Developments in leptogenesis

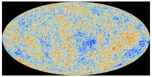
Mathias Garny (CERN)

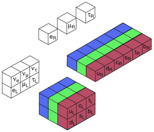
WIN MPIK June 9, 2015

Physics beyond the Standard Model

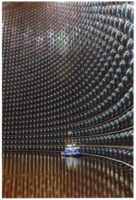
Collider exp.

Baryon
asymmetry





+ ?



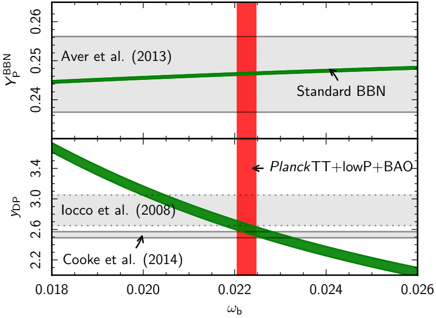
Neutrino exp.

Dark matter

Baryon asymmetry

$$Y_P = 4 n_{He} / n_b$$

$$y_{DP} = n_D / n_H \cdot 10^5$$



$$\omega_b = \Omega_b h^2 = \eta / (2.74 \cdot 10^{-8})$$

Consistent value inferred from Big Bang Nucleosynthesis ($T \sim$ keV) and the cosmic microwave background ($T \sim$ eV)

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = \begin{cases} (6.15 \pm 0.15) \cdot 10^{-10} & \text{WMAP9} \\ (6.10 \pm 0.08) \cdot 10^{-10} & \text{Planck} \end{cases}$$

WMAP9 1212.5226, Planck 1502.01589

Baryogenesis

- Electroweak baryogenesis (not in the SM, EWPT cross-over for $m_H \gtrsim 72\,\text{GeV}$; MSSM: light RH stop would show up in direct search + Higgs properties)
- Leptogenesis
- Affleck-Dine
- GUT baryogenesis
- ...

Baryogenesis via leptogenesis

Fukugita, Yanagida 86

Light neutrino masses via seesaw mechanism (focus on type-I)*

$$\mathcal{L} \quad = \quad \mathcal{L}_{SM} + \tfrac{1}{2}\bar{N}i\partial\!\!\!/ N - \tfrac{1}{2}\bar{N}\hat{M}N - \bar{\ell}\widetilde{\phi}hP_R N - \bar{N}P_L h^\dagger \widetilde{\phi}^\dagger \ell$$

$$m_\nu = -v_{EW}^2 h \hat{M}^{-1} h^T$$

$$0.06\text{eV} \lesssim \sum m_\nu \lesssim 0.14..0.59\text{eV} \quad \rightarrow \quad \text{TeV} \lesssim M_i \lesssim M_{GUT} \text{ for } m_e/v_{EW} < h_{ij} < 1$$

Lyα BOSS 1410.7244 .. Planck 1502.01589 (0.23eV w BAO)

* *recent analysis in type-II: Lavignac, Schmauch 1503.00629*

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- B-violation via L-violating Majorana masses M_i
- CP-violation via Yukawa couplings $\text{Im}[(h^\dagger h)_{ij}] \neq 0$
- Out-of-equilibrium (inverse) decay $N_i \leftrightarrow \ell\phi^\dagger$ and $N_i \leftrightarrow \ell^c\phi$

$$(\Gamma_i/H)|_{T=M_i} \quad \simeq \quad \left.\frac{(h^\dagger h)_{ii} M_i/8\pi}{1.66 g_* T^2/M_{pl}}\right|_{T=M_i}$$

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$$\simeq \tilde{m}_i/\mathrm{meV}$$

Baryogenesis via leptogenesis

Fukugita, Yanagida 86

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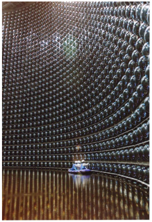
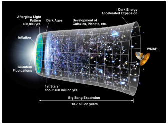
$$\simeq \quad \tilde{m}_i/\text{meV} \quad \sim \mathcal{O}(1-100) \leftrightarrow$$ leptogenesis works well for observed ν mass scale

Leptogenesis



$m_\nu,\ \theta_{ij},\ \delta_{CP}$

$\leftrightarrow$



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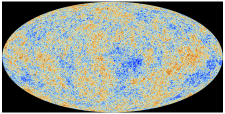


$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.10 \pm 0.08) \cdot 10^{-10}$$

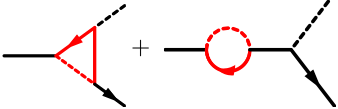
- Theory of leptogenesis
- Testing leptogenesis

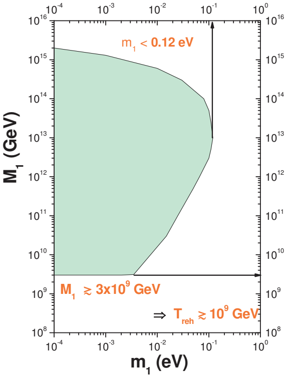
Vanilla Leptogenesis

$$\frac{dN_{N_i}}{dt} = -\underbrace{\Gamma_{N_i}}_{\text{equilibration rate}}\left(N_{N_i} - N_{N_i}^{eq}\right)$$

$$\frac{dN_{B-L}}{dt} = \underbrace{\sum_i \Gamma_{\not{C}\not{P},i}\left(N_{N_i} - N_{N_i}^{eq}\right)}_{\text{source term}} - \underbrace{\Gamma_W N_{B-L}}_{\text{washout term}}$$

$\Gamma_{\not{C}\not{P},i} \propto$





Di Bari 1206.3168 (unflavoured)

- Lower bound $M_{N_1} \gtrsim 10^9$ GeV (unless $\Delta M_N / M_{N_1} \ll 1$)

  Davidson, Ibarra 02; Hamaguchi, Murayama, Yanagida 01

- Upper bound $m_{\nu_1} \lesssim 0.12\,\text{eV}$ (unflavoured), $\sim 1\,\text{eV}$ (flavoured)

Developments: theory

Systematic approach based on CTP/Kadanoff-Baym

- Resonant enhancement
- Flavor effects
- Thermal corrections

- Partial spectator equilibration *Garbrecht, Schwaller 1404.2915*
- Non-relativistic expansion *Bodeker, Wormann 1311.2593*
- ...

Systematic approach based on CTP/Kadanoff-Baym

Statistical propagator $\quad S_F^{ij}(x,y) = \langle N_i(x)\bar{N}_j(y) - \bar{N}_j(y)N_i(x)\rangle/2$

Spectral function $\quad S_\rho^{ij}(x,y) = i\langle N_i(x)\bar{N}_j(y) + \bar{N}_j(y)N_i(x)\rangle$

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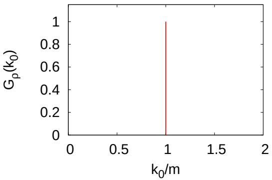
Boltzmann limit

- on-shell quasi-stable particles



$$S_\rho^{ij}(k) \sim \delta^{ij}\delta(k^2 - m_i^2)$$

- equilibrium-like
  fluctuation-dissipation relation

$$S_F^{ii}(t,k) = \left(\frac{1}{2} - f_k^i(t)\right) S_\rho^{ii}(k)$$

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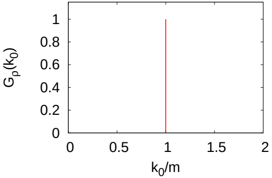

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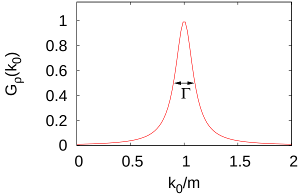
CTP/Kadanoff-Baym

- spectrum with (thermal) width

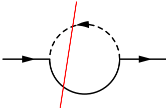
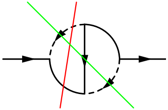
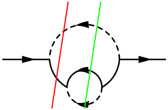


$$S_\rho^{ij}(t,k) \propto \frac{\delta^{ij} 2k_0\Gamma_i(t)}{(k^2 - m_{th,i}^2(t))^2 + k_0^2\Gamma_i(t)^2} + \ldots$$

- coherent $N_1 - N_2$ transitions

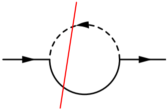
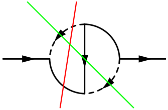
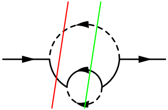
$$S_F^{ij}(t,k) = \begin{pmatrix} S_F^{11} & S_F^{12} \\ S_F^{21} & S_F^{22} \end{pmatrix}$$

CTP/Kadanoff-Baym approach to leptogenesis

			
$N \leftrightarrow \ell\phi^\dagger$ $N \leftrightarrow \ell^c\phi$	$\vert tree\vert^2$	tree $\times$ vertex-corr.	tree $\times$ wave-corr.
$\ell\phi^\dagger \leftrightarrow \ell^c\phi$		s $\times$ t	s $\times$ s, t $\times$ t

$$\frac{dn_L}{dt} = i\int_0^t dt' \int \frac{d^3p}{(2\pi)^3}\, \mathrm{tr}\Big[\Sigma_{\ell\,\rho\,\mathbf{p}}^{\alpha\gamma}(t,t')S_{\ell\,F\,\mathbf{p}}^{\gamma\beta}(t',t) - \Sigma_{\ell\,F\,\mathbf{p}}^{\alpha\gamma}(t,t')S_{\ell\,\rho\,\mathbf{p}}^{\gamma\beta}(t',t) - S_{\ell\,\rho\,\mathbf{p}}^{\alpha\gamma}(t,t')\Sigma_{\ell\,F\,\mathbf{p}}^{\gamma\beta}(t',t) + S_{\ell\,F\,\mathbf{p}}^{\alpha\gamma}(t,t')\Sigma_{\ell\,\rho\,\mathbf{p}}^{\gamma\beta}(t',t)\Big]$$

CTP/Kadanoff-Baym approach to leptogenesis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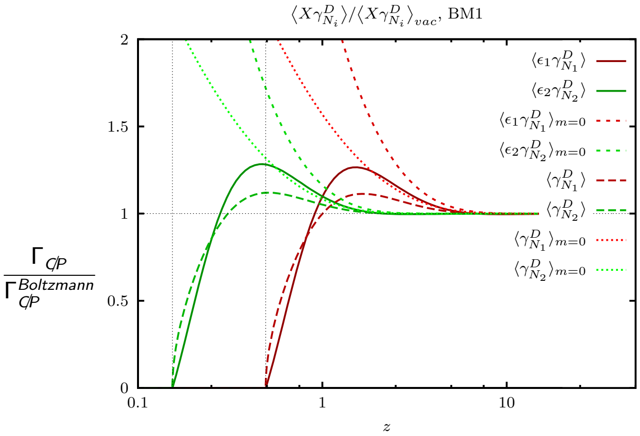
$\ell\phi^\dagger \leftrightarrow \ell^c\phi$		s $\times$ t	s $\times$ s, t $\times$ t

- unified description of CP-violating decay, inverse decay, scattering
- no need for real intermediate state subtraction
- flavor-covariant by construction, (partial) flavor coherence
- no problems with unstable particles in asymptotic in/out states, finite-width (important for resonant enhancement)

Thermal correction to CP asymmetry

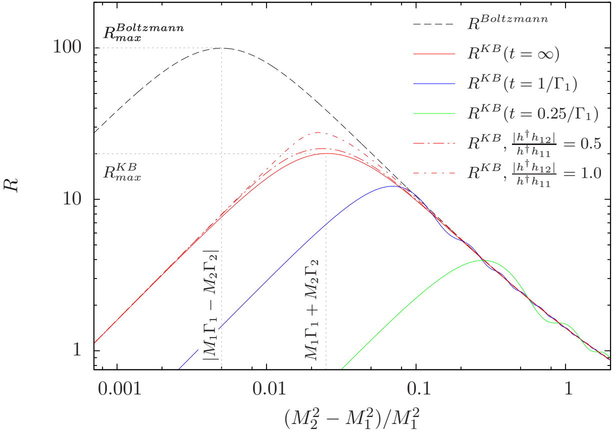


Bose enhancement at $M_N \sim T$, suppression for large T due to thermal masses

Frossard, MG, Hohenegger, Kartavtsev, Mitrouskas 12

Symmetry quantum statistics vs thermal loop corr. important for soft leptogenesis ($\epsilon^{vac} = 0 \quad \Rightarrow \quad \epsilon^{th} = 0$) *Garbrecht, Ramsey-Musolf 13*

Resonant enhancement



$$R^{Boltzmann}_{max} = M_1 M_2/(2|\Gamma_1 M_1 - \Gamma_2 M_2|),\ R^{KB}_{max} \simeq M_1 M_2/(2(\Gamma_1 M_1 + \Gamma_2 M_2))$$

MG, Kartavtsev, Hohenegger Annals Phys. 328 (2013) 26

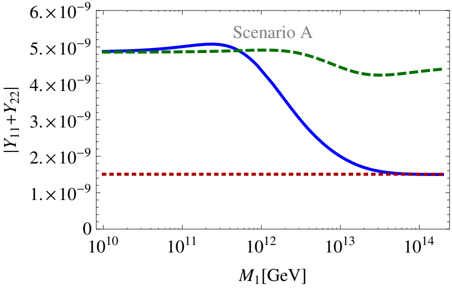
related works: Iso, Shimada, Yamanaka 1312.7680; Dev, Millington, Pilaftsis, Teresi 1403.1003; Iso Shimada 1404.4806; Garbrecht, Gautier, Klaric 1406.4190

Flavoured leptogenesis

- Effect of charged-lepton Yukawas (flavor effects)

$$\ell_\tau \leftrightarrow \tau_R \phi \quad \text{vs} \quad (h_{1e}\ell_e + h_{1\mu}\ell_\mu + h_{1\tau}\ell_\tau)\phi \leftrightarrow N_1$$

- Unflavoured: $\Gamma_{LR} \ll H \Rightarrow$ project on flavor that couples to N_1
- Flavoured: $\Gamma_{LR} \gg H \Rightarrow$ project on flavor that couples to τ (and $\perp$ or e, μ)



- KB/CTP: matrix-valued, flavor covariant eqs.
- Interpolate between both regimes, off-diagonal comp. important

Garbrecht, Glowna, Schwaller 1303.5498; Beneke, Garbrecht, Fidler, Herranen, Schwaller 1007.4783

Flavoured leptogenesis

Source term $N_1 \to \ell_a \phi \quad (\mathcal{O}(h^4))$

$$S_{ab} = \sum_j \Big[\underbrace{(h_{a1} h^T_{1c} h^*_{cj} h_{jb} - h^*_{b1} h^\dagger_{1c} h_{cj} h^*_{ja})}_{\mathrm{Tr} \propto \epsilon_1} \underbrace{S^{LNV}}_{\propto M_1 M_j} + \underbrace{(h_{a1} h^\dagger_{1c} h_{cj} h_{jb} - h^*_{b1} h^T_{1c} h^*_{cj} h^*_{ja})}_{\mathrm{Tr}=0} \underbrace{S^{LFV}}_{\propto T^2} \Big]$$

Garbrecht, Drewes 12

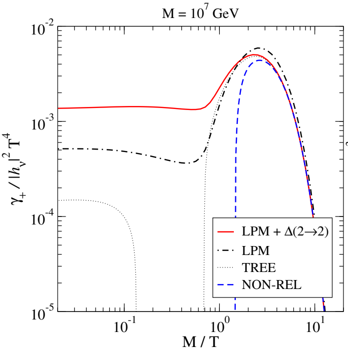
Washout $\ell_a \phi \to N_1$

$$W_{ab} \propto h_{a1} h^\dagger_{1b}$$

- Potentially large effects for ultrarelativistic N's, which decay after sphaleron freeze-out *Garbrecht, Drewes 12, cf. also Pilaftsis et. al. 14*
- Use freedom in h_{ai} to 'hide' asymmetry from washout when $N_{1,2,3}$ have comparable masses $\Rightarrow$ possibility of GeV-scale leptogenesis w/o need for resonant enhancement *Garbrecht, Drewes 14*

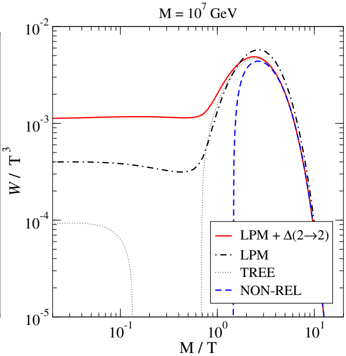
Thermal corrections from SM top/gauge int.

equilibration rate



washout rate

Laine et al 1411.1765



$T \ll M_N$: Important to add virtual and $1 \to 3$ to scatterings, $g^2 \log(g)$ cancel

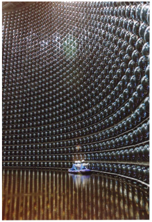
$T \gg M_N$: Rates enhanced by factor ~ 6 (resummation of soft gauge bosons).

cf. also Besak Bodeker 1208.1288; Laine 1307.4909; Garbrecht, Glowna, Herranen 1302.0743; Garbrecht, Glowna, Schwaller 1303.5498

Developments: theory (summary)

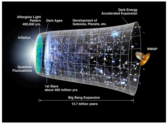
- Systematic approach based on CTP/Kadanoff-Baym
  - Basic mechansim confirmed, quantitative corrections of $\mathcal{O}(1)$
  - Some models are not viable ($\epsilon^{vac} = 0$)
- Resonant enhancement:
  - saturation; decays vs oscillations
  - no extra enhancement in double degenerate limit $M_1 \to M_2, \Gamma_1 \to \Gamma_2$
- Flavor effects:
  - transition between flavored/unflavored $M_N = 10^{12\pm1}, 10^{9\pm1}$GeV
  - finite-T enhancement of flavored asymmetries $\propto (T/M_N)^2$
- Thermal corrections: no thermal blocking
- ...

Leptogenesis

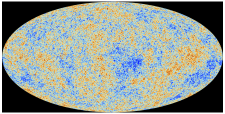


m_ν, θ_{ij}, δ_{CP}

$\leftrightarrow$



$\leftrightarrow$



$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.10 \pm 0.08) \cdot 10^{-10}$$

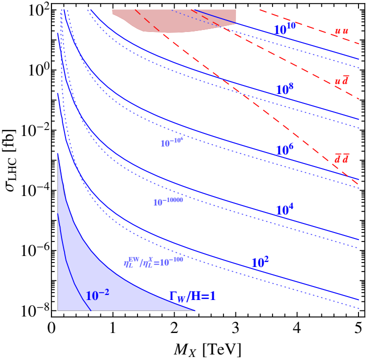
- Theory of leptogenesis
- Testing leptogenesis

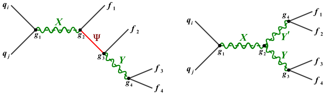
Falsifying high-scale Baryogenesis

Prediction: no LNV beyond Weinberg operator $LLHH/\Lambda$. Observation of additional LNV would imply washout of lepton/baryon asymmetry at $T \gtrsim T_{ew}$.

Falsifying high-scale Baryogenesis

Prediction: no LNV beyond Weinberg operator $LLHH/\Lambda$. Observation of additional LNV would imply washout of lepton/baryon asymmetry at $T \gtrsim T_{ew}$.
E.g. at LHC ($pp \to X \to \ell^\pm \ell^\pm jj$) *Deppisch, Harz 1408.5351, 1312.4447* → talk by J. Harz





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

Falsifying high-scale Baryogenesis

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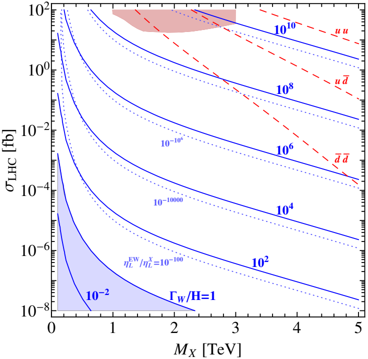
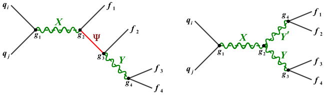


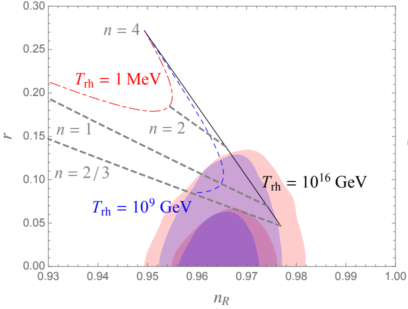


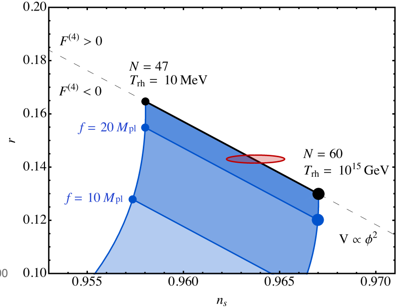
$$\log_{10}\frac{\Gamma_W}{H} \gtrsim 6.9 + 0.6\left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\rm LHC}}{\text{fb}}$$

Similar argument for $0\nu\beta\beta$ *Deppisch, Harz, Huang, Hirsch, Päs 1503.04825* and W_R *Hambye+ 08*; does not apply to EW-scale scenarios ($W_R > 3\,$TeV *Dev, Mohapatra, 1408.2820*); loop-hole τ-flavor if no LFV observed

High-scale baryogenesis and inflation

- Preference for larger n_s for higher T_R ($n_s - 1 \propto -1/N$) for generic slow-roll models, dependence on EoS during reheating and inflaton potential





Creminelli, Nacir, Simonovic, Trevisan, Zaldarriaga 14; Dai, Kamionkowski, Wang 14; Gong, Leung, Pi 15

- Non-thermal leptogenesis (via Higgs-oscillations after inflation *Kusenko+ 15*; $U(1)_{B-L}$ phase transition *Buchmüller, Domcke, Kamada, Schmitz 13*)

EW-scale Leptogenesis (resonant)

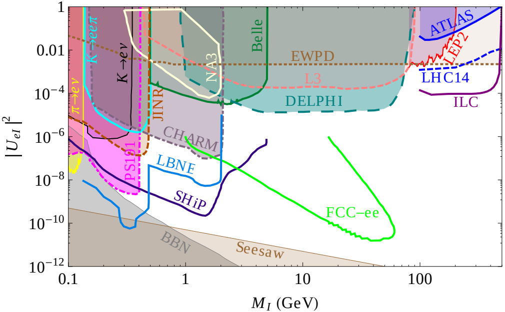
- Leptogenesis for $M_N < 10^9\text{GeV}$ with resonant enhancement
- Generically tiny Yukawa couplings $\Rightarrow$ difficult
- RG-induced splitting is not enough *Dev, Milington, Pilaftsis, Teresi 1504.07640*
- Testable in specific regions of parameter space (hide asymmetry in L_τ, stronger coupling to e, μ compatible with signal in LFV and LNV)

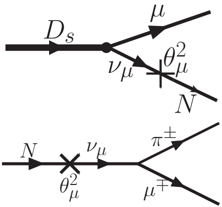
Dev, Milington, Pilaftsis, Teresi 1404.1003

$\rightarrow$ talk by B. Dev

Low-scale Leptogenesis

- Leptogenesis with GeV-scale RH neutrinos via resonant or thermal enhancement
- Search for active-sterile mixing $\theta^2 = U^2 \sim v^2 h^2 / M_N^2$
- Beam-dump (SHiP) $D \to \ell N$, $N \to \pi^{\pm} \ell^{\mp}$
- $Z \to N\nu$ with displaced vertex ($M_N < 45\text{GeV}$) or off-shell





Seesaw: $U^2 \gtrsim \mathcal{O}(m_\nu / M_N)$

Leptogenesis: $U^2 \lesssim \begin{cases} 10^{-6..8} & N = 2,\ \text{resonant enh. } (\nu\text{MSM}) \\ 10^{-4..5} & N = 3,\ \text{thermal enh.} \end{cases}$

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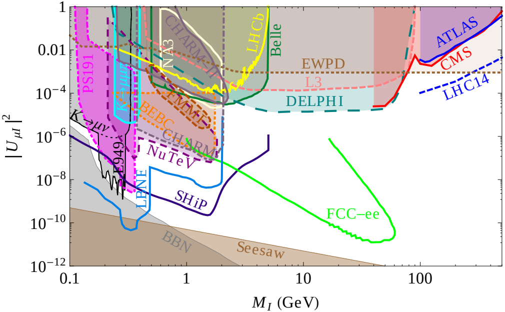

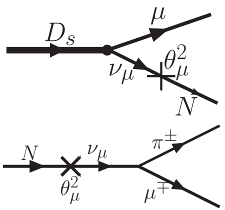

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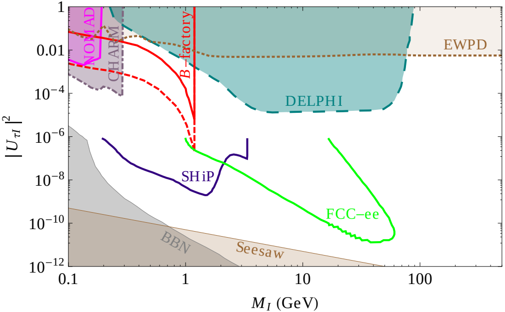

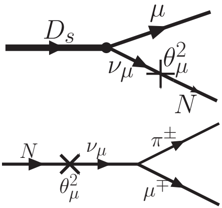

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Conclusion

- Lots of progress in theory of leptogenesis, both on qualitative and quantitative level
- So far all measurements are consistent with expectations for typical leptogenesis scenarios (no low-energy LNV beyond Weinberg, sub-eV neutrino masses, large reheating temp.)
- Observation of $0\nu\beta\beta$ compatible with $\sum m_\nu$ [or primordial tensors r or $n_s \gtrsim 0.965$] would strengthen the generic leptogenesis scenario; observation of LNV at LHC or non-standard $0\nu\beta\beta$ would falsify it
- Specific scenarios can be tested (low-scale leptogenesis via resonant (SHiP) or thermal enhancement (LHCb))

Hierarchical limit

$$
\begin{aligned}
\partial_t n_L^{KB} &= 16\pi\epsilon_1 \int_{\mathbf{p},\mathbf{q},\mathbf{q'},\mathbf{k},\mathbf{k'}} \frac{k\cdot k'}{M_1}(2\pi)^3\delta(p-k-q)(2\pi)^3\delta(p-k'-q') \\
&\quad \times \mathrm{Re}\,\frac{\Gamma_{\ell\phi}}{(\omega_p-k-q)^2+\Gamma_{\ell\phi}^2/4}\,\frac{\Gamma_{\ell\phi}}{(\omega_p-k'-q')^2+\Gamma_{\ell\phi}^2/4} \\
&\quad \times (f_{N_1}(p)-f_{N_1}^{eq}(p))(1-f_\ell(k)+f_\phi(q))(1-f_\ell(k')+f_\phi(q')) \\
\partial_t n_L^{Boltzmann} &= 16\pi\epsilon_1 \int_{\mathbf{p},\mathbf{q},\mathbf{q'},\mathbf{k},\mathbf{k'}} \frac{k\cdot k'}{M_1}(2\pi)^4\delta(p-k-q)(2\pi)^4\delta(p-k'-q') \\
&\quad \times 2\pi\delta(\omega_p-k_0-q_0)\,2\pi\delta(\omega_p-k_0'-q_0') \\
&\quad \times (f_{N_1}(p)-f_{N_1}^{eq}(p))(1-f_\ell(k)+f_\phi(q))
\end{aligned}
$$

The 'width' of lepton and Higgs $\Gamma_{\ell\phi}=\Gamma_\ell+\Gamma_\phi$ leads to a replacement of the on-shell delta function in the Boltzmann equations by a Breit-Wigner curve

MG, Kartavtsev, Hohenegger, Lindner 09; Beneke, Garbrecht, Herranen, Schwaller 10; Anisimov, Buchmüller, Drewes, Mendizabal 11

Hierarchical limit

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$$\times(f_{N_1}(p)-f_{N_1}^{eq}(p))(1-f_\ell(k)+f_\phi(q))(1-f_\ell(k')+f_\phi(q'))$$

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Thermal correction to loop in CP asymmetry, comparable to quantum statistical corrections

MG, Kartavtsev, Hohenegger, Lindner 09; Beneke, Garbrecht, Herranen, Schwaller 10; Anisimov, Buchmüller, Drewes, Mendizabal 11

Degenerate case

Analytical result for $\mathrm{Re}(h^\dagger h)_{12} \ll (h^\dagger h)_{ii}$ (mass basis $\sim$ 'int. basis')

$$n_L(t) = \frac{\mathrm{Im}[(h^\dagger h)_{12}^2]}{8\pi} \frac{M_1 M_2 (M_2^2 - M_1^2)}{(M_2^2 - M_1^2)^2 + (M_1\Gamma_1 - M_2\Gamma_2)^2} \int \frac{d^3p\, d^3q\, d^3k}{(2\pi)^9\, \omega_p\, 2q\, 2k}\, 4k\cdot p$$
$$\times (2\pi)^3 \delta(\mathbf{p} - \mathbf{k} - \mathbf{q}) \frac{\Gamma_{\ell\phi}}{(\omega_p - k - q)^2 + \Gamma_{\ell\phi}^2/4} (1 + f_\phi - f_\ell) f_{FD}(\omega_p)$$
$$\times \left[\sum_{l=1,2} \frac{1 - e^{-\Gamma_{pl} t}}{\Gamma_{pl}} - 4\,\mathrm{Re}\left(\frac{1 - e^{-i(\omega_{p1} - \omega_{p2})t} e^{-(\Gamma_{p1} + \Gamma_{p2})t/2}}{\Gamma_{p1} + \Gamma_{p2} + 2i(\omega_{p1} - \omega_{p2})} \right) \right]$$

$$n_L^{Boltzmann}(t) = \frac{\mathrm{Im}[(h^\dagger h)_{12}^2]}{8\pi} \frac{M_1 M_2 (M_2^2 - M_1^2)}{(M_2^2 - M_1^2)^2 + (M_1\Gamma_1 - M_2\Gamma_2)^2} \int \frac{d^3p\, d^3q\, d^3k}{(2\pi)^9\, \omega_p\, 2q\, 2k}\, 4k\cdot p$$
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- Regulator $M_1\Gamma_1 - M_2\Gamma_2$ is confirmed

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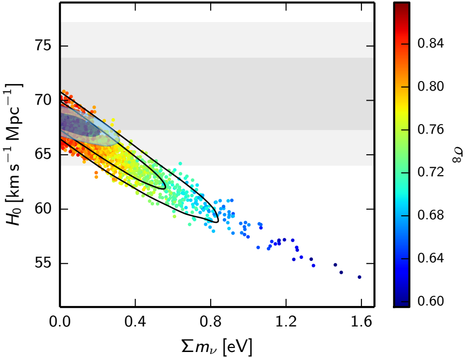
\end{aligned}
$$

- Regulator $M_1\Gamma_1 - M_2\Gamma_2$ is confirmed
- Additional oscillating contribution due to coherent N_1—N_2 transitions

Neutrino mass



Planck 1502.01589