Search for hidden particles at SHiP. Lecture 5. Shern-Simons portal. NHL, νMSM.

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Chern-Simons portal. Effective Lagrangian

Effective Chern-Simons interaction is coupling of a new (pseudo) vector particle X_μ to the SM particles in the form of 4-dimension operators:

$$\mathcal{L}_{CS} = c_z \epsilon^{\mu\nu\lambda\rho} X_\mu Z_\nu \partial_\lambda Z_\rho + c_\gamma \epsilon^{\mu\nu\lambda\rho} X_\mu Z_\nu \partial_\lambda A_\rho + \left\{ c_w \epsilon^{\mu\nu\lambda\rho} X_\mu W_\nu^- \partial_\lambda W_\rho^+ + h.c. \right\},$$

where A_μ, Z_μ, W_μ stand for the photon, $W^\pm$ and Z-boson fields, and c_z; c_γ; c_w are some dimension-less coefficients. Obviously, coefficients c_z and c_γ are real, but c_w can be complex. This Lagrangian is not gauge invariant under the group $SU_W(2) \times U_Y(1)$ of the SM and can be considered only as low-energy limit of some SM extension.

Ignatios Antoniadis, Alexey Boyarsky, Sam Espahbodi, Oleg Ruchayskiy, and James D. Wells, Nucl. Phys., B824: 296313, 2010.

Sergey Alekhin et al. A facility to Search for Hidden Particles at the CERN SPS: the SHiPphysics case. Rept. Prog. Phys., 79(12): 124201, 2016

Effective Lagrangian

Effective Lagrangian can be written in the gauge invariant form with help of 6-dimension operators

$$\mathcal{L}_1 = \frac{C_Y}{\Lambda_Y^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger H B_{\lambda\rho} \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.$$

$$\mathcal{L}_2 = \frac{C_{SU(2)}}{\Lambda_{SU(2)}^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger F_{\lambda\rho} H \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.,$$

where the Λ_Y, $\Lambda_{SU(2)}$ are new scales of the theory, C_Y, $C_{SU(2)}$ are new dimensionless coupling constants. In further calculations, it is convenient to redefine the constants as follows

$$\mathcal{L}_1 = \frac{C_1}{v^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger H B_{\lambda\rho} \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.$$

$$\mathcal{L}_2 = \frac{C_2}{v^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger F_{\lambda\rho} H \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.,$$

where v is the vacuum expectation value of the Higgs field; H – scalar field of the Higgs doublet; $B_{\mu\nu}$, $F_{\mu\nu}$ – field strength tensors of the $U_Y(1)$ and $SU_W(2)$ gauge fields; $C_1 = c_1 + ic_{1i}$, $C_2 = c_2 + ic_{2i}$ are some dimension-less complex coefficients.

Effective Lagrangian

In the low energy limit (after spontaneously breaking of the $SU_W(2) \times U_Y(1)$ symmetry) in the unitary gauge we can rewrite this Lagrangian in terms of the Z_μ, $W^\pm$ fields and the electromagnetic field A_μ. It contains new interactions

$$\mathcal{L}_1 = X_\mu \left[c_W \partial_\lambda A_\rho - s_W \partial_\lambda Z_\rho\right] \left(1 + \frac{h}{v}\right) \left[2c_1 \frac{\partial_\nu h}{v} + c_{1i} \frac{e}{s_W c_W} Z_\nu \left(1 + \frac{h}{v}\right)\right] \epsilon^{\mu\nu\lambda\rho},$$

$$\mathcal{L}_2 = X_\mu \left(1 + \frac{h}{v}\right) \left\{ \left[\frac{g^2(c_2 + ic_{2i})}{2} \left(1 + \frac{h}{v}\right) W_\nu^- \partial_\lambda W_\rho^+ + h.c.\right] + \right.$$
$$+ ig^3 c_2 W_\nu^- W_\rho^+ V_\lambda^3 \left(1 + \frac{h}{v}\right) - iW_\lambda^- W_\rho^+ \left[c_{2i} g^2 \frac{\partial_\nu h}{v} - \frac{c_2 g^3}{2c_W} Z_\nu \left(1 + \frac{h}{v}\right)\right] +$$
$$\left. + \partial_\lambda V_\rho^3 \left[\frac{g^2 c_2}{2c_W} \left(1 + \frac{h}{v}\right) Z_\nu - c_{2i} g \frac{\partial_\nu h}{v}\right] \right\} \epsilon^{\mu\nu\lambda\rho}$$

Effective Lagrangian

Comparing terms of three particles interactions in Lagrangians we get

$$c_z = -c_{1i}g' + c_2\frac{g^2}{2},$$
$$c_\gamma = +c_{1i}g + c_2\frac{gg'}{2},$$
$$c_w = (c_2 + ic_{2i})\frac{g^2}{2}.$$

Constraints on the Chern-Simons model parameters

The bounds on c_z; c_w and c_γ in the range of masses $M_X <$ few GeV come from the possible contributions of the Chern-Simons interactions to the Z or W total width. This contributions are dominated by the longitudinal component of X-boson:

$$\Gamma(Z \to \gamma X) = c_\gamma^2 \frac{\cos\theta_W M_W}{96\pi} \left(\frac{M_Z^2}{M_X^2} + 1 \right);$$

$$\Gamma(W^+ \to X u \bar{d}) = [Re\, c_w]^2 \frac{G_F V_{ud}^2}{288\sqrt{2}\pi^3} \frac{M_W^5}{M_X^2}.$$

It can be hidden in the uncertainty of experimental measurement of Γ^W_{tot} or Γ^Z_{tot} !

Full width $\Gamma_W = 2.085 \pm 0.042$ GeV.
Full width $\Gamma_Z = 2.4952 \pm 0.0023$ GeV.

Constraints on the Chern-Simons model parameters

From the uncertainty of the full width of $W^{\pm}, Z$ bosons one can get:
$c_z^2, c_w^2 < 10^{-3} \left(\frac{M_X}{1GeV}\right)^2$.

In case of c_γ a significantly stronger bound comes from the measuring of the single photon events at LEP (Large ElectronPositron Collider). There the branching at the level $Br < 10^{-6}$ was established for photons with the mass above 15 GeV. This leads to the strong bound $c_\gamma^2 \lesssim 10^{-9} \left(\frac{M_X}{1GeV}\right)^2$.

L3 Collaboration, M. Acciarri et al., Search for new physics in energetic single photon production in e^+e^- annihilation at the Z resonance, Phys.Lett. B412 (1997) 20-209.

Constraints on the Chern-Simons model parameters

For successful investigation of X-particle in SHiP we will we require the particle to be able to pass 60 meters (decay volume of the SHiP detector) and having mass $M_X < 5$ GeV.

To make some estimation we need to know total decay width of the X-particle as function of its mass.

This is the task that needs to be done in the near future.

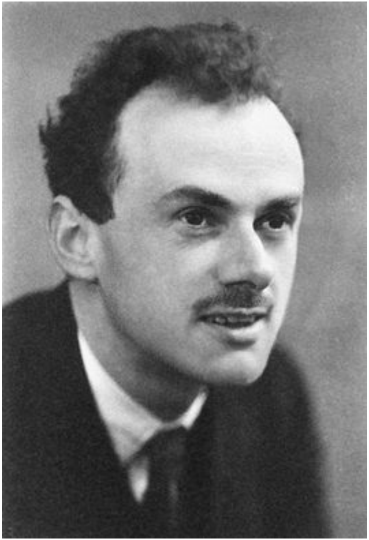
Heavy neutral leptons (HNL)

From observation of neutrino oscillations we conclude that neutrino are massive particles. **But there is a problem !** SM is a theory that contains only left-handed massless neutrinos!

There are only three way to introduce in the Field Theory massive neutrinos:

1. Dirac way: let's simply add to the SM **new** right-handed neutrinos (**sterile neutrinos**) that not (or very weakly) interact with other SM particles:
   $\mathcal{L}_m^D = -m\bar{\psi}\psi = -m(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$
2. Majorana way: **we do not need a new particles**. Let's suppose that neutrino are true neutral particles $\chi = \nu + \nu^C$, then $\nu_L^C \equiv \nu_R$:
   $\mathcal{L}_m^M = -m(\bar{\nu}_L \nu_L^C + \bar{\nu}_L^C \nu_L)$.
3. Dirac-Majorana way: **Boys do not quarrel ! Let's join your variants!**
   Let's add to theory sterile right-handed neutrino, as Dirac in way, and let's do left-handed and right-handed neutrinos true neutral, as in Majorana way:
   $\mathcal{L}_m^{DM} = -m_1(\bar{\nu}_L \nu_L^C + \bar{\nu}_L^C \nu_L) - m_2(\bar{\nu}_R \nu_R^C + \bar{\nu}_R^C \nu_R)$.

Dirac and Majorana formalism



Paul Adrien Maurice Dirac

Ettore Majorana

Dirac and Majorana formalism

Dirac formalism:

$$L^D = \sum_{n=1}^{3} (i\overline{\nu_{nL}}\gamma^\mu \partial_\mu \nu_{nL} + i\overline{\nu_{nR}}\gamma^\mu \partial_\mu \nu_{nR}) - \sum_{m,n=1}^{3} \Big(\overline{\nu_{nL}} M^D_{nm} \nu_{mR} + \overline{\nu_{nR}} \left(M^D\right)^+_{nm} \nu_{mL}\Big).$$

We have to make quadratic mass term to have a massive state of neuntino!

$$M = UmV^+, \quad UU^+ = VV^+ = 1, \quad m \equiv diag(m_1, m_2, m_3)$$

$$\overline{\nu_L} M^D \nu_R = \overline{\nu_L} UmV^+ \nu_R = \overline{(U^+ \nu_L)} m (V^+ \nu_R) = \overline{\nu'_L} m \nu'_R,$$

$$\nu_{lL}(x) = \sum_{i=1}^{3} U_{li} \nu'_{iL}(x), \quad \nu_{lR}(x) = \sum_{i=1}^{3} V_{li} \nu'_{iR}(x),$$

Decomposition coefficients determine the probability of finding a flavour neutrino in a certain mass state!

Dirac and Majorana formalism

Majorana formalism:

$$\mathcal{L}^M = \frac{i}{2}\overline{\nu_L}\gamma^\mu \partial_\mu \nu_L + \frac{i}{2}\overline{\nu_L^c}\gamma^\mu \partial_\mu \nu_L^c - \left(\overline{\nu_L^c}\, \frac{M^M}{2}\, \nu_L + \overline{\nu_L}\, \frac{\left(M^M\right)^+}{2}\, \nu_L^c \right),$$

where matrix M^M is symmetric matrix.

$$m = U^T M^M U, \quad UU^+ = 1, \quad M = M^T$$

$$\nu_{lL}(x) = \sum_{i=1}^{3} U_{li} n_{iL}(x)$$

Decomposition coefficients determine the probability of finding a flavour neutrino in a certain mass state!

Dirac and Majorana formalism

Dirac-Majorana formalism

$$\mathcal{L}^{DM} = \frac{i}{2}\overline{N_L}\gamma^{\mu}\partial_{\mu}N_L + \frac{i}{2}\overline{N_L^c}\gamma^{\mu}\partial_{\mu}N_L^c - \left(\overline{N_L^c}\,\frac{M^{DM}}{2}\,N_L + h.c.\right).$$

$$M^{DM} = \begin{pmatrix} M^L & (M^D)^T \\ M^D & M^R \end{pmatrix}, \qquad N_L = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix};\; N_L^c = \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}.$$

After diagonalization of mass matrix we have $N_L + N_L$ massive Majorana particles.

$$\nu_{lL}(x) = \sum_{i=1}^{3} V_{li}\nu'_{iL}(x) + \sum_{i=4}^{N} V_{li}\nu'^{c}_{iR}(x)$$

Active neutrino has a transition probability to become a sterile neutrino!

See-saw mechanism

Let's consider one left and one right neutrino in Dirac-Majorana formalism. Let $M^D \ll M^R$

$$m_{\binom{1}{2}} = \frac{M^R}{2}\left[1 \pm \sqrt{1+\left(\frac{2M^D}{M^R}\right)^2}\right] \simeq$$

$$\simeq \frac{M^R}{2}\left[1 \pm \left(1 + \frac{1}{2}\left(\frac{2M^D}{M^R}\right)^2\right)\right],$$

$$m_1 \simeq M^R; \quad m_2 \simeq -(M^D)^2/M^R.$$

What particles are neutrinos?

Are neutrinos Dirac or Majorana type particles?
Neutrino oscillations can not answer this question!

Massless neutrino in the SM: Lagrangian SM has a symmetry

$$\begin{cases} \nu_n \to e^{i\alpha_n}\nu_n \\ e_n \to e^{i\alpha_n}e_n \end{cases} ; \quad \begin{cases} \overline{\nu_n} \to e^{-i\alpha_n}\overline{\nu_n} \\ \overline{e_n} \to e^{-i\alpha_n}\overline{e_n} \end{cases}$$

and we have conservation laws for the flavour lepton number **separately**:

$$\sum_i L_e^i = const, \qquad \sum_i L_\mu^i = const, \qquad \sum_i L_\tau^i = const.$$

What particles are neutrinos?

Neutrino are massive and are of Dirac type: Lagrangian has a symmetry

$$\nu_{IL}(x) \to e^{i\alpha}\nu_{IL}(x); \quad \nu_{IR}(x) \to e^{i\alpha}\nu_{IR}(x)$$

and we have conservation laws for the **total** flavour lepton number:

$$\sum_i L_e^i + \sum_i L_\mu^i + \sum_i L_\tau^i = const.$$

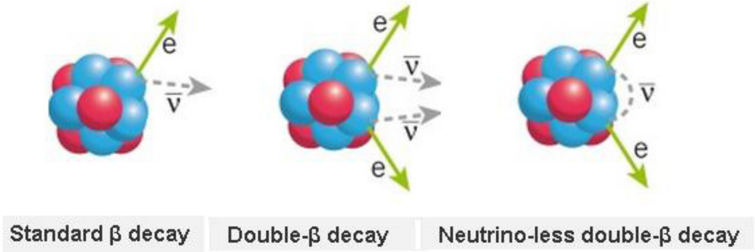
Neutrino are massive and are of Majorana type: **Lagrangian has no symmetry**

$$\nu_L \to e^{i\alpha}\nu_L \quad \nu_L^c \to e^{-i\alpha}\nu_L^c, \quad \overline{\nu_L^c} \to \overline{\nu_L^c}\, e^{i\alpha} \quad \Rightarrow \quad \overline{\nu_L^c}\nu_L \to e^{2i\alpha}\overline{\nu_L^c}\nu_L \neq \overline{\nu_L^c}\nu_L.$$

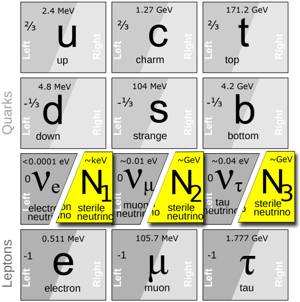
Any lepton number is not conserved!

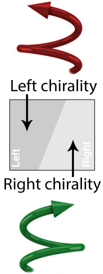
What particles are neutrinos?

The unconditional proof of the Majorana nature of the neutrino would be the detection of the neutrino-less double β-decay!

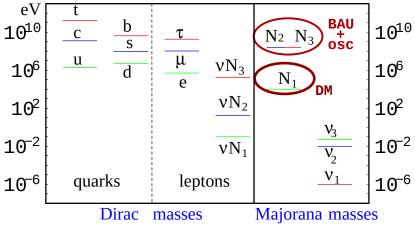


Neutrino minimal Standard Model (νMSM)

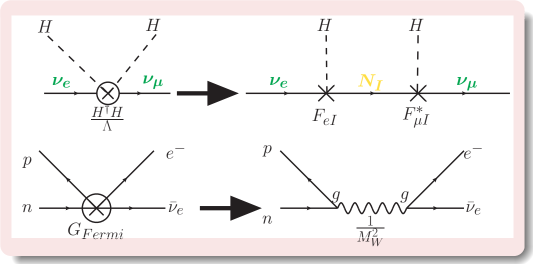




- **Neutrino oscillations:** particles N_2, N_3
- **Baryon asymmetry:** same particles N_2, N_3
  - masses $\mathcal{O}(100)$ MeV – $\mathcal{O}(80)$ GeV
- **Dark matter:** particle N_1
  - mass $1 - 50$ keV
- **Inflation:** Higgs field coupled to gravity
  - Inflationary parameters for $M_{\text{Higgs}} \sim 126$ GeV in perfect agreement with observations



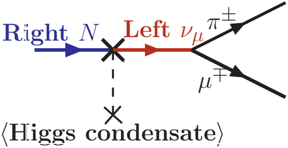
- **Neutrino Minimal Standard Model (νMSM)**
- Masses of right-handed neutrinos as of other order of masses of other leptons
- Yukawas as those of electron or smaller
- Review: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]



Neutrino oscillations: requires **at least two** new particles – right-handed (or sterile) neutrinos

- Sterile neutrinos behave as **superweakly interacting** massive neutrinos with a smaller Fermi constant $\boxed{U^2 \times G_F}$
- Mixing angle $U^2 \ll 1$:

$$U^2 < \frac{m_{\text{atm}}}{M_{\text{sterile}}}$$

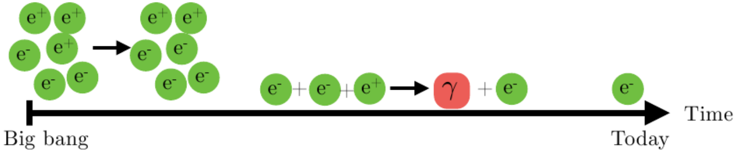


- Sterile neutrinos carry no charges w.r.t. Standard Model interactions

Baryon asymmetry of the Universe

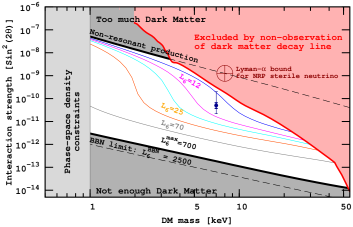
All BSM puzzles are resolved with the particles lighter than M_W

- Need source of CP violation in the early Universe (CP phase of the CKM matrix is not enough!) $\Rightarrow$ CP-violating phase in the active-sterile Yukawa matrix (similar to the quark sector)
- Need particles not in equilibrium at temperatures ~ 100 GeV (even neutrinos stay in equilibrium with the plasma up until ~ 1 MeV temperature) $\Rightarrow$ sterile neutrinos are interacting **super**-weakly
- Need at least two sterile neutrinos
- masses as low as $\mathcal{O}(100)$ MeV (degenerate spectrum)
- Can be **the same** particle that generate neutrino masses and oscillations



Dark matter particle should be

- Massive, neutral, cosmologically long-lived
- Neutrino is **too light** (to be cosmological dark matter and explain mass of small galaxies)
- Good candidate: sterile neutrino with mass $1 - 50$ keV
- Decaying dark matter (lifetime $\tau > 10^{27}$ sec)



ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

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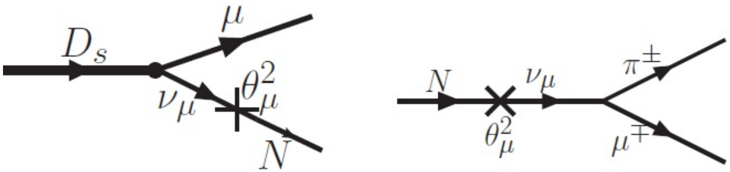
PRL (2014) [1402.4119]

Energy: 3.5 keV. Statistical error for line position $\sim 30 - 50$ eV.
Lifetime: $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
Possible origin: decay $\text{DM} \to \gamma + \nu$ (fermion) or $\text{DM} \to \gamma + \gamma$ (boson)

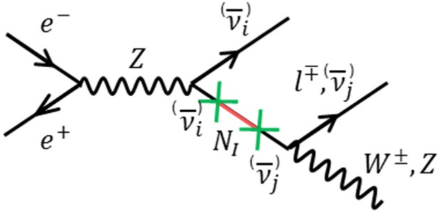
3.5 keV line. Current status

- Several other groups confirmed the existence of the line in the Perseus cluster **[1411.0050]** Milky Way center **[1405.7943,1408.1699,1411.1758]**
- Interpretation as Potassium emission line? (K XVIII ion has transitions at 3.47 keV and 3.51 keV)
  - Impossible to give simultaneous explanation for Milky Way, Andromeda galaxy and Persesus cluster at the same time
- Non-observation from the outskirts of galaxy clusters (our original work, **[1408.4115]**)
  - Does not contradict to DM interpretation: DM distribution is sharply peaked in the center
- Dwarf spheroidal galaxies? Perfect targets: dark, dense. Not enough sensitivity with the current data **[1408.3531]**
- $\Rightarrow$ Need more data!!

Search of the HNL in the laboratory

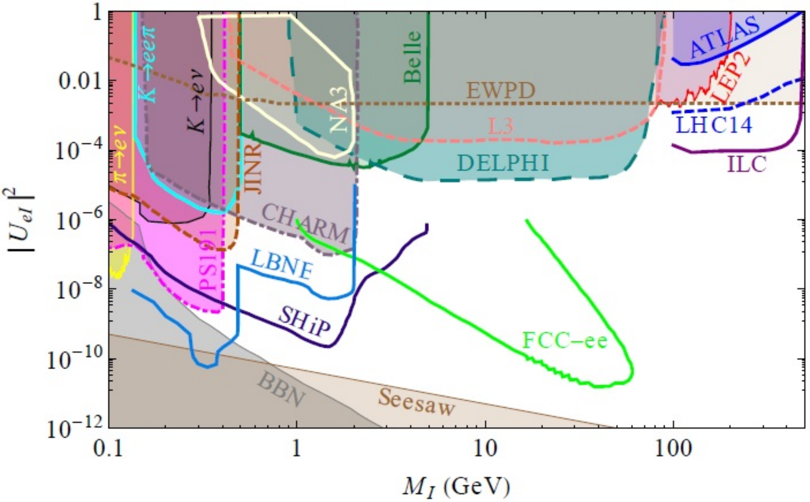


Production (left) and subsequent decay (right) of the particle N_I (SHiP case).



Feynman diagram dominating the production of right-handed neutrinos at the Z pole (not the SHiP case).

Example of the model restrictions



Limits on the mixing between the electron neutrino and a single HNL in the mass range 100 MeV – 500 GeV. The similar restrictions exist for muon- and tau-neutrinos.