Leptoquark effects in rare hyperon and kaon processes

Jusak Tandean
NCTS

Based on

Jhih-Ying Su & JT, arXiv:1912.xxxxx

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National Center for Theoretical Sciences, Hsinchu, Taiwan

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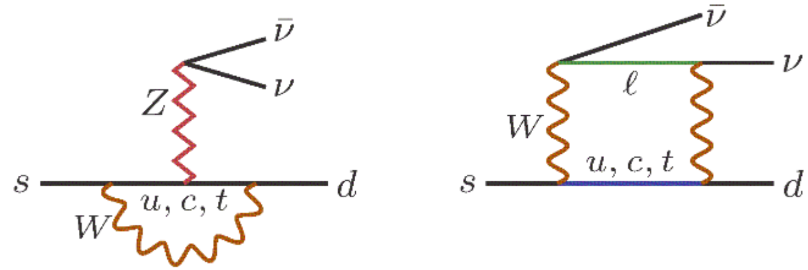
- Introduction
  - Rare hadron decays with missing energy
- Kaon & hyperon decays as complementary probes of new *ds* quark interactions with invisible fermions
- Leptoquark contributions to rare hyperon and kaon decays
- Conclusions

- In the standard model (SM) the strangeness-changing neutral current decays of light hadrons with missing energy ($\not{E}$) arise mainly from the loop-induced quark transition $s \to d\nu\nu$.

SM



- Such decays are therefore highly suppressed in the SM, with branching fractions of order 10^{-10} or less
  - E.g. SM predictions:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(8.5^{+1.0}_{-1.2}\right) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = \left(3.2^{+1.1}_{-0.7}\right) \times 10^{-11}$$

Bobeth & Buras, 2018

- Thus, observing significantly larger branching fractions of these processes at ongoing or upcoming experiments would likely be indicative of new physics (NP).

- Measurements: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.7(1.1) \times 10^{-10}$ PDG, 2019

  $\mathcal{B}\big(K_L \to \pi^0 \nu\bar{\nu}\big) < 3.0 \times 10^{-9}$ at 90% CL KOTO, 2019

  SM predictions: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \big(8.5^{+1.0}_{-1.2}\big) \times 10^{-11}$

  $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \big(3.2^{+1.1}_{-0.7}\big) \times 10^{-11}$ Bobeth & Buras, 2018

Summary and prospects

NA 62 preliminary result

- Two events in signal region observed in 2017 data
- 2016+2017 NA62 result

$$BR(K^+ \to \pi^+ \nu\nu) < 1.85 \times 10^{-10} \text{ @ } 90\ \%\ \text{CL}$$

$$BR(K^+ \to \pi^+ \nu\nu) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$$

- Constraints on the largest enhancements allowed by NP models

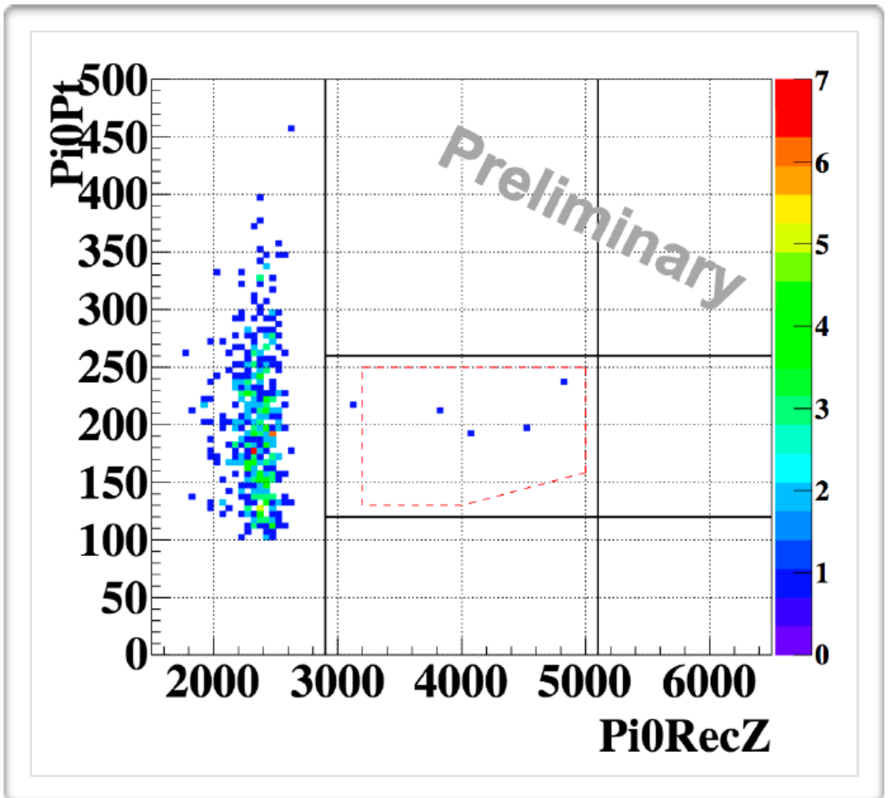
- 2018 data analysis in progress (factor 2 more data)
  - ⋆ On-going studies to increase signal efficiency
- Hardware improvements foreseen from 2021 to mitigate the upstream background

R Marchevski @ PIC 2019

$K_L \to \pi^0 \nu\nu$ (2016-2018 data)

KOTO preliminary result

- SES = 6.9×10^{-10}
- Four candidate events observed in the signal region.
- Will study the nature of the events inside the box.



Preliminary

	#BG
KLpi0pi0	<0.18
KLpi+pi-pi0	<0.02
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09
KL2gamma	0.00 ± 0.00
Upstream π^0	0.00±0.01
Hadron cluster	0.02 ±0.00
CV-pi0	<0.10
CV-eta	0.03±0.01
Total	0.05±0.02

YC Tung @ PIC 2019

- $K \to \pi \not{E}$

  Measurements: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.7(1.1) \times 10^{-10}$ E949 2008, PDG 2019

  $\mathcal{B}\big(K_L \to \pi^0 \nu\bar{\nu}\big) < 3.0 \times 10^{-9}$ at 90% CL KOTO, 2019

- $K \to \pi\pi' \not{E}$

  Measurements: $\mathcal{B}(K^+ \to \pi^+\pi^0 \nu\bar{\nu}) < 4.3 \times 10^{-5}$ at 90% CL E787, 2001

  $\mathcal{B}\Big(K_L \to \pi^0\pi^0 \nu\bar{\nu}\Big) < 8.1 \times 10^{-7}$ at 90% CL E391a, 2011

- $K_{L,S} \to \not{E}$ still have no direct-search limits, but indirectly limits can be inferred from the data on their visible decay channels:

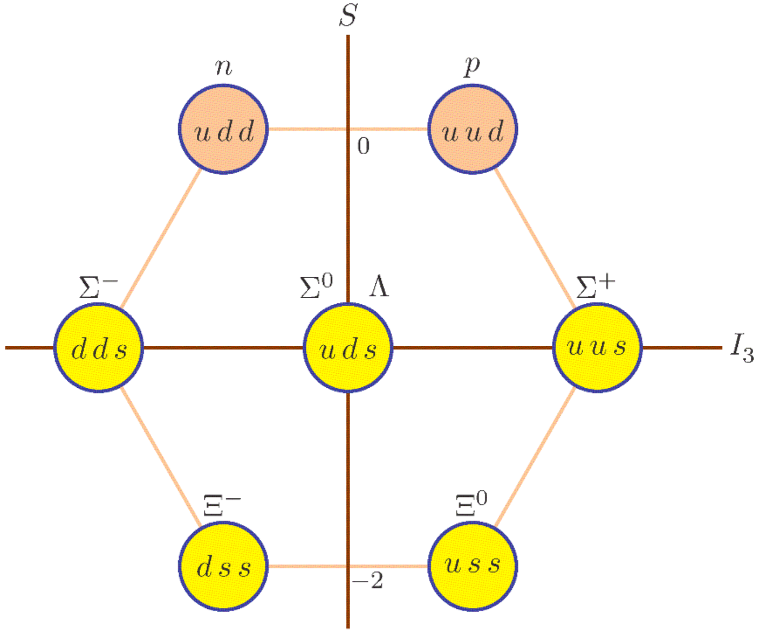
  $\mathcal{B}(K_L \to \not{E}) < 6.3 \times 10^{-4}$ & $\mathcal{B}(K_S \to \not{E}) < 1.1 \times 10^{-4}$ at 95% CL

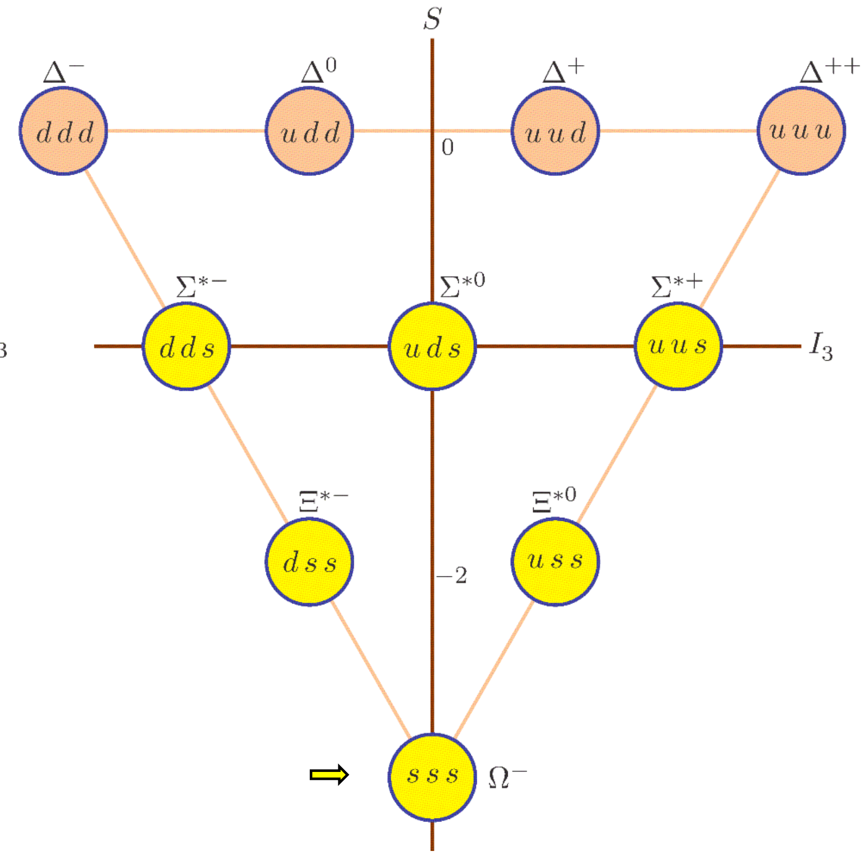
  Gninenko, 2015

- No data yet in the baryon sector.

Flavor-SU(3) octet of spin-1/2 baryons & decuplet of spin-3/2 baryons

- **Hyperons**





* Effective Lagrangian for $sdf\bar{f}$ interactions at low energies

$$\mathcal{L}_f = -\Big[\overline{d}\gamma^\eta s\,\overline{f}\gamma_\eta\big(\mathrm{c}_f^{\mathrm{V}} + \gamma_5\mathrm{c}_f^{\mathrm{A}}\big)f + \overline{d}\gamma^\eta\gamma_5 s\,\overline{f}\gamma_\eta\big(\tilde{\mathrm{c}}_f^{\mathrm{V}} + \gamma_5\tilde{\mathrm{c}}_f^{\mathrm{A}}\big)f$$
$$+\,\overline{d}s\,\overline{f}\big(\mathrm{c}_f^{\mathrm{S}} + \gamma_5\mathrm{c}_f^{\mathrm{P}}\big)f + \overline{d}\gamma_5 s\,\overline{f}\big(\tilde{\mathrm{c}}_f^{\mathrm{S}} + \gamma_5\tilde{\mathrm{c}}_f^{\mathrm{P}}\big)f\Big] + \mathrm{H.c.}$$

f describes an electrically neutral, colorless, invisible, spin-$\frac{1}{2}$, Dirac particle.
Model-independently $\mathrm{c}_f^{\mathrm{V,A,S,P}}$ & $\tilde{\mathrm{c}}_f^{\mathrm{V,A,S,P}}$ are generally complex free parameters.

* It contributes to $|\Delta S| = 1$ kaon and hyperon decays with missing energy.
  - $K \to \pi f\bar{f}$
  - $K \to \pi\pi' f\bar{f}$
  - $K \to f\bar{f}$
  - $\mathfrak{B} \to \mathfrak{B}' f\bar{f}$, $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$
  - $\Omega^- \to \Xi^- f\bar{f}$

* $\mathcal{L}_f$ can accommodate $s \to d\nu\bar{\nu}$ in the SM, with $\mathrm{c}_\nu^{\mathrm{V}} = -\mathrm{c}_\nu^{\mathrm{A}} = -\tilde{\mathrm{c}}_\nu^{\mathrm{V}} = \tilde{\mathrm{c}}_\nu^{\mathrm{A}}$ and $\mathrm{c}_\nu^{\mathrm{S,P}} = \tilde{\mathrm{c}}_\nu^{\mathrm{S,P}} = 0$

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$$+ \boxed{\bar{d}s}\,\bar{f}\big(\mathtt{C}_f^{\mathrm{S}} + \gamma_5\mathtt{C}_f^{\mathrm{P}}\big)f + \boxed{\bar{d}\gamma_5 s}\,\bar{f}\big(\tilde{\mathtt{c}}_f^{\mathrm{S}} + \gamma_5\tilde{\mathtt{c}}_f^{\mathrm{P}}\big)f\Big] + \mathrm{H.c.}$$

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- Mesonic matrix elements which don't vanish:

$$\langle 0|\overline{d}\gamma^\eta\gamma_5 s|\overline{K}^0\rangle = \langle 0|\overline{s}\gamma^\eta\gamma_5 d|K^0\rangle = -if_K p_K^\eta, \qquad \langle 0|\overline{d}\gamma_5 s|\overline{K}^0\rangle = \langle 0|\overline{s}\gamma_5 d|K^0\rangle = iB_0 f_K$$

$$\langle\pi^-|\bar{d}\gamma^\eta s|K^-\rangle = -\langle\pi^+|\bar{s}\gamma^\eta d|K^+\rangle = \left(p_K^\eta + p_\pi^\eta\right)f_+ + \left(f_0 - f_+\right)q_{K\pi}^\eta\,\frac{m_K^2 - m_\pi^2}{q_{K\pi}^2}$$

$$\langle\pi^-|\bar{d}s|K^-\rangle = \langle\pi^+|\bar{s}d|K^+\rangle = B_0 f_0\,, \qquad B_0 = \frac{m_K^2}{\hat{m} + m_s}\,, \qquad q_{K\pi} = p_K - p_\pi$$

$$\left\langle\pi^0(p_0)\,\pi^-(p_-)\middle|\bar{d}\left(\gamma^\eta, 1\right)\gamma_5 s\middle|K^-\right\rangle = \frac{i\sqrt{2}}{f_K}\left[\left(p_0^\eta - p_-^\eta, 0\right) + \frac{(p_0 - p_-)\cdot\tilde{q}}{m_K^2 - \tilde{q}^2}\left(\tilde{q}^\eta, -B_0\right)\right]$$

$$\left\langle\pi^0(p_1)\,\pi^0(p_2)\middle|\bar{d}\left(\gamma^\eta, 1\right)\gamma_5 s\middle|\overline{K}^0\right\rangle = \frac{i}{f_K}\left[\left(p_1^\eta + p_2^\eta, 0\right) + \frac{(p_1 + p_2)\cdot\tilde{q}}{m_K^2 - \tilde{q}^2}\left(\tilde{q}^\eta, -B_0\right)\right]$$

f_K is the kaon decay constant, $f_{+,0}$ represent form factors depending on $q_{K\pi}^2$

$\tilde{q} = p_{K^-} - p_0 - p_- = p_{\bar{K}^0} - p_1 - p_2$

- Vanishing ones:

$$\langle 0|\overline{d}(\gamma^\eta, 1)s|\overline{K}^0\rangle = \langle 0|\overline{s}(\gamma^\eta, 1)d|K^0\rangle = (0, 0)$$

$$\langle\pi^-|\bar{d}(\gamma^\eta, 1)\gamma_5 s|K^-\rangle = \langle\pi^+|\bar{s}(\gamma^\eta, 1)\gamma_5 d|K^+\rangle = (0, 0)$$

- The baryonic matrix elements are estimated with aid of chiral perturbation theory (χPT) at leading order:

$$\langle \mathfrak{B}' | \bar{d}\gamma^\eta s | \mathfrak{B} \rangle = \mathcal{V}_{\mathfrak{B}'\mathfrak{B}}\, \bar{u}_{\mathfrak{B}'} \gamma^\eta u_{\mathfrak{B}}, \qquad \langle \mathfrak{B}' | \bar{d}\gamma^\eta \gamma_5 s | \mathfrak{B} \rangle = \bar{u}_{\mathfrak{B}'} \left(\gamma^\eta \mathcal{A}_{\mathfrak{B}'\mathfrak{B}} - \frac{\mathcal{P}_{\mathfrak{B}'\mathfrak{B}}}{B_0} \mathsf{Q}^\eta \right) \gamma_5 u_{\mathfrak{B}},$$

$$\langle \mathfrak{B}' | \bar{d} s | \mathfrak{B} \rangle = \mathcal{S}_{\mathfrak{B}'\mathfrak{B}}\, \bar{u}_{\mathfrak{B}'} u_{\mathfrak{B}}, \qquad \langle \mathfrak{B}' | \bar{d}\gamma_5 s | \mathfrak{B} \rangle = \mathcal{P}_{\mathfrak{B}'\mathfrak{B}}\, \bar{u}_{\mathfrak{B}'} \gamma_5 u_{\mathfrak{B}}, \qquad \mathsf{Q} = p_{\mathfrak{B}} - p_{\mathfrak{B}'}$$

$\mathfrak{B}'\mathfrak{B}$	$n\Lambda$	$p\Sigma^+$	$\Lambda\Xi^0$	$\Sigma^0\Xi^0$	$\Sigma^-\Xi^-$
$\mathcal{V}_{\mathfrak{B}'\mathfrak{B}}$	$-\sqrt{\frac{3}{2}}$	-1	$\sqrt{\frac{3}{2}}$	$\frac{-1}{\sqrt{2}}$	1
$\mathcal{A}_{\mathfrak{B}'\mathfrak{B}}$	$\frac{-1}{\sqrt{6}}(D+3F)$	$D-F$	$\frac{-1}{\sqrt{6}}(D-3F)$	$\frac{-1}{\sqrt{2}}(D+F)$	$D+F$

$$\mathcal{S}_{\mathfrak{B}'\mathfrak{B}} = \frac{m_{\mathfrak{B}} - m_{\mathfrak{B}'}}{m_s - \hat{m}} \mathcal{V}_{\mathfrak{B}'\mathfrak{B}}\,, \qquad \mathcal{P}_{\mathfrak{B}'\mathfrak{B}} = \mathcal{A}_{\mathfrak{B}'\mathfrak{B}} B_0 \frac{m_{\mathfrak{B}'} + m_{\mathfrak{B}}}{m_K^2 - \mathsf{Q}^2}$$

$$\langle \Xi^- | \bar{d}\gamma^\eta \gamma_5 s | \Omega^- \rangle = \mathcal{C}\, \bar{u}_\Xi \left(u_\Omega^\eta + \frac{\tilde{\mathsf{Q}}^\eta\, \tilde{\mathsf{Q}}_\kappa}{m_K^2 - \tilde{\mathsf{Q}}^2} u_\Omega^\kappa \right), \qquad \langle \Xi^- | \bar{d}\gamma_5 s | \Omega^- \rangle = \frac{B_0\, \mathcal{C}\, \tilde{\mathsf{Q}}_\kappa}{\tilde{\mathsf{Q}}^2 - m_K^2} \bar{u}_\Xi u_\Omega^\kappa$$

$$\langle \Xi^- | \bar{d}\gamma^\eta s | \Omega^- \rangle = \langle \Xi^- | \bar{d} s | \Omega^- \rangle = 0\,, \qquad \tilde{\mathsf{Q}} = p_{\Omega^-} - p_{\Xi^-}$$

- Most of them don't vanish in leading-order χPT.

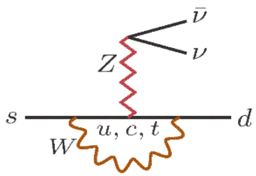
- $$\mathcal{L}_f = -\Big[\overline{d}\gamma^\eta s\,\overline{f}\gamma_\eta\big(\mathtt{C}_f^{\rm V}+\gamma_5\mathtt{C}_f^{\rm A}\big)f + \overline{d}\gamma^\eta\gamma_5 s\,\overline{f}\gamma_\eta\big(\tilde{\mathtt{c}}_f^{\rm V}+\gamma_5\tilde{\mathtt{c}}_f^{\rm A}\big)f$$
$$+\,\overline{d}s\,\overline{f}\big(\mathtt{C}_f^{\rm S}+\gamma_5\mathtt{C}_f^{\rm P}\big)f + \overline{d}\gamma_5 s\,\overline{f}\big(\tilde{\mathtt{c}}_f^{\rm S}+\gamma_5\tilde{\mathtt{c}}_f^{\rm P}\big)f\Big] + {\rm H.c.}$$

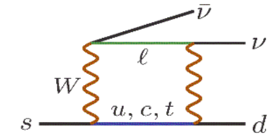
Decay mode	$K\to\pi f\bar{f}$	$K\to f\bar{f}$	$K\to\pi\pi' f\bar{f}$	$\mathfrak{B}\to\mathfrak{B}' f\bar{f}$	$\Omega^-\to\Xi^- f\bar{f}$
Couplings	$\mathtt{C}_f^{\rm V,\,A,\,S,\,P}$	$\tilde{\mathtt{c}}_f^{\rm A,\,S,\,P}$	$\tilde{\mathtt{c}}_f^{\rm V,\,A,\,S,\,P}$	$\mathtt{C}_f^{\rm V,A,S,P}$, $\tilde{\mathtt{c}}_f^{\rm V,A,S,P}$	$\tilde{\mathtt{c}}_f^{\rm V,\,A,\,S,\,P}$

NP couplings affecting FCNC kaon & hyperon decays with missing energy carried by spin-1/2 fermions $f\bar{f}$ with nonzero mass, $m_f > 0$.

$\tilde{\mathtt{c}}_f^{\rm A}$ no longer contributes to $K\to f\bar{f}$ if $m_f = 0$.

SM predictions for hyperon decays with missing energy





* Lagrangian for $s \to d\nu\bar\nu$

$$\mathcal{L}_{\rm SM} = \frac{-\alpha_{\rm e} G_{\rm F}}{\sqrt{8}\,\pi s_{\rm W}^2} \sum_{l=e,\mu,\tau} \left(V_{td}^* V_{ts} X_t + V_{cd}^* V_{cs} X_c^l\right) \overline{d}\gamma^\eta (1-\gamma_5) s\, \overline{\nu_l}\gamma_\eta (1-\gamma_5)\nu_l + \text{H.c.}$$

$X_{t,c}$ are t- and c-quark contributions

* Branching fractions $\mathcal{B}(\mathfrak{B} \to \mathfrak{B}'\nu\bar\nu)_{\rm SM} = \sum_l \mathcal{B}(\mathfrak{B} \to \mathfrak{B}'\nu_l\bar\nu_l)_{\rm SM}$

for $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$

with $\mathrm{c}_{\nu_l}^{\rm V} = -\mathrm{c}_{\nu_l}^{\rm A} = -\tilde{\mathrm{c}}_{\nu_l}^{\rm V} = \tilde{\mathrm{c}}_{\nu_l}^{\rm A} = \dfrac{\alpha_{\rm e} G_{\rm F}}{\sqrt{8}\,\pi s_{\rm W}^2}\left(\lambda_t X_t + \lambda_c X_c^l\right)$ and $\mathrm{c}_{\nu_l}^{\rm S,P} = \tilde{\mathrm{c}}_{\nu_l}^{\rm S,P} = 0$

Similarly for $\mathcal{B}(\Omega^- \to \Xi^-\nu\bar\nu)_{\rm SM}$

* Predictions for branching fractions

$\Lambda \to n\nu\bar\nu$	$\Sigma^+ \to p\nu\bar\nu$	$\Xi^0 \to \Lambda\nu\bar\nu$	$\Xi^0 \to \Sigma^0\nu\bar\nu$	$\Xi^- \to \Sigma^-\nu\bar\nu$	$\Omega^- \to \Xi^-\nu\bar\nu$
7.1×10^{-13}	4.3×10^{-13}	6.3×10^{-13}	1.0×10^{-13}	1.3×10^{-13}	4.9×10^{-12}

JT, 1901.10447

* Estimated BESIII sensitivity for branching fractions

HB Li, 1612.01775

$\Lambda \to n\nu\bar\nu$	$\Sigma^+ \to p\nu\bar\nu$	$\Xi^0 \to \Lambda\nu\bar\nu$	$\Xi^0 \to \Sigma^0\nu\bar\nu$	$\Xi^- \to \Sigma^-\nu\bar\nu$	$\Omega^- \to \Xi^-\nu\bar\nu$
3×10^{-7}	4×10^{-7}	8×10^{-7}	9×10^{-7}	—	2.6×10^{-5}

- $K_{L,S} \to \not{E}$ still have no direct-search limits, but indirectly upper limits on them can be inferred from the data on their visible decay channels:

Gninenko, 2015

$$\mathcal{B}(K_L \to \not{E}) < 6.3 \times 10^{-4} \;\;\&\;\; \mathcal{B}(K_S \to \not{E}) < 1.1 \times 10^{-4}$$ both at 95% CL

SM predictions: $\mathcal{B}(K_L \to \not{E}) \sim 1 \times 10^{-10}$ & $\mathcal{B}(K_S \to \not{E}) \sim 2 \times 10^{-14}$

- $K \to \pi\pi' \not{E}$

Measurements: $\mathcal{B}(K^+ \to \pi^+\pi^0\nu\bar{\nu}) < 4.3 \times 10^{-5}$ at 90% CL

$\mathcal{B}\big(K_L \to \pi^0\pi^0\nu\bar{\nu}\big) < 8.1 \times 10^{-7}$ at 90% CL

PDG 2019

SM predictions: $\mathcal{B}(K^+ \to \pi^+\pi^0\nu\bar{\nu}) \sim 10^{-14}$

$\mathcal{B}(K_L \to \pi^0\pi^0\nu\bar{\nu}) \sim 10^{-13}$

Littenberg & Valencia, 1996
Chiang & Gilman, 2000
Kamenik & Smith, 2012

- Implication: NP effects on $K \to \not{E}$ and $K \to \pi\pi'\not{E}$ can still be large.

NP that contributes via operators having mainly/only parity-odd quark parts (and coupling constants $\tilde{\mathrm{c}}_f^{\mathrm{V,A,S,P}}$) is not yet stringently constrained.

Decay mode	$K \to \pi f \bar{f}$	$K \to f \bar{f}$	$K \to \pi\pi' f \bar{f}$
Couplings	$\mathrm{c}_f^{\mathrm{V}}, \mathrm{c}_f^{\mathrm{A}}, \mathrm{c}_f^{\mathrm{S}}, \mathrm{c}_f^{\mathrm{P}}$	$\tilde{\mathrm{c}}_f^{\mathrm{A}}, \tilde{\mathrm{c}}_f^{\mathrm{S}}, \tilde{\mathrm{c}}_f^{\mathrm{P}}$	$\tilde{\mathrm{c}}_f^{\mathrm{V}}, \tilde{\mathrm{c}}_f^{\mathrm{A}}, \tilde{\mathrm{c}}_f^{\mathrm{S}}, \tilde{\mathrm{c}}_f^{\mathrm{P}}$

$m_f > 0$

- NP contributing only via operators with axial-vector *ds* part
  - with the couplings assumed to be real.

$$\mathcal{L}_f \supset -\bar{d}\gamma^\eta\gamma_5 s\, \bar{f}\gamma_\eta\left(\tilde{\mathbf{c}}_f^{\rm V} + \gamma_5\tilde{\mathbf{c}}_f^{\rm A}\right)f \;+ \text{H.c.}$$

- The constraints come mainly from $K_L \to \pi^0\pi^0 \not{E}$ and lead to

$$\left(\mathrm{Re}\,\tilde{\mathbf{c}}_f^{\rm V}\right)^2 + \left(\mathrm{Re}\,\tilde{\mathbf{c}}_f^{\rm A}\right)^2 < 9.4\times10^{-14}\,\mathrm{GeV}^{-4}$$

This translates into

$$\mathcal{B}\left(\Lambda \to n f\bar{f}\right) < 6.6\times10^{-6}\,, \qquad \mathcal{B}\left(\Sigma^+ \to p f\bar{f}\right) < 1.7\times10^{-6}$$

$$\mathcal{B}\left(\Xi^0 \to \Lambda f\bar{f}\right) < 9.4\times10^{-7}\,, \qquad \mathcal{B}\left(\Xi^0 \to \Sigma^0 f\bar{f}\right) < 1.3\times10^{-6}$$

$$\mathcal{B}\left(\Omega^- \to \Xi^- f\bar{f}\right) < 7.5\times10^{-5}$$

JT, 1901.10447

- The upper values of these limits exceed the BESIII sensitivity levels.

Estimated BESIII sensitivity for branching fractions Li, 2017

$\Lambda \to n\nu\bar{\nu}$	$\Sigma^+ \to p\nu\bar{\nu}$	$\Xi^0 \to \Lambda\nu\bar{\nu}$	$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	$\Omega^- \to \Xi^-\nu\bar{\nu}$
3×10^{-7}	4×10^{-7}	8×10^{-7}	9×10^{-7}	2.6×10^{-5}

- With $m_f > 0$, maximal branching fractions of hyperon modes can be higher.

$$\mathcal{L}_f \supset -\overline{d}\gamma_5 s\, \overline{f}\left(\tilde{\mathbf{c}}_f^{\rm S} + \gamma_5 \tilde{\mathbf{c}}_f^{\rm P}\right) f - \overline{d}\gamma^\eta \gamma_5 s\, \overline{f}\gamma_\eta\left(\tilde{\mathbf{c}}_f^{\rm V} + \gamma_5 \tilde{\mathbf{c}}_f^{\rm A}\right) f + \text{H.c.}$$

Decay mode	$K \to f\bar{f}$	$K \to \pi\pi' f\bar{f}$	$\mathfrak{B} \to \mathfrak{B}' f\bar{f}$	$\Omega^- \to \Xi^- f\bar{f}$
Couplings	$\tilde{\mathbf{c}}_f^{\rm A}, \tilde{\mathbf{c}}_f^{\rm S}, \tilde{\mathbf{c}}_f^{\rm P}$	$\tilde{\mathbf{c}}_f^{\rm V}, \tilde{\mathbf{c}}_f^{\rm A}, \tilde{\mathbf{c}}_f^{\rm S}, \tilde{\mathbf{c}}_f^{\rm P}$	$\tilde{\mathbf{c}}_f^{\rm V}, \tilde{\mathbf{c}}_f^{\rm A}, \tilde{\mathbf{c}}_f^{\rm S}, \tilde{\mathbf{c}}_f^{\rm P}$	$\tilde{\mathbf{c}}_f^{\rm V}, \tilde{\mathbf{c}}_f^{\rm A}, \tilde{\mathbf{c}}_f^{\rm S}, \tilde{\mathbf{c}}_f^{\rm P}$

$m_f > 0$

Ignoring $\mathrm{c}_f^{\rm V,A,S,P}$

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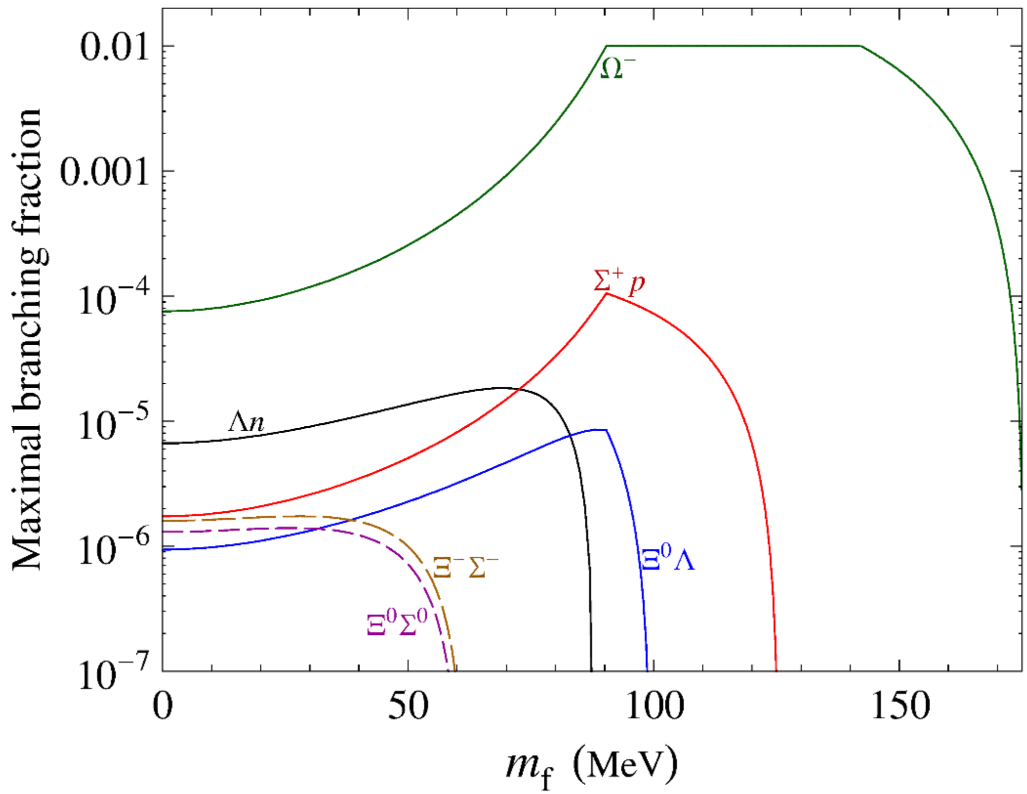


Li, Su, JT, 1905.08759

FIG. 3: The maximal branching fractions of $\mathfrak{B} \to \mathfrak{B}' f\bar{f}$ with $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$ and of $\Omega^- \to \Xi^- f\bar{f}$ versus m_f, induced by the contribution of $\mathrm{Re}\,\tilde{\mathbf{c}}_f^{\rm V}$ alone, subject to the $K_L \to \pi^0\pi^0 \not{E}$ constraint and the perturbativity and Ω^- data requirements for $m_f > 90$ MeV.

Scalar leptoquark contributions

- $\tilde{S}_1\left(\bar{3}, 1, \frac{1}{3}\right) = \tilde{S}_1^{1/3}, \qquad \tilde{S}_2\left(3, 2, \frac{1}{6}\right) = \begin{pmatrix} \tilde{S}_2^{2/3} \\ \tilde{S}_2^{-1/3} \end{pmatrix}, \qquad S_3\left(\bar{3}, 3, \frac{1}{3}\right) = \begin{pmatrix} S_3^{1/3} & \sqrt{2}\, S_3^{4/3} \\ \sqrt{2}\, S_3^{-2/3} & -S_3^{1/3} \end{pmatrix}$

- $\tilde{S}_1\left(\bar{3},1,\frac{1}{3}\right)=\tilde{S}_1^{1/3}$, $\quad \tilde{S}_2\left(3,2,\frac{1}{6}\right)=\begin{pmatrix}\tilde{S}_2^{2/3}\\ \tilde{S}_2^{-1/3}\end{pmatrix}$, $\quad S_3\left(\bar{3},3,\frac{1}{3}\right)=\begin{pmatrix}S_3^{1/3} & \sqrt{2}\,S_3^{4/3}\\ \sqrt{2}\,S_3^{-2/3} & -S_3^{1/3}\end{pmatrix}$

- Yukawa Lagrangian

$$\mathcal{L}_{\mathrm{LQ}}=\left(\mathrm{Y}^{\mathrm{LL}}_{1,jy}\,\overline{q^{c}_j}\varepsilon l_y+\tilde{\mathrm{Y}}^{\mathrm{RR}}_{1,jy}\,\overline{d^{c}_j}N_y\right)\tilde{S}_1+\mathrm{Y}^{\mathrm{RL}}_{2,jy}\,\overline{d_j}\tilde{S}_2^{\mathrm{T}}\varepsilon l_y+\tilde{\mathrm{Y}}^{\mathrm{LR}}_{2,jn}\,\overline{q_j}\tilde{S}_2N_y+\mathrm{Y}^{\mathrm{LL}}_{3,jy}\,\overline{q^{c}_j}\varepsilon S_3 l_y+\mathrm{H.c.}$$

family indices $j,y=1,2,3$ are summed over, q_j (l_y) and d_j denote LH quark (lepton) doublet and RH down-type quark singlet, respectively, and $\varepsilon=i\tau_2$

- $\tilde{S}_1\left(\bar{3},1,\tfrac{1}{3}\right)=\tilde{S}_1^{1/3}\,,\qquad \tilde{S}_2\left(3,2,\tfrac{1}{6}\right)=\begin{pmatrix}\tilde{S}_2^{2/3}\\ \tilde{S}_2^{-1/3}\end{pmatrix},\qquad S_3\left(\bar{3},3,\tfrac{1}{3}\right)=\begin{pmatrix}S_3^{1/3} & \sqrt{2}\,S_3^{4/3}\\ \sqrt{2}\,S_3^{-2/3} & -S_3^{1/3}\end{pmatrix}$

- Yukawa Lagrangian

$$\mathcal{L}_{\rm LQ}=\left(\mathrm{Y}_{1,jy}^{\rm LL}\,\overline{q_j^{\rm c}}\varepsilon l_y+\tilde{\mathrm{Y}}_{1,jy}^{\rm RR}\,\overline{d_j^{\rm c}}N_y\right)\tilde{S}_1+\mathrm{Y}_{2,jy}^{\rm RL}\,\overline{d_j}\tilde{S}_2^{\rm T}\varepsilon l_y+\tilde{\mathrm{Y}}_{2,jn}^{\rm LR}\,\overline{q_j}\tilde{S}_2N_y+\mathrm{Y}_{3,jy}^{\rm LL}\,\overline{q_j^{\rm c}}\varepsilon S_3 l_y+\mathrm{H.c.}$$

family indices $j,y=1,2,3$ are summed over, q_j (l_y) and d_j denote LH quark (lepton) doublet and RH down-type quark singlet, respectively, and $\varepsilon=i\tau_2$

- At tree level the LQs can mediate $sdff'$ interactions, $f=\nu$ or N

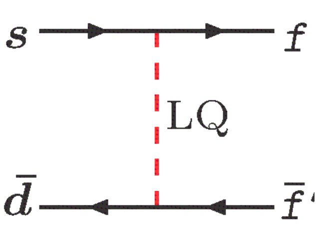
$$\mathcal{L}_{ff'}=-\left[\overline{d}\gamma^\eta s\,\overline{f}\gamma_\eta\left(\mathrm{C}_{ff'}^{\rm V}+\gamma_5\mathrm{C}_{ff'}^{\rm A}\right)f'+\overline{d}\gamma^\eta\gamma_5 s\,\overline{f}\gamma_\eta\left(\tilde{\mathrm{C}}_{ff'}^{\rm V}+\gamma_5\tilde{\mathrm{C}}_{ff'}^{\rm A}\right)f'\right]+\mathrm{H.c.}$$

$$\mathrm{C}_{\nu\nu'}^{\rm V}=-\mathrm{C}_{\nu\nu'}^{\rm A}=\frac{-\mathrm{Y}_{1,1x}^{\rm LL*}\mathrm{Y}_{1,2y}^{\rm LL}}{8m_{\tilde{S}_1}^2}+\frac{\mathrm{Y}_{2,2x}^{\rm RL*}\mathrm{Y}_{2,1y}^{\rm RL}}{8m_{\tilde{S}_2}^2}-\frac{\mathrm{Y}_{3,1x}^{\rm LL*}\mathrm{Y}_{3,2y}^{\rm LL}}{8m_{S_3}^2}$$

$$\tilde{\mathrm{C}}_{\nu\nu'}^{\rm V}=-\tilde{\mathrm{C}}_{\nu\nu'}^{\rm A}=\frac{\mathrm{Y}_{1,1x}^{\rm LL*}\mathrm{Y}_{1,2y}^{\rm LL}}{8m_{\tilde{S}_1}^2}+\frac{\mathrm{Y}_{2,2x}^{\rm RL*}\mathrm{Y}_{2,1y}^{\rm RL}}{8m_{\tilde{S}_2}^2}+\frac{\mathrm{Y}_{3,1x}^{\rm LL*}\mathrm{Y}_{3,2y}^{\rm LL}}{8m_{S_3}^2}$$

$$\mathrm{C}_{NN'}^{\rm V}=\mathrm{C}_{NN'}^{\rm A}=\frac{-\tilde{\mathrm{Y}}_{1,1x}^{\rm RR*}\tilde{\mathrm{Y}}_{1,2y}^{\rm RR}}{8m_{\tilde{S}_1}^2}+\frac{\tilde{\mathrm{Y}}_{2,2x}^{\rm LR*}\tilde{\mathrm{Y}}_{2,1y}^{\rm LR}}{8m_{\tilde{S}_2}^2}$$

$$\tilde{\mathrm{C}}_{NN'}^{\rm V}=\tilde{\mathrm{C}}_{NN'}^{\rm A}=\frac{-\tilde{\mathrm{Y}}_{1,1x}^{\rm RR*}\tilde{\mathrm{Y}}_{1,2y}^{\rm RR}}{8m_{\tilde{S}_1}^2}-\frac{\tilde{\mathrm{Y}}_{2,2x}^{\rm LR*}\tilde{\mathrm{Y}}_{2,1y}^{\rm LR}}{8m_{\tilde{S}_2}^2}$$



Scalar leptoquark contributions

- $$\mathcal{L}_{ff'} = -\left[\overline{d}\gamma^\eta s\,\overline{f}\gamma_\eta\left(\mathrm{C}^{\mathrm{V}}_{ff'} + \gamma_5 \mathrm{C}^{\mathrm{A}}_{ff'}\right)f' + \overline{d}\gamma^\eta\gamma_5 s\,\overline{f}\gamma_\eta\left(\tilde{\mathrm{C}}^{\mathrm{V}}_{ff'} + \gamma_5 \tilde{\mathrm{C}}^{\mathrm{A}}_{ff'}\right)f'\right] + \mathrm{H.c.}$$

$$\mathrm{C}^{\mathrm{V}}_{\nu\nu'} = -\mathrm{C}^{\mathrm{A}}_{\nu\nu'} = \frac{-\mathrm{Y}^{\mathrm{LL}*}_{1,1x}\mathrm{Y}^{\mathrm{LL}}_{1,2y}}{8m^2_{\tilde{S}_1}} + \frac{\mathrm{Y}^{\mathrm{RL}*}_{2,2x}\mathrm{Y}^{\mathrm{RL}}_{2,1y}}{8m^2_{\tilde{S}_2}} - \frac{\mathrm{Y}^{\mathrm{LL}*}_{3,1x}\mathrm{Y}^{\mathrm{LL}}_{3,2y}}{8m^2_{S_3}}$$

$$\tilde{\mathrm{C}}^{\mathrm{V}}_{\nu\nu'} = -\tilde{\mathrm{C}}^{\mathrm{A}}_{\nu\nu'} = \frac{\mathrm{Y}^{\mathrm{LL}*}_{1,1x}\mathrm{Y}^{\mathrm{LL}}_{1,2y}}{8m^2_{\tilde{S}_1}} + \frac{\mathrm{Y}^{\mathrm{RL}*}_{2,2x}\mathrm{Y}^{\mathrm{RL}}_{2,1y}}{8m^2_{\tilde{S}_2}} + \frac{\mathrm{Y}^{\mathrm{LL}*}_{3,1x}\mathrm{Y}^{\mathrm{LL}}_{3,2y}}{8m^2_{S_3}}$$

$$\mathrm{C}^{\mathrm{V}}_{NN'} = \mathrm{C}^{\mathrm{A}}_{NN'} = \frac{-\tilde{\mathrm{Y}}^{\mathrm{RR}*}_{1,1x}\tilde{\mathrm{Y}}^{\mathrm{RR}}_{1,2y}}{8m^2_{\tilde{S}_1}} + \frac{\tilde{\mathrm{Y}}^{\mathrm{LR}*}_{2,2x}\tilde{\mathrm{Y}}^{\mathrm{LR}}_{2,1y}}{8m^2_{\tilde{S}_2}}$$

$$\tilde{\mathrm{C}}^{\mathrm{V}}_{NN'} = \tilde{\mathrm{C}}^{\mathrm{A}}_{NN'} = \frac{-\tilde{\mathrm{Y}}^{\mathrm{RR}*}_{1,1x}\tilde{\mathrm{Y}}^{\mathrm{RR}}_{1,2y}}{8m^2_{\tilde{S}_1}} - \frac{\tilde{\mathrm{Y}}^{\mathrm{LR}*}_{2,2x}\tilde{\mathrm{Y}}^{\mathrm{LR}}_{2,1y}}{8m^2_{\tilde{S}_2}}$$

Decay mode	$K \to \pi f \bar{f}$	$K \to f \bar{f}$	$K \to \pi\pi' f \bar{f}$	$\mathfrak{B} \to \mathfrak{B}' f \bar{f}$	$\Omega^- \to \Xi^- f \bar{f}$
Couplings	$\mathrm{C}_f^{\mathrm{V,A,S,P}}$	$\tilde{\mathrm{C}}_f^{\mathrm{A,S,P}}$	$\tilde{\mathrm{C}}_f^{\mathrm{V,A,S,P}}$	$\mathrm{C}_f^{\mathrm{V,A,S,P}}$, $\tilde{\mathrm{C}}_f^{\mathrm{V,A,S,P}}$	$\tilde{\mathrm{C}}_f^{\mathrm{V,A,S,P}}$

Scalar leptoquark contributions

- $$\mathcal{L}_{ff'} = -\left[\bar{d}\gamma^\eta s\,\bar{f}\gamma_\eta\left(\mathtt{C}^{\mathrm{V}}_{ff'} + \gamma_5 \mathtt{C}^{\mathrm{A}}_{ff'}\right)f' + \bar{d}\gamma^\eta\gamma_5 s\,\bar{f}\gamma_\eta\left(\tilde{\mathtt{C}}^{\mathrm{V}}_{ff'} + \gamma_5\tilde{\mathtt{C}}^{\mathrm{A}}_{ff'}\right)f'\right] + \mathrm{H.c.}$$

$$\mathtt{C}^{\mathrm{V}}_{\nu\nu'} = -\mathtt{C}^{\mathrm{A}}_{\nu\nu'} = \frac{-\mathrm{Y}^{\mathrm{LL}*}_{1,1x}\mathrm{Y}^{\mathrm{LL}}_{1,2y}}{8m^2_{\tilde{S}_1}} + \frac{\mathrm{Y}^{\mathrm{RL}*}_{2,2x}\mathrm{Y}^{\mathrm{RL}}_{2,1y}}{8m^2_{\tilde{S}_2}} - \frac{\mathrm{Y}^{\mathrm{LL}*}_{3,1x}\mathrm{Y}^{\mathrm{LL}}_{3,2y}}{8m^2_{S_3}} \approx 0$$

$$\tilde{\mathtt{C}}^{\mathrm{V}}_{\nu\nu'} = -\tilde{\mathtt{C}}^{\mathrm{A}}_{\nu\nu'} = \frac{\mathrm{Y}^{\mathrm{LL}*}_{1,1x}\mathrm{Y}^{\mathrm{LL}}_{1,2y}}{8m^2_{\tilde{S}_1}} + \frac{\mathrm{Y}^{\mathrm{RL}*}_{2,2x}\mathrm{Y}^{\mathrm{RL}}_{2,1y}}{8m^2_{\tilde{S}_2}} + \frac{\mathrm{Y}^{\mathrm{LL}*}_{3,1x}\mathrm{Y}^{\mathrm{LL}}_{3,2y}}{8m^2_{S_3}}$$

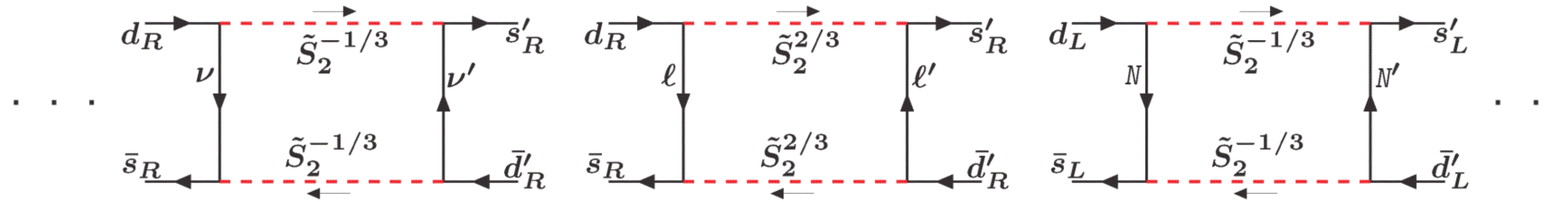
$$\mathtt{C}^{\mathrm{V}}_{NN'} = \mathtt{C}^{\mathrm{A}}_{NN'} = \frac{-\tilde{\mathrm{Y}}^{\mathrm{RR}*}_{1,1x}\tilde{\mathrm{Y}}^{\mathrm{RR}}_{1,2y}}{8m^2_{\tilde{S}_1}} + \frac{\tilde{\mathrm{Y}}^{\mathrm{LR}*}_{2,2x}\tilde{\mathrm{Y}}^{\mathrm{LR}}_{2,1y}}{8m^2_{\tilde{S}_2}} \approx 0$$

$$\tilde{\mathtt{C}}^{\mathrm{V}}_{NN'} = \tilde{\mathtt{C}}^{\mathrm{A}}_{NN'} = \frac{-\tilde{\mathrm{Y}}^{\mathrm{RR}*}_{1,1x}\tilde{\mathrm{Y}}^{\mathrm{RR}}_{1,2y}}{8m^2_{\tilde{S}_1}} - \frac{\tilde{\mathrm{Y}}^{\mathrm{LR}*}_{2,2x}\tilde{\mathrm{Y}}^{\mathrm{LR}}_{2,1y}}{8m^2_{\tilde{S}_2}}$$

Decay mode	$K \to \pi f \bar{f}$	$K \to f\bar{f}$	$K \to \pi\pi' f\bar{f}$	$\mathfrak{B} \to \mathfrak{B}' f\bar{f}$	$\Omega^- \to \Xi^- f\bar{f}$
Couplings	$\mathtt{C}_f^{\mathrm{V,A,S,P}}$	$\tilde{\mathtt{C}}_f^{\mathrm{A,S,P}}$	$\tilde{\mathtt{C}}_f^{\mathrm{V,A,S,P}}$	$\mathtt{C}_f^{\mathrm{V,A,S,P}}$, $\tilde{\mathtt{C}}_f^{\mathrm{V,A,S,P}}$	$\tilde{\mathtt{C}}_f^{\mathrm{V,A,S,P}}$

- At least two different LQs are needed.

Constraints from kaon mixing



$$\mathcal{H}^{\rm LQ}_{|\Delta S|=2} = \left[\frac{\left(\sum_x \mathrm{Y}^{\rm LL}_{1,1x}\mathrm{Y}^{\rm LL*}_{1,2x}\right)^2}{128\pi^2\, m^2_{\tilde{S}_1}} + \frac{\left(\sum_n \tilde{\mathrm{Y}}^{\rm LR}_{2,2n}\tilde{\mathrm{Y}}^{\rm LR*}_{2,1n}\right)^2}{128\pi^2\, m^2_{\tilde{S}_2}} + \frac{5\left(\sum_x \mathrm{Y}^{\rm LL}_{3,1x}\mathrm{Y}^{\rm LL*}_{3,2x}\right)^2}{128\pi^2\, m^2_{S_3}}\right] \bar{s}_L\gamma^\eta d_L\, \bar{s}_L\gamma_\eta d_L$$
$$+ \left[\frac{\left(\sum_n \tilde{\mathrm{Y}}^{\rm RR}_{1,1n}\tilde{\mathrm{Y}}^{\rm RR*}_{1,2n}\right)^2}{128\pi^2\, m^2_{\tilde{S}_1}} + \frac{\left(\sum_x \mathrm{Y}^{\rm RL}_{2,2x}\mathrm{Y}^{\rm RL*}_{2,1x}\right)^2}{64\pi^2\, m^2_{\tilde{S}_2}}\right] \bar{s}_R\gamma^\eta d_R\, \bar{s}_R\gamma_\eta d_R$$

Kaon mixing constraints can be avoided by assigning the nonzero elements of the 1st and 2nd rows of each contributing Yukawa matrix to different columns.

- At tree level the LQs can mediate lepton-flavor-violating $sd\ell\ell'$ interactions

$$\mathcal{L}_{\ell\ell'} = -\Big[\overline{d}\gamma^\eta s\,\overline{\ell}\gamma_\eta\big(\mathtt{V}_{\ell\ell'}+\gamma_5\mathtt{A}_{\ell\ell'}\big)\ell' + \overline{d}\gamma^\eta\gamma_5 s\,\overline{\ell}\gamma_\eta\big(\tilde{\mathtt{V}}_{\ell\ell'}+\gamma_5\tilde{\mathtt{A}}_{\ell\ell'}\big)\ell'\Big] + \mathbf{H.c.}$$

$$\mathtt{V}_{\ell\ell'} = -\mathtt{A}_{\ell\ell'} = \frac{\mathtt{Y}^{\mathrm{RL}*}_{2,2x}\mathtt{Y}^{\mathrm{RL}}_{2,1y}}{8m^2_{\tilde{S}_2}} - \frac{\mathtt{Y}^{\mathrm{LL}*}_{3,1x}\mathtt{Y}^{\mathrm{LL}}_{3,2y}}{4m^2_{S_3}}, \qquad \tilde{\mathtt{V}}_{\ell\ell'} = -\tilde{\mathtt{A}}_{\ell\ell'} = \frac{\mathtt{Y}^{\mathrm{RL}*}_{2,2x}\mathtt{Y}^{\mathrm{RL}}_{2,1y}}{8m^2_{\tilde{S}_2}} + \frac{\mathtt{Y}^{\mathrm{LL}*}_{3,1x}\mathtt{Y}^{\mathrm{LL}}_{3,2y}}{4m^2_{S_3}}$$

- If $xy = 12, 21$, corresponding to $\ell\ell' = e\mu, \mu e$, the first (last) 2 terms induce $K \to \pi e\mu$ $(K_L \to e\mu)$. Their bounds can be evaded with $xy \neq 12, 21$. Likewise, constraints from $\mu \to e\gamma, 3e$ and $\mu \to e$ transitions are avoided.

- If $xy = 13, 31, 23, 32$, the tau decays $\tau \to eK^{(*)}, \mu K^{(*)}$ are induced but their bounds are not too severe.

- With only $\tilde{S}_1$ and $\tilde{S}_2$ being present and the choices

$$\mathrm{Y}_1^{\mathrm{LL}} = \begin{pmatrix} 0 & y_{1,12} & 0 \\ 0 & 0 & y_{1,23} \\ 0 & 0 & 0 \end{pmatrix}, \qquad \mathrm{Y}_2^{\mathrm{RL}} = \begin{pmatrix} 0 & 0 & y_{2,13} \\ 0 & y_{2,22} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

the $\tau \to \ell K^{(*)}$ restrictions translate into $(f f' = \nu_\mu \nu_\tau)$

$$\mathcal{B}(\Lambda \to n f \bar{f}') < 1.7 \times 10^{-7}, \qquad \mathcal{B}(\Sigma^+ \to p f \bar{f}') < 4.7 \times 10^{-8}$$

$$\mathcal{B}(\Xi^0 \to \Lambda f \bar{f}') < 2.5 \times 10^{-8}, \qquad \mathcal{B}(\Xi^0 \to \Sigma^0 f \bar{f}') < 3.5 \times 10^{-8}$$

$$\mathcal{B}(\Omega^- \to \Xi^- f \bar{f}') < 2.0 \times 10^{-6}$$

These are not far below the proposed BESIII sensitivity reach

Li, 2017

$\Lambda \to n\nu\bar{\nu}$	$\Sigma^+ \to p\nu\bar{\nu}$	$\Xi^0 \to \Lambda\nu\bar{\nu}$	$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	$\Omega^- \to \Xi^-\nu\bar{\nu}$
3×10^{-7}	4×10^{-7}	8×10^{-7}	9×10^{-7}	2.6×10^{-5}

- The kaon mixing restrictions can be evaded as before.
- The constraints come mainly from $K_L \to \pi^0 \pi^0 \not{E}$ and lead to

$$(\mathrm{Re}\,\tilde{\mathbf{c}}^{\mathrm{V}}_{NN'})^2 + (\mathrm{Re}\,\tilde{\mathbf{c}}^{\mathrm{A}}_{NN'})^2 < 9.4 \times 10^{-14}\,\mathrm{GeV}^{-4}$$

This translates into

$$\mathcal{B}(\Lambda \to n N \bar{N}') < 6.6 \times 10^{-6}\,, \qquad \mathcal{B}(\Sigma^+ \to p N \bar{N}') < 1.7 \times 10^{-6}$$

$$\mathcal{B}(\Xi^0 \to \Lambda N \bar{N}') < 9.4 \times 10^{-7}\,, \qquad \mathcal{B}(\Xi^0 \to \Sigma^0 N \bar{N}') < 1.3 \times 10^{-6}$$

$$\mathcal{B}(\Omega^- \to \Xi^- N \bar{N}') < 7.5 \times 10^{-5}$$

JT, 1901.10447

- Their upper values exceed the proposed BESIII sensitivity reach.

Li, 2017

$\Lambda \to n\nu\bar{\nu}$	$\Sigma^+ \to p\nu\bar{\nu}$	$\Xi^0 \to \Lambda\nu\bar{\nu}$	$\Xi^0 \to \Sigma^0\nu\bar{\nu}$	$\Omega^- \to \Xi^-\nu\bar{\nu}$
3×10^{-7}	4×10^{-7}	8×10^{-7}	9×10^{-7}	2.6×10^{-5}

Conclusions

- FCNC hyperon & kaon decays with missing energy are potentially sensitive to physics beyond the SM, but they do not probe the same set of the underlying NP operators.
- Ongoing & future experiments on the hyperon ones can provide useful information on possible NP effects which is complementary to that from the kaon sector.
- The forthcoming measurements by BESIII, and future ones at super charm-tau factories, on the hyperon modes can help test different NP scenarios.