Neutrinos and Collider Physics

Frank Deppisch
f.deppisch@ucl.ac.uk

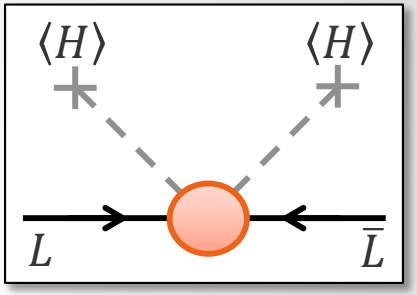
University College London

Nu@Fermilab | 21-25/07/2015

Effective Mass and Seesaw

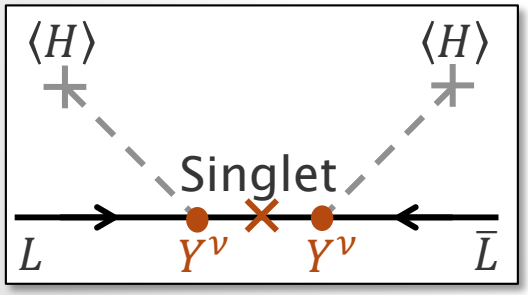
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

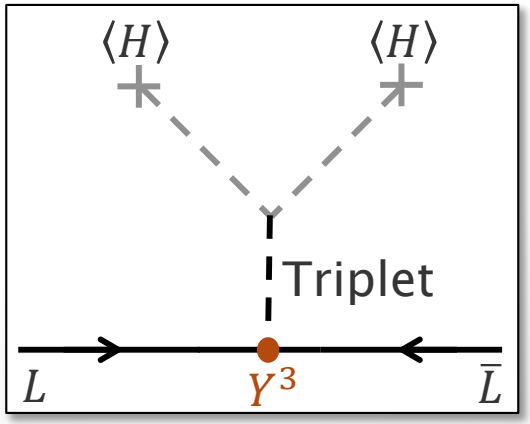


- Seesaw Mechanisms
  - Three possible mediators at tree level

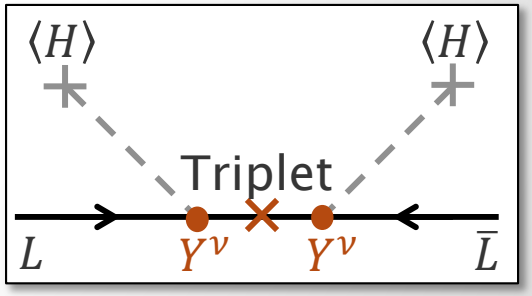
Seesaw I



Seesaw II



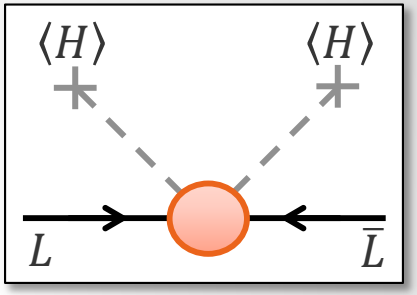
Seesaw III



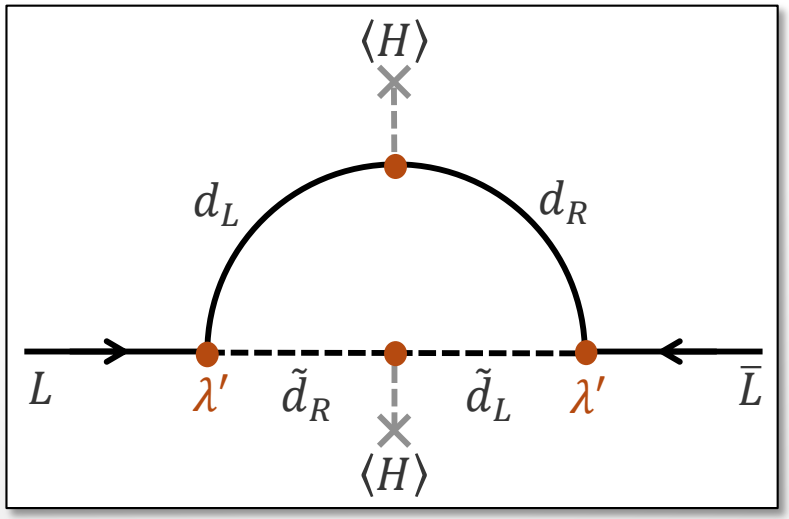
Effective Mass and Seesaw

- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$



- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. R-Parity Violating SUSY



Heavy Sterile Neutrinos
Low Scale Singlet Seesaw Models

University College London

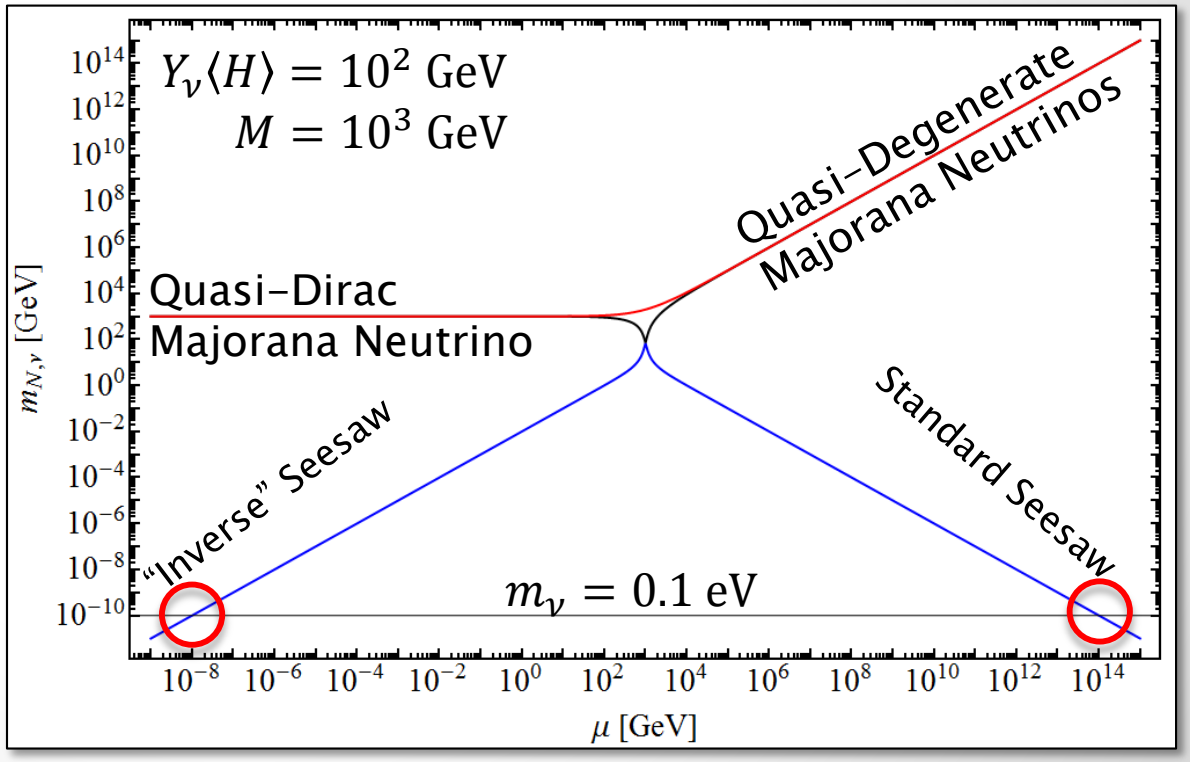
- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings

$$Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}$$

  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

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

    - Large Yukawa couplings $\approx 10^{-2}$
    - Quasi-Dirac heavy neutrino



Heavy Sterile Neutrinos
Low Scale Singlet Seesaw Models

University College London

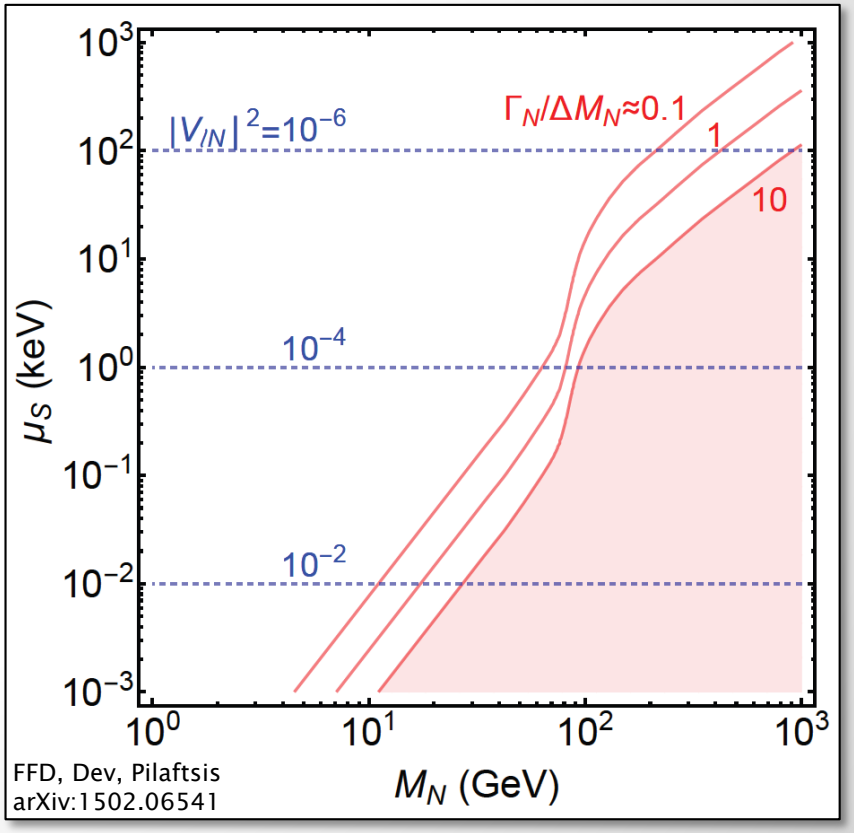
- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings

$$Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}$$

  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

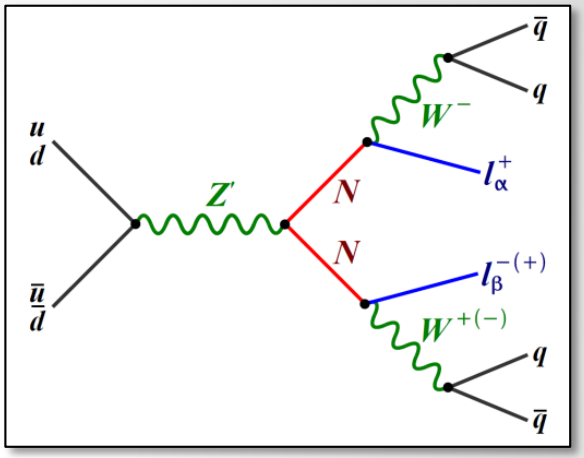
$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

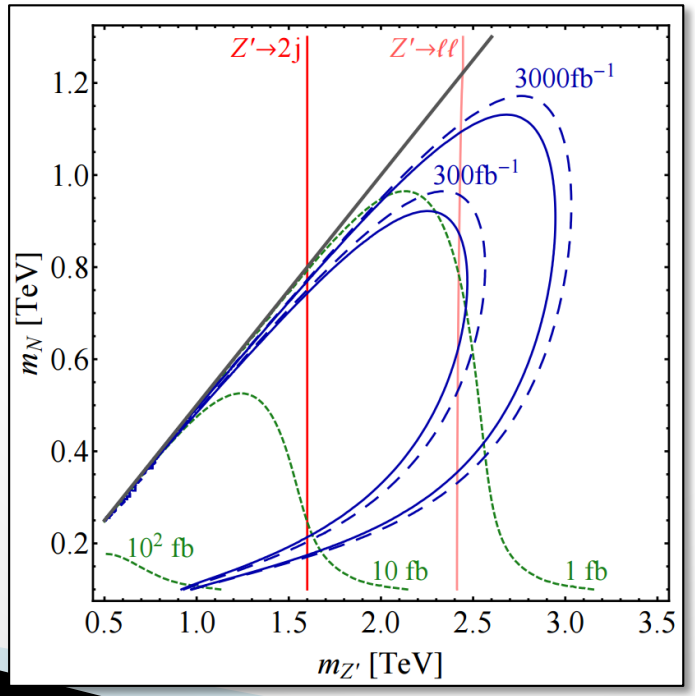
    - LNV in resonant N production suppressed by $\frac{\Delta m_N}{\Gamma_N} \approx \frac{\mu}{\Gamma_N}$

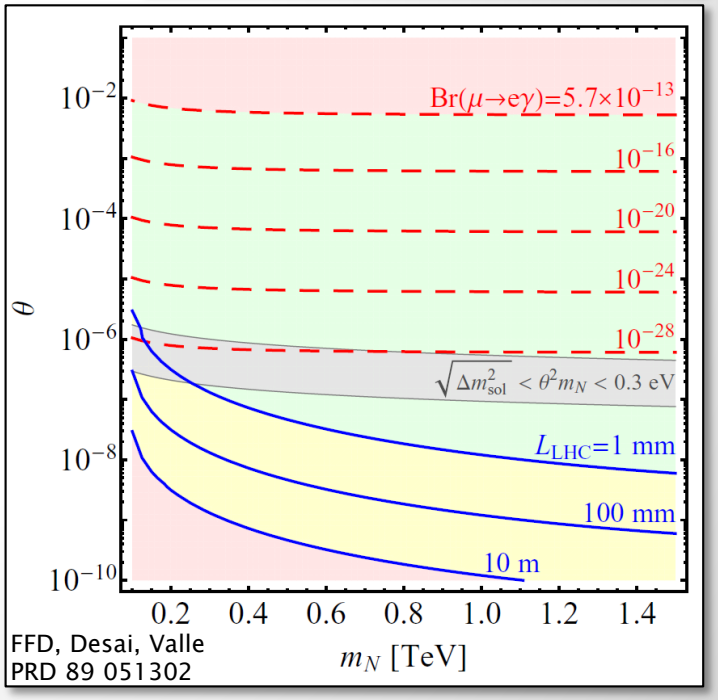


Extended Gauge Sectors
Additional U(1)

- Production at LHC via Z' portal
- Ability to measure small couplings via displaced vertices
- Charged LFV through heavy portal
  - N can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$







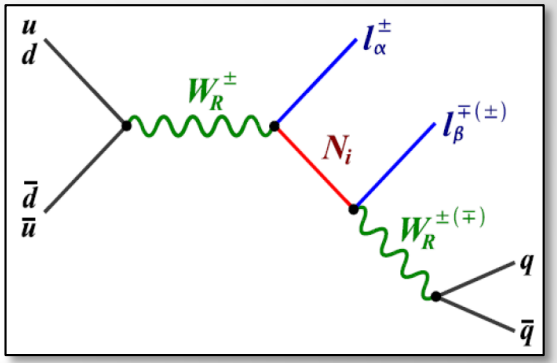
FFD, Desai, Valle
PRD 89 051302

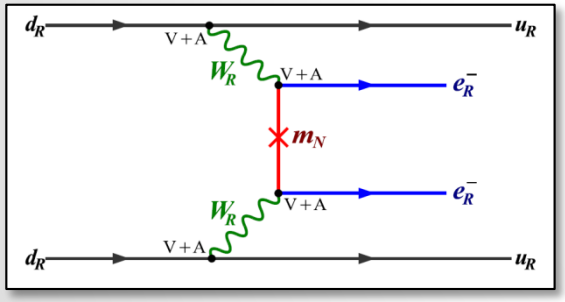
Extended Gauge Sectors
Left-Right Symmetric Models

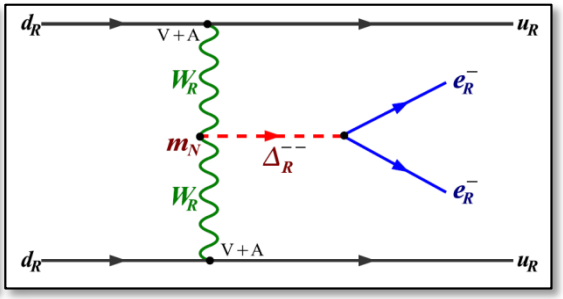
- Extension of the Standard Model

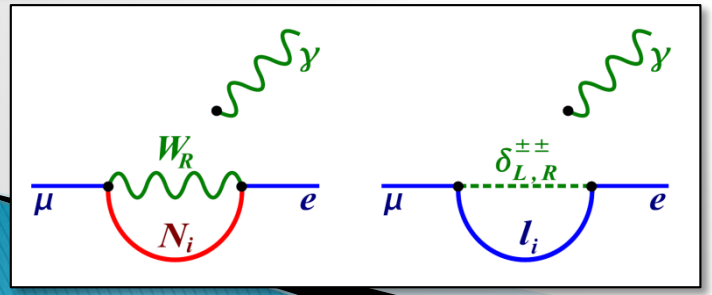
$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

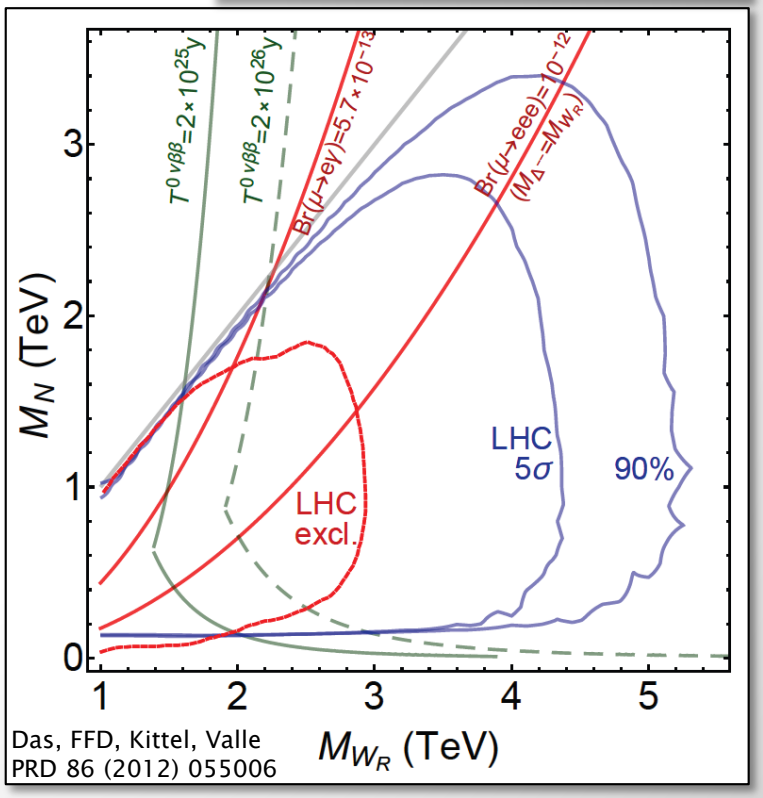
- Production of heavy neutrinos with gauge coupling strengths via right-handed charged current
  (Keung, Senjanovic '83)
- Complementarity to $0\nu\nu\beta$ and charged LFV











Das, FFD, Kittel, Valle
PRD 86 (2012) 055006

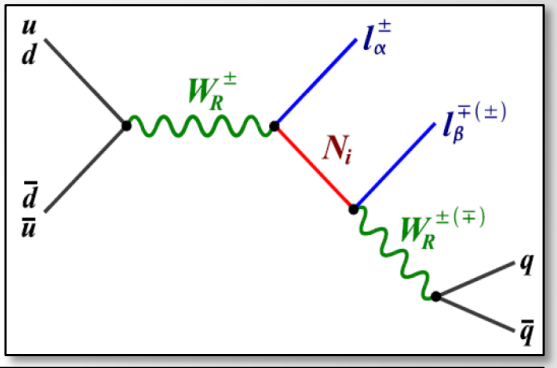
Extended Gauge Sectors
Left-Right Symmetric Models

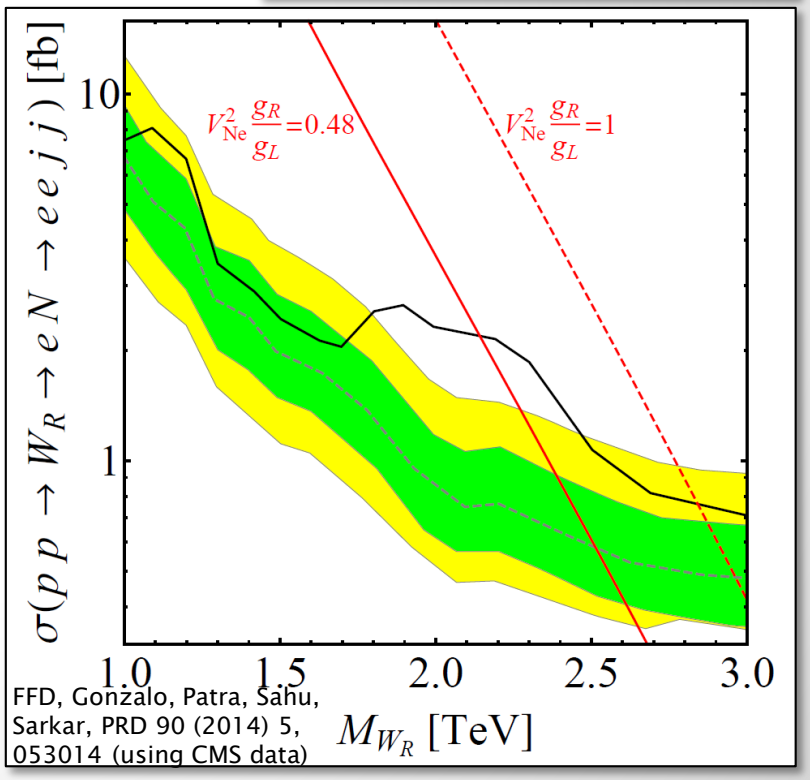
University College London

- Extension of the Standard Model

$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Production of heavy neutrinos with gauge coupling strengths via right-handed charged current
  (Keung, Senjanovic '83)
- Complementarity to $0\nu\nu\beta$ and charged LFV
- 2.8σ hint for excess at CMS
  - Not compatible with minimal LR symmetry $g_R = g_L$
  - Only one 1 out of 14 potential signal events is LNV
  - Only ee, no $\mu\mu$
  - No clear discrete excess in $m^2_{lqq} = m^2_N$
- No excess at ATLAS
  - Search only for SS leptons



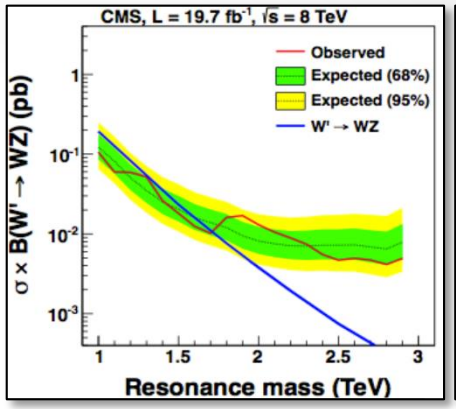


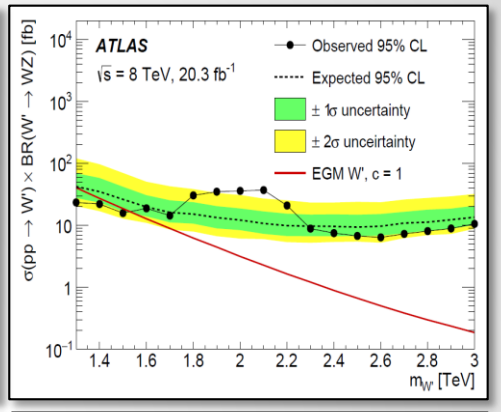
FFD, Gonzalo, Patra, Sahu, Sarkar, PRD 90 (2014) 5, 053014 (using CMS data)

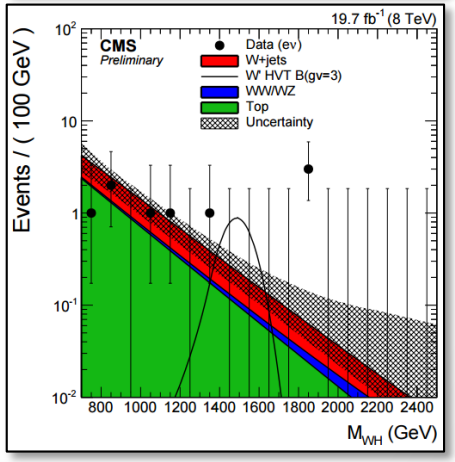
Extended Gauge Sectors Excesses @ 2 TeV

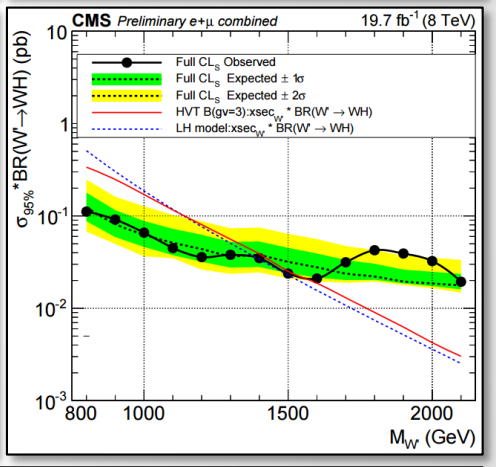
University College London

- Excesses in other resonant searches around 2 TeV
  - WW, ZZ or WZ
    - up to 3.4σ @ ATLAS (hadronic)
    - no excess in semi-leptonic ch. lνj
  - HW
    - 2σ @ CMS (leptonic)
    - tension with hadronic ch.
  - jj
    - small excesses @ ATLAS and CMS (1.5σ,1.9σ)
    - tension with tb channel







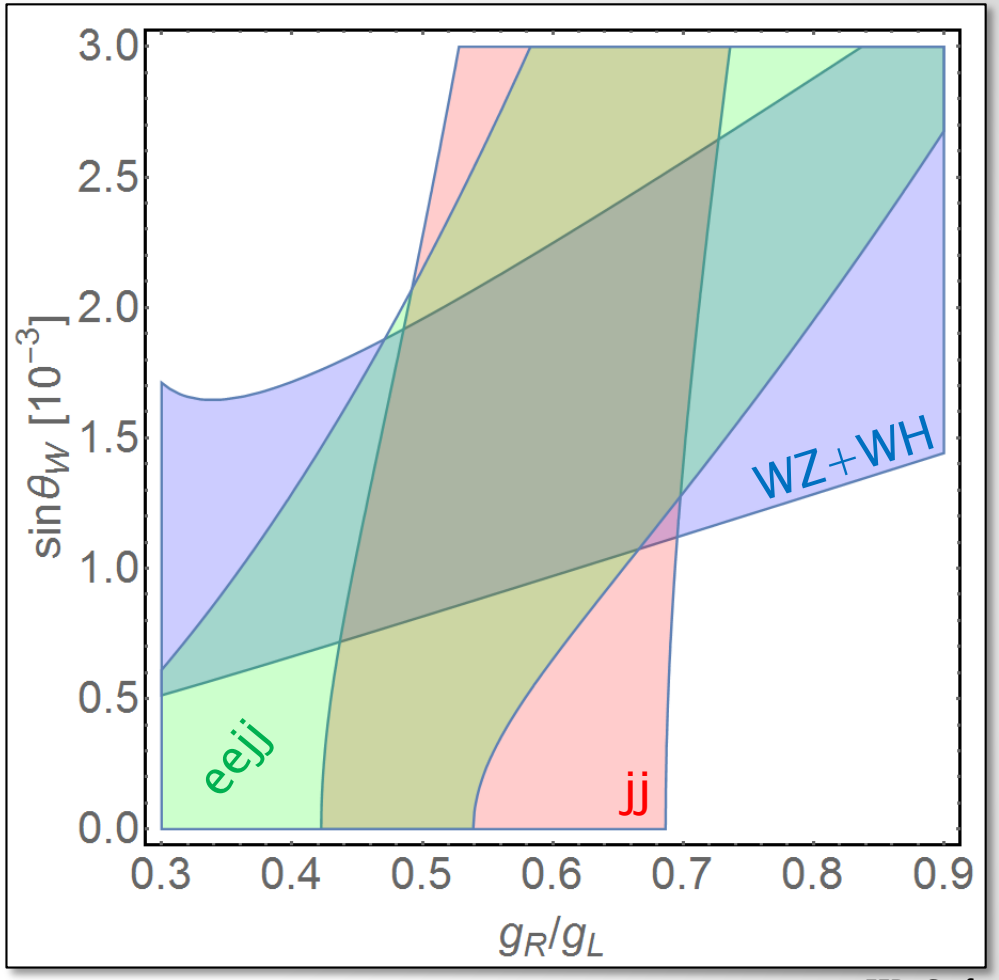


Process	Fitted cross section [fb]	Upper bound (90% CL)
$pp \to X \to WZ^1$	$5.9^{+5.3}_{-3.5}$	13.7
$pp \to X \to ZZ^1$	$5.5^{+5.1}_{-3.7}$	12.8
$pp \to X \to WH$	$4.5^{+6.2}_{-3.9}$	17.0
$pp \to X \to jj$	91^{+53}_{-45}	170
$pp \to X \to tb$	0^{+11}_{-0}	38
$pp \to X \to tb$ (without ATLAS $bb\ell\nu$ [13])	0^{+39}_{-0}	60

Brehmer, Hewett, Kopp, Rizzo, Tattersall, arXiv:1507.00013

Extended Gauge Sectors
Excesses @ 2 TeV

- Combined interpretation in effective LR model
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to WZ)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to WH)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to jj)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to Ne) \times \mathrm{Br}(N \to ejj) = 0.8 \pm 0.6$ fb
- Model parameters
  - $m_{W_R} = 1.9$ TeV
  - $m_N = 1.6$ TeV
  - g_R/g_L: Ratio of $\mathrm{SU(2)_{R/L}}$ gauge couplings
  - $\sin\theta_W$: $W - W_R$ mixing angle
  - $\sin\theta_N = 0$: $\nu - N$ mixing angle

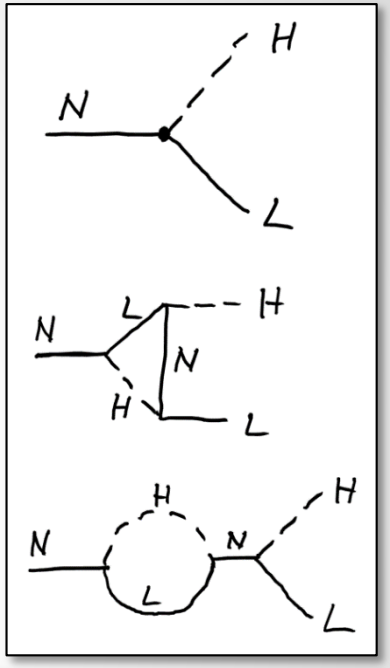


FFD, Graf, preliminary

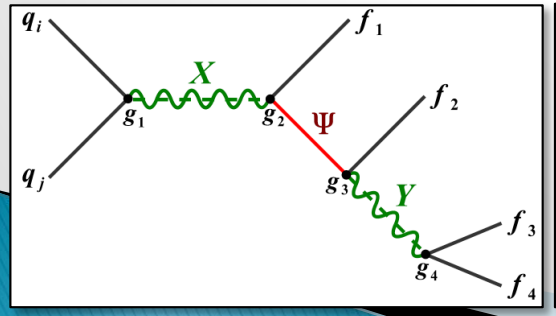
Baryon Asymmetry
Leptogenesis

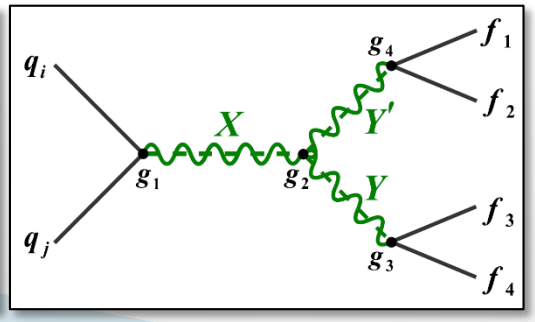
- Classic Scenario
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\,\mathrm{GeV}$
    - Observed asymmetry

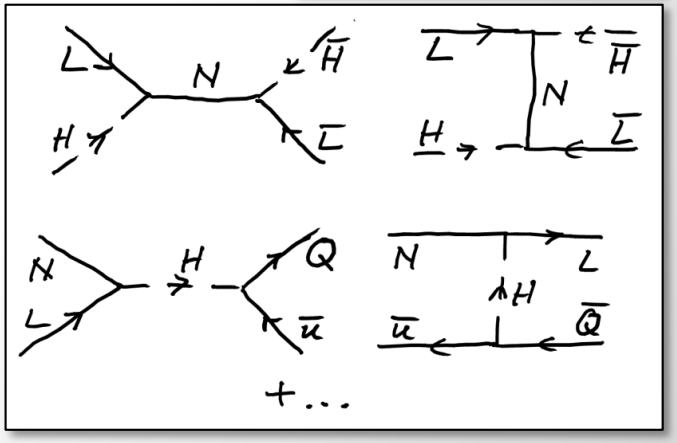
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$



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







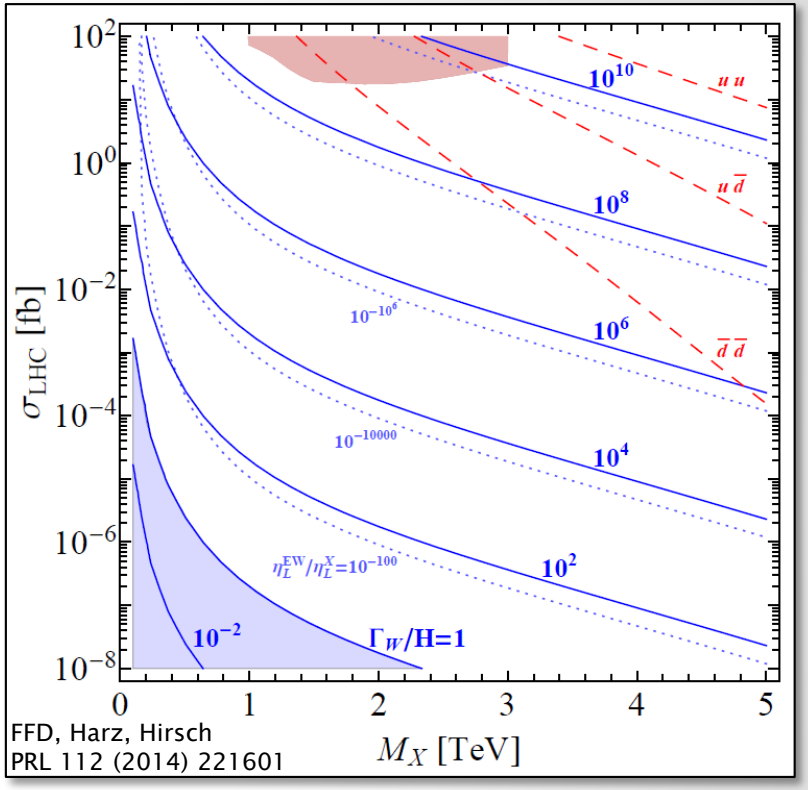
Baryon Asymmetry
Constraint on High-scale Baryogenesis

University College London

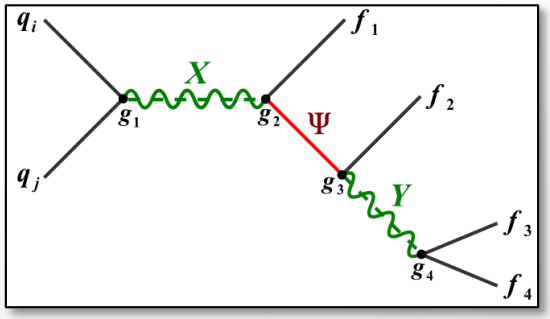
- Compare LHC cross section with lepton number asymmetry washout

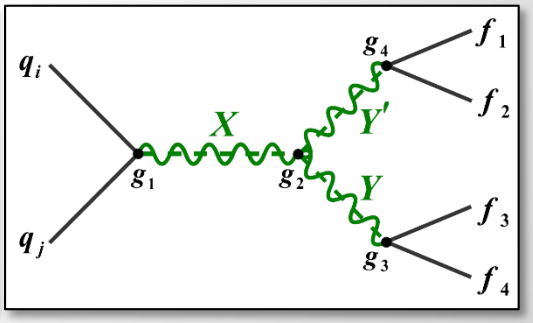
$$\frac{\Gamma_W}{H} > 3 \times 10^{-3} \frac{M_P M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})} \times (s\,\sigma_{\mathrm{LHC}})$$

  - Lower limit on total washout rate
  - Observation of LNV @ LHC corresponds to highly effective washout $\Gamma_W/H \gg 1$
  - Excludes baryogenesis models that generate asymmetry above M_X



FFD, Harz, Hirsch
PRL 112 (2014) 221601





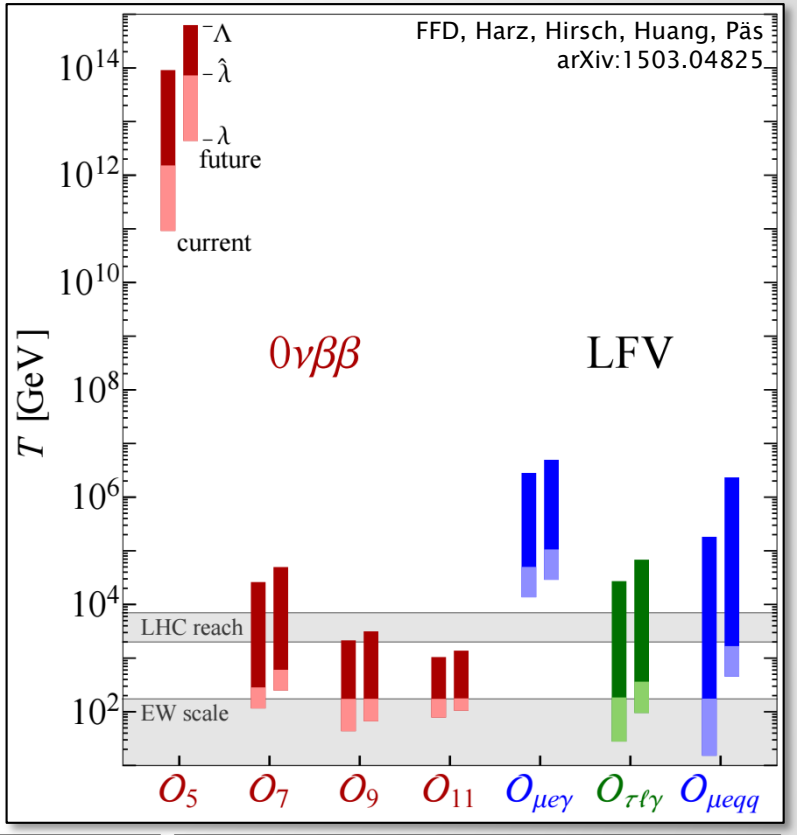
Baryon Asymmetry
Synergy with $0\nu\beta\beta$ and LFV

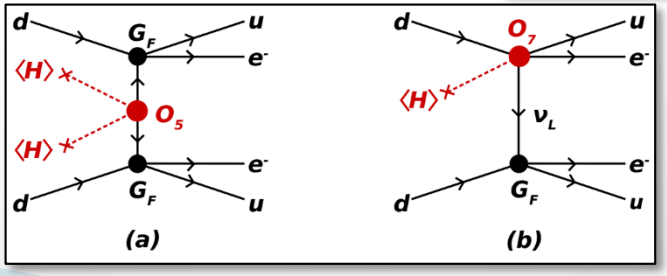
- LNV effective operators are of mass dimensions 5, 7, 9, 11, …
- $0\nu\beta\beta$ sensitive to operators at scales

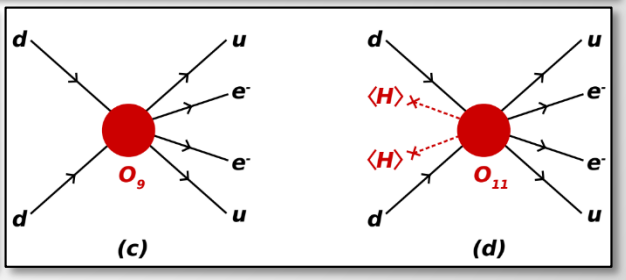
$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\text{yr} \rightarrow m_\nu \approx 0.1\text{ eV} \rightarrow \Lambda_5 \approx 10^{14}\text{GeV}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\text{yr} \rightarrow \Lambda_9 \approx 1\text{ TeV}$$

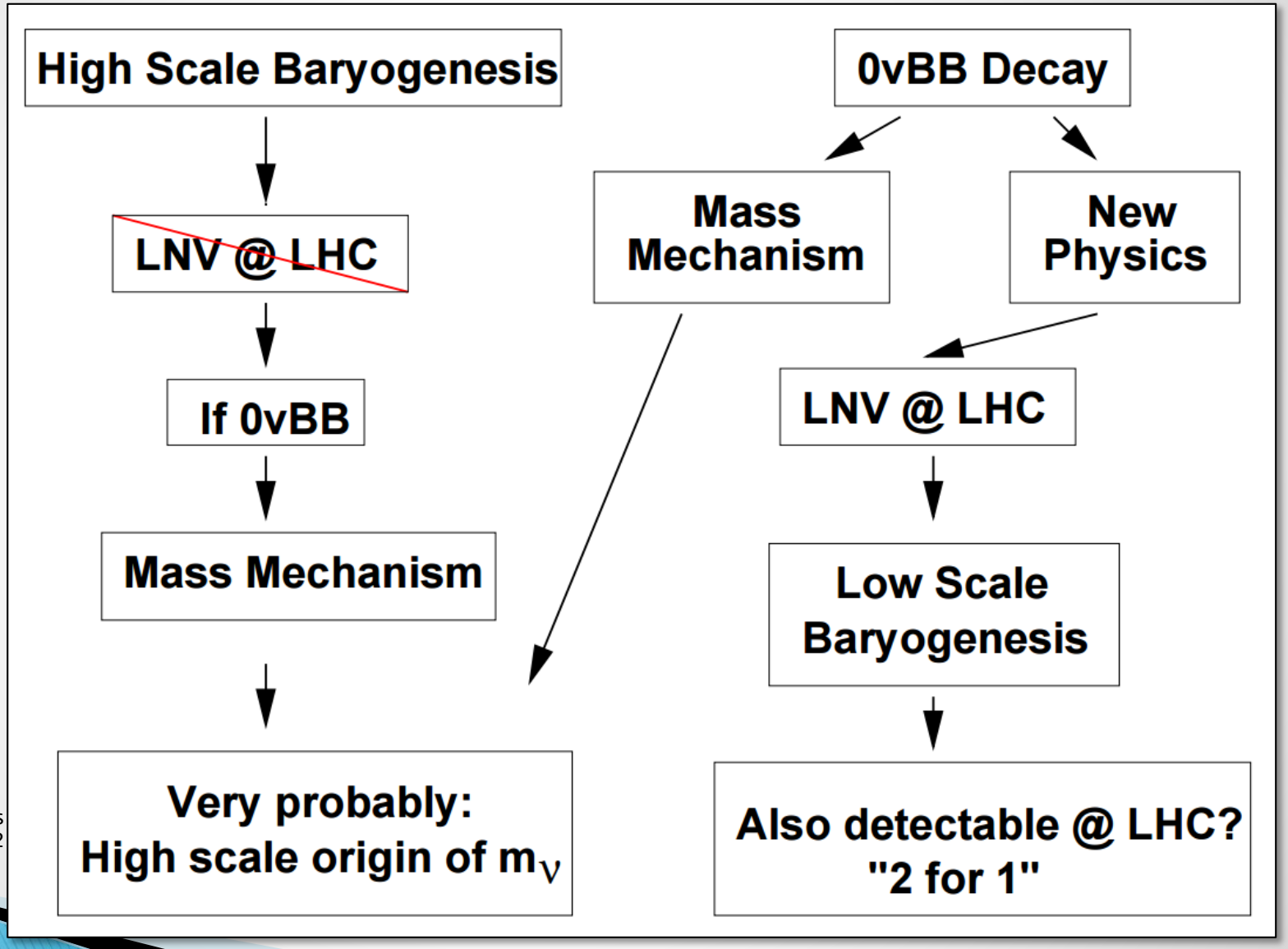
- LHC can deep-probe anatomy of LNV operators at TeV scale
- Observation of LNV and LFV would
  - give information at what temperatures operators are in equilibrium
  - can provide strong constraint on baryogenesis models and falsify high-scale scenarios







Conclusion



Harz, Huang, Päs
arXiv:1505.07632