Sifting through the SM for the hints of an ALP

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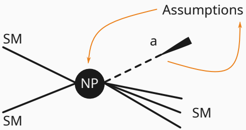
ECFA HF WG1

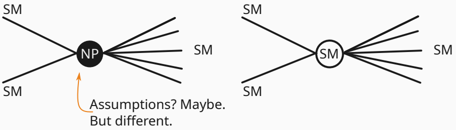
1st Workshop of WG1-SRCH Group

Direct vis à vis Indirect



Exotic Signatures

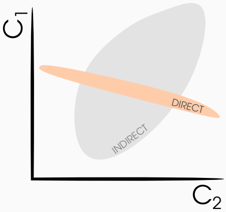
- Missing
- Displaced etc



Precision SM

- Branching Frac
- Shape etc

complementary→



Overview

Shift Symmetric $a \to a + c$

- $aG\tilde{G} \quad aW\tilde{W} \quad aB\tilde{B}$
- $\frac{1}{f_a}\partial_\mu a\, [\, \bar{q}^i_L T^a_{ij} q^j_L \;+\; L \leftrightarrow R\,]$
- Mass $\to$ QCD anomaly

The 'bare' mass

- $\frac{1}{2}m_a^2 a^2$

Periodic Symmetry? $a \to a + \frac{2\pi}{n}$

- $aGG \quad aWW \quad aBB$, $\frac{1}{f_a}a\bar{q}\gamma^\mu q\, j_\mu$

! e.g., Leading terms of $\sin(a), \cos(a)$

The Operators

$\mathcal{L} \supset \sum_a C_a \mathcal{O}^a$

- $\mathcal{O}^i_{L/R}$: $\frac{1}{f_a}\partial_\mu a \cdot \overline{q}_{L/R}\, t^i\, \gamma^\mu q_{L/R}$
- $\mathcal{O}^i_{LR}$: $\frac{a}{f_a} \cdot \overline{q}_L t^i M\, q_R$

- $\mathcal{O}_W$: $-\frac{a}{f_a} \cdot \overline{q}_L Q^W \gamma_\mu q_L\, j^\mu_\pm$
- $\mathcal{O}_Z$: $-\frac{a}{f_a} \cdot \left(\overline{q}_L Q^Z_L\, \gamma_\mu q_L + L \leftrightarrow R\right) j^\mu_Z$

How? Modify G_F (e.g.)

- Match this modified Lag to the chiral Lag and get operators
  - $\frac{1}{f_a}\partial_\mu a \bar{q}_L t^3 \gamma_\mu q_L \rightarrow -i f_\pi \xi \partial_\mu a\, Tr[U^\dagger_\pi t^3 \partial_\mu U_\pi]$ etc.
  - $\xi \equiv \frac{f_\pi}{f_a} \longrightarrow$ Power counting parameter for ALP physics

The effects

Chiral Lagrangian

- In flavour basis
  - $a - \pi_0$ two-point functions $\rightarrow$ redefined π^0
  - $a\, \mathcal{O}(\pi_0, \pi_+, j^\mu_\pm, \cdots)$

$\implies$ $\pi^0\, \mathcal{O}(\pi_0, \pi_+, j^\mu_\pm, \cdots)$ In mass basis

CP odd – ALP-like part

$\rightarrow$ Modifies the $\langle K^+/\pi^+|\mathcal{O}|\pi^0\rangle$ form factors

- Goes on to mess up light-Meson mass spectrum
- Modifies Meson decay Sum rules

CP even – Portal-like part

- Modifies amplitudes involving ALPs in final states

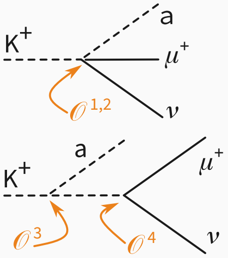
SM χPT

$$\mathcal{L} = i G_F V_{\bar{s}u} \Big[f^+_{SM}(q^2) \{ K^+ \partial_\mu \pi_0 - \partial_\mu K^+ \pi_0 \} + f^-_{SM}(q^2) \partial_\mu (K^+ \pi_0) \Big] \, j^{\mu}_{-,\ell}$$

$$q \equiv p_K - p_\pi$$

The ALP: Two qualitatively different effects

- $a - \pi^0(/\eta)$ mixing: Changes defn. of π^0
  - Modifies $f^+|_{K^+\pi^0}$, not $f^+|_{K^0\pi^+}$: *ratio*
- New operators sourced by the ALP
  - $K^+ \partial_\mu a \, j^\mu_- \neq \partial_\mu K^+ \, a \, j^\mu_-$
  - $\partial^\mu a \, \partial_\mu K^+ K^- + \text{h.c.}$
  - Rotated to SM π^0 through $a - \pi^0$ mixing



Distortion of Shape of diff. distribution

SM+ALP χPT

$$\mathcal{L} = iG_F V_{\bar{s}u}\left[\tilde{f}^{\,+}(q^2)\{K^+\partial_\mu\pi_0 - \partial_\mu K^+\pi_0\} + \tilde{f}^{\,-}(q^2)\partial_\mu(K^+\pi_0)\right] j^{\,\mu}_{-,\ell}$$

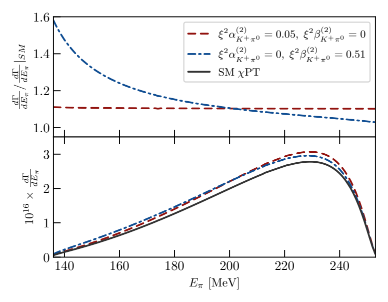
$\partial_\mu(K^+\pi^0) \rightarrow$ Brings out lepton mass

$$\tilde{f}_+(q^2) \rightarrow \left[1 + \frac{\xi^2\alpha^{(2)}_{K^+\pi^0}}{f^{\,+}(0)}\right] f^{\,+}_{\mathrm{SM}}(q^2)$$

$$\tilde{f}_-(q^2) \rightarrow \left[1 + \frac{\xi^2\beta^{(2)}_{K^+\pi^0}}{f^{\,-}(0)}\right] f^{\,-}_{\mathrm{SM}}(q^2)$$

$$\alpha^{(2)}_{K^+\pi^0} \equiv \alpha^{(2)}_{K^+\pi^0}(C_i)$$

$$\beta^{(2)}_{K^+\pi^0} \equiv \beta^{(2)}_{K^+\pi^0}(C_i)$$



Distortion of differential spectrum

$$\overline{|\mathcal{A}|}^2_{K_{l3}} = 2G_F^2|V_{\bar{s}u}|^2 C_{\rm cor}\left[1+2\,\xi^2\frac{\alpha^{(2)}_{K^+\pi^0}}{f^+_{SM}(0)}\right](2H\cdot p_\ell\ H\cdot p_{\nu_\ell} - H^2 p_\ell\cdot p_{\nu_\ell}),$$

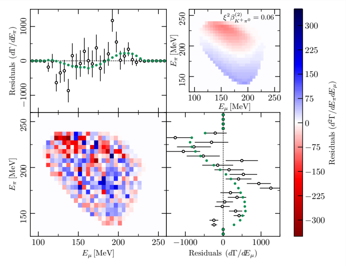
$$H_\mu \equiv f^+_{\rm SM}(q^2)\,Q_\mu + \left[1+\xi^2\left(\frac{\beta^{(2)}_{K^+\pi^0}}{f^-_{SM}(0)} - \frac{\alpha^{(2)}_{K^+\pi^0}}{f^+_{SM}(0)}\right)\right] f^-_{\rm SM}(q^2)\,q_\mu.$$

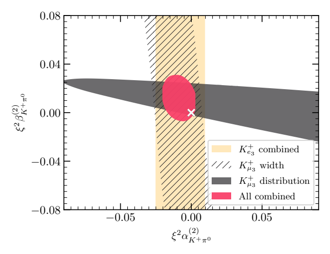
$$Q \equiv p_K + p_\pi; \quad q \equiv p_K - p_\pi$$

$C_{cor} \rightarrow$ EW and EM corrections

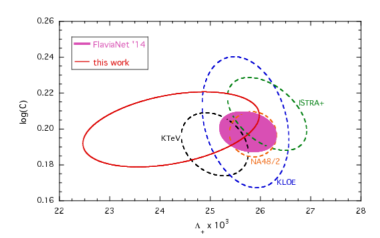
Bounds

NA48/2: $K^+_{e_3}, K^+_{\mu_3}$





ETM Coll. (Lattice)



- Indirect: 3 Gev
- Direct $\sim$ 30 GeV
- Natural Next step:
  - $K \to a\mu\nu$ as bg for $K \to \mu\nu$ (.3%)
  - $\tau \to aK\nu$ as bg for $\tau \to K\nu$ (1%)

! SCALE !

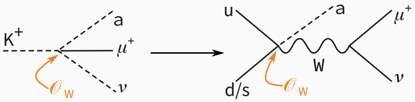
The direct channels

Flat direction

$$\alpha^{(2)}_{K^+\pi^0} = \frac{C_3}{2}\left(\alpha^{(1)}_{K^+a} - 4\, C_W^2 + \frac{C_3}{4}\right)$$

- Strength of $K^+ \to \pi^0 e^+ \nu$
- Strength of $K^+ \to a\, e^+ \nu$
- CP even part

At colliders



In progress:A.Budhraja,S. Mukherjee,TS.Roy

- No G_F suppression
- *But* model dependence

Summary

- Low lying ALPs modify χPT in non-trivial ways
- These modifications can be observed and categorized
  - Meson mass spectrum
  - Differential widths (also sum rules)
- These modifications will complement direct searches
  - More precise computations of SM parameters needed
- Interplay between high-energy and flavour experiments

Thank You

Questions/Input/Critique?

2112.13147[hep-ph] for details