Disentangling new physics in rare meson decays

Martin A. Mojahed
Johannes-Gutenberg Universität Mainz
Technische Universität München

Based on a work with
Andrzej J. Buras (TUM) and Julia Harz (JGU): 2405.06742

Introduction and Motivation

The rare processes $K \to \pi\nu\bar{\nu}$ and $B \to K(K^*)\nu\bar{\nu}$ belong to theoretically cleanest (FCNC) processes.

Still room between SM prediction and experimental measurements (experimental bounds):

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm exp} = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11},$$
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (8.60 \pm 0.42) \times 10^{-11},$$
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = (13 \pm 4) \times 10^{-6},$$
$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = (4.92 \pm 0.30) \times 10^{-6},$$

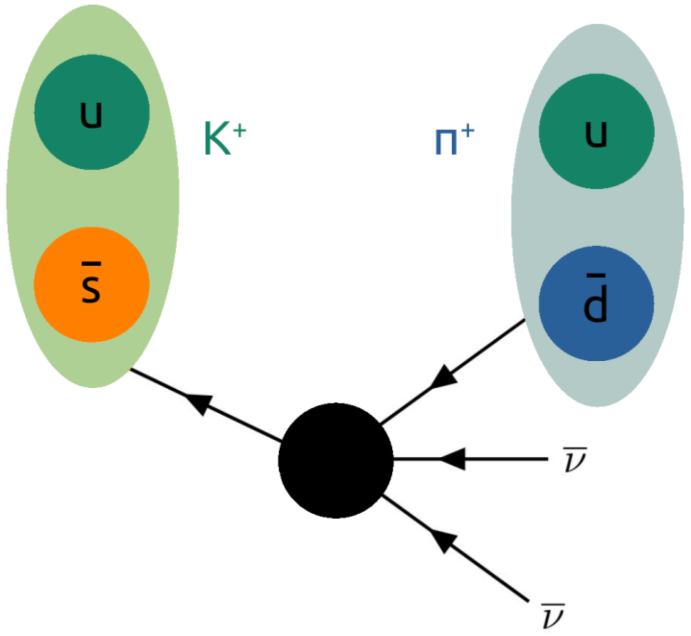
Good place to search for new physics, for example hints of lepton-number violation (LNV).

Overview I: Formalism

Parametrize new physics (NP) with effective operators:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{X=L,R} C_{\nu d}^{\text{VLX}} \mathcal{O}_{\nu d}^{\text{VLX}} + \left(\sum_{X=L,R} C_{\nu d}^{\text{SLX}} \mathcal{O}_{\nu d}^{\text{SLX}} + C_{\nu d}^{\text{TLL}} \mathcal{O}_{\nu d}^{\text{TLL}} + \text{h.c.} \right) ,$$

Unlike charged semileptonic decay, we cannot determine the nature of the final state neutrinos $(\nu\nu,\ \nu\bar{\nu},\ \bar{\nu}\bar{\nu})$.

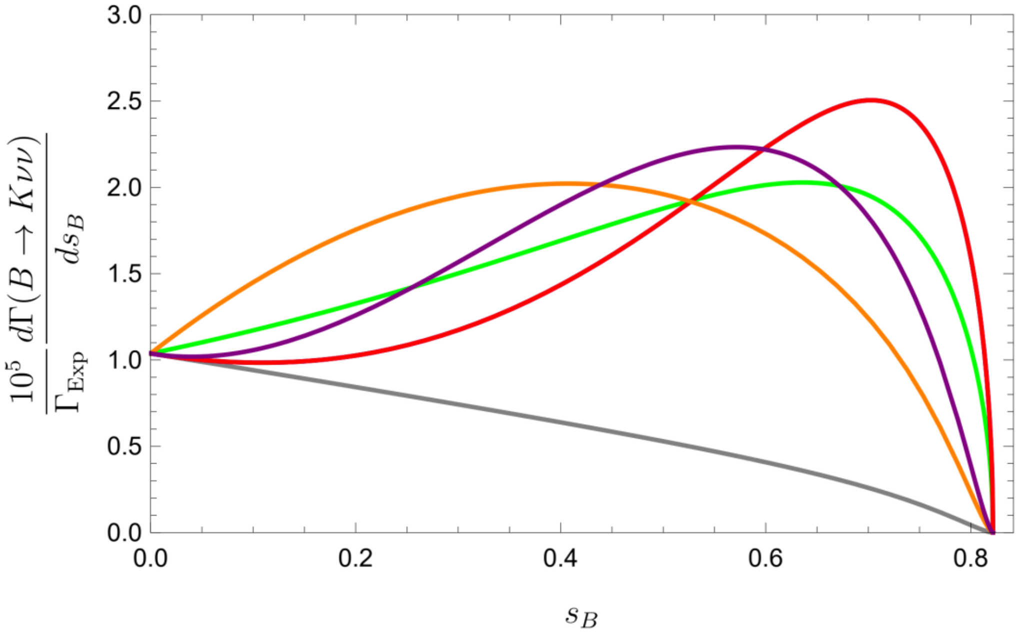


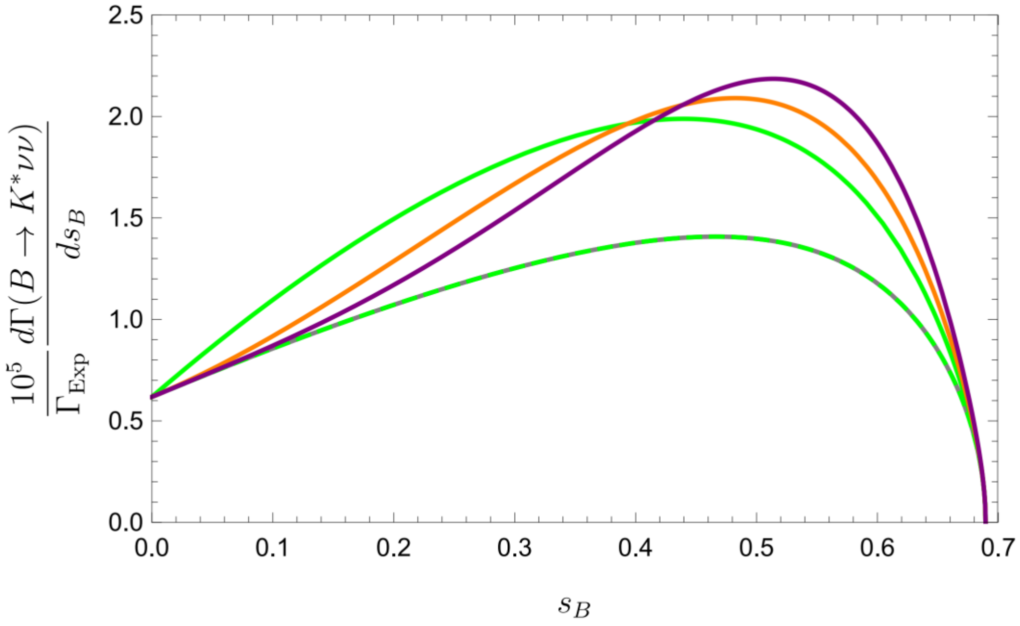
Measure missing invariant mass s, which leads to kinematic distributions $\frac{d\Gamma}{ds}$.

Overview II: The main idea in a nutshell

Observation: Different operators give rise to different kinematic distributions.

Idea: Analyze kinematic distribution to disentangle contributing operators.





LEFT setup:

Jenkins et. al. (2017)
Aebischer et. al. (2017)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{X=L,R} C_{\nu d}^{\rm VLX} \mathcal{O}_{\nu d}^{\rm VLX} + \left(\sum_{X=L,R} C_{\nu d}^{\rm SLX} \mathcal{O}_{\nu d}^{\rm SLX} + C_{\nu d}^{\rm TLL} \mathcal{O}_{\nu d}^{\rm TLL} + {\rm h.c.} \right),$$

$$\begin{aligned}
\mathcal{O}_{\nu d}^{\rm VLL} &= (\overline{\nu_L}\gamma^\mu \nu_L)(\overline{d_L}\gamma_\mu d_L)\ , \\
\mathcal{O}_{\nu d}^{\rm VLR} &= (\overline{\nu_L}\gamma^\mu \nu_L)(\overline{d_R}\gamma_\mu d_R)\ , \\
\mathcal{O}_{\nu d}^{\rm SLL} &= (\overline{\nu_L^c}\nu_L)(\overline{d_R} d_L)\ , \\
\mathcal{O}_{\nu d}^{\rm SLR} &= (\overline{\nu_L^c}\nu_L)(\overline{d_L} d_R)\ , \\
\mathcal{O}_{\nu d}^{\rm TLL} &= (\overline{\nu_L^c}\sigma_{\mu\nu}\nu_L)(\overline{d_R}\sigma^{\mu\nu} d_L)\ .
\end{aligned}$$

LNV

Example

$$\mathcal{D}^{\text{exp}}_{BK}(s) \equiv \frac{d\Gamma(B \to K\nu\widehat{\nu})}{ds}, \; \mathcal{D}^{\text{exp}}_{BK}(s) = C^{BK}_S f^{BK}_S(s) + C^{BK}_T f^{BK}_T(s) + C^{BK}_V f^{BK}_V(s),$$

$$C^{BK}_S = \sum_{\alpha\leq\beta}\left(1-\frac{1}{2}\delta_{\alpha\beta}\right)\left(\left|C^{\text{SLL}}_{\nu d,\alpha\beta bs} + C^{\text{SLR}}_{\nu d,\alpha\beta bs}\right|^2 + \left|C^{\text{SLL}}_{\nu d,\alpha\beta sb} + C^{\text{SLR}}_{\nu d,\alpha\beta sb}\right|^2\right),$$

$$C^{BK}_T = \sum_{\alpha<\beta}\left(\left|C^{\text{TLL}}_{\nu d,\alpha\beta bs}\right|^2 + \left|C^{\text{TLL}}_{\nu d,\alpha\beta sb}\right|^2\right),$$

$$C^{BK}_V = \sum_{\alpha,\beta}\left(1-\frac{1}{2}\delta_{\alpha\beta}\right)\left|C^{\text{VLL}}_{\nu d,\alpha\beta sb} + C^{\text{VLR}}_{\nu d,\alpha\beta sb}\right|^2,$$

$$C^{BK}_S = \frac{D^{\text{exp}}_{BK}(s_1)\left[f^{BK}_V(s_2)f^{BK}_T(s_3) - f^{BK}_V(s_3)f^{BK}_T(s_2)\right] + \text{cyclic}}{f^{BK}_S(s_1)\left[f^{BK}_V(s_2)f^{BK}_T(s_3) - f^{BK}_V(s_3)f^{BK}_T(s_2)\right] + \text{cyclic}},$$

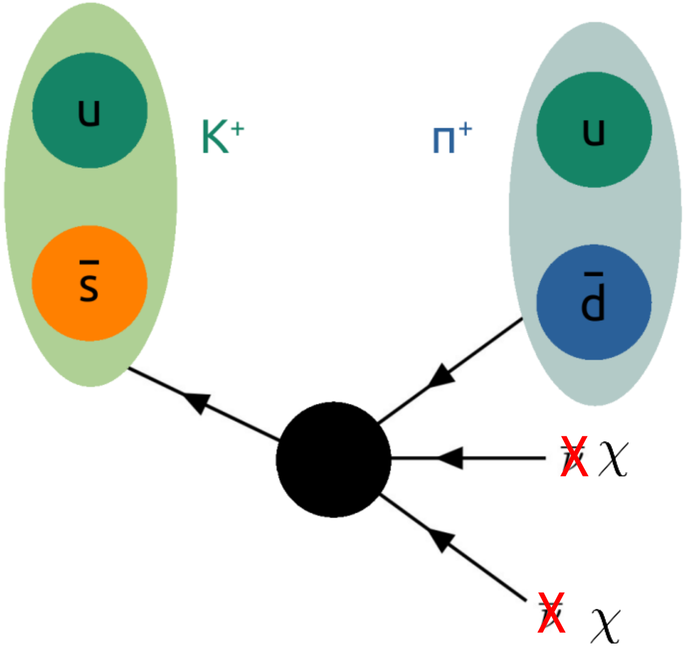
$$C^{BK}_V = \frac{D^{\text{exp}}_{BK}(s_1)\left[f^{BK}_S(s_2)f^{BK}_T(s_3) - f^{BK}_S(s_3)f^{BK}_T(s_2)\right] + \text{cyclic}}{f^{BK}_V(s_1)\left[f^{BK}_S(s_2)f^{BK}_T(s_3) - f^{BK}_S(s_3)f^{BK}_T(s_2)\right] + \text{cyclic}},$$

$$C^{BK}_T = \frac{D^{\text{exp}}_{BK}(s_1)\left[f^{BK}_S(s_2)f^{BK}_V(s_3) - f^{BK}_S(s_3)f^{BK}_V(s_2)\right] + \text{cyclic}}{f^{BK}_T(s_1)\left[f^{BK}_S(s_2)f^{BK}_V(s_3) - f^{BK}_S(s_3)f^{BK}_V(s_2)\right] + \text{cyclic}}.$$

A Loophole

The final state neutrinos are not detected:

What if the invisible part of the final state is not a pair of neutrinos?

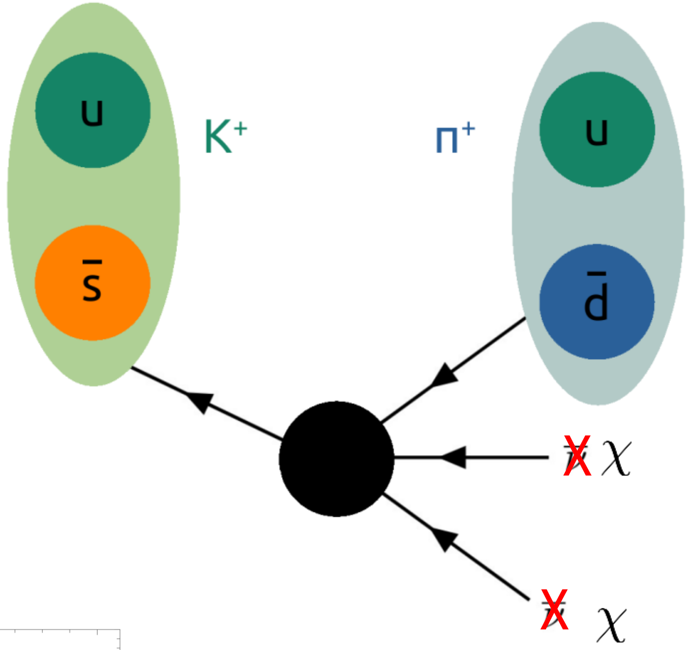


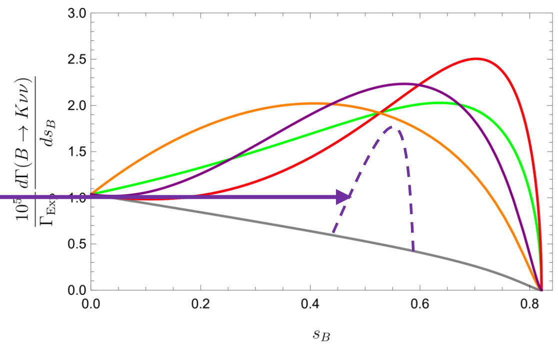
Dark final state particles

Since neutrinos not detected, the invisible final state could e.g. be two dark sector particles $\chi\chi$.

We have taken into account the possibility of having two final state dark particles with spin 0, spin ½ and spin 1.

Note: A single invisible boson would lead to kinematic distributions with a single bump.





Defining "kinematic structure"

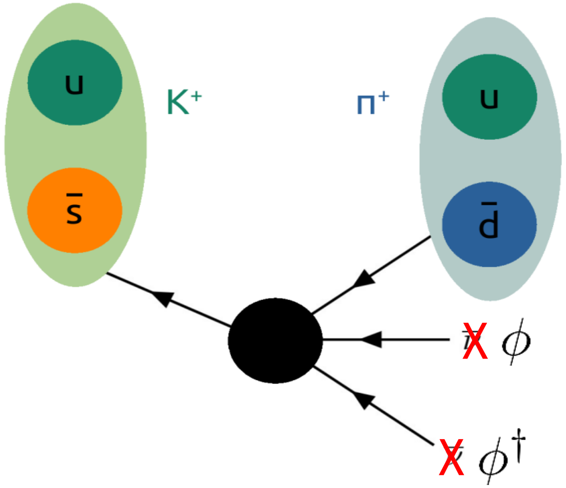
Operator: $\mathcal{O}^{S}_{ab\phi} = (\overline{q_a} q_b)(\phi^\dagger \phi)$

Contribution to decay rate: $$\frac{d\Gamma(K^+ \to \pi^+ + \text{inv})}{ds} = \frac{B_+^2}{256\pi^3 m_{K^+}^3} \lambda^{1/2}(m_{K^+}^2, m_{\pi^+}^2, s) \left| f_0^{K^+}(s) \right|^2 \left| C^S_{ds\phi} \right|^2$$

No dependence on s. → $\frac{B_+^2}{256\pi^3 m_{K^+}^3}$

Kinematic structure. → $\lambda^{1/2}(m_{K^+}^2, m_{\pi^+}^2, s) \left| f_0^{K^+}(s) \right|^2$

Wilson coefficient. → $\left| C^S_{ds\phi} \right|^2$



Going beyond LEFT: Dark LEFT

Aebischer et. al. (2022)
He et. al. (2022)
Buras, Harz, MAM (2024)

Type	Operator	Kinematic structure in $K \to \pi + \not{E}$
(SM)LEFT	$\mathcal{O}_{\nu d}^{\rm SLL}, \mathcal{O}_{\nu d}^{\rm SLR}$	$s\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{\nu d}^{\rm VLL}, \mathcal{O}_{\nu d}^{\rm VLR}$	$\lambda^{3/2}\,\lvert f_+^K\rvert^2$
	$\mathcal{O}_{\nu d}^{\rm TLL}$	$s\,\lambda^{3/2}\,\lvert f_T^K\rvert^2$
Scalar DM	$\mathcal{O}_{sd\phi}^{S}$	$\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sd\phi}^{V}$	$\lambda^{3/2}\,\lvert f_+^K\rvert^2$
Fermion DM	$\mathcal{O}_{sd\chi1}^{S}, \mathcal{O}_{sd\chi2}^{S}$	$s\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sd\chi1}^{V}, \mathcal{O}_{sd\chi2}^{V}$	$\lambda^{3/2}\,\lvert f_+^K\rvert^2$
	$\mathcal{O}_{sd\chi1}^{T}, \mathcal{O}_{sd\chi2}^{T}$	$s\,\lambda^{3/2}\,\lvert f_T^K\rvert^2$
Vector DM: A	$\mathcal{O}_{sdA}^{S}$	$s^2\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sdA2}^{V}$	$s^2\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sdA3}^{V}, \mathcal{O}_{sdA6}^{V}$	$s\,\lambda^{3/2}\,\lvert f_+^K\rvert^2$
	$\mathcal{O}_{sdA4}^{V}, \mathcal{O}_{sdA5}^{V}$	$s^2\,\lambda^{3/2}\,\lvert f_+^K\rvert^2$
	$\mathcal{O}_{sdA1}^{T}$	$s^2\,\lambda^{3/2}\,\lvert f_T^K\rvert^2$
Vector DM: B	$\mathcal{O}_{sdB1}^{S}, \mathcal{O}_{sdB2}^{S}$	$s^2\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sdB1}^{T}, \mathcal{O}_{sdB2}^{T}$	$s^2\,\lambda^{3/2}\,\lvert f_T^K\rvert^2$

Type	Operator	Kinematic structure in $B \to K^* + \not{E}$
(SM)LEFT	$\mathcal{O}_{\nu d}^{\rm SLL}, \mathcal{O}_{\nu d}^{\rm SLR}$	$s\lambda^{3/2}\lvert A_0\rvert^2$
	$\mathcal{O}_{\nu d}^{\rm VLL}, \mathcal{O}_{\nu d}^{\rm VLR}$	$\lambda^{1/2}\Big[\frac{s\lambda}{(m_B+m_{K^*})^2}\lvert V_0\rvert^2 + s(m_B+m_{K^*})^2\lvert A_1\rvert^2 + 32m_B^2m_{K^*}^2\lvert A_{12}\rvert^2\Big]$
	$\mathcal{O}_{\nu d}^{\rm TLL}$	$\lambda^{1/2}\Big[\lambda\lvert T_1\rvert^2 + (m_B^2-m_{K^*}^2)^2\lvert T_2\rvert^2 + \frac{8m_B^2m_{K^*}^2 s}{(m_B+m_{K^*})^2}\lvert T_{23}\rvert^2\Big]$
Scalar DM	$\mathcal{O}_{sb\phi}^{P}$	$\lambda^{3/2}\lvert A_0\rvert^2$
	$\mathcal{O}_{sb\phi}^{A}$	$\lambda^{1/2}\Big[s(m_B+m_{K^*})^2\lvert A_1\rvert^2 + 32m_B^2m_{K^*}^2\lvert A_{12}\rvert^2\Big]$
	$\mathcal{O}_{sb\phi}^{V}$	$s\lambda^{3/2}\lvert V_0\rvert^2$
Fermion DM	$\mathcal{O}_{sb\chi1}^{P}, \mathcal{O}_{sb\chi2}^{P}$	$s\lambda^{3/2}\lvert A_0\rvert^2$
	$\mathcal{O}_{sb\chi1}^{A}, \mathcal{O}_{sb\chi2}^{A}$	$\lambda^{1/2}\Big[s(m_B+m_{K^*})^2\lvert A_1\rvert^2 + 32m_B^2m_{K^*}^2\lvert A_{12}\rvert^2\Big]$
	$\mathcal{O}_{sb\chi1}^{V}, \mathcal{O}_{sb\chi2}^{V}$	$s\lambda^{3/2}\lvert V_0\rvert^2$
	$\mathcal{O}_{sb\chi1}^{T}, \mathcal{O}_{sb\chi2}^{T}$	$\lambda^{1/2}\Big[\lambda\lvert T_1\rvert^2 + (m_B^2-m_{K^*}^2)^2\lvert T_2\rvert^2 + \frac{8m_B^2m_{K^*}^2 s}{(m_B+m_{K^*})^2}\lvert T_{23}\rvert^2\Big]$
Vector DM: A	$\mathcal{O}_{sbA}^{P}$	$s^2\lambda^{3/2}\lvert A_0\rvert^2$
	$\mathcal{O}_{sbA1}^{T}$	$s\lambda^{3/2}\lvert T_1\rvert^2$
	$\mathcal{O}_{sbA2}^{T}$	$s\lambda^{1/2}\Big[(m_B^2-m_{K^*}^2)^2\lvert T_2\rvert^2 + \frac{8m_B^2m_{K^*}^2 s}{(m_B+m_{K^*})^2}\lvert T_{23}\rvert^2\Big]$
	$\mathcal{O}_{sbA3}^{V}, \mathcal{O}_{sbA6}^{V}$	$s^2\lambda^{3/2}\lvert V_0\rvert^2$
	$\mathcal{O}_{sbA4}^{V}, \mathcal{O}_{sbA5}^{V}$	$s^3\lambda^{3/2}\lvert V_0\rvert^2$
	$\mathcal{O}_{sbA2}^{A}$	$s^2\lambda^{3/2}\lvert A_0\rvert^2$
	$\mathcal{O}_{sbA3}^{A}, \mathcal{O}_{sbA6}^{A}$	$s\lambda^{1/2}\Big[s(m_B+m_{K^*})^2\lvert A_1\rvert^2 + 32m_B^2m_{K^*}^2\lvert A_{12}\rvert^2\Big]$
	$\mathcal{O}_{sbA4}^{A}, \mathcal{O}_{sbA5}^{A}$	$s^2\lambda^{1/2}\Big[s(m_B+m_{K^*})^2\lvert A_1\rvert^2 + 32m_B^2m_{K^*}^2\lvert A_{12}\rvert^2\Big]$
Vector DM: B	$\mathcal{O}_{sbB1}^{P}, \mathcal{O}_{sbB2}^{P}$	$s^2\lambda^{3/2}\lvert A_0\rvert^2$
	$\mathcal{O}_{sbB1}^{T}, \mathcal{O}_{sbB2}^{T}$	$s\lambda^{1/2}\Big[\lambda\lvert T_1\rvert^2 + (m_B^2-m_{K^*}^2)^2\lvert T_2\rvert^2 + \frac{8m_B^2m_{K^*}^2 s}{(m_B+m_{K^*})^2}\lvert T_{23}\rvert^2\Big]$

Implications of an observation of LNV in rare meson decays

What we could learn from observation of NP in rare meson decays.

Question:

Imagine one would find that a lepton-number violating (LNV) operator is contributing to rare meson decays.

What would be the ramifications for

1) UV physics?
2) Leptogenesis (LG)?

LNV in rare meson decays

As an example, we consider the following SMEFT operator:

$$\mathcal{O}_{\bar{d}LQLH1} = \epsilon_{ij}\epsilon_{mn}\left(\bar{d}L^i\right)\left(\overline{Q^{Cj}}L^m\right)H^n .$$

This operator generates scalar and tensor currents in LEFT.

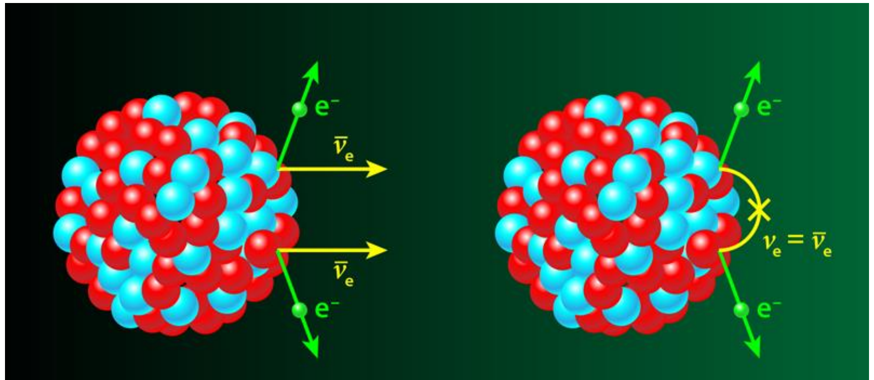
Lower bound on the associated new physics (NP) scale from Belle II: $\Lambda_{\rm NP} \approx 3.0\,\mathrm{TeV}$.

1) UV physics (I)

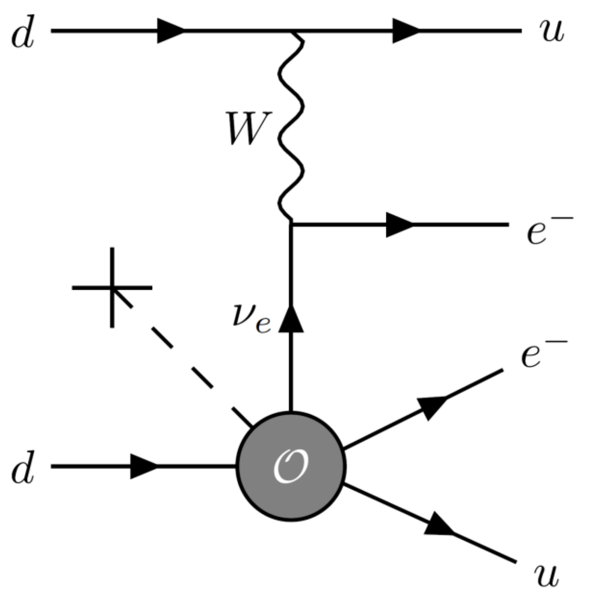
LNV operators are tightly constrained by non-observation of neutrinoless double beta decay.

Radiative corrections to neutrinoless double beta decay leads to the following lower bound on the NP scale:

$$\Lambda_{\rm NP} \approx 242\,\mathrm{TeV}.$$



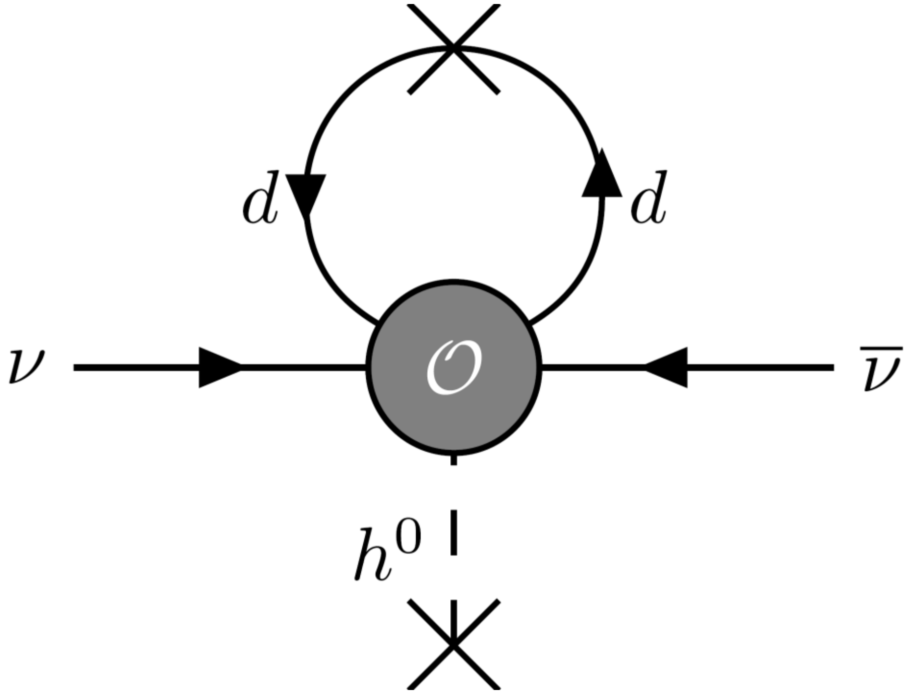
APS/Alan Stonebraker, taken from https://physics.aps.org/articles/v16/13



1) UV physics (II)

Higher-dimensional LNV operators give radiative contributions to a Majorana neutrino mass,

$$\delta m_\nu \approx \frac{y_d v^2}{16\pi^2 \Lambda_{\rm NP}}.$$

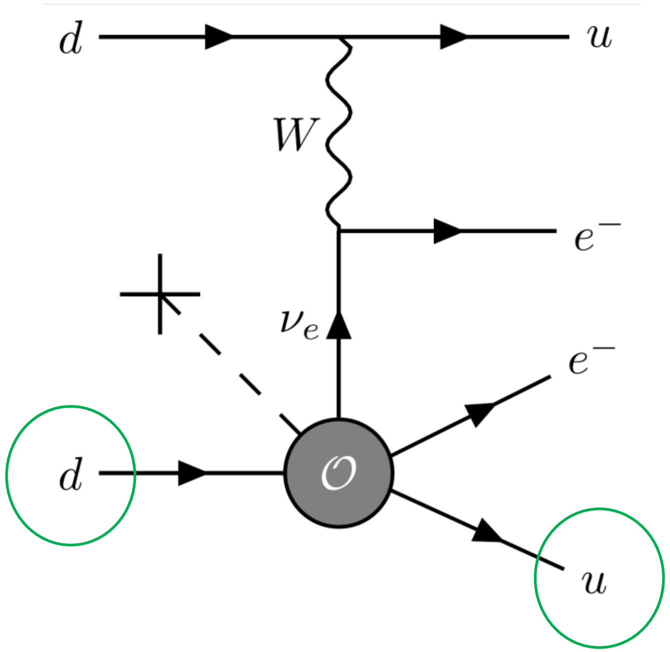


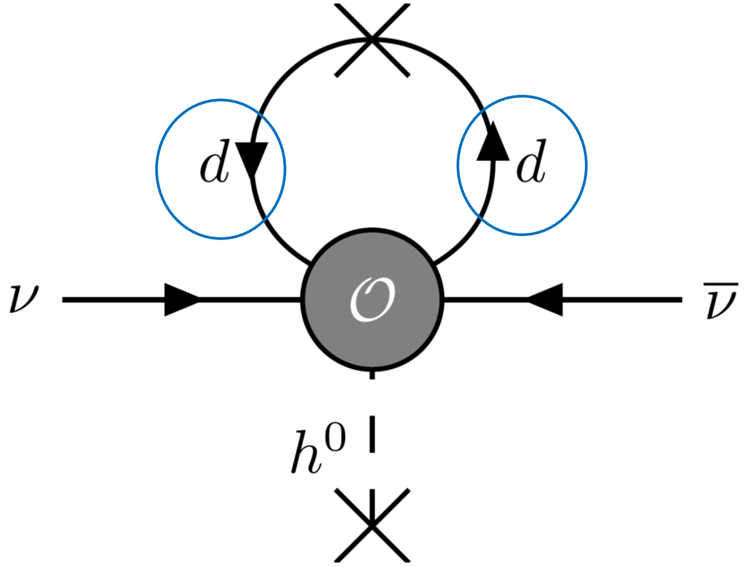
Requiring this contribution to not exceed 0.1 eV yields a lower limit on the NP scale

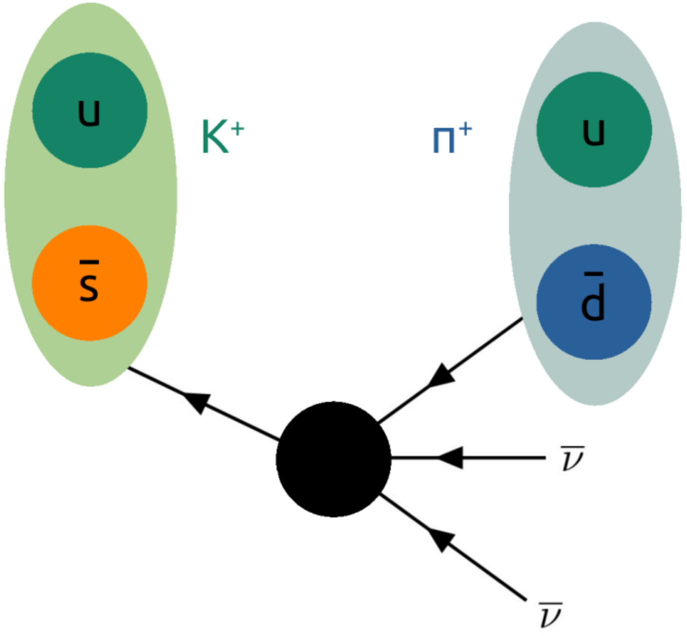
$$\Lambda_{\rm NP} \approx 5 \cdot 10^4 \ \text{TeV} \ (10^9 \,\text{GeV})$$

for the first (second) generation down-type quark Yukawa coupling.

1) UV physics (III)



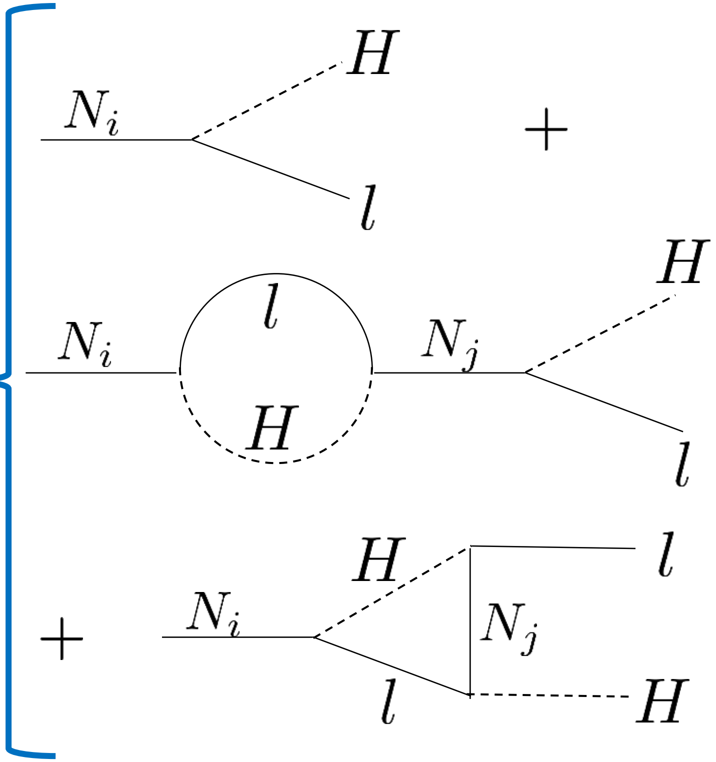




Conclusion: Flavor non-democratic UV physics.

2) Leptogenesis

Leptogenesis denotes a class of scenarios for baryogenesis where a lepton asymmetry is generated via CP-violating decays of right-handed neutrinos.

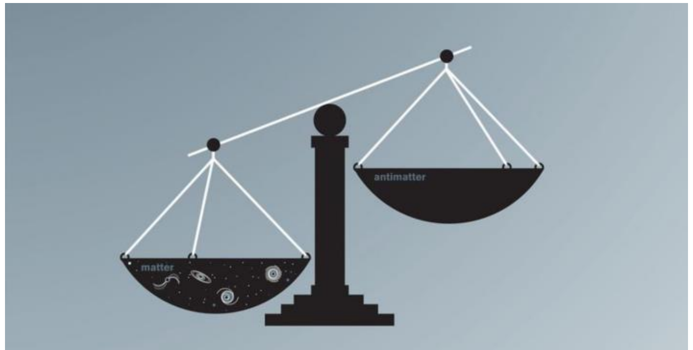


Sphalerons: Lepton asymmetry → baryon asymmetry.

LNV operator: Contributes to diminishing the generated lepton asymmetry.

Highly efficient in the low TEV range down to the electroweak scale.

Observation of LNV in rare meson decays → High-scale LG under tension!

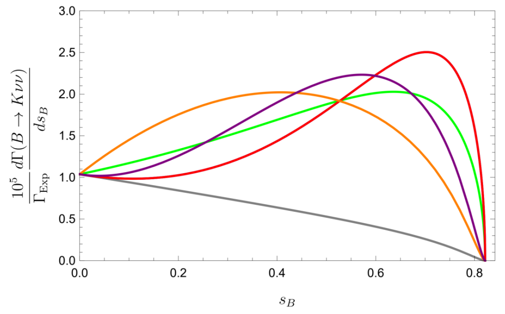


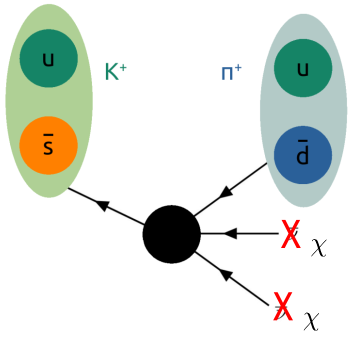
Credit: Symmetry Magazine/ Sandbox Studio, Chicago

Summary

- We considered strategies to disentangle NP in the processes $K \to \pi\nu\overline{\nu}$ and $B \to K(K^*)\nu\overline{\nu}$ using kinematic distributions (and beyond).
- It is very often possible to disentangle LEFT operators from two dark scalars or two dark vectors by analyzing kinematic distributions.
- We discussed implications of an observation of LNV NP in rare meson decays.

Take home message: By analyzing kinematic distributions of the rare processes $K \to \pi\nu\overline{\nu}$ and $B \to K(K^*)\nu\overline{\nu}$: Disentangle effective operator origin of NP → Search for e.g. LNV.





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Scalar DM	$\mathcal{O}_{sd\phi}^{S}$	$\lambda^{1/2}\,\lvert f_0^K\rvert^2$
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	$\mathcal{O}_{sd\chi1}^{V}, \mathcal{O}_{sd\chi2}^{V}$	$\lambda^{3/2}\,\lvert f_+^K\rvert^2$
	$\mathcal{O}_{sd\chi1}^{T}, \mathcal{O}_{sd\chi2}^{T}$	$s\,\lambda^{3/2}\,\lvert f_T^K\rvert^2$
Vector DM: A	$\mathcal{O}_{sdA}^{S}$	$s^2\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sdA2}^{V}$	$s^2\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sdA3}^{V}, \mathcal{O}_{sdA6}^{V}$	$s\,\lambda^{3/2}\,\lvert f_+^K\rvert^2$
	$\mathcal{O}_{sdA4}^{V}, \mathcal{O}_{sdA5}^{V}$	$s^2\,\lambda^{3/2}\,\lvert f_+^K\rvert^2$
	$\mathcal{O}_{sdA1}^{T}$	$s^2\,\lambda^{3/2}\,\lvert f_T^K\rvert^2$
Vector DM: B	$\mathcal{O}_{sdB1}^{S}, \mathcal{O}_{sdB2}^{S}$	$s^2\,\lambda^{1/2}\,\lvert f_0^K\rvert^2$
	$\mathcal{O}_{sdB1}^{T}, \mathcal{O}_{sdB2}^{T}$	$s^2\,\lambda^{3/2}\,\lvert f_T^K\rvert^2$

Thank you for your attention!