Falsifying High-Scale Leptogenesis at the LHC

based on

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

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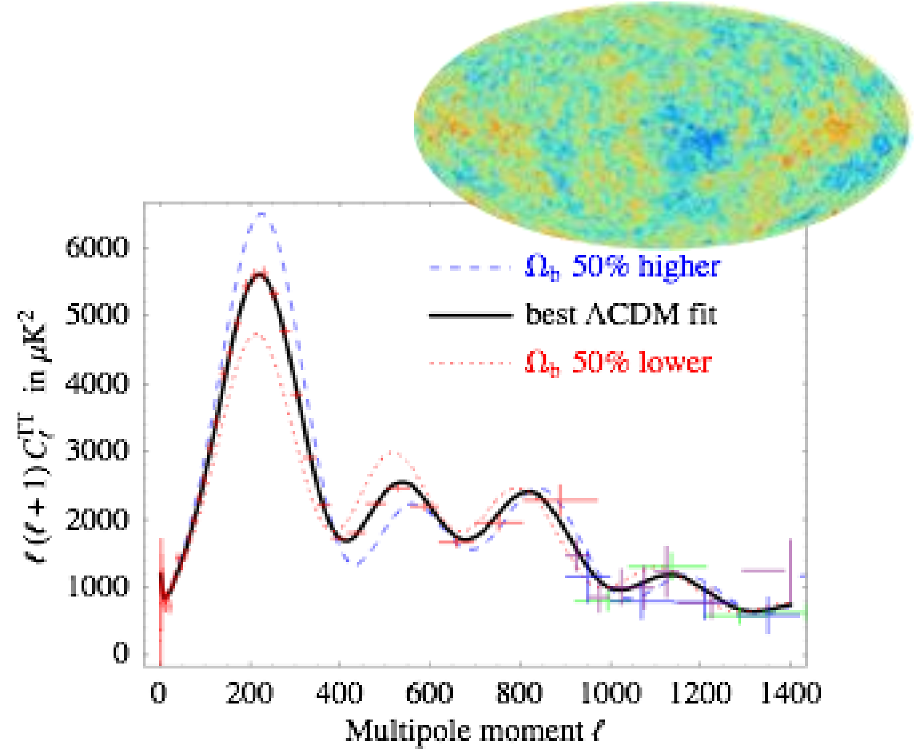
21/07/2104
SUSY 2014, Manchester

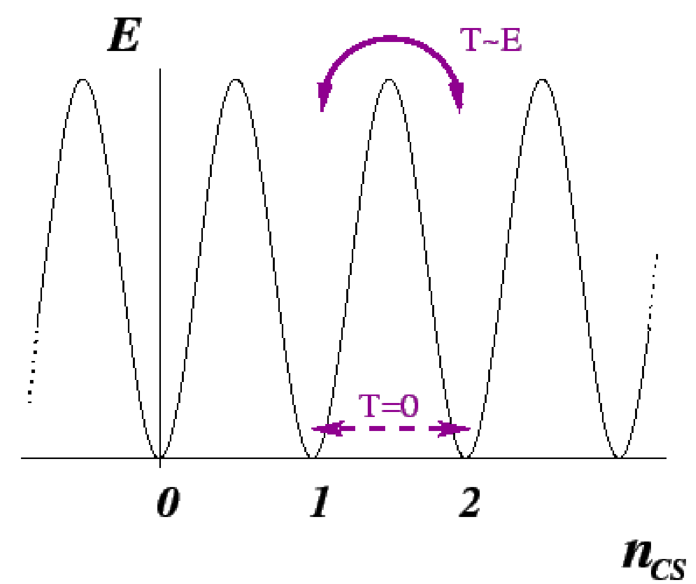
- Clear evidence for physics beyond the standard model: observation of baryon asymmetry of the Universe (BAU)

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



- Popular scenario for explaining BAU: Leptogenesis (LG)
    - (B-L)-violation
    - *CP* violation
    - departure from thermal equilibrium

- Lepton asymmetry converted to observed baryon asymmetry by (B+L)-violating sphaleron interactions



⇨ Is there a possibility to test or at least to falsify Leptogenesis?

Motivation

Is it possible to draw conclusions

on high-scale Leptogenesis

from observing lepton-number violating processes

at the LHC?

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YES!

- Popular scenario: right handed neutrinos
- Boltzmann equations describe evolution of number density / (B-L) asymmetry

$$\frac{dN_{N_1}}{dz} = -(D + S)(N_{N_1} - N_{N_1}^{\rm eq})$$

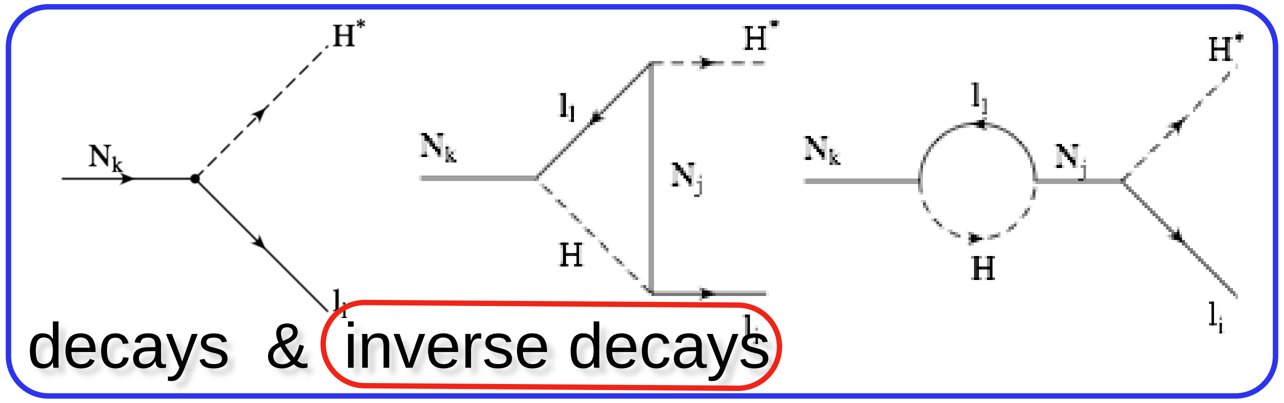
$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D(N_{N_1} - N_{N_1}^{\rm eq}) - W N_{B-L}$$

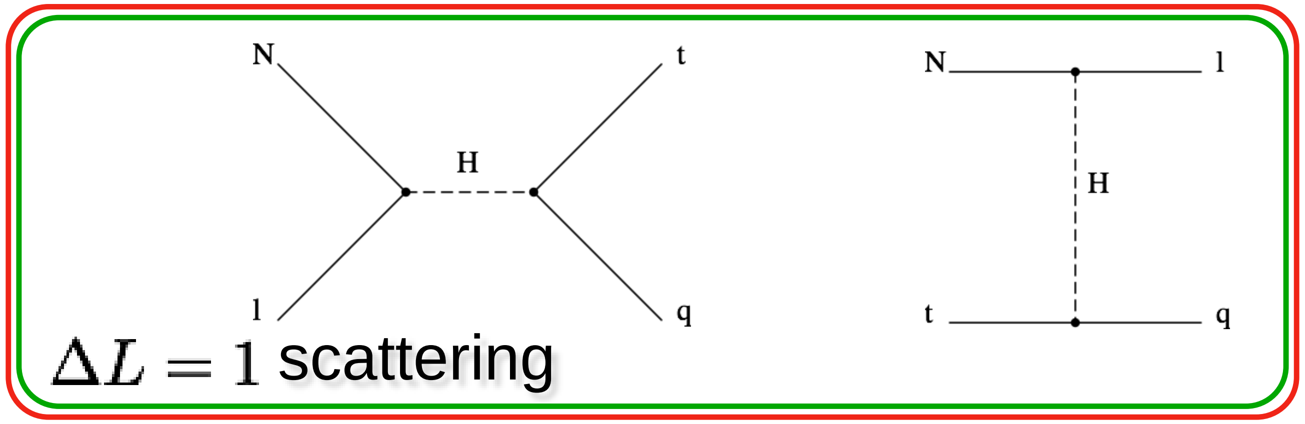
- Out-of-equilibrium condition:

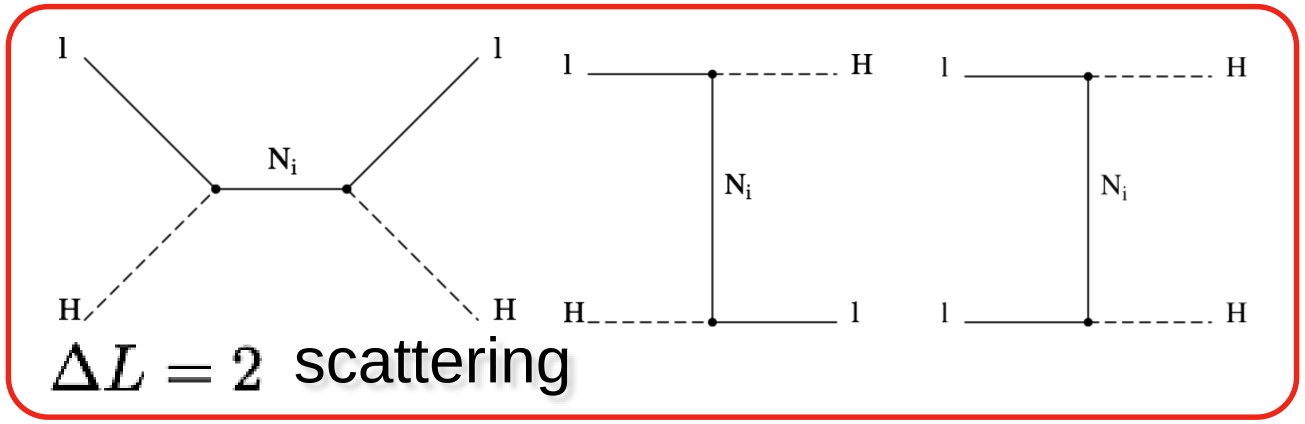
$$\frac{\Gamma_D}{H} << 1$$

- no remaining asymmetry if washout too large

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







Interplay of different Processes to Leptogenesis

- Popular scenario: right handed neutrinos
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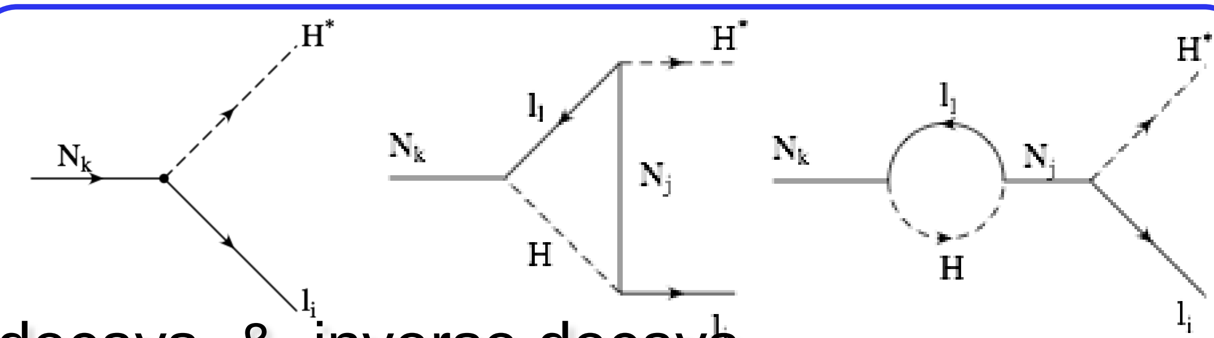
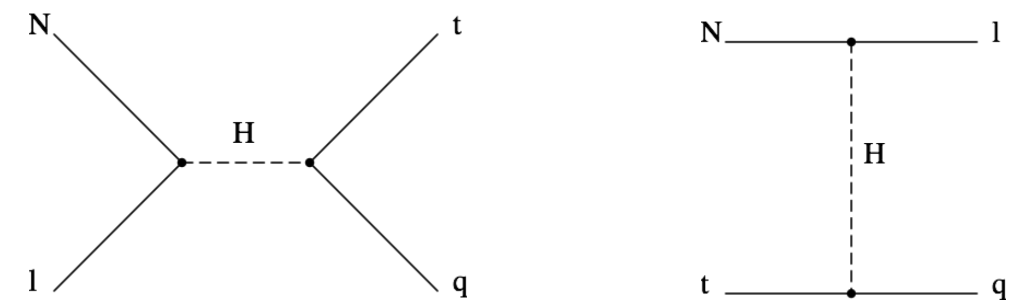
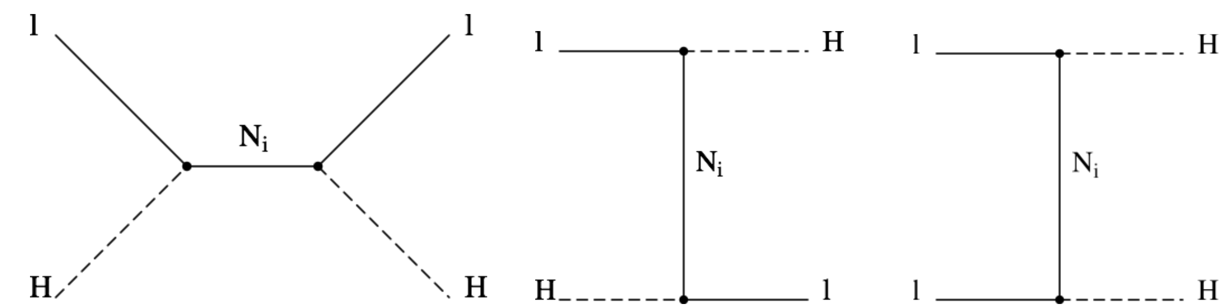


decays & inverse decays



$\Delta L = 1$ scattering

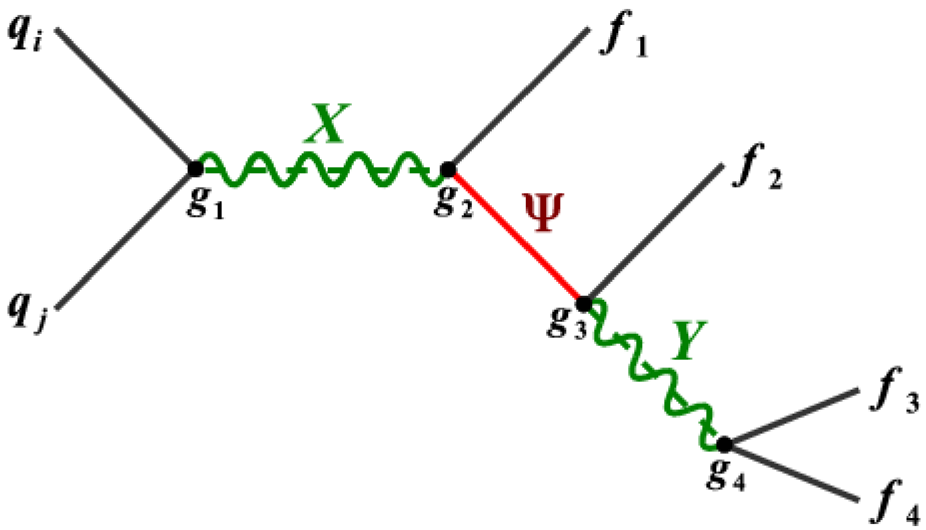


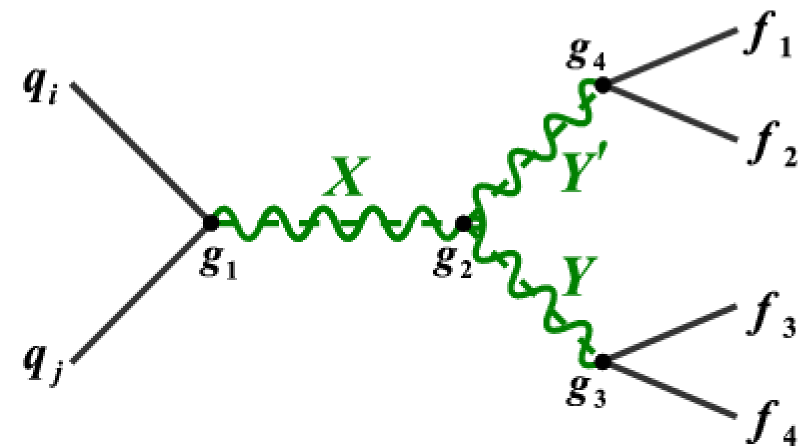
$\Delta L = 2$ scattering

⇒ conservative assumption of just considering $\Delta L = 2$ processes for washout

Possible LNV Signatures at LHC

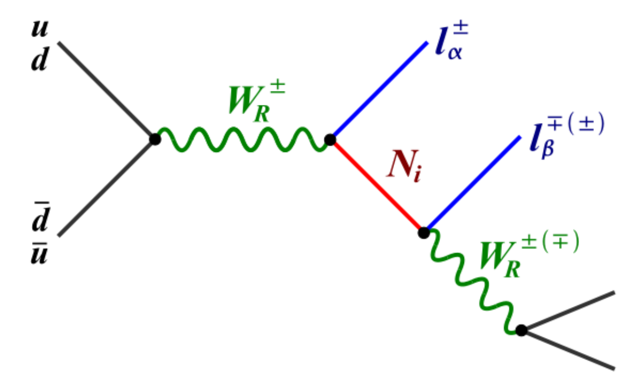
- $\Delta L = 2$ LNV at LHC through resonant same-sign dilepton signals $pp \to l^{\pm}l^{\pm} + 2\text{ jets}$





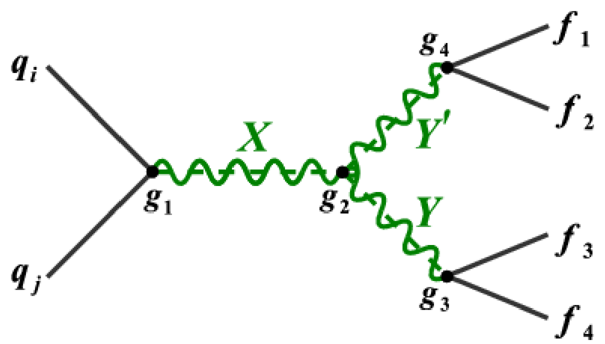
→ Realisation e.g. via resonant W_R production in LR-symmetric models with heavy Majorana neutrinos

J.-M. Frere, T. Hambye, G. Vertongen, JHEP 0901 (2009)
S. Das, F. Deppisch, O. Kittel, J. Valle, Phys. Rev. D86 (2012)

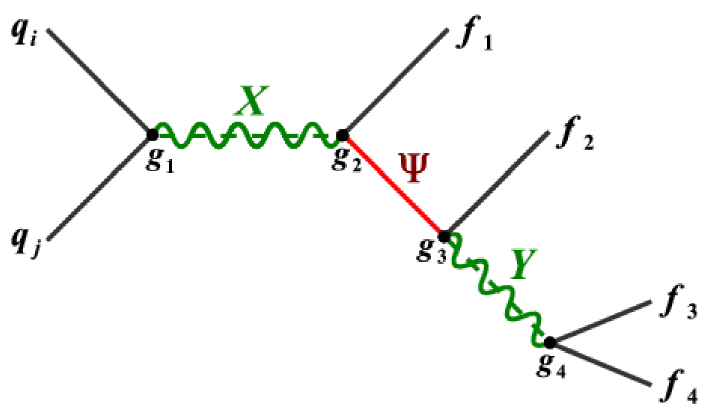


- Model independent approach: unspecified heavy states and couplings
- study the impact of hypothetical observation of the resonant $\Delta L = 2$ process $pp \to l^{\pm}l^{\pm} + 2\text{ jets}$

- Parton-level cross section:
  Approximation by Breit-Wigner resonance



$$\sigma(Q^2) = \frac{4\pi}{9}(2J_X + 1)\frac{\Gamma(X \to q_1 q_2)\Gamma(X \to 4f)}{(Q^2 - M_X^2)^2 + M_X^2 \Gamma_X^2}$$



- Total LHC cross section:
  Integrating over PDFs in narrow-width approximation

$$\sigma_{\mathrm{LHC}} = \frac{4\pi^2}{9s}(2J_X + 1)\frac{\Gamma_X}{M_X} f_{q_1 q_2}\left(\frac{M_X}{\sqrt{s}}, M_X^2\right) \times \mathrm{Br}(X \to q_1 q_2)\mathrm{Br}(X \to 4f)$$

with $$f_{q_1 q_2}\left(\frac{M}{\sqrt{s}}\right) \approx A_{q_1 q_2} \times \exp\left(-C_{q_1 q_2}\frac{M}{\sqrt{s}}\right)$$

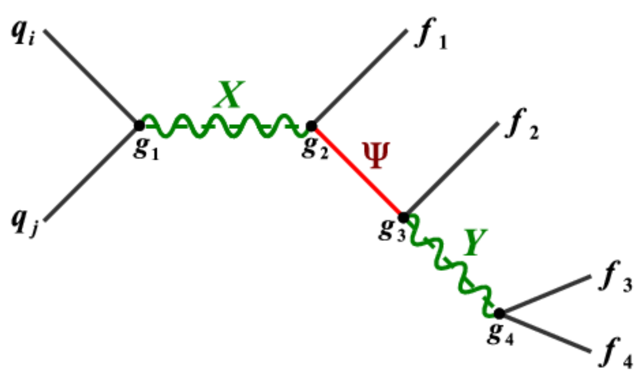
A. Leike, Phys. Rept. 317 (1999)

- Relating washout rate with LHC cross section

$$\frac{\Gamma_W}{H} = \frac{\gamma}{n_\gamma H}$$

$$H \approx 1.66\sqrt{g_\star}T^2/M_\mathrm{P}$$
$$n_\gamma \approx 2T^3/\pi^2$$

$$\gamma(qq \leftrightarrow l^\pm l^\pm qq) = \frac{T}{32\pi^4}\int_0^\infty ds\ s^{3/2}\sigma(s) K_1\left(\frac{\sqrt{s}}{T}\right)$$



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

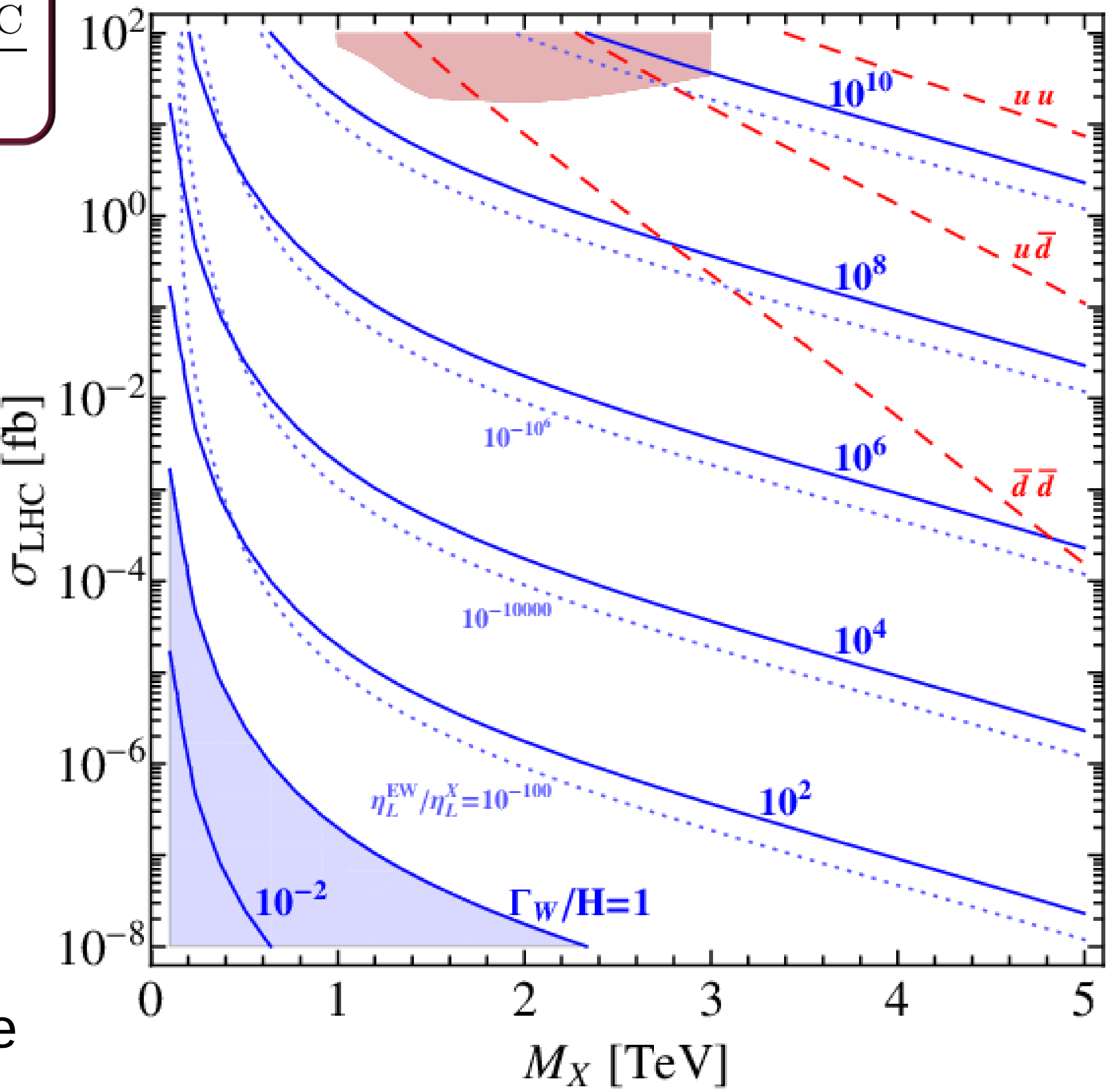
$$\frac{\Gamma_W}{H} = \frac{0.028}{\sqrt{g_*}}\frac{M_\mathrm{P} M_X^3}{T^4}\frac{K_1\left(M_X/T\right)}{f_{q_1 q_2}\left(M_X/\sqrt{s}\right)} \times \left(s\sigma_\mathrm{LHC}\right)$$

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

- relation independent of branching ratios of particle X
- valid for all coupling strengths

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

- For any realistic cross section at LHC with $\sigma_{\text{LHC}} > 10^{-2}$ fb washout highly effective $\frac{\Gamma_W}{H} >> 1$
- 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 M_X

- Now: assuming classical Leptogenesis with one heavy Neutrino

- Solving Boltzmann equations for η_L and η_N assuming LHC process as only source for washout

- Conversion of lepton number to baryon asymmetry

$$\eta_B = -d_{\text{rec}} r_{B/L} \eta_L(T_c)$$

with

$$r_{B/L} = \frac{8N_g + 4N_H}{14N_g + 9N_H} \approx 1/2$$

$$d_{\text{rec}} \approx 1/27$$

$$T_c \approx 135 \text{ GeV}$$

- Upper limit on baryon asymmetry

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

⇒ Upper limit on baryon asymmetry as a function of LG parameters M_N and ϵ and observables M_X and σ_{LHC}

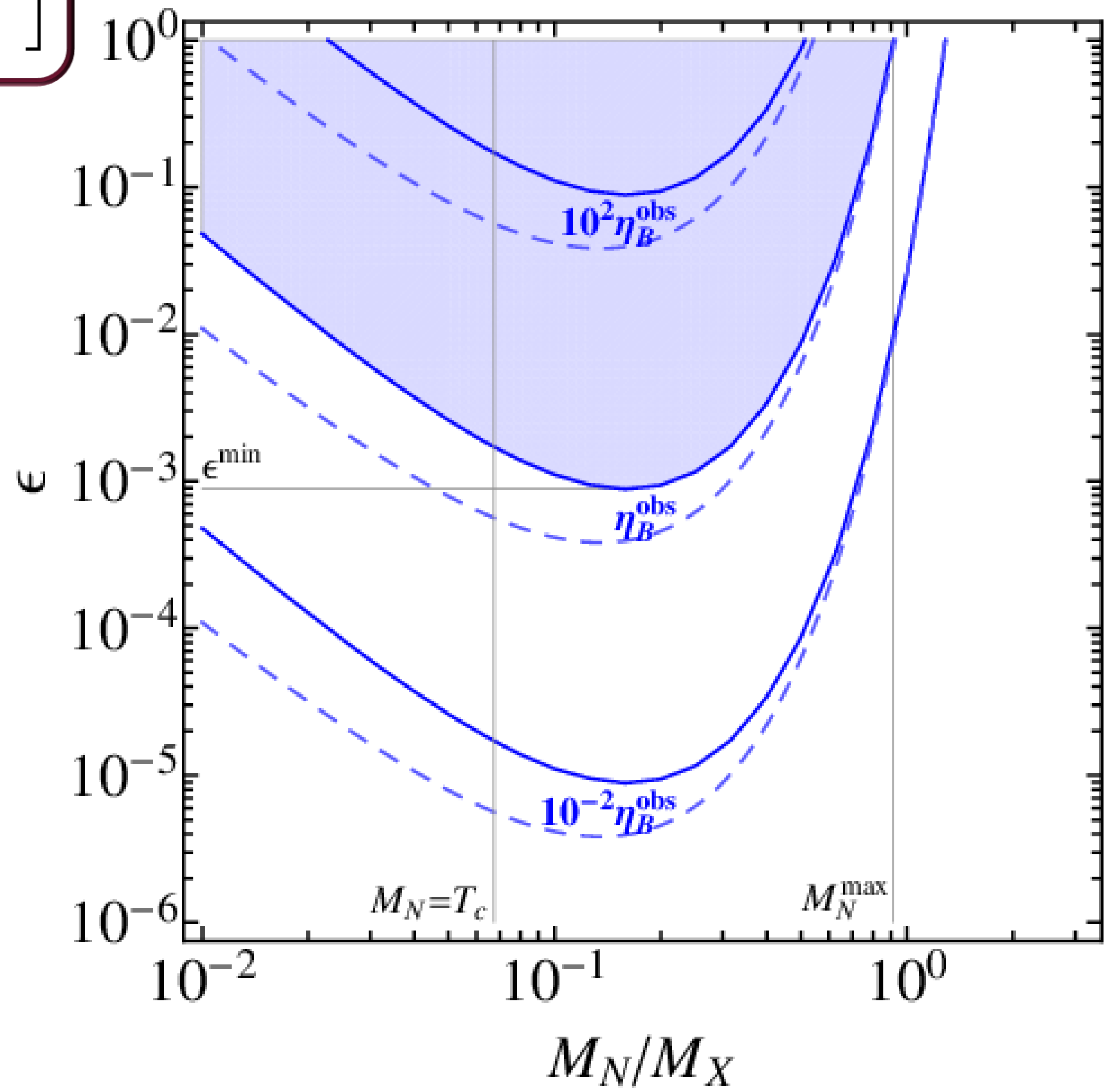
Impact on Baryon Asymmetry

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

- For $M_N < M_X$
  - Strong constraints on resonant LG models
  - Lower limit on CP-asymmetry

    $$\epsilon > \epsilon^{\rm min} \approx 10^{-3}$$

- For $M_N > M_X$
  - conservative upper limit for η_B
  - not possible to generate large enough baryon asymmetry at all



$\sigma_{\rm LHC} = 0.1$ fb
$M_X = 2$ TeV

Observation of LNV process at the LHC excludes high scale Leptogenesis models

Possible Caveats

A few caveats have to be considered:

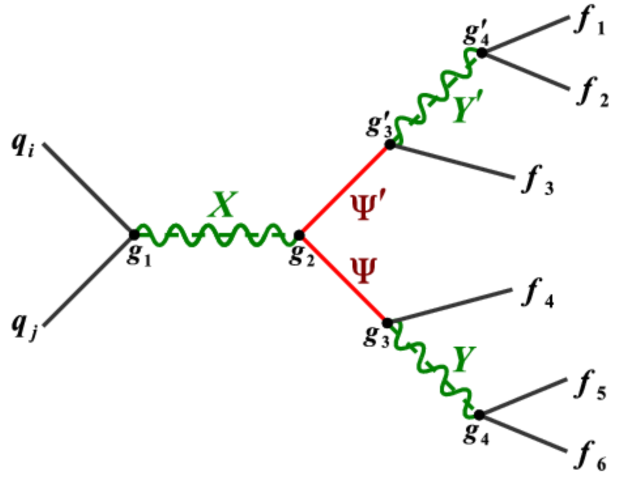
- Leptogenesis in the regime $M_N < M_X$
  - So far only model-independent limit on CP-asymmetry
  - E.g. resonant sub-TeV scale leptogenesis still possible
- Possible generation of LNV only in the third family
  - No experimental proof that $e^{\pm}e^{\pm} \leftrightarrow \tau^{\pm}\tau^{\pm}$ was in equilibrium
  - Necessary: non-zero observation of $pp \to l^{\pm}l^{\pm}qq$

    either by $ll = ee, \mu\mu \text{ and } \tau\tau$

    and/or $ll = e\mu \text{ and } e(\mu)\tau$
- LNV process at LHC involves right-handed leptons
  - SM sphaleron processes only affect electroweak fermion doublets
  - But: left- and right-handed fermions are in thermal equilibrium around EW-scale → conclusion applies as well

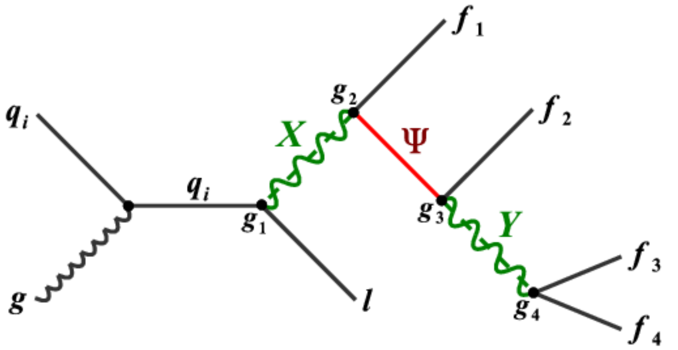
Conclusions

- Observation of LNV @ LHC corresponds to large washout



- Exclusion of a large number of high-scale Leptogenesis models

- Argumentation can be easily adapted to other cases



- Motivation for looking for LNV at the LHC in as many channels as possible!

Backup

Boltzmann Equations & Lepton Asymmetry

- Boltzmann equations can be expressed as

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

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

- with

$$\delta\eta_N = \frac{\eta_N}{\eta_N^{\mathrm{eq}}} - 1 \qquad \eta_L = \frac{n_L}{n_\gamma}$$

$$z = \frac{M_X}{T} \qquad r_N = \frac{M_N}{M_X}$$

- for $r_N < 1$
  - heavy neutrino decays cannot be compensated by washout for $z > 1$
- for $r_N > 1$
  - Washout always effective for $z > 1$
  - over-proportional drop-off