Constraining Lepton Number Violating Interactions with Rare Kaon Decays

Julia Harz

in collaboration with F. Deppisch and K. Fridell

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HiDDeN Webinar

Technische Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Outline

Motivation

- Neutrinos as a window to new physics
- Why lepton-number violation?

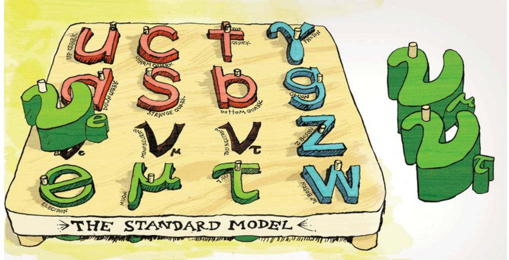
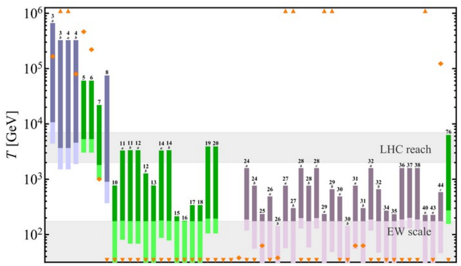


Illustration by Sandbox Studio, Chicago

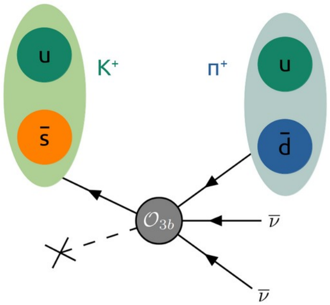
Lepton-number violating interactions

- Operators
- Testability (0νββ, neutrino masses)
- Leptogenesis



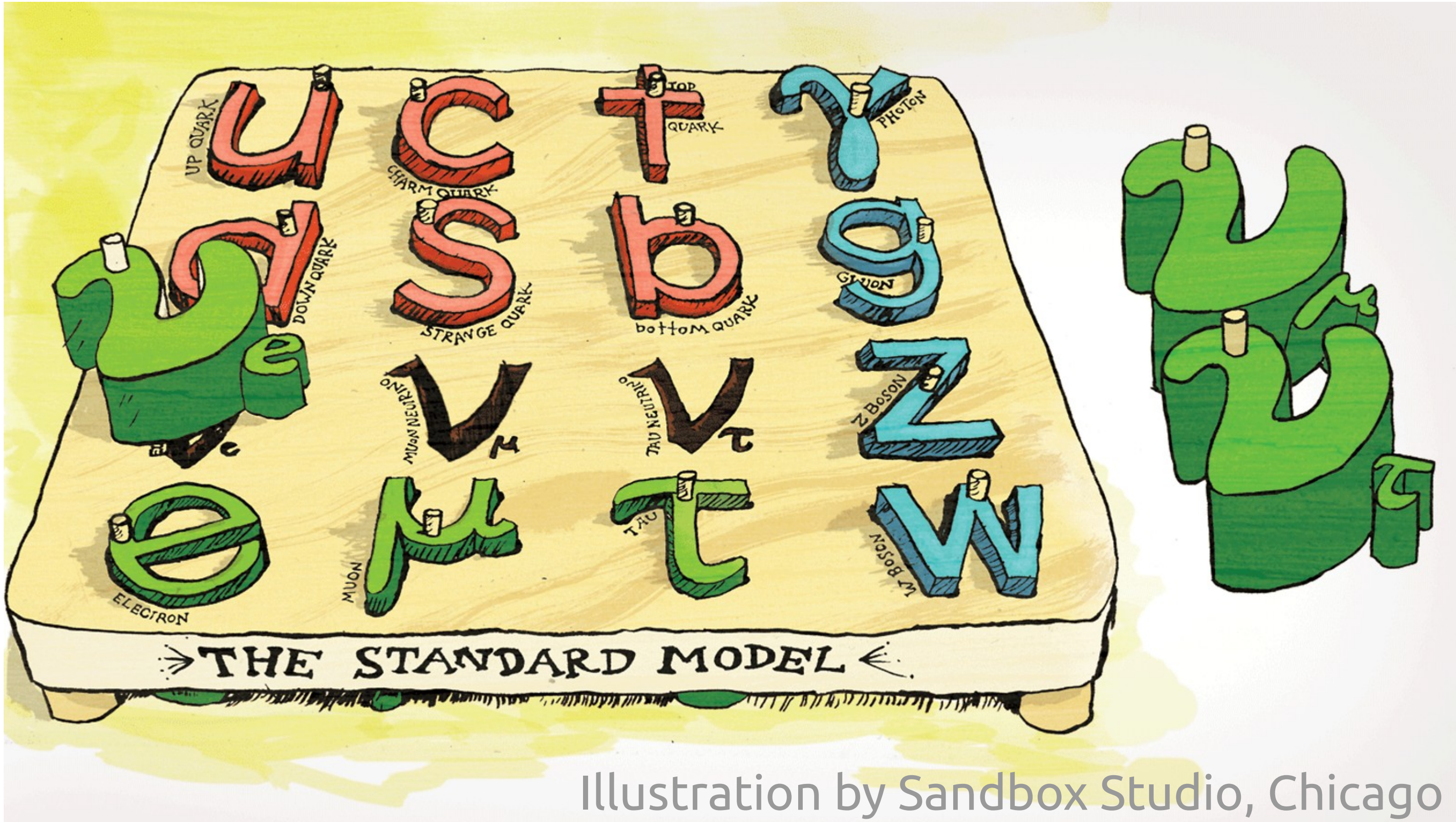
Rare Kaon decays

- Recap: Kaons in the Standard Model
- LNV interactions in Kaon decays
- Confronting LNV interactions with E949, KOTO, NA62
- Complementarity of constraints
- UV complete example: Leptoquarks



Introduction

Neutrinos – what do we know?



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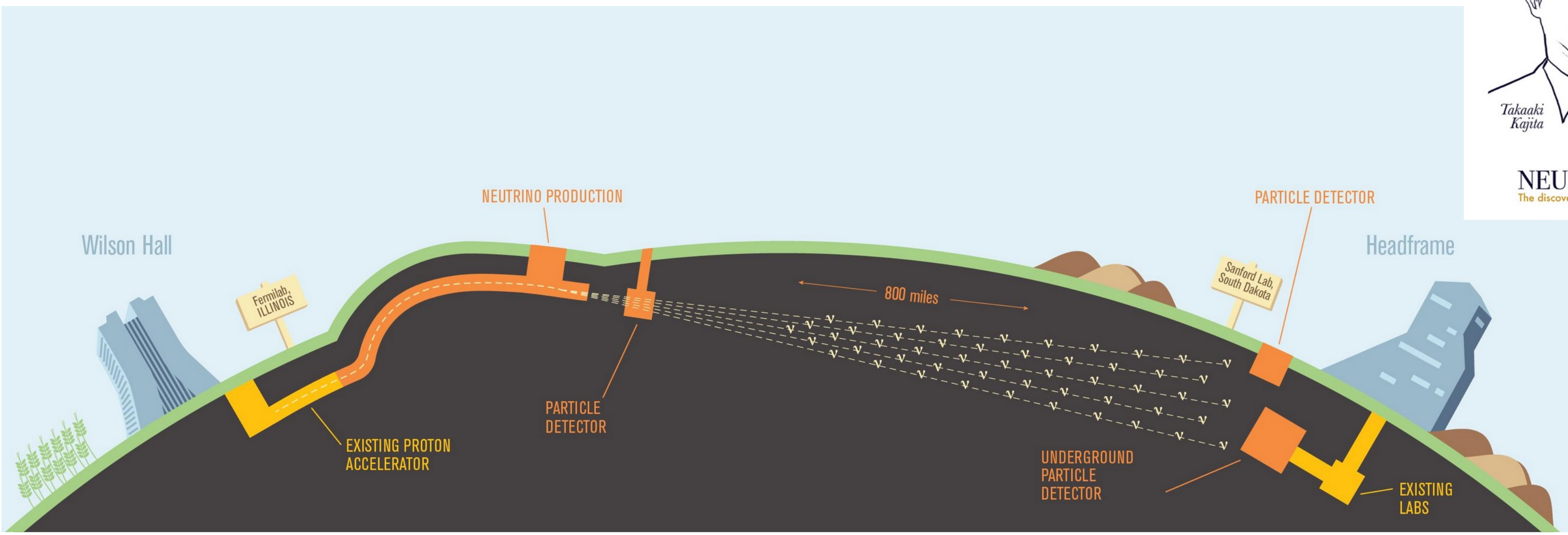
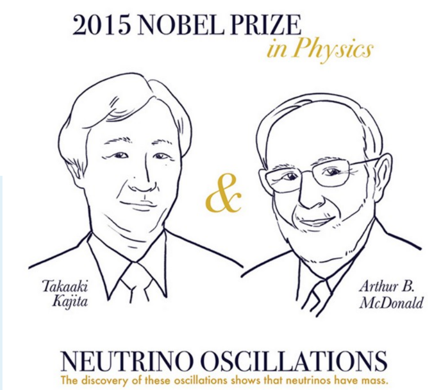
“Neutrinos, the Standard Model misfits”

Neutrinos – what do we know?





ν_e ν_μ

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Neutrino **oscillations** require **massive** neutrinos, forbidden in the Standard Model.

How do neutrinos get their masses?

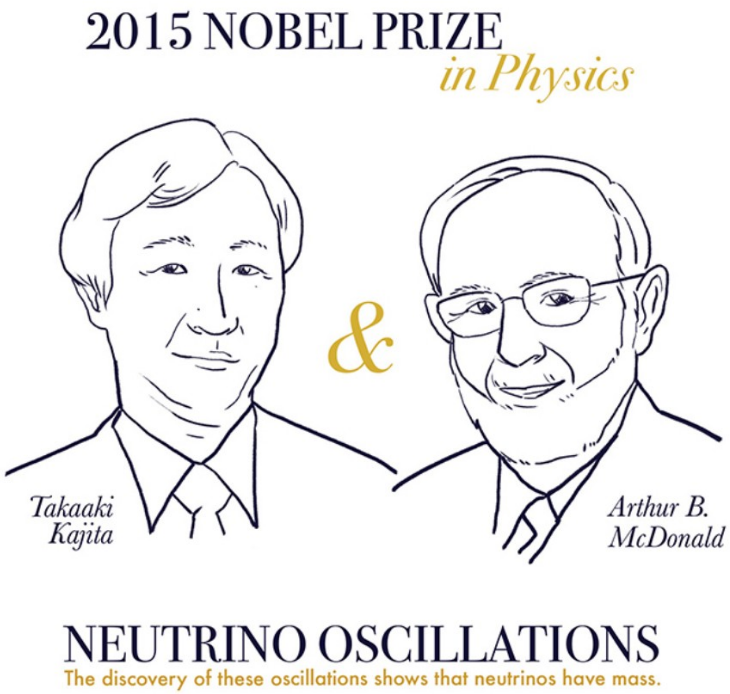
Neutrinos – what do we know?

- Neutrinos in the Standard Model are **massless**

$$L_i \to \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \qquad m_\nu = 0$$

- Neutrino **mixing**

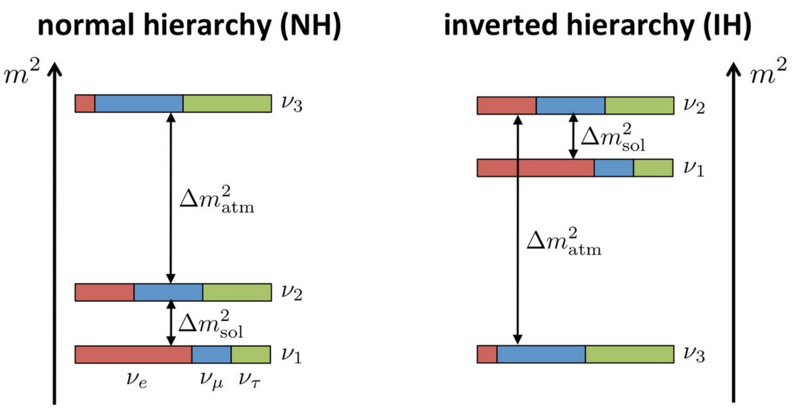
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Neutrino **oscillations** require **massive** neutrinos

$$P(\nu_i \to \nu_j) \propto \Delta m_{ij}^2 \qquad \begin{array}{l} \Delta m_{12}^2 \sim 7.59 \times 10^{-5} \mathrm{eV}^2 \\ \Delta m_{23}^2 \sim \Delta m_{31}^2 \sim 2.3 \times 10^{-3} \mathrm{eV}^2 \end{array}$$

- **Normal** vs. **inverted** hierarchy



How do neutrinos get their masses?
What nature do neutrinos have? Are they their own anti-particles?

Why Lepton-Number Violation?

- Masses of the active neutrinos cannot be explained within the SM
- **BUT** right-handed neutrinos could help

Dirac mass

1/2

$$y_\nu L \epsilon H \nu_R^c \supset m_D \nu_L \nu_R^c$$

-1/2 0

hypercharge

Majorana mass

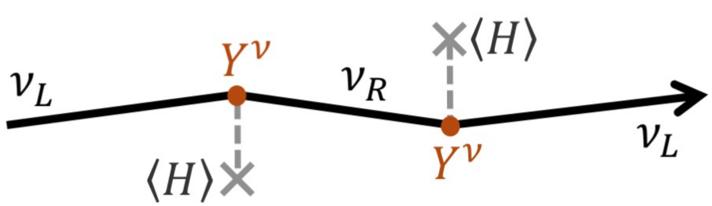
$$m_M \overline{\nu}_R \nu_R^c$$

0 0

- tiny Yukawa couplings

$$m_\nu / \Lambda_{EW} \leq 10^{-12}$$

- Lepton number no accidental symmetry anymore



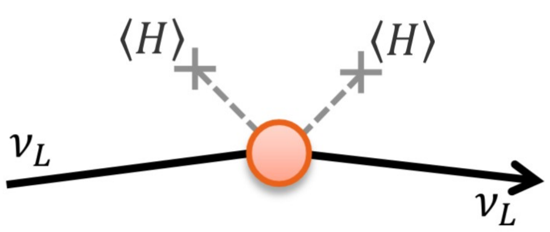
-1/2 1/2

$$m_M \overline{\nu}_L \nu_L^c \qquad LLHH$$

1/2 1/2 -1/2 1/2

not at tree-level within the SM possible

- higher dimensional operator
- Lepton number violation (**LNV**)



Lepton Number Violating Operators and their implications

Lepton-Number Violation

- LNV occurs only at odd mass dimension:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

$$\mathcal{O}_1^{(5)} = \underbrace{L^\alpha}_{3/2} \underbrace{L^\beta}_{3/2} \underbrace{H^\rho}_{1} \underbrace{H^\sigma}_{1} \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

mass dimension

$$\mathcal{O}_{3a}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta}\epsilon_{\rho\sigma}$$

$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

$$\mathcal{O}_{8}^{(7)} = L^\alpha \bar{e}^c \bar{u}^c d^c H^\beta \epsilon_{\alpha\beta}$$

$$\mathcal{O}_{14b}^{(9)} = L^\alpha L^\beta \bar{Q}_\alpha \bar{u}^c Q^\rho d^c \epsilon_{\beta\rho}$$

$$\mathcal{O}_{16}^{(9)} = L^\alpha L^\beta e^c d^c \bar{e}^c \bar{u}^c \epsilon_{\alpha\beta}$$

Babu, Leung (2001), de Gouvea, Jenkins (2007), Deppisch, Graf, JH, Huang (2017)

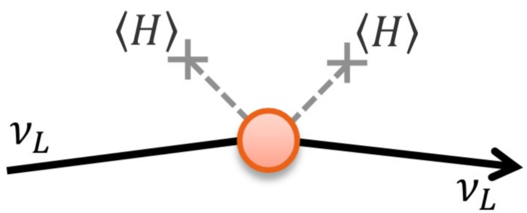
Radiative neutrino mass generation

- LNV occurs only at odd mass dimension:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

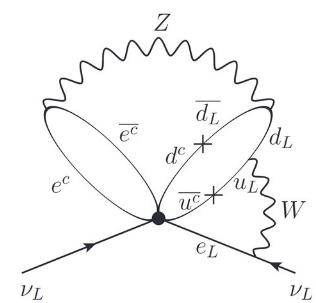
$$\boxed{\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}}$$

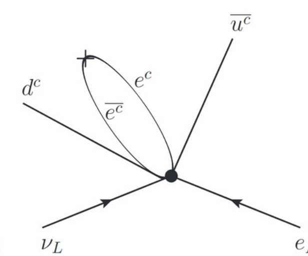
$$\boxed{\mathcal{O}_{16}^{(9)} = L^\alpha L^\beta e^c d^c \bar{e}^c \bar{u}^c \epsilon_{\alpha\beta}}$$



$$m_\nu \approx \frac{v^2}{\Lambda_1}$$

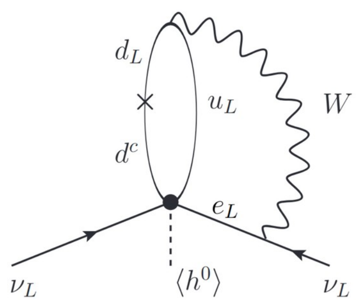
$$\mathcal{O}_{3a}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta}\epsilon_{\rho\sigma}$$
$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$



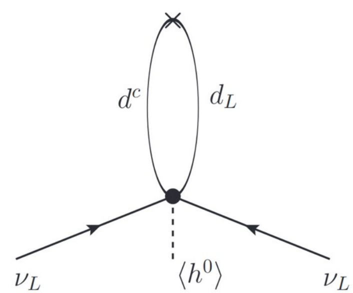


$$m_\nu \approx \frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda_{16}}$$

$$L^\alpha = \begin{pmatrix}\nu_L \\ e_L\end{pmatrix}^\alpha, \quad Q^\alpha = \begin{pmatrix}u_L \\ d_L\end{pmatrix}^\alpha, \quad H = \begin{pmatrix}h^+ \\ h^0\end{pmatrix}$$
$$e^c_\alpha, \; u^c_\alpha, \; d^c_\alpha$$



$$m_\nu \approx \frac{y_d g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda_{3a}}$$

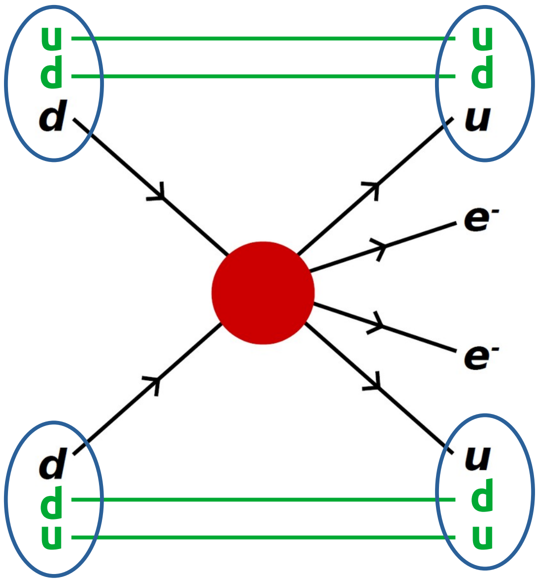


$$m_\nu \approx \frac{y_d}{16\pi^2}\frac{v^2}{\Lambda_{3b}}$$

Deppisch, Graf, JH, Huang (2017)

Probing LNV interactions – 0νββ decay

Neutrinoless double beta decay



Most stringent limits are currently set by GERDA and Kamland-Zen:

$$T_{1/2}^{\mathrm{Ge}} \geq 8.0 \times 10^{25}\ \mathrm{y} \qquad T_{1/2}^{\mathrm{Xe}} \geq 1.07 \times 10^{26}\ \mathrm{y}$$

$$\boxed{T_{1/2}^{-1} = \mid m_{\beta\beta} \mid^2 G^{0\nu} \mid M^{0\nu} \mid^2}$$

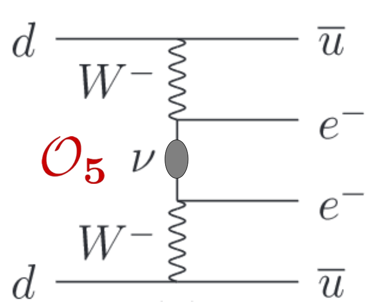
particle physics

atomic physics

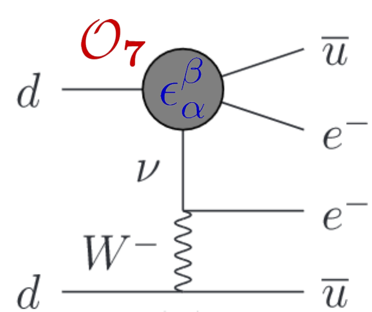
nuclear physics

$\stackrel{?}{=}$

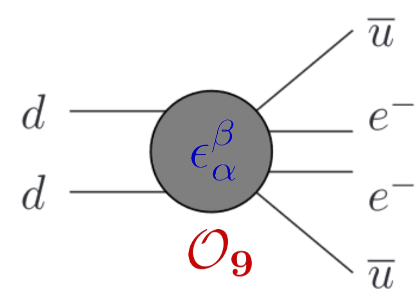
standard mass mechanism



long range contribution

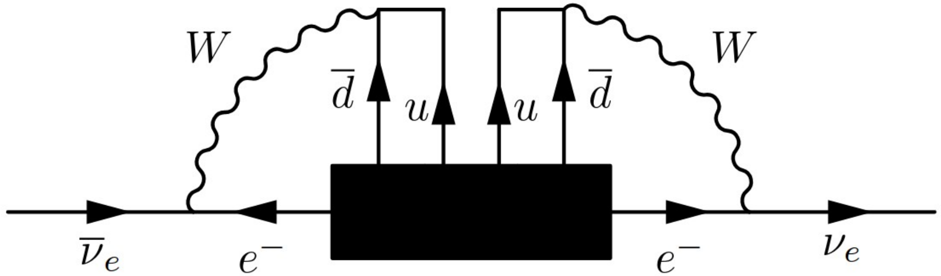


short range contribution



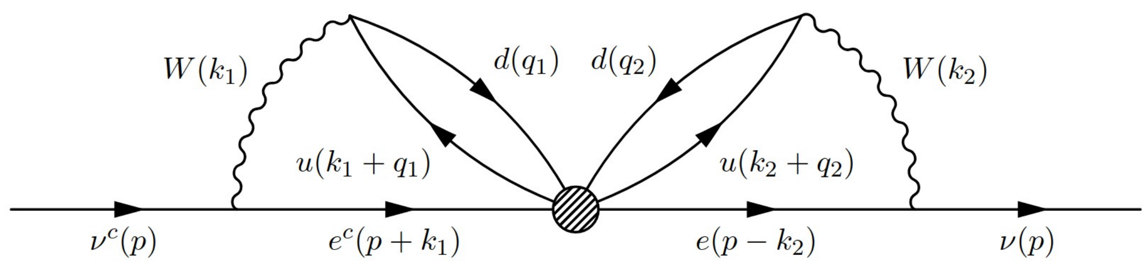
0νββ decay probes only first generation!

Schechter-Valle Theorem – Black Box Theorem



Schechter, Valle (1982)

Any ΔL = 2 operator that leads to 0vbb will induce a **Majorana mass contribution** via loop



Dürr, Merle, Lindner (2011)

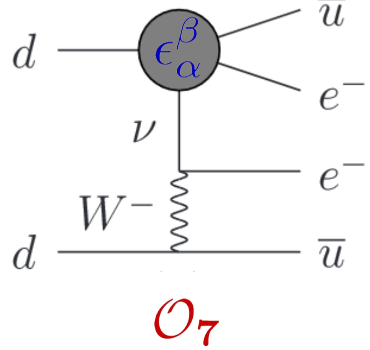
9-dim ΔL = 2 operator will lead to 0vbb but only **tiny contribution** to neutrino mass

$$\delta m_\nu = 10^{-28}\mathrm{eV}$$

Observation of 0νββ decay does not imply that the mass mechanism is the dominant contribution.

Constraining LNV interactions

long range contribution



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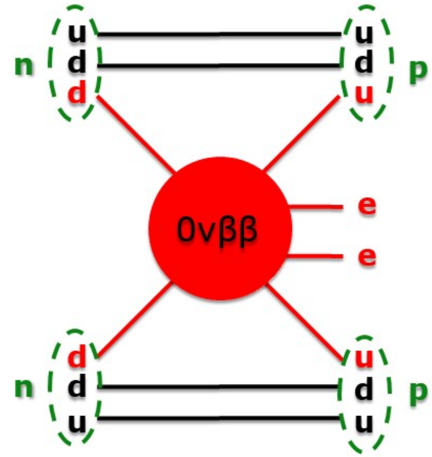
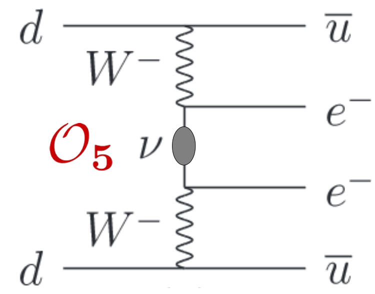


$\overset{?}{=}$

standard mass mechanism



$$\boxed{T_{1/2}^{-1} = G_{0\nu}|\mathcal{M}|^2|\epsilon_\alpha^\beta|^2}$$

$$\boxed{T_{1/2}^{-1} = G_{0\nu}\mid\mathcal{M}\mid^2\mid m_{\beta\beta}\mid^2}$$

Leptonic and hadronic current with different chirality structure:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\{j^\mu_{V-A}J^\dagger_{V-A,\mu} + \sum_{\alpha,\beta}\epsilon_\alpha^\beta j_\beta J_\alpha^\dagger\}$$

$$j_\beta = \bar{e}\mathcal{O}_\beta\nu$$

$$J_\alpha^\dagger = \bar{u}\mathcal{O}_\alpha d$$

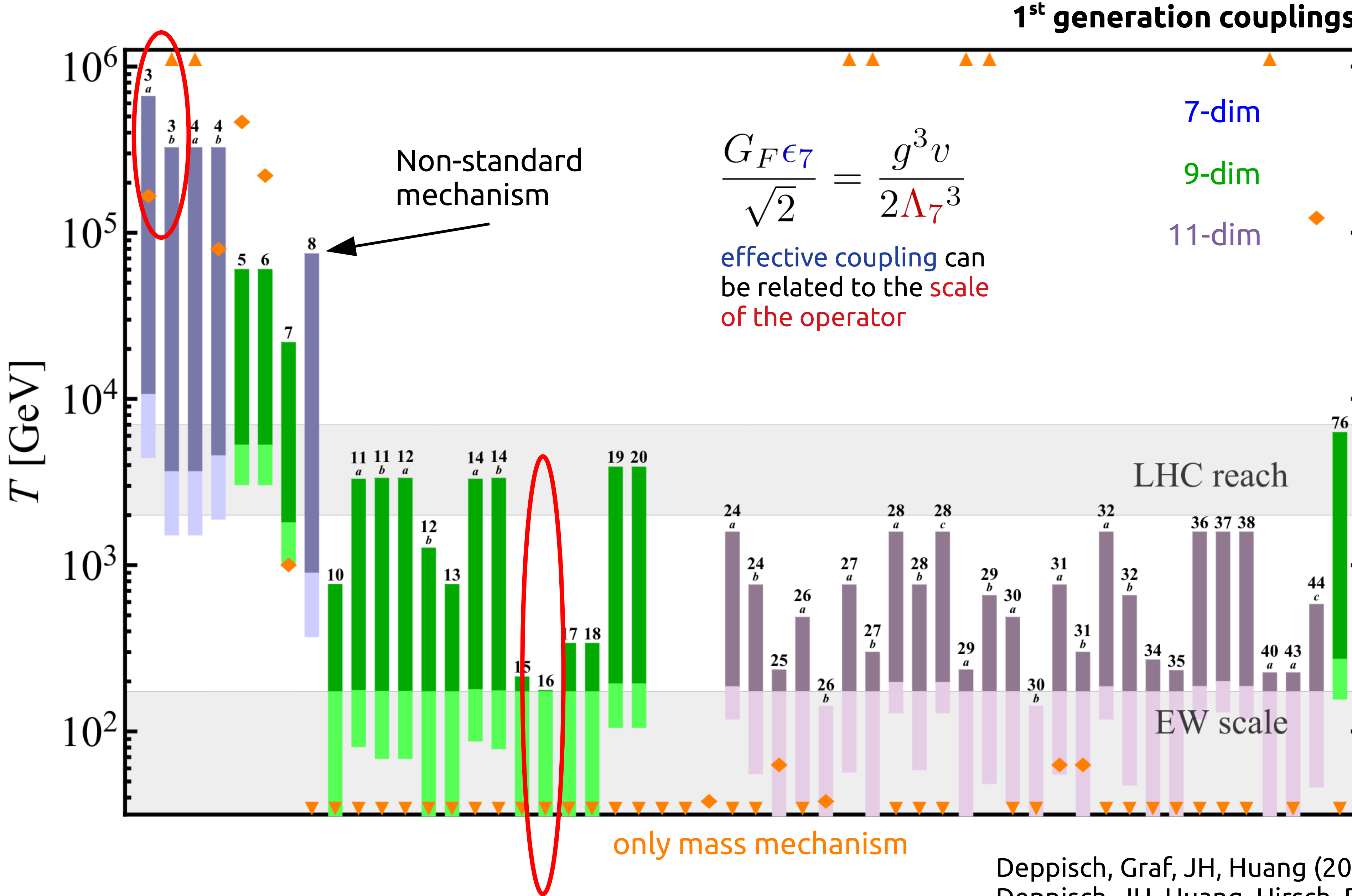
$$\mathcal{O}_{V\pm A} = \gamma^\mu(1\pm\gamma_5)$$

$$\mathcal{O}_{S\pm P} = (1\pm\gamma_5)$$

$$\mathcal{O}_{T_{R,L}} = \frac{i}{2}[\gamma_\mu,\gamma_\nu](1\pm\gamma_5)$$

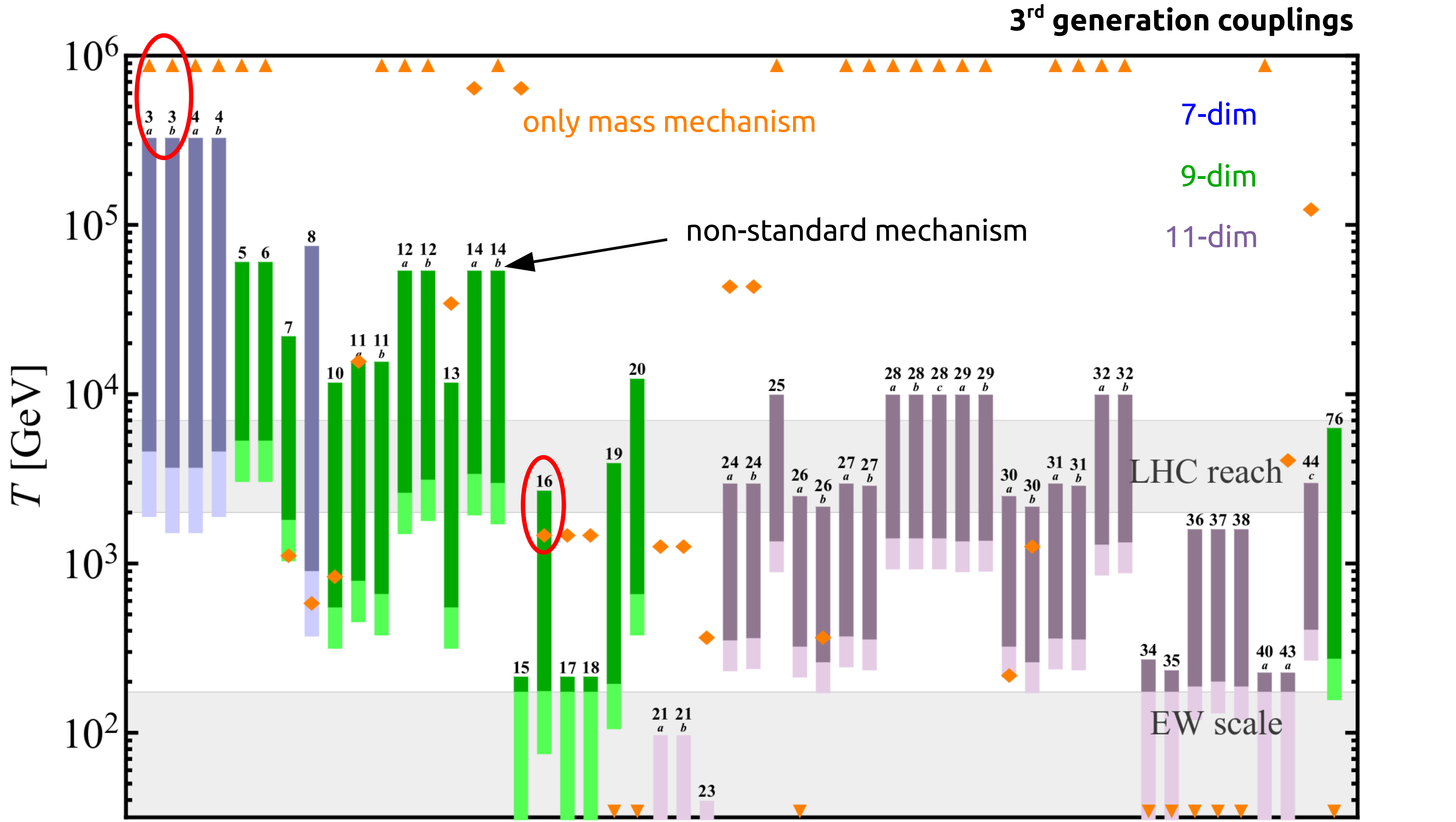
$\lvert\epsilon\rvert \times 10^8$	ϵ_ν	ϵ_{V-A}^{V+A}	ϵ_{V+A}^{V+A}	$\epsilon_{S\pm P}^{S+P}$	$\epsilon_{T_R}^{T_R}$
^{76}Ge	41	0.21	37	0.66	0.07
^{76}Xe	26	0.11	22	0.26	0.03

Scales of New Physics



Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

Scales of New Physics



Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

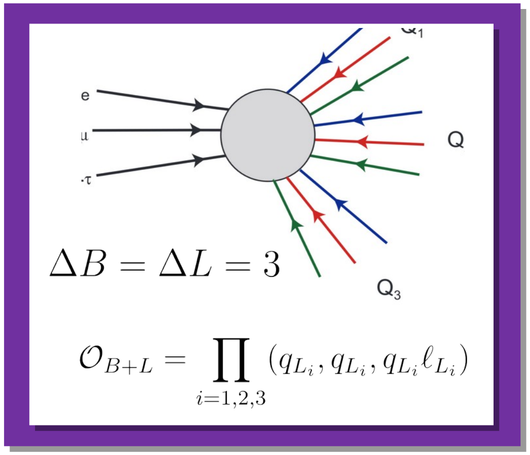
Implications on Leptogenesis

- generation of lepton asymmetry via heavy neutrino decays
- competition with lepton number violating (LNV) washout processes
- conversion to baryon asymmetry via sphaleron processes

Fukugita et al. 1986

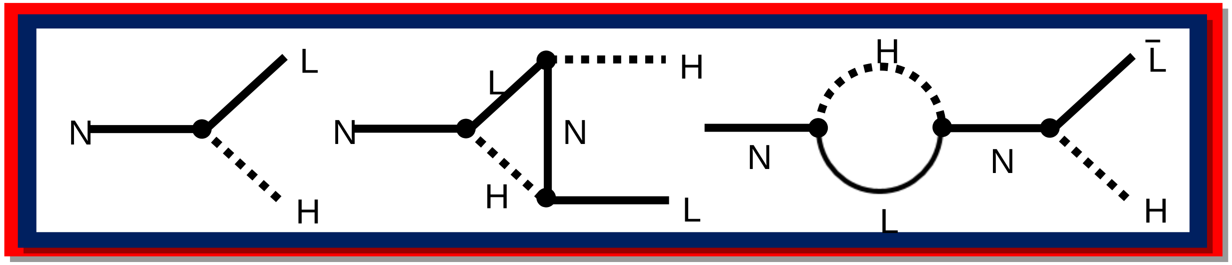
$$Hz\frac{dN_{N_1}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_1} - N_{N_1}^{\rm eq})$$

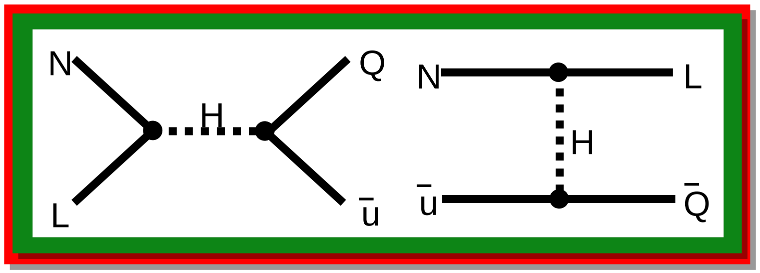
$$Hz\frac{dN_L}{dz} = \epsilon_1 \Gamma_D (N_{N_1} - N_{N_1}^{\rm eq}) - \Gamma_W N_L$$

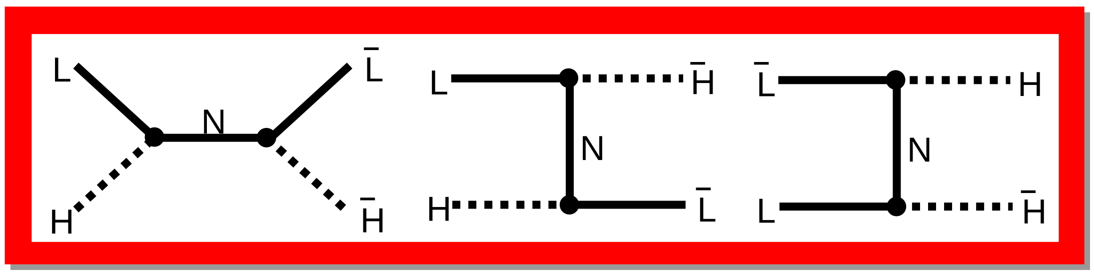


sphaleron processes

$\Delta L = 1$ source of CP violation





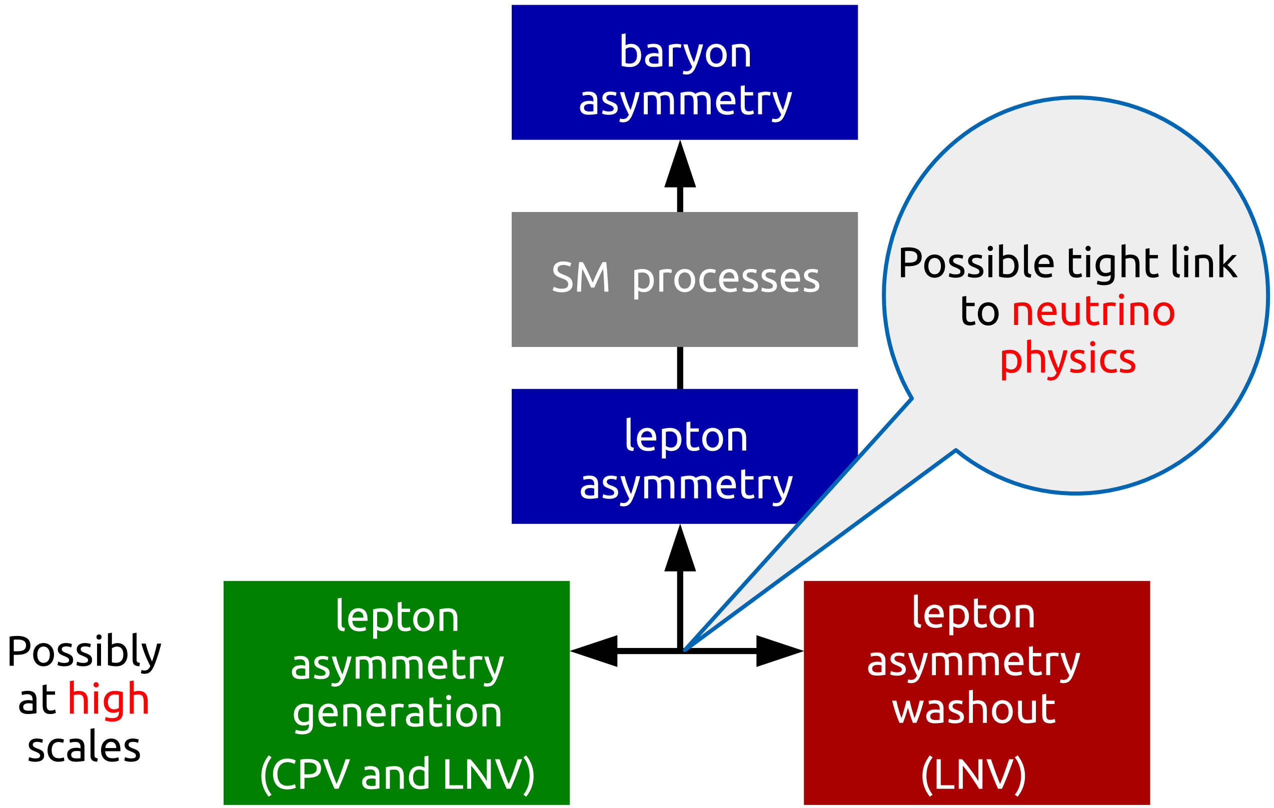


$\Delta L = 1$ scattering processes

$\Delta L = 2$ washout processes

Implications on Leptogenesis

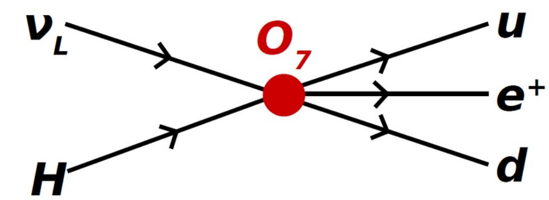
The generation of a baryon asymmetry – baryogenesis – can be created by a lepton asymmetry – leptogenesis:



In turn, lepton number violation (LNV) can destroy a lepton asymmetry, and thus even a baryon asymmetry!

Lepton Asymmetry Washout

- LNV operator would cause washout of **pre-existing** net lepton asymmetry in the early Universe



$$\mathcal{O}_7 = (L^i d^c)(\bar{e^c}\bar{u^c})H^j \epsilon_{ij}$$

$$zHn_\gamma \frac{d\,\eta_{L_e}}{d\,z} = -\left(\frac{n_{L_e} n_{\bar{e^c}}}{n^{\text{eq}}_{L_e} n^{\text{eq}}_{\bar{e^c}}} - \frac{n_{u^c} n_{\bar{d^c}} n_{\bar{H}}}{n^{\text{eq}}_{u^c} n^{\text{eq}}_{\bar{d^c}} n^{\text{eq}}_{\bar{H}}}\right) \gamma^{\text{eq}}(L_e \bar{e^c} \to u^c \bar{d^c} \bar{H})$$

$$zHn_\gamma \frac{d\eta_{\Delta L_e}}{dz} = -c_D \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}} \eta_{\Delta L_e}$$

$$\gamma^{eq} \propto \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}}$$

c_D operator specific factor

η_L lepton density

- washout efficient if

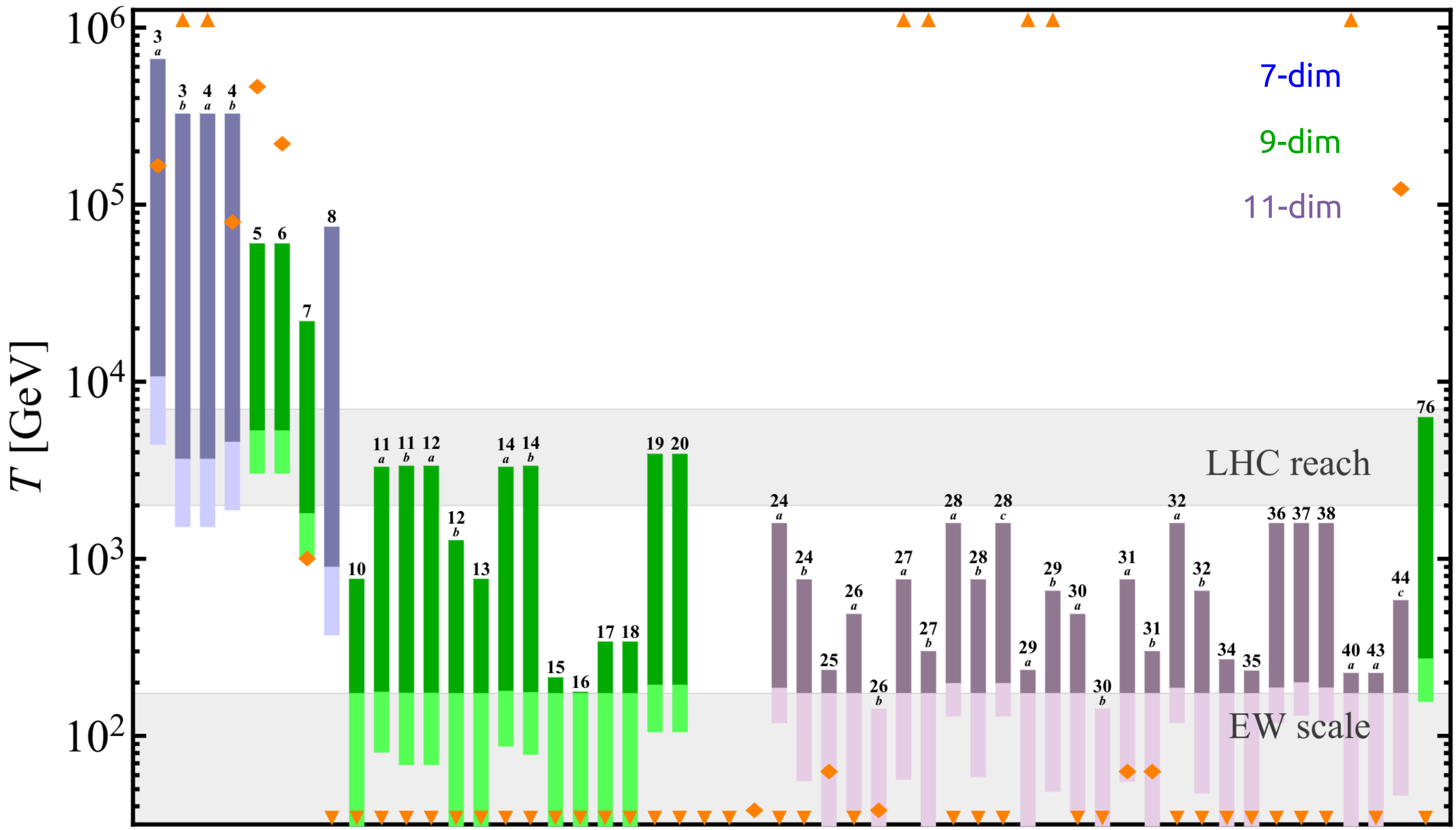
$$\frac{\Gamma_W}{H} \equiv \frac{c_D}{n_\gamma H} \frac{T^{2D-4}}{\Lambda_D{}^{2D-8}} = c'_D \frac{\Lambda_{\text{Pl}}}{\Lambda_D} \left(\frac{T}{\Lambda_D}\right)^{2D-9} > 1$$

If 0νββ is observed, washout efficient in the temperature interval

$$\Lambda_D \left(\frac{\Lambda_D}{c'_D \Lambda_{\text{Pl}}}\right)^{\frac{1}{2D-9}} \equiv \lambda_D < T < \Lambda_D$$

Lepton asymmetry washout

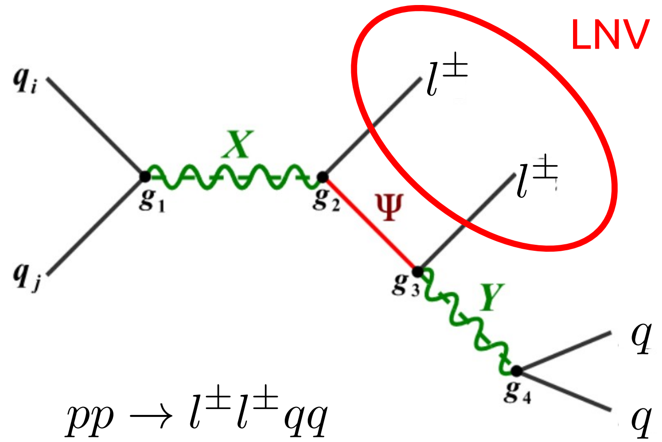
1[st] generation couplings



Deppisch, Graf, JH, Huang (2017)
Deppisch, JH, Huang, Hirsch, Päs (2015)

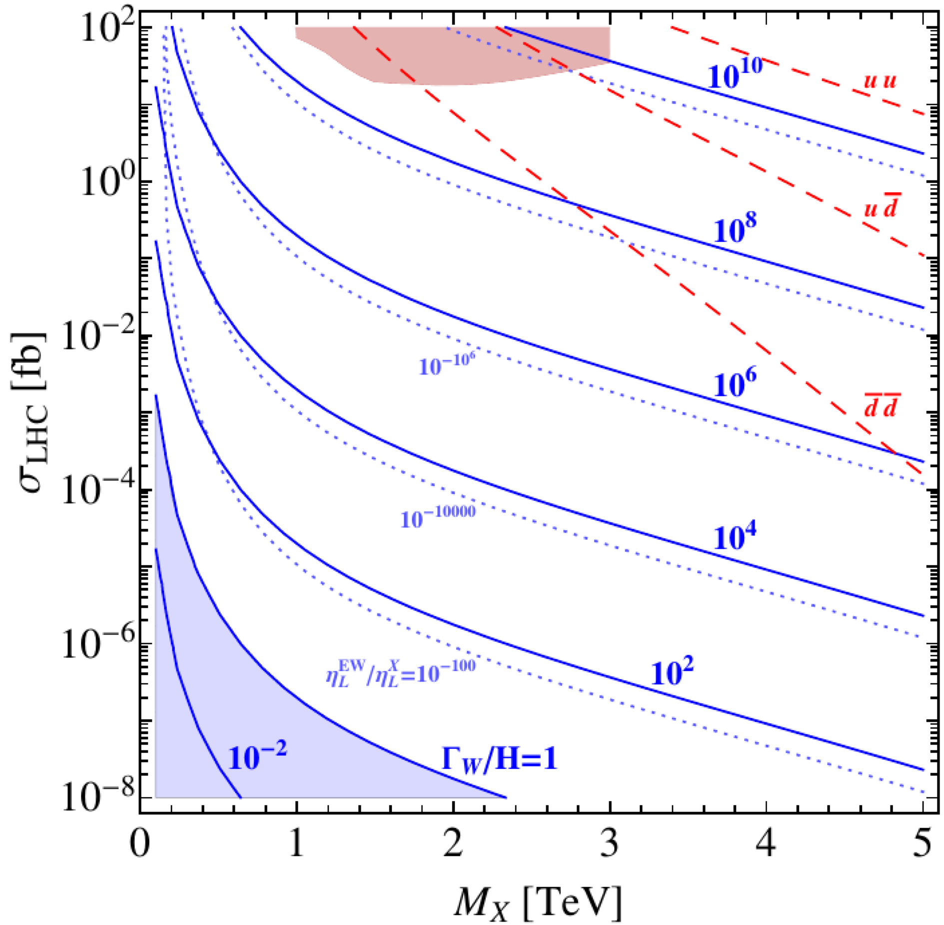
Probing LNV interactions – LHC

Washout processes could be observable at the LHC



$pp \to l^\pm l^\pm qq$

$$\log_{10}\frac{\Gamma_W}{H} > 6.9 + 0.6\left(\frac{M_X}{\text{TeV}} - 1\right) + \log_{10}\frac{\sigma_{\text{LHC}}}{\text{fb}}$$



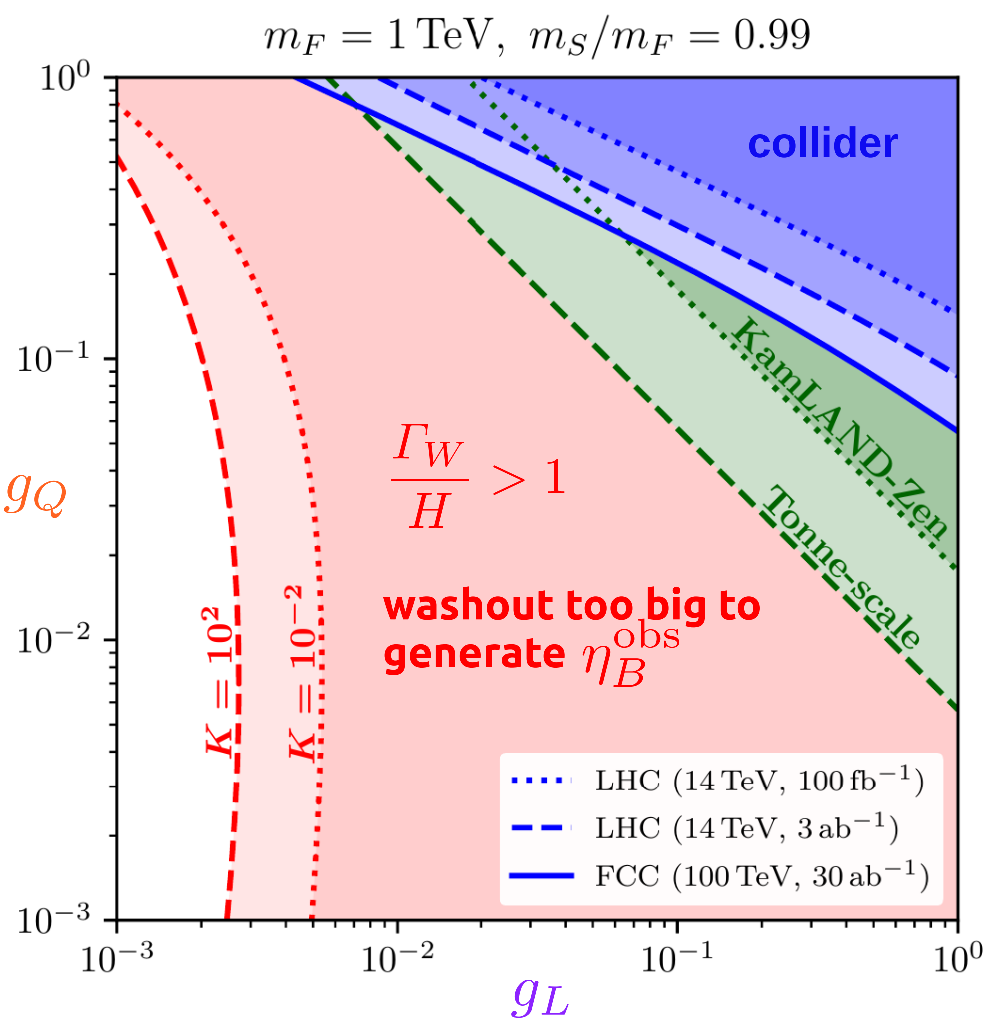
Observation of any washout process at LHC would falsify high scale baryogenesis!

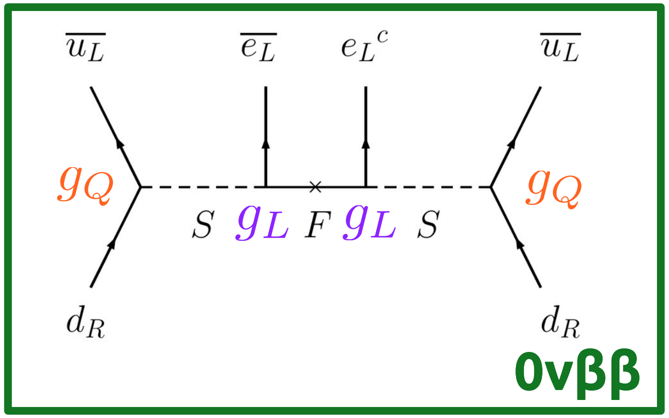
(scale of asymmetry generation *above* M_X)

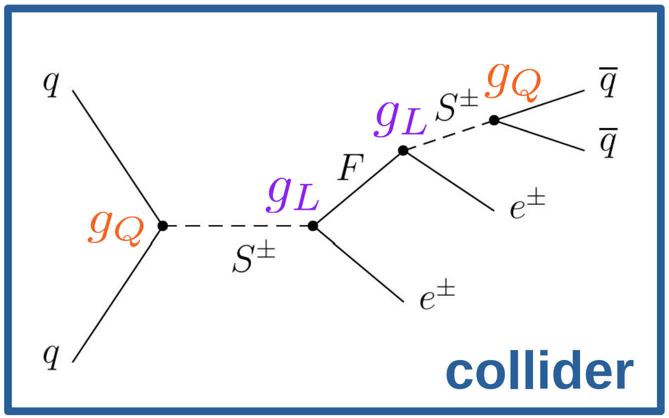
Deppisch, JH, Hirsch, Phys. Rev. Lett. (2014)
Deppisch, JH, Hirsch, Päs, Int. J. Mod. Phys. A (2015)

Combining LHC & 0νββ

$$\mathcal{L} = g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + g_S (S^\dagger S)^2 + \lambda_{HS} (S^\dagger H)^2 + \text{h.c.}$$





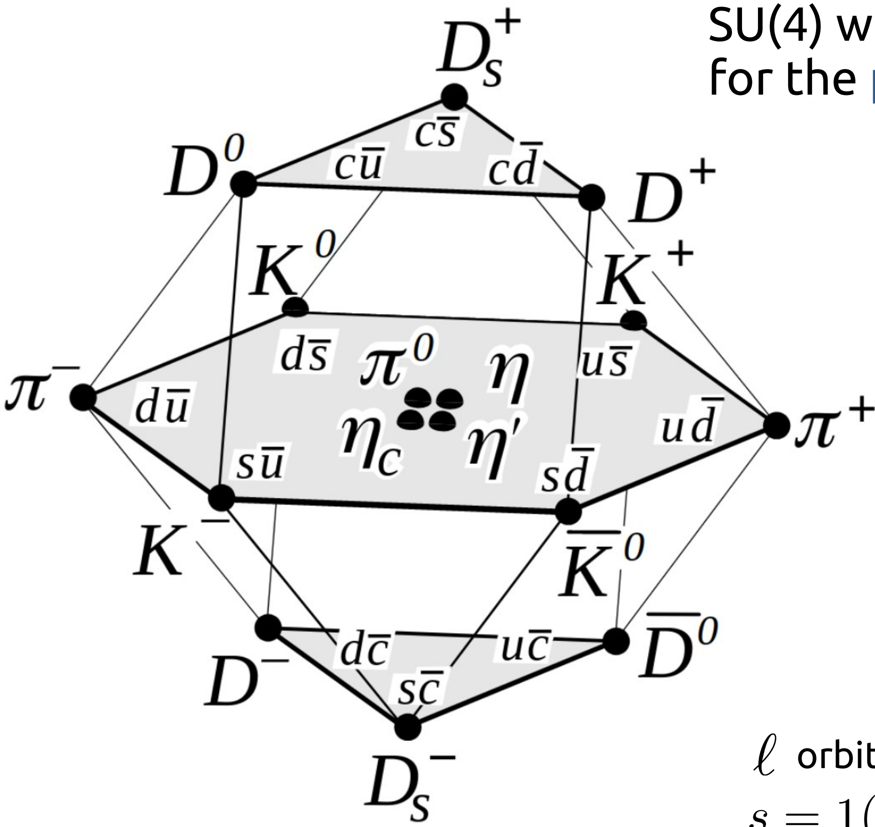


Comprehensive analysis confirms EFT results and shows interesting interplay between collider and 0νββ reach.

JH, Ramsey-Musolf, Shen, Urrutia, in preparation

Kaon decays as a probe for LNV?

Recap: Kaons in the Standard Model



0^{-+}

SU(4) weight diagram showing the 16-plets for the **pseudoscalar** mesons

J^{PC}

$$|\ell - s| < J < |\ell + s|$$

$$C = (-1)^{\ell + s}$$

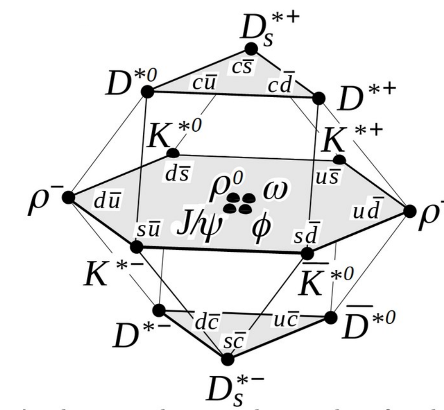
$$P = (-1)^{\ell + 1}$$

ℓ orbital angular momentum of $q\bar{q}'$

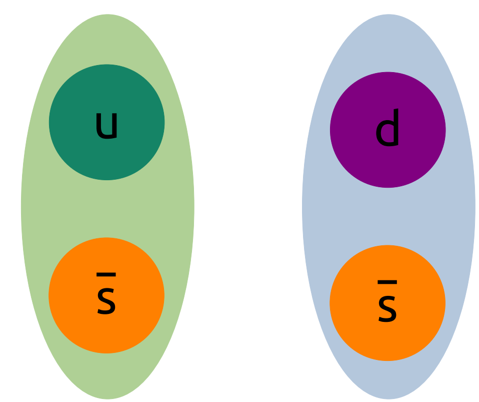
$s = 1(0)$ (anti) parallel spin of quarks

$$CP\,|K^0\rangle = -\,|\bar{K}^0\rangle$$

$$CP\,|\bar{K}^0\rangle = -\,|K^0\rangle$$

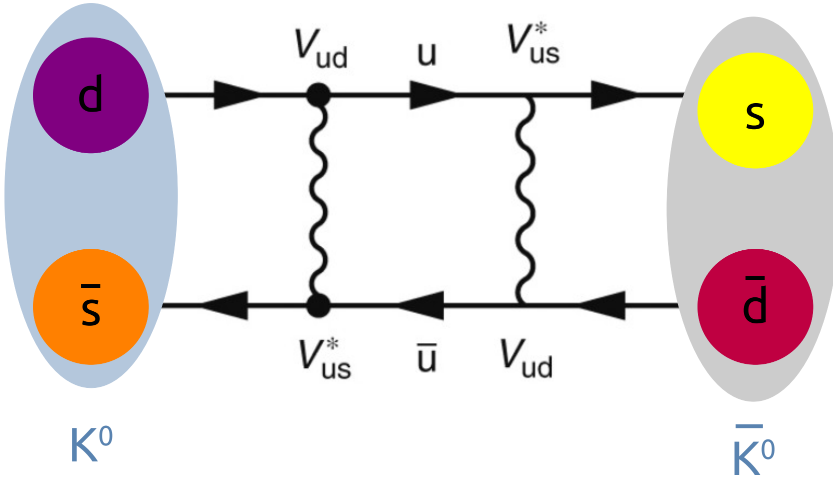


1^{--}



K^+ K^0

Recap: Kaons in the Standard Model



Neutral mesons can mix

$$CP\,|K^0\rangle = -\,|\bar{K}^0\rangle$$
$$CP\,|\bar{K}^0\rangle = -\,|K^0\rangle$$

CP eigenstates:

$$CP\,|K_1^0\rangle = CP\left(\frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right)\right) = +\,|K_1^0\rangle$$
$$CP\,|K_2^0\rangle = CP\left(\frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right)\right) = -\,|K_2^0\rangle$$

Expected decays:

$K_1^0 \rightarrow 2\pi$ fast

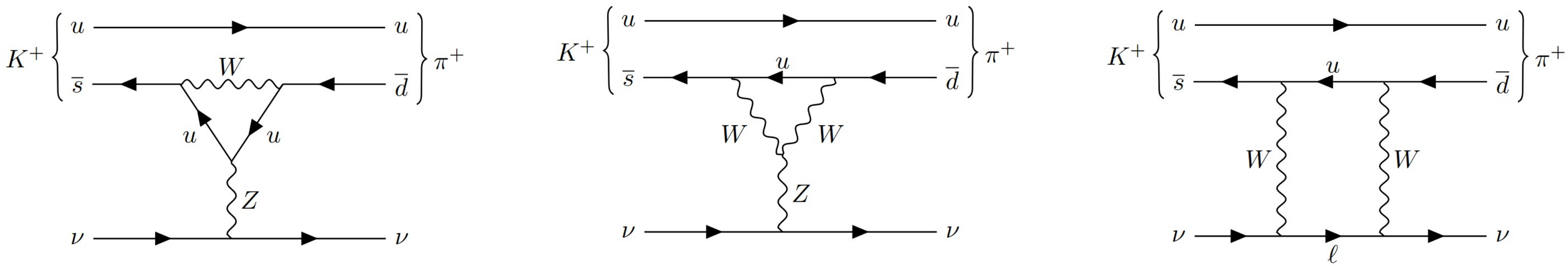
$K_2^0 \rightarrow 3\pi$ slow

BUT: In 1964, Cronin and Fitch realised that physical states are no pure CP eigenstates!

$$|K_S^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_1^0\rangle + \epsilon\,|\bar{K}_2^0\rangle\right) \qquad |K_L^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_2^0\rangle + \epsilon\,|\bar{K}_1^0\rangle\right)$$

Indirect CP violation!

Recap: Rare Kaon decays in the SM



$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \tilde{\kappa}^+ \left[\left(\frac{\Im(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2 + \left(\frac{\Re(V_{cs}^* V_{cd})}{\lambda} P_c + \frac{\Re(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\Im(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2$$

GIM suppression!

Buchalla, Buras (1999)

$\lambda \approx 0.225$ Wolfenstein parameter

$X_t = 1.48$ short-distance top quark contribution (NLO QCD and NNLO EW)

$\mathrm{P}_c = 0.404$ higher order charm quark contributions

$\tilde{\kappa}^+ = \kappa^+(1 + \Delta_{\mathrm{EM}})$
$\Delta_{\mathrm{EM}} = -0.003$ long distance EW corrections

Small hadronic uncertainty!

Mescia, Smith (2007)

$$\kappa^+ = (0.5173 \pm 0.025) \times 10^{-10} (|V_{us}| / 0.0225)^8$$

$$\kappa_L = (2.231 \pm 0.013) \times 10^{-10} (|V_{us}| / 0.0225)^8$$

Due to relation to more frequent decay $K \to \pi \ell^+ \nu_\ell$

Golden Channel!

Experimental Status and Perspective

Theory

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

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

Buras, Buttazzo, Girrbach-Noe, Knegjens (2015)

Experiment

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{E949}} = \left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10}$$

E949 collaboration (2009)

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{NA62}} < 1.78 \times 10^{-10}$$

NA62 collaboration (2020)

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} = \left(2.1^{+4.1}_{-1.7}\right) \times 10^{-9}$$

KOTO collaboration (2019)

Grossmann-Nir bound

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 4.4 \times \mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$$

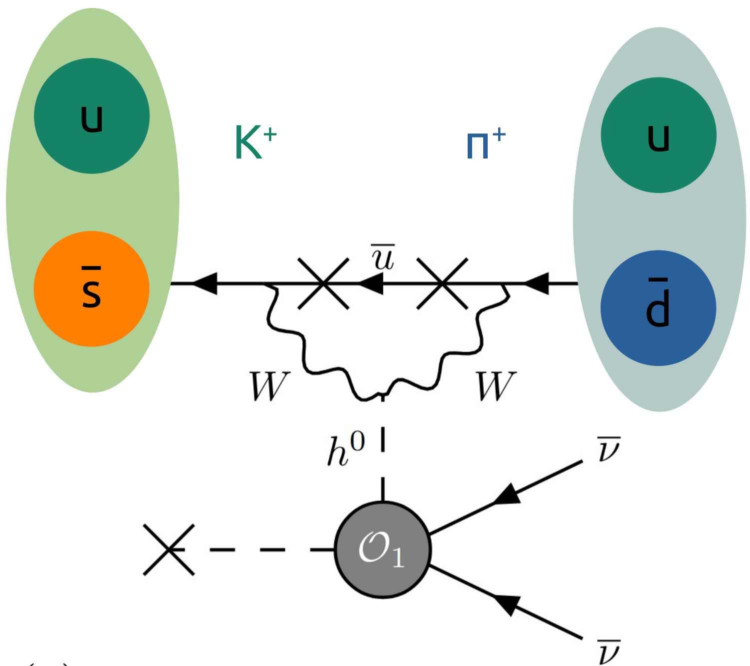
Future Limit:

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})^{\mathrm{future}}_{\mathrm{NA62}} \lesssim 1.11 \times 10^{-10}$$

“SM sensitivity”

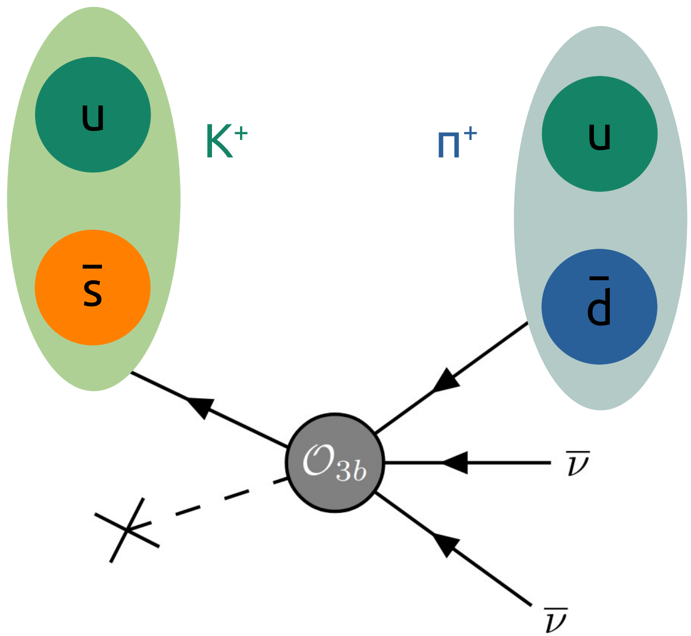
To what extent can NP (e.g. LNV) still hide?

Constraining LNV interactions with rare kaon decays



$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

- GIM suppressed



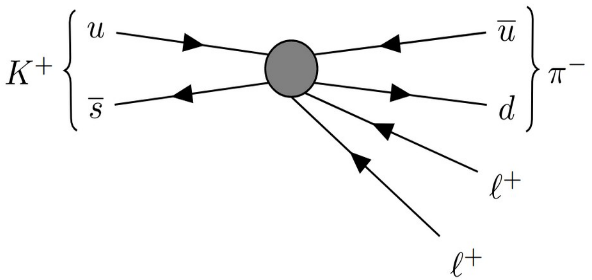
$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

- No GIM suppression
- Includes first and second generation

Not explicit LNV!

How are higher dimensional operators constraint by rare kaon decays?

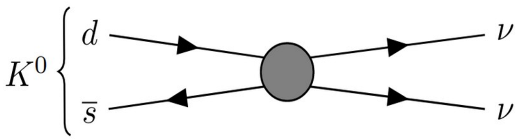
Probing LNV interactions – Meson decays



Same sign leptonic final state

- LNV is directly tested
- dim-9 only
- For first generation 0νββ stronger
- constraints too weak

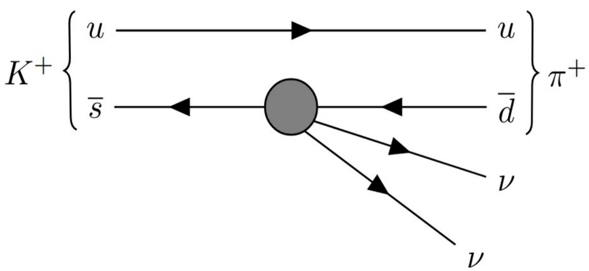
Liu, Zhang, Zhou (2016)
Quintero (2017)
Chun, Das, Mandal, Mitra, Sinha (2019)



Decay into neutrino final state

- No experiments
- dim-7

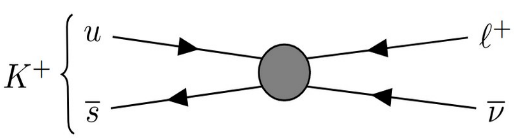
Gninenko (2014)



Neutrino final state

- LNV needs to be independently confirmed
- dim-7

Deppisch, Fridell, JH (2020)

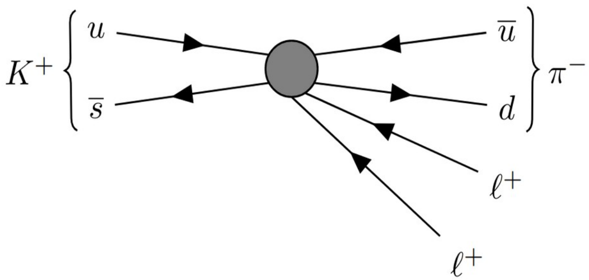


Charged lepton + neutrino final state

- Neutrino needs to be detected (Cooper et al. 1982)
- dim-7

Deppisch, Fridell, JH (2020)

Probing LNV interactions – Meson decays



Same sign leptonic final state

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Liu, Zhang, Zhou (2016)
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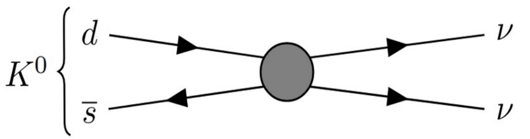
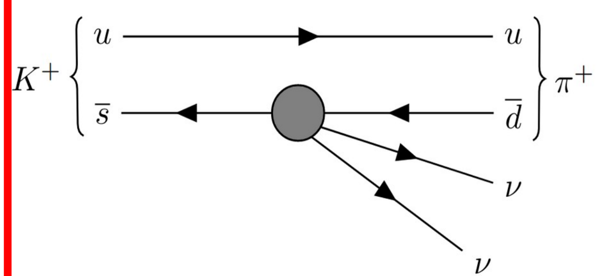


Decay into neutrino final state

- No experiments
- dim-7

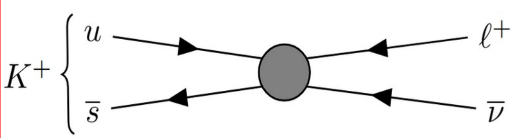
Gninenko (2014)



Neutrino final state

- LNV needs to be independently confirmed
- dim-7

Deppisch, Fridell, JH (2020)



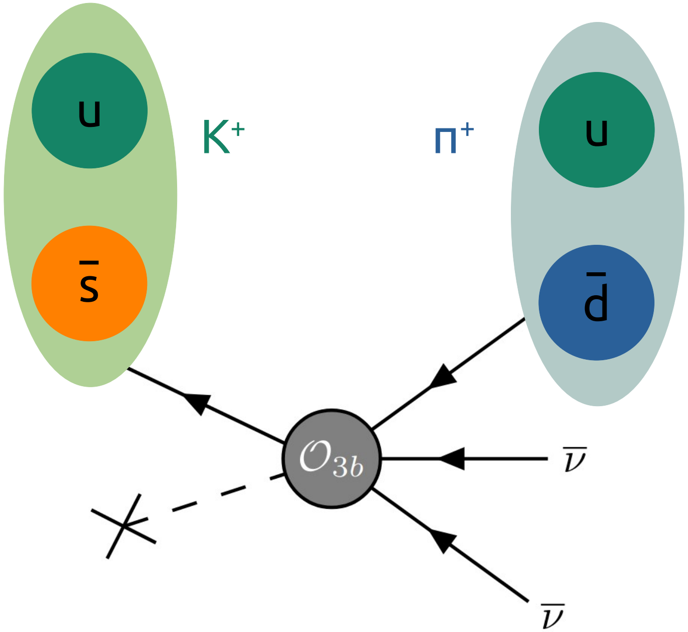
Charged lepton + neutrino final state

- Neutrino needs to be detected (Cooper et al. 1982)
- dim-7

Deppisch, Fridell, JH (2020)

Calculating LNV Branching Ratio I

$$\boxed{\langle\pi(p')|\,\bar{d}s\,|K(p)\rangle\,\nu_i(k)\nu_j(k')}$$



Possible SU(2)$_L$ contraction:

$$\mathcal{O}_{3b}^{(7)} = L_i^\alpha L_j^\beta Q_a^\rho d_b^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma} \rightarrow h^0 d_a^c d_{L_b}\nu_{L_i}\nu_{L_j}$$

Contraction of spinor indices:

$$h^0 d_a^c d_{L_b}\nu_{L_i}\nu_{L_j} \rightarrow c_1^{ijab} h^0 \left(d_a^c d_{L_b}\right)\left(\nu_{L_i}\nu_{L_j}\right) + c_2^{ijab} h^0 \left(d_a^c \nu_{L_i}\right)\left(\nu_{L_j} d_{L_b}\right)$$

Fierz transformation:

$$c_1^{ijab} - \frac{c_2^{ijab}}{2} h^0 \left(d_a^c d_{L_b}\right)\left(\nu_{L_i}\nu_{L_j}\right) - \frac{c_2^{ijab}}{2} h^0 \left(d_a^c \sigma^{\mu\nu} d_{L_b}\right)\left(\nu_{L_j}\sigma_{\mu\nu}\nu_{L_i}\right) + h.c.$$

Tensor contribution vanishes if neutrinos same flavour

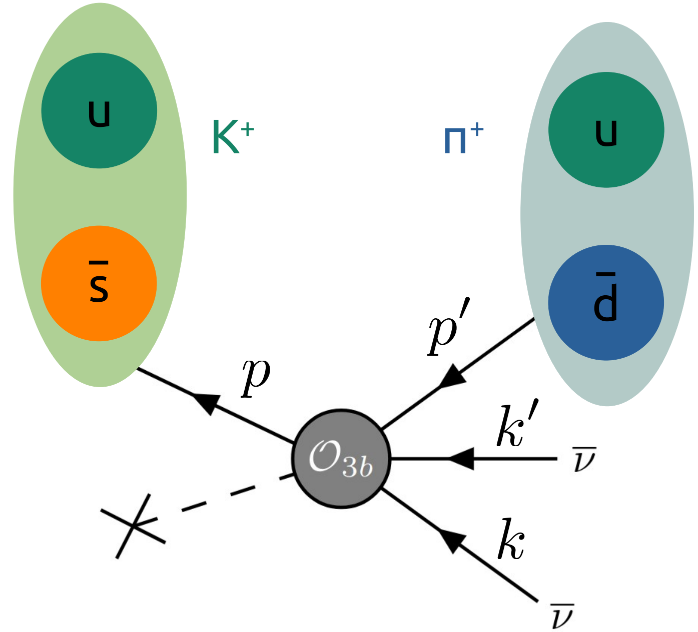
In Dirac notation (assumption of real couplings) :

$$\underbrace{c_1^{ijab} - \frac{c_2^{ijab}}{2}}_{\frac{1}{\Lambda_{ijab}^3}} h^0 \left[\left(\bar{d}_a d_b\right)\left(\bar{\nu}_i \nu_j\right) + \left(\bar{d}_a \gamma_5 d_b\right)\left(\bar{\nu}_i \gamma_5 \nu_j\right)\right]$$

vanishes due to pseudoscalar nature of kaons and pions

$$\boxed{i\mathcal{M} = \frac{v}{\Lambda_{ijsd}^3}\langle\pi(p')|\,\bar{d}s\,|K(p)\rangle\,\nu_i(k)\nu_j(k')}$$

Calculating LNV Branching Ratio II



$$i\mathcal{M} = \frac{v}{\Lambda^3_{ijsd}} \underbrace{\langle \pi(p')|\, \bar{d}s \,|K(p)\rangle}_{\frac{m_K^2 - m_\pi^2}{m_s - m_d} f_0^K(s)} \nu_i(k)\nu_j(k')$$

$$|\mathcal{M}|^2 = \frac{v^2}{\Lambda^6_{ijsd}} \left(\frac{m_K^2 - m_\pi^2}{m_s - m_d} f_0^K(s) \right)^2 s$$

$$f_0^K(s) = f_+^K(0) \left(1 + \lambda_0 \frac{s}{m_\pi^2} \right)$$

$$f_+^{K^+}(0) = 0.9778$$
$$f_+^{K_L}(0) = 0.9544$$

$$\boxed{\frac{\Gamma(K \to \pi \nu_i \nu_j)}{ds\, dt} = \frac{1}{1+\delta_{ij}} \frac{1}{(2\pi)^3} \frac{1}{32 m_K^3} |\overline{\mathcal{M}}|^2}$$

$$t = (k' + p')^2$$
$$s = (p - p')^2 = (k + k')^2$$

- Usage of **known hadronic matrix elements / form factors**
- **Alternative approach:** SMEFT matched on chiral perturbation theory

Li, Ma, Schmidt (2019)

Constraining power at E949

- **SM**, lepton number **conserving vector** current

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

- **BSM**, lepton number **violating scalar** current

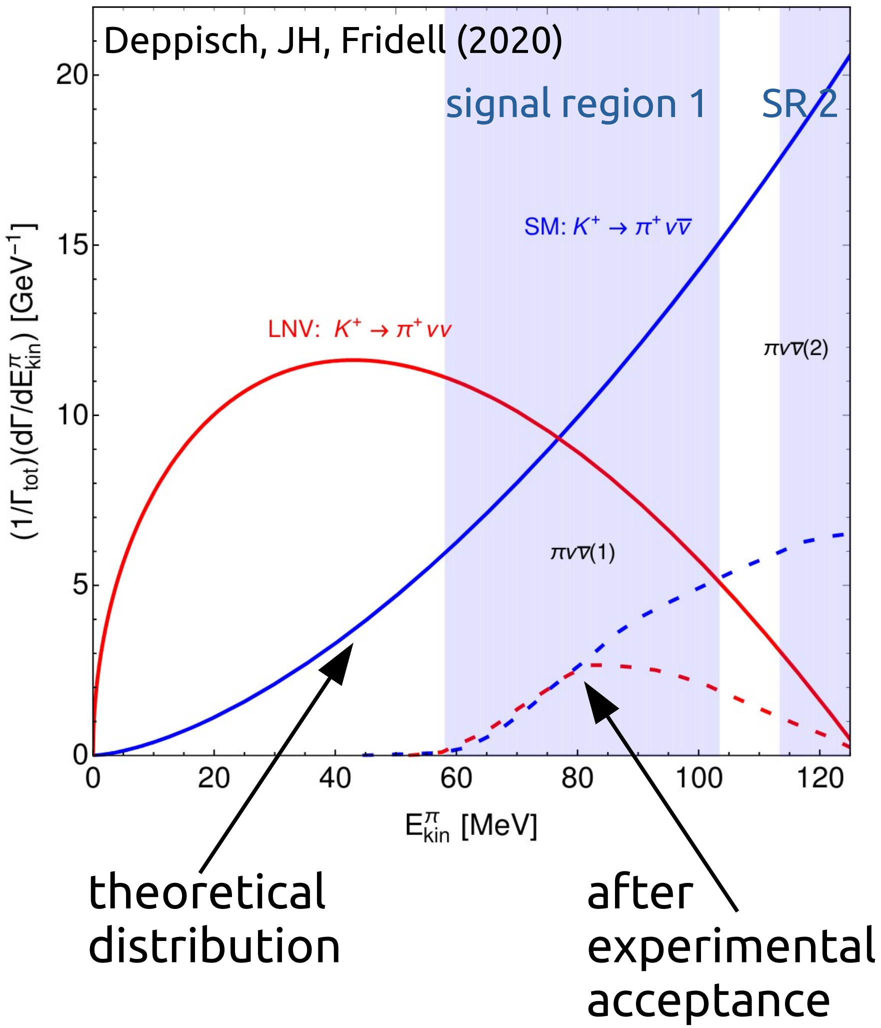
$$\mathcal{L}_{\rm BSM}^{K\to\pi\nu\nu} = \frac{v}{\Lambda_{\rm BSM}^2}\left(\nu_i\nu_j\right)\left(\bar{d}s\right)$$

→ **different phase space distribution**

- **different acceptance:**

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

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



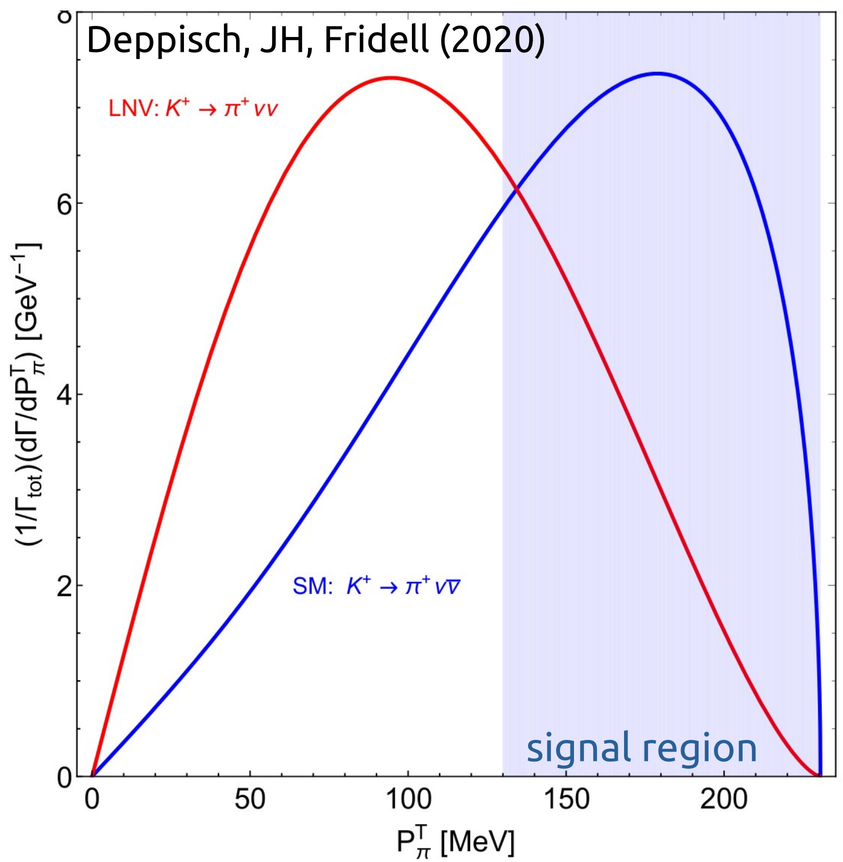
Constraining power at KOTO

$$\langle \pi^0 | \bar{d} s | \bar{K}^0 \rangle = \langle \pi^0 | \bar{s} d | K^0 \rangle$$
$$\langle \pi^0 | \bar{d} \gamma^\mu s | \bar{K}^0 \rangle = - \langle \pi^0 | \bar{s} \gamma^\mu d | K^0 \rangle$$

$$\boxed{i\mathcal{M}\left(K_L \to \pi^0 \nu\nu\right) = \frac{1}{\sqrt{2+2|\epsilon|^2}} \Big(F(1+\epsilon) \langle \pi^0 | C | K^0 \rangle + F^*(1-\epsilon) \langle \pi^0 | C | \bar{K}^0 \rangle \Big) \nu\nu}$$

LNV mode → scalar current → real part

LNC mode → vector current → imaginary part

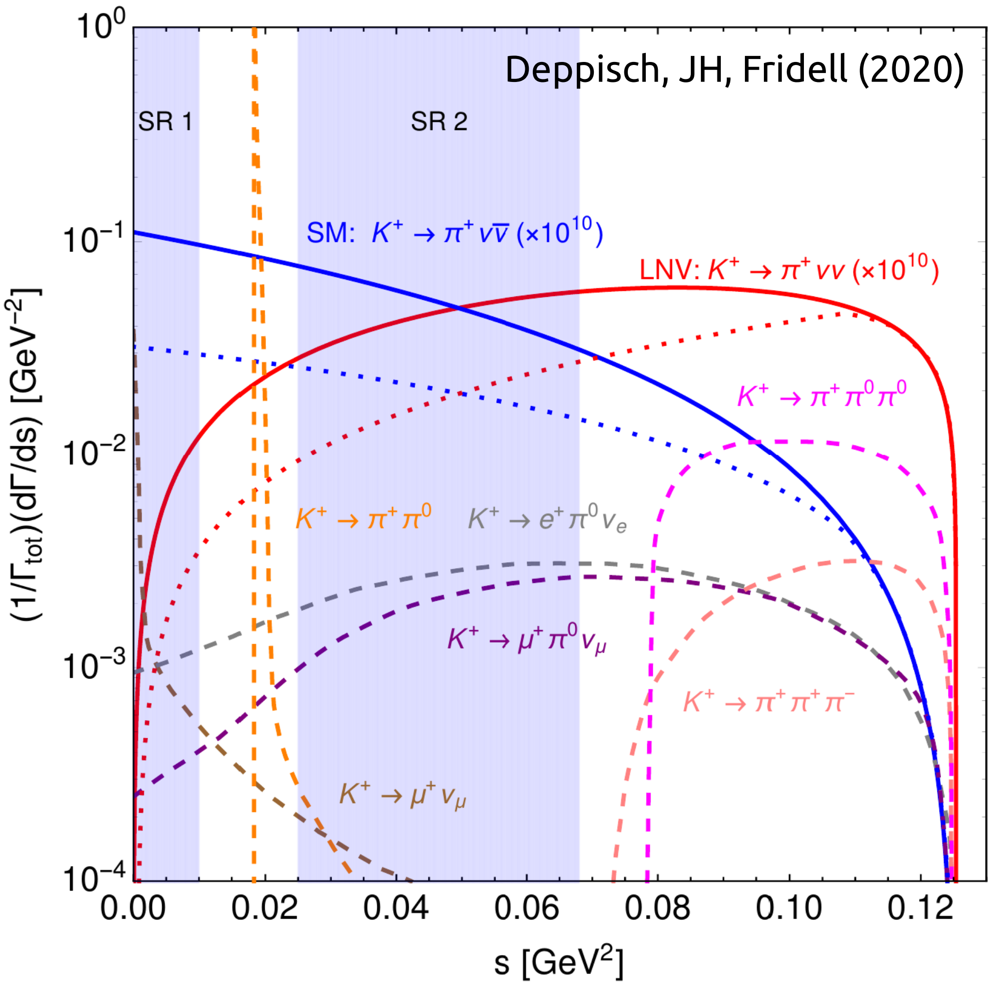


→ no CP phase needed in the LNV case

→ different phase space distribution

→ current signal region more sensitive to SM current

Constraining power at NA62



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

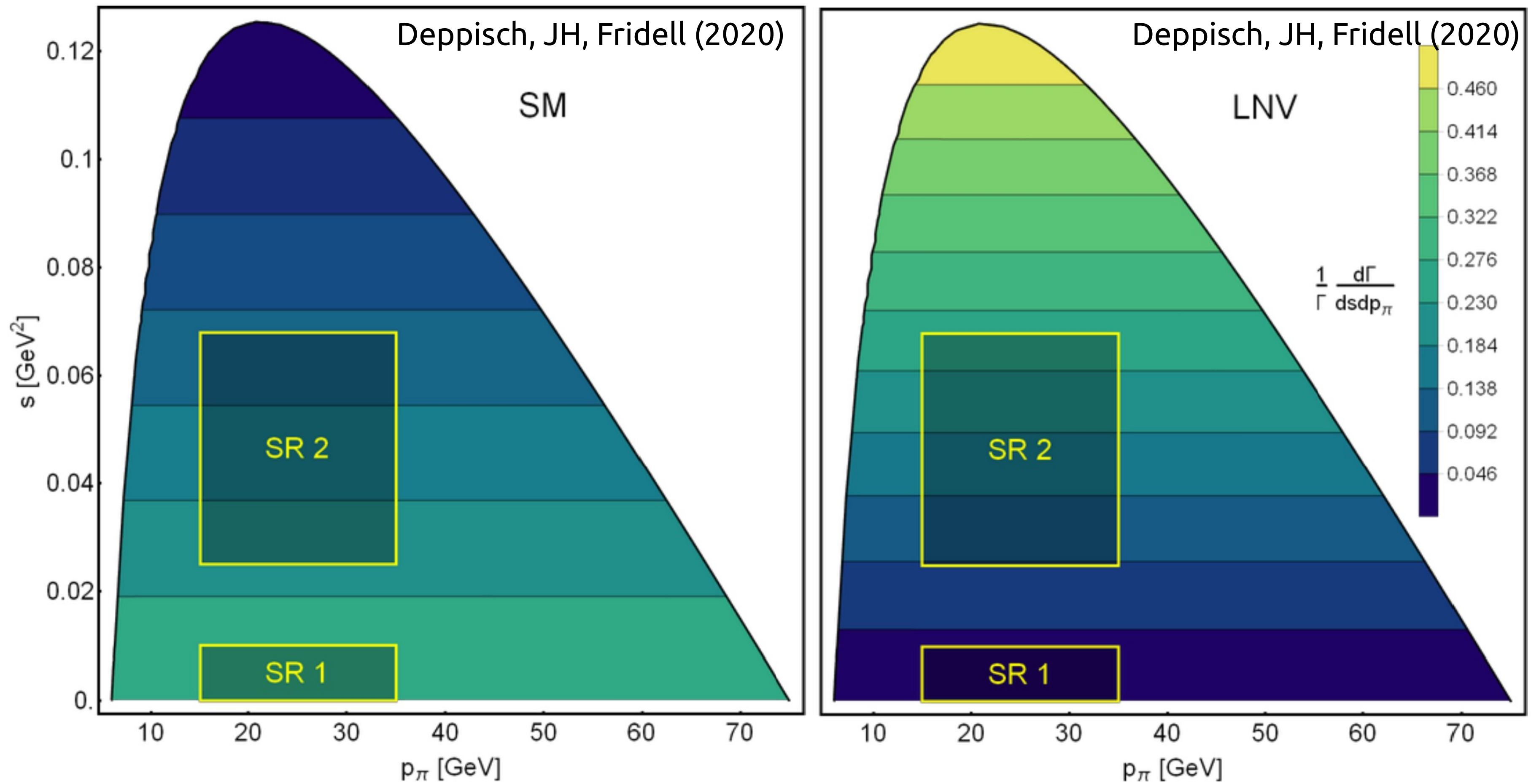
Summary of sensitivity to scalar current (based on kinematics only):

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%

Experiments are generally more sensitive to vector currents

Possibility to disentangle a possible signal by improving on experimental sensitivity and strategy?

Constraining power at NA62



For **LNV** more events in **SR1** expected.
for **LNC** more events in **SR2** expected.

Constraints on the New Physics Scale

After integrating over the differential distributions:

$$\boxed{\begin{aligned} \mathrm{BR}_{\mathrm{LNV}}(K^+ \to \pi^+ \nu_i \nu_j) &= 10^{-10} \left(\frac{19.2 \text{ TeV}}{\Lambda_{ijsd}} \right)^6 \\ \mathrm{BR}_{\mathrm{LNV}}(K_L \to \pi^0 \nu_i \nu_j) &= 10^{-10} \left(\frac{24.9 \text{ TeV}}{\Lambda_{ijsd}} \right)^6 \end{aligned}}$$

LNV signal might give additional contribution besides SM contribution:

$$\mathrm{BR}(K \to \pi \nu \nu) = \mathrm{BR}_{\mathrm{SM}}(K \to \pi \nu \bar{\nu}) + \sum_{i \leq = j}^{3} \mathrm{BR}_{\mathrm{LNV}}(K \to \pi \nu_i \nu_j)$$

Different experimental acceptance for different currents:

$$N(K \to \pi \nu \nu) = \Big(\mathrm{BR}(K \to \pi \nu \bar{\nu})_{\mathrm{SM}} A_{\mathrm{SM}} + \mathrm{BR}(K \to \pi \nu \nu)_{\mathrm{LNV}} A_{\mathrm{LNV}} \Big) N_K$$

$$\boxed{\mathrm{BR}(K \to \pi \nu \bar{\nu})_{\mathrm{SM}} + \left(\frac{A_{\mathrm{LNV}}}{A_{\mathrm{SM}}} \right) \times \sum_{i \leq j = 1}^{3} \mathrm{BR}(K \to \pi \nu_i \nu_j)_{\mathrm{LNV}} < 3.35 \times 10^{-10}} \quad \frac{A_{\mathrm{LNV}}}{A_{\mathrm{SM}}} = 0.41$$

Putting pieces together

1st generation couplings

$\mathcal{O}$	$1/\Lambda^2_{K\to\pi\nu\nu}$	$\sum_i \Lambda^{\text{E949}}_{iisd}$ [TeV]	m_ν	Λ^{m_ν} [TeV]
1^{y_d}	$\frac{v^3}{\Lambda^5}$	2.4	$\frac{y_d}{16\pi^2}\frac{v^4}{\Lambda^3}$	11.6
$3b$	$\frac{v}{\Lambda^3}$	11.5	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}$	5.2×10^4
$3b^{H^2}$	$f(\Lambda)\frac{v}{\Lambda^3}$	5.7	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f(\Lambda)$	330
5	$\frac{1}{16\pi^2}\frac{v}{\Lambda^3}$	2.6	$\frac{y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	330
10	$\frac{1}{16\pi^2}\frac{y_e v}{\Lambda^3}$	0.8	$\frac{y_e y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	9.6×10^{-4}
$11b$	$\frac{1}{16\pi^2}\frac{y_d v}{\Lambda^3}$	0.8	$\frac{y_d^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	8.9×10^{-3}
$14b$	$\frac{1}{16\pi^2}\frac{y_u v}{\Lambda^3}$	2.9	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	4.1×10^{-3}
66	$f(\Lambda)\frac{v}{\Lambda^3}$	5.1	$\frac{y_d}{16\pi^2}\frac{v^2}{\Lambda}f(\Lambda)$	330

Sensitivity to different flavors than most constraining 0νββ !

Process	Experimental limit	$\mathcal{O}$	$\Lambda^{\text{NP}}_{ijkn}$ [TeV]
$K^+\to\pi^+\nu\nu$	$\text{BR}^{\text{NA62}}_{\text{future}} < 1.11\times10^{-10}$ x	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 19.6$
$K^+\to\pi^+\nu\nu$	$\text{BR}^{\text{NA62}}_{\text{current}} < 1.78\times10^{-10}$ [67]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 17.2$
$K_L\to\pi^0\nu\nu$	$\text{BR}^{\text{KOTO}}_{\text{current}} < 3.0\times10^{-9}$ [71]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 12.3$

Similar analysis for charged final states

$\mathcal{O}$	$1/\Lambda^2_{M^+\to\ell_i^+\bar{\nu}_j}$	$\Lambda_{\mu eus}$ [TeV]	$\Lambda_{\mu eud}$ [TeV]	m_ν	Λ^{m_ν} [TeV]
$3a$	$\frac{v}{\Lambda^3}$	2.2	1.7	$\frac{y_d g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	69
$3a^{H^2}$	$f(\Lambda)\frac{v}{\Lambda^3}$	1.3	1.1	$\frac{y_d g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}f(\Lambda)$	0.4
$4a$	$\frac{v}{\Lambda^3}$	2.2	1.7	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}$	2.4×10^4
$4a^{H^2}$	$f(\Lambda)\frac{v}{\Lambda^3}$	1.3	1.1	$\frac{y_u}{16\pi^2}\frac{v^2}{\Lambda}f(\Lambda)$	150
$4b^\dagger$	$\frac{v}{\Lambda^3}$	2.2	1.7	$\frac{y_u g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	33
$4b^{\dagger H^2}$	$f(\Lambda)\frac{v}{\Lambda^3}$	1.3	1.1	$\frac{y_u g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	0.2
6	$f(\Lambda)\frac{v}{\Lambda^3}$	1.3	1.1	$\frac{y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	150
7	$\frac{v^3}{\Lambda^5}$	0.8	0.7	$\frac{y_e g^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}f(\Lambda)$	0.6
8	$\frac{v}{\Lambda^3}$	2.2	1.7	$\frac{y_e y_d y_u g^2}{(16\pi^2)^2}\frac{v^4}{\Lambda^3}$	4.3×10^{-4}
8^{H^2}	$f(\Lambda)\frac{v}{\Lambda^3}$	1.3	1.1	$\frac{y_e y_d y_u g^2}{(16\pi^2)^2}\frac{v^4}{\Lambda^3}f(\Lambda)$	7.9×10^{-5}
$11a$	$\frac{1}{16\pi^2}\frac{y_d v}{\Lambda^3}$	0.2	0.1	$\frac{y_d^2 g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1.2×10^{-5}
$12a$	$\frac{1}{16\pi^2}\frac{y_u v}{\Lambda^3}$	0.6	0.5	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	1.9×10^{-3}
$12b^*$	$\frac{1}{16\pi^2}\frac{y_u v}{\Lambda^3}$	0.7	0.6	$\frac{y_u^2 g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	2.6×10^{-6}
13	$\frac{1}{16\pi^2}\frac{y_e v}{\Lambda^3}$	0.2	0.2	$\frac{y_e y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	4.5×10^{-4}
$14a$	$\frac{1}{16\pi^2}\frac{(y_u+y_d)v}{\Lambda^3}$	0.6	0.5	$\frac{y_u y_d g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	5.6×10^{-6}
16	$\frac{1}{16\pi^2}\frac{y_e v}{\Lambda^3}$	0.1	0.1	$\frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	7.4×10^{-9}
19	$\frac{1}{16\pi^2}\frac{y_d v}{\Lambda^3}$	0.1	0.1	$\frac{y_e y_u y_d^2 g^2}{(16\pi^2)^3}\frac{v^4}{\Lambda^3}$	2.4×10^{-6}
20	$\frac{1}{16\pi^2}\frac{y_u v}{\Lambda^3}$	0.5	0.4	$\frac{y_e y_u^2 y_d g^2}{(16\pi^2)^3}\frac{v^4}{\Lambda^3}$	1.8×10^{-6}

Summary

Process	Experimental limit	$\mathcal{O}$	$\Lambda^{\rm NP}_{ijkn}$ [TeV]	$\hat{\lambda}$ [TeV]
$K^+ \to \pi^+ \nu\nu$	$\mathrm{BR}^{\rm NA62}_{\rm future} < 1.11 \times 10^{-10}$	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 19.6$	0.213
$K^+ \to \pi^+ \nu\nu$	$\mathrm{BR}^{\rm NA62}_{\rm current} < 1.78 \times 10^{-10}$ [67]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 17.2$	0.196
$K_L \to \pi^0 \nu\nu$	$\mathrm{BR}^{\rm KOTO}_{\rm current} < 3.0 \times 10^{-9}$ [71]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 12.3$	0.178
$B^+ \to \pi^+ \nu\nu$	$\mathrm{BR} < 1.4 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibd} > 1.4$	0.174
$B^+ \to K^+ \nu\nu$	$\mathrm{BR} < 1.6 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibs} > 1.4$	0.174
$B^0 \to \pi^0 \nu\nu$	$\mathrm{BR} < 9 \times 10^{-6}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibd} > 1.5$	0.174
$B^0 \to K^0 \nu\nu$	$\mathrm{BR} < 2.6 \times 10^{-5}$ [52]	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iibs} > 1.3$	0.174
$K^+ \to \mu^+ \bar{\nu}_e$	$\mathrm{BR} < 3.3 \times 10^{-3}$ [32]	$\mathcal{O}_{3a}$	$\Lambda_{\mu esu} > 2.4$	0.174
$\pi^+ \to \mu^+ \bar{\nu}_e$	$\mathrm{BR} < 1.5 \times 10^{-3}$ [32]	$\mathcal{O}_{3a}$	$\Lambda_{\mu eud} > 1.9$	0.174
$\pi^0 \to \nu\nu$	$\mathrm{BR} < 2.9 \times 10^{-13}$ [78]	$\mathcal{O}_{3b}$	$\Lambda_{\nu\nu ud} > 3.4$	0.174
$0\nu\beta\beta$	$T^{136\rm Xe}_{1/2} \geq 1.07 \times 10^{26}$ yrs [79]	$\mathcal{O}_{3b}$	$\Lambda_{eeud} > 330$	3.5
$\mu^- \to e^+$	$R^{\rm Ti}_{\mu^- e^+} < 1.7 \times 10^{-12}$ [80]	$\mathcal{O}_{14b}$	$\Lambda_{\mu eud} > 0.01$	0.174

Bright future perspective – B-meson constraints still in LHC reach. Could imply strong lepton asymmetry washout*).

***) If LNV interaction is confirmed.**

Outlook: Leptoquarks

UV complete example: Leptoquarks I

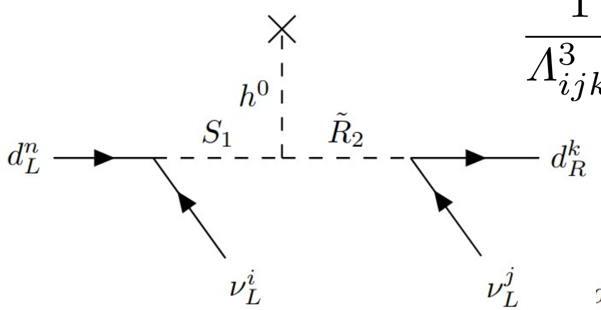
$$\boxed{\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mu S_1 H^{\dagger\alpha}\tilde{R}_{2\alpha} - g_1^{ik}\bar{L}_{i\alpha}\, i\sigma_2^{\alpha\beta}\tilde{R}^*_{2\beta}\overline{d}^c_k - g_2^{jn} Q^\alpha_n L^\beta_j \epsilon_{\alpha\beta} S_1 - g_3^{jn}\bar{u}^c_n e_j S_1 + \text{h.c.}}$$

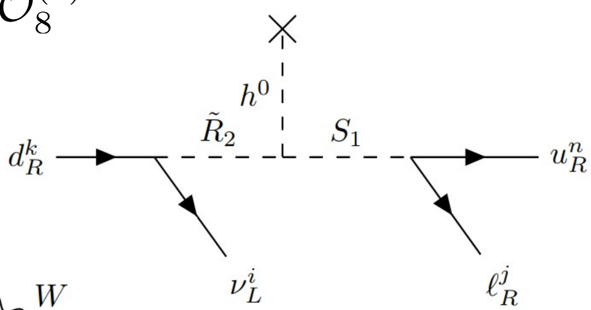
Cata, Mannel (2019)

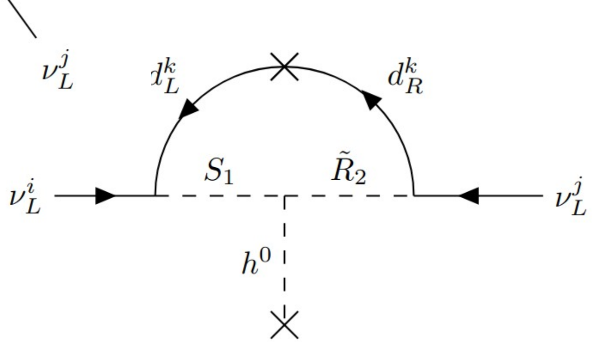
$$\tilde{R}_2 \in 3,\ 2,\ 1/6, \qquad S_1 \in \bar{3},\ 1,\ 1/3$$

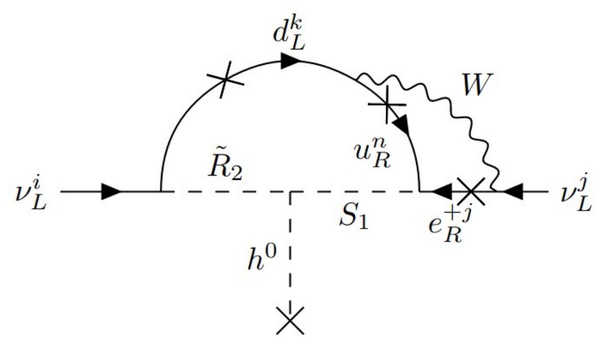
	L	B
$\tilde{R}_2$	-1	$+\frac{1}{3}$
S_1	-1	$-\frac{1}{3}$

$$\mathcal{L}_{7D} = \underbrace{\frac{\mu g_1^{ik} g_2^{jn}}{m^2_{\tilde{R}_2} m^2_{S_1}}}_{\frac{1}{\Lambda^3_{ijkn}}} \underbrace{L^\alpha_i H^\beta d^c_k Q^\mu_n L^\nu_j \epsilon_{\alpha\beta}\epsilon_{\mu\nu}}_{\mathcal{O}^{(7)}_{3b}} + \underbrace{\frac{\mu g_1^{ik} g_3^{jn}}{m^2_{\tilde{R}_2} m^2_{S_1}}}_{\frac{1}{\Lambda^3_{ijkn}}} \underbrace{L^\alpha_i H^\beta d^c_k u^c_n e^c_j \epsilon_{\alpha\beta}}_{\mathcal{O}^{(7)}_{8}}$$







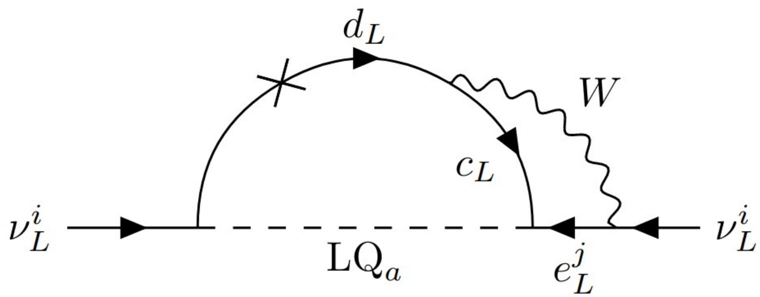


UV complete example: Leptoquarks II

$$\boxed{\mathcal{L} \supset \mathcal{L}_{\rm SM} + \mu S_1 H^{\dagger\alpha}\tilde{R}_{2\alpha} - g_1^{ik}\bar{L}_{i\alpha}i\sigma_2^{\alpha\beta}\tilde{R}^*_{2\beta}\overline{d}^c_k - g_2^{jn}Q^\alpha_n L^\beta_j \epsilon_{\alpha\beta}S_1 - g_3^{jn}\bar{u}^c_n e_j S_1 + \text{h.c.}}$$

Cata, Mannel (2019)

$$(m_\nu)_i = \sum_j \frac{3\sin(2\theta) g^2 V_{cd}\tilde{g}_1^{id}\tilde{g}_2^{jc}U_{ji}}{512\pi^4} m_d I(m^2_{\rm LQ_1}, m^2_{\rm LQ_2}, m^2_W)$$



1. gen / 2. gen / 3. gen

$$\tilde{g}_1 \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

1. gen / 2. gen / 3. gen

$$\tilde{g}_2 \sim \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$(m_\nu)_i \approx 0.08 eV$$

A contribution of Leptoquarks to rare kaon decays would imply a non-trivial flavour pattern to explain smallness of neutrino masses.

Conclusions

- **Majorana** neutrino masses might be based on **higher dimensional LNV operators** (e.g. dim-7)
- Strongest limit comes from **$0\nu\beta\beta$ decay**, but first generation only
- **Rare kaon decays** into same sign charged final states **(dim-9) only weakly constrained**
- **Rare kaon decays** into neutrino final states **(dim-7)** sets **competitive** limits (beyond first generation only) **BUT** no final conclusion of LNV interaction
- There is a **potential to disentangle** a vector from a scalar current in rare kaon decay experiments
- An observation of LNV in this range can imply **strong lepton-asymmetry washout**
- UV complete example: **leptoquarks**

Thank you for your attention!