Loop Effects in Probing Lepton Number Violation

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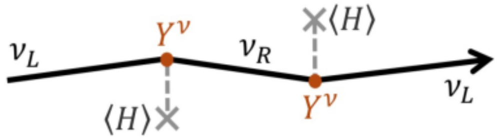
Lepton Number (Violation)

- non-perturbative Standard Model (SM) dynamics: B + L number violated by sphalerons

- B – L number is conserved ↔ non-anomalous global symmetry of the SM → accidental? may be a relict! → violation at low energies subtle ↔ corresponding to B – L preserving gauge symmetry broken at certain high-energy scale

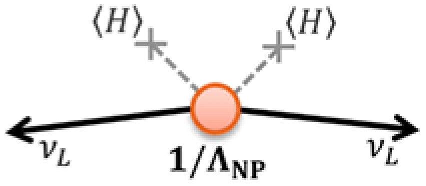
- the manifestation at experimentally accessible scales suppressed by powers of the new-physics scale

- tightly related to the puzzle of neutrino masses and baryon asymmetry of the Universe



$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$

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



Dirac mass → as other fermions, but tiny

Majorana mass → lepton number violation

Double Beta Decays

- two-neutrino double beta decay

  $$2\nu\beta\beta: \ (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

- neutrinoless double beta decay
  → LNV, mediated by Majorana neutrinos

  $$0\nu\beta\beta: \ (A,Z) \rightarrow (A,Z+2) + 2e^-$$

- experiments: $\mathrm{T}_{1/2}^{2\nu\beta\beta} \sim 10^{18}$ - 10^{21} y

  $$\mathrm{T}_{1/2}^{0\nu\beta\beta} \sim (0.1 \text{ eV}/m_\nu)^2 \times 10^{26} \text{ y}$$

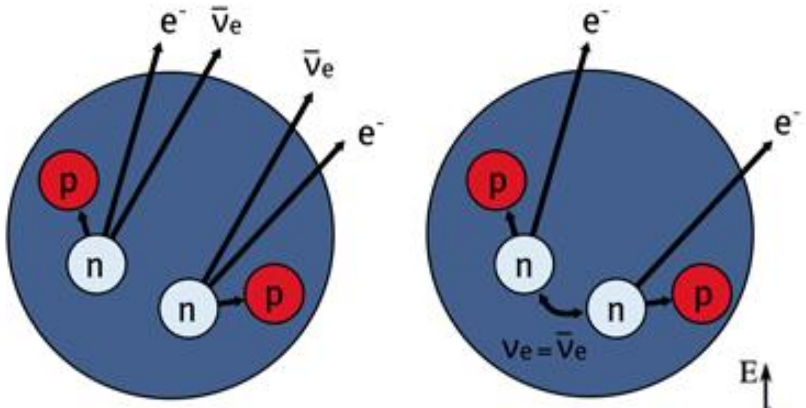
  KamLAND-Zen, LEGEND, CUORE, NEMO-3, CUPID, (n)EXO, …

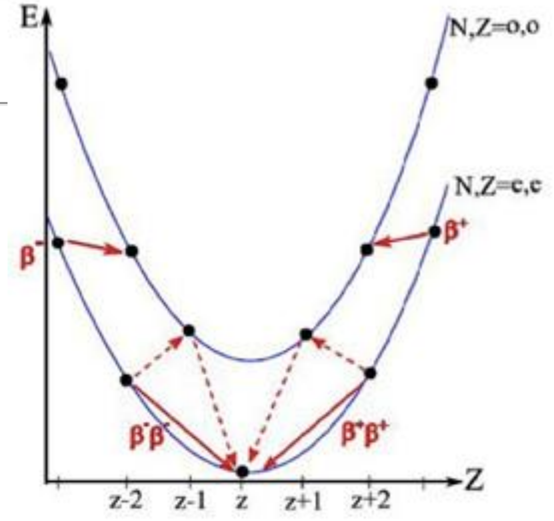
- a variety of isotopes: ^{76}Ge, ^{136}Xe, …

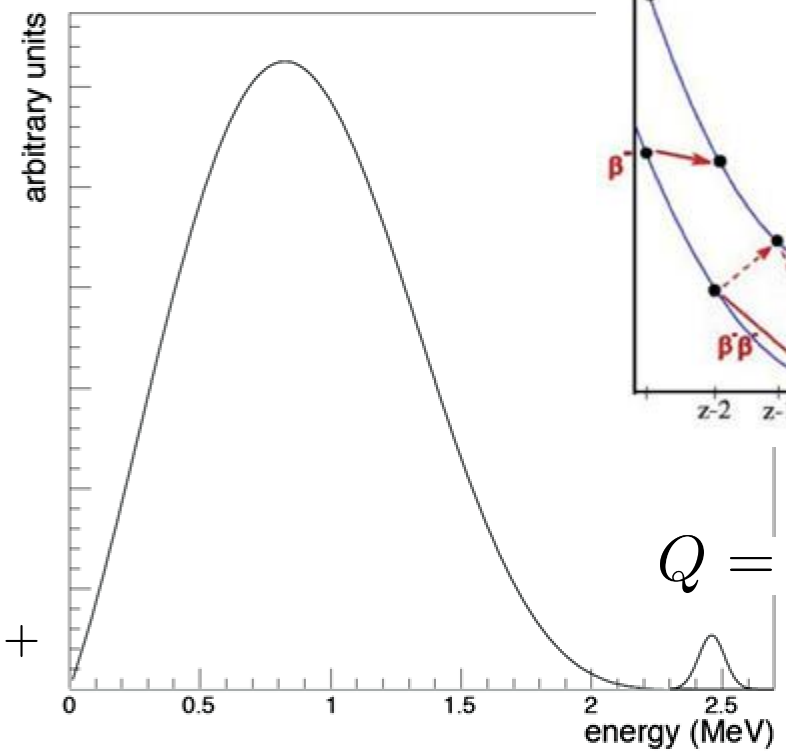
- variants: $0\nu\beta^+\beta^+: \ (A,Z) \rightarrow (A,Z-2) + 2e^+$

  $$0\nu\beta^+ EC: \ (A,Z) + e^- \rightarrow (A,Z-2) + e^+$$

  $$0\nu ECEC: \ (A,Z) + 2e^- \rightarrow (A,Z-2)$$



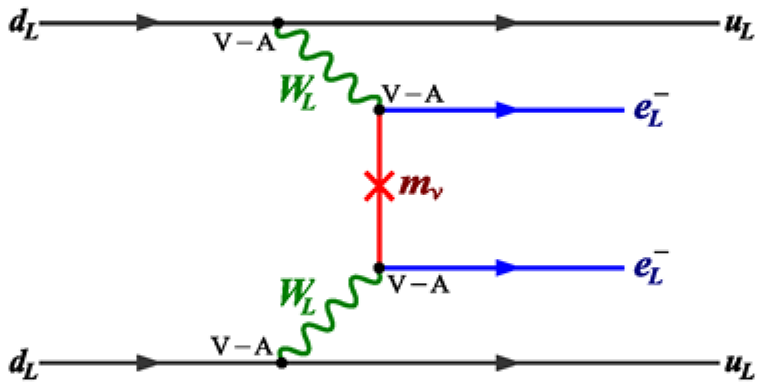




$$Q = E_i - E_f - 2m_e$$

Neutrinoless Double Beta Decay

- standard mechanism with light neutrino exchange:

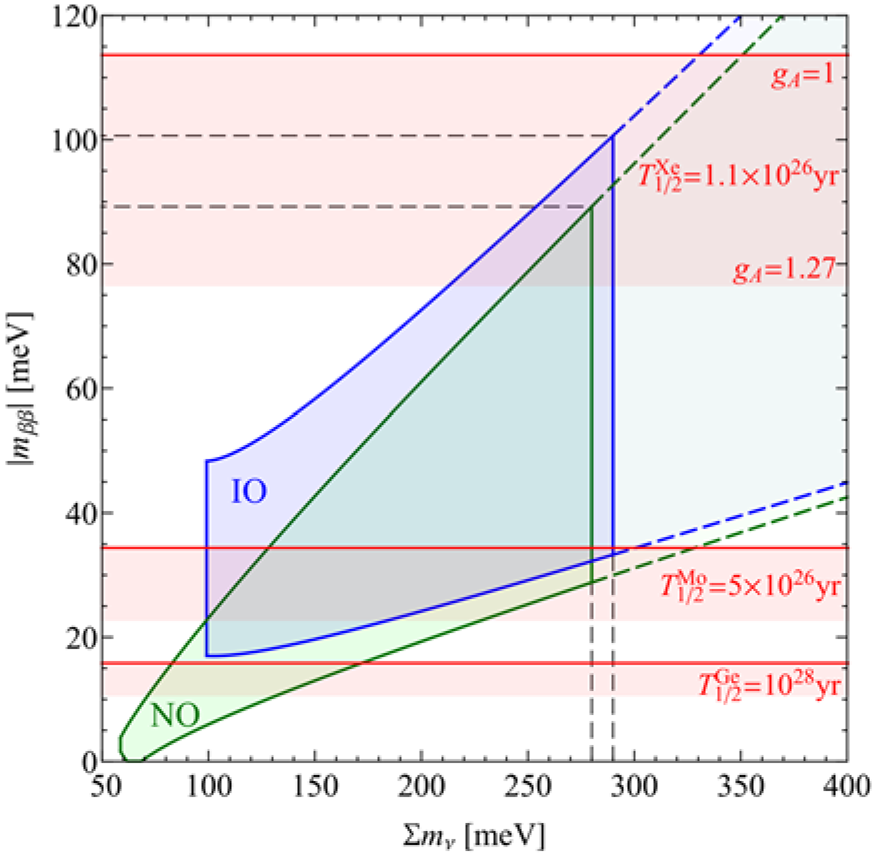


$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 \mathcal{G}_{0\nu} |\mathcal{M}_{0\nu}|^2$$

- half-life limit → bound on effective neutrino mass:

$$\frac{10^{25}\ \mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$

F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]

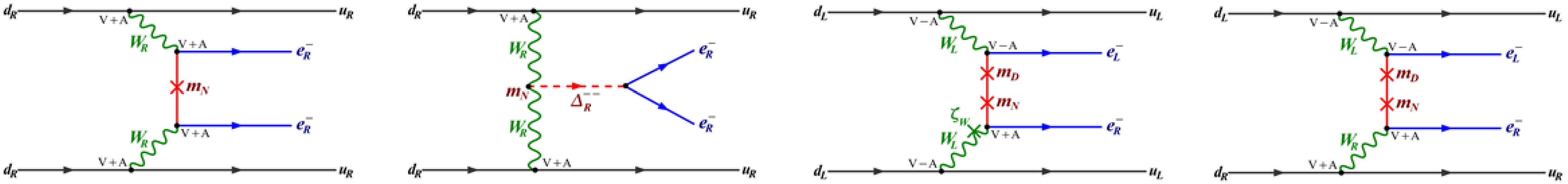


$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\phi_{12}} + m_3 s_{13}^2 e^{i(\phi_{13}-2\delta)}$$

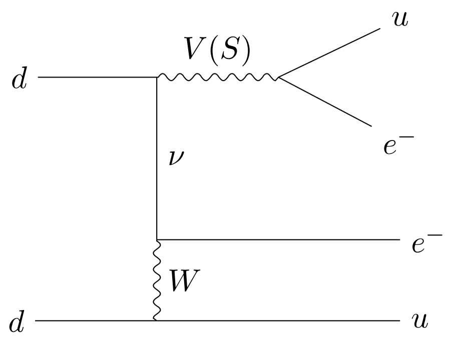
$$A_{\mu\nu}^{\mathrm{lep}} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \bar{e}_2 \gamma_\nu (1-\gamma_5) \frac{q + m_i}{q^2 - m_i^2}(1-\gamma_5)\gamma_\mu e_1^c \approx \bar{e}_2 \frac{\gamma_\nu(1-\gamma_5)\gamma_\mu}{4q^2} e_1^c \boxed{\sum_{i=1}^{3} U_{ei}^2 m_i} \equiv m_{\beta\beta}$$

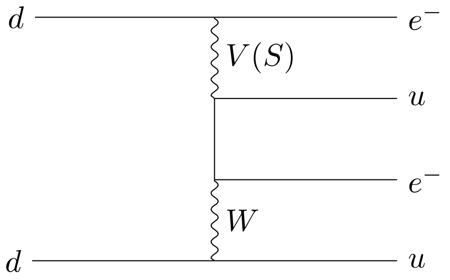
New Physics & 0νββ

- plethora of New Physics scenarios may be responsible for 0νββ
- left-right symmetric models $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$



- leptoquarks (scalar, vector)





- R-parity violating SUSY, Majorons, Extra Dimensions ...

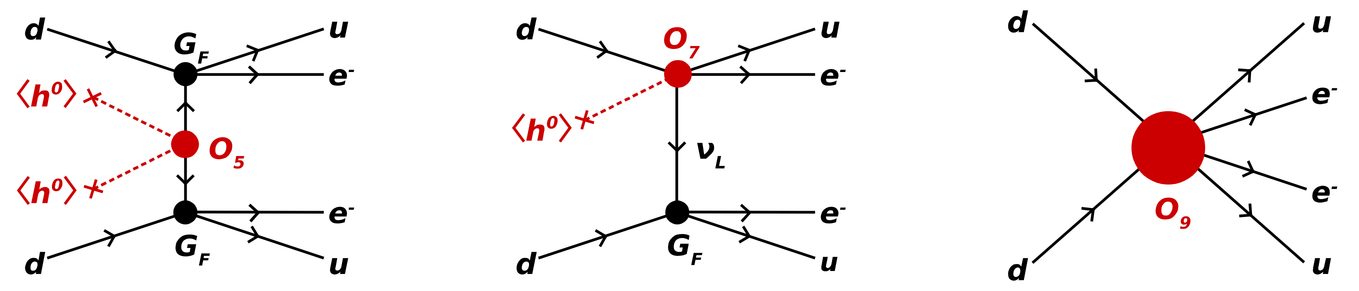
F. F. Deppisch, M. Hirsch, H. Päs: J. Phys. G 39 (2012), 124007

Effective Approach to 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (e.g. 9804374, 0008182, 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119, …), long-range and short-range mechanisms

- 0νββ half-life limit sets constraints on effective couplings – accurate calculation of nuclear matrix elements and phase-space factors is crucial for estimating these limits

- generally: $T_{1/2}^{-1} = |C|^2 G_{0\nu} |M_{0\nu}|^2$



(a) (b) (c)

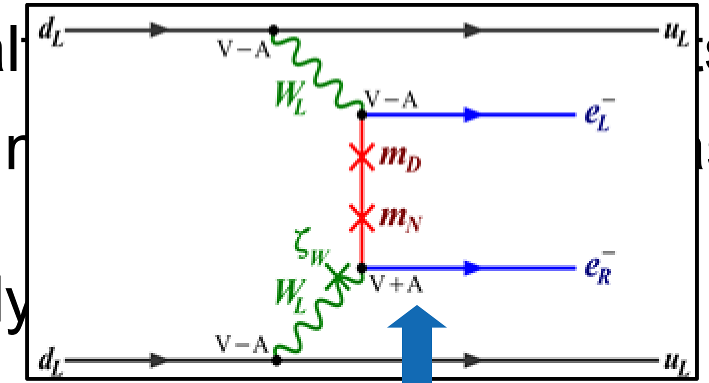
$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big[C^{(6)}_{\rm VL}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_R}\gamma_\mu \nu_L^c) + C^{(6)}_{\rm VR}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_R}\gamma_\mu \nu_L^c)$$
$$+ C^{(6)}_{\rm SL}\,(\overline{u_R} d_L)\,(\overline{e_L}\nu_L^c) + C^{(6)}_{\rm SR}\,(\overline{u_L} d_R)\,(\overline{e_L}\nu_L^c)$$
$$+ C^{(6)}_{\rm T}\,(\overline{u_L}\sigma^{\mu\nu} d_R)\,(\overline{e_L}\sigma_{\mu\nu}\nu_L^c)\Big] + h.c.$$

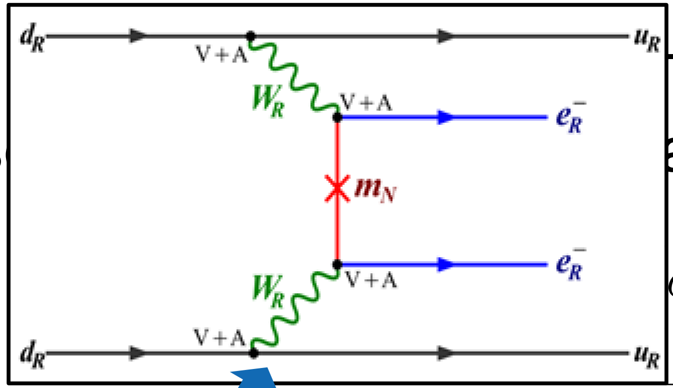
$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big[C^{(7)}_{\rm VL}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c) + C^{(7)}_{\rm VR}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c)\Big] + h.c.$$

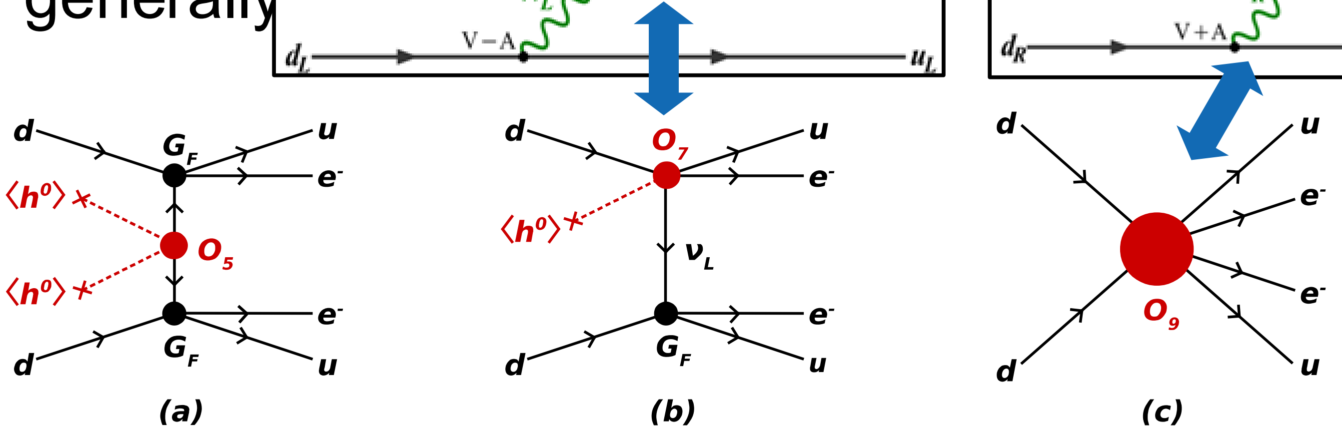
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \Big[\Big(C^{(9)}_{i,R}\,(\overline{e_R} e_R^c) + C^{(9)}_{i,L}\,(\overline{e_L} e_L^c)\Big)\,\mathcal{O}_i + C^{(9)}_i\,(\bar{e}\gamma_\mu\gamma_5 e^c)\,\mathcal{O}_i^\mu\Big]$$

Effective Approach to 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (e.g. 9804374, 0008182, 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119, …), long-range and short-range mechanisms
- 0νββ hal ts – accurate calculation of nuclear r s al for estimating these limits
- generally







$$C_{\mathrm{VL}}^{(6)}\left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_R}\gamma_\mu\nu_L^c\right)+C_{\mathrm{VR}}^{(6)}\left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_R}\gamma_\mu\nu_L^c\right)$$
$$+C_{\mathrm{SL}}^{(6)}\left(\overline{u_R}d_L\right)\left(\overline{e_L}\nu_L^c\right)+C_{\mathrm{SR}}^{(6)}\left(\overline{u_L}d_R\right)\left(\overline{e_L}\nu_L^c\right)$$
$$+C_{\mathrm{T}}^{(6)}\left(\overline{u_L}\sigma^{\mu\nu}d_R\right)\left(\overline{e_L}\sigma_{\mu\nu}\nu_L^c\right)\Big]+h.c.$$

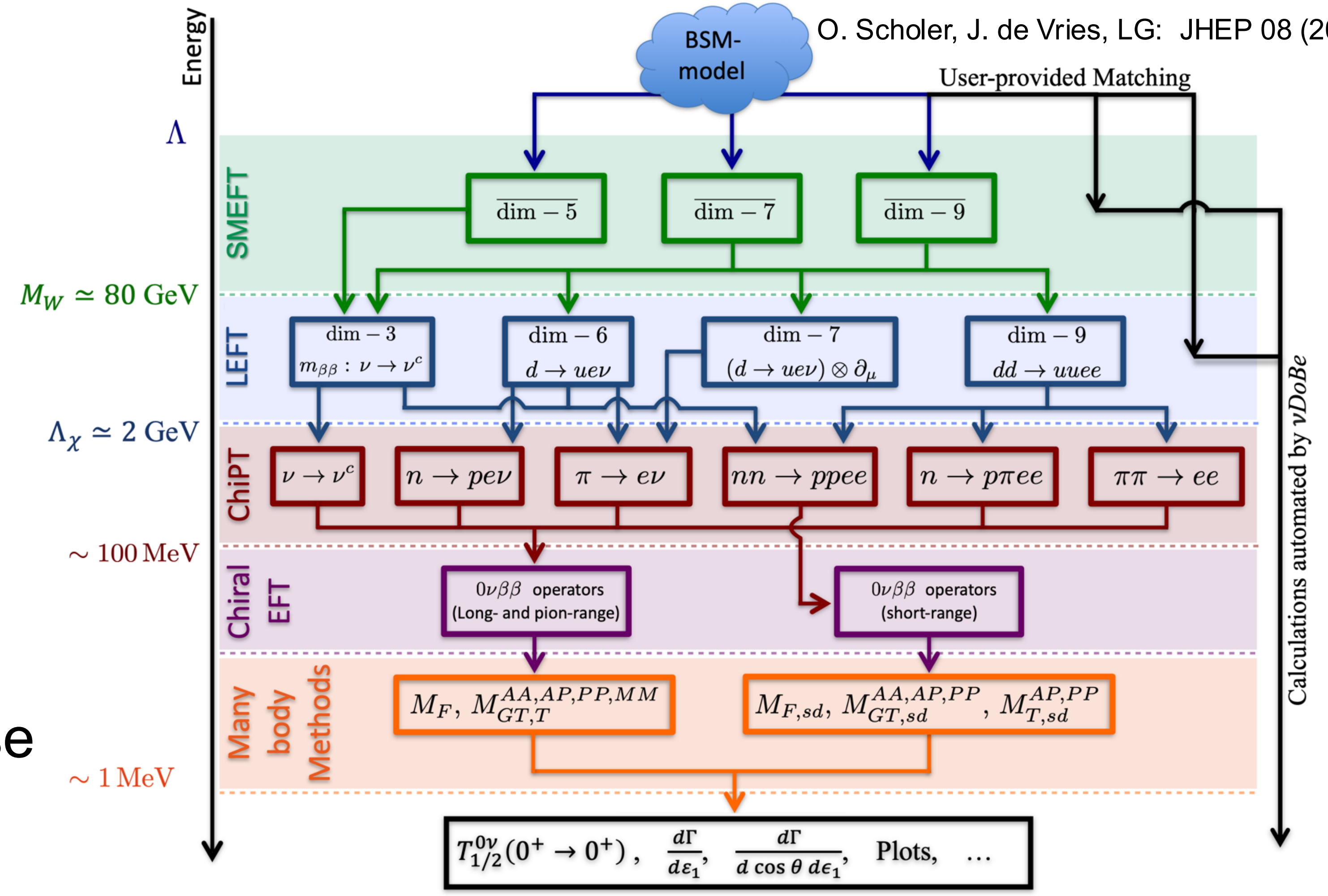
$$\mathcal{L}_{\Delta L=2}^{(7)}=\frac{2G_F}{\sqrt{2}v}\left[C_{\mathrm{VL}}^{(7)}\left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu_L^c\right)+C_{\mathrm{VR}}^{(7)}\left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_L}\overleftrightarrow{\partial}_\mu\nu_L^c\right)\right]+h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(9)}=\frac{1}{v^5}\sum_i\left[\left(C_{i,R}^{(9)}\left(\overline{e_R}e_R^c\right)+C_{i,L}^{(9)}\left(\overline{e_L}e_L^c\right)\right)\mathcal{O}_i+C_i^{(9)}\left(\overline{e}\gamma_\mu\gamma_5e^c\right)\mathcal{O}_i^\mu\right]$$

νDoBe: A Python Tool for 0νββ

- user inputs:
  - scale + selection of operators
  - isotope(s), type of NMEs
- data inputs:
  - nuclear matrix elements
  - phase-space factors
  - low-energy constants
- outputs:
  - half-life formula for the given case
  - limits on selected couplings
  - $m_{\beta\beta}$ vs. m_ν plots, etc.
  - chosen contour plots showing correlations of different parameters, ...

O. Scholer, J. de Vries, LG: JHEP 08 (2023) 043



download: https://github.com/OScholer/nudobe
online tool: https://nudobe.streamlit.app

https://nudobe.streamlit.app

νDoBe - Online

If you use results of this tool in your scientific work, please add a citation to: **arxiv:2304.05415**.

For more advanced analyses, you can download the full code from gitHub.

You have any suggestions/comments on how to improve the tool?

=> Contact:

Oliver Scholer: scholer@mpi-hd.mpg.de

Lukas Graf: lukas.graf@berkeley.edu

Jordy de Vries: j.devries4@uva.nl

Please specify what you would like to do:

-

-

Define a model

Study operator limits

Which NME approximation do you want to use?

IBM2

Do you wish to define your model in terms of LEFT or SMEFT Wilson coefficients?

-

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If you want you can give your model name. This name will be displayed in all plots

Model

Made with Streamlit

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-

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LEFT

SMEFT

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Which NME approximation do you want to use?

SM

Do you wish to define your model in terms of LEFT or SMEFT Wilson coefficients?

SMEFT

☐ Allow for complex phases?

Does your model generate SMEFT operators at multiple scales? If 'Yes' you will need to define a scale for each operator.

No

Set the scale at which your SMEFT model is generated [TeV].

50 − +

Set the dimensionless Wilson coefficients:

Dimension 5

LH(5) [1e-12]

1,00 − +

Dimension 7

LH(7)

0,00 − +

LHD1(7)

0,00 − +

νDoBe - Online

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Model

Half-lives

Download half-lives as .csv or as .tex file.

	10^24 years
48Ca	431,000.0000
76Ge	651,000.0000
82Se	170,000.0000
124Sn	146,000.0000
130Te	88,500.0000
136Xe	129,000.0000

Angular correlation

$$\frac{d\Gamma}{d\cos\theta d\bar{\epsilon}_1} = a_0\left(1 + \frac{a_1}{a_0}\cos\theta\right)$$

Manage app

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SMEFT

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50

Set the dimensionless Wilson coefficients:

Dimension 5

LH(5) [1e-12]

1,00

Dimension 7

LH(7)

0,00

LHD1(7)

0,00

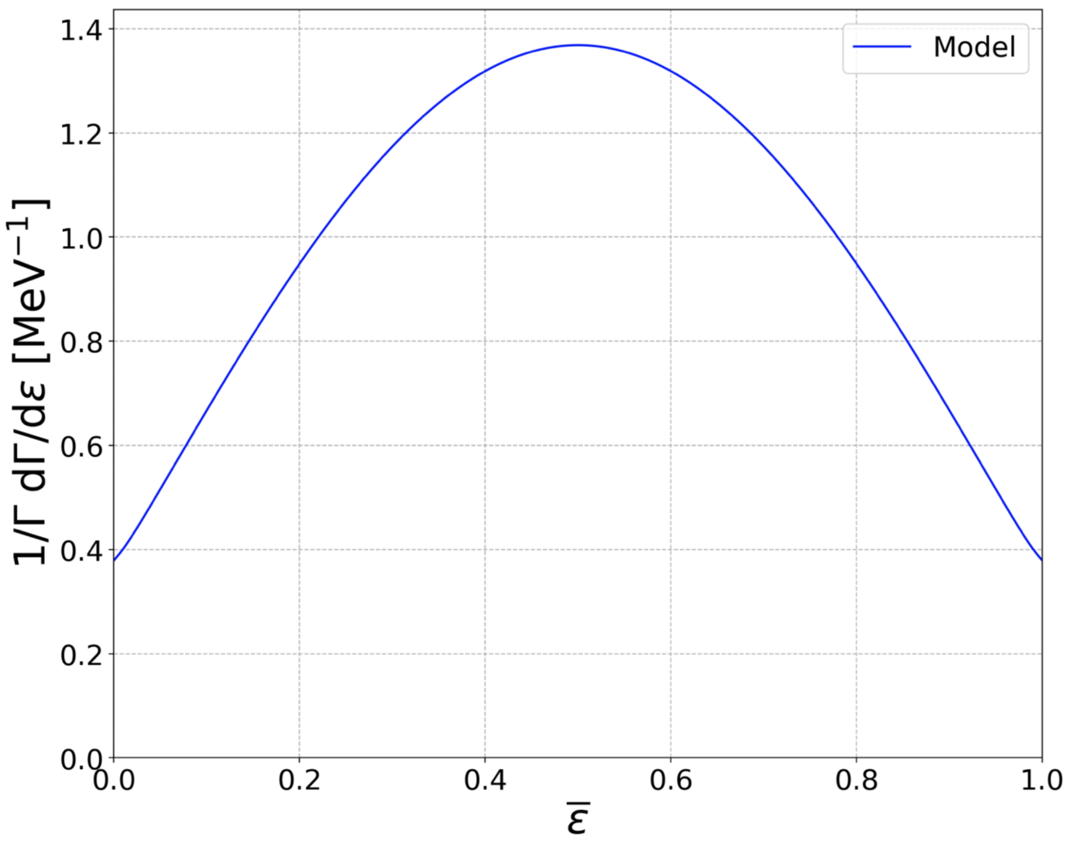
Normalized single electron spectrum

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\epsilon_1}\left(\{C_i\}, \bar{\epsilon}\right) \propto \sum_k g_{0k}\left(\epsilon, \Delta M - \epsilon, R\right) \left|A_k(\{C_i\})\right|^2 p_1 p_2 \epsilon \left(\Delta M - \epsilon\right)$$

Choose an isotope:

76Ge

☐ Compare to mass mechanism?



Half-life ratios

Choose the reference isotope:

76Ge

☐ Compare to mass mechanism? ☐ Vary unknown LECs?

Manage app

Unraveling the signal:
source of LNV?

Distinguishing 0νββ Mechanisms

- phase-space observables – electron energy spectra, angular correlation $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta\,\mathrm{d}\tilde{\epsilon}_1} = a_0\left(1+\frac{a_1}{a_0}\cos\theta\right)$
- comparison with other ββ modes → β+β+, ECβ+, ECEC - typically suppressed
- decay rate ratios for different isotopes $\mathrm{R}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{|\mathcal{M}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})|^2 G^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}$
  - → ratio of half-lives = ratio of NMEs x ratio of PSFs,
    the unknown coupling drops out
  - distinguishing 2 specific operators quantified using $\mathrm{R}_{ij}(^{A}X) = \frac{R^{\mathcal{O}_i}(^{A}X)}{R^{\mathcal{O}_j}(^{A}X)}$
- applied to the “master formula” framework of 1806.02780

V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti: JHEP 12 [1806.02780]

  - PSFs → 4 distinguishable groups of operators
  - ratios: in principle 12 distinguishable groups of operators
    - main issues: nuclear uncertainties: NMEs + unknown low energy constants
      → solution? hopefully: ab initio + LQCD and/or complementarity

LG, M. Lindner, O. Scholer: PRD 106 (2022)

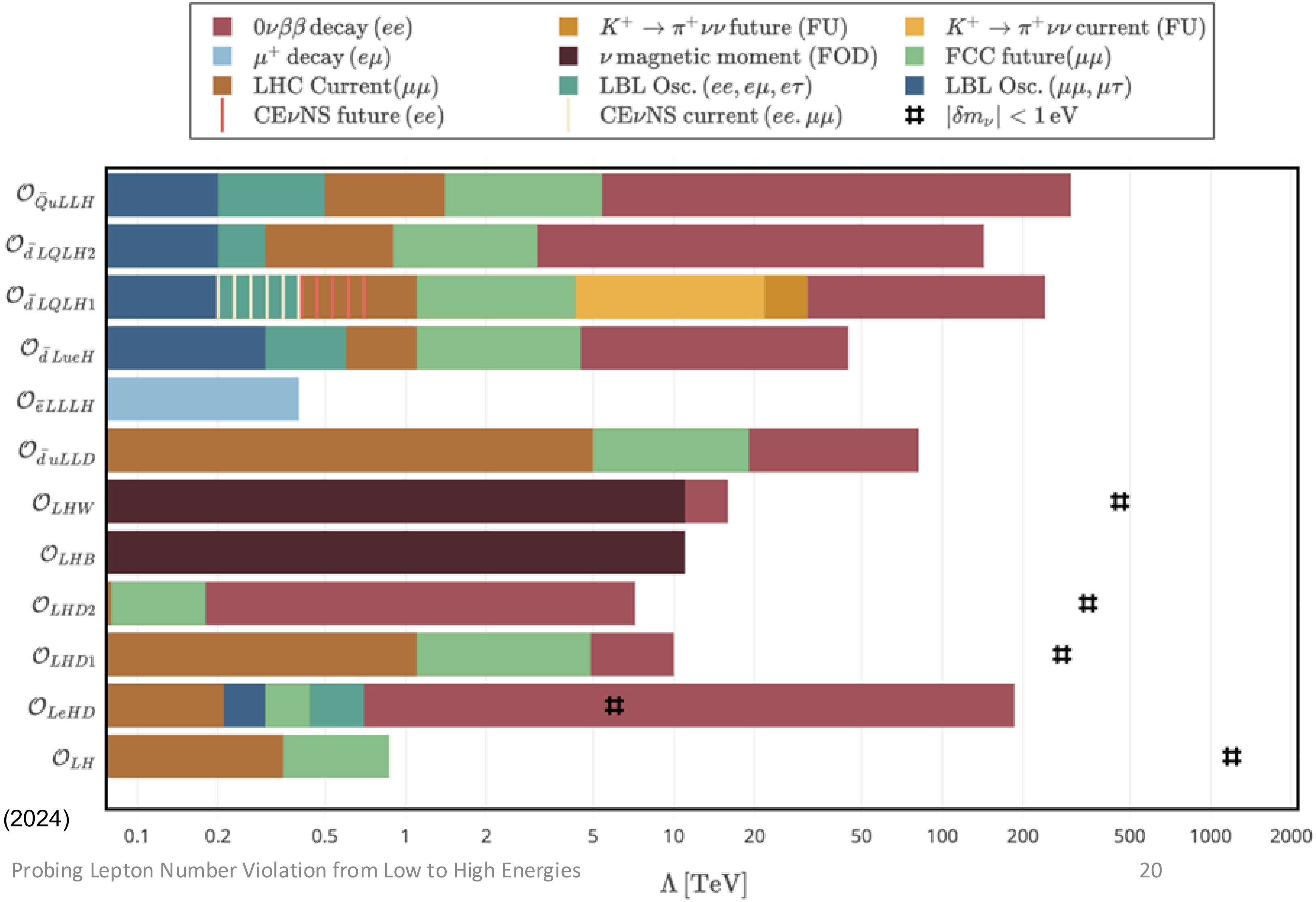
Complementary Probes

- $0\nu\beta\beta$ usually the best test, but what about other flavours? Can other probes help to pinpoint the LNV mechanism?
- rare meson decays → lepton number violating B or K decays
  Deppisch, Fridell, Harz: JHEP 12 (2020)
  Felkl, Li, Schmidt: JHEP 12 (2021)
- neutral current LNV NSI @CEvNS, charged current LNV NSI @LBL oscillation exp.
  Bolton, Deppisch: PRD 99 (2019)
- lepton number violating tau decays Li, Ma, Schmidt: PRD 101 (2020)
- non-standard muon decay, μ^- to e^+ conversion Berryman, de Gouvêa et al.: PRD (2017)
  B. Armbruster et al.: PRL 90 (2003)
- neutrino magnetic moment
  V. Cirigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti: JHEP 12 (2017)
- colliders – LNV probed by same-sign dilepton searches, or individual models
  K. Fridell, LG, J. Harz, C. Hati: 2306.08709

Complementary Probes @SMEFT dim 7

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

K. Fridell, LG, J. Harz, C. Hati, JHEP 05 (2024)

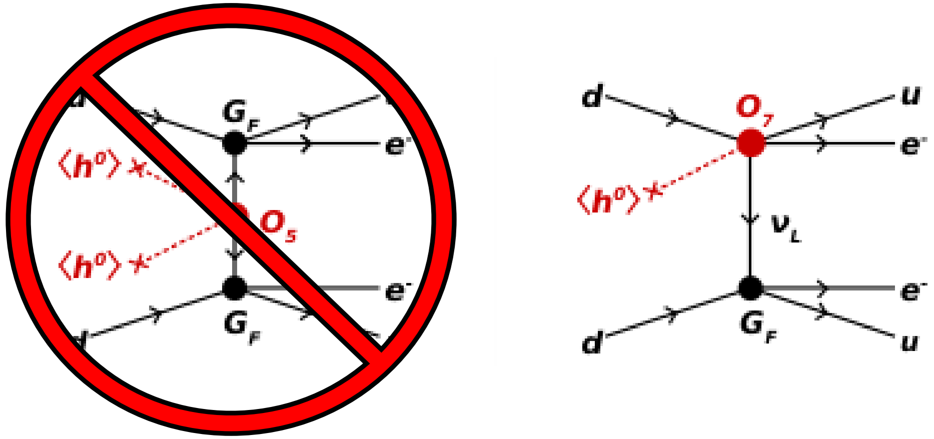


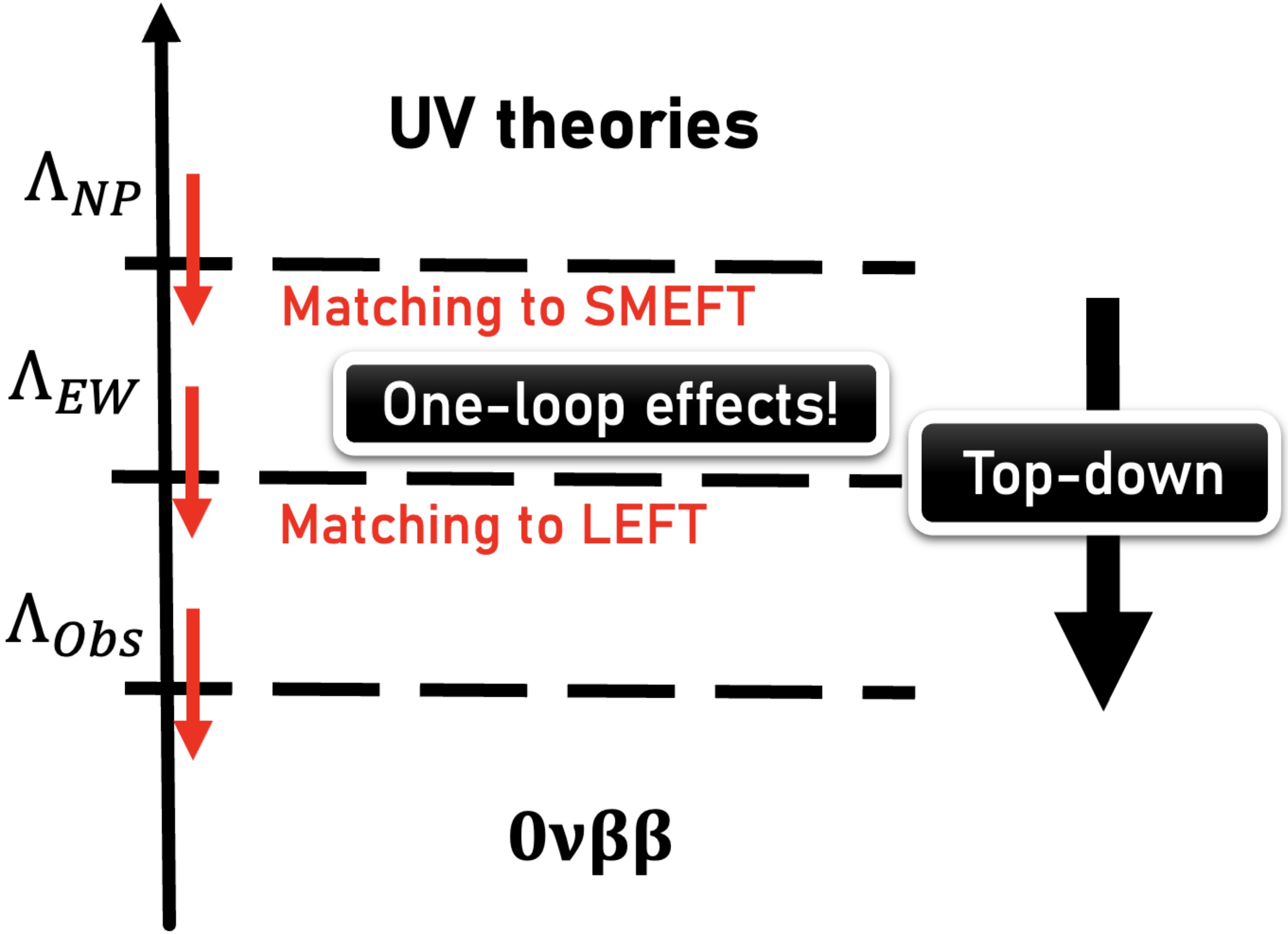
So far: everything at tree-level.

What about loop effects?

One-loop Effects & 0νββ

- RGE running from the new-physics scale down to the EW scale
- matching of a UV model onto the SMEFT basis of operators





RGE running in SMEFT

- the RGE effects introduce a mixing between dim-5, dim-6 and dim-7 operators

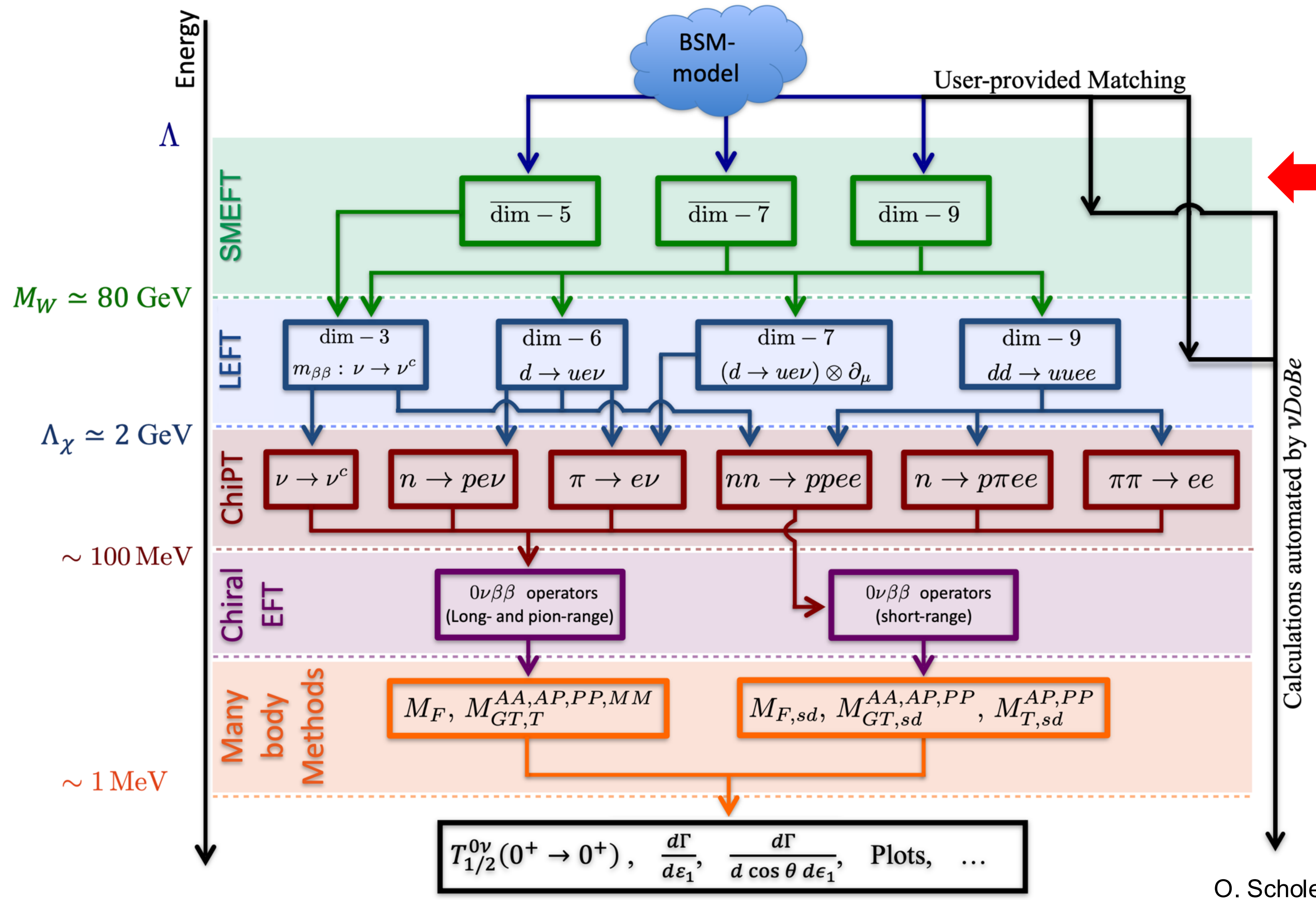
$$\begin{aligned}\dot{C}^{(5)} =& \ \gamma^{(5,5)} C^{(5)} + \hat{\gamma}^{(5,5)} C^{(5)} C^{(5)} C^{(5)} + \gamma_i^{(5,6)} C^{(5)} C_i^{(6)} \\ & + \gamma_i^{(5,7)} C_i^{(7)}, \\ \dot{C}_i^{(7)} =& \ \gamma_{ij}^{(7,7)} C_j^{(7)} + \gamma_i^{(7,5)} C^{(5)} C^{(5)} C^{(5)} + \gamma_{ij}^{(7,6)} C^{(5)} C_j^{(6)}\end{aligned}$$

D. Zhang, JHEP 10 (2023)
D. Zhang, JHEP 02 (2024)

- additional operators can contribute to 0vbb, new dominant contributions can be triggered

- may be important in specific models, when running from a scale **Λ** down to the electroweak scale

RGE running in SMEFT

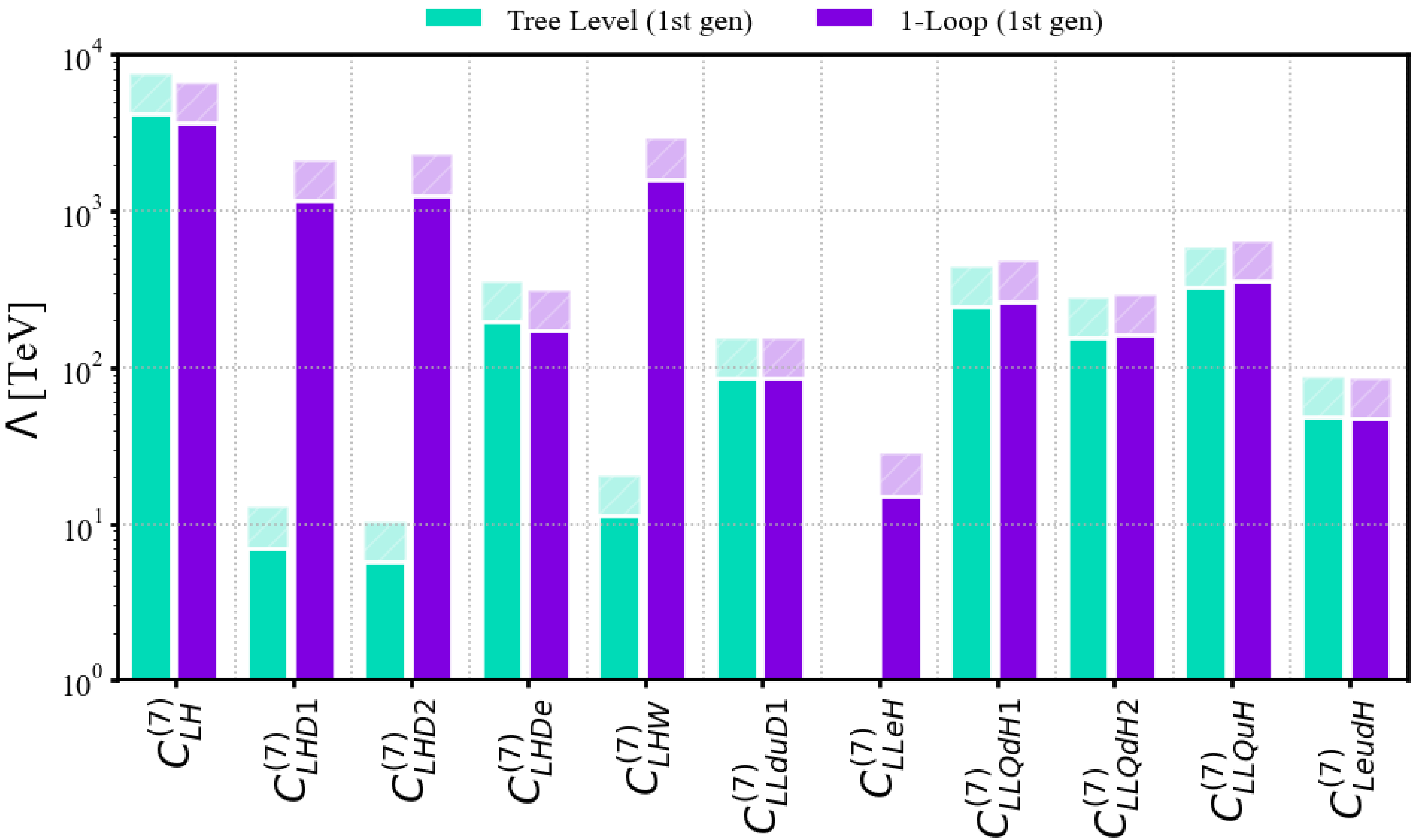


operator mixing, dim 5, 6 and 7

O. Scholer, J. de Vries, LG: JHEP 08 (2023) 043

Tree-level vs One-loop Limits

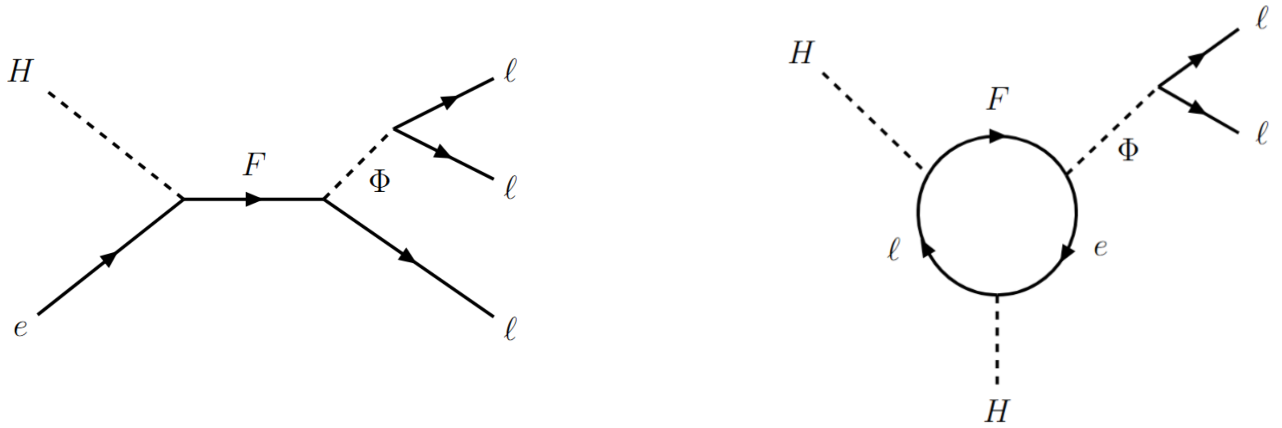
L. Graf, C. Hati, A. Martin-Galan, O. Scholer: 2504.00081



Example 1: UV completion of $\mathcal{O}^{(7)}_{LL\bar{e}H}$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Φ	1	1	1
F	1	2	3/2

$$\mathcal{L}_{UV} \subset f_1 \bar{L} P_R i\tau_2 L^C \Phi^\dagger + f_2 \overline{e^C} P_R F H^\dagger + \bar{F} P_R i\tau_2 L^C \Phi$$



- operator $\mathcal{O}^{(7)}_{LL\bar{e}H} = \epsilon_{ij}\epsilon_{mn}(\bar{e}L_i)(L_j^T C L_m)H_n$ generated at tree level
- no Weinberg contribution at tree level

Example 1: UV completion of $\mathcal{O}_{LL\bar{e}H}^{(7)}$

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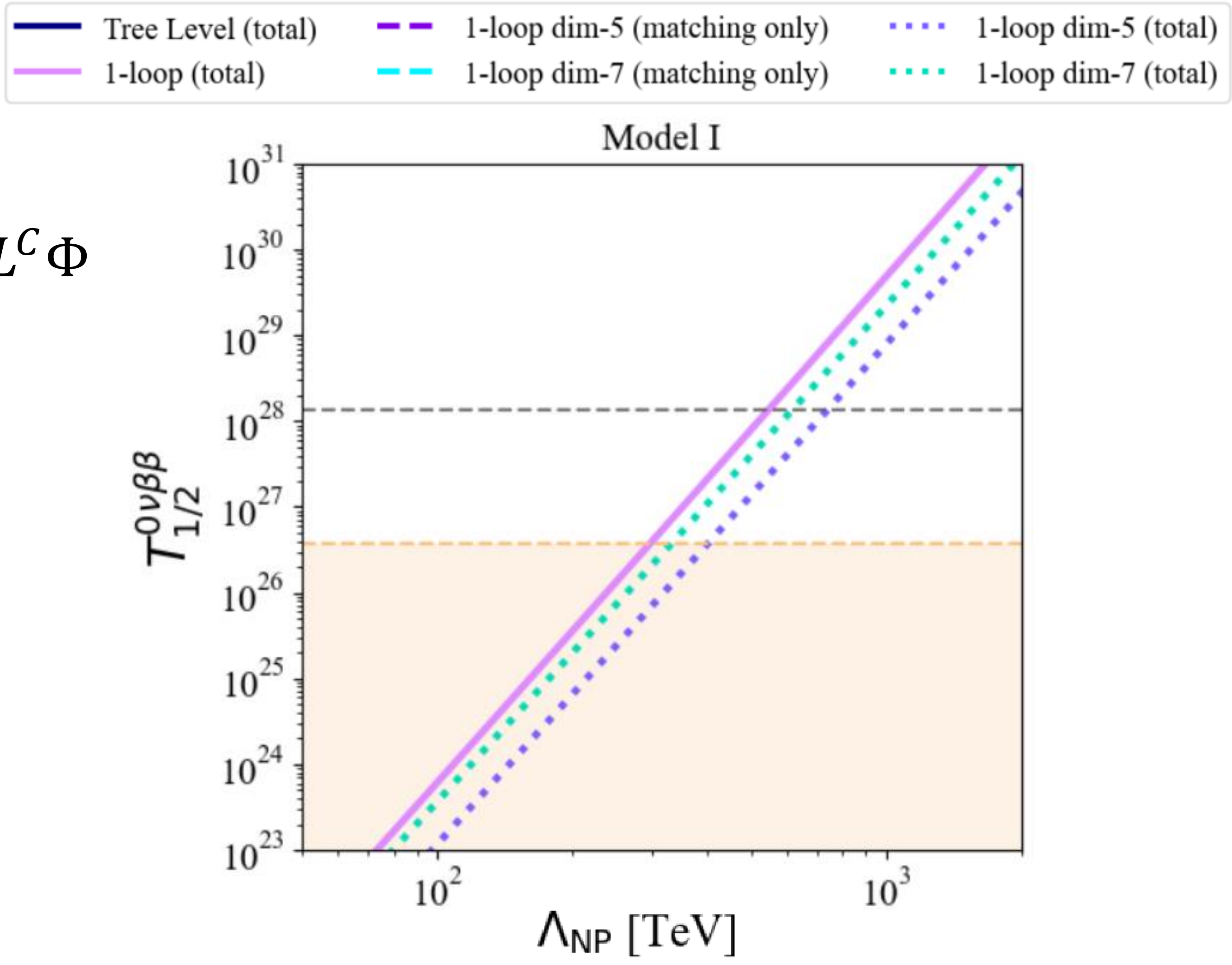
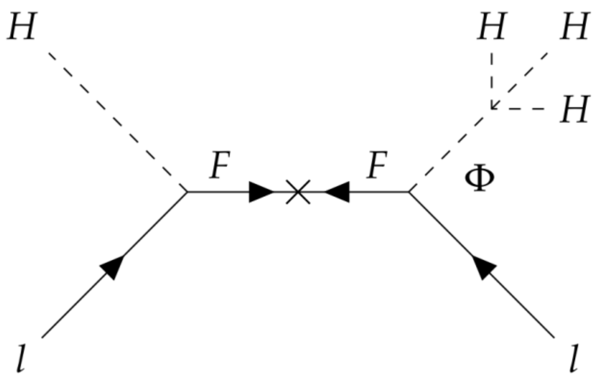
- dimension-5 matching contribution cancelled due to flavour structure
- limits from 0νββ via mixing

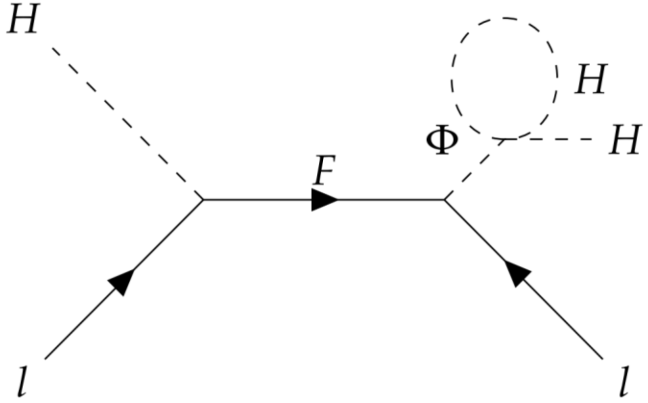


Example 2: UV completion of $O_{LH}^{(7)}$

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Σ	1	3	1
S	1	4	3/2

$$\mathcal{L}_{UV} \subset h_1 \overline{L^C} P_L \Sigma H^\dagger + h_2 \bar{\Sigma} P_L L S + \lambda_S HHHS^\dagger$$





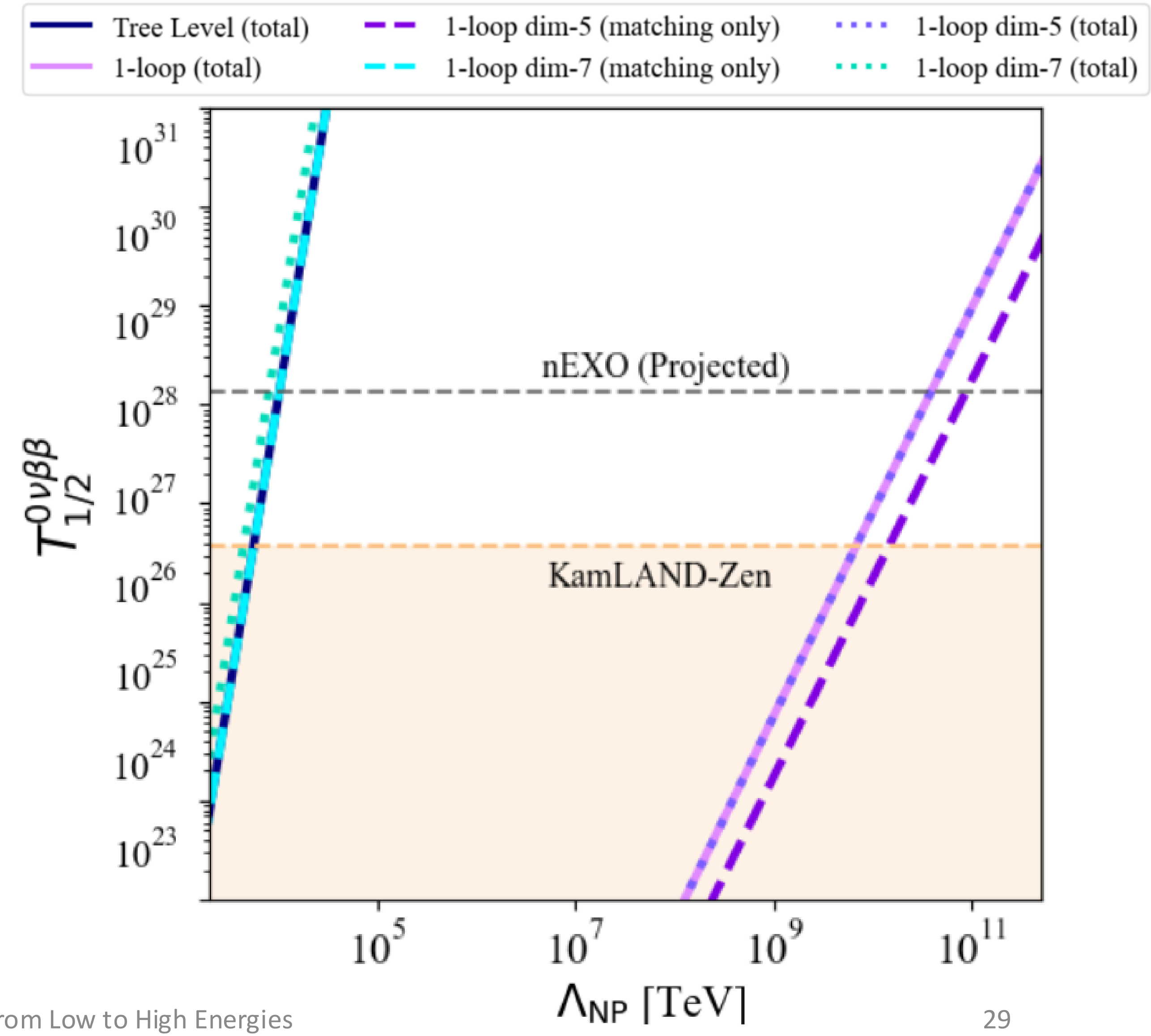
- operator $O_{LH}^{(7)} = \epsilon_{ij}\epsilon_{mn}(L_i^T C L_m) H_j H_n (H^\dagger H)$ generated at tree level
- no tree-level Weinberg contribution

Example 2: UV completion of $O_{LH}^{(7)}$

- operator $O_{LH}^{(7)} = \epsilon_{ij}\epsilon_{mn}(L_i^T C L_m) H_j H_n (H^\dagger H)$

  $\mathcal{L}_{UV} \subset h_1 \overline{L^C} P_L \Sigma H^\dagger + h_2 \bar{\Sigma} P_L L S + \lambda_S H H H S^\dagger$

- dominance of Weinberg operator over dimension-7 operator



Conclusion & Outlook

- $0\nu\beta\beta$ – complex process, access to new physics – a variety of different mechanisms besides the standard light neutrino exchange can contribute to $0\nu\beta\beta$ → effective description
- combining various contributions → involved, tedious calculations with a variety of inputs → νDoBe tool developed and available online
- to unravel the underlying new physics – necessary to distinguish the dominant LNV interaction; other low-energy experiments, but also high-energy data useful
- loop effects important, can affect the phenomenological studies
- one-loop RGE analysis for $\Delta L = 2$ dimension-7 SMEFT operators → significantly improved limits on the new-physics scales for some operators
- specific UV models analysed, running and mixing effects can be more important than one-loop matching

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Thank you!