A frequentist analysis of three right-handed neutrinos with GAMBIT

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TeVPA, 2 Dec 2019

[M. Chrzaszcz, M. Drewes, T.G., J. Harz, S. Krishnamurthy, C. Weniger, arXiv:1908.02302]

NeutrinoBit

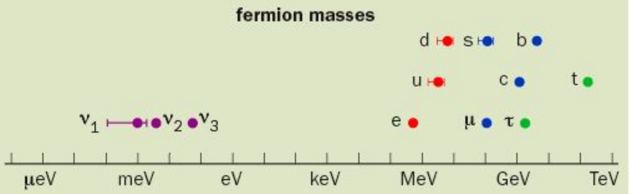
Outline

Right-handed neutrinos

Right-handed neutrinos

- **Right-handed neutrinos** $N_{1,2,3}$
- N_j are **SM singlets** $\quad N_j \in \{\mathbf{1}, \mathbf{1}, 0\}$
- Yukawa couplings $\rightarrow$ **Dirac** mass terms

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi = M_D^{ij} \nu_i N_j$$



- $Y_\nu / Y_t \lesssim 10^{12-15}$

Seesaw mechanism

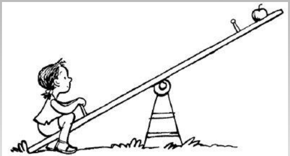
- **Majorana** mass term for N_j

$$\mathcal{L} \supset Y_\nu^{ij} L_i N_j \phi + M^{ij} N_i N_j$$
$$= M_D^{ij} \nu_i N_j + M_M^{ij} N_i N_j$$

$$M_\nu = \begin{pmatrix} \delta m_\nu^{1-loop} & M_D \\ M_D^T & M_M \end{pmatrix}$$

- "Naturally" **light neutrino masses**

$$m_\nu \sim M_D^T M_M^{-1} M_D, \quad m_N \sim M_M$$



- Neutrino **mixing** matrix

$$\mathcal{U}_\nu = \begin{pmatrix} V_\nu & \Theta \\ \Theta^T & V_N \end{pmatrix} \approx \begin{pmatrix} 1 - \frac{1}{2}\theta\theta^\dagger & \theta \\ -\theta^\dagger & 1 - \frac{1}{2}\theta^\dagger\theta \end{pmatrix} \begin{pmatrix} U_\nu & 0 \\ 0 & U_N \end{pmatrix}$$

The Casas-Ibarra parametrization

- Θ parametrizes the active - sterile neutrino **mixing**
- CI parametrization [J. A. Casas & A. Ibarra, Nuc. Phys. B618, (1-2), 2001]

$$\Theta = iU_\nu \sqrt{m_\nu^{diag}} \mathcal{R} \sqrt{\tilde{M}^{diag}}^{-1}$$

$$\tilde{M}_{IJ} \simeq \tilde{M}_{IJ}^{\text{diag}} = M_I \delta_{IJ} \left(1 - \frac{M_I^2}{v^2} l(M_I)\right)$$

- Rotation matrix $\mathcal{R} = \mathcal{R}^{23}\mathcal{R}^{13}\mathcal{R}^{12}$

$$\mathcal{R}_{ii}^{ij} = \mathcal{R}_{jj}^{ij} = \cos\omega_{ij}$$
$$\mathcal{R}_{ij}^{ij} = -\mathcal{R}_{ji}^{ij} = \sin\omega_{ij}$$

Symmetry protected limit

- Approximate $B - L$ symmetry $F_{\alpha I} = \Theta_{\alpha I} M_I / v$

$$M_M = \begin{pmatrix} M(1-\mu) & 0 & 0 \\ 0 & M(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix},$$

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix},$$

- Two-degenerate RHNs $\rightarrow$ pseudo-Dirac fermion $\mu, \epsilon_\alpha, \epsilon'_\alpha \ll 1$

$$M_1 \sim M_2, \quad \Theta_{\alpha 1} \sim i\Theta_{\alpha 2}$$

- Oscillation data does not constraint $|U_{\alpha_I}|^2 \equiv |\Theta_{\alpha I}|^2$
- Upper limit purely from other experimental constraints

Model parameters

- Light (left-handed) neutrino masses

$$m_{\nu_i} \quad i \in \{1,2,3\} \quad \rightarrow \quad m_{\nu_0},\ \Delta m^2_{12},\ \Delta m^2_{3l}$$

- Heavy (right-handed) neutrino masses

$$M_I \quad I \in \{1,2,3\} \quad \rightarrow \quad M_1,\ \Delta M_{21},\ M_3$$

- Active neutrino mixing parameters

$$\{\theta_{12},\ \theta_{13},\ \theta_{23}, \quad \alpha_1,\ \alpha_2, \quad \delta_{CP}\}$$

- Active-sterile neutrino mixing angles

$$\Re(\omega_{ij}), \Im(\omega_{ij})$$

Scanning strategy

GAMBIT

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GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org   EPJC **77** (2017) 784   arXiv:1705.07908

- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source
- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON
Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

Scanning strategy

- Likelihood is mostly flat
- Saturate couplings upper limits
  - → Differential model ΔM_{21}
  - → Coupling slide

$$s \log |U_{\alpha I}|^2 + m \log M_I$$

- Split the M_I range

$$[0.06, 0.3162],\ [0.3162, 2],\ [2, 60],\ [60, 500]$$

- Diver 1.0.4, [19200, 10^{-10}, λjDE]

[GAMBIT Scanner WG, Eur.Phys.J. C77(2017) 761]

- Postprocess, combine and symmetrize

Parameter	Value/Range	Prior
Active neutrino parameters		
θ_{12} [rad]	$[0.547684, 0.628144]$	flat
θ_{23} [rad]	$[0.670206, 0.925025]$	flat
θ_{13} [rad]	$[0.139452, 0.155509]$	flat
m_{ν_0} [eV]	$[10^{-7}, 0.23]$	log
Δm^2_{21} [10^{-5} eV^2]	$[6, 9]$	flat
Δm^2_{3l} [10^{-3}eV^2]	$[\pm 2, \pm 3]$	flat
α_1, α_2 [rad]	$[0, 2\pi]$	flat
Sterile neutrino parameters		
δ [rad]	$[0, 2\pi]$	flat
Re ω_{ij} [rad]	$[0, 2\pi]$	flat
Im ω_{ij}	$[-15, 15]$	flat
M_I [GeV]	$[0.06, 500]$	log
$R_{\rm order}$	[1,6]	flat
Nuisance parameters		
m_H [GeV]	$[124.1, 127.3]$	flat

Likelihoods and observables

Likelihoods and observables

- Active neutrino parameters

  [I.Esteban, M.C.Gonzalez-Garcia, M.Maltoni, I.Martinez-Soler, T.Schwetz in JHEP 1701 (2017) 087]

	NH	IH
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.307^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.554^{+0.023}_{-0.033}$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.02227^{+0.00074}_{-0.00074}$
δ_{CP}	234^{+43}_{-31}	278^{+26}_{-29}
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$7.40^{+0.21}_{-0.20}$
$\frac{\Delta m^2_{3l}}{10^{-5}\ \mathrm{eV}^2}$	$2.494^{+0.033}_{-0.031}$	$-2.465^{+0.032}_{-0.031}$

- Gaussian likelihoods
- Planck limit $\sum m_\nu < 0.23$ eV

- Modified **Fermi constant**

$$G_\mu^2 = G_F^2(1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee})$$

- EWPO parameters [PDG]

$$m_W = 80.385(15)$$
$$s^2_{eff} = 0.23155 \pm 0.00005$$

- EWPO decays [PDG]

$$\Gamma_{\rm inv} = 0.499 \pm 0.016$$
$$\Gamma_{W\to e\bar\nu_e} = 0.223 \pm 0.006$$
$$\Gamma_{W\to \mu\bar\nu_\mu} = 0.222 \pm 0.005$$
$$\Gamma_{W\to \tau\bar\nu_\tau} = 0.237 \pm 0.006$$

Likelihoods and observables

- Direct searches for RHN in meson, tau and gauge boson decays
- Beam dump and peak search experiments
- M_i vs $|\Theta_{\alpha i}|^2$ exclusion limits
- Poisson likelihoods

PIENU	0.06 - 0.129 GeV	Θ_{ei}
PS191	0.02 - 0.45 GeV	$\Theta_{ei}, \Theta_{\mu i}$
E949	0.175 - 0.3 GeV	$\Theta_{\mu i}$
CHARM	0.01 - 2.8 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$
NuTeV	0.25 - 2 GeV	$\Theta_{\mu i}$
DELPHI (S)	3 - 50 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$
DELPHI (L)	0.5 - 4.2 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$
ATLAS	50 - 500 GeV	$\Theta_{ei}, \Theta_{\mu i}$
CMS	1 - 10^3 GeV	$\Theta_{ei}, \Theta_{\mu i}$

- Big Bang Nucleosynthesis

$$\begin{array}{ll} N_I \to \pi^0 \nu_\alpha & N_I \to H^+ l_\alpha^- \\ N_I \to \eta \nu_\alpha & N_I \to \rho^0 \nu_\alpha \\ N_I \to \eta' \nu_\alpha & N_I \to \rho^+ l_\alpha^- \\ N_I \to \nu_\alpha \bar{\nu_\beta} \nu_\beta & N_I \to l^-_{\alpha\neq\beta} l^+_\beta \nu_\beta \\ N_I \to \nu_\alpha l^+_\beta l^-_\beta & N_I \to \nu_\alpha u \bar{u} \\ N_I \to \nu_\alpha d \bar{d} & N_I \to l_\alpha u_n \bar{d_m} \end{array}$$

$\rightarrow$ Conservative limit $\tau_N < 0.1s$

[O.Ruchayskiy, A.Ivashko, JCAP1210(2012) 014]

- CKM Unitarity

$$K_L \to \pi^+ e^- \bar{\nu}_e \to |V_{us}^{CKM}| = 0.2163(6)$$

$$\tau \to K\nu \to |V_{us}^{CKM}| = 0.2214(22)$$

[FlaviaNet, HFAG, PDG]

$$\rightarrow \; |V_{us}^{CKM}|^2 + |V_{ud}^{CKM}|^2 = 1$$

Likelihoods and observables

- Lepton flavour violating decays

Process	Branch. Frac.
$\mu^- \to e^- \gamma$	4.2×10^{-13}
$\tau^- \to e^- \gamma$	5.4×10^{-8}
$\tau^- \to \mu^- \gamma$	5.0×10^{-8}
$\mu^- \to e^- e^- e^+$	1.0×10^{-12}
$\tau^- \to e^- e^- e^+$	1.4×10^{-8}
$\tau^- \to \mu^- \mu^- \mu^+$	1.2×10^{-8}
$\tau^- \to \mu^- e^- e^+$	1.1×10^{-8}
$\tau^- \to e^- e^- \mu^+$	0.84×10^{-8}
$\tau^- \to e^- \mu^- \mu^+$	1.6×10^{-8}
$\tau^- \to \mu^- \mu^- e^+$	0.98×10^{-8}
$\mu - e$ (Ti)	4.3×10^{-12}
$\mu - e$ (Au)	7×10^{-13}
$\mu - e$ (Pb)	4.6×10^{-11}

[MEG,BaBar,Belle,SINDRUM,SINDRUM II,ATLAS,LHCb]

- Upper bounds on $|\Theta_{\alpha I}|^2$
- One-sided gaussian likelihoods

- Lepton Universality

$$R^X_{\alpha\beta} = \frac{\Gamma(X^+ \to l^+_\alpha \nu_\alpha)}{\Gamma(X^+ \to l^+_\beta \nu_\beta)}\,, \quad \pi,\ K,\ \tau,\ W$$

$$R_Y = \frac{\Gamma(B^{0/\pm} \to Y^{0/\pm} l^+_\alpha l^-_\alpha)}{\Gamma(B^{0/\pm} \to Y^{0/\pm} l^+_\beta l^-_\beta)}\,, \quad K,\ K^*$$

$\to$ R_D and R_{D^*} not impacted

- Neutrinoless Double β Decay

$T^{0\nu}_{1/2} \geq 2.1 \times 10^{25}$ yr [GERDA]

$T^{0\nu}_{1/2} \geq 1.07 \times 10^{26}$ yr [KamLAND-Zen]

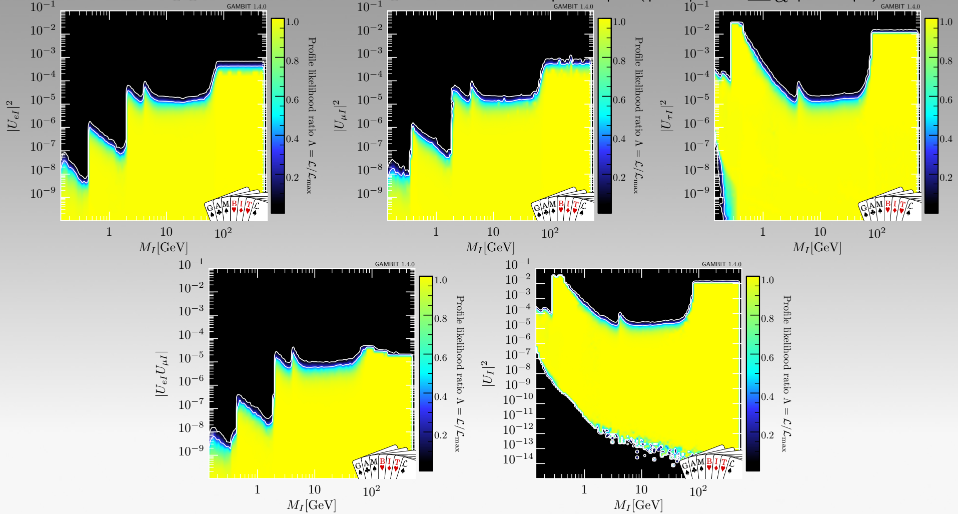
$\to$ Negligible in $B - L$ limit

$\to$ $[T^{0\nu}_{1/2}]^{-1} \propto \left|\sum_I \Theta^2_{eI} M_I\right|^2$

Results

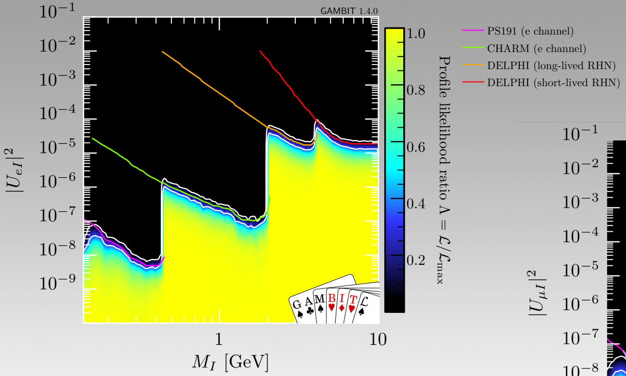
For NH, unless otherwise stated

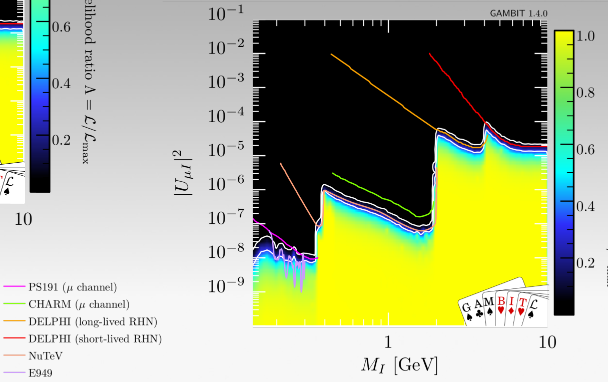
- “Capped” likelihood plots M_I vs $|U_{\alpha I}|^2$ ($|U_I|^2 = \sum_\alpha |U_{\alpha I}|^2$)



Results

- Upper limits from direct searches for $M_I < 80$ GeV





Results

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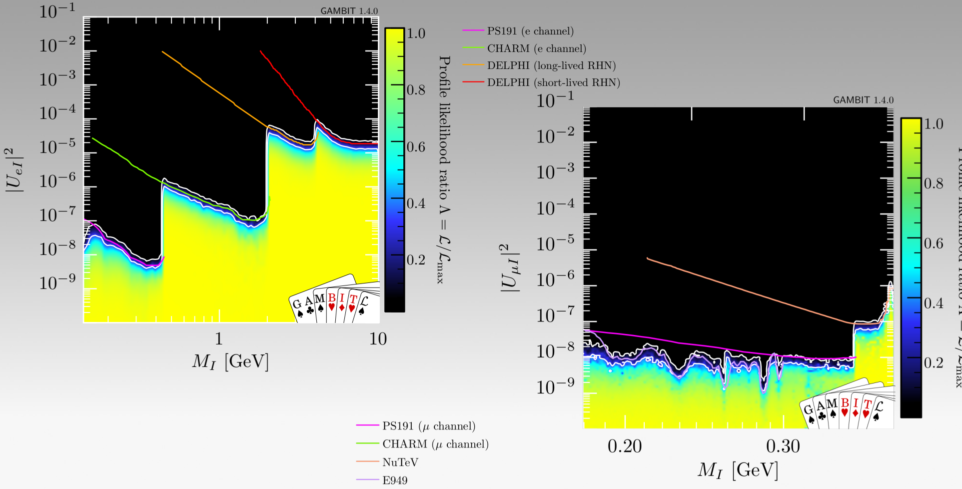

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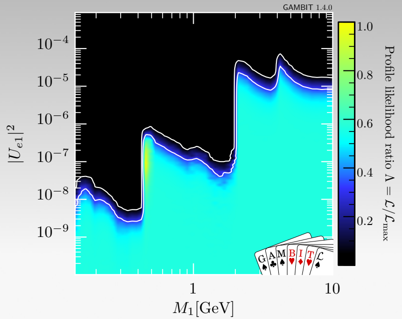
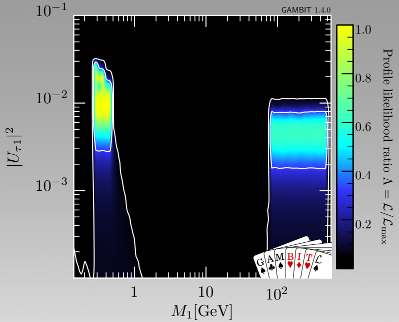
- Full likelihood
- Excess in lnL at large $|U_\tau|^2$
  - $\rightarrow$ Invisible width Γ_Z
  - $\rightarrow$ Fit to CKM entries
  - $\rightarrow$ Lepton universality R_τ

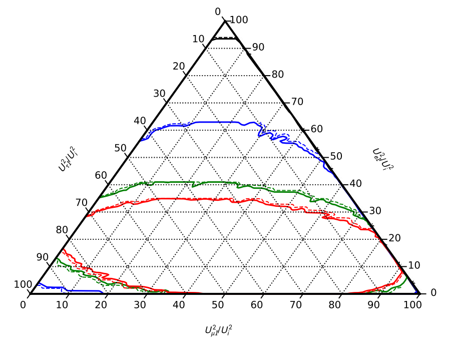


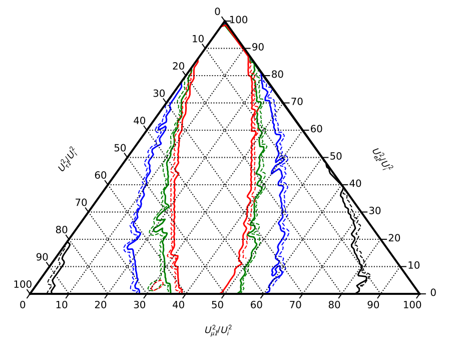


- Excess in lnL at large $|U_e|^2$
  - $\rightarrow$ Lepton universality R_K
- Low significance $\lesssim 1\sigma$

Results

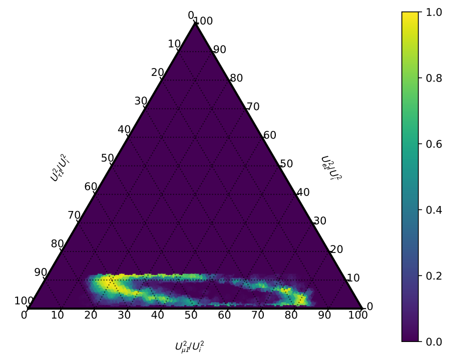
- Flavour mixing pattern ($m_{\nu_0} = (1, 10^{-1}, 10^{-2})$ meV)
- Massless neutrino limit $m_{\nu_0} \to 0$

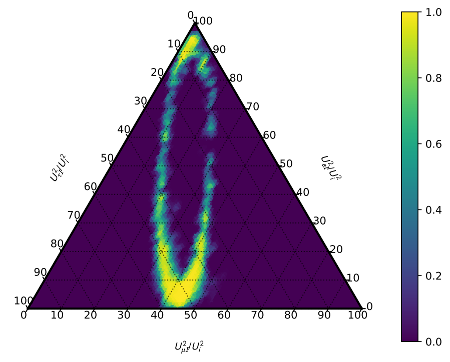




Results

- $m_{\nu_0} \to 0 \rightsquigarrow M_3$ is totally decoupled $\rightsquigarrow$ 2 RHN model
- Symmetric $(B-L)$ vs fine-tuned points
  - $\to$ NO: $(\omega_{12}, \omega_{13}, \omega_{23}) \sim (0, \pi/2, \omega)$
  - $\to$ IO: $(\omega_{12}, \omega_{13}, \omega_{23}) \sim (\omega, 0, 0)$





Summary and Outlook

Summary and Outlook

- Fully explore the parameter space $M_I \in [0.06, 100]$ GeV
- Saturate direct detection limits
  - $\rightarrow$ Maximal $|U_{\alpha I}|^2 \rightarrow$ "large" Yukawas $F \sim 10^{-2}$
  - $\rightarrow$ Proper statistical combination of likelihoods
- Reach BBN bounds, no seesaw lower limit
- 3RHN model is a better fit than SM ($\sim 2\sigma$)
  - $\rightarrow$ Γ_Z, CKM, R_K, R_τ
- Recover symmetry protected scenario, approximate $B - L$
  - $\rightarrow$ Massless neutrino limit $m_{\nu_0} \rightarrow 0 \rightsquigarrow M_3$ decouples ($\Theta_{\alpha 3} \rightarrow 0$)
  - $\rightarrow$ Pseudo-Dirac pair $M_1 \sim M_2$, $\Theta_{\alpha 1} \sim i\Theta_{\alpha 2}$
  - $\rightarrow$ Weaker constraints (oscillations, $0\nu\beta\beta$,...) $\rightsquigarrow$ higher couplings
  - $\rightarrow$ $B - L$ symmetric subset is equivalent to the 2RHN model

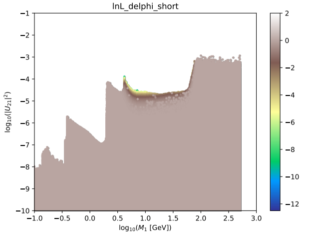
Backup

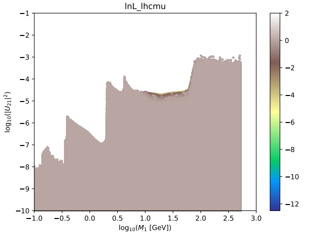
Why a global fit

- Proper use of **nuisance parameters**

$$\Delta m^2_{12},\ \Delta m^2_{3l},\ \theta_{12},\ \theta_{13},\ \theta_{23},\ \delta_{CP},\ m_H$$

- Combination of different **likelihoods**





- Statistical interpretation of the results
- Smart scanning strategies

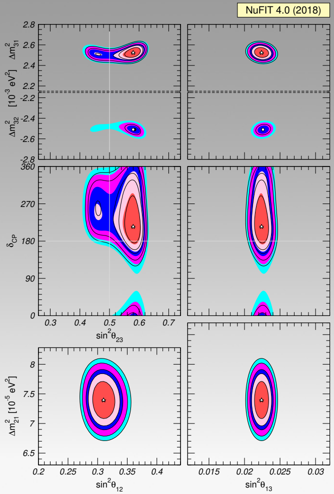
Likelihoods and observables

- Active neutrino parameters

  [E. Fernandez-Martinez, J. Hernandez-Garcia, J. Lopez-Pavon, JHEP **1608** (2016) 033]

	NH	IH
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.306^{+0.012}_{-0.012}$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.587^{+0.020}_{-0.024}$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.02179^{+0.00076}_{-0.00076}$
δ_{CP}	261^{+51}_{-59}	277^{+40}_{-46}
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.50^{+0.19}_{-0.17}$
$\frac{\Delta m^2_{3l}}{10^{-5}\ \mathrm{eV}^2}$	$2.524^{+0.039}_{-0.040}$	$-2.514^{+0.038}_{-0.041}$

- 2D gaussian likelihoods
- Planck limit $\sum m_\nu < 0.23$ eV



Likelihoods and observables

- Modified **Fermi constant**

$$G_\mu^2 = G_F^2(1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee})$$

- EWPO parameters

$$\sin^2 2\theta_w = [\sin^2 2\theta_w]_{SM}\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee}}$$

$$\frac{m_W^2}{[m_W^2]_{SM}} = \frac{[s_w^2]_{SM}}{s_w^2}\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee}}\,,$$

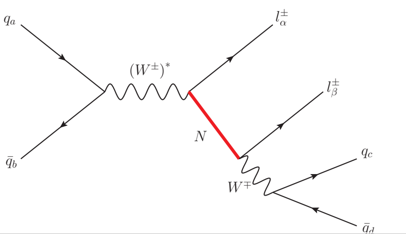
Obs.	**Value**
m_W	$80.385(15)$
s^2_{eff}	0.23155 ± 0.00005
Γ_{inv}	0.499 ± 0.016
$\Gamma_{W\to e\bar{\nu}_e}$	0.223 ± 0.006
$\Gamma_{W\to \mu\bar{\nu}_\mu}$	0.222 ± 0.005
$\Gamma_{W\to \tau\bar{\nu}_\tau}$	0.237 ± 0.006

- EWPO decays $\Gamma_{\text{inv}} = \frac{G_\mu m_Z^3}{12\sqrt{2}\pi}\sum_{ij}\frac{(V_\nu V_\nu^\dagger)_{ij}}{\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee})}}$

$$\Gamma_{W\to l_\alpha\bar{\nu}} = \frac{G_\mu m_W^3}{6\sqrt{2}\pi}\frac{(1-\frac{1}{2}(\theta\theta^\dagger)_{\alpha\alpha})(1-x_\alpha)^2(1+x_\alpha)}{\sqrt{1-(\theta\theta^\dagger)_{\mu\mu}-(\theta\theta^\dagger)_{ee})}}$$

Likelihoods and observables

- Direct searches for RHN in **meson**, **tau** and **gauge boson** decays
- **Beam dump** and **peak search** experiments
- M_i vs $|\Theta_{\alpha i}|^2$ exclusion limits
- Poisson likelihoods



PIENU	0.06 - 0.129 GeV	Θ_{ei}	[M. Aoki et al, Phys. Rev. D, 84(5), 2011]
PS191	0.02 - 0.45 GeV	$\Theta_{ei}, \Theta_{\mu i}$	[G. Bernardi et al, Phys. Lett. B, 203(3), 1988]
E949	0.175 - 0.3 GeV	$\Theta_{\mu i}$	[A. V. Artamonov et al, Phys. Rev. D 91, 2015]
CHARM	0.01 - 2.8 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$	[CHARM, Phys. Lett. B166(4), 1986]
NuTeV	0.25 - 2 GeV	$\Theta_{\mu i}$	[FNAL-E815, Phys. Rev. Lett. 83, 1999]
DELPHI (S)	3 - 50 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$	[DELPHI, Z. Phys. C, 74(1), 1997]
DELPHI (L)	0.5 - 4.2 GeV	$\Theta_{ei}, \Theta_{\mu i}, \Theta_{\tau i}$	[DELPHI, Z. Phys. C, 74(1), 1997]
ATLAS	50 - 500 GeV	$\Theta_{ei}, \Theta_{\mu i}$	[ATLAS, JHEP 07:162, 2015]
CMS	1 - 10^3 GeV	$\Theta_{ei}, \Theta_{\mu i}$	[CMS, arXiv:1802.02965v1]

Likelihoods and observables

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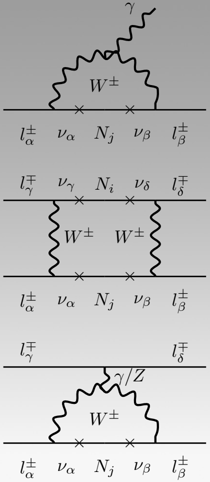
- Lepton flavour violating decays

Process	Branch. Frac.	Reference
$\mu^- \to e^-\gamma$	4.2×10^{-13}	[MEG]
$\tau^- \to e^-\gamma$	5.4×10^{-8}	[BaBar,Belle]
$\tau^- \to \mu^-\gamma$	5.0×10^{-8}	[BaBar, Belle]
$\mu^- \to e^-e^-e^+$	1.0×10^{-12}	[SINDRUM]
$\tau^- \to e^-e^-e^+$	1.4×10^{-8}	[BaBar, Belle]
$\tau^- \to \mu^-\mu^-\mu^+$	1.2×10^{-8}	[ATLAS, BaBar, Belle, LHCb]
$\tau^- \to \mu^-e^-e^+$	1.1×10^{-8}	[BaBar, Belle]
$\tau^- \to e^-e^-\mu^+$	0.84×10^{-8}	[BaBar, Belle]
$\tau^- \to e^-\mu^-\mu^+$	1.6×10^{-8}	[BaBar, Belle]
$\tau^- \to \mu^-\mu^-e^+$	0.98×10^{-8}	[BaBar, Belle]
$\mu - e$ (Ti)	4.3×10^{-12}	[SINDRUM II]
$\mu - e$ (Au)	7×10^{-13}	[SINDRUM II]
$\mu - e$ (Pb)	4.6×10^{-11}	[SINDRUM II]



- Upper bounds on $|\Theta_{\alpha I}|^2$
- One-sided gaussian likelihoods

Likelihoods and observables

- **Big Bang Nucleosynthesis** $\rightarrow$ lower bound on $|U_I|^2$

$$N_I \to \pi^0\nu_\alpha,\ N_I \to H^+ l^-_\alpha,\ N_I \to \eta\nu_\alpha,\ N_I \to \eta'\nu_\alpha,\ N_I \to \rho^+ l^-_\alpha,$$
$$N_I \to \rho^0\nu_\alpha,\ N_I \to \sum_{\alpha,\beta}\nu_\alpha\bar{\nu_\beta}\nu_\beta,\ N_I \to l^-_{\alpha\neq\beta} l^+_\beta \nu_\beta,\ N_I \to \nu_\alpha l^+_\beta l^-_\beta,$$
$$N_I \to \nu_\alpha u\bar{u},\ N_I \to \nu_\alpha d\bar{d},\ N_I \to l_\alpha u_n \bar{d_m}$$

$\rightarrow$ Conservative limit on the lifetime $\tau_N \propto M_I^{-5} < 0.1s$

- **Neutrinoless Double β Decay**

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A}\left| m_p \sum_I \frac{\Theta^2_{eI} M_I}{\langle p^2\rangle + M_I^2}\right|^2 ,\qquad \begin{array}{l} T^{0\nu}_{1/2} \geq 2.1\times 10^{25}\ \text{yr, GERDA (Ge)} \\ T^{0\nu}_{1/2} \geq 1.07\times 10^{26}\ \text{yr, KamLAND-Zen (Xe)}\end{array}$$

$\rightarrow$ Loses effectiviness in $B-L$ limit

Likelihoods and observables

- **Lepton Universality**

$$R^X_{\alpha\beta} = \frac{\Gamma(X^+ \to l^+_\alpha \nu_\alpha)}{\Gamma(X^+ \to l^+_\beta \nu_\beta)}\,, \quad X = \pi,\ K,\ \tau,\ W$$

$$R_Y = \frac{\Gamma(B^{0/\pm} \to Y^{0/\pm} l^+_\alpha l^-_\alpha)}{\Gamma(B^{0/\pm} \to Y^{0/\pm} l^+_\beta l^-_\beta)}\,, \quad Y = K,\ K^*$$

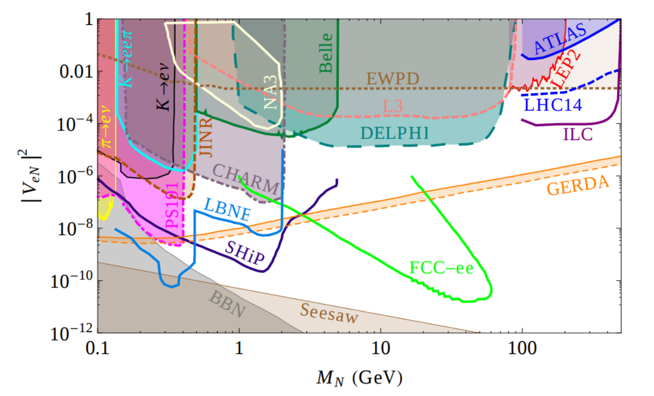
$\to$ R_D and R_{D^*} are not impacted

- **CKM Unitarity** $\quad |V^{CKM}_{us}|^2 + |V^{CKM}_{ud}|^2 = 1$

$$|(V^{exp}_{CKM})^i_{us,ud}|^2 = |(V_{CKM})_{us,ud}|^2[1 + f^i(\Theta)]\,,$$

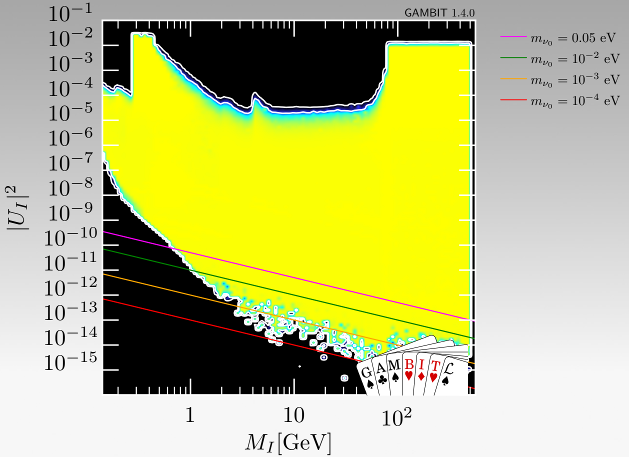
$$\text{e.g. } K_L \to \pi^+ e^- \bar{\nu}_e : 1 + f^1(\Theta) = \frac{G_F^2}{G_\mu^2}[1 - (\theta\theta^\dagger)_{ee}]$$

- Upper limits from direct searches + EWPO

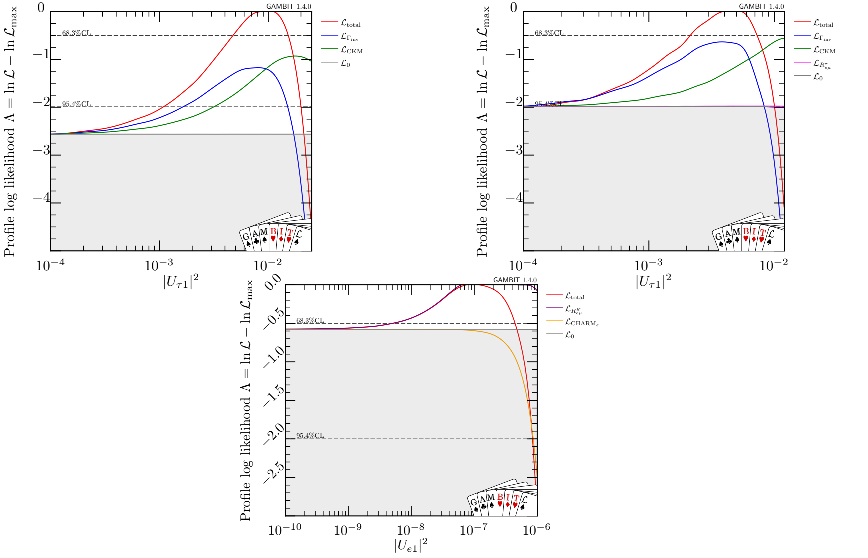


Results

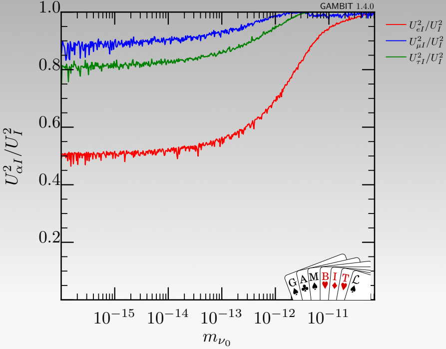
- Lower limits: seesaw and BBN limits ($U_I^2 \gtrsim m_{\nu_0}/M_I$)

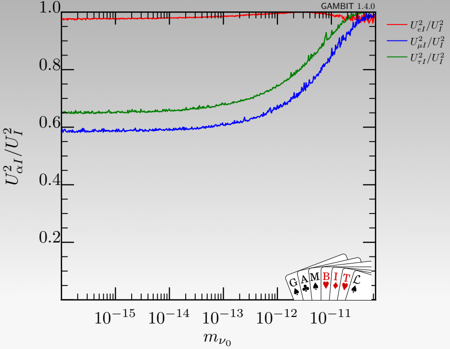


Results


GAMBIT 1.4.0
Profile log likelihood $\Lambda = \ln\mathcal{L} - \ln\mathcal{L}_{\max}$
68.3%CL
95.4%CL
$\mathcal{L}_{\rm total}$
$\mathcal{L}_{\Gamma_{\rm inv}}$
$\mathcal{L}_{\rm CKM}$
$\mathcal{L}_{R^{\tau}_{e\mu}}$
$\mathcal{L}_{R^{K}_{e\mu}}$
$\mathcal{L}_{{\rm CHARM}_e}$
$\mathcal{L}_0$
$|U_{\tau 1}|^2$
$|U_{e1}|^2$

- Flavour mixing pattern ($m_{\nu_0} = (1, 10^{-1}, 10^{-2})$ meV)
- Massless neutrino limit $m_{\nu_0} \to 0$





Summary and Outlook