Erratum and Addendum to: How to find neutral leptons of the \( \nu \)MSM?

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Erratum to: JHEP10(2007)015
Steadily growing interest to the subject of GeV-scale sterile neutrinos responsible for the active neutrino mixing and matter-antimatter asymmetry of the Universe brought us to submit the Erratum to our 6 year old paper [1] published in JHEP 0710 (2007) 015. There we have discussed low-energy phenomenology of Neutrino Minimal Standard Model (νMSM), an extension of Standard Model of particle physics where with three sterile neutrinos of masses below electroweak scale one can explain neutrino oscillations, dark matter phenomena and baryon asymmetry of the Universe. The original paper [1] must be corrected with respect to the following issues.

- lines 5–7 from bottom on page 9 must be replaced with
  
  \begin{align*}
  \text{model I :} & \quad f_\nu^2 : f_\mu^2 : f_\tau^2 \approx 52 : 1 : 1, \quad \kappa = 2, \\
  \text{model II :} & \quad f_\nu^2 : f_\mu^2 : f_\tau^2 \approx 1 : 16 : 3.8, \quad \kappa = 1, \\
  \text{model III :} & \quad f_\nu^2 : f_\mu^2 : f_\tau^2 \approx 0.061 : 1 : 4.3, \quad \kappa = 1.
  \end{align*}

- The upper limits on active-to-sterile mixing $U^2$ shown in figure 1 (and then used in the paper) were taken directly from published results of CERN PS191 experiment [2, 3]. However, the analysis of [2, 3] did not include contribution from the weak neutral currents to sterile neutrino decays. The account for the neutral currents has been recently done in [4], where the updated limits can be found. They deviate by a factor 1–2 from those used in the paper.

- The upper limit on active-to-sterile mixing $U^2$ coming from the successful baryogenesis in the early Universe was adopted from [5]. With significant progress in understanding of the oscillationary processes in the primordial plasma happened after the publication of the paper this limit was revised. The most recent results on this subject can be found in ref. [6]. That upper limit on $U^2$ is by a factor about 20 weaker than what was adopted in [1], enlarging the cosmologically interesting region of model parameter space.

- Eq. (B.2) must be replaced with

\[
\frac{d\text{Br} (H \to H' l^\pm_\alpha N)}{dE_N} = \tau_H |U_\alpha|^2 \frac{|V_{HH'}|^2 G_F^2}{64\pi^3 M_H^2} \\
\times \int dq^2 \left( f_+^2(q^2) \left( q^2 \left( M_H^2 + M_{H'}^2 \right) - (M_H^2 - M_{H'}^2)^2 \right) \right) \\
+ 2f_+(q^2)f_-(q^2) \left( M_H^2 \left( 2M_H^2 - 2M_{H'}^2 - 4E_N M_H - M_l^2 + M_N^2 + q^2 \right) \\
+ M_{H'}^2 \left( 4E_N M_H + M_l^2 - M_N^2 - q^2 \right) \right) \\
+ f_+^2(q^2) \left( \left( 4E_N M_H + M_l^2 - M_N^2 - q^2 \right) \left( 2M_H^2 - 2M_{H'}^2 - 4E_N M_H - M_l^2 + M_N^2 + q^2 \right) \right) \\
- \left( 2M_H^2 + 2M_{H'}^2 - q^2 \right) \left( q^2 - M_N^2 - M_N^2 \right) \right),
\]
In eq. (B.3) the factor in front of integral must be replaced with
\[ \tau_H \cdot |U_\alpha|^2 \cdot \frac{|V_{iH}|^2 G_F^2}{32\pi^3 M_H^2}. \]

Discussion of sterile neutrino production in beam-dump (to say fixed target) must be corrected as follows.

- The last equation on page 21 must be replaced with
  \[ \sigma_{pp \to s} \sim \sigma_{pp}^{\text{total}}, \quad \sigma_{pp \to c} \sim 10^{-3} \cdot \sigma_{pp}^{\text{total}}, \quad \sigma_{pp \to b} \sim 10^{-5} \cdot \sigma_{pp}^{\text{total}}. \]

- The first sentence and formula on page 24 must be replaced with
  The total number of neutrinos produced by \( N_{\text{POT}} \) incident upon a target protons with energy \( E \) is given by
  \[ N_N(E) = \sum_{Q=s,\bar{s},c,\bar{c},b,\bar{b}} \xi_Q \cdot \frac{\sigma_{pA \to Q}(E)}{\sigma_{pA}^{\text{total}}(E)} \cdot N_{\text{POT}}(E), \]
  where \( A \) refers to the target material.

- The formula on page 25 must be replaced with
  \[ N_N(E) = \sum_{Q=s,\bar{s},c,\bar{c},b,\bar{b}} \xi_Q \cdot \chi_Q(E) \cdot N_{\text{POT}}(E). \]

- In table 1 the column with \( M_{pp} \) at the top must be omitted. The entries in the column with \( \chi_s \) at the top must be replaced with numbers 1.8, 1.6, 1.0, 2.2 (starting from top).

- Right after the formula on page 25 it must be written:
The introduced above quantity \( \chi_Q \) has a meaning of the number of heavy quarks produced per one incident proton. For the heaviest charm and bottom quarks, rarely produced in collisions, it coincides with ratio of the inclusive quark production cross section to the total hadron cross section, and these ratios are presented in table 1. For the strange quark this quantity is not small, may exceed unit, and may be estimated as a product of total multiplicity (average number of secondary particles in proton-proton collision, from about 7 to 15 [7] for the experiments from table 1), and the fraction of \( s\bar{s} \)-pairs in a final state of hadron collisions (that is \( \approx 1/7 \) [8]) saturated by light quark production. This product is presented in table 1 as \( \chi_s \).

- The third formula on page 27 must be replaced with
  \[ N_H(E) = N_{\text{POT}}(E) \cdot \chi_Q(E) \cdot \text{Br} (Q \to H). \]

- The fourth formula on page 27 must be replaced with
  \[ N_N^{\text{decays}} = N_{\text{POT}} \cdot \frac{\Delta l}{\tau_N} \cdot \sum_{Q,H} \chi_Q \cdot \xi_{Q,H} \cdot \frac{M_N}{\langle p_L^N \rangle_H}. \]
  and summation goes over all hadrons and all strange, charm, beauty quarks and antiquarks.
As a net result, the contributions of charm and beauty quarks to the sterile neutrino production have been overestimated in [1] by factors 6.5, 5.5, 3.5 and 7.5 corresponding to the experiments in Table 1 listed from top. The contributions of strange quarks to sterile neutrino production have been underestimated in [1] by factor 2.

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References

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