Low-energy flavor probes of light vector bosons

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Work with Di Luzio, Paradisi, Ponce-Díaz. To appear soon, 2303.XXXXX

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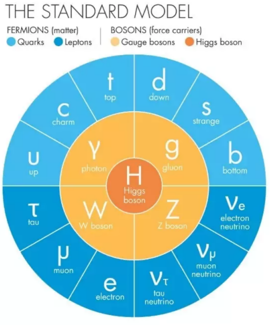
The Standard Model of particle physics



- The **Standard Model** (SM) is extremely successful in explaining the behaviour of the particles we know
- It leaves important **open questions** unanswered → call for **New Physics (NP)**!

Light Vector Bosons

Light Vector Bosons (VBs) have receieved a lot of attention as **weakly coupled NP** candidates (see, e.g., [Essig *et al.*,'13] or [Bjorken, Essig, Schuster, Toro,'09] and references therein)

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Key Point: Longitudinal component

By the **equivalence theorem**, if the VBs have a **longitudinal component** $\to$ Energy-enhanced processes $\propto E^2/m_X^2$.

e.g. $\Gamma(t \to b + W) \propto m_t \times (m_t^2/m_W^2)$ in the SM, with $E = m_t$

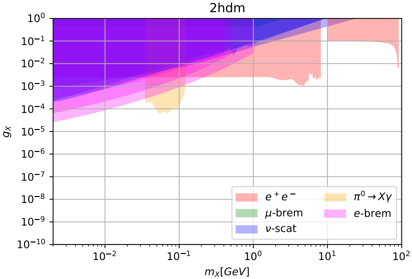
[Dror, Lasenby, Pospelov,'17]

Light Vector Bosons searches

Searches for generic vector bosons (X) have been obtained by recasting dark photon (A') analyses using DarkCast ([Ilten, Soreq, Williams, Xue,'18] and [Baruch, Ilten, Soreq, Williams,'22])

Recasting equation

$$\sigma_X \,\mathrm{BR}\,(X \to \mathcal{F})\,\epsilon\,(\tau_X) = \sigma_{A'}\,\mathrm{BR}\,(A' \to \mathcal{F})\,\epsilon\,(\tau_{A'})$$



$K^{\pm} \to \pi^{\pm} + X$ in χPT

We considered the flavour-violating channel $K^{\pm} \to \pi^{\pm} + X$ to probe generic light VBs ([Di Luzio, Levati, Paradisi, Ponce Díaz, '23]).

Light vector bosons interaction Lagrangian

$$\mathcal{L}_X = g_x X_\mu \sum_f \bar{f} \gamma^\mu \left(x_V^f + x_A^f \gamma_5 \right) f$$

We computed the full tree-level contributions to the decay rate of $K^{\pm} \to \pi^{\pm} + X$ in **Chiral Perturbation theory** (χPT)

Chiral Perturbation theory: a quick recap - I

χPT is an effective field theory describing strong interactions at low energies (see, e.g. [Pich,'95]).

- Symmetries: $\mathrm{G}^0_{\mathrm{QCD}} \supset SU(3)_L \times SU(3)_R \longrightarrow SU(3)_V$

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Leading order chiral lagrangian

$$\mathcal{L}^0_{\mathrm{QCD}} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + i\gamma^\mu(\bar{q}_L D_\mu q_L + \bar{q}_R D_\mu q_R)$$

$$\mathcal{L}^{\mathcal{O}(\mathrm{p}^2)}_{\chi\mathrm{PT}} = \frac{f^2}{4} \mathrm{Tr}(\partial^\mu U^\dagger \partial_\mu U) \qquad \text{with } q^T = (u, d, s)$$

Chiral Perturbation theory: a quick recap - II

External gauge and scalar **fields** enter as sources in $\mathcal{L}_{\text{QCD}}$:

$$\mathcal{L}_{\text{QCD}} = \mathcal{L}^0_{\text{QCD}} + \bar{q}\gamma^\mu(2r_\mu P_R + 2\ell_\mu P_L)q - \bar{q}(s - i\gamma_5 p)q$$

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Dirac bilinears arise from **functional derivatives** of $S_{\chi\text{PT}}$:

$$\bar{q}^j_{L/R}\gamma^\mu q^i_{L/R} \to \frac{\delta S_{\chi\text{PT}}}{\delta(\ell/r)^{ji}_\mu} \quad \text{and} \quad \bar{q}^j_{L/R} q^i_{R/L} \to -\frac{\delta S_{\chi\text{PT}}}{\delta(s \mp ip)_{ji}}$$

Chiral Perturbation theory: a quick recap - II

External gauge and scalar **fields** enter as sources in $\mathcal{L}_{\rm QCD}$:

$$\mathcal{L}_{\rm QCD} = \mathcal{L}^0_{\rm QCD} + \bar{q}\gamma^\mu(2r_\mu P_R + 2\ell_\mu P_L)q - \bar{q}(s - i\gamma_5 p)q$$

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where, at order $\mathcal{O}(\mathrm{p}^2)$, $S_{\chi\rm PT}$ reads:

$$S_{\chi\rm PT} = \int d^4x\, \frac{f^2}{4}\mathrm{Tr}\left[D_\mu U^\dagger D^\mu U + U^\dagger\chi + \chi^\dagger U\right]$$

$$D_\mu U = \partial_\mu U + iU\ell_\mu - ir_\mu U, \qquad \chi = 2B_0(s + ip)$$

Weak interactions in the Chiral Lagrangian

The most general effective $\Delta S = 1$ Lagrangian reads:

$\Delta S = 1$ weak chiral Lagrangian

$$\mathcal{L}_{\text{eff}}^{\Delta S=1} = -\frac{G_f f^4}{\sqrt{2}} V_{ud} V_{us}^* \Big\{ g_{27} \left(L^3_{\mu,\,2} L_1^{\mu,\,1} + \frac{2}{3} L^1_{\mu,\,2} L_1^{\mu,\,3} - \frac{1}{3} L^3_{\mu,\,2} Tr(L^\mu) \right) + g_8^s L^3_{\mu,\,2} Tr(L^\mu) + g_8 \left(\mathrm{Tr}\left[\lambda L_\mu L^\mu\right] + e^2 g_{\text{ew}} f^2 \mathrm{Tr}\left[\lambda U^\dagger Q U\right] \right) \Big\}$$

where $L_\mu = iU^\dagger D_\mu U$ is the left-handed chiral current and $\lambda = \frac{1}{2}(\lambda_6 - i\lambda_7)$.

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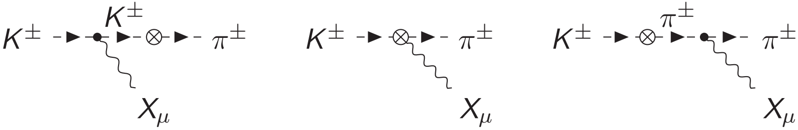
where $L_\mu = iU^\dagger D_\mu U$ is the left-handed chiral current and $\lambda = \frac{1}{2}(\lambda_6 - i\lambda_7)$.

Together with the LO Chiral Lagrangian this gives us all the vertices we need to compute the transition amplitude!

The decay rate of $K^\pm \to \pi^\pm X$

There are three diagrams contributing:



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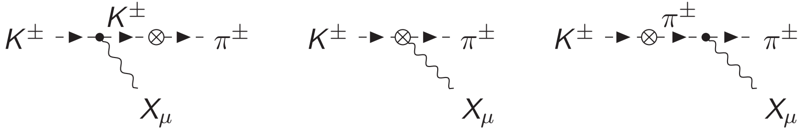

In the **flavor universal** case $(\mathbf{x_V^f}, \mathbf{x_A^f} \propto \mathbf{1})$ we obtain:

$$\frac{\Gamma}{m_K} \simeq \frac{G_f^2 f^4}{8\pi} \left(V_{ud} V_{us}^*\right)^2 g_x^2 \frac{m_K^2}{m_X^2} \cdot \left[g_8 \left(x_A^u + x_A^d \right) + g_8^s \left(x_A^u + 2x_A^d \right) + \frac{4}{3} g_{27} \left(x_A^u - x_A^d \right) \right]^2$$

where $m_K \gg m_X$, $g_8 = 3.07 \pm 0.14$, $g_8^s = -1.16 \pm 0.37$ and $g_{27} = 0.29 \pm 0.02$.

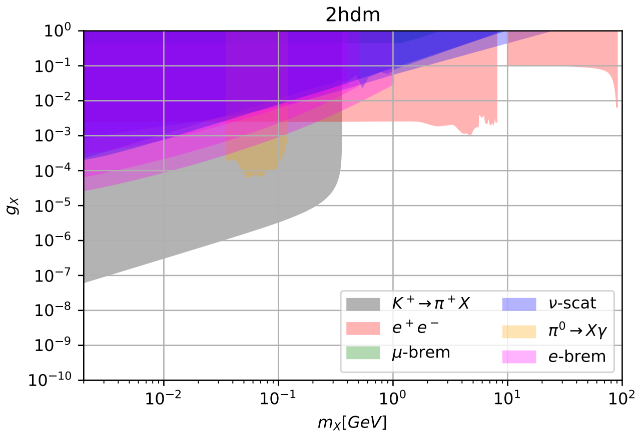

Figure: Constraints in the plane $g_x - m_X$ for the 2-Higgs-doublet model in [Baruch, Ilten, Soreq, Williams,'22]. The gray exclusion band arises from our study imposing the experimental bounds on $K^{\pm} \to \pi^{\pm} + X$.

Some comments on our result

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Some comments on our result

- **One-loop** contributions [Dror,Lasenby,Pospelov,'17] can dominate over tree-level ones. However, **tree-level effects do not depend on the UV completion details**
- Flavor non-universal couplings $(\mathbf{x_V^f}, \mathbf{x_A^f} \not\propto \mathbf{1})$ imply larger tree-level **FCNC effects** than in the flavor-universal case
- Access to the **vectorial couplings in a flavor-universal** case can be obtained by looking at NLO effects in χPT.

Summary

- We constructed the chiral EFT Lagrangian for $\Delta S = 1$ processes in the presence of new light vector bosons.
- $K^{\pm} \to \pi^{\pm} + X$ provides the most stringent bounds to the **axial couplings** of new light vector bosons (for $m_X < m_K$).
- Our (tree-level) results are **model-independent**, i.e. they do not rely on any specific **UV completion**.

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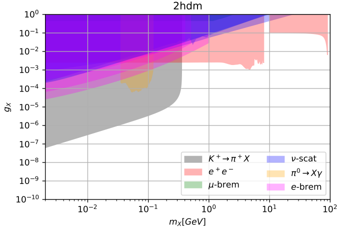
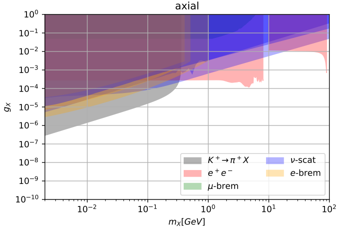
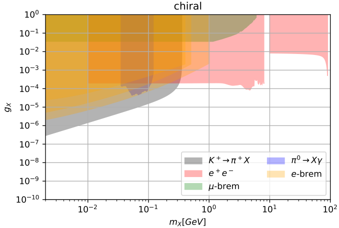
Thanks for your attention!

Backup Material

Tree-level results

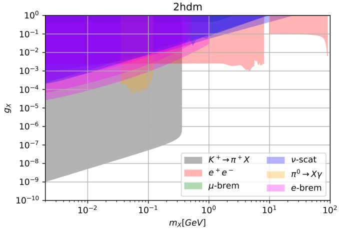


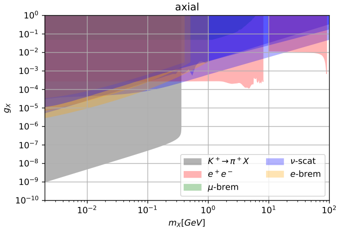


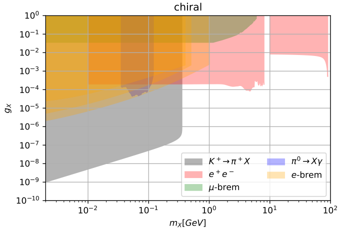


	x_e^V	x_ν^V	$x_{u,c,t}^V$	$x_{d,s,b}^V$	x_e^A	x_ν^A	$x_{u,c,t}^A$	$x_{d,s,b}^A$
Axial	0	1/4	0	0	-1	-1/4	1	-1
Chiral	-1	0	1	1	-1	0	1	-1
2HDM	0.044	0.05	1.021	0.015	-0.1	0.05	-0.95	-0.1

One-Loop-level results







	x_e^V	x_ν^V	$x_{u,c,t}^V$	$x_{d,s,b}^V$	x_e^A	x_ν^A	$x_{u,c,t}^A$	$x_{d,s,b}^A$
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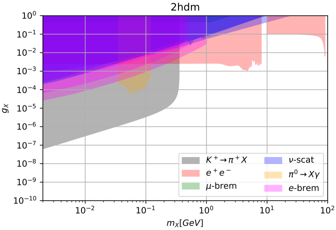
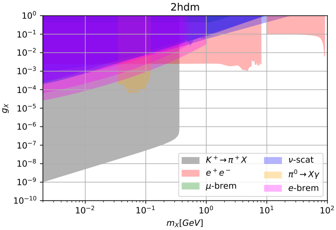
Comparison between tree- and loop-level: 2HDM





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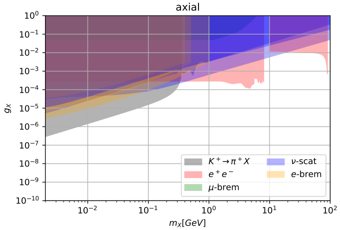
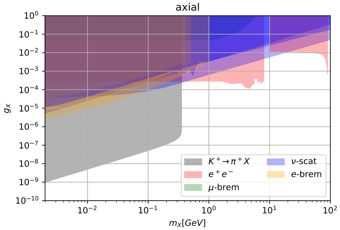
Comparison between tree- and loop-level: Axial





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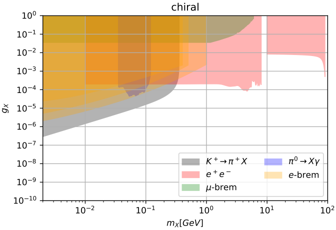
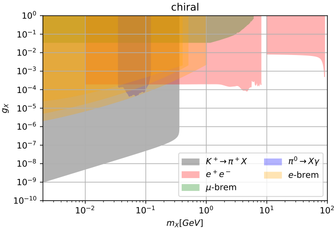
Comparison between tree- and loop-level: Chiral





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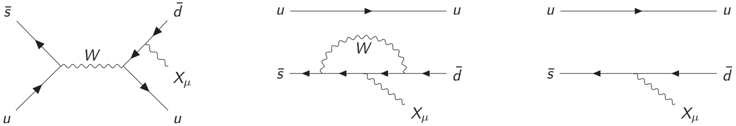
On the relative strength of contributions

$\propto G_f f^2 (V_{ud} V_{us}^*)$ $\qquad$ $\propto \frac{g^2}{16\pi^2} \frac{m_t^2}{m_W^2} V_{td} V_{ts}^*$ $\qquad$ $\propto V_{CKM} X_A^f V_{CKM}^\dagger$



$$\frac{\mathcal{A}_{Tree}}{\mathcal{A}_{Loop}} = \frac{G_f f^2 (V_{ud} V_{us}^*)}{\frac{g^2}{16\pi^2} \frac{m_t^2}{m_W^2} (V_{td} V_{ts}^*)} \simeq \frac{G_f f^2 \lambda}{\frac{g^2}{16\pi^2} \frac{m_t^2}{m_W^2} \lambda^5} \simeq 10^{-2}$$

Universal vs non-universal case

Flavor **universal** case ($G = -\frac{G_f}{\sqrt{2}} V_{ud} V_{us}^*$):

$$|\bar{\mathcal{M}}|^2 = 4G^2 f^4 g_x^2 \left[g_8 \left(x_A^u + x_A^d \right) + g_8^s \left(x_A^u + 2x_A^d \right) + \frac{4}{3} g_{27} \left(x_A^u - x_A^d \right) \right]^2 \left[\left(\frac{m_K^2 - m_\pi^2}{m_X} \right)^2 + m_X^2 - 2(m_K^2 + m_\pi^2) \right]$$

Flavor **non-universal** case :

$$|\bar{\mathcal{M}}|^2 = \frac{g_x^2}{m_X^2 \left(m_K^2 - m_\pi^2 \right)^2} [(m_K - m_\pi)^2 - m_X^2][(m_K + m_\pi)^2 - m_X^2] \left[\frac{x_{sd}^{\text{eff}}}{2} (m_K^2 - m_\pi^2) + 2g_{ew}^2 f^4 G g_8 (x_V^s - x_V^d) + f^2 G \left(g_8^s (m_K^2 - m_\pi^2)(x_A^u + x_A^d + x_A^s) + \frac{2}{3} g_{27} m_K^2 (2x_A^d - x_V^d + 2x_A^s + x_V^s - 4x_A^u) + g_8 m_\pi^2 (x_A^d - x_V^d + x_A^s + x_V^s + 2x_A^u) - \frac{2}{3} g_{27} m_\pi^2 (2x_A^d + x_V^d + 2x_A^s - x_V^s - 4x_A^u) - g_8 m_K^2 (x_A^d + x_V^d + x_A^s - x_V^s + 2x_A^u) \right) \right]^2$$