# Constraining lepton number violating interactions with rare meson decays

## Based on Frank F. Deppisch, KF, Julia Harz, arXiv:2009.04494, JHEP 12 (2020) 186


Kåre Fridell
Technical University of Munich
kare.fridell@tum.de


## Introduction

- The nature of neutrinos, and especially the origin of their masses, is one of the biggest mysteries in particle physics.
- Incorporating Dirac masses for neutrinos leads to the theoretical issue that the corresponding Yukawa coupling are very small (order $10^{-12}$).
- Another possibility is that right-handed neutrinos have a Majorana mass, where the mass term violates lepton number by two units.
- Lepton number violation (LNV) is also connected to the baryon asymmetry of the Universe (BAU): it could be possible that heavy right-handed neutrinos generate this asymmetry via LNV decays (leptogenesis).
- Lepton number and baryon number are related in the early Universe via rapid sphaleron processes, therefore violation of *lepton number* can create an asymmetry in *baryon number*.
- On the other hand, the LNV mass term can also act to *reduce* the baryon asymmetry (washout), rather than *create* it, depending on the details of the process. This limits the viability of high-scale leptogenesis.
- Therefore, finding LNV in experiments has consequences both for neutrino masses and the BAU.

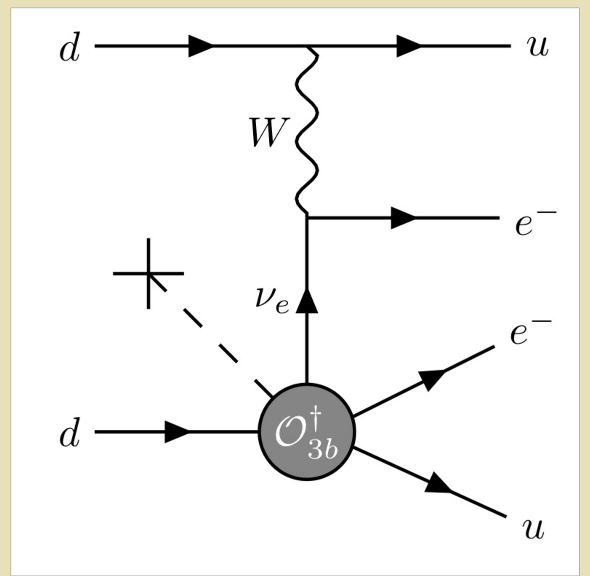
Deppisch et al (2015), Deppisch et al (2018)

## Searches for lepton number violation

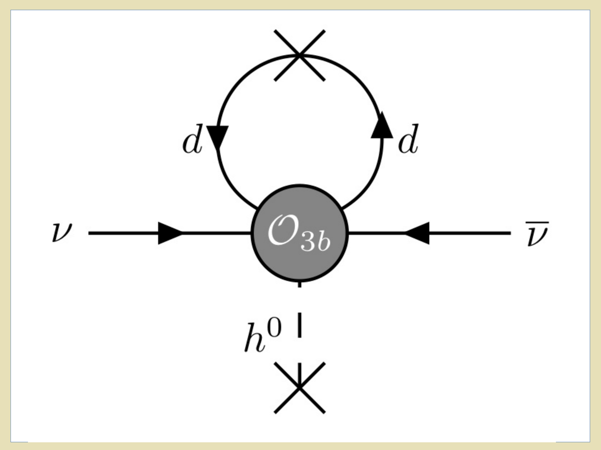
- The most sensitive probe of LNV is neutrinoless double beta decay (0νββ), the half-life of 0νββ is constrained to $T_{1/2} > 10^{26}$ years in Xenon.
- In 0νββ, two nuclei beta decay simultaneously, without generating any neutrinos (as the name suggests), therefore, since two electrons are produced, the whole process is LNV by two units.
- However, 0νββ only constrains LNV for first generation leptons and quarks. In principle, LNV could arise in the second or third generation without inducing 0νββ at tree-level.
- For flavoured LNV, experimental probes include $\mu^-$ to $e^+$ converion in nuclei, and meson decays.
- LNV can manifest in decays of mesons into two same-sign charged leptons, one charged lepton and one neutrino, or two neutrinos, with the additional possibility of a lighter meson in the final state.
- Depending on the initial (and possibly also final) meson, a different quark flavour structure of LNV is probed.
- Depending on the final state leptons, a different lepton flavour structure is being probed, where neutrinos have undetermined flavour experimentally.

KamLAND-Zen Collaboration (2016)
Littenberg, Shrock (1991)
Li, Ma, Schmidt (2019)

Neutrinoless double beta decay diagram for the operator $\mathcal{O}_{3b}$.



Neutrino mass diagram for the operator $\mathcal{O}_{3b}$.

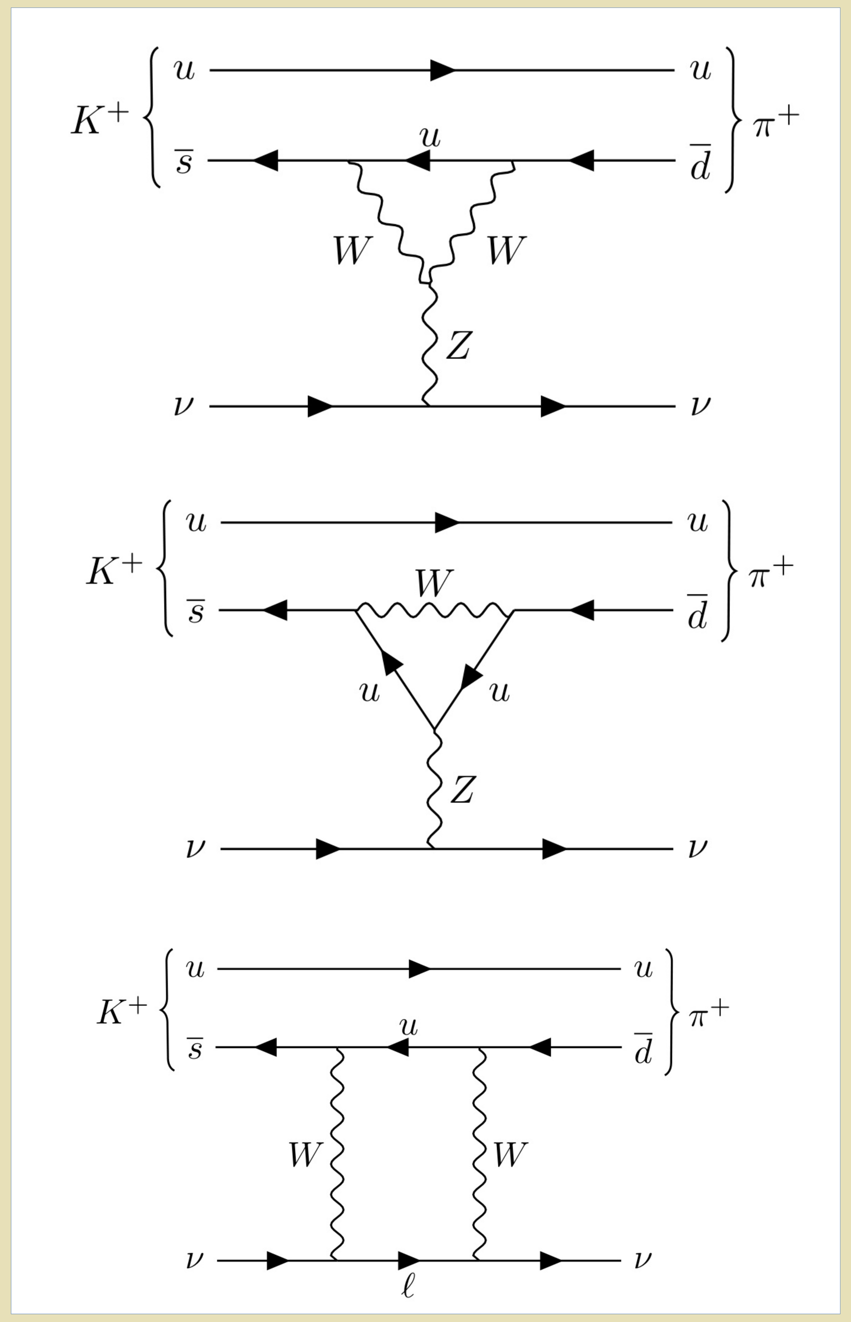


## Rare kaon decays in the SM

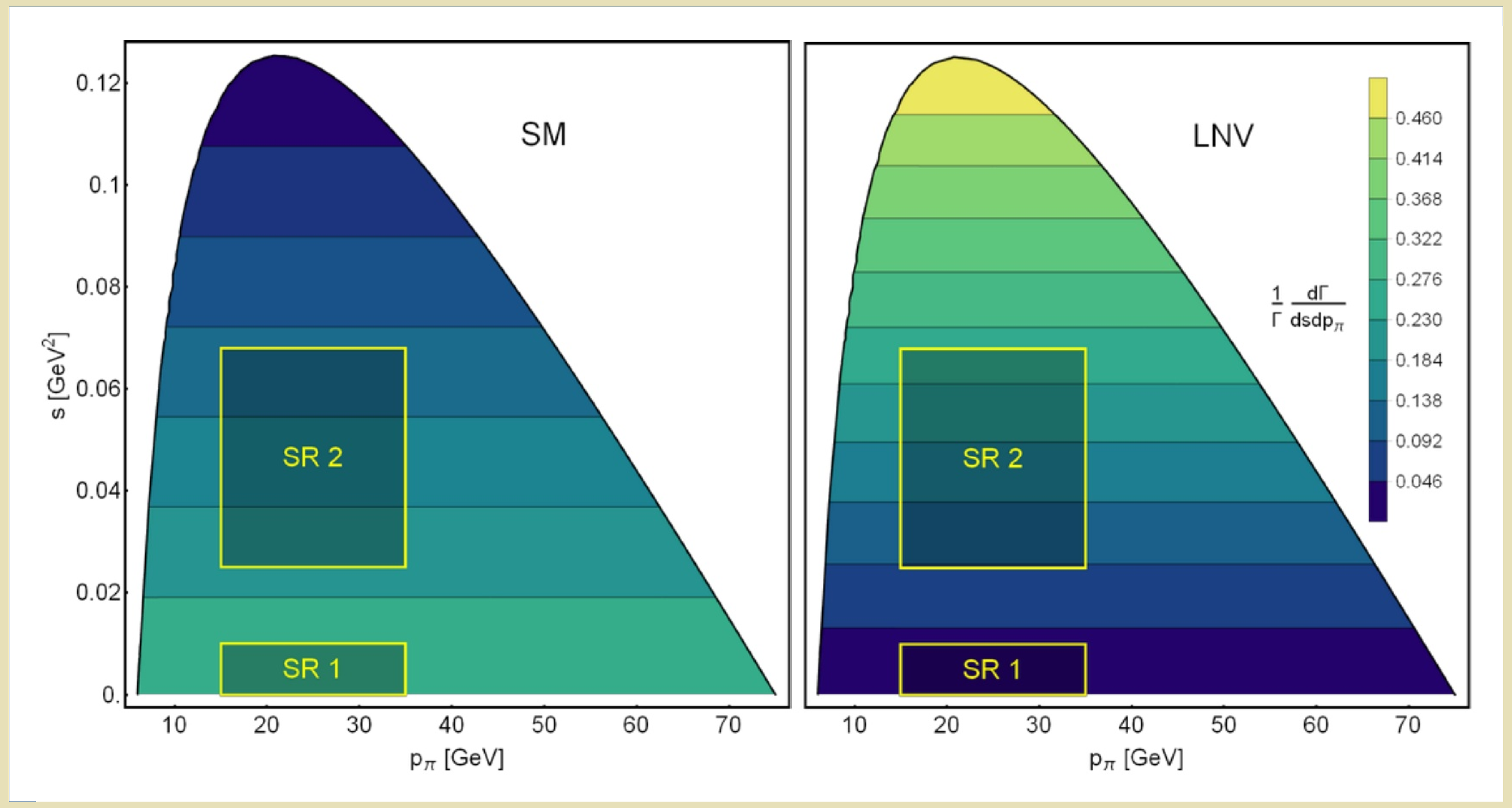
- The rare decay of a kaon into a pion and two neutrinos, K→ πνν, is a theoretically very clean process.
- It occurs in the SM through 1-loop electroweak penguin and box diagrams (see diagrams to the right).
- The branching ratio is very small due to GIM suppression, and it can be calculated to a high degree of accuracy due to a relation to the more rapid decays $K^+\to \pi^0 e^+\nu$ and $K_L\to \pi^- e^+\nu$.
- Stringent experimental constraints have been produced for the neutral decay mode $K_L\to \pi^0\nu\nu$ in the KOTO experiment at J-PARC and for the charged decay mode $K^+\to \pi^+\nu\nu$ in the NA62 experiment at CERN (and also in the past at the E949 experiment at BNL).
- The charged and neutral modes are related via the Grossman-Nir bound $BR(K_L\to \pi^0\nu\nu) < 4.4 BR(K^+\to \pi^+\nu\nu)$.
- The theoretical and experimental contraints are:

$$\text{Theory: } BR(K^+\to\pi^+\nu\bar\nu)_{SM} = (8.4\pm1.0)\times10^{-11}$$
$$\text{Theory: } BR(K_L\to\pi^0\nu\bar\nu)_{SM} = (3.4\pm0.6)\times10^{-11}$$
$$\text{Experiment: } BR(K^+\to\pi^+\nu\bar\nu)_{NA62} = (10.6^{+4.0}_{-4.3})\times10^{-11}, \quad \text{at 68 \% CL}$$
$$\text{Experiment: } BR(K_L\to\pi^0\nu\bar\nu)_{KOTO} < 4.9\times10^{-9}, \quad \text{at 90\% CL}$$

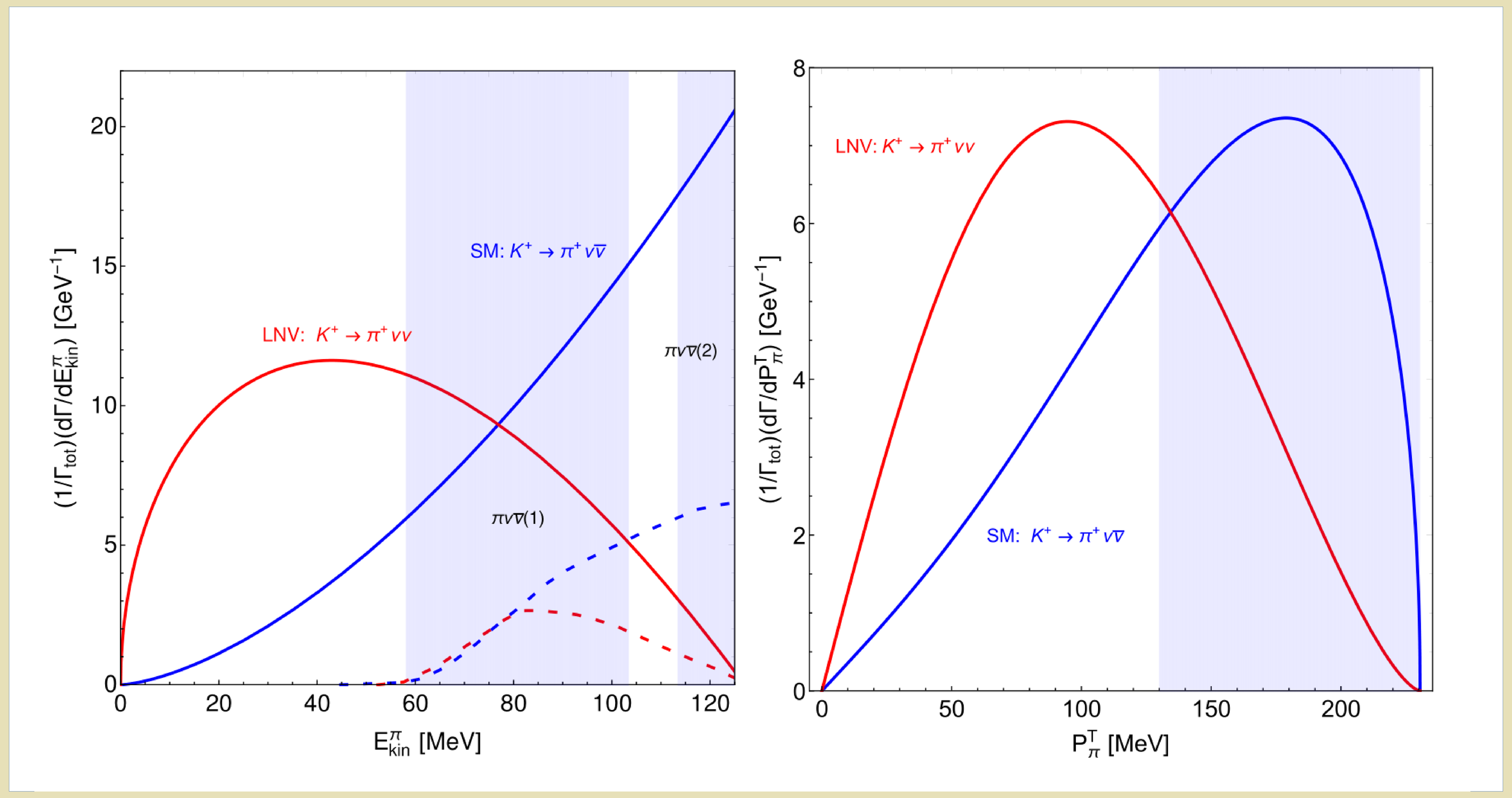
Buras et al (2015), NA62 Collaboration (2021), KOTO collaboration (2020)



Diagrams for the rare kaon decay in the SM

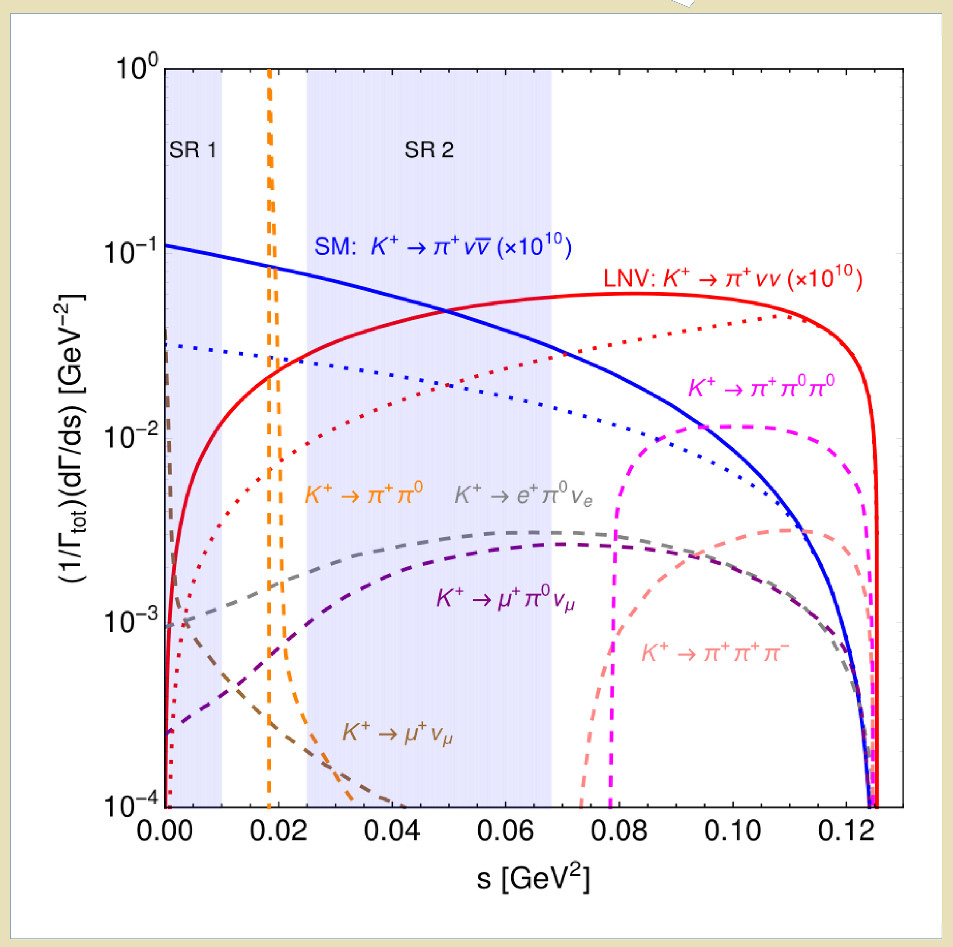



Distribution of events in the pion momentum-squared missing energy (s) plane for the LNV BSM rare kaon decay as well as the SM decay. Yellow colors indicate many events and blue colors indicate few events. In shaded boxes, the two signal regions of the NA62 experiments are shown.




Distribution of events at the E949 experiment with respect to the pion kinetic energy (left) and the KOTO experiment with respect to the pion transverse momentum (right).

Distribution of events at the NA62 experiment. Here it can be seen that the LNV and SM modes have a different distribution in the pion momentum, which could tell apart LNV from the expected SM mode.




## Rare kaon decays beyond the SM

- To study LNV in rare meson decays, it is convenient to use the Standard Model effective field theory (SMEFT).
- In SMEFT, operators that violate lepton number by two units have odd mass dimension D, with the lowest-dimensional one being the D=5 Weinberg operator.
- In a general sense (there are exceptions), the lower the dimension of an operator is, the more impactful an experimental limit on the Wilson coefficient is at constraining the scale of new physics.
- Charged LNV in meson decays require at least a D=9 operator, while the rare decay K→ πνν can be mediated by a D=7 operator denoted $\mathcal{O}_{3b}$.
- Whether the rare kaon decay is LNV depends on the nature of the neutrinos in the final state.
- If the final state consists of a neutrino + antineutrino pair (as in the SM), the decay is not LNV, and the process is described by a D=6 operator.
- If the final state consists of two neutrinos or two anti-neutrinos, the process is LNV, and the corresponding operator is D=7 (or even higher such as D=9, 11, ...).
- Experimentally the final state neutrinos are not observed, they are inferred from missing energy, and the LNV nature of the decay is not directly determined.

## Distinguishing LNV from LNC

- The SM D=6 operator, which is *not* LNV, gives rise to a vector current in rare kaon decays.
- A D=7 LNV operator would instead give rise to a scalar current.
- Since the neutrinos are not detected in meson decay experiments, the only observable particle in the final state of rare kaon decays is the pion.
- The distribution of momentum for the pion is indeed different for a scalar- or vector current.
- The pion momentum distribution difference can be seen as arising from the difference in how much energy is stored in the neutrinos depending on their helicities.
- If the neutrinos have the same helicity (LNV), their preferred direction is back-to-back, and if their have opposite helicities (*not* LNV) their preferred direction is parallel to each other. This can be thought of as related to conservation of angular momentum in the neutrino system: their spin vectors are opposite.
- The greater the opening angle between the neutrinos, the greater the missing energy is in the experiment, and the less momentum is left to the pion.
- Therefore, by carefully measuring the pion momentum distribution, the LNV nature can be constrained.

## Results & Conclusion

- Rare kaon decays constitute a good complementary search for LNV to other probes such as 0νββ decay or $\mu^-$ to $e^+$ conversion.
- We find that the experimental limits on rare kaon decays translate into limits on the LNV operator scale at order 20 TeV.
- This limit is stronger than that coming from other meson decays, but weaker than 0νββ decay. However, the flavour content of the rare kaon decay is different than that of 0νββ decay, making the limit stand out.
- If observed close to the current experimental sensitivity, LNV in rare kaon decays would imply a strong washout of lepton number down to almost the electroweak breaking scale.
- This would imply, in case of such a discovery, that high-scale leptogenesis is not possible in the conventional way.
- However, probing the pion momentum distribution in rare kaon decays would require many events, and is not within the scope of current experiments.
- We find that the rare kaon decay is a great probe of LNV that could shed light on both the neutrino mass as well as the origin on the matter-antimatter asymmetry

Rare kaon decay diagram for the operator $\mathcal{O}_{3b}$.