Lepton Number Violation:

From the Cosmos to the Lab

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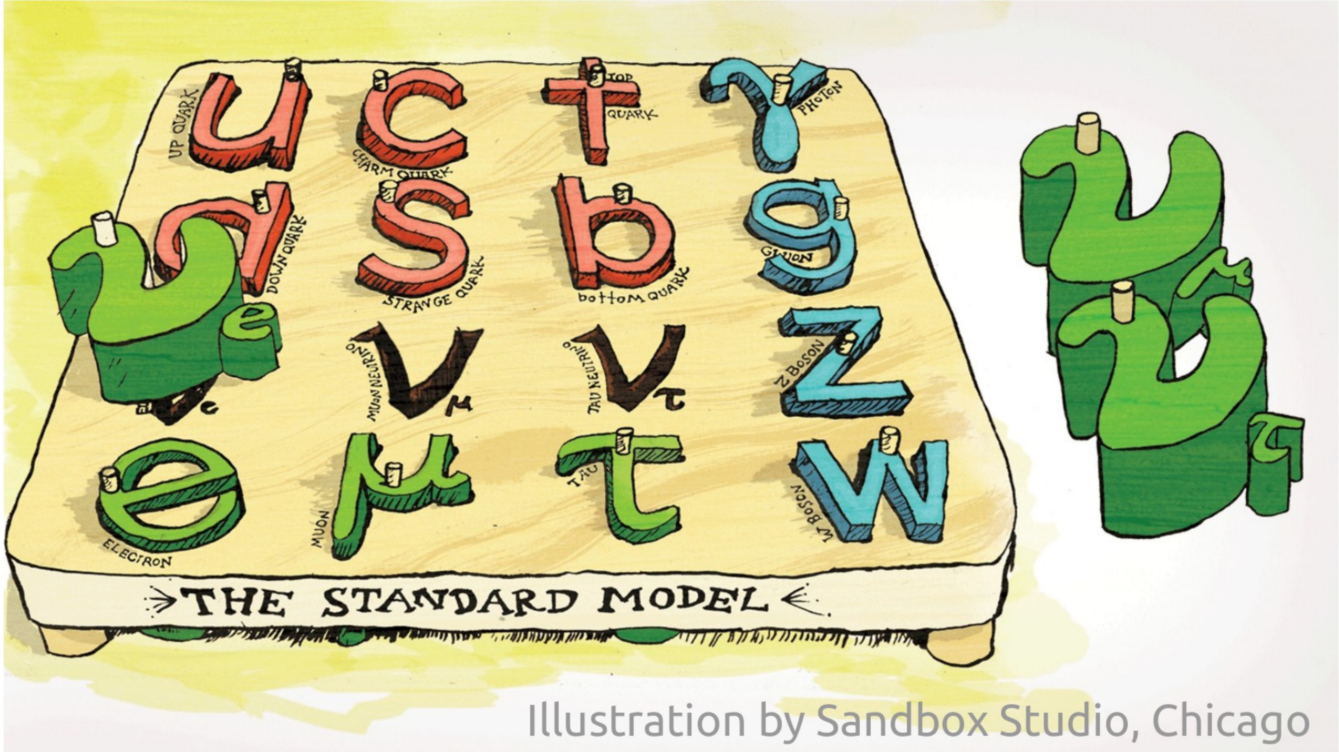
FLASY 2025, Rome

30.06. - 04.07.2025

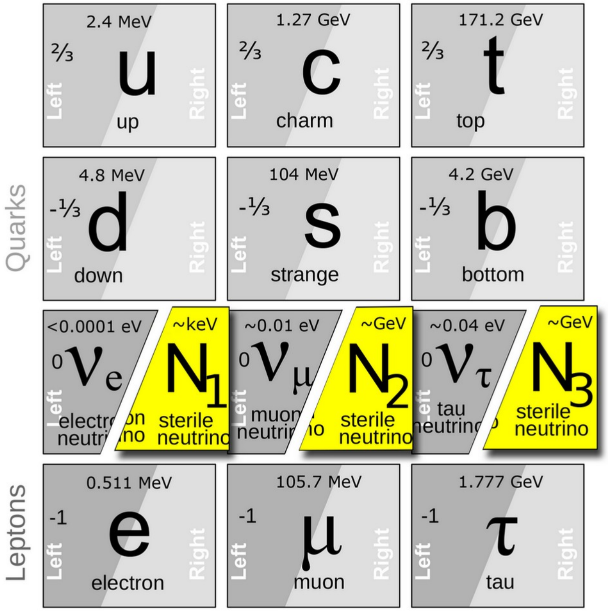
Credit: Ella Dreiner

Why is there more matter than antimatter?



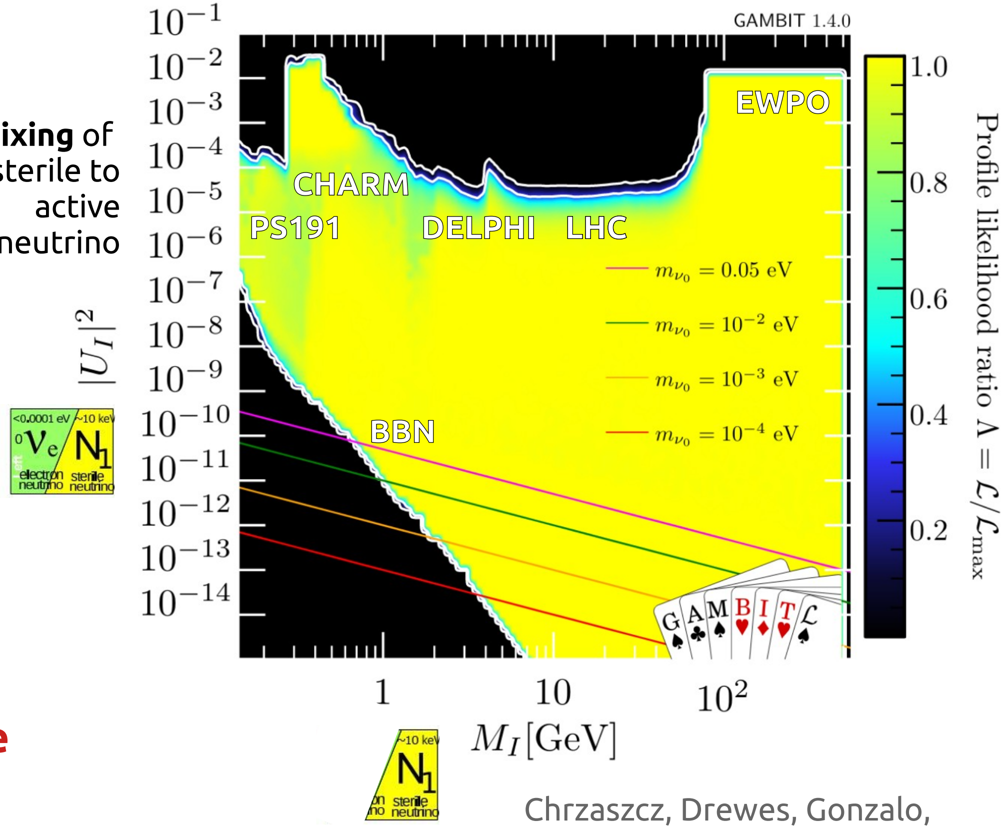
Where do neutrinos get their mass from?

Extending the SM with right-handed neutrinos



Global fit: SM extended with 3 right-handed neutrinos

mixing of sterile to active neutrino



Chrzaszcz, Drewes, Gonzalo, JH, Krishnamurthy, Weniger (2020)

➡ **right-handed neutrinos can explain the mass generation of the SM neutrinos**

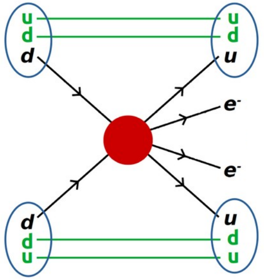
The nature of Neutrinos – Majorana vs Dirac

Right-handed neutrinos can give rise to two different mass terms:

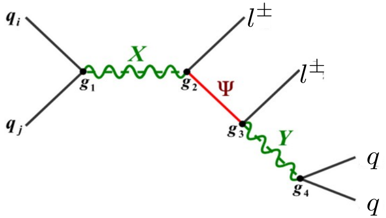
Dirac	Majorana
$M_D \nu_L \overline{\nu}_R$	$M_M \overline{\nu}_R \nu_R^c$
Lepton number conservation (LNC)	Lepton number violation (LNV)

- LNV interaction smoking gun signal for Majorana nature
- LNV interaction could source baryogenesis via leptogenesis

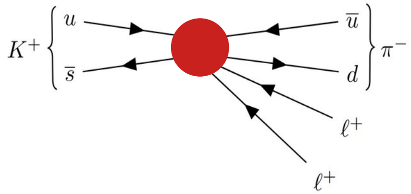
neutrinoless double beta decay



collider (LHC)



meson decay



LNV: ΔL = 2

Standard Model Effective Field Theory (SMEFT)

- **General interactions can be described by the Standard Model Effective Field Theory (SMEFT)**

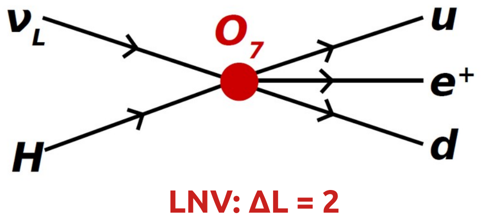
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + C_5 \mathcal{O}_5 + \sum_i C_6^i \mathcal{O}_6^i + \sum_i C_7^i \mathcal{O}_7^i + \dots$$

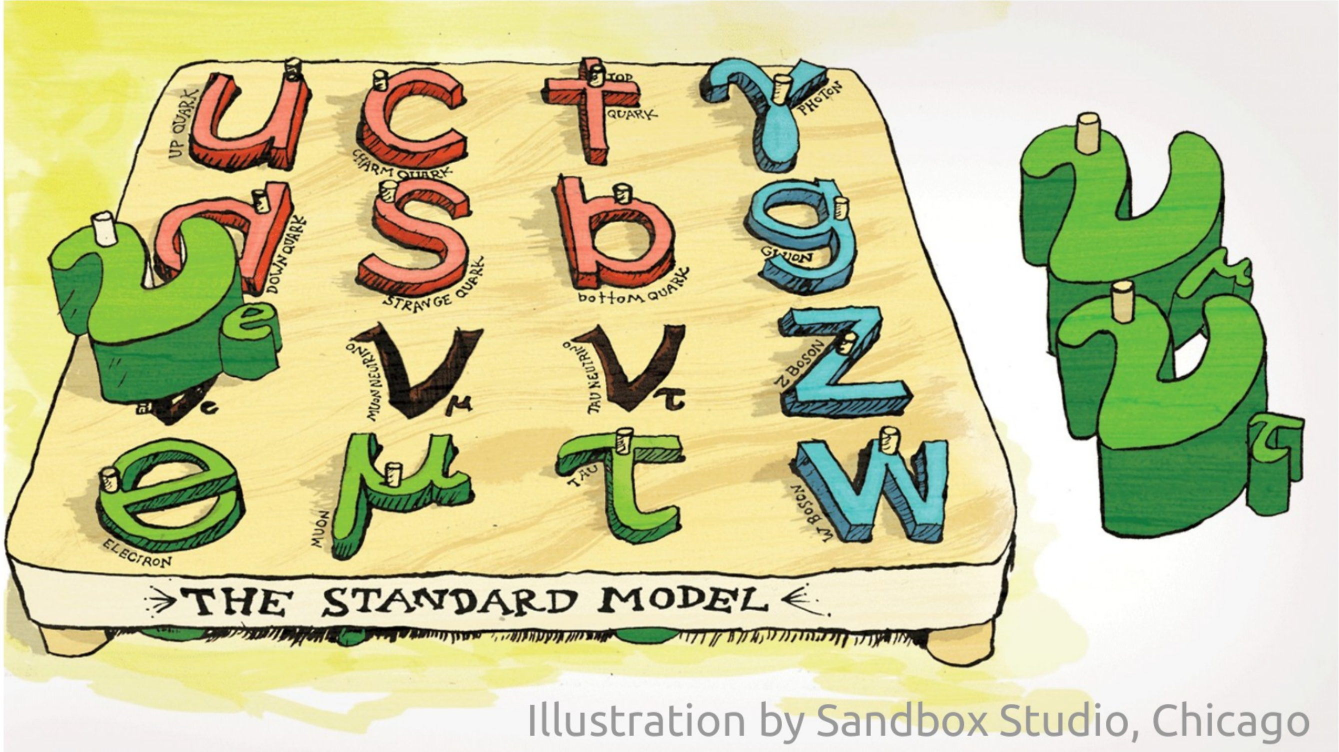
LNV (dim-5) LNC (dim-6) LNV (dim-7)

- **At dim-7 several LNV ($\Delta L = 2$) SMEFT operators exist, e.g.**

$\mathcal{O}$	Operator
$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^c}^j L_t^m\right)H^n$
$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p}L_r^i\right)\left(\overline{L_s^c}^j L_t^m\right)H^n$

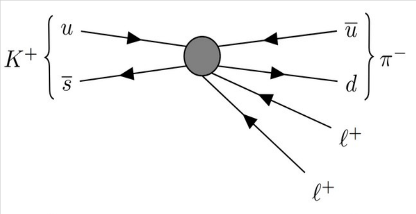
⋮





Lepton Number Violation (LNV) & Meson decays

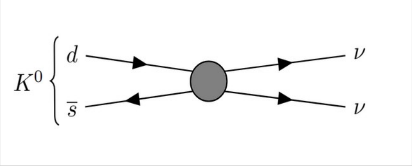
Probing LNV interactions with Kaon decays



Same-sign leptonic final state

- LNV is directly tested
- dim-9 SMEFT only
- for first generation, 0νββ stronger
- constraints very weak

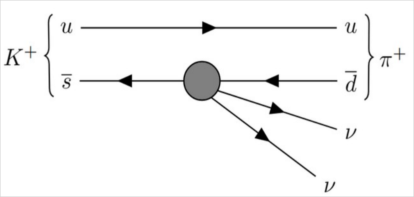
Liu, Zhang, Zhou (2016)
Quintero (2017)
Chun, Das, Mandal, Mitra, Sinha (2019)



Decay into neutrino final state

- No explicit experimental searches?
- dim-7 SMEFT

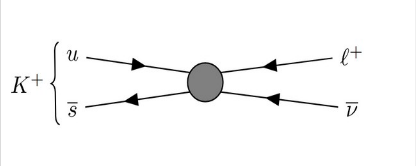
Gninenko (2014)



Neutrino final state

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

Li, Ma, Schmidt (2019)
Deppisch, Fridell, JH (2020)
Buras, JH, Mojahed (2024)

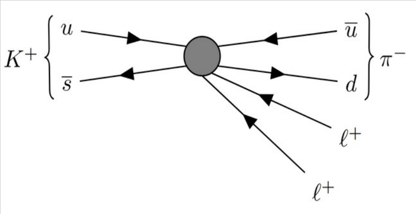


Charged lepton + neutrino final state

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

Deppisch, Fridell, JH (2020)

Probing LNV interactions with Kaon decays



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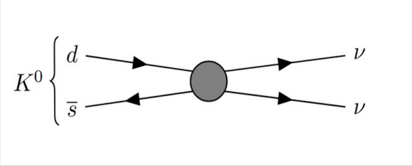

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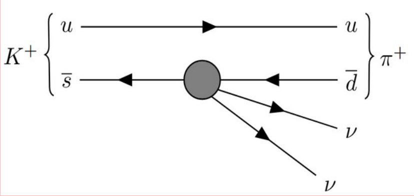

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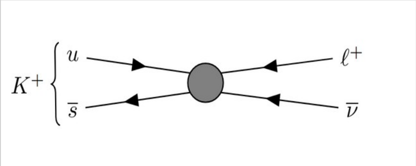


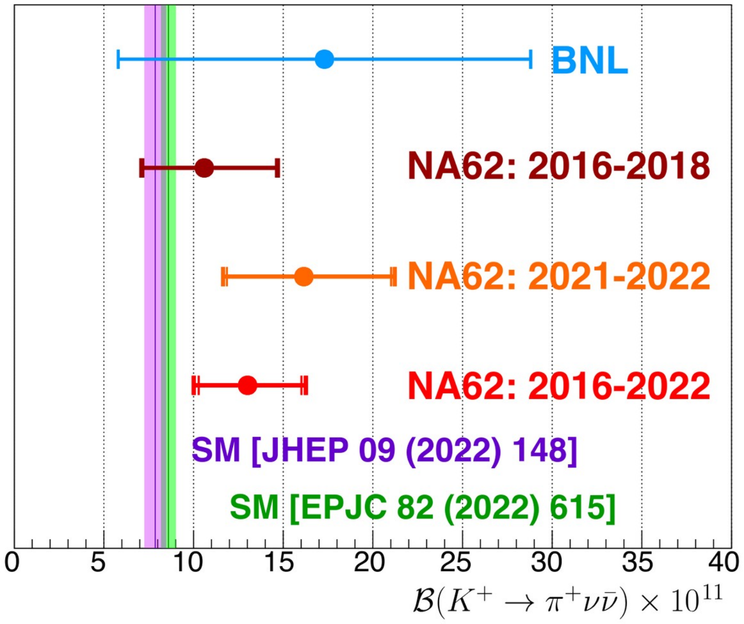
Charged lepton + neutrino final state

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

Deppisch, Fridell, JH (2020)

Lepton number violation in Kaon decays

Precise theoretical predictions with unprecedented measurements



Theoretical prediction:

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

Buras, Buttazzo, Girrbach-Noe, Knegjens (2015)
Buras, Venturini (2021)

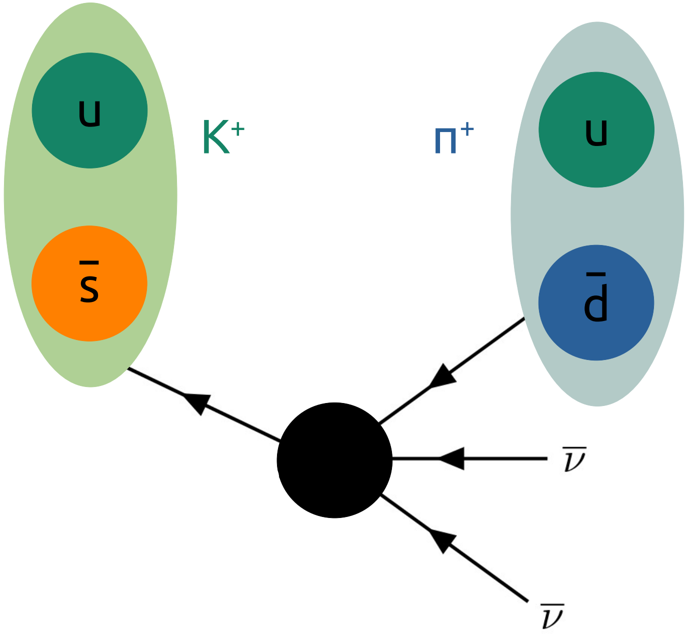
Golden Channel!

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

→ **Do the latest NA62 leave room for new physics?**

Buras, JH, Mojahed (2025)
Deppisch, Fridell, JH (2020)

Lepton number violation in Kaon decays?



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

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

Allow for most generic NP contribution from dim-6 LEFT operators:

Dim-6 LEFT operators (lepton number conserving)

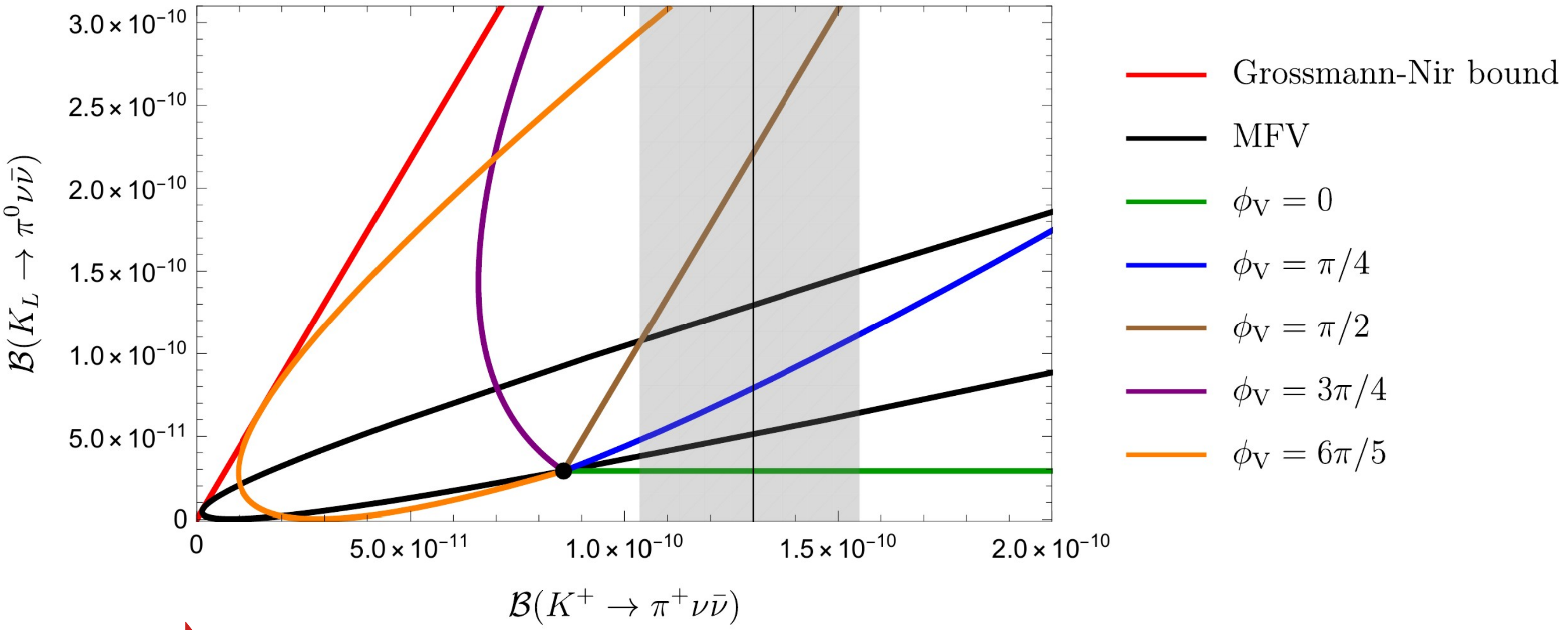
$$\mathcal{O}^V_{uL} = (\overline{u_L}\gamma^\mu u_L)(\overline{\nu}\gamma^\mu \nu)\,, \qquad \mathcal{O}^V_{dL} = (\overline{d_L}\gamma^\mu d_L)(\overline{\nu}\gamma^\mu \nu)\,,$$
$$\mathcal{O}^V_{uR} = (\overline{u_R}\gamma^\mu u_R)(\overline{\nu}\gamma^\mu \nu)\,, \qquad \mathcal{O}^V_{dR} = (\overline{d_R}\gamma^\mu d_R)(\overline{\nu}\gamma^\mu \nu)\,,$$

Dim-6 LEFT operators (lepton number violating)

$$\mathcal{O}^S_{uRL} = (\overline{u_R}u_L)(\overline{\nu^C}\nu)\,, \qquad \mathcal{O}^S_{dRL} = (\overline{d_R}d_L)(\overline{\nu^C}\nu)\,,$$
$$\mathcal{O}^S_{uLR} = (\overline{u_L}u_R)(\overline{\nu^C}\nu)\,, \qquad \mathcal{O}^S_{dLR} = (\overline{d_L}d_R)(\overline{\nu^C}\nu)\,,$$
$$\mathcal{O}^T_{u} = (\overline{u_R}\sigma^{\mu\nu}u_L)(\overline{\nu^C}\sigma_{\mu\nu}\nu)\,, \qquad \mathcal{O}^T_{d} = (\overline{d_R}\sigma^{\mu\nu}d_L)(\overline{\nu^C}\sigma_{\mu\nu}\nu)\,.$$

Note:
- **For flavour diagonal contributions tensor contribution vanishes**
- **In the presence of light RHNs, LNV and LNC identification may be different within νSMEFT**

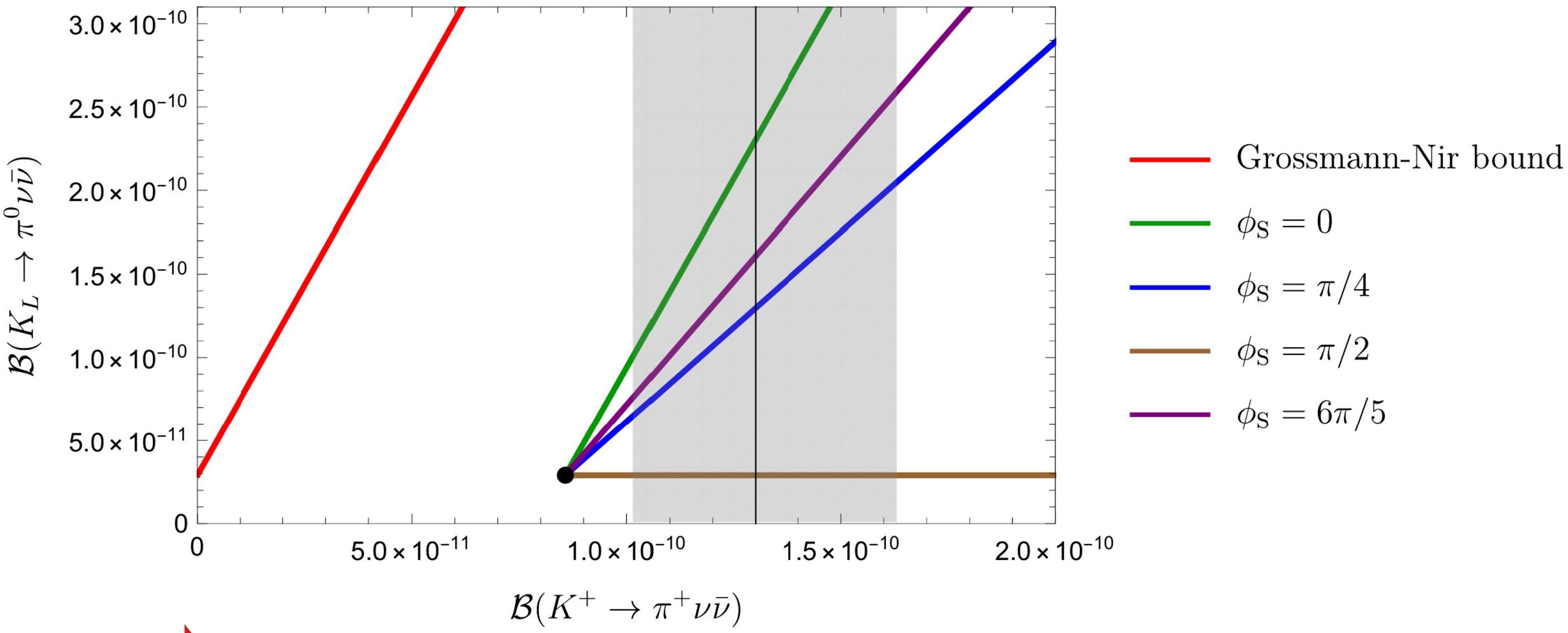
New *vector* contribution in $K^+ \to \pi^+\nu\nu$ and $K_L \to \pi^0\nu\nu$



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

Buras, JH, Mojahed (2025)

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



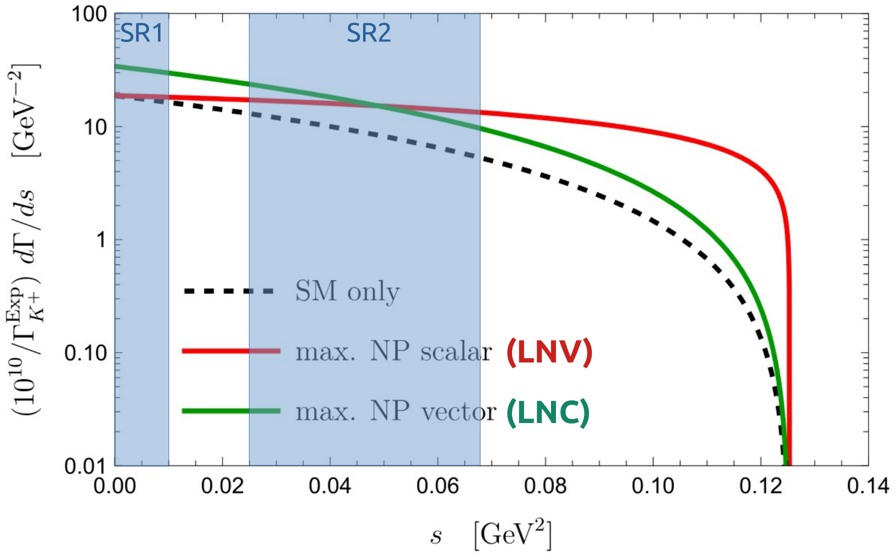
- **Scalar contribution can *only* lead to larger BRs than in the SM**
- **Scalar contribution confined between blue and brown line**

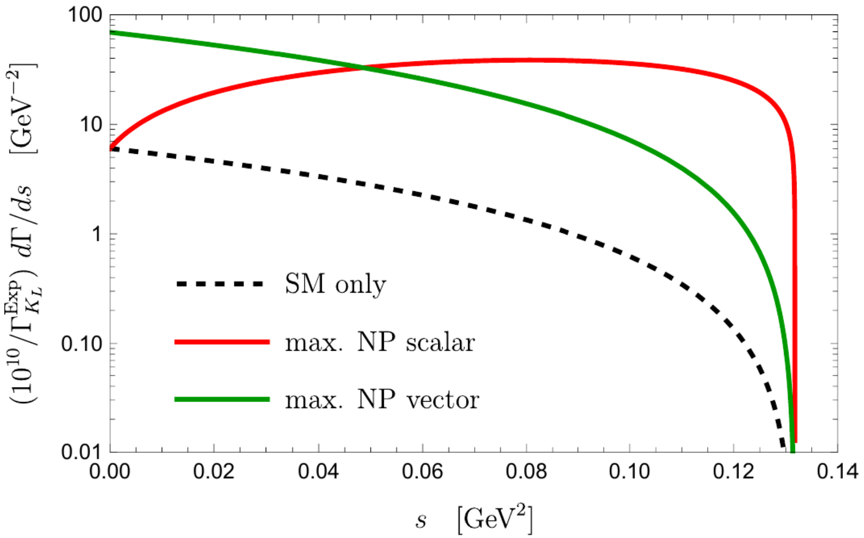
Buras, JH, Mojahed (2025)

Disentangling the NP contribution

Allow for a NP scalar or vector contribution additionally to the SM such that the experimental upper bound $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 1.63 \times 10^{-10}$ 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, Mojahed (2025)

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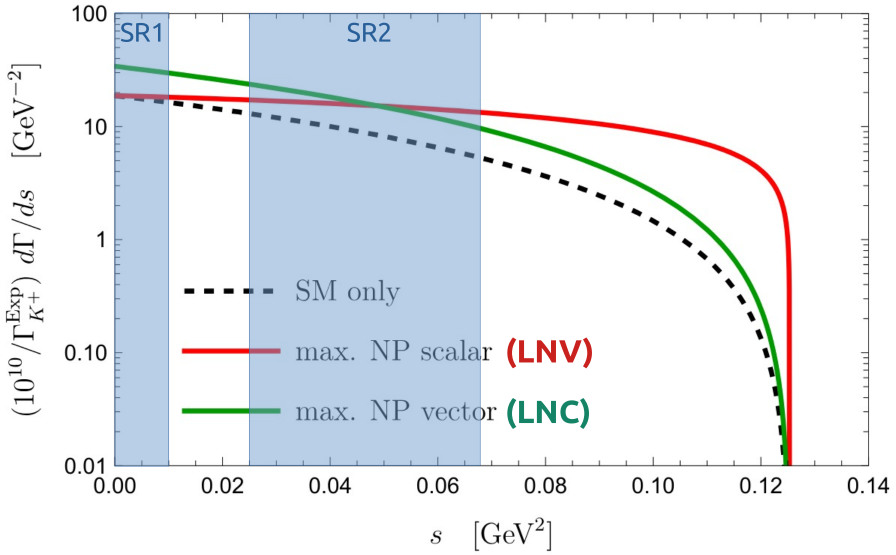
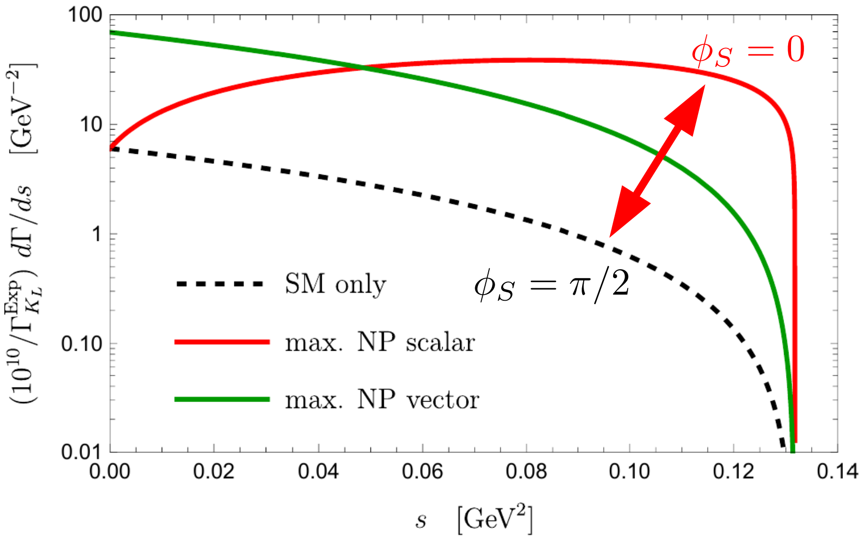


independent of scalar phase



dependent on scalar phase

comparing K_L and K^+ distributions can help to identify CP phase in scalar sector

Buras, JH, Mojahed (2025)

Disentangling the NP contribution

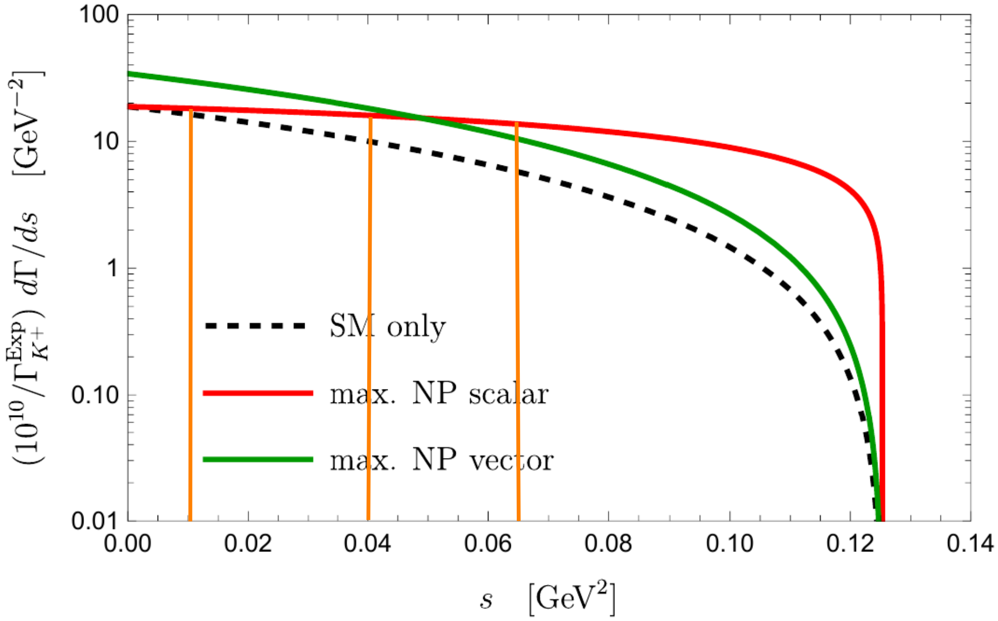
$$\mathcal{D}_+^{\rm exp}(s) \equiv \frac{d\Gamma(K^+ \to \pi^+\nu\widehat{\nu})}{ds} = C_S^+ f_S^+(s) + C_V^+ f_V^+(s) + C_T^+ f_T^+(s)$$

Measuring distribution at three different values s_1, s_2 and s_3:

$$C_S^+ = \frac{D_+^{\rm exp}(s_1)\left[f_V^+(s_2)f_T^+(s_3) - f_V^+(s_3)f_T^+(s_2)\right] + \text{cyclic}}{f_S^+(s_1)\left[f_V^+(s_2)f_T^+(s_3) - f_V^+(s_3)f_T^+(s_2)\right] + \text{cyclic}}$$

$$C_V^+ = \frac{D_+^{\rm exp}(s_1)\left[f_S^+(s_2)f_T^+(s_3) - f_S^+(s_3)f_T^+(s_2)\right] + \text{cyclic}}{f_V^+(s_1)\left[f_S^+(s_2)f_T^+(s_3) - f_S^+(s_3)f_T^+(s_2)\right] + \text{cyclic}}$$

$$C_T^+ = \frac{D_+^{\rm exp}(s_1)\left[f_S^+(s_2)f_V^+(s_3) - f_S^+(s_3)f_V^+(s_2)\right] + \text{cyclic}}{f_T^+(s_1)\left[f_S^+(s_2)f_V^+(s_3) - f_S^+(s_3)f_V^+(s_2)\right] + \text{cyclic}}$$



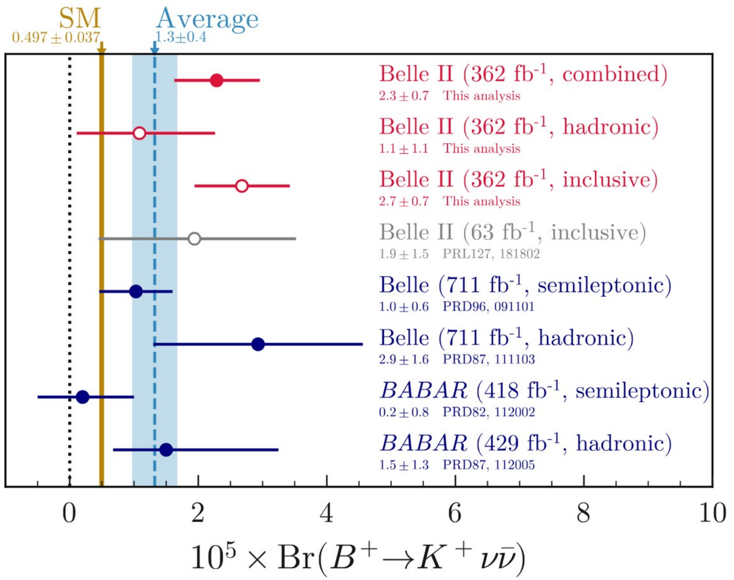
measuring non-zero C_S or C_T implies the existence of a scalar or tensor current
measuring non-zero C_V not in agreement with SM, implies new vector currents

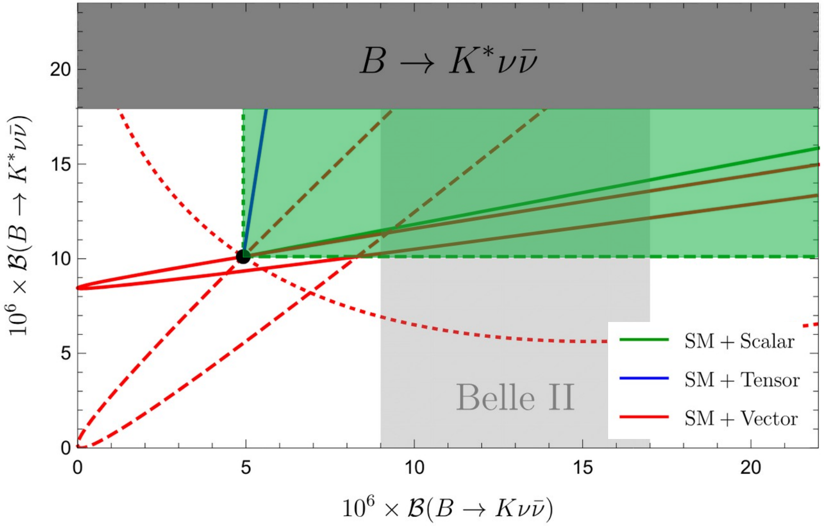
Buras, JH, Mojahed (2025)

Lepton number violation in B-decays?

Belle II reports deviation from SM

$$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})^{\mathrm{SD}}_{\mathrm{SM}} = (4.92 \pm 0.30) \times 10^{-6}$$

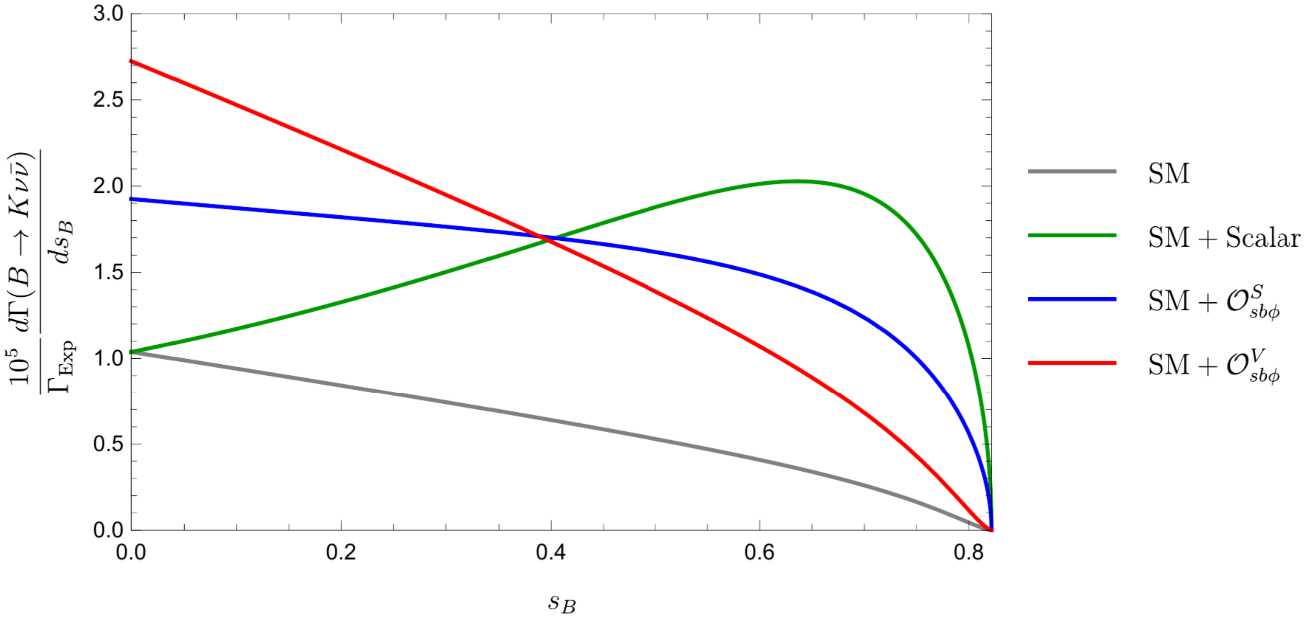




Scalar currents are confined to green area
tensor current disfavoured See also Felkl, Giri, Mohanta, Schmidt (2023)
Buras, JH, Mojahed (2025)

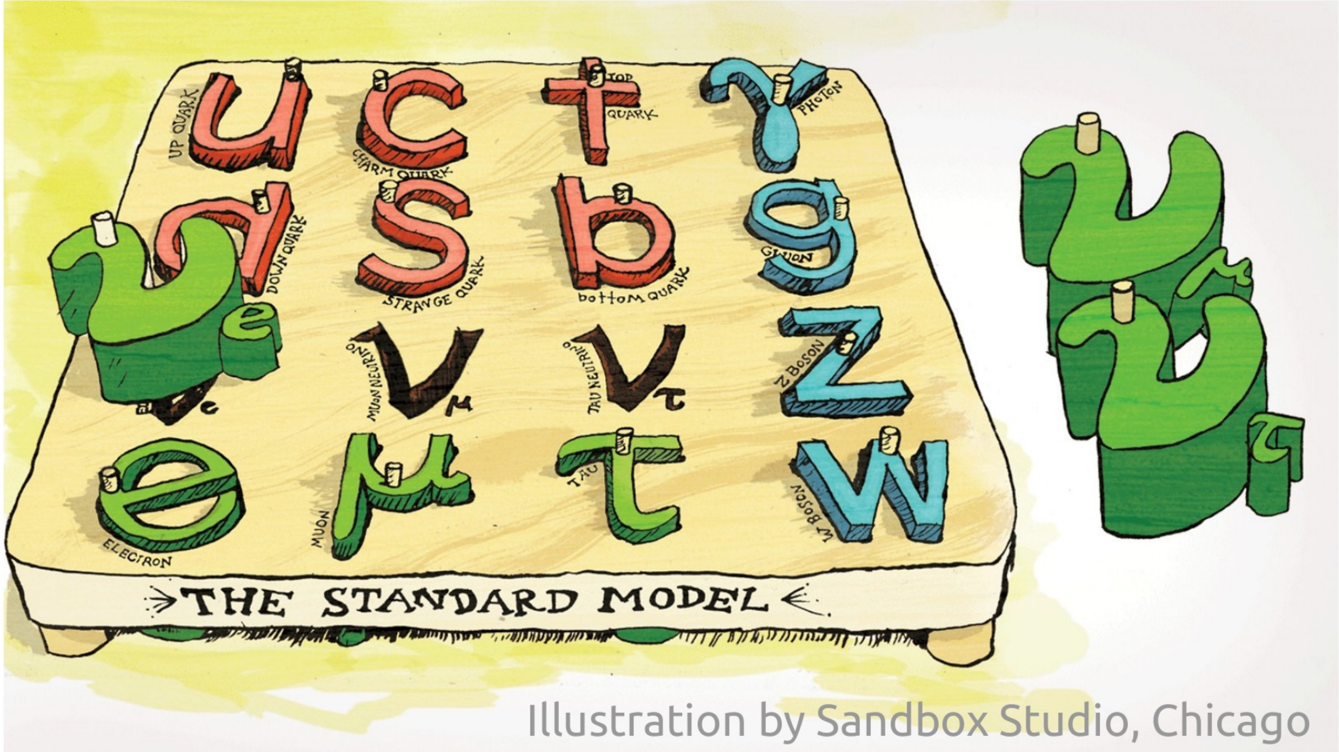
Neutrinos or dark sector particles?

Example for comparison with dark sector final state particles: scalar dark matter



Distinguishable from various dark final states via kinematic distributions,
dark fermions with similar Dirac structure as scalar SMEFT would require further analysis

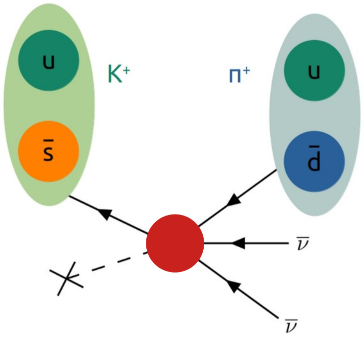
Buras, JH, Mojahed (2025)



Search for Lepton Number Violation (LNV)

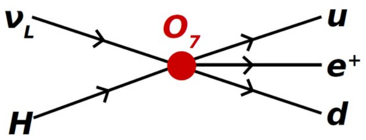
A comprehensive survey of dim-7 LNV operators

Non-exhaustive list of references!!



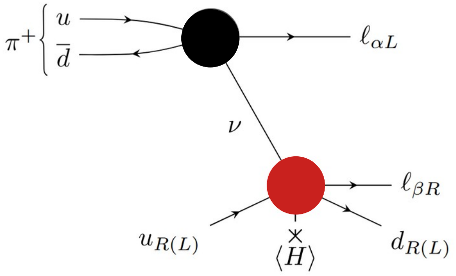
Meson decays

See also: Li, Ma, Schmidt (2019)



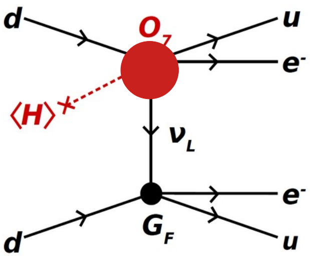
LNV: ΔL = 2

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



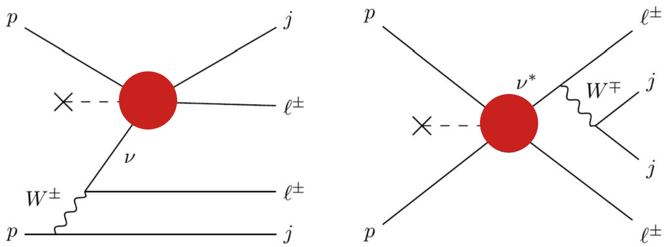
Neutrino oscillations

See also: Bolton, Deppisch (2019)



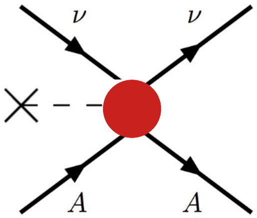
Neutrinoless double beta decay

See also: Cirigiliano et al. (2017)



Collider searches

See also: Cepedello, Hirsch, Helo (2017), Deppisch, Dev, Pilaftsis (2015), del Aguila et al. (2012)



Coherent elastic neutrino nucleus scattering (CEvNS)

See also: Lindner, Rodejohann,Xu (2017)

A comprehensive survey of dim-7 LNV operators

Type	$\mathcal{O}$	Operator
$\Psi^2 H^4$	$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^i L_r^m\right) H^j H^n \left(H^\dagger H\right)$
$\Psi^2 H^3 D$	$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^i \gamma_\mu e_r\right) H^j \left(H^m iD^\mu H^n\right)$
$\Psi^2 H^2 D^2$	$\mathcal{O}_{LHD1}^{pr}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^i D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
	$\mathcal{O}_{LHD2}^{pr}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{L_p^{c}}^i D_\mu L_r^j\right)\left(H^m D^\mu H^n\right)$
$\Psi^2 H^2 X$	$\mathcal{O}_{LHB}^{pr}$	$g\epsilon_{ij}\epsilon_{mn}\left(\overline{L_p^{c}}^i \sigma_{\mu\nu} L_r^m\right) H^j H^n B^{\mu\nu}$
	$\mathcal{O}_{LHW}^{pr}$	$g'\epsilon_{ij}\left(\epsilon\tau^I\right)_{mn}\left(\overline{L_p^{c}}^i \sigma_{\mu\nu} L_r^m\right) H^j H^n W^{I\mu\nu}$
$\Psi^4 D$	$\mathcal{O}_{\bar{d}uLLD}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}\gamma_\mu u_r\right)\left(\overline{L_s^{c}}^i iD^\mu L_t^j\right)$
$\Psi^4 H$	$\mathcal{O}_{\bar{e}LLLH}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{e_p}L_r^i\right)\left(\overline{L_s^{c}}^j L_t^m\right) H^n$
	$\mathcal{O}_{\bar{d}LueH}^{prst}$	$\epsilon_{ij}\left(\overline{d_p}L_r^i\right)\left(\overline{u_s^c}e_t\right) H^j$
	$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	$\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{c}}^j L_t^m\right) H^n$
	$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	$\epsilon_{im}\epsilon_{jn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{c}}^j L_t^m\right) H^n$
	$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	$\epsilon_{ij}\left(\overline{Q_p}u_r\right)\left(\overline{L_s^c}L_t^i\right) H^j$

Basis according to Lehmann (2014), Liao, Ma (2017)

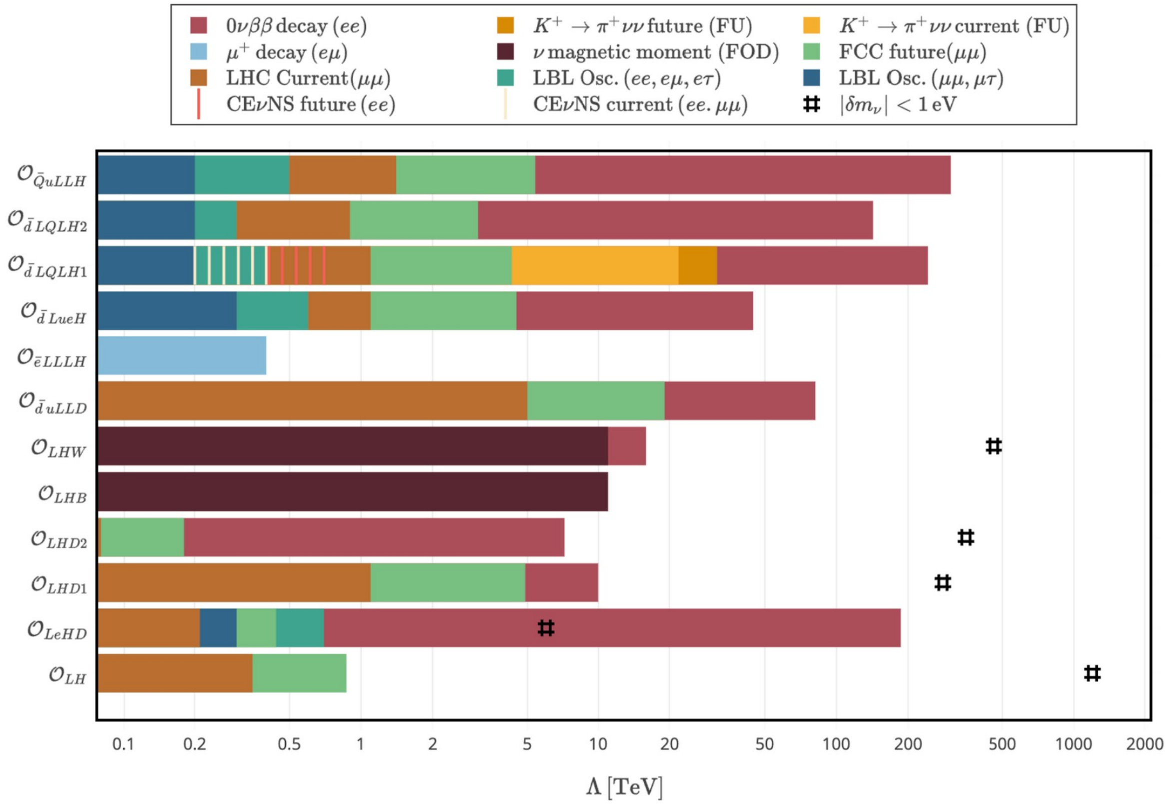
Fridell, Graf, JH, Hati (2023)

A comprehensive survey of dim-7 LNV operators

Operator	Collider	$0\nu\beta\beta$	LBL Osc.	μ_ν	μ^+-decay	CEνNS	Meson decay
$\mathcal{O}_{LH}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LeHD}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{LHD1}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LHD2}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{LHB}$	-	-	-	✓	-	✓	-
$\mathcal{O}_{LHW}$	-	✓	-	✓	-	✓	-
$\mathcal{O}_{\bar{d}uLLD}$	✓	✓	-	-	-	-	-
$\mathcal{O}_{\bar{e}LLLH}$	-	-	-	-	✓	-	-
$\mathcal{O}_{\bar{d}LueH}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{\bar{d}LQLH1}$	✓	✓	✓	-	-	✓	✓
$\mathcal{O}_{\bar{d}LQLH2}$	✓	✓	✓	-	-	-	-
$\mathcal{O}_{\bar{Q}uLLH}$	✓	✓	✓	-	-	✓	-

Fridell, Graf, JH, Hati (2023)

A comprehensive survey of dim-7 LNV operators



Potential to disentangle different operators due to interplay of different observables

Fridell, Graf, JH, Hati (2023)

Limitations of the EFT analysis – LHC

Validity of the EFT dependent on momentum exchange

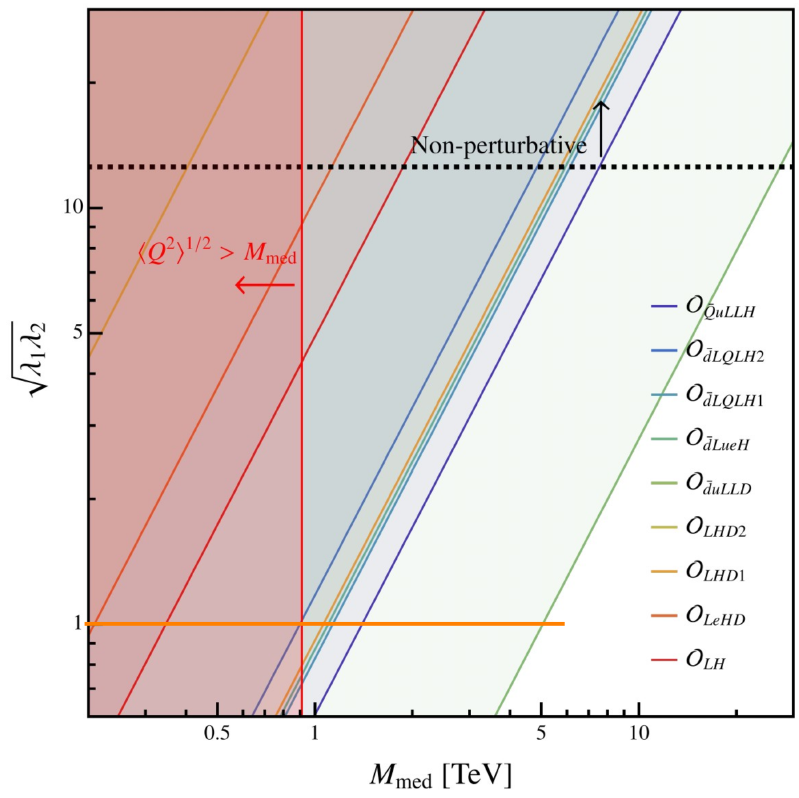
$$\frac{g^2}{Q^2 - M_{\rm med}^2} = -\frac{g^2}{M_{\rm med}^2}\left(1 + \frac{Q^2}{M_{\rm med}^2} + \mathcal{O}\left(\frac{Q^4}{M_{\rm med}^4}\right)\right)$$

generally valid only when $M_{\rm med}^2 > Q^2$

Limits on the new physics' masses dependent on actual UV model couplings:

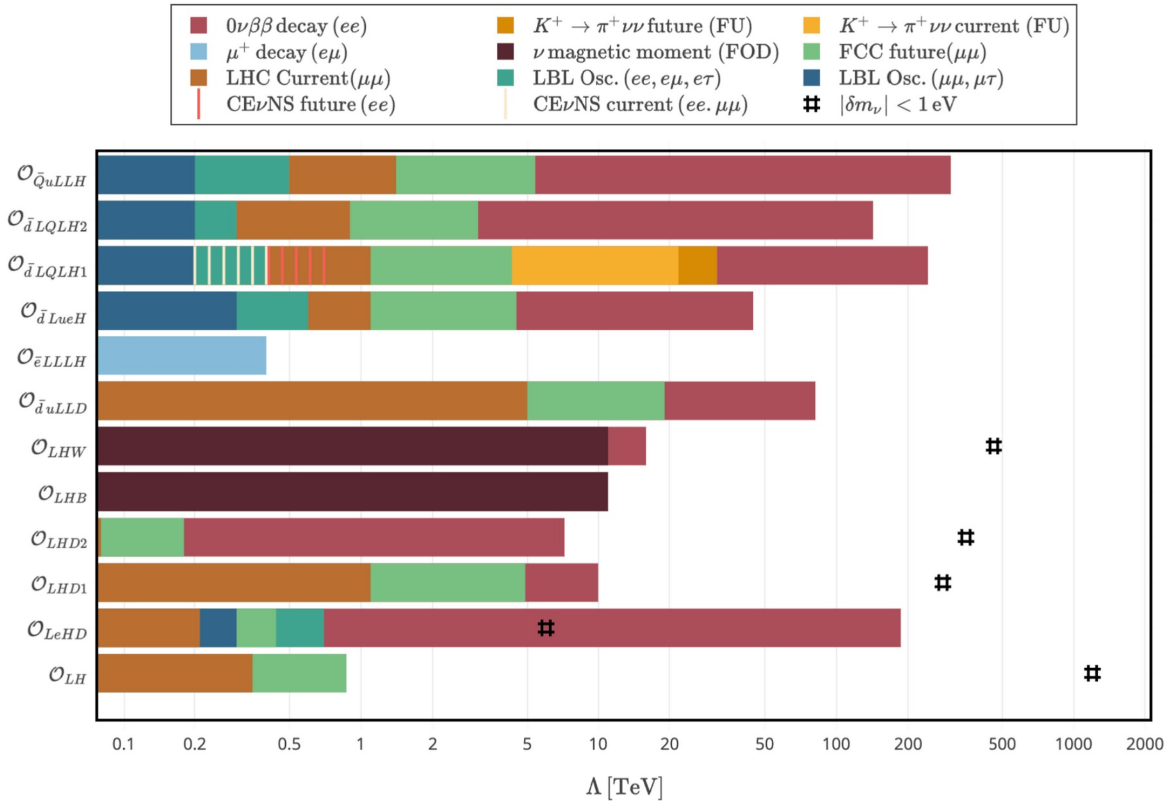
$$\frac{\lambda_1\lambda_2}{M_{\rm med}^3} = \frac{1}{(\Lambda_{\rm LNV})^3}$$

Careful interpretation of EFT limits crucial



Fridell, Graf, JH, Hati (2023)

A comprehensive survey of dim-7 LNV operators



For neutrino mass limits see also: Cirigliano et al. (2017)

Neutrino mass limits can be competitive, but are heavily dependent on the actual model

Fridell, Graf, JH, Hati (2023)

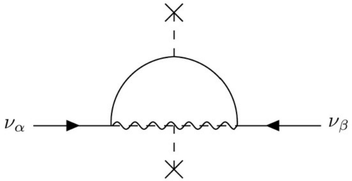
Limitations of the EFT analysis – simplified models

Identification of all possible tree-level UV completions incl. their neutrino mass topology

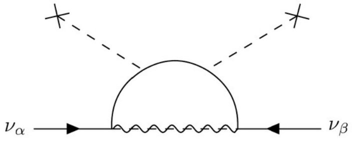
$$\mathcal{O}_{\bar{d}LQLH1} = \epsilon_{ij}\epsilon_{mn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{cj}}L_t^m\right)H^n$$

	Δ	φ	S_1	$\tilde{R}_2$	S_3	N	Σ	$Q_5^\dagger$	T_2
Δ		●						●	●
φ	●					○	○		
S_1				I		○		II	
$\tilde{R}_2$			I		I	○	○		II
S_3				I			○	II	
N		○	○	○					
Σ		○		○	○				
$Q_5^\dagger$	●		II		II				
T_2	●			II					

For exploding dim-7 operators see also:
Gargalionis, Volkas (2021)



topology I



topology II

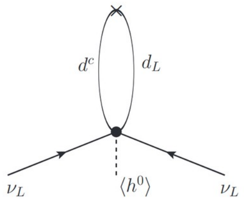
Fridell, Graf, JH, Hati (2024)

Limitations of the EFT analysis – neutrino masses

Example: $\epsilon_{ij}\epsilon_{mn}\left(\overline{d_p}L_r^i\right)\left(\overline{Q_s^{cj}}L_t^m\right)H^n$

- **Naive dimensional analysis** $(m_\nu)_{ij}$

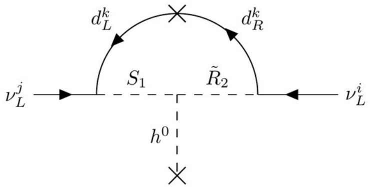
Gouvea, Jenkins (2007)



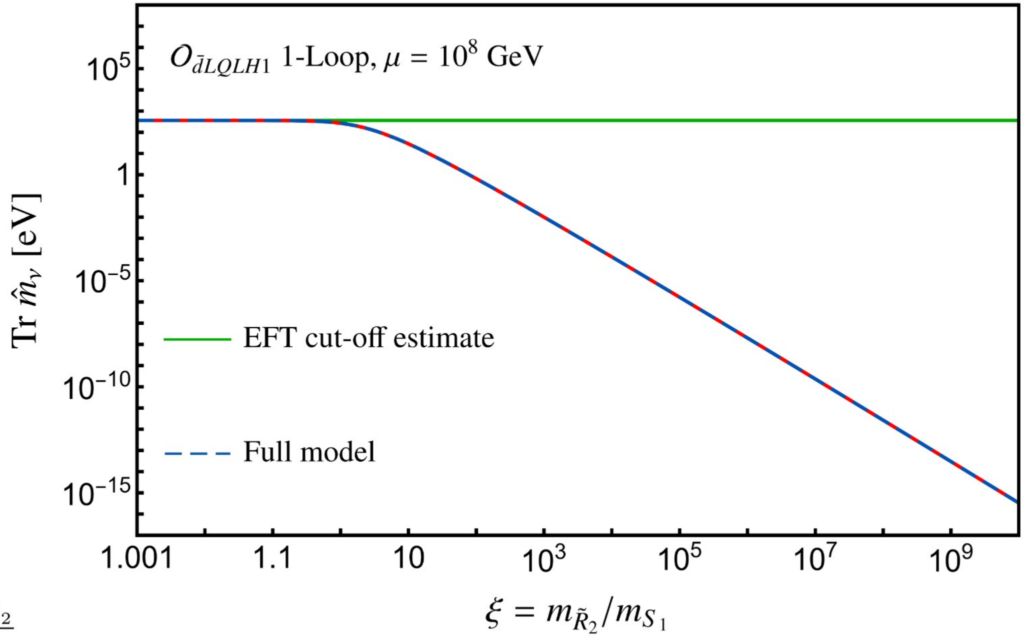
$$y_d^{ps}\frac{1}{16\pi^2}\frac{v^2}{\Lambda}$$

- **Actual UV model analysis** $(m_\nu)_{ij}$

Babu, Dev, Jana, Thapa (2019)



$$\sum_k \frac{3\sin(2\theta)\, y_{kk}^d v g_1^{ik} g_2^{kj}}{32\pi^2}\log\frac{m_{\mathrm{LQ}_2}^2}{m_{\mathrm{LQ}_1}^2}$$



Large mass hierarchies in the new physics are not captured – is there an intermediate way?

Fridell, Graf, JH, Hati (2024)

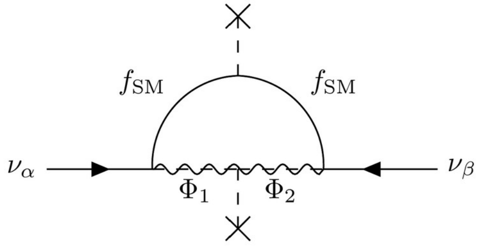
A simplified multi-scale approach

Based on dimensional regularisation and method of regions

Beneke, Smirnov (1998)
Manohar (1997)

Generalised to general topology I (1-loop)

$$(m_\nu)^{\text{I}}_{ij} \approx \frac{1}{16\pi^2} \frac{v\mu}{m^2_{\Phi_1} - m^2_{\Phi_2}} \log\left(\frac{m^2_{\Phi_1}}{m^2_{\Phi_2}}\right) \left(\lambda_{\Phi_1} M_f \lambda^T_{\Phi_2} + \lambda_{\Phi_2} M^T_f \lambda^T_{\Phi_1}\right)_{ij}$$



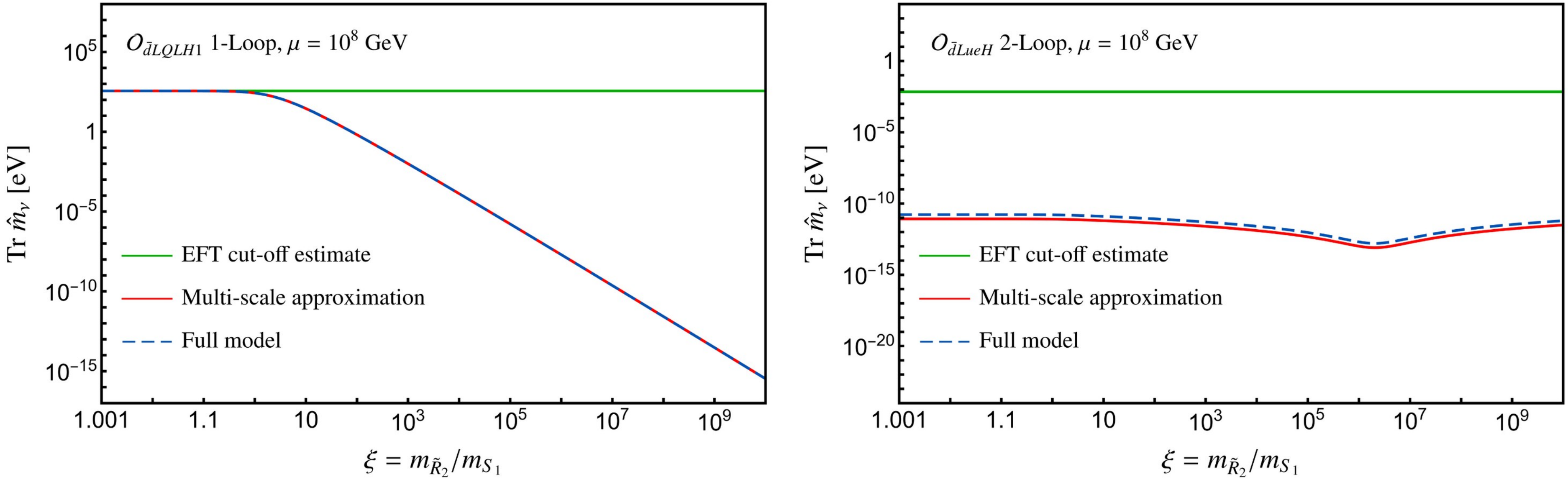
topology I (1-loop)

Generalised to general topology I (2-loop)

$$(m_\nu)^{\text{I, two-loop}}_{ij} \approx \frac{1}{(16\pi^2)^2} \frac{v^3\mu}{m^2_{\Phi_1} - m^2_{\Phi_2}} \left[f_\ell(m_{\Phi_1}, m_W) - f_\ell(m_{\Phi_2}, m_W)\right] \times \left(\lambda_{\Phi_1} M_f \lambda^T_{\Phi_2} + \lambda_{\Phi_2} M^T_f \lambda^T_{\Phi_1}\right)_{ij}$$

Fridell, Graf, JH, Hati (2024)

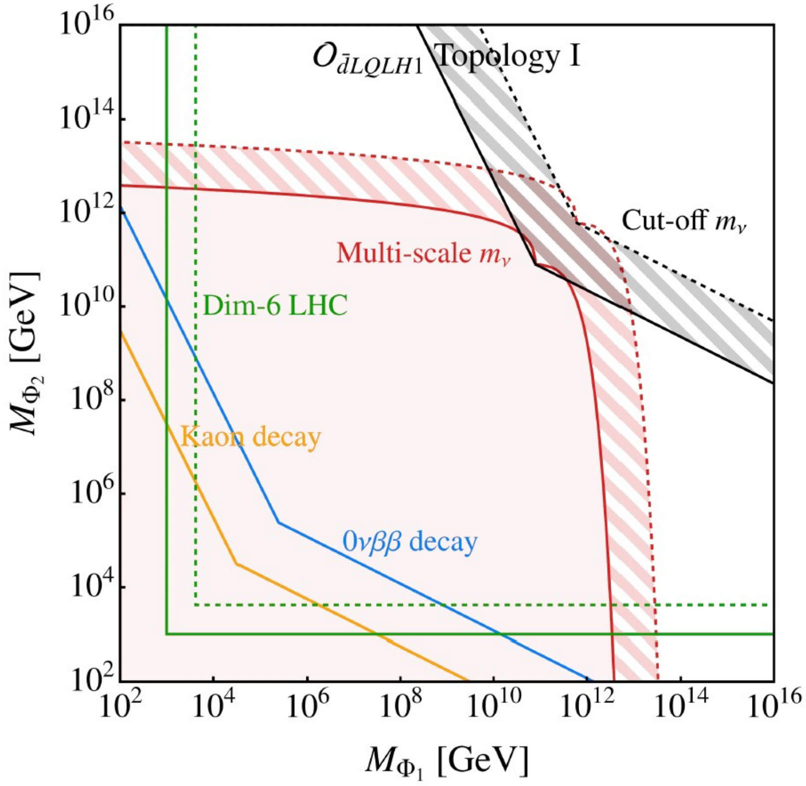
A simplified multi-scale approach

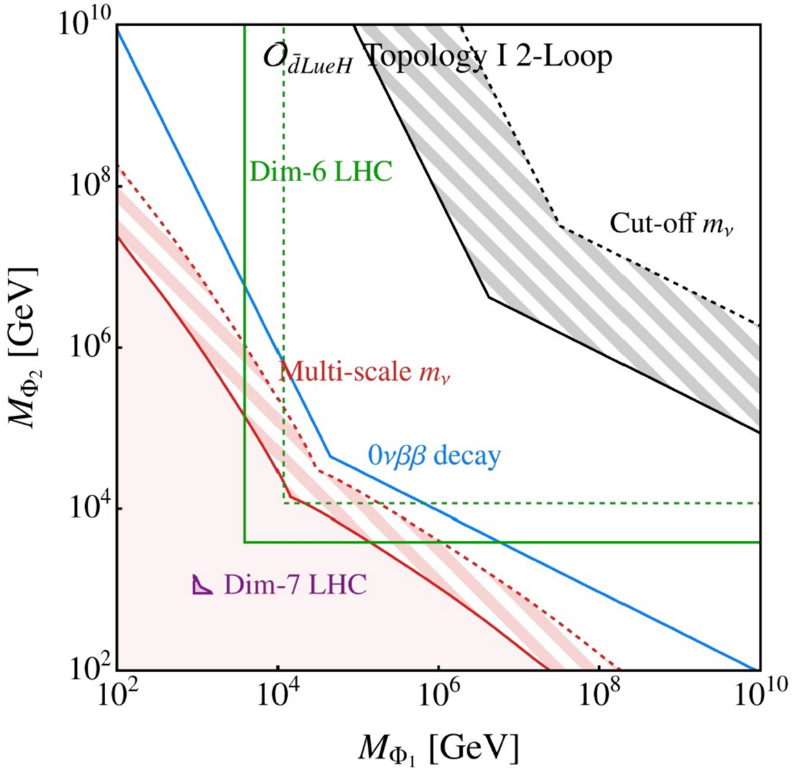


The simplified multi-scale approach captures all relevant features of a UV theory

Fridell, Graf, JH, Hati (2024)

Impact on the parameter space





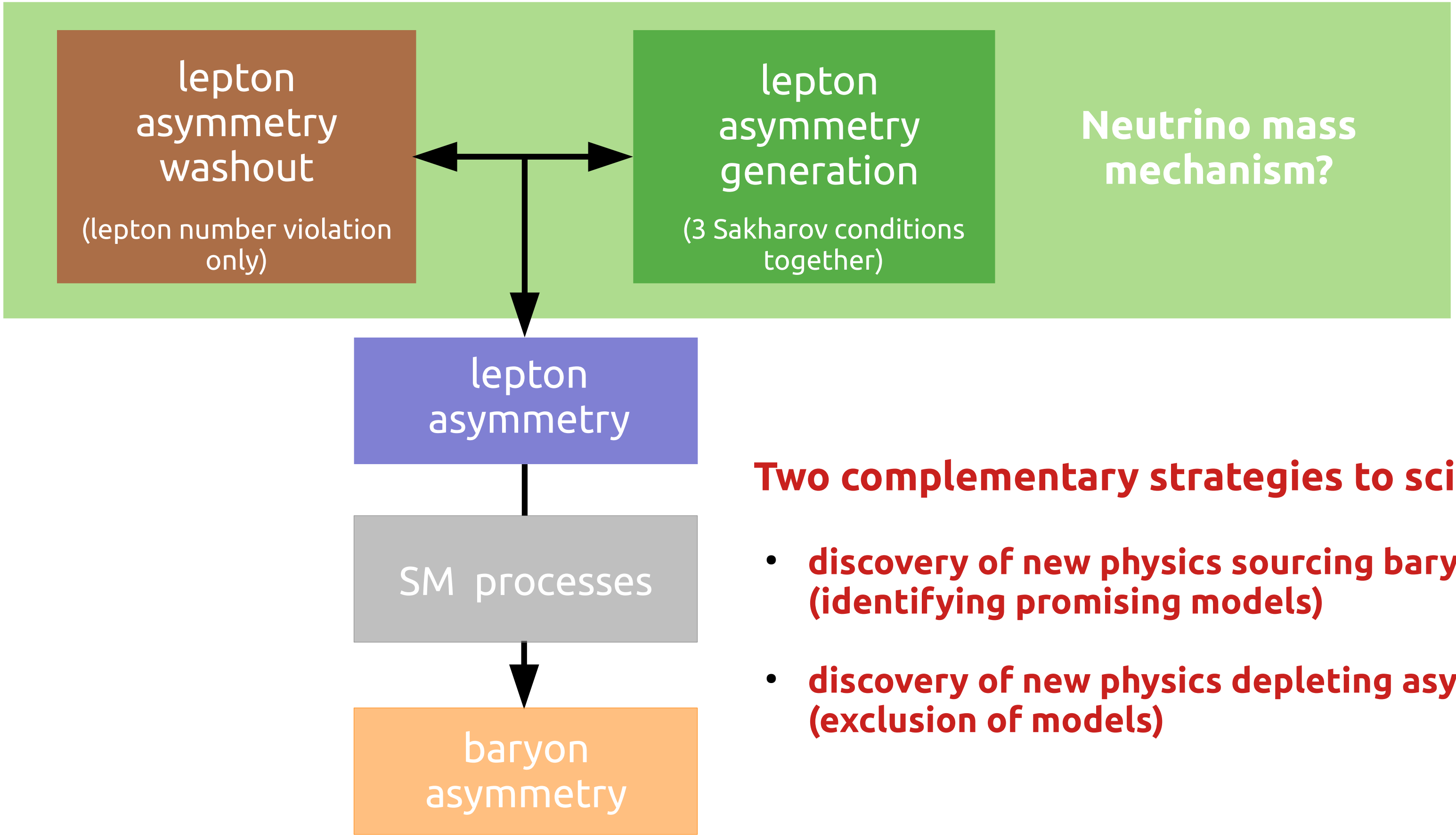
The simplified multi-scale approach as a more reliable estimate
Opens up parameter space featuring interplay of experimental observables

Fridell, Graf, JH, Hati (2024)

Credit: Ella Dreiner

From the lab to the cosmos: link to leptogenesis

Basic principle of leptogenesis



Two complementary strategies to scientifically progress:

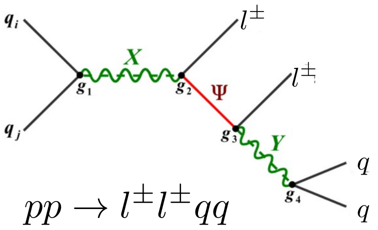
- **discovery of new physics sourcing baryon asymmetry (identifying promising models)**
- **discovery of new physics depleting asymmetry (exclusion of models)**


Credit: Ella Dreiner

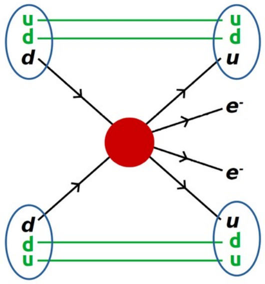
Implications of low-scale LNV new physics on baryogenesis

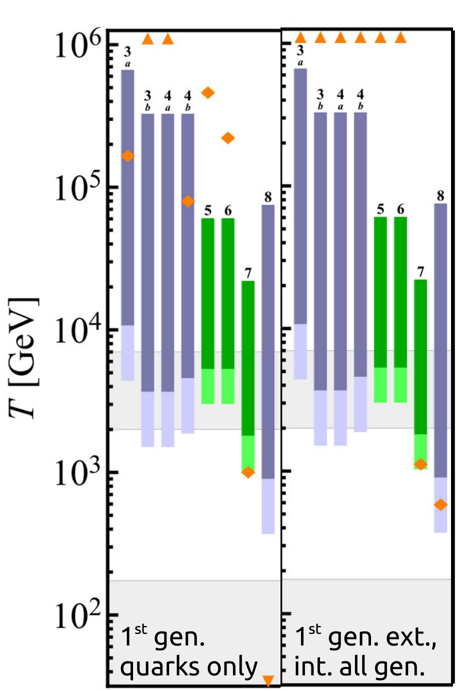
Falsifying baryogenesis with LHC & 0νββ decay

Observation of any LNV washout process at the LHC would falsify high-scale baryogenesis
Deppisch, JH, Hirsch (2014)



Observation of neutrinoless double beta decay with new physics from > dim-5 LNV operators would falsify high-scale baryogenesis
Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)





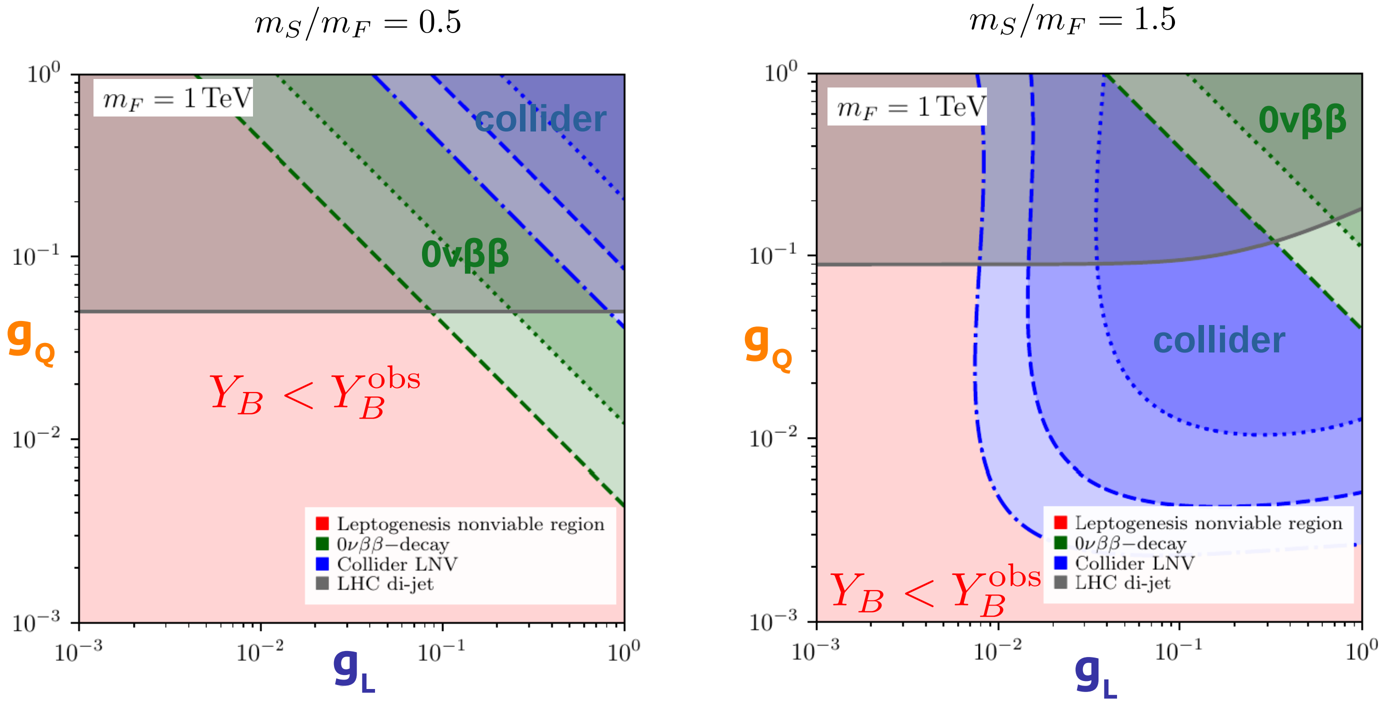
Asymmetry stored in another flavour sector?
→ measurement in all flavours
→ low-scale LFV leading to equilibration

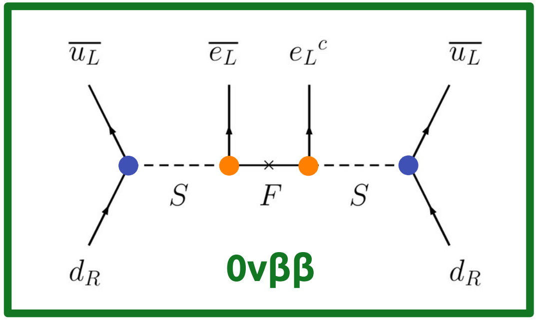
For the impact **BNV interactions** from Nnbar oscillations, meson oscillations and the LHC on Baryogenesis, see
Fridell, JH, Hati (2021)

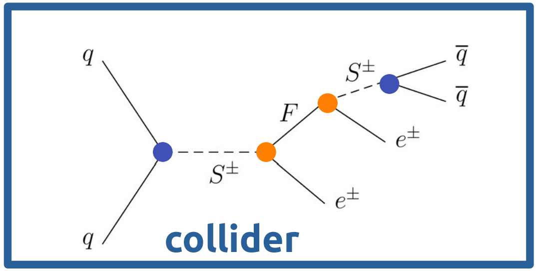
BUT: Limitations of EFT approach

Falsifying baryogenesis with LHC & 0νββ decay

Impact of observation of TeV-scale LNV on standard leptogenesis $\tilde{\mathcal{L}} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F$







➡ **Depending on mass hierarchy of new physics, collider or 0νββ decay is more sensitive**

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

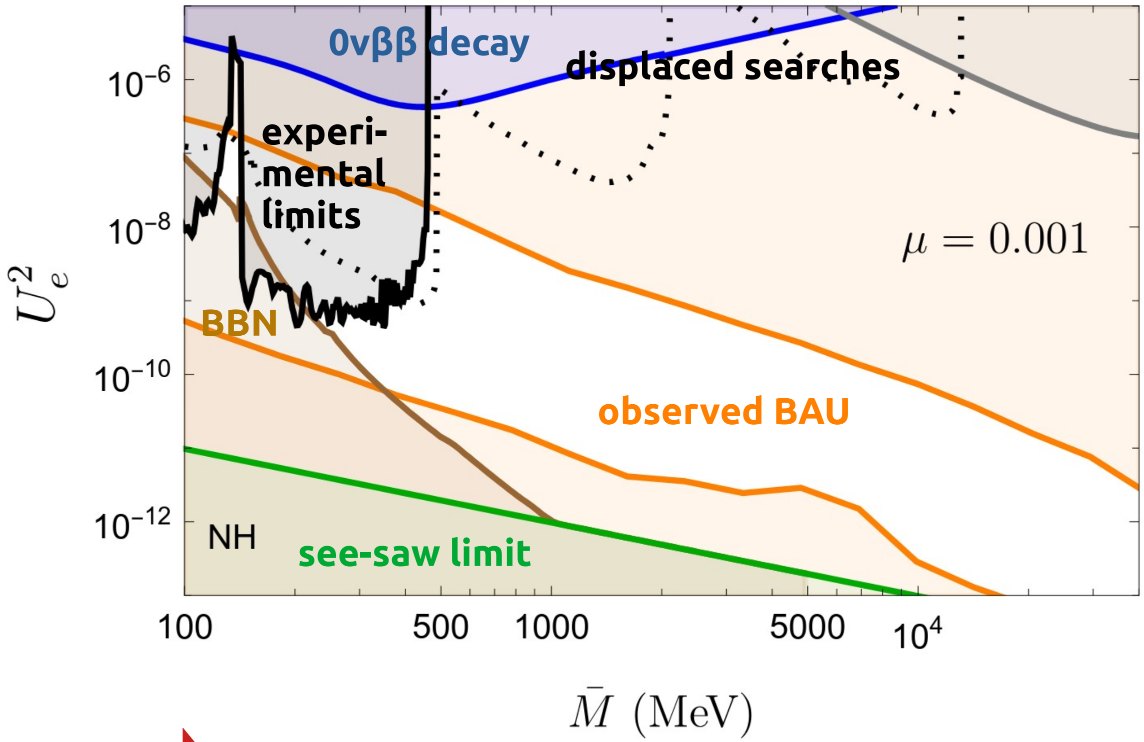
Credit: Ella Dreiner

Implications of new low-scale LNC physics on baryogenesis and neutrinoless double beta decay

Julia Harz

Low-scale leptogenesis

Low-scale leptogenesis is an interesting alternative possibility to high-scale leptogenesis



- Testability via collider searches
- Link to neutrinoless double beta decay

de Vries, Drewes, Georis, Klaric, Plakkot (1998)

Several works on low-scale leptogenesis by other authors: Drewes et al, Klaric et al, Hernandez et al., etc.

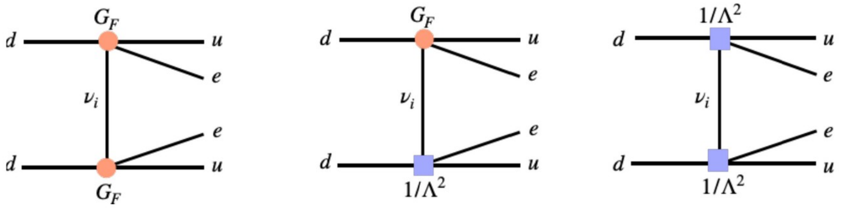
How is the parameter space impacted by new LNC non-standard interactions (NSIs)?

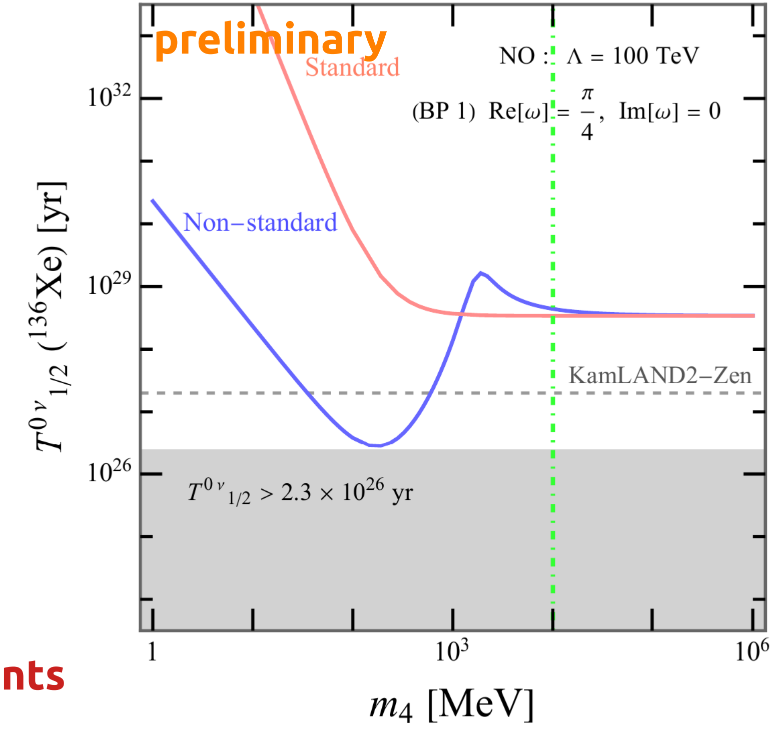
Impact of LNC operators on 0νββ decay

LNC νSMEFT operators can lead to an altered half life of neutrinoless double beta decay

See also Dekens, de Vries, Fuyuto, Mereghetti, Zhou(2020)

$$\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$$



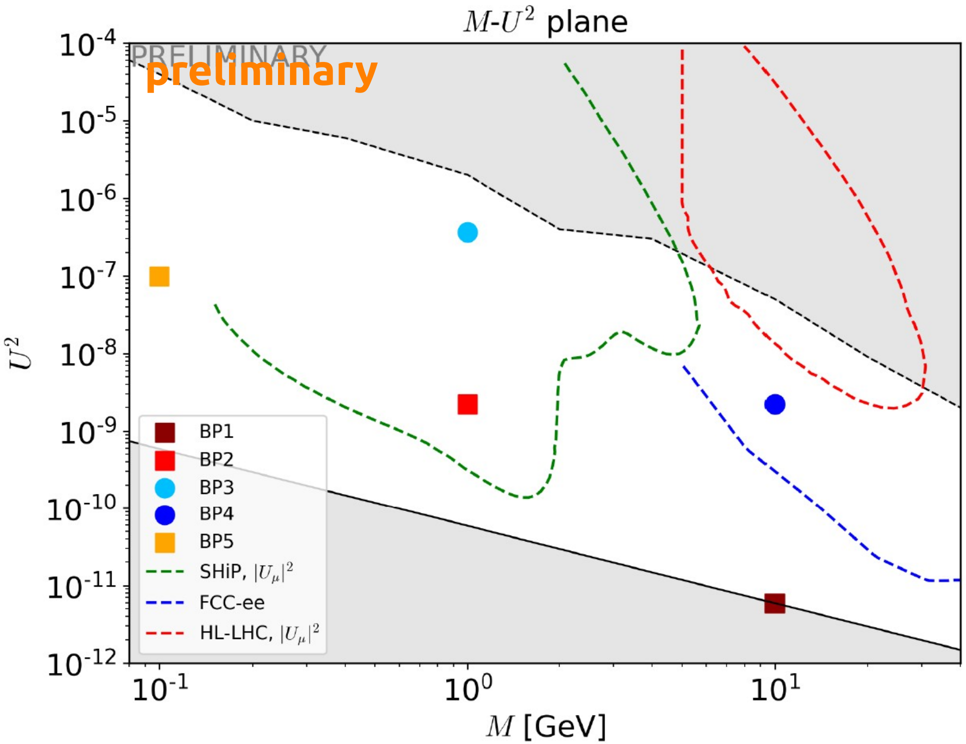


Fuyuto, JH, Weber (in preparation)

Even though LNC, the operator opens up promising detection possibilities at next-generation experiments

Impact of LNC operators on low-scale leptogenesis

Investigation of the impact of a new LNC νSMEFT interaction $\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$
on the low-scale leptogenesis parameter space

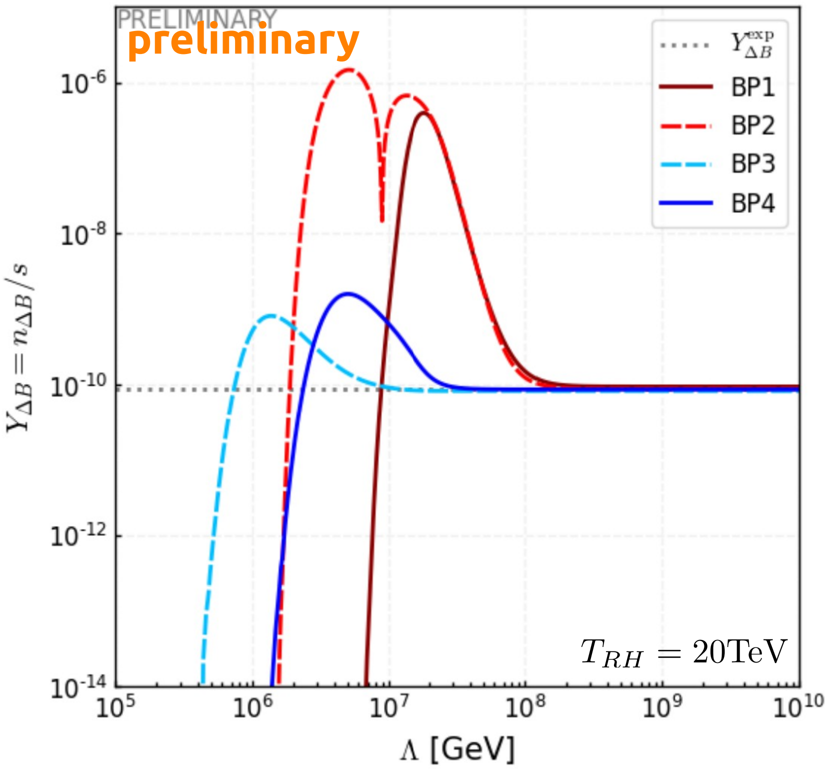


For parameter study of standard low-scale LG:
Drewes et al, Hernandez et al.

Fuyuto, JH, Weber (in preparation)

Impact of LNC operators on low-scale leptogenesis

$$\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$$

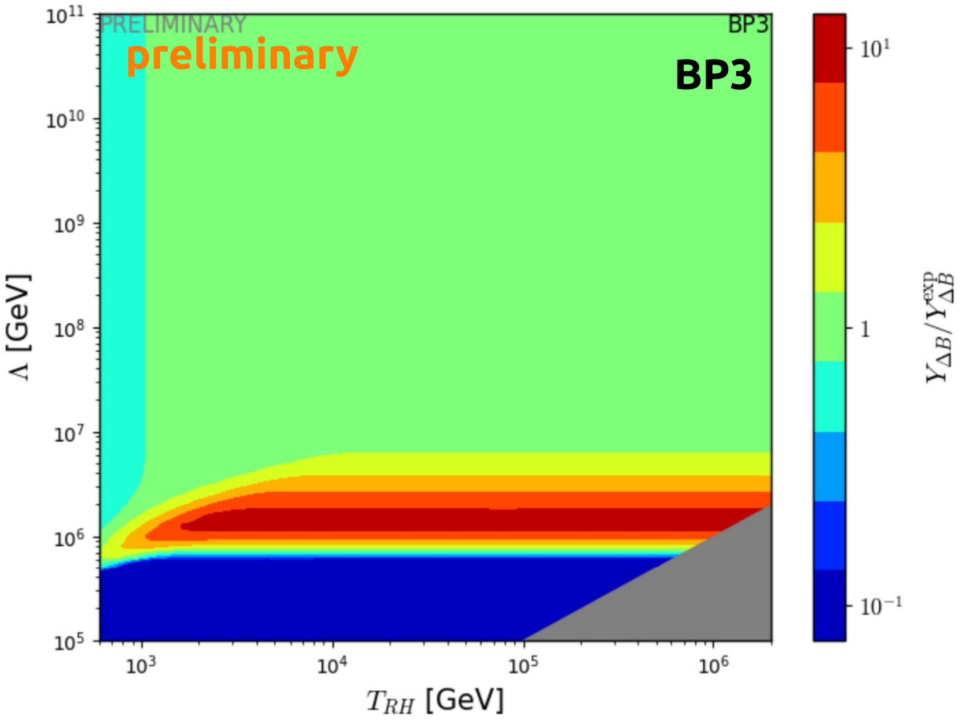


➡ **enhancement or reduction of the BAU depending on Δ wrt standard scenario possible**

➡ **New LNC interaction can lead to enhancement of the BAU!**

Fuyuto, JH, Weber (in preparation)

Impact of LNC operators on low-scale leptogenesis

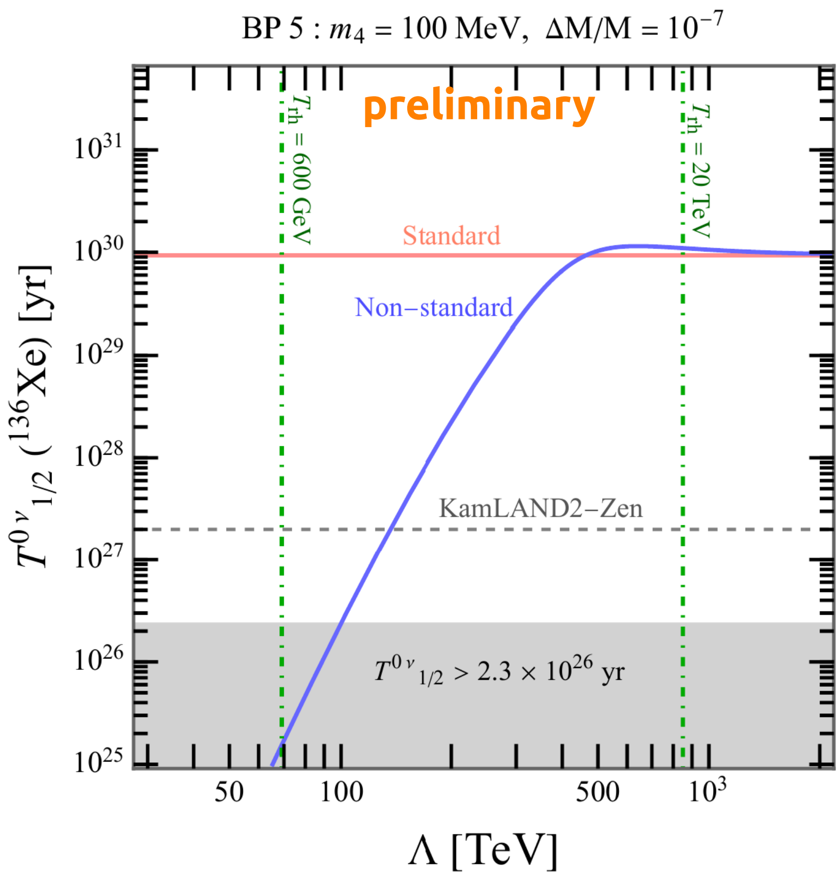


$$\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$$

- **dynamics can be independent of the highest temperature of the thermal history (T_{RH}) in the overdamped regime**
- **At 0νββ decay accessible parameter space in tension with BAU**

Fuyuto, JH, Weber (in preparation)

Impact of LNC operators on low-scale leptogenesis



$$\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$$

➡ **For small mass splittings and small RHN neutrino masses observation at 0νββ decay experiments and correct BAU still possible**

Fuyuto, JH, Weber (in preparation)

Conclusions

- Observation of Lepton Number Violation (LNV) would have far reaching consequences on neutrino physics and leptogenesis

- “invisible” decay modes as in B- or Kaon-decays can give relevant insights

- Only comprehensive consideration of ALL observables can help disentangling the new physics (operator)

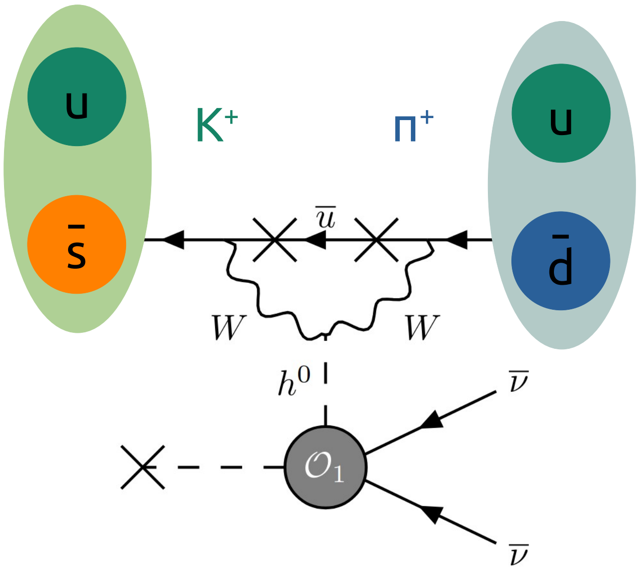
- Simplified models and multi-scale approach for model independent study with reliable limits

- Leptogenesis will be impacted, even for new low-scale lepton-number conserving interactions

Exciting complementary insights from the early Universe and laboratory experiments!

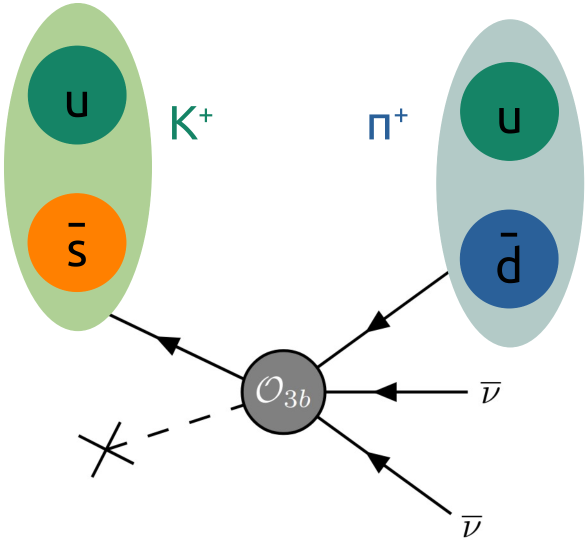
Thank you for your attention!

Lepton number violation in 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



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

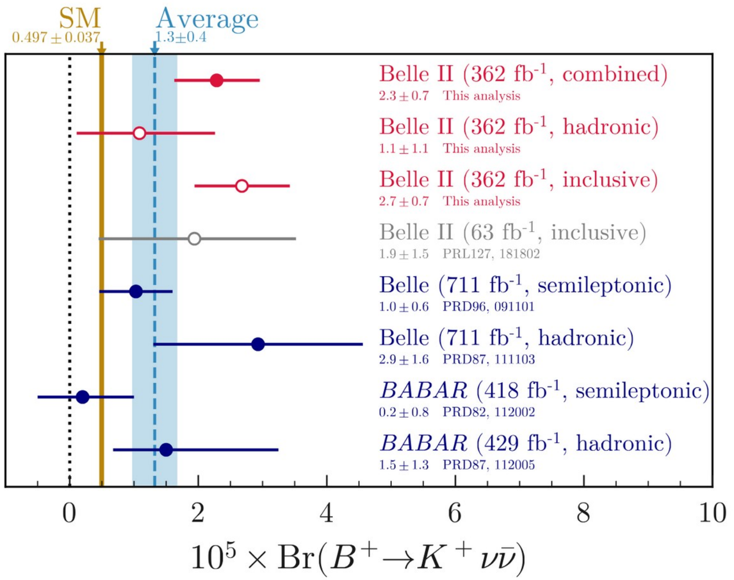
- No GIM suppression
- Majorana contribution to neutrino masses

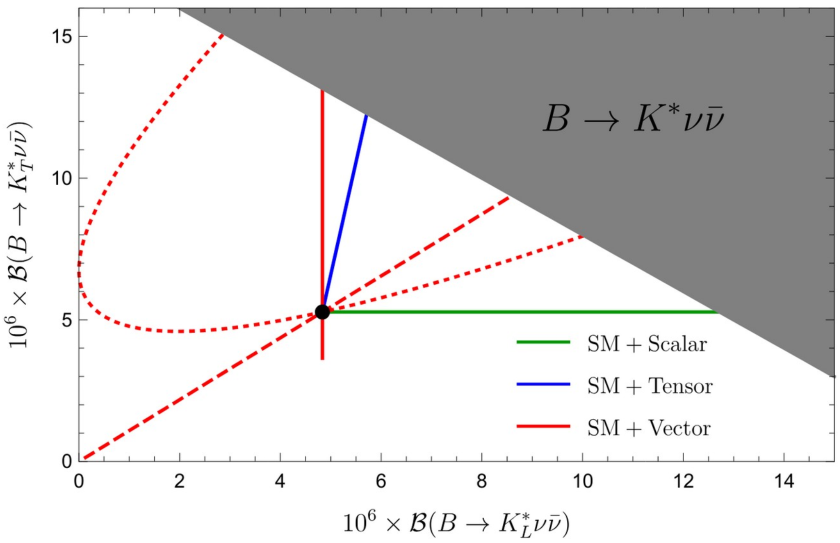
Footprints of Majorana neutrinos in rare meson decays?

Lepton number violation in B-decays

Belle II reports deviation from SM

$$\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})^{\mathrm{SD}}_{\mathrm{SM}} = (4.92 \pm 0.30) \times 10^{-6}$$





Tensor (scalar) current confined to blue (green) line, beyond indication for vector current

Buras, JH, Mojahed (2025)

Limitations of the EFT analysis – LHC

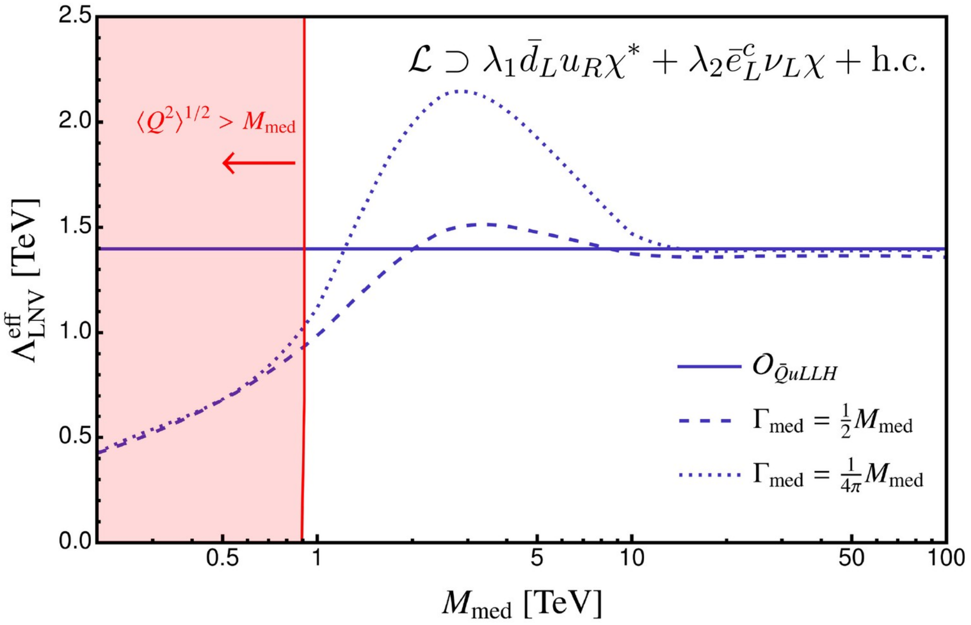
Validity of the EFT dependent on momentum exchange

$$\frac{g^2}{Q^2 - M_{\text{med}}^2} = -\frac{g^2}{M_{\text{med}}^2}\left(1 + \frac{Q^2}{M_{\text{med}}^2} + \mathcal{O}\left(\frac{Q^4}{M_{\text{med}}^4}\right)\right)$$

generally valid only when $M_{\text{med}}^2 > Q^2$

With an invariant mass of lepton and quark pairs of 510 GeV, one finds an average momentum transfer of

Q ~ 900 GeV



Resonances can lead to stricter limits

EFT analysis leads to an underestimation for smaller widths

Fridell, Graf, JH, Hati (2023)

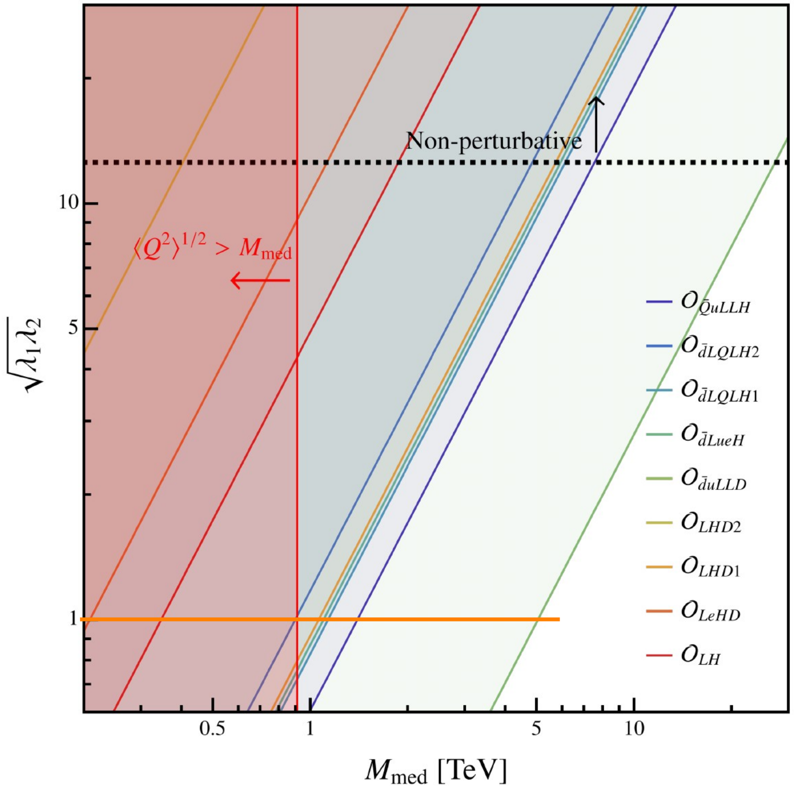
Limitations of the EFT analysis – LHC

Limits on the new physics' masses dependent on actual UV model couplings:

$$\frac{\lambda_1 \lambda_2}{M_{\rm med}^3} = \frac{1}{(\Lambda_{\rm LNV})^3}$$

➡ **Careful interpretation of EFT limits necessary**

➡ **For large momentum observables simplified models more reliable**



Fridell, Graf, JH, Hati (2023)

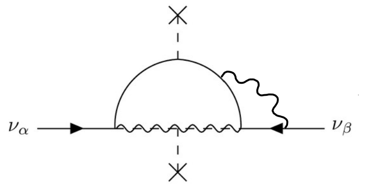
Limitations of the EFT analysis – simplified models

Identification of all possible tree-level UV completions incl. their neutrino mass topology

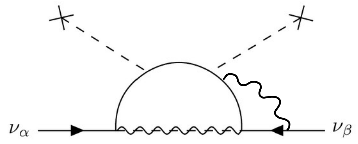
For exploding dim-7 operators see also:
Gargalionis, Volkas (2021)

$$\mathcal{O}_{\bar{d}LueH} = \epsilon_{ij}\left(\overline{d_p}L_r^i\right)\left(\overline{u_s^c}e_t\right)H^j$$

	S_1	$\tilde{R}_2$	N	$\Delta_1^\dagger$	$Q_5^\dagger$	Q_7	W_1'	V_3	U_1	$\bar{V}_2^\dagger$
S_1		I*	○		II*					
$\tilde{R}_2$	I*			II*		II*				
N	○						○		○	
$\Delta_1^\dagger$		II*					II*			II*
$Q_5^\dagger$	II*							II*		II*
Q_7		II*						II*	II*	
W_1'			○	II*				I*		
V_3					II*	II*	I*			
U_1			○			II*				I*
$\bar{V}_2^\dagger$				II*	II*				I*	



topology I*



topology II*

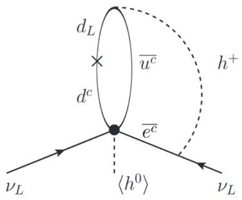
Fridell, Graf, JH, Hati (2024)

Limitations of the EFT analysis – neutrino masses

Example 2: $\epsilon_{ij}\left(\overline{d_p} L^i_r\right)\left(\overline{u^c_s} e_t\right) H^j$

- **Naive dimensional analysis** $(m_\nu)_{ij}$

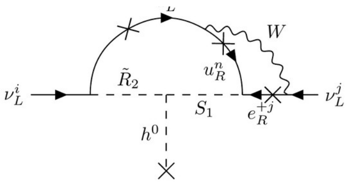
Gouvea, Jenkins (2007)



$$\sum_{ij} y_u^{sj} y_d^{jp} y_e^{ti} \frac{1}{(16\pi^2)^2} \frac{v^2}{\Lambda}$$

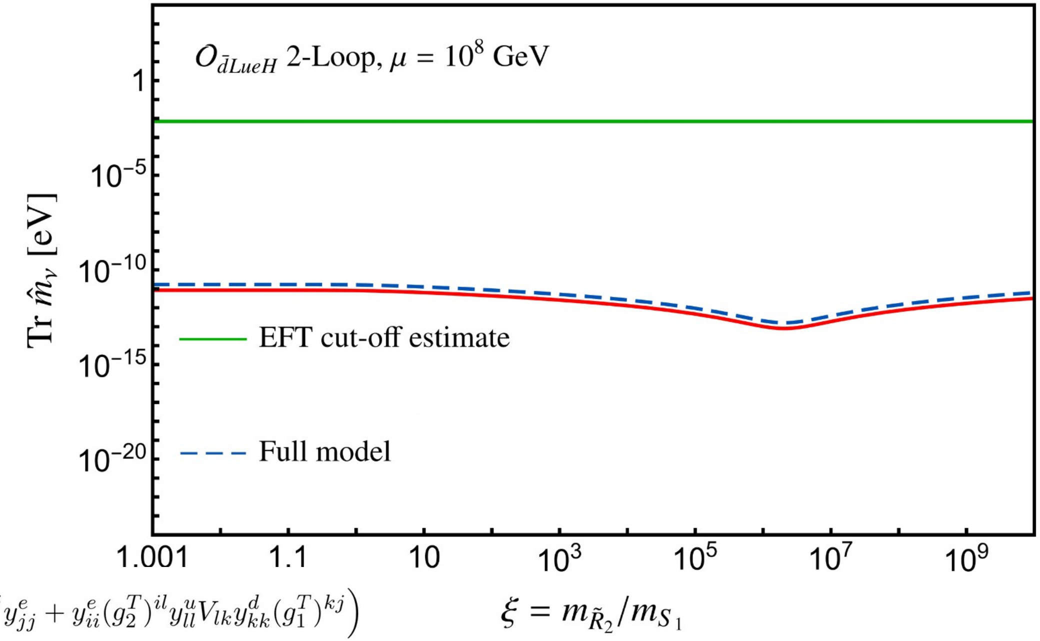
- **Actual UV model analysis** $(m_\nu)_{ij}$

Babu, Julio (2010)



$$(m_\nu)_{ij} = \frac{3\sin(2\theta) v^3 g^2}{(16\pi^2)^2\, m^2_{\mathrm{LQ}_1}} \left(g_1^{ik} y^d_{kk} V^T_{kl} y^u_{ll} (g_2)^{lj} y^e_{jj} + y^e_{ii} (g_2^T)^{il} y^u_{ll} V_{lk} y^d_{kk} (g_1^T)^{kj}\right) \times I_{jkl}(m^2_{\mathrm{LQ}_1}, m^2_{\mathrm{LQ}_2}, m^2_W),$$

$$\approx \left(1 - \frac{m^2_{\mathrm{LQ}_1}}{m^2_{\mathrm{LQ}_2}}\right) \times \left[1 + \frac{\pi^2}{3} + \frac{m^2_{\mathrm{LQ}_1} \log \frac{m^2_{\mathrm{LQ}_2}}{m^2_W} - m^2_{\mathrm{LQ}_2} \log \frac{m^2_{\mathrm{LQ}_1}}{m^2_W}}{m^2_{\mathrm{LQ}_1} - m^2_{\mathrm{LQ}_2}} + \frac{1}{2} \frac{m^2_{\mathrm{LQ}_1} \log^2 \frac{m^2_{\mathrm{LQ}_2}}{m^2_W} - m^2_{\mathrm{LQ}_2} \log^2 \frac{m^2_{\mathrm{LQ}_1}}{m^2_W}}{m^2_{\mathrm{LQ}_1} - m^2_{\mathrm{LQ}_2}}\right].$$

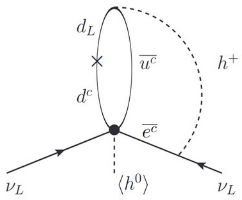


Fridell, Graf, JH, Hati (2024)

Limitations of the EFT analysis – neutrino masses

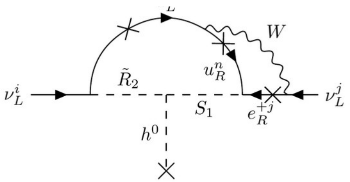
Example 2: $\epsilon_{ij}\left(\overline{d_p}L_r^i\right)\left(\overline{u_s^c}e_t\right)H^j$

- **Naive dimensional analysis** $(m_\nu)_{ij}$



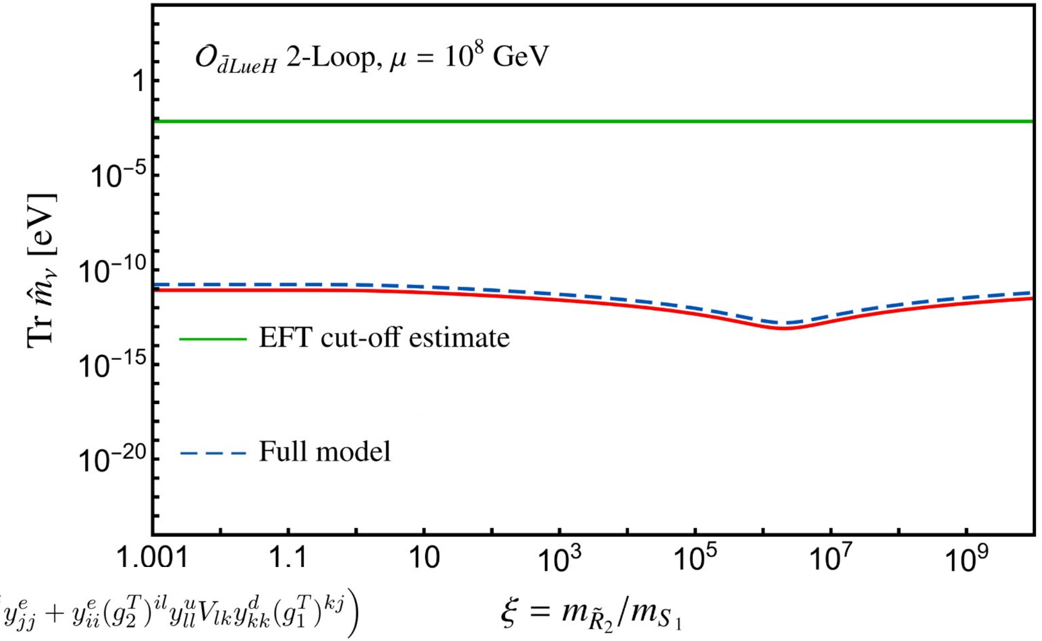
$$\sum_{ij} y_u^{sj} y_d^{jp} y_e^{ti} \frac{1}{(16\pi^2)^2}\frac{v^2}{\Lambda}$$

- **Actual UV model analysis** $(m_\nu)_{ij}$



Babu, Julio (2010)

$$(m_\nu)_{ij} = \frac{3\sin(2\theta)v^3 g^2}{(16\pi^2)^2\, m_{\mathrm{LQ}_1}^2}\left(g_1^{ik}y_{kk}^d V_{kl}^T y_{ll}^u (g_2)^{lj} y_{jj}^e + y_{ii}^e (g_2^T)^{il} y_{ll}^u V_{lk} y_{kk}^d (g_1^T)^{kj}\right)$$
$$\times I_{jkl}(m_{\mathrm{LQ}_1}^2, m_{\mathrm{LQ}_2}^2, m_W^2)\,,$$



Is there an intermediate way to correctly estimate neutrino masses without full UV calculation?

Fridell, Graf, JH, Hati (2024)

A simplified multi-scale approach

Based on dimensional regularisation and method of regions

Beneke, Smirnov (1998)
Manohar (1997)

1) Integrating out first heavy scale (hard region)

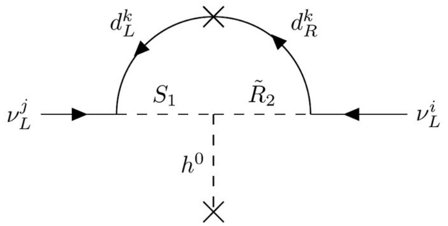
$$I_1^{\text{I-EFT}} \approx -\, c_m \frac{i}{16\pi^2} \frac{1}{(m_{\tilde{R}_2}^2 - m_{S_1}^2)} \left[1 + \log\left(\frac{\mu_r^2}{m_{S_1}^2} \right) \right]$$

2) Matching to recover full result (soft region)

$$I_1{}^{\text{ana}} \approx c_m \frac{i}{16\pi^2} \frac{1}{(m_{\tilde{R}_2}^2 - m_{S_1}^2)} \left[1 + \log\left(\frac{\mu_r^2}{m_{\tilde{R}_2}^2} \right) \right]$$

3) Total result combining both contributions

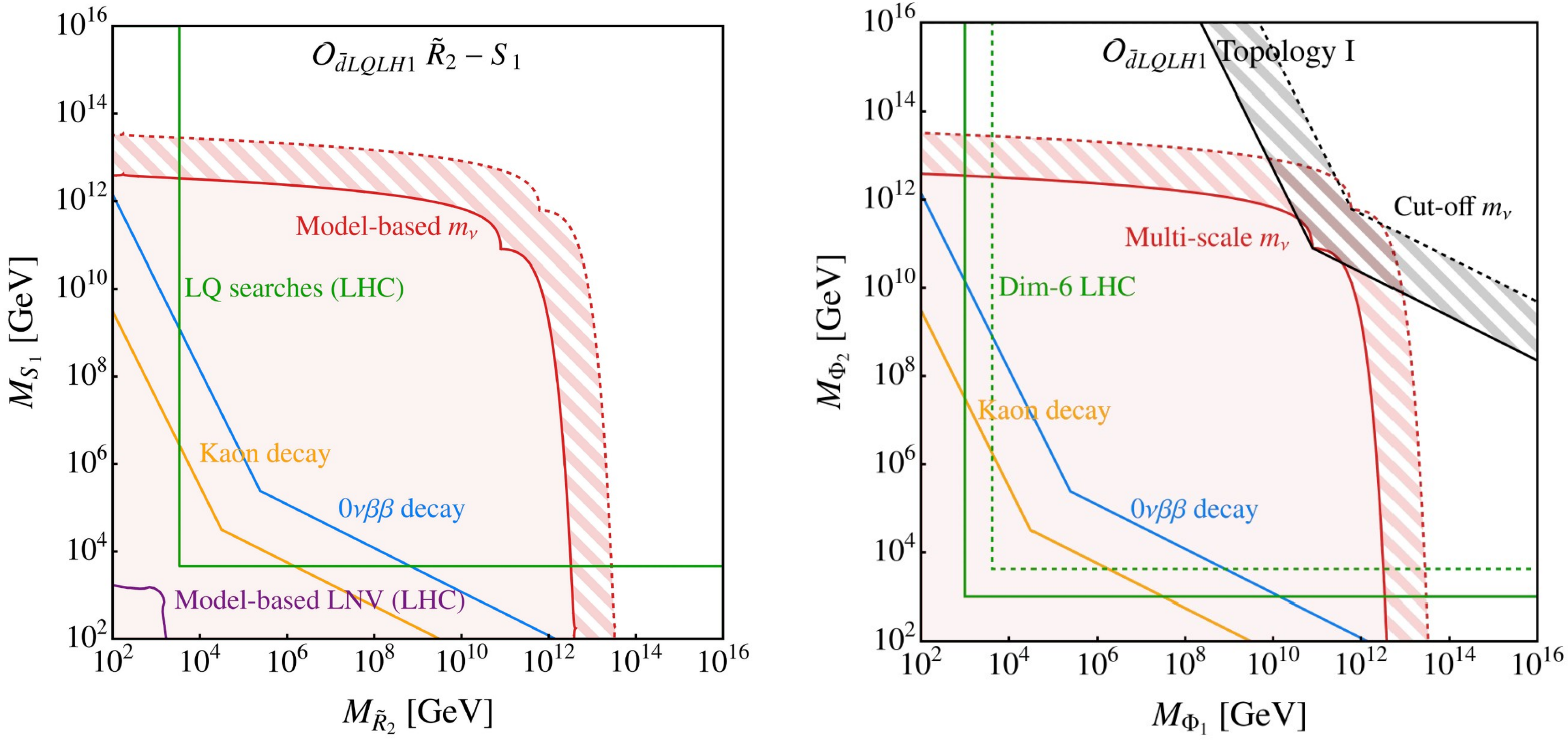
$$\begin{aligned} I_{1\,\overline{\text{MS}}}^{\text{total}} &= I_1{}^{\text{EFT}} + I_1{}^{\text{ana}} \\ &\approx c_m \frac{i}{16\pi^2} \frac{1}{(m_{\tilde{R}_2}^2 - m_{S_1}^2)} \log\left(\frac{m_{S_1}^2}{m_{\tilde{R}_2}^2} \right) \end{aligned}$$



Example for topology I (1-loop)

Fridell, Graf, JH, Hati (2024)

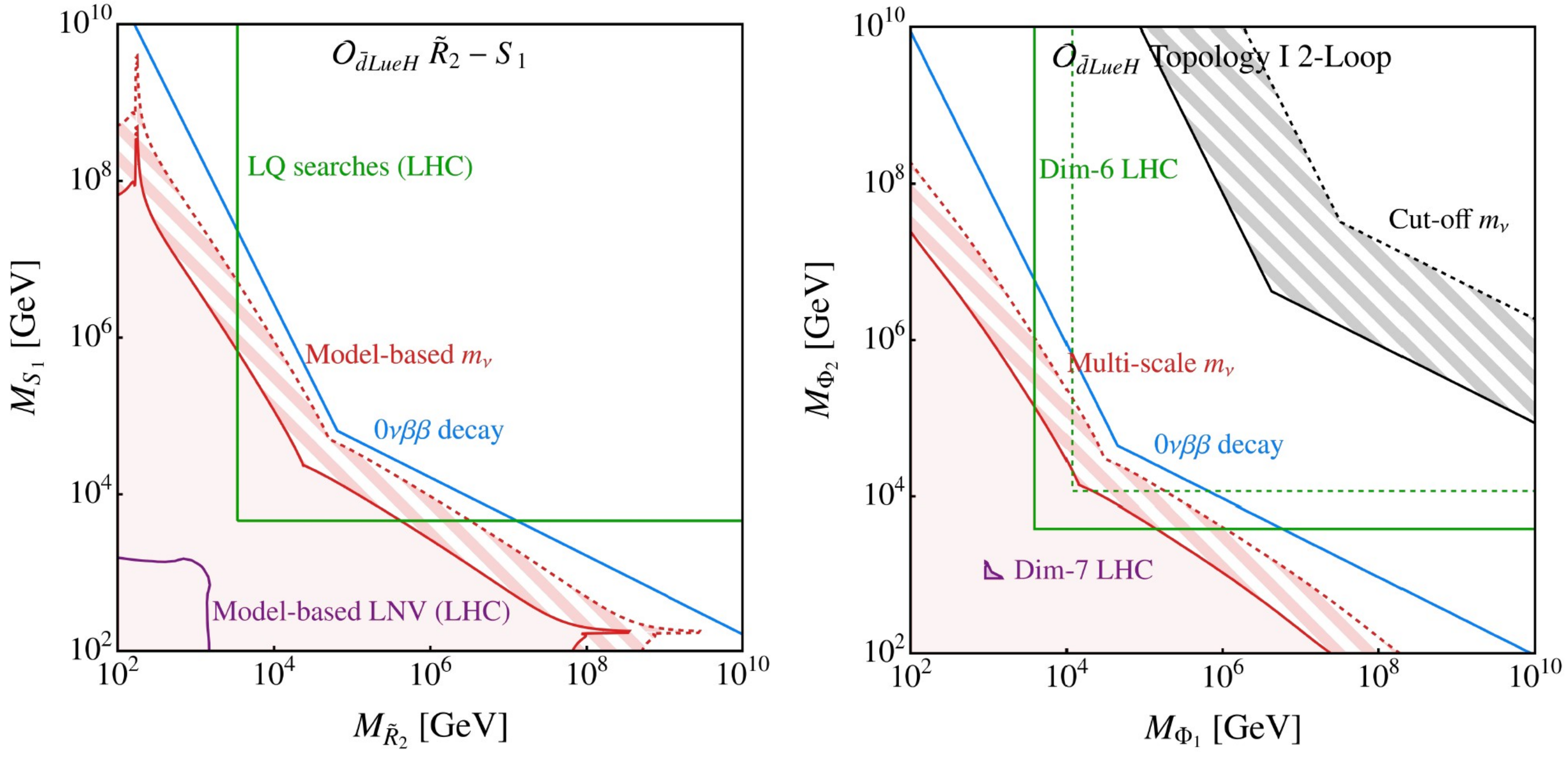
Impact on the parameter space – 1-loop



The simplified multi-scale approach is a more reliable estimate than the NDA approach, capturing the main features of a possible UV model

Fridell, Graf, JH, Hati (2024)

Impact on the parameter space – 2-loop



Opens up parameter space implying interesting interplay of experimental observables

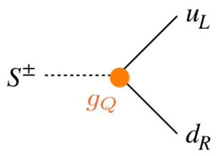
Fridell, Graf, JH, Hati (2024)

Falsifying baryogenesis with LHC & 0νββ decay

Impact of observation of TeV-scale LNV on standard leptogenesis

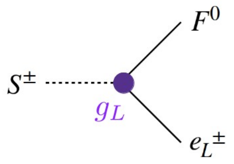
High-scale source of lepton asymmetry

$$\mathcal{L} \supset y_\nu \bar{L} H N - \frac{m_N}{2} \bar{N}^c N + \text{h.c.}$$



TeV-scale LNV "washout" interactions

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



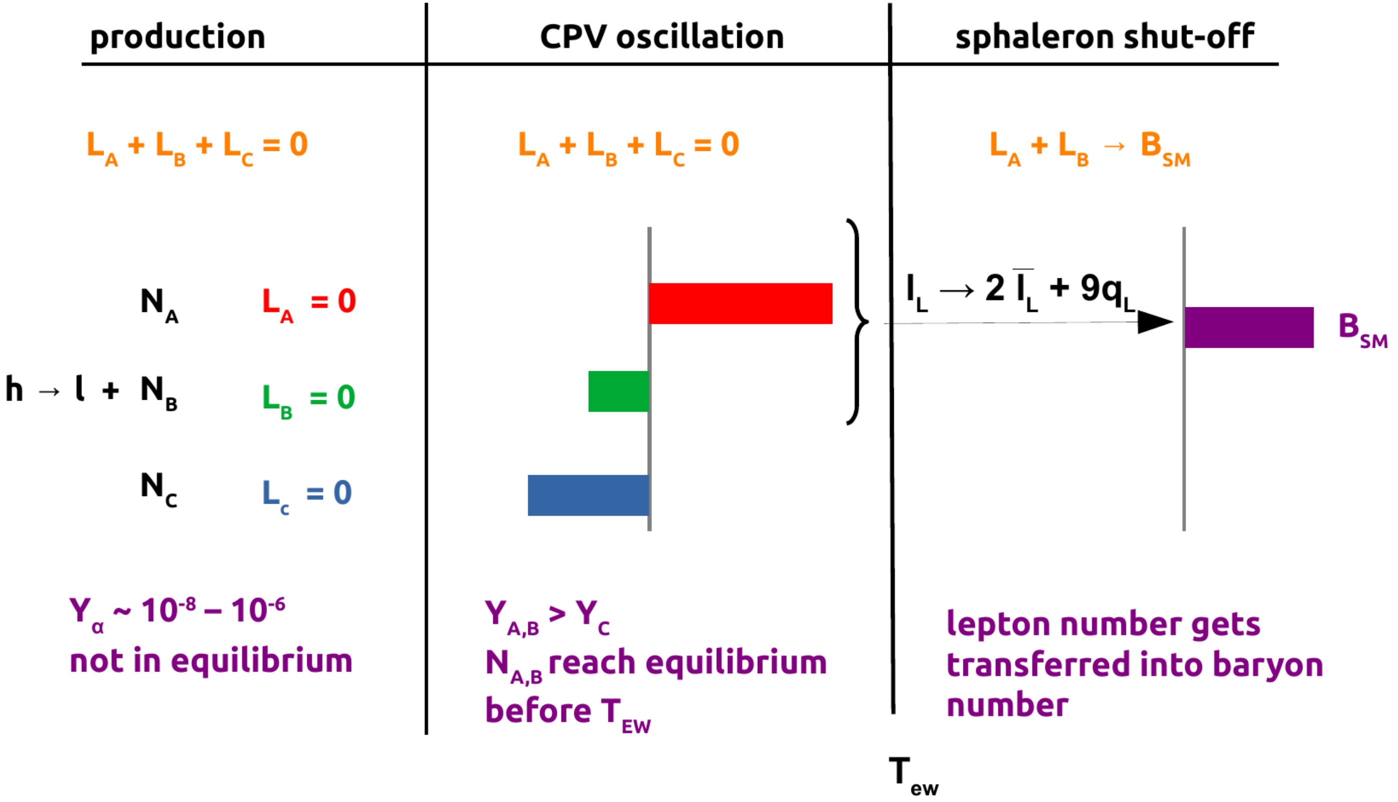
LNV

Link to EFT study:

$$\frac{1}{\Lambda^5} = \frac{g_L^2 g_Q^2}{m_S^4 m_F}$$

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Concept of low-scale leptogenesis



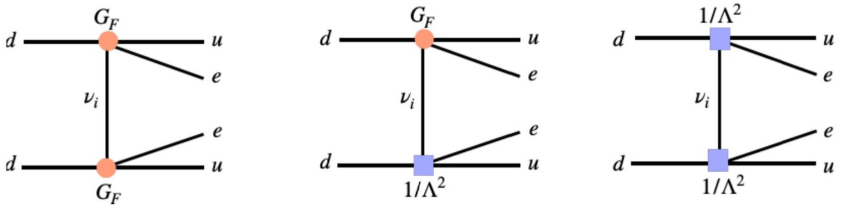
Akhmedov, Rubakov, Smirnov (1998)

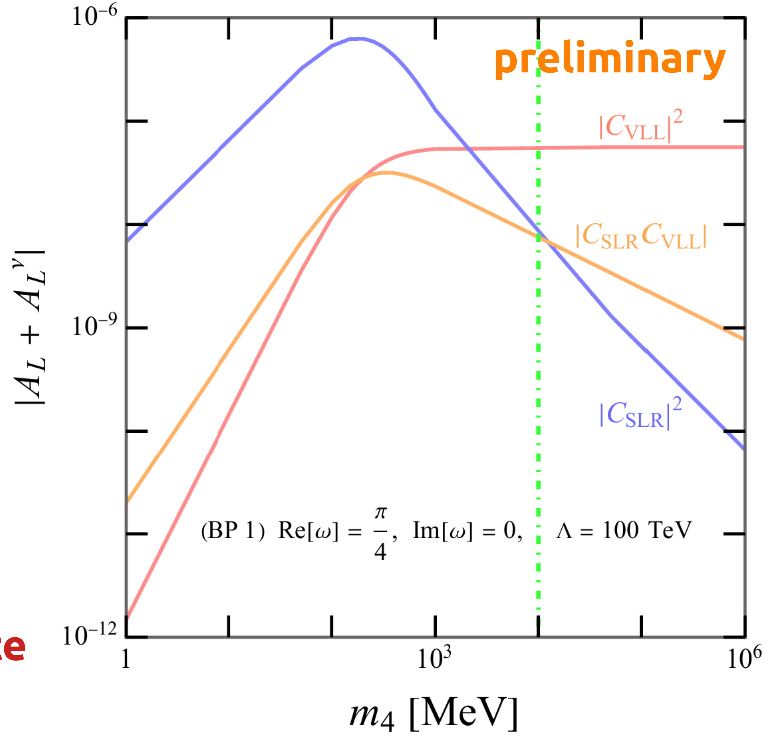
Impact of LNC operators on 0νββ decay

LNC νSMEFT operators can lead to an altered half life of neutrinoless double beta decay

See also Dekens, de Vries, Fuyuto, Mereghetti, Zhou(2020)

$$\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$$





Fuyuto, JH, Weber (in preparation)

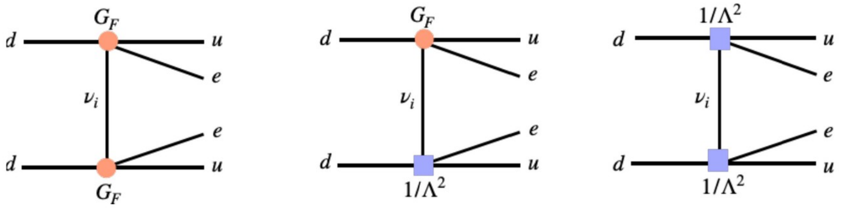
➡ **LNC operator can even lead to enhanced (!) decay rate**

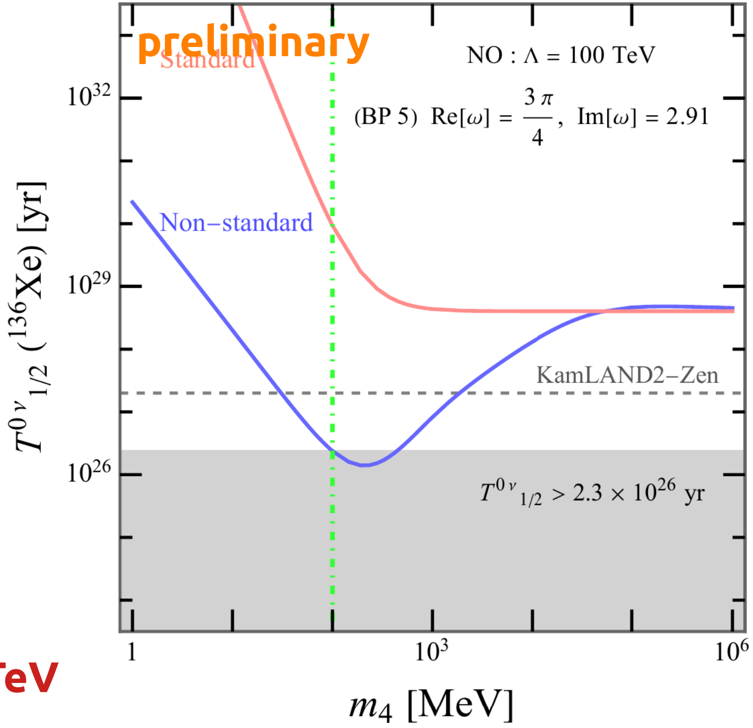
Impact of LNC operators on 0νββ decay

LNC νSMEFT operators can lead to an altered half life of neutrinoless double beta decay

See also Dekens, de Vries, Fuyuto, Mereghetti, Zhou(2020)

$$\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$$



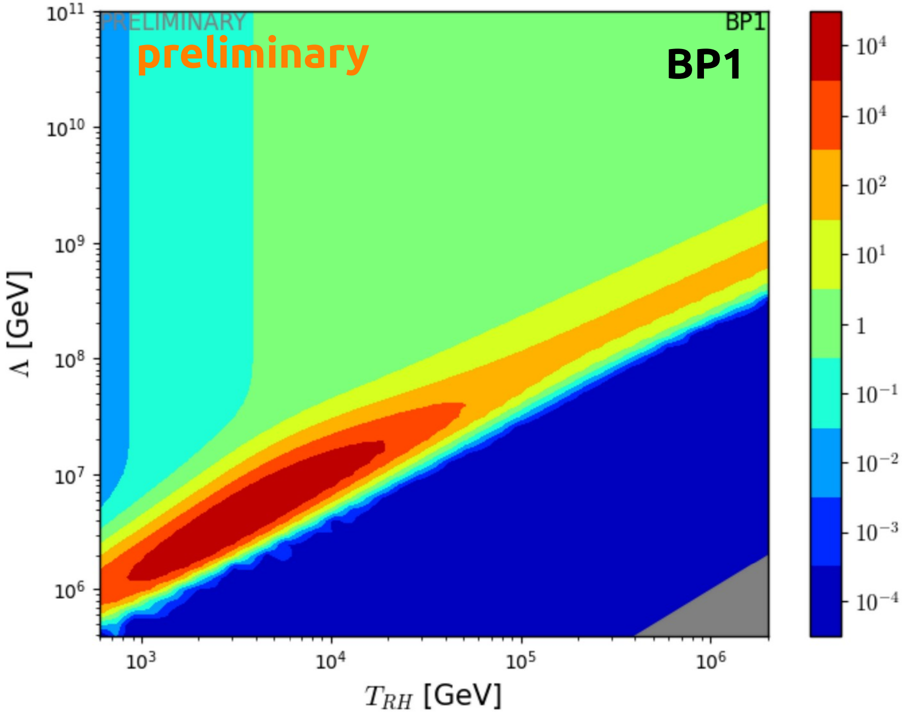


Fuyuto, JH, Weber (in preparation)

For RHN masses in the GeV range, 0νββ decay experiments become sensitive to NP scales Λ ~ 100 TeV

Impact of LNC operators on low-scale leptogenesis

$$\mathcal{O}_6 = \frac{G_{\alpha I}}{\Lambda^2}(\overline{L_\alpha}\nu_{R,I})(\overline{u_R}Q)$$



- dynamics can be sensitive to highest temperature of the thermal history (T_{RH}) in the oscillatory regime
- parameter space with too large BAU can be excluded

Fuyuto, JH, Weber (in preparation)

Credit: Ella Dreiner

Implications of high-scale LNV new physics on baryogenesis and GWs

Large lepton asymmetries, baryogenesis and GWs

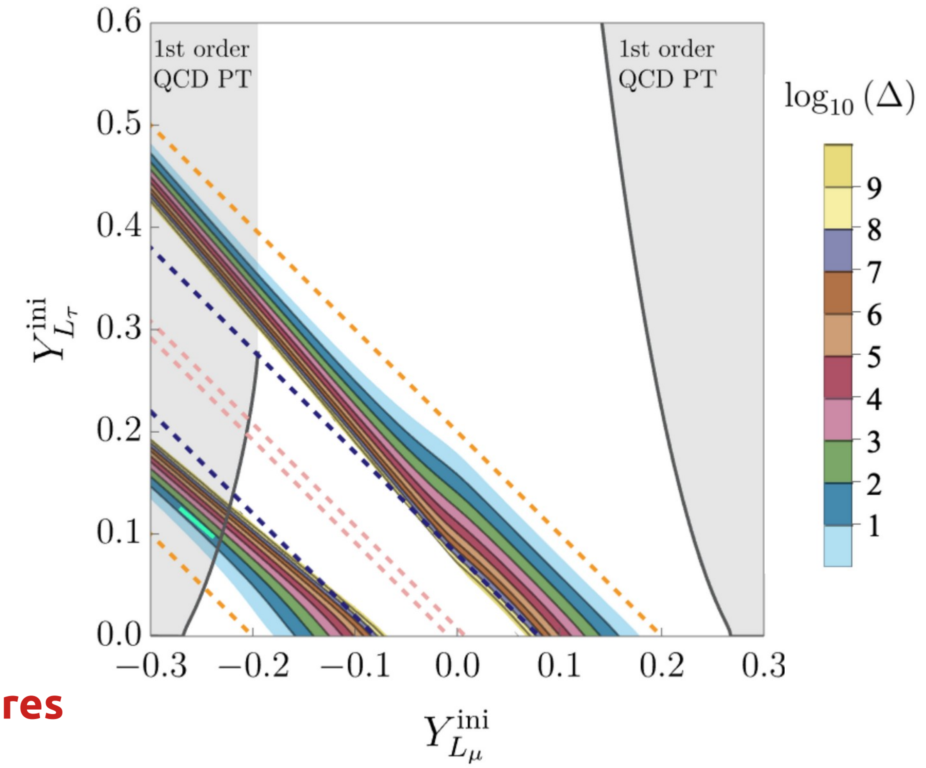
Large lepton asymmetries are constrained by CMB and BBN to

$$|Y_L| \leq 1.2 \times 10^{-2}$$

and can lead to

- **1st order QCD phase transition sourcing GWs potentially in reach of proposed μAres experiment**
- **non-restoration of the EW symmetry at large temperatures suppressing sphaleron processes**

➡ **successful freeze-in of baryon asymmetry requires scenarios with late time entropy dilution**



Gao, Harz, Hati, Lu, Oldengott, White (2023, 2024)