Extension of the Standard Model with Chern-Simons type interaction

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together with
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Introduction

The Standard Model and Beyond

- In the past, the structure of the Standard Model was predicting where to expect new particles
- Higgs boson was the last predicted particle to be discovered
- Standard Model is consistent up to the Planck scale

- **But we know that Standard Model is incomplete!**

There are well-established phenomena that are not explained by the Standard Model:

- Neutrino masses and oscillations of active neutrinos
- Dark matter and Dark energy
- Baryon asymmetry of the Universe

What physics is responsible for it?

Unsolved problems may imply the existence of new particles

We did not detect them because either

they are **heavy**
(energy frontier)

OR

they are light but
very weakly interacting
(intensity frontier)

Portals as a window to New Physics

- The BSM Lagrangian can be represented as: $\mathcal{L}_{full} = \mathcal{L}_{SM} + \mathcal{L}_{BSM} + \mathcal{L}^{int}_{SM,BSM}$
- The interaction part ("portal") allows to experimentally detect new particles.
- The general requirement of gauge invariance and renormalizability determines the explicit expression for the portal Lagrangian.
- If the "portal particles" are long-lived, they can be searched at the intensity frontier experiments.

Examples of portals $\mathcal{L}^{int}_{SM,BSM}$ with renormalized interaction:

- **Scalar** portal: $(\mu S + \lambda S^2)(H^\dagger H)$
- **Vector** portal: $F'_{\mu\nu} F^{\mu\nu}_Y$
- **Neutrino** portal: $y_{\alpha I}(\bar{L}_\alpha \cdot \tilde{H}) N_I$

Examples of portals with non-renormalized effective interaction:

- **Axion**: $\frac{g_i}{\Lambda} a\, F^i_{\mu\nu} \tilde{F}^{i,\mu\nu}$
- **Chern-Simons boson** (CS boson):

$$\frac{C_1}{\Lambda_1^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger H B_{\lambda\rho} \cdot \epsilon^{\mu\nu\lambda\rho} + \frac{C_2}{\Lambda_2^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger F_{\lambda\rho} H \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.$$

What new particles are they?

What nature of the BSM particles?

- We do not know the exact nature of the particles in the new physics.
- They can be scalars, pseudoscalars (axionlike particles), vectors or fermions.
- Therefore, all possible variants should be considered.

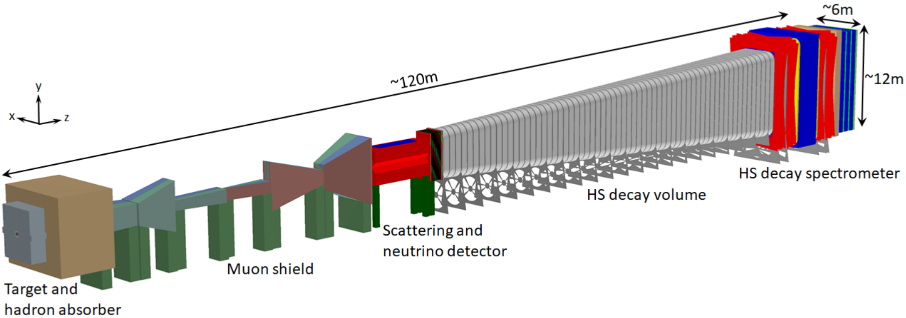
Motivation

- The scalar, pseudoscalar, vector and fermion extension of the SM are well investigated theoretically.
- The extension of the SM with the Chern-Simons type of interaction is not investigated sufficiently.
- We will focus our attention on the Chern-Simons extension of the SM.

How to search for new hidden particles

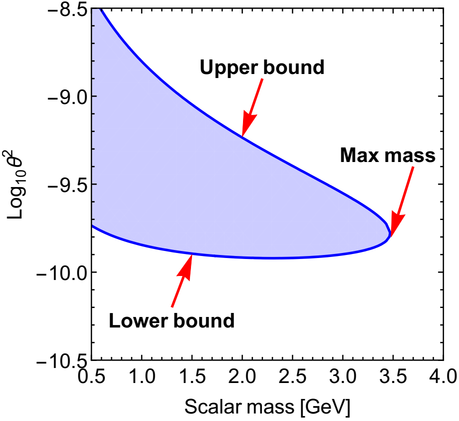
Intensity frontier experiments

To search for light BSM particles we need the intensity frontier experiments such as MATHUSLA, FACET, FASER, SHiP, NA62, DUNE, LHCb, etc.



SHIP Collaboration, *The SHiP experiment at the proposed CERN SPS Beam Dump Facility*, arXiv:2112.01487 (2022)

What do we need to build a sensitivity region?



Sensitivity region $N_{\mathrm{det}} > 3$

The number of detected particles:

$$N_{\mathrm{det}} \approx N_{\mathrm{prod}} \times \epsilon_{\mathrm{tot}} \times P_{\mathrm{decay}}$$

where

- N_{prod} is a number of produced S-particles
- $\epsilon_{\mathrm{tot}} = \epsilon_{\mathrm{geom}} \times \mathrm{Br}_{\mathrm{vis}} \times \epsilon_{\mathrm{det}}$
- P_{decay} is a probability of S-particle decay inside the decay volume. It depends on decay length $l_{\mathrm{decay}} = c\gamma\tau$, where τ is a S particle lifetime

We need the full decay width of the BSM particles (we need all decay channels) and channels of its production.

Phenomenology of Chern-Simons Portal

Chern-Simons modification to the Standard Model

The gauge invariant Lagrangian of the Chern-Simons interaction is presented in the form of dimension-6 operators:

$$\mathcal{L}_1 = \frac{c_1}{v^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger H B_{\lambda\rho} \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.$$
$$\mathcal{L}_2 = \frac{c_2}{v^2} \cdot X_\mu (\mathfrak{D}_\nu H)^\dagger F_{\lambda\rho} H \cdot \epsilon^{\mu\nu\lambda\rho} + h.c.$$

X_μ is **Stückelberg** vector field which is required by gauge invariance of the theory.

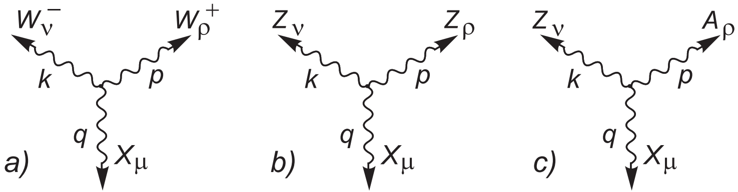
In the low energy limit (unitary gauge) the **effective Lagrangian** of three particle interaction of CS boson with gauge SM bosons is of dimension-4 form:

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

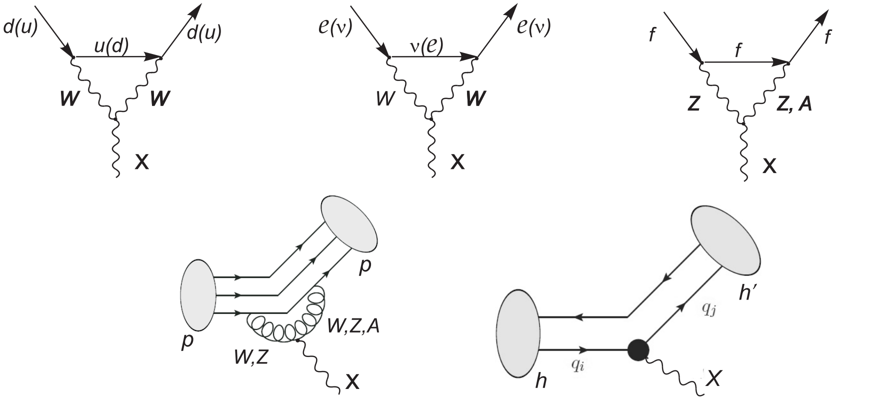
It looks like a renormalized Lagrangian!

I. Antoniadis, A. Boyarsky, S. Espahbodi, O. Ruchayskiy, J.D. Wells, *Anomaly driven signatures of new invisible physics at the Large Hadron Collider*, Nucl. Phys. B **824**, 296 (2010)

Vertex diagrams of the interaction of the CS boson with vector fields of the SM



Interaction of CS boson with SM particles



Chern-Simons GeV-scale bosons effective loop interaction with the SM fermions of different flavour

Production of the CS bosons

Quark decay of $d_\alpha \to X + d_\beta$ via the loop diagram

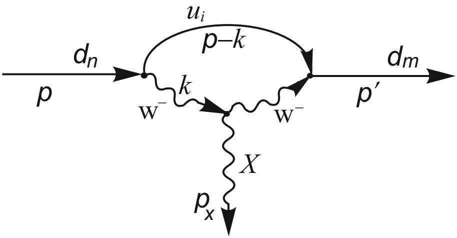


Diagram of the decay of the d_n-quark into the d_m-quark and the CS boson (X). The interaction of the CS boson with W bosons is described by $c_W = \Theta_{W1} + i\Theta_{W2}$.

The given loop diagram does not contain divergence, since the divergence term is proportional to the off-diagonal element of the unit matrix V^+V, where V is the CKM matrix

$$\sum_i (V^+)_{bi} V_{is} \ln \frac{\Lambda^2}{D(m_i)}\Big|_{\Lambda\to\infty} = \underbrace{(V^+V)_{bs}}_{=0} \ln \Lambda^2\big|_{\Lambda\to\infty} - \sum_i (V^+)_{bi} V_{is} \ln D(m_i)$$

Therefore, we can write

$$\sum_{i=u,c,t} (V^+)_{bi} V_{is} \ln \frac{\Lambda^2}{D(m_i)}\Big|_{\Lambda\to\infty} = \sum_{i=u,c,t} (V^+)_{bi} V_{is} \ln \frac{M_W^2}{D(m_i)}$$

Result of loop calculation

$$M_{fi} = \frac{g^2}{32\pi^2}\,\frac{m_t^2}{M_W^2}\,V^+_{d_m t}\,V_{td_n}\,\overline{d_m}(p')\,J^{\mu,d}(p,p')\,d_n(p)\epsilon^{*\lambda x}_{\mu}$$

$$J^\mu = \Big(a_L^d\,\hat{P}_R\,\gamma_\rho\,\gamma_\lambda\,\gamma_\nu\,\hat{P}_L +$$
$$b_L^d\,\frac{p'_\lambda\,p_\nu}{M_W^2}\,\hat{P}_R\,\gamma_\rho\,\hat{P}_L + c_L^d\,\frac{m'\,p'_\lambda}{M_W^2}\,\hat{P}_L\,\gamma_\rho\,\gamma_\nu\,\hat{P}_L + d_L^d\,\frac{m'\,p_\lambda}{M_W^2}\,\hat{P}_L\,\gamma_\rho\,\gamma_\nu\,\hat{P}_L +$$
$$b_R^d\,\frac{mm'}{M_W^2}\,\frac{p'_\lambda\,p_\nu}{M_W^2}\,\hat{P}_L\,\gamma_\rho\,\hat{P}_R + c_R^d\,\frac{m\,p'_\lambda}{M_W^2}\,\hat{P}_R\,\gamma_\rho\,\gamma_\nu\,\hat{P}_R + d_R^d\,\frac{m\,p_\lambda}{M_W^2}\,\hat{P}_R\,\gamma_\rho\,\gamma_\nu\,\hat{P}_R\Big)\,\epsilon^{\mu\nu\lambda\rho}$$

We see a difficult structure of interaction of the CS bosons with fermions!

Coefficients of effective interaction

coeff.	value	coef.	value$\cdot 10^6$
a_L^d	$-0.13\,i\,\Theta_{W1}$	a_L^{up}	$(-0.98+1.13i)\Theta_{W1}$
b_L^d	$0.05i\Theta_{W1}+4\cdot 10^{-5}\Theta_{W2}$	b_L^{up}	$(-6.4+7.4i)\Theta_{W1}-(1.1+0.98i)\Theta_{W2}$
c_L^d	$-0.058\,i\,\Theta_{W1}-0.098\,\Theta_{W2}$	c_L^{up}	$(0.27-0.31i)\Theta_{W1}+(0.57+0.49i)\Theta_{W2}$
d_L^d	$0.086\,i\,\Theta_{W1}+0.098\,\Theta_{W2}$	d_L^{up}	$(0.38-0.44i)\Theta_{W1}-(0.57+0.49i)\Theta_{W2}$
b_R^d	$-0.028\,i\,\Theta_{W1}$	b_R^{up}	$(-0.64+0.75i)\Theta_{W1}$
c_R^d	$0.086\,i\,\Theta_{W1}-0.098\,\Theta_{W2}$	c_R^{up}	$(0.87-i)\theta_{W1}+(1.1+0.98i)\Theta_{W2}$
d_R^d	$-0.058\,i\,\Theta_{W1}+0.098\,\Theta_{W2}$	d_R^{up}	$(-0.23+0.25i)\Theta_{W1}-(1.1+0.98i)\Theta_{W2}$

Table: Coefficients in the expression for the amplitude of a heavy quark decay into a down-type quark and the CS boson. Superscript d stands for the decay of down-type quark $d_n \to d_m + X$, superscript up is for the decay of up-type quark $u_n \to u_m + X$.

Effective Lagrangian

If $\Theta_{W1} \neq 0$, then the effective Lagrangian of the interaction of the CS boson (with a mass up to several GeV) with down-type quarks of different generations takes the form

$$\mathcal{L}^{CS}_{quarks} = \sum_{m<n} \Theta_{W1} \left(C_{mn}\, \overline{d_m}\, \gamma^\mu\, \hat{P}_L\, d_n X_\mu + C^+_{nm}\, \overline{d_n}\, \gamma^\mu\, \hat{P}_L\, d_m X_\mu \right)$$

$$C_{mn} = \frac{3a}{2\sqrt{2}\pi^2}\, G_F\, m_t^2\, V^+_{d_m t} V_{t d_n}$$

$$|C_{sb}| = 1.97 \cdot 10^{-4}, \quad |C_{db}| = 4.43 \cdot 10^{-5}, \quad |C_{ds}| = 1.77 \cdot 10^{-6}$$

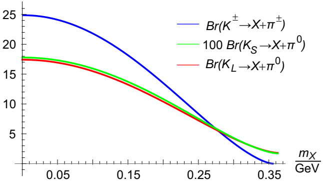
$\hat{C}\hat{P}\overline{d_m}\, \gamma^\mu\, \hat{P}_L\, d_n X_\mu = \overline{d_n}\, \gamma^\mu\, \hat{P}_L\, d_m X_\mu, \quad \hat{C}\hat{P} X_\mu = -X^\mu$

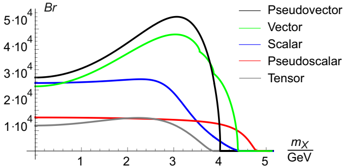
That is, the CP parity of the CS boson is the same as that of the Z boson. The interaction Lagrangian will be CP invariant only if the C_{mn} matrix is real.

- The interaction of the CS boson with the upper quarks of different generations can be neglected.
- The interaction of the CS boson with quarks of the same flavour is an unsolved problem due to renormalization problems.

Production of the CS bosons in mesons decays

Process	final meson	$\lim_{m_X\to 0}\left(\frac{m_X}{1\text{GeV}}\right)^2 \frac{\text{Br}(m_X)}{\theta_{W1}^2}$	Closing mass [GeV]
$K^\pm \to X\pi^\pm$	pseudo scalar	$2.49\cdot 10^1$	0.35
$K_L^0 \to X\pi^0$	pseudo scalar	$1.56\cdot 10^1$	0.36
$K_S^0 \to X\pi^0$	pseudo scalar	$1.61\cdot 10^{-1}$	0.36
$B^\pm \to X\pi^\pm$	pseudo scalar	$2.37\cdot 10^2$	5.14
$B^\pm \to XK^\pm$	pseudo scalar	$7.73\cdot 10^3$	4.79
$B^\pm \to XK_0^{*,\pm}(700)$	scalar	$1.43\cdot 10^4$	4.46
$B^\pm \to XK^{*,\pm}(892)$	vector	$9.14\cdot 10^3$	4.39
$B^\pm \to XK_1^\pm(1270)$	pseudo vector	$1.72\cdot 10^4$	4.01
$B^\pm \to XK_1^\pm(1400)$	pseudo vector	$2.34\cdot 10^2$	3.88
$B^\pm \to XK^{*,\pm}(1410)$	vector	$3.99\cdot 10^3$	3.86
$B^\pm \to XK_0^{*,\pm}(1430)$	scalar	$1.85\cdot 10^3$	3.85
$B^\pm \to XK_2^{*,\pm}(1430)$	tensor	$6.03\cdot 10^3$	3.85
$B^\pm \to XK^{*,\pm}(1680)$	vector	$2.53\cdot 10^3$	3.56





Y. Borysenkova, P. Kashko, M. Tsarenkova, K. Bondarenko, V. Gorkavenko, *J. Phys. G: Nucl. Part. Phys.* **49**, 085003 (2022)

Decay channels of the CS boson

Effective loop interaction with the SM fermions of same flavour

Statement of the problem

We can hope that the main channel for the production of the CS boson is the decay of mesons.

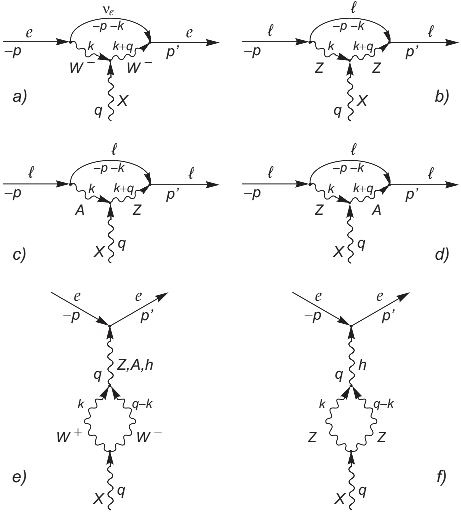
We can consider some channels of decay of CS boson into mesons using its interaction with down-type quarks of different flavours.

But we can not consider the decay of the CS boson into the same quarks $X \to q\bar{q}$ and can not consider decay into lepton pairs $X \to \ell^- \ell^+$.

In this case, divergences remain in the theory. This divergence can not be removed via counterterms of the CS boson interaction with fermions because the initial Lagrangian does not contain these terms. We must find a way to eliminate them.

Next, for the convenience of calculations, we will consider the loop interactions of the CS boson with two leptons.

CS boson decay into leptons in the unitary gauge



Let us limit ourselves to consideration to considering the operators of dimension 4

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

It would be nice if he sum of divergences from all those decay modes should cancel.

Results of calculations

The divergent part of the diagrams can be presented as

$$M_{fi}^{div} \sim \bar{\ell}(p') I^{\mu} \ell(-p) \epsilon_{\mu}^{\lambda x}$$

where I^{μ} has a complicated form

$$I^{\mu} = (A\, \gamma_{\rho}\gamma_{\lambda}\gamma_{\nu} + B\, q_{\lambda}\gamma_{\rho}\, \not{q}\gamma_{\nu} + C\, q_{\lambda}\gamma_{\rho}\, \not{p}\gamma_{\nu} + D\, q_{\rho}\gamma_{\lambda}\gamma_{\nu} + E\, q_{\lambda}\gamma_{\rho} p_{\nu})\, \epsilon^{\mu\nu\lambda\rho}$$

Results of calculations

$$A = \gamma^5 \frac{g}{2}\left[\frac{\Theta^1_W g}{2} + \frac{c_z g}{\cos^2\theta_W} t_3^f\left[t_3^f - 2q_f\sin^2\theta_W\right] - \frac{c_\gamma q_f e}{\cos\theta_W} t_3^f\right] -$$

$$- \frac{g}{2}\left[\frac{\Theta^1_W g}{2} + \frac{c_z g}{\cos^2\theta_W}\left(t_3^f\left[t_3^f - 2q_f\sin^2\theta_W\right] + 2q_f^2\sin^4\theta_W\right) - \frac{c_\gamma q_f e}{\cos\theta_W}\left(t_3^f - 2q_f\sin^2\theta_W\right)\right],$$

$$B = -\gamma^5 \frac{g}{4M_W^2}\left[\frac{c_w^* g}{2} + c_z g t_3^f\left[t_3^f - 2q_f\sin^2\theta_W\right] - c_\gamma q_f e\cos\theta_W t_3^f\right] +$$

$$+ \frac{g}{4M_W^2}\left[\frac{c_w^* g}{2} + c_z g\left(t_3^f\left[t_3^f - 2q_f\sin^2\theta_W\right] + 2q_f^2\sin^4\theta_W\right) - c_\gamma q_f e\cos\theta_W\left(t_3^f - 2q_f\sin^2\theta_W\right)\right],$$

$$C = i\Theta^2_W \frac{g^2}{4M_W^2}(1-\gamma^5), \qquad D = \frac{g q_f t_3^f e}{2\cos\theta_W}\frac{m_f}{M_Z^2} c_\gamma \gamma^5,$$

$$E = \gamma^5 \frac{g}{3M_W^2}\left[\frac{\Theta^1_W g}{2} + c_z g t_3^f\left[t_3^f - 2q_f\sin^2\theta_W\right] - c_\gamma q_f e\cos\theta_W t_3^f\right] -$$

$$- \frac{g}{3M_W^2}\left[\frac{\Theta^1_W g}{2} + c_z g\left(t_3^f\left[t_3^f - 2q_f\sin^2\theta_W\right] + 2q_f^2\sin^4\theta_W\right) - c_\gamma q_f e\cos\theta_W\left(t_3^f - 2q_f\sin^2\theta_W\right)\right].$$

We got cumbersome expressions!

Result of problem consideration in the unitary gauge

It would be good to have some relationships between coefficients Θ^1_W, Θ^2_W, c_γ, c_z of the interaction Lagrangian, under which the divergent terms of the loop diagrams are eliminated, i.e. the condition $A = B = C = D = E = 0$ would be satisfied. But that's not true.

The system of the other equations $A = B = C = D = E = 0$ has only a trivial solution $\Theta^1_W = \Theta^2_W = c_z = c_\gamma = 0$.

The problem remains unresolved and it needs additional consideration in a more general approach of non-unitary gauge.

Yu. Borysenkova, V. Gorkavenko, I. Hrynchak, O. Khasai, M. Tsarenkova, *Divergences in the effective loop interaction of the Chern-Simons bosons with leptons. The unitary gauge case*, arXiv:2405.00164 (2024)

Summary

- We considered one of the possible BSM portals, the CS portal.
- We get effective Lagrangian of the CS interaction with quarks of different flavours.
- We analyzed the production of the CS boson in decays of mesons.
- We considered the effective loop interaction of CS boson with two same leptons in unitary gauge including all diagrams with XWW, XZZ, XZA interactions in the third order of perturbation theory. We do not get cancellation of the divergent parts of diagrams.
- The problem has to be considered more carefully in the non-unitary R_ξ gauge.

Thank for your attention!