Testing the origin of neutrino masses and baryon asymmetry

Jacobo López-Pavón

New ν Physics: From Colliders to Cosmology 11 April 2025, IPPP (Durham University)









Project CNS2022-136013 funded by MICIU/AEI/10.13039/501100011033 and the European Union NextGenerationEU/PRTRCNS2022-136013



AGENCIA Estatal de Financiado po la Unión Euror



Minimal model: Seesaw Model

• Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_i) to the SM field content:

Minkowski 77; Gell-Mann, Ramond, Slansky 79 Yanagida 79; Mohapatra, Senjanovic 80

Mass Matrix





Minkowski 77; Gell-Mann, Ramond, Slansky 79 Yanagida 79; Mohapatra, Senjanovic 80

Mixing



Non unitary PMNS matrix

• Constraints from EW and CLFV precision data

Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006 Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040 "Direct" Searches

• Sterile neutrino oscillations, kinks in beta decays & peak searches in semileptonic meson decays, beam-dump experiments, colliders...

Current Constraints



ARS Leptogenesis

https://github.com/mhostert/Heavy-Neutrino-Limits Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2304.06772 See also talks by Lyon, Saimpert, Silva, Kretz, Mitra, Lutz and Sfar.

ProtoDUNE in beam dump configuration?



See talk by Jelle Groot for other beam dump searches

North Area & SPS accelerator @CERN



North Area & SPS accelerator @CERN



TT20 transfer line

North Area

Beam

Two kiloton-scale liquid Argon Time Projection Chambers (LArTPCs) constructed to prototype and consolidate the technology of the DUNE Far Detector.

ProtoDUNE in beam dump configuration?



https://indico.cern.ch/event/1460367/contributions/6240613/attachments/3001559/5289608/BSM@protoDUNE_NeutrinoWkshp_Animesh.pdf https://indico.cern.ch/event/1381368/contributions/5963281/attachments/2888251/5062517/molina_LLP2024_2072024_v2.pdf



Constraint on HNL mixing from active sector

 Generation of light neutrino masses imposes constraints on mixing between HNLs and active neutrinos from active neutrino sector







Abdullahi et al 2203.08039 Drewes, Klaric, JLP 2207.02742 Caputo, Hernandez, JLP, Salvado, 1704.08721



DUNE forecast assuming $\delta = -\pi/2$

Abdullahi et al 2203.08039 Drewes, Klaric, JLP 2207.02742



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719 Hernandez, JLP, Rius, Sandner 2207.01651 Hernandez, JLP, Rius, Sandner 2305.14427

Sakharov conditions



Baryon number violation

Sphalerons translate lepton asymmetry into baryon asymmetry.

C and CP violation





New sources of CP violation in lepton sector encoded in the Yukawa couplings (not enough CP in quark sector) (Gavela, Hernandez Orloff, Pene, Quimbay 1994)



Departure from thermal equilibrium

 $\Gamma_N \le H(T) \quad T > T_{EW}$



Low Scale Leptogenesis (ARS)



Baryon asymmetry: flavor structure



• Flavor correlations implied by reproducing observed matter-antimatter asymmetry in the region of parameter space that can be covered by FCC-ee for $\Delta M/M = 10^{-2}$

Hernandez, JLP, Rius, Sandner 2207.01651

Baryon asymmetry: ovbb decay



• Correlation with neutrinoless decay rate implied by reproducing observed baryon asymmetry in region of parameter space that can be probed by SHiP for

$$\Delta M/M = 10^{-2}$$

See also talk by Vaisakh Plakkot and Jelle Groot

Predicting Y_B in minimal model $n_R=2$

• Baryon asymmetry depends on all the unknown parameters

SHiP & FCC-ee sensitive to $|\theta_{\alpha}|, M, \Delta M$ $(\theta_{\alpha})^2 \propto e^{-i\beta} y^2 f(\delta, \phi, M, \Delta M)$ Neutrinoless double beta decay sensitive to β through interference between light and heavy contribution Non physical phase if HNLs are degenerate

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Simplest scenario: degenerate HNLs

• Measurement of CP violation in neutrino oscillations, HNL mass and mixing with electron, muon and tau flavours can suffice to pin down matter-antimatter asymmetry.



	$M^{\rm true}/{\rm GeV}$	$(U_e^2)_{\rm true}$	$(U^2_\mu)_{ m true}$	$(U_{ au}^2)_{ m true}$	$\delta^{\rm true}/{\rm rad}$
NH	31.60	2.843×10^{-12}	1.087×10^{-11}	1.234×10^{-11}	5.396
IH	20.731	3.291×10^{-11}	4.823×10^{-12}	3.465×10^{-12}	5.402

FCC-ee +	DUNE/T2HK
----------	-----------

Hernandez, JLP, Rius, Sandner 2305.14427

Conclusions

- Introducing HNLs allows to explain the origin of neutrino masses and baryon asymmetry of our universe
- Low Scale Minimal Seesaw Models are testable and highly predictive: mechanisms generating neutrino masses and Baryon asymmetry can be potentially tested
- Strong complementarity among different observables as neutrino oscillations, cosmology, neutrinoless double beta decay and HNLs direct searches.
- In non minimal models HNLs may present new interactions and thus a different phenomenology (Left-Right symmetric models, dark U(1) extensions, etc).
 See also talks by Ruiz, Groot, Mitra and Lutz
- Low energy effects of additional new physics at higher energies can be studied via an extension of the SMEFT including the HNLs as building blocks
 Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040
 See also talks by Titov and Bates

Thank you!

H

<u>n</u> 1 . III 🤅



Potentially Testable $N_R=2$



Potentially Testable $N_R=3$



Abada, Arcadi, Domcke, Drewes, Klaric, Lucente 1810.12463

Neutrino oscillation bounds on Flavor structure



Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

Direct searches of HNLs

• Direct detection requires:

$$\theta_{\alpha i} \gg \sqrt{m/M} \, \overleftrightarrow \, R_{ij} \gg 1$$
$$\longleftrightarrow \, \theta_{\alpha i}^2 \propto e^{-2\theta i} e^{2\gamma} f\left(\delta, \phi_1, M_j\right)$$

$$\begin{split} \bullet & |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 \simeq \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 = \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 2}|^2 = \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 1}|^2 = \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e2}|^2 / |\theta_{\mu 1}|^2 = \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = \\ & \bullet |\theta_{e1}|^2 / |\theta_{\mu 1}|^2 = \\ & \bullet$$

PMNS CP-phases from HNLs searches



Potential determination of the PMNS Majorana phase!

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719 Caputo, Hernandez, Kekic, JLP, Salvado 1611.05000

Baryon asymmetry: PMNS CP phases



- PMNS CP-phase correlations implied by reproducing observed baryon asymmetry in region of parameter space that can be covered by FCC-ee for $\Delta M/M = 10^{-2}$

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

Constraint on HNL mixing from active sector $W_{1\alpha}$ V_{α} V_{α}



Neutrinoless double beta decay



Predicting Y_B in minimal model $n_R=2$

• Neutrinoless double beta decay effective mass in the IH case



JLP, Pascoli, Wong 2012



Leptogenesis in Minimal Model n_R=2

Non very degenerate solutions



Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Neutrinoless double beta decay signal?



• Outstanding complementarity among neutrino oscillations, $0\nu\beta\beta$ decay and cosmology.

• Extremely relevant input in order to probe New Physics models responsible for ν mass generation.

Posibilities:

- Dominated by New Physics as HNL contribution

- Cosmological bound could be relaxed. For instance, if neutrinos decay (new interactions required) Escudero, JLP, Rius, **Sandner** 2007.04994
Simplest scenario: degenerate HNLs

• Measurement of CP violation in neutrino oscillations, HNL mass and mixing with electron, muon and tau flavours can suffice to pin down matter-antimatter asymmetry.



	$M^{\rm true}/{\rm GeV}$	$(U_e^2)_{\rm true}$	$(U^2_\mu)_{ m true}$	$(U_{\tau}^2)_{\rm true}$	$\delta^{\rm true}/{\rm rad}$
NH	31.60	2.843×10^{-12}	1.087×10^{-11}	1.234×10^{-11}	5.396
IH	20.731	3.291×10^{-11}	4.823×10^{-12}	3.465×10^{-12}	5.402

FCC-ee

Hernandez, JLP, Rius, Sandner 2305.14427

Minimal Model with approximated LNC

$$M_{\nu} = \begin{pmatrix} \overline{\nu}^{c} & \overline{N}_{1} & \overline{N}_{2} \\ 1 & -1 & 1 & L \\ 0 & Y_{1}^{T} v / \sqrt{2} & \epsilon Y_{2}^{T} v / \sqrt{2} \\ Y_{1} v / \sqrt{2} & \mu' & M \\ \epsilon Y_{2} v / \sqrt{2} & M & \mu \end{pmatrix} \begin{pmatrix} 1 & \nu \\ -1 & N_{1}^{c} \\ 1 & N_{2}^{c} \end{pmatrix}$$

Light nu masses suppressed with LNV parameters

$$m_{\nu} = \mu \frac{v^2}{2M^2} Y_1^T Y_1 + \frac{v^2}{2M} \epsilon Y_2^T Y_1 + \frac{v^2}{2M} Y_1^T \epsilon Y_2$$

• Quasi-Dirac heavy neutrinos with large mixing:

 $M_2 \approx M_1 \approx M$ $\Delta M \approx \mu' + \mu$ $U_{\nu N} \sim Y_1 v / M$

Beam dump configuration

North area EHN1 Neutrino Platform



 $l_{det} \sim 700 \, m$

- Proton energy: 400 GeV (instead of 80-120 GeV as in neutrino experiments)
- ~5-7x10¹² protons/spill with a spill duration of 4.8 s \rightarrow 3-5x10¹⁸PoT/year
- No decay volume
- *ProtoDUNE detectors:* Liquid Argon Time Projection Chambers with large fiducial volume and excellent imaging capabilities to identify decay products
- Detectors at the surface.

Production



From Pythia **S.Urrea**

• Implementation of heavy meson production? Production of BSM particles fom D decays extremely relevant.

Time Scale & Statistics

 In our pheno analysis we assume 5 years of data taking and 3.5x10¹⁸PoT/year (~5-7x10¹² protons/spill with a spill duration of 4.8 s). This could be done before LS4.







Shutdown/Technical stop Protons physics Ions Commissioning with beam Hardware commissioning unless otherwise stated, results obtained considering **Background Free** scenario

Last update: November 24

HNL decays







1) LLPs: Heavy Neutral Leptons

HNLs arising in low-scale seesaw models can accommodate **the origin of neutrino masses** and **baryon asymmetry**



$$\mathcal{L} \supset -\frac{m_W}{v} \overline{N} U^*_{\alpha 4} \gamma^{\mu} l_{L\alpha} W^+_{\mu} - \frac{m_Z}{\sqrt{2}v} \overline{N} U^*_{\alpha 4} \gamma^{\mu} \nu_{L\alpha} Z_{\mu}$$

Parent	2-body dec	ay 3-body decay	Parent	2-body decay	3-body decay
$\pi^+ \rightarrow$	e^+N_4		$D^+ \rightarrow$	e^+N_4	$e^+\overline{K^0}N_4$
	$\mu^+ N_4$	NEW		$\mu^+ N_4$	$\mu^+ \overline{K^0} N_4$
$K^+ \rightarrow$	e^+N_4	$\pi^0 e^+ N_4$		$ au^+ N_4$	
	$\mu^+ N_4$	$\pi^0 \mu^+ N_4$	$D_s^+ \rightarrow$	e^+N_4	
$\tau^- \rightarrow$	$\pi^- N_4$	$e^-\overline{\nu}N_4$		$\mu^+ N_4$	
	$ ho^- N_4$	$\mu^-\overline{ u}N_4$		$\tau^+ N_4$	

HNL production branching ratios and decay widths from Coloma et al. 2007.03701

Work in progress: courtesy of S. Urrea

 A Geant4 implementation of the target, dump, and magnets has been used to validate our results and compute the possible neutrino flux and HNL signal.



More details in:

https://indico.cern.ch/event/1460367/contributions/6240613/attachments/3001559/5289608/BSM@protoDUNE_NeutrinoWkshp_Animesh.pdf https://indico.cern.ch/event/1381368/contributions/5963281/attachments/2888251/5062517/molina_LLP2024_2072024_v2.pdf

H. Sieber, J. Hernandez Garcia, C. Hasnip, J. Martin-Albo, P. Sajitha, L. Molina Bueno, S. Urrea

J. Hernández-García, S. Urrea



1) LLPs: Heavy Neutral Leptons

HNLs arising in low-scale seesaw models can accommodate the origin of neutrino masses and baryon asymmetry



No background considered for any of the lines. We need a realistic background estimation.

2) Stable Particles: Millicharged Particles



 χe^{-} scattering

Detector

 Millicharged particles (MCPs): fermions with an effective charge eε, arising from the mixing of the SM photon and a massless Dark Photon

$$\frac{d\sigma}{dT} = \pi \alpha \underbrace{\mathcal{E}^2}_{\chi} \underbrace{\frac{2E_{\chi}^2 m_e + T^2 m_e - T\left(m_{\chi}^2 + m_e\left(2E_{\chi} + m_e\right)\right)}{T^2 \left(E_{\chi}^2 - \underbrace{m_{\chi}^2}_{\chi}\right) m_e^2}}$$

Harnik, Liu, and Palamar 1902.03246

2) Stable Particles: Millicharged Particles



Coloma, JLP, Molina-Bueno, Urrea 2304.06765

1) LLPs: Model independent approach

$$N_{dec} = N_{dec} \left(\text{BR} \left(M \to \Psi \right) \text{BR} \left(\Psi \to visible \right) \epsilon_{det}, c\tau_{\Psi}/m_{\Psi} \right)$$



Leptogenesis: Kinetic Equations

• Equations for the density matrix in the Raffelt-Sigl formalism

Ghiglieri, Laine '17 $\frac{d\rho_N(k)}{dt} = -\left[i[H,\rho_N(k)]\right] - \left[\frac{1}{2}\left\{\Gamma_N^a,\rho_N\right\} + \frac{1}{2}\left\{\Gamma_N^p, 1-\rho_N\right\}\right]$ Oscillations Scattering $\bar{\rho}_N \left(H \to H^* \right)$ $\frac{d\mu_{B/3-L_{\alpha}}}{dt} = f\left(\rho_N, \bar{\rho}_N, \mu_{B/3-L_{\alpha}}\right)$

Leptogenesis: Kinetic Equations

$$\begin{split} xH_{u}\frac{\mathrm{d}r_{N}}{\mathrm{d}x} &= -i[\langle H\rangle, r_{N}] - \frac{\langle \gamma_{N}^{(0)} \rangle}{2} \{Y^{\dagger}Y, r_{N} - 1\} - x^{2}\frac{\langle s_{N}^{(0)} \rangle}{2} \{MY^{T}Y^{*}M, r_{N} - 1\} \\ &+ \langle \gamma_{N}^{(1)} \rangle Y^{\dagger}\mu Y - x^{2}\langle s_{N}^{(1)} \rangle MY^{T}\mu Y^{*}M \\ &- \frac{\langle \gamma_{N}^{(2)} \rangle}{2} \{Y^{\dagger}\mu Y, r_{N}\} + x^{2}\frac{\langle s_{N}^{(2)} \rangle}{2} \{MY^{T}\mu Y^{*}M, r_{N}\}, \\ xH_{u}\frac{\mathrm{d}r_{\bar{N}}}{\mathrm{d}x} &= -i[\langle H^{*} \rangle, r_{\bar{N}}] - \frac{\langle \gamma_{N}^{(0)} \rangle}{2} \{Y^{T}Y^{*}, r_{\bar{N}} - 1\} - x^{2}\frac{\langle s_{N}^{(0)} \rangle}{2} \{MY^{\dagger}YM \\ &- \langle \gamma_{N}^{(1)} \rangle Y^{T}\mu Y^{*} + x^{2}\langle s_{N}^{(1)} \rangle MY^{\dagger}\mu YM \\ &+ \frac{\langle \gamma_{N}^{(2)} \rangle}{2} \{Y^{T}\mu Y^{*}, r_{\bar{N}}\} - x^{2}\frac{\langle s_{N}^{(2)} \rangle}{2} \{MY^{\dagger}\mu YM, r_{\bar{N}}\}, \\ xH_{u}\frac{\mathrm{d}\mu_{B/3-L_{\alpha}}}{\mathrm{d}x} &= \frac{\int_{k} \rho_{F}}{\int_{k} \rho_{F}'} \left[\frac{\langle \gamma_{N}^{(0)} \rangle}{2} (Yr_{N}Y^{\dagger} - Y^{*}r_{\bar{N}}Y^{T}) - x^{2}\frac{\langle s_{N}^{(0)} \rangle}{2} (Y^{*}Mr_{N}MY^{\dagger} + Y \\ &+ x^{2}\frac{\langle s_{N}^{(2)} \rangle}{2} \mu_{\alpha} \left(YMr_{\bar{N}}MY^{\dagger} + Y^{*}Mr_{N}MY^{T}\right)\right]_{\alpha\alpha}, \end{split}$$

• Stiff non-linear system with several relevant time scales: very hard to numerically explore parameter space.

Leptogenesis: parameter scan $Y_B^{\rm exp} \simeq 8.65(8) \times 10^{-11}$

Bayesian posterior probabilities (using nested sampling Montecarlo MultiNest)

$$\log \mathcal{L} = -\frac{1}{2} \left(\frac{Y_B(t_{\rm EW}) - Y_B^{\rm exp}}{\sigma_{Y_B}} \right)^2$$



Leptogenesis: Kinetic Equations

Hernandez, JLP, Rius, **Sandner**; arXiv:2207.01651

• AMIQS: publicly available software developed by **Stefan Sandner** introduced relevant optimizations that allows a faster scan.



https://github.com/stefanmarinus/amiqs 10.5281/zenodo.6866454

- Dependence on the parameters of the model and correlation between the baryon asymmetry and other observables not easy to understand just from a numerical scan.
- Our ultimate goal is to study this connection with future experimental measurements in order to be able to test leptogenesis.

Analytical understanding required

Towards analytical understanding

Hernandez, JLP, Rius, Sandner; arXiv:2207.01651

- Identify the different non-thermal regimes and characteristic time-scales
- Set up a perturbative approximation of the equations $\,(\epsilon \ll 1,\,\mu/M \ll 1)\,$
- Identify the CP invariants that control the flavour parameter dependencies

$$\begin{split} I_{0} &= \operatorname{Im}\left(\operatorname{Tr}\left[Y^{\dagger}Y\,M^{\dagger}MY^{\dagger}Y_{l}^{\dagger}Y\right]\right)\\ &\equiv \sum_{\alpha}y_{l_{\alpha}}^{2}\,\Delta_{\alpha}\left(\delta,\phi,\Delta m_{\mathrm{atm}}^{2},\Delta m_{\mathrm{sol}}^{2},U^{2},M,\theta\right)\\ I_{1} &= \operatorname{Im}\left(\operatorname{Tr}\left[Y^{\dagger}Y\,M^{\dagger}MM^{*}(Y^{\dagger}Y)^{*}M\right]\right)\\ &\equiv \sum_{\alpha}\,\Delta_{\alpha}^{M}\left(\delta,\phi,\Delta m_{\mathrm{atm}}^{2},\Delta m_{\mathrm{sol}}^{2},U^{2},M,\theta\right) \end{split}$$

• Write the CP invariants in terms of observable parameters: find bounds and correlations implied by the matter-antimatter asymmetry

Non thermal equilibrium regimes



Example: overdamped regime (NH)

$$\left(\sum_{\alpha} \mu_{B/3-L_{\alpha}}\right)^{\mathrm{ov-wLNV}} \simeq \frac{\kappa x^2}{6\gamma_0 + \kappa\gamma_1} \frac{\gamma_0^2}{\gamma_0^2 + 4\omega^2} \frac{c_H M_P^*}{T_{EW}^3} \left(\Delta_{\mathrm{LNC}}^{\mathrm{ov}} - \frac{24}{5} \frac{s_0 x^3}{T_{EW}^2} \Delta_{\mathrm{LNV}}^{\mathrm{ov}}\right)$$

$$\Delta_{\rm LNC}^{\rm ov} = \frac{1}{\left[\operatorname{Tr}\left(Y^{\dagger}Y\right)\right]^2} \sum_{\alpha} \frac{\Delta_{\alpha}}{\left(YY^{\dagger}\right)_{\alpha\alpha}} \approx -(M_2^2 - M_1^2) \frac{v^2 \sqrt{\Delta m_{\rm atm}^2}}{8M^3 U^4} s_{\theta}$$

$$\left(\sum_{\alpha} \Delta_{\alpha} = 0, \ \Delta_{\rm LNC}^{\rm ov} \propto \sum_{\alpha} \frac{\Delta_{\alpha}}{\Gamma_{\alpha}}\right)$$

$$\Delta_{\rm LNV}^{\rm ov} = \frac{1}{\left[\operatorname{Tr}\left(Y^{\dagger}Y\right)\right]^2} \sum_{\alpha} \Delta_{\alpha}^M \approx -M_1 M_2 (M_2^2 - M_1^2) \frac{\sqrt{\Delta m_{\rm atm}^2}}{4MU^2} s_{\theta}$$

$$\left(\sum_{\alpha} \Delta^M_{\alpha} \neq 0\right)$$

Non thermal equilibrition

In principle, $\Gamma(T_{\rm EW}) < H(T_{\rm EW})$ is required ($\Gamma \propto Tr \left[Y^{\dagger}Y \right] T$)



BUT approximate L symmetry and flavour effects can lead to slow modes.

Non thermal equilibrium regimes $\Delta M = 0$

• "Thermal oscillation rate"

$$\Gamma_{\rm osc}^{\rm thm} \sim \rho y y' T$$

• LN symmetry

$$\Gamma_{\rm LN}^{\rm slow} \propto y'^2 T$$

• Flavor

$$\Gamma_{\alpha}(T) \propto \epsilon_{\alpha} \Gamma(T), \quad \epsilon_{\alpha} \equiv \frac{(YY^{\dagger})_{\alpha\alpha}}{\operatorname{Tr}[YY^{\dagger}]} = \frac{y_{\alpha}^2}{y^2} + \mathcal{O}\left(y'^2/y^2\right)$$

• wHC

$$\Gamma^{\rm slow}_M \propto \left(\frac{M}{T}\right)^2 \Gamma \leq \Gamma$$

Non thermal equilibrium: degenerate N's



• Regime 1 – Flavoured with wHC.

 $\Gamma_{\rm LN}(T_{\rm EW}), \Gamma_M(T_{\rm EW}), \Gamma_\alpha(T_{\rm EW}) < H_u(T_{\rm EW}) < \Gamma(T_{\rm EW}).$

• Regime 2 – Flavoured with sHC.

 $\Gamma_{\rm LN}(T_{\rm EW}), \Gamma_{\alpha}(T_{\rm EW}) < H_u(T_{\rm EW}) < \Gamma_M(T_{\rm EW}), \Gamma(T_{\rm EW}).$

Analytical understanding $\Delta M = 0$

- Identify the different non-thermal regimes and characteristic time-scales
- Set up a perturbative approximation of the equations $(\epsilon \ll 1, \mu/M \ll 1)$
- Identify the CP invariants that control the flavor parameter dependencies

$$\begin{split} \tilde{I}_0 &\equiv \operatorname{Im}\left(\operatorname{Tr}\left[Y^{\dagger}YM_R^*Y^TY^*M_RY^{\dagger}Y_lY_l^{\dagger}Y\right]\right) \equiv \sum_{\alpha} y_{l_{\alpha}}^2 \Delta_{\alpha} \\ &\equiv \sum_{\alpha} y_{l_{\alpha}}^2 \Delta_{\alpha} \left(\delta, \phi, \Delta m_{\operatorname{atm}}^2, \Delta m_{\operatorname{sol}}^2, U^2, M, \right) \end{split}$$

• Write the CP invariants in terms of observable parameters: find bounds and correlations implied by the matter-antimatter asymmetry

Example $\Delta M = 0$: Regime 2

$$\sum_{\alpha} \mu_{B-L_{\alpha/3}} = -x_M^3 \frac{1}{T_{EW}^2} \frac{8\gamma_0 \kappa^2 (\gamma_1 s_0 + \gamma_0 s_1)(s_0 \omega + \gamma_0 \omega_M)}{6(4\gamma_0 s_0 + \gamma_1 s_0 \kappa + \gamma_0 s_1 \kappa)(\gamma_0^2 + 4\omega^2)} \Delta_{\alpha}^{\text{fw}}$$

$$\Delta_{\alpha}^{\text{fw}}$$

$$\sum_{\alpha} \frac{10^{-9}}{10^{-10}} \frac{10^{-9}}{10^{-10}} \frac{10^{-9}}{10^{-10}} \frac{10^{-10}}{10^{-10}} \frac{10^{-10}}{10^{-$$

Degenerate vs Non Degenerate case



Flavor pattern vs sensitivity



- Interpretation of ATLAS data depends on assumptions about "flavor mixing pattern" Tastet, Ruchayskiya, Timiryasov 2107.12980
- Same conclusion applies to other experimental searches.

The New Physics Scale



https://github.com/mhostert/Heavy-Neutrino-Limits Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

The New Physics Scale



https://github.com/mhostert/Heavy-Neutrino-Limits Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

Bounds from CLFV



2N-SS	Normal Ordering		Inverted Ordering	
211-00	68% CL	95%CL	68% CL	95%CL
$\eta_{ee} = \frac{\left \theta_e\right ^2}{2}$	$6.4 \cdot 10^{-6}$	$9.4\cdot10^{-6}$	$[0.98, 4.4] \cdot 10^{-4}$	$5.5\cdot 10^{-4}$
$\eta_{\mu\mu}=rac{ heta_{\mu} ^2}{2}$	$6.9\cdot 10^{-5}$	$1.3\cdot 10^{-4}$	$[0.20, 1.0] \cdot 10^{-6}$	$3.2\cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{ \theta_{\tau} ^2}{2}$	$8.6 \cdot 10^{-5}$	$2.1\cdot 10^{-4}$	$[0.94, 2.8] \cdot 10^{-5}$	$4.5\cdot 10^{-5}$
$\operatorname{Tr}\left[\eta\right] = \frac{ \theta ^2}{2}$	$1.6\cdot 10^{-4}$	$2.9\cdot 10^{-4}$	$[1.1, 4.8] \cdot 10^{-4}$	$6.0\cdot 10^{-4}$
$ \eta_{e\mu} = \frac{\left \theta_e \theta_\mu^*\right }{2}$	$8.3 \cdot 10^{-6}$	$1.2\cdot 10^{-5}$	$[0.37, 1.0] \cdot 10^{-5}$	$1.3\cdot 10^{-5}$
$ \eta_{e\tau} = \frac{ \theta_e \theta_\tau^* }{2}$	$1.5\cdot 10^{-5}$	$2.2\cdot 10^{-5}$	$[0.25, 1.2] \cdot 10^{-4}$	$1.4\cdot 10^{-4}$
$ \eta_{\mu\tau} = \frac{ \theta_{\mu}\theta_{\tau}^* }{2}$	$7.2 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.38, 3.0] \cdot 10^{-6}$	$3.5 \cdot 10^{-5}$

2N-SS	Normal Ordering		Inverted Ordering	
211-00	68% CL	95%CL	68% CL	95%CL
$\eta_{ee} = \frac{\left \theta_e\right ^2}{2}$	$6.4 \cdot 10^{-6}$	$9.4\cdot10^{-6}$	$[0.98, 4.4] \cdot 10^{-4}$	$5.5\cdot 10^{-4}$
$\eta_{\mu\mu}=rac{ heta_{\mu} ^2}{2}$	$6.9\cdot 10^{-5}$	$1.3\cdot 10^{-4}$	$[0.20, 1.0] \cdot 10^{-6}$	$3.2\cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{ \theta_{\tau} ^2}{2}$	$8.6 \cdot 10^{-5}$	$2.1\cdot 10^{-4}$	$[0.94, 2.8] \cdot 10^{-5}$	$4.5\cdot 10^{-5}$
$\mathrm{Tr}\left[\eta\right] = \frac{ \theta ^2}{2}$	$1.6\cdot 10^{-4}$	$2.9\cdot 10^{-4}$	$[1.1, 4.8] \cdot 10^{-4}$	$6.0\cdot 10^{-4}$
$ \eta_{e\mu} = \frac{\left \theta_e \theta_\mu^*\right }{2}$	$8.3 \cdot 10^{-6}$	$1.2\cdot 10^{-5}$	$[0.37, 1.0] \cdot 10^{-5}$	$1.3\cdot 10^{-5}$
$ \eta_{e\tau} = \frac{ \theta_e \theta_\tau^* }{2}$	$1.5\cdot 10^{-5}$	$2.2\cdot 10^{-5}$	$[0.25, 1.2] \cdot 10^{-4}$	$1.4\cdot 10^{-4}$
$ \eta_{\mu\tau} = \frac{ \theta_{\mu}\theta_{\tau}^* }{2}$	$7.2 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.38, 3.0] \cdot 10^{-6}$	$3.5 \cdot 10^{-5}$

3N-SS	Normal Ord	ering	Inverted Ordering	
011-00	68% CL	95% CL	68%CL	95% CL
$\eta_{ee} = \frac{ \theta_e ^2}{2}$	$[0.28, 0.99] \cdot 10^{-3}$	$1.3\cdot 10^{-3}$	$[0.31, 1.0] \cdot 10^{-3}$	$1.4 \cdot 10^{-3}$
$\eta_{\mu\mu} = \frac{ \theta_{\mu} ^2}{2}$	$1.3\cdot 10^{-7}$	$1.1\cdot 10^{-5}$	$1.2\cdot 10^{-7}$	$1.0 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\left \theta_{\tau}\right ^2}{2}$	$[0.3, 3.9] \cdot 10^{-4}$	$1.0\cdot 10^{-3}$	$1.7\cdot 10^{-4}$	$8.1 \cdot 10^{-4}$
$\operatorname{Tr}\left[\eta\right] = rac{ heta ^2}{2}$	$[0.35, 1.3] \cdot 10^{-3}$	$1.9\cdot 10^{-3}$	$[0.33, 1.0] \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$
$ \eta_{e\mu} = \frac{\left \theta_e \theta_\mu^*\right }{2}$	$8.5 \cdot 10^{-6}$	$1.2\cdot 10^{-5}$	$8.5\cdot 10^{-6}$	$1.2 \cdot 10^{-5}$
$ \eta_{e\tau} = \frac{ \theta_e \theta_\tau^* }{2}$	$[1.3, 5.1] \cdot 10^{-4}$	$9.0\cdot10^{-4}$	$3.3\cdot 10^{-4}$	$8.0 \cdot 10^{-4}$
$ \eta_{\mu\tau} = \frac{ \theta_{\mu}\theta_{\tau}^* }{2}$	$5.0 \cdot 10^{-6}$	$5.7 \cdot 10^{-5}$	$3.8 \cdot 10^{-6}$	$1.8 \cdot 10^{-5}$

G-SS	LFC	Bound	LFV Bound		
	68% CL	$95\% \mathrm{CL}$	68% CL	95% CL	
η_{ee}	$[0.33, 1.0] \cdot 10^{-3}$	$[0.081, 1.4] \cdot 10^{-3}$	-	-	
$\eta_{\mu\mu}$	$1.5 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	-	-	
$\eta_{ au au}$	$1.6\cdot 10^{-4}$	$8.9\cdot 10^{-4}$	-	-	
$\mathrm{Tr}\left[\eta ight]$	$[0.28, 1.2] \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	-	-	
$ \eta_{e\mu} $	$1.4\cdot10^{-4}$	$3.4\cdot10^{-4}$	$8.4\cdot 10^{-6}$	$1.2\cdot 10^{-5}$	
$ \eta_{e au} $	$4.2\cdot 10^{-4}$	$8.8\cdot\mathbf{10^{-4}}$	$5.7\cdot 10^{-3}$	$8.1\cdot 10^{-3}$	
$ \eta_{\mu au} $	$9.4\cdot 10^{-6}$	$1.8\cdot 10^{-4}$	$6.6 \cdot 10^{-3}$	$9.4 \cdot 10^{-3}$	

$$|\mathbb{I} - \alpha| = \begin{pmatrix} [0.081, 1.4] \cdot 10^{-3} & 0 & 0\\ < 2.4 \cdot 10^{-5} & < 1.4 \cdot 10^{-4} & 0\\ < 1.8 \cdot 10^{-3} & < 3.6 \cdot 10^{-4} & < 8.9 \cdot 10^{-4} \end{pmatrix}$$
Observable	SM prediction	Experimental value	
$M_W \simeq M_W^{\rm SM} \left(1 + 0.20 \left(\eta_{ee} + \eta_{\mu\mu}\right)\right)$	$80.356(6) {\rm GeV}$	$80.373(11) {\rm GeV}$	-
$s_{\rm eff}^{2 \ {\rm Tev}} \simeq s_{\rm eff}^{2 \ {\rm SM}} \left(1 - 1.40 \left(\eta_{ee} + \eta_{\mu\mu}\right)\right)$	0.23154(4)	0.23148(33)	[76]
$s_{\text{eff}}^{2 \text{ LHC}} \simeq s_{\text{eff}}^{2 \text{ SM}} \left(1 - 1.40 \left(\eta_{ee} + \eta_{\mu\mu}\right)\right)$	0.23154(4)	0.23129(33)	[76]
$\Gamma_{\rm inv}^{\rm LHC} \simeq \Gamma_{\rm inv}^{\rm SM} \left(1 - 0.33 \left(\eta_{ee} + \eta_{\mu\mu}\right) - 1.33 \eta_{\tau\tau}\right)$	$0.50145(5) { m GeV}$	$0.523(16) { m ~GeV}$	[77]
$\Gamma_Z \simeq \Gamma_Z^{\text{SM}} \left(1 + 1.08 \left(\eta_{ee} + \eta_{\mu\mu} \right) - 0.27 \eta_{\tau\tau} \right)$	$2.4939(9) { m GeV}$	$2.4955(23) { m ~GeV}$	[76]
$\sigma_{\rm had}^0 \simeq \sigma_{\rm had}^{0 \ \text{SM}} \left(1 + 0.50 \left(\eta_{ee} + \eta_{\mu\mu} \right) + 0.53 \eta_{\tau\tau} \right)$	41.485(8) nb	41.481(33) nb	[76]
$R_e \simeq R_e^{\rm SM} \left(1 + 0.27 \left(\eta_{ee} + \eta_{\mu\mu}\right)\right)$	20.733(10)	20.804(50)	[76]
$R_{\mu} \simeq R_{\mu}^{\rm SM} \left(1 + 0.27 \left(\eta_{ee} + \eta_{\mu\mu}\right)\right)$	20.733(10)	20.784(34)	[76]
$R_{\tau} \simeq R_{\tau}^{\rm SM} \left(1 + 0.27 \left(\eta_{ee} + \eta_{\mu\mu} \right) \right)$	20.780(10)	20.764(45)	[76]
$R^{\pi}_{\mu e} \simeq \left(1 - \left(\eta_{\mu \mu} - \eta_{ee}\right)\right)$	1	1.0010(9)	[78]
$R^{\pi}_{\tau\mu} \simeq (1 - (\eta_{\tau\tau} - \eta_{\mu\mu}))$	1	0.9964(38)	[78]
$R_{\mu e}^K \simeq \left(1 - \left(\eta_{\mu\mu} - \eta_{ee}\right)\right)$	1	0.9978(18)	[78]
$R^{\tau}_{\mu e} \simeq \left(1 - \left(\eta_{\mu\mu} - \eta_{ee}\right)\right)$	1	1.0018(14)	[78]
$R_{\tau\mu}^{\tau} \simeq \left(1 - \left(\eta_{\tau\tau} - \eta_{\mu\mu}\right)\right)$	1	1.0010(14)	[78]

	-		
$\left V_{ud}^{\beta}\right \simeq \sqrt{1 - \left V_{us}\right ^2} \left(1 + \eta_{\mu\mu}\right)$	$\sqrt{1-\left V_{us} ight ^2}$	0.97373(31)	[76]
$\left V_{us}^{\tau \to K\nu}\right \simeq \left V_{us}\right \left(1 + \eta_{ee} + \eta_{\mu\mu} - \eta_{\tau\tau}\right)$	$ V_{us} $	0.2236(15)	[79]
$\left V_{us}^{\tau \to K,\pi}\right \simeq \left V_{us}\right \left(1 + \eta_{\mu\mu}\right)$	$ V_{us} $	0.2234(15)	[76]
$\left V_{us}^{K_L \to \pi e \nu}\right \simeq \left V_{us}\right \left(1 + \eta_{\mu\mu}\right)$	$ V_{us} $	0.2229(6)	[76]
$\left V_{us}^{K_L \to \pi \mu \nu}\right \simeq \left V_{us}\right \left(1 + \eta_{ee}\right)$	$ V_{us} $	0.2234(7)	[76]
$\left V_{us}^{K_S \to \pi e\nu}\right \simeq \left V_{us}\right \left(1 + \eta_{\mu\mu}\right)$	$ V_{us} $	0.2220(13)	[76]
$\left V_{us}^{K_S \to \pi \mu \nu}\right \simeq \left V_{us}\right \left(1 + \eta_{ee}\right)$	$ V_{us} $	0.2193(48)	[76]
$\left V_{us}^{K^{\pm} \to \pi e \nu} \right \simeq \left V_{us} \right \left(1 + \eta_{\mu \mu} \right)$	$ V_{us} $	0.2239(10)	[76]
$\left V_{us}^{K^{\pm} \to \pi \mu \nu} \right \simeq \left V_{us} \right \left(1 + \eta_{ee} \right)$	$ V_{us} $	0.2238(12)	[76]
$\left \frac{V_{us}}{V_{ud}}\right ^{K,\pi\to\mu\nu} \simeq \frac{ V_{us} }{\sqrt{1- V_{us} ^2}}$	$\frac{\left V_{us}\right }{\sqrt{1-\left V_{us}\right ^2}}$	0.23131(53)	[76]

The New Physics Scale

• For very light scales M, HNLs (in this regime usually called sterile neutrinos) participate in **neutrino oscillations**. In simplified 3+1 scenario:

TeV

GeV

MeV

keV

e<



Dasgupta, Kopp 2106.05913; Dentler, Hernández-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz 1803.10661 Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637;



TeV

GeV

MeV

keV

e<

Cortesy of J. Hernandez-Garcia



le S

GeV

e<

Caputo, Hernandez, Kekic, JLP, Salvado arXiv:1611.05000 Blondel, Graverini, Serra, Shaposhnikov 1411.5230







 Many EW and CLFV processes affected: determination of G_F via muon decay, W boson mass, weak mixing angle, ratios of Z fermionic decays, invisible width of the Z, ratios of weak decays constraining EW universality, weak decays constraining CKM unitarity, CLFV decays...

Baryon asymmetry

 After the Big-Bang same amount of matter and antimatter generated, but observed universe mainly made out of matter only!



$$\eta_B \equiv \frac{n_B - n_{\overline{B}}}{n_{\gamma}} = (6.13 \pm 0.04) \times 10^{-10}$$

Sakharov conditions





D'onofrio, Rummukainen, Trangberg 2014



At one loop: CP asymmetry generated via interference effects

$$\epsilon = \frac{\Gamma(N \to lH) - \Gamma(N \to l^c H^c)}{\Gamma(N \to lH) + \Gamma(N \to l^c H^c)} \propto Im(Y^{\dagger}Y)_{ij}^2$$