Implications of rare kaon decays on lepton number violating interactions

Kåre Fridell

Technische Universität München

kare.fridell@tum.de

In collaboration with

F. Deppisch, J. Harz

Based on

arXiv:2008.XXXXX

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Lepton number violation (LNV)

Neutrino masses are a clear sign of physics beyond the Standard Model (BSM)

Well motivated scenario: Majorana mass

$$\nu \equiv \nu^c$$

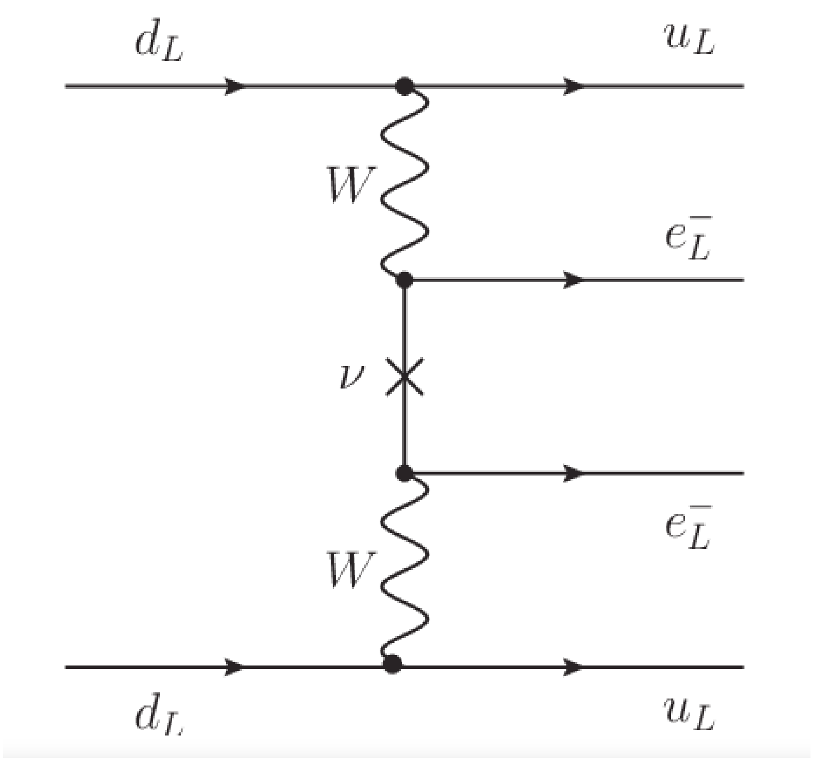
Neutrino Majorana mass implies lepton number violation (LNV)

Interesting wrt Leptogenesis

Neutrinoless double beta decay (0νββ):

+Most sensitive probe of LNV

-Only sensitive to electron flavor



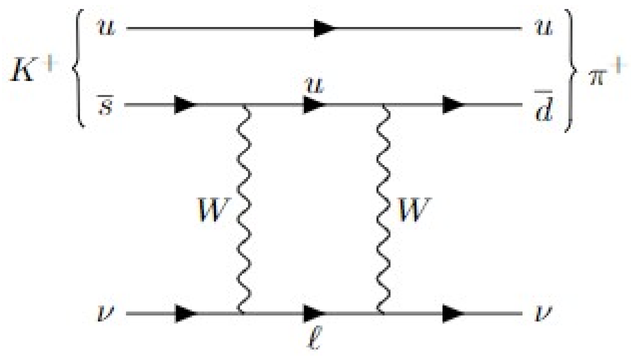
Any other place to look for LNV?

Rare kaon decays

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (8.4 \pm 1.0) \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (3.4 \pm 0.6) \times 10^{-11}$$

Buras et al, JHEP 2015



$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{NA62}} < 1.78 \times 10^{-10}, \quad \text{at } 90\% \text{ CL}$$

NA62 collaboration, arXiv:2007.08218

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} < 3.0 \times 10^{-9}, \quad \text{at } 90\% \text{ CL}$$

KOTO collaboration, Phys. Rev. Lett. (2019)

See also other talks @ ICHEP 2020

NA62 (Marchevski)
KOTO (Shimizu)

SM: Neutrino+anti-neutrino LNC

Consequence of LNV in K decays?

BSM: two neutrinos/anti-neutrinos LNV

Observable?

Beyond the Standard Model

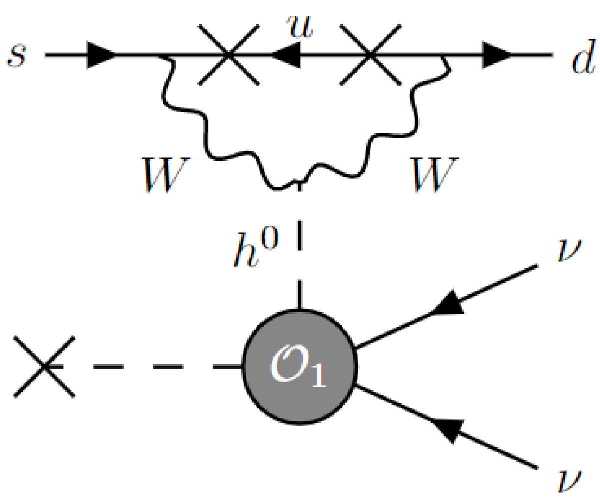
The SM decay is a lepton number conserving (LNC) dimension 6 process

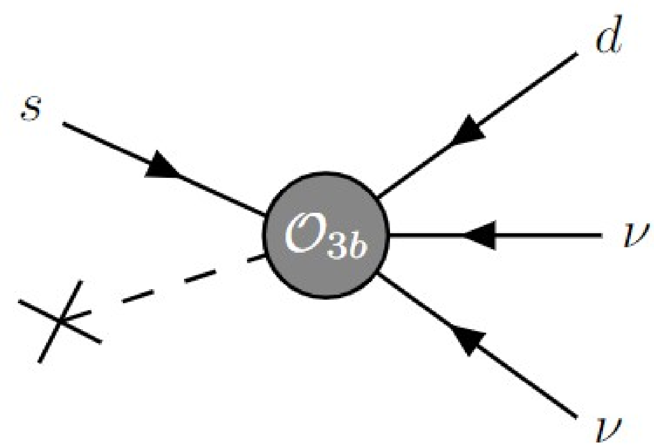
A BSM decay can be a LNV dimension 7 process

$$\mathcal{L}_{\rm EFT} = \sum_i C_i \mathcal{O}_i + \text{h.c.} \quad \text{Wilson coefficient: } C_i \propto \frac{1}{\Lambda^{(D-4)}}, \; \Lambda = \text{New Physics (NP) scale}$$

$$\mathcal{O}_1 = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

$$\mathcal{O}_{3b} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$





-Weinberg operator is GIM suppressed

+One possible operator at mass dimension 7

Detection prospects

SM: LNC, vector current

$$\mathcal{L}_{\mathrm{SM}}^{K\to\pi\nu\bar{\nu}} = \frac{1}{\Lambda_{\mathrm{SM}}^2}\sum_{i=1}^{3}\left(\bar{\nu}_i\gamma^\mu\nu_i\right)\left(\bar{d}\gamma_\mu s\right)$$

BSM: (can be) LNV, scalar current

$$\mathcal{L}_{\mathrm{BSM}}^{K\to\pi\nu\nu} = \langle\pi\nu\nu|\mathcal{O}_{3b}|K\rangle = \frac{v}{\Lambda_{\mathrm{BSM}}^3}\bar{s}d\nu_i\nu_j$$

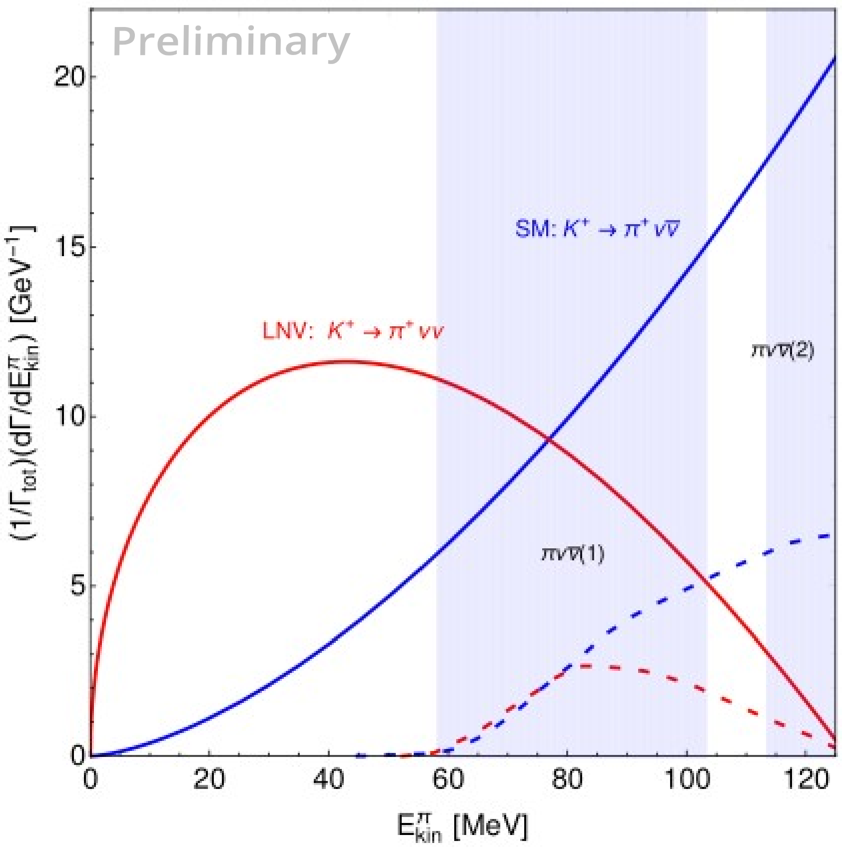
$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu})_{\mathrm{E949}}^{\mathrm{vector}} < 3.35\times10^{-10},\ \text{at } 90\%\ \mathrm{CL}$$

$$\mathrm{BR}(K^+\to\pi^+\nu\bar{\nu})_{\mathrm{E949}}^{\mathrm{scalar}} < 21\times10^{-10},\ \text{at } 90\%\ \mathrm{CL}$$

Different current → different distribution

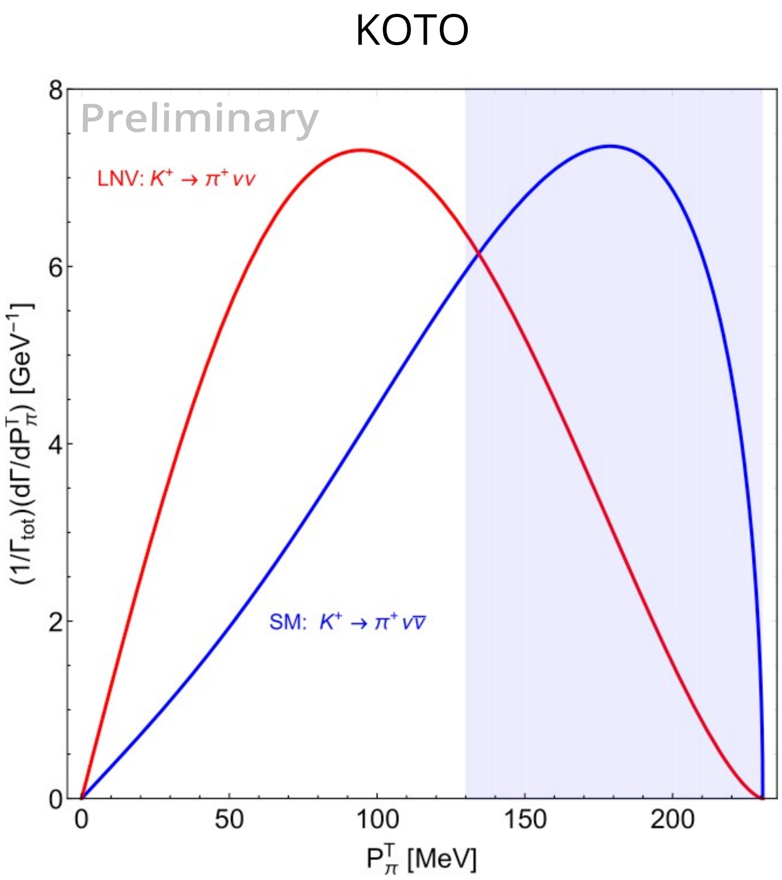
Dashed lines: after experimental acceptance

Search at E949:



Deppisch, KF, Harz arXiv:2008.XXXXX

Phase space: KOTO



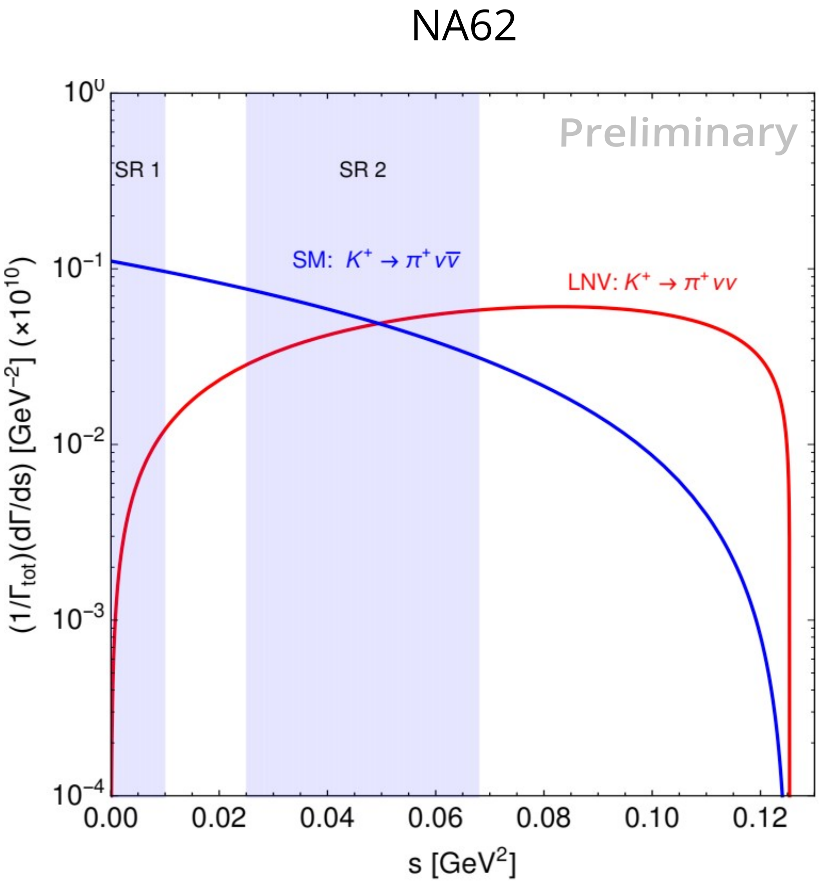
Deppisch, KF, Harz arXiv:2008.XXXXX

Experiment	SM (Vector)	LNV (Scalar)
NA62 SR 1	6%	0.3%
NA62 SR 2	17%	15%
E949 $\pi\nu\bar{\nu}(1)$	29%	2%
E949 $\pi\nu\bar{\nu}(2)$	45%	38%
KOTO	64%	30%

All three experiments are more sensitive to vector currents than to scalar currents

At E949 and NA62:
different # of events in each signal region

Phase space: NA62



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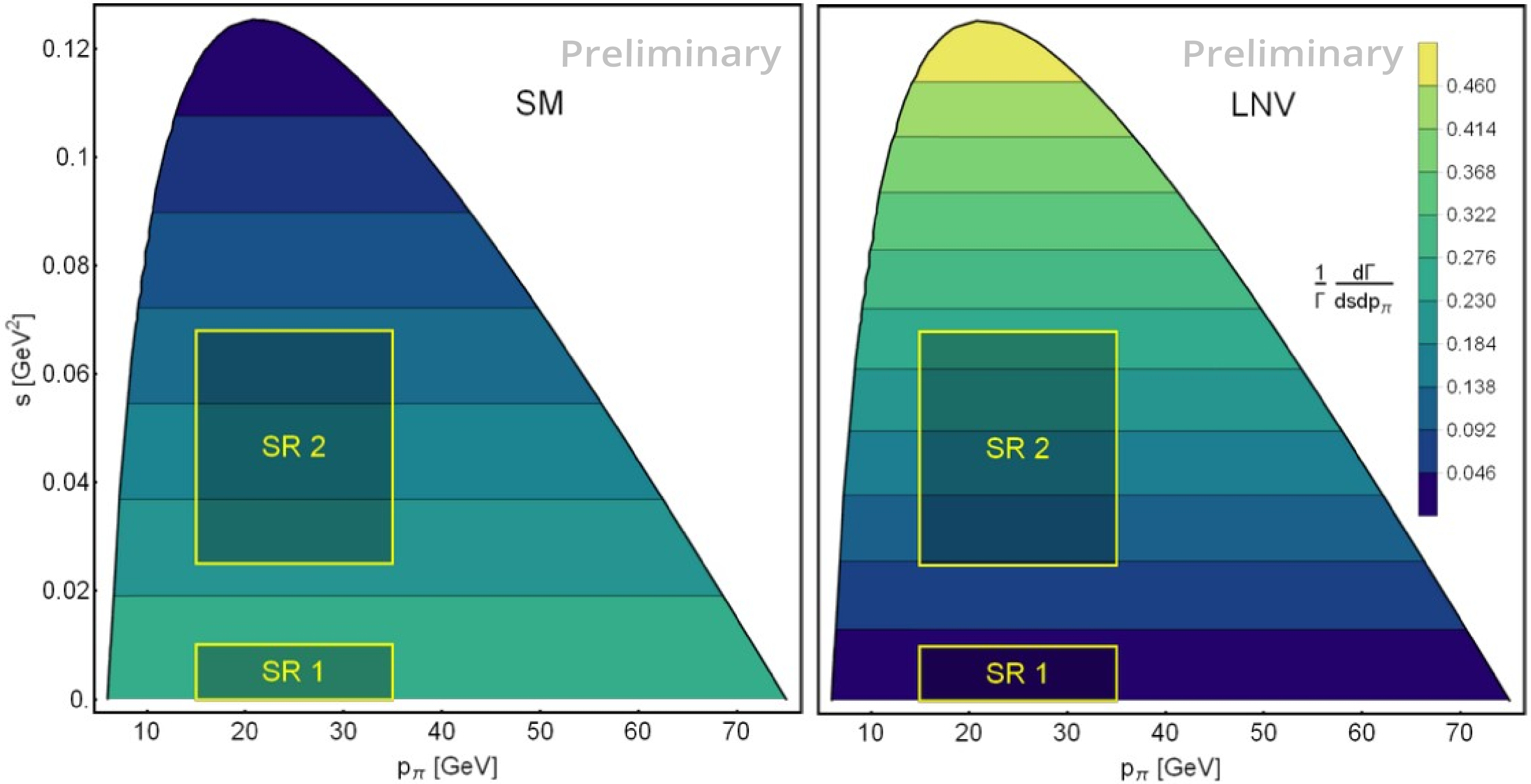


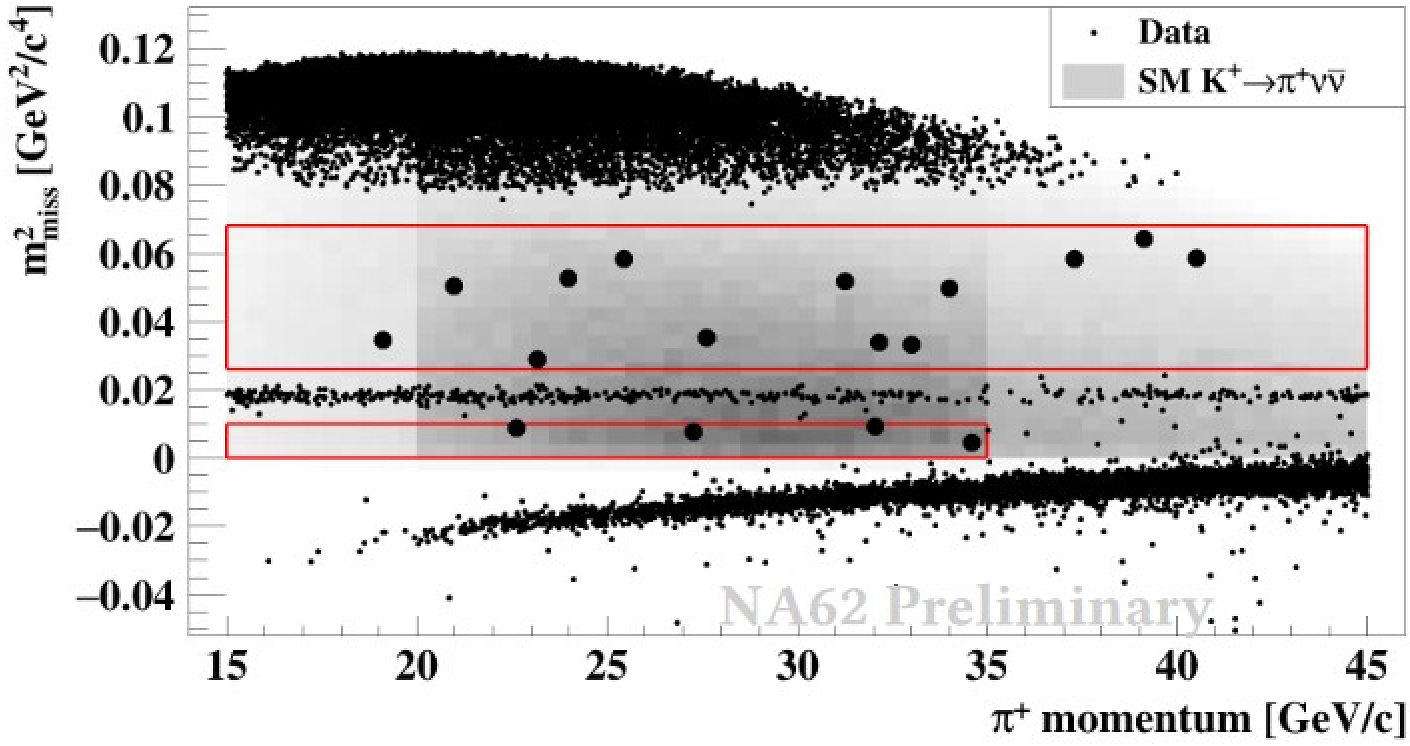
Missing energy s: $s = (E_K - E_\pi)^2$

Deppisch, KF, Harz arXiv:2008.XXXXX

For a given s, the distribution is independent of the pion momentum.

LNC: More events in SR 1, LNV: More events in SR 2

Reported @ ICHEP 2020

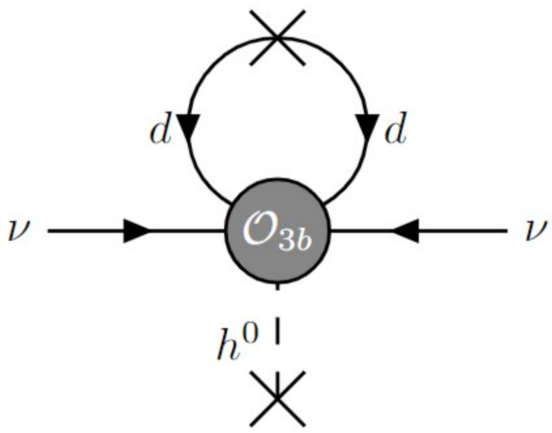


See talk by R. Marchevski on behalf of the NA62 collaboration

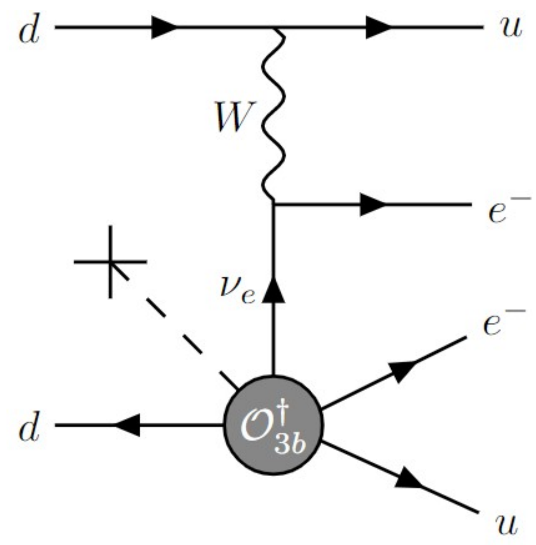
https://youtu.be/kH9sg-9BXG4?t=10359

Another side of dim-7 LNV

Radiative neutrino mass



Neutrinoless double beta decay (0νββ)



Radiative neutrino mass depends on the UV completion: non-trivial corrections

0νββ is only sensitive to electron neutrinos and up/down quarks

Implications for leptogenesis

$$\frac{d\eta_{\Delta L}}{dz} \propto -\eta_{\Delta L} \frac{\Lambda_{\rm Pl}}{\Lambda_{\rm BSM}} \left(\frac{T}{\Lambda_{\rm BSM}} \right)^{2D-9}$$

Lepton asymmetry can be translated into a baryon asymmetry via sphalerons

Washout: process that reduces asymmetry

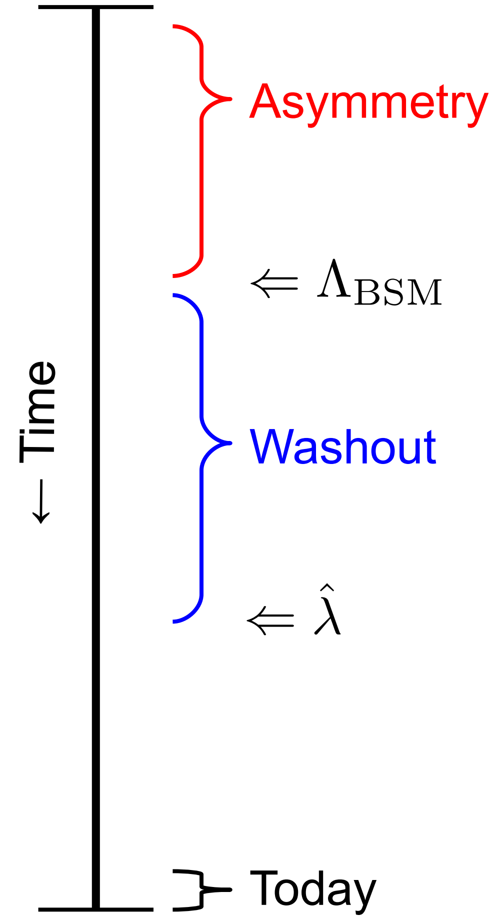
Assuming preexisting asymmetry: washout acts to remove it

$$\hat{\lambda} = f\left(\eta_B^{\rm obs}, \Lambda_{\rm BSM}, \ldots\right)$$

$$\eta_B^{\rm obs} = (6.20 \pm 0.015) \times 10^{-10}$$

Planck collaboration (2018)

Strong washout: $\hat{\lambda} \lesssim T \lesssim \Lambda_{\rm BSM}$



NP scales, washout scales

$$\mathrm{BR}(K \to \pi\nu\bar{\nu})_{\mathrm{tot}} = \mathrm{BR}(K \to \pi\nu\bar{\nu})_{\mathrm{SM}} + \left(\frac{A_{\mathrm{LNV}}}{A_{\mathrm{SM}}}\right) \times \sum_{i \leq j = 1}^{3} \mathrm{BR}(K \to \pi\nu_i\nu_j)_{\mathrm{LNV}}$$

Relative acceptance: $\left(\frac{A_{\mathrm{LNV}}}{A_{\mathrm{SM}}}\right)$

Strong washout: $\hat{\lambda} \lesssim T \lesssim \Lambda_{\mathrm{BSM}}$

$\mathcal{O}_{3b}$: $K^+ \to \pi^+\nu\nu$: $\Lambda_{\mathrm{BSM}}^{\mathrm{NA62}} > 17.2\ \mathrm{TeV}$ $\Rightarrow$ $\hat{\lambda} > 0.196\ \mathrm{TeV}$

$K_L \to \pi^0\nu\nu$: $\Lambda_{\mathrm{BSM}}^{\mathrm{KOTO}} > 12.3\ \mathrm{TeV}$ $\Rightarrow$ $\hat{\lambda} > 0.178\ \mathrm{TeV}$

Rare kaon decays are probing NP scales of order 10 TeV

Conclusion

- Scalar/vector distribution difference is significant in kaon decays
- Distinguishing LNV from LNC in rare kaon decays may be plausible
- An observation of LNV in rare kaon decays would put high scale leptogenesis under tension

Thanks for listening

Backup: leptoquarks

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \tilde{R}_2^{\dagger\alpha}(\Box + m^2_{\tilde{R}_2})\tilde{R}_{2\alpha} - S_1^*(\Box + m^2_{S_1})S_1$$
$$+ \mu S_1 H^{\dagger\alpha}\tilde{R}_{2\alpha} - g_1^{ik}\bar{L}_{i\alpha} i\sigma_2^{\alpha\beta}\tilde{R}^*_{2\beta}d_k - g_2^{jn}\bar{Q}^{c\alpha}_n L_j^\beta \epsilon_{\alpha\beta}S_1$$
$$- g_3^{jn}\bar{u}^c_n e_j S_1 + \text{h.c.}$$

$$\mathcal{L}_{7D} = \frac{\mu g_1^{ik} g_2^{jn}}{m^2_{\tilde{R}_2} m^2_{S_1}} L_i^\alpha H^\beta d_k^c Q_n^\mu L_j^\nu \epsilon_{\alpha\beta}\epsilon_{\mu\nu} + \frac{\mu g_1^{ik} g_3^{jn}}{m^2_{\tilde{R}_2} m^2_{S_1}} L_i^\alpha H^\beta d_k^c u_n^c e_j^c \epsilon_{\alpha\beta}$$

O. Cata and T. Mannel, arXiv:1903.01799