Testing the seesaw mechanism and leptogenesis at future accelerator-based experiments

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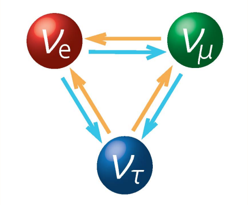
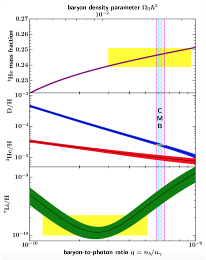
Based on collaboration with M. Drewes, J. Klarić and A. Wendels
arXiv:2407.13620

6$^{\text{th}}$ New Physics Opportunities at Neutrino Facilities Workshop
May 27, 2026

Right-handed neutrinos

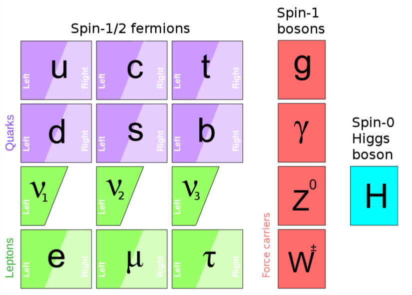


Neutrino oscillations/masses



[Particle Data Group]

Baryon asymmetry



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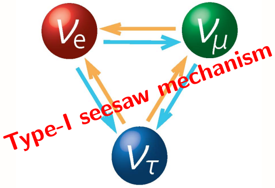

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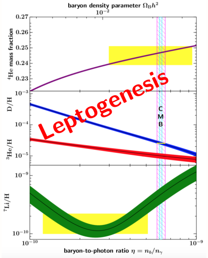

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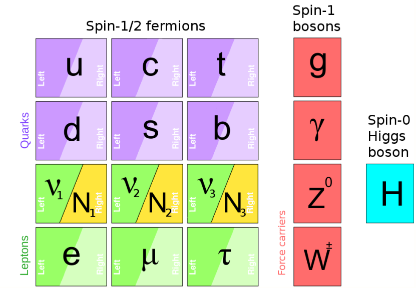


Type-I seesaw mechanism

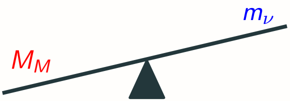
Type-I seesaw Lagrangian

$$\mathcal{L} \supset \; Y_{\alpha i} (\bar{\ell}_\alpha \tilde{\phi}) \nu_{Ri} + \frac{1}{2} \bar{\nu}^c_{Ri} (M_M)_{ij} \nu_{Rj} + \text{h.c.}$$

Yukawa **Majorana**

Seesaw relation

$$m_\nu = -v^2 \left(Y \cdot \, M_M{}^{-1} \cdot Y^t \right)$$



$$\nu \simeq U^\dagger_\nu (\nu_L - \theta \nu^c_R) + \text{h.c.}$$

Light neutrinos

$$N \simeq U^\dagger_N (\nu_R + \theta^t \nu^c_L) + \text{h.c.}$$

Heavy neutrinos (HNL)

Type-I seesaw mechanism

Type-I seesaw Lagrangian (below EWSB)

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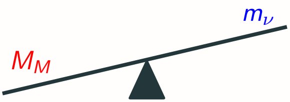

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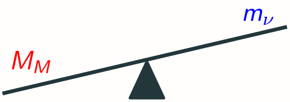

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Heavy neutrinos (HNL)

- $n \geq 2$ HNL generations needed to explain light neutrino masses
  - What is our prior on n?
    - $n = 2$: Minimality (νMSM)
    - $n = 3$: Flavour symmetries, gauge extensions (LRSM,...)

Leptogenesis

Sakharov conditions:

- ⋆ C- and CP-violation
- ⋆ Deviation from thermal equilibrium
- ⋆ Baryon number violation

Leptogenesis

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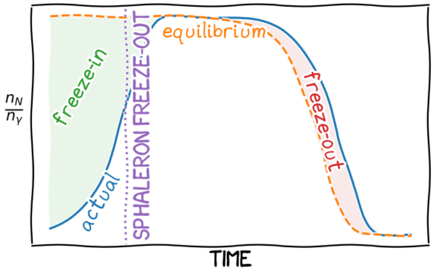

[Klariċ/Shaposhnikov/Timiryasov, 2103.16545]

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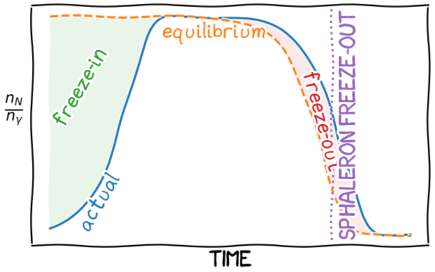

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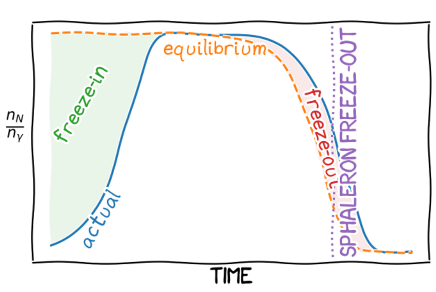
- ⋆ Baryon number violation
  - · Weak sphaleron process

Efficient for 130 GeV $\lesssim T \lesssim 10^{12}$ GeV



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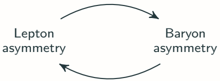

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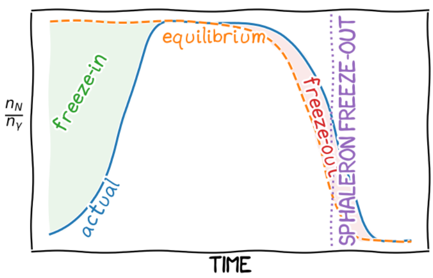

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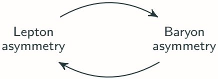

Thermal leptogenesis

[Fukugita/Yanagida '86]

Leptogenesis

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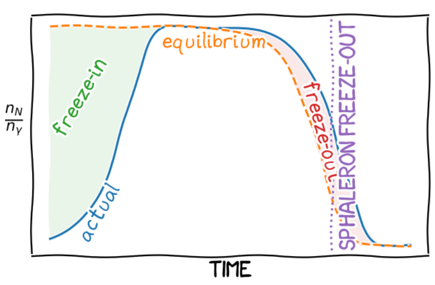

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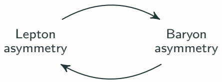
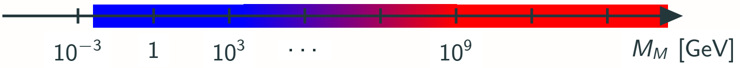
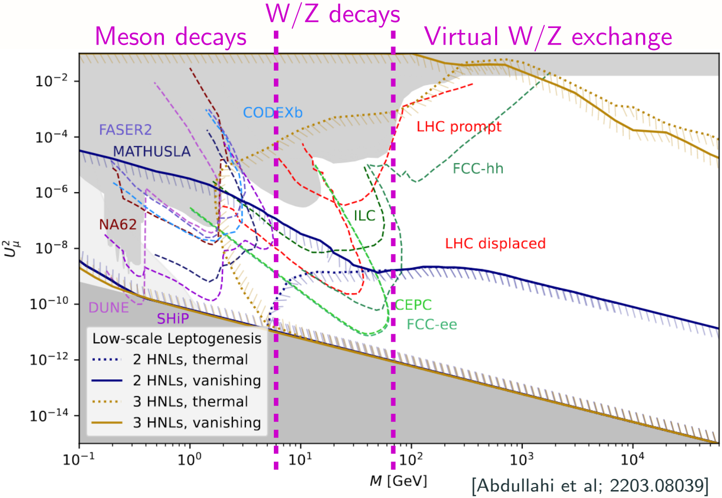




Low-scale leptogenesis
[Akhmedov/Rubakov/Smirnov '98, Pilaftsis/Underwood '03, Asaka/Shaposhnikov '05, ...]

Thermal leptogenesis
[Fukugita/Yanagida '86]

Probing the seesaw mechanism and leptogenesis



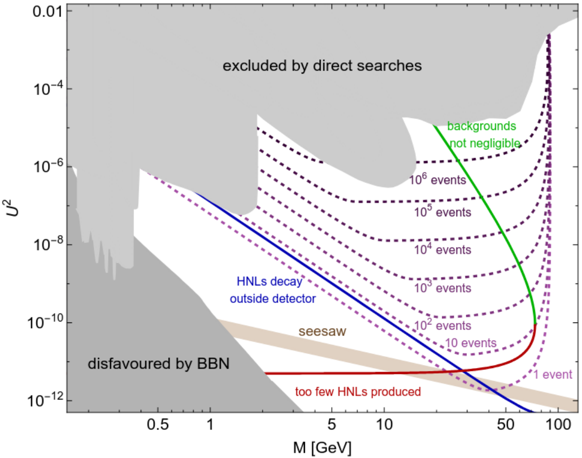
[Abdullahi et al; 2203.08039]

$n = 2$ lines from [Klarić/Shaposhnikov/Timiryasov, 2103.16545]

$n = 3$ lines from [Drewes/YG/Klarić; 2106.16226]

- Can potentially produce enough HNLs to test the seesaw mechanism and leptogenesis!

Potential number of events at FCC-ee



[Drewes/Klarić/Li; 2511.23461]

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Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$Y = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} \mathcal{R} \sqrt{M_M}$$

n=2	n=3
2 CP-violating phases	**3 CP-violating phases**
3 PMNS angles (3/3 fixed)	**3 PMNS angles** (3/3 fixed)
2 light neutrino masses (2/2 fixed)	**3 light neutrino masses** (2/3 fixed)
1 complex Euler angle	**3 complex Euler angles**
2 Majorana masses	**3 Majorana masses**
6 free parameters	13 free parameters

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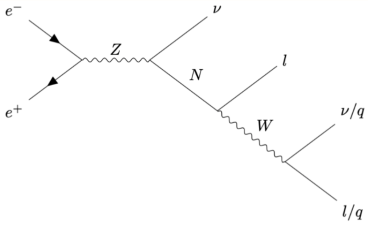
How much can we constrain the remaining parameters?

Constraining model parameters from collider observables

- Flavour composition of semileptonic decays gives information on the flavour ratios $U^2_{\alpha i}/U^2$ & seesaw parameters!



[Credit: Lovisa Rygaard]

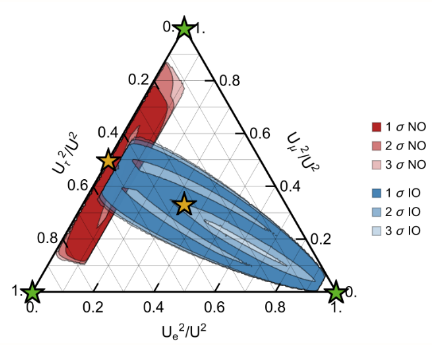
- Number of events governed by

$$\epsilon \sim e^{-2\gamma} \sim \frac{U^2}{m_\nu/\bar{M}}$$

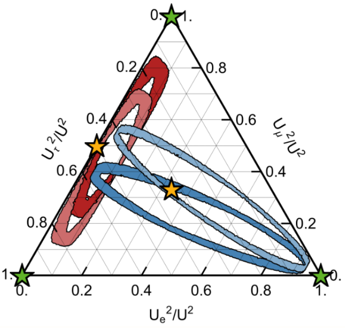
- For $n = 2$, $U^2_{\alpha i} \sim \mathcal{O}(1/\epsilon) + \mathcal{O}(1) + \ldots$
- For $n = 3$, $U^2_{\alpha i} \sim \mathcal{O}(1/\epsilon) + \mathcal{O}(1/\sqrt{\epsilon}) + \mathcal{O}(1) + \ldots$

$\Longrightarrow$ Better parameter reconstruction (partly) compensates the larger dimensionality!

Impact of low energy measurements on $\frac{U_\alpha^2}{U^2}$



Current ν oscillation data



DUNE projections

[Drewes/Klaric/Lopez-Pavon, '22]

- DUNE measurement of δ could constrain the mixing to each SM flavour, hence leptogenesis

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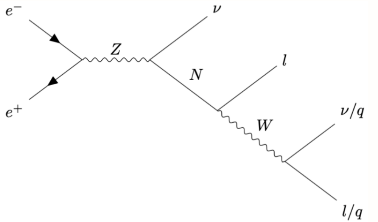

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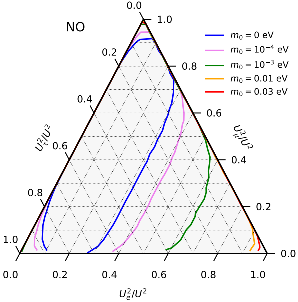
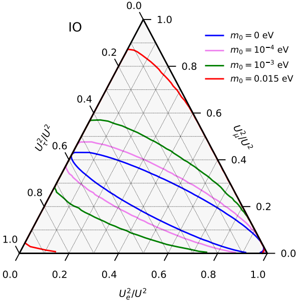
Constraining m_0



Normal ordering



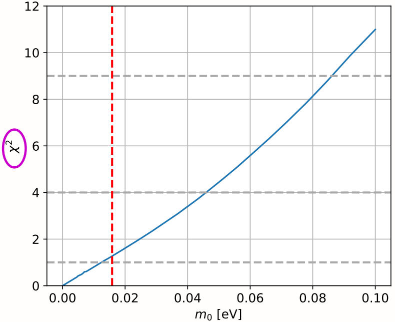
Inverted ordering

[Drewes/YG/Klarić/Wendels; 2407.13620]

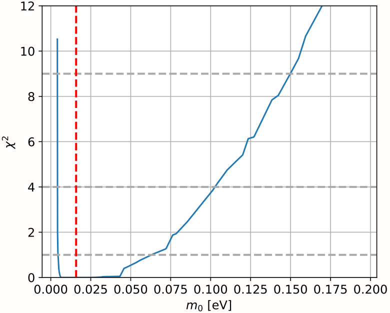
- For optimistic scenarios ($\sim 10^5$ events at FCC-ee), can measure flavour ratios $\frac{U_\alpha^2}{U^2}$ at percent level!
- Can give a hint on value of m_0!

Constraining m_0

Idealised detector
Only statistical uncertainty
Based on number of events



$m_0 = 0$ eV



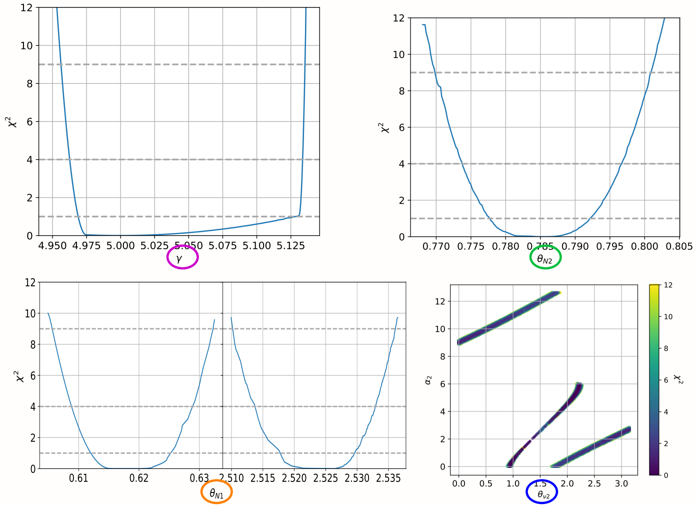
$m_0 = 0.01$ eV

[Drewes/YG/Klarić/Wendels; 2407.13620]

- Constraints on m_0 will not match Planck but better than KATRIN (though more indirect + model dependent): Complementarity!
- Can exclude $m_0 = 0$ if flavour ratios outside typical $m_0 = 0$ region.

Constraining model parameters from collider observables

$$Y = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} R_{13}(\theta_{\nu 2}) R_{23}(\theta_{\nu 1}) R_{12}(\omega + i\gamma) R_{23}(\theta_{N1}) R_{13}(\theta_{N2}) \sqrt{M_M}$$



[Drewes/YG/Klarić/Wendels; 2407.13620]

Discrete flavour symmetries

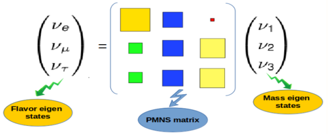
- Discrete symmetries provide dynamical origin to ν mixing pattern

$G_f \times$ CP

G_l - - - - - - → ← - - - $G_\nu \times$ CP

Charged lepton sector

[Credits: Newton Nath]



Neutrino sector

Discrete flavour symmetries

- Discrete symmetries provide dynamical origin to ν mixing pattern

$$\Delta(6n^2)\times \mathrm{CP} \sim ((\mathcal{Z}_n \times \mathcal{Z}_n) \rtimes \mathcal{S}_3) \times \mathrm{CP}$$

$\mathcal{Z}_3$ - - - - - →

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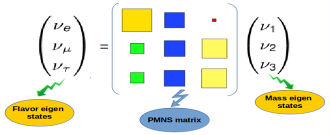


← - - - $\mathcal{Z}_2\times \mathrm{CP}$

Neutrino sector

In our setup

- 13 → 6 or 7 free parameters: For Case 1),

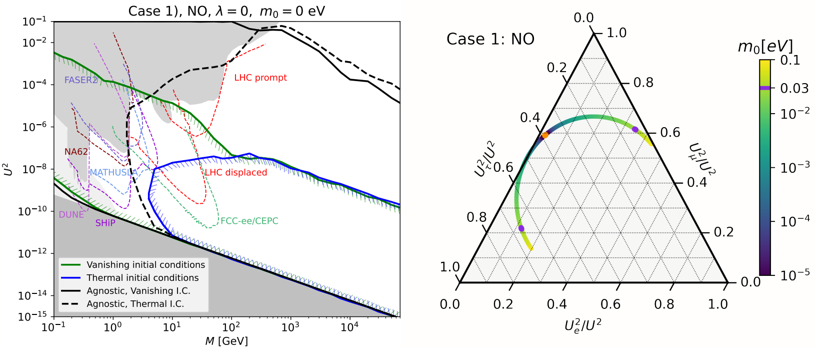
$$m_0,\ M_1 \approx M_2 \approx M_3,\ \theta_R,\ \phi_s.$$

⟶ Better analytical understanding of the parameter space.

- Can relate low- and high-scale parameters. For Case 1):

$$\sin(\delta) = 0,\ |\sin(\alpha)| = |\sin(6\phi_s)|,\ \sin(\beta) = 0.$$

- Flavour symmetries have reduced parameter space but highly predictive!



[Drewes/YG/Hagedorn/Klarić; 2412.10254]

What should I take home?

- Right-handed neutrinos provide minimal solution for ν masses + baryon asymmetry
- Large mixing angle opens up the possibility of testing leptogenesis by combining information from colliders, $0\nu\beta\beta$, ν oscillations, ...
- In particular, future lepton colliders can act as discovery and precision machines in one
- Combined with flavour symmetric explanation of PMNS: very predictive!
- Similar analysis can be done for DUNE, SHiP, ... but more intricate.

Thanks for your attention!
ご清聴ありがとうございました。

Appendix

How to reach large coupling? B-L approximate symmetry

Naive seesaw bound

$$m_\nu = -v^2 \left(Y \cdot M_M^{-1} \cdot Y^t \right) \Leftrightarrow U_i^2 \sim \frac{m_\nu}{M_i} \sim 10^{-10} \frac{\text{GeV}}{M_i}$$

B-L approximate symmetry

Majorana mass

$$\bar{M} \cdot \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

Yukawa coupling

Pseudo-Dirac pair — Decoupled

$$\begin{pmatrix} y_e(1+\epsilon_e) & iy_e(1-\epsilon_e) & y_e\epsilon'_e \\ y_\mu(1+\epsilon_\mu) & iy_\mu(1-\epsilon_\mu) & y_\mu\epsilon'_\mu \\ y_\tau(1+\epsilon_\tau) & iy_\tau(1-\epsilon_\tau) & y_\tau\epsilon'_\tau \end{pmatrix}$$

Technically natural: Small m_ν from small symmetry breaking parameters $\mu, \epsilon, \epsilon' \ll 1$

Consistent with large production cross-section at colliders $\sigma \propto U^2$.

Low-scale models

- Traditionally, 2 main mechanisms:

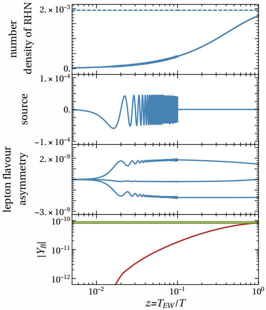
ARS Leptogenesis

Asymmetry produced during freeze-in from CP-violating HNL oscillations

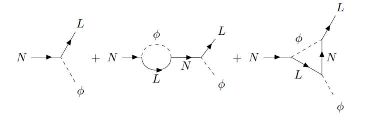
$\overset{?}{\longleftrightarrow}$

Resonant leptogenesis

Resonant enhancement of CP-violation from small mass splittings



[Drewes/Garbrecht/Gueter/Klarić; 1606.06690]



Decay asymmetry:

$$\epsilon_i \simeq \frac{\mathrm{Im}(Y^\dagger Y)^2_{ij}}{(Y^\dagger Y)_{ii}(Y^\dagger Y)_{jj}} \frac{(M^2_{N_i}-M^2_{N_j})\cdot M_{N_i}\Gamma_N}{(M^2_{N_i}-M^2_{N_j})^2+M^2_{N_i}\Gamma^2_N}$$

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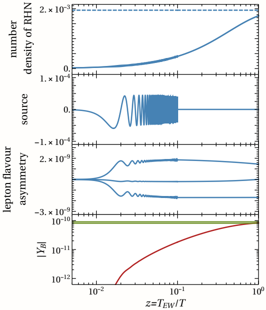

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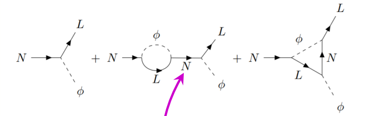

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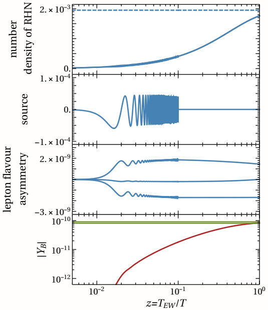
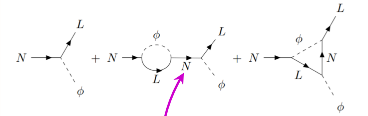


[Drewes/Garbrecht/Gueter/Klarić; 1606.06690]



Decay asymmetry:

$$\epsilon_i \simeq \frac{\mathrm{Im}(Y^\dagger Y)_{ij}^2}{(Y^\dagger Y)_{ii}(Y^\dagger Y)_{jj}} \frac{(M_{N_i}^2 - M_{N_j}^2)\cdot M_{N_i}\Gamma_N}{(M_{N_i}^2 - M_{N_j}^2)^2 + M_{N_i}^2\Gamma_N^2}$$

$\longrightarrow$ Two regimes of the same mechanism! Represented by the same set of kinetic equations (cfr. [Garbrecht; 1812.02651] for a review)

Quantum kinetic equations

$$i\frac{\mathrm{d}}{\mathrm{d}t}\rho = [H, \delta\rho] - \frac{i}{2}\{\Gamma, \delta\rho\} - i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$i\frac{\mathrm{d}}{\mathrm{d}t}\bar{\rho} = -[H, \delta\bar{\rho}] - \frac{i}{2}\{\Gamma, \delta\bar{\rho}\} + i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$\frac{\mathrm{d}}{\mathrm{d}t} n_{\Delta_a} = -\frac{2i\mu_a}{T}\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3} \mathrm{Tr}[\Gamma_a] f_F(1-f_F) + i\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3} \mathrm{Tr}[\tilde{\Gamma}_a(\delta\bar{\rho} - \delta\rho)].$$

Matrix of densities

Effective Hamiltonian

Lepton asymmetry

Interaction rates

- **Interaction rates** can be
  - ⋆ Fermion number **conserving** $\sim (Y^\dagger Y)T$
  - ⋆ Fermion number **violating** $\sim (Y^t Y^*)\frac{M^2}{T}$
- Refined calculation subject to intensive studies over the last years, e.g. Anisimov/Bedak/Bödeker '10, Garny/Kartavtsev/Hohenegger '11, Drewes/Garbrecht/Gueter/Klarić '16, Hernandez/Kekic/Lopez-Pavon/Racker/Salvado '16, Ghiglieri/Laine '16 '18, Klarić/Shaposhnikov/Timiryasov '21, ...

Quantum kinetic equations

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Washout term

Source term

$$\frac{\mathrm{d}}{\mathrm{d}t} n_{\Delta_a} = -\frac{2i\mu_a}{T}\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3} \mathrm{Tr}[\Gamma_a] f_F(1-f_F) + i\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3} \mathrm{Tr}[\tilde{\Gamma}_a(\delta\bar{\rho} - \delta\rho)],$$

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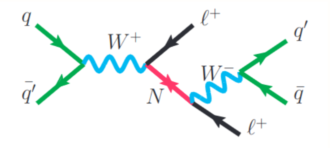
Lepton number violation at colliders

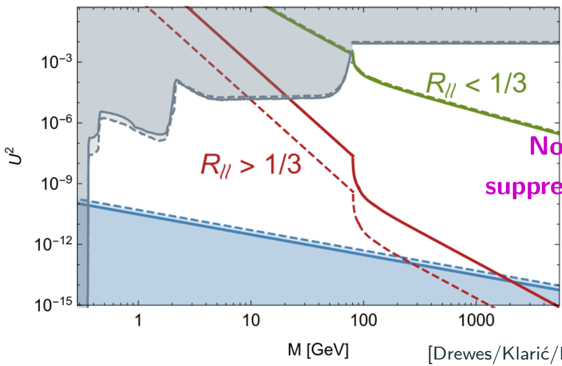


[CMS collaboration; 1806.10905]

- Large U^2 but lepton number conserved if $\mu, \epsilon \to 0$
- Ratio of lepton number violating to conserving decays parametrised by

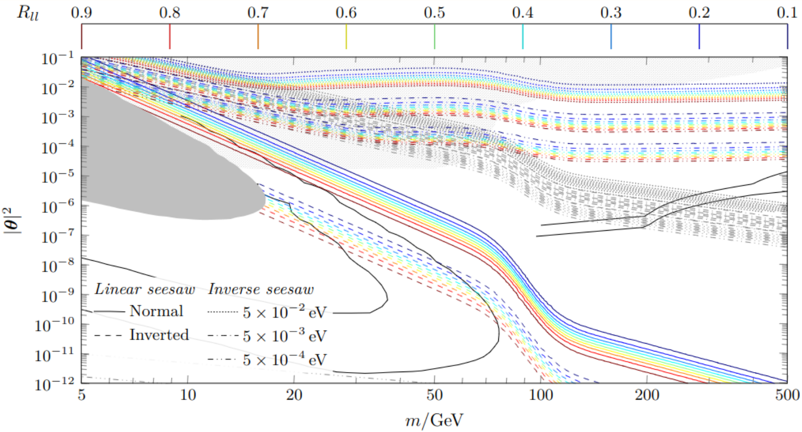
$$R_{ll} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$

Not always strongly suppressed for sizeable U^2!



[Drewes/Klarić/Klose; 1907.13034]

Lepton number violation at colliders

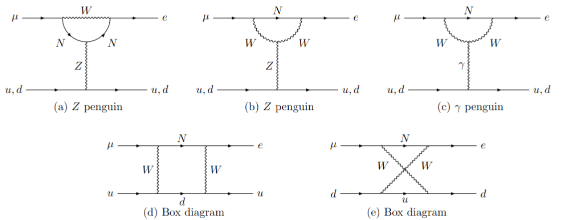


[Antusch/Hajer/Rosskopp, 2307.06208]

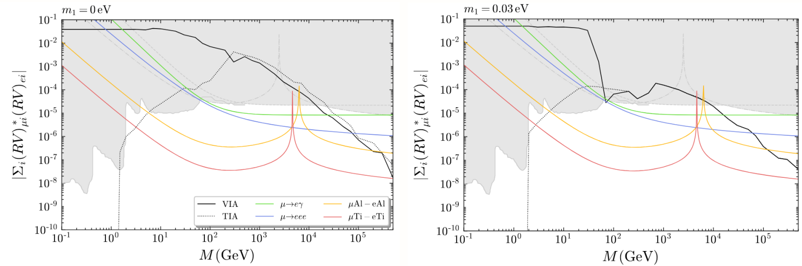
In practice, decoherence effects can make testability prospects even more optimistic!

Testing leptogenesis through CLFV experiments

- HNLs also lead to charge lepton flavour violation.



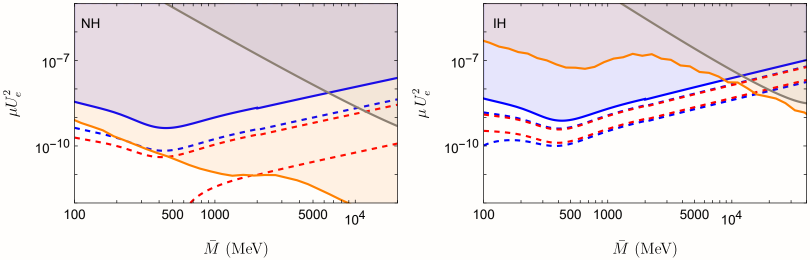
[Urquia-Calderon/Timiryasov/Ruchayskiy; 2206.04540]



[Granelli/Klarić/Petcov; 2206.04342]

$0\nu\beta\beta$ and leptogenesis

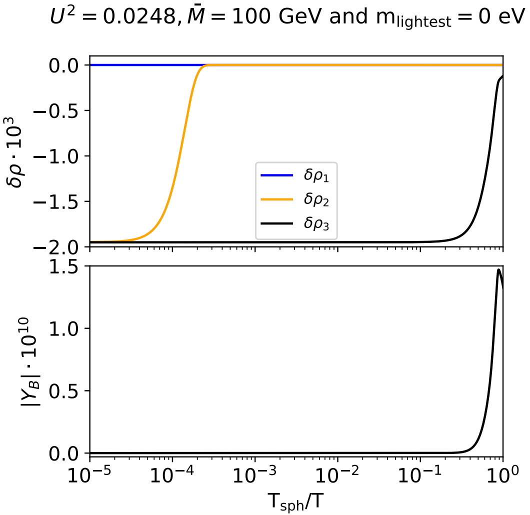
- For $n = 2$:



[de Vries/Drewes/YG/Klarić/Plakkot; 2407.10560]

- For IH, constraints from $0\nu\beta\beta$ stronger for large splitting and $\bar{M} \lesssim 10$ GeV.
- Non-observation of $0\nu\beta\beta$ in the future would severely constrain μU_e^2.

Why such large mixings?



[YG; 2305.06663]

- Large mixing angles allow late equilibration of one HNL $U_i^2 \ll 1$
  $\hookrightarrow$ Late BAU production, less time for washout

CP-violating combinations

- Perturbatively,

$$Y_B \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\, (\delta\rho - \delta\bar{\rho})\right) \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\, [H_N, \Gamma]\right)$$

$$H_N = \frac{M_M^2}{2E} + h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*, \;\; \Gamma, \tilde{\Gamma} = \pm\gamma_+(T) Y^\dagger Y + \gamma_-(T) Y^t Y^*$$

- BAU production governed by

$$C_{\mathrm{LFV},\alpha} = i\,\mathrm{Tr}\left(\left[M_M^2, Y^\dagger Y\right] \, Y^\dagger P_\alpha Y \right),$$

$$C_{\mathrm{LNV},\alpha} = i\,\mathrm{Tr}\left(\left[M_M^2, Y^\dagger Y\right] \, Y^T P_\alpha Y^* \right),$$

$$C_{\mathrm{DEG},\alpha} = i\,\mathrm{Tr}\left(\left[Y^T Y^*, Y^\dagger Y\right] \, Y^T P_\alpha Y^* \right),$$

Flavour violating only ($C_{\mathrm{LFV},\alpha}$)

$\sum_\alpha C_{\mathrm{LFV},\alpha} = 0$

Violates lepton number ($C_{\mathrm{LNV},\alpha}$)

$\sum_\alpha C_{\mathrm{LNV},\alpha} \neq 0$

Flavour violating only, can be $\neq 0$ for $\Delta M = 0$! ($C_{\mathrm{DEG},\alpha}$)

CP-violating combinations

- Perturbatively,

$$Y_B \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ (\delta\rho - \delta\bar{\rho})\right) \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ [H_N, \Gamma]\right)$$

$$H_N = \frac{M_M^2}{2E} + h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*,\ \ \Gamma, \tilde{\Gamma} = \pm\gamma_+(T) Y^\dagger Y + \gamma_-(T) Y^t Y^*$$

- For Case 1) and s odd,

$$C_{\mathrm{LFV},\alpha} \sim \frac{8}{3}\, M^2\, \kappa\, y_2 y_3\, (y_2^2 - y_3^2)\, \sin\theta_{L,\alpha}\, \sin\theta_R\, \cos 3\,\phi_s,$$

$$C_{\mathrm{LNV},\alpha} \sim \frac{8}{3} M^2 \kappa y_2 y_3 \left(y_3^2 \cos(2\theta_R) - y_2^2\right) \sin\theta_{L,\alpha}\, \sin\theta_R\, \cos 3\,\phi_s,$$

$$C_{\mathrm{DEG},\alpha} = 0,$$

where

$$\theta_{L,\alpha} = \theta_L + \rho_\alpha \frac{4\,\pi}{3} \text{ with } \rho_e = 0,\ \rho_\mu = +1,\ \rho_\tau = -1\ .$$

Case 1), BAU vs ϕ_s

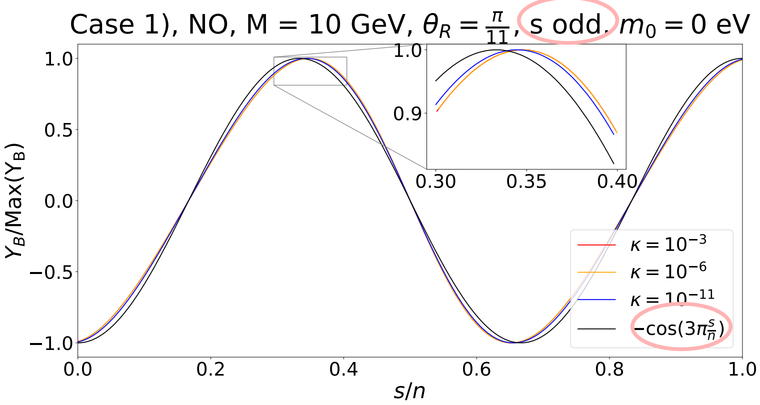


Figure 1: Vanishing initial conditions, $\lambda = 0$

[Drewes/YG/Hagedorn/Klarić; 2203.08538]

- Correlation between Y_B and low-energy observables. Here,

$$\sin(\alpha) = \sin(6\pi\frac{s}{n}).$$

CP-violating combinations

- Perturbatively,

$$Y_B \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha \, (\delta\rho - \delta\bar{\rho})\right) \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha \, [H_N, \Gamma]\right)$$

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$$C_{\mathrm{LNV},\alpha} \sim \frac{8}{3} M^2 \kappa y_2 y_3 \left(y_3^2 \cos(2\theta_R) - y_2^2\right) \sin\theta_{L,\alpha} \, \sin\theta_R \, \sin 3\,\phi_s,$$

$$C_{\mathrm{DEG},\alpha} = 0,$$

where

$$\theta_{L,\alpha} = \theta_L + \rho_\alpha \frac{4\,\pi}{3} \text{ with } \rho_e = 0, \;\; \rho_\mu = +1, \;\; \rho_\tau = -1 \, .$$

Case 1), BAU vs ϕ_s

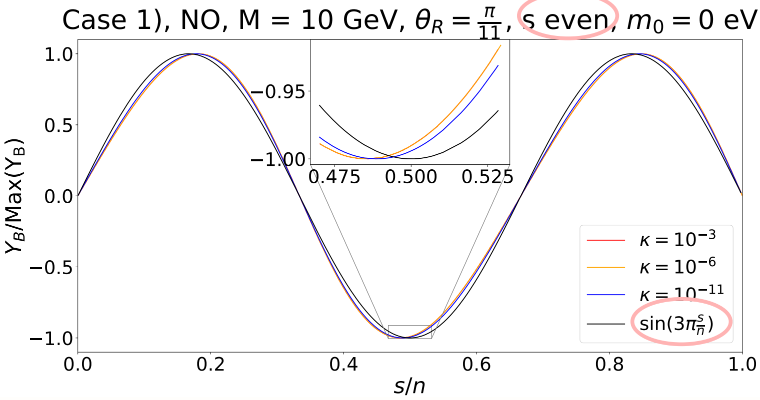

Figure 2: Vanishing initial conditions, $\lambda = 0$

[Drewes/YG/Hagedorn/Klarić; 2203.08538]

- Correlation between Y_B and low-energy observables. Here,

$$\sin(\alpha) = \sin(6\pi\frac{s}{n}).$$