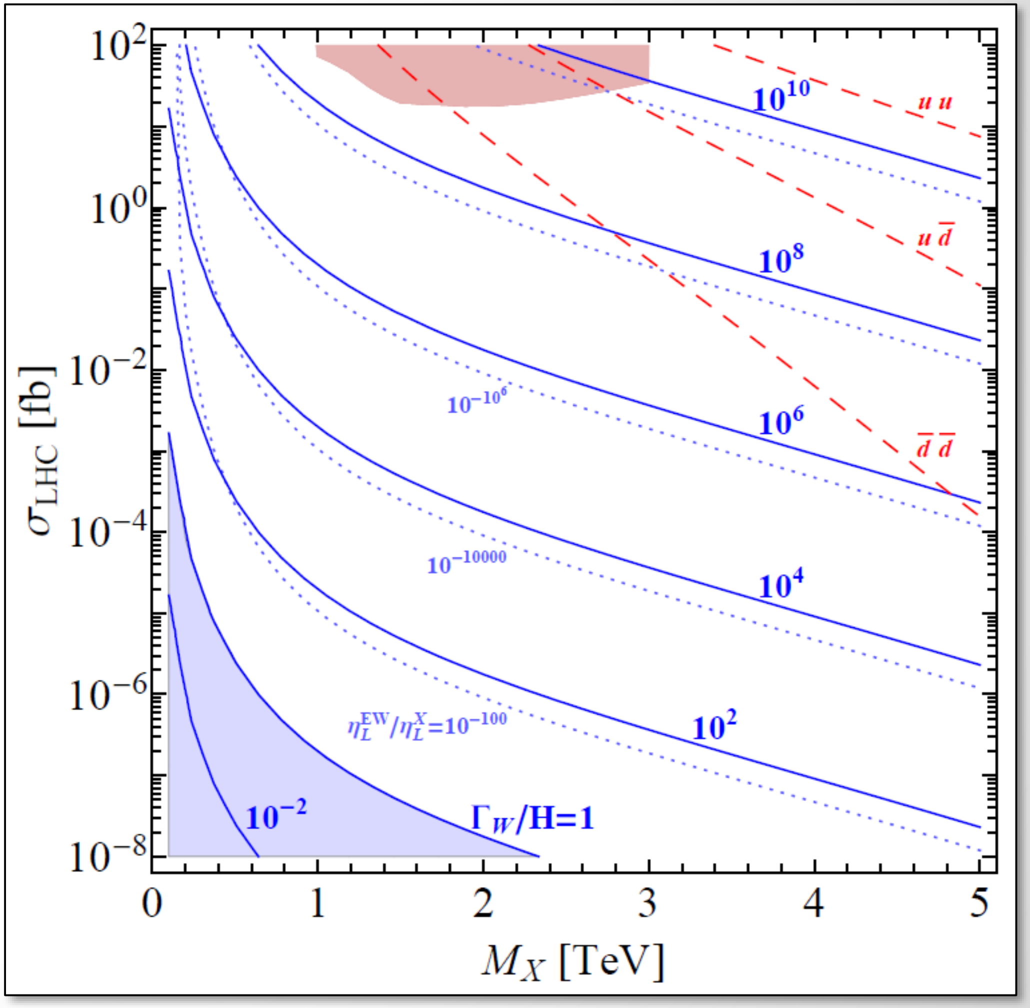

Caveats

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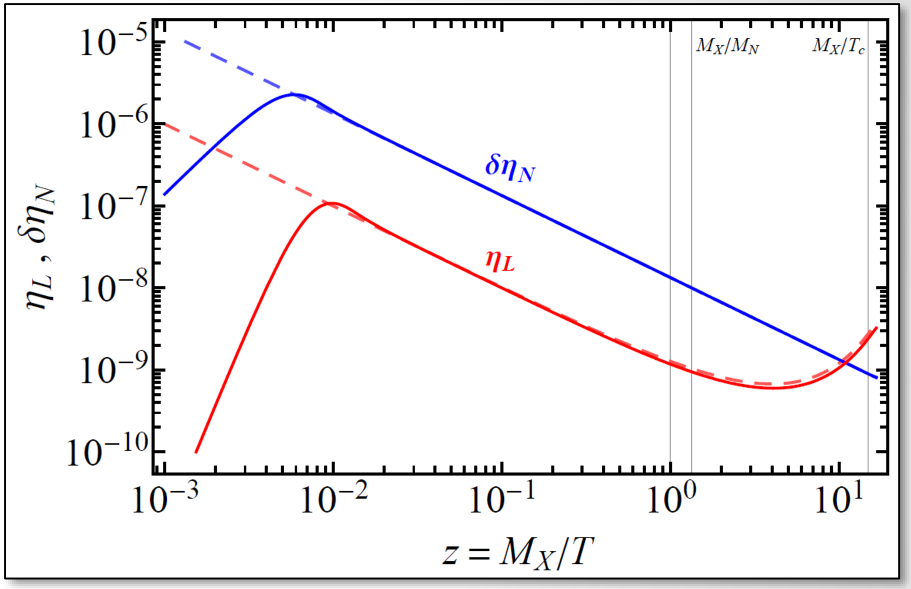
- Cannot exclude scenarios that generate a lepton number asymmetry below observed scale M_X
  - But strong limits still apply
- Asymmetry can be present in one lepton generation only
  - Unambiguous falsification requires observation of LNV in all flavours (or observation of low energy LFV such as $\tau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



- 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

- **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

- **LNV a crucial BSM signature**
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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

Heavy Sterile Neutrinos

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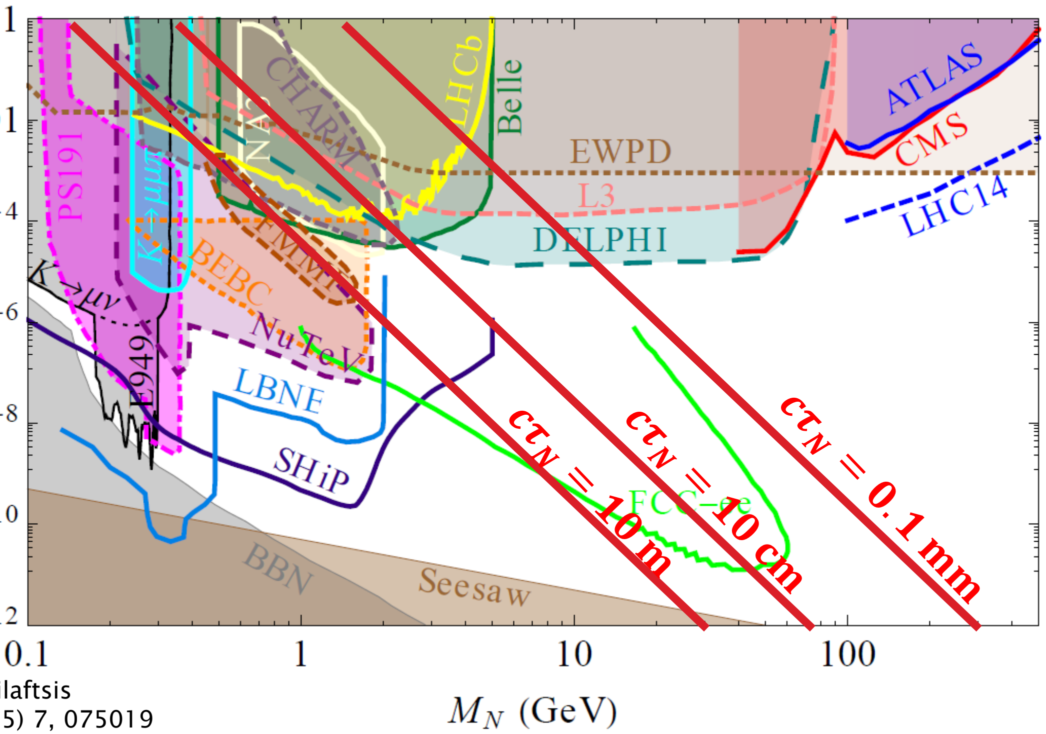
- Constraints on coupling to leptons $|V_{lN}|$
- Neutrinoless Double Beta Decay
  - GERDA
  - stringent for pure Majorana N
- Peak Searches in Meson Decays
  - $\pi, K \to e\nu$
  - Belle
- Beam Dump Experiments
  - e.g. PS191, CHARM
  - LBNE
- LNV Meson Decays
  - $K \to ee\pi$
  - SHiP
- Z Decays
  - LEP: L3, Delphi
  - FCC-ee
- Electroweak Precision Tests
  - EWPD: Fit of electroweak precision observables, lepton universality observables



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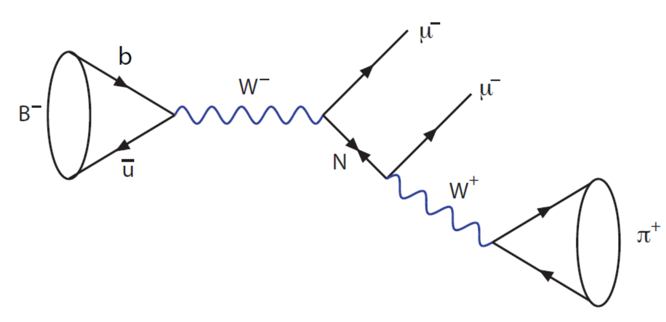
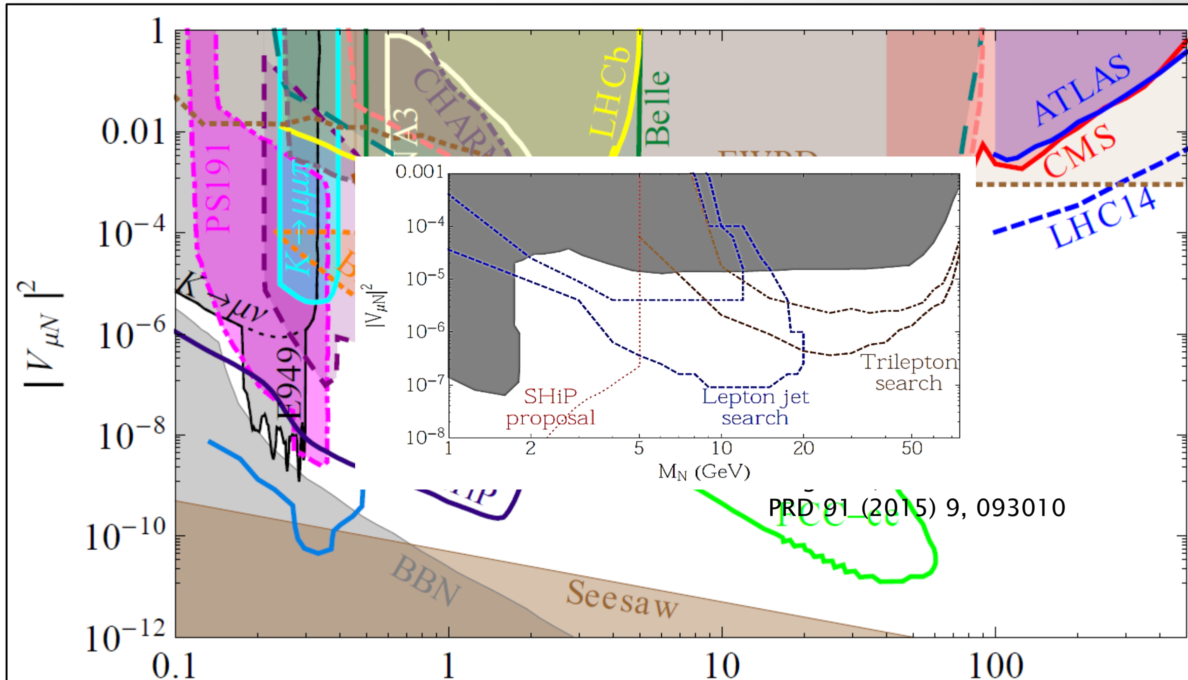


Heavy Sterile Neutrinos

- Constraints on coupling to leptons $|V_{lN}|$
- LEP2, ILC
  $e^+e^- \to N\nu,\ N \to eW, \nu Z, \nu H$
- LHC (ATLAS, CMS, LHC14)
  - Drell-Yan Production
  - Majorana N
    - Same-sign dilepton signal
  - (Quasi-)Dirac N
    - Trilepton signal
  - Modified searches for
    - Lighter neutrinos
    - Long-lived neutrinos



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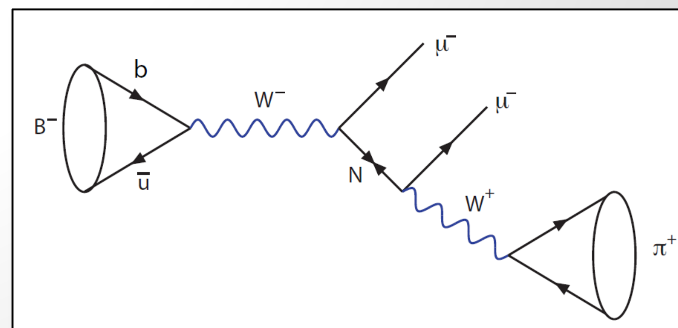
PRD 91 (2015) 9, 093010



Not so
Heavy Sterile Neutrinos

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