$(g-2)$ and neutrino masses

work with A. Alvarez, C. Arbeláez, A. Banik, R. Fonseca, B. Hermann,

M. Hirsch, W. Porod, M. Sarazin, M. Schnelke

Ricardo Cepedello

University of Würzburg

IPA 2022, Vienna

September 8, 2022

The (g-2) anomaly

[Resonaances blog (Jester)]

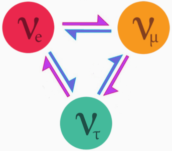
not updated with new lattice results [2206.06582, 2206.15084]

$$a_\mu = (251 \pm 59) \times 10^{-11} \ (4.2\,\sigma)$$

[Muon g-2 colab.(2021)]

$\Updownarrow$

Neutrinos masses

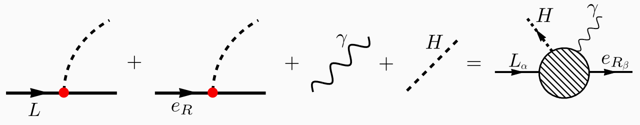


[https://globalfit.astroparticles.es]

[see for example: Jana, Vishnu, Rodejohann, Saad (2020); Escribano, Terol, Vicente (2021); Chowdhury, Ehsanuzzaman, Saad (2022)]

(g-2) and cLFV $\longleftrightarrow$ neutrino masses

INGREDIENTS:



At low energy, this is the effective electromagnetic dipole moment operator:

$$c_R^{\alpha\beta}\bar{\ell}_\alpha \sigma_{\mu\nu} P_R \ell_\beta F^{\mu\nu}$$ [Crivellin 2018]

$$(g-2)_\alpha = -\frac{8m_\alpha}{e}\,\mathrm{Re}[c_R^{\alpha\alpha}] \qquad d_\alpha = -2\,\mathrm{Im}[c_R^{\alpha\alpha}]$$

$$\mathrm{Br}(\ell_\alpha \to \ell_\beta \gamma) = \frac{m_\alpha^3}{4\pi\Gamma_\alpha}(|c_R^{\alpha\beta}|^2 + |c_R^{\beta\alpha}|^2)$$

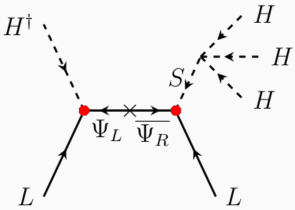
Small m_ν with low mass scalar and large couplings?

Loop suppression or Higher-dimension

BNT model

BNT model

Approach here: dimension 7 operator $LLHH(H^\dagger H) \Rightarrow m_\nu = c\,\frac{\langle H \rangle^3}{\Lambda^2}$



[Babu, Nandi, Tavartkiladze (2009)]

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$\Psi_{L,R}$	**1**	**3**	1
S	**1**	**4**	$\frac{3}{2}$

- New physics mass scale of $\mathcal{O}(1-10)$ TeV
- Particles with many electrical charges ($S^{\pm\pm\pm}$, $\Psi^{\pm\pm}$, ...)
- Yukawa matrices that enter in CLFV processes, $(g-2)$ and EDM

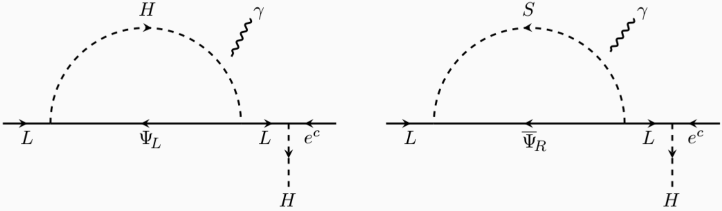
[BNT pheno see: Gosh, Jana, Nandi (2018)]

$(g\text{-}2)_\alpha$ in the BNT

[Arbeláez, RC, Fonseca, Hirsch, PRD 102 (2020)]

Effective EM dipole moment operator: $c_R^{\alpha\beta}\,\overline{\ell_\alpha}\sigma_{\mu\nu}P_R\ell_\beta F^{\mu\nu}$

$$a_\alpha = -4\frac{m_{\ell_\alpha}}{e}\,\mathrm{Re}\,c_R^{\alpha\alpha} \qquad \mathrm{Br}\left(\ell_\beta \to \ell_\alpha\gamma\right) = \frac{m_{\ell_\beta}^3}{4\pi\Gamma_{\ell_\beta}}\left(\left|c_R^{\alpha\beta}\right|^2 + \left|c_R^{\beta\alpha}\right|^2\right)$$



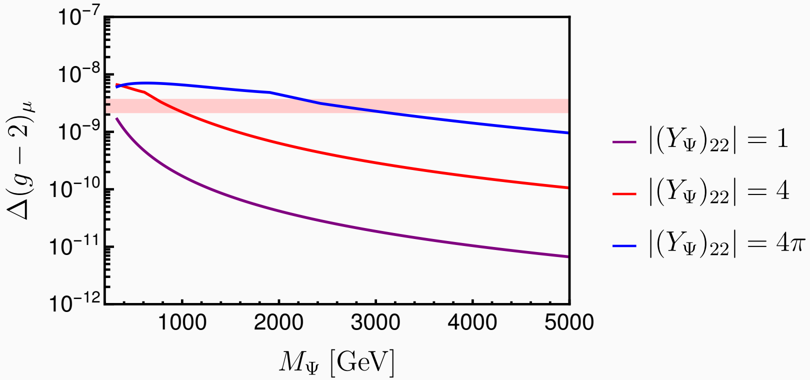
$(g-2)_\alpha$ is proportional to $m_{\ell_\alpha}^2$

⇒ The diagonal of the Yukawas is related to $(g-2)$.

⇒ The off-diagonal participates in $(\ell_\alpha \to \ell_\beta + \gamma)$.

$(g\text{-}2)_\mu$ in the BNT

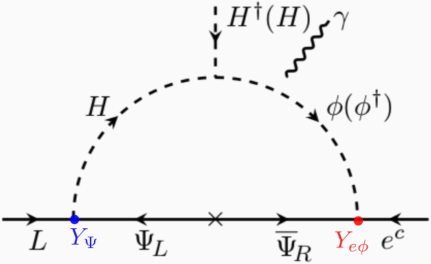
[Arbeláez, RC, Fonseca, Hirsch, PRD 102 (2020)]



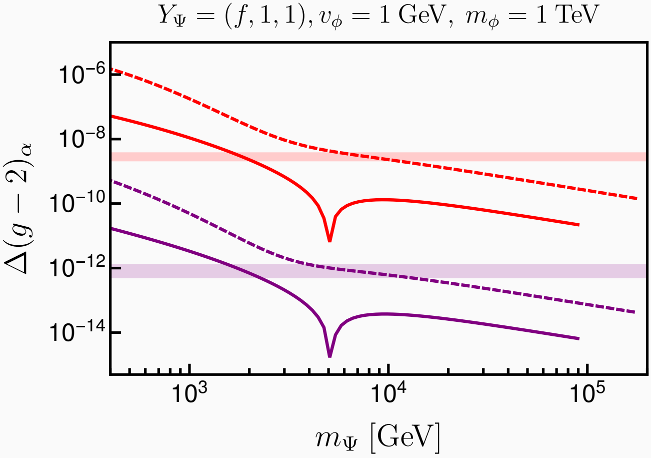
$M_\Psi < (1-3)$ TeV for a *reasonable* (perturbative) value of the Yukawas

Extended BNT model (BNTϕ) [Arbeláez, RC, Fonseca, Hirsch, PRD 102 (2020)]

To soften this one can add $\phi \equiv (\mathbf{1}, \mathbf{3}, 0)$.

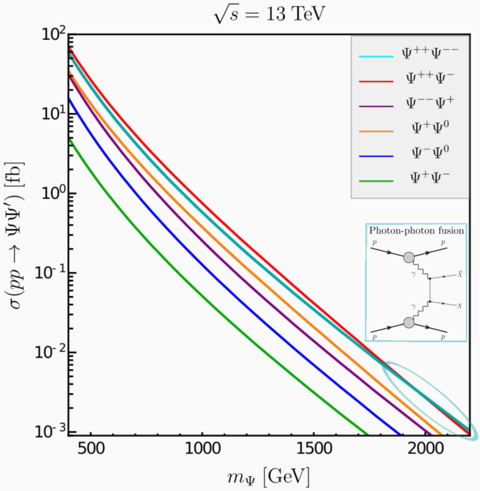


$(g-2)_\alpha$ is proportional to $m_\Psi \, m_{\ell_\alpha}$



Full lines: $Y_{e\phi} = 1$, Dashed lines: $Y_{e\phi} = 4\pi$

Production cross-sections



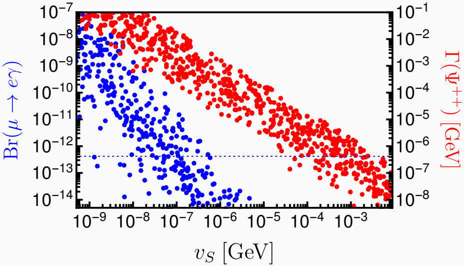
- High-lumi LHC: more than 100 (20) events for $m_\Psi = 1.5\,(1.8)$ TeV before cuts
- Current (non-dedicated) multi-lepton searches by CMS: optimistic rough estimate $m_\Psi > (800 - 900)$ GeV

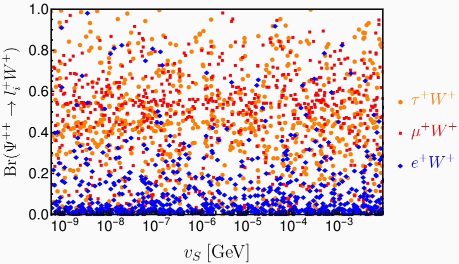
Branching Ratios

[Arbeláez, RC, Fonseca, Hirsch, PRD 102 (2020)]

Neutrino data requires that at least one Yukawa matrix to be non-diagonal:

$\Rightarrow$ flavour violating decays of Ψ^{++}





The upper limit on $\mathrm{Br}(\mu \to e\gamma)$ does not restrict the possibility to have flavour violating decays for Ψ.

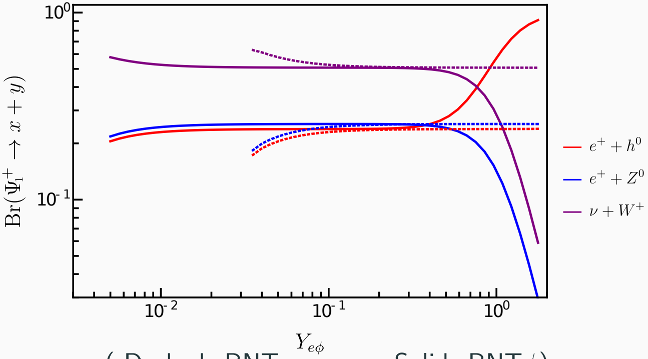
Branching Ratios

[Arbeláez, RC, Fonseca, Hirsch, PRD 102 (2020)]

BUT to explain a_μ and obey the upper bound from cLFV decays at the same time we need large diagonal Yukawa matrices.

$\Rightarrow$ Heavy fermion decays are very nearly **flavour diagonal**.

Enhancement of the decay $\Psi^+ \to e^+ h^0$, particular of the $BNT\phi$ model.



(Dashed: BNT Solid: BNTϕ)

Scotogenic T1-2A model

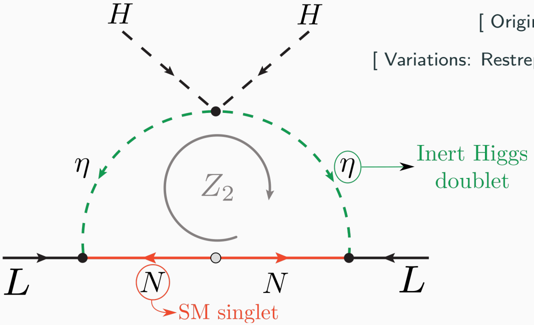
Scotogenic model (a primer)

Radiative mass generation $\Longrightarrow$ naturally **suppressed** neutrino masses

Tree-level is forbidden by the Z_2 symmetry $\Longrightarrow$ stable **DM candidate**

[Original: Ma (2006)]

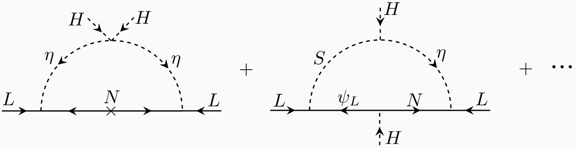
[Variations: Restrepo et al (2013)]



Scotogenic T1-2A model

[Restrepo, Zapata, Yaguna (2020)]
[Sarazin, Bernigaud, Herrmann (2021)]

Neutrino masses:



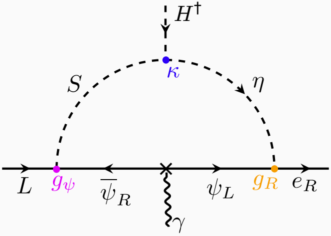
	N_i	$\psi_{L,R}$	η	S	H	L_i	$e_{R,\,i}$
$SU(2)_L$	**1**	**2**	**2**	**1**	**2**	**2**	**1**
$U(1)_Y$	0	-1	+1	0	+1	-1	-2
$\mathbb{Z}_2$	-1	-1	-1	-1	+1	+1	+1

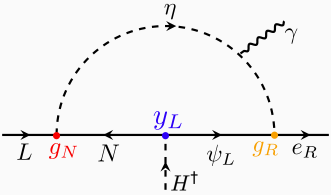
$$-\mathcal{L} \supset g_N\, N_i\, L\, \eta + g_R\, \eta^\dagger\, \psi_L\, e_R^c + g_\psi\, \overline{\psi}_R\, L\, S$$

$$+ y_L\, \psi_L\, H\, N_i + y_R\, \psi_R\, H\, \overline{N}_i + \kappa\, \eta^\dagger\, H\, S + \text{h.c.}$$

$\Rightarrow$ Three light neutrino masses with **two copies of** N.

(g-2) and cLFV





How to make $(g-2)_\mu$ large enough with small Br($\mu \to e\gamma$) ??

- Low new physics mass scale
- Large couplings and Yukawas, mainly lepton diagonal
- Link through the neutrino oscillation data fit

Neutrino structure: $m_\nu \sim Y^T.M.Y$, with $Y = \begin{pmatrix} g_{\psi_e} & g_{\psi_\mu} & g_{\psi_\tau} \\ g_{N1_e} & g_{N1_\mu} & g_{N1_\tau} \\ g_{N2_e} & g_{N2_\mu} & g_{N2_\tau} \end{pmatrix}$.

Leptogenesis in a nut-shell

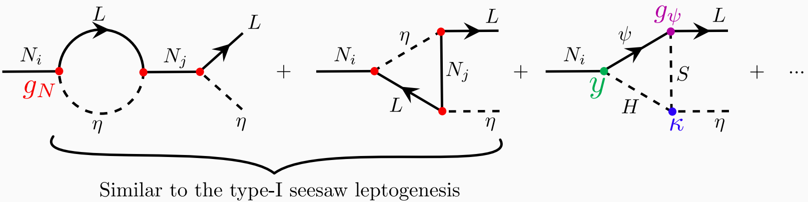
Sakharov conditions for leptogenesis:

$\Delta L \neq 0$ processes that violate C/CP symmetry and fall out of equilibrium at a certain time in the thermal evolution of the Universe.

Majorana m_ν: $\Delta L = 2$
Lepton number violating couplings:
g_N, y, ...

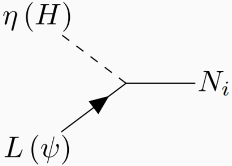
Decay parameter

$$K_i = \frac{\Gamma_N^{tree}}{H(T = M_N)}$$

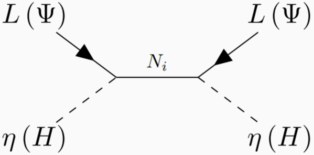


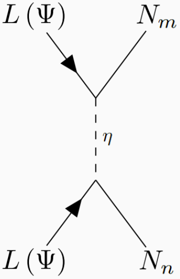
Washout Processes

- Attempt to erase any lepton asymmetry generated.
- Inverse decays, i.e. production of the N_i



- Two-to-two scatterings that modify lepton number, for e.g.





Washout Processes

- Effectiveness of processes determined by ratio of relevant rate w.r.t. the Hubble parameter, i.e.

$$W_D = \frac{\langle \Gamma_{N_i} \rangle}{H(M_i)\, z_i}\,, \qquad \Delta W = \frac{\langle \sigma v \rangle_{\Delta L \neq 0}}{H(M_i)\, z_i}$$

  where $\langle \ldots \rangle$ denotes velocity averaging.

- Define decay parameter

$$K_i = \frac{\Gamma_{N_i}^{\rm tree}}{H(M_i)}$$

  This can be related to the SM neutrino masses.

  See for e.g. **W. Buchmuller, P. Di Bari and M. Plumacher (2004)** or **S. Davidson, E. Nardi and Y. Nir (2008)**

- Different washout regimes characterized by values of K_i
- $K_i > 3$: strong washout regime, where inverse decays are dominant source of washout.

Boltzmann Equations

Define variables $z_i = \frac{M_i}{T}$, so $z_2 = \frac{M_2}{M_1} z_1$.

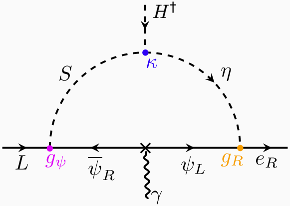
$$\frac{dN_{N_i}}{dz_i} = -z_i\, K_i\, \frac{\mathcal{K}_1(z_i)}{\mathcal{K}_2(z_i)} \left(N_{N_i} - N_{N_i}^{\text{eq.}}\right) \rightarrow \text{Out of equilib. decays of } N_i$$

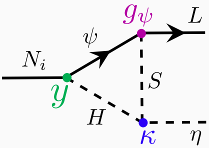
$$\frac{dN_{B-L}}{dz_1} = -\underbrace{z_1 \left[\sum_{i=1}^{2} \epsilon_i\, K_i\, \frac{\mathcal{K}_1(z_i)}{\mathcal{K}_2(z_i)} \left(N_{N_i} - N_{N_i}^{\text{eq}}\right)\right]}_{\text{production of asymmetry}} - \underbrace{(W_D + \Delta W) N_{B-L}}_{\text{washout of asymmetry}} .$$

Choice of Parameters: $(g-2)_\mu \leftrightarrow$ leptogenesis

The neutral component of the vector-like doublet $\psi_{L,R}$ seems to be the preferred DM candidate [Sarazin, Bernigaud, Herrnmann (2021)]

We choose N_i to drive leptogenesis.





Pushing $(g-2)$ to be large g_R ↑↑, κ ↑↑ and g_ψ ↑↑, while reducing the new physics mass scale.

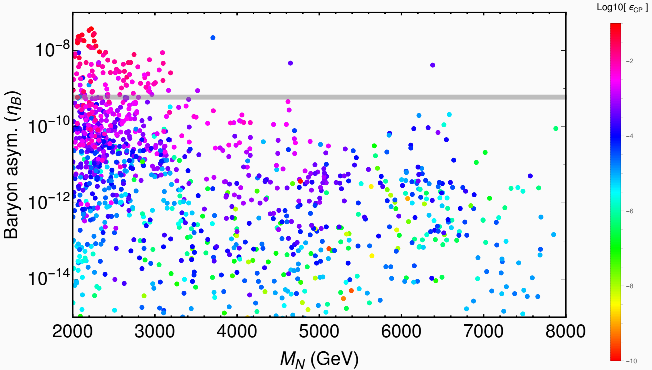
$\implies$ pushes also the CP asymmetry to be large, leading to a **larger lepton number asymmetry**!!

Price to pay: **strong washout regime**!

Results (work in progress) [Alvarez, Banik, RC, Herrmann, Porod, Sarazin, Schnelke]

Preliminary results from a MCMC scan.

All points satisfy DM contraints, cLFV bounds and fit $(g-2)_\mu$.

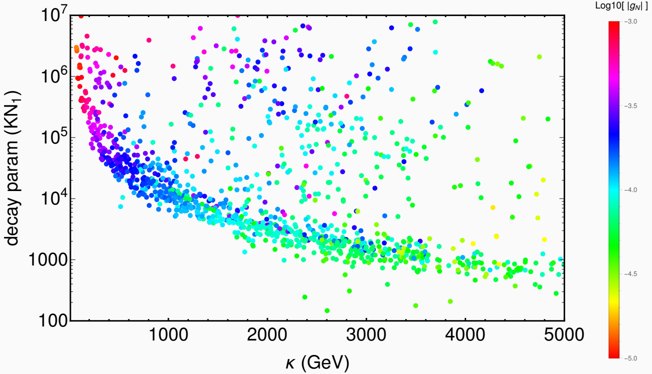


Low-scale leptogenesis despite being in the strong washout regime

[Analogoues to Hugle, Platscher, Schmitz (2018)]

Results (work in progress) [Alvarez, Banik, RC, Herrmann, Porod, Sarazin, Schnelke]

$(g-2)$ together with neutrino masses pushes the asymmetry to larger values.



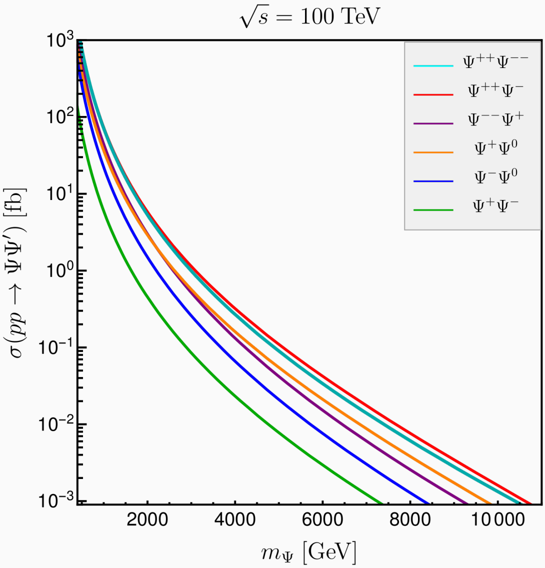
$\Longrightarrow$ Larger κ implies **larger lepton asymmetry**, but also **less wash-out**!!

Summary

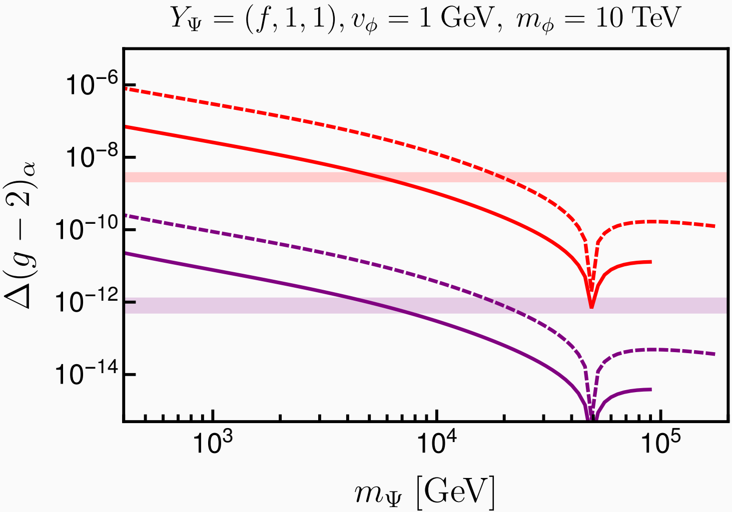
- Neutrino mass mechanisms can be connected to $(g-2)$.
- $(g-2)$ pushes toward **larger couplings** and a **lower new physics mass scale**, while the interplay between the neutrino fit and cLFV constraints affects the flavour structure.
- Depending on the model interesting **pheno** can be found in very different scenarios: LHC, leptogenesis, ...
- **Flavour effects** should also affect strongly in leptogenesis (work to be done!)

Backup (more... really?)

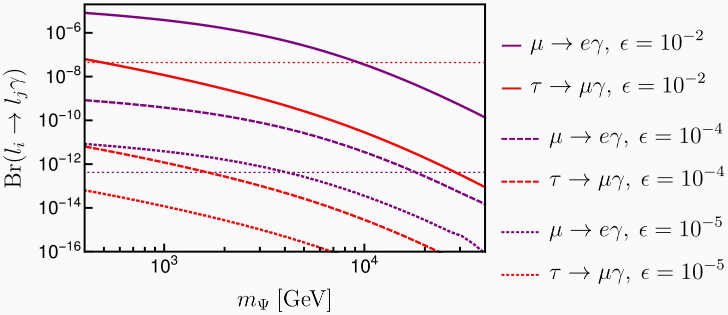
Production cross-section with 100 TeV



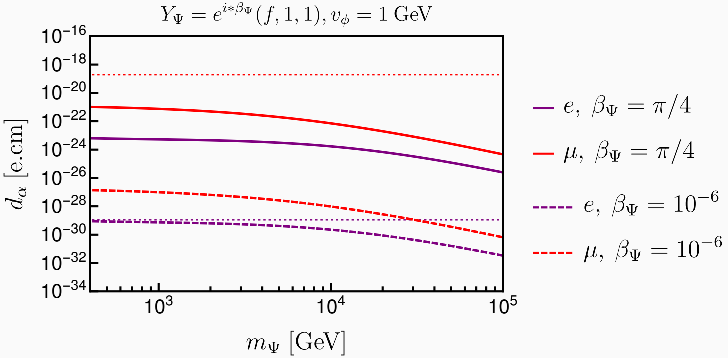
(g-2)$_\alpha$ in the BNTϕ



CLFV decays in the BNTϕ

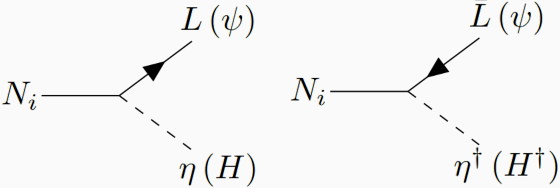


EDM in the BNTϕ



Lepton Asymmetry ϵ

- Difference between decay rates of the N_i into leptons and anti-leptons.

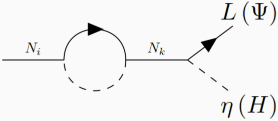


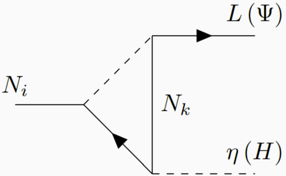
- At tree-level, this is 0; generated at lowest order by interference between tree-level and one-loop diagrams.

ϵ for this model

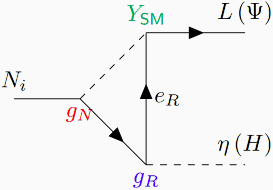
- Have the usual self-energy and triangle diagrams in "vanilla leptogenesis". These can be related to the SM neutrino masses.

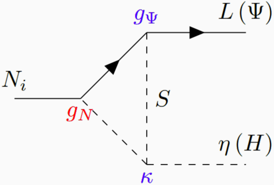
T. Hugle, M. Platscher and K. Schmitz (2018)





- But also have additional triangle diagrams with different coupling combinations.





Solving the Equations

- Start at $T \gg M_2$ with the initial conditions

$$N_{N_i} = N_{N_i}^{\text{eq.}} \quad \text{and} \quad N_{B-L} = 0$$

- Track the number densities down to low temperatures and ascertain $N_{B-L}^f = N_{B-L}(z_1 \gg 1)$

- This value is converted to be compared to the observed baryon-to-photon ratio η_B as

$$\eta_B = \left(\frac{3}{4} \, C_{\text{sph.}} \, \frac{g_*^0}{g_*} \right) N_{B-L}^f$$

where $C_{\text{sph.}} = \frac{8}{23}$, $g_*^0 = \frac{43}{11}$ and $g_* = 122.25$.