Probing new physics with rare hyperon and kaon decays involving light invisible particles

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Based on

JT, arXiv:1901.10447 [JHEP 04 (2019) 104]

G Li, JY Su, JT, arXiv:1905.08759

New Physics with Exotic and Long-Lived Particles: A Joint ICISE-CBPF Workshop

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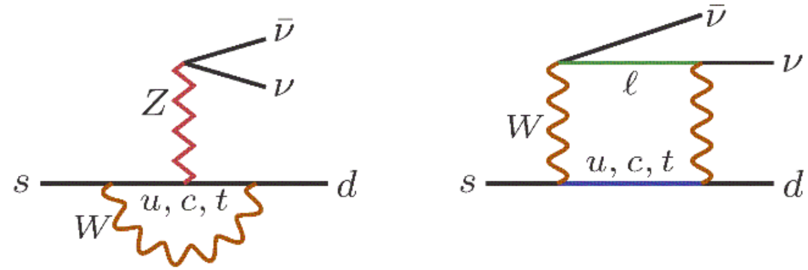
- Introduction
  - $|\Delta S|=1$ neutral-current hadron decays with missing energy ($\not{E}$) & their data
- New interactions *ds* quarks with invisible fermions
  - Kaon & hyperon decays as complementary probes of new physics.
  - Kaon constraints & enhanced hyperon rates.
- New *ds* quark interactions with invisible spin-0 bosons
- 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).

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

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.

Data available

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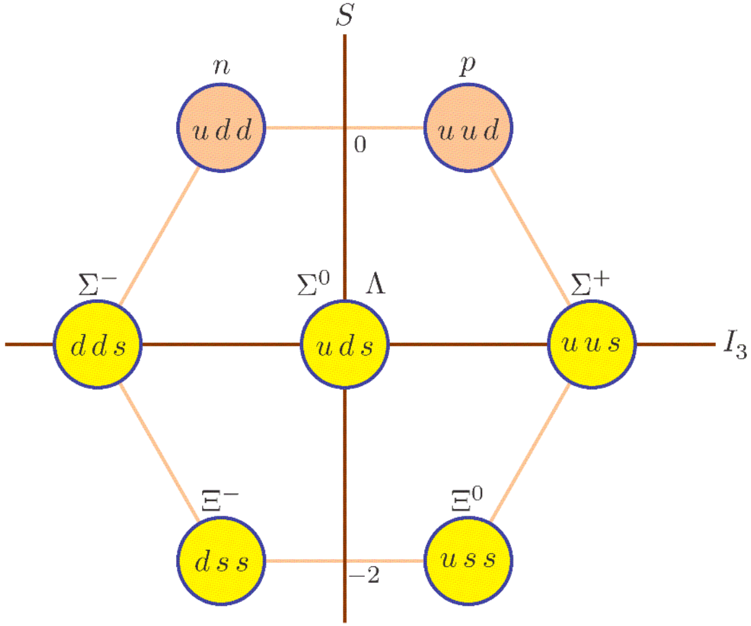
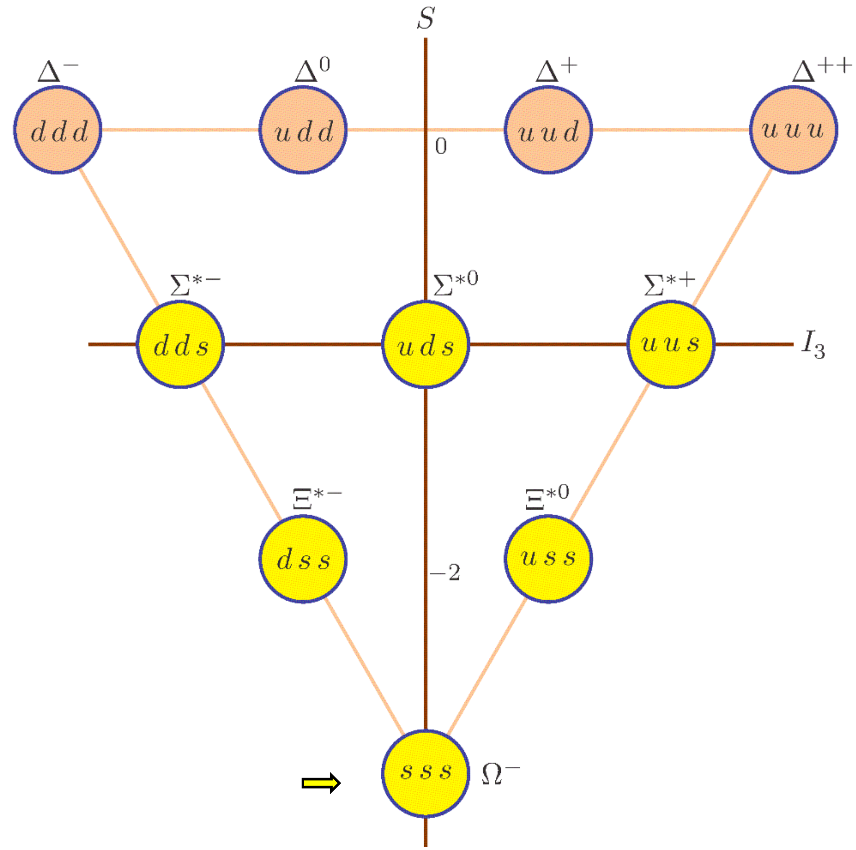
- No data yet in the baryon sector.
- BESIII is going to search for hyperon decays with missing energy.

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

- **Hyperons**





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

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

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

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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:

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

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

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

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

New-physics couplings contributing to $K \to \pi \not{E}$, $K \to \not{E}$, and $K \to \pi\pi' \not{E}$ if $\not{E}$ is carried by spin-1/2 fermions $f\bar{f}$ and their mass is nonzero, $m_f > 0$.

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

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

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

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

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

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

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

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

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

Contributions of various couplings to kaon & hyperon modes

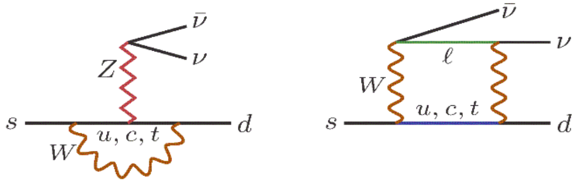
- $$\mathcal{L}_f = -\Big[\bar{d}\gamma^\eta s\, \bar{f}\gamma_\eta\big(\mathrm{c}_f^{\mathrm{V}} + \gamma_5 \mathrm{c}_f^{\mathrm{A}}\big)f + \bar{d}\gamma^\eta\gamma_5 s\, \bar{f}\gamma_\eta\big(\tilde{\mathrm{c}}_f^{\mathrm{V}} + \gamma_5\tilde{\mathrm{c}}_f^{\mathrm{A}}\big)f + \bar{d}s\, \bar{f}\big(\mathrm{c}_f^{\mathrm{S}}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

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

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

$\tilde{\mathrm{c}}_f^{\mathrm{A}}$ 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 $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$

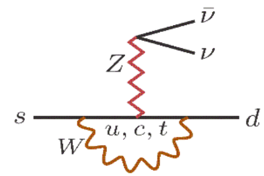
with $\mathrm{c}_{\nu_l}^{\rm V} = -\mathrm{c}_{\nu_l}^{\rm A} = -\tilde{\mathrm{c}}_{\nu_l}^{\rm V} = \tilde{\mathrm{c}}_{\nu_l}^{\rm A} = \dfrac{\alpha_{\rm e} G_{\rm F}}{\sqrt{8}\,\pi s_{\rm W}^2}\left(\lambda_t X_t + \lambda_c X_c^l\right)$ and $\mathrm{c}_{\nu_l}^{\rm S,P} = \tilde{\mathrm{c}}_{\nu_l}^{\rm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

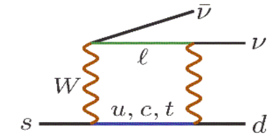
Similarly for $\mathcal{B}(\Omega^- \to \Xi^-\nu\bar\nu)_{\rm SM}$

* 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}

SM predictions for hyperon decays with missing energy





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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}

* 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}

Constraints from kaon sector

★ $K \to \pi \not{E}$

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

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

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

★ Implication: the effects of new physics on these modes cannot be substantial.

NP that contributes via operators having mainly/only parity-even quark parts (and coupling constants $\mathtt{c}_f^{\mathrm{V,A,S,P}}$) is already well constrained.

$$\mathcal{L}_f = -\Big[\overline{d}\gamma^\eta s\,\overline{f}\gamma_\eta\left(\mathtt{c}_f^{\mathrm{V}} + \gamma_5 \mathtt{c}_f^{\mathrm{A}}\right)f + \overline{d}\gamma^\eta\gamma_5 s\,\overline{f}\gamma_\eta\left(\tilde{\mathtt{c}}_f^{\mathrm{V}} + \gamma_5\tilde{\mathtt{c}}_f^{\mathrm{A}}\right)f$$

$$+ \overline{d}s\,\overline{f}\left(\mathtt{c}_f^{\mathrm{S}} + \gamma_5\mathtt{c}_f^{\mathrm{P}}\right)f + \overline{d}\gamma_5 s\,\overline{f}\left(\tilde{\mathtt{c}}_f^{\mathrm{S}} + \gamma_5\tilde{\mathtt{c}}_f^{\mathrm{P}}\right)f\Big] + \mathrm{H.c.}$$

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

$m_f > 0$

- $K_{L,S} \to \not{E}$ 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: $\mathcal{B}(K^+ \to \pi^+\pi^0\nu\bar{\nu}) \sim 10^{-14}$ Littenberg & Valencia, 1996

  $\mathcal{B}(K_L \to \pi^0\pi^0\nu\bar{\nu}) \sim 10^{-13}$ 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 $\big($and coupling constants $\tilde{\mathbf{c}}_f^{\mathrm{V,A,S,P}}\big)$ 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	$\mathrm{C}_f^{\mathrm{V}}, \mathrm{C}_f^{\mathrm{A}}, \mathrm{C}_f^{\mathrm{S}}, \mathrm{C}_f^{\mathrm{P}}$	$\tilde{\mathbf{c}}_f^{\mathrm{A}}, \tilde{\mathbf{c}}_f^{\mathrm{S}}, \tilde{\mathbf{c}}_f^{\mathrm{P}}$	$\tilde{\mathbf{c}}_f^{\mathrm{V}}, \tilde{\mathbf{c}}_f^{\mathrm{A}}, \tilde{\mathbf{c}}_f^{\mathrm{S}}, \tilde{\mathbf{c}}_f^{\mathrm{P}}$

$m_f > 0$

- Consider new physics contributing to hyperon decays with missing energy only via operators with parity-odd quark parts
  - assuming f to be a nonstandard particle with negligible mass.

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

With $m_f \simeq 0$, for the two-body decays ($\tilde{\mathrm{c}}_f^{\mathrm{A}}$ no longer affects $K \to f\bar{f}$ if $m_f = 0$)

$$\mathcal{B}\left(K_L \to f\bar{f}\right) = 2.9\left[\left(\mathrm{Im}\,\tilde{\mathrm{c}}_f^{\mathrm{S}}\right)^2 + \left(\mathrm{Re}\,\tilde{\mathrm{c}}_f^{\mathrm{P}}\right)^2\right] 10^{14}\ \mathrm{GeV}^4\,,$$
$$\mathcal{B}\left(K_S \to f\bar{f}\right) = 5.1\left[\left(\mathrm{Re}\,\tilde{\mathrm{c}}_f^{\mathrm{S}}\right)^2 + \left(\mathrm{Im}\,\tilde{\mathrm{c}}_f^{\mathrm{P}}\right)^2\right] 10^{11}\ \mathrm{GeV}^4$$

leading to

$$\left|\tilde{\mathrm{c}}_f^{\mathrm{S}}\right|^2 + \left|\tilde{\mathrm{c}}_f^{\mathrm{P}}\right|^2 = \frac{3.4\times 10^{-15}}{\mathrm{GeV}^4}\,\mathcal{B}\left(K_L \to f\bar{f}\right) + \frac{2.0\times 10^{-12}}{\mathrm{GeV}^4}\,\mathcal{B}\left(K_S \to f\bar{f}\right)$$

and for the four-body decays

$$\mathcal{B}\left(K^- \to \pi^-\pi^0 f\bar{f}\right) = \left[6.3\left(\left|\tilde{\mathrm{c}}_f^{\mathrm{V}}\right|^2 + \left|\tilde{\mathrm{c}}_f^{\mathrm{A}}\right|^2\right) + 2.0\left(\left|\tilde{\mathrm{c}}_f^{\mathrm{S}}\right|^2 + \left|\tilde{\mathrm{c}}_f^{\mathrm{P}}\right|^2\right)\right] 10^5\ \mathrm{GeV}^4\,,$$
$$\mathcal{B}\left(K_L \to \pi^0\pi^0 f\bar{f}\right) = \left\{8.5\left[\left(\mathrm{Re}\,\tilde{\mathrm{c}}_f^{\mathrm{V}}\right)^2 + \left(\mathrm{Re}\,\tilde{\mathrm{c}}_f^{\mathrm{A}}\right)^2\right] + 16\left[\left(\mathrm{Im}\,\tilde{\mathrm{c}}_f^{\mathrm{S}}\right)^2 + \left(\mathrm{Re}\,\tilde{\mathrm{c}}_f^{\mathrm{S}}\right)^2\right]\right\} 10^6\ \mathrm{GeV}^4$$

- NP contributing only via operators with pseudocalar *ds* part.

$$\mathcal{L}_f \supset -\overline{d}\gamma_5 s\,\overline{f}\left(\tilde{\mathbf{c}}_f^{\mathrm{S}} + \gamma_5\tilde{\mathbf{c}}_f^{\mathrm{P}}\right)f + \mathrm{H.c.}$$

- The constraints from $K \to \not{E}$ are stronger than from $K \to \pi\pi'\not{E}$

  leading to $$|\tilde{\mathbf{c}}_f^{\mathrm{S}}|^2 + |\tilde{\mathbf{c}}_f^{\mathrm{P}}|^2 < 2.2 \times 10^{-16}\,\mathrm{GeV}^{-4}$$

  This translates into

$$\mathcal{B}\left(\Lambda \to n f \bar{f}\right) < 5.0 \times 10^{-9}\,, \qquad \mathcal{B}\left(\Sigma^+ \to p f \bar{f}\right) < 3.0 \times 10^{-9}$$

$$\mathcal{B}\left(\Xi^0 \to \Lambda f \bar{f}\right) < 9.3 \times 10^{-10}\,, \qquad \mathcal{B}\left(\Omega^- \to \Xi^- f \bar{f}\right) < 3.0 \times 10^{-7}$$

- NP contributing only via operators with pseudocalar *ds* part.

$$\mathcal{L}_f \supset -\bar{d}\gamma_5 s\, \bar{f}\left(\tilde{\mathbf{c}}_f^{\mathrm{S}} + \gamma_5 \tilde{\mathbf{c}}_f^{\mathrm{P}}\right) f + \mathrm{H.c.}$$

- The constraints from $K \to \not{E}$ are stronger than from $K \to \pi\pi'\not{E}$

  leading to $|\tilde{\mathbf{c}}_f^{\mathrm{S}}|^2 + |\tilde{\mathbf{c}}_f^{\mathrm{P}}|^2 < 2.2 \times 10^{-16}\,\mathrm{GeV}^{-4}$

  This translates into

$$\mathcal{B}\left(\Lambda \to n f \bar{f}\right) < 5.0 \times 10^{-9}\,, \qquad \mathcal{B}\left(\Sigma^+ \to p f \bar{f}\right) < 3.0 \times 10^{-9}$$

$$\mathcal{B}\left(\Xi^0 \to \Lambda f \bar{f}\right) < 9.3 \times 10^{-10}\,, \qquad \mathcal{B}\left(\Omega^- \to \Xi^- f \bar{f}\right) < 3.0 \times 10^{-7}$$

- These numbers are still 2 to 3 orders of magnitude beyond the expected BESIII reach.

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}

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

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

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

$$\left(\text{Re}\,\tilde{\mathbf{c}}_f^{\rm V}\right)^2 + \left(\text{Re}\,\tilde{\mathbf{c}}_f^{\rm A}\right)^2 < 9.4\times 10^{-14}\,\text{GeV}^{-4}$$

This translates into

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

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

$$\mathcal{B}\left(\Omega^-\to \Xi^- f\bar{f}\right) < 7.5\times 10^{-5}$$

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

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

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

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

This translates into

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

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

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

- 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 $m_f > 0$, more possibilities could arise.

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

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	$\tilde{c}_f^{A},\ \tilde{c}_f^{S},\ \tilde{c}_f^{P}$	$\tilde{c}_f^{V},\ \tilde{c}_f^{A},\ \tilde{c}_f^{S},\ \tilde{c}_f^{P}$	$\tilde{c}_f^{V},\ \tilde{c}_f^{A},\ \tilde{c}_f^{S},\ \tilde{c}_f^{P}$	$\tilde{c}_f^{V},\ \tilde{c}_f^{A},\ \tilde{c}_f^{S},\ \tilde{c}_f^{P}$

$m_f > 0$

Ignoring $c_f^{V,A,S,P}$

- If NP contributes mainly via $\tilde{c}_f^{A,S,P}$ & m_f is nonnegligible, the $K \to f\bar{f}$ constraints turn out to be stricter than the $K \to \pi\pi' f\bar{f}$ ones & cause the hyperon rates to become smaller than their $m_f = 0$ values.

NP-enhanced hyperon rates ($m_f > 0$)

Li, Su, JT, 1905.08759

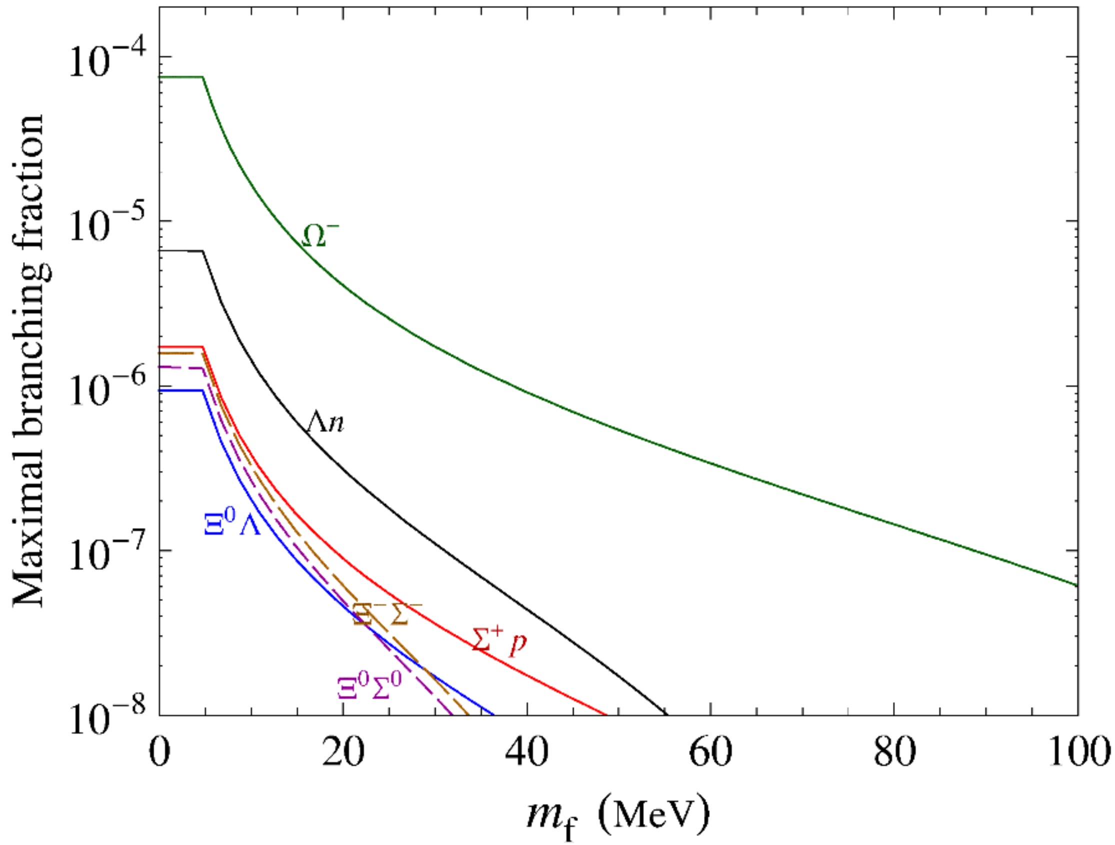

FIG. 2: The maximal branching fractions of $\mathfrak{B} \to \mathfrak{B}' f\bar{f}$ with $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$ and of $\Omega^- \to \Xi^- f\bar{f}$ versus m_f, induced by the contribution of $\mathrm{Re}\,\tilde{\mathbf{c}}_{\mathbf{f}}^{\mathbf{A}}$ alone, subject to the $K_L \to \pi^0\pi^0 \not{E}$ and $K_L \to \not{E}$ constraints, with the latter becoming more important for $m_f > 5$ MeV.

- With $m_f > 0$, even more interesting possibilities could arise.

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

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

$m_f > 0$

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

- If instead only $\tilde{\mathrm{c}}_f^{\mathrm{V}}$ is nonvanishing, it evades the $K \to f\bar{f}$ constraints completely & is subject only to the milder $K \to \pi\pi' f\bar{f}$ ones.

- With $m_f > 0$, even more interesting possibilities could arise.

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

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

$m_f > 0$

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

- If instead only $\tilde{\mathrm{c}}_f^{\mathrm{V}}$ is nonvanishing, it evades the $K \to f\bar{f}$ constraints completely & is subject only to the milder $K \to \pi\pi' f\bar{f}$ ones.
  - ★ As m_f grows, the $K_L \to \pi^0\pi^0 f\bar{f}$ constraint gets increasingly weaker and finally no longer applies for $m_f > 114$ MeV.
  - ★ Consequently, as m_f grows, the upper limits of the hyperon branching fractions also rise & for $m_f > 114$ MeV only $\Sigma^+ \to p f\bar{f}$ & $\Omega^- \to \Xi^- f\bar{f}$ can serve as direct probes of $\tilde{\mathrm{c}}_f^{\mathrm{V}}$.
  - ★ The size of $\tilde{\mathrm{c}}_f^{\mathrm{V}}$ cannot be too large & needs to be consistent with perturbativity and Ω^- data requirements.

NP-enhanced hyperon rates ($m_f > 0$)

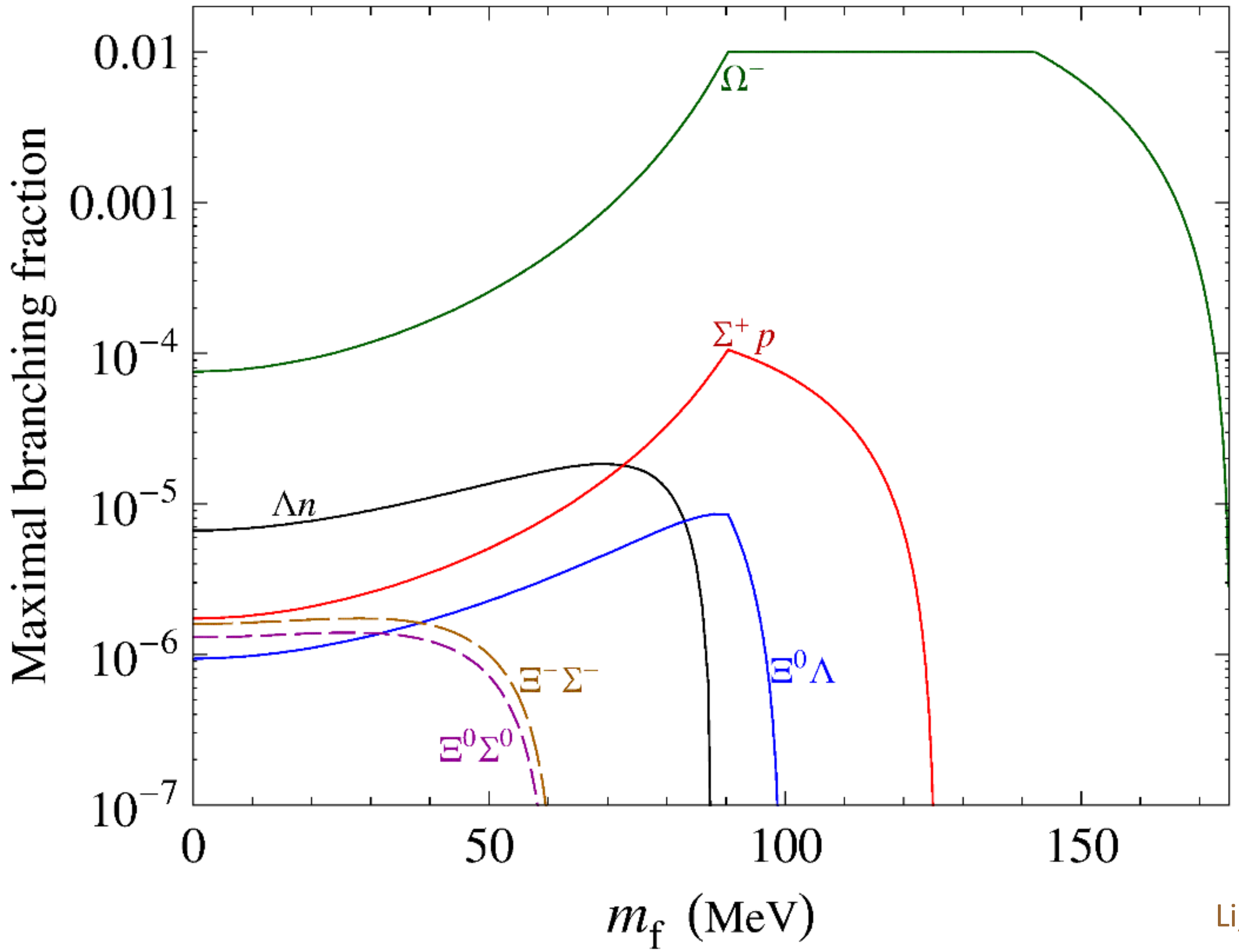

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FIG. 3: The maximal branching fractions of $\mathfrak{B} \to \mathfrak{B}' f \bar{f}$ with $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0 \Lambda, \Xi^0 \Sigma^0, \Xi^- \Sigma^-$ and of $\Omega^- \to \Xi^- f \bar{f}$ versus m_f, induced by the contribution of $\mathrm{Re}\, \tilde{\mathbf{c}}_{\mathbf{f}}^{\mathbf{V}}$ 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.

- Effective Lagrangian for $ds\phi\phi$ interactions at low energies

$$\mathcal{L}_\phi = -\Big[\big(\mathrm{c}_\phi^{\mathrm{V}}\,\overline{d}\gamma^\eta s + \mathrm{c}_\phi^{\mathrm{A}}\,\overline{d}\gamma^\eta\gamma_5 s\big) i\big(\phi^\dagger\partial_\eta\phi - \partial_\eta\phi^\dagger\phi\big) + \big(\mathrm{c}_\phi^{\mathrm{S}}\,\overline{d}s + \mathrm{c}_\phi^{\mathrm{P}}\,\overline{d}\gamma_5 s\big)\phi^\dagger\phi\Big] + \mathrm{H.c.}$$

ϕ is a complex SM-gauge-singlet field charged under some symmetry of a nonstandard dark sector or odd under a Z_2 symmetry which does not affect SM particles.

Model-independently $\mathrm{c}_\phi^{\mathrm{V,A,S,P}}$ are generally complex free parameters.

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

TABLE II: New-physics couplings contributing to $K \to \not{E}$ and $K \to \pi\pi'\not{E}$ if $\not{E}$ is carried away by spinless bosons $\phi\bar\phi$ or spin-1/2 fermions $f\bar f$ and their masses are nonzero, $m_{\phi,f} > 0$. All these couplings belong to operators involving parity-odd ds quark bilinears.

NP-enhanced hyperon rates ($m_\phi > 0$)

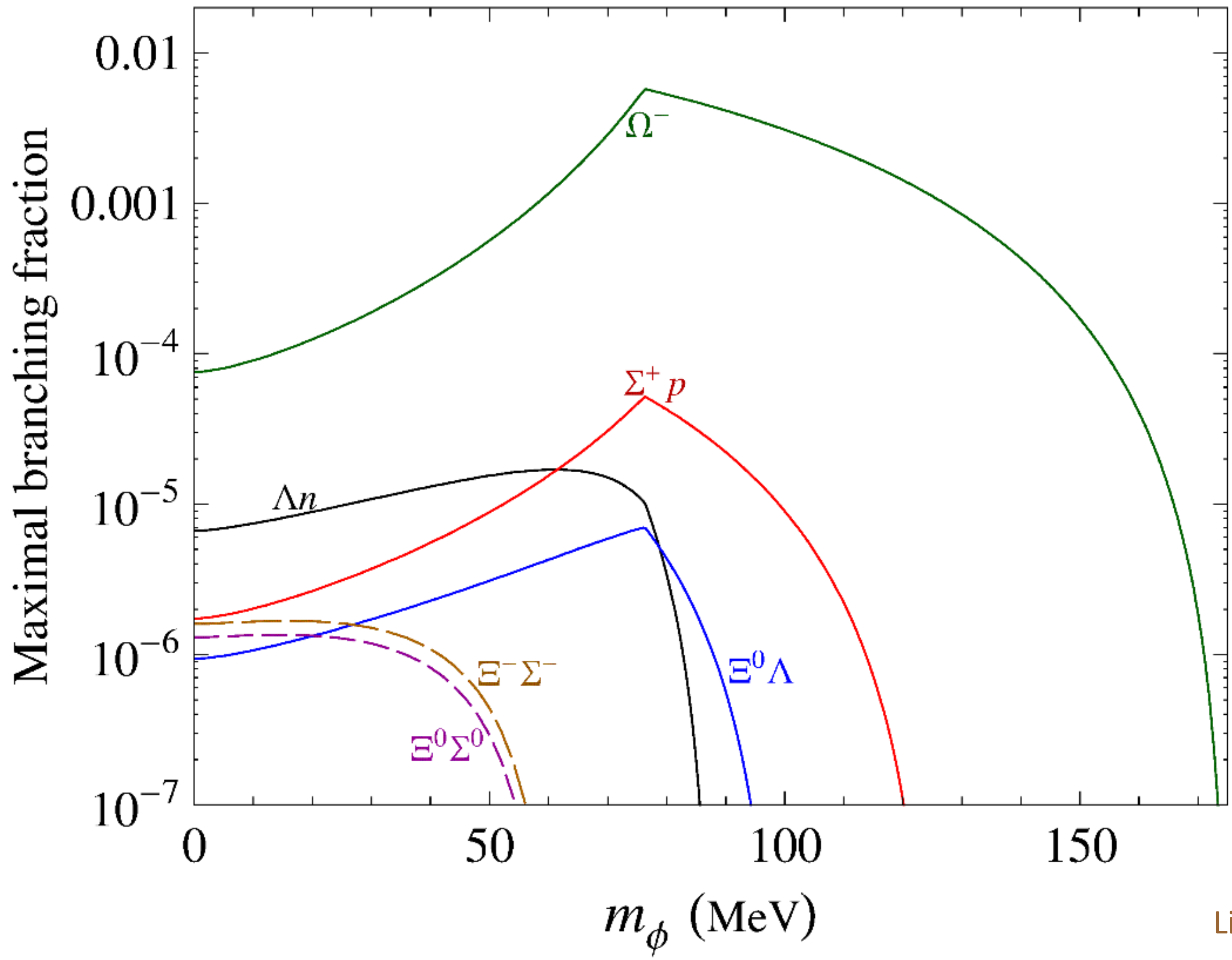

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FIG. 1: The maximal branching fractions of $\mathfrak{B} \to \mathfrak{B}' \phi\bar{\phi}$ with $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$ and of $\Omega^- \to \Xi^-\phi\bar{\phi}$, indicated on the plot by the $\mathfrak{B}\mathfrak{B}'$ and Ω^- labels, respectively, versus m_ϕ, induced by the contribution of $\mathrm{Re}\,\mathbf{c}_\phi^{\mathbf{A}}$ alone, subject to the $K_L \to \pi^0\pi^0 \not{E}$ constraint and the perturbativity requirement for $m_\phi > 76$ MeV.

Conclusions

- Flavor-changing neutral current 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.
- The proposed BESIII measurements on the hyperon modes may test parts of the NP parameter space better than present kaon data can.
- Two of the hyperon modes serve as the only direct probes of certain types of NP involving invisible particles in the 114-175 MeV mass range.
- Ongoing & future experiments on these rare hyperon decays can offer useful information on possible NP effects which is complementary to that gained from the kaon sector.