

Footprints of Majorana Neutrinos in Rare Meson Decays

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in collaboration with **F. Deppisch** and **K. Fridell** (hep-ph/2009.04494)
and **A. J. Buras** (upcoming work)

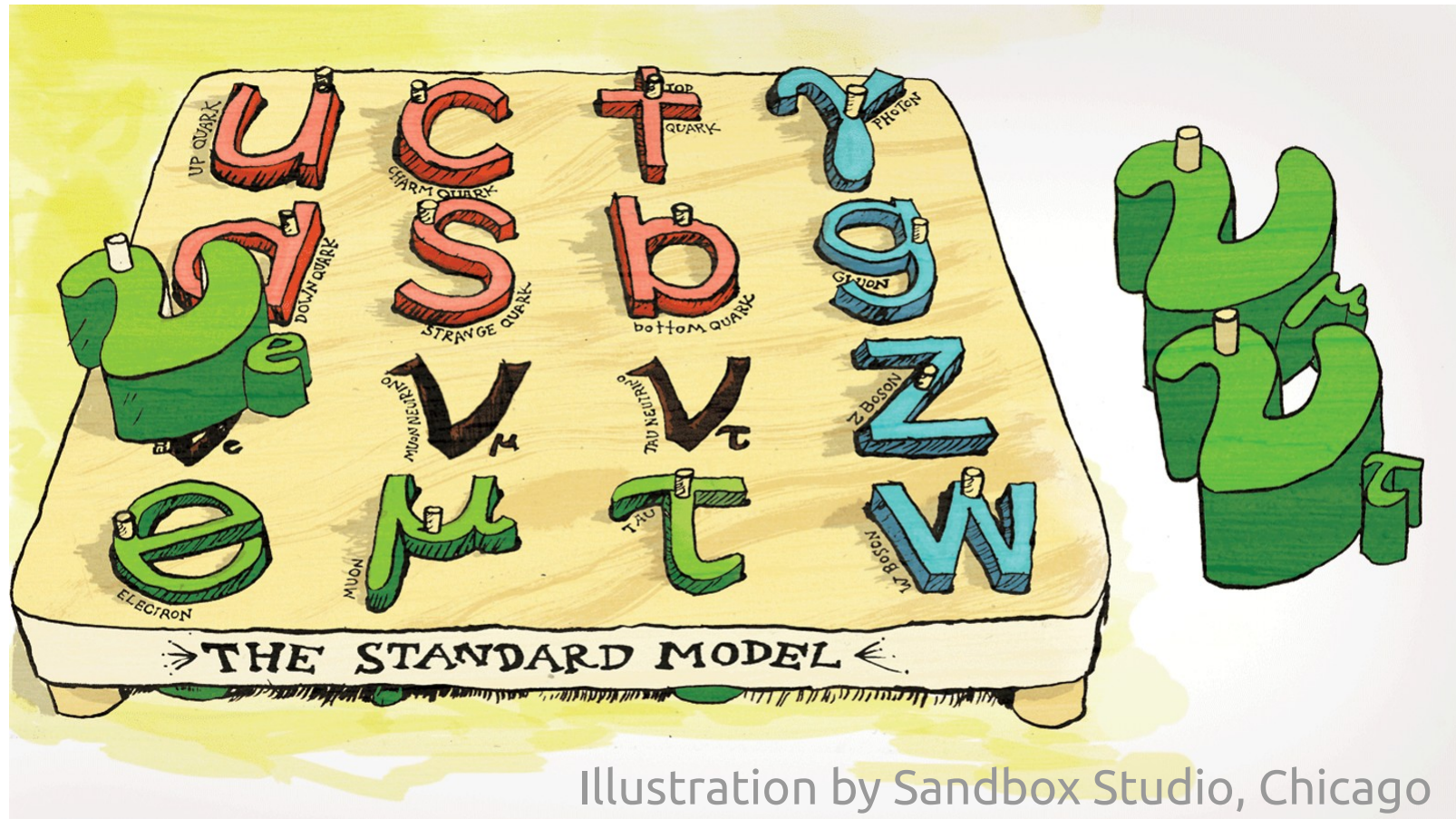
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ICHEP conference 2022



Technische Universität München



Neutrinos – the Standard Model misfits

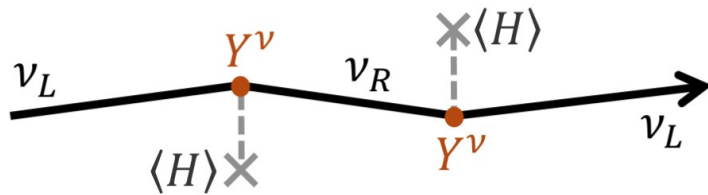


Neutrinos - Dirac or Majorana?

Dirac mass

$$y_\nu L \epsilon H \bar{\nu}_R \supset m_D \nu_L \bar{\nu}_R$$

→ **lepton number no accidental symmetry anymore**



Majorana mass

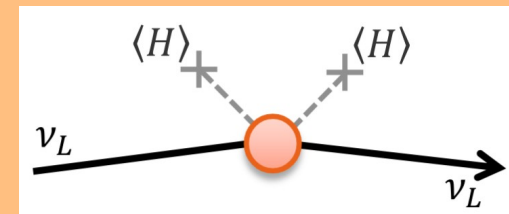
$$m_M \bar{\nu}_R \nu_R^c$$

→ higher dimensional operator

$$m_M \bar{\nu}_L \nu_L^c \quad LLHH$$

not at tree-level within the SM possible

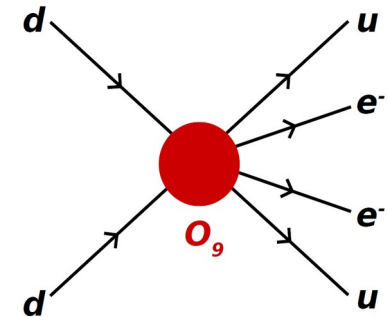
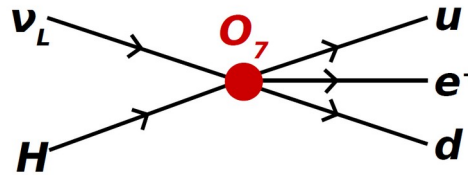
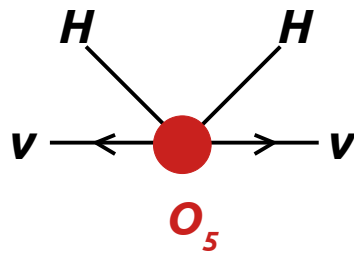
→ **Lepton number violation (LNV)**



Lepton Number Violation

LNV occurs only at odd mass dimension beyond dim-4:

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



See surveys of all LNV operators up to dim-11 e.g. in
Babu, Leung (2001), Gouvea, Jenkins (2008), Graf, JH, Deppisch, Huang (2018)

Lepton Number Violation

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

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

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

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

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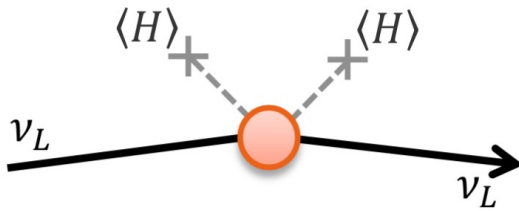
Lepton Number Violation

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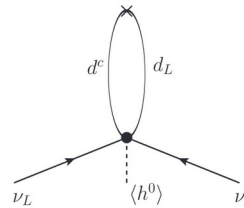
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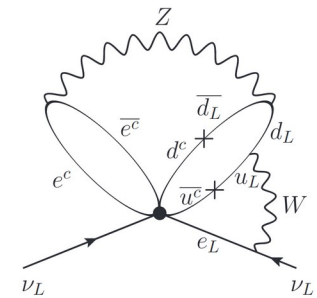
$$\mathcal{O}_{16}^{(9)} = L^\alpha L^\beta e^c d^c \bar{e}^c \bar{u}^c \epsilon_{\alpha\beta}$$



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



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

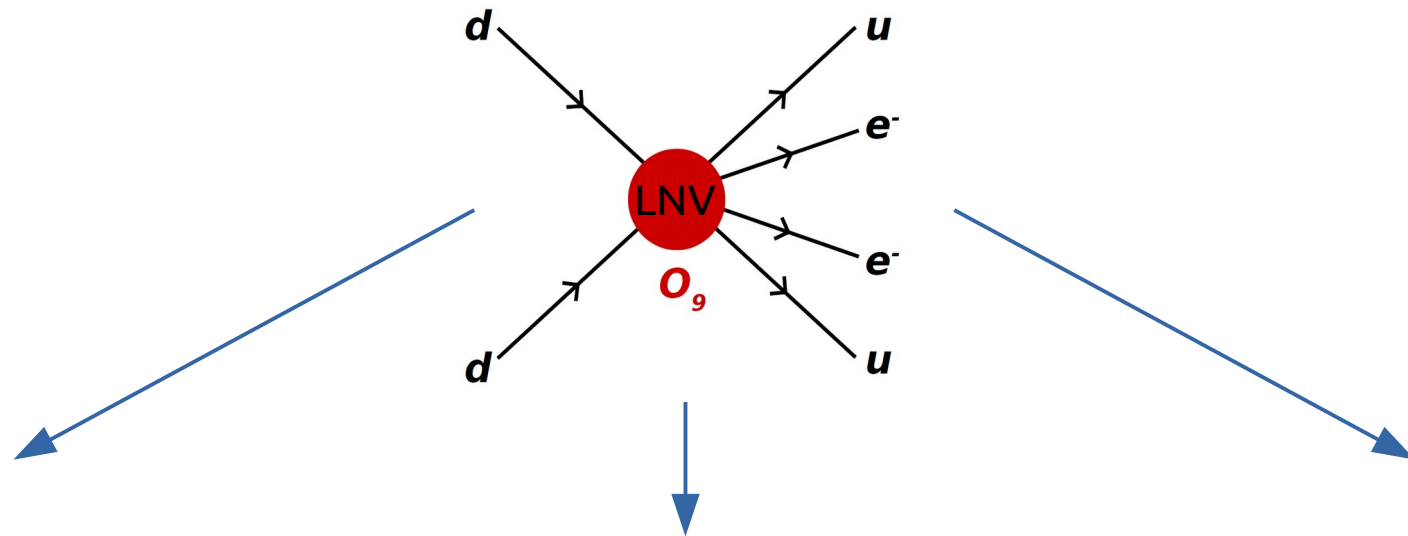


$$m_\nu \approx \frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda_{16}}$$

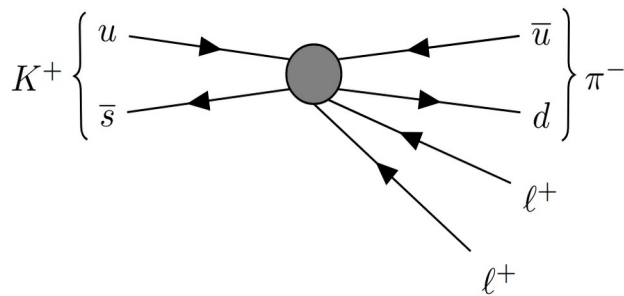
→ the discovery of a higher dimensional operator will point towards a Majorana contribution to neutrino masses

Gouvea, Jenkins (2008), Graf, JH, Deppisch, Huang (2018)

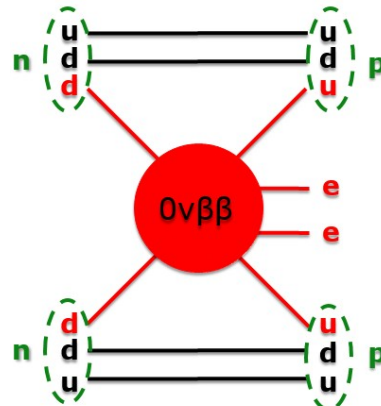
Probing LNV interactions



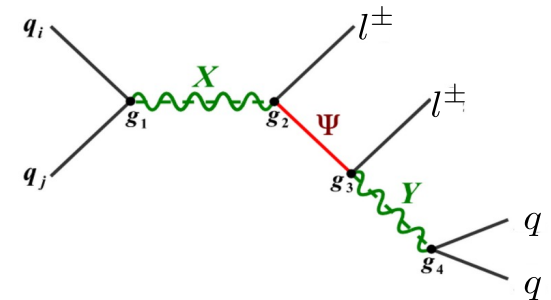
rare meson decays



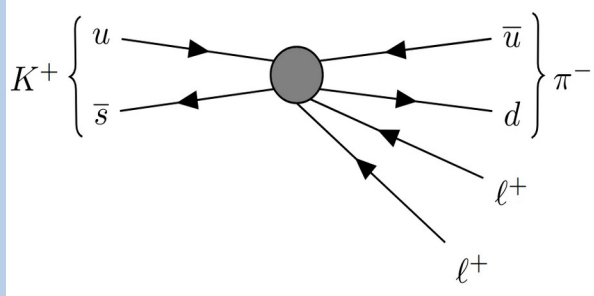
neutrinoless double beta decay



colliders



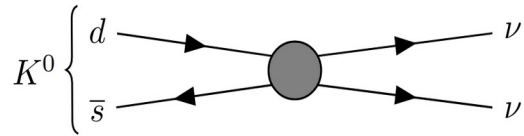
Probing LNV interactions with Kaon decays



Same-sign leptonic final state

- LNV is directly tested
- dim-9 SMEFT only
- for first generation, $0\nu\beta\beta$ stronger
- constraints very weak

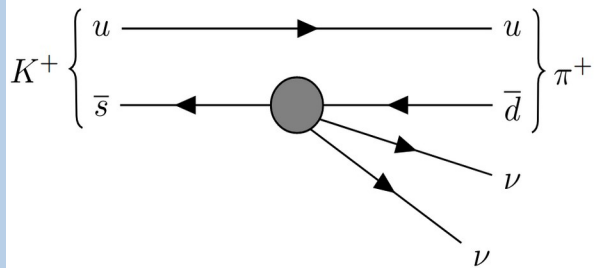
Liu, Zhang, Zhou (2016)
Quintero (2017)
Chun, Das, Mandal, Mitra, Sinha (2019)



Decay into neutrino final state

- No experimental searches?
- dim-7 SMEFT

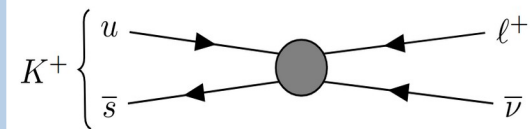
Gninenko (2014)



Neutrino final state

- LNV needs to be independently confirmed
- dim-7 SMEFT

Li, Ma, Schmidt (2019)
Deppisch, Fridell, JH (2020)
Buras, JH (2022)

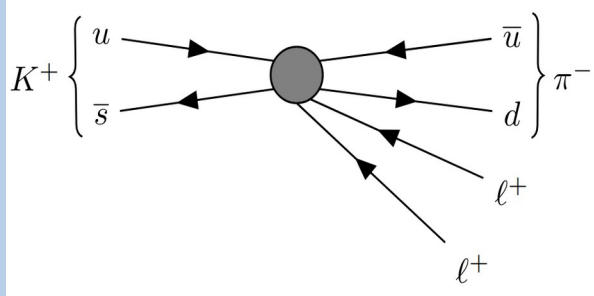


Charged lepton + neutrino final state

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

Deppisch, Fridell, JH (2020)

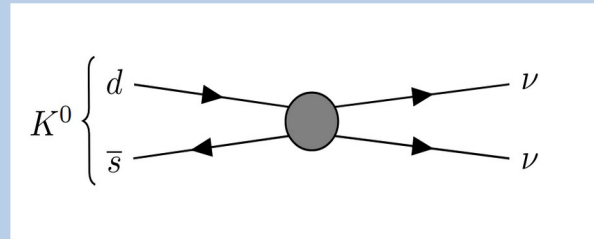
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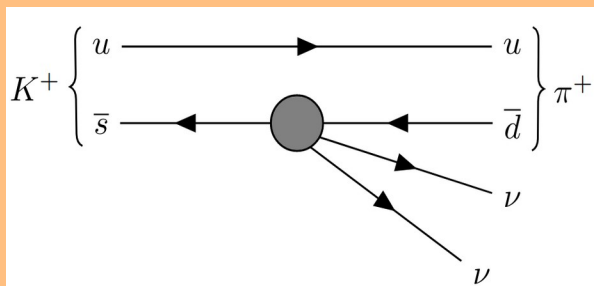
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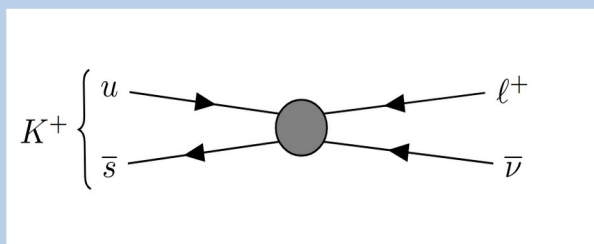
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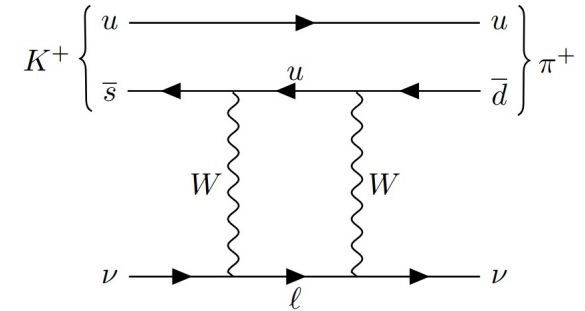
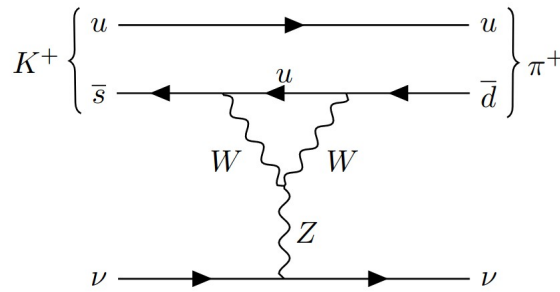
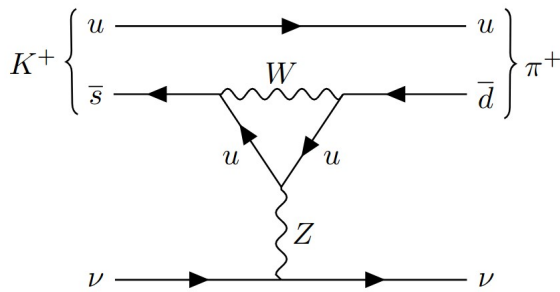


Charged lepton + neutrino final state

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

Deppisch, Fridell, JH (2020)

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ in the Standard Model



Branching Ratios:

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa^+ (1 + \Delta_{EM}) \left[\left(\frac{\text{Im}(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2 + \left(\frac{\text{Re}(V_{cs}^* V_{cd})}{\lambda} P_c + \frac{\text{Re}(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2 \right]$$

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

GIM suppressed in the SM!

Buchalla, Buras (1999)

Small hadronic uncertainties due to relation to well measured $K \rightarrow \pi \ell^+ \nu_\ell$:

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

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

Mescia, Smith (2007)

Theoretical and experimental status

Theoretical prediction

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (8.60 \pm 0.42) \times 10^{-11}$$

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{SM}} = (2.94 \pm 0.15) \times 10^{-11}$$

Buras, Buttazzo, Girschbach-Noe, Kneijens (2015)
updated by Buras, Venturini (2021)

Golden Channel!

Experimental measurements

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{E949}} = (1.73_{-1.05}^{+1.15}) \times 10^{-10}$$

E949 collaboration (2009)

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{NA62}} = (10.6_{-3.5}^{+4.0} \pm 0.9) \times 10^{-11}$$

NA62 collaboration (2021)

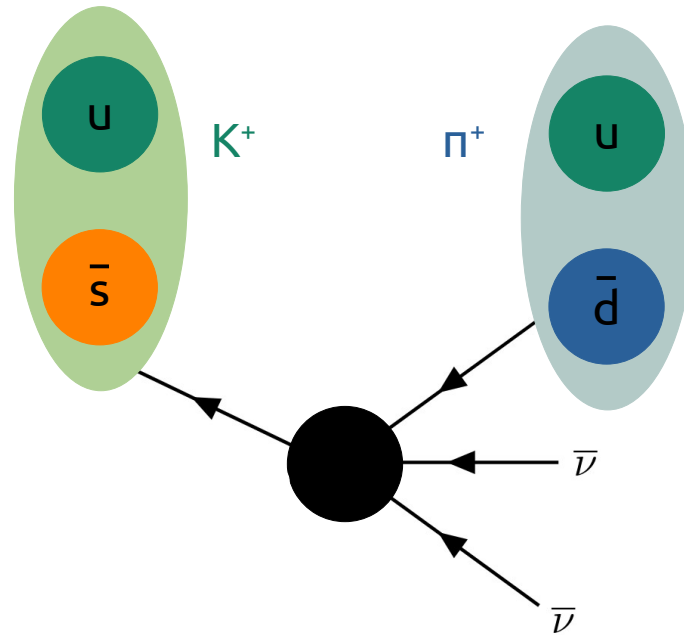
$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{KOTO}} = (2.1_{-1.1(-1.7)}^{+2.0(+4.1)}) \times 10^{-9}$$

KOTO collaboration (2019)

→ **NA62 aims to reach SM sensitivity!**

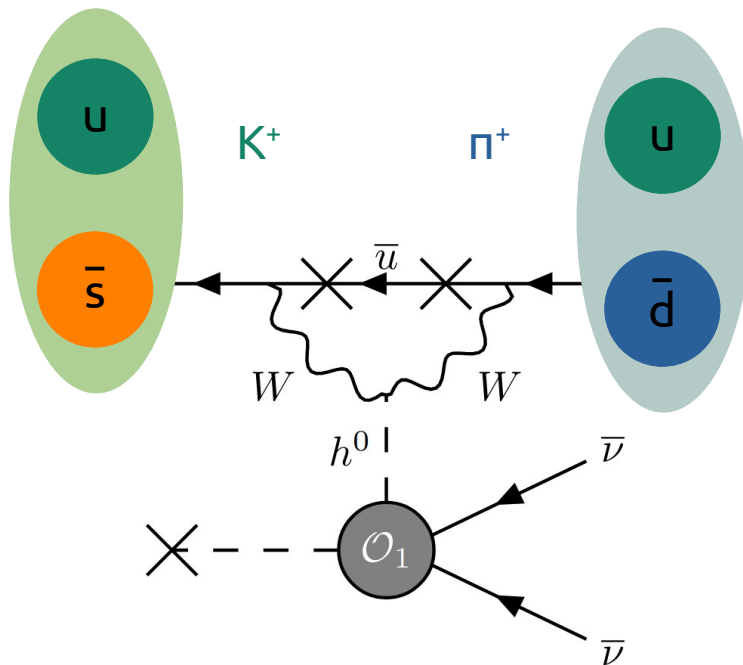
What would a deviation from the SM expectation imply for new physics?

Constraining new physics in rare kaon decays



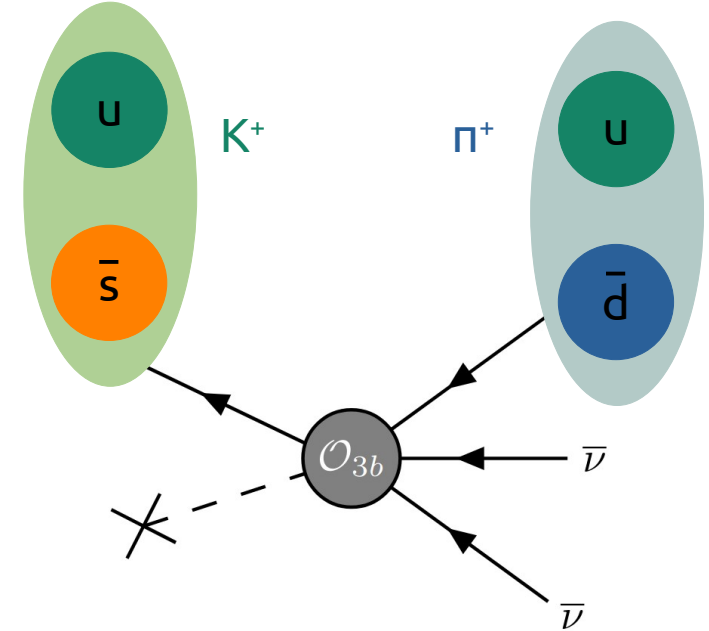
As neutrinos are not explicitly measured, a new physics contribution could also be lepton number violating!

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
- Majorana neutrino mass



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

- No GIM suppression
- **Majorana contribution to neutrino masses**

→ **Footprints of Majorana neutrinos in rare meson decays?**

→ **BUT: no unambiguous signal of LNV – is there a way to disentangle LNV from LNC?**

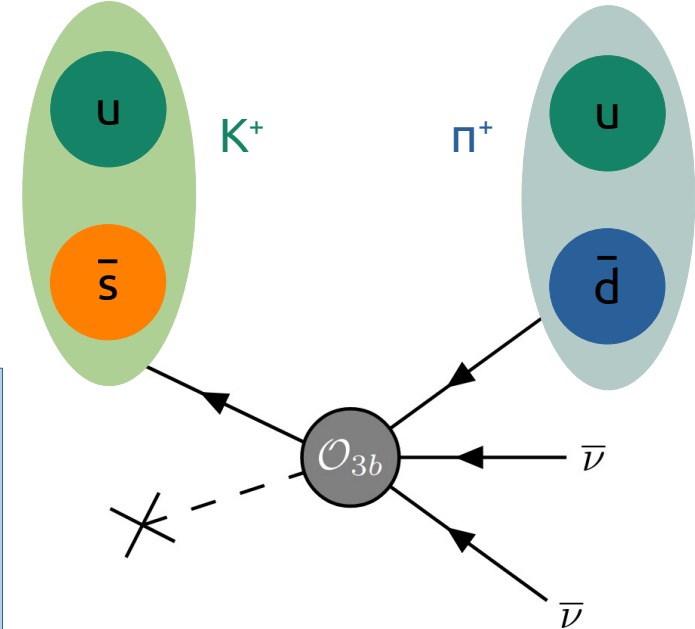
Lepton number violating vs conserving current

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

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

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

$$|\mathcal{M}|^2 = \frac{6}{\Lambda_{\text{SM}}^4} [m_K^2 (t - m_\pi^2) - t (s + t - m_\pi^2)] f_+^K(s)^2$$



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

$$\mathcal{L}_{\text{BSM}}^{K \rightarrow \pi \nu \nu} = \frac{v}{\Lambda_{\text{BSM}}^3} (\nu_i \nu_j) (\bar{d} s)$$

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

Li, Ma, Schmidt (2019)
Deppisch, JH, Fridell (2020)
Buras, JH (2022)

LVN vs LVN current – KOTO

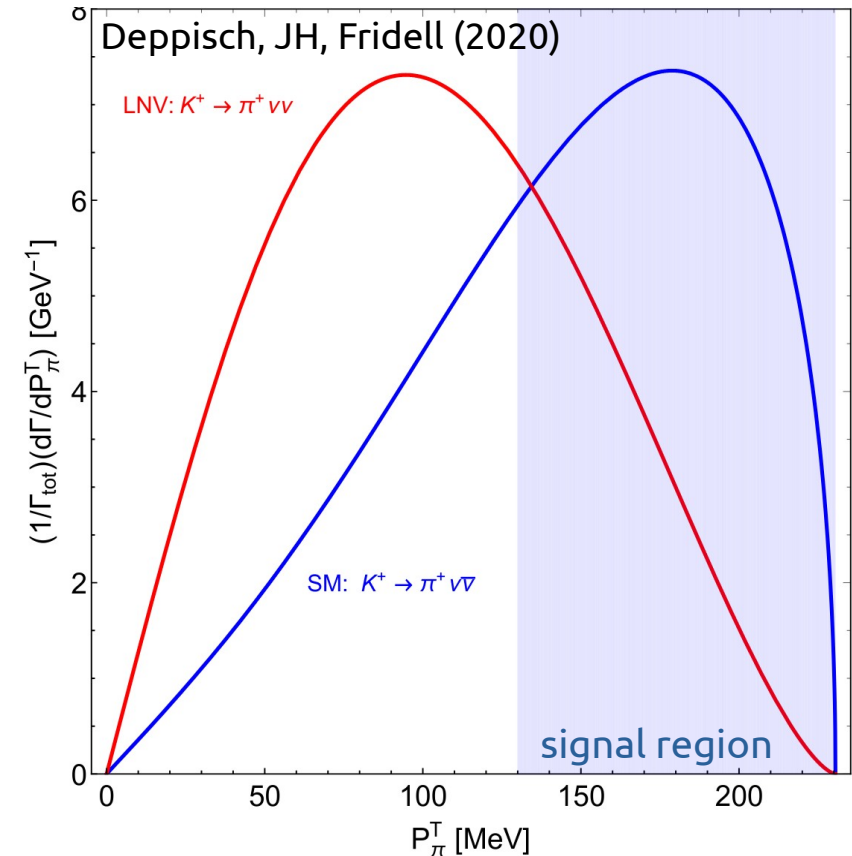
$$\begin{aligned}\langle \pi^0 | \bar{d}s | \bar{K}^0 \rangle &= \langle \pi^0 | \bar{s}d | K^0 \rangle \\ \langle \pi^0 | \bar{d}\gamma^\mu s | \bar{K}^0 \rangle &= - \langle \pi^0 | \bar{s}\gamma^\mu d | K^0 \rangle\end{aligned}$$

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

LVN mode → scalar current → real part

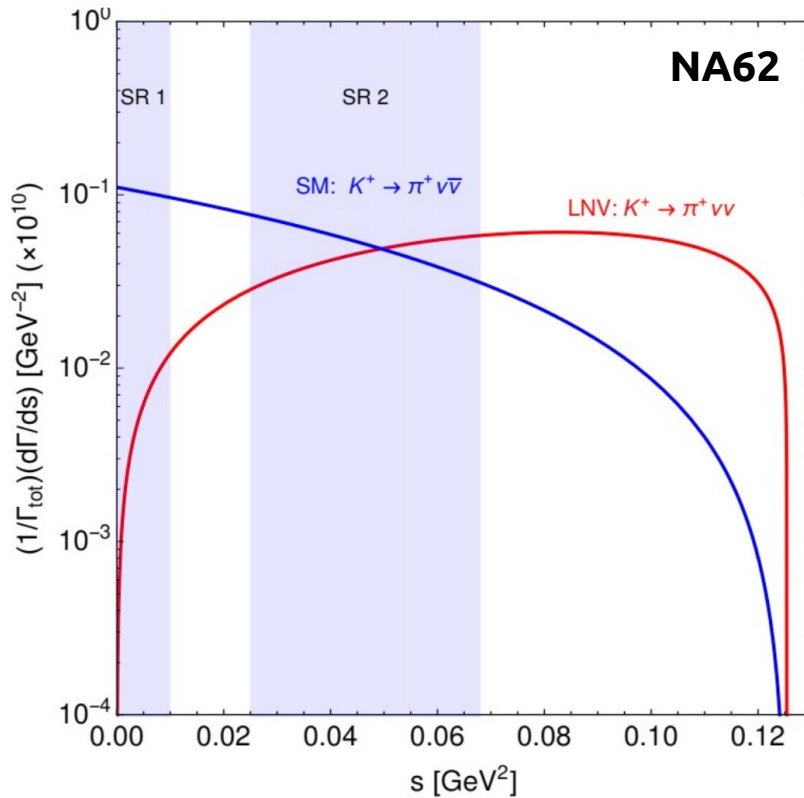
LVN mode → vector current → imaginary part

- **no CP phase needed in the LVN case**
- **different phase space distribution**



Deppisch, Fridell, JH (2020)

LVN vs LVN current – NA62



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

$$\text{BR}_{\text{LVN}}(K^+ \rightarrow \pi^+ \nu_i \nu_j) = 10^{-10} \left(\frac{19.2 \text{ TeV}}{\Lambda_{ijsd}} \right)^6$$

$$\text{BR}_{\text{LVN}}(K_L \rightarrow \pi^0 \nu_i \nu_j) = 10^{-10} \left(\frac{24.9 \text{ TeV}}{\Lambda_{ijsd}} \right)^6$$

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

- scalar and vector current lead to different phase space distribution
- competitive limits on the new scale of physics

Deppisch, Fridell, JH (2020)

Complementarity with other LNV observables

Process	Experimental limit	\mathcal{O}	$\Lambda_{ijkn}^{\text{NP}}$ [TeV]
$K^+ \rightarrow \pi^+ \nu \nu$	$\text{BR}_{\text{future}}^{\text{NA62}} < 1.11 \times 10^{-10}$	\mathcal{O}_{3b}	$\sum_i \Lambda_{iisd} > 19.6$
$K^+ \rightarrow \pi^+ \nu \nu$	$\text{BR}_{\text{current}}^{\text{NA62}} < 1.78 \times 10^{-10}$	\mathcal{O}_{3b}	$\sum_i \Lambda_{iisd} > 17.2$
$K_L \rightarrow \pi^0 \nu \nu$	$\text{BR}_{\text{current}}^{\text{KOTO}} < 3.0 \times 10^{-9}$	\mathcal{O}_{3b}	$\sum_i \Lambda_{iisd} > 12.3$
$B^+ \rightarrow \pi^+ \nu \nu$	$\text{BR} < 1.4 \times 10^{-5}$	\mathcal{O}_{3b}	$\sum_i \Lambda_{iibd} > 1.4$
$B^+ \rightarrow K^+ \nu \nu$	$\text{BR} < 1.6 \times 10^{-5}$	\mathcal{O}_{3b}	$\sum_i \Lambda_{iibs} > 1.4$
$B^0 \rightarrow \pi^0 \nu \nu$	$\text{BR} < 9 \times 10^{-6}$	\mathcal{O}_{3b}	$\sum_i \Lambda_{iibd} > 1.5$
$B^0 \rightarrow K^0 \nu \nu$	$\text{BR} < 2.6 \times 10^{-5}$	\mathcal{O}_{3b}	$\sum_i \Lambda_{iibs} > 1.3$
$K^+ \rightarrow \mu^+ \bar{\nu}_e$	$\text{BR} < 3.3 \times 10^{-3}$	\mathcal{O}_{3a}	$\Lambda_{\mu esu} > 2.4$
$\pi^+ \rightarrow \mu^+ \bar{\nu}_e$	$\text{BR} < 1.5 \times 10^{-3}$	\mathcal{O}_{3a}	$\Lambda_{\mu eud} > 1.9$
$\pi^0 \rightarrow \nu \nu$	$\text{BR} < 2.9 \times 10^{-13}$	\mathcal{O}_{3b}	$\Lambda_{\nu \nu ud} > 3.4$
$0\nu\beta\beta$	$T_{1/2}^{136\text{Xe}} \geq 1.07 \times 10^{26} \text{ yrs}$	\mathcal{O}_{3b}	$\Lambda_{eeud} > 330$
$\mu^- \rightarrow e^+$	$R_{\mu^- e^+}^{\text{Ti}} < 1.7 \times 10^{-12}$	\mathcal{O}_{14b}	$\Lambda_{\mu eud} > 0.01$

- While limits weaker than from $0\nu\beta\beta$ decay, different flavours are probed
- B-meson constraints still in LHC reach

General NP contribution in $K^+ \rightarrow \pi^+ \nu \nu$ or $K_L \rightarrow \pi^0 \nu \nu$

NOW: allow for most generic NP contribution from dim-6 operators.

Dim-6 LEFT operators (lepton number conserving)

$$\begin{aligned}\mathcal{O}_{uL}^V &= (\overline{u_L} \gamma^\mu u_L) (\overline{\nu} \gamma^\mu \nu), & \mathcal{O}_{dL}^V &= (\overline{d_L} \gamma^\mu d_L) (\overline{\nu} \gamma^\mu \nu), \\ \mathcal{O}_{uR}^V &= (\overline{u_R} \gamma^\mu u_R) (\overline{\nu} \gamma^\mu \nu), & \mathcal{O}_{dR}^V &= (\overline{d_R} \gamma^\mu d_R) (\overline{\nu} \gamma^\mu \nu),\end{aligned}$$

Dim-6 LEFT operators (lepton number violating)

$$\begin{aligned}\mathcal{O}_{uRL}^S &= (\overline{u_R} u_L) (\overline{\nu^C} \nu), & \mathcal{O}_{dRL}^S &= (\overline{d_R} d_L) (\overline{\nu^C} \nu), \\ \mathcal{O}_{uLR}^S &= (\overline{u_L} u_R) (\overline{\nu^C} \nu), & \mathcal{O}_{dLR}^S &= (\overline{d_L} d_R) (\overline{\nu^C} \nu), \\ \mathcal{O}_u^T &= (\overline{u_R} \sigma^{\mu\nu} u_L) (\overline{\nu^C} \sigma_{\mu\nu} \nu), & \mathcal{O}_d^T &= (\overline{d_R} \sigma^{\mu\nu} d_L) (\overline{\nu^C} \sigma_{\mu\nu} \nu).\end{aligned}$$

For flavour diagonal contributions tensor contribution vanishes.

Li, Ma, Schmidt (2019)

General NP contribution in $K^+ \rightarrow \pi^+ \nu \nu$ or $K_L \rightarrow \pi^0 \nu \nu$

Most generic Branching ratios:

$$\begin{aligned}
 \mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) &= 36.27 G_F^{-2} \sum_{\alpha \leq \beta} \left(1 - \frac{1}{2} \delta_{\alpha\beta}\right) \left| C_{dRL}^{S, sd\alpha\beta} + C_{dLR}^{S, sd\alpha\beta} + C_{dRL}^{S, ds\alpha\beta} + C_{dLR}^{S, ds\alpha\beta} \right|^2 \\
 &\quad + 0.236 G_F^{-2} \sum_{\alpha, \beta} \left| C_{dL}^{V, sd\alpha\beta} + C_{dR}^{V, sd\alpha\beta} - C_{dL}^{V, ds\alpha\beta} - C_{dR}^{V, ds\alpha\beta} \right|^2 \\
 \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= 17.05 G_F^{-2} \sum_{\alpha \leq \beta} \left(1 - \frac{1}{2} \delta_{\alpha\beta}\right) \left(\left| C_{dRL}^{S, sd\alpha\beta} + C_{dLR}^{S, sd\alpha\beta} \right|^2 + \left| C_{dRL}^{S, ds\alpha\beta} + C_{dLR}^{S, ds\alpha\beta} \right|^2 \right) \\
 &\quad + 0.219 G_F^{-2} \sum_{\alpha, \beta} \left| C_{dL}^{V, sd\alpha\beta} + C_{dR}^{V, sd\alpha\beta} \right|^2,
 \end{aligned}$$

Parameterization:

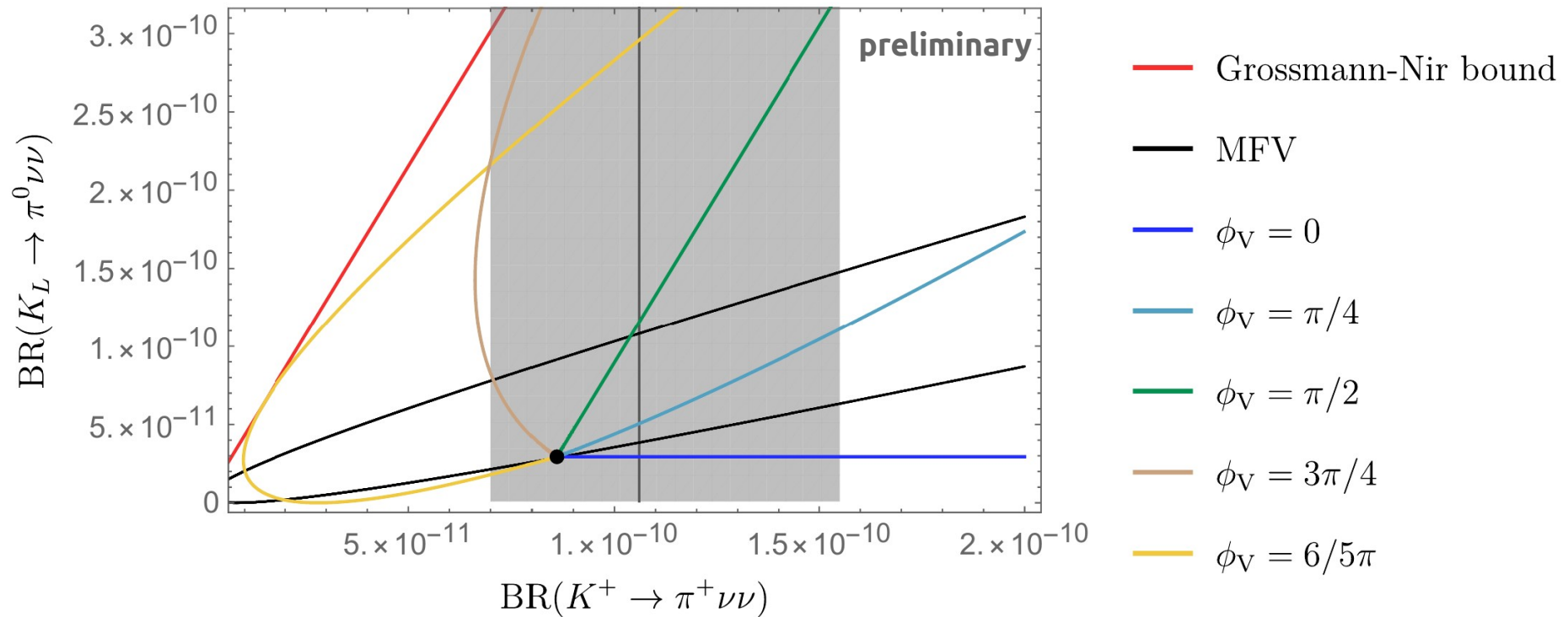
$$\begin{aligned}
 C_{dL}^{V, sd\alpha\beta} + C_{dR}^{V, sd\alpha\beta} &= (|C_{SM}| e^{i\phi_{SM}} + |C_V| e^{i\phi_V}) \delta_{\alpha\beta} & C_{dRL}^{S, sd\alpha\beta} + C_{dLR}^{S, sd\alpha\beta} &= |C_S| e^{i\phi_S} \delta_{\alpha\beta}, \\
 C_{dL}^{V, ds\alpha\beta} + C_{dR}^{V, ds\alpha\beta} &= (|C_{SM}| e^{-i\phi_{SM}} + |C_V| e^{-i\phi_V}) \delta_{\alpha\beta}, & C_{dRL}^{S, ds\alpha\beta} + C_{dLR}^{S, ds\alpha\beta} &= |C_S| e^{-i\phi_S} \delta_{\alpha\beta}.
 \end{aligned}$$

Identify SM parameters:

$$\begin{aligned}
 \mathcal{B}_{SM}(K_L \rightarrow \pi^0 \nu \bar{\nu}) &= 12 J_2^{K_L} |C_{SM}|^2 \sin^2 \phi_{SM}, & \mathcal{B}_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) &= 3 J_2^{K^+} |C_{SM}|^2 \\
 |C_{SM}| &= 1.33 \times 10^{-10} \text{ GeV}^{-2}, & \phi_{SM} &= 0.09 \pi.
 \end{aligned}$$

Buras, JH (2022), to appear

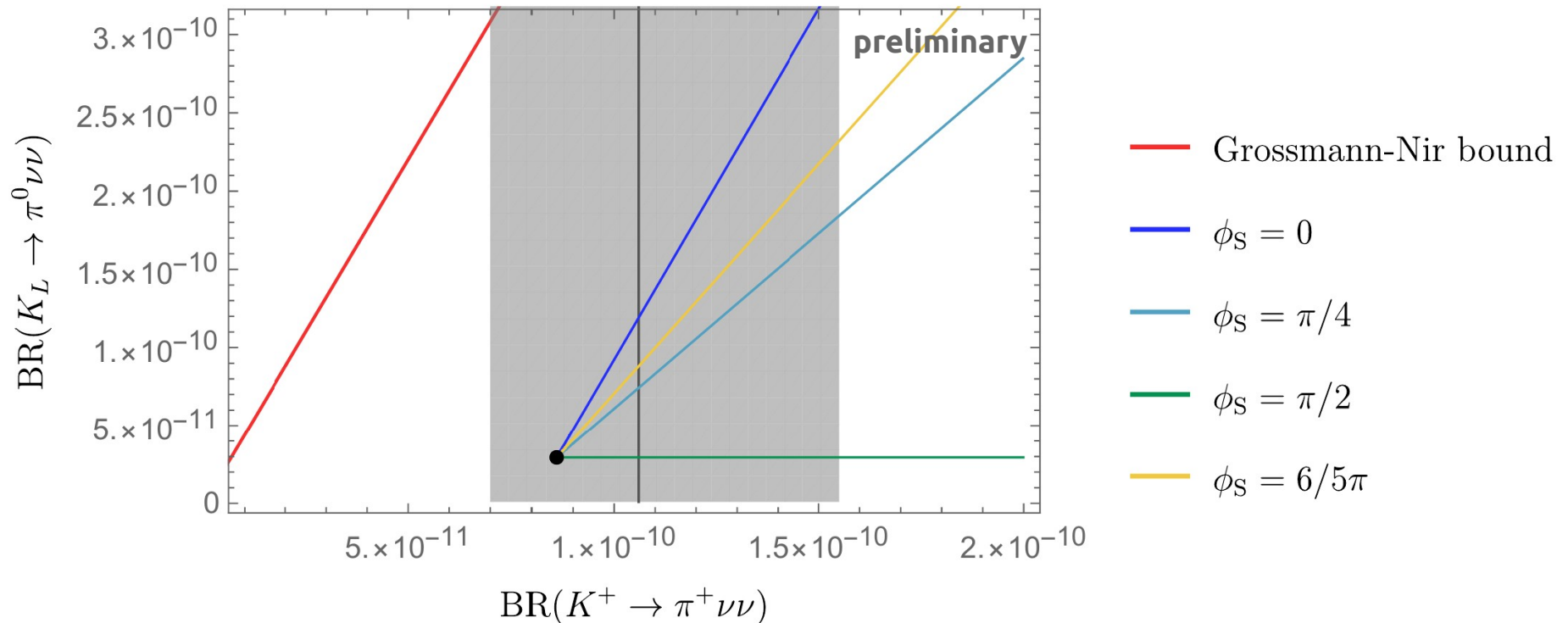
New vector contribution in $K^+ \rightarrow \pi^+ \nu \nu$ and $K_L \rightarrow \pi^0 \nu \nu$



- Vector contribution can lead to larger and smaller BRs than in the SM
- Vector contribution can lie everywhere below Grossman-Nir bound

Buras, JH (2022), to appear

New scalar contribution in $K^+ \rightarrow \pi^+ \nu \nu$ and $K_L \rightarrow \pi^0 \nu \nu$



→ Scalar contribution can only lead to larger BRs than in the SM

→ Scalar contribution confined between blue and green line

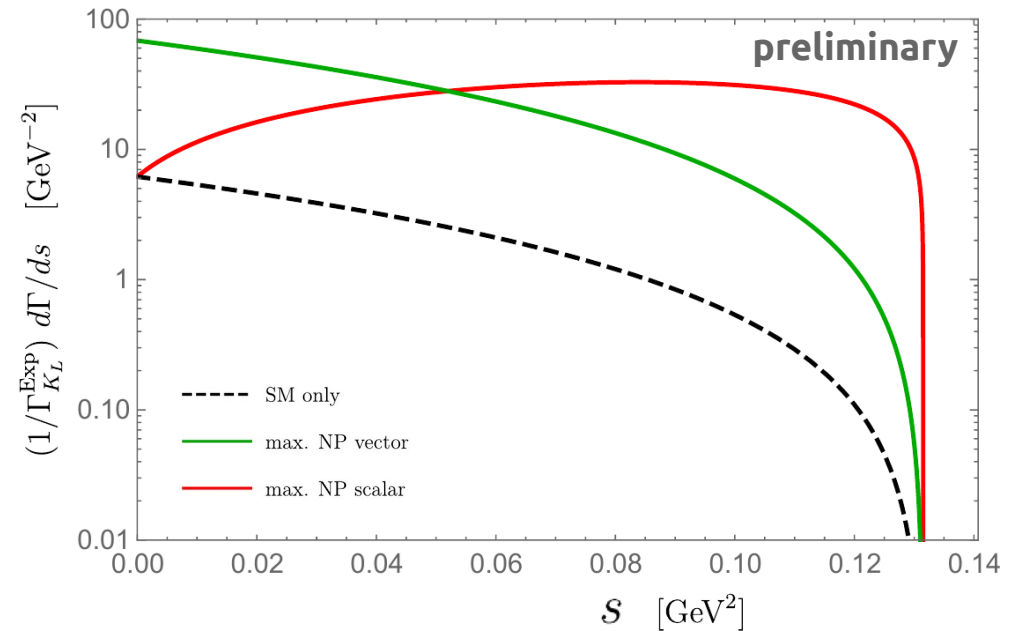
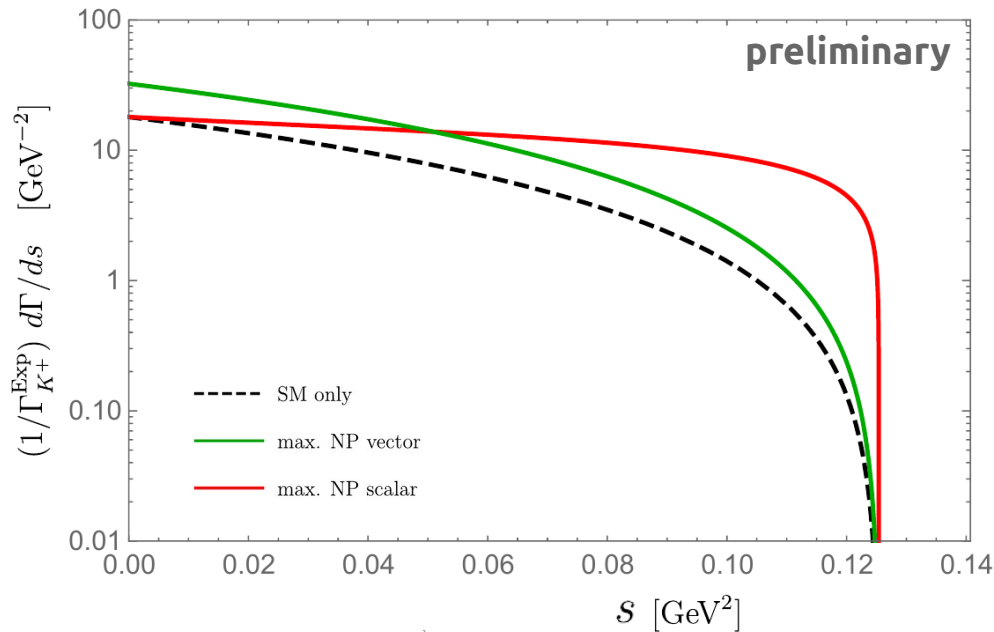
→ Measuring a lower BR than in the SM implies (also) a vector contribution.

Buras, JH (2022), to appear

Disentangling the NP contribution

Allow for a NP scalar or vector contribution additionally to the SM such that the experimental upper bound $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.55 \times 10^{-10}$ is saturated.

We fixed $\phi_V = \pi/2$ and $\phi_S = 0$.



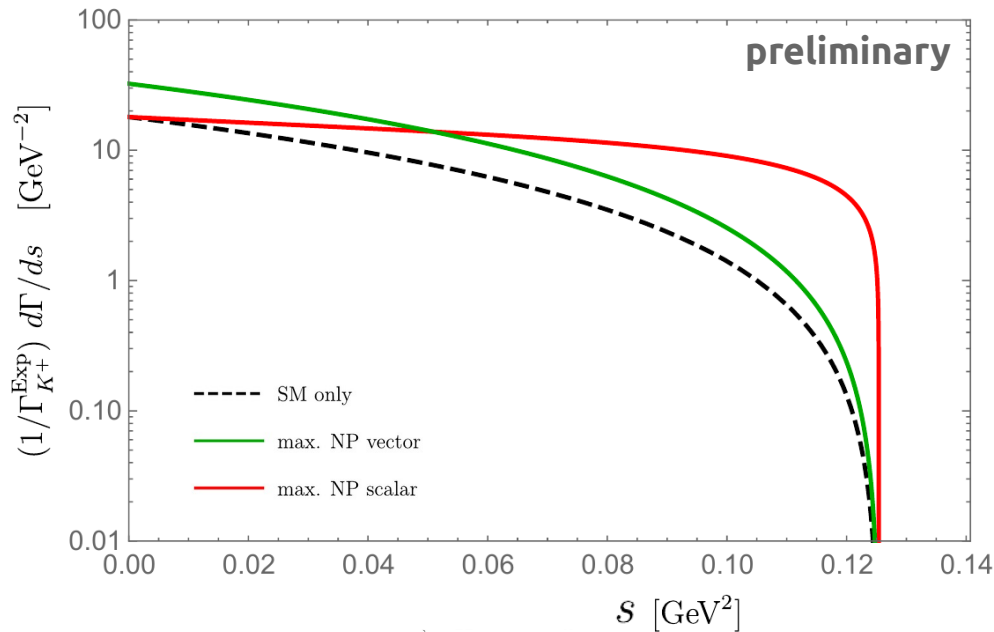
→ A NP scalar contribution additionally to the SM leads to a striking difference in the distribution when comparing to a vector contribution only.

Buras, JH (2022), to appear

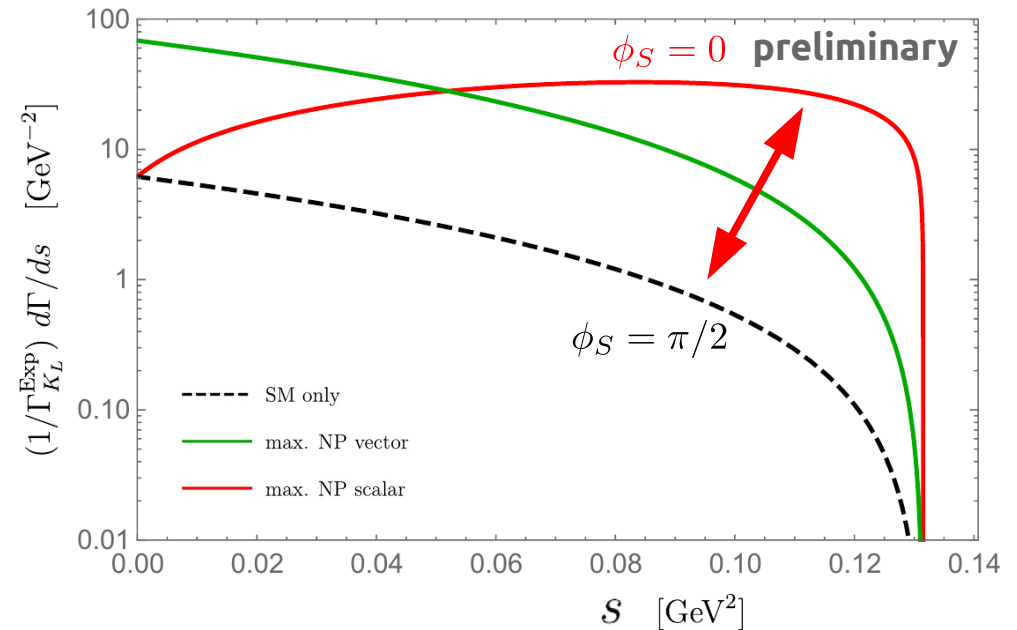
Disentangling the NP contribution

Allow for a NP scalar or vector contribution additionally to the SM such that the experimental upper bound $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.55 \times 10^{-10}$ is saturated.

We fixed $\phi_V = \pi/2$ and $\phi_S = 0$.



independent of scalar phase

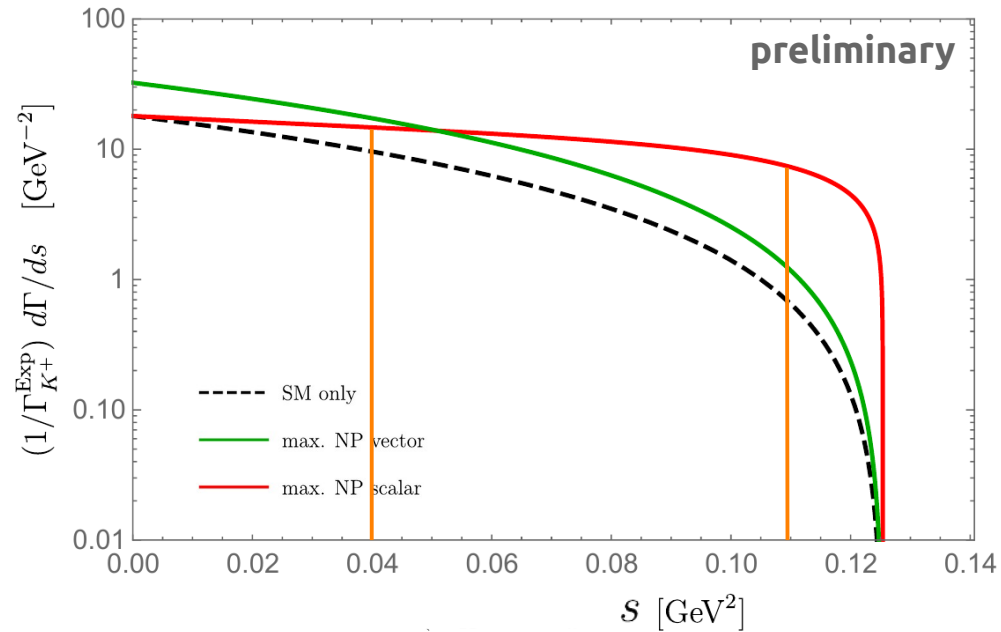


dependent on scalar phase

→ additional insight by comparing K_L and K^+ distributions!

Buras, JH (2022), to appear

Proposal to disentangle a possible NP contribution



Measuring distribution at two different values s_1 and s_2 :

$$\mathcal{D}_+^{\text{exp}}(s) \equiv \frac{d\Gamma(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{ds} = C_S^+ f_S^+(s) + C_V^+ f_V^+(s)$$

$$C_V^+ = \frac{f_S^+(s_2) \mathcal{D}_+^{\text{exp}}(s_1) - f_S^+(s_1) \mathcal{D}_+^{\text{exp}}(s_2)}{f_V^+(s_1) f_S^+(s_2) - f_V^+(s_2) f_S^+(s_1)}$$

$$C_S^+ = \frac{f_V^+(s_2) \mathcal{D}_+^{\text{exp}}(s_1) - f_V^+(s_1) \mathcal{D}_+^{\text{exp}}(s_2)}{f_S^+(s_1) f_V^+(s_2) - f_S^+(s_2) f_V^+(s_1)},$$

- **measuring non-zero C_s implies the existence of a scalar current**
- **measuring non-zero C_v not in agreement with SM, implies new vector currents**

Buras, JH (2022), to appear

Conclusions

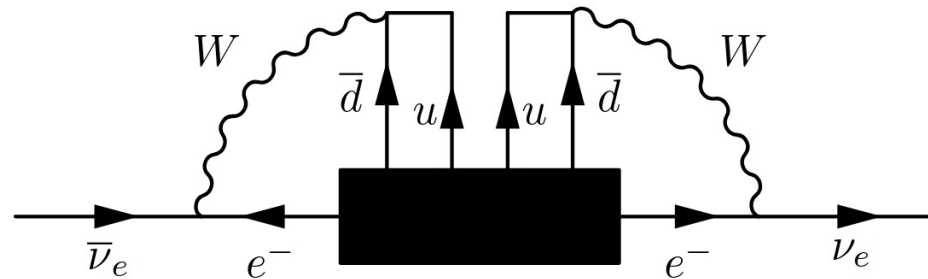
- Observation of LNV interactions would imply Majorana contribution to neutrino masses
- A deviation from the SM expectation in the golden channel $K^+ \rightarrow \pi^+ \nu \nu$ would point towards new physics (either LNV or LNC)
- While not a clear proof of LNV, pion energy distribution provides possibility to disentangle scalar LNV from vector LNC contribution
- Interplay between $K^+ \rightarrow \pi^+ \nu \nu$ and $K_L \rightarrow \pi^0 \nu \nu$ can give further insights
- In case of a deviation from SM consistent with LNV contribution, interplay with other experiments is crucial, such as collider searches and $0\nu\beta\beta$ decay

→ For experiments: dedicated analyses and limits for different currents highly interesting!

Thank you for your attention!

Does LNV directly imply Majorana neutrinos?

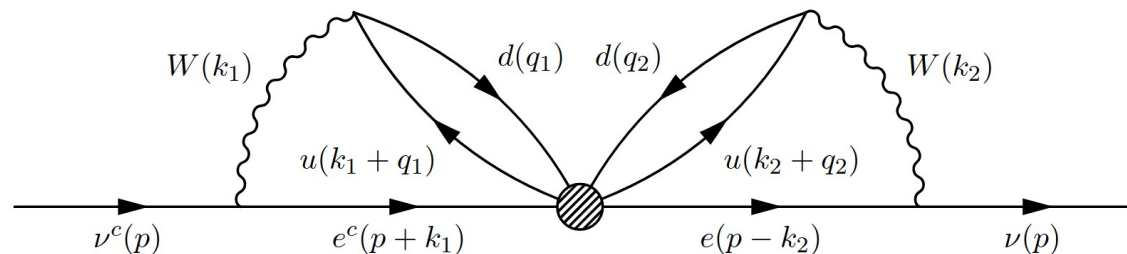
- **Schechter-Valle Theorem (“Black box” theorem)**



Schechter, Valle (1982)

Any $\Delta L = 2$ operator that leads to 0vbb will induce a **Majorana mass contribution** via loops.

- **Caveat**



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

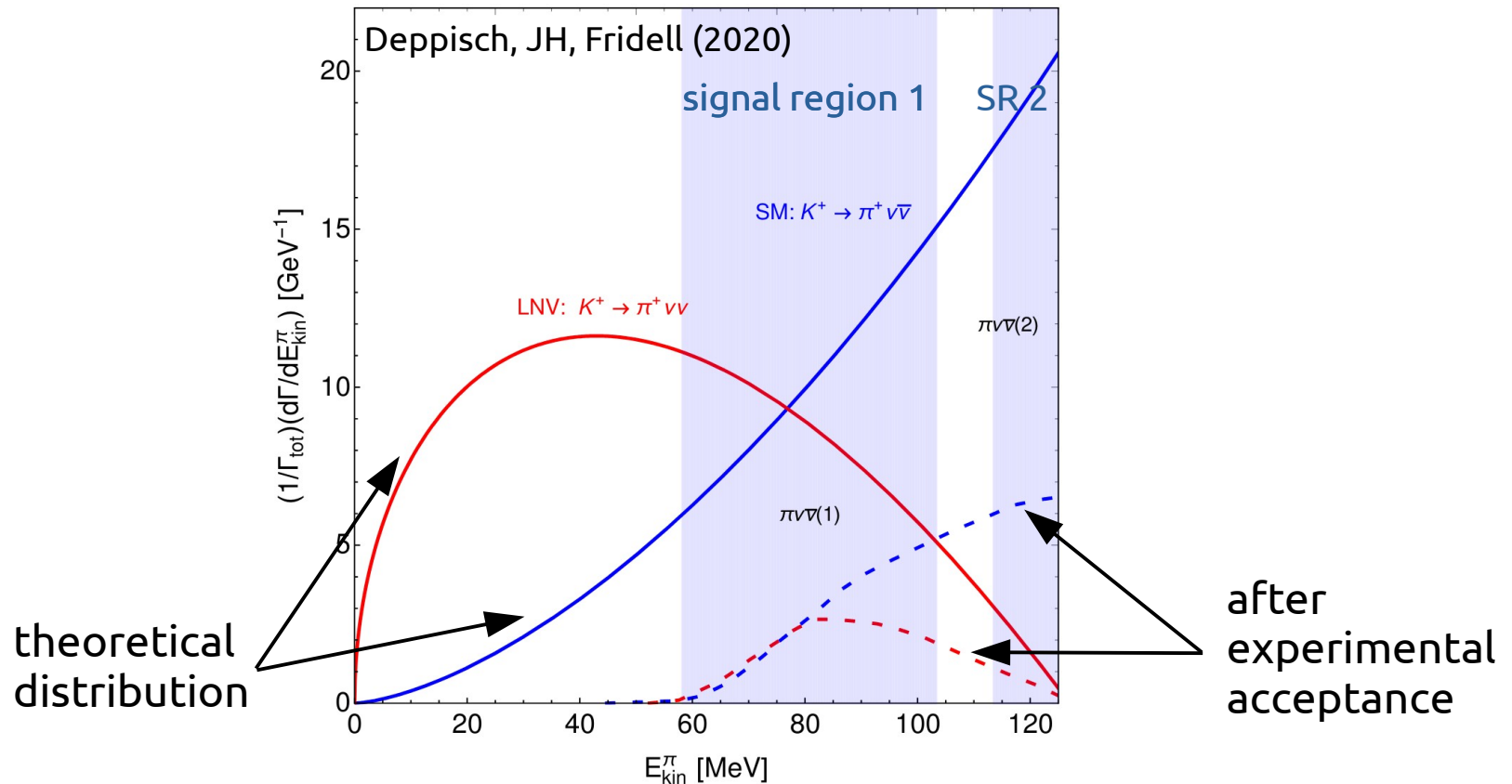
Dürr, Merle, Lindner (2011)

E.g. 9-dim $\Delta L = 2$ operator will lead to 0vbb while contributing only little to the neutrino mass.

Observation of LNV implies some Majorana nature of neutrinos, but not necessarily the dominant contribution.

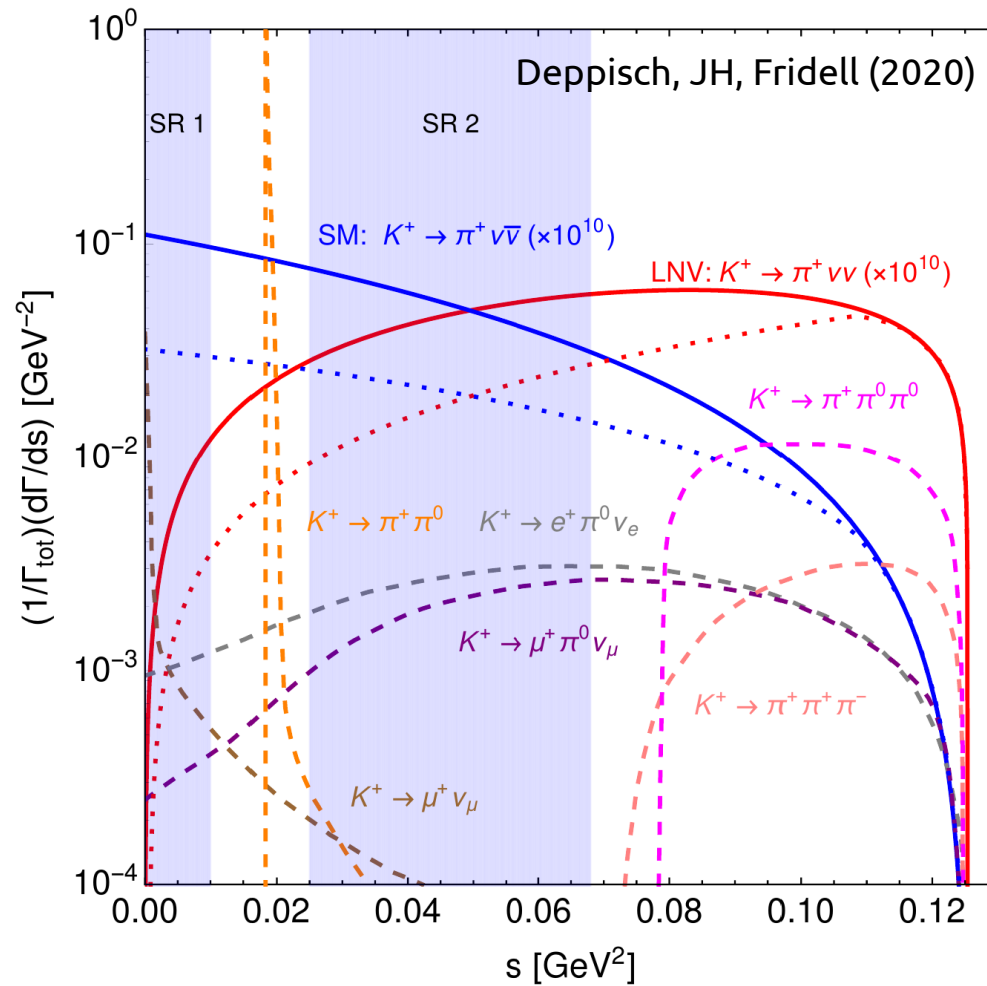
Limits from E949

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



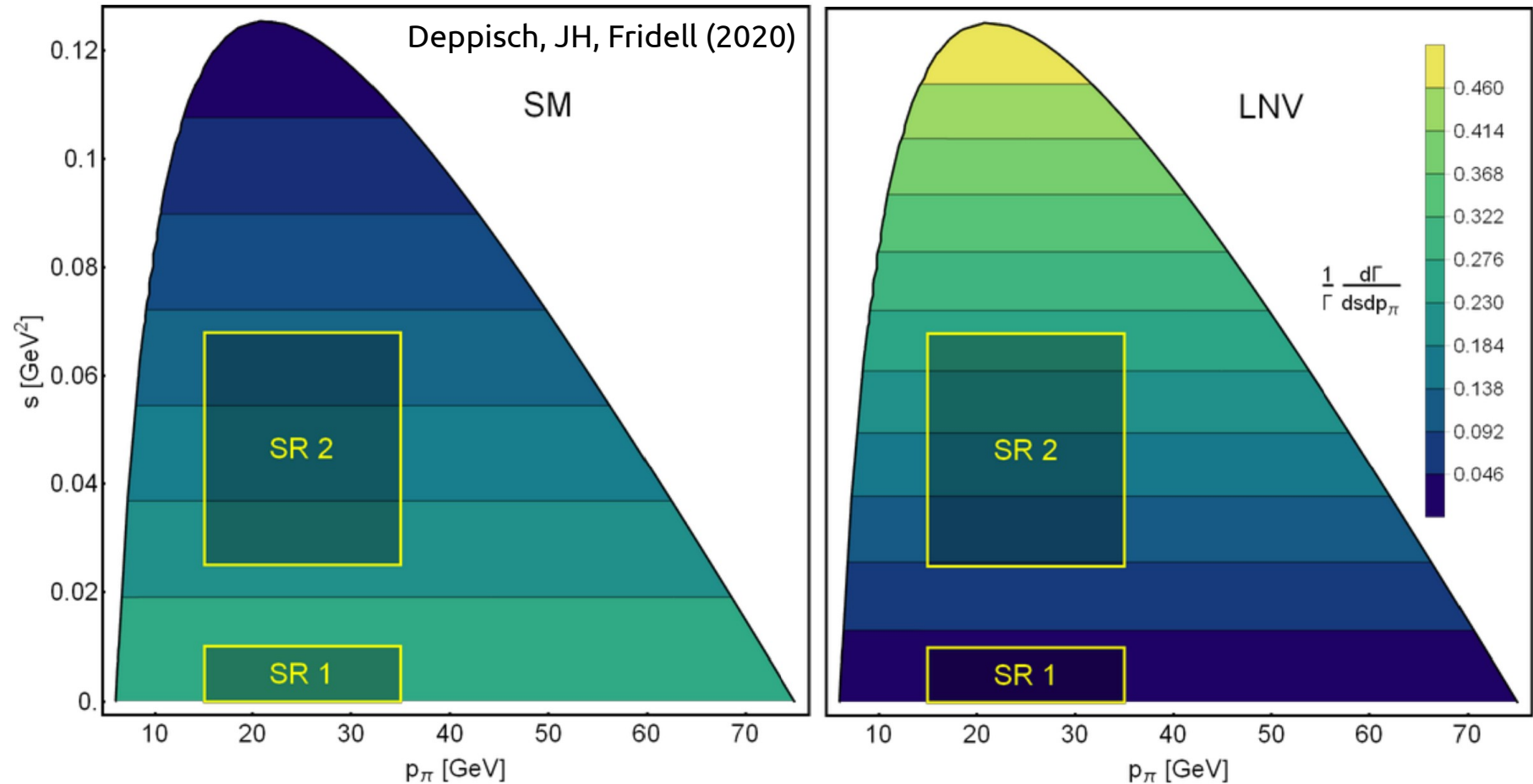
→ LNV and LNC current lead to a different phase space distribution

Limits and prospects of NA62



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

Disentangling LNV and LNC currents at NA62



Disentangling LNV and LNC currents at NA62

Summary of sensitivities for a 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%

→ Possibility to disentangle a LNV scalar vs LNC vector current by improving on experimental sensitivity and strategy?

Analysis for charged final states

\mathcal{O}	$1/\Lambda^2_{M \rightarrow \ell_i^+ \bar{\nu}_j}$	$\Lambda_{\mu eus}$ [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}

Constraints on the scale of New Physics

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

Sensitivity to different flavors than most constraining $0\nu\beta\beta$!

\mathcal{O}	$1/\Lambda_{K \rightarrow \pi \nu \nu}^2$	$\sum_i \Lambda_{iisd}^{\text{E949}}$ [TeV]	m_ν	Λ^{m_ν} [TeV]
$1y_d$	$\frac{v^3}{\Lambda^5}$	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

1st generation couplings