Fundamental Symmetries and Rare Decays

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IMPRS Seminar

based on
J.H., PRL **111**, 021801 (2013),
J.H., Werner Rodejohann,
EPL **103**, 32001 (2013).

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Introduction

Symmetries:

unbroken	Poincaré (Lorentz), CPT, $SU(3)_C$, $U(1)_{\text{EM}}$
broken	C, CP, $SU(2)_L \times U(1)_Y$, lepton numbers L_α, ...
?	Baryon number B, total lepton number L, strong CP

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Discovery of (broken) symmetries always exciting, test via rare decays at low energies.

- Here: focus on $B - L$ and $U(1)_{\text{EM}}$ (later), the abelian symmetries.

Baryon and lepton number

- B and L classically conserved in the Standard Model.
- $B + L$ theoretically broken non-perturbatively by 6 units.
- $B - L$ globally conserved.

Fate of fundamental $U(1)_{B-L}$ from experiments. Linked to neutrino nature and matter–antimatter asymmetry.

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$$\text{Dirac neutrinos} \;\Rightarrow \begin{cases} B-L \text{ conserved,} \\ \Delta(B-L) = 4,\, 6,\, 42, \ldots \neq 2\,. \end{cases}$$

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Can we test lepton number violation by higher units?

Effective operators

- Lowest order new processes: $\Delta(B-L) = 4$:

$$\mathcal{O}_{d=6}: \quad \overline{\nu}_R^c \nu_R \, \overline{\nu}_R^c \nu_R$$

$$\mathcal{O}_{d=8}: \quad |H|^2 \, \overline{\nu}_R^c \nu_R \, \overline{\nu}_R^c \nu_R \,, \quad (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, \overline{\nu}_R^c \nu_R \,, \quad F_Y^{\mu\nu} \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R \, \overline{\nu}_R^c \nu_R$$

$$\begin{aligned} \mathcal{O}_{d=10}: \quad & (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \,, \quad |H|^2 (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, \overline{\nu}_R^c \nu_R \,, \\ & F_Y^{\mu\nu} (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \, \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R \,, \quad W_a^{\mu\nu} (\overline{L}^c \tilde{H}^*)(\tilde{H}^\dagger \tau^a L) \, \overline{\nu}_R^c \sigma_{\mu\nu} \nu_R \,, \\ & (\overline{u}_R d_R^c)(\overline{d}_R \tilde{H}^\dagger L)(\overline{\nu}_R^c \nu_R) \,, \dots \end{aligned}$$

$$\mathcal{O}_{d=18}: \quad (\overline{d}_R d_R^c \, \overline{u}_R^c u_R \, \overline{e}_R^c e_R)(\overline{d}_R d_R^c \, \overline{u}_R^c u_R \, \overline{e}_R^c e_R) \,, \dots$$

$$\mathcal{O}_{d=20}: \quad \left[(\overline{(D_\mu L)}^c \tilde{H})(H^\dagger D_\nu L) \right]^2 \supset (\overline{e}_L^c W_\mu^+ W_\nu^+ e_L)(\overline{e}_L^c W^{+\mu} W^{+\nu} e_L) \,, \dots$$

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$$(\overline{u}_R d_R^c)(\overline{d}_R \tilde{H}^\dagger L)(\overline{\nu}_R^c \nu_R) \,, \dots$$

$$\mathcal{O}_{d=18}: \quad \boxed{(\overline{d}_R d_R^c \; \overline{u}_R^c u_R \; \overline{e}_R^c e_R)(\overline{d}_R d_R^c \; \overline{u}_R^c u_R \; \overline{e}_R^c e_R)} \,, \dots$$

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- ν vs. $\overline{\nu}$ undetectable, use only charged particles, e.g. $\mathcal{O}_{d=18}$.

Dominant at low energies: Neutrinoless quadruple beta decay $0\nu4\beta$

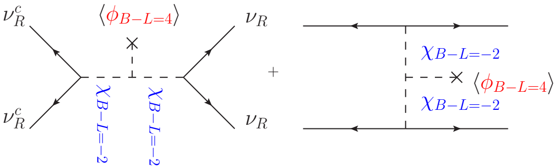
$$4d \to 4u + 4e^- \quad \Leftrightarrow \quad 4n \to 4p + 4e^- \,.$$

UV completion

- One scalar $\phi_{B-L=4}$ to break $B-L$, one scalar $\chi_{B-L=-2}$ as mediator.

$$\mathcal{L} \supset y_{\alpha\beta}\,\overline{L}_\alpha H \nu_{R,\beta} + \kappa_{\alpha\beta}\,\chi_{B-L=-2}\,\overline{\nu}_{R,\alpha}\nu^c_{R,\beta} + \text{h.c.}$$

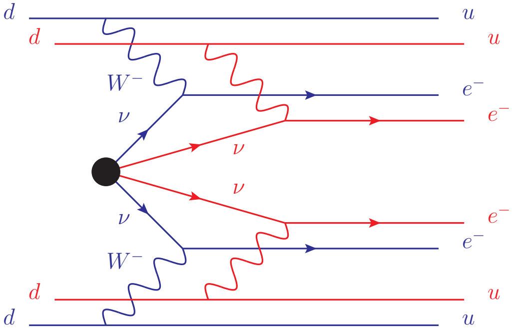
- Neutrinos are Dirac (and $\Delta L = 2$ forbidden) if $\langle \chi_{B-L=-2} \rangle = 0$.
- Scalar potential $V(H,\phi,\chi) \supset -\mu\,\phi_{B-L=4}(\chi_{B-L=-2})^2 + \text{h.c.}$
- Lepton number violation $\Delta L = 4$ still possible![1]
  $\overline{\nu}^c_R \nu_R\ \overline{\nu}^c_R \nu_R =$



[1] Heeck and Rodejohann, EPL **103**, 32001 (2013) [arXiv:1306.0580].

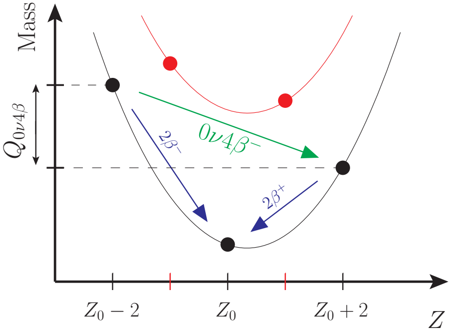
Neutrinoless quadruple beta decay $0\nu4\beta$

$(A, Z) \to (A, Z+4) + 4\,e^-$ via $\mathcal{O} = (\overline{\nu}_L^c \nu_L)^2/\Lambda^2$:



Candidate nuclei

- Experimental aspects of $0\nu4\beta$ independent of underlying mechanism.
- Need beta-stable initial state:



- Decay modes: $0\nu4\beta$ and $2\nu2\beta$ ($0\nu2\beta$ forbidden here).

Candidates for nuclear $\Delta L = 4$ processes

	$Q_{0\nu4\beta}$	Other decays	NA/%
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{19}$ y	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 2 \times 10^{21}$ y	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079 MeV	$\tau^{2\nu2\beta}_{1/2} \simeq 7 \times 10^{18}$ y	5.6
	$Q_{0\nu4\mathrm{EC}}$		
${}^{124}_{54}\mathrm{Xe} \to {}^{124}_{50}\mathrm{Sn}$	0.577 MeV	—	0.095
${}^{130}_{56}\mathrm{Ba} \to {}^{130}_{52}\mathrm{Te}$	0.090 MeV	$\tau^{2\nu2\mathrm{EC}}_{1/2} \sim 10^{21}$ y	0.106
${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$	1.138 MeV	$\tau^{\alpha}_{1/2} \simeq 75$ y	—
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	2.063 MeV	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y	—
	$Q_{0\nu3\mathrm{EC}\beta^+}$		
${}^{148}_{64}\mathrm{Gd} \to {}^{148}_{60}\mathrm{Nd}$	0.116 MeV	$\tau^{\alpha}_{1/2} \simeq 75$ y	—
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	1.041 MeV	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y	—
	$Q_{0\nu2\mathrm{EC}2\beta^+}$		
${}^{154}_{66}\mathrm{Dy} \to {}^{154}_{62}\mathrm{Sm}$	0.019 MeV	$\tau^{\alpha}_{1/2} \simeq 3 \times 10^{6}$ y	—

Best candidate: Neodymium ${}^{150}_{60}\mathrm{Nd}$

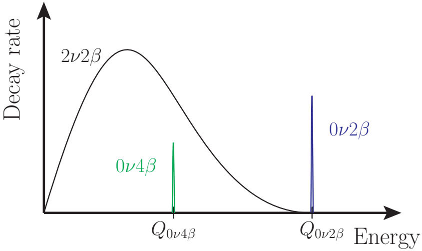
Decay channels:

- ${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{62}\mathrm{Sm}$ via $2\nu 2\beta$ ($\tau_{1/2}^{2\nu 2\beta} \simeq 7 \times 10^{18}\,\mathrm{y}$):

$$0 < \sum E_{e,i} < 3.371\,\mathrm{MeV}.$$

- ${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$ via $0\nu 4\beta$:

$$\sum E_{e,i} = Q_{0\nu 4\beta} = 2.079\,\mathrm{MeV}.$$



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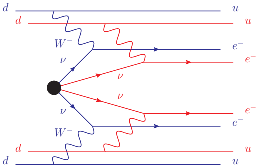

- Very naive comparison with competing channel $2\nu 2\beta$:

$$\frac{\tau_{1/2}^{0\nu 4\beta}}{\tau_{1/2}^{2\nu 2\beta}} \simeq \left(\frac{Q_{0\nu 2\beta}}{Q_{0\nu 4\beta}}\right)^{11} \left(\frac{\Lambda^4}{q^{12} G_F^4}\right) \simeq 10^{46} \left(\frac{\Lambda}{\mathrm{TeV}}\right)^4,$$

with $|q| \sim p_\nu \sim 1\,\mathrm{fm}^{-1} \simeq 100\,\mathrm{MeV}$.

- Estimated rate in toy model unobservably small. Elaborate models with resonances overcome this?

Rare decays in QED

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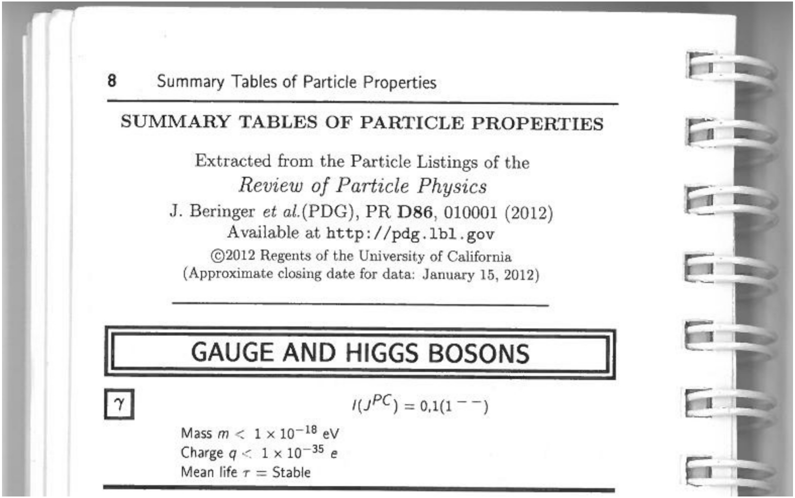

8 Summary Tables of Particle Properties

SUMMARY TABLES OF PARTICLE PROPERTIES

Extracted from the Particle Listings of the
Review of Particle Physics
J. Beringer *et al.*(PDG), PR **D86**, 010001 (2012)
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GAUGE AND HIGGS BOSONS

γ $I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ e
Mean life τ = Stable

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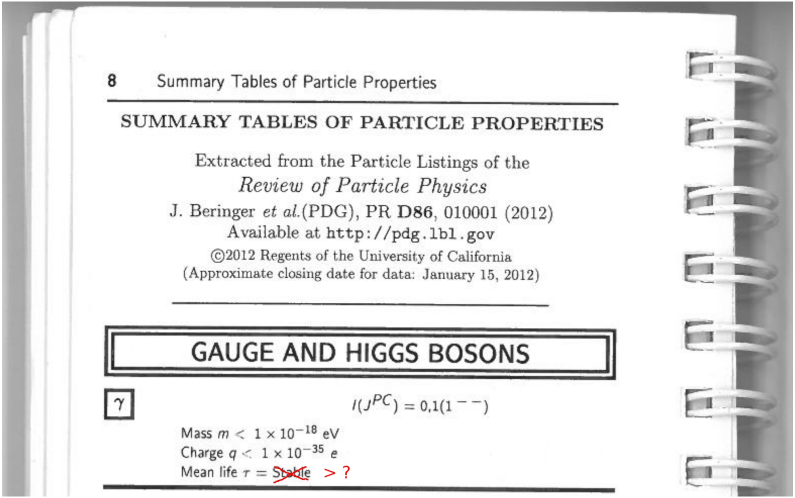

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Mean life τ = ~~Stable~~ $> ?$

Massive photons

- Standard argument: $\mathcal{L} \supset \frac{1}{2} m^2 A_\mu A^\mu$ breaks gauge invariance $A_\mu \to A_\mu - \partial_\mu \theta(x)$.
- True, but theory *still* renormalizable, unitary, charge conserved etc.
- Formal reason: Stückelberg mechanism:

$$\frac{1}{2} m^2 A_\mu A^\mu \to \Delta L \equiv \frac{1}{2}(mA^\mu + \partial^\mu \sigma)(mA_\mu + \partial_\mu \sigma)\,.$$

- Real scalar σ transforms as $\sigma \to \sigma + m\theta(x)$, gauge invariance restored.
- Mass term $\frac{1}{2} m^2 A_\mu A^\mu$ is just gauge *fixing*, not *breaking*.

$U(1)$ gauge bosons can have mass without symmetry breaking.

Massive photons II

Theory:[2]

- QED $U(1)_{\text{EM}} \subset$ Standard Model $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Stückelberg mass for hypercharge boson m_Y^2 gives photon mass + corrections m_γ^2/M_Z^2 to SM.
- Not possible in Grand Unified Theories $SU(3)_C \times SU(2)_L \times U(1)_Y \subset SU(5) \subset SO(10) \subset E_6$.

Experiment:[3]

- Coulomb's law $V(r) = -\frac{e}{r} e^{-mr}$ gives $m \lesssim 10^{-14}\,\mathrm{eV}$.
- Solar wind magnetic field: $m \lesssim 10^{-18}\,\mathrm{eV}$.
- Galactic magnetic field: $m \lesssim 10^{-26}\,\mathrm{eV}$.

Massive photon not crazy, simplest SM extension.

[2] Ruegg and Ruiz-Altaba, arXiv:hep-th/0304245.
[3] Goldhaber and Nieto, arXiv:0809.1003.

Unstable photons

- Massive photon can kinematically decay,[4] e.g. to lightest neutrino: $\gamma \to \nu\nu$.
- Model-independent limit on τ_γ: well-known low-energy photons.

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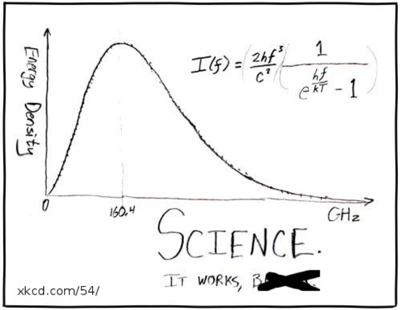
- Model-independent limit on τ_γ: well-known low-energy photons.
- Blackbody spectrum from cosmic microwave background!



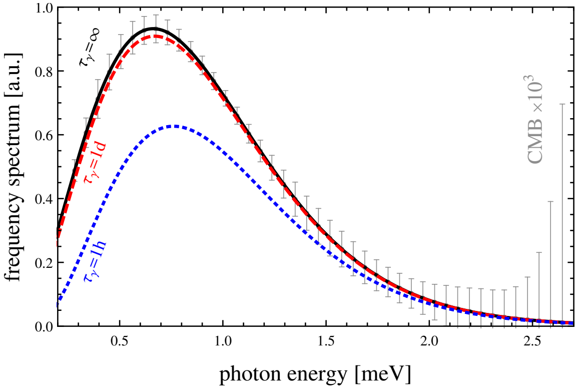
[4] Heeck, PRL **111** (2013), 021801 [arXiv:1304.2821].

Unstable photons

- Modified blackbody spectrum:

$$\rho(E,T)\mathrm{d}E \simeq \frac{1}{\pi^2}\frac{E^3\mathrm{d}E}{\exp(\sqrt{E^2-m^2}/T)-1}\sqrt{1-\frac{m^2}{E^2}}\exp\left(-\frac{m}{E}\frac{d_L}{\tau_\gamma}\right)$$

with comoving distance to CMB $d_L \simeq 47$ billion lightyears.



Limit on photon decay

- Fit to precise (10^{-4}) COBE data: $m < 3 \times 10^{-6}\,\mathrm{eV}$ and model-independent limit on photon lifetime:

$$\tau_\gamma > 3\,\mathrm{yr}\left(\frac{m}{10^{-18}\,\mathrm{eV}}\right) \quad \text{at 95\% C.L.}$$

- Visible photons are boosted: $\tau_\gamma(\text{red light}) \sim 10^{18}\tau_\gamma$.

Caution:

- Assumed free-streaming CMB photons: interactions with ionized plasma generate plasma-mass for γ.
- Model-*dependent* limits far stronger, because $\gamma \to XX$ implies milli-charged X.[5]

[5] Davidson, Hannestad, and Raffelt, arXiv:hep-ph/0001179.

Summary

Fundamental abelian symmetries of SM:

$U(1)_{B-L}$

- global, local, unbroken, broken by 2, 4, 6, ... units?
- Now: $\Delta L = 2$ via $0\nu 2\beta$.
- In principle: $\Delta L = 4$ via $0\nu 4\beta$; experimentally (and theoretically) challenging.
- $\Delta L = 4$ lowest LNV of Dirac neutrinos.

$U(1)_{\mathrm{EM}}$

- Photon can be massive (gauge invariant!).
- *Could* (kinematically) decay, e.g. $\gamma \to \nu\nu$.
- First model-independent bound: $\tau_\gamma > 3\,\mathrm{yr}$.
- Severe implications: photon decay (or mass) would kill GUTs.

Phenomenology of LNV Dirac neutrinos

Quick summary:

- Even with Dirac neutrinos, we can have LNV.
- Lowest order is then $\Delta(B-L) = \Delta L = 4$, via $\mathcal{O}_{d=6} = (\overline{\nu}_R^c \nu_R)^2/\Lambda^2$.

How to check for $\Delta L = 4$?

- Neutrinoless quadruple beta decay $(A, Z) \to (A, Z+4) + 4\, e^-$.
- Collider process $e^- e^- \to W^- W^- W^- W^- \ell^+ \ell^+$.
- Rare meson decays etc.?

All tough, many particles in final state!

$\Delta L = 4$ can however easily be relevant in the early Universe
$\Rightarrow$ new Dirac leptogenesis mechanism predicting $3.14 \lesssim N_{\text{eff}} \lesssim 3.29$.[6]

[6] Heeck, PRD **88**, 076004 (2013) [arXiv:1307.2241].

Comments on $0\nu4\beta$

- Background: electrons from $2\nu2\beta$ kick out two more e^-.
  $\Rightarrow$ 4 e^- with $\sum E_i \sim Q_{0\nu4\beta}$ possible.
- $0\nu4\beta$ to excited state ${}^{150}_{64}\mathrm{Gd}^*$: Q reduced by $0.6\,\mathrm{MeV}$ (2^+) or $1.2\,\mathrm{MeV}$ (0^+), but more photons...
- Nuclear matrix elements impossible (?) to calculate.
  $\Rightarrow$ No way to extract fundamental couplings from $\tau_{0\nu4\beta}$ (?)
- $0\nu6\beta$ etc. all involve beta-unstable nuclei.
  $\Rightarrow$ $0\nu2\beta$ and $0\nu4\beta$ somewhat unique.
- Very different $\Delta(B-L)=4$ decay: $4n \to 3p + 3e^-$, mimics $0\nu3\beta$.
  Candidate:

$$
{}^{148}_{60}\mathrm{Nd} \xrightarrow{931.6\,\mathrm{MeV}} {}^{147}_{63}\mathrm{Eu} + 3e^-
$$

$$
\hookrightarrow \quad {}^{147}_{62}\mathrm{Sm}\ \left(\tau^{\beta^+}_{1/2} \simeq 24\,\mathrm{d}\right)
$$

followed by the β^+ decay into ${}^{147}_{62}\mathrm{Sm}$ with half-life $24\,\mathrm{d}$.

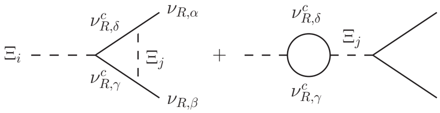
Dirac $B-L$: Leptogenesis

Leptogenesis via $\Delta L = 4$?

- Scalar potential $V(H,\phi,\chi) \supset -\mu\, \phi_{B-L=4} (\chi_{B-L=-2})^2$ breaks complex $\chi_{B-L=-2} = (\Xi_1 + i\,\Xi_2)/\sqrt{2}$ into two real scalars with mass

$$m_1^2 = m_c^2 - 2\mu \langle \phi_{B-L=4} \rangle\,, \qquad m_2^2 = m_c^2 + 2\mu \langle \phi_{B-L=4} \rangle\,.$$

- Heavy mediator scalar Ξ_j decays to $\nu_R \nu_R$ or $\overline{\nu}_R \overline{\nu}_R$ out-of-equilibrium in early Universe.[7]



- *CP* violation requires *second* scalar $\chi_{B-L=-2}$.

Asymmetry in ν_R. How to translate to baryon asymmetry?

[7] Heeck, PRD **88**, 076004 (2013) [arXiv:1307.2241].

Baryon Asymmetry

$$Y_{\nu_R} \equiv \frac{n_{\nu_R}}{s} \sim \frac{1}{g_*} \frac{\Gamma\left(\Xi_i \to \nu_R \nu_R\right) - \Gamma\left(\Xi_i \to \nu_R^c \nu_R^c\right)}{\Gamma\left(\Xi_i \to \nu_R \nu_R\right) + \Gamma\left(\Xi_i \to \nu_R^c \nu_R^c\right)} .$$

- Dirac-Yukawa coupling $Y_\nu = m_\nu / \langle H \rangle$ too small to equilibrate ν_R...

Add second Higgs doublet H_2 with large Yukawa $\overline{L} H_2 \nu_R$:

- Neutrinophilic H_2 with small VEV $\langle H_2 \rangle \sim 1\,\mathrm{eV}$
  $\Rightarrow$ Dirac neutrinos light with large Yukawas.
- H_2 moves Y_{ν_R} to Y_{ν_L}.
- Sphalerons move Y_{ν_L} to Y_B.

$\Rightarrow$ Different from neutrinogenesis, similar to standard leptogenesis!

- Necessary thermalization of $\nu_R \Rightarrow N_\mathrm{eff} > 3$!
- $3.14 \lesssim N_\mathrm{eff} \lesssim 3.29$ depending on H_2^+ mass and Yukawa coupling.
- Specific collider signatures of neutrinophilic H_2.[8]

[8] S. M. Davidson and H. E. Logan, PRD **80**, 095008 (2009).