Kaon Factories and X17

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March 24, 2026

2026 Meeting at the ECT*: The X17 Particle, Status, and New Ideas
Based on arXiv:2602.19479

Introduction

Kaon factories

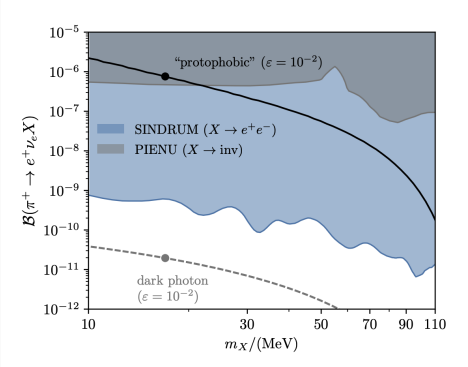
High-intensity ($\sim 10^{11}$ decays) kaon experiments sensitive to rare new physics

- **NA48 / NA48/2**: $K_S \to \pi^0 e^+ e^-$, $K^\pm \to \pi^\pm \pi^0 e^+ e^-$, $K_{L,S} \to \pi^+ \pi^- e^+ e^-$.
- **KTeV**: $K_L \to \pi^0 \pi^0 e^+ e^-$
- **NA62**: $K^+ \to \pi^+ \pi^0 e^+ e^- e^+ e^-$

BR's at the level of $\mathcal{O}(10^{-8})$ or better

Question: can we use these decays to constrain new $X \to e^+ e^-$?

Comparison with pion bounds



Hostert, Pospelov, PRD 108 (2023) 5, 055011, arXiv:2306.15077

- Pion decays sensitive to new physics
- Enjoys longitudinal enhancement for couplings to non-conserved currents
- e.g. Protophobic model $g_p = 0$ excluded by $\pi^+ \to e^+\nu_e X_{ee,\mathrm{inv}}$

The Chiral Perturbation Theory

Cirigliano, Ecker, Neufeld, Pich, Portoles
Kaon Decays and the SM: Rev.Mod.Phys. 84 (2012) 399,
arXiv:1107.6001

$\mathcal{L}_{\text{chiral order}}$ (# of LECs)	loop order
$\mathcal{L}_{p^2}(2) + \mathcal{L}^{\text{odd}}_{p^4}(0) + \mathcal{L}^{\Delta S=1}_{G_8 p^2}(1) + \mathcal{L}^{\Delta S=1}_{G_{27} p^2}(1)$ $+ \mathcal{L}^{\text{emweak}}_{G_8 e^2 p^0}(1) + \mathcal{L}^{\text{em}}_{e^2 p^0}(1) + \mathcal{L}^{\text{lepton}}_{\text{kin}}(0)$	$L = 0$
$+ \mathcal{L}_{p^4}(10) + \mathcal{L}^{\text{odd}}_{p^6}(23) + \mathcal{L}^{\Delta S=1}_{G_8 p^4}(22)$ $+ \mathcal{L}^{\Delta S=1}_{G_{27} p^4}(28) + \mathcal{L}^{\text{emweak}}_{G_8 e^2 p^2}(14)$ $+ \mathcal{L}^{\text{em}}_{e^2 p^2}(13) + \mathcal{L}^{\text{lepton}}_{e^2 p^2}(5)$	$L \leq 1$
$+ \mathcal{L}_{p^6}(90)$	$L \leq 2$

Particle zoo:

$\pi, K, \eta \ldots$

+ EM, Weak physics

$SU(3)$-**flavor symmetric ChPT for** $\Delta S = 1$

$$\mathcal{L}^{\Delta S=1}_{G_8 p^2} = -F^4 G_8 \mathrm{Tr}\left(\lambda D_\mu U^\dagger D^\mu U + \text{h.c.}\right)$$

- Octet G_8 dominates over 27-plet G_{27}.
- Rates suppressed by $G_8 \sim g_8 \sqrt{2} G_F V^*_{us} V_{ud}$.

Goldstone equivalence / longitudinal enhancement X_μ couples to current J_μ with $\partial^\mu J_\mu \neq 0$:

$$g_X X_\mu J^\mu \longrightarrow -\frac{g_X}{m_X} \phi \, \partial_\mu J^\mu$$

- Longitudinal mode $\sim (E/m_X)^2 \Rightarrow (m_K/m_X)^2$ enhancement when $m_X \ll m_K$.

New vector/axial-vector boson X:

$$\mathcal{L} = X_\mu \left(\sum_{f=u,d,s,e} \bar{f}(g_f^V \gamma^\mu + g_f^A \gamma^\mu \gamma^5) f \right). \tag{1}$$

Chiral Lagrangian:

$$\mathcal{L}^{\Delta s=1}_{G_8 p^2} = -F^4 G_8 \mathrm{Tr}\left(\lambda D_\mu U^\dagger D^\mu U + \text{h.c.} \right) \tag{2}$$

$F^2 G_8 \simeq -7.7 \times 10^{-8}$, $\lambda \equiv (\lambda_6 - i\lambda_7)/2$ to select $\bar{s} \to \bar{d}$

$$\begin{aligned} D_\mu U &= \partial_\mu U - iX_\mu [G_V, U] && \text{vector} \\ D_\mu U &= \partial_\mu U - iX_\mu \{G_A, U\} && \text{axial-vector} \end{aligned} \tag{3}$$

where $G_{V,A} = -\mathrm{diag}(g_u^{V,A}, g_d^{V,A}, g_s^{V,A})$.

$U = e^{i\Phi/F}$, $F \simeq 93$ MeV

$$\Phi = \begin{pmatrix} \pi^0 + \frac{\eta_8}{\sqrt{3}} & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{\eta_8}{\sqrt{3}} & K_L - iK_S \\ \sqrt{2}K^- & K_L + iK_S & -\frac{2\eta_8}{\sqrt{3}} \end{pmatrix}$$

We then rotate the fields to diagonalize the kinetic term and expand $\mathcal{L}^{\Delta s=1}_{G_8 p^2}$ in powers of $1/F$

X decays

Direct constraints on the coupling to electrons:

- KLOE bound: $\sqrt{(g_e^V)^2 + (g_e^A)^2} = e\varepsilon < 6 \times 10^{-4}$
- NA64 bound: $\sqrt{(g_e^V)^2 + (g_e^A)^2} > g_e^{\mathrm{NA64}} = 2.1 \times 10^{-4}$

Estimated lab frame path length in Kaon factories: $\langle p \rangle \sim 60$ GeV
$\ell = cv\gamma\tau_0 \sim (0.1\mathrm{cm} - 5\mathrm{cm})$

Channels

Overview of channels

Channel	Experiment	Role
$K \to \pi X$	NA48	3-body; $X \to e^+e^-$
$K \to \pi\gamma X$	NA48/2	Radiative
$K_L \to \pi^0\pi^0(X \to e^+e^-)$	KTeV	**Strongest limit** $\mathcal{O}(10^{-5})$
$K_L \to \pi^+\pi^-(X \to e^+e^-)$	NA48/2	Complementary
$K^+ \to \pi^+\pi^0(X \to e^+e^-)$	NA48/2	Complementary u, d, s
$K^+ \to \pi^+XX$	NA62	Double $(m_K/m_X)^2$ enhancement

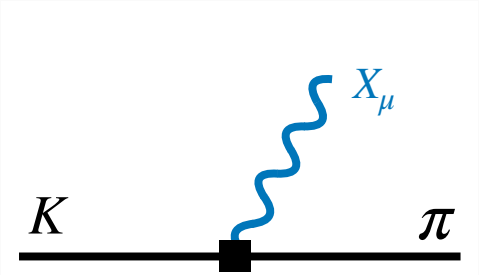
Channel 1: $K^+ \to \pi^+ X_{ee}$

- $K_S \to \pi^0 e^+ e^-$ large Dalitz backgrounds
- For lighter bosons, conservative limit: $BR(K^+ \to \pi^+ e^+ e^-) \lesssim 10^{-5}$

(See e.g. Alves, arXiv:1710.03764, Baker *et al*, 1988)

$$\mathcal{L}_{K\pi X} \supset \kappa_8 \, g^X_{K\pi^+} X_\mu \left(K^+ i\overleftrightarrow{\partial_\mu} \pi^- + \text{h.c.} \right)$$

$$g^X_{K\pi^+} \equiv 2g^A_u + g^A_d + g^A_s + (g^V_d - g^V_s)\frac{1+r}{1-r}$$

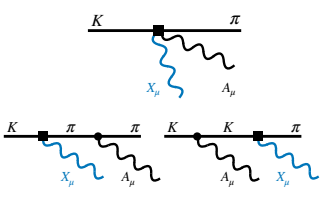


$$r \equiv m_\pi^2 / m_K^2$$

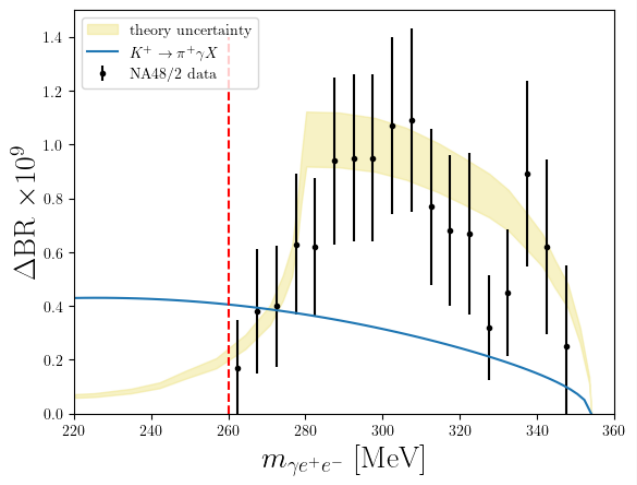
Channel 2: $K^+ \to \pi^+ \gamma X_{ee}$

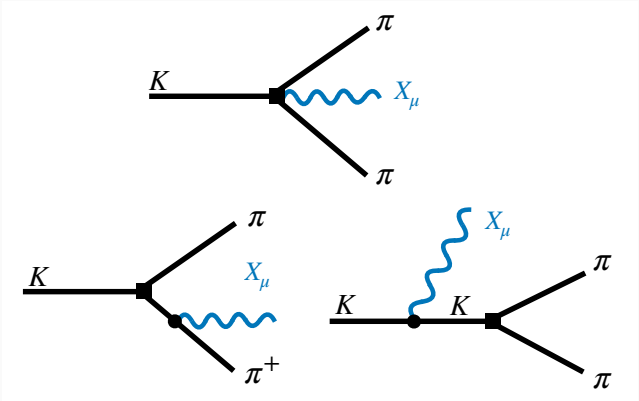
Channel summary

- NA48/2 data binned over the Dalitz system $\gamma e^+ e^-$
- $\to$ sets a bound on the $m_{\gamma X}$ signal hypothesis
- Cut at $m_{\gamma e^+ e-} > 260$ MeV to avoid background contamination
- Also depends on $g^X_{K\pi^+}$



PLB 2008, arXiv:0711.4313




π
K
X_μ
π
π
K
X_μ
π^+
X_μ
K
K
π
π

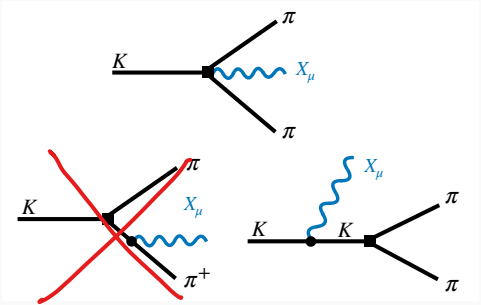
Channel 3: $K_L \to \pi^0\pi^0(X \to e^+e^-)$

Phys. Rev. Lett. 89, 211801, arXiv:hep-ex/0210056

- KTeV: 1 event $\Rightarrow$
  $\mathcal{B}(K_L \to \pi^0\pi^0 e^+e^-) < 6.6 \times 10^{-9}$
  (90% CL).
- **Leading limit** on light X.

$$\mathcal{B}(K_L \to \pi^0\pi^0 X_{17}) \simeq 42.3 \times \left(\frac{17\ \text{MeV}}{m_X}\right)^2 \times \left(0.22(g^X_{K\pi^0\pi^0})^2 - 0.75 g^X_{K\pi^0\pi^0} g^V_{U_3} + (g^V_{U_3})^2\right)$$

$$g^X_{K\pi^0\pi^0} \equiv \frac{1}{2}\left(g_d^V + 3g_d^A - g_s^V + g_s^A\right) + r\frac{g_s^A - g_d^A}{1-r}$$



$r \equiv m_\pi^2/m_K^2$, $g^V_{U_3} \equiv g^V_u - g^V_d$

See also Iwai *et al* arXiv:2602.15117

strong bounds on pseudoscalars

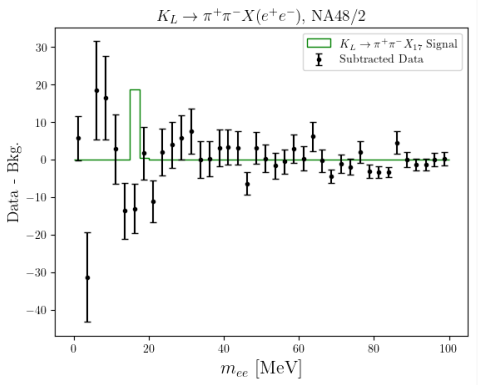
Channel 4: $K_L \to \pi^+\pi^-(X \to e^+e^-)$

- NA48:

  $\mathcal{B}(K_L \to \pi^+\pi^- e^+e^-) = (3.08 \pm 0.20) \times 10^{-7}$

- Bump hunt analysis; construct a binned χ^2 in m_{ee}
- Assume energy res. $\sigma/E = 3.2\sqrt{E} + 9/E + 0.42$ in GeV
- Need to assume efficiency for K_L with X based on $K_L \to \pi^+\pi^-\pi^0_D$
- Constrain complementary combinations of couplings to u, d, s at $\mathcal{O}(10^{-4})$.

EJC 2003



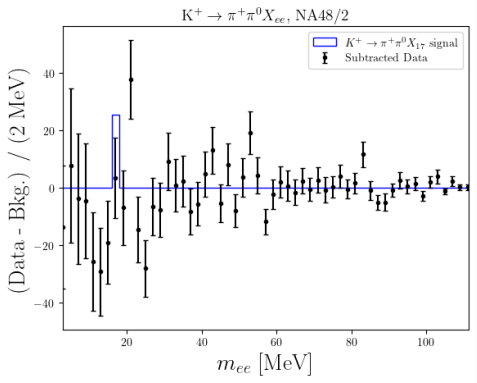
Channel 5: $K^+ \to \pi^+\pi^0(X \to e^+e^-)$

- NA48/2:

  $\mathcal{B}(K^+ \to \pi^+\pi^0 e^+e^-) = (4.24 \pm 0.14) \times 10^{-6}$

- Recast via binned χ^2 in m_{ee}
- Acceptance depends on signal assumption ("IB" or "M" type)
- Complementary combination of u, d, s couplings.

PLB 2019, arXiv:1809.02873



Note: Radiation off kaon leg suppressed by $m_e^2 - m_{e_0}^2$, as it is for

Channel 6: $K^+ \to \pi^+ XX$ (double emission)

- Double emission of X: $K^+ \to \pi^+ XX$ with $X \to e^+ e^-$ (or invisible).
- Rate gets **double** $(m_K/m_X)^4$ enhancement, compensates partially for g_X^4 suppression.
- Provides additional constraints on parameter space of light X beyond single-emission channels.

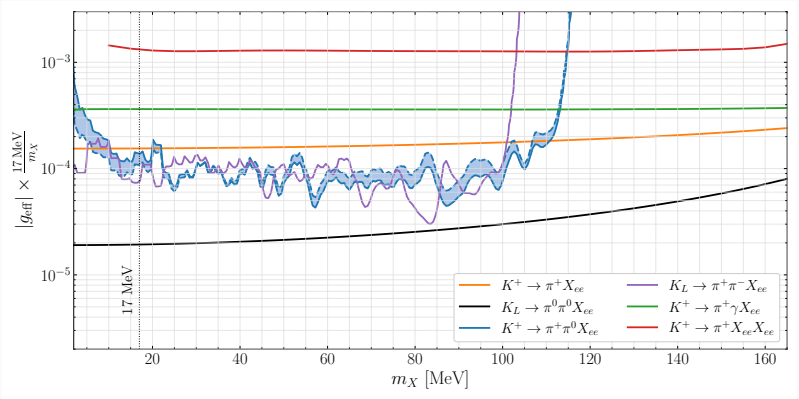
Couplings galore

6 unknowns, 6 channels: $g_u^{V,A}, g_d^{V,A}, g_s^{V,A}$

Channel	Pure V Couplings	Pure A Couplings	SU(3) Limit $g_u^{V,A} = g_d^{V,A} = g_s^{V,A} = g^{V,A}$	BR 90% U.L. @17 MeV
$K_L \to \pi^0\pi^0 X_{ee}$	$g_{U_3}^V$	$g_{U_0}^A + g_{U_3}^A \frac{1-2r}{1-r}$	$g_{U_0}^A \to g_{\text{eff}} = 2g^A$	6.6×10^{-9}
$K_L \to \pi^+\pi^- X_{ee}$	$(2g_{T_3}^V - g_{U_3}^V), g_{U_3}^V, g_{T_3}^V$	$g_{U_0}^A + \mathcal{O}(r)$	$g_{U_0}^A \to g_{\text{eff}} = 2g^A$	2.18×10^{-8}
$K^+ \to \pi^+ X_{ee}$, $K^+ \to \pi^+\gamma X_{ee}$	$g_{U_3}^V$	$g_{T_0}^A + g_{V_0}^A$	$g_{T_0}^A + g_{V_0}^A \to g_{\text{eff}} = 4g^A$	10^{-5}, 1.5×10^{-9}
$K^+ \to \pi^+\pi^0 X_{ee}$	$g_{T_3}^V,\ g_{V_3}^V$	$-g_{T_3}^A/3$, $g_{T_0}^A + g_{U_0}^A + 2\frac{g_{T_3}^A - g_{V_3}^A r}{1-r}$	$g_{T_0}^A + g_{V_0}^A \to g_{\text{eff}} = 4g^A$	$[1.15, 1.89] \times 10^{-8}$
$K^+ \to \pi^+ X_{ee} X_{ee}$	$(g_{V_3}^V - g_{T_3}^V)^2 \frac{1+r}{1-r}$, $-4\frac{(g_{T_3}^V)^2 + (g_{V_3}^V)^2 r}{1-r}$	$-(g_{U_0}^A)^2 + 4\frac{(g_{T_3}^A)^2 + (g_{V_3}^A)^2 r}{1-r}$	$g_{T_0}^V g_{V_0}^A - (g_{U_0}^A)^2$ $\to g_{\text{eff}}^2 = 4g^A(g^V - g^A)$	3.14×10^{-9}

Limits

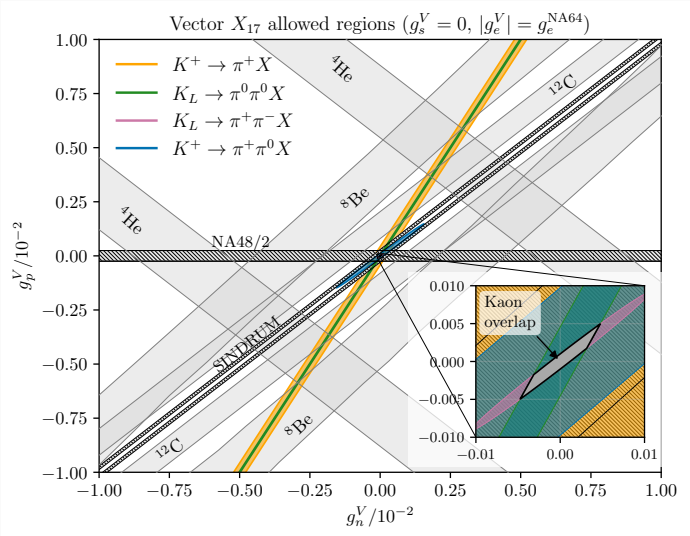
Limits by mass (all channels)



- "Effective" coupling: choose a factorizable combination
- Simple limit: $u = d = s \to g_{U_3}^{V,A}, g_{T_3}^{V,A}, g_{V_3}^{V,A} \to 0$
- In general, limits overconstrain complementary combinations at $\mathcal{O}(10^{-5} - 10^{-4})$

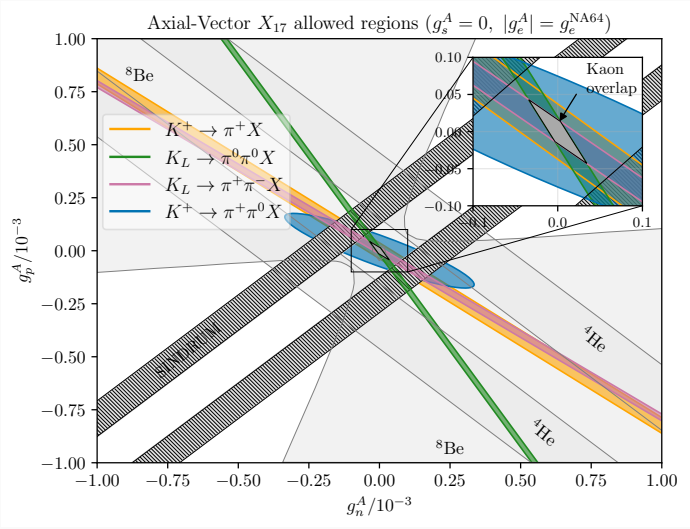
2D exclusions: Vector ($g_s^V = 0$)

$$g_p^V = 2g_u^V + g_d^V,\ g_n^V = 2g_d^V + g_u^V$$

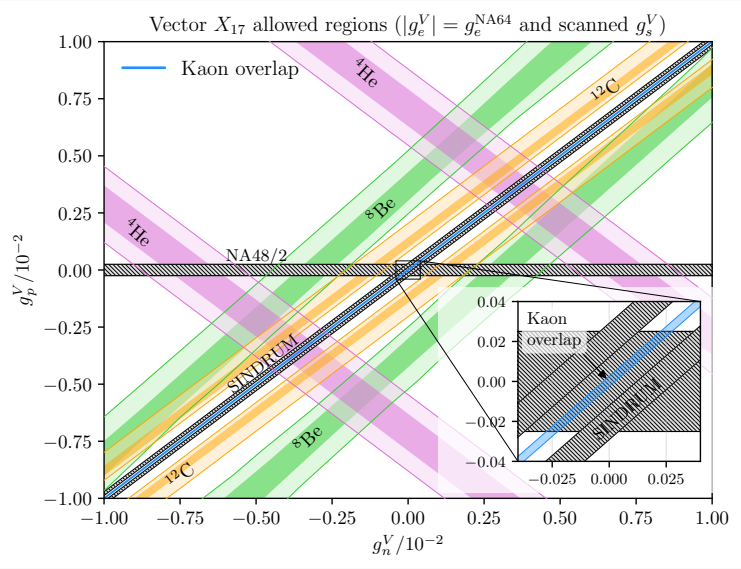


2D exclusions: Axial-vector ($g_s^A = 0$)

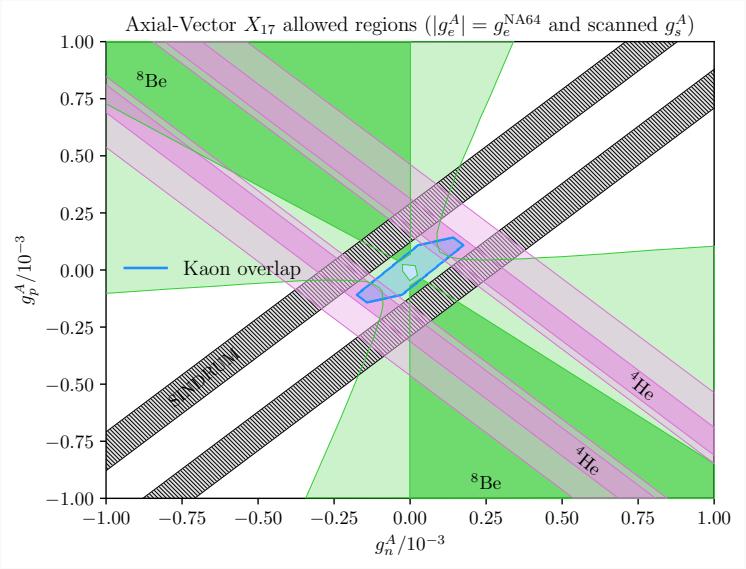
$$g_p^A = \kappa^u g_u^A + \kappa^d g_d^A,\ g_n^A = \kappa^u g_d^A + \kappa^d g_u^A$$



2D exclusions: Vector (profile over strange coupling)



2D exclusions: Axial-vector (profile over strange coupling)



Conclusion

Conclusion

- Rare kaon decays constrain light vector and axial-vector bosons to $\mathcal{O}(10^{-5})$–$\mathcal{O}(10^{-3})$ (effective couplings).
- **Strongest limit**: $K_L \to \pi^0\pi^0(X \to e^+e^-)$ (KTeV).
- Multiple channels overconstrain flavor/coupling combinations.
- Significant **tension** between vector/axial-vector explanations and kaon/pion data.
- **Further work**: π^- capture (e.g. $\pi^- + (A, Z) \to X + (A, Z-1)$), $\eta \to \pi^+\pi^- X_{ee}$
- **Outlook**: need more independent measurements to tell us more: fine tuning, or nuclear physics?

Question for discussion

Ex: $K^+ \to \pi^+\pi^0$ described by G_{27}, otherwise isospin breaking at order G_8,
$\mathcal{A} \propto m_\pi^2 - m_{\pi^0}^2$

Shameless Numerology:

Consider isospin breaking effects $\sim \dfrac{\sqrt{m_\pi^2 - m_{\pi^0}^2}}{2} \simeq 17.75$ MeV

What role do isospin breaking effects play in the interpretation of the X17 anomaly?

Thank you!

Thank you!

Backup Deck

Coupling dictionary

$g_i^{V,A} \equiv \langle I_{0,\pm,3}\, g^{V,A} \rangle_{I=T,U,V}$		$g_i^{V,A} \equiv \langle \lambda_i\, g^{V,A} \rangle$	
$g_{T_0}^{V,A}$	$g_u^{V,A} + g_d^{V,A}$	$g_1^{V,A}$	0
$g_{U_0}^{V,A}$	$g_d^{V,A} + g_s^{V,A}$	$g_2^{V,A}$	0
$g_{V_0}^{V,A}$	$g_u^{V,A} + g_s^{V,A}$	$g_3^{V,A}$	$g_u^{V,A} - g_d^{V,A}$
$g_{T_3}^{V,A}$	$g_u^{V,A} - g_d^{V,A}$	$g_4^{V,A}$	0
$g_{U_3}^{V,A}$	$g_d^{V,A} - g_s^{V,A}$	$g_5^{V,A}$	0
$g_{V_3}^{V,A}$	$g_u^{V,A} - g_s^{V,A}$	$g_6^{V,A}$	0
$g_{T_\pm,U_\pm,V_\pm}^{V,A}$	0	$g_7^{V,A}$	0
		$g_8^{V,A}$	$\frac{1}{\sqrt{3}}\left(g_u^{V,A} + g_d^{V,A} - 2g_s^{V,A}\right)$

Diagonalization

We diagonalize the kinetic terms:

$$
\begin{aligned}
\pi^+ &\to \pi^+ - \frac{2\kappa_8}{1-r} K^+, \\
K^+ &\to K^+ + \frac{2\kappa_8 r}{1-r} \pi^+, \\
\pi^0 &\to \pi^0 + \frac{2\kappa_8}{1-r} K_L, \\
K_L &\to K_L - \frac{2\kappa_8 r}{1-r} \pi^0 + \frac{2\kappa_8 r_\eta}{r_\eta - 1} \eta_8, \\
\eta_8 &\to \eta_8 - \frac{2\kappa_8 r_\eta}{r_\eta - 1} K_L,
\end{aligned}
\tag{4}
$$

$r = m_\pi^2/m_K^2$, $r_\eta = m_\eta^2/m_K^2$.

Backup: $K \to \pi\pi X_{\text{inv}}$

- Invisible X: searches for $K \to \pi\pi +$ missing.
- E787: $\mathcal{B}(K^+ \to \pi^+\pi^0\nu\bar{\nu}) \lesssim 4.3 \times 10^{-5}$ (90% CL).
- E391a: $\mathcal{B}(K_L \to \pi^0\pi^0\nu\bar{\nu}) \lesssim 8.1 \times 10^{-7}$ (90% CL).
- Same topology constrains light invisible X (e.g. $K_L \to \pi^0\pi^0 X_{\text{inv}}$).

(same topology as $K \to \pi\pi X$.)

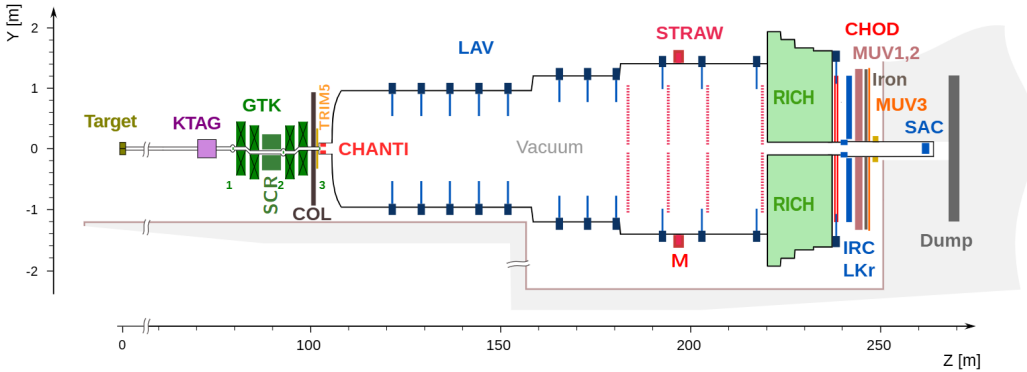
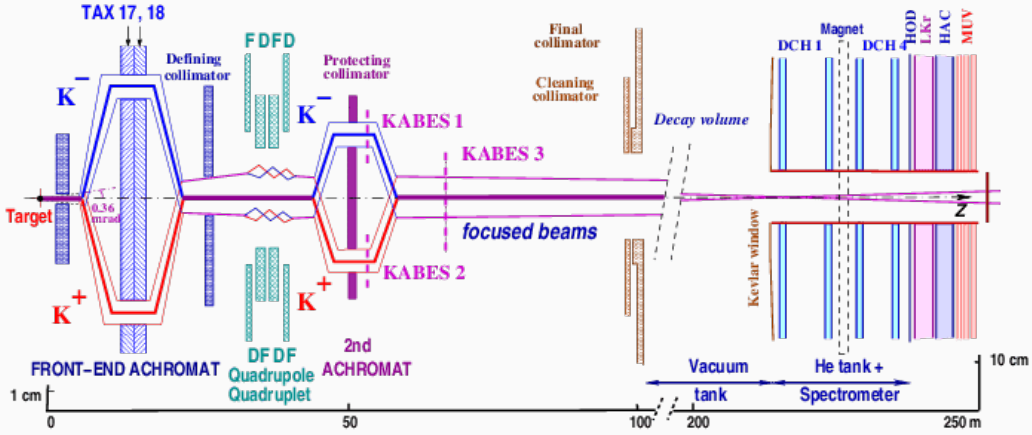
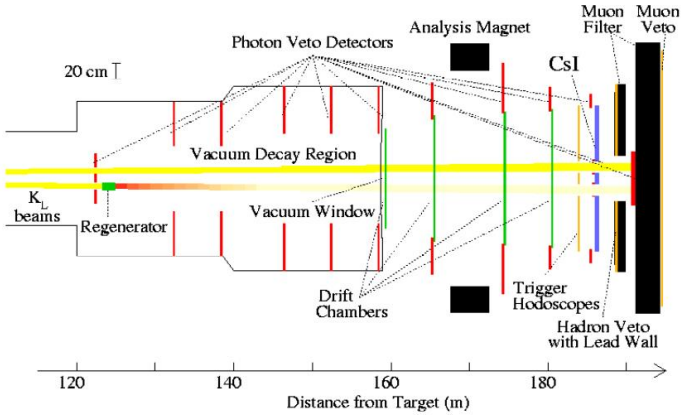


Figure 1: Schematic side view of the NA62 beamline and detector used in 2018.

NA48/2


TAX 17, 18
Defining collimator
FDFD
Protecting collimator
Final collimator
Cleaning collimator
Magnet
DCH 1
DCH 4
HOD
LKr
HAC
MUV
K⁻
K⁻
KABES 1
KABES 3
Decay volume
Target
0.36 mrad
focused beams
Kevlar window
z
K⁺
K⁺
KABES 2
FRONT-END ACHROMAT
DF DF Quadrupole Quadruplet
2nd ACHROMAT
Vacuum tank
He tank + Spectrometer
1 cm
10 cm
0
50
100
200
250 m

KTeV Detector