CP violation in Tau decays

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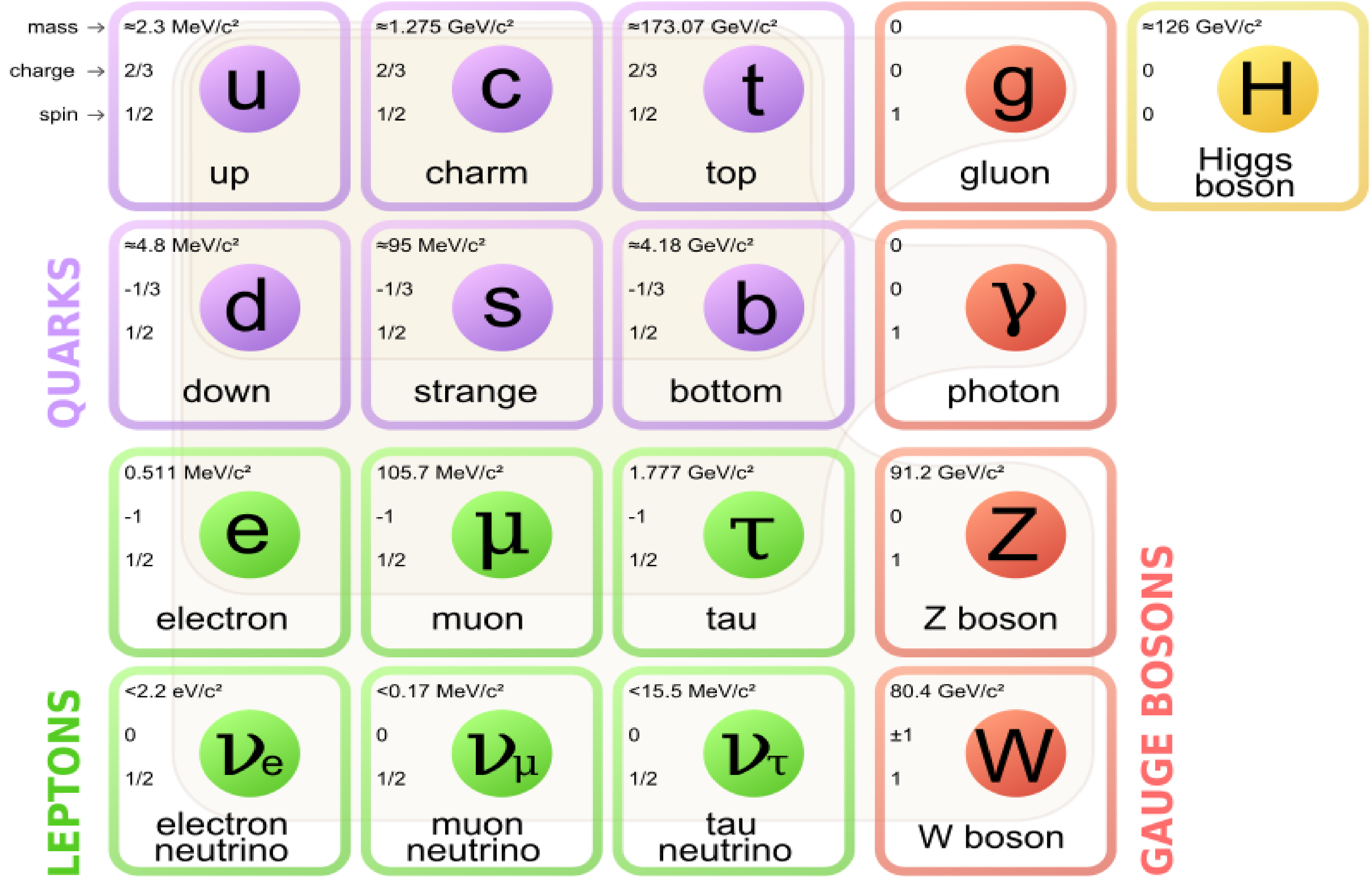
SU(5) scalar leptoquark and its role in $\tau \to K_S\pi\nu$

The Standard Model of Particle Physics



Physics beyond The Standard Model:

Hints for Physics beyond Standard Model includes:

- Neutrino masses :

In the Standard Model neutrino are massless. There recent data shows that Neutrino are oscillating which indicate that neutrino should have masses.

* Hierarchy problem :

This problem is associated with the absence of a symmetry protecting the Higgs mass at the electroweak scale when the natural cutoff scale is at or above the GUT scale 10^{16} GeV.

* Baryon asymmetry of the universe :

Our universe is made out of mostly matter? Why not antimatter?

The strength of the charge conjugation-parity (CP) violation in the SM is not sufficient to account for the cosmological baryon asymmetry.

- Dark matter candidate:

the SM does not have a viable candidate for the cold dark matter of the universe.

- Gauge coupling unification.

Candidates for Physics beyond Standard Model:

Some Possible Extensions of Physics beyond Standard Model:

* Enlarging the gauge symmetry group of the Standard Model, e.g.:

- SU(3) X SU(2) X U(1) X U(1)
- SU(3) X SU(2) X U(1) X SU(2)
- SU(5)
- ……………

- Enlarging the scalar sector by adding more scalars e.g.:

Two Higgs doublets models, three Higgs doublets models

- Enlarging the Fermion sector by adding new fermions for instance See-saw mechanisms .

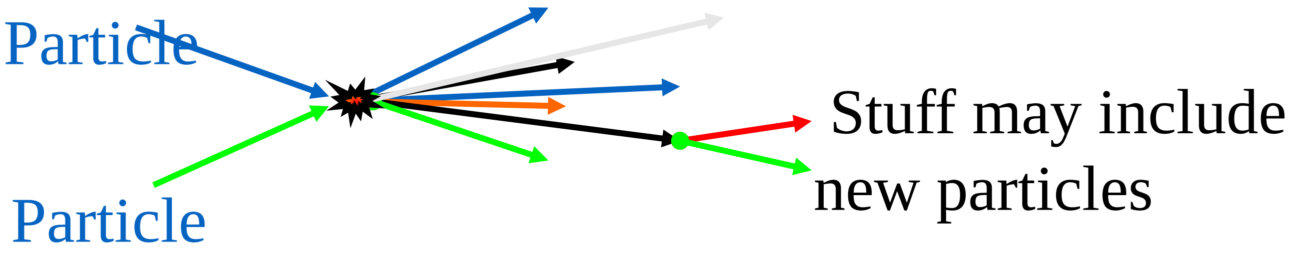
- Enlarging both the scalar and fermion sectors. For instance Supersymmetry

Search for new Physics beyond Standard Model:

(a) Direct Search (b) Indirect Search

(a) Direct Search:

It is Search for new particles through their signatures while passing through detectors in colliders or other Experiments.



– Particle Colliders with different center of mass energies :

A- Electron positron Colliders e.g. :

KEKB: Belle (Japan) center of mass energy 10 GeV

PEP-II: BaBar detector (USA) : center of mass energy 10 GeV (shut down in 2008)

B - Hadron Colliders e.g. :

- Tevatron (USA): center of mass energy 1 TeV shut down 2011
- Large Hadron Collider (CERN) center of mass energy 14 TeV

Indirect search:

Through the observation of some physical measurements such as :

CP violation, branching ratios …..etc. in some experiments that study B mesons, D mesons and Tau lepton decays. (BELLE, BABAR, LHCb)

CP Violation in tau decays:

Direct CP asymmetry in semi-leptonic decays is an intriguing hint for new physics beyond the standard model.

There is 2.8 discrepancy between the experimental measured value and the SM expectation of the CP asymmetry of the decay mode of tau lepton to kaon pion and neutrino final state.

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{us}^{\star} \sum_{i=V,A,S,P,T} C_i(\mu)\, Q_i(\mu),$$

V_{us} is the us Cabibbo-Kobayashi-Maskawa (CKM) matrix element

$$Q_V = \left(\bar{\nu}_\tau \gamma_\mu \tau\right)\left(\bar{s}\gamma^\mu u\right),$$

$$Q_A = \left(\bar{\nu}_\tau \gamma_\mu \gamma_5 \tau\right)\left(\bar{s}\gamma^\mu u\right),$$

$$Q_S = \left(\bar{\nu}_\tau \tau\right)\left(\bar{s}u\right),$$

$$Q_P = \left(\bar{\nu}_\tau \gamma_5 \tau\right)\left(\bar{s}u\right),$$

$$Q_T = \left(\bar{\nu}_\tau \sigma_{\mu\nu}(1+\gamma_5)\tau\right)\left(\bar{s}\sigma^{\mu\nu} u\right),$$

with $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$. The Wilson coefficients, C_i, corresponding to the operators Q_i

$$C_i = C_i^{SM} + C_i^{NP},$$

The amplitude can be calculated using the effective hamiltonian via calculating the

$$\langle K^- \pi^0 | \bar{s}\gamma^\mu u | 0 \rangle = \frac{1}{\sqrt{2}} \Big((p_K - p_\pi)^\mu f_+(s) + (p_K + p_\pi)^\mu f_-(s) \Big),$$

$$\langle K^- \pi^0 | \bar{s} u | 0 \rangle = \frac{(M_K^2 - M_\pi^2)}{\sqrt{2}(m_s - m_u)} f_0(s) = \frac{\Delta_{K\pi}^2}{\sqrt{2}(m_s - m_u)} f_0(s)$$

$$\langle K^- \pi^0 | \bar{s}\sigma^{\mu\nu} u | 0 \rangle = \frac{i(p_K^\mu p_\pi^\nu - p_K^\nu p_\pi^\mu)}{\sqrt{2} M_K} B_T(s).$$

$$s = (p_K + p_\pi)^2 \qquad \Delta_{K\pi}^2 = M_K^2 - M_\pi^2. \qquad f_-(s) = \frac{\Delta_{K\pi}^2}{s}\big(f_0(s) - f_+(s)\big),$$

$$\begin{aligned}\mathcal{A} = -\frac{G_F V_{us} C_V}{\sqrt{2}} \Bigg\{ & \Big((p_K - p_\pi)^\mu f_+(s) + (p_K + p_\pi)^\mu f_-(s) \Big) \Big(\bar{u}(p_\nu)\gamma_\mu L u(p_\tau) \Big) \\ & + \frac{C_S\, \Delta_{K\pi}^2}{(m_s - m_u)\, C_V} f_0(s) \Big(\bar{u}(p_\nu) R u(p_\tau) \Big) \\ & + i \frac{(p_K^\mu p_\pi^\nu - p_K^\nu p_\pi^\mu)\, C_T}{M_K C_V} B_T(s) \Big(\bar{u}(p_\nu)\sigma_{\mu\nu} R u(p_\tau) \Big) \Bigg\} .\end{aligned}$$

The differential decay width is given as

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s} = G_F^2|V_{us}|^2|C_V|^2 S_{\mathrm{EW}} \frac{\lambda^{1/2}(s, M_\pi^2, M_K^2)(m_\tau^2 - s)^2\Delta_{K\pi}^4}{1024\pi^3 m_\tau s^3} \times \left[\frac{(m_\tau^2 + 2s)\lambda(s, M_\pi^2, M_K^2)}{3m_\tau^2\Delta_{K\pi}^4}\left(|f_+(s) - T(s)|^2 + \frac{2(m_\tau^2 - s)^2}{9sm_\tau^2}|T(s)|^2\right) + |S(s)|^2\right],$$

where $\lambda(x, y, z)$ is given by $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$, $S_{\mathrm{EW}} = 1.0194$ accounts for the electroweak running down to m_τ and

$$S(s) = f_0(s)\left(1 + \frac{s\, C_S}{m_\tau(m_s - m_u)\, C_V}\right),$$
$$T(s) = \frac{3s}{m_\tau^2 + 2s}\frac{m_\tau\, C_T}{M_K C_V}\, B_T(s).$$

In the SM, at tree-level, the Wilson coefficients C_i reduces to

$$C_V^{SM} = -C_A^{SM} = 1, \qquad C_{S,P,T}^{SM} = 0,$$

$$\Gamma_{SM} = \frac{G_F^2 |V_{us}|^2 S_{\rm EW} \Delta_{K\pi}^4}{1024\pi^3 m_\tau}$$
$$\int_{(M_K+M_\pi)^2}^{m_\tau^2} ds \left(\frac{\lambda^{1/2}(s, M_\pi^2, M_K^2)(m_\tau^2 - s)^2}{s^3} \times \left[\frac{(m_\tau^2 + 2s)\lambda(s, M_\pi^2, M_K^2)}{3m_\tau^2 \Delta_{K\pi}^4} |f_+(s)|^2 + |f_0(s)|^2 \right] \right),$$

The CP asymmetry in total decay rate of $\tau^- \to K^- \pi^0 \nu_\tau$ is given by:

$$A_{CP} = \frac{\Gamma(\tau^- \to K^- \pi^0 \nu_\tau) - \Gamma(\tau^+ \to K^+ \pi^0 \nu_\tau)}{\Gamma(\tau^- \to K^- \pi^0 \nu_\tau) + \Gamma(\tau^+ \to K^+ \pi^0 \nu_\tau)}.$$

Clearly, from the expression of Γ_{SM}, direct CP asymmetry in the decay rate will vanish due to the absence of the weak phase, C_V^{SM} is real, and also due to the remark that the form factors $f_+(s)$ and $f_0(s)$ do not interfere and hence the relative strong phase essential for CP asymmetry vanishes.

Assuming that NP contributions are obtained via
integrating out heavy particles, above the electroweak breaking scale, we can set $C_V^{NP} = 0$.
In this case, the direct CP asymmetry in total decay rate of $\tau^- \to K^-\pi^0\nu_\tau$ is given by:

$$A_{CP}^{NP} = -\frac{G_F^2|V_{us}|^2 S_{\rm EW}\, Im\, C_T^{NP}}{512\pi^3 m_\tau^2 M_K \Gamma_\tau {\rm BR}(\tau \to K\pi\nu_\tau)} \times \int_{(M_\pi+M_K)^2}^{m_\tau^2} {\rm d}s \frac{\lambda^{3/2}(s, M_\pi^2, M_K^2)(m_\tau^2 - s)^2}{s^2} |f_+(s)||B_T(s)| \sin\left(\delta_+(s) - \delta_T(s)\right),$$

where $\delta_+(s)$, $\delta_T(s)$ are the phases of $f_+(s)$ and $B_T(s)$. Estimation of the CP asymmetry in the previous equation requires information on the form factor $f_+(s)$ and $B_T(s)$. Empirically, $\tau \to \pi K_S \nu_\tau$ spectrum can give information on the form factor $f_+(s)$ which is mainly dominated by the $K^*(892)$ resonance

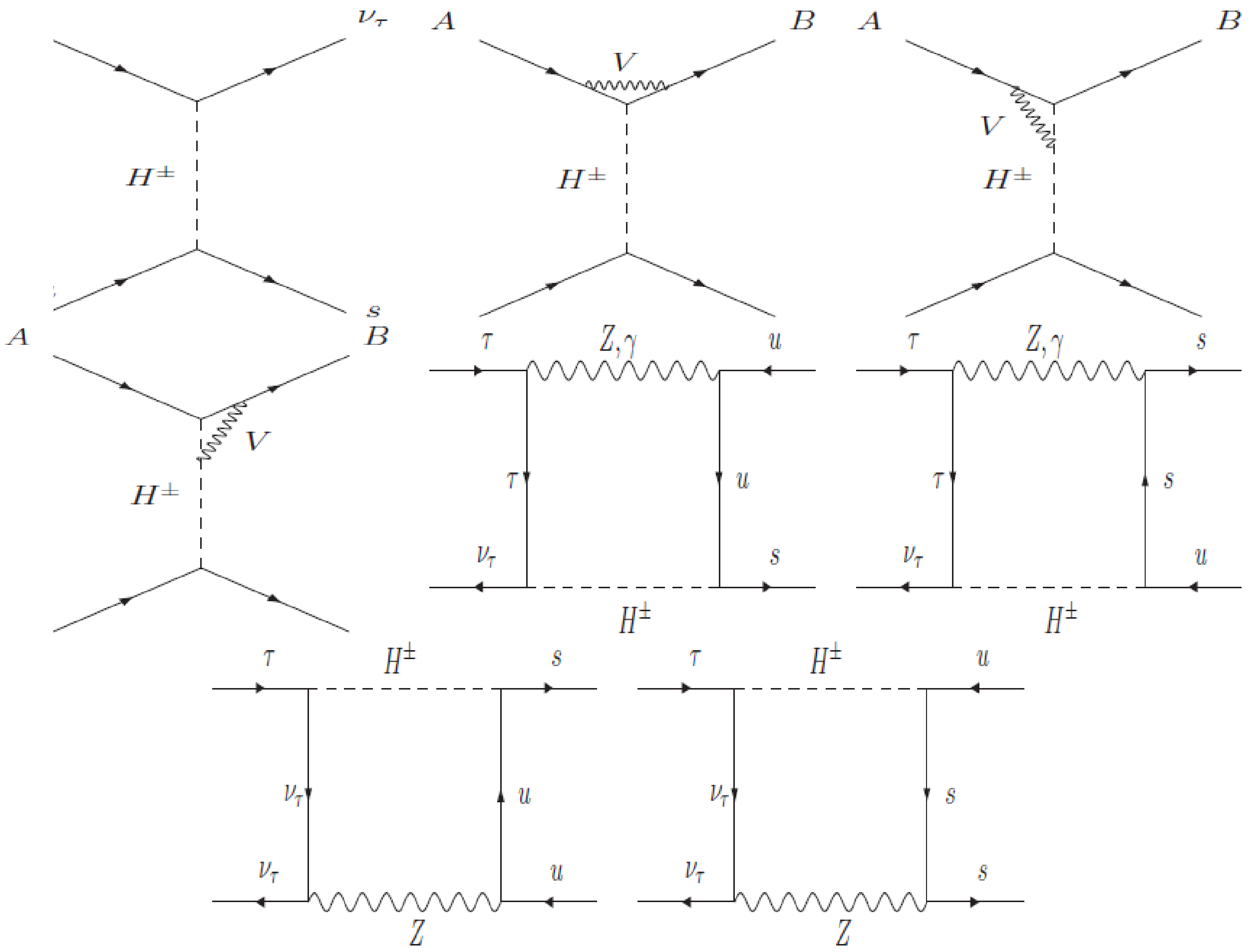
$$|A_{CP}^{NP}| \lesssim 1.4 \times 10^{-2}\, Im\, C_T^{NP},$$

CP asymmetry of $\tau^- \to K^-\pi^0\nu_\tau$ in 2HDM III.

$$\mathcal{L}^{eff}_{H^\pm} = \bar{u}\Gamma^{H^\pm\,LR\,\mathrm{eff}}_{us} P_R s + \bar{u}\Gamma^{H^\pm\,RL\,\mathrm{eff}}_{us} P_L s + \frac{m_\tau \tan\beta}{v}(\bar{\nu}_\tau P_R \tau) + h.c.$$

$$\Gamma^{H^\pm\,LR\,\mathrm{eff}}_{us} = \sin\beta\left(V_{12}\frac{m_s}{v_d} - \sum_{j=1}^{3} V_{1j}\epsilon^d_{j2}\tan\beta\right),$$

$$\Gamma^{H^\pm\,RL\,\mathrm{eff}}_{us} = \cos\beta\left(\frac{m_u}{v_u}V_{12} - \sum_{j=1}^{3} V_{j2}\epsilon^{u\star}_{j1}\tan\beta\right),$$



$$C_V^{H^\pm} \simeq \frac{8m_W^2 m_s m_\tau^2 \sin^2\beta s_w^2}{3v\, V_{us}^\star c_w^2 \cos\beta}\left((-\frac{1}{2}+s_w^2)\, g(x_s,x_\tau,x_Z) + \frac{4v^2\,\pi\alpha\, m_u c_w^2}{m_W^2 m_s s_w^2} k(x_u,x_\tau)\right)(V_{cs}^*\,\epsilon_{21}^u + V_{ts}^*\,\epsilon_{31}^u),$$

$$C_S^{H^\pm} \simeq -\frac{4v\, m_\tau \sin^2\beta}{V_{us}^\star\, m_H^2 \cos\beta}(V_{cs}^*\,\epsilon_{21}^u + V_{ts}^*\,\epsilon_{31}^u),$$

$$C_T^{H^\pm} \simeq -\frac{4v m_\tau \sin^2\beta}{V_{us}^\star m_H^2 \cos\beta}\left(\frac{2m_W^2 m_H^2 s_w^2}{3v^2 c_w^2} f(x_u,x_Z) - \frac{2m_W^2 m_H^2 s_w^2}{v^2\, c_w^2}(-\frac{1}{2}+\frac{1}{3}s_w^2) h(x_s,x_\tau,x_Z) + \frac{8\pi\alpha\, m_H^2}{3} f(x_u,x_\tau) \right.$$
$$\left. + \frac{4\pi\alpha m_H^2}{3} f(x_s,x_\tau) - \frac{m_W^2 m_H^2(-\frac{1}{2}+\frac{1}{3}s_w^2)}{v^2 c_w^2} f(x_s,x_Z)\right)(V_{cs}^*\,\epsilon_{21}^u + V_{ts}^*\epsilon_{31}^u).$$

$$g(x_i,x_j,x_k) = \frac{x_i log x_i}{(x_i-1)(x_i-x_j)(x_i-x_k)} + \frac{x_j log x_j}{(x_j-1)(x_j-x_i)(x_j-x_k)}$$
$$+ \frac{x_k log x_k}{(x_k-1)(x_k-x_i)(x_k-x_j)},$$

$$k(x_i,x_j) = \frac{-1}{(x_i-x_j)}\left(\frac{1}{1-x_i} log x_i - (x_i \leftrightarrow x_j)\right),$$

$$f(x_i,x_j) = \frac{1}{(x_i-x_j)}\left(\frac{x_i}{1-x_i} log x_i - (x_i \leftrightarrow x_j)\right),$$

$$h(x_i,x_j,x_k) = \frac{x_i^2 log x_i}{(x_i-1)(x_i-x_j)(x_i-x_k)} + \frac{x_j^2 log x_j}{(x_j-1)(x_j-x_i)(x_j-x_k)}$$
$$+ \frac{x_k^2 log x_k}{(x_k-1)(x_k-x_i)(x_k-x_j)},$$

$$C_S^{H^\pm} \simeq -0.76 V_{ts}^* \, \epsilon_{31}^u,$$

$$C_T^{H^\pm} \simeq 7.49 \times 10^{-3} V_{ts}^* \, \epsilon_{31}^u.$$

Knowing that $Re(V_{ts}) \simeq \mathcal{O}(10^{-2})$ and the bound $2.7 \times 10^{-3} \leq\mid \epsilon_{31}^u \mid\leq 2.0 \times 10^{-2}$ from the process $B \to \tau\nu$ [58], it is clearly trivial that the $B \to \tau\nu$ process sets more severe bound on ϵ_{31}^u compared to the model-independent EDM bound. Consequently, one expects a strong bound $Im\, C_T^{H^\pm} < 10^{-6}$

$$\left|A_{CP}^{H^\pm}\right| \lesssim \mathcal{O}(10^{-8}),$$

B. $\tau^- \to K^- \pi^0 \nu_\tau$ in Leptoquarks models.

Leptoquark particles are scalars or vectors bosons that have both baryon and lepton number

They appear for instance in grand unified theories (GUTs) and SUSY models with R-parity violation.

Scalar leptoquarks S may couple to both left or right handed quark chiralities. Let us consider the exchange of the following scalar leptoquarks:

- $S_{1/2}$ with charge 2/3 and $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge numbers given as $(3, 2, 7/3)$; and
- the S_0 with charge $-1/3$ and $(3, 1, -2/3)$ gauge numbers.

$$\mathcal{L}^I = \left[\kappa_{1i}^L \bar{u}_R \nu_{i_L} + \kappa_{23}^R \bar{s}_L \tau_R\right] S_{1/2} + \text{h.c.},$$

$$\mathcal{L}^{II} = \left[-\xi_{13}^L \bar{u}_L \tau_L^c + \xi_{2i}^L \bar{s}_L \nu_{i_L}^c + \xi_{13}^R \bar{u}_R \tau_R^c\right] S_0 + \text{h.c.},$$

$$C_V^I = 0, \qquad C_S^I = \frac{\kappa_{23}^R \kappa_{1i}^{L*}}{4\sqrt{2}\, G_F V_{us}^* \, M_{S_{1/2}}^2}, \qquad C_T^I = \frac{1}{4} C_3^I,$$

$$C_V^{II} = \frac{\xi_{2i}^L \xi_{13}^{L*}}{4\sqrt{2}\, G_F V_{us}^* M_{S_0}^2}, \qquad C_S^{II} = \frac{\xi_{2i}^L \xi_{13}^{R*}}{4\sqrt{2}\, G_F V_{us}^* M_{S_0}^2} \qquad C_T^{II} = \frac{1}{4} C_S^{II}.$$

$$\left|A_{CP}^{II}\right| \lesssim \mathcal{O}(10^{-7}),$$

SU(5) scalar leptoquark and its role in $\tau \to K_S \pi \nu$

As previously advocated, extending the Higgs sector of SU(5) by 45_H helps to solve some of the problems that this simple example of GUT model faces [18–21]. The 45_H transforms under the SM gauge as

$$45_H = (8,2)_{1/2} \oplus (1,2)_{1/2} \oplus (3,1)_{-1/3} \oplus (3,3)_{-1/3} \oplus (6^*,1)-1/3 \oplus (3^*,2)_{-7/6} \oplus (3^*,1)_{4/3}. \quad (3.1)$$

The 45_H scalar triplets are defined as:

$$\begin{aligned}
(3^*,2)^{ij}_{c\ -7/6} &\equiv (45_H)^{ij}_c \equiv \Phi^{ij}_c, \\
(3^*,1)^{ab}_{k\ 4/3} &\equiv (45_H)^{ab}_k \equiv \Phi^{ab}_k, \\
[(3,1)^{ib}_c \oplus (3,3)^{ib}_c]_{-1/3} &\equiv (45_H)^{ib}_c \equiv \Phi^{ib}_c.
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\phi_{i1}} &= -2Y^2_{AB}\bar{u}_{Bi}P_L e_A \phi^{i1*} - 4Y^4_{AB}\bar{e}_B P_L u_A \phi_{i1} - 2Y^{2*}_{AB}\bar{e}_A P_R u_{Bi}\phi^{i1} - 4Y^{4*}_{AB}\bar{u}_A P_R e_B \phi^*_{i1}, \\
\mathcal{L}_{\phi_{i2}} &= 2Y^2_{AB}V^{\text{PMNS}}_{AK}\bar{u}_{Bi}P_L \nu_k \phi^{i2*} - 4Y^4_{DB}V^{\text{CKM}}_{DK}\bar{e}_B P_L d_K \phi_{i2} + 2Y^{2*}_{AB}V^{\text{PMNS}*}_{AK}\bar{\nu}_K P_R u_{Bi}\phi^{i2} \\
&\quad -4Y^{4*}_{DB}V^{\text{CKM}*}_{DK}\bar{d}_K P_R e_B \phi^*_{i2}
\end{aligned} \quad (3.4)$$

The transition $\tau \to s\bar{u}v_\tau$ generating the decay process $\tau \to K_S^0\pi^-(K^-\pi^0)\nu_\tau$ can be obtained upon integrating the leptoquark ϕ_{i2}. Doing so and after using Fierz identities, we find that

$$\mathcal{L}_{\text{eff}} = -\frac{4}{m_{\phi_{i2}}^2} Y_{A1}^{2*} Y_{D3}^{4*} V_{D2}^{\text{CKM}*} V_{A3}^{\text{PMNS}*} \left[(\bar{\nu}_\tau P_R \tau)(\bar{s} P_R u) + \frac{1}{4} (\bar{\nu}_\tau \sigma_{\mu\nu} P_R \tau)(\bar{s} \sigma^{\mu\nu} P_R u) \ + \ \text{h.c.} \right]. \tag{3.11}$$

The Yukawa couplings Y^2 and Y^4 are generally complex. In this case, the Wilson coefficients C_i, corresponding to the operators Q_i in eq. (2.2) are given by

$$C_V = 0, \qquad C_S = \frac{2\sqrt{2}\, Y_{A1}^{2*} Y_{D3}^{4*} V_{D2}^{\text{CKM}*} V_{A3}^{\text{PMNS}*}}{G_F V_{us}^* \, m_{\phi_{i2}}^2}, \qquad C_T = \frac{1}{4} C_S. \tag{3.12}$$

$$|C_S| \lesssim \frac{(m_u + m_s) m_\tau}{m_K^2} \left(\frac{\mathcal{B}_{Exp}}{\mathcal{B}_{SM}} - 1 \right)^{\frac{1}{2}} \simeq 0.67.$$

With the parameter space selection, it is critical to check that the predicted result of the branching ratio of $\tau^- \to K^-\nu_\tau$ to ensure that it remains within the experimental limits. The experimental results for the branching ratio of $\tau^- \to K^-\nu_\tau$ is given as $\mathcal{B}_{\text{Exp.}} = (6.96 \pm 0.10) \times 10^{-3}$

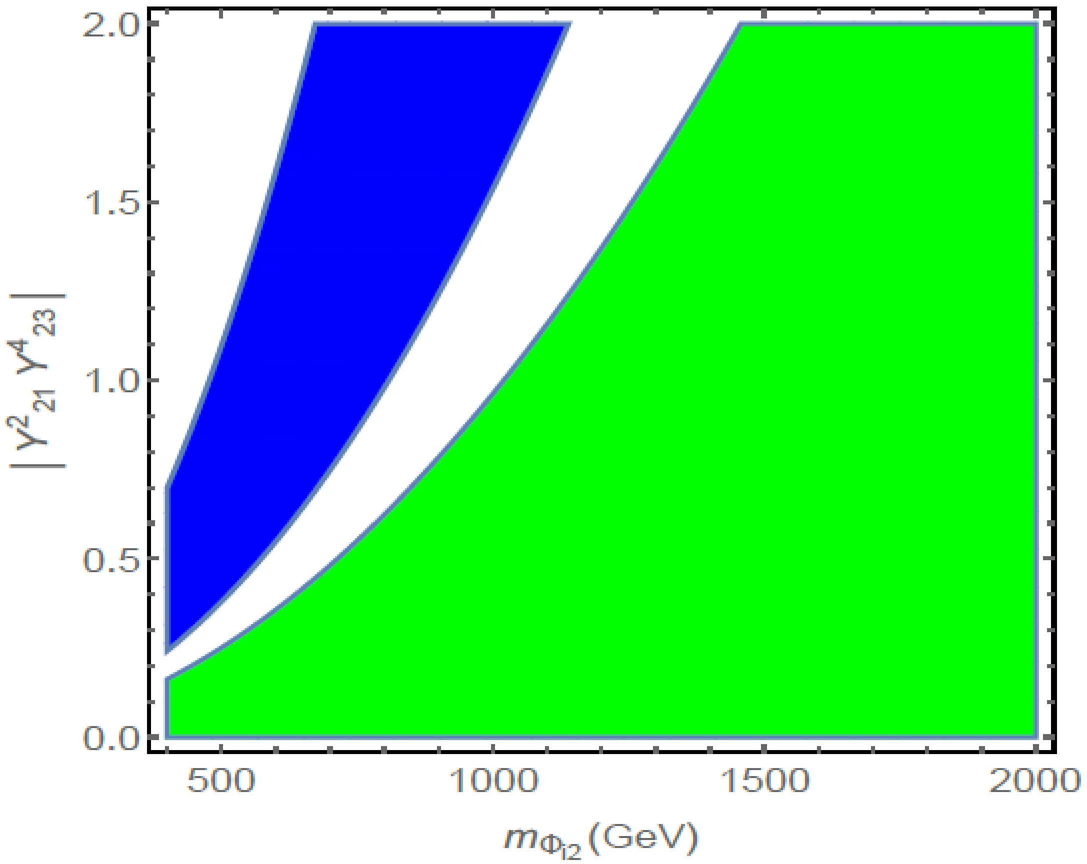


Figure 1. Allowed region of the parameter space $(m_{\phi_{i2}}, |Y^2_{21} Y^4_{23}|)$ in blue (Green) color satisfying the obtained bound in eq. (4.1) (eq. (4.6)).

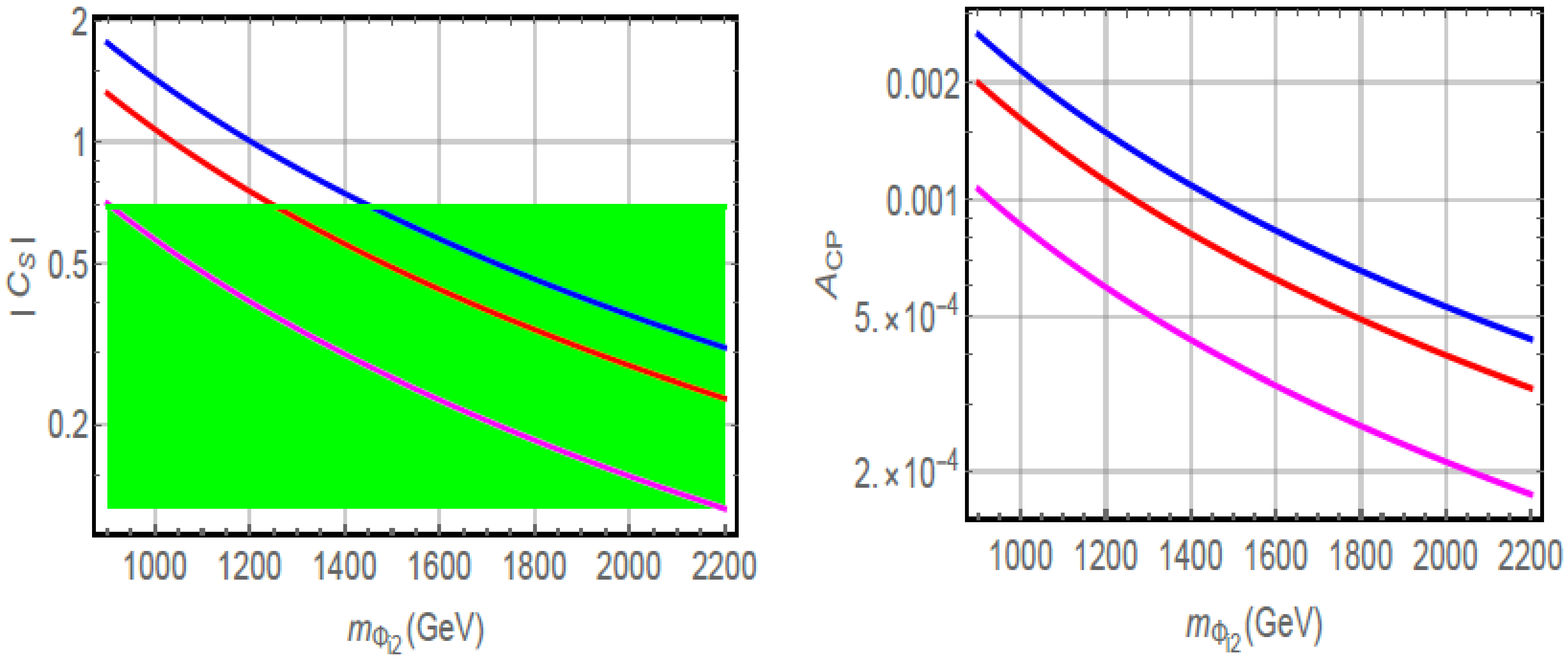


Figure 2. $|C_S|$ (A_{CP}) of the process $\tau^- \to K^-\pi^0\nu_\tau$ left (right) as function of leptoquark mass $|Y_{21}^2 Y_{23}^4| = 0.8, 1.5, 2.0$ in magenta, red and blue colors respectively. The green region represent the 1σ bound in eq. (4.6).

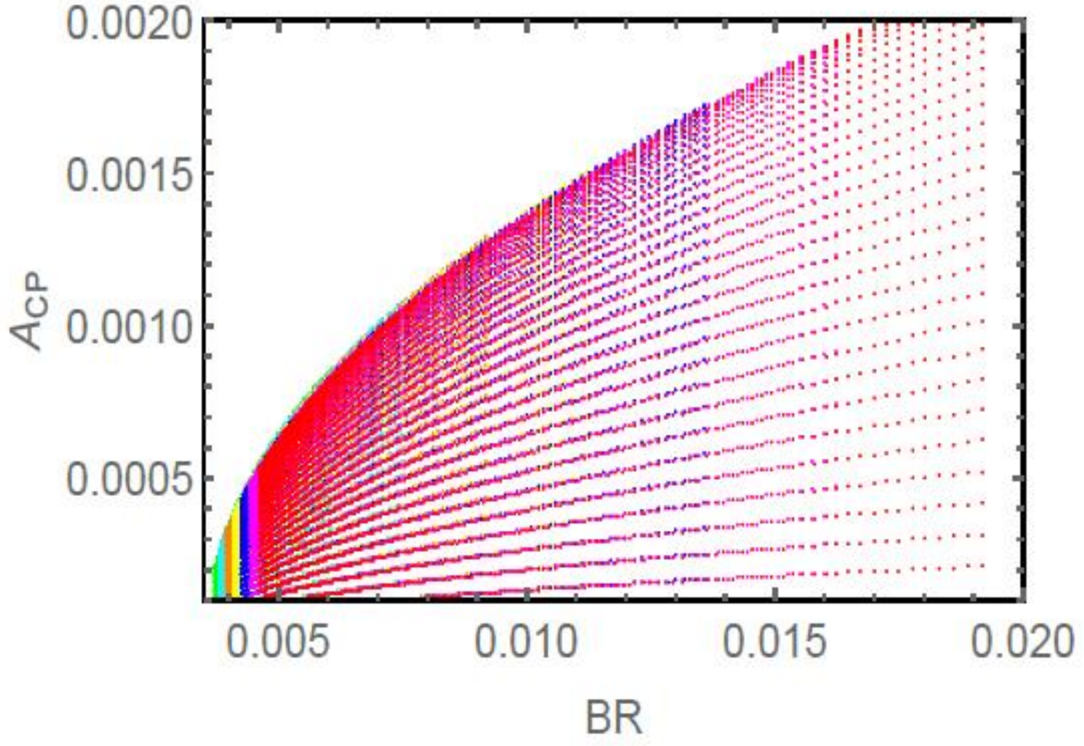


Figure 3. Correlation of BR and $A_{\rm CP}$. An explanation of colors in the figure is given in the text.


Thank You