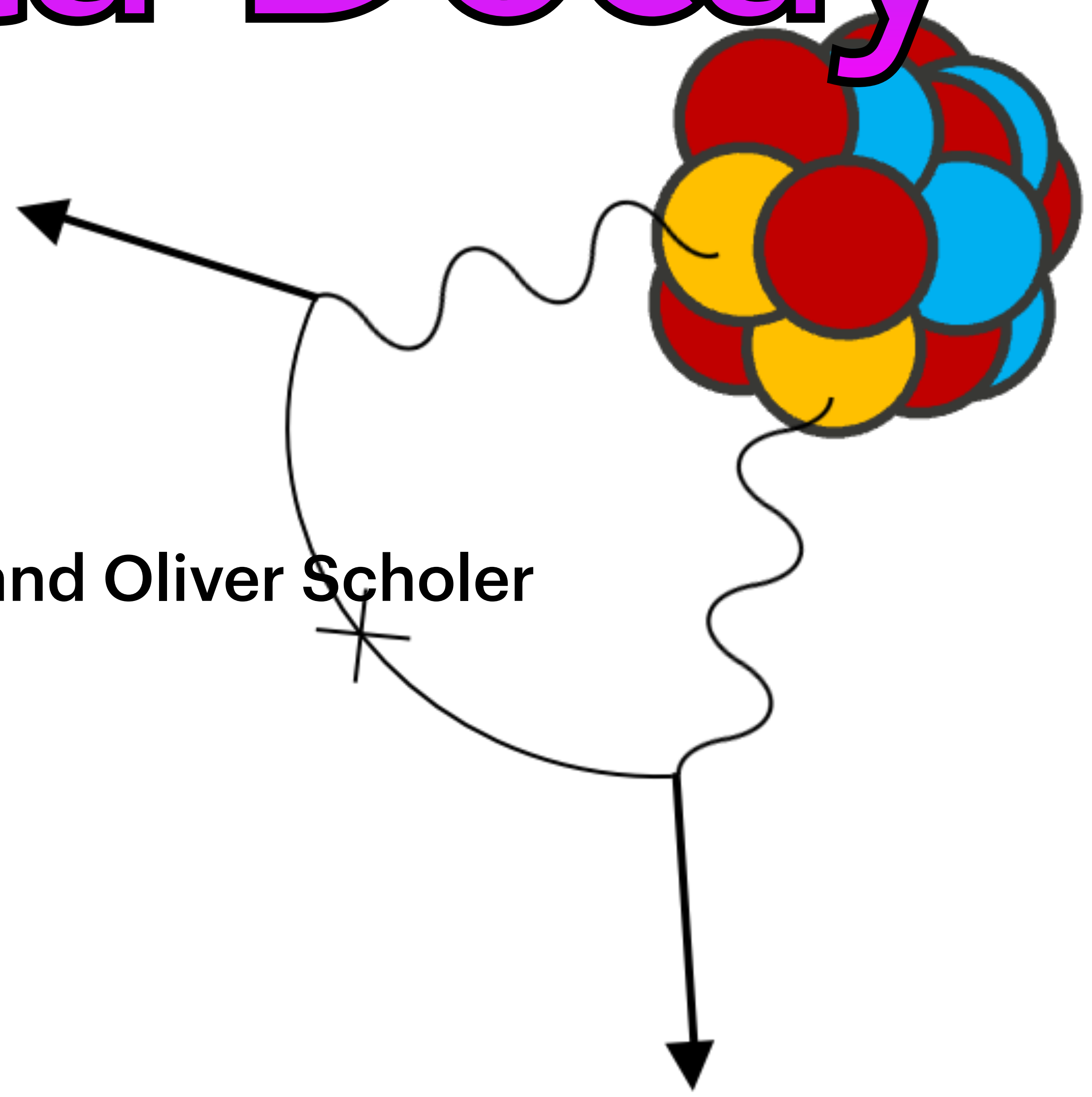
Importance of Loop Effects in Neutrinoless Doble Beta Decay



PASCOS 2025

Based on arXiv:2504.00081 in collaboration with Lukáš Gráf, Chandan Hati and Oliver Scholer

Ana Martín Galán

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Introduction

Effective Field Theories

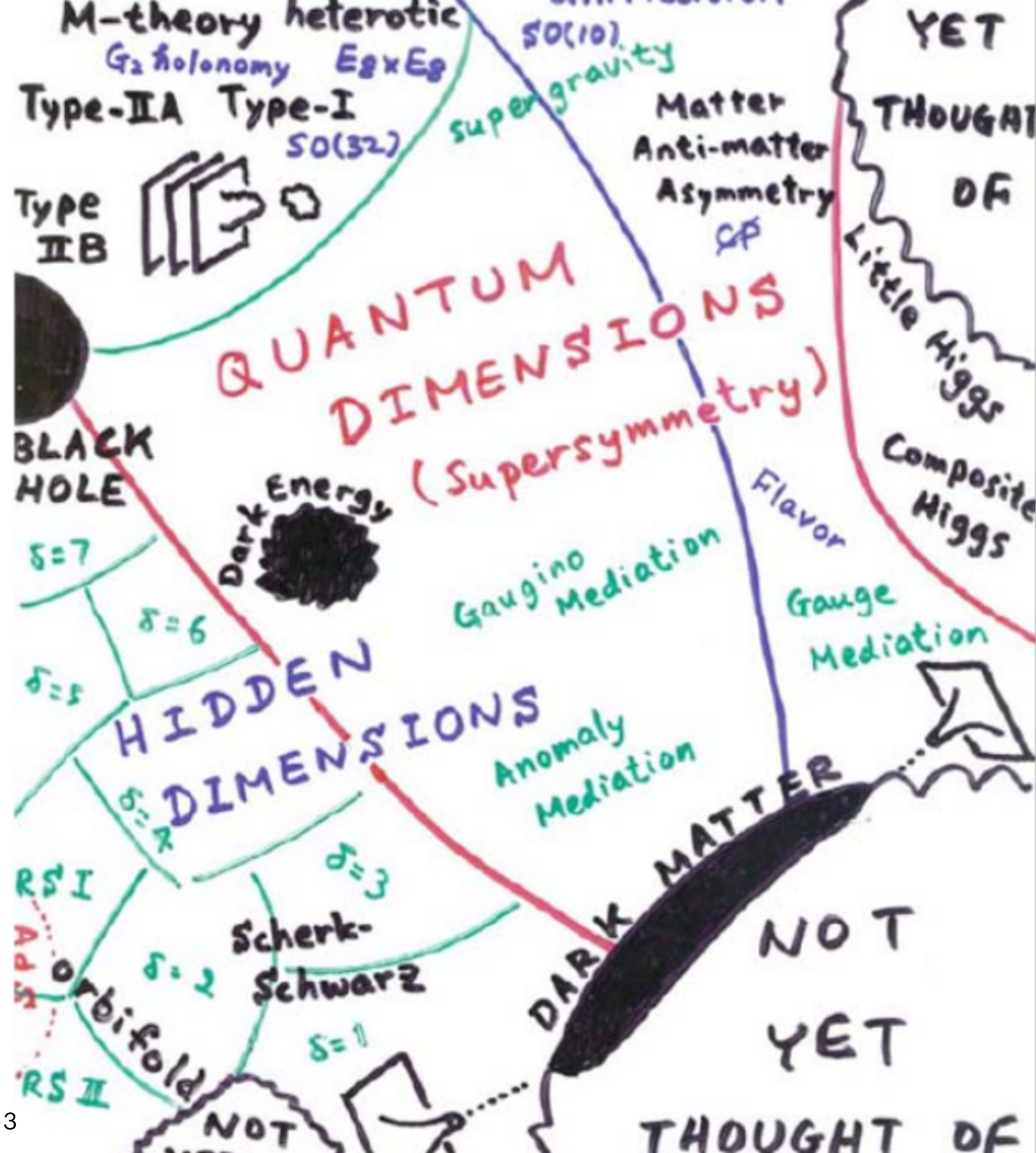
Advantages:

- Simplifying heavy *dofs*
- Model independent observables

Good tool for hunting new physics!

Construction of an EFT:

- Energy scale
- Relevant degrees of freedom
- Symmetries



[Image: H. Murayama]

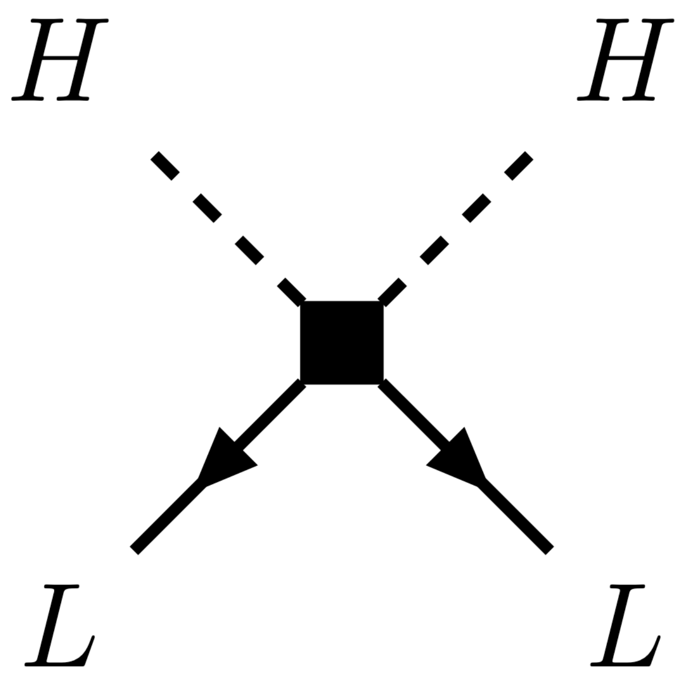
Introduction

Approaches to EFTs

But... Why Lepton Number Violation?

Lepton number is an accidental global symmetry of Standard Model

Smoking gun for New Physics!

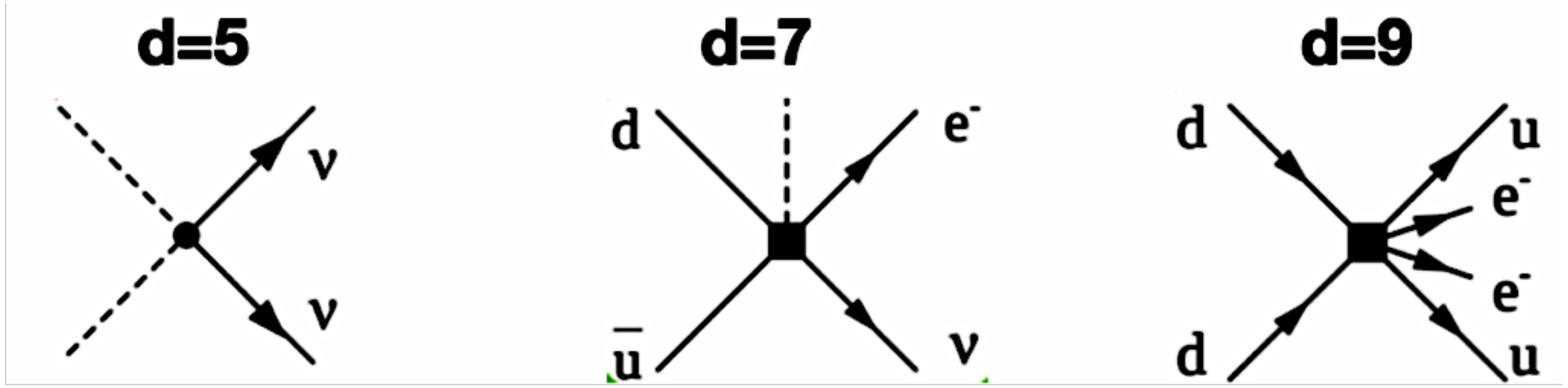


Neutrino mass mechanisms: Majorana vs Dirac

LNV operators in SMEFT

$\Delta L = 2$ LNV operators are odd dimensional in SMEFT [Kobach '16]

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{\mathscr{C}_5}{\Lambda}\mathcal{O}_5 + \sum_i \frac{\mathscr{C}_7^i}{\Lambda}\mathcal{O}_7^i + \sum_i \frac{\mathscr{C}_9^i}{\Lambda}\mathcal{O}_9^i + \cdots$$



. . .

[Weinberg '79]

[Babu, Leung '79]
[de Gouvea, Jenkins '08]
[Lehman '14]

[Graesser '16]
[Liao, Ma '08]

But… Why dimension 7?

We can generate models without tree level Weinberg

	$\mathcal{O}_{LH}$	$\mathcal{O}_{LeHD}$	$\mathcal{O}_{\bar{e}LLLH}$	$\mathcal{O}_{\bar{d}LueH}$	$\mathcal{O}_{\bar{d}LQLH1}$	$\mathcal{O}_{\bar{d}LQLH2}$	$\mathcal{O}_{\bar{Q}uLLH}$
$\mathcal{S}$	Δ, N, Σ						
Ξ	Δ, Σ						
h			$\varphi, N, \Delta_3^\dagger$			$\varphi, U, Q_5^\dagger$	
Δ	$\mathcal{S}, \Xi, \Delta, \varphi, \Theta_1, \Theta_3, \Sigma$	$\Sigma, \Delta_1^\dagger$	$\varphi, \Sigma, \Delta_3^\dagger$		$\varphi, Q_5^\dagger, T_2$		$\varphi, Q_7, T_1^\dagger$
φ	Δ, N, Σ		h, Δ, N, Σ		Δ, N, Σ	h, Σ	Δ, N, Σ
Θ_1	Δ, Σ						
Θ_3	$\Delta, \Sigma_1^\dagger$						
S_1				$\tilde{R}_2, N, Q_5^\dagger$	$\tilde{R}_2, N, Q_5^\dagger$		
$\tilde{R}_2$				$S_1, \Delta_1^\dagger, Q_7$	S_1, S_3, N, Σ, T_2	S_3, Σ, U	
S_3					$\tilde{R}_2, \Sigma, Q_5^\dagger$	$\tilde{R}_2, \Sigma, Q_5^\dagger$	
N	$\mathcal{S}, \varphi, \Delta_1^\dagger$	$\Delta_1^\dagger$	h, φ	S_1, W_1', U_1	$\varphi, S_1, \tilde{R}_2$		$\varphi, U_1, \bar{V}_2^\dagger$
Σ	$\mathcal{S}, \Xi, \Delta, \varphi, \Theta_1, \Delta_1^\dagger, F_4$	$\Delta, \Delta_1^\dagger$	Δ, φ		$\varphi, \tilde{R}_2, S_3$	$\varphi, \tilde{R}_2, S_3$	$\varphi, \bar{V}_2^\dagger, U_3$
$\Sigma_1^\dagger$	Θ_3						

[Friedell et al. '24]

But... Why dimension 7?

We can generate models without tree level Weinberg

	$\mathcal{O}_{LH}$	$\mathcal{O}_{LeHD}$	$\mathcal{O}_{\bar{e}LLLH}$	$\mathcal{O}_{\bar{d}LueH}$	$\mathcal{O}_{\bar{d}LQLH1}$	$\mathcal{O}_{\bar{d}LQLH2}$	$\mathcal{O}_{\bar{Q}uLLH}$
$\mathcal{S}$	Δ, N, Σ						
Ξ	Δ, Σ						
h			$\varphi, N, \Delta_3^\dagger$			$\varphi, U, Q_5^\dagger$	

Competition between dim 5 and dim 7!

	$\mathcal{O}_{LH}$	$\mathcal{O}_{LeHD}$	$\mathcal{O}_{\bar{e}LLLH}$	$\mathcal{O}_{\bar{d}LueH}$	$\mathcal{O}_{\bar{d}LQLH1}$	$\mathcal{O}_{\bar{d}LQLH2}$	$\mathcal{O}_{\bar{Q}uLLH}$
S_3					$R_2, \Sigma, Q_5^\dagger$	$R_2, \Sigma, Q_5^\dagger$	
N	$\mathcal{S}, \varphi, \Delta_1^\dagger$	$\Delta_1^\dagger$	h, φ	S_1, W_1', U_1	$\varphi, S_1, \tilde{R}_2$		$\varphi, U_1, \bar{V}_2^\dagger$
Σ	$\mathcal{S}, \Xi, \Delta, \varphi, \Theta_1, \Delta_1^\dagger, F_4$	$\Delta, \Delta_1^\dagger$	Δ, φ		$\varphi, \tilde{R}_2, S_3$	$\varphi, \tilde{R}_2, S_3$	$\varphi, \bar{V}_2^\dagger, U_3$
$\Sigma_1^\dagger$	Θ_3						

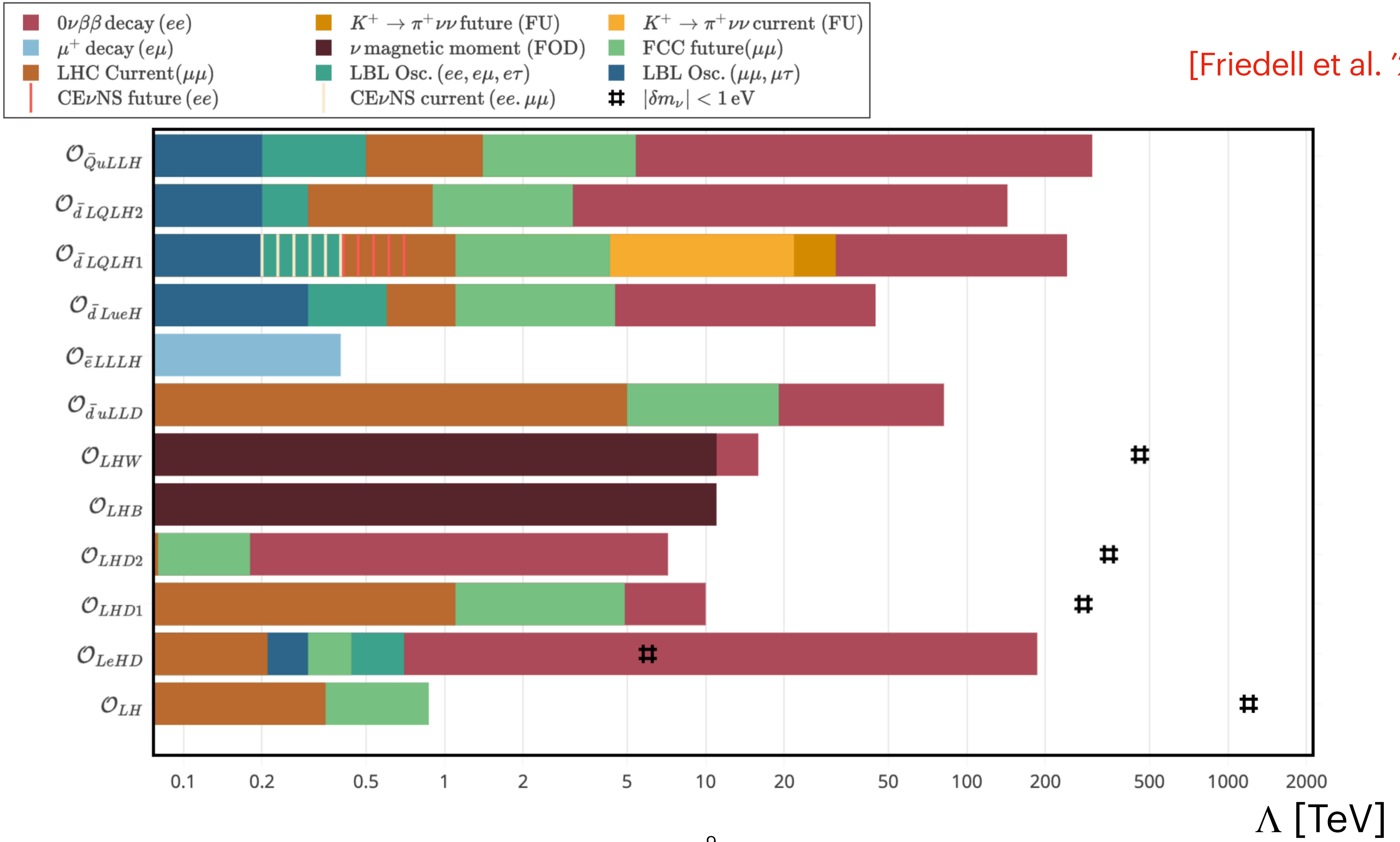
[Friedell et al. ’24]

Dimension 7 LNV operators in SMEFT

[Friedell et al. '23]

- 12 independent operators with $\Delta L = 2$
- First time derived in [Lehman '14]
- Improvement and reduction of redundant operators in [Liao, Ma '17]

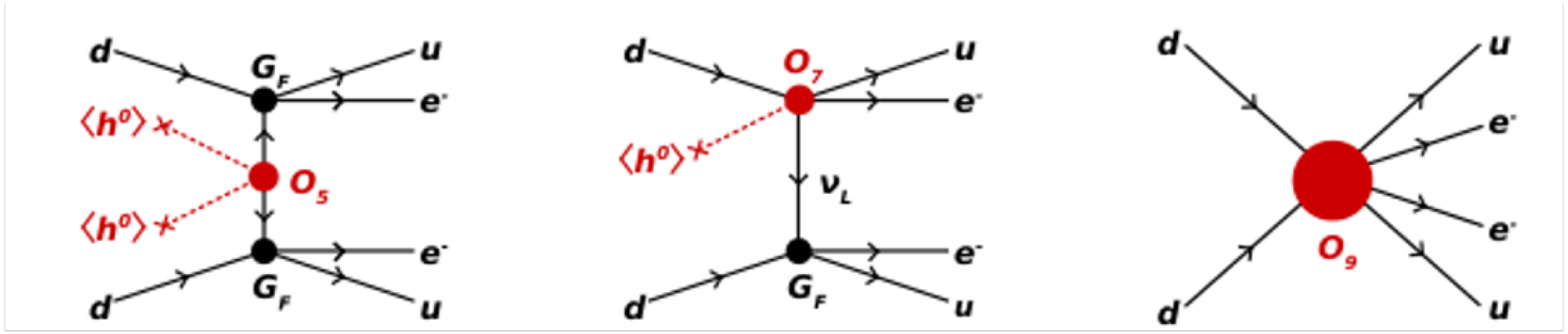
Type	$\mathcal{O}$	Operator
$\Psi^2 H^4$	$\mathcal{O}_{LH}^{pr}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i L_r^m)H^j H^n(H^\dagger H)$
$\Psi^2 H^3 D$	$\mathcal{O}_{LeHD}^{pr}$	$\epsilon_{ij}\epsilon_{mn}(\overline{L_p^c}^i \gamma_\mu e_r)H^j(H^m iD^\mu H^n)$
$\Psi^2 H^2 D^2$	$\mathcal{O}_{LHD1}^{pr}$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



[Friedell et al. ’23]

Effective Approach to Neutrinoless Double Beta decay

Different mechanisms beyond the standard scenario may contribute to $0\nu\beta\beta$



Atomic phase space

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

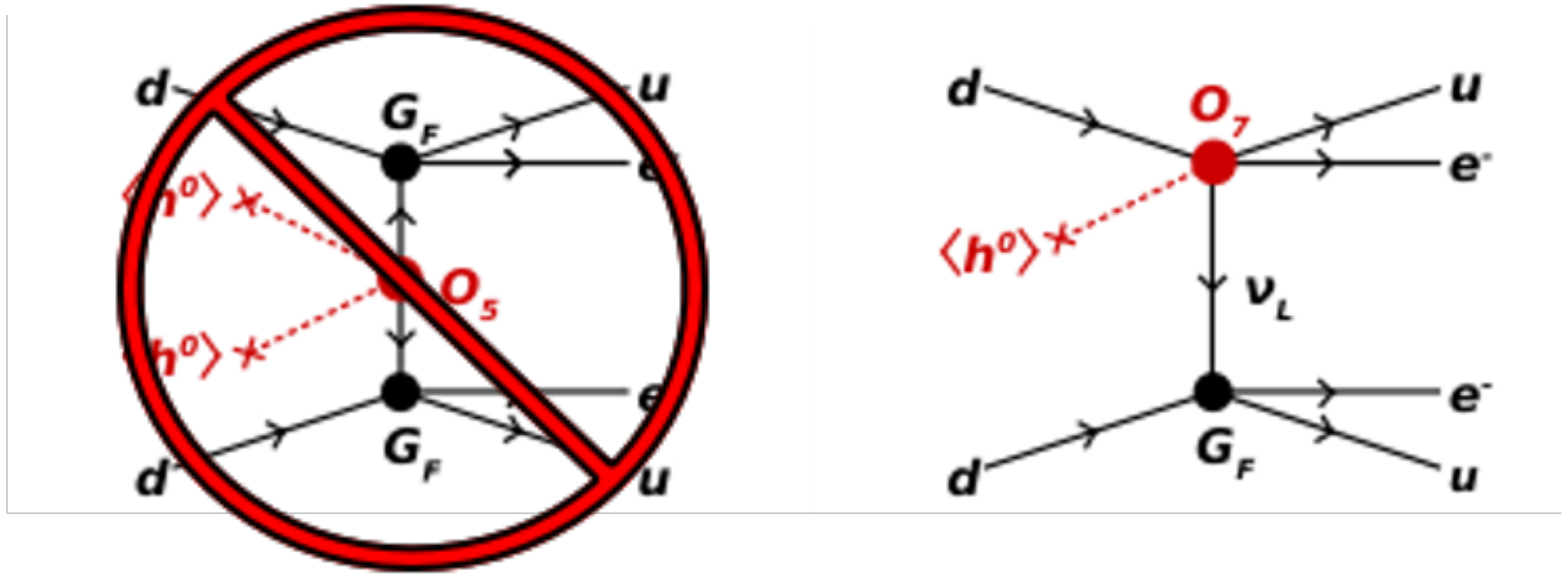
Wilson Coefficient

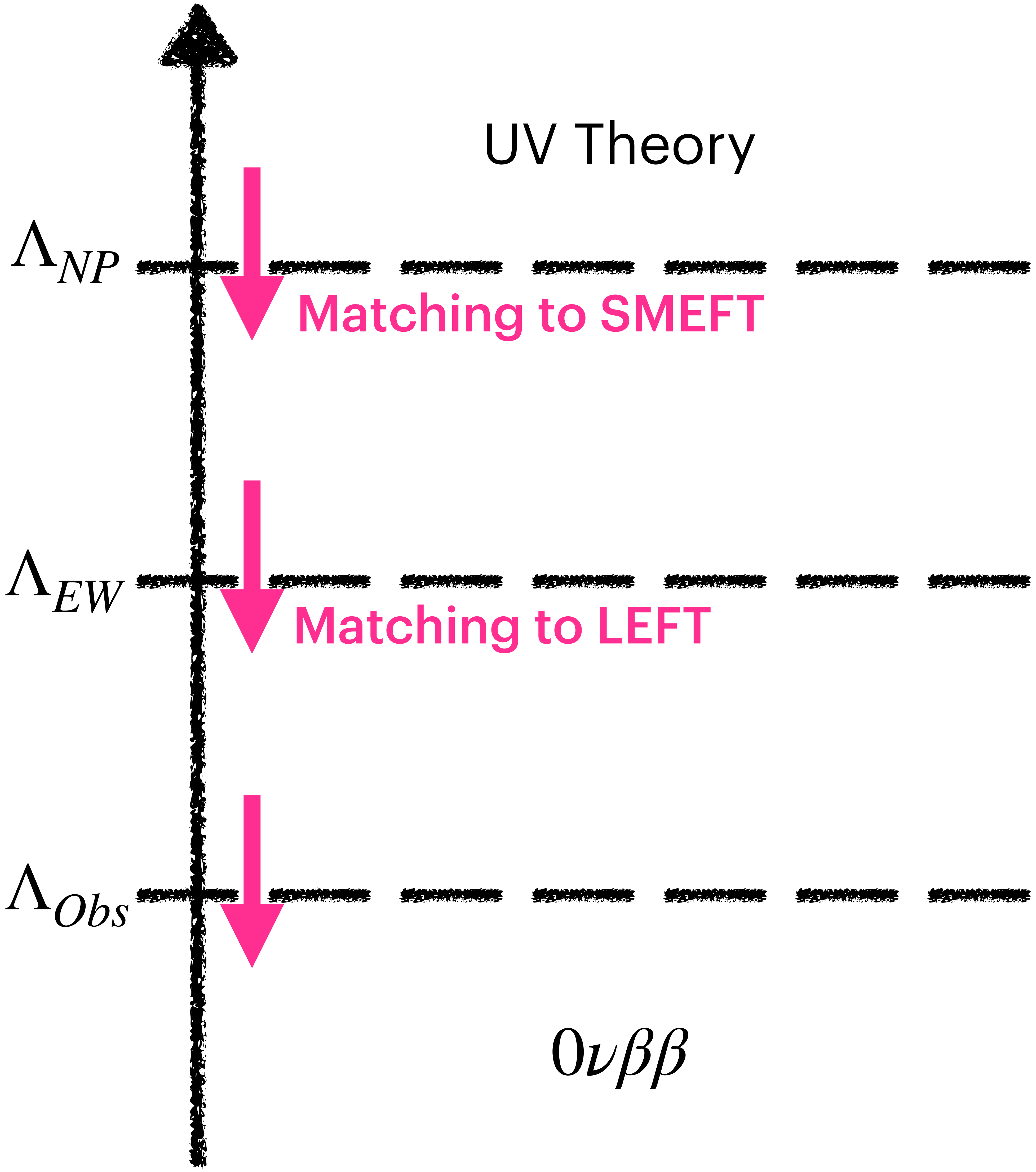
Nuclear matrix element

[Deppish et al. '18]
[Cirigliano et al. '18]
[Hirsch et al. '97]

One loop effects in Neutrinoless Double Beta Decay

- One loop effects in the previous constraints of $0\nu\beta\beta$.
- One loop effects in UV competitions.



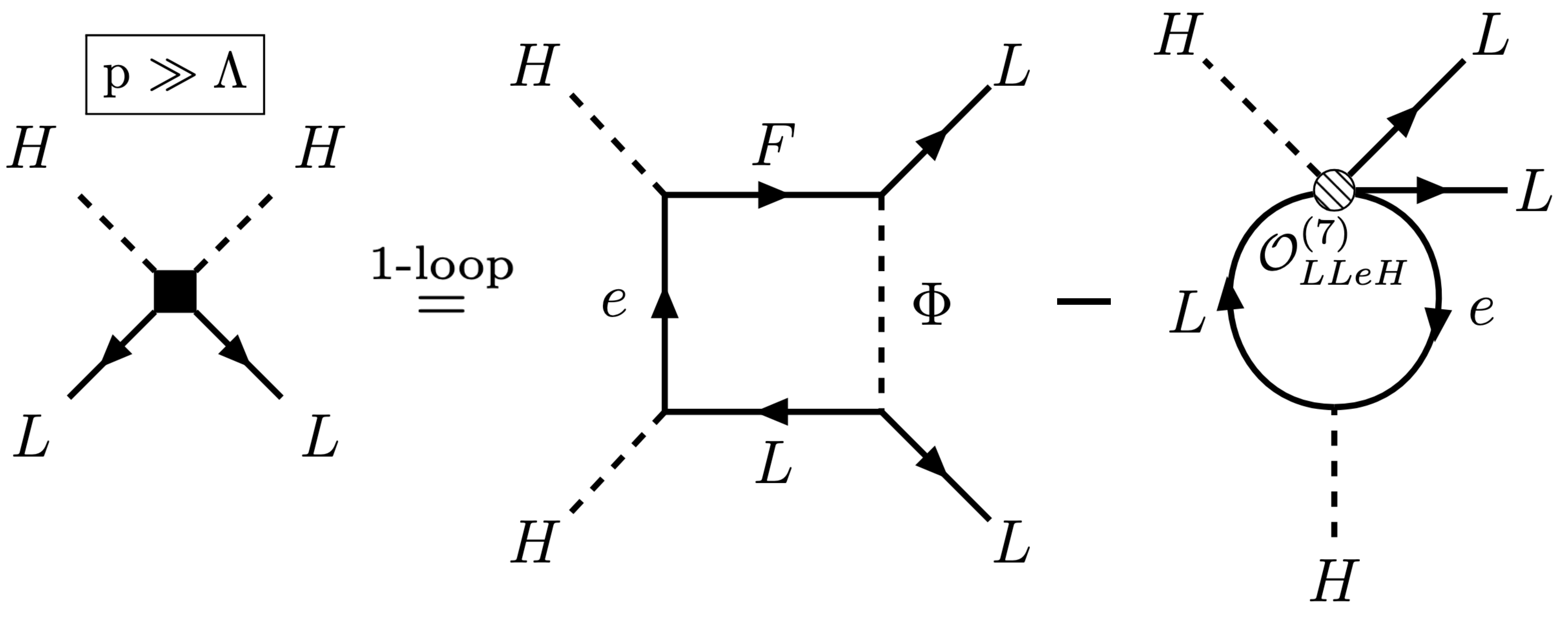


[arXiv:2504.00081 - Gráf, Hati, AMG, Scholer '25]

One loop contributions

[Zhang '23]
[Zhang '24]

Matching



Renormalization Group Equations

$$\dot{C}^{(5)} = \gamma^{(5,5)} C^{(5)} + \hat{\gamma}^{(5,5)} C^{(5)} C^{(5)} C^{(5)} + \gamma_i^{(5,6)} C^{(5)} C_i^{(6)} + \gamma_i^{(5,7)} C_i^{(7)},$$

$$\dot{C}_i^{(7)} = \gamma_{ij}^{(7,7)} C_j^{(7)} + \gamma_i^{(7,5)} C^{(5)} C^{(5)} C^{(5)} + \gamma_{ij}^{(7,6)} C^{(5)} C_j^{(6)}$$

- Mixing between dim 5, dim 6 and dim 7 operators.
- Potential generation of dim 5 or dim 7 LNV operators via mixing

[arXiv:2504.00081 - Gráf, Hati, AMG, Scholer '25]

Workflow

[Scholer et al. '23]
[Fuentes et al. '23]
[Carmona et al. '22]

New bounds

Switch on one SMEFT WC to specific value at scale Λ → Running and matching from LEFT, ChiPT… to SMEFT → New bounds!

νDoBe

Crosscheck with MME and Machete

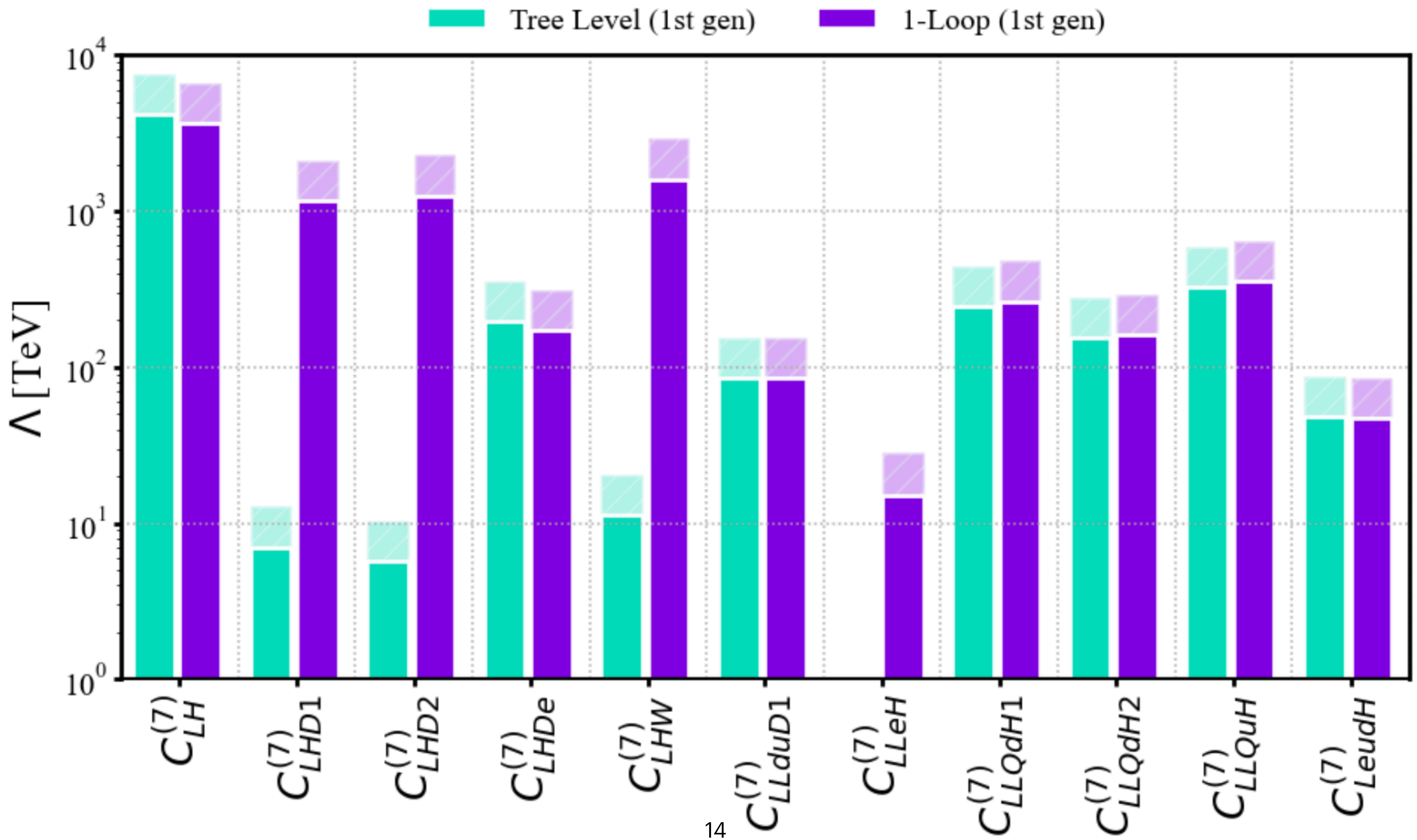
UV Models

UV matching → Running and matching to LEFT, ChiPT, Chiral EFT… → New bounds!

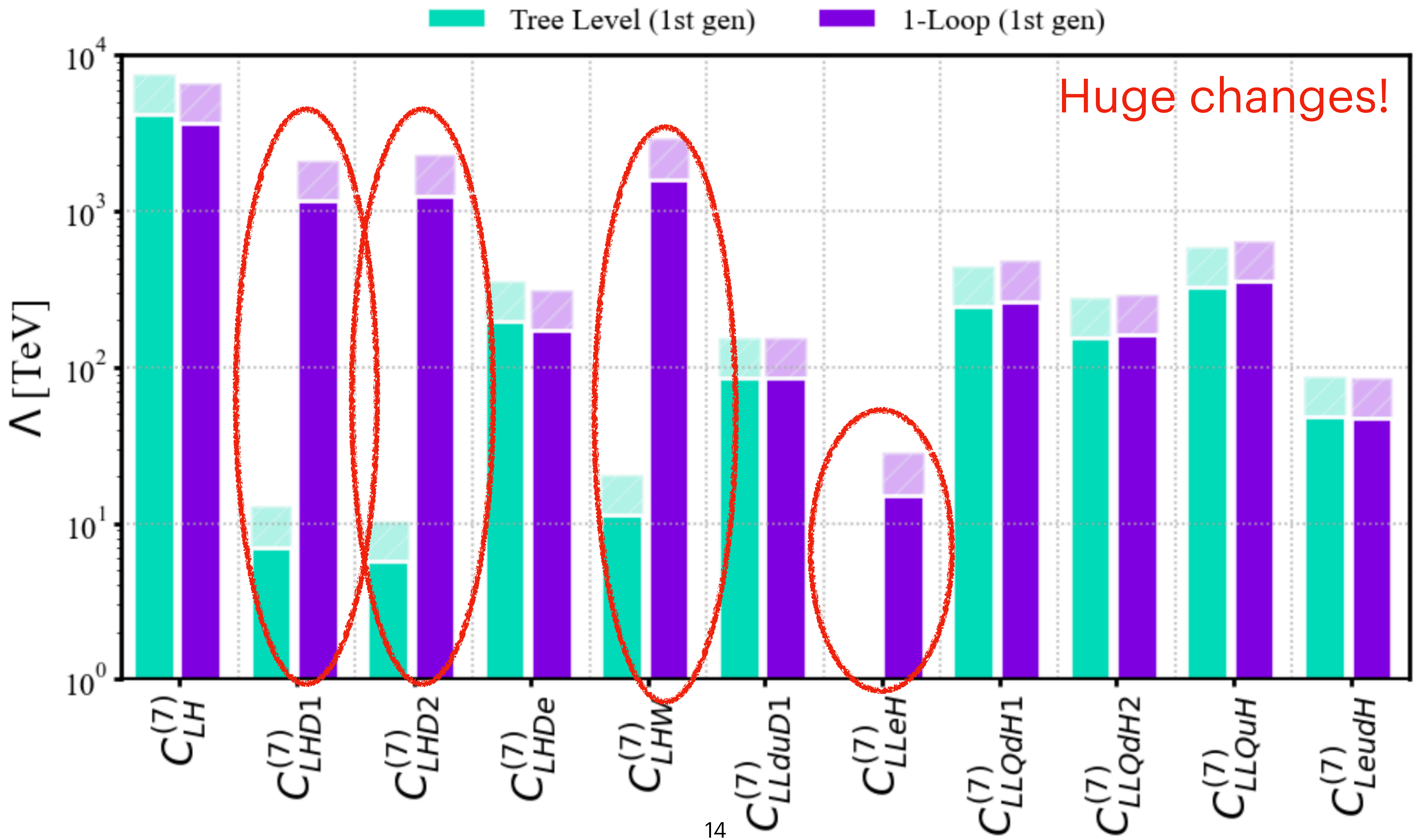
UV models without Weinberg at tree level

νDoBe

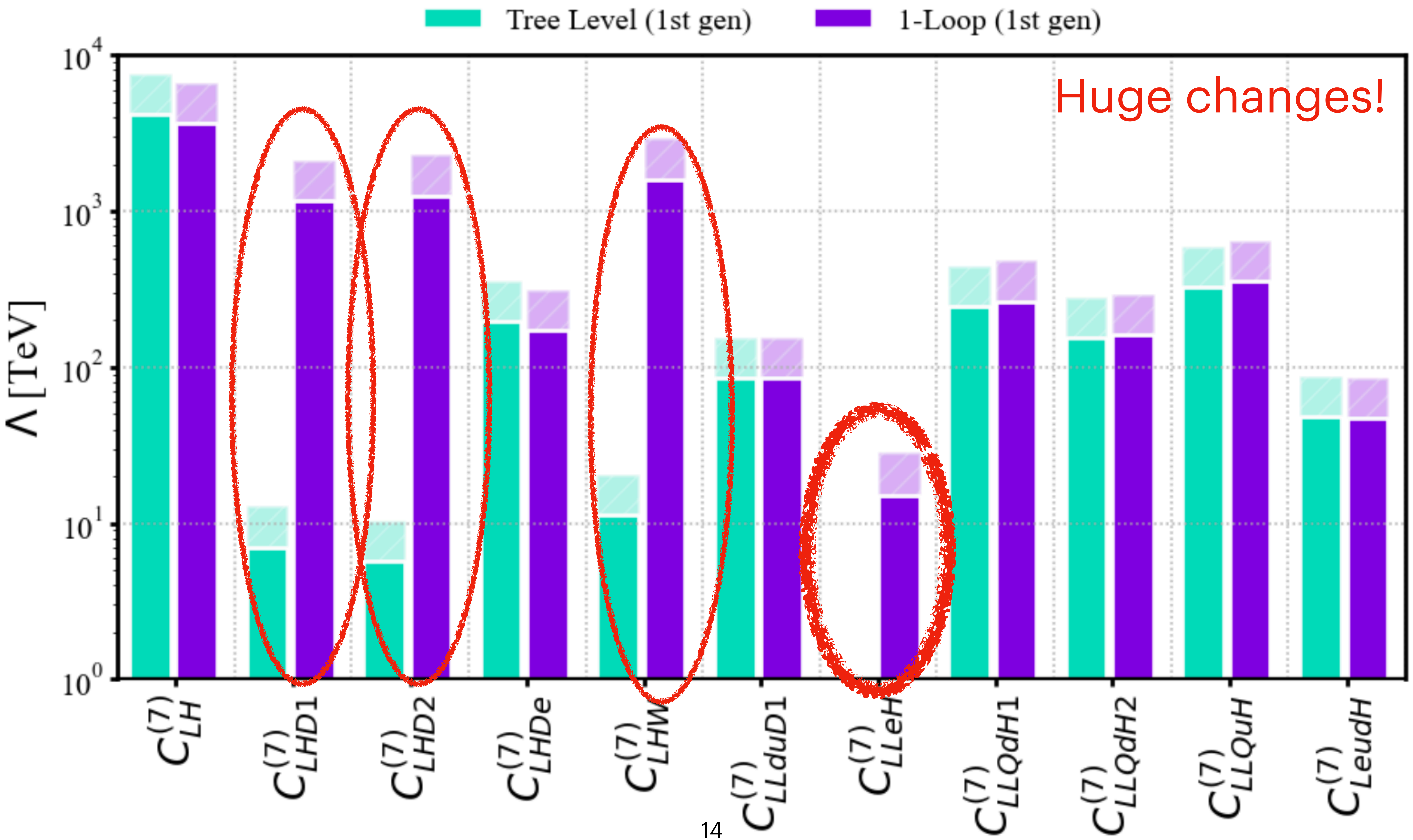
Bottom up new bounds



Bottom up new bounds



Bottom up new bounds



Top down model example $\mathcal{O}^{(7)}_{LL\bar{e}H}$

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

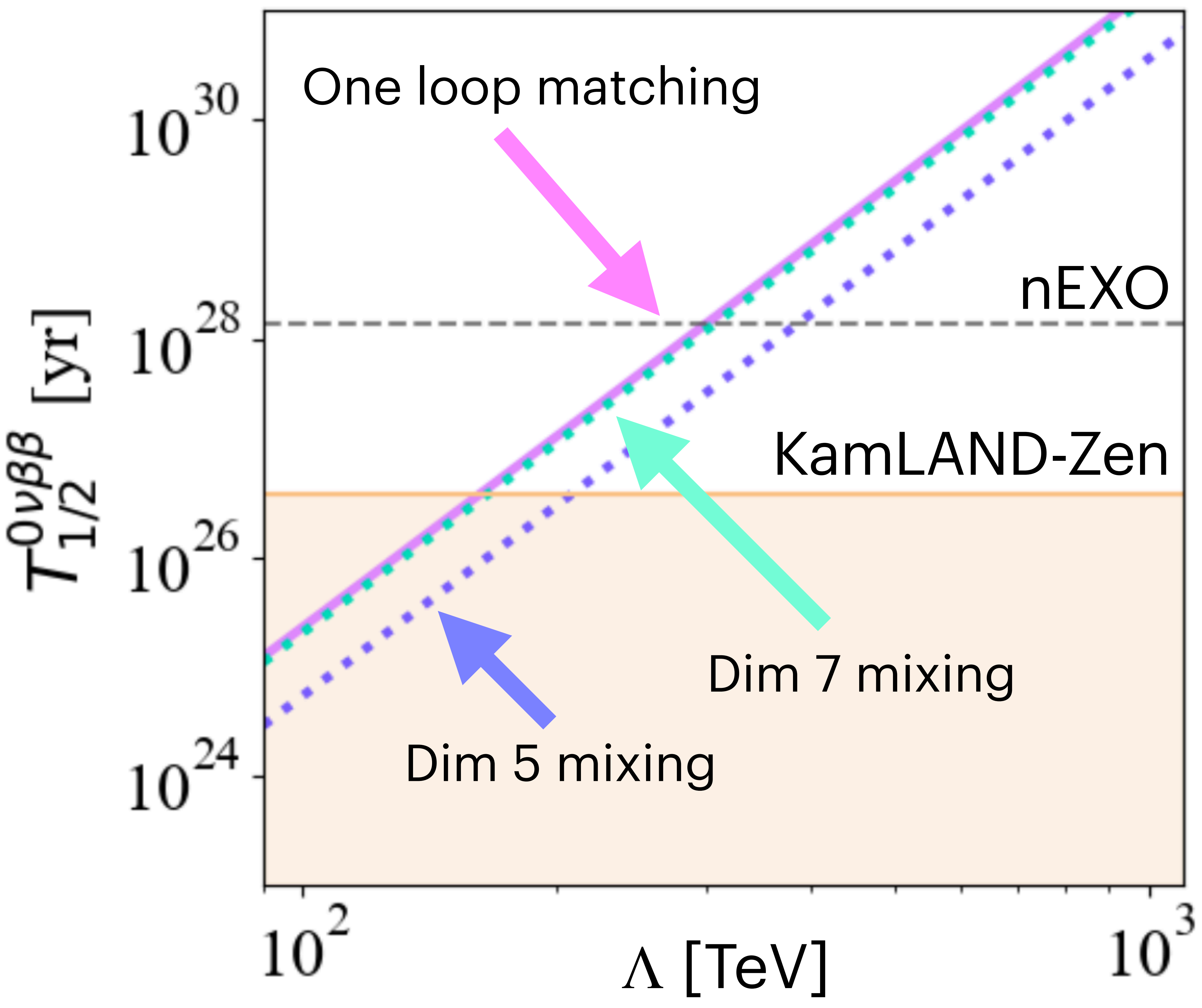
$$\mathcal{L}_{UV} \subset f_1 \bar{L} P_R i\tau_2 L^C \Phi^\dagger + f_2 \overline{e^C} P_R F H^\dagger + \bar{F} P_R i\tau_2 L^C \Phi$$

- Generation of $\mathcal{O}^{(7)}_{LL\bar{e}H} = \epsilon_{ij}\epsilon_{mn}(\bar{e}L_i)(L_j^T C L_m)H_n$ at tree level.
- One loop dim 5 matching contribution cancelled due to symmetric Yukawa-like term.

New and strongest bound from $0\nu\beta\beta$ at one loop.

No tree level contribution to $0\nu\beta\beta$

Vanishing matching contribution



Conclusions and next steps

- EFTs are powerful tools for probing new physics.
- LNV signals new physics. Higher dimensional operators provide insights.
- Dimension 7 operators can compete with Weinberg operator.
- $0\nu\beta\beta$ decay sets the strongest bounds with complementarity of other experiments.
- Loop effects tighten constraints and alter the previous prediction for $0\nu\beta\beta$.
- Operator mixing can induce $0\nu\beta\beta$ even if absent at tree level.
- WIP: expanding this analysis to other observables.

Loop effects can be important and must not be ignored in general.

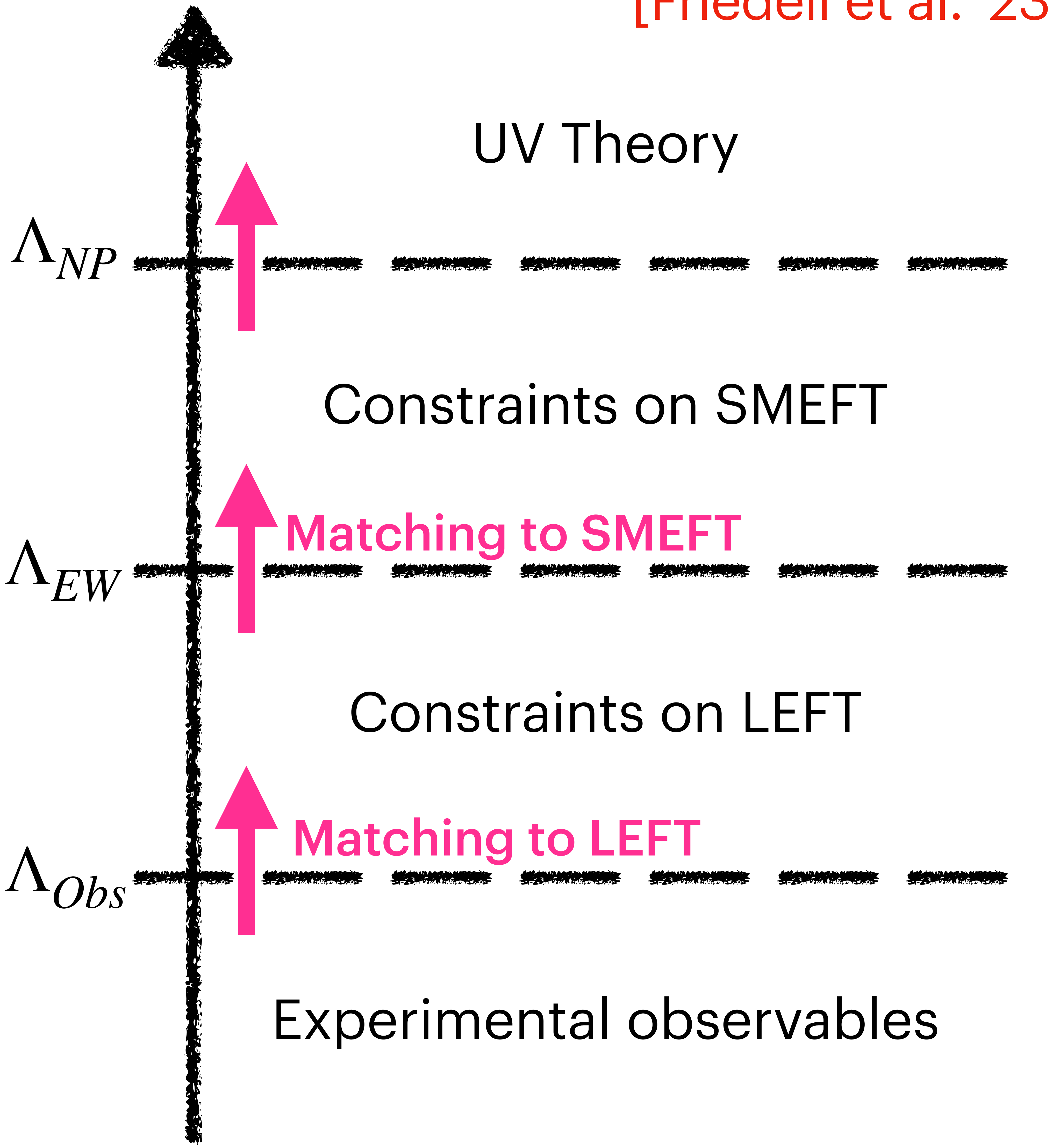
Thank you!

Backup

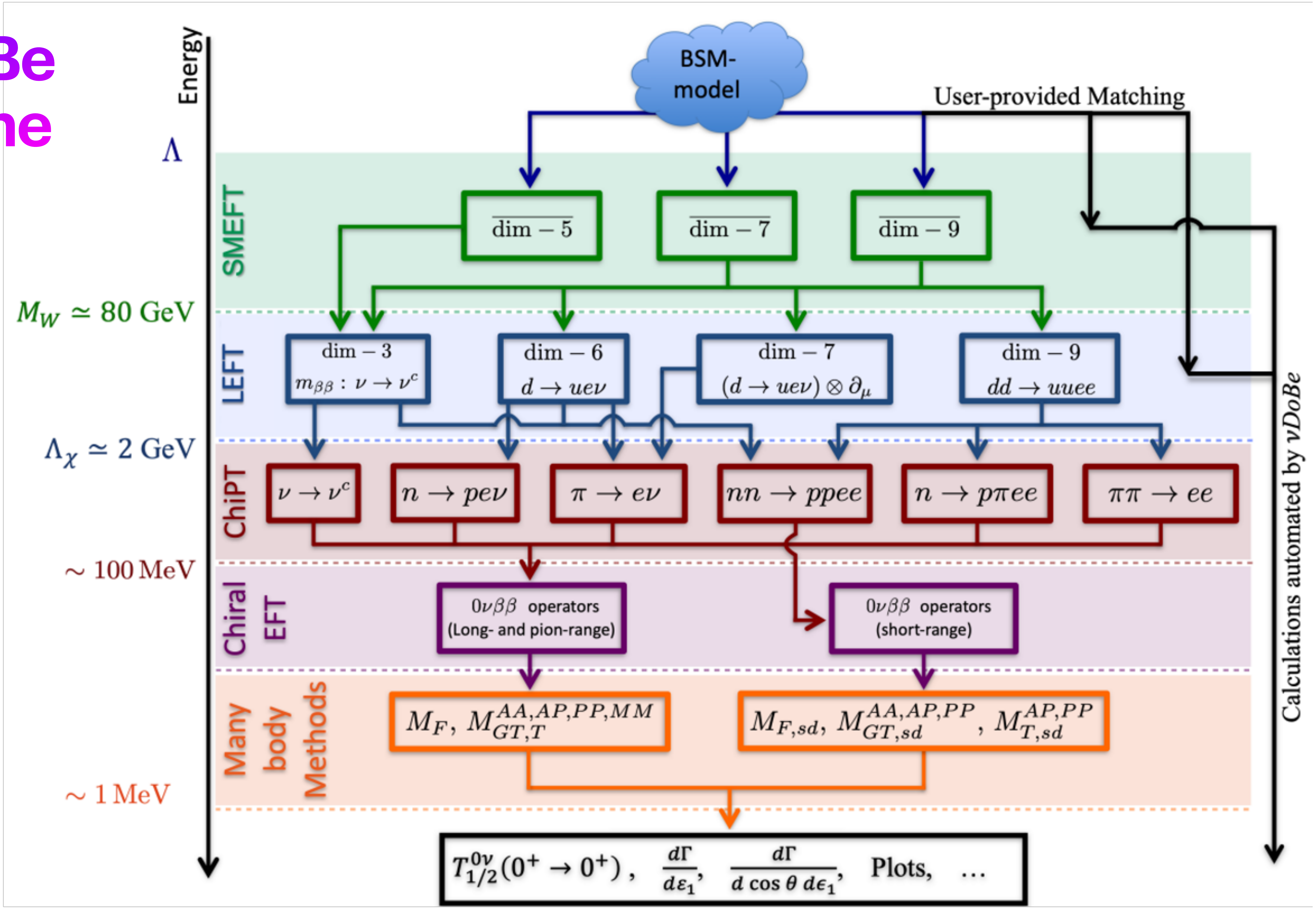
Matching from SMEFT to LEFT

[Friedell et al. '23]

O	Operator	Matching
$O^{S,prst}_{e\nu;LL}$	$(\overline{e_{Rp}}e_{Lr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{e\nu;LL} = -\frac{\sqrt{2}v}{8}\left(2C^{prst}_{\bar{e}LLLH} + C^{psrt}_{\bar{e}LLLH} + s \leftrightarrow t\right)$
$O^{S,prst}_{e\nu;RL}$	$(\overline{e_{Lp}}e_{Rr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{e\nu;RL} = -\frac{\sqrt{2}v}{2}\left(C^{sr}_{LeHD}\delta^{tp} + C^{tr}_{LeHD}\delta^{sp}\right)$
$O^{T,prst}_{e\nu;LL}$	$(\overline{e_{Rp}}\sigma_{\mu\nu}e_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{T,prst}_{e\nu;LL} = +\frac{\sqrt{2}v}{32}\left(C^{psrt}_{\bar{e}LLLH} - C^{ptrs}_{\bar{e}LLLH}\right)$
$O^{S,prst}_{d\nu;LL}$	$(\overline{d_{Rp}}d_{Lr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{d\nu;LL} = -\frac{\sqrt{2}v}{8}V_{xr}\left(C^{ptxs}_{\bar{d}LQLH1} + C^{psxt}_{\bar{d}LQLH1}\right)$
$O^{T,prst}_{d\nu;LL}$	$(\overline{d_{Rp}}\sigma_{\mu\nu}d_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{T,prst}_{d\nu;LL} = -\frac{\sqrt{2}v}{32}V_{xr}\left(C^{ptxs}_{\bar{d}LQLH1} - C^{psxt}_{\bar{d}LQLH1}\right)$
$O^{S,prst}_{u\nu;RL}$	$(\overline{u_{Lp}}u_{Rr})(\overline{\nu^c_s}\nu_t)$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{u\nu;RL} = +\frac{\sqrt{2}v}{4}\left(C^{prst}_{\bar{Q}uLLH} + C^{prts}_{\bar{Q}uLLH}\right)$
$O^{S,prst}_{du\nu e;LL}$	$(\overline{d_{Rp}}u_{Lr})(\overline{\nu^c_s}e_{Lt})$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{du\nu e;LL} = +\frac{\sqrt{2}v}{8}\left(2C^{ptrs}_{\bar{d}LQLH1} + C^{ptrs}_{\bar{d}LQLH2} - C^{psrt}_{\bar{d}LQLH2}\right)$
$O^{S,prst}_{du\nu e;RL}$	$(\overline{d_{Lp}}u_{Rr})(\overline{\nu^c_s}e_{Lt})$	$\frac{4G_F}{\sqrt{2}}c^{S,prst}_{du\nu e;RL} = +\frac{\sqrt{2}v}{2}V^*_{xp}C^{xrts}_{\bar{Q}uLLH}$
$O^{T,prst}_{du\nu e;LL}$	$(\overline{d_{Rp}}\sigma_{\mu\nu}u_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}e_{Lt})$	$\frac{4G_F}{\sqrt{2}}c^{T,prst}_{du\nu e;LL} = +\frac{\sqrt{2}v}{32}\left(2C^{ptrs}_{\bar{d}LQLH1} + C^{ptrs}_{\bar{d}LQLH2} + C^{psrt}_{\bar{d}LQLH2}\right)$
$O^{V,prst}_{du\nu e;LR}$	$(\overline{d_{Lp}}\gamma_\mu u_{Lr})(\overline{\nu^c_s}\gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}}c^{V,prst}_{du\nu e;LR} = +\frac{\sqrt{2}v}{2}V^*_{rp}C^{st}_{LeHD}$
$O^{V,prst}_{du\nu e;RR}$	$(\overline{d_{Rp}}\gamma_\mu u_{Rr})(\overline{\nu^c_s}\gamma^\mu e_{Rt})$	$\frac{4G_F}{\sqrt{2}}c^{V,prst}_{du\nu e;RR} = +\frac{\sqrt{2}v}{4}C^{psrt}_{\bar{d}LueH}$
$O^{S,prst}_{d\nu;RL}$	$(\overline{d_{Lp}}d_{Rr})(\overline{\nu^c_s}\nu_t)$	
$O^{S,prst}_{u\nu;LL}$	$(\overline{u_{Rp}}u_{Lr})(\overline{\nu^c_s}\nu_t)$	Not induced by $d=7$ $\Delta L=2$ SMEFT operators
$O^{T,prst}_{u\nu;LL}$	$(\overline{u_{Rp}}\sigma_{\mu\nu}u_{Lr})(\overline{\nu^c_s}\sigma^{\mu\nu}\nu_t)$	



NuDoBe pipeline

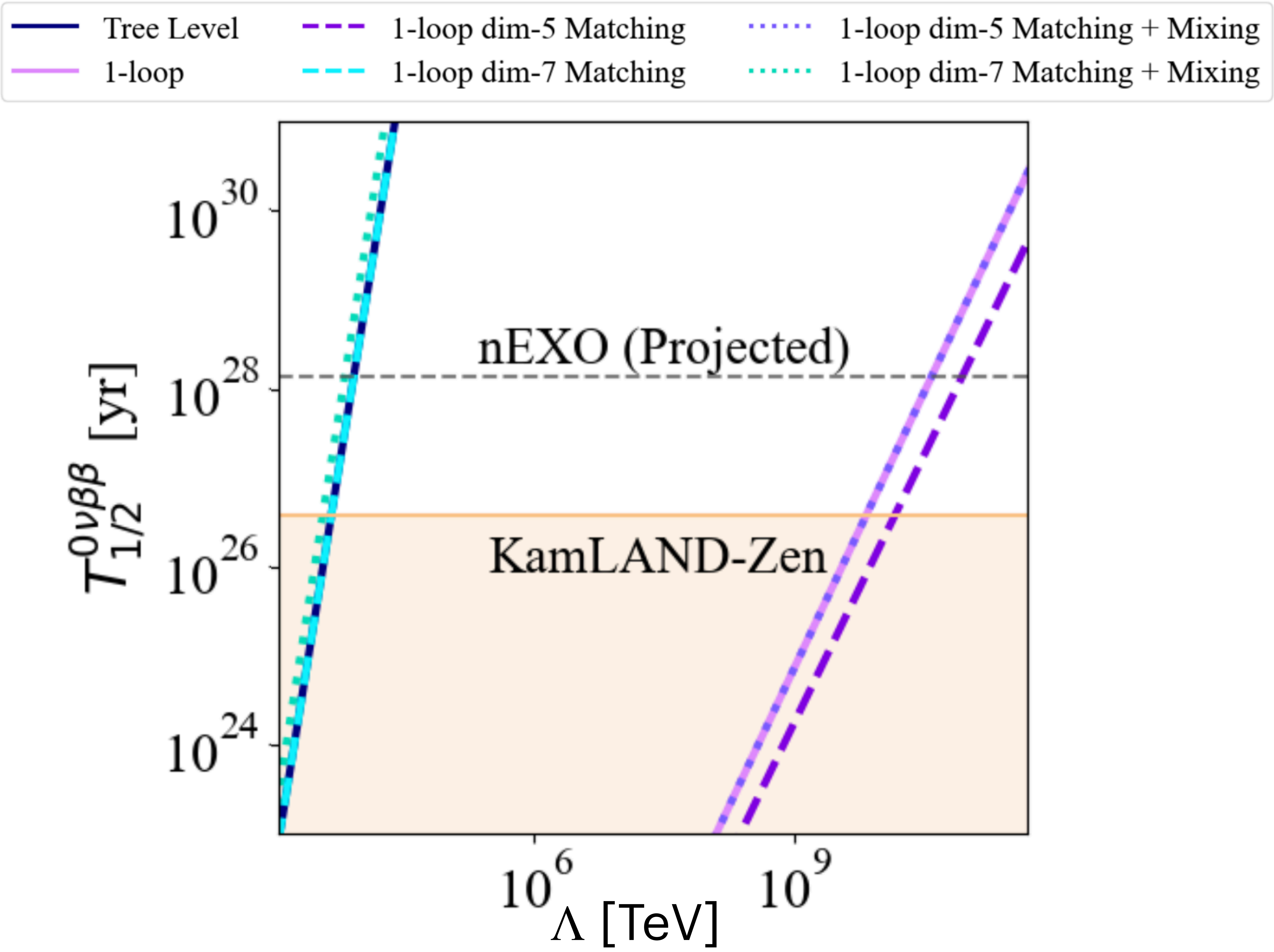


Model example $\mathcal{O}_{LH}^{(7)}$

[Babu 09']

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

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



Model example: non-trivial matching

[Aoki et al. 20']

+ $U(1)'$ with charge q

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
χ	1	2	3/2
η	1	2	1/2
Σ'	1	3	1

$$\mathscr{L}_{UV} \subset y_1 \overline{L}\Sigma'\tilde{\chi} + y_2\overline{\hat{L}^C}\Sigma'\tilde{\eta} + \kappa(\chi^\dagger H)(\tilde{\eta}^\dagger H)$$