# Rare hyperon decays in and beyond the standard model


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*Based on*

XG He, JT, G Valencia, arXiv:1806.08350 [JHEP 10 (2018) 040]

arXiv:1903.01242 [JHEP 07 (2019) 022]

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

G Li, JY Su, JT, arXiv:1905.08759

Workshop on form factor, polarization and CP violation in quantum-correlated hyperon-anti-hyperon production

Fudan University, Shanghai, China

7 July 2019

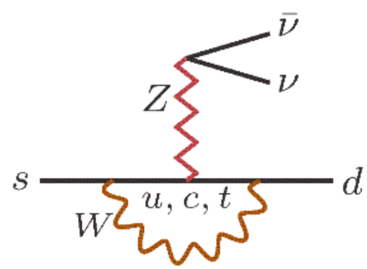
- Introduction
- $\Sigma^+ \to p\mu^+\mu^-$ & $\Sigma^+ \to pe^+e^-$
- Lepton-flavor-violating hyperon decays
- Hyperon decays with missing energy
- Conclusions

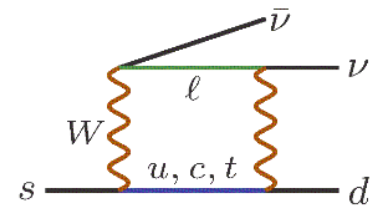
- In the standard model (SM) they receive a short-distance contribution induced by loop diagrams and also a long-distance contribution.

- SD-dominated modes

  such as $\Sigma^+ \to p \nu \nu$

SM:

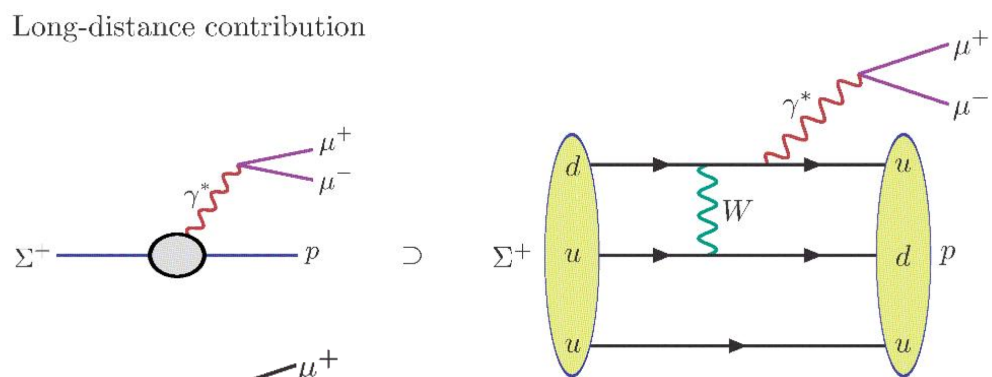


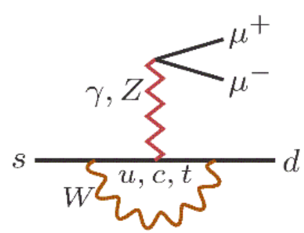

- LD-dominated modes

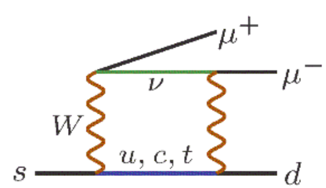
  such as $\Sigma^+ \to p \mu^+ \mu^-$

SM:




  - Negligible SD SM contribution




- There are also modes forbidden in the SM, such as $\Sigma^+ \to p e^+ \mu^-$

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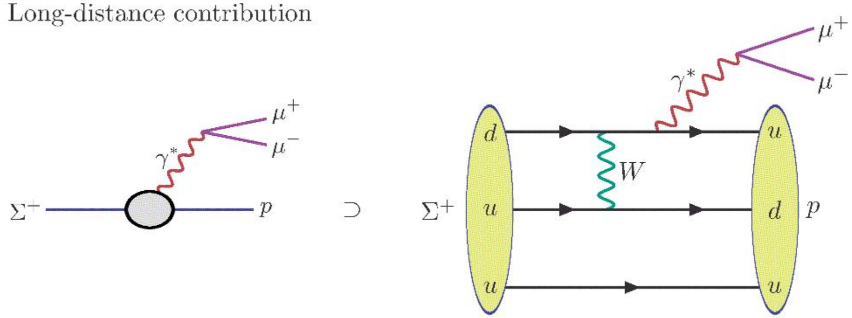
- Long-distance contribution mainly from $\Sigma^+ \to p\gamma^* \to p\mu^+\mu^-$

$$\mathcal{M}_{\rm SM}^{\rm LD} = \frac{-ie^2 G_{\rm F}}{q^2}\, \bar{u}_p (a + \gamma_5 b)\sigma_{\kappa\nu} q^\kappa u_\Sigma\, \bar{u}_\mu \gamma^\nu v_{\bar{\mu}} - e^2 G_{\rm F}\, \bar{u}_p \gamma_\kappa (c + \gamma_5 d) u_\Sigma\, \bar{u}_\mu \gamma^\kappa v_{\bar{\mu}}$$

$a, b, c, d$ are form factors depending on $q^2 = M_{\mu\mu}^2$

Lyagin & Ginzburg, 1962
Bergstrom, Safadi, Singer, 1988
He, JT, Valencia, 2005




- The LD dominance leads to significant uncertainties in the predicted rate.

- Long-distance contribution mainly from $\Sigma^+ \to p\gamma^* \to p\mu^+\mu^-$

$$\mathcal{M}_{\rm SM}^{\rm LD} = \frac{-ie^2 G_{\rm F}}{q^2}\,\bar{u}_p(a+\gamma_5 b)\sigma_{\kappa\nu}q^\kappa u_\Sigma\,\bar{u}_\mu\gamma^\nu v_{\bar{\mu}} - e^2 G_{\rm F}\,\bar{u}_p\gamma_\kappa(c+\gamma_5 d)u_\Sigma\,\bar{u}_\mu\gamma^\kappa v_{\bar{\mu}}$$

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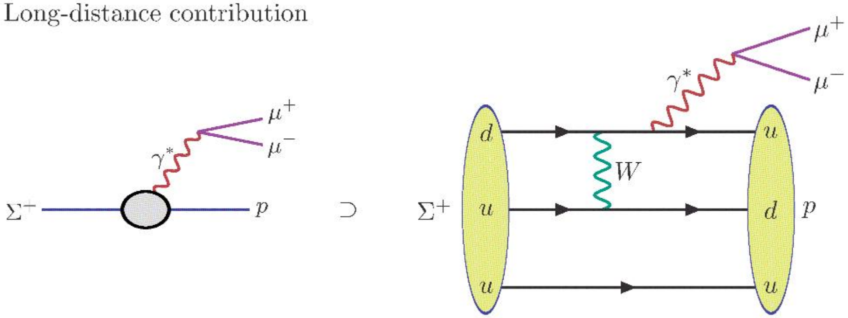
Long-distance contribution




- The LD dominance leads to significant uncertainties in the predicted rate.

- Nevertheless, one can construct observables which are sensitive to terms in the amplitude not dominated by LD contributions.
  - Such observables are then potentially sensitive to SD effects beyond the SM.

# Differential rate of $\Sigma^+ \to p\mu^+\mu^-$ in SM

He, JT, Valencia, 1806.08350

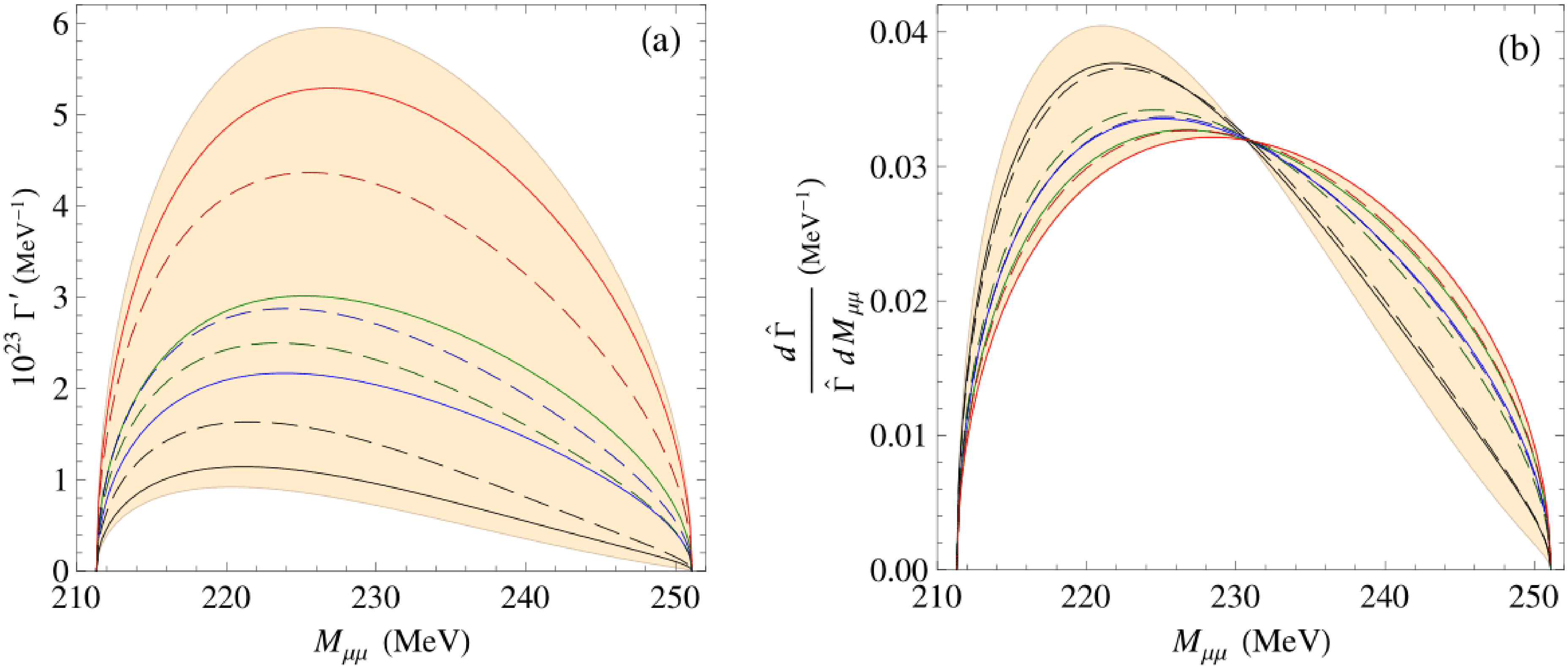



**Figure 2.** (a) The dimuon invariant-mass distribution, $\Gamma' = d\Gamma(\Sigma^+ \to p\mu^+\mu^-)/dq^2$ versus $M_{\mu\mu} = \sqrt{q^2}$, calculated in the SM with $\text{Im}(a,b,c,d)$ formulas derived in relativistic (solid curves) or heavy-baryon (dashed curves) $\chi$PT. From bottom to top, the black, blue, green, and red solid [dashed] curves correspond to $\text{Re}(a,b)/\text{MeV} = (13.3,-6.0), (-13.3,6.0), (6.0,-13.3), (-6.0,13.3)$ $[(11.0,-7.4), (-11.0,7.4),\ (7.4,-11.0), (-7.4,11.0)]$, respectively. The light-orange (shaded) region enveloping the curves corresponds to the parameter space represented by the benchmark points in figure 1. (b) The related differential rate $(d\hat{\Gamma}/dM_{\mu\mu})/\hat{\Gamma} = 2\Gamma' M_{\mu\mu}/\hat{\Gamma}$ normalized by $\hat{\Gamma} = \Gamma(\Sigma^+ \to p\mu^+\mu^-)$.

# Branching fraction of $\Sigma^+ \to p\mu^+\mu^-$ in SM

He, JT, Valencia, 1806.08350

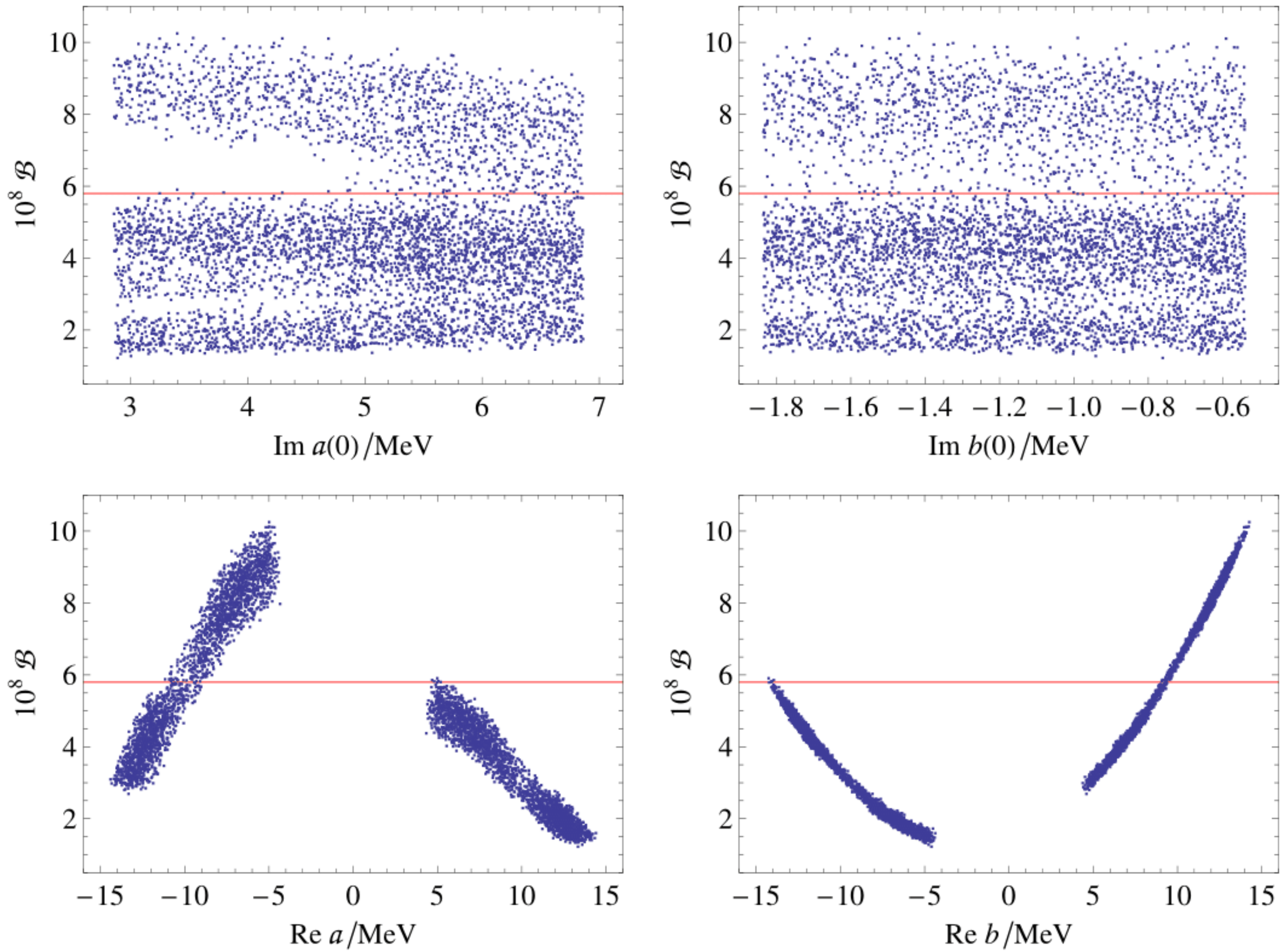



**Figure 1**. Sample points of $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) \times 10^8$ in relation to the preferred ranges of Im$(a, b)$ at $q^2 = 0$ and of Re$(a, b)$, as explained in the text. Each horizontal red line marks the $2\sigma$ upper-limit of the LHCb measurement [2].

# Evidence for the Rare Decay $\Sigma^+ \to p\mu^+\mu^-$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 22 December 2017; published 31 May 2018)

A search for the rare decay $\Sigma^+ \to p\mu^+\mu^-$ is performed using $pp$ collision data recorded by the LHCb experiment at center-of-mass energies $\sqrt{s} = 7$ and 8 TeV, corresponding to an integrated luminosity of 3 $\mathrm{fb}^{-1}$. An excess of events is observed with respect to the background expectation, with a signal significance of 4.1 standard deviations. No significant structure is observed in the dimuon invariant mass distribution, in contrast with a previous result from the HyperCP experiment. The measured $\Sigma^+ \to p\mu^+\mu^-$ branching fraction is $(2.2^{+1.8}_{-1.3}) \times 10^{-8}$, where statistical and systematic uncertainties are included, which is consistent with the standard model prediction.

A signal yield of $10.2^{+3.9}_{-3.5}$ is observed.

- Amplitude accommodating SM and potential NP contributions

$$\mathcal{M} = \bar{u}_p\big[iq_\kappa(\tilde{\mathrm{A}}+\gamma_5\tilde{\mathrm{B}})\sigma^{\nu\kappa} - \gamma^\nu(\tilde{\mathrm{C}}+\gamma_5\tilde{\mathrm{D}})\big]u_\Sigma\,\bar{u}_\mu\gamma_\nu v_{\bar{\mu}} + \bar{u}_p\gamma^\nu(\tilde{\mathrm{E}}+\gamma_5\tilde{\mathrm{F}})u_\Sigma\,\bar{u}_\mu\gamma_\nu\gamma_5 v_{\bar{\mu}}$$
$$+\,\bar{u}_p(\tilde{\mathrm{G}}+\gamma_5\tilde{\mathrm{H}})u_\Sigma\,\bar{u}_\mu v_{\bar{\mu}} + \bar{u}_p(\tilde{\mathrm{J}}+\gamma_5\tilde{\mathrm{K}})u_\Sigma\,\bar{u}_\mu\gamma_5 v_{\bar{\mu}}$$

$\tilde{\mathrm{A}}, \tilde{\mathrm{B}}, \ldots, \tilde{\mathrm{K}}$ are complex coefficients

- Look for observables sensitive to the small SD contribution.

- One of them turns out to be the muon forward-backward asymmetry.

- Forward-backward asymmetry

$$\mathcal{A}_{\rm FB} = \frac{\int_{-1}^{1} dc_\theta \, {\rm sgn}(c_\theta)\, \Gamma''}{\int_{-1}^{1} dc_\theta \, \Gamma''} \,, \qquad \Gamma'' = \frac{d^2\Gamma(\Sigma^+ \to p\mu^+\mu^-)}{dq^2\, dc_\theta} \,, \quad c_\theta = \cos\theta$$

$\theta$ angle between $\mu^-$ and $p$ directions in dimuon's rest frame

$$\mathcal{A}_{\rm FB} = \frac{\beta^2 \bar{\lambda}}{64\pi^3\,\Gamma'\, m_\Sigma^3} {\rm Re}\Big\{ \big[ {\rm M}_+ \tilde{\bf A}^* \tilde{\rm F} - {\rm M}_- \tilde{\bf B}^* \tilde{\rm E} - \big(\tilde{\bf A}^* \tilde{\rm G} + \tilde{\bf B}^* \tilde{\rm H}\big) m_\mu + \tilde{\bf C}^* \tilde{\rm F} + \tilde{\bf D}^* \tilde{\rm E} \big] q^2 - \big( {\rm M}_+ \tilde{\bf C}^* \tilde{\rm G} - {\rm M}_- \tilde{\bf D}^* \tilde{\rm H} \big) m_\mu \Big\}$$

with $\beta = \sqrt{1 - 4m_\mu^2/q^2}\,, \quad \bar{\lambda} = \hat{m}_-^2 \hat{m}_+^2\,, \quad \hat{m}_\pm^2 = {\rm M}_\pm^2 - q^2\,, \quad {\rm M}_\pm = m_\Sigma \pm m_p$

- Integrated forward-backward asymmetry

$$\tilde{A}_{\rm FB} = \frac{1}{\Gamma(\Sigma^+ \to p\mu^+\mu^-)} \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \int_{-1}^{1} dc_\theta \, {\rm sgn}(c_\theta)\, \Gamma'' \,,$$

$q^2_{\rm min} = 4m_\mu^2\,, \quad q^2_{\rm max} = (m_\Sigma - m_p)^2$

- It's the main observable that could provide a window into NP modifying part of the SM amplitude not dominated by LD effects.

⋆ Polarization asymmetries of the muons

$$\frac{d\Gamma^-(\varsigma_x^-,\varsigma_y^-,\varsigma_z^-)}{dq^2} = \frac{\Gamma'}{2}\left(1 + \mathcal{P}_T^-\varsigma_x^- + \mathcal{P}_N^-\varsigma_y^- + \mathcal{P}_L^-\varsigma_z^-\right)$$

$$\hat{z} = \frac{p_\mu}{|p_\mu|}, \quad \hat{y} = \frac{p_p \times p_\mu}{|p_p \times p_\mu|}, \quad \hat{x} = \hat{y}\times\hat{z}, \quad (\varsigma_x^-)^2 + (\varsigma_y^-)^2 + (\varsigma_z^-)^2 = 1$$

$$\mathcal{P}_L^- = \frac{\beta^2\sqrt{\bar\lambda}}{192\pi^3\,\Gamma'\,m_\Sigma^3}\,\mathrm{Re}\Big\{\big[-3\big(2M_+\tilde{A}^*\tilde{E} + \tilde{H}^*\tilde{K}\big)q^2 - 2\big(\hat{m}_+^2 + 3q^2\big)\tilde{C}^*\tilde{E} + 6m_\mu M_+\tilde{F}^*\tilde{H}\big]\hat{m}_-^2 + \big[3\big(2M_-\tilde{B}^*\tilde{F} - \tilde{G}^*\tilde{J}\big)q^2 - 2\big(\hat{m}_-^2 + 3q^2\big)\tilde{D}^*\tilde{F} - 6m_\mu M_-\tilde{E}^*\tilde{G}\big]\hat{m}_+^2\Big\}$$

$$\mathcal{P}_N^- = \frac{\beta^2\bar\lambda\sqrt{q^2}}{256\pi^2\,\Gamma'\,m_\Sigma^3}\,\mathrm{Im}\Big\{2\big[(M_+\tilde{A}+\tilde{C})^*\tilde{F} + (\tilde{D} - M_-\tilde{B})^*\tilde{E}\big]m_\mu - \big(\tilde{A}^*\tilde{G} + \tilde{B}^*\tilde{H}\big)q^2 - \big(\tilde{C}^*\tilde{G} - \tilde{E}^*\tilde{J}\big)M_+ + \big(\tilde{D}^*\tilde{H} - \tilde{F}^*\tilde{K}\big)M_-\Big\}$$

$$\mathcal{P}_T^- = \frac{\beta\bar\lambda\sqrt{q^2}}{256\pi^2\,\Gamma'\,m_\Sigma^3}\,\mathrm{Re}\Big\{2\big[2\big(M_+\tilde{A}+\tilde{C}\big)^*\big(\tilde{D} - M_-\tilde{B}\big) - M_-\tilde{A}^*\tilde{E} + M_+\tilde{B}^*\tilde{F}\big]m_\mu - M_+\tilde{C}^*\tilde{J} + M_-\tilde{D}^*\tilde{K} + \beta^2\big(M_+\tilde{E}^*\tilde{G} - M_-\tilde{F}^*\tilde{H}\big)\Big\} - \frac{\beta\bar\lambda\,\mathrm{Re}\big[\big(\tilde{A}^*\tilde{J} + \tilde{B}^*\tilde{K}\big)q^4 + 2\big(\tilde{C}^*\tilde{E} + \tilde{D}^*\tilde{F}\big)M_+M_-m_\mu\big]}{256\pi^2\,\Gamma'\,m_\Sigma^3\sqrt{q^2}}$$

⋆ Integrated polarization asymmetries $\tilde{P}_{L,N,T}^- = \frac{1}{\Gamma(\Sigma^+ \to p\mu^+\mu^-)}\int_{q^2_{\min}}^{q^2_{\max}} dq^2\,\Gamma'\,\mathcal{P}_{L,N,T}^-$

# Branching fraction & muon asymmetries of $\Sigma^+ \to p\mu^+\mu^-$ in SM

| $\frac{\mathrm{Re}\,a}{\mathrm{MeV}}$ | $\frac{\mathrm{Re}\,b}{\mathrm{MeV}}$ | $10^8\,\mathcal{B}$ | $10^5\,\tilde{A}_{\mathrm{FB}}$ | $10^5\,\tilde{P}_{\mathrm{L}}^-$ | $10^6\,\tilde{P}_{\mathrm{N}}^-$ | $\tilde{P}_{\mathrm{T}}^-$ (%) |
|---|---|---|---|---|---|---|
| 13.3 | −6.0 | 1.6 | 3.7 | −7.0 | −0.2 | 59 |
| −13.3 | 6.0 | 3.5 | −1.4 | 4.5 | −9.6 | 50 |
| 6.0 | −13.3 | 5.1 | 0.9 | −5.1 | −1.1 | 23 |
| −6.0 | 13.3 | 9.1 | −0.3 | 3.3 | −3.1 | 17 |
| 11.0 | −7.4 | 2.4 | 2.7 | −5.7 | −7.3 | 41 |
| −11.0 | 7.4 | 4.7 | −0.7 | 4.1 | −10 | 36 |
| 7.4 | −11.0 | 4.0 | 1.4 | −5.2 | −5.0 | 26 |
| −7.4 | 11.0 | 7.4 | −0.3 | 3.6 | −6.0 | 21 |

TABLE I: Sample values of the branching fraction $\mathcal{B}$ of $\Sigma^+ \to p\mu^+\mu^-$ and the corresponding integrated asymmetries $\tilde{A}_{\mathrm{FB}}$ and $\tilde{P}^-_{\mathrm{L,N,T}}$ computed within the SM including the SD and LD contributions. In the evaluation of the $\mathcal{B}$, $\tilde{A}_{\mathrm{FB}}$, and $\tilde{P}^-_{\mathrm{L,N,T}}$ entries in the first [last] four rows, the relativistic [heavy baryon] expressions for $\mathrm{Im}(a,b,c,d)$ have been used, as explained in the text.

- Some of the asymmetries are tiny in the SM.
  - They are potentially sensitive to NP effects.

## $\Sigma^+ \to p e^+ e^-$

- The existing data $\dfrac{\Gamma(\Sigma^+ \to p e^+ e^-)}{\Gamma(\Sigma^+ \to p \pi^0)} = (1.5 \pm 0.9) \times 10^{-5}$ translates into

  Ang *et al.*, 1969

  $$\mathcal{B}(\Sigma^+ \to p e^+ e^-) = (7.7 \pm 4.6) \times 10^{-6}$$

- The SM predicts $8.4 \times 10^{-6} \leq \mathcal{B}(\Sigma^+ \to p e^+ e^-)_{\rm SM} \leq 11.0 \times 10^{-6}$

  He, JT, Valencia, hep-ph/0506067
  1806.08350

- The Dalitz decay contribution

$$\mathcal{B}(\Sigma^+ \to p e^+ e^-)_{\rm Dalitz} = \frac{2\alpha(0)}{3\pi} \left[ \ln \frac{2(m_\Sigma - m_p)}{m_e} - \frac{13}{6} \right] \mathcal{B}(\Sigma^+ \to p\gamma)$$

  accounts for more than 88% of $\mathcal{B}(\Sigma^+ \to p e^+ e^-)_{\rm SM}$ .

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- Charged-lepton-flavor violation (CLFV) has been much searched for in $|\Delta S|=1$ kaon decays (with negative outcomes so far), but not yet been pursued experimentally in the hyperon sector.
- The situation may change in the near future if LHCb starts to look for CLFV in $|\Delta S|=1$ hyperon decays.
- To explore hyperon and kaon decays manifesting CLFV and how their experimental constraints may complement each other, it is useful to perform a model-independent study using the SM-gauge-invariant effective Lagrangian.

- The most general SM-gauge-invariant effective Lagrangian of lowest dimension contributing to $dse\mu$ interactions

$$\mathcal{L}_{\rm NP} = \frac{1}{\Lambda_{\rm NP}^2}\left[\sum_{k=1}^{5} \mathcal{C}_k^{ijxy}\mathcal{Q}_k^{ijxy} + \left(\mathcal{C}_6^{ijxy}\mathcal{Q}_6^{ijxy} + {\rm H.c}\right)\right]$$

$\Lambda_{\rm NP}$ is a heavy mass scale, $\mathcal{C}_{1,\ldots,6}^{ijxy}$ are generally complex coefficients,

$i,j,x,y = 1,2,3$ are family indices (summed over)

$$\mathcal{Q}_1^{ijxy} = \overline{q_i}\gamma^\eta q_j\,\overline{l_x}\gamma_\eta l_y\,, \quad \mathcal{Q}_2^{ijxy} = \overline{q_i}\gamma^\eta \tau_{\rm I} q_j\,\overline{l_x}\gamma_\eta \tau_{\rm I} l_y\,, \quad \mathcal{Q}_3^{ijxy} = \overline{d_i}\gamma^\eta d_j\,\overline{e_x}\gamma_\eta e_y$$

$$\mathcal{Q}_4^{ijxy} = \overline{d_i}\gamma^\eta d_j\,\overline{l_x}\gamma_\eta l_y\,, \quad \mathcal{Q}_5^{ijxy} = \overline{q_i}\gamma^\eta q_j\,\overline{e_x}\gamma_\eta e_y\,, \quad \mathcal{Q}_6^{ijxy} = \overline{l_i}e_j\,\overline{d_x}q_y$$

- In the mass basis of the down-type fermions

$$q_i = P_L\begin{pmatrix}\sum_j\left(\mathcal{V}_{\rm CKM}^\dagger\right)_{ij}U_j \\ D_i\end{pmatrix}, \quad l_i = P_L\begin{pmatrix}\sum_j\left(\mathcal{U}_{\rm PMNS}\right)_{ij}\nu_j \\ E_i\end{pmatrix}, \quad e_i = P_R E_i\,, \quad d_i = P_R D_i$$

- The terms with operators $Q_k^{e\mu}$ and $Q_k^{\mu e}$ contributing to $s \to d e^\mp \mu^\pm$ transitions

$$\mathcal{L}_{\rm NP} \supset \frac{1}{\Lambda_{\rm NP}^2} \sum_{k\,=\,1}^{6,6\prime} \left( c_k^{e\mu} Q_k^{e\mu} + c_k^{\mu e} Q_k^{\mu e} \right)$$

$$c_{k'}^{e\mu(\mu e)} = \mathcal{C}_{k'}^{1212(1221)}, \qquad Q_{k'}^{e\mu(\mu e)} = \mathcal{Q}_{k'}^{1212(1221)}, \qquad k' = 1, ..., 5$$

$$c_6^{e\mu(\mu e)} = \mathcal{C}_6^{1212(2112)}, \qquad Q_6^{e\mu} = \mathcal{Q}_6^{1212(2112)}$$

$$c_{6\prime}^{e\mu(\mu e)} = \mathcal{C}_6^{2121(1221)*}, \qquad Q_{6\prime}^{e\mu(\mu e)} = \left[ \mathcal{Q}_6^{2121(1221)} \right]^\dagger$$

- It's convenient to separate terms with parity-even and -odd quark couplings

$$\mathcal{L}_{\rm NP} \supset \frac{-1}{\Lambda_{\rm NP}^2} \sum_{\ell,\ell'} \Big[ \overline{d}\gamma^\kappa s\, \overline{\ell}\gamma_\kappa (\mathrm{V}_{\ell\ell'} + \gamma_5 \mathrm{A}_{\ell\ell'})\ell' + \overline{d}\gamma^\kappa\gamma_5 s\, \overline{\ell}\gamma_\kappa (\tilde{\mathrm{V}}_{\ell\ell'} + \gamma_5 \tilde{\mathrm{A}}_{\ell\ell'})\ell'$$
$$+ \overline{d}s\, \overline{\ell}(\mathrm{S}_{\ell\ell'} + \gamma_5 \mathrm{P}_{\ell\ell'})\ell' + \overline{d}\gamma_5 s\, \overline{\ell}(\tilde{\mathrm{S}}_{\ell\ell'} + \gamma_5 \tilde{\mathrm{P}}_{\ell\ell'})\ell' \Big] + \mathrm{H.c.}$$

where $\ell^{(\prime)} = e, \mu$ but $\ell \neq \ell'$

$$4\,\mathrm{V}_{e\mu} = -c_1^{e\mu} - c_2^{e\mu} - c_3^{e\mu} - c_4^{e\mu} - c_5^{e\mu}, \qquad 4\,\mathrm{A}_{e\mu} = c_1^{e\mu} + c_2^{e\mu} - c_3^{e\mu} + c_4^{e\mu} - c_5^{e\mu}$$

$$4\,\tilde{\mathrm{V}}_{e\mu} = c_1^{e\mu} + c_2^{e\mu} - c_3^{e\mu} - c_4^{e\mu} + c_5^{e\mu}, \qquad 4\,\tilde{\mathrm{A}}_{e\mu} = -c_1^{e\mu} - c_2^{e\mu} - c_3^{e\mu} + c_4^{e\mu} + c_5^{e\mu}$$

$$4\,\mathrm{S}_{e\mu} = -c_6^{e\mu} - c_{6\prime}^{e\mu} = -4\,\tilde{\mathrm{P}}_{e\mu}, \qquad 4\,\mathrm{P}_{e\mu} = -c_6^{e\mu} + c_{6\prime}^{e\mu} = -4\,\tilde{\mathrm{S}}_{e\mu}$$

- Kaon constraints

$$\mathcal{B}(K_L \to e^\pm \mu^\mp) < 4.7 \times 10^{-12}, \quad \mathcal{B}(K_L \to \pi^0 e^\pm \mu^\mp) < 7.6 \times 10^{-11}$$
$$\mathcal{B}(K^+ \to \pi^+ e^- \mu^+) < 1.3 \times 10^{-11}, \quad \mathcal{B}(K^+ \to \pi^+ \mu^- e^+) < 5.2 \times 10^{-10}$$

PDG

and $\mathcal{B}(K_L \to \pi^0 \pi^0 e^\pm \mu^\mp) < 1.7 \times 10^{-10}$, all at 90% CL

- Constraints from other processes which get contributions from some of the same [SU(2) gauge-invariant] operators, especially
  - $K \to \pi\nu\nu$
  - $\mu \to e$ conversion in nuclei

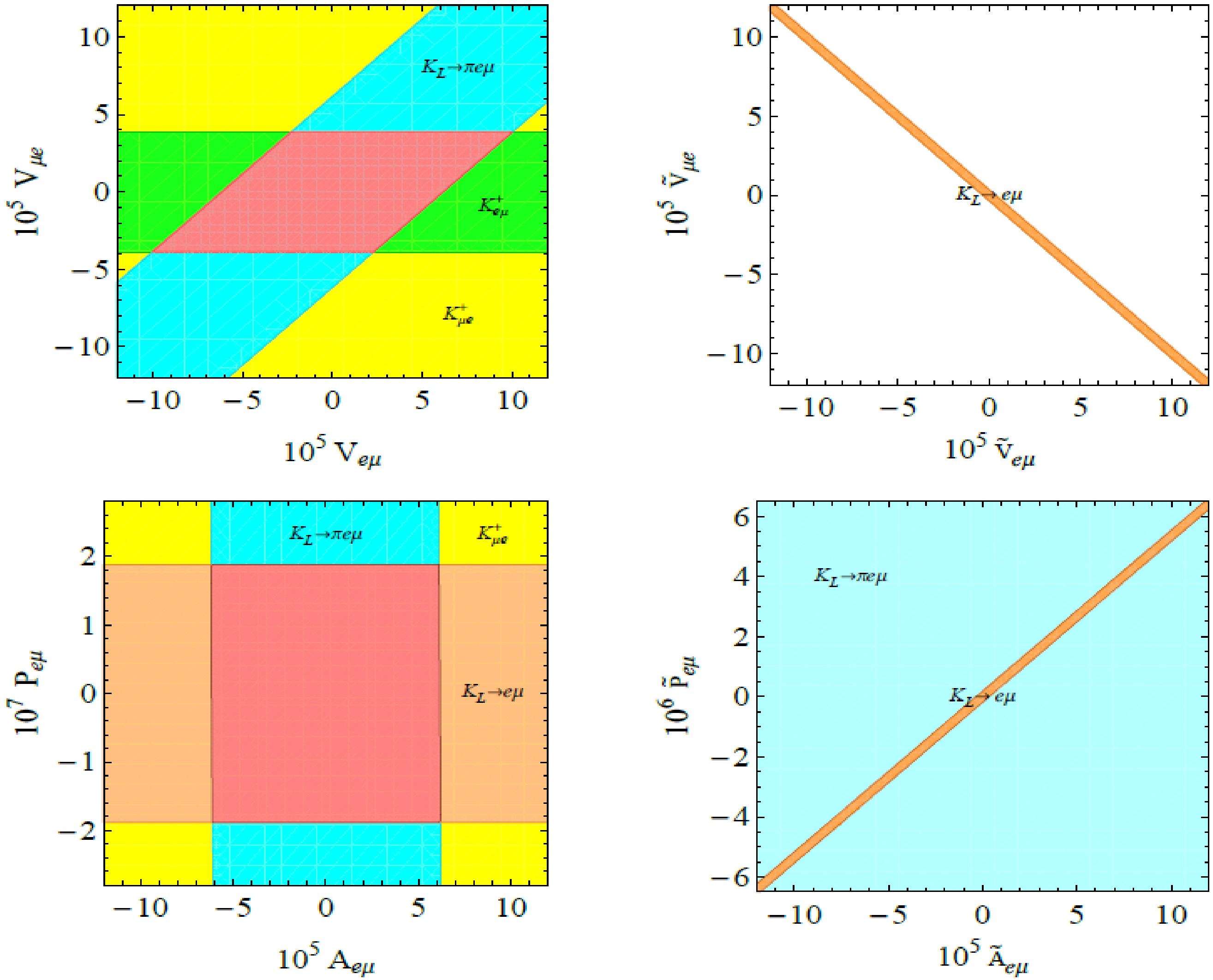



Figure 1: Regions of $\mathtt{V}_{\mu e}$ versus $\mathtt{V}_{e\mu}$ (top left), $\tilde{\mathtt{V}}_{\mu e}$ versus $\tilde{\mathtt{V}}_{e\mu}$ (top right), $\mathtt{P}_{e\mu}$ versus $\mathtt{A}_{e\mu}$ (bottom left), and $\tilde{\mathtt{P}}_{e\mu}$ versus $\tilde{\mathtt{A}}_{e\mu}$ (bottom right), all taken to be real, for $\Lambda_{\rm NP} = 1\,$TeV, allowed by the experimental limits on the branching-fractions of $K_L \to \pi^0 e^\pm \mu^\mp$, $K^+ \to \pi^+ e^- \mu^+$, $K^+ \to \pi^+ \mu^- e^+$, and $K_L \to e^\pm \mu^\mp$ (indicated by $K_L \to \pi e\mu$, $K^+_{e\mu}$, $K^+_{\mu e}$, and $K_L \to e\mu$, respectively). In the left (right) plot at the bottom, the bound from $K_L \to e^\pm\mu^\mp$ ($K_L \to \pi e^\pm \mu^\mp$) is included because they are affected by $\tilde{\mathtt{S}}_{e\mu} = -\mathtt{P}_{e\mu}$ ($\mathtt{S}_{e\mu} = -\tilde{\mathtt{P}}_{e\mu}$), from eq. (7). In each of the four cases, all the other couplings are set to zero.

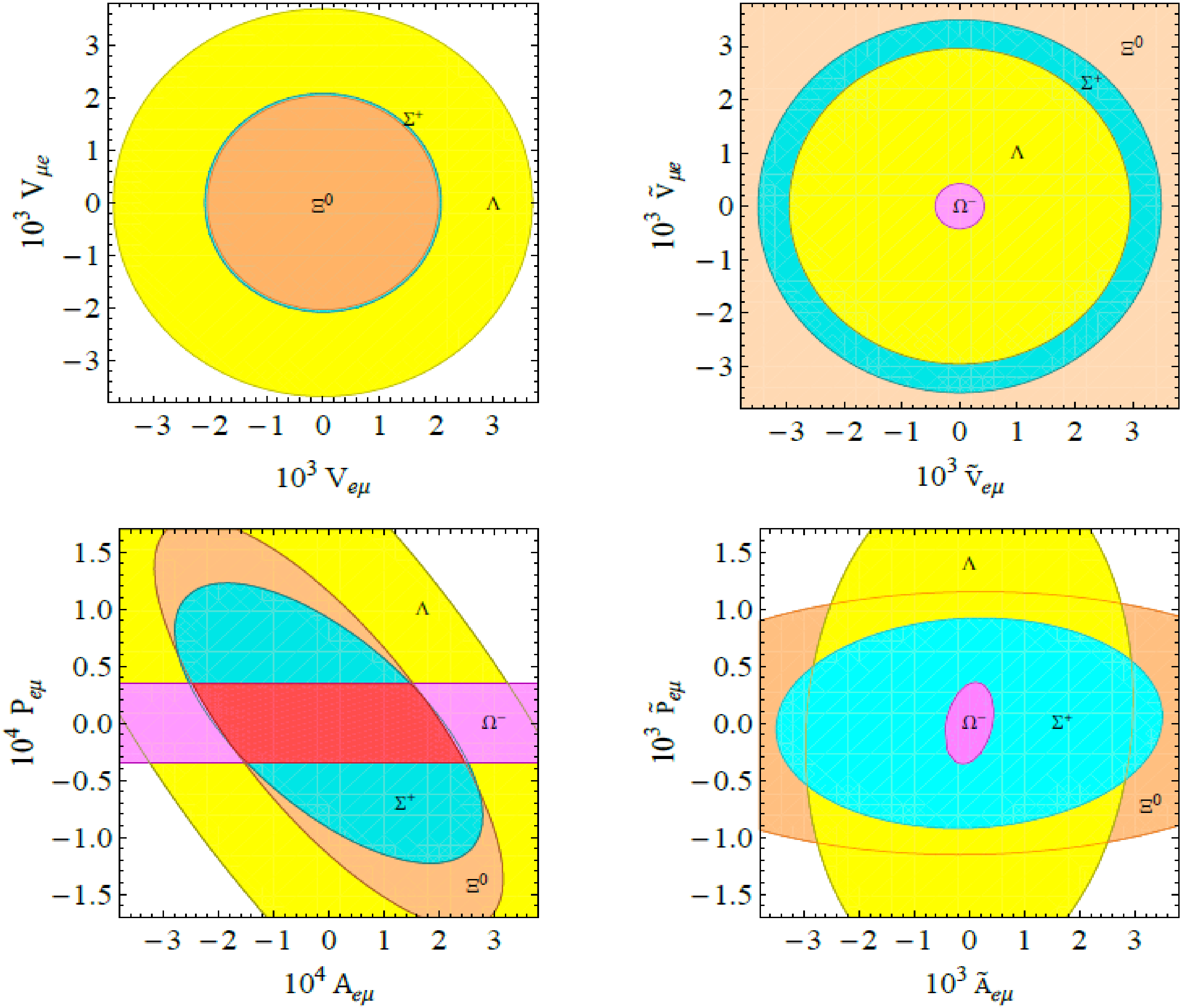



Figure 2: Allowed regions of $\mathtt{V}_{\mu e}$ versus $\mathtt{V}_{e\mu}$ (top left), $\tilde{\mathrm{V}}_{\mu e}$ versus $\tilde{\mathrm{V}}_{e\mu}$ (top right), $\mathtt{P}_{e\mu}$ versus $\mathtt{A}_{e\mu}$ (bottom left), and $\tilde{\mathrm{P}}_{e\mu}$ and $\tilde{\mathrm{A}}_{e\mu}$ (bottom right), all taken to be real, for $\Lambda_{\rm NP} = 1\,\mathrm{TeV}$, subject to assumed limits of $10^{-10}$ on the hyperon branching fractions in eqs. (31)-(34), labeled by $\Lambda$, $\Sigma^+$, $\Xi^0$, and $\Omega^-$, respectively. The bottom plots take into account eq. (7). In each case the other couplings are set to zero.

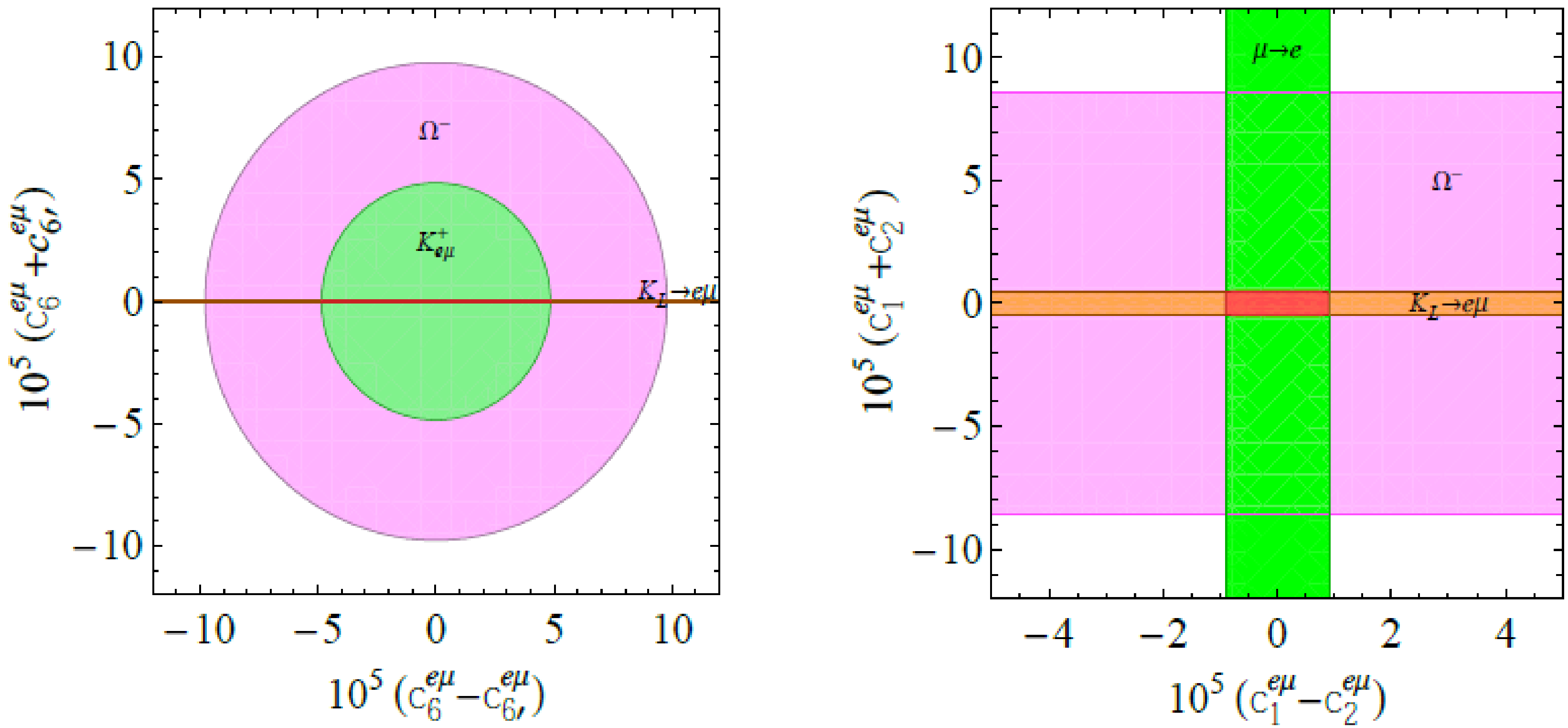



Figure 3: Comparative constraints on combinations of LFV couplings $c_k^{\ell\ell'}$ from eq. (4) that produce operators with definite parity, under the assumption that $c_k^{e\mu} = c_k^{\mu e}$, they are real, $\Lambda_{\rm NP} = 1\,{\rm TeV}$, and $\mathcal{B}(\Omega^- \to \Xi^- \mu^\pm e^\mp) < 10^{-12}$.

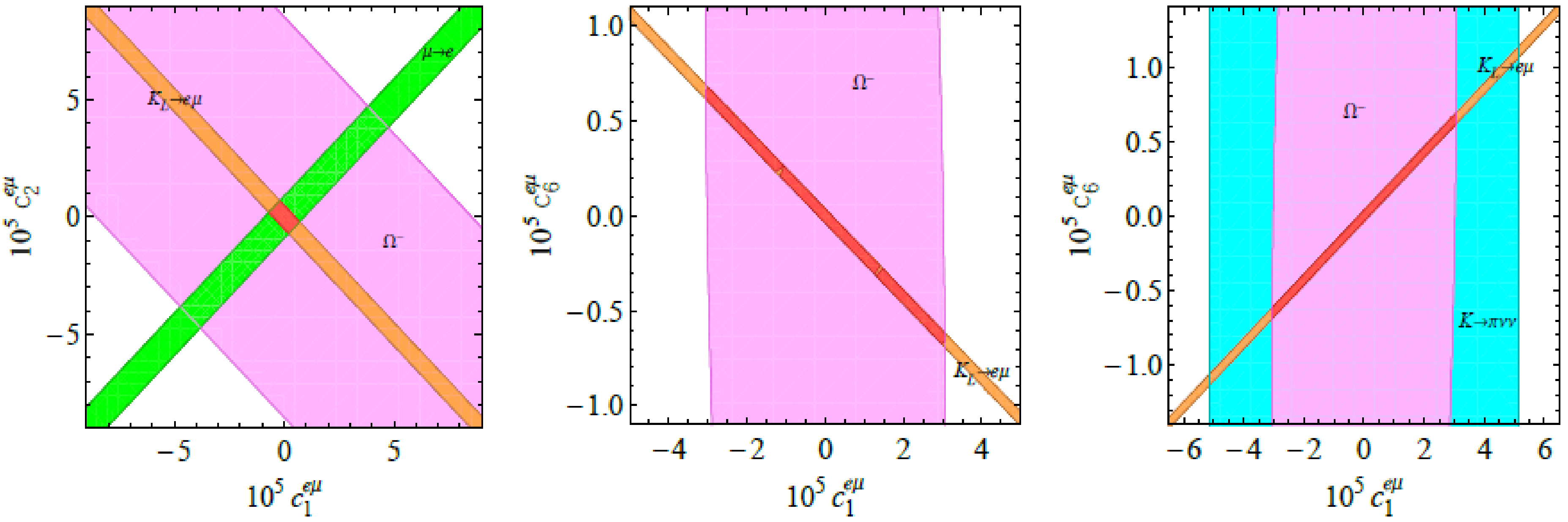



Figure 4: Comparative constraints on selected LFV couplings in eq. (4), for $\Lambda_{\rm NP} = 1\,{\rm TeV}$, from current 90%-CL upper bounds on NP effects in $K_L \to \mu^\pm e^\mp$, $K^+ \to \pi^+\nu\bar{\nu}$, and $\mu^- \to e^-$ conversion in gold and a possible future bound of $\mathcal{B}(\Omega^- \to \Xi^-\mu^\pm e^\mp) < 10^{-12}$, under the general assumption that the couplings are real and $c_k^{e\mu} = c_k^{\mu e}$. The specific choices for the nonzero ones are described in the text.

- Introduction
- $\Sigma^+ \to p\mu^+\mu^-$ & $\Sigma^+ \to pe^+e^-$
- Lepton-flavor-violating hyperon decays
- Hyperon decays with missing energy
- Conclusions

JT, 1901.10447
Li, Su, JT, 1905.08759

# Available data on $|\Delta S|=1$ neutral-current decays with missing energy

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

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

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9}$ 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

$\mathcal{B}(K_L \to \pi^0 \pi^0 \nu\bar{\nu}) < 8.1 \times 10^{-7}$ 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.

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

  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.

- BESIII is going to search for hyperon decays with missing energy.

* 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 $\mathrm{c}_\nu^{\mathrm{S,P}} = \tilde{\mathrm{c}}_\nu^{\mathrm{S,P}} = 0$

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

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

$f$ describes an electrically neutral, colorless, invisible, spin-$\frac{1}{2}$, Dirac particle.

Model-independently $\mathrm{c}_f^{V,A,S,P}$ & $\tilde{\mathrm{c}}_f^{V,A,S,P}$ 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 $\mathrm{c}_\nu^V = -\mathrm{c}_\nu^A = -\tilde{\mathrm{c}}_\nu^V = \tilde{\mathrm{c}}_\nu^A$ and $\mathrm{c}_\nu^{S,P} = \tilde{\mathrm{c}}_\nu^{S,P} = 0$

- Mesonic matrix elements which don't vanish:

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

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

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

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

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

$f_K$ 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:

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

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

- The baryonic matrix elements are estimated with aid of chiral perturbation theory ($\chi$PT) 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 $\chi$PT.

## Contributions of various couplings to kaon & hyperon modes

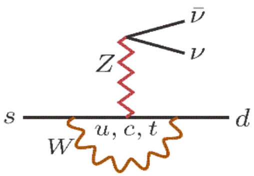
- $$\mathcal{L}_f = -\Big[\bar{d}\gamma^\eta s\,\bar{f}\gamma_\eta\big(\mathrm{c}_f^{\rm V}+\gamma_5\mathrm{c}_f^{\rm A}\big)f + \bar{d}\gamma^\eta\gamma_5 s\,\bar{f}\gamma_\eta\big(\tilde{\mathrm{c}}_f^{\rm V}+\gamma_5\tilde{\mathrm{c}}_f^{\rm A}\big)f + \bar{d}s\,\bar{f}\big(\mathrm{c}_f^{\rm S}+\gamma_5\mathrm{c}_f^{\rm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

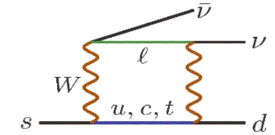
| Decay mode | $K\to\pi f\bar{f}$ | $K\to f\bar{f}$ | $K\to\pi\pi' f\bar{f}$ | $\mathfrak{B}\to\mathfrak{B}' f\bar{f}$ | $\Omega^-\to\Xi^- f\bar{f}$ |
|---|---|---|---|---|---|
| Couplings | $\mathrm{c}_f^{\rm V,\,A,\,S,\,P}$ | $\tilde{\mathrm{c}}_f^{\rm A,\,S,\,P}$ | $\tilde{\mathrm{c}}_f^{\rm V,\,A,\,S,\,P}$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

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

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

# SM predictions for hyperon decays with missing energy




∗ Lagrangian for $s \to d\nu\bar{\nu}$

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

$X_{t,c}$ 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

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

∗ Estimated BESIII sensitivity for branching fractions

HB Li, 1612.01775

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

★ $K \to \pi \not{E}$

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

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = (3.2^{+1.1}_{-0.7}) \times 10^{-11}$ 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.

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

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

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

  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 $\big($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 | $\mathrm{C}_f^{\mathrm{V}}, \mathrm{C}_f^{\mathrm{A}}, \mathrm{C}_f^{\mathrm{S}}, \mathrm{C}_f^{\mathrm{P}}$ | $\tilde{\mathbf{c}}_f^{\mathrm{A}}, \tilde{\mathbf{c}}_f^{\mathrm{S}}, \tilde{\mathbf{c}}_f^{\mathrm{P}}$ | $\tilde{\mathbf{c}}_f^{\mathrm{V}}, \tilde{\mathbf{c}}_f^{\mathrm{A}}, \tilde{\mathbf{c}}_f^{\mathrm{S}}, \tilde{\mathbf{c}}_f^{\mathrm{P}}$ |

$m_f > 0$

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

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

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

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

  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

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

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

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

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

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

This translates into

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

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

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

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

Estimated BESIII sensitivity for branching fractions — Li, 2017

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

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

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

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

- If NP contributes mainly via $\tilde{\mathbf{c}}_f^{\rm A,S,P}$ & $m_f$ 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.

Li, Su, JT, 1905.08759

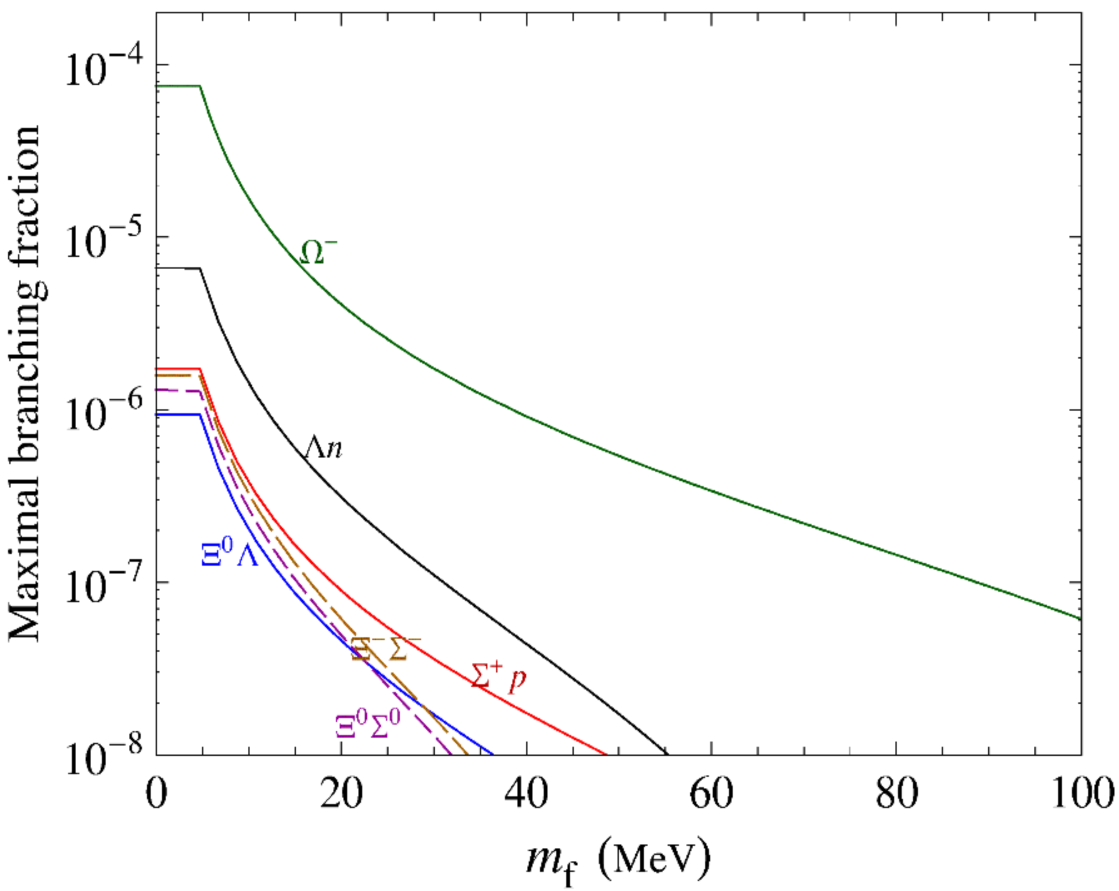



FIG. 2: The maximal branching fractions of $\mathfrak{B} \to \mathfrak{B}' f \bar{f}$ with $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$ and of $\Omega^- \to \Xi^- f \bar{f}$ versus $m_f$, induced by the contribution of $\mathrm{Re}\,\tilde{\mathbf{c}}_{\mathbf{f}}^{\mathbf{A}}$ 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.

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

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

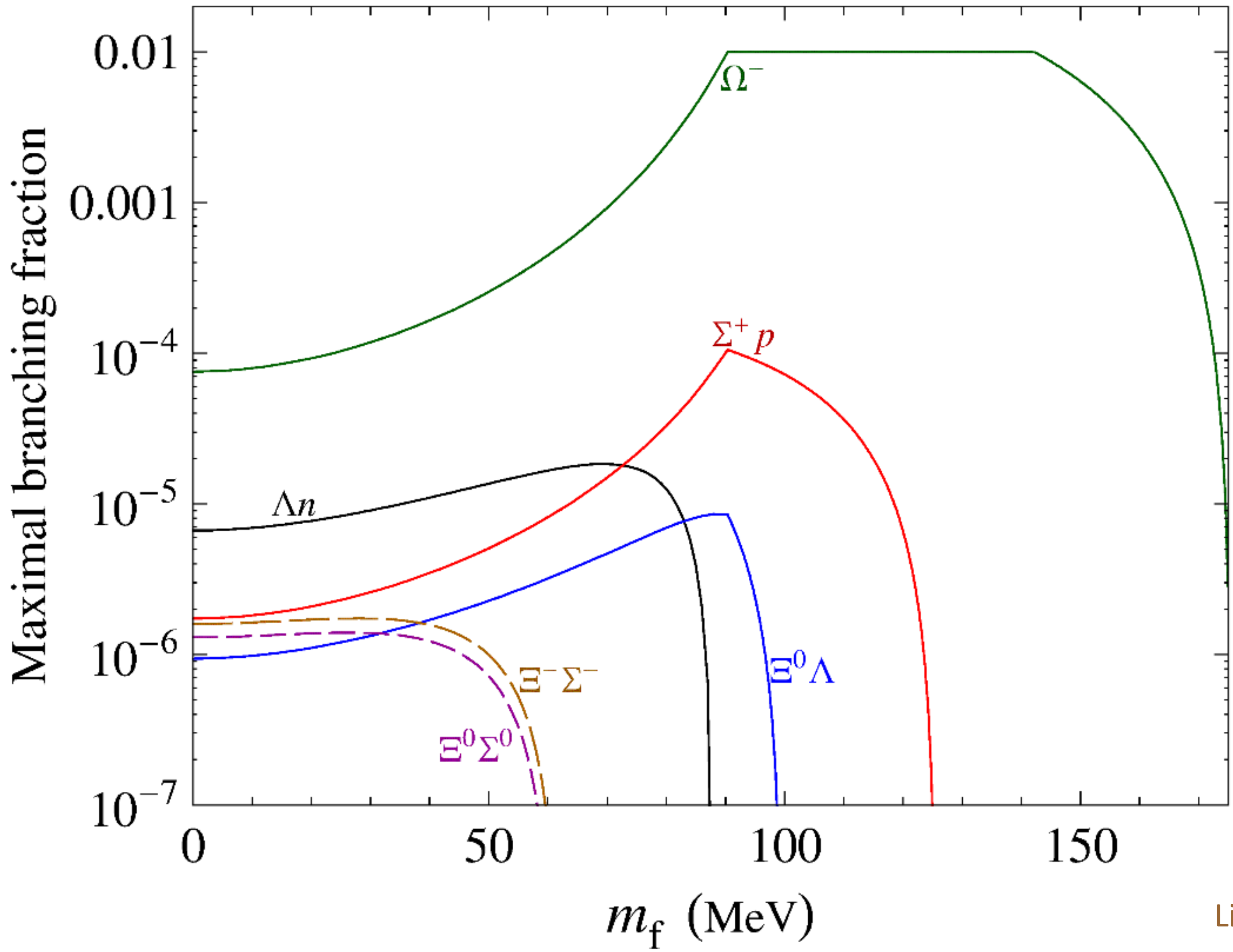
$m_f > 0$

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

- If instead only $\tilde{c}_f^{V}$ 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 $\tilde{c}_f^{V}$.
  - The size of $\tilde{c}_f^{V}$ cannot be too large & needs to be consistent with perturbativity and $\Omega^-$ data requirements.

Li, Su, JT, 1905.08759

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




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 $\mathrm{Re}\,\tilde{\mathbf{c}}_{\mathbf{f}}^{\mathbf{V}}$ alone, subject to the $K_L \to \pi^0 \pi^0 \not{E}$ constraint and the perturbativity and $\Omega^-$ data requirements for $m_f > 90$ MeV.

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

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

$\phi$ 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 $\mathbf{c}_\phi^{\rm V,A,S,P}$ 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 | $c_\phi^{\rm P}$ | $c_\phi^{\rm A}$, $c_\phi^{\rm P}$ | $\tilde c_f^{\rm A}$, $\tilde c_f^{\rm S}$, $\tilde c_f^{\rm P}$ | $\tilde c_f^{\rm V}$, $\tilde c_f^{\rm A}$, $\tilde c_f^{\rm S}$, $\tilde c_f^{\rm P}$ |

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 ($m_\phi > 0$)

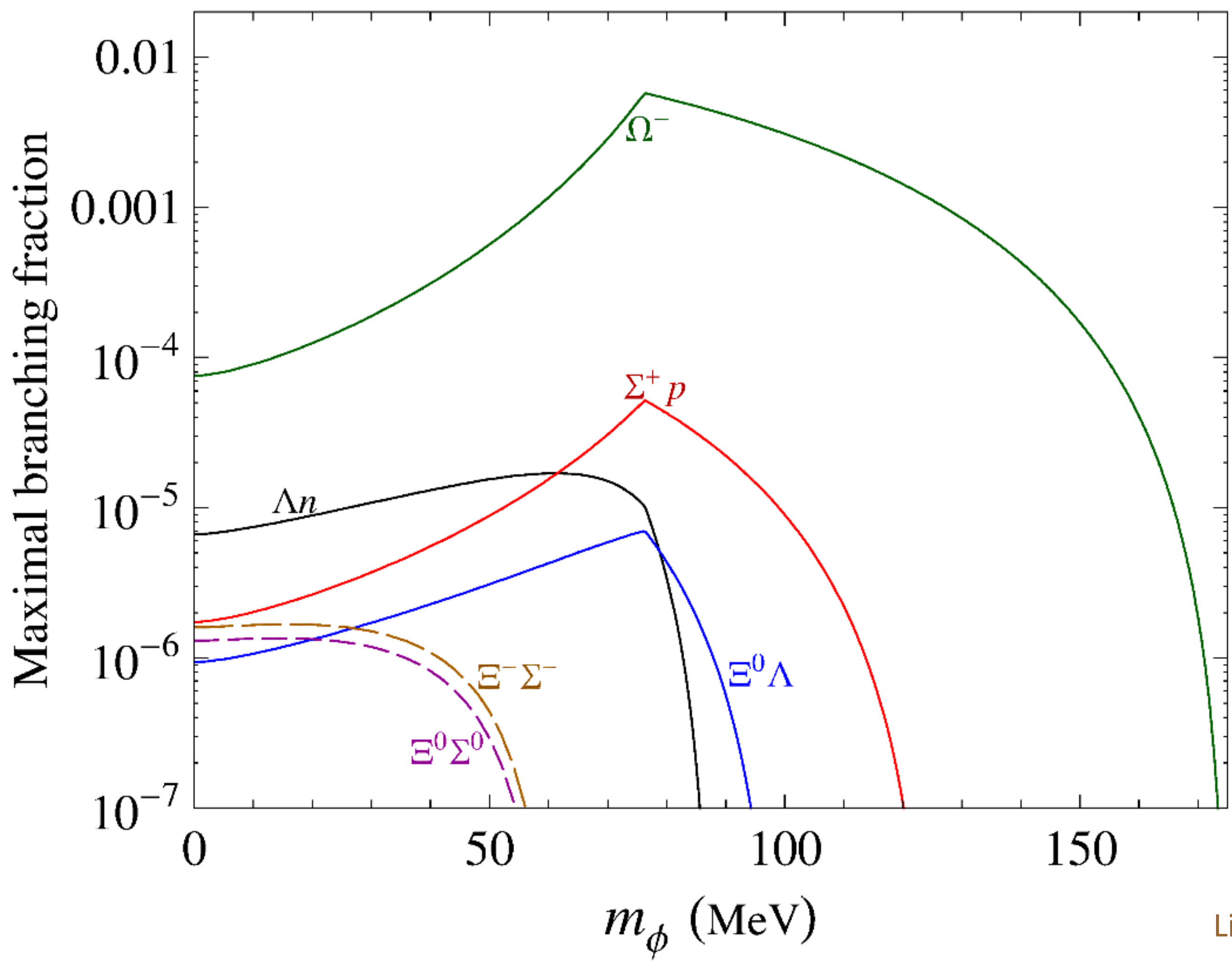



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FIG. 1: The maximal branching fractions of $\mathfrak{B} \to \mathfrak{B}'\phi\bar{\phi}$ with $\mathfrak{B}\mathfrak{B}' = \Lambda n, \Sigma^+ p, \Xi^0\Lambda, \Xi^0\Sigma^0, \Xi^-\Sigma^-$ and of $\Omega^- \to \Xi^-\phi\bar{\phi}$, indicated on the plot by the $\mathfrak{B}\mathfrak{B}'$ and $\Omega^-$ labels, respectively, versus $m_\phi$, 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.

- Introduction
- $\Sigma^+ \to p\mu^+\mu^-$ & $\Sigma^+ \to pe^+e^-$
- Lepton-flavor-violating hyperon decays
- Hyperon decays with missing energy
- Conclusions

- After a long hiatus, in the near future we can expect to see new results on rare hyperon decays from at least two ongoing major experiments.
- LHCb will likely produce improved data on $\Sigma^+ \to p\mu^+\mu^-$ soon and perhaps also a new finding on its muon forward-backward asymmetry. In addition, LHCb may eventually provide the first limit on CLFV in the hyperon sector.
- BESIII will hopefully supply the first results on rare hyperon decays with missing energy. Under certain conditions, the acquired data may test parts of the potential NP parameter space better than what present kaon data can offer.
- These efforts will yield long-awaited important information which will be complementary to that gained from kaon measurements.